ipcc

INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Impacts, Adaptation and Vulnerability

Summary for Policymakers

WGII

Working Group II contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

Summary for Policymakers

Drafting Authors: Hans-O. Pörtner (Germany), Debra C. Roberts (South Africa), Helen Adams (United Kingdom), Carolina Adler (Switzerland/Chile/Australia), Paulina Aldunce (Chile), Elham Ali (Egypt), Rawshan Ara Begum (Malaysia/Australia/Bangladesh), Richard Betts (United Kingdom), Rachel Bezner Kerr (Canada/USA), Robbert Biesbroek (The Netherlands), Joern Birkmann (Germany), Kathryn Bowen (Australia), Edwin Castellanos (Guatemala), Gueladio Cissé (Mauritania/Switzerland/France), Andrew Constable (Australia), Wolfgang Cramer (France), David Dodman (Jamaica/United Kingdom), Siri H. Eriksen (Norway), Andreas Fischlin (Switzerland), Matthias Garschagen (Germany), Bruce Glavovic (New Zealand/South Africa), Elisabeth Gilmore (USA/Canada), Marjolijn Haasnoot (The Netherlands), Sherilee Harper (Canada), Toshihiro Hasegawa (Japan), Bronwyn Hayward (New Zealand), Yukiko Hirabayashi (Japan), Mark Howden (Australia), Kanungwe Kalaba (Zambia), Wolfgang Kiessling (Germany), Rodel Lasco (Philippines), Judy Lawrence (New Zealand), Maria Fernanda Lemos (Brazil), Robert Lempert (USA), Debora Ley (Mexico/Guatemala), Tabea Lissner (Germany), Salvador Lluch-Cota (Mexico), Sina Loeschke (Germany), Simone Lucatello (Mexico), Yong Luo (China), Brendan Mackey (Australia), Shobha Maharaj (Germany/Trinidad and Tobago), Carlos Mendez (Venezuela), Katja Mintenbeck (Germany), Vincent Möller (Germany), Mariana Moncassim Vale (Brazil), Mike D Morecroft (United Kingdom), Aditi Mukherji (India), Michelle Mycoo (Trinidad and Tobago), Tero Mustonen (Finland), Johanna Nalau (Australia/Finland), Andrew Okem (SouthAfrica/Nigeria), Jean Pierre Ometto (Brazil), Camille Parmesan (France/USA/United Kingdom), Mark Pelling (United Kingdom), Patricia Pinho (Brazil), Elvira Poloczanska (United Kingdom/Australia), Marie-Fanny Racault (United Kingdom/France), Diana Reckien (The Netherlands/Germany), Joy Pereira (Malaysia), Aromar Revi (India), Steven Rose (USA), Roberto Sanchez-Rodriguez (Mexico), E. Lisa F. Schipper (Sweden/United Kingdom), Daniela Schmidt (United Kingdom/Germany), David Schoeman (Australia), Rajib Shaw (Japan), Chandni Singh (India), William Solecki (USA), Lindsay Stringer (United Kingdom), Adelle Thomas (Bahamas), Edmond Totin (Benin), Christopher Trisos (South Africa), Maarten van Aalst (The Netherlands), David Viner (United Kingdom), Morgan Wairiu (Solomon Islands), Rachel Warren (United Kingdom), Pius Yanda (Tanzania), Zelina Zaiton Ibrahim (Malaysia)

Drafting Contributing Authors: Rita Adrian (Germany), Marlies Craig (South Africa), Frode Degvold (Norway), Kristie L. Ebi (USA), Katja Frieler (Germany), Ali Jamshed (Germany/Pakistan), Joanna McMillan (German/Australia), Reinhard Mechler (Austria), Mark New (South Africa), Nick Simpson (South Africa/Zimbabwe), Nicola Stevens (South Africa)

Visual Conception and Information Design: Andrés Alegría (Germany/Honduras), Stefanie Langsdorf (Germany)

Date: 27 February 2022 06:00 UTC

Table of Contents

SPM.A: Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group II (WGII) contribution to the Sixth Assessment Report (AR6) of the IPCC[1]. The report builds on the WGII contribution to the Fifth Assessment Report (AR5) of the IPCC, three Special Reports[2], and the Working Group I (WGI) contribution to the AR6 cycle.

This report recognizes the interdependence of climate, ecosystems and biodiversity[3], and human societies (Figure SPM.1) and integrates knowledge more strongly across the natural, ecological, social and economic sciences than earlier IPCC assessments. The assessment of climate change impacts and risks as well as adaptation is set against concurrently unfolding non-climatic global trends e.g., biodiversity loss, overall unsustainable consumption of natural resources, land and ecosystem degradation, rapid urbanisation, human demographic shifts, social and economic inequalities and a pandemic.

The scientific evidence for each key finding is found in the 18 chapters of the underlying report and in the 7 cross-chapter papers as well as the integrated synthesis presented in the Technical Summary (hereafter TS) and referred to in curly brackets {}. Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language[4]. The WGII Global to Regional Atlas (Annex I) facilitates exploration of key synthesis findings across the WGII regions.

---

[1] Decision IPCC/XLVI-3, The assessment covers scientific literature accepted for publication by 1 September 2021.

[2] The three Special Reports are: 'Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5)'; 'Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL)'; 'IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)'

[3] Biodiversity: Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.

[4] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99-100% probability, very likely 90-100%, likely 66-100%, as likely as not 33-66%, unlikely 0-33%, very unlikely 0-10%, exceptionally unlikely 0-1%. Assessed likelihood is typeset in italics, e.g., *very likely*. This is consistent with AR5 and the other AR6 Reports.

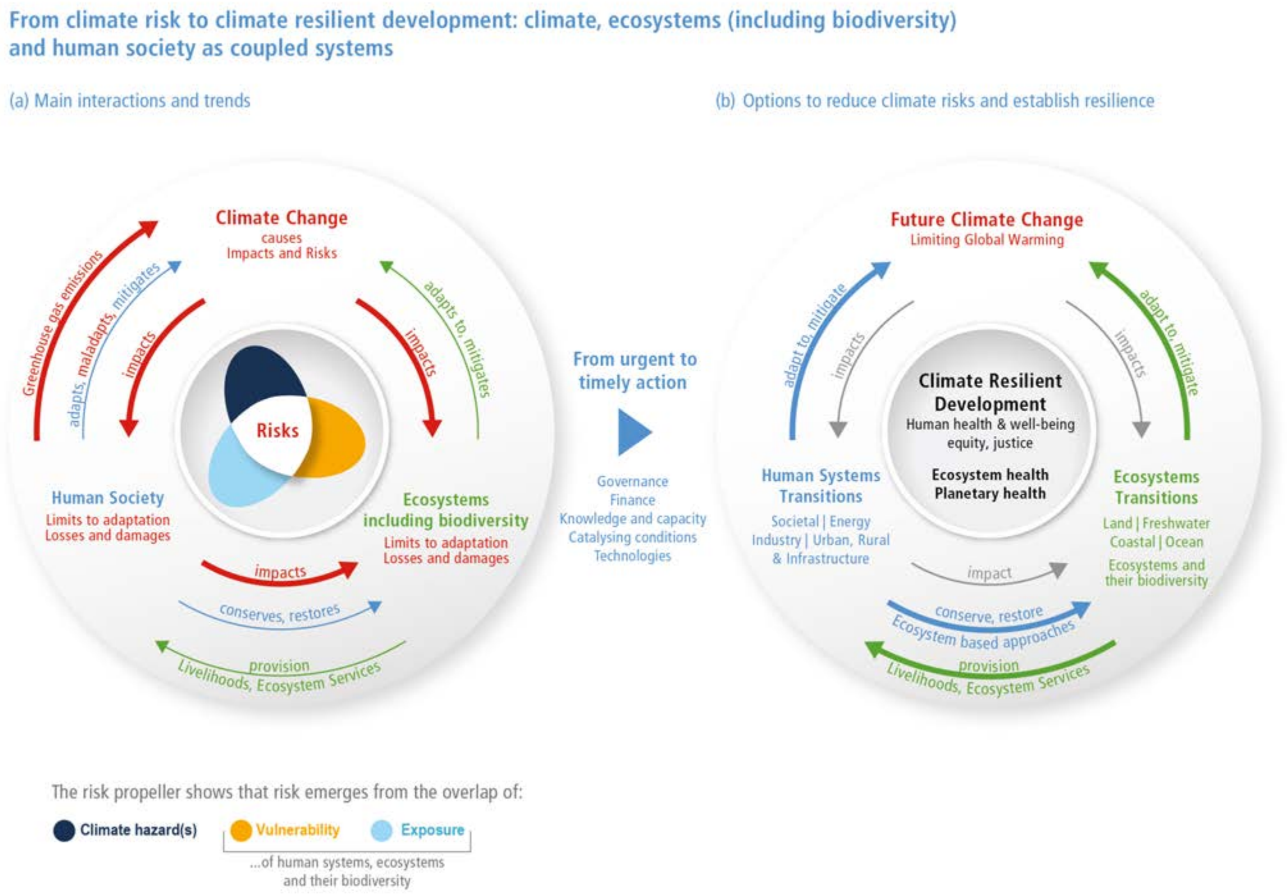


Figure SPM.1: This report has a strong focus on the interactions among the coupled systems climate, ecosystems (including their biodiversity) and human society. These interactions are the basis of emerging risks from climate change, ecosystem degradation and biodiversity loss and, at the same time, offer opportunities for the future. (a) Human society causes climate change. Climate change, through hazards, exposure and vulnerability generates impacts and risks that can surpass limits to adaptation and result in losses and damages. Human society can adapt to, maladapt and mitigate climate change, ecosystems can adapt and mitigate within limits. Ecosystems and their biodiversity provision livelihoods and ecosystem services. Human society impacts ecosystems and can restore and conserve them. (b) Meeting the objectives of climate resilient development thereby supporting human, ecosystem and planetary health, as well as human well-being, requires society and ecosystems to move over (transition) to a more resilient state. The recognition of climate risks can strengthen adaptation and mitigation actions and transitions that reduce risks. Taking action is enabled by governance, finance, knowledge and capacity building, technology and catalysing conditions. Transformation entails system transitions strengthening the resilience of ecosystems and society (Section D). In a) arrow colours represent principle human society interactions (blue), ecosystem (including biodiversity) interactions (green) and the impacts of climate change and human activities, including losses and damages, under continued climate change (red). In b) arrow colours represent human system interactions (blue), ecosystem (including biodiversity) interactions (green) and reduced impacts from climate change and human activities (grey). {1.2, Figure 1.2, Figure TS.1}

The concept of risk is central to all three AR6 Working Groups. A risk framing and the concepts of adaptation, vulnerability, exposure, resilience, equity and justice, and transformation provide alternative, overlapping, complementary, and widely used entry points to the literature assessed in this WGII report.

Across all three AR6 working groups, **risk**[5] provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors and communities; and how to best reduce adverse

[5] Risk is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems

consequences for current and future generations. In the context of climate change, risk can arise from the dynamic interactions among climate-related **hazards**[6] (see Working Group I), the **exposure**[7] and **vulnerability**[8] of affected human and ecological systems. The risk that can be introduced by human responses to climate change is a new aspect considered in the risk concept. This report identifies 127 key risks[9]. {1.3, 16.5}

The vulnerability of exposed human and natural systems is a component of risk, but also, independently, an important focus in the literature. Approaches to analysing and assessing vulnerability have evolved since previous IPCC assessments. Vulnerability is widely understood to differ within communities and across societies, regions and countries, also changing through time.

Adaptation[10] plays a key role in reducing exposure and vulnerability to climate change. Adaptation in ecological systems includes autonomous adjustments through ecological and evolutionary processes. In human systems, adaptation can be anticipatory or reactive, as well as incremental and/ or transformational. The latter changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts. Adaptation is subject to hard and soft limits[11].

Resilience[12] in the literature has a wide range of meanings. Adaptation is often organized around resilience as bouncing back and returning to a previous state after a disturbance. More broadly the term describes not just the ability to maintain essential function, identity and structure, but also the capacity for transformation.

This report recognises the value of diverse forms of **knowledge** such as scientific, as well as Indigenous knowledge and local knowledge in understanding and evaluating climate adaptation processes and actions to reduce risks from human-induced climate change. AR6 highlights adaptation solutions which are effective, **feasible**[13], and conform to principles of **justice**[14]. The term climate justice, while used in different ways in different contexts by different communities, generally includes three principles: *distributive justice* which refers to the allocation of burdens and benefits among individuals, nations and generations; *procedural justice* which refers to who decides and participates in decision-making; and *recognition* which entails basic respect and robust engagement with and fair consideration of diverse cultures and perspectives.

---

[6] Hazard is defined as the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. Physical climate conditions that may be associated with hazards are assessed in Working Group I as climatic impact-drivers.

[7] Exposure is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected.

[8] Vulnerability in this report is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

[9] Key risks have potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate related hazards with vulnerabilities of societies and systems exposed.

[10] Adaptation is defined, in human systems, as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate this.

[11] Adaptation Limits: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

- Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks.
- Soft adaptation limit - Options may exist but are currently not available to avoid intolerable risks through adaptive action.

[12] Resilience in this report is defined as the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation.

[13] Feasibility refers to the potential for an adaptation option to be implemented.

[14] Justice is concerned with setting out the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society. *Social justice* comprises just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity and support according to principles of justice and fairness. *Climate justice* comprises justice that links development and human rights to achieve a rights-based approach to addressing climate change.

Effectiveness refers to the extent to which an action reduces vulnerability and climate-related risk, increases resilience, and avoids maladaptation[15].

This report has a particular focus on transformation[16] and system transitions in energy; land, ocean, coastal and freshwater ecosystems; urban, rural and infrastructure; and industry and society. These transitions make possible the adaptation required for high levels of human health and wellbeing, economic and social resilience, ecosystem health[17], and planetary health[18] (Figure SPM.1). These system transitions are also important for achieving the low global warming levels (WGIII) that would avoid many limits to adaptation[11]. The report also assesses economic and non-economic losses and damages[19]. This report labels the process of implementing mitigation and adaptation together in support of sustainable development for all as climate resilient development[20].

[START BOX SPM.1 HERE]

Box SPM.1: AR6 Common Climate Dimensions, Global Warming Levels and Reference Periods

Assessments of climate risks consider possible future climate change, societal development and responses. This report assesses literature including that based on climate model simulations that are part of the fifth and sixth Coupled Model Intercomparison Project phase (CMIP5, CMIP6) of the World Climate Research Programme. Future projections are driven by emissions and/or concentrations from illustrative Representative Concentration Pathways (RCPs)[21] and Shared Socio-economic Pathways (SSPs)[22] scenarios, respectively[23]. Climate impacts literature is based primarily on climate projections assessed in AR5 or earlier, or assumed global warming levels, though some recent impacts literature uses newer projections based on the CMIP6 exercise. Given differences in the impacts literature regarding socioeconomic details and assumptions, WGII chapters contextualize impacts with respect to exposure, vulnerability and adaptation as appropriate for their literature, this includes assessments regarding sustainable development and climate resilient development. There are many emissions and socioeconomic pathways that are consistent with a given global warming outcome. These represent a broad range of possibilities as available in the literature assessed that affect future climate change exposure and vulnerability. Where available, WGII also assesses literature that is based on an integrative SSP-RCP framework where climate projections obtained under the RCP scenarios are analysed against the backdrop of various illustrative SSPs[22]. The WGII assessment combines multiple lines of evidence including impacts modelling driven by climate projections, observations, and process understanding. {1.2, 16.5, 18.2, CCB CLIMATE, WGI SPM.C, WGI Box SPM.1, WGI 1.6, WGI Ch.12, AR5 WGI}

---

[15] Maladaptation refers to actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.

[16] Transformation refers to a change in the fundamental attributes of natural and human systems.

[17] Ecosystem health: a metaphor used to describe the condition of an ecosystem, by analogy with human health. Note that there is no universally accepted benchmark for a healthy ecosystem. Rather, the apparent health status of an ecosystem is judged on the ecosystem's resilience to change, with details depending upon which metrics (such as species richness and abundance) are employed in judging it and which societal aspirations are driving the assessment.

[18] Planetary health: a concept based on the understanding that human health and human civilisation depend on ecosystem health and the wise stewardship of ecosystems.

[19] In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic.

[20] In the WGII report, climate resilient development refers to the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all.

[21] RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing (in watts per square meter, or $W m^{-2}$) resulting from the scenario in the year 2100.

[22] SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway describing the socio-economic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square meter, or $W m^{-2}$) resulting from the scenario in the year 2100.

[23] IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed.

A common set of reference years and time periods are adopted for assessing climate change and its impacts and risks: the reference period 1850–1900 approximates pre-industrial global surface temperature, and three future reference periods cover the near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100). {CCB CLIMATE}

Common levels of global warming relative to 1850-1900 are used to contextualize and facilitate analysis, synthesis and communication of assessed past, present and future climate change impacts and risks considering multiple lines of evidence. Robust geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached. {16.5, CCB CLIMATE, WGI 4.2, WGI CCB11.1, WGI Box SPM.1}

WGI assessed increase in global surface temperature is 1.09 [0.95 to 1.20][24] °C in 2011-2020 above 1850-1900. The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C).[25] Considering all five illustrative scenarios assessed by WGI, there is at least a greater than 50% likelihood that global warming will reach or exceed 1.5°C in the near-term, even for the very low greenhouse gas emissions scenario[26]. {WGI CCB 2.3, WGI SPM A1.2, WGI SPM B1.3, WGI Table SPM.1}

[END BOX SPM.1 HERE]

SPM.B: Observed and Projected Impacts and Risks

Since AR5, the knowledge base on observed and projected impacts and risks generated by climate hazards, exposure and vulnerability has increased with impacts attributed to climate change and key risks identified across the report. Impacts and risks are expressed in terms of their damages, harms, economic, and non-economic losses. Risks from observed vulnerabilities and responses to climate change are highlighted. Risks are projected for the near-term (2021-2040), the mid (2041-2060) and long term (2081-2100), at different global warming levels and for pathways that overshoot 1.5°C global warming level for multiple decades[27]. Complex risks result from multiple climate hazards occurring concurrently, and from multiple risks interacting, compounding overall risk and resulting in risks transmitting through interconnected systems and across regions.

Observed Impacts from Climate Change

SPM.B.1 Human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability. Some development and adaptation efforts have reduced vulnerability. Across sectors and regions the most vulnerable people and systems are observed to be disproportionately affected. The rise in weather

[24] In the WGI report, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

[25] Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

[26] Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high greenhouse gas emissions scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high greenhouse gas emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high greenhouse gas emissions scenarios (SSP2-4.5 and SSP3-7.0), *more likely than not* to be exceeded under the low greenhouse gas emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low greenhouse gas emissions scenario (SSP1-1.9). Furthermore, for the very low greenhouse gas emissions scenario (SSP1-1.9), it is *more likely than not* that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.

[27] Overshoot: In this report, pathways that first exceed a specified global warming level (usually 1.5°C, by more than 0.1°C), and then return to or below that level again before the end of a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot is also characterized. The overshoot duration can vary from at least one decade up to several decades.

and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt. (*high confidence*) (Figure SPM.2) {1.3, 2.3, 2.4, 2.6, 3.3, 3.4, 3.5, 4.2, 4.3, 5.2, 5.12, 6.2, 7.2, 8.2, 9.6, 9.8, 9.10, 9.11, 10.4, 11.3, 12.3, 12.4, 13.10, 14.4, 14.5, 15.3, 16.2, CCP1.2, CCP3.2, CCP4.1, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB DISASTER, CCB MIGRATE, Figure TS.5, TS B1

SPM.B.1.1 Widespread, pervasive impacts to ecosystems, people, settlements, and infrastructure have resulted from observed increases in the frequency and intensity of climate and weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, drought and fire weather (*high confidence*). Increasingly since AR5, these observed impacts have been attributed[28] to human-induced climate change particularly through increased frequency and severity of extreme events. These include increased heat-related human mortality (*medium confidence*), warm-water coral bleaching and mortality (*high confidence*), and increased drought related tree mortality (*high confidence*). Observed increases in areas burned by wildfires have been attributed to human-induced climate change in some regions (*medium* to *high confidence*). Adverse impacts from tropical cyclones, with related losses and damages[19], have increased due to sea level rise and the increase in heavy precipitation (*medium confidence*). Impacts in natural and human systems from slow-onset processes[29] such as ocean acidification, sea level rise or regional decreases in precipitation have also been attributed to human induced climate change (*high confidence*). {1.3, 2.3, 2.4, 2.5, 3.2, 3.4, 3.5, 3.6, 4.2, 5.2, 5.4, 5.6, 5.12, 7.2, 9.6, 9.8, 9.7, 9.8, 9.11, 11.3, Box 11.1, Box 11.2, Table 11.9, 12.3, 12.4, 13.3, 13.5, 13.10, 14.2,14.5, 15.7, 15.8, 16.2, Box CCP5.1, CCP1.2, CCP2.2, CCP7.3, CCB EXTREME, CCB ILLNESS, CCB DISASTER, WG1 9, WGI 11.3-11.8, WGI SPM.3, SROCC Ch. 4}

SPM.B.1.2 Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater and coastal and open ocean marine ecosystems (*high confidence*). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (*high confidence*). Widespread deterioration of ecosystem structure and function, resilience and natural adaptive capacity, as well as shifts in seasonal timing have occurred due to climate change (*high confidence*), with adverse socioeconomic consequences (*high confidence*). Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations (*very high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*), as well as mass mortality events on land and in the ocean (*very high confidence*) and loss of kelp forests (*high confidence*). Some losses are already irreversible, such as the first species extinctions driven by climate change (*medium confidence*). Other impacts are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). (Figure SPM.2a). {2.3, 2.4, 3.4, 3.5, 4.2, 4.3, 4.5, 9.6, 10.4, 11.3, 12.3, 12.8, 13.3, 13.4, 13.10, 14.4, 14.5, 14.6, 15.3, 16.2, CCP1.2; CCP3.2, CCP4.1, CCP5.2, CCP6.1, CCP6.2, CCP7.2, CCP7.3, CCP5.2, Figure CCP5.4, CCB PALEO, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB MOVING PLATE, Figure TS.5, TS B1, SROCC 2.3}

---

[28] Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence. {Annex II Glossary, CWGB ATTRIB}

[29] Impacts of climate change are caused by slow onset and extreme events. Slow onset events are described among the climatic-impact drivers of the WGI AR6 and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization (https://interactive-atlas.ipcc.ch).

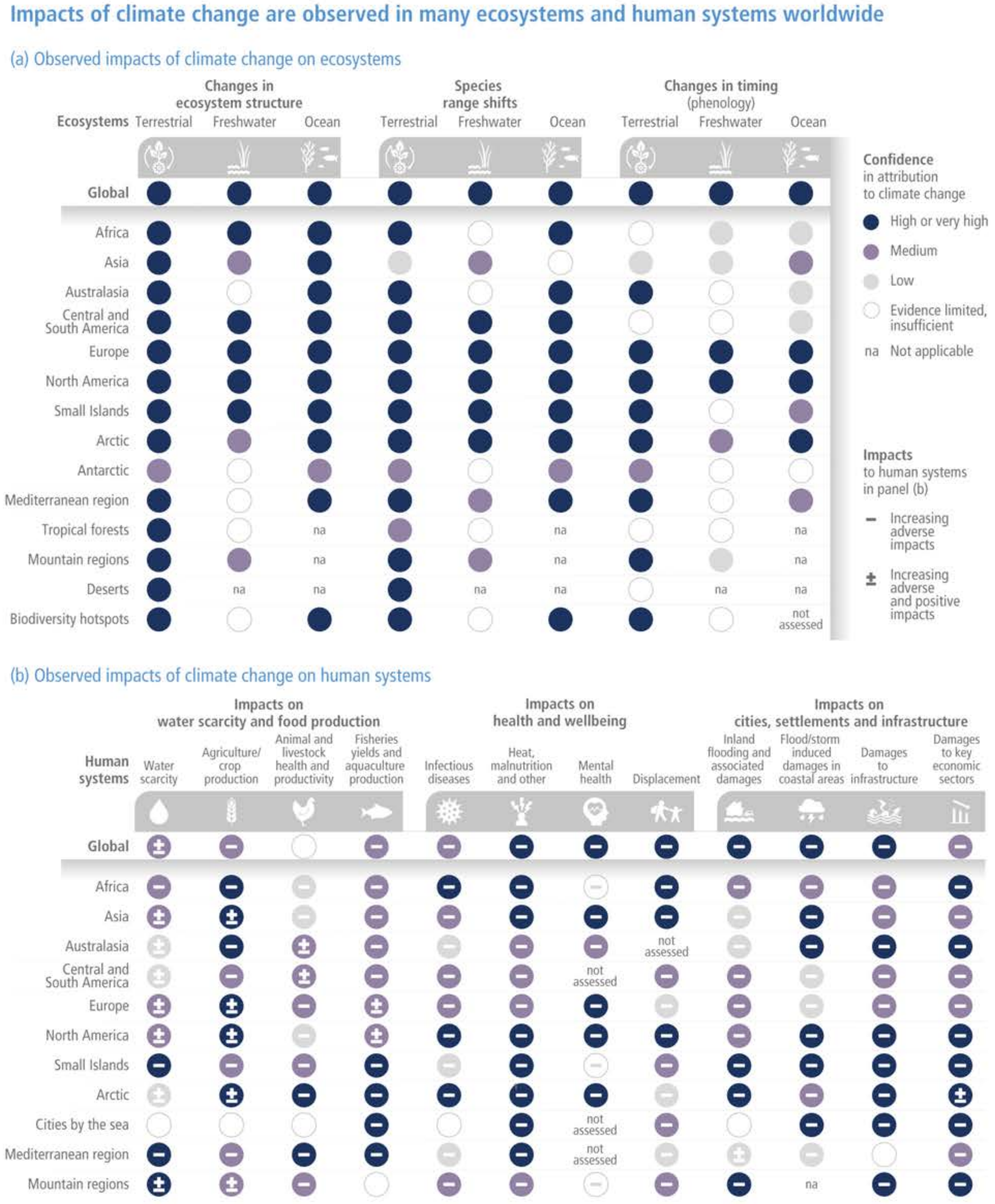


Figure SPM.2: Observed global and regional impacts on ecosystems and human systems attributed to climate change. Confidence levels reflect uncertainty in attribution of the observed impact to climate change. Global assessments focus on large studies, multi-species, meta-analyses and large reviews. For that reason they can be assessed with higher confidence than regional studies, which may often rely on smaller studies that have more limited data. Regional assessments consider evidence on impacts across an entire region and do not focus on any country in particular. (a) Climate change has already altered terrestrial, freshwater and ocean ecosystems at global scale, with multiple impacts evident at regional and local scales where there is sufficient literature to make an assessment. Impacts are evident on ecosystem structure, species geographic ranges and timing of seasonal life cycles (phenology) (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.1). (b) Climate change has already had diverse adverse impacts on human systems, including on water security and food production, health and well-being, and cities, settlements and infrastructure. The + and – symbols indicate the direction of observed impacts, with a – denoting an increasing adverse impact and a ± denoting that, within a region or globally, both adverse and positive impacts have been observed (e.g., adverse impacts in one area or food item may occur with positive impacts in another area or food item). Globally, '–' denotes an overall adverse impact; 'Water scarcity' considers, e.g., water availability in general, groundwater, water quality, demand for water, drought in cities. Impacts on food production were assessed by excluding non-climatic drivers of production increases; Global assessment for agricultural production is based on the impacts on global aggregated production; 'Reduced animal and livestock health and productivity' considers, e.g., heat stress, diseases, productivity, mortality; 'Reduced fisheries yields and aquaculture production' includes marine and freshwater fisheries/production; 'Infectious diseases' include, e.g., water-borne and vector-borne diseases; 'Heat, malnutrition and other' considers, e.g., human heat-related morbidity and mortality, labour productivity, harm from wildfire, nutritional deficiencies; 'Mental health' includes impacts from extreme weather events, cumulative events, and vicarious or anticipatory events; 'Displacement' assessments refer to evidence of displacement attributable to climate and weather extremes; 'Inland flooding and associated damages' considers, e.g., river overflows, heavy rain, glacier outbursts, urban flooding; 'Flood/storm induced damages in coastal areas' include damages due to, e.g., cyclones, sea level rise, storm surges. Damages by key economic sectors are observed impacts related to an attributable mean or extreme climate hazard or directly attributed. Key economic sectors include standard classifications and sectors of importance to regions (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.2).

SPM.B.1.3 Climate change including increases in frequency and intensity of extremes have reduced food and water security, hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years globally (*medium confidence*), related negative impacts were mainly in mid- and low latitude regions but positive impacts occurred in some high latitude regions (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from shellfish aquaculture and fisheries in some oceanic regions (*high confidence*). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity[30] and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, Small Islands and the Arctic (*high confidence*). Jointly, sudden losses of food production and access to food compounded by decreased diet diversity have increased malnutrition in many communities (*high confidence*), especially for Indigenous Peoples, small-scale food producers and low-income households (*high confidence*), with children, elderly people and pregnant women particularly impacted (*high confidence*). Roughly half of the world's population currently experience severe water scarcity for at least some part of the year due to climatic and non-climatic drivers (*medium confidence*). (Figure SPM.2b) {3.5, Box 4.1, 4.3, 4.4, 5.2, 5.4, 5.8, 5.9, 5.12, 7.1, 7.2, 9.8, 10.4, 11.3, 12.3, 13.5, 14.4, 14.5, 15.3, 16.2, CCP5.2, CCP6.2}

SPM.B.1.4 Climate change has adversely affected physical health of people globally (*very high confidence)* and mental health of people in the assessed regions (*very high confidence*). Climate change impacts on health are mediated through natural and human systems, including economic and social conditions and disruptions (*high confidence*). In all regions extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases has increased (*very high confidence*). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (*high confidence*). Animal and human diseases, including zoonoses, are emerging in new areas (*high confidence*). Water and food-borne disease risks have increased regionally from climate-sensitive aquatic pathogens, including *Vibrio* spp. (*high confidence*), and from toxic substances from harmful freshwater cyanobacteria (*medium confidence*). Although diarrheal diseases have decreased globally, higher temperatures, increased rain and flooding have increased the occurrence of diarrheal diseases, including cholera (*very high confidence*) and other gastrointestinal infections (*high confidence*). In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from weather and climate extreme events (*very high confidence*), and loss of livelihoods and culture (*high confidence*). Increased exposure to wildfire smoke, atmospheric dust, and aeroallergens have been associated with climate-sensitive cardiovascular and respiratory distress (*high confidence*). Health services have been disrupted by extreme events such as floods (*high confidence*). {4.3, 5.12, 7.2, Box 7.3, 8.2, 8.3, Figure 8.10,

[30] Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and used to assess the need for humanitarian action (IPC Global Partners, 2019).

Box 8.6, 9.10, Figure 9.33, Figure 9.34, 10.4, 11.3, 12.3, 13.7, 14.4, 14.5, Figure 14.8, 15.3, 16.2, Table CCP5.1, CCP5.2.5, CCP6.2, Figure CCP6.3, Table CCB ILLNESS.1}

SPM.B.1.5 In urban settings, observed climate change has caused impacts on human health, livelihoods and key infrastructure (*high confidence*). Multiple climate and non-climate hazards impact cities, settlements and infrastructure and sometimes coincide, magnifying damage (*high confidence*). Hot extremes including heatwaves have intensified in cities (*high confidence*), where they have also aggravated air pollution events (*medium confidence*) and limited functioning of key infrastructure (*high confidence*). Observed impacts are concentrated amongst the economically and socially marginalized urban residents, e.g., in informal settlements (*high confidence*). Infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events, with resulting economic losses, disruptions of services and impacts to wellbeing (*high confidence*). {4.3, 6.2, 7.1, 7.2, 9.9, 10.4, 11.3, 12.3, 13.6, 14.5, 15.3, CCP2.2, CCP4.2, CCP5.2}

SPM.B.1.6 Overall adverse economic impacts attributable to climate change, including slow-onset and extreme weather events, have been increasingly identified (*medium confidence*). Some positive economic effects have been identified in regions that have benefited from lower energy demand as well as comparative advantages in agricultural markets and tourism (*high confidence*). Economic damages from climate change have been detected in climate-exposed sectors, with regional effects to agriculture, forestry, fishery, energy, and tourism (*high confidence*), and through outdoor labour productivity (*high confidence*). Some extreme weather events, such as tropical cyclones, have reduced economic growth in the short-term (*high confidence*). Non-climatic factors including some patterns of settlement, and siting of infrastructure have contributed to the exposure of more assets to extreme climate hazards increasing the magnitude of the losses (*high confidence*). Individual livelihoods have been affected through changes in agricultural productivity, impacts on human health and food security, destruction of homes and infrastructure, and loss of property and income, with adverse effects on gender and social equity (*high confidence*). {3.5, 4.2, 5.12, 6.2, 7.2, 8.2, 9.6, 10.4, 13.10, 14.5, Box 14.6, 16.2, Table 16.5, 18.3, CCP6.2, CCB GENDER, CWGB ECONOMICS}

SPM.B.1.7 Climate change is contributing to humanitarian crises where climate hazards interact with high vulnerability (*high confidence*). Climate and weather extremes are increasingly driving displacement in all regions (*high confidence*), with small island states disproportionately affected (*high confidence*). Flood and drought-related acute food insecurity and malnutrition have increased in Africa (*high confidence*) and Central and South America (*high confidence*). While non-climatic factors are the dominant drivers of existing intrastate violent conflicts, in some assessed regions extreme weather and climate events have had a small, adverse impact on their length, severity or frequency, but the statistical association is weak (*medium confidence*). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (*medium confidence*). {4.2, 4.3, 5.4, 7.2, 9.8, Box 9.9, Box 10.4, 12.3, 12.5, CCB MIGRATE, CCB DISASTER, 16.2}

Vulnerability and Exposure of Ecosystems and People

SPM.B.2 Vulnerability of ecosystems and people to climate change differs substantially among and within regions (*very high confidence*), driven by patterns of intersecting socio-economic development, unsustainable ocean and land use, inequity, marginalization, historical and ongoing patterns of inequity such as colonialism, and governance[31] (*high confidence*). Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*). A high proportion of species is vulnerable to climate change (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Current unsustainable development patterns are increasing exposure of ecosystems and people to climate hazards (*high confidence*). {2.3, 2.4, 3.5, 4.3, 6.2, 8.2, 8.3, 9.4, 9.7, 10.4, 12.3, 14.5, 15.3, CCP5.2, CCP6.2, CCP7.3, CCP7.4, CCB GENDER}

[31] Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local.

SPM.B.2.1 Since AR5 there is increasing evidence that degradation and destruction of ecosystems by humans increases the vulnerability of people (*high confidence*). Unsustainable land-use and land cover change, unsustainable use of natural resources, deforestation, loss of biodiversity, pollution, and their interactions, adversely affect the capacities of ecosystems, societies, communities and individuals to adapt to climate change (*high confidence*). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (*high confidence*). {2.3, 2.5, 2.6, 3.5, 3.6, 4.2, 4.3, 4.6, 5.1, 5.4, 5.5, 5.7, 5.8, 7.2, 8.1, 8.2, 8.3, 8.4, 8.5, 9.6, 10.4, 11.3, 12.2, 12.5. 13.8, 14.4, 14.5, 15.3, CCP1.2, CCP1.3, CCP2.2, CCP3, CCP4.3, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCP7.4, CCB ILLNESS, CCB MOVING PLATE, CCB SLR}

SPM.B.2.2 Non-climatic human-induced factors exacerbate current ecosystem vulnerability to climate change (*very high confidence*). Globally, and even within protected areas, unsustainable use of natural resources, habitat fragmentation, and ecosystem damage by pollutants increase ecosystem vulnerability to climate change (*high confidence*). Globally, less than 15% of the land, 21% of the freshwater and 8% of the ocean are protected areas. In most protected areas, there is insufficient stewardship to contribute to reducing damage from, or increasing resilience to, climate change (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.6, 4.2, 4.3, 5.8, 9.6, 11.3, 12.3, 13.3, 13.4, 14.5, 15.3, CCP1.2 Figure CCP1.15, CCP2.1, CCP2.2, CCP4.2, CCP5.2, CCP 6.2, CCP7.2, CCP7.3, CCB NATURAL}

SPM.B.2.3 Future vulnerability of ecosystems to climate change will be strongly influenced by the past, present and future development of human society, including from overall unsustainable consumption and production, and increasing demographic pressures, as well as persistent unsustainable use and management of land, ocean, and water (*high confidence*). Projected climate change, combined with non-climatic drivers, will cause loss and degradation of much of the world's forests (*high confidence*), coral reefs and low-lying coastal wetlands (*very high confidence*). While agricultural development contributes to food security, unsustainable agricultural expansion, driven in part by unbalanced diets[32], increases ecosystem and human vulnerability and leads to competition for land and/or water resources (*high confidence*). {2.2, 2.3, 2.4, 2.6, 3.4, 3.5, 3.6, 4.3, 4.5, 5.6, 5.12, 5.13, 7.2, 12.3, 13.3, 13.4, 13.10, 14.5, CCP1.2, CCP2.2, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB NATURAL, CCB HEALTH}

SPM.B.2.4 Regions and people with considerable development constraints have high vulnerability to climatic hazards (*high confidence*). Global hotspots of high human vulnerability are found particularly in West-, Central- and East Africa, South Asia, Central and South America, Small Island Developing States and the Arctic (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Between 2010-2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (*high confidence*). Vulnerability at different spatial levels is exacerbated by inequity and marginalization linked to gender, ethnicity, low income or combinations thereof (*high confidence*), especially for many Indigenous Peoples and local communities (*high confidence*). Present development challenges causing high vulnerability are influenced by historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities (*high confidence*). {4.2, 5.12, 6.2, 6.4, 7.1, 7.2, Box 7.1, 8.2, 8.3, Box 8.4, Figure 8.6, Box 9.1, 9.4, 9.7, 9.9, 10.3, 10.4, 10.6, 12.3, 12.5, Box 13.2, 14.4, 15.3, 15.6, 16.2, CCP6.2, CCP7.4}

SPM.B.2.5 Future human vulnerability will continue to concentrate where the capacities of local, municipal and national governments, communities and the private sector are least able to provide infrastructures and basic services (*high confidence*). Under the global trend of urbanization, human vulnerability will also concentrate in informal settlements and rapidly growing smaller settlements (*high confidence*). In rural areas vulnerability will be heightened by compounding processes including high emigration, reduced habitability and high reliance on climate-sensitive livelihoods (*high confidence*). Key infrastructure systems including sanitation, water, health, transport, communications and energy will be increasingly vulnerable if design

[32] Balanced diets feature plant-based foods, such as those based on coarse grains, legumes fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable and low-greenhouse gas emissions systems, as described in SRCCL.

standards do not account for changing climate conditions (*high confidence*). Vulnerability will also rapidly rise in low-lying Small Island Developing States and atolls in the context of sea level rise and in some mountain regions, already characterised by high vulnerability due to high dependence on climate-sensitive livelihoods, rising population displacement, the accelerating loss of ecosystem services and limited adaptive capacities (*high confidence*). Future exposure to climatic hazards is also increasing globally due to socio-economic development trends including migration, growing inequality and urbanization (*high confidence*). {4.5, 5.5, 6.2, 7.2, 8.3, 9.9, 9.11, 10.3, 10.4, 12.3, 12.5, 13.6, 14.5, 15.3, 15.4, 16.5, CCP2.3, CCP4.3, CCP5.2, CCP5.3, CCP5.4, CCP6.2, CCB MIGRATE}

Risks in the near term (2021-2040)

SPM.B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3, Box SPM.1) {WGI Table SPM.1, 16.4, 16.5, 16.6, CCP1.2, CCP5.3, CCB SLR, WGI SPM B1.3}

SPM.B.3.1 Near-term warming and increased frequency, severity and duration of extreme events will place many terrestrial, freshwater, coastal and marine ecosystems at high or very high risks of biodiversity loss (*medium to very high confidence*, depending on ecosystem). Near-term risks for biodiversity loss are moderate to high in forest ecosystems (*medium confidence*), kelp and seagrass ecosystems (*high* to *very high confidence*), and high to very high in Arctic sea-ice and terrestrial ecosystems (*high confidence*) and warm-water coral reefs (*very high confidence*). Continued and accelerating sea level rise will encroach on coastal settlements and infrastructure (*high confidence*) and commit low-lying coastal ecosystems to submergence and loss (*medium confidence*). If trends in urbanisation in exposed areas continue, this will exacerbate the impacts, with more challenges where energy, water and other services are constrained (*medium confidence*). The number of people at risk from climate change and associated loss of biodiversity will progressively increase (*medium confidence*). Violent conflict and, separately, migration patterns, in the near-term will be driven by socio-economic conditions and governance more than by climate change (*medium confidence*). (Figure SPM.3) {2.5, 3.4, 4.6, 6.2, 7.3, 8.7, 9.2, 9.9, 11.6, 12.5, 13.6, 13.10, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCP6.3, CCB SLR, CCB MIGRATE}

SPM.B.3.2 In the near term, climate-associated risks to natural and human systems depend more strongly on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios (*high confidence*). Regional differences exist, and risks are highest where species and people exist close to their upper thermal limits, along coastlines, in close association with ice or seasonal rivers (*high confidence*). Risks are also high where multiple non-climate drivers persist or where vulnerability is otherwise elevated (*high confidence*). Many of these risks are unavoidable in the near-term, irrespective of emission scenario (*high confidence*). Several risks can be moderated with adaptation (*high confidence*). (Figure SPM.3, Section C) {2.5, 3.3, 3.4, 4.5, 6.2, 7.1, 7.3, 8.2, 11.6, 12.4, 13.6, 13.7, 13.10, 14.5, 16.4, 16.5, CCP2.2, CCP4.3, CCP5.3, CCB SLR, WGI Table SPM.1}

SPM.B.3.3 Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3b) {16.5, 16.6, CCB SLR}

Mid to Long-term Risks (2041–2100)

SPM.B.4 Beyond 2040 and depending on the level of global warming, climate change will lead to numerous risks to natural and human systems (*high confidence*). For 127 identified key risks, assessed mid- and long-term impacts are up to multiple times higher than currently observed (*high confidence*). The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions, and projected adverse impacts and related losses and damages escalate with every increment of global warming (*very high confidence*). (Figure SPM.3) {2.5, 3.4, 4.4, 5.2, 6.2, 7.3, 8.4, 9.2, 10.2, 11.6, 12.4, 13.2, 13.3, 13.4, 13.5, 13.6, 13.7, 13.8, 14.6, 15.3, 16.5, 16.6, CCP1.2; CCP2.2, CCP3.3, CCP4.3, CCP5.3, CCP6.3, CCP7.3}

SPM.B.4.1 Biodiversity loss, and degradation, damages to and transformation of ecosystems are already key risks for every region due to past global warming and will continue to escalate with every increment of global warming (*very high confidence*). In terrestrial ecosystems, 3 to 14% of species assessed[33] will *likely* face very high risk of extinction[34] at global warming levels of 1.5°C, increasing up to 3 to 18% at 2°C, 3 to 29% at 3°C, 3 to 39% at 4°C, and 3 to 48% at 5°C. In ocean and coastal ecosystems, risk of biodiversity loss ranges between moderate and very high by 1.5°C global warming level and is moderate to very high by 2°C but with more ecosystems at high and very high risk (*high confidence*), and increases to high to very high across most ocean and coastal ecosystems by 3°C (*medium* to *high confidence*, depending on ecosystem). Very high extinction risk for endemic species in biodiversity hotspots is projected to at least double from 2% between 1.5°C and 2°C global warming levels and to increase at least tenfold if warming rises from 1.5°C to 3°C (*medium confidence*). (Figure SPM.3c, d, f) {2.4, 2.5, 3.4, 3.5,12.3, 12.5, Table 12.6, 13.4, 13.10, 16.4, 16.6, CCP1.2, Figure CCP1.6; Figure CCP1.7, CCP5.3, CCP6.3, CCB PALEO}

SPM.B.4.2 Risks in physical water availability and water-related hazards will continue to increase by the mid- to long-term in all assessed regions, with greater risk at higher global warming levels (*high confidence*). At approximately 2°C global warming, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20%, and global glacier mass loss of 18 ± 13% is projected to diminish water availability for agriculture, hydropower, and human settlements in the mid- to long-term, with these changes projected to double with 4°C global warming (*medium confidence*). In small islands, groundwater availability is threatened by climate change (*high confidence*). Changes to streamflow magnitude, timing and associated extremes are projected to adversely impact freshwater ecosystems in many watersheds by the mid- to long-term across all assessed scenarios (*medium confidence*). Projected increases in direct flood damages are higher by 1.4 to 2 times at 2°C and 2.5 to 3.9 times at 3°C compared to 1.5°C global warming without adaptation (*medium confidence*). At global warming of 4°C, approximately 10% of the global land area is projected to face increases in both extreme high and low river flows in the same location, with implications for planning for all water use sectors (*medium confidence*). Challenges for water management will be exacerbated in the near, mid and long term, depending on the magnitude, rate and regional details of future climate change and will be particularly challenging for regions with constrained resources for water management (*high confidence*). {2.3, Box 4.2, 4.4, 4.5, Figure 4.20, 15.3, CCB DISASTER, CCP5.3, SROCC 2.3}

SPM.B.4.3 Climate change will increasingly put pressure on food production and access, especially in vulnerable regions, undermining food security and nutrition (*high confidence*). Increases in frequency, intensity and severity of droughts, floods and heatwaves, and continued sea level rise will increase risks to food security (*high confidence*) in vulnerable regions from moderate to high between 1.5°C and 2°C global warming level, with no or low levels of adaptation (*medium confidence*). At 2°C or higher global warming level in the mid-term, food security risks due to climate change will be more severe, leading to malnutrition and micro-nutrient deficiencies, concentrated in Sub-Saharan Africa, South Asia, Central and South America and Small Islands (*high confidence)*. Global warming will progressively weaken soil health and ecosystem

[33] Numbers of species assessed are in the tens of thousands globally.

[34] The term 'very high risks of extinction' is used here consistently with the IUCN categories and criteria and equates with 'critically endangered'.

services such as pollination, increase pressure from pests and diseases, and reduce marine animal biomass, undermining food productivity in many regions on land and in the ocean (*medium confidence*). At 3ºC or higher global warming level in the long term, areas exposed to climate-related hazards will expand substantially compared with 2ºC or lower global warming level (*high confidence*), exacerbating regional disparity in food security risks (*high confidence*). (Figure SPM.3) {1.1, 3.3, CCB SLR, 4.5, 5.2, 5.4, 5.5, 5.8, 5.9, 5.12, CCB MOVING PLATE, 7.3, 8.3, 9.11,13.5,15.3, 16.5, 16.6}

SPM.B.4.4 Climate change and related extreme events will significantly increase ill health and premature deaths from the near- to long-term (*high confidence*). Globally, population exposure to heatwaves will continue to increase with additional warming, with strong geographical differences in heat-related mortality without additional adaptation (*very high confidence*). Climate-sensitive food-borne, water-borne, and vector-borne disease risks are projected to increase under all levels of warming without additional adaptation (*high confidence*). In particular, dengue risk will increase with longer seasons and a wider geographic distribution in Asia, Europe, Central and South America and sub-Saharan Africa, potentially putting additional billions of people at risk by the end of the century (*high confidence*). Mental health challenges, including anxiety and stress, are expected to increase under further global warming in all assessed regions, particularly for children, adolescents, elderly, and those with underlying health conditions (*very high confidence*). {4.5, 5.12, Box 5.10, 7.3, Fig 7.9, 8.4, 9.10, Fig 9.32, Fig 9.35, 10.4, Fig 10.11, 11.3, 12.3, Fig 12.5, Fig 12.6, 13.7, Fig 13.23, Fig 13.24, 14.5, 15.3, CCP6.2}

SPM.B.4.5 Climate change risks to cities, settlements and key infrastructure will rise rapidly in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*). Globally, population change in low-lying cities and settlements will lead to approximately a billion people projected to be at risk from coastal-specific climate hazards in the mid-term under all scenarios, including in Small Islands (*high confidence*). The population potentially exposed to a 100-year coastal flood is projected to increase by about 20% if global mean sea level rises by 0.15 m relative to 2020 levels; this exposed population doubles at a 0.75 m rise in mean sea level and triples at 1.4 m without population change and additional adaptation (*medium confidence*). Sea level rise poses an existential threat for some Small Islands and some low-lying coasts (*medium confidence*). By 2100 the value of global assets within the future 1-in-100 year coastal floodplains is projected to be between US$7.9 and US$12.7 trillion (2011 value) under RCP4.5, rising to between US$8.8 and US$14.2 trillion under RCP8.5 (*medium confidence*). Costs for maintenance and reconstruction of urban infrastructure, including building, transportation, and energy will increase with global warming level (*medium confidence*), the associated functional disruptions are projected to be substantial particularly for cities, settlements and infrastructure located on permafrost in cold regions and on coasts (*high confidence*). {6.2, 9.9, 10.4, 13.6, 13.10, 15.3, 16.5, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCB SLR, SROCC 2.3, SROCC CCB9}

SPM.B.4.6 Projected estimates of global aggregate net economic damages generally increase non-linearly with global warming levels (*high confidence*).[35] The wide range of global estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates (*high confidence*). The existence of higher estimates than assessed in AR5 indicates that global aggregate economic impacts could be higher than previous estimates (*low confidence*).[36] Significant regional variation in aggregate economic damages from climate change is projected (*high confidence*) with estimated economic damages per capita for developing countries often higher as a fraction of income (*high confidence*). Economic damages, including both those represented and those not represented in economic markets, are projected to be lower at 1.5°C than at 3°C or higher global warming levels (*high confidence*). {4.4, 9.11, 11.5, 13.10, Box 14.6, 16.5, CWGB ECONOMICS}

SPM.B.4.7 In the mid- to long-term, displacement will increase with intensification of heavy precipitation and associated flooding, tropical cyclones, drought and, increasingly, sea level rise (*high confidence*). At progressive levels of warming, involuntary migration from regions with high exposure and low adaptive

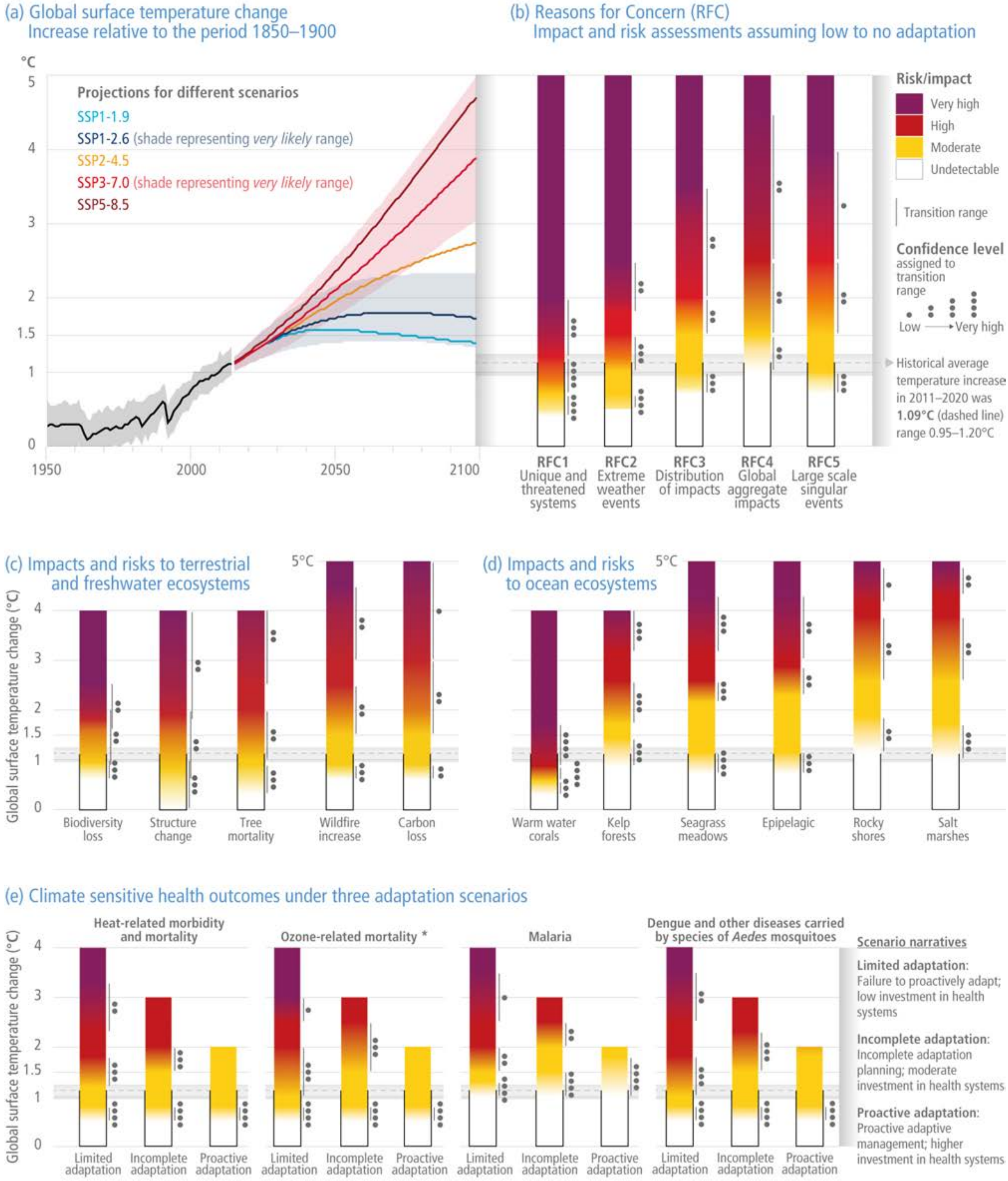
---

[35] The assessment found estimated rates of increase in projected global economic damages that were both greater than linear and less than linear as global warming level increases. There is evidence that some regions could benefit from low levels of warming (*high confidence*). {CWGB ECONOMICS}

[36] *Low confidence* assigned due to the assessed lack of comparability and robustness of global aggregate economic damage estimates. {CWGB ECONOMICS}

capacity would occur (*medium confidence*). Compared to other socioeconomic factors the influence of climate on conflict is assessed as relatively weak (*high confidence*). Along long-term socioeconomic pathways that reduce non-climatic drivers, risk of violent conflict would decline (*medium confidence*). At higher global warming levels, impacts of weather and climate extremes, particularly drought, by increasing vulnerability will increasingly affect violent intrastate conflict (*medium confidence*). {7.3, 16.5, CCB MIGRATE, TSB7.4}

Global and regional risks for increasing levels of global warming



* Mortality projections include demographic trends but do not include future efforts to improve air quality that reduce ozone concentrations.

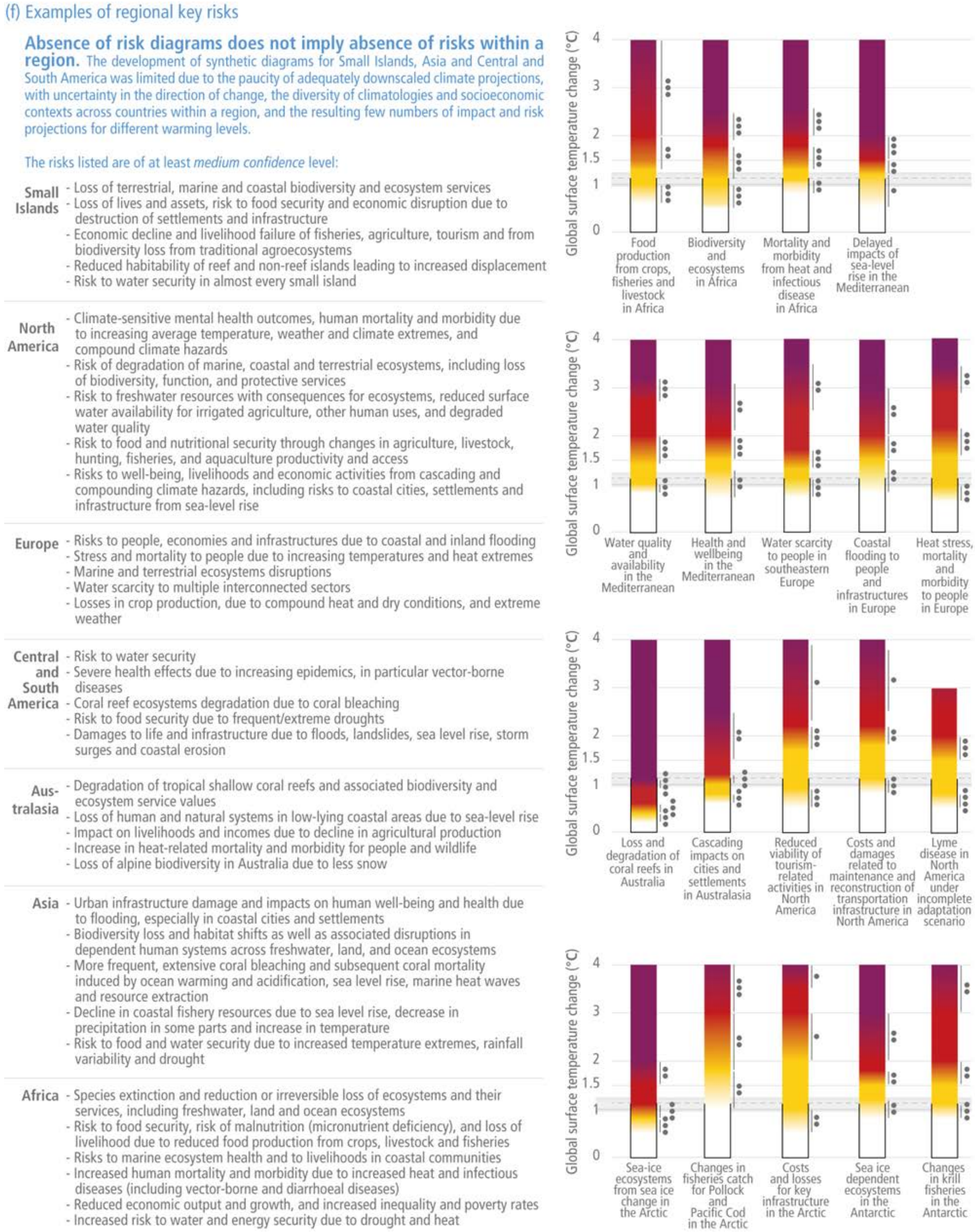


Figure SPM.3: Synthetic diagrams of global and sectoral assessments and examples of regional key risks. Diagrams show the change in the levels of impacts and risks assessed for global warming of 0-5°C global surface temperature change relative to pre-industrial period (1850-1900) over the range. (a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. *Very likely* ranges are shown for SSP1-2.6 and SSP3-

7.0 (WGI Figure SPM.8). Assessments were carried out at the global scale for (b), (c), (d) and (e). (b) The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories. Diagrams are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localized and comprises incremental adjustments to existing practices). However, the transition to a very high risk level has an emphasis on irreversibility and adaptation limits. Undetectable risk level (white) indicates no associated impacts are detectable and attributable to climate change; moderate risk (yellow) indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk (red) indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level (purple) indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. The horizontal line denotes the present global warming of 1.09°C which is used to separate the observed, past impacts below the line from the future projected risks above it. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing. Assessment methods are described in SM16.6 and are identical to AR5, but are enhanced by a structured approach to improve robustness and facilitate comparison between AR5 and AR6. Risks for (c) terrestrial and freshwater ecosystems and (d) ocean ecosystems. For c) and d), diagrams shown for each risk assume low to no adaptation. The transition to a very high risk level has an emphasis on irreversibility and adaptation limits. (e) Climate-sensitive human health outcomes under three scenarios of adaptation effectiveness. The assessed projections were based on a range of scenarios, including SRES, CMIP5, and ISIMIP, and, in some cases, demographic trends. The diagrams are truncated at the nearest whole ºC within the range of temperature change in 2100 under three SSP scenarios in panel (a). (f) Examples of regional key risks. Risks identified are of at least *medium confidence* level. Key risks are identified based on the magnitude of adverse consequences (pervasiveness of the consequences, degree of change, irreversibility of consequences, potential for impact thresholds or tipping points, potential for cascading effects beyond system boundaries); likelihood of adverse consequences; temporal characteristics of the risk; and ability to respond to the risk, e.g., by adaptation. The full set of 127 assessed global and regional key risks is given in SM16.7. Diagrams are provided for some risks. The development of synthetic diagrams for Small Islands, Asia and Central and South America were limited by the availability of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socio-economic contexts across countries within a region, and the resulting low number of impact and risk projections for different warming levels. Absence of risks diagrams does not imply absence of risks within a region. (Box SPM.1) {16.5, 16.6, Figure 16.15, SM16.3, SM16.4, SM16.5, SM16.6 (methodologies), SM16.7, Figure 2.11, Figure SM3.1, Figure 7.9, Figure 9.6, Figure 11.6, Figure 13.28, Figure CCP6.5, Figure CCP4.8, Figure CCP4.10, Figure TS.4, WGI Figure SPM.8, WGI SPM A.1.2, Box SPM.1, WGI Ch. 2}

Complex, Compound and Cascading Risks

SPM.B.5 Climate change impacts and risks are becoming increasingly complex and more difficult to manage. Multiple climate hazards will occur simultaneously, and multiple climatic and non-climatic risks will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Some responses to climate change result in new impacts and risks. (*high confidence*) {1.3, 2.4, Box 2.2, Box 9.5, 11.5, 13.5, 14.6, Box 15.1, CCP1.2, CCP2.2, CCB DISASTER, CCB INTERREG, CCB SRM, CCB COVID}

SPM.B.5.1 Concurrent and repeated climate hazards occur in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Increasing concurrence of heat and drought events are causing crop production losses and tree mortality (*high confidence*). Above 1.5°C global warming increasing concurrent climate extremes will increase risk of simultaneous crop losses of maize in major food-producing regions, with this risk increasing further with higher global warming levels (*medium confidence*). Future sea level rise combined with storm surge and heavy rainfall will increase compound flood risks (*high confidence*). Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (*high confidence*). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (*high confidence*). Risks to food safety from climate change will further compound the risks to health by increasing food contamination of crops from mycotoxins and contamination of seafood from harmful algal blooms, mycotoxins, and chemical contaminants (*high confidence*). {5.2, 5.4, 5.8, 5.9, 5.11, 5.12, 7.2, 7.3, 9.8, 9.11, 10.4, 11.3, 11.5, 12.3, 13.5, 14.5, 15.3, Box 15.1, 16.6, CCP1.2, CCP6.2, Figure TS10C, WG1 SPM A.3.1, A.3.2 and C.2.7}

SPM.B.5.2 Adverse impacts from climate hazards and resulting risks are cascading across sectors and regions (*high confidence*), propagating impacts along coasts and urban centres (*medium confidence*) and in mountain regions (*high confidence*). These hazards and cascading risks also trigger tipping points in sensitive ecosystems and in significantly and rapidly changing social-ecological systems impacted by ice melt, permafrost thaw and changing hydrology in polar regions (*high confidence*). Wildfires, in many regions, have affected ecosystems and species, people and their built assets, economic activity, and health (*medium to high confidence*)**.** In cities and settlements, climate impacts to key infrastructure are leading to losses and damages across water and food systems, and affect economic activity, with impacts extending beyond the area directly impacted by the climate hazard (*high confidence*). In Amazonia, and in some mountain regions, cascading impacts from climatic (e.g., heat) and non-climatic stressors (e.g., land use change) will result in irreversible and severe losses of ecosystem services and biodiversity at 2°C global warming level and beyond (*medium confidence*). Unavoidable sea level rise will bring cascading and compounding impacts resulting in losses of coastal ecosystems and ecosystem services, groundwater salinisation, flooding and damages to coastal infrastructure that cascade into risks to livelihoods, settlements, health, well-being, food and water security, and cultural values in the near to long-term (*high confidence*). (Figure SPM.3) {2.5, 3.4, 3.5, Box 7.3, Box 8.7, Box 9.4, Box 11.1, 11.5, 12.3, 13.9, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.2, CCP5.2, CCP5.3, CCP6.2, CCP6.3, Box CCP6.1, Box CCP6.2, CCB EXTREMES, Figure TS.10, WGI SPM Figure SPM.8d}

SPM.B.5.3 Weather and climate extremes are causing economic and societal impacts across national boundaries through supply-chains, markets, and natural resource flows, with increasing transboundary risks projected across the water, energy and food sectors (*high confidence*). Supply chains that rely on specialized commodities and key infrastructure can be disrupted by weather and climate extreme events. Climate change causes the redistribution of marine fish stocks, increasing risk of transboundary management conflicts among fisheries users, and negatively affecting equitable distribution of food provisioning services as fish stocks shift from lower to higher latitude regions, thereby increasing the need for climate-informed transboundary management and cooperation (*high confidence*). Precipitation and water availability changes increases the risk of planned infrastructure projects, such as hydropower in some regions, having reduced productivity for food and energy sectors including across countries that share river basins (*medium confidence*). {Figure TS.10e-f, 3.4, 3.5, 4.5, 5.8, 5.13, 6.2, 9.4, Box 9.5,14.5, Box 14.5, Box 14.6, CCP5.3, CCB EXTREMES, CCB MOVING PLATE, CCB INTERREG, CCB DISASTER}

SPM B.5.4 Risks arise from some responses that are intended to reduce the risks of climate change, including risks from maladaptation and adverse side effects of some emission reduction and carbon dioxide removal measures (*high confidence*). Deployment of afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods, especially if implemented at large scales, especially in regions with insecure land tenure (*high confidence*). {Box 2.2, 4.1, 4.7, 5.13, Table 5.18, Box 9.3, Box 13.2, CCB NATURAL, CWGB BIOECONOMY}

SPM B.5.5 Solar radiation modification approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood (*high confidence*). Solar radiation modification approaches have potential to offset warming and ameliorate some climate hazards, but substantial residual climate change or overcompensating change would occur at regional scales and seasonal timescales (*high confidence*). Large uncertainties and knowledge gaps are associated with the potential of solar radiation modification approaches to reduce climate change risks. Solar radiation modification would not stop atmospheric CO_2 concentrations from increasing or reduce resulting ocean acidification under continued anthropogenic emissions (*high confidence*). {XWGB SRM}

Impacts of Temporary Overshoot

SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)[37], then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Figure SPM.3) {2.5, 3.4, 12.3, 16.6, CCB SLR, CCB DEEP, Box SPM.1}

SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).[38] Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*). {2.5, 3.4, 12.3, 13.2, 16.5, 16.6, CCP 1.2, CCP5.3, CCP6.1, CCP6.2, CCP2.2, CCB SLR, Box TS4, SROCC 2.3, SROCC 5.4, WG1 SPM B5 and C3}

SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)[39] such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*). {2.4, 2.5, CCP4.2, WG1 SPM B.4.3, SROCC 5.4}

SPM.C: Adaptation Measures and Enabling Conditions

Adaptation, in response to current climate change, is reducing climate risks and vulnerability mostly via adjustment of existing systems. Many adaptation options exist and are used to help manage projected climate change impacts, but their implementation depends upon the capacity and effectiveness of governance and decision-making processes. These and other enabling conditions can also support Climate Resilient Development (Section D).

Current Adaptation and its Benefits

---

[37] In this report, overshoot pathways exceed 1.5°C global warming and then return to that level, or below, after several decades.

[38] Despite limited evidence specifically on the impacts of a temporary overshoot of 1.5°C, a much broader evidence base from process understanding and the impacts of higher global warming levels allows a high confidence statement on the irreversibility of some impacts that would be incurred following such an overshoot.

[39] At the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere (-3.4 ± 0.9 Gt yr^{-1}) than they emit ($+1.6 \pm 0.7$ Gt yr^{-1}), a net sink of -1.9 ± 1.1 Gt yr^{-1}. However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources.

SPM.C.1 Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). However, adaptation progress is unevenly distributed with observed adaptation gaps[40] (*high confidence*). Many initiatives prioritize immediate and near-term climate risk reduction which reduces the opportunity for transformational adaptation (*high confidence*). {2.6, 5.14, 7.4, 10.4, 12.5, 13.11, 14.7, 16.3, 17.3, CCP5.2, CCP5.4}

SPM.C.1.1 Adaptation planning and implementation have continued to increase across all regions (*very high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). Decision support tools and climate services are increasingly being used (*very high confidence*). Pilot projects and local experiments are being implemented in different sectors (*high confidence*). Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation as well as reduction of risks and damages (*very high confidence*). {1.4, CCB ADAPT, 2.6, CCB NATURE, 3.5, 3.6, 4.7, 4.8, 5.4, 5.6, 5.10, 6.4.2, 7.4, 8.5, 9.3, 9.6, 10.4, 12.5, 13.11, 15.5, 16.3, 17.2, 17.3, 17.5 CCP5.4}

SPM.C.1.2 Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (*high confidence*). Most observed adaptation is fragmented, small in scale, incremental, sector-specific, designed to respond to current impacts or near-term risks, and focused more on planning rather than implementation (*high confidence*). Observed adaptation is unequally distributed across regions *(high confidence)*, and gaps are partially driven by widening disparities between the estimated costs of adaptation and documented finance allocated to adaptation (*high confidence*)*.* The largest adaptation gaps exist among lower income population groups (*high confidence*). At current rates of adaptation planning and implementation the adaptation gap will continue to grow (*high confidence*). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in the next decade, is important to close adaptation gaps, recognising that constraints remain for some regions (*high confidence*). {1.1, 1.4, 5.6, 6.3, Figure 6.4, 7.4, 8.3, 10.4, 11.3, 11.7, 15.2, Box 13.1, 13.11, 15.5, Box16.1, Figure 16.4, Figure 16.5, 16.3, 16.5, 17.4, 18.2, CCP2.4, CCP5.4, CCB FINANCE, CCB SLR}

---

[40] Adaptation gaps are defined as the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities.

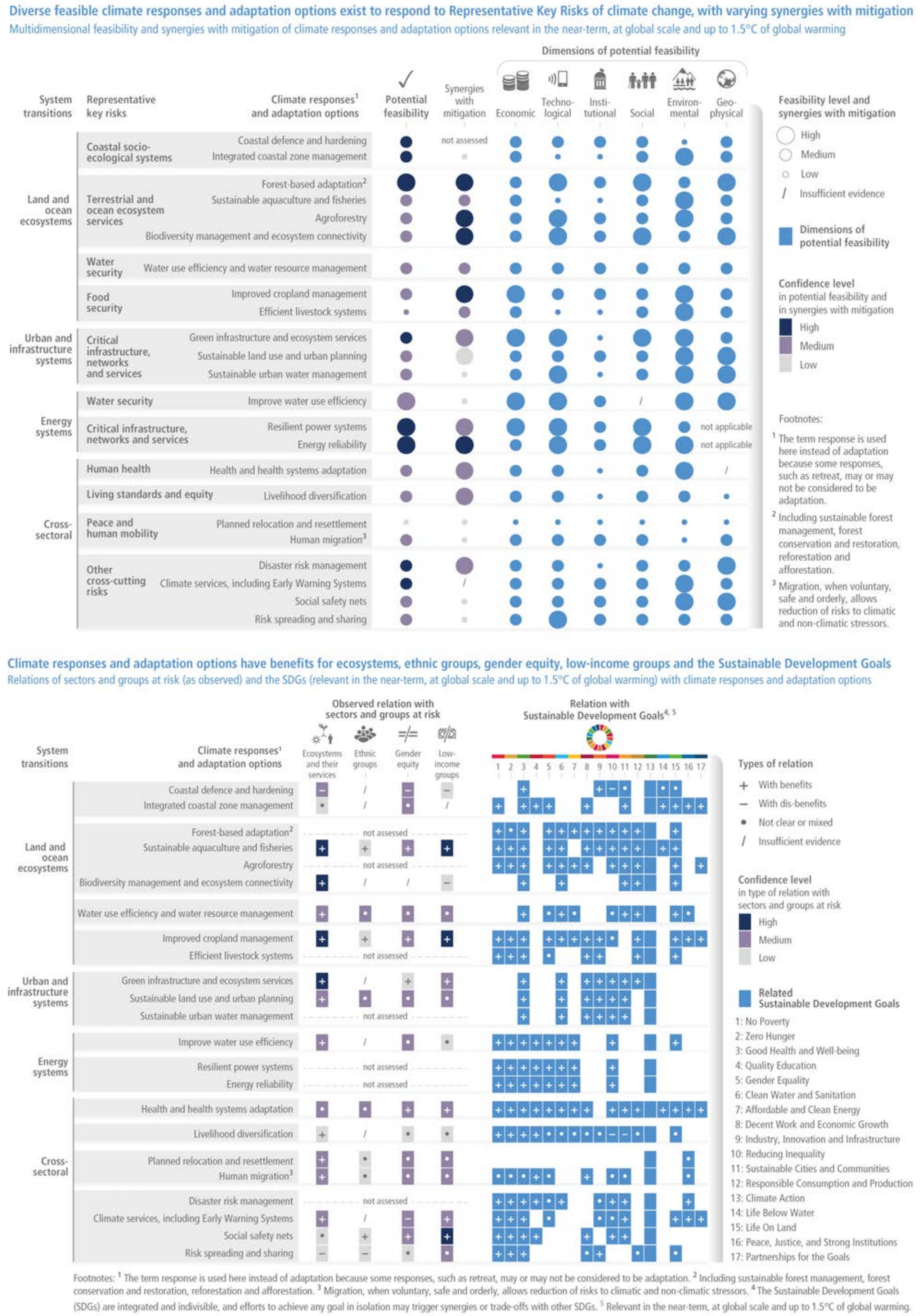


Figure SPM.4: (a) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks (RKRs), are assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. Climate responses and adaptation options at global scale are drawn from a set of options assessed in AR6 that have robust evidence across the feasibility dimensions. This figure shows the six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) that are used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. Insufficient evidence is denoted by a dash. {CCB FEASIB., Table SMCCB FEASIB.1.1; SR1.5 4.SM.4.3}

Figure SPM.4: (b) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks, are assessed at global scale for their likely ability to reduce risks for ecosystems and social groups at risk, as well as their relation with the 17 Sustainable Development Goals (SDGs). Climate responses and adaptation options are assessed for observed benefits (+) to ecosystems and their services, ethnic groups, gender equity, and low-income groups, or observed dis-benefits (-) for these systems and groups. Where there is highly diverging evidence of benefits/ dis-benefits across the scientific literature, e.g., based on differences between regions, it is shown as not clear or mixed (•). Insufficient evidence is shown by a dash. The relation with the SDGs is assessed as having benefits (+), dis-benefits (-) or not clear or mixed (•) based on the impacts of the climate response and adaptation option on each SDG. Areas not coloured indicate there is no evidence of a relation or no interaction with the respective SDG. The climate responses and adaptation options are drawn from two assessments. For comparability of climate responses and adaptation options see Table SM17.5. {17.2, 17.5; CCB FEASIB}

Future Adaptation Options and their Feasibility

SPM.C.2 There are feasible[41] and effective[42] adaptation options which can reduce risks to people and nature. The feasibility of implementing adaptation options in the near-term differs across sectors and regions (*very high confidence*). The effectiveness of adaptation to reduce climate risk is documented for specific contexts, sectors and regions (*high confidence*) and will decrease with increasing warming (*high confidence*). Integrated, multi-sectoral solutions that address social inequities, differentiate responses based on climate risk and cut across systems, increase the feasibility and effectiveness of adaptation in multiple sectors (*high confidence*). (Figure SPM.4) {Figure TS.6e, 1.4, 3.6, 4.7, 5.12, 6.3, 7.4, 11.3, 11.7, 13.2, 15.5, 17.6, CCB FEASIB, CCP2.3}

Land, Ocean and Ecosystems Transition

SPM.C.2.1 Adaptation to water-related risks and impacts make up the majority of all documented adaptation (*high confidence*). For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives (*medium confidence*). Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk (*medium confidence*). On-farm water management, water storage, soil moisture conservation and irrigation are some of the most common adaptation responses and provide economic, institutional or ecological benefits and reduce vulnerability (*high confidence*). Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits, but needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization (*medium confidence*). Large scale irrigation can also alter local to regional temperature and precipitation patterns (*high confidence*), including both alleviating and exacerbating temperature extremes (*medium confidence*). The effectiveness of most water-related adaptation options to reduce projected risks declines with increasing warming (*high confidence*). {4.1,

[41] In this report, feasibility refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

[42] Effectiveness refers to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk.

4.6, 4.7, Box 4.3, Box 4.6, Box 4.7, Figure 4.28, Figure 4.29, Table 4.9, 9.3, 9.7, 11.3, 12.5, 13.1, 13.2, 16.3, CCP5.4, Figure 4.22}

SPM.C.2.2 Effective adaptation options, together with supportive public policies enhance food availability and stability and reduce climate risk for food systems while increasing their sustainability (*medium confidence*). Effective options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture (*high confidence*). Institutional feasibility, adaptation limits of crops and cost effectiveness also influence the effectiveness of the adaptation options (*limited evidence*, *medium agreement*). Agroecological principles and practices, ecosystem-based management in fisheries and aquaculture, and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability and ecosystem services (*high confidence*). These services include pest control, pollination, buffering of temperature extremes, and carbon sequestration and storage (*high confidence*). Trade-offs and barriers associated with such approaches include costs of establishment, access to inputs and viable markets, new knowledge and management (*high confidence*) and their potential effectiveness varies by socio-economic context, ecosystem zone, species combinations and institutional support (*medium confidence*). Integrated, multi-sectoral solutions that address social inequities and differentiate responses based on climate risk and local situation will enhance food security and nutrition (*high confidence*). Adaptation strategies which reduce food loss and waste or support balanced diets[33] (as described in the IPCC Special Report on Climate Change and Land) contribute to nutrition, health, biodiversity and other environmental benefits (*high confidence*). {3.2, 4.7, 4.6, Box 4.3, 5.4, 5.5, 5.6, 5.8, 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 7.4, Box 5.10, Box 5.13, 6.3, 10.4, 12.5, 13.5, 13.10, 14.5, CWGB BIOECONOMY, CCB MOVING PLATE, CCB NATURAL, CCB FEASIB, CCP5.4, CCB HEALTH}

SPM.C.2.3 Adaptation for natural forests[43] includes conservation, protection and restoration measures. In managed forests[44], adaptation options include sustainable forest management, diversifying and adjusting tree species compositions to build resilience, and managing increased risks from pests and diseases and wildfires. Restoring natural forests and drained peatlands and improving sustainability of managed forests, generally enhances the resilience of carbon stocks and sinks. Cooperation, and inclusive decision making, with local communities and Indigenous Peoples, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful forest adaptation in many areas. (*high confidence*) {2.6, Box 2.2, CCB NATURAL, CCB FEASIB, CCB INDIG, 5.6, 5.13, 11.4, 12.5, 13.5, Box 14.1, Box 14.2, Table 5.23, Box CCP7.1, CCP7.5}.

SPM.C.2.4 Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change, reduces the vulnerability of biodiversity to climate change (*high confidence*). The resilience of species, biological communities and ecosystem processes increases with size of natural area, by restoration of degraded areas and by reducing non-climatic stressors (*high confidence*). To be effective, conservation and restoration actions will increasingly need to be responsive, as appropriate, to ongoing changes at various scales, and plan for future changes in ecosystem structure, community composition and species' distributions, especially as 1.5°C global warming is approached and even more so if it is exceeded (*high confidence*). Adaptation options, where circumstances allow, include facilitating the movement of species to new ecologically appropriate locations, particularly through increasing connectivity between conserved or protected areas, targeted intensive management for vulnerable species and protecting refugial areas where species can survive locally (*medium confidence*). {2.3, Figure 2.1, 2,6, Table 2.6, 2.6, 3.6, Box 3.4, 4.6, Box 11.2, 12.3, 12.5, 3.3, 13.4, 14.7, Box 4.6, CCP5.4, CCB FEASIB}

SPM.C.2.5 Effective Ecosystem-based Adaptation[44] reduces a range of climate change risks to people, biodiversity and ecosystem services with multiple co-benefits (*high confidence*). Ecosystem-based Adaptation

---

[43] In this report, the term natural forests describes those which are subject to little or no direct human intervention, whereas the term managed forests describes those where planting or other management activities take place, including those managed for commodity production.

[44] Ecosystem based Adaptation (EbA) is recognised internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), which includes a broader range of approaches with safeguards, including those that contribute to adaptation and mitigation. The term 'Nature-based Solutions' is widely but not universally used in the scientific literature. The term is the subject of ongoing debate, with concerns that it may lead to the misunderstanding that NbS on its own can provide a global solution to climate change.

is vulnerable to climate change impacts, with effectiveness declining with increasing global warming (*high confidence*). Urban greening using trees and other vegetation can provide local cooling (*very high confidence*). Natural river systems, wetlands and upstream forest ecosystems reduce flood risk by storing water and slowing water flow, in most circumstances (*high confidence*). Coastal wetlands protect against coastal erosion and flooding associated with storms and sea level rise where sufficient space and adequate habitats are available until rates of sea level rise exceeds natural adaptive capacity to build sediment (*very high confidence*). {2.4, 2.5, 2.6, Table 2.7, 3.4, 3.5, 3.6, Figure 3.26, 4.6, Box 4.6, Box 4.7, 5.5, 5.14, Box 5.11, 6.3, 6.4, Figure 6.6, 7.4, 8.5, 8.6, 9.6, 9.8, 9.9, 10.2, 11.3, 12.5, 13.3, 13.4, 13.5, 14.5, Box 14.7, 16.3, 18.3, CCB HEALTH, CCB NATURAL, CCB MOVING PLATE, CCB FEASIB.3, CWGB BIOECONOMY, CCP5.4}

Urban, Rural and Infrastructure Transition

SPM.C.2.6 Considering climate change impacts and risks in the design and planning of urban and rural settlements and infrastructure is critical for resilience and enhancing human well-being (*high confidence*). The urgent provision of basic services, infrastructure, livelihood diversification and employment, strengthening of local and regional food systems and community-based adaptation enhance lives and livelihoods, particularly of low-income and marginalised groups (*high confidence*). Inclusive, integrated and long-term planning at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems and financial and technological resources and capabilities foster urban and rural system transition (*high confidence*). Effective partnerships between governments, civil society, and private sector organizations, across scales provide infrastructure and services in ways that enhance the adaptive capacity of vulnerable people (*medium to high confidence*). {5.12, 5.13, 5.14, Box 6.3, 6.3, 6.4, Box 6.6, Table 6.6, 7.4, 12.5, 13.6, 14.5, Box14.4, Box17.4, CCB FEASIB, CCP2.3, CCP2.4, CCP5.4}

SPM.C.2.7 An increasing number of adaptation responses exist for urban systems, but their feasibility and effectiveness is constrained by institutional, financial, and technological access and capacity, and depends on coordinated and contextually appropriate responses across physical, natural and social infrastructure (*high confidence*). Globally, more financing is directed at physical infrastructure than natural and social infrastructure (*medium confidence*) and there is *limited evidence* of investment in the informal settlements hosting the most vulnerable urban residents (*medium* to *high confidence*). Ecosystem-based adaptation (e.g., urban agriculture and forestry, river restoration) has increasingly been applied in urban areas (*high confidence).* Combined ecosystem-based and structural adaptation responses are being developed, and there is growing evidence of their potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection (*medium confidence*). {3.6, Box 4.6, 5.12, 6.3, 6.4, Table 6.8, 7.4, 9.7, 9.9, 10.4, Table 10.3, 11.3, 11.7, Box 11.6, 12.5, 13.2, 13.3, 13.6, 14.5, 15.5, 17.2, Box 17.4, CCB FEASIB, CCP2.3, CCP 3.2, CCP5.4, CCB SLR, SROCC ES}

SPM C.2.8: Sea level rise poses a distinctive and severe adaptation challenge as it implies dealing with slow onset changes and increased frequency and magnitude of extreme sea level events which will escalate in the coming decades (*high confidence*). Such adaptation challenges would occur much earlier under high rates of sea level rise, in particular if low-likelihood, high impact outcomes associated with collapsing ice sheets occur (*high confidence*). Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation (*high confidence*)[45]. These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes (*high confidence*). {CCB SLR, CCP2.3, 6.2, 10.4, 11.7, Box 11.6, 13.2.2, 14.5.9.2, 15.5, SROCC ES: C3.2, WGI SPM B5, C3}

SPM.C.2.9 Approximately 3.4 billion people globally live in rural areas around the world, and many are highly vulnerable to climate change. Integrating climate adaptation into social protection programs, including cash transfers and public works programmes, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure. Social safety nets are increasingly being reconfigured to build adaptive capacities of the most vulnerable in rural and also urban communities. Social

[45] The term 'response' is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation.

safety nets that support climate change adaptation have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion and food security. (*high confidence*) {5.14, 9.4, 9.10, 9.11, 12.5, 14.5, CCB GENDER, CCB FEASIB, CCP5.4}

Energy System Transition

SPM.C.2.10 Within energy system transitions, the most feasible adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Energy generation diversification, including with renewable energy resources and generation that can be decentralised depending on context (e.g., wind, solar, small scale hydroelectric) and demand side management (e.g., storage, and energy efficiency improvements) can reduce vulnerabilities to climate change, especially in rural populations (*high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (*very high confidence*). {4.6, 4.7, Figure 4.28, Figure 4.29, 10.4, Table 11.8, Figure 13.19, Figure 13.16, 13.6, 18.3, CCB FEASIB, CWGB BIOECONOMY, CCP5.2, CCP5.4}

Cross-cutting Options

SPM.C.2.11 Strengthening the climate resiliency of health systems will protect and promote human health and wellbeing (*high confidence*). There are multiple opportunities for targeted investments and finance to protect against exposure to climate hazards, particularly for those at highest risk. Heat Health Action Plans that include early warning and response systems are effective adaptation options for extreme heat (*high confidence*). Effective adaptation options for water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems (*very high confidence*). For vector-borne diseases, effective adaptation options include surveillance, early warning systems, and vaccine development (*very high confidence*). Effective adaptation options for reducing mental health risks under climate change include improving surveillance, access to mental health care, and monitoring of psychosocial impacts from extreme weather events (*high confidence*). Health and well-being would benefit from integrated adaptation approaches that mainstream health into food, livelihoods, social protection, infrastructure, water and sanitation policies requiring collaboration and coordination at all scales of governance (*very high confidence*). {5.12, 6.3, 7.4, 9.10, Box 9.7, 11.3, 12.5, 13.7, 14.5, CCB FEASIB, CCB ILLNESS, CCB COVID}.

SPM.C.2.12 Increasing adaptive capacities minimises the negative impacts of climate-related displacement and involuntary migration for migrants and sending and receiving areas (*high confidence*). This improves the degree of choice under which migration decisions are made, ensuring safe and orderly movements of people within and between countries (*high confidence*). Some development reduces underlying vulnerabilities associated with conflict, and adaptation contributes by reducing the impacts of climate change on climate sensitive drivers of conflict (*high confidence*). Risks to peace are reduced, for example, by supporting people in climate-sensitive economic activities (*medium confidence*) and advancing women's empowerment (*high confidence*). {7.4, 12.5, CCB MIGRATE, Box 9.8, Box 10.2, CCB FEASIB}

SPM.C.2.13 There are a range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined (*high confidence*). For example, climate services that are inclusive of different users and providers can improve agricultural practices, inform better water use and efficiency, and enable resilient infrastructure planning (*high confidence*). {2.6, 3.6, 4.7, 5.4, 5.5, 5.6, 5.8, 5.9, 5.12, 5.14, 9.4, 9.8, 10.4, 12.5, 13.11, CCB MOVING PLATE, CCB FEASIB, CCP5.4}

Limits to Adaptation

SPM.C.3 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, primarily financial, governance, institutional and policy constraints (*high confidence*). Hard limits to adaptation have been reached in some ecosystems (*high confidence*). With increasing global warming, losses and damages will increase and additional human and natural systems will reach adaptation limits (*high confidence*). {Figure TS.7, 1.4, 2.4, 2.5, 2.6, CCB SLR, 3.4, 3.6, 4.7, Figure 4.30, 5.5, Table 8.6, Box 10.7, 11.7, Table 11.16, 12.5 13.2, 13.5, 13.6, 13.10, 13.11, Figure 13.21, 14.5, 15.6, 16.4, Figure 16.8, Table 16.3, Table 16.4, CCP1.2, CCP1.3, CCP2.3, CCP3.3, CCP5.2, CCP5.4, CCP6.3, CCP7.3}

SPM.C.3.1 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, which primarily consist of financial, governance, institutional and policy constraints (*high confidence*). For example, individuals and households in low lying coastal areas in Australasia and Small Islands and smallholder farmers in Central and South America, Africa, Europe and Asia have reached soft limits (*medium confidence*). Inequity and poverty also constrain adaptation, leading to soft limits and resulting in disproportionate exposure and impacts for most vulnerable groups (*high confidence*). Lack of climate literacy[46] at all levels and limited availability of information and data pose further constraints to adaptation planning and implementation (*medium confidence*). {1.4, 4.7, 5.4, Table 8.6, 8.4, 9.1, 9.4, 9.5, 9.8, 11.7, 12.5 13.5, 15.3, 15.5, 15.6, 16.4, Figure 16.8, 16.4, Box 16.1, CCP5.2, CCP5.4, CCP6.3}

SPM.C.3.2 Financial constraints are important determinants of soft limits to adaptation across sectors and all regions (*high confidence*). Although global tracked climate finance has shown an upward trend since AR5, current global financial flows for adaptation, including from public and private finance sources, are insufficient for and constrain implementation of adaptation options especially in developing countries (*high confidence*). The overwhelming majority of global tracked climate finance was targeted to mitigation while a small proportion was targeted to adaptation (*very high confidence*). Adaptation finance has come predominantly from public sources (*very high confidence*). Adverse climate impacts can reduce the availability of financial resources by incurring losses and damages and through impeding national economic growth, thereby further increasing financial constraints for adaptation, particularly for developing and least developed countries (*medium confidence*). {1.4, 2.6, 3.6, 4.7, Figure 4.30, 5.14, 7.4, Table 8.6, 8.4, 9.4, 9.9, 9.11, 10.5, 12.5, 13.3, 13.11, Box 14.4, 15.6, 16.2, 16.4, Figure 16.8, Table 16.4, 17.4, 18.1, CCB FINANCE, CCP2.4, CCP5.4, CCP6.3, Figure TS 7}

SPM.C.3.3 Many natural systems are near the hard limits of their natural adaptation capacity and additional systems will reach limits with increasing global warming (*high confidence*). Ecosystems already reaching or surpassing hard adaptation limits include some warm water coral reefs, some coastal wetlands, some rainforests, and some polar and mountain ecosystems (*high confidence*). Above 1.5°C global warming level, some ecosystem-based adaptation measures will lose their effectiveness in providing benefits to people as these ecosystems will reach hard adaptation limits (*high confidence*). {1.4, 2.4, 2.6, 3.4, 3.6, CCB SLR, 9.6, Box11.2, 13.4, 14.5, 15.5, 16.4, 16.6, 17.2, CCP1.2, CCP5.2, CCP6.3, CCP7.3, Figure SPM.4}

SPM.3.4 In human systems, some coastal settlements face soft adaptation limits due to technical and financial difficulties of implementing coastal protection (*high confidence*). Above 1.5°C global warming level, limited freshwater resources pose potential hard limits for Small Islands and for regions dependent on glacier and snow-melt (*medium confidence*). By 2°C global warming level, soft limits are projected for multiple staple crops in many growing areas, particularly in tropical regions (*high confidence*). By 3°C global warming level, soft limits are projected for some water management measures for many regions, with hard limits projected for parts of Europe (*medium confidence*). Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). {1.4, 4.7, 5.4, 5.8, 7.2, 7.3, 8.4, Table 8.6, 9.8, 10.4, 12.5, 13.2, 13.6, 16.4, 17.2, CCB SLR, CCP1.3. Box CCP1.1, CCP2.3, CCP3.3, CCP4.4, CCP5.3}

SPM.C.3.5 Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. With increasing global warming, losses and damages increase and become increasingly difficult to avoid, while strongly concentrated among the poorest vulnerable

[46] Climate literacy encompasses being aware of climate change, its anthropogenic causes and implications.

populations. (*high confidence*) {1.4, 2.6, 3.4, 3.6, 6.3, Figure 6.4, 8.4, 13.7, 13.2, 13.10, 17.2, CCB LOSS, CCB SLR, CCP2.3, CCP4.4, CWGB ECONOMIC}

Avoiding Maladaptation

SPM.C.4 There is increased evidence of maladaptation[15] across many sectors and regions since the AR5. Maladaptive responses to climate change can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {1.3, 1.4, 2.6., Box 2.2, 3.2, 3.6, Box 4.3, Box 4.5, 4.6, 4.7, Figure 4.29, 5.6, 5.13, 8.2, 8.3, 8.4, 8.6, 9.6, 9.7, 9.8, 9.9, 9.10, 9.11, Box 9.5, Box 9.8, Box 9.9, Box 11.6, 13.11, 13.3, 13.4, 13.5, 14.5, 15.5, 15.6, 16.3, 17.3, 17.4, 17.6, 17.2, 17.5, CCP5.4, CCB NATURAL, CCB SLR, CCB DEEP, CWGB BIOECONOMY, CCP2.3, CCP2.3}

SPM.C.4.1 Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation if long-term impacts of the adaptation option and long-term adaptation commitment are not taken into account (*high confidence*). The implementation of these maladaptive actions can result in infrastructure and institutions that are inflexible and/or expensive to change (*high confidence*). For example, seawalls effectively reduce impacts to people and assets in the short-term but can also result in lock-ins and increase exposure to climate risks in the long-term unless they are integrated into a long-term adaptive plan (*high confidence*). Adaptation integrated with development reduces lock-ins and creates opportunities (e.g., infrastructure upgrading) (*medium confidence*). {1.4, 3.4, 3.6, 10.4, 11.7, Box 11.6, 13.2, 17.2, 17.5, 17.6, CCP 2.3, CCB SLR, CCB DEEP}

SPM.C.4.2 Biodiversity and ecosystem resilience to climate change are decreased by maladaptive actions, which also constrain ecosystem services. Examples of these maladaptive actions for ecosystems include fire suppression in naturally fire-adapted ecosystems or hard defences against flooding. These actions reduce space for natural processes and represent a severe form of maladaptation for the ecosystems they degrade, replace or fragment, thereby reducing their resilience to climate change and the ability to provide ecosystem services for adaptation. Considering biodiversity and autonomous adaptation in long-term planning processes reduces the risk of maladaptation. (*high confidence*) {2.4, 2.6, Table 2.7, 3.4, 3.6, 4.7, 5.6, 5.13, Table 5.21, 5.13, Box 13.2, 17.2, 17.5, Table 5.23, Box 11.2, 13.2, CCP5.4}

SPM.C.4.3 Maladaptation especially affects marginalised and vulnerable groups adversely (e.g., Indigenous Peoples, ethnic minorities, low-income households, informal settlements), reinforcing and entrenching existing inequities. Adaptation planning and implementation that do not consider adverse outcomes for different groups can lead to maladaptation, increasing exposure to risks, marginalising people from certain socio-economic or livelihood groups, and exacerbating inequity. Inclusive planning initiatives informed by cultural values, Indigenous knowledge, local knowledge, and scientific knowledge can help prevent maladaptation. (*high confidence*) (Figure SPM.4) {2.6, 3.6, 4.3, 4.6, 4.8, 5.12, 5.13, 5.14, 6.1, Box 7.1, 8.4, 11.4, 12.5, Box 13.2, 14.4, Box 14.1, 17.2, 17.5, 18.2, 17.2., CCP2.4}

SPM.C.4.4 To minimize maladaptation, multi-sectoral, multi-actor and inclusive planning with flexible pathways encourages low-regret[47] and timely actions that keep options open, ensure benefits in multiple sectors and systems and indicate the available solution space for adapting to long-term climate change (*very high confidence*). Maladaptation is also minimized by planning that accounts for the time it takes to adapt (*high confidence*), the uncertainty about the rate and magnitude of climate risk (*medium confidence*) and a wide range of potentially adverse consequences of adaptation actions (*high confidence*). {1.4, 3.6, 5.12, 5.13, 5.14, 11.6, 11.7, 17.3, 17.6, CCP2.3, CCP2.4, CCB SLR, CCB DEEP; CCP5.4}

---

[47] From AR5, an option *that would generate net social and/or economic benefits under current climate change and a range of future climate change scenarios*, and represent one example of robust strategies.

Enabling Conditions

SPM.C.5 Enabling conditions are key for implementing, accelerating and sustaining adaptation in human systems and ecosystems. These include political commitment and follow-through, institutional frameworks, policies and instruments with clear goals and priorities, enhanced knowledge on impacts and solutions, mobilization of and access to adequate financial resources, monitoring and evaluation, and inclusive governance processes. (*high confidence*) {1.4, 2.6, 3.6, 4.8, 6.4, 7.4, 8.5, 9.4, 10.5, 11.4, 11.7, 12.5, 13.11, 14.7, 15.6, 17.4, 18.4, CCB INDIG, CCB FINANCE, CCP2.4, CCP5.4}

SPM.C.5.1 Political commitment and follow-through across all levels of government accelerate the implementation of adaptation actions (*high confidence*). Implementing actions can require large upfront investments of human, financial and technological resources (*high confidence*), whilst some benefits could only become visible in the next decade or beyond (*medium confidence*). Accelerating commitment and follow-through is promoted by rising public awareness, building business cases for adaptation, accountability and transparency mechanisms, monitoring and evaluation of adaptation progress, social movements, and climate-related litigation in some regions (*medium confidence*). {3.6, 4.8, 5.8, 6.4, 8.5, 9.4, 11.7, 12.5, 13.11, 17.4, 17.5, 18.4, CCB COVID, CCP2.4}

SPM.C.5.2 Institutional frameworks, policies and instruments that set clear adaptation goals and define responsibilities and commitments and that are coordinated amongst actors and governance levels, strengthen and sustain adaptation actions (*very high confidence*). Sustained adaptation actions are strengthened by mainstreaming adaptation into institutional budget and policy planning cycles, statutory planning, monitoring and evaluation frameworks and into recovery efforts from disaster events (*high confidence*). Instruments that incorporate adaptation such as policy and legal frameworks, behavioural incentives, and economic instruments that address market failures, such as climate risk disclosure, inclusive and deliberative processes strengthen adaptation actions by public and private actors (*medium confidence*). {1.4, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 9.4, 10.4, 11.7, Box 11.6, Table 11.17, 13.10, 13.11, 14.7, 15.6, 17.3, 17.4, 17.5, 17.6, 18.4, CCB DEEP, CCP2.4, CCP5.4, CCP6.3}

SPM.C.5.3 Enhancing knowledge on risks, impacts, and their consequences, and available adaptation options promotes societal and policy responses (*high confidence*). A wide range of top-down, bottom-up and co-produced processes and sources can deepen climate knowledge and sharing, including capacity building at all scales, educational and information programmes, using the arts, participatory modelling and climate services, Indigenous knowledge and local knowledge and citizen science (*high confidence*). These measures can facilitate awareness, heighten risk perception and influence behaviours (*high confidence*). {1.3, 3.6, 4.8, 5.9, 5.14, 6.4, Table 6.8, 7.4, 9.4, 10.5, 11.1, 11.7, 12.5, 13.9, 13.11, 14.3, 15.6, 15.6, 17.4, 18.4, CCB INDIG, CCP2.4.1}.

SPMC.5.4 With adaptation finance needs estimated to be higher than those presented in AR5, enhanced mobilization of and access to financial resources are essential for implementation of adaptation and to reduce adaptation gaps (*high confidence*). Building capacity and removing some barriers to accessing finance is fundamental to accelerate adaptation, especially for vulnerable groups, regions and sectors (*high confidence*). Public and private finance instruments include inter alia grants, guarantee, equity, concessional debt, market debt, and internal budget allocation as well as savings in households and insurance. Public finance is an important enabler of adaptation (*high confidence*). Public mechanisms and finance can leverage private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers, for example via public-private partnerships (*high confidence*). Financial and technological resources enable effective and ongoing implementation of adaptation, especially when supported by institutions with a strong understanding of adaptation needs and capacity (*high confidence*). {4.8, 5.14, 6.4, Table 6.10, 7.4, 9.4, Table 11.17, 12.5, 13.11, 15.6, 17.4, 18.4, BOX 18.9, CCP5.4, CCB FINANCE}.

SPM.C.5.5 Monitoring and evaluation (M&E) of adaptation are critical for tracking progress and enabling effective adaptation (*high confidence*). M&E implementation is currently limited (*high confidence*) but has increased since AR5 at local and national levels. Although most of the monitoring of adaptation is focused towards planning and implementation, the monitoring of outcomes is critical for tracking the effectiveness and progress of adaptation *(high confidence)*. M&E facilitates learning on successful and effective adaptation measures, and signals when and where additional action may be needed. M&E systems are most effective when supported by capacities and resources and embedded in enabling governance systems (*high confidence*). {1.4, 2.6, 6.4, 7.4, 11.7, 11.8, 13.2, 13.11, 17.5, 18.4, CCB PROGRESS, CCB NATURAL, CCB ILLNESS, CCB DEEP, CCP2.4}.

SPM.C.5.6 Inclusive governance that prioritises equity and justice in adaptation planning and implementation leads to more effective and sustainable adaptation outcomes (*high confidence*). Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, processes, and interventions that address context specific inequities such as based on gender, ethnicity, disability, age, location and income (*high confidence*). These approaches, which include multi-stakeholder co-learning platforms, transboundary collaborations, community-based adaptation and participatory scenario planning, focus on capacity-building, and meaningful participation of the most vulnerable and marginalised groups, and their access to key resources to adapt (*high confidence*). {1.4, 2.6, 3.6, 4.8, 5.4, 5.8, 5.9, 5.13, 6.4, 7.4, 8.5, 11.8, 12.5, 13.11, 14.7, 15.5, 15.7, 17.3, 17.5, 18.4, CCB HEALTH, CCB GENDER, CCB INDIG, CCP2.4, CCP5.4, CCP6.4}

SPM.D: Climate Resilient Development

Climate Resilient Development integrates adaptation measures and their enabling conditions (Section C) with mitigation to advance sustainable development for all. Climate resilient development involves questions of equity and system transitions in land, ocean and ecosystems; urban and infrastructure; energy; industry; and society and includes adaptations for human, ecosystem and planetary health. Pursuing climate resilient development focuses on both where people and ecosystems are co-located as well as the protection and maintenance of ecosystem function at the planetary scale. Pathways for advancing climate resilient development are development trajectories that successfully integrate mitigation and adaptation actions to advance sustainable development. Climate resilient development pathways may be temporarily coincident with any RCP and SSP scenario used throughout AR6, but do not follow any particular scenario in all places and over all time.

Conditions for Climate Resilient Development

SPM.D.1 Evidence of observed impacts, projected risks, levels and trends in vulnerability, and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in AR5. Comprehensive, effective, and innovative responses can harness synergies and reduce trade-offs between adaptation and mitigation to advance sustainable development. (*very high confidence*) {2.6, 3.4, 3.6, 4.2, 4.6, 7.2, 7.4, 8.3, 8.4, 9.3, 10.6, 13.3, 13.8, 13.10, 14.7, 17.2, 18.3, Figure 18.1, Table 18.5, Box 18.1}

SPM.D.1.1 There is a rapidly narrowing window of opportunity to enable climate resilient development. Multiple climate resilient development pathways are still possible by which communities, the private sector, governments, nations and the world can pursue climate resilient development – each involving and resulting from different societal choices influenced by different contexts and opportunities and constraints on system transitions. Climate resilient development pathways are progressively constrained by every increment of warming, in particular beyond 1.5°C, social and economic inequalities, the balance between adaptation and mitigation varying by national, regional and local circumstances and geographies, according to capabilities including resources, vulnerability, culture and values, past development choices leading to past emissions and future warming scenarios, bounding the climate resilient development pathways remaining, and the ways in which development trajectories are shaped by equity, and social and climate justice. (*very high confidence*) {2.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 9.4, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, 18.5, CCP2.3, CCP3.4, CCP4.4, CCP5.3, CCP5.4, Table CCP5.2, CCP6.3, CCP7.5, Figure TS14.d}

SPM.D.1.2 Opportunities for climate resilient development are not equitably distributed around the world (*very high confidence*). Climate impacts and risks exacerbate vulnerability and social and economic inequities and consequently increase persistent and acute development challenges, especially in developing regions and sub-regions, and in particularly exposed sites, including coasts, small islands, deserts, mountains and polar regions. This in turn undermines efforts to achieve sustainable development, particularly for vulnerable and marginalized communities (*very high confidence*). {2.5, 4.4, 4.7, 6.3, 9.4, Box 6.4, Figure 6.5, Table 18.5, CWGB URBAN, CCB HEALTH, CCP2.2, CCP3.2, CCP3.3, CCP5.4, CCP6.2}

SPM.D.1.3 Embedding effective and equitable adaptation and mitigation in development planning can reduce vulnerability, conserve and restore ecosystems, and enable climate resilient development. This is especially challenging in localities with persistent development gaps and limited resources (*high confidence*). Dynamic trade-offs and competing priorities exist between mitigation, adaptation, and development. Integrated and inclusive system-oriented solutions based on equity and social and climate justice reduce risks and enable climate resilient development (*high confidence*). {1.4, 2.6, 3.6, 4.7, 4.8, Box 4.5, Box 4.8, 5.13, 7.4, 8.5, 9.4, 10.6, Box 9.3, Box 2.2, 12.5, 12.6, 13.3, 13.4, 13.10, 13.11, 14.7, 18.4, CCB HEALTH, SRCCL, CCB DEEP, CCP2, CCP5.4}

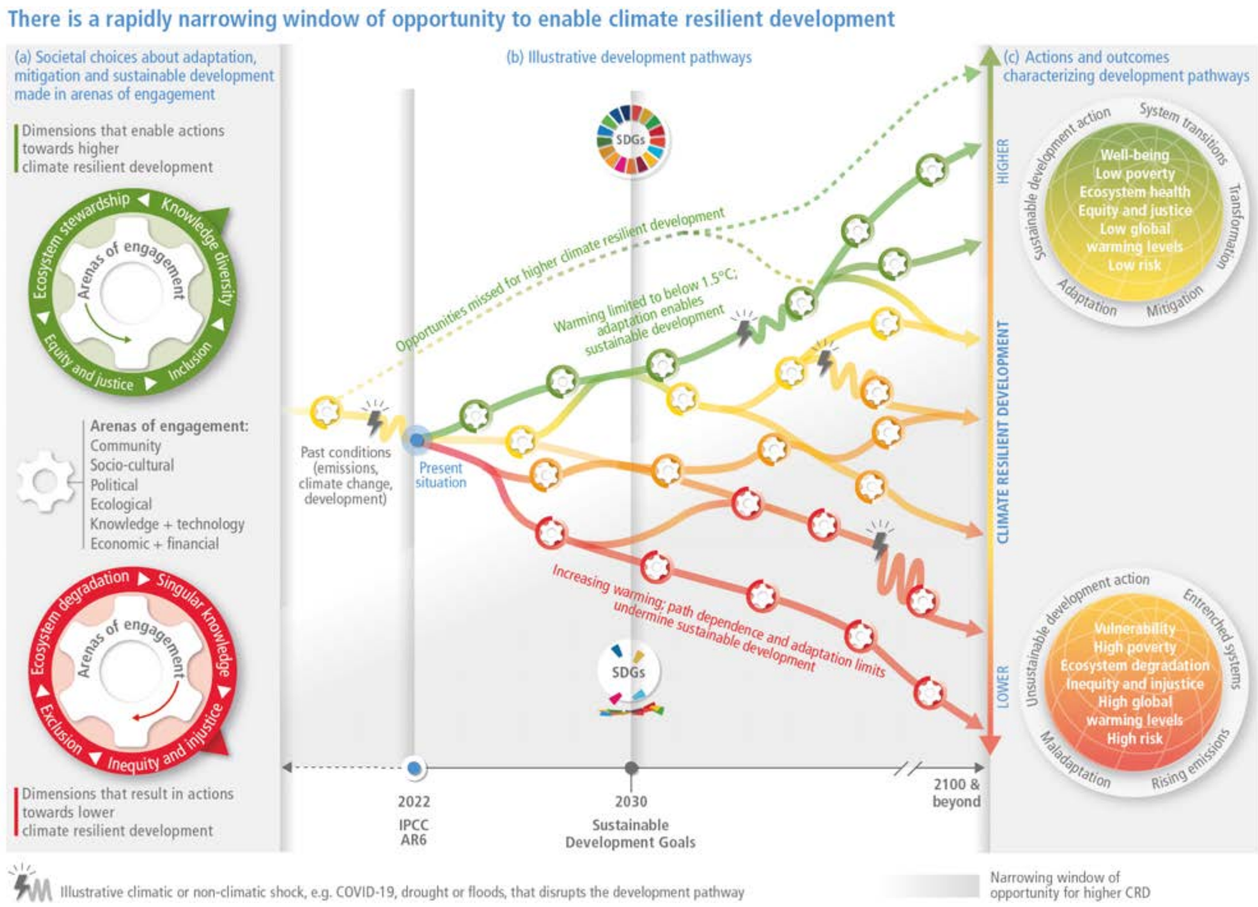


Figure SPM.5: Climate resilient development (CRD) is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. This figure builds on Figure SPM.9 in AR5 WGII (depicting climate resilient pathways) by describing how CRD pathways are the result of cumulative societal choices and actions within multiple arenas. Panel (a): Societal choices towards higher CRD (green cog) or lower CRD (red cog) result from interacting decisions and actions by diverse government, private sector and civil society actors, in the context of climate risks, adaptation limits and development gaps. These actors engage with adaptation, mitigation and development actions in political, economic and financial, ecological, socio-cultural, knowledge and technology, and community arenas from local to international levels. Opportunities for climate resilient development are not equitably distributed around the world. Panel (b): Cumulatively, societal choices, which are made continuously, shift global development pathways towards higher (green) or lower (red) climate resilient development. Past conditions (past emissions, climate change and development) have already eliminated some development pathways towards higher CRD (dashed green line). Panel (c): Higher CRD is characterised by outcomes that advance sustainable development for all. Climate resilient development is progressively harder to achieve with global warming levels beyond 1.5°C. Inadequate progress towards the Sustainable Development Goals (SDGs) by 2030 reduces climate resilient development prospects. There is a narrowing window of opportunity to shift pathways towards more climate resilient development futures as reflected by the adaptation limits and increasing climate risks, considering the remaining carbon budgets. (Figure SPM.2, Figure SPM.3) {2.6, 3.6, 7.2, 7.3, 7.4, 8.3, 8.4, 8.5, 16.4, 16.5, 17.3, 17.4, 17.5, 18.1, 18.2, 18.3, 18.4, Figure 18.1, Figure 18.2, Figure 18.3, Box 18.1, CCB COVID, CCB GENDER, CCB HEALTH, CCB INDIG, CCB SLR, AR6 WGI Table SPM.1 and Table SPM.2, SR1.5 Figure SPM.1, Figure TS.14b}

Enabling Climate Resilient Development

SPM.D.2 Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (*very high confidence*). Climate resilient development is facilitated by international cooperation and by governments at all levels working with communities, civil society, educational bodies, scientific and other institutions, media, investors and businesses; and by developing partnerships with traditionally marginalised groups, including women, youth, Indigenous Peoples, local communities and ethnic minorities (*high confidence*). These partnerships are most effective when supported by enabling political leadership, institutions, resources, including finance, as well as climate services, information and decision support tools (*high confidence*). (Figure SPM.5) {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.4, 17.6, 18.4, 18.5, CCP2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.2.1 Climate resilient development is advanced when actors work in equitable, just and enabling ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes (*high confidence*). These practices build on diverse knowledges about climate risk and chosen development pathways account for local, regional and global climate impacts, risks, barriers and opportunities (*high confidence*). Structural vulnerabilities to climate change can be reduced through carefully designed and implemented legal, policy, and process interventions from the local to global that address inequities based on gender, ethnicity, disability, age, location and income (*very high confidence*). This includes rights-based approaches that focus on capacity-building, meaningful participation of the most vulnerable groups, and their access to key resources, including financing, to reduce risk and adapt (*high confidence).* Evidence shows that climate resilient development processes link scientific, Indigenous, local, practitioner and other forms of knowledge, and are more effective and sustainable because they are locally appropriate and lead to more legitimate, relevant and effective actions (*high confidence*). Pathways towards climate resilient development overcome jurisdictional and organizational barriers, and are founded on societal choices that accelerate and deepen key system transitions (*very high confidence*). Planning processes and decision analysis tools can help identify 'low regrets' options[47] that enable mitigation and adaptation in the face of change, complexity, deep uncertainty and divergent views (*medium confidence*). {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, Box 8.7, Box 9.2, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.2.2 Inclusive governance contributes to more effective and enduring adaptation outcomes and enables climate resilient development (*high confidence*). Inclusive processes strengthen the ability of governments and other stakeholders to jointly consider factors such as the rate and magnitude of change and uncertainties, associated impacts, and timescales of different climate resilient development pathways given past development choices leading to past emissions and scenarios of future global warming (*high confidence*). Associated societal choices are made continuously through interactions in arenas of engagement from local to international levels. The quality and outcome of these interactions helps determine whether development pathways shift towards or away from climate resilient development (*medium confidence*). (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG}

SPM.D.2.3 Governance for climate resilient development is most effective when supported by formal and informal institutions and practices that are well-aligned across scales, sectors, policy domains and timeframes. Governance efforts that advance climate resilient development account for the dynamic, uncertain and context-specific nature of climate-related risk, and its interconnections with non-climate risks. Institutions[48] that enable climate resilient development are flexible and responsive to emergent risks and facilitate sustained and timely action. Governance for climate resilient development is enabled by adequate and appropriate human and technological resources, information, capacities and finance. (*high confidence*) {2.7, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

Climate Resilient Development for Natural and Human Systems

SPM.D.3 Interactions between changing urban form, exposure and vulnerability can create climate change-induced risks and losses for cities and settlements. However, the global trend of urbanisation also offers a critical opportunity in the near-term, to advance climate resilient development (*high confidence*). Integrated, inclusive planning and investment in everyday decision-making about urban infrastructure, including social, ecological and grey/physical infrastructures, can significantly increase the adaptive capacity of urban and rural settlements. Equitable outcomes contributes to multiple benefits for health and well-being and ecosystem services, including for Indigenous Peoples, marginalised and vulnerable communities (*high confidence*). Climate resilient development in urban areas also supports adaptive capacity in more rural places through maintaining peri-urban supply chains of goods and services and financial flows (*medium confidence*). Coastal cities and settlements play an especially important role in advancing climate resilient development (*high confidence*). {6.2, 6.3, 18.3, Table 6.6, Box 9.8, CCP6.2, CCP2.1. CCP2.2, CWGB URBAN}

SPM.D.3.1 Taking integrated action for climate resilience to avoid climate risk requires urgent decision making for the new built environment and retrofitting existing urban design, infrastructure and land use. Based on socioeconomic circumstances, adaptation and sustainable development actions will provide multiple benefits including for health and well-being, particularly when supported by national governments, non-governmental organisations and international agencies that work across sectors in partnerships with local communities. Equitable partnerships between local and municipal governments, the private sector, Indigenous Peoples, local communities, and civil society can, including through international cooperation, advance climate resilient development by addressing structural inequalities, insufficient financial resources, cross-city risks and the integration of Indigenous knowledge and Local knowledge. (*high confidence*) {6.2, 6.3, 6.4, 7.4, 8.5, 9.4, 10.5. 12.5, 17.4, 18.2, Table 6.6, Table 17.8, Box 18.1, CCP2.4, CCB GENDER, CCB INDIG, CCB FINANCE, CWGB URBAN}

SPM.D.3.2 Rapid global urbanisation offers opportunities for climate resilient development in diverse contexts from rural and informal settlements to large metropolitan areas (*high confidence*). Dominant models of energy intensive and market-led urbanisation, insufficient and misaligned finance and a predominant focus on grey infrastructure in the absence of integration with ecological and social approaches, risks missing opportunities for adaptation and locking in maladaptation (*high confidence*). Poor land use planning and siloed approaches to health, ecological and social planning also exacerbates, vulnerability in already marginalised

[48] Institutions: Rules, norms and conventions that guide, constrain or enable human behaviours and practices. Institutions can be formally established, for instance through laws and regulations, or informally established, for instance by traditions or customs. Institutions may spur, hinder, strengthen, weaken or distort the emergence, adoption and implementation of climate action and climate governance.

communities (*medium confidence*). Urban climate resilient development is observed to be more effective if it is responsive to regional and local land use development and adaptation gaps, and addresses the underlying drivers of vulnerability (*high confidence*). The greatest gains in well-being can be achieved by prioritizing finance to reduce climate risk for low-income and marginalized residents including people living in informal settlements (*high confidence*). {5.14, 6.1, 6.2, 6.3, 6.4, 6.5, 7.4, 8.5, 8.6, 9.8, 9.9, 10.4, 18.2, Table 17.8, Table 6.6, Figure 6.5, CCB HEALTH, CCP2.2, CCP5.4, CWGB URBAN}

SPM.D.3.3 Urban systems are critical, interconnected sites for enabling climate resilient development, especially at the coast. Coastal cities and settlements play a key role in moving toward higher climate resilient development given firstly, almost 11% of the global population – 896 million people – lived within the Low Elevation Coastal Zone[49] in 2020, potentially increasing to beyond 1 billion people by 2050, and these people, and associated development and coastal ecosystems, face escalating climate compounded risks, including sea level rise. Secondly, these coastal cities and settlements make key contributions to climate resilient development through their vital role in national economies and inland communities, global trade supply chains, cultural exchange, and centres of innovation. (*high confidence*) {6.2, Box 15.2, CCP2.1, CCP2.2, Table CCP2.4, CCB SLR}

SPM.D.4 Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, in light of the threats climate change poses to them and their roles in adaptation and mitigation (*very high confidence*). Recent analyses, drawing on a range of lines of evidence, suggest that maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). {2.4, 2.5, 2.6, 3.4, Box 3.4, 3.5, 3.6, 12.5, 13.3, 13.4, 13.5, 13.10, CCB NATURAL, CCB INDIG}

SPM.D.4.1 Building the resilience of biodiversity and supporting ecosystem integrity[50] can maintain benefits for people, including livelihoods, human health and well-being and the provision of food, fibre and water, as well as contributing to disaster risk reduction and climate change adaptation and mitigation.{2.2, 2.5, 2.6, Table 2.6, Table 2.7, 3.5, 3.6, 5.8, 5.13, 5.14, 12.5, Box 5.11 CCP5.4, CCB NATURAL, CCB ILLNESS, CCB COVID, CCB GENDER, CCB INDIG, CCB MIGRATE}

SPM.D.4.2 Protecting and restoring ecosystems is essential for maintaining and enhancing the resilience of the biosphere (*very high confidence*). Degradation and loss of ecosystems is also a cause of greenhouse gas emissions and is at increasing risk of being exacerbated by climate change impacts, including droughts and wildfire *(high confidence)*. Climate resilient development avoids adaptation and mitigation measures that damage ecosystems (*high confidence*). Documented examples of adverse impacts of land-based measures intended as mitigation, when poorly implemented, include afforestation of grasslands, savannas and peatlands, and risks from bioenergy crops at large scale to water supply, food security and biodiversity (*high confidence*). {2.4, 2.5, Box 2.2, 3.4, 3.5, Box 3.4, Box 9.3, CCP7.3, CCB NATURAL, CWGB BIOECONOMY}

SPM.D.4.3 Biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, which will make climate resilient development progressively harder to achieve beyond 1.5°C warming (*very high confidence*). Consequences of current and future global warming for climate resilient development include reduced effectiveness of EbA and approaches to climate change mitigation based on ecosystems and amplifying feedbacks to the climate system (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.5, 3.6, 12.5, 13.2, 13.3, 13.10, 14.5, 14.5, 15.3, 17.3, 17.6, Box 14.3, Box 3.4, Table 5.2, CCP5.3, CCP5.4, Figure TS.14d, CCB EXTREMES, CCB ILLNESS, CCB NATURAL, CCB SLR, SR1.5, SRCCL, SROCC}

---

[49] LECZ, coastal areas below 10 m of elevation above sea level that are hydrologically connected to the sea

[50] Ecosystem integrity refers to the ability of ecosystems to maintain key ecological processes, recover from disturbance, and adapt to new conditions.

Achieving Climate Resilient Development

SPM.D.5 It is unequivocal that climate change has already disrupted human and natural systems. Past and current development trends (past emissions, development and climate change) have not advanced global climate resilient development (*very high confidence*). Societal choices and actions implemented in the next decade determine the extent to which medium- and long-term pathways will deliver higher or lower climate resilient development (*high confidence*). Importantly climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5°C global warming is exceeded in the near term (*high confidence*). These prospects are constrained by past development, emissions and climate change, and enabled by inclusive governance, adequate and appropriate human and technological resources, information, capacities and finance (*high confidence*). {1.2, 1.4, 1.5, 2.6, 2.7, 3.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 8.5, 8.6, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 13.11, 14.7, 15.3, 15.6, 15.7, 16.2, 16.4, 16.5, 16.6, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, Table CCP5.2, CCP5.3, CCP5.4, CCP6.3, CCP6.4, CCP7.5, CCP7.6, Figure TS.14d, CCB DEEP, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.5.1 Climate resilient development is already challenging at current global warming levels (*high confidence*). The prospects for climate resilient development will be further limited if global warming levels exceeds 1.5°C (*high confidence*) and not be possible in some regions and sub-regions if the global warming level exceeds 2°C (*medium confidence*). Climate resilient development is most constrained in regions/subregions in which climate impacts and risks are already advanced, including low-lying coastal cities and settlements, small islands, deserts, mountains and polar regions (*high confidence*). Regions and subregions with high levels of poverty, water, food and energy insecurity, vulnerable urban environments, degraded ecosystems and rural environments, and/or few enabling conditions, face many non-climate challenges that inhibit climate resilient development which are further exacerbated by climate change (*high confidence*). {1.2, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, CCP2.3, CCP3.4, CCP4.4, Box 6.6. CCP5.3, Table CCP5.2, CCP6.3, CCP7.5, Figure TS.14d}

SPM.D.5.2 Inclusive governance, investment aligned with climate resilient development, access to appropriate technology and rapidly scaled-up finance, and capacity building of governments at all levels, the private sector and civil society enable climate resilient development. Experience shows that climate resilient development processes are timely, anticipatory, integrative, flexible and action focused. Common goals and social learning build adaptive capacity for climate resilient development. When implementing adaptation and mitigation together, and taking trade-offs into account, multiple benefits and synergies for human well-being as well as ecosystem and planetary health can be realised. Prospects for climate resilient development are increased by inclusive processes involving local knowledge and Indigenous Knowledge as well as processes that coordinate across risks and institutions. Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for vulnerable regions, sectors and groups. (*high confidence*) (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.5.3 The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all. (*very high confidence*) {1.2, 1.4, 1.5, 16.2, 16.4, 16.5, 16.6, 17.4, 17.5, 17.6, 18.3, 18.4, 18.5, CWGB URBAN, CCB DEEP, Table SM16.24, WGI SPM, SROCC SPM, SRCCL SPM}

Chapter 1: Point of Departure and Key Concepts

Coordinating Lead Authors: Rawshan Ara Begum (Malaysia/Australia/Bangladesh) and Robert Lempert (USA)

Lead Authors: Elham Ali (Egypt), Tor Arve Benjaminsen (Norway), Thomas Bernauer (Switzerland), Wolfgang Cramer (France/Germany), Xuefeng Cui (China), Katharine Mach (USA), Gustavo Nagy (Uruguay), Nils Christian Stenseth (Norway), Raman Sukumar (India), and Philippus Wester (Nepal/Netherlands)

Contributing Authors: Ed Carr (USA), Vanesa Castán Broto (United Kingdom), Connor Joseph Cavanagh (Norway), Eva Davidsdottir (Norway), Marjolin Haasnoot (The Netherlands), Timo Leiter (Germany/United Kingdom), Martina Linnenluecke (Australia), Judy Lawrence (New Zealand), Lorena Gonzalez Lopez (Mexico), Leonardo Martinez-Diaz (USA), Md. Shahin Mia (Malaysia/Bangladesh), Tero Mustonen (Finland), Ben Orlove (USA), Karishma V. Patel (USA), S.V.R.K. Prabhakar (Japan/India), Benjamin L. Preston (USA), Nicholas P. Simpson (South Africa), Jo Skeie Hermansen (Norway), Asif Raihan (Bangladesh), William Solecki (USA), Joe Thwaites (United Kingdom), Christopher Trisos (South Africa), Michael Weisberg (USA)

Review Editors: Roberto Sánchez Rodríguez (Mexico) and Michael Sutherland (Trinidad and Tobago/Jamaica)

Chapter Scientist: Karishma V. Patel (USA)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

The IPCC Working Group II contribution to the Sixth Assessment Report addresses the challenges of climate action in the context of sustainable development with a particular focus on climate change impacts, adaptation and vulnerability. This chapter frames the point of departure and key concepts building on the IPCC's Fifth Assessment Report (WGII AR5), the Special Report on Global Warming of 1.5°C, the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) and the Special Report on Climate Change and Land (SRCCL); as well as the WGI contributions to the Sixth Assessment Report and compliments the contribution of the WGIII Sixth Assessment Report which will be published after this report.

Since IPCC AR5, human influence on the Earth's climate has become unequivocal, increasingly apparent, and widespread, reflected in both the growing scientific literature and in the perception and experiences of people worldwide (*high confidence*). Current changes in the climate system and those expected in the future will increasingly have significant and deleterious impacts on human and natural systems. The impacts of climate change and extreme weather events have adversely affected, or caused the loss of ecosystems including terrestrial, freshwater, ocean and coastal ecosystems, including tropical coral reefs; reduced food security; contributed to migration and displacement; damaged livelihoods, health and security of people; and increased inequality. Climate change impacts are concurrent and interact with other significant societal changes that have become more salient since AR5, including a growing and urbanising global population; significant inequality and demands for social justice; rapid technological change; continuing poverty, land and water degradation, biodiversity loss; food insecurity; and a global pandemic. {1.1.1, 1.3, Cross-Working Group Box ATTRIB in Chapter 1}

Since AR5, climate action has grown in salience worldwide across all levels of government as well as among non-governmental organisations, small and large enterprises and citizens (*high confidence*). At the international level the Paris Agreement and the Sustainable Development Goals (SDGs), along with other targets and frameworks such as the Sendai Framework for Disaster Risk Reduction, the Convention on Biological Diversity (CBD) Aichi targets, the Addis Ababa Action Agenda for finance and the New Urban Agenda, provide overarching goals and policy context. These agreements also provide policy goals used by this IPCC Report to assess climate action across all levels of society. {1.1.2, 1.4.1, 1.4.3}

IPCC's assessments have grown and changed substantially over the last three decades. Compared to earlier IPCC assessments, this report emphasizes a common risk-solution framing across all three working groups. This report focuses on solutions for risk reduction and adaptation, provides more integration across the natural and social sciences, applies a more comprehensive risk framework; assesses adaptation directly in the context of sectoral or regional risks; engages with different forms of knowledge, including Indigenous knowledge and local knowledge; and includes an increasing focus on social justice. {1.1.4, 1.4.2, Cross-Chapter Box ADAPT in Chapter 1}

Adaptation plays a key role in reducing risks and vulnerability from climate change. Implementing adaptation and mitigation actions together with SDGs helps to exploit synergies, reduce trade-offs and makes all three more effective. From a risk perspective, limiting atmospheric greenhouse gas concentrations reduces climate-related hazards while adaptation and sustainable development reduce exposure and vulnerability to those hazards. Adaptation facilitates development, which is increasingly hindered by impacts and risks from climate change. Development facilitates adaptation by expanding the resources and capacity to reduce climate risks and vulnerability. {1.1.3, 1.5.1, 1.5.3}

The concepts of risk and risk management have become increasingly central to climate change literature, research, practice and decision making (*medium confidence*). Risk, defined as the potential for adverse consequences for human and ecological systems, recognising the diversity of values and objectives associated with such systems, provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change; how these impacts differentially affect different regions, sectors and populations; how to allocate resources best to manage the resulting risks and how to evaluate the responses that reduce residual risks for current and future generations, economies and ecosystems. {1.2.1, 1.3.1, 1.4.2}

The concepts of adaptation, vulnerability, resilience and risk provide overlapping, alternative entry points for the climate change challenge (*high confidence*). Vulnerability is a component of risk, but also an important focus independently, improving understanding of the differential impacts of climate change on people of different gender, race, wealth, social status and other attributes. Vulnerability also provides an important link between climate adaptation and disaster risk reduction. Resilience, which can refer to either a process or outcome, encompasses not just the concept of maintaining essential function, identity and structure, but also maintaining a capacity for transformation. Such transformations bring forth questions of justice, power and politics. {1.2.1, 1.4.1}

Risks from climate change differ through space and time and cascade across and within regions and systems. The total risk in any location may thus differ from the sum of individual risks if these interactions, as well as risks from responses themselves, are not considered (*high confidence*). The risks of climate change responses include the possibility of mitigation or adaptation responses not achieving their intended objectives or having trade-offs or adverse side effects for other societal objectives. Another core area of complexity in climate risk is the behaviour of systems, which includes multiple stressors unfolding together, cascading or compounding interactions within and across sectors and regions and non-linear responses and the potential for surprises, all of which is crucial for effective decision-making and decision-support methods. The key risks assessed in this report become important in interaction with the cultures, values, ethics, identities, experiences and knowledge systems of affected communities and societies. {1.3.1}

Increasingly, impacts are detected and attributed to the changing climate. Improved understanding of deep history (palaeoclimate and biotic responses) suggests that past climate changes have already caused substantial ecological, evolutionary and socio-economic impacts (*high confidence*). Many recent impacts are not detected, due to a shortage of monitoring and robust attribution analysis (*high confidence*). Detection and attribution assessments inform the risk assessment by demonstrating the sensitivity of a system to climate change, and they can inform the loss and damage estimates including those involved in potential climate litigation cases. Robust detection and attribution methods now exist, they play a significant role in increasing awareness and willingness to act among decision makers and the general population. {1.3.2.1, Cross-Working Group Box ATTRIB in Chapter 1, Cross-Chapter Box PALEO in Chapter 1}

Narratives play an important role in communicating climate risks and motivating solutions. A narrative describes a chronological chain of events, often with a premise and conclusions. In the AR6, as in previous IPCC assessments, climate change scenarios and related narratives (also called storylines) are central in the analysis, synthesis and communication of climate change impacts and of adaptation and mitigation responses. AR6 employs narratives to describe the assumptions, evolution and driving forces for the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) and links these to Global Warming Levels (GWLs) as a complement to RCPs and SSPs for framing impacts (Ch1 Cross-Chapter Box CLIMATE). Narratives can also be enablers of transformation by communicating societal goals and the actions needed to achieve them {1.2.2, 1.3.3, 1.5.2}

AR6 highlights adaptation solutions and the extent to which they are successful and adequate at reducing climate risk, increasing resilience and pursuing other climate-related societal goals. For adaptation, a solution is defined as an option which is effective, feasible and conforms to principles of justice. Effectiveness refers to the extent to which an action is anticipated or is observed to reduce climate-related risk. Feasibility refers to the extent to which a measure is considered possible and desirable in a particular context. A successful action is one observed to be effective, feasible and just. Adequacy refers to a set of solutions that together are sufficient to avoid dangerous, intolerable, or severe climate risks. {1.4}

Indigenous knowledge and local knowledge (IK and LK) can provide important understanding for acting effectively on climate risk and can help diversify knowledge that may enrich adaptation policy and practice (*high confidence*). Indigenous Peoples have been faced with adaptation challenges for centuries and have developed strategies for resilience in changing environments that can enrich and strengthen current and future adaptation efforts. Valuing IK and LK is also important for recognition, a key component of climate justice. {1.3.2.3}

AR6 highlights three principles of climate justice: distributive justice, procedural justice and recognition. Distributive justice refers to the allocation of burdens and benefits among individuals, nations and generations; procedural justice refers to who decides and participates in decision-making; and recognition entails basic respect and robust engagement with and fair consideration of diverse cultures and perspectives. This report considers all three principles in the assessment of adaptation options and evaluates the extent to which better outcomes are obtained by choosing just ones. Since potential trade-offs exist among the principles, adaptation assessments will in general involve normative judgements as well as science-based evidence. {1.4.1.1}

Concepts of justice and measures of well-being are increasingly used to evaluate the extent to which climate change adaptation is equitable and effective (*medium confidence*). AR6 employs evaluation frameworks based on both single and multi-criteria to assess adaptation effectiveness and consistency with principles of justice. Single criteria frameworks aggregate many attributes into a one number or ranking, often quantified using benefit-cost analysis or measures of social welfare. Existing decision processes often favour such single criteria, which also correlate well with many measures of social progress and sustainable development. Multi-criteria frameworks simultaneously report several different biophysical and socio-economic attributes, which provides more information on potential trade-offs and synergies and can engage with emerging concepts of well-being. {1.4.1.1, 1.4.1.2}
The concepts of enablers, catalysts and the solution space help AR6 assess ways to speed the implementation of and expand the range of adaptation solutions. Many potential solutions exist, which have not yet been implemented despite the gap between current and adequate levels of adaption. Enablers enhance the feasibility of adaptation options and include governance, finance and knowledge**.** Catalysts accelerate and motivate the adaptation decision-making process. The concept of solution space -- defined as the space within which opportunities and constraints determine why, how, when and who adapts to climate risks – helps this report assess how human choices and exogenous changes can expand and contract the set of effective, feasible and just solutions. {1.4.2}

Effective governance, adaptation finance and nature-based solutions are important enablers for expanding the solutions space and reducing adaptation gaps (*high confidence*). Actors at many scales and in many sectors are adapting already and can take additional and more significant adaptation action. These include individuals and households, communities, governments at all levels, private sector businesses, non-governmental organisations and religious groups and social movements. Many forms of adaptation (depending on the type of climatic risk and societal context) are likely to be more effective, cost-efficient, and potentially also more equitable when organized collectively. Stronger governance and adaptation finance capabilities are usually associated with more ambitious adaptation plans and more effective implementation of such plans. {1.4.2, 1.4.2}

Monitoring and Evaluation (M&E) of adaptation refers to a broad range of activities necessary for tracking adaptation progress over time, improving adaptation effectiveness and successful iterative risk management. Monitoring usually refers to continuous information gathering whereas evaluation denotes more comprehensive assessments of effectiveness and equity, often resulting in recommendations for decision makers. In some literatures M&E refers solely to efforts undertaken after implementation. In other literatures, M&E refers both to efforts conducted before and after implementation. Since AR5, a growing literature provides initial inventories of adaptation plans and implementation worldwide, but information on effectiveness remains scare (*high confidence*). {1.4.3, Cross-Chapter Box ADAPT in Chapter 1}

The concept of limits to adaptation is dynamic in terms of the temporal, spatial and contextual dimensions of climate change risks, impacts and response. Socioeconomic, technological, governance and institutional systems or policies can be changed or transformed in responses to the different dimensions of adaptation limits to climate change and extreme events. Adaptation limits can be soft or hard. Soft adaptation limits occur when options may exist but are currently not available to avoid intolerable risks through adaptive actions and hard adaptation limits occur when no adaptive actions are possible to avoid intolerable risks. The level of greenhouse gas reduction, adaptation and risk management measures are the key factors determining if and when adaptation limits are reached. When a limit (soft) is reached, then intolerable risks and impacts may occur and additional adaptations (incremental or transformational) would be required. Transformational adaptation can allow a system to extend beyond its soft limits and prevent soft limits to become hard limits. The loss and damage associated with the future climate change impacts, beyond the limits to adaptation, is an area of increasing focus, although yet to be fully developed in terms of methods of assessing including non-economic values and identifying means to avoid and reduce both economic (loss of asset, infrastructure, land etc.) and non-economic (loss of societal beliefs and values, cultural heritage, biodiversity and ecosystem services) losses and damages. {1.4.4.1, 1.4.4.2}

Key concepts in this report provide a framework for assessing the urgency of climate change adaptation. Adaptation is urgent to the extent that soft adaptation limits are currently being approached or exceeded and that achieving levels of adaptation adequate to address these soft limits requires action at a speed and scale faster than that represented by current trends (*high confidence*). In addition, adaptation is urgent to the extent that any needed expansion of the future solution space requires near-term strengthening and expansion of enablers such as governance, finance and information. Finally, adaptation is urgent to the extent that current maladaptation and socio-economic trends, such as rapid urbanisation and continued inequalities, lock in patterns of vulnerability and exposure that increase future risk (*high confidence*). {1.1.3, 1.4.4, 1.5.1}

AR6 highlights the role of transformation in meeting the Paris Agreement, the SDG and other policy goals. Transformation, and the related term transition, are pluralistic concepts, embracing the idea of major, fundamental changes in society or natural systems as opposed to changes that are minor, marginal, or incremental. AR6 has a particular focus on transformational adaptation, which changes the fundamental attributes of a socio-economic system in anticipation of climate change and its impacts. AR6 describes transitions in five systems: energy, land and ecosystem, urban and infrastructure, industrial and societal. In the past, transformations of such scale have been associated not only with technological and economic changes, but with shifts in most aspects of society. {1.2.1.3, 1.4.4, 1.5.1}

Future transformation could be deliberate, envisioned and intended by at least some societal actors, who seek to expand the solution space, overcome soft limits to adaptation, reduce residual risk to tolerable levels and achieve societal goals. If such a transformation is not pursued or is not successful and risk remains above intolerable levels a forced transformation may occur less consistent with societal goals. The literature describes incremental and transformational change as linked processes. The transformational adaptation literature suggests shifts from incremental to transformational processes are made possible by knowledge and skills, as well adjustments to vision, agendas and coalitions achieved through monitoring and learning. The socio-ecological and sustainability transitions literature suggests that actors seeking deliberate transformation may take incremental steps that aim to induce societal tipping point behaviour in the near or longer-term. Alternative pathways for pursuing deliberate transformations range from a focus on modernisation of sectors such as energy, agriculture and use of natural resources to proposals for degrowth that aim for intentional decreases in both GDP and coupled GHG emissions. {1.2.1.3, 1.4.4, 1.5.1}

Transformation is understood as a collective action challenge among actors with both common and differing values interacting with a mix of competition and cooperation. Significant innovations often begin in niches or protected spaces, sometimes introduced by new entrants or outsiders. The drivers of transformation are multi-dimensional, involving social, cultural, economic, environmental, technical and political processes the combination of which create the potential for abrupt and systemic change, the stability of entrenched and interlocked power structures and the importance of individual beliefs and behaviours. Decision frameworks that consider multiple objectives and multiple scenarios can avoid privileging some views over others and help multiple actors to identify resilient and equitable solutions to complex, deeply uncertain challenges. Nonetheless, common goals and narratives are both enablers of transformation and help align the activities of multiple, loosely co-ordinated actors. {1.5.2}.

This report employs the climate resilient development concept to inform co-ordinated implementation of adaptation and mitigation solutions to support sustainable development for all. As a transformation that emerges from the choices of many different actors, climate resilient development follows no single or preferred pathway and no single best combination of adaptation, mitigation and sustainable development strategies. All pathways involve complex trade-offs and synergies among different actions. The climate resilient development concept helps assess the extent to which solutions currently exist to meet societal goals or the extent to which an expanded solution space is required. The concept also helps assess the role of various actors, including governments, citizens, civil society, knowledge institutions, media, investors and businesses as well as assessing the need for arenas of engagement in which they can interact. {1.2.3, 1.5.2, 1.5.3}

1.1 The Current Urgent Moment

1.1.1 A Changing Climate in a Changing World

Numerous additional significant climate-related changes have unfolded worldwide since publication of the IPCC Fifth Assessment Report (AR5) in 2014 (IPCC, 2014a). Consistent with projections, multiple, concurrent, changes in the physical climate system have grown more salient, including increasing global temperatures, loss of ice volume, rising sea levels and changes in global precipitation patterns (WGI AR6 Chapter 1). The changes in the physical climate system, most notably more intensive extreme events, have adversely affected natural and human systems around the world, contributing to a loss and degradation of ecosystems including tropical coral reefs; reduced water and food security; increased damage to infrastructure; additional mortality and morbidity; human migration and displacement; damaged livelihoods; increased mental health issues; and increased inequality. Since AR5, a growing literature attributes change in particular climate variables to observed damages to specific, localized human and natural systems in many regions of the world, as shown in Figure 1.1 (Chapter 1 BOX ATTRIBUTE).

Concurrently, since AR5, a growing share of people around the world perceive a changing climate, regard these changes as significant, and consider climate action as a matter of high urgency (Wilson and Orlove, 2019; Section 17.4.5). A survey, representing over half the world's population, found that almost two-thirds of people across 50 countries view climate change as an emergency (Flynn et al., 2021), compared to just over half across 23 countries in 2013 (Fagan, 2019). The highest level of support for climate action is among small-island developing states (74%), followed by high income countries (72%), middle income countries (62%), and, then, least developed countries (58%) (Flynn et al., 2021). Notably after mid-2018, global media showed a large increase number of mentions of "global warming", "climate change" and similar terms (Thackeray et al., 2020). The business communities' now consistently includes climate change, including "climate action failure" as a major risk (World Economic Forum, 2021). In late 2019, protests calling for strengthened climate action reached an unprecedented level of over 6000 events in 185 countries, with a reported estimate of 7.6 million participants, largely led by the "Fridays for Future" youth movement (Chase-Dunn and Almeida, 2020).

Since AR5, governments, businesses and civil society have increasingly responded with planning and actions aimed at reducing current and future risks from climate change (Section 1.1.2; Chapter 16 and 17). Concern with climate change has increasingly motivated actions by governments, the private sector, and civil society (Hale et al., 2021; Section 18.4.3). As described in this report, however, current climate policies and actions alone are not sufficient to meet stated policy goals (Section 1.1.3) *(high confidence*).

This report addresses the challenges of climate action in the context of sustainable development. Climate action takes place in a world already undergoing some of the most rapid and significant societal and environmental change in decades (IPCC, 2018c, Box 1.1), including: species and ecosystems lost due to land- and sea-use change and pollution (IPBES, 2019a); a growing and urbanising world population (Gerten et al., 2019; van Vliet et al., 2017); technology reshaping the workplace through automation (Schwab, 2017) and information dissemination through social media (Mavrodieva et al., 2019; Pearce et al., 2019), and increasing inequalities due to gender, poverty, age, race and ethnicity (Cross-Chapter Box GENDER in Chapter 18). Economic inequality grows within nations even as it has narrowed among them (UN Department of Economic and Social Affairs, 2020). International polycentric governance and nonstate actors play an important role (Beck and Mahony, 2018; Sections 1.4.2 and 17.1.2.1). In 2020 and 2021, a global pandemic dramatically affected the lives of most of the world's population, likely accelerating many of the changes already underway (Cross-Chapter Box COVID in Chapter 7).

The point of departure for this AR6 Working Group II report thus lies in rapid and significant changes in our climate and our world, growing attentiveness to those changes, a gap between current climate action and that needed to address policy goals, and a growing literature that improves understanding and informs potential responses. This chapter defines key concepts and the connections among them useful for comprehending and evaluating these changes, the risks they generate, and options for incremental and transformative solutions that could reduce climate-related risks, impacts and vulnerability.

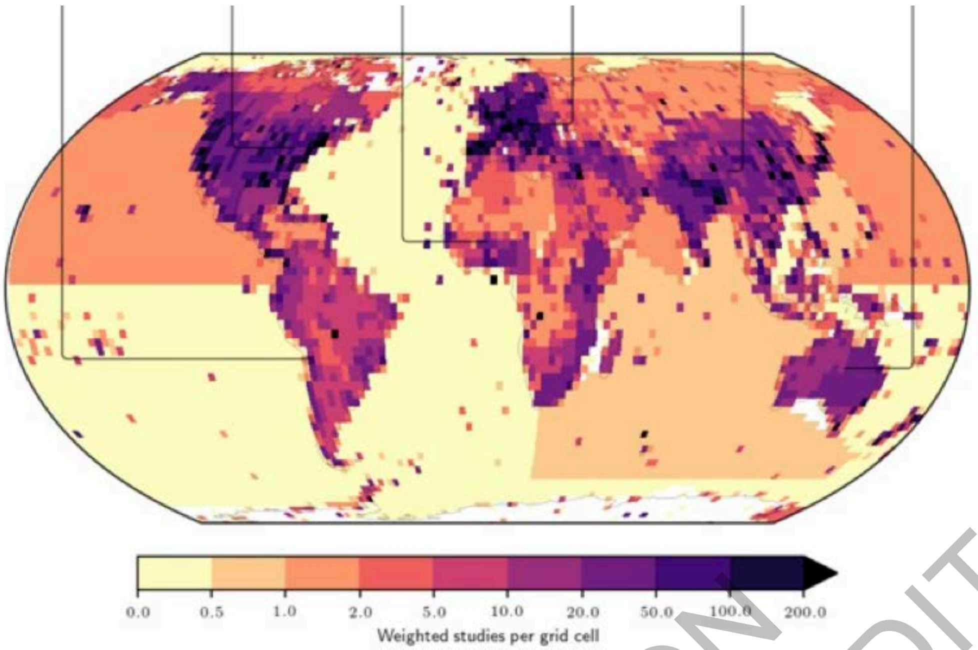


Figure 1.1: Evidence of climate change impacts in many regions of the world. Global density map shows climate impact evidence, derived by machine-learning from 77,785 studies. Bar charts show the number of studies per continent and impact category. Bars are coloured by the climate variable predicted to drive impacts. Colour intensity indicates the percentage of cells a study refers to where a trend in the climate variable can be attributed (partially attributable: >0% of grid cells, mostly attributable: >50% of grid cells) From Callaghan et al. (2021)

1.1.2 Policy Context

Since AR5, climate action has grown at all levels of governance as well as among non-governmental organisations, small and large enterprises, and citizens. Two international agreements – the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement and the 2030 Agenda for Sustainable Development – jointly provide overarching goals for climate action. The 2015 Paris Agreement frames direct local, national, and private sector actions aligned with long-term goals addressing mitigation, adaptation, and finance. For mitigation, the agreement calls for "holding the increase in global average temperature to well below 2°C above pre-industrial levels", "pursuing efforts to limit the temperature increase to 1.5°C," and "reaching net-zero greenhouse gas emissions in the second half of this century" (UNFCCC, 2016). For adaptation, the agreement calls for "increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience" (UNFCCC, 2016, Article 2) as well as a dedicated "global goal on adaptation" (Lesnikowski et al., 2017; Persson, 2019b). For finance, the agreement seeks to make "financial flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development."

The 2030 Agenda for Sustainable Development, adopted in 2015 by UN member states, sets out 17 Sustainable Development Goals (SDGs), frames policies for achieving a more sustainable future and aligns efforts globally to prioritizing ending extreme poverty, protecting the planet, and promoting more peaceful, prosperous, and inclusive societies. SDG 13 ("Climate Action") provides benchmarks to align the Paris Agreement's call to "strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty." Since AR5, several new international conventions have identified climate change adaptation and risk reduction as important global priorities for sustainable development, including the Sendai Framework for Disaster Risk Reduction (SFDRR) (Tozier de la Poterie and Baudoin, 2015; UNISDR, 2015), the finance-oriented Addis Ababa Action Agenda (UN, 2015), and the New Urban Agenda (UN, 2017). For example, the SFDRR recognizes some disasters as "exacerbated by climate change and increasing in frequency and intensity, significantly [impeding] progress towards sustainable development" (UNISDR, 2015). The Convention on Biological Diversity (CBD) is one of the key international legal instruments for sustainable development for "the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources" (CBD, 2011). The CBD and its Aichi targets recognizes that biodiversity is affected by climate change, with negative consequences for human well-being, but biodiversity, through the ecosystem services, contributes to both climate-change mitigation and adaptation (CBD, 2010). There is concern that many of the proposed post-2020 Biodiversity-targets of the Convention on Biological Diversity (CBD) may not be met due to climate change impacts (Arneth et al., 2020; post-2020 biodiversity targets from Chapter 2).

At the national level, over 2,315 laws and policies that address climate change now exist in 196 countries and a number of territories as of May 2021 (Grantham Research Institute on Climate Change and the Environment and Sabin Center for Climate Change Law, 2021). Sub-national and non-state actors, including city and state governments and firms and investors, have also increasingly launched climate actions (Hale et al., 2021). Climate change litigation is gaining salience for both governments and corporations as the number of cases filed around the world grew from 834 between 1986 and 2014 to 1,006 since 2015 and growing (Setzer and Higham, 2021).

[START BOX 1.1 HERE]

Box 1.1: Summary of IPCC AR5 and Special Report findings

The IPCC WGII AR6 builds upon key findings of the IPCC AR5, three subsequent special reports, and the simultaneous assessment of the IPCC WGI and WGIII AR6. The findings and assessment approaches adopted across these reports have implications for the point of departure in the WGII AR6, including the strong recognition of the urgency for climate action, the enhanced focus on risk, and the aim to connect the search for near-term climate solutions with longer-term transitions. Headline conclusions of the IPCC AR5 include the following, directly quoted (IPCC, 2014a):

- Human influence on the climate system is clear.
- Recent climate changes have had widespread impacts on human and natural systems.
- Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems.
- Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change.
- Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development.
- Effective implementation depends on policies and cooperation at all scales and can be enhanced through integrated responses that link adaptation and mitigation with other societal objectives.

Compared to previous IPCC assessments of impacts, adaptation and vulnerability, the IPCC WGII AR5 assessment highlighted new data and more formal approaches for attributing observed climate changes and impacts (Cramer et al., 2014; IPCC, 2014c), a more formal approach to risk in WGII (IPCC, 2014c; Jones et al., 2014), and an expanded assessment of adaptation (Chambwera et al., 2014; IPCC, 2014c; Klein et al., 2014a; Mimura et al., 2014; Noble et al., 2014).

At the time of the IPCC AR5, very few scientific studies relevant to the impacts of global warming of 1.5°C above pre-industrial levels were available. In 2018, the IPCC concluded a Special Report on the impacts of global warming of 1.5°C levels and related global greenhouse gas emission pathways, following an invitation expressed in the Decision text of the Paris Agreement (UNFCCC, 2015a). The report assessed available literature on global warming of 1.5°C and on comparison between global warming of 1.5°C and 2°C above preindustrial levels. It also addressed possible pathways for achieving the ambitious goals of the Paris Agreement. Key findings from this report include the following, directly quoted (IPCC, 2018d):

- Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate.
- Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C. Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C.

- In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045-2055 interquartile range).
- Pathways reflecting current nationally stated mitigation ambitions as submitted under the Paris Agreement would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030.

In 2019, a Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) was published, motivated by the observation that many of the world's most exposed people to risks caused by climate change live in the mountains or near the coast. Key findings include the following, directly quoted (IPCC, 2019c):

- Over the last decades, global warming has led to widespread shrinking of the cryosphere and unabated ocean warming with an uptake of more than 90% of the excess heat in the climate system. Marine heatwaves have doubled in frequency since 1982 and the oceans acidify (*virtually certain*). Global mean sea level is rising, with acceleration in recent decades. Increases in tropical cyclone winds and rainfall exacerbate extreme sea level events and coastal hazards.
- All these trends have impacted ecosystems, food security, water resources, water quality, livelihoods, health and well-being, infrastructure, transportation, tourism and recreation, as well as the culture of human societies, particularly for Indigenous peoples.
- The Greenland and Antarctic Ice Sheets are projected to lose mass at an increasing rate throughout the 21st century and beyond. Projected ecosystem responses include losses of species habitat and diversity, and degradation of ecosystem functions. Warm-water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C.
- Increased mean and extreme sea level, alongside ocean warming and acidification, are projected to exacerbate risks for human communities in low-lying coastal areas. People with the highest exposure and vulnerability are often those with lowest capacity to respond.
- Services provided by ocean and cryosphere-related ecosystems can be supported by protection, restoration, precautionary ecosystem-based management of renewable resource use, and the reduction of pollution and other stressors.
- Coastal communities face challenging choices in crafting context-specific and integrated responses to sea level rise that balance costs, benefits and trade-offs of available options and that can be adjusted over time.

Also in 2019, IPCC published a Special Report on Climate Change and Land, addressing greenhouse gas (GHG) fluxes in land-based ecosystems, land use and sustainable land management in relation to climate change adaptation and mitigation, desertification, land degradation and food security. Key findings include the following, directly quoted (IPCC, 2019c):

- Human use directly affects more than 70% of the global, ice-free land surface. Land also plays an important role in the climate system. Climate change has adversely impacted food security and terrestrial ecosystems as well as contributed to desertification and land degradation in many regions. Changes in land conditions, either from land-use or climate change, affect global and regional climate.
- Pathways with higher demand for food, feed, and water, more resource-intensive consumption and production, and more limited technological improvements in agriculture yields result in higher risks from water scarcity in drylands, land degradation, and food insecurity. Most of the response options assessed contribute positively to sustainable development and other societal goals. Sustainable land management, including sustainable forest management, can prevent and reduce land degradation, maintain land productivity, and sometimes reverse the adverse impacts of climate change on land degradation. It can also contribute to mitigation and adaptation.
- Response options throughout the food system, from production to consumption, including food loss and waste, can be deployed and scaled up to advance adaptation and mitigation. All assessed modelled pathways that limit warming to 1.5°C or well below 2°C require land-based mitigation and land-use change.

- The effectiveness of decision-making and governance is enhanced by the involvement of local stakeholders (particularly those most vulnerable to climate change including Indigenous peoples and local communities, women, and the poor and marginalised) in policies for land-based climate change adaptation and mitigation.
- Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits.

In 2021, IPCC Working Group 1 published its Sixth Assessment Report on The Physical Science Basis. Key findings from the report include the following, directly quoted from its SPM quoted (IPCC, 2019c):
:

- The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.
- Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide and other greenhouse gas emissions occur in the coming decades.
- Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.
- With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels. Low-likelihood outcomes, such as ice sheet collapse, abrupt ocean circulation changes, some compound extreme events and warming substantially larger than the assessed very likely range of future warming cannot be ruled out and are part of risk assessment.
- From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO2 emissions, reaching at least net zero CO2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in Chapter 4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.

Other assessment processes also inform the IPCC AR6. For example, a recent joint workshop between IPBES and IPCC, the first of its kind, made key observations relevant to the work of IPCC AR6 WG2 (Pörtner et al., 2021). In this broad context, the workshop explored diverse facets of the interaction between climate and biodiversity, from current trends to the role and implementation of nature-based solutions and the sustainable development of human society. Key highlighting synopsis of the workshop include the following, directly quoted from the workshop report:

- Limiting global warming to ensure a habitable climate and protecting biodiversity are mutually supporting goals, and their achievement is essential for sustainably and equitably providing benefits to people.
- Several land- and ocean-based actions to protect, sustainably manage and restore ecosystems have co-benefits for climate mitigation, climate adaptation and biodiversity objectives.
- Measures narrowly focused on climate mitigation and adaptation can have direct and indirect negative impacts on nature and nature's contributions to people.
- Measures narrowly focusing on protection and restoration of biodiversity have generally important knock-on benefits for climate change mitigation, but those benefits may be sub-optimal compared to measures that account for both biodiversity and climate.
- Treating climate, biodiversity and human society as coupled systems is key to successful outcomes from policy interventions.
- Transformative change in governance of socio-ecological systems can help create climate and biodiversity resilient development pathways.

[END BOX 1.1 HERE]

1.1.3 Adaptation Efforts and Gaps

Adaptation to climate change plays a key role in reducing climate-related risks along with mitigation and sustainable development. From a risk perspective (Section 1.2), emission reductions and carbon removal can both reduce the greenhouse gas forcing and thus climate-related hazards while adaptation and sustainable development reduce exposure and vulnerability to those hazards.

Important synergies and trade-offs exist among adaptation and mitigation actions (Section 1.5, Chapter 18). Limiting atmospheric concentrations of greenhouse gases reduces the extent of adaptation needed to keep risk within tolerable levels (Section 1.3; Chapter 16). From a global perspective, understanding of adaptation and its limits can inform judgements about the best balance among levels of mitigation and adaptation .Such judgements underlie the mitigation goals of the Paris Agreement. From a more local perspective, there exist a wide range of mitigation scenarios (Cross-Chapter Box CLIMATE in Chapter 1), including those which meet or miss the Paris Agreement goals, and overshoot scenarios in which global mean temperature exceed targets for several decades before dropping to desired levels. Such scenarios inform assessments of the level of adaptation that may be required (Section 1.4, Chapter 17).

Adaptation and sustainable development are also interlinked (Section 18.1). Adaptation facilitates development, which is hindered by impacts and risks from climate change. Development facilitates adaptation by expanding the resources and capacity available to manage climate risks. Viewed from a climate justice perspective, some argue that a more just society is more capable of successful adaptation while others argue that only adaptation that results in a more just society can be judged successful (Section 1.4.1, Chapter 18).

Two concepts – adaptation gaps and limits to adaptation – help frame this report's assessment of the extent to which current adaptation efforts are adequate to meet societal goals. **Adaptation gaps** are defined as "the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities" (UNEP et al., 2021). Limits to adaptation describe the extent to which no plausible level of adaptation can meet societal goals (Section 1.4.4). Within the limits, adaptation gaps can be closed by increased and more successful adaptation actions. Beyond the limits, only mitigation can close adaptation gaps.

Numerous climate-related impacts already cause severe damages in many places and are projected to increase in the future (Chapter 16). Adaptation can reduce these risks, often significantly, but limits to adaptation have already been reached or are being approached in some sectors and regions (Sections 16.3.1, 16.4). While natural systems worldwide are changing in response to climate change, many are not adapting sufficiently quickly to retain their resilience in the face of current and projected future climate change (Section 16.4). For human systems, numerous lines of evidence suggest that in many regions and sectors current infrastructure, settlement patterns, policies, practices, and institutions remain inadequate for current changes in climate conditions (Section 16.2). Inadequate or insufficient adaptation to current conditions is called an adaptation deficit.

In response, adaptation efforts have increased significantly since AR5 (Sections 16.3, 17.2, 17.5.2, Chapter 1 Cross-Chapter Box ADAPT in Chapter 1). Assessing the adequacy and effectiveness of these efforts as called for in Article 7 of the Paris Agreement remains challenging (Section 1.3.2.2), because much adaptation is not recorded in the literature and because assessment depends on judgements of effectiveness (Section 1.4.1.2), judgements about societal goals including climate justice (Section 1.4.1.1), and expectations about future greenhouse gas concentration pathways and other socio-economic conditions (16.5, Cross-Chapter Box DEEP in Chapter 17).

Knowledge about adaptation has significantly expanded since AR5 (Cross-Chapter Box ADAPT in Chapter 1). While understanding regarding the extent of adaptation gaps remains limited, the available evidence suggests significant adaptation gaps exist (*high confidence*). Many current adaptation efforts constitute adaptation planning, rather than implementation (Section 16.3). Most current implementation efforts represent incremental as opposed to transformational adaptation despite the proximity to adaptation limits (Sections 17.2 and 17.5.2). Some current adaptation efforts are considered maladaptive because they increase some climate-related risks even if they reduce others (Sections 1.4.2.4 and 17.5; Chapter 16). Gaps exist in key enablers of adaptation, such as finance (Cross-Chapter Box FINANCE in Chapter 17). Given the long-time scales involved with many adaptation actions and the potential to significantly reduce longer-term costs with near-term actions, closing many adaptation gaps requires actions over the next few years by governments, business, civil society and individuals at a scale and speed significantly faster than that represented by current trends.

1.1.4 What is New in the History of Interdisciplinary Climate Change Assessment

Interdisciplinary climate change assessment, which has played a prominent role in science–society interactions on the climate issue since 1988, has advanced in important ways since AR5 (Mach and Field, 2017; Mitchell et al., 2006; Oppenheimer et al., 2019). Building on a substantially expanded scientific and technical literature (Burkett et al., 2014; Minx et al., 2017), this AR6 report emphasizes at least three broad themes.

First, this AR6 assessment has an increased focus on risk- and solutions-frameworks. The risk framing can move beyond the limits of single best estimates or most-likely outcomes and include high-consequence outcomes for which probabilities are low or in some cases unknown (Jones et al., 2014; Mach and Field, 2017). In this report, the risk framing for the first time spans all three working groups, includes risks from the responses to climate change, considers dynamic and cascading consequences (Section 1.3.1.1), describes with more geographic detail risks to people and ecosystems, and assesses such risks over a range of scenarios (Chapter 16). The focus on solutions encompasses the interconnections among climate responses, sustainable development, and transformation—and the implications for governance across scales within the public and private sectors (Section 17.5.2, Chapter 18). The assessment therefore includes climate-related decision-making and risk management, climate-resilient development pathways, implementation and evaluation of adaptation, and also limits to adaptation and loss and damage (Cross-Chapter Box LOSS in Chapter 17, Section 1.4.4). Specific focal areas reflect contexts increasingly important for the implementation of responses, such as cities (Chapter 6).

Second, emphases on social justice and different forms of expertise have emerged (Section 1.4.1.1, 17.5.2). As climate change impacts and implemented responses increasingly occur, there is heightened awareness of the ways that climate responses interact with issues of justice and social progress. In this report, there is expanded attention to inequity in climate vulnerability and responses, the role of power and participation in processes of implementation, unequal and differential impacts, and climate justice. The historic focus on scientific literature has also been increasingly accompanied by attention to and incorporation of Indigenous knowledge, local knowledge, and associated scholars (Section 1.3.2.3, Chapter 12).

Third, AR6 has a more extensive focus on the role of transformation in meeting societal goals (Section 1.5).

To support these three themes, this report assesses a literature with an increasing diversity of topics and geographical areas covered. The diversity is encompassed through sectoral and regional chapters (Chapters 2-15) as well as cross-chapter papers and boxes. The literature also increasingly evaluates the lived experiences of climate change—the physical changes underway, the impacts for people and ecosystems, the perceptions of the risks, and adaptation and mitigation responses planned and implemented. In particular, scientific capabilities to attribute individual extreme weather and climate events to greenhouse gas emissions have gone from hypothetical to standard and routine over the last three decades, and societal perceptions of these events and their impacts for people and ecosystems are now being studied as well (Figure 1.1; Cross-Working Group Box: ATTRIBUTION in Chapter 1; see synthesis in Chapter 16).

Finally, climate change assessment has become increasingly integrative across multiple disciplines within the natural and social sciences. This report's chapters combine experts across working groups and disciplines, such as natural and social sciences, engineering, humanities, law, and business administration. In this assessment cycle, the special reports (Allen et al., 2018; IPCC, 2019a; IPCC, 2019b) all emphasize such integration, and the chapter teams in the present report integrate disciplinary perspectives and also science-policy interactions inherent in climate change impacts, adaptation and vulnerability. There has been increasing real-time assessment of the assessment process itself, including interpersonal dynamics and how they shape key findings (Oppenheimer et al., 2019). Additionally, best practices are being adopted from applied decision and policy analysis, decision support, and co-production, in order to increase assessment relevance and usability for decision-making (Hall et al., 2019; Mach et al., 2019). Methods of integration in this report include systematic review, meta-analysis, multi-criteria integration, and expert elicitation (see synthesis in Chapter 16). The emphasis on knowledge for action has also included the role of public communication, stories, and narratives within assessment and associated outreach (Section 1.2.2).

1.2 Different Entry Points for Understanding Climate Change Impacts, Adaptation, and Vulnerability

This section introduces key concepts used in this report and the connections between them that present different entry points for understanding climate change impacts, adaptation, and vulnerability.

1.2.1 Overlapping, Complementary Entry Points

Many actors from different research and practice communities engage with understanding and responding to climate risk. Not surprisingly, there thus exist alternative, overlapping, and complementary entry points to the discussion widely used throughout the literature and this report.

The concepts of risk and risk management have in recent years been central to climate change research and practice related to impacts, adaptation, and vulnerability. The concepts provide a framework for understanding climate change and its increasingly severe, interconnected, and irreversible impacts. They support the implementation of solutions that reduce adverse consequences, pursue opportunities, and enable beneficial outcomes for people, economies, and nature (IPCC, 2014c; IPCC, 2018d). All three AR6 Working Groups now apply a common risk framework (IPCC, 2020).

Additional concepts—adaptation, vulnerability, exposure, resilience, and transformation —also provide important framings for the climate change challenge.

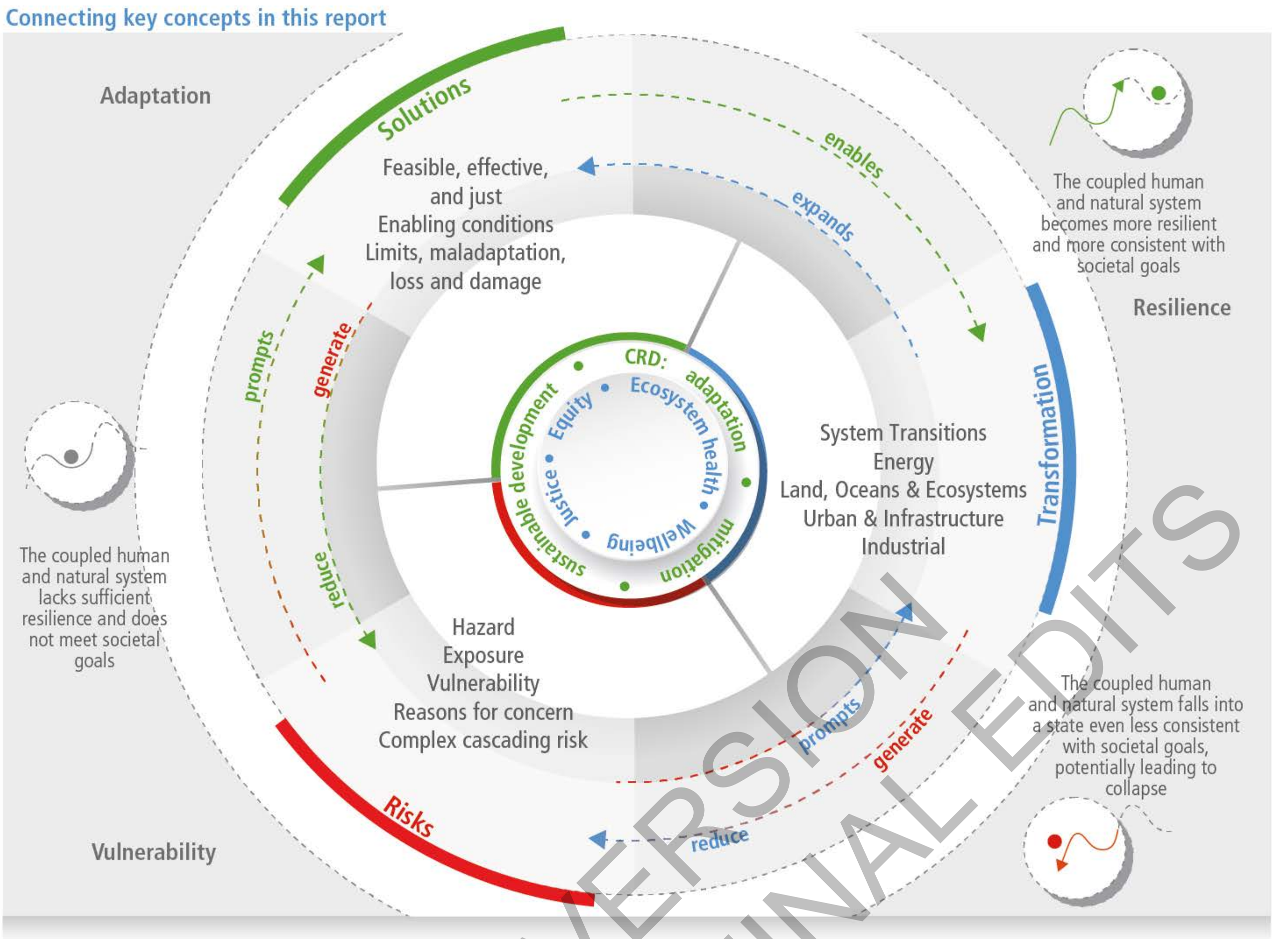


Figure 1.2: Connecting Key Concepts in this Report The current coupled human and natural system is insufficiently resilient and does not meet societal goals of equity, well-being, and ecosystem health. Meeting the objectives of the Paris Agreement, Sustainable Development Goals, and other policy statements requires the system to move to a new and more resilient state. Key concepts used in this report help illuminate our current situation and potential solutions. These key concepts are usefully organized around the concepts of risk, solutions, and transformation. Risk can prompt solutions and transformation. Both solutions and transformation seek to reduce some risks but may also generate others. Solutions can enable transformation, and transformation can expand the set of feasible solutions.

Figure 1.2 displays the connections among many of the key concepts used in this report. This chapter, the Summary for Policymakers, Technical Summary, and sectoral and regional chapters are organized around the concepts of risks (Section 1.3), solutions (Section 1.4), and transformation (Section 1.5).

Key concepts that contribute to an understanding of risk include its components hazards, exposure, and vulnerability (Section 1.2.1.1); the recognition that risks may be complex and cascading (Section 1.3.1.2); and the reasons for concern framework used to summarize the most policy-relevant risks (Section 1.3.1.1). Key concepts that contribute to an understanding of solutions include the enablers of governance, finance, and knowledge (Section 1.4.2); learning processes supported by monitoring and evaluation (Section 1.4.3); and nature-based solutions (Section 1.4.2). Transformation is supported by systems transitions in energy, land, infrastructure, industry, and society (Section 1.5.1), which if successful can contribute to climate resilient development (Section 1.5).

The centre of Figure 1.2 shows societal goals of equity, effectiveness, well-being, and climate justice as articulated by the Paris Agreement, Sustainable Development Goals, and other policies and plans (Section 1.4.1). The ring around these goals shows the limits to adaptation (Section 1.4.4), potential for maladaptation (Sections 1.4.2. 17.5.2), and loss and damage (Section 1.4.4.2) that present barriers to reaching these goals.

The concept of vulnerability can provide a unique window into the effects of climate change on different communities, individuals, and ecosystems, in particular as human systems are affected by race, gender, wealth inequalities, and other attributes (Section 1.2.1.2). The concept of adaptation can provide a unique window into the process of adjustment to climate change by human and natural systems (Section 1.2.1.3). Resilience (Section 1.3.1.4) is a broad concept, encompassing both outcomes and processes, an ability to main essential function, and an ability to transform.

The ball and cup diagrams (Holling, 1973) in Figure 1.2 indicate that the current coupled human and natural system is not resilient, nor does it meet societal goals of equity, well-being, and ecosystem health. Some types of transformation may prove inevitable (Section 1.5.1), either a deliberate transformation that results in a more resilient state consistent with societal goals or a forced transformation to a system state inconsistent with the goals.

1.2.1.1 Risk Framing

Risk in this report is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system. In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs or negative side-effects (see Annex II: Glossary). **Risk management** is defined as plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks (see Annex II: Glossary).

A risk framing is increasingly used to assess climate change impacts on human and natural systems (Connelly et al., 2018; IPCC, 2012; Mach and Field, 2017; O'Neill et al., 2017; see also WGII AR6 Sections 1.2.4.1, 16.1, and 17.3 and Cross-Chapter Box CLIMATE; Oppenheimer et al., 2014). A risk framing reflects key dimensions of the climate challenge. These features include the changing likelihoods of many different outcomes (including adverse consequences and beneficial opportunities), uncertainties that will persist, and different and contested values, priorities, and goals (Jones and Preston, 2011; Mach et al., 2016). The IPCC AR6 and associated Special Reports apply a broad definition of risk (WGI AR6 Cross-Chapter Box 1.3. WGI AR6 uses the Climatic Impact Driver (CID) terminology, rather than hazard, to neutrally assess changing climatic conditions that are relevant to human and natural systems, leaving the determination of positive/negative consequences and resulting impacts and risks for WGII assessment (WGI AR6 Section 12.3). In most cases throughout this WGII report, the term "risk" refers to the risks of climate change impacts. The full assessment, however, incorporates all relevant risks from climate change impacts and responses.

The broad definition of risk involves quantitative and integrative understandings of risk (Mach and Field, 2017; Oppenheimer et al., 2014; see also Section 17.3). Risk is sometimes defined as the probability of a consequence, multiplied by the magnitude of that consequence, acknowledging both the diversity of possible consequences and the relevance of values. Yet it also applies in circumstances where probabilities cannot be fully quantified (e.g., Adger et al., 2013). For example, in some cases the probability and magnitude of consequences may be more uncertain, dependent on complex dimensions of the climate (e.g., a cyclone, high tide, and heatwave co-occurring) or the vulnerability of different communities (e.g., the ways in which social networks and community cohesion support most-vulnerable individuals during disasters) (Ford et al., 2018). The determinants of risk vary dynamically through space and time (Jurgilevich et al., 2017; Viner et al., 2020). They interact, compound, and cascade (Adger et al., 2018; Dawson, 2015; see also Section 16.1.2).

A risk framing supports connections with solutions (Adger et al., 2018; Jones and Preston, 2011; Mach et al., 2016). First, a risk framing connects the present with the future. (Papathoma-Kohle et al., 2016). For instance, whether wildfire or drought, recent experiences have demonstrated limits to current response capacities, relevant to future preparedness (e.g., evacuation of large communities on tight time frames or water management simultaneously responsive to intensifying drought and flooding). Second, a risk framing emphasizes that uncertainties and complex interactions are integral to decision-making (Dawson, 2015; Jones et al., 2014). The uncertainties include high-impact, low-probability outcomes and deep uncertainties for which core processes are not understood and meaningful probabilities cannot be applied (Adler et al., 2016see also Section 17.2.1 and Cross-Chapter Box DEEP in Chapter 17; Chapter 7 in SRCCL, IPCC, 2019a; Cross-Chapter Box 5 in SROCC, IPCC, 2019b). In these circumstances, risk assessment can occur through tools used for risk management across contexts, such as insurance, business, social protection, security, and policy planning, and decision-making can be iterative and support dynamic adaptive pathways through time (Aven, 2016; Jones and Preston, 2011; Watkiss et al., 2015; see also Section 17.3.2)

Iterative risk management (Vervoort and Gupta, 2018) emphasizes that anticipating and responding to climate change does not consist of a single set of judgments at a single point in time, but rather an "ongoing cycle of assessment, action, reassessment, learning, and response" (USGCRP, 2018). It is consistent with most approaches applied for implementing adaptation (Jones et al., 2014; Jones and Preston, 2011). For instance, the Paris Agreement is organized as a polycentric process (see Section 1.4) of iterative risk management in which national governments pledge to take specific actions, those actions are monitored and assessed, and nations asked to update their pledges in light of that assessment.

1.2.1.2 Vulnerability

Vulnerability is a component of risk, but also an important focus independently. Vulnerability in this report is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (see Annex II: Glossary). Over the past several decades, approaches to analysing and assessing vulnerability have evolved. An early emphasis on top-down, biophysical evaluation of vulnerability included -and often started with - exposure to climate hazards in assessing vulnerability. From this starting point, attention to bottom-up, social and contextual determinants of vulnerability, which often differ, has emerged, although this approach is incompletely applied or integrated across contexts (Bergstrand et al., 2015; Rufat et al., 2015; Spielman et al., 2020; Taberna et al., 2020). Vulnerability is now widely understood to differ within communities and across societies, also changing through time (Jurgilevich et al., 2017; Kienberger et al., 2013; see also Chapter 16). In the WGII AR6, assessment of the vulnerability of people and ecosystems encompasses the differing approaches that exist within the literature, both critiquing and harmonizing them based on available evidence. In this context, **exposure** is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected (Annex II: Glossary). Potentially affected places and settings can be defined geographically, as well as more dynamically, for example through transmission or interconnections through markets or flows of people.

Vulnerability is also a link between the climate risk and disaster risk communities, recognizing complementarities and differences between these communities. **Disaster risk management** is the set of processes that improve understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, increasing human security, well-being, and sustainable development (see Annex II: Glossary). Climate risk and disaster risk are increasingly addressed together, bridging the climate change adaptation and disaster risk reduction communities (e.g., IPCC, 2012; UNDRR, 2019, especially Chapter 13 in that report). Building from the scientific literature and adaptation and risk reduction practice, the IPCC Special Report on Extremes resulted in several major IPCC advances that continue to the present report, including emphasis on risk and climate-related extremes (e.g., Burton et al., 2012; Lavell et al., 2012) and re-conceptualisation of vulnerability to encompass both social and biophysical orientations (i.e., bridging contextual/bottom-up and climate-driven/top-down approaches) (Cardona et al., 2012; Polsky et al., 2007). Linking disaster risk reduction and climate change adaptation can also be an important basis for discussion in climate negotiations regarding the allocation of funds needed for tackling climate change, especially in developing countries and small island developing states (Begum et al., 2014). The integration of disaster risk management and climate change adaptation in the IPCC AR6 is seen for example in the assessment of key risks within and across sectors and regions, along with global-scale reasons for concern, which is attuned to extreme events and disasters (Oppenheimer et al., 2014; see also Chapter 16). Additionally, the assessment of adaptation has prioritized these interconnections (e.g., Mimura et al., 2014), as have literature and practice especially in the context of sustainable development (e.g., Schipper et al., 2016).

1.2.1.3 Adaptation

Adaptation in this report is defined, in human systems, as the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects (see Annex II: Glossary). Adaptation planning in human systems generally entails a process of iterative risk management. Different types of adaptation have been distinguished, including anticipatory versus reactive, autonomous versus planned, and incremental versus transformational adaptation (IPCC WGII glossaries for the TAR, AR4, AR5, and AR6; Chapters 16–18). Adaptation is often seen as having five general stages: 1) awareness, 2) assessment, 3) planning, 4) implementation, and 5) monitoring and evaluation (Jones et al., 2014; Mimura et al., 2014; Moser and Boykoff, 2013; Noble et al., 2014; see also Section 17.4). Government, non-government, and private-sector actors have adopted a wide variety of specific approaches to adaptation that, to varying degrees, address these five general stages. Adaptation in natural systems includes “autonomous” adjustments through ecological and evolutionary processes. It also involves the use of nature through ecosystem-based adaptation. The role of species, biodiversity, and ecosystems in such adaptation options can range from the rehabilitation or restoration of ecosystems (e.g., wetlands or mangroves) to hybrid combinations of “green and grey” infrastructure (e.g., horizontal levees) (Chapters 2-3; IPBES, 2018).

The IPCC assessment of adaptation has evolved through time. The WGII AR4 included one chapter dedicated to adaptation, the WGII AR5 expanded to four, and the WGII AR6 mainstreams adaptation comprehensively throughout the report. Adaptation science is rapidly evolving, including evaluation of adaptation effectiveness, feasibility, implementation, and maladaptation, although major knowledge gaps persist in modeling and analysis (CCB ADAPT; Chapter 16; Section 1.4; Holman et al., 2019). The WGII AR6 emphasizes assessment of observed adaptation-related responses to climate change, governance and decision-making in adaptation, and the role of adaptation in reducing key risks and global-scale reasons for concern, as well as limits to such adaptation (e.g., Chapters 16 and 17). The assessment approach includes adaptation needs, options, planning, and implementation across sectors and regions, as well as adaptation opportunities, constraints, and also limits (Capela Lourenço et al., 2019; Eisenack et al., 2014; Herrmann and Guenther, 2017; Klein et al., 2014b; Lehmann et al., 2015; Moser et al., 2019b; Oberlack, 2017; Oberlack and Eisenack, 2014; Roggero, 2015; Russel et al., 2020; Sieber et al., 2018; Thaler et al., 2019; see also Chapters 16 and 17).

Since AR5, more adaptation has progressed (IPCC, 2014a; Lesnikowski et al., 2016; see also Sections 16.2.5 and 17.2) and the focus of activity has expanded to include social, institutional, and governance dimensions beyond engineered and technical options and to decision processes beyond technocratic, linear framings (IPCC, 2014a; see also Chapter 17). Adaptation includes increasing attention to implementation, monitoring and evaluation, and learning through time, not just planning processes (Section 17.3 and 17.5.1). On the one hand, an important advance has been recognition of generalized capacities, such as resources and knowledge, necessary for the feasibility of effective adaptation. Adaptation thereby strongly overlaps with risk management and with the building of resilience and sustainable development (Chapters 17–18).

1.2.1.4 Resilience, Including Connections with Development Pathways and Transformation

Resilience in this report is defined as the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation (see Annex II: Glossary). Resilience is an entry point commonly used, although under a wide spectrum of meanings (Aldunce et al., 2015; Fisichelli et al., 2016; Flood and Schechtman, 2014; Meerow et al., 2016; Moser et al., 2019a; Reghezza-Zitt et al., 2012; Tanner et al., 2015). Resilience as a system trait overlaps with concepts of vulnerability, adaptive capacity, and thereby risk, and resilience as a strategy overlaps with risk management, adaptation, and also transformation (Moser et al., 2019a; Woodruff et al., 2018). Implemented adaptation is often organized around resilience as bouncing back and returning to a previous state after a disturbance (Fisichelli et al., 2016).

In much of the literature, resilience encompasses not just maintaining essential function, identity, and structure, but also maintaining a capacity for adaptation, learning, and transformation. Since the earliest framings of resilience around stability and persistence, ecology and allied fields have come to recognize that while systems are often persistent in the face of disturbance, disturbance also creates opportunity for transformation and the emergence of new pathways (Section 1.5.2) (Allen and Holling, 2010; Doppelt, 2017; Folke, 2006; Folke et al., 2010; Gelcich et al., 2010; Stockholm Resilience Center, 2015). Across this literature, disturbance is framed as outside the system in question, for which the timeframes and spatial scales of disturbances, impacts, and responses are central to outcomes (Béné et al., 2011; Brown, 2014; Hamborg et al., 2020). Endogenous processes of transformation are presented as emergent, characterized by thresholds, and as a result very difficult to anticipate (Hughes et al., 2013; Scheffer et al., 2001; Scheffer et al., 2015; Scheffer et al., 2012; Suding and Hobbs, 2009; Walker and Meyers, 2004). In the last 5 years (2016-2020), the concept of resilience has gained prominence as a core theme in the climate change adaptation literature (Nalau and Verrall, 2021).

Often, development and adaptation communities of practice default to persistence and stability in their use of resilience (Cote and Nightingale, 2012; MacKinnon and Derickson, 2013). Such a framing aligns resilience with a long-standing but increasingly questioned belief that sustainable development can be achieved through incremental adjustments in behaviour and advances in technology that allow for the persistence of existing socio-economic and socio-ecological arrangements (Banerjee, 2003; Klauer, 1999; Redclift, 2005; UN Inter-agency Task Force on Financing for Development 2019; Chap 18; Section 1.5). However, the literature increasingly suggests that the achievement of sustainable development will require transformative change in socio-ecological systems at scales ranging from the community to the globe. The concept of climate resilient development, initially introduced in AR5 and now a key focus in this report (see Chapter 18), engages with such transformations and the associated questions of justice, power, and politics as shaped by internal, endogenous social factors and their interactions with other drivers of change (Carr, 2019; Eriksen et al., 2015; Nightingale, 2015b; Nightingale et al., 2019; see also Chapter 18).

1.2.2 Narratives, Storylines, Scenarios and Pathways

The concepts of narratives, storylines, scenarios, and pathways play an important role in this report. While distinct concepts, they are inter-related and sometimes confused.
A **narrative** is a story with a chronological order or, when cast in the form of an argument, with premises and conclusions (Adger et al., 2001; Roe, 1991). Narratives enable people to envision what various potential futures may mean for environments and livelihoods and in this way facilitate the development of scenarios for the future (Miller et al., 2015). Narratives can also play a key role in enabling collective action (Section 1.5) by helping disparate groups co-create a common vision of a desirable future and achieve a common understanding of actions needed to move towards that future (Linnér and Wibeck, 2019; Muiderman et al., 2020).

A narrative contains a storyline in addition to a set of actors (Elliott, 2005). A **storyline** is a series of events including their causal connections within a narrative. The IPCC and climate change literature more broadly often use the terms storylines and narratives interchangeably (O'Neill et al., 2017; see also WGI AR6 Cross-Chapter Box 6 in Chapter 1 and Sections 1.4.4 and 10.5.3). A **scenario storyline** refers to a narrative description of a scenario including its main characteristics, relationships between driving forces and how these factors evolve (AR6 WG1 Section 1.4.4.2). Storylines are used to assess risks related to low-likelihood, but high-impact events (Sutton, 2018). In this use of the terms, narratives and storylines do not include specific actors. There is also a critical literature on the use of narratives and storylines based on projected scenarios, which points out the conservative character of these concepts whose performative effect tends to preserve the status quo and the current socio-economic relationships. (Chollet and Felli, 2015; Demortain, 2019; Lövbrand et al., 2015; Malm and Hornborg, 2014; Theys J. and Cornu, 2019).

Standard research communication may fail to engage policymakers, media and the public at large (WGI AR6 Section 1.2.4). Rather, policies and decision-making tend to be based on narratives and storylines (Roe, 1994; Roe, 2017). Although mathematical models and narratives are often presumed to be antithetical, in practice they may be complementary and work together (Morgan and Wise, 2017). Communicating research insights through storylines and narratives may have a better chance of transmitting key messages. AR6 employs these communication tools in many places, for instance storylines for constructing and communicating regional climate information or climate services (WGI AR6 Chapter 10, Chapter 12) or "Low-Likelihood High Warming Storylines" (Chapter 4). To better communicate deep uncertainty in sea level rise projections, WGI uses storylines to describe the physical events that would have to unfold to generate its high-end estimates (Cross-Chapter Box DEEP in Chapter 17).

Scenarios are defined in IPCC reports as plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships (Annex II: Glossary). Scenarios are neither predictions nor forecasts but rather 'foresights', which imply envisioning challenging futures (Vervoort and Gupta, 2018). Scenarios are used to provide a view of the potential consequences and implications of developments and actions in a 'what-if' mode of exploring the future (AR6 WGIII Section 1.5.1; AR6 WGI Section 1.6.1). They may be presented as numerical or mental models. Climate change scenarios are generated by climate modellers to highlight possible alternative greenhouse gas emission pathways and are used to develop and integrate projections of emissions and their climate change impacts and for analysing and contrasting climate policy choices. Cross-Chapter Box CLIMATE in Chapter 1 describes scenarios used in this report.

Pathways are one element of a larger scenario (O'Neill et al., 2017), focusing on just one element of a larger system of drivers, emissions or concentrations. Scenarios provide one means to represent deep uncertainty when there is disagreement or uncertainty about conceptual models (IPCC, 2019b; Cross-Chapter Box DEEP in Chapter 17). In addition, scenarios provide several important functions in decision support. A lack of strong association with probabilities enables scenarios to promote buy-in from parties to a decision who hold different expectations about the future, helping them to expand the range of futures and options they consider. The process of generating scenarios can serve as the focus of participatory stakeholder exercises and processes, and scenarios can also be used to support risk management by stress testing alternative policies and identifying robust and adaptive policies under conditions of deep uncertainty (Cross-Chapter Box DEEP in Chapter 17).

[START CROSS-CHAPTER BOX CLIMATE HERE]

Cross-Chapter Box CLIMATE: Climate Reference Periods, Global Warming Levels, and Common Climate Dimensions

Authors: Steven Rose (USA), Richard Betts (United Kingdom), Philippus Wester (Nepal/Netherlands), Aris Koutroulis (Greece)

This Cross-Chapter Box sets out common climate dimensions to contextualize and facilitate AR6 WGII analyses, presentation, synthesis, and communication of assessed, observed and projected climate change impacts across WGII Chapters and Cross-Chapter Papers. "Common climate dimensions" are defined as common Global Warming Levels (GWLs), time periods, and levels of other variables as needed by WGII authors for consistent communications. The set of climate variable ranges given below were derived from the AR6 WGI report and supporting resources and help contextualize and inform the projection of potential future climate impacts and key risks. The information enables the mapping of climate variable levels to climate projections and vice versa, with ranges of results provided to characterize the physical uncertainties relevant to assessing climate impacts risk.

AR6 WGI Reference Periods, Climate Projections and Global Warming Levels

AR6 WGI adopts a common set of reference years and time periods to assess observed and projected climate change, namely the pre-industrial (PI) period, the current 'modern' period and future reference time periods. The IPCC Glossary defines the pre-industrial period as "the multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850-1900 is used to approximate pre-industrial global mean surface temperature (GMST)". The 'modern' period is defined as 1995 to 2014 in AR6, while three future reference periods are used for presenting climate change projections, namely near-term (2021-2040), mid-term (2041-2060) and long-term (2081-2100), in both the AR6 WGI and WGII reports. Importantly, the historical rate of warming assessed by WGI in AR6 is different to that assessed in AR5 and SR1.5, due to methodological updates (see WGI Cross-Chapter Box 2.3 in Chapter 2 for details). This means that the 'modern' period is assessed as slightly warmer compared to 1850-1900 than it would have been with AR5-era methods. This also has implications for the projected timing of reaching policy-relevant levels of global warming, which need to be understood.

To explore and investigate climate futures, climate change projections are developed using sets of different input projections. These inputs consist of sets of projections of greenhouse gas emissions, aerosols or aerosol precursor emissions, land use change, and concentrations designed to facilitate evaluation of a large climate space and enable climate modelling experiments. For AR5 (and the CMIP5 climate model experiments), the input projections were referred to as Representative Concentration Pathways (RCPs). For AR6 (and the CMIP6 climate model experiments), new sets of inputs are used and referred to as SSP scenarios, where SSP refers to socioeconomic assumptions called the Shared Socio-Economic Pathways (SSPs).

The RCPs are a set of four trajectories that span a large radiative forcing range, defined as increased energy input at surface level in Watts per square meter, ranging from 2.6 W m^{-2} (RCP2.6) to 8.5 W m^{-2} (RCP8.5) by the end of the 21st century, with RCP4.5 and RCP6.0 as intermediate scenarios, and RCP2.6 a peak and decline scenario reaching 3 W m^{-2} before 2100. A range of emissions scenarios compatible with each specific RCP was also assessed in AR5 (Ciais et al., 2013).

A core set of five SSP scenarios, namely SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, was selected in the AR6 WGI report with the objective to fill certain gaps identified in the RCPs (see AR6 WG1 Cross-Chapter Box 1.4 in Chapter 1). The first number in the label is the particular set of socioeconomic assumptions driving the emissions and other climate forcing inputs taken up by climate models and the second number is the radiative forcing level reached in 2100. WG1 Cross-Chapter Box 1.4 in Chapter 1 provides a comparison of this core set of SSP scenarios with scenarios used in previous reports, with SSP1–1.9 a low overshoot scenario consistent with limiting global average warming to 1.5°C, and SSP1-2.6 a scenario consistent with limiting warming to 2°C.

Also of importance to the impact literature and the WGII report are SSP-RCP combinations, that is, studies that employ climate outcomes based on RCPs and socio-economic assumptions based on SSPs. SSPs can be paired with a range of different RCPs because SSPs can be combined with mitigation policy assumptions to produce a range of emissions pathways. In addition to the SSPs, there are many other emissions pathways and societies consistent with any global mean temperature outcome. These represent uncertainty and broad ranges of possibilities that affect climate change exposure and vulnerability (Rose and and M. Scott, 2020; Rose and Scott, 2018). Furthermore, there are large uncertainties in translating emissions scenarios into concentration pathways due to uncertainties in climate-carbon cycle feedbacks (Booth et al., 2017; Jones et al., 2013).

The plausibility of emissions levels as high as the emissions scenario conventionally associated with the RCP8.5 and SSP5–8.5 concentration pathways has been called into question since AR5, as has the emissions pathway feasibility of the low scenarios (Hausfather and Peters, 2020; Rose and and M. Scott, 2020). However, these views are contested (Schwalm et al., 2020, for RCP8.5), and it is important to realise that emissions scenarios and concentration pathways are not the same thing, and higher concentration pathways such as RCP8.5 could arise from lower emissions scenarios if carbon cycle feedbacks are stronger than assumed in the integrated assessment models (IAMs) used to create the standard scenarios (Booth et al., 2017). In the majority of full-complexity Earth System Models, these feedbacks are stronger than in the IAMs (Jones et al., 2013), so the RCP8.5 concentration pathway cannot be ruled out purely through consideration of the economic aspects of emissions scenarios. Nonetheless, the likelihood of a climate outcome, and the overall distribution of climate outcomes, are a function of the emissions scenario's likelihood. Note that the original RCPs were created explicitly to facilitate a broad range of climate modelling experiments, with the expectation that other issues, such as socioeconomic uncertainty, could be subsequently explored (Moss et al., 2010).

An important feature of the AR6 cycle is a stronger emphasis on the use of future Global Warming Levels (GWLs) to support consistency and comparability across the three IPCC Working Groups' contributions to the AR6 and improve communication. The common range of GWLs relative to the 1850 to 1900 period, termed the "Tier 1" range by WGI, are 1.5, 2.0, 3.0, and 4.0°C. The use of GWLs assists in the comparison of climate states across climate change scenarios (projections) and in assessing the broader literature as well as for cross-chapter and cross-working group comparisons. They facilitate the integration of climate projections, impacts, adaptation challenges and mitigation challenges within and across the three WGs as there is a close connection between the level of global warming and climate change impacts. Of particular interest is the timing of when the "Tier 1" global warming levels are reached, relative to the period 1850–1900, under the five SSP x–y scenarios, as well as RCP scenarios . For climate change impacts and adaptation responses, linking GWLs to RCP and SSP climate projections using a climate information translation resource is of great relevance for the WGII contribution to AR6.

AR6 WGII Common Climate Dimensions

WGII's common climate dimensions include (1) a common range of GWLs from WGI, (2) common ranges for other climate variables, (3) information for translating climate variable levels to climate projections and vice versa. See Table Cross-Chapter Box CLIMATE.1 for global warming level ranges by time periods for RCP and SSP climate projections, and Table Cross-Chapter Box CLIMATE.2 for information regarding the timing for when GWLs are reached in climate projections. The common GWL range is based on WGI's "Tier 1" dimensions of integration range: 1.5, 2, 3, and 4°C. The first table illustrates the greater levels of projected global warming with higher emissions pathways, as well as the increasing uncertainty in the climate response over time for a given pathway. The second table illustrates significant uncertainty in the timing for passing GWL thresholds which can narrow for a given GWL the higher the emissions pathway. Finally, given the importance of geographic heterogeneity in projected changes in future climate, Table Cross-Chapter Box CLIMATE.3a and 3b are provided with ranges for select climate variables (temperature, precipitation, ocean) by global warming level and continent (or ocean biome). The ranges illustrate spatial heterogeneity in potential physical changes in levels and uncertainty that are relevant to assessing climate impacts risk. There is significantly more spatial heterogeneity than represented in the table that is relevant to local decision makers (see, for instance, WGI AR6 Interactive Atlas).

The common climate dimensions can be used as a dimension of integration for impacts studies in WGII, for example by providing a common framework for comparison of projected impacts for different studies (Figure Cross-Chapter Box CLIMATE.1). Moreover, GWL bands are needed in WGII to map the diverse temperature levels found across WGII's literature. The GWL's also facilitate integration with WGIII's global emissions projections categorisation by global mean temperature (WGIII Chapter 3).

Table Cross-Chapter Box CLIMATE.1: GWL ranges by time periods for CMIP5 (RCP) and CMIP6 (SSP) climate projections (20-yr averages). Temperature anomalies relative to 1850-1900. Full ranges for CMIP raw results (across all models and ensemble runs) and WGI AR6 assessed very likely (5-95%) ranges. *Sources: Hauser et al. (2019); WGI AR6 SPM,* Table *SPM.1*

Projection	Full ranges 2021-2040	Full ranges 2041-2060	Full ranges 2081-2100	WG1 AR6 assessed *very likely* (5-95%) ranges 2021-2040	WG1 AR6 assessed *very likely* (5-95%) ranges 2041-2060	WG1 AR6 assessed *very likely* (5-95%) ranges 2081-2100
RCP2.6	1.0 to 2.2	1.0 to 2.3	0.9 to 2.3	n/a	n/a	n/a
RCP4.5	1.1 to 2.2	1.4 to 2.7	1.8 to 3.3	n/a	n/a	n/a
RCP6.0	1.0 to 2.0	1.3 to 2.5	2.3 to 3.6	n/a	n/a	n/a
RCP8.5	1.1 to 2.6	1.7 to 3.7	3.0 to 6.2	n/a	n/a	n/a
SSP1-1.9	1.0 to 2.4	1.1 to 2.7	1.0 to 2.5	1.2 to 1.7	1.2 to 2.0	1.0 to 1.8
SSP1-2.6	1.0 to 2.4	1.2 to 2.9	1.3 to 3.1	1.2 to 1.8	1.3 to 2.2	1.3 to 2.4
SSP2-4.5	0.9 to 2.5	1.3 to 3.3	1.9 to 4.4	1.2 to 1.8	1.6 to 2.5	2.1 to 3.5
SSP3-7.0	1.0 to 2.6	1.5 to 3.7	2.7 to 6.2	1.2 to 1.8	1.7 to 2.6	2.8 to 4.6
SSP5-8.5	1.0 to 2.7	1.6 to 4.0	3.1 to 7.2	1.3 to 1.9	1.9 to 3.0	3.3 to 5.7

Table Cross-Chapter Box CLIMATE.2: Timing for when 20-year average GWLs are reached in CMIP5 (RCP) and CMIP6 (SSP) climate projections. GWL anomalies relative to 1850-1900. Ranges based on CMIP raw results (all models and ensemble runs), and WGI AR6 assessed results. For each GWL and RCP/SSP, the earliest and latest 20-year window when a 20-year average GWL is reached across the CMIP models and ensemble members is reported, or the very likely (5-95%) assessed range is reported. n entry "n.c." means the GWL is not reached during the period 2021-2100. *Sources: Hauser et al. (2019); WGI AR6 TS Cross-Section Box TS.1, Table 1*

CMIP5 full ranges

GWL	RCP2.6	RCP4.5	RCP6.0	RCP8.5
4°C	n.c.	n.c.	n.c.	2047 - 2066 to 2080 - 2099
3°C	n.c.	2054 - 2073 to 2070 - 2089	2062 - 2081 to 2080 - 2099	2030 - 2049 to 2077 - 2096
2°C	2015 - 2034 to 2079 - 2098	2014 - 2033 to 2075 - 2094	2023 - 2042 to 2068 - 2087	2004 - 2023 to 2048 - 2067
1.5°C	1998 - 2017 to 2075 - 2094	1998 - 2017 to 2051 - 2070	2001 - 2020 to 2050 - 2069	1990 - 2009 to 2035 - 2054

CMIP6 full ranges

GWL	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
4°C	n.c.	n.c.	2061 - 2080 to 2081 - 2100	2046 - 2065 to 2081 - 2100	2042 - 2061 to 2081 - 2100
3°C	n.c.	2050 - 2069 to 2068 - 2087	2034 - 2053 to 2081 - 2100	2030 - 2049 to 2081 - 2100	2027 - 2046 to 2079 - 2098
2°C	2009 - 2028 to 2063 - 2082	2008 - 2027 to 2075 - 2094	2009 - 2028 to 2080 - 2099	2008 - 2027 to 2060 - 2079	2008 - 2027 to 2055 - 2074
1.5°C	1997 - 2016 to 2058 - 2077	1997 - 2016 to 2073 - 2092	1997 - 2016 to 2051 - 2070	1997 - 2016 to 2042 - 2061	1997 - 2016 to 2038 - 2057

WGI AR6 assessed *very likely* (5-95%) ranges

GWL	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
4°C	n.c.	n.c	n.c	2070 - 2089 to n.c.	2058 - 2077 to n.c.
3°C	n.c.	n.c	2061 - 2080 to n.c.	2050 - 2069 to n.c.	2042 - 2061 to 2074 - 2093
2°C	n.c.	2031 - 2050 to n.c.	2028 - 2047 to 2075 - 2094	2026 - 2045 to 2053 - 2072	2023 - 2042 to 2044 - 2063
1.5°C	2013 - 2032 to n.c	2012 - 2031 to n.c.	2012 - 2031 to 2037 - 2056	2013 - 2032 to 2033 - 2052	2011 - 2030 to 2029 - 2048

Table Cross-Chapter Box CLIMATE.3a: Projected continental level result ranges for select temperature and precipitation climate change variables by global warming level. Ranges are 5th and 95th percentiles from SSP5-8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 projections. *Source: WGI AR6 Interactive Atlas (https://interactive-atlas.ipcc.Chapter/).*

Climate variable	Global warming level	All Regions	North America	Europe	Asia	Centra-South America	Africa	Australia	Antarctica
Mean temperature (degrees C)	4°C	12 to 15	8 to 11	5 to 9	12 to 14	24 to 27	26 to 29	24 to 27	-33 to -27
	3°C	11 to 14	6 to 11	4 to 7	10 to 14	23 to 26	25 to 28	23 to 26	-35 to -26
	2°C	10 to 13	5 to 9	3 to 6	8 to 12	22 to 25	24 to 27	22 to 25	-36 to -27
	1.5°C	9 to 12	4 to 8	2 to 5	8 to 12	22 to 24	24 to 26	22 to 24	-36 to -27
Mean daily minimum temperature (degrees C)	4°C	8 to 11	4 to 8	1 to 6	6 to 11	19 to 24	21 to 25	18 to 23	-38 to -29
	3°C	6 to 11	2 to 8	0 to 5	4 to 10	19 to 22	19 to 23	17 to 21	-39 to -30
	2°C	5 to 10	0 to 6	-2 to 4	3 to 9	17 to 21	18 to 22	16 to 20	-40 to -31
	1.5°C	4 to 9	-1 to 5	-2 to 3	2 to 8	17 to 21	17 to 22	16 to 19	-41 to -32
Minimum of daily minimum temperatures (degrees C)	4°C	-12 to -5	-25 to -15	-22 to -14	-18 to -9	11 to 15	10 to 14	5 to 10	-64 to -48
	3°C	-13 to -6	-27 to -15	-24 to -15	-20 to -11	10 to 15	8 to 14	4 to 10	-64 to -50
	2°C	-15 to -8	-30 to -18	-27 to -17	-22 to -13	9 to 14	7 to 13	3 to 9	-65 to -51
	1.5°C	-16 to -9	-32 to -20	-28 to -19	-23 to -14	8 to 14	6 to 12	3 to 9	-66 to -51
Mean maximum daily temperature (degrees C)	4°C	16 to 19	12 to 15	8 to 11	15 to 18	27 to 32	30 to 35	28 to 33	-31 to -25
	3°C	15 to 19	11 to 15	7 to 11	14 to 18	27 to 32	30 to 37	27 to 34	-32 to -25
	2°C	14 to 18	9 to 13	6 to 9	13 to 17	26 to 31	29 to 36	27 to 33	-33 to -25
	1.5°C	13 to 17	8 to 12	5 to 9	12 to 16	25 to 30	28 to 35	26 to 33	-33 to -26
Maximum of daily maximum temperatures (degrees C)	4°C	32 to 37	32 to 38	28 to 33	35 to 40	36 to 43	40 to 47	41 to 49	-12 to -5
	3°C	31 to 39	31 to 38	28 to 34	35 to 41	35 to 44	39 to 51	41 to 54	-12 to -3
	2°C	30 to 37	30 to 36	26 to 33	33 to 39	34 to 43	38 to 50	39 to 53	-13 to -4
	1.5°C	29 to 36	29 to 35	25 to 31	32 to 39	33 to 42	38 to 49	39 to 52	-14 to -5

Number of days with maximum temperature above 35°C – bias adjusted	**4°C**	81 to 106	36 to 50	11 to 22	57 to 77	138 to 194	153 to 210	140 to 168	0 to 0
	3°C	66 to 87	27 to 40	6 to 15	44 to 59	100 to 153	131 to 183	124 to 147	0 to 0
	2°C	52 to 68	19 to 29	4 to 8	33 to 45	61 to 106	116 to 151	102 to 124	0 to 0
	1.5°C	45 to 58	16 to 24	2 to 5	30 to 39	43 to 85	107 to 133	94 to 115	0 to 0
Number of days with maximum temperature above 40°C – bias adjusted	**4°C**	28 to 40	9 to 16	1 to 5	19 to 26	21 to 68	69 to 92	53 to 83	0 to 0
	3°C	20 to 30	5 to 11	1 to 2	14 to 21	9 to 32	56 to 77	41 to 64	0 to 0
	2°C	14 to 21	2 to 6	0 to 1	9 to 15	3 to 13	41 to 57	27 to 45	0 to 0
	1.5°C	11 to 17	2 to 4	0 to 0	8 to 12	1 to 8	35 to 47	22 to 38	0 to 0
Near-surface total precipitation (mm/day)	**4°C**	2 to 3	2 to 3	2 to 2	2 to 3	4 to 5	2 to 3	1 to 2	1 to 1
	3°C	2 to 3	2 to 3	2 to 2	2 to 3	3 to 5	2 to 3	1 to 2	1 to 1
	2°C	2 to 3	2 to 3	2 to 2	2 to 3	3 to 5	2 to 3	1 to 2	1 to 1
	1.5°C	2 to 3	2 to 3	2 to 2	2 to 3	3 to 5	2 to 3	1 to 2	1 to 1
Maximum 1-day precipitation amount (mm)	**4°C**	35 to 55	40 to 53	27 to 35	36 to 52	47 to 90	29 to 67	43 to 68	9 to 13
	3°C	31 to 52	34 to 50	23 to 33	30 to 50	37 to 88	25 to 66	38 to 69	8 to 12
	2°C	29 to 50	32 to 48	22 to 32	28 to 47	37 to 85	22 to 59	36 to 66	8 to 11
	1.5°C	28 to 48	31 to 47	21 to 31	27 to 45	35 to 84	21 to 58	36 to 64	8 to 11
Maximum 5-day precipitation amount (mm)	**4°C**	79 to 99	75 to 93	53 to 71	81 to 105	118 to 168	68 to 113	81 to 124	20 to 29
	3°C	66 to 99	68 to 87	48 to 68	70 to 101	97 to 165	60 to 118	76 to 129	19 to 27
	2°C	64 to 93	65 to 84	47 to 65	66 to 95	93 to 162	55 to 107	73 to 122	18 to 26
	1.5°C	63 to 91	63 to 83	46 to 64	64 to 93	92 to 160	52 to 105	74 to 119	18 to 25
Consecutive dry days (precipitation < 1 mm)	**4°C**	36 to 80	23 to 31	26 to 38	35 to 68	31 to 88	48 to 146	45 to 109	44 to 99
	3°C	36 to 88	21 to 33	25 to 43	35 to 76	29 to 82	49 to 160	40 to 127	45 to 120
	2°C	37 to 88	21 to 32	24 to 40	36 to 74	29 to 77	49 to 161	38 to 128	45 to 127
	1.5°C	36 to 87	22 to 31	25 to 37	36 to 74	28 to 77	49 to 159	40 to 125	46 to 131

Table Cross-Chapter Box CLIMATE.3b: Projected sea surface temperature change ranges by global warming level and ocean biome (degrees Celsius). Ranges are 5th and 95th percentiles from SSP5-8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 projections. *Source: WGI AR6 Interactive Atlas (https://interactive-atlas.ipcc.Chapter/).*

Global warming level	All ocean biomes	Northern Hemisphere - High Latitudes	Northern Hemisphere - Subtropics	Equatorial	Southern Hemisphere - Subtropics	Southern Hemisphere - High Latitudes	Gulf of Mexico	Eastern Boundaries	Amazon River	Arabian Sea	Indonesian Flowthrough
4°C	1.9 to 2.4	2.0 to 3.3	2.2 to 2.8	2.1 to 3.0	1.8 to 2.4	1.3 to 2.0	2.1 to 2.8	2.1 to 2.7	1.7 to 2.5	2.3 to 2.9	1.9 to 2.7

3˚C	1.3	to	1.7	1.2	to	2.2	1.4	to	2.4	1.4	to	2.2	1.2	to	1.7	0.7	to	1.4	1.5	to	2.3	1.4	to	2.1	1.2	to	2.0	1.6	to	2.2	1.3	to	1.9
2˚C	0.6	to	1.0	0.5	to	1.4	0.7	to	1.4	0.7	to	1.3	0.5	to	1	0.3	to	0.8	0.6	to	1.4	0.6	to	1.3	0.6	to	1.3	0.6	to	1.3	0.5	to	1.2
1.5˚C	0.2	to	0.7	0.1	to	0.9	0.2	to	1.0	0.2	to	0.8	0.2	to	0.6	0.1	to	0.5	0.2	to	1.0	0.2	to	0.9	0.2	to	0.9	0.2	to	0.9	0.1	to	0.8

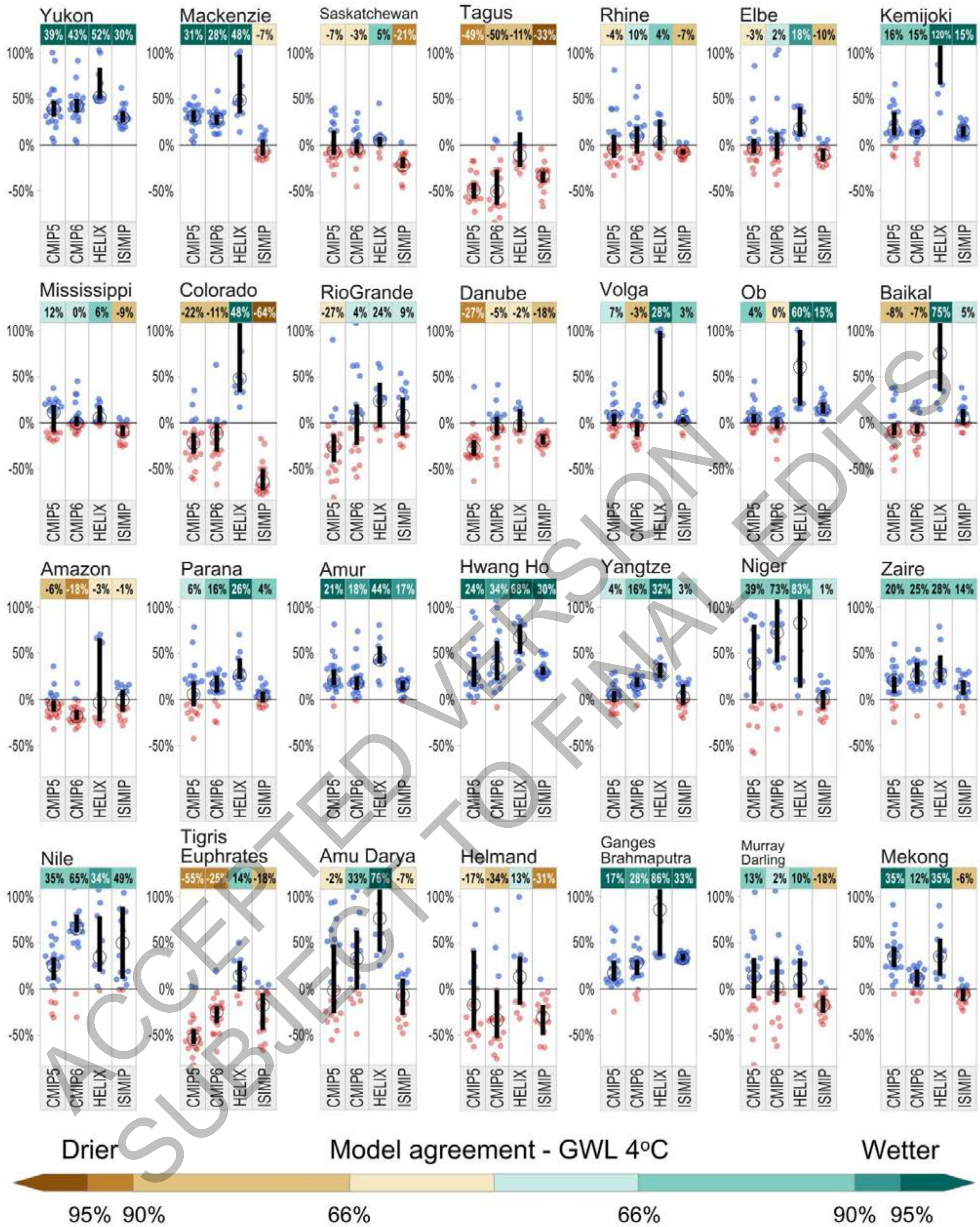


Figure Cross-Chapter Box CLIMATE.1: Illustration of the use of Global Warming Levels (GWLs) as a dimension of integration for impact studies: projected changes in river flows in major basins at 4°C global warming from four different multi-model ensembles. Results are shown for projected flow changes direct from Earth System Models (ESMs) in CMIP5 and CMIP6, for the JULES (Joint UK Land Environment Simulator) land surface model driven by meteorological outputs of the HadGEM3 and EC-Earth model in the HELIX (High-End cLimate Impacts and eXtremes) ensemble (Betts et al., 2018; Koutroulis et al., 2019), and 9 hydrological models driven by a subset of 5 CMIP5 ESMs in the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP; Warszawski et al., 2014). Dots show results from individual models, blue for increased flows and red for decreased flows, black circles show the median for each ensemble, and black bars show the 95% confidence range in the median. See Chapter 4 Figure 4.11 for further details.

To contextualize reported impacts by warming level for the influence of other determinants of risk where appropriate and feasible (e.g., level of exposure/vulnerability, level of adaptation, time period), common time periods for the past and future are available to align with WGI's historical and projected time windows. Given differences in available literature, WGII chapters and CCPs contextualize impacts with respect to exposure, vulnerability and adaptation as they see fit and appropriate for their literature.

Common ranges for other "climate" variables, such as min/max temperature and regional climates, are available based on WGI projections, with feasible combinations with GWLs taken into consideration using the WGI Interactive Atlas. Climate information translation may have been necessary within chapters for mapping the WGII literature and assessments to the common climate dimensions. WGII's climate impacts literature is based primarily on climate projections circa AR5 and earlier or assumed temperature levels, though some recent impacts literature uses newer climate projections based on the CMIP6 exercise. Thus, it was important to be able to map climate variable levels to climate projections of different vintages and vice versa and adjust variables, when possible, to a common reference year. Note that WGII Chapters and CCPs only provide climate impact information for the common climate dimensions that their literature supports and only provide information for dimensions where there is sufficient evidence.

Interpretation of the update in projected time of reaching 1.5°C global warming from SR1.5 to AR6

In an assessment using multiple lines of evidence including models, observational constraints and improved understanding of climate sensitivity, WG1 project a central estimate of the 20-year average warming crossing the 1.5°C GWL in the early 2030s in all scenarios assessed except SSP5-8.5 (Lee et al., 2021). This is about ten years earlier than the midpoint of the likely range (2030–2052) assessed in the SR1.5, which assumed continuation of the observed warming rate reported at that time. However, this does not imply that the projected impacts of 1.5°C will be reached ten years earlier, because roughly half of the ten-year difference is a result of updating the diagnosed historical rate of warming due to methodological advances, new datasets and other improvements (Gulev et al., 2021). The other half of the ten-year difference arises because, for central estimates of climate sensitivity, most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5 (*medium confidence*).

The revised historical warming rate does not necessarily contribute to a change in timing of estimated impacts. It depends on how impacts are calculated relative to climate. Because the revised historical warming results in a redefinition of the 1.5°C GWL relative to the modern time period (1995-2014) rather than a different level of overall change (Figure Cross-Chapter Box CLIMATE.2), impacts assessed relative to the modern time period are unaffected. There are, in effect 'old' and 'new' definitions of the 1.5°C GWL with different levels of impacts, and the impacts assessed for the 'old' 1.5°C GWL now apply to a different level of global warming. However, the timing of impacts assessed relative to pre-industrial (e.g., aggregate economic impact estimates), are affected and we are closer to impact levels associated with 1.5°C and 2°C.

To illustrate with a worked example: in SR1.5, the historical warming between 1850-1900 and the modern period of 2006-2015 was assessed as 0.87°C, implying that the 1.5°C GWL would be accompanied by impacts associated with 0.63°C warming from the modern period. However, AR6 WG1 (Gulev et al., 2021) revised the assessment of warming between 1850-1900 and 2006-2015 to 0.94°C, implying that the 1.5°C GWL would be accompanied by a slightly lower level of impacts associated with only 0.56°C warming from the modern period. So, while the redefined 1.5°C GWL would be reached earlier, it would also be accompanied by a lower level of impacts (Figure Cross-Chapter Box CLIMATE.2). The impacts associated with the 'old' 1.5°C GWL would now be seen at 1.57°C global warming relative to 1850-1900, reached at the time of the 'old' 1.5°C GWL, if the same future level of warming were to be used as in SR1.5.

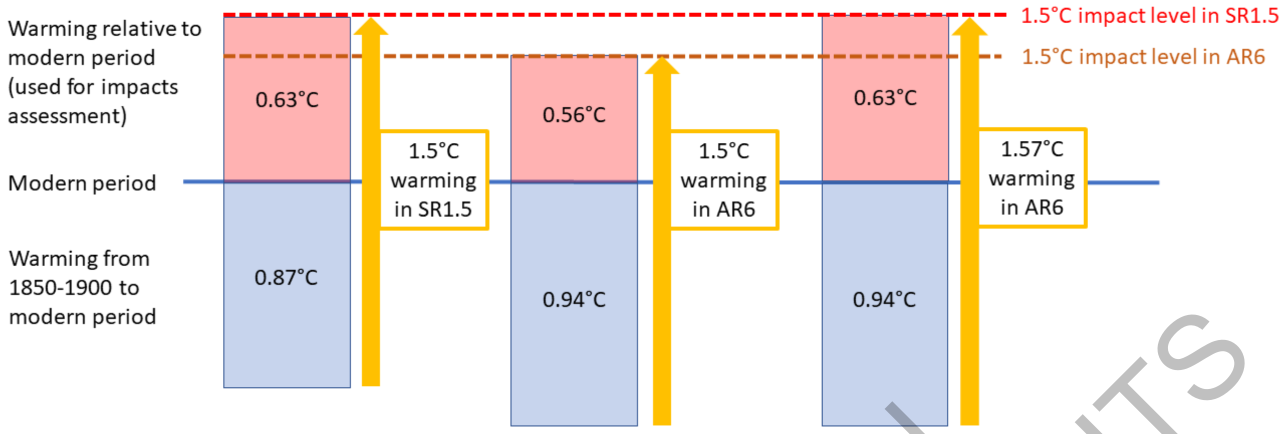


Figure Cross-Chapter Box CLIMATE.2: Definitions of the 1.5°C Global Warming Level (GWL) in SR1.5 and AR6 WG1. GWLs are defined relative to 1850-1900 but impacts at the GWL are typically assessed in association with warming relative to a modern period 1995-2014, which in SR1.5 was 2006-2015. Revised assessment of the historical warming between 1850-1900 and the modern period (0.87°C in SR1.5 to 0.94°C in AR6) has the effect of slightly reducing the warming between the modern period and the 1.5°C GWL (0.63°C in SR1.5 to 0.56°C in AR6), and the impacts at the GWL previously defined as 1.5°C in SR1.5 now occur at 1.57°C global warming with the AR6 definition. Warming values are central estimates. Heights of the bars are not to scale.

However, in addition to this redefinition of the historical warming rate, the assessed future warming in AR6 is also slightly faster than the continuation of reported recent warming used in SR1.5. This means that both the 'old' and 'new' 1.5°C GWLs are projected to be reached earlier than they would have been using the SR1.5 method. This and the revised historical warming diagnosis contribute approximately equally to the assessment of 1.5°C global warming being reached about ten years earlier than projected in SR1.5.

Central estimates of impacts associated with a specifically defined 1.5°C GWL could therefore be considered to be projected to be reached approximately 5 years earlier than implied by SR1.5. However, uncertainties in regional climate responses at a given GWL are large (Table Cross-Chapter Box CLIMATE.3a) and natural climate variability occurs in parallel with ongoing warming, so the potential for impacts higher than central estimates could be a more urgent consideration for risk assessments and adaptation planning than the earlier projected timing of reaching 1.5°C (*high confidence*). It should also be noted that individual years may exceed 1.5°C above 1850-1900 sooner, but this is not the same as exceedance of the 1.5°C GWL which refers to the 20-year mean.

[END CROSS-CHAPTER BOX CLIMATE HERE]

1.3 Understanding and Evaluating Climate Risks

Understanding of climate change has advanced in important ways that shape the AR6 assessment. This section describes advances in the understanding of the complex nature of climate change risks, the deep integration of social sciences, and increased utilization of Indigenous knowledge and local knowledge. These multifaceted dimensions of understanding climate change and evaluating risks are introduced here.

1.3.1 Nature of Climate Risk

Since AR5, understanding of the nature of climate risk has advanced substantially. The AR6 assesses the serious, complex, and cascading climate risks unfolding across sectors and regions. These risks are shaped by many societal factors including cultural norms and social practice, socioeconomic development, underlying physical and social vulnerability, and societal responses themselves (Section 1.2.1.1). Throughout, there is increased attention to the important role of different forms of knowledge, especially Indigenous knowledge and local knowledge, in the understanding and the management of the changing climate.

1.3.1.1 The Nature of Climate Risk as Assessed in this Report

Greater understanding of climate-related risks is emerging; however, there are important shortcomings for the information in some regions and sectors and for developing versus developed countries. These risks assume significance in interaction with the cultures, values, ethics, identities, experiences, and knowledge systems of affected communities and societies, as well as their governance, finances, capabilities, and resources. The key risk assessment in the IPCC AR5 informed the long-term temperature goal in the 2015 Paris Agreement—limiting the increase in global mean temperature to well below 2°C and pursuing efforts towards limiting warming to 1.5°C (Oppenheimer et al., 2014; Pachauri et al., 2014). The IPCC Special Report on Global Warming of 1.5°C, responding to an invitation by UNFCCC, used new scientific information to provide a specific risk assessment associated with the ambitious warming levels targeted by the Paris Agreement (Hoegh-Guldberg et al., 2019), and the Special Reports on Oceans and Land further advanced the methods of transparent risk assessment (Zommers et al., 2020). The current assessment expands significantly from the previous reports, aiming to inform and advance understanding of the following core themes: (1) the ways changes in vulnerability and exposure modulate risks of climate change impacts and risk complexity in addition to warming; (2) the knowledge basis relevant to continued refinement of temperature goals; (3) the effectiveness of adaptation solutions; (4) the management of risks at higher levels of warming, should ambitious climate change mitigation be unsuccessful, including limits to adaptation; and (5) the benefits of climate change mitigation and emissions reductions (Section 16.1).

This report evaluates key risks—potentially severe risks—meriting society's full attention globally and regionally across sectors, in order to inform judgments about dangerous anthropogenic interference with the climate system (Mach et al., 2016; Oppenheimer et al., 2014; see also Sections 16.1.2 and 16.4; WGI AR6 Section 1.2.4.1). As described detail in Chapter 16, evaluation of key risks is based on expert judgment applied to all relevant lines of evidence, with attention to the role of societal values in determining the importance of a risk. Specific criteria considered relate to the magnitude of adverse consequences, including the potential for irreversibility, thresholds, or cascading effects; the likelihood of adverse consequences; the timing of the risk; and the ability to respond to the risk (Section 16.5.1).

The key risk assessment conveys increasing urgency given the growing visibility of climate change impacts in the current world (Sections 1.1 and 16.1). Representative key risks emerging across sectors and regions include risks to coastal socio-ecological systems and terrestrial and ocean ecosystems, risks associated with critical infrastructure, networks, and services; risks to living standards and human health; risks to food and water security; and risks to peace and migration (Section 16.5). Compared to the AR5, the emphasis on human dimensions of key climate-related risks has continued and increased, for instance the potentially severe impacts for cultural heritage (IPCC, 2014c; Pachauri et al., 2014; see also Section 16.4). These human dimensions are essential for understanding vulnerability, impacts, and risks central to ensuring human well-being, human security, sustainable development, and poverty reduction in a changing climate.

To encompass the nature of climate risk, IPCC assessment since the Third Assessment Report has used five overarching domains, named "reasons for concern", to assess increasing risk for societies and ecosystems under climate change (IPCC, 2014b; O'Neill et al., 2017; see also Section 16.5; WGI AR6 Section 1.2.4.1). The reasons-for-concern approach has enabled evidence to combine with expert judgment, in order to provide a holistic assessment across multiple lines of evidence (O'Neill et al., 2017). The approach also respects the uncertainties inherent to climate risk and highlights the ways in which values are relevant in connecting scientific knowledge to societal decision-making and risk management. The different reasons for concern underscore that there is no single metric that can reflect all dimensions of climate-related risk and the diversity of consequences for lives and livelihoods, health and well-being, economic and sociocultural assets, infrastructure, and ecosystems (Mach and Field, 2017; see also Section 1.4.1.2).

The AR6 Reasons for Concern framework enables integration across key risks and representative key risks, including how risks vary with the magnitude of global warming, socioeconomic development pathways, and levels of adaptation (Section 16.6). Risk levels are determined through a formal elicitation approach for both representative key risks and reasons for concern, following the authors' assessment of the literature. The reasons for concern consider *unique and threatened systems* (RFC1), such as coral reefs or Arctic Sea ice systems that have especially high vulnerability and low capacity to adapt. They also include the role of *extreme weather events* (RFC2), such as heat waves, heavy rain, drought, coastal flooding, or wildfires. The reasons for concern address both the *distributional* and the *aggregate impacts* of climate change (RFC3, RFC4), including the unfairness factor for populations that have contributed little in terms of historic emissions but that are disproportionately vulnerable to the impacts of a changing climate. The final reason for concern relates to *large-scale singular events*, nonlinearities, and tipping points (RFC5), including ice sheet collapse and ecosystem regime shifts.

1.3.1.2 The Complexities of Climate Risk

The AR6 assessment incorporates the inherently complex nature of climate risk, vulnerability, exposure, and impacts, which includes feedbacks, cascades, non-linear behaviour, and the potential for surprise (Figure 1.3, 1.4). Many different overlapping and complementary terms and methods are used to evaluate and understand complex climate risk relevant to this report, such as aggregated, compounding, or cascading risks, all of which are considered here as relevant to complex climate risk (Pescaroli and Alexander, 2018; Simpson, In review).

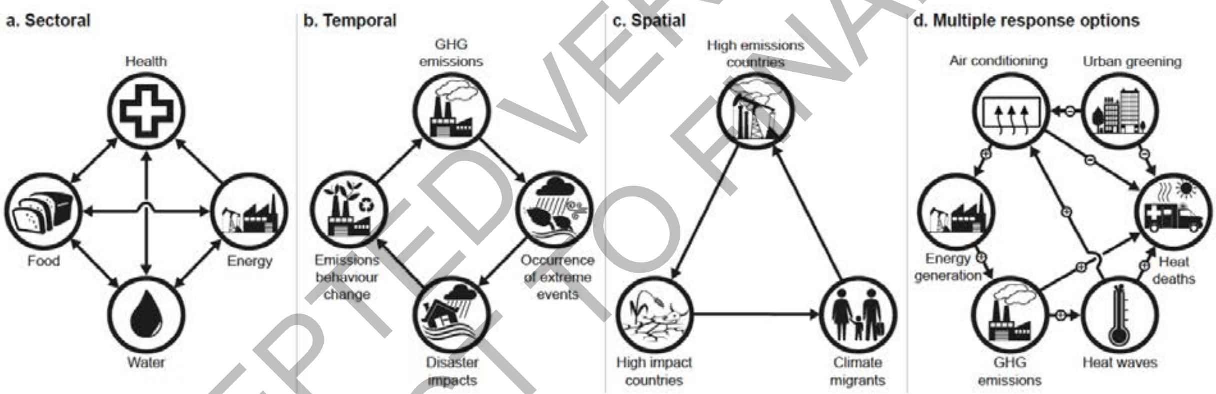


Figure 1.3: Different interactions can decrease or increase climate-related risks. Key examples include interactions (a) among sectors, (b) through time, (c) across regions, or (d) between impacts and responses. The specific interactions indicated within each panel of this figure are illustrative, not comprehensive or indicative of relative importance. Source: (Simpson, In review)

The dynamic nature of risk and its determinants is one important dimension of complexity. The risk of climate change impacts can be usefully understood as resulting from dynamic interactions among climate-related hazards, the exposure and vulnerability of affected human and ecological systems, and also responses (see AR6 Glossary; Section 1.2.1; WGI AR6 Cross-Chapter Box 2 in Chapter 1; Oppenheimer et al., 2014). The determinants of risk all can vary and change through space and time in response to socioeconomic development and decision-making (Figures 1.4 and 1.5, Section 16.1). Hazards are affected by current and future changes in climate, including altered climate variability and shifts in frequency and intensity of extreme events (WGI AR6 Chapter 12). Such hazards can be sudden, e.g., a heat wave or heavy rain event, or slower onset, e.g., land loss, degradation, and erosion linked to multiple climate hazards compounding. The severity of climate change impacts will depend strongly on vulnerability, which is also dynamic and includes the sensitivity and adaptive capacity of affected human and ecological systems (Ford et al., 2018; Jurgilevich et al., 2017; McDowell et al., 2016; Viner et al., 2020). As a result, risks vary at fine scale across communities and societies and also among people within societies, for example dependent on intersecting inequalities and context-specific factors such as culture, gender, religion, ability and disability, or ethnicity (Carr and Thompson, 2014; Jones and Boyd, 2011; Kuruppu, 2009; also Section 16.1.4). The dynamic social distribution of impacts is the subject of increasing attention within climate assessment and responses), including the role of adaptation, iterative risk management, and climate-resilient sustainable development (Section 16.1).

Another core area of complexity in climate risk is the behaviour of complex systems, which includes multiple stressors unfolding together, cascading or compounding interactions, and non-linear responses and the potential for surprises (Clarke et al., 2018; Kopp et al., 2017; Yokohata et al., 2019). Risks and responses, including their determinants, can all interact dynamically in shaping the complexity of climate risk (Figure 1.4). The combined effects of multiple stressors or compound hazards and risks are unlikely to be assessed through simple addition of the independent effects and instead require system approaches to understanding risk. While some components may cancel out each other, others may non-linearly increase risk. Non-linearities can result from abrupt climate changes, tipping points or thresholds in responses, alternative stable states, low-probability/high-consequence outcomes, or events that cannot be predicted based on current understanding (WGI AR6 Section 1.4.4.3).

The nature of climate risk also involves risks from responses themselves (Figure 1.4). The risks of climate change responses include the possibility of responses not achieving their intended objectives or having trade-offs or adverse side effects for other societal objectives (Annex II: Glossary; Section 16.1). In particular, human responses may create novel hazards and unexpected side effects and entail opportunity costs and path dependencies (Boonstra, 2016). Such feedback loops can unfold at local and global scales, including large-scale interactions among climate, ecological, and human systems with human behaviour and decision-making affecting such interactions. Response risks can originate from uncertainty in implementation, maladaptation, action effectiveness, technology development or adoption, or transitions in systems (see Sections 1.4 and 1.5). Typical risks may be related to regulation, litigation, competition, socio-politics, or reputation. Interactions across responses can importantly involve co-benefits for other objectives, such as for human health and well-being which may be improved from both reduced air pollution (e.g., WGI Chapter 6, WGIII) and enhanced adaptation to climate change. The nature of risk also entails residual impacts that will occur even with ambitious societal responses, given limits to adaptation at sectoral and regional levels (Section 1.4, Sections 16.1 and 16.4). In some cases, the losses will be irreversible.

Due to these complexities, the challenge of assessing risks of climate change is not well bounded, will be framed differently by individuals and groups, involves large and deep uncertainties, and will have unclear solutions and pathways to solutions (Renn, 2008; Rittel and Webber, 1973; see also Sections 1.5.2 and 17.2.1). Challenges also include the degree to which time is running out, there is no central authority, those seeking the solutions are also causing the problem, and the present is favoured over the future (Sun and Yang, 2016; see also Section 17.2.1). Both the needs for and the limits to adaptation responses fundamentally depend on progress achieved in reducing greenhouse gas emissions and limiting the magnitude of climate change that occurs, interlinked with socioeconomic development trajectories and the many social and political factors shaping climate risks and responses.

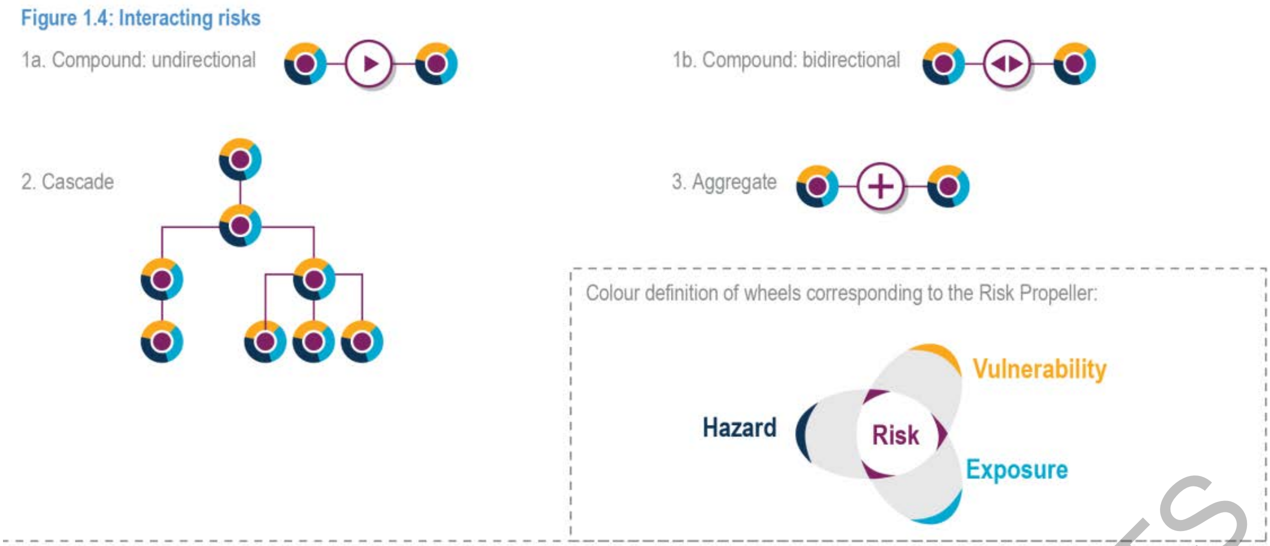


Figure 1.4: Increasingly complex climate-related risks. Risk results from interactions among the determinants of risk—hazard, vulnerability, and exposure, shaped by responses—which can interact in complex ways. Different risks and responses can compound (e.g., often linked to compounding hazards; 1a and 1b), cascade (e.g., with one event triggering another; 2), and aggregate (e.g., with independent determinants of risks co-occurring; 3). This complex nature of risk is central in the AR6 assessment. Figure adapted from Simpson et al., 2021.

a)

Figure 1.5: Risk in IPCC assessment through time. (a) An explicit risk framing emerged in the IPCC SREX and WGII AR5. (b) In the current assessment, the role of responses in modulating the determinants of risk is a new emphasis (the "wings" of the hazard, vulnerability, and exposure "propellers" represents the ways in which responses modulate each of these risk determinants). (c) As the risk assessment spans working groups, the differential role of risk determinants for risk related to impacts, adaptation, and vulnerability versus risk related to mitigation becomes an increasingly important feature of climate risk assessment as well as management.

1.3.2 Assessing, Evaluating, and Understanding Climate Impacts and Risks

Multiple, diverse sources of information underlie our understanding of climate risks and response, including climate change science, diverse social sciences, and Indigenous knowledge and local knowledge.

1.3.2.1 Detection and Attribution of Climate Change and Its Impacts

Anthropogenic climate change is unequivocal and ongoing. The detection of specific changes in the climate and their diverse impacts on people and nature is advancing, with robust attribution of climate change to greenhouse gas emissions as well as to other contributing factors (e.g., socio-economic development, land-use change). In the AR6, advances include increasing ability to link individual extreme weather and climate events to emissions of greenhouse gases, increasing identification of impacts for societies and economies, and strong linkages in the attribution methods across working groups (Cross-Working Group Box: ATTRIBUTION in Chapter 1).

[START CROSS-WORKING GROUP BOX: ATTRIBUTION HERE]

Cross-Working Group Box: ATTRIBUTION: Attribution in the IPCC Sixth Assessment Report

Authors: Pandora Hope (Australia), Wolfgang Cramer (France/Germany), Maarten van Aalst (Netherlands), Greg Flato (Canada), Katja Frieler (Germany), Nathan Gillett (Canada/United Kingdom), Christian Huggel (Switzerland), Jan Minx (Germany), Friederike Otto (United Kingdom /Germany), Camille Parmesan (France/ United Kingdom /USA), Joeri Rogelj (United Kingdom /Belgium), Maisa Rojas (Chile), Sonia I. Seneviratne (Switzerland), Aimee Slangen (Netherlands), Daithi Stone (New Zealand), Laurent Terray (France), Robert Vautard (France), Xuebin Zhang (Canada)

Introduction

Changes in the climate system are becoming increasingly apparent, as are the climate-related impacts on natural and human systems. Attribution is the process of evaluating the contribution of one or more causal factors to such observed changes or events. Typical questions addressed by the IPCC are for example: 'To what degree is an observed change in global temperature induced by anthropogenic greenhouse gas and aerosol concentration changes or influenced by natural variability?' or 'What is the contribution of climate change to observed changes in crop yields that are also influenced by changes in agricultural management?' Changes in the occurrence and intensity of extreme events can also be attributed, addressing questions such as: 'Have human greenhouse gas emissions increased the likelihood or intensity of an observed heat wave?'

This Cross-Working Group Box briefly describes why attribution studies are important. It also describes some new developments in the methods used and provides recommendations for interpretation.

Attribution studies serve to evaluate and communicate linkages associated with climate change, for example: between the human-induced increase in greenhouse gas concentrations and the observed increase in air temperature or extreme weather events (WGI Chapters 3, 10 and 11); or between observed changes in climate and changing species distributions and food production (e.g., Verschuur et al., 2021; WGII Chapter 2 and others; summarised in Chapter 16) or between climate change mitigation policies and atmospheric greenhouse gas concentrations (WGI Chapter 5; WGIII Chapter 14). As such, they support numerous statements made by the IPCC (IPCC, 2013; IPCC, 2014c; WGI Section 1.3; Appendix 1A) (IPCC, 2013b, 2014b; WGI Chapter 1, Section 1.3, Appendix 1A).

Attribution assessments can also serve to monitor mitigation and assess the efficacy of applied climate protection policies (e.g., Banerjee et al., 2020; Nauels et al., 2019; WGI Section 4.6.3)), inform and constrain projections (Gillett et al., 2021; Ribes et al., 2021; WGI Section 4.2.3) or inform the loss and damages estimates and potential climate litigation cases by estimating the costs of climate change (Frame et al., 2020; Huggel et al., 2015; Marjanac et al., 2017). These findings can thus inform mitigation decisions as well as risk management and adaptation planning (e.g., Climate & Development Knowledge Network, 2017).

Steps towards an attribution assessment

The unambiguous framing of what is being attributed to what is a crucial first step for an assessment (Easterling et al., 2016; Hansen et al., 2016; Stone et al., 2021), followed by the identification of the possible and plausible drivers of change and the development of a hypothesis or theory for the linkage (see Figure ATTRIBUTION.1). The next step is to clearly define the indicators of the observed change or event and note the quality of the observations. There has been significant progress in the compilation of fragmented and distributed observational data, broadening and deepening the data basis for attribution research (Cohen et al., 2018; Poloczanska et al., 2013; Ray et al., 2015; WGI Section 1.5). The quality of the observational record of drivers should also be considered (e.g., volcanic eruptions: WGI Chapter 2, Section 2.2.2). Impacted systems also change in the absence of climate change; this baseline and its associated modifiers such as agricultural developments or population growth need to be considered, alongside the exposure and vulnerability of people depending on these systems.

There are many attribution approaches, and several methods are detailed below. In physical and biological systems, attribution often builds on the understanding of the mechanisms behind the observed changes and numerical models are used, while in human systems other methods of evidence-building are employed. Confidence in the attribution can be increased if more than one approach is used and the model is evaluated as fit-for-purpose (Hegerl et al., 2010; Otto et al., 2020a; Philip et al., 2020; Vautard et al., 2019; WGI Section 1.5). Finally, appropriate communication of the attribution assessment and the accompanying confidence in the result (e.g., Lewis et al., 2019).

Attribution methods

Attribution of changes in atmospheric greenhouse gas concentrations to anthropogenic activity

AR6 WGI Chapter 5 presents multiple lines of evidence that unequivocally establish the dominant role of human activities in the growth of atmospheric CO_2, including through analysing changes in atmospheric carbon isotope ratios and the atmospheric O_2-N_2 ratio (WGI Section 5.2.1.1). Decomposition approaches can be used to attribute emissions underlying those changes to various drivers such as population, energy efficiency, consumption or carbon intensity (Hoekstra and van den Bergh, 2003; Raupach et al., 2007; Rosa and Dietz, 2012). Combined with attribution of their climate outcomes, the attribution of the sources of greenhouse gas emissions can inform the attribution of anthropogenic climate change to specific countries or actors (Matthews, 2016; Nauels et al., 2019; Otto et al., 2017; Skeie et al., 2017), and in turn inform discussions on fairness and burden sharing (WGIII Chapter 14).

Attribution of observed climate change to anthropogenic forcing

Changes in large-scale climate variables (e.g., global mean temperature) have been reliably attributed to anthropogenic and natural forcings (e.g., Bindoff and et al., 2014; Hegerl et al., 2010; WGI Section 1.3.4). The most established method is to identify the 'fingerprint' of the expected space-time response to a particular climate forcing agent such as the concentration of anthropogenically induced greenhouse gases or aerosols, or natural variation of solar radiation. This technique disentangles the contribution of individual forcing agents to an observed change (e.g., Gillett et al., 2021). New statistical approaches have been applied to better account for internal climate variability and the uncertainties in models and observations (e.g., Naveau et al., 2018; Santer et al., 2019; WGI Section 3.2). There are many other approaches, for example, global mean sea-level change has been attributed to anthropogenic climate forcing by attributing the individual contributions from, for example, glacier melt or thermal expansion, while also examining which aspects of the observed change are inconsistent with internal variability (WGI Section 3.5.2 and WGI Section 9.6.1.4).

Specific regional conditions and responses may simplify or complicate attribution on those scales. For example, some human forcings, such as regional land use change or aerosols, may enhance or reduce regional signals of change (Boé et al., 2020; Lejeune et al., 2018; Thiery et al., 2020; Undorf et al., 2018; see also WGI Sections 10.4.2, 11.1.6, and 11.2.2). In general, regional climate variations are larger than the global mean climate, adding additional uncertainty to attribution (e.g., in regional sea-level change, WGI Section 9.6.1). These statistical limitations may be reduced by 'process-based attribution', focusing on the physical processes known to influence the response to external forcing and internal variability (WGI Section 10.4.2).

Attribution of weather and climate events to anthropogenic forcing

New methods have emerged since AR5 to attribute the change in likelihood or characteristics of weather or climate events or classes of events to underlying drivers (Jézéquel et al., 2018; National Academies of Sciences, 2016; Stott et al., 2016; Wang et al., 2020; Wehner et al., 2019; WGI Sections 10.4.1 and 11.2.2). Typically, historical changes, simulated under observed forcings, are compared to a counterfactual climate simulated in the absence of anthropogenic forcing. Another approach examines facets of the weather and thermodynamic status of an event through process-based attribution (Grose et al., 2020; Hauser et al., 2016; Shepherd et al., 2018; WGI Section 10.4.1 and Chapter 11). Events where attributable human influences have been found include hot and cold temperature extremes (including some with wide-spread impacts), heavy precipitation, and certain types of droughts and tropical cyclones (e.g., Herring et al., 2021; Vogel et al., 2019; WGI Section 11.9). Event attribution techniques have sometimes been extended to 'end-to-end' assessments from climate forcing to the impacts of events on natural or human systems (Otto et al., 2017; examples in WGII Table 16.1, SI of WGII Chapter 16, Section 16.2).

Attribution of observed changes in natural or human systems to climate-related drivers

The attribution of observed changes to climate-related drivers across a diverse set of sectors, regions and systems is part of each chapter in the WGII contribution to the AR6 and is synthesised in WGII Chapter 16 (Section 16.2). The number of attribution studies on climate change impacts has grown substantially since AR5, generally leading to higher confidence levels in attributing the causes of specific impacts. New studies include the attribution of changes in socio-economic indicators such as economic damages due to river floods (e.g., Sauer et al., 2021; Schaller et al., 2016), the occurrence of heat related human mortality (e.g., Sera et al., 2020; Vicedo-Cabrera et al., 2018), or economic inequality (e.g., Diffenbaugh and Burke, 2019).

Impact attribution covers a diverse set of qualitative and quantitative approaches, building on experimental approaches, observations from remote sensing, long-term in situ observations, and monitoring efforts, teamed with local knowledge, process understanding and empirical or dynamical modelling (WGII Section 16.2; Cramer et al., 2014; Stone et al., 2013). The attribution of a change in a natural or human system (e.g., wild species, natural ecosystems, crop yields, economic development, infrastructure or human health) to changes in climate-related systems (i.e., climate, and ocean acidification, permafrost thawing or sea-level rise) requires accounting for other potential drivers of change, such as technological and economic changes in agriculture affecting crop production (Butler et al., 2018; Hochman et al., 2017), changes in human population patterns and vulnerability affecting flood or wildfire induced damages (Huggel et al., 2015; Sauer et al., 2021), or habitat loss driving declines in wild species (IPBES, 2019b). These drivers are accounted for by estimating a baseline condition that would exist in the absence of climate change. The baseline might be stationary and be approximated by observations from the past, or it may change over time and be simulated by statistical or process-based impact models (Cramer et al., 2014; WGII Section 16.2). Assessment of multiple independent lines of evidence, taken together, can provide rigorous attribution when more quantitative approaches are not available (Parmesan et al., 2013). These include palaeodata, physiological and ecological experiments, natural 'experiments' from very long-term datasets indicating consistent responses to the same climate trend/event, and 'fingerprints' in species' responses that are uniquely expected from climate change (e.g. poleward range boundaries expanding and equatorial range boundaries contracting in a coherent pattern world-wide, Parmesan and Yohe, 2003). Meta-analyses of species/ecosystem responses, when conducted with wide geographic coverage, also provide a globally coherent signal of climate change at an appropriate scale for attribution to anthropogenic climate change (Parmesan et al., 2013; Parmesan and Yohe, 2003).

Impact attribution does not always involve attribution to anthropogenic climate forcing. However, a growing number of studies include this aspect (e.g., Diffenbaugh and Burke, 2019 for the attribution of economic inequality between countries; Frame et al., 2020 for the attribution of damages induced by Hurricane Harvey; or Schaller et al., 2016for flood damages).

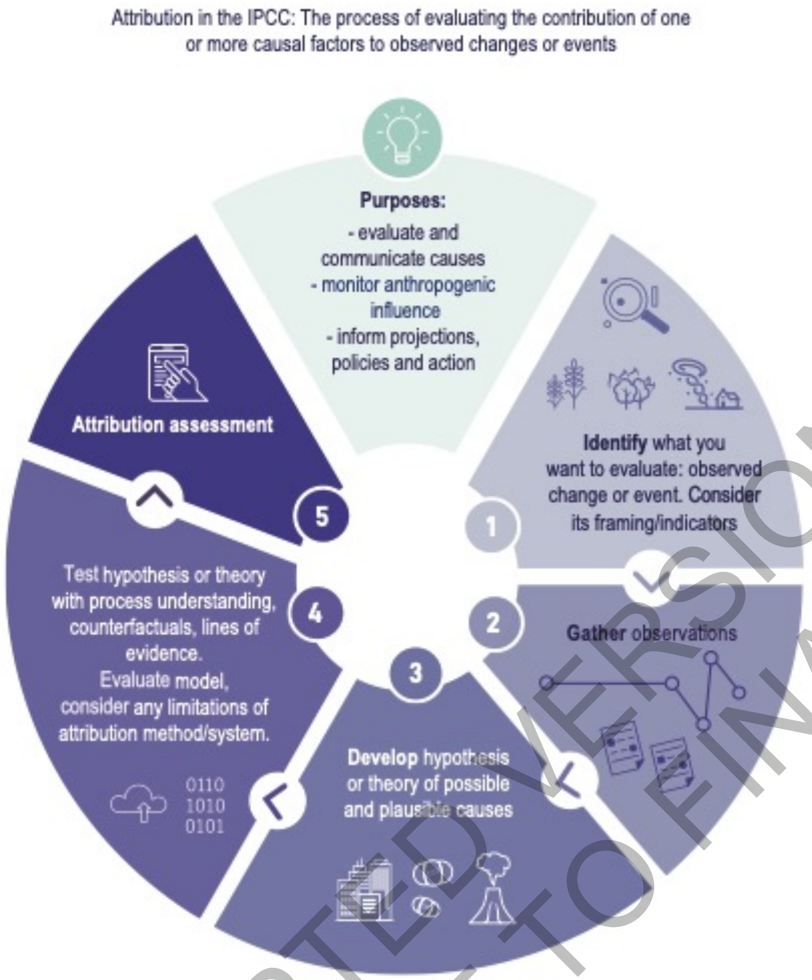


Figure Cross-Working Group Box: ATTRIBUTION.1: Schematic of the steps to develop an attribution assessment, and the purposes of such assessments. Methods and systems used to test the attribution hypothesis or theory include model-based fingerprinting, other model-based methods, evidence-based fingerprinting, process-based approaches, empirical or decomposition methods and the use of multiple lines of evidence. Many of the methods are based on the comparison of the observed state of a system to a hypothetical counterfactual world that does not include the driver of interest to help estimate the causes of the observed response.

[END CROSS-WORKING GROUP BOX: ATTRIBUTION HERE]

Impacts occurring today can be put into context through understanding of long-term changes on Earth, introduced in the Cross-Chapter Box PALEO (see below). Climate has always varied and changed in the past, and this change often caused substantial ecological, evolutionary and socio-economic impacts. Adaptation of ecosystems and societies occurred through responses as diverse as migration to mass extinction. Humankind is at the verge of leaving the Holocene climatic envelope, in which all human achievement since the advent of agriculture has occurred. In some systems, the changes and losses will be irreversible.

[START CROSS-CHAPTER BOX PALEO HERE]

Cross-Chapter Box PALEO: Vulnerability and Adaptation to Past Climate Changes

Authors: Wolfgang Kiessling (Germany, Chapter 3, Cross-Chapter Paper 1), Timothy A. Kohler (USA, Chapter 14), Wolfgang Cramer (France, Chapter 1, Cross-Chapter Paper 4), Gusti Anshari (Indonesia, Chapter 2), Jo Skeie Hermansen (Norway, CA Chapter 1), Darrell S. Kaufman (USA, WG 1, Chapter 2), Guy Midgley (South Africa, Chapter 16), Nussaïbah Raja (Mauritius, CA Chapter 3), Daniela N. Schmidt (UK/Germany, Chapter 13), Nils Chr. Stenseth (Norway, Chapter 1), Sukumar Raman (India, Chapter 1)

Understanding how Earth's biota have responded to past climate dynamics is essential to understanding current and future climate-related risks, as well as the adaptive capacity and vulnerabilities of ecosystems and the human livelihoods depending on them. Here we assess climate impacts on long geological time scales (Figure PALEO.1), as well as for the last 70 kyr of *Homo sapiens*' existence (Figure PALEO.2). Climate responses of natural and human systems are intertwined through the physiological limits of wild animals, livestock, plants and humans, subject to a slow evolutionary dynamic (Pörtner, 2021; Sections 2.6.1 and 3.3).

Climate has always changed, often with severe effects on nature, including species loss

Observations provided by the historical, archaeological, and paleontological records, together with paleoclimatic data, demonstrate that climatic variability has high potential to affect biodiversity and human society (*high confidence*). The evolution of the Earth's biota has been punctuated by global biodiversity crises often triggered by rapid warming (*high confidence*) (Benton, 2018; Figure PALEO.1; Bond and Grasby, 2017; Foster et al., 2018). These so-called hyperthermal events were marked by rapid warming of >1°C, which coincided with global disturbances of the carbon and water cycles, and by reduced oxygen and pH in seawater (Clapham and Renne, 2019; Foster et al., 2018). Magnitudes of global temperature shifts in hyperthermal events were sometimes greater than those predicted for the current century but extended over longer periods of time. Rates inferred from paleo records that are coarsely resolved are inevitably lower than those from direct observations during recent decades, and caution must be exercised when describing the rate of recent temperature changes as unprecedented (Kemp et al., 2015). Mass extinctions, each with greater than 70% marine species extinctions, occurred when the magnitude of temperature change exceeded 5.2°C (Song et al., 2021), albeit species extinctions occurred at lower magnitudes of warming (*medium confidence*).

Adaptation options to rapid climate change are limited

Responses of biota to rapid climate change have included range shifts (*very high confidence*), phenotypic plasticity (*high confidence*), evolutionary adaptation (*medium confidence*), and species extinctions, including mass extinctions (*very high confidence*). While knowledge about the relative roles of these processes in promoting survival during times of climate change is still limited (Nogués-Bravo et al., 2018), they have influenced the evolutionary trajectories of species and entire ecosystems (*high confidence*), and also the course of human history (*medium confidence*). The combined ecological and evolutionary responses to ancient rapid warming events ranged from extinction of 81% of marine animal species and 70% of terrestrial tetrapod species on land at the end of the Permian period (~ 252 million years ago, Ma) (Smith and Botha, 2005; Stanley, 2016) to low rates of species extinctions but biome- and range-shifts on land and in the ocean at the Palaeocene-Eocene Thermal Maximum (PETM, ~ 56 Ma) (Figure PALEO.1; Fraser and Lyons, 2020; Huurdeman et al., 2021; Ivany et al., 2018). Temperature and deoxygenation were key drivers of past biotic responses in the oceans (Gibbs et al., 2016; Section 3.3; Penn et al., 2018) (*high confidence*), whereas on land the interplay between temperature and precipitation is less well established in ancient hyperthermals (Frank et al., 2021) (*medium confidence*). Climate-driven extinction risk increased by up to 40% when a short-term climate change added to a long-term trend in the same direction, for example when a long-term warming trend was followed by rapid warming (Mathes et al., 2021).

Organismic traits associated with extinctions during ancient climate changes help identify present-day vulnerabilities and conservation priorities (Barnosky et al., 2017; Calosi et al., 2019; Reddin et al., 2020; Chapters 2 and 3; Cross-Chapter Paper 1). Marine invertebrates and fishes are at greater extinction risk in response to warming than terrestrial ones because of reduced availability of thermal refugia in the sea (Pinsky et al., 2019) (*high confidence*). Terrestrial plants showed reduced extinction during past rapid warming compared to animals (*high confidence*), although they readily adjusted their ranges and reorganized vegetation types (Heimhofer et al., 2018; Huurdeman et al., 2021; Lindström, 2016; Slater et al., 2019; Yu et al., 2015).

Population range shifts including migrations are common adaptations to climate changes across multiple time scales and ecological systems in the past and in response to current warming (*high confidence*). Poleward expansions and retractions (Fordham et al., 2020; Reddin et al., 2018; Williams et al., 2018) as well as migration upslope and downslope in response to warming and cooling were common adaptations (Iglesias et al., 2018; Ortega-Rosas et al., 2008). During warming periods, diversity loss was common near the equator (*medium confidence*)(Kiessling et al., 2012; Kröger, 2017; Yasuhara et al., 2020) while diversity gains and forest expansion occurred in high latitudes (Brovkin et al., 2021). Comparison of contemporary shells and skeletons with historical collections in museums (Barnes et al., 2011) and the analysis of skeletons of long-lived organisms (Cantin et al., 2010) indicate significant climate-induced change in organismic growth rates today (*high agreement, medium confidence*).

Humankind has responded to regional climate variability within a narrow Holocene climatic envelope

Early human evolution (beginning ~2.1 Ma) occurred in a highly variable climate characterized by glacial-interglacial cycles. This variability may have favoured key hominin adaptations such as bipedality, increased brain size, complex sociality, and more diverse tools (Potts, 1998; Potts et al., 2020) (*medium confidence*), but extinctions of five species of *Homo* have also been attributed partly to climate change (Raia et al., 2020) (*low confidence*). The "out-of-Africa" dispersal of anatomically modern humans may have been driven by climate variability (Tierney et al., 2017; Timmermann and Friedrich, 2016) (*medium confidence, low agreement*). Most late Pleistocene megafaunal extinctions are attributed to direct and indirect human impacts (Sandom et al., 2014), although some were likely accelerated by climate change (Carotenuto et al., 2018; Saltré et al., 2019; Wan and Zhang, 2017; Westaway et al., 2017) (*low confidence*).

The emergence of agriculture (~10.2 ka) in SW Asia was associated with stable (within ± 1°C global mean annual on multi-century time scale; *WGI Chapter 2*) warm and moist conditions (Palmisano et al., 2021; Richerson et al., 2001; Rohling et al., 2019). Variability in resource availability and agricultural production, entrained by climatic variability, is implicated in the disruption and decline of numerous past human societies (*medium confidence*) (Cookson et al., 2019; d'Alpoim Guedes and Bocinsky, 2018; Jones, 2019; Park et al., 2019). These crises are partially caused by regional climate anomalies including Holocene "Rapid Climate Change Events" (Rohling et al., 2019) not visible in the globally averaged conditions shown in Fig. Palaeo.2. Such anomalies affected human population size (Clark et al., 2019; Kuil et al., 2019; Riris and Arroyo-Kalin, 2019), health (Campbell and Ludlow, 2020), social stability/conflict (Büntgen et al., 2011; Kohler et al., 2014), and triggered migrations (Chiotis, 2018; D'Andrea et al., 2011; Pei et al., 2018; Schwindt et al., 2016) or retarded them (Betti et al., 2020; FAQ 14.2). Populations have also been impacted by sea-level change in coastal areas (Turney and Brown, 2007; Cross-Chapter Box SLR in Chapter 3).

Evidence for widespread droughts ~4.2 ka lasting for several centuries in some regions has been tentatively linked to declines of the Akkadian Empire (Carolin et al., 2019; Weiss, 2017), the Indus Valley (Giosan et al., 2018; Sengupta et al., 2020) and the Egyptian Old Kingdom and Yangtze River Valley (Ran and Chen, 2019). Deteriorating climates often exacerbate accumulating weaknesses in social systems to which population growth and urban expansion contribute (Knapp and Manning, 2016; Lawrence et al., 2021; Scheffer et al., 2021). The rather narrow climatic niche favoured by human societies over the last six thousand years is poised to move on the Earth's surface at speeds unprecedented in this time span (IPCC, 2021), with consequences for human well-being and migration that could be profound under high-emission scenarios (Xu et al., 2020). This will overturn the long-lasting stability of interactions between humans and domesticated plants and animals as well as challenge the habitability for humans in several world regions (Horton et al., 2021) (*medium confidence*).

Climate change destroys unique natural archives and important cultural heritage sites

Climate change not only impacts past ecosystems and societies but also the remains they have left. The progressive loss of archaeological and historical sites and natural archives of paleo environmental data WGI Chapter 2 constitutes often-overlooked impacts of climate change (Anderson et al., 2017; Climate Change

Cultural Heritage Working Group International, 2019; Cross-Chapter Box SLR in Chapter 3; Hollesen et al., 2018). These archives include peat bogs and coastal archives lost to sea-level rise, droughts and fires, degradation through permafrost thaw, and dissolution. The ancient cultural diversity documented by such sites is an important resource for future adaptation (Burke et al., 2021; Rockman and Hritz, 2020). Since many of these sites constitute anchors for indigenous knowledge, their loss is not just data lost to science; it also interrupts intergenerational transmission of knowledge (Green et al., 2009).

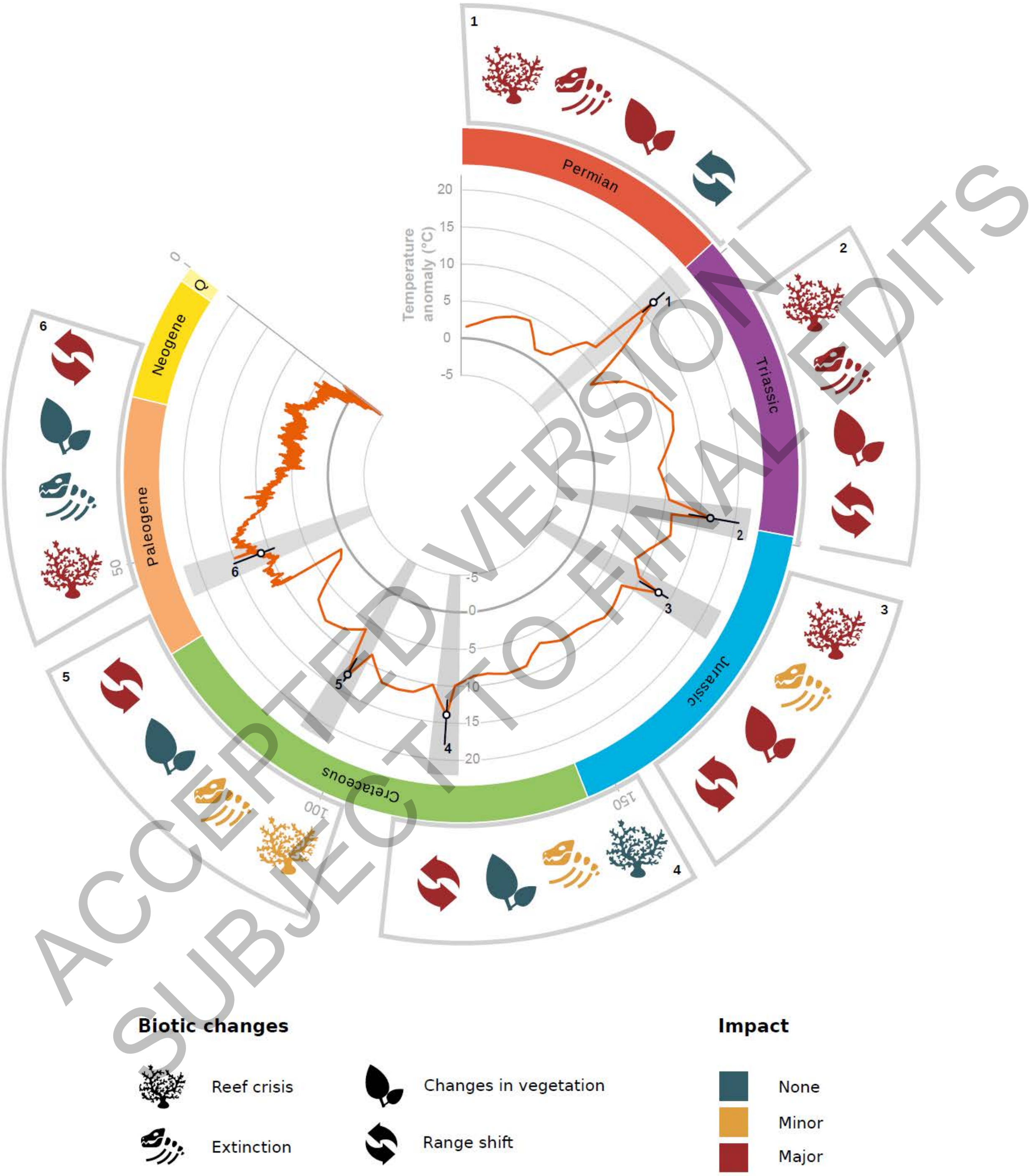


Figure Cross-Chapter Box PALEO.1: Biological responses to six well-known ancient rapid warming events (hyperthermals) over the last 300 million years. Temperature anomalies (mean temperature difference to pre-industrial (1850–1900), solid orange curve) derived from climate modelling (300–66 Ma) (Haywood et al., 2019) and deep-sea proxy data (66–0.1 Ma) (Hansen et al., 2013). Temperature peaks underneath the grey bars indicate well-known hyperthermals with temperature anomalies derived from temperature-sensitive proxy data (Foster et al., 2018). Error bars indicate uncertainties in peak warming events (ranges in the literature). Insets show observed impacts to the biosphere. Q = Quaternary.

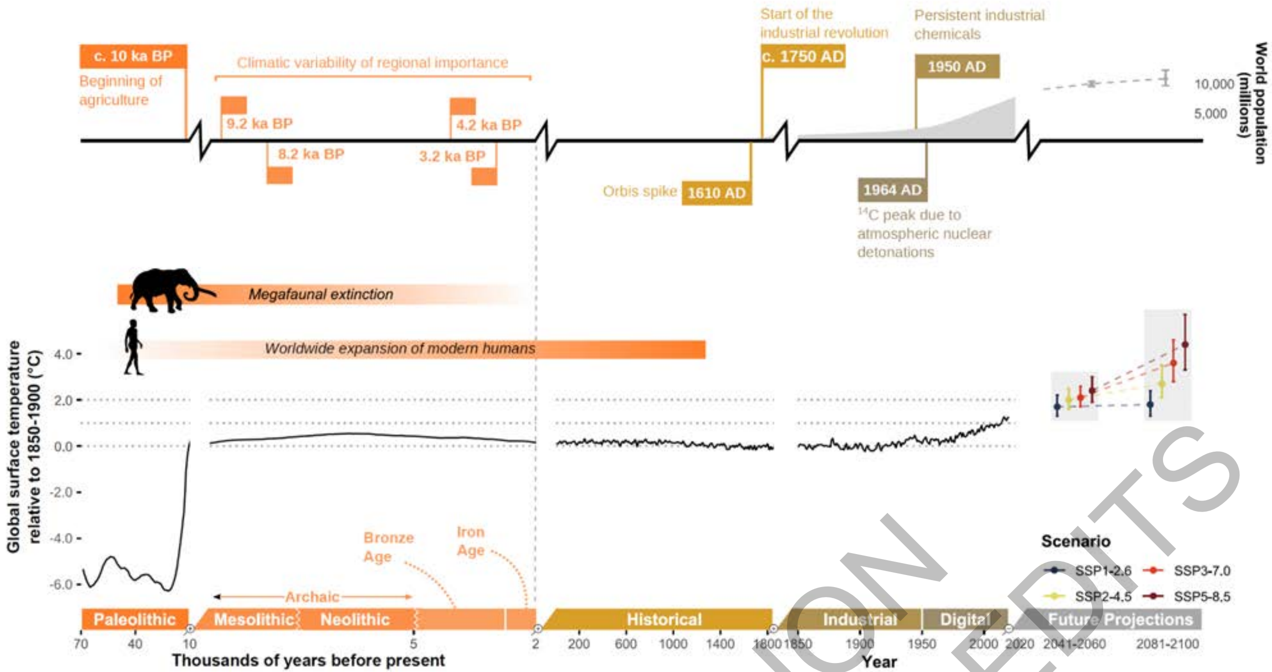


Figure Cross-Chapter Box PALEO 2: Humankind is embarking on a trajectory beyond the global temperatures experienced since at least the advent of agriculture. Global surface temperature change for the last 70,000 years [relative to 1850-1900; data from AR6-WGI-Ch2] alongside projections (with 5-95% range; AR6-WGI-Ch4) and major events in human societies. Global climatic parameters do not always capture regional variability of importance to specific societies. The "Orbis Spike" represents a pronounced dip in atmospheric CO_2 from the Law Dome ice core (Antarctica) (MacFarling Meure et al., 2006) marking the globalization in biota and trade of the Columbian Exchange and population declines and afforestation in the Americas. This, and the 1964 ^{14}C peak, have been suggested as possible markers for the onset of the Anthropocene (Lewis and Maslin, 2015). Population trends from United Nations (2019).

[END CROSS-CHAPTER BOX PALEO HERE]

1.3.2.2 Perceiving Climate Risk and Human Response

Since AR5, social science literature on how individuals and societies perceive and respond to climate risk has dramatically advanced (Jones et al., 2014; Neaves and Royer, 2017; Renn, 2008; Taylor et al., 2014; Van Valkengoed and Steg, 2019). The literature is increasingly integrating and advancing long-standing scholarship on environmental and social governance, human dimensions of environmental change, risk perception and communication, and enabling conditions for effective policy making. These emergent literatures on climate risk, human action, and solution reflect into three broad areas of analysis: 1) root drivers (i.e., role of cultural norms and social practice, social structures and economic development status that shape physical and social vulnerability; 2) context specific barriers and enablers (i.e., governance structures, institutional structure and function, risk perceptions, access to financing and knowledge availability and needs) and 3) the solution-proximate decision space (i.e., climate urgency and catalysing conditions, risk communication strategies, monitoring and evaluation strategies) (see Jorgenson et al., 2019; Solecki et al., 2017).

These three areas are deeply embedded in the social sciences and reflect fundamental questions of how and why humans and their institutions act and respond (Chapter 17). In the past two decades, these basic issues have been applied to research of climate change, dynamic risk, and adaptation. Underlying this analysis, particularly of root drivers and barriers and enablers are assertions regarding the foundational properties of individual and collective behaviour (i.e., self-interest, optimisation, rationality, bounded rationality), how they are structured, and how these properties can be revealed. This literature draws on several academic disciplines including anthropology, economics, geography, political science, psychology, sociology, and urban studies. Climate change social science research is often interdisciplinary or transdisciplinary and hence utilizes a variety of methods to derive new knowledge (Orlove et al., 2020).

In contrast to previous assessments, AR6 is increasingly focused on the needs for and challenges of assessing the societal response to climate change. The accurate tabulation of adaptation, a key question for examining the solution space is difficult (Chapter 16, Cross-Chapter Box ADAPT in Chapter 1), since many forms of adaptation activity are under-represented in the peer-reviewed and grey literature. Moreover, the related question of assessing the effectiveness of adaptation, that is, the extent to which it reduces risk, is also difficult. Estimating risk reduction often involves counterfactuals, for instance, quantifying the damage a flood would have caused had a community not adapted prior to a storm or projecting the damage averted by today's adaptation in some future storm (see Cross-Chapter Box PROGRESS in Chapter 17). Many socio-economic drivers affect risk, so attribution for any observed or projected changes must be allocated among those due to adaptation and those due to economic development, cultural changes, and other types of policies and trends. For instance, many measures of sustainable development overlap with those for adaptive capacity and both can reduce climate risk while also yielding benefits irrespective of future climate regimes (UNEP, 2018). There also exist many different goals for adaptation both among and within different jurisdictions, so that adaptation efforts deemed effective by some individuals may not be deemed effective by others (Dilling et al., 2019).

1.3.2.3 Indigenous Knowledge and Local Knowledge

While scientific knowledge is vital, Indigenous knowledge (IK) and local knowledge (LK) are also necessary for understanding and acting effectively on climate risk (IPCC, 2014a; SROCC Chapter 1,IPCC, 2019b; see also Section 2.4). **Indigenous knowledge** refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (IPCC, 2019a). **Local knowledge** is defined as the understandings and skills developed by individuals and populations, specific to the places where they live (IPCC, 2019a). These definitions relate to the debates on the world's cultural diversity (UNESCO, 2018a), which are increasingly connected to climate change debates (UNESCO, 2018b). However, there is agreement that, in the same way that there is not a unique definition of Indigenous Peoples because it depends on self-determination, there is not a single definition of neither Indigenous knowledge nor local knowledge. Therefore, contextualisation is highly needed. IK and LK will shape perceptions of climate risk which are vital to managing climate risk in day-to-day activities to longer term actions.

Such experience-based and practical knowledge is obtained over generations through observing and working directly within various environments. Knowledge may be place-based and rooted in local cultures, especially when it reflects the beliefs of long-settled communities who have strong ties to their natural environments (Orlove et al., 2010). Other times, knowledge may be embedded in institutions or oral traditions that mobilise them across contexts, for example, as migrant populations bring their knowledge across different regions, and have global relevance. Scientific insights often confirm findings from both IK and LK (Ignatowski and Rosales, 2013), but IK and LK also provide specific, alternative ways to understand environmental change including tacit and embodied aspects of knowledge (Mellegård and Boonstra, 2020), that may be crucial to foster local action and which are not easily captured in scientific knowledge (including cultural indicators, scales and interconnectedness between ecosystems). Multiple knowledge systems (i.e. IK, LK, disciplinary knowledge, technical expertise) may coevolve in iterative and interactive processes whereby they influence each other, but at the same time, they may have specific characteristics so that they cannot be reduced to each other, or subsumed under it and they all have relevance to understand the interactions between society and climate (Bremer et al., 2019).

Moreover, IK and LK may be particularly relevant to ensure that climate action not only does not cause further harm, but also addresses historical injustices committed against Indigenous Peoples and other marginalised social groups, recognising them as active agents of their own change (Nursey-Bray et al., 2019). There are between 370 and 500 in at least 90 countries belonging to about 5,000 different ethnic groups that are classified as 'Indigenous' (Sangha et al., 2019). While there is no single, universal definition of Indigenous Peoples, self-determination is a core criteria within both the ILO Convention on Indigenous and Tribal Peoples (1989) and the UN Declaration on the Rights of Indigenous Peoples distinct social and cultural groups that retain collective ancestral ties to the lands they inhabited or to the lands from which they have been displaced. Indigenous peoples attribute cultural and spiritual values to land, environmental features and landscapes (ILO, 2013; ILO, 2019). Indigenous Peoples suffer disproportionally. For example they are three times more likely to live in extreme poverty than non-Indigenous Peoples; they are also more likely to suffer discrimination and violence (UN, 2020). At the same time, Indigenous Peoples have long led climate change and environmental protection agendas.

Indigenous Peoples have been faced with adaptation challenges for centuries and have developed coping strategies in changing environments (Coates, 2004). Along with other local groups, they hold relevant knowledge about the environment and environmental change, the impact of those changes on ecosystems and livelihoods, and possible effective adaptive responses (see Cross-Chapter Box INDIG in Chapter 18). Therefore, the participation of Indigenous Peoples in climate change decisions and the inclusion of Indigenous knowledge in the IPCC assessment process should be of high priority (following recommendations in UN, 2020 and UNESCO, 2018b). Furthermore, the participation of scientifically trained climate specialists with indigenous backgrounds is valuable to the work of IPCC because the assessment must reflect a diverse range of views and expertise (for examples of IK please see Cross-Chapter Box INDIG in Chapter 18). Including IK & LK in the IPCC assessment process is supported by Article 31 in the UN Declaration on the Rights of Indigenous Peoples (2007) which calls for the use of IK and LK to be protected and validated by Indigenous Peoples themselves and include them as active participants in the assessment (Klenk et al., 2017). Paying special attention to the mechanism whereby some forms of knowledge have been excluded in previous reports- such as the use of technical knowledge or acronyms, or the deployment of discipline-specific validation mechanism- is a first step towards developing an inclusive assessment that reflects a wide range of voices.

The AR4 was the first IPCC report to explicitly discuss the value of IK and LK in adaptation and mitigation processes. AR5 recognized the importance of creating synergies across disciplines in the production of knowledge, acknowledging the importance of 'non-scientific sources such as Indigenous knowledge, which may not follow discipline conventions but nevertheless reflects the outcomes of learning across generations (Burkett et al., 2014) and explains the importance of including local and Indigenous knowledge and diverse stakeholder interests, values, and in local decision-making processes (Jones et al., 2014). Such processes should not only be done in partnership with IK and LK knowledge holders but, when possible, led by them (Inuit Tapiriit Kanatami, 2018). Recent IPCC reports have included distinct sections dedicated to IK and LK (e.g., SROCC, IPCC, 2019b). The IPCC Special Report on Climate Change and Land (SRCCL) includes a section on "Local and Indigenous knowledge for addressing land degradation" (2019a) and the IPCC Special Report on Ocean and Cryosphere (SROCC) describes local knowledge as 'what non-Indigenous communities, both rural and urban, use on a daily and lifelong basis,' a type of knowledge which is recognized as 'multi-generational, embedded in community practices and cultures, and adaptive to changing conditions' (2019b). The IPCC Special Report on Global Warming of 1.5°C emphasized the high vulnerability of Indigenous Peoples to climate change, and stated that disadvantaged and vulnerable populations including Indigenous Peoples and certain local communities are at disproportionately higher risk of suffering adverse consequences with global warming of 1.5°C and beyond (IPCC, 2018b). The report also assessed evidence in relation to the importance of including IK and LK in adaptation options, explaining their role in early warning systems and arguing that they are part of a range of approaches to catalyse wide-scale values and consistent with adapting to and limiting global warming to 1.5°C (IPCC, 2018b).

Since AR5, several academic publications have directly addressed the challenges of including IK and LK in climate research (David-Chavez and Gavin, 2018; Ford et al., 2016; Yeh, 2016) and demonstrated its value in building resilience to extreme events related to climate change (Janif et al., 2016; Olazabal et al., 2021). For instance, IK and LK has proved useful in land management methods that reduce wildfire risk (Cook et al., 2012)(Mistry et al., 2016; Nepstad et al., 2006; Welch et al., 2013). Since Indigenous knowledge is traditionally communicated through storytelling and oral history, there is a practical challenge integrating it in a assessment that prioritises scientific knowledge, and a need for increased critical engagement towards a co-production of knowledge (Ford et al., 2016). Scholars now recognize the ontological and epistemological differences in approaches, understandings and effects of climate change (Yeh, 2016). One common strategy has been assessing Indigenous observations of climate change alongside scientific data (Klein et al., 2014a) as a means to bridge the gap between scientific inquiry and Indigenous knowledge systems (Fernández-Llamazares et al., 2017). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Convention on Biological Diversity (CBD) have helped illustrate how to bridge multiple knowledge systems, particularly those conceived from different ontologies. Rather than viewing Indigenous knowledge as a single source of knowledge to be compared with scientific data, recent scholarship suggests assessments such as the IPCC directly involve Indigenous researchers (Yumagulova et al., 2019) to ensure ethical and equitable engagement with Indigenous knowledge. Such partnership with and leadership of Indigenous Peoples on climate research is also consistent with the UN Declaration on the Rights of Indigenous Peoples (e.g., Bawaka Country et al., 2015; Inuit Tapiriit Kanatami, 2018; Cross-Chapter Box INDIG in Chapter 18).

1.3.3 Regional Assessment

As climate change is a multiscale phenomenon from the local to the global, the assessment of climate risks and climate change impacts is strongly spatial, with a focus on regional climate change. The term "regions" is used in different ways throughout the AR6 assessment as the use of the term varies across disciplines and context.

First, there are chapters dedicated to regional assessment in AR6 WGII (Chapters 9-14 and Cross-Chapter Papers 4 and 6), and within the content of these and other chapters of AR6, the term region is often used to describe continental and sub-continental regions, oceanic regions, hemispheres, or more specific localities within these geographic areas. Building on the continental domains defined in AR5 WGII and to ensure consistency with WGI Chapter 12 and the WGI Atlas, AR6 WGII uses a Continental Set of Regions, namely Africa, Asia, Australasia, Europe, North America, Central & South America, Small Islands, Polar Regions, and the Ocean.

Second, the term regions is used to categorize areas around the globe with common topographical characteristics or biological characteristics. For example, Chapter 2 introduces regions in its discussion of biomes, as in arid, grassland, savanna, tundra, tropical, temperate, and boreal forested regions. Chapter 3 adds reference to an area's orientation with bodies of water, using terms such as deltaic, coastal, intercoastal, freshwater, and salty. In addition, Cross-Chapter Paper 2 uses a coastal region typology based on physical geomorphology considering elevation, coastal type, and topography (see Cross-Chapter Paper 2, pg. 5; Barragán and de Andrés, 2015; Haasnoot et al., 2019a; Kay and and Adler, 2017).

Third, Cross-Chapter Papers are dedicated to *typological regions*, defined in the Annex II: Glossary as regions that share one or more specific features (known as 'typologies'), such as geographic location (e.g., *coastal*), physical processes (e.g., *monsoons*), and biological (e.g., coral reefs, tropical forests, deserts), geological (e.g., mountains) or *anthropogenic* (e.g., megacities) formation, and for which it is useful to consider the common climate features. Typological regions are generally discontinuous (such as monsoon areas, mountains, deserts, and megacities) and are specifically used to integrate across similar climatological, geological and human domains.

Understanding climate risks across regions also requires attention to the capabilities of developing countries and scientists across country contexts in conducting climate assessments. Substantial unevenness of available climate observations, risks assessments, and scientific literature across regions and country capacities substantially challenges a globally comprehensive assessment (Connelly et al., 2018).

1.3.4 Evaluating and Characterising the Degree of Certainty in Assessment Findings

Since 1990, IPCC assessments have included designated terms and other approaches for communicating the expert judgments made by authors (Mastrandrea and Mach, 2011). The goal of such methods has been consistent treatment of uncertainties in assessing and communicating the current state of knowledge. Because terms such as "probable" or "likely" hold very different meanings to different people, a standardized approach is essential for enabling consistent interpretation (WGI AR6 Section 1.2.3.1). Since its 2001 assessment, IPCC authors have applied common guidance on expert judgment across the working groups (IPCC, 2005; Moss and Schneider, 2000). The AR5, iteratively building from past IPCC guidance, was the first report to apply a single framework consistently across the working groups and their diverse topics and associated disciplines (Figure 1.3; Mastrandrea et al., 2010; Mastrandrea and Mach, 2011). The outcome was increased comparability of assessment conclusions across the full spectrum of the physical science basis of climate change and resulting impacts, risks, and responses (Mach et al., 2017).

This framework for expert judgment is again being applied in the AR6 and associated special reports in the assessment cycle (Mastrandrea et al., 2010; see also WGI AR6 Box 1.1). Under the framework, the assessment of scientific understanding and uncertainties begins with evaluation of **evidence** and **agreement**—especially the type, amount, quality, and consistency of evidence and the degree of agreement (steps 1–3 in Figure 1.6). Evidence assessed can reflect observations, experimental results, process-based understanding, statistical analyses, or model outputs. Evidence is most robust when it consists multiple lines of consistent, independent, and high-quality evidence. The degree of agreement considers the extent of established, competing, or speculative explanations for a given topic or phenomenon across the scientific community. Together, this evaluation of evidence and agreement forms a traceable account for each key finding in the assessment. Subsequently, the framework proceeds to evaluation of levels of **confidence**, which integrate evidence and agreement (steps 3–5 in Figure 1.6). Confidence reflects qualitative judgments of the validity of findings. It thereby facilitates, more readily, comparisons across assessment conclusions. Increasing evidence and agreement corresponds to increasing confidence (step 4 in Figure 1.6).

If uncertainties can be quantified, the framework involves a further option of characterising assessment findings with **likelihood** terms or more precise presentations of probability (steps 5–6 in Figure 1.6). The relevant probabilities can pertain to single events or broader outcomes. Probabilistic judgments can be based on statistical or modeling analyses, elicitation of expert views, or other quantitative analyses. Where appropriate, authors can present probability more precisely with complete probability distributions or percentile ranges, also considering tails of distributions important for risk management. Usually, likelihood assignments are underpinned by high or very high confidence in the findings.

Confidence is often most applicable in characterising key findings in WGII assessment (Mach et al., 2017). This tendency results from the diverse lines of evidence across disciplines relevant to climate change impacts, adaptation, and vulnerability. By contrast, likelihood is more common in WGI assessment.

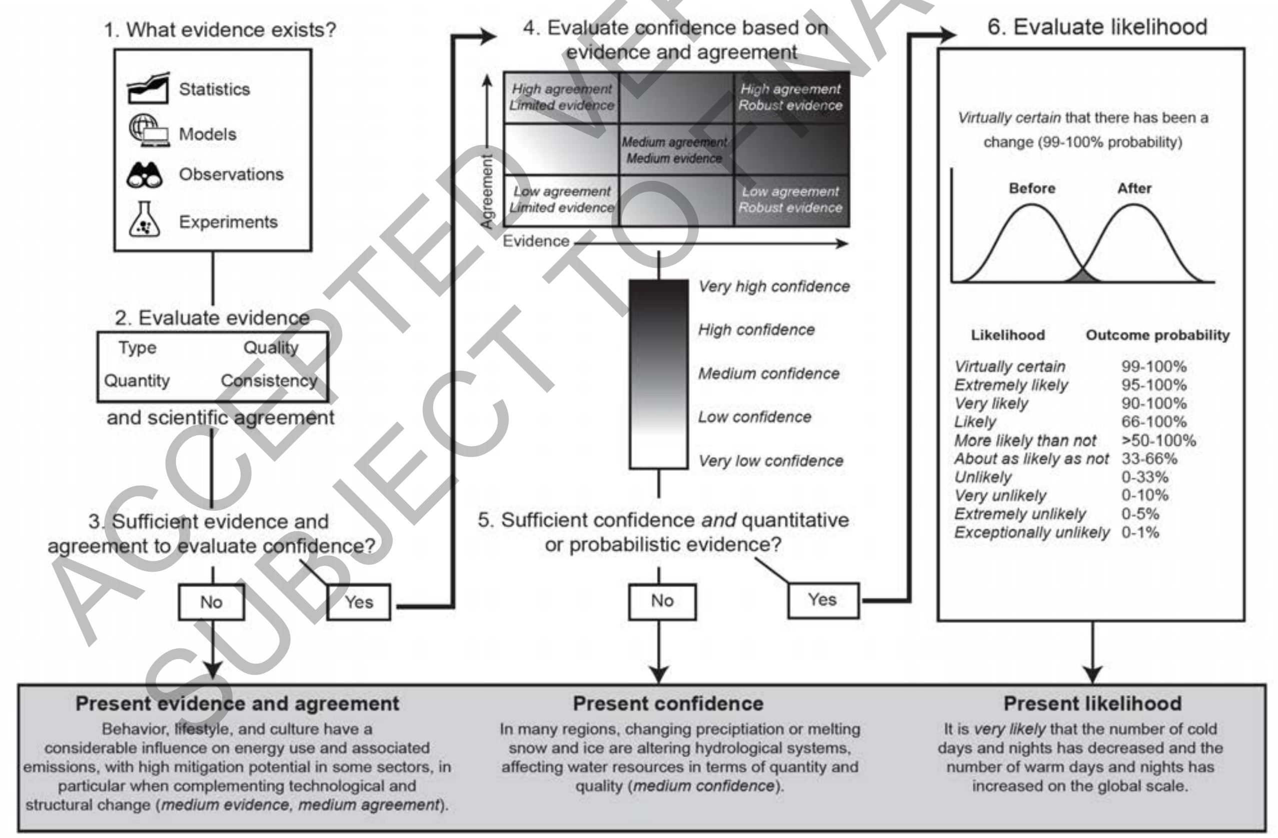


Figure 1.6: The IPCC AR5 and AR6 framework for applying expert judgment in the evaluation and characterisation of assessment findings. This illustration depicts the process assessment authors apply in evaluating and communicating the current state of knowledge. Guidance for the application of this framework is described in full detail in Mastrandrea et al., 2010. In addition to scientific knowledge, Indigenous knowledge and local knowledge are central to understanding and acting effectively on climate risk (Section 1.3.2.3). The diagram in this figure is reproduced from Mach et al. (2017)

The guidance to authors additionally identifies other practices and approaches relevant in applying expert judgment and developing assessment findings (Mach and Field, 2017; Mastrandrea et al., 2010; Mastrandrea and Mach, 2011). First, authors are encouraged to carefully consider appropriate generalisation within assessment findings, emphasising insights that are integrative, nuance, and rigorous (IAC, 2010; Mastrandrea et al., 2010; NEAA, 2010). Second, authors are instructed to attend to potential biases, including in group dynamics, such as tendencies towards overconfidence and anchoring or Type I (false positive) error aversion (Anderegg et al., 2014; Brysse et al., 2013; Mastrandrea et al., 2010; Morgan, 2014). Third, particular attention is drawn to the importance of evaluating and communicating ranges of potential outcomes to inform decision-making and risk management (Mastrandrea et al., 2010). In some cases, deep uncertainties related to parameters or processes that are unknown or disagreed upon strongly benefit from dedicated methods of assessment and decision support (see Cross-Chapter Box DEEP in Chapter 17). Fourth, the guidance explores the different ways that framings of conclusions can shape their interpretation by readers. Finally, the guidance underscores the importance of reflecting upon all sources of uncertainty, which can include deep, difficult-to-quantify, and easy-to-underestimate uncertainties arising from incomplete understanding of relevant processes or competing conceptualisations across the literature (Mastrandrea et al., 2010). A detailed review of literature assessing IPCC uncertainty characterization methods is provided in WGI AR6 1.2.3.1.

1.4 Societal Responses to Climate Change Risks

AR6 highlights the concept of **solutions**, defined as *effective*, *feasible,* and *just* means of reducing climate risk, increasing resilience, and pursuing other climate-related societal goals. This section introduces key concepts used in this report to assess the goals associated with adaptation, its process and governance, its implementation, monitoring and evaluation, and its limits.

The term solutions has various synonyms used across this and previous IPCC reports, including options, measures, actions, and responses. All denote policies, technologies, processes, investments, or other activities undertaken in reaction to or with the intent to address some aspect of climate change (Chapter 17). The term solutions has drawbacks, suggesting a finality, that is, the problem is solved. Solving climate change in this sense is not likely for the foreseeable future. In addition, the word solutions sometimes denotes a narrow set of responses, such as “technical solution,” as opposed to more wide-ranging actions as might be involved in a transition to resilience. Nonetheless, AR6 highlights the term solutions because, compared to these other terms, when acted upon or incorporated in policy, it denotes effectiveness and some degree of progress at achieving desired goals.

Assessing successful adaptation is, however, difficult (Cross-Chapter Box ADAPT in Chapter 1). WGIII Section 1.6 summarizes four broad analytic frameworks -- aggregate efficiency; ethics and equity; transition dynamics; and psychology and politics -- relevant to mitigation and concludes that failure to integrate understanding across them has been a fundamental reason for inadequate progress to date in reducing greenhouse gas emissions. While the four analytic frameworks used in WGIII also all contribute to the understanding of adaptation, an integrated view remains elusive because adaptation differs strongly from mitigation. In particular, the goals of adaptation are harder to define and measure than those for mitigation. The feasibility, effectiveness, and success of many adaptation actions depend more strongly on context. A different, often more diffuse set of actors are involved, and it is often hard to distinguish what activities count as adaptation.

Given these challenges, this report provides an assessment of adaptation solutions based on the attributes **justice**, **feasibility**, and **effectiveness**, as shown in Figure 1.7.

A solution is just when its outcomes, the process of implementing the action, and the process of choosing the action respects principles of distributive, procedural, and recognitional **justice** (Section 1.4.1.1). Any assessment of justice depends on an understanding of potential outcomes of alternative options (Chapter 16) as well as processes of decision-making (Chapter 17). Consideration of justice necessarily introduces normative elements into any assessment of what constitutes a solution.

A solution is **effective** to the extent it reduces climate risk. Effectiveness can refer to whether an adaptation-related action reduces risk (Section 1.4.1.2, Chapter 16) or the extent to which an action achieves its intended outcomes within a stated time frame (Chapter 17). Effectiveness can also include measures of economic efficiency, assessment of net benefits over costs, and the extent to which an action enhances broader and multi-dimensional measures of societal well-being (Section 1.4.1.2). Assessments of effectiveness will often involve uncertainty, which may affect judgements about the comparative effectiveness and justice of alternative options (Chapters 16 and 17, Cross-Chapter Box DEEP in Chapter 17). Assessment of effectiveness also involves consideration of maladaptation (Section 1.4.2.4) in which an action, often inadvertently, increases risk or vulnerability for some or all affected individuals or communities.

A solution is **feasible** to the extent it is consider possible and desirable, taking into consideration barriers, enablers, synergies, and trade-offs (Section 1.4.2). AR6 assesses the feasibility of a wide range of adaptation options (Cross-Chapter Box FEASIB in Chapter 18), building on the approach of the SR1.5 report, which uses five dimensions of feasibility: geophysical, environmental-ecological, technological, economic, socio-cultural, institutional. In addition, feasibility can also refer to a specific set of actions, so that feasibility in any particular situation may depend on specific conditions of governance capacity, financial capacity, public opinion, interest group pressure, and the distribution of political and economic power (Chapter 17). For instance, a particular jurisdiction may find either of two options feasible when implemented alone but might lack the capacity to implement them both at the same time. Feasibility can be a context-dependent and time-varying attribute. Many solutions, for instance those that seek to unlock financing or build public support for certain actions, aim at increasing the feasibility of future adaptation responses (Sections 1.4.2 and 1.5).

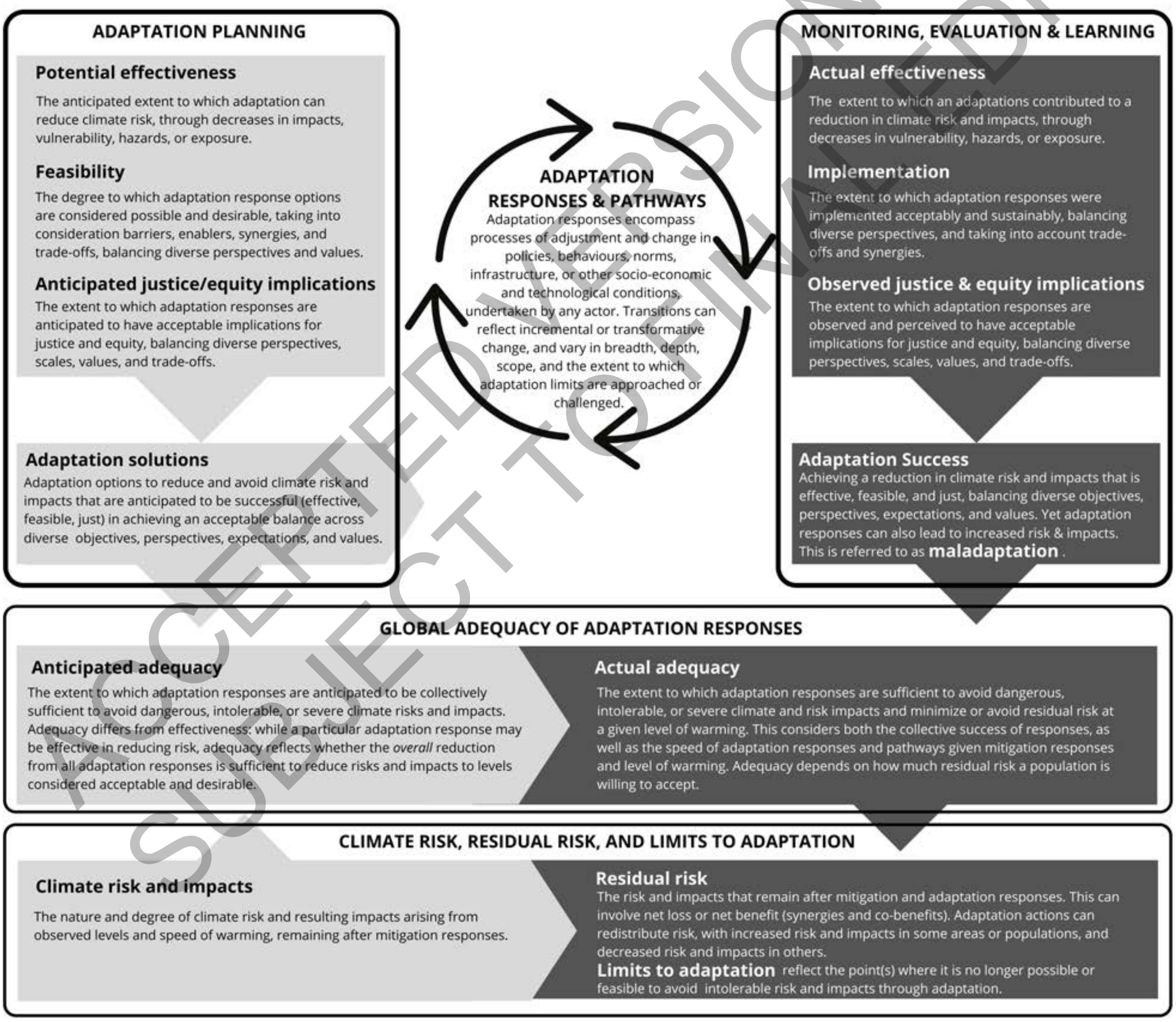


Figure 1.7: **Assessing adaptation solutions and success**. A solution is defined as an adaptation option which is effective, feasible, and conforms to principles of justice. These attributes can be assessed ex ante during adaptation planning. During implementation, the overall success of a response can be judged via monitoring and evaluation of these attributes. Adaptation unfolds as an iterative learning process of assessment, implementation, monitoring, adjustment, and learning. A set of responses is adequate to the extent that they sufficiently reduce climate risk to levels considered tolerable. Adaptation may not fully avoid residual risks, but the more adequate the response, the less

residual risk. Remains. Adaptation also has limits beyond which it is no longer possible to avoid intolerable risks and impacts.

1.4.1 What is Equitable, Just and Effective Adaptation?

Articulating the goals of adaptation is an important initial step in the decision-making process (Jones et al 2014). Adaptation often involves trade-offs among various options of adaptation, mitigation and sustainable development as well as judgements based on science, engineering, and economics and questions of distribution and democratic participation (Jafry et al., 2018). Articulating the goals of adaptation at the international, national, and local levels thus requires engaging with the concepts of equity, justice, and effectiveness (*high confidence*).

1.4.1.1 Equitable Adaptation Informed by Concepts of Justice

Assessing climate action involves ethical considerations that the literature often describes as climate justice. The term 'climate justice,' however, has been used in different ways in different contexts and by different communities. Grassroot organisations and activists often focus on unequal global power relations, wealth, and interests within communities, within nations, and along the North-South divide, as well as the historical responsibility for climate change (Chatterton et al., 2013). Some national governments also view climate justice as the right of developing countries to industrialize. Balancing these issues, international climate change negotiations have primarily focused on current capacities and responsibilities for addressing climate change as reflected in the UNFCCC principle of 'common but differentiated responsibilities' (Fisher, 2015).

Since principles of justice are substantive normative commitments that have been debated for centuries, it would be unrealistic to expect a universal consensus. Nevertheless, there is broad agreement about the core issues. Just normative principles are ones that result in fair and equitable allocation of goods, vulnerabilities and risks (Caney, 2014; Jafry et al., 2018; Schlosberg, 2009; Schlosberg, 2013)

It is common to distinguish between distributive justice, procedural justice and recognition (Forsyth, 2018; Fraser, 1999; Olazabal et al., 2021; Reckien et al., 2017; Schlosberg, 2003; Schlosberg, 2009). The first refers to the distribution of burdens and benefits; the second to who decides and participates in decision-making; while recognition entails basic respect and robust engagement with and fair consideration of diverse values, cultures, perspectives, and worldviews. Recognition is closely to distributive and procedural justice (Hourdequin, 2016). Without recognition, actors may not benefit from the two other aspects of justice (*medium confidence*). Recognition thus represents both a normative principle as well as an underlying cause of unjust distribution and lack of democratic participation (Svarstad and Benjaminsen, 2020). However, recognition is still under-represented in climate justice compared to general scholarship and debate on justice principles (Benjaminsen et al., 2021; Chu and Michael, 2018).

Three principles of distributive justice are especially relevant to adaptation: *fairness between individuals*, *fairness between states*, and *fairness between generations* (Fleurbaey et al., 2014*)*. Fairness between individuals means that the distribution of goods, vulnerabilities, and risks of climate change should not fall on individuals for arbitrary reasons. It would be arbitrary if, say, a family were disproportionately affected by climate-induced drought by chance alone. Similarly, an adaptation action that protects some and creates risks for others is unfair if the final distribution of burdens and benefits is arbitrary.

The second consideration of distributive justice is *international justice*, or fairness between states. An important idea in international climate negotiations has been *common but differentiated responsibilities* and respective capabilities (CBDR**)** **(**stated in Principle 7 in the Rio Declaration (1992)as well as by the Kyoto Protocol (1997). The principle reflects the underlying idea that *all* countries must address climate change, but the form of climate action depends on the situation the country finds itself in. Developed countries may find themselves in a position where they can decarbonize more rapidly and ensure financial flows, while the responsibilities of LDCs and SIDS may primarily come in the form of adaptation actions. This means that uneven distribution of wealth and power between (and within) countries is a key driver of climate injustice.

The third consideration of distributive justice relevant to climate adaptation is fairness between generations and the obligation to ensure that future generations are guaranteed at least a minimally decent life (Jonas, 1985; Llavador et al., 2010). For example, youth climate activists and political philosophers have argued that today's children, as well as generations yet unborn, will be exposed to far greater risks than most living adults so that policymakers should work to avoid shifting all burdens of adaptation to future generations.

Procedural justice addresses the fairness of the processes by which decisions are made and the legitimacy of those making the decisions (Gutmann and Thompson, 2009; Kitcher, 2011). Criteria include transparency, the application of neutral principles among parties, respect for participants' rights, and inclusive participation in decision-making, which often takes the form of participatory processes. Article 6 of the Framework Convention creates a binding commitment on parties to promote public participation in addressing climate change. Increased participation by civil society in climate policy discussion, including new forums such as the Local Communities and Indigenous People's Platform of the UNFCCC work toward this goal (UNFCCC, 2021). Genuine, not merely formal, participation requires communities be well-acquainted with the climate change risks they face and are given a full voice in the process of adaptation planning. Many local communities, especially those most vulnerable to climate change, remain excluded, which is inconsistent with principles of procedural justice. In addition to a normative principle, models of decision making also suggest that diverse, representative decision makers can be expected to make better decisions than more limited groups (Hong and Page, 2004; Landemore, 2013; Singer, 2019).

In AR5 WGIII discussions of justice and ethical concepts were combined with discussions of economic principles while the adaptation chapters did not explicitly discuss climate justice. This report moves beyond AR5 by connecting the assessment of policy choices to normative principles and showing how better outcomes are obtained by choosing just ones.

1.4.1.2 Equitable and Effective Adaptation Informed by Concepts and Measures of Well-Being

Planning and assessment of effective and just adaptation require appropriate measures of both criteria. This report uses both single and multi-criteria measures.

Local and regional decision makers employ benefit-cost analysis to efficiently allocate scarce resources among alternative adaptation efforts and among adaptation and other societal needs. Decision makers at national and global levels can employ measures of social welfare to consider trade-offs and synergies among adaptation, mitigation, and development. Such measures can avoid wasteful allocation of resources and help avoid maladaptation. Such measures also prove useful because well-established approaches exist to evaluate such quantities, and because income is highly correlated with a wide range of indicators of social progress and climate change adaptation capacity (Dasgupta et al., 2018).

Aggregate, monetized economic measures are, however, insufficient to address fully issues of climate justice or to reflect that wide range of worldviews and values that different people bring to questions of climate action and development (Chambwera et al., 2014). While recent work has enriched the consideration of distributive justice in aggregate social welfare functions (Adler, 2012), multi-objective approaches that separately report several biophysical and socio-economic attributes can prove valuable (17.3.3). Many adaptation measures, in particular those that encompass transformational social changes (Section 1.5), involve complicated trade-offs among multi-dimensional benefits and costs (Adger, 2016). Different people commonly value such trade-offs differently, particularly in heterogeneous societies. Multi-objective measures can thus enhance transparency, fairness, legitimacy, and participation by highlighting the different outcomes that different people and communities might find important, making the specific trade-offs more transparent and explicit, and avoiding privileging any particular view on the appropriate trade-offs (Lempert et al., 2018; Siders, 2019b; Siders and Keenan, 2020).

The SDGs and Key Representative Risks (Chapter 16) exemplify such multi-criteria measures. In addition, many communities increasingly measure policy outcomes using multi-objective measures, often organized around the concept of well-being and designed to allocate resources and implement policies to advance social progress (City of Santa Monica, 2018; Lee et al., 2015). Similarly, the Human Development Index (HDI), which derives from the capabilities approach, combines income (as Gross National Income-GNI and Parity Purchasing Power-PPP) with an education and a health indicator and integrates human and socio-economic factors (Herrero et al., 2012; Leal Filho et al., 2018; Nagy et al., 2018; UNDP, 2018; USEPA, 2016). The inequality-adjusted HDI value, or IHDI, can be interpreted as the level of human development when inequality is accounted for (UNDP, 2018).

The multi-criteria concept of well-being has been increasingly employed as a structured framework for measuring social progress in many areas of public policy (Lamb and Steinberger, 2017) including climate and health (Chapter 7) and, to a lesser extent in other areas of the climate change adaptation literature (Singh et al., 2021). Wellbeing reflects the ability of a person to pursue and realize the goals that they value (Sen, 1985). The disaster risk management community employs well-being to evaluate mental health impacts in terms of peoples' abilities to cope with trauma and loss because of natural disasters (Berry et al., 2010; MacDonald et al., 2015; Willox et al., 2015). The term appears in the literature with concepts such as human security (Adger, 2010; Koren and Butler, 2006; Pasgaard et al., 2017), subjective wellbeing or happiness (Fanning and O'Neill, 2019; Rehdanz et al., 2015; Sekulova and van den Bergh, 2013), welfare (Gough, 2015), and living standards or quality of life (Degorska and Degorski, 2018; Rao and Min, 2018).

Recent work has used quantified measures of well-being and multi-objective decision support tools) to balance among equity and efficiency objectives in disaster risk management (Markhvida et al., 2020; Section 1.5.2; Chapter 17). Rather than focus on the economic value of lost assets, the well-being measure evaluates disaster impacts and recovery policies by considering the fraction of consumption lost at the household level for different income cohorts. Not surprisingly, poor households account for twice as much of the disaster losses when evaluated by effects on well-being rather than by asset losses. The most effective policy responses also differ when using well-being and asset loss-based measures. Ciullo et. al. (2020) compare flood control strategies using multi-objective decision criteria that include both benefit-cost and distributional components, show how the favoured strategy can depend on whether one seeks equitable risk or equitable risk reduction, and propose tools that can help embed both ethical and efficiency considerations in adaptation decisions. Widespread use of such approaches could strengthen consideration of climate justice along with efficiency in the evaluation of climate risks and adaptation. (Dryzek et al., 2013; Section 1.5.2).

1.4.2 Enabling and Governing Adaptation

Adaptation actions taken by individuals, social groups, and organisations in response to climate and environmental stimuli depend, in part, on the options they have (see Chapters 16 and 17). Actions previously taken can reduce the scale of responses needed subsequently, increase the options available, reduce barriers to additional action, and increase capacity to respond. Successful adaptation sufficient to meet Paris and SDG Goals needs to involve actors at many scales and in many sectors, including individuals and households, communities, governments at all levels, private sector businesses, non-governmental organisations, religious groups and social movements. This report highlights the increased range of societal actors engaged in adaptation and the need for multi-level and polycentric governance. The section describes key concepts related to the process of adaptation and assessment of how human choices and exogenous changes can expand and contract the set of available solutions.

1.4.2.1 Adaptation Process and Expanding the Solution Space

Adaptation actions include those taken with the explicit intention of reducing climate risk, as well as actions taken without reference to climate change, e.g., building community resilience irrespective of any particular hazard. Adaptation actions can include those aimed at reducing a specific risk, or actions aimed at systemic changes and also include adjustments to current practices, or transformational changes. In addition, the success of adaptation in one place or jurisdiction can depend on activities in other places or jurisdictions.

Adaptation actions span a vast range of activities. Successful adaptation generally requires a portfolio of actions, often implemented by multiple actors in different sectors, often in different places and over time (Section 17.2.2). Useful taxonomies include categorizing such actions around Representative Key Risks (RKRs) (Figure 17.3), and by human systems and scenarios of adaptation extent for four components of adaptation (depth, scope, speed, and limits) (Table 16.2). As shown in Chapter 17, for instance, ecosystem-based adaptation, hardening buildings and physical barriers, and changes to zoning and planned retreat can reduce risks to coastal socio-ecological systems. Restoration and protection of forests, enhancing ecosystem connectivity through corridors, and ecosystem-based adaptation can reduce risks to terrestrial and ocean ecosystems. Increased use of grey, green, and blue infrastructure, and upgrading design standards, city plans, and more redundancy in power systems and other networks can reduce risks associated with critical infrastructure. Insurance and diversified or changed livelihoods can reduce risks to living standards and equity. Improved health care systems, disaster management and early warning can reduce risks to human health. Better management of land, soil and fisheries; and changing diets and reducing food waste can reduce risks to food security. Improved water efficiency, and policies to reduce demand can reduce risks to water security.

Previous IPCC reports have described in detail adaptation for individual actors as an iterative risk management process of scoping (identifying risks, vulnerabilities, objectives, and decision-making criteria), analysis (identifying options, assessing risks, evaluating trade-offs), and implementation (implementing chosen options, monitoring, and reviewing and learning) (Jones et. al. 2014). This AR6 report expands the focus to consider adaptation processes with multiple actors and a richer temporal dimension in which actions taken at one time can expand or contract the set of feasible, effective, and just options available at another time, thereby increasing or decreasing the ability of adaptation to reduce risks (Section 17.1). This AR6 report also expands the focus to include decision processes the implement both adaptation and mitigation (Chapter 18) as well as a heightened attention to Monitoring and Evaluation (M&E), which is a key prerequisite for successful iterative risk management and achieving effective and just adaptation outcomes at local to global levels (Section 1.4.3, 17.5.2). The challenges of implications for adaptation, mitigation and sustainable development outcomes result from decision-making process at different levels (Bertram et al., 2016, Von Stechow et al., 2015). To overcome these challenges often require significant learning and innovative ways of linking science, practice and policy at all scales (Shaw and Kristjanson, 2014).

Two concepts – enabling conditions and catalysing conditions – help frame this report's assessment of factors that over time can help expand the set of available solutions (Section 17.4). Enabling conditions enhance the feasibility of adaptation and mitigation options (cross-AR6 glossary). Enablers include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance, and changes in human behaviour and lifestyles. Chapter 17 (see also WGIII Figure 1.4) identifies three broad categories of enabling conditions: (Section 17.4): governance; finance and knowledge. Catalysing conditions motivate and accelerate the adaptation decision-making process, leading to more frequent and more substantial adaptation (Chapter 17). While enablers make adaptation more feasible and effective, catalysing conditions provide an impetus for action. These later conditions include a sense of urgency (Section 17.4.5.1); system shocks, such as those from natural disasters; policy entrepreneurs; and social movements.

The concept of the **solution space** provides a framework for assessing how the options available for adaptation for any particular community are not constant over time and can depend on the past, current and future choices of many actors. The solution space is defined as the space within which opportunities and constraints determine why, how, when and who adapts to climate risks (Haasnoot et al., 2020). The concept aims to capture the dynamic inter-temporal, spatial and jurisdictional interconnections among adaptation actions. A larger solution space indicates people and organisations with more options for adapting to and reducing their risk from climate change. Both human choices and exogenous changes in human and natural systems affect the future solution space. For instance, changes such as the magnitude and rate of climate change may shrink the space. Economic growth can generate more resources that expand the solution space as can implemented adaptation actions such as pilot projects, awareness raising, and changes in laws and regulations.

AR5 used the concept of solution space in its SPM Figure 8. Several AR6 chapters, in particular 13, 14, and 18, use the concept to address challenges salient in AR6. In any assessment of solutions, what is feasible, effective, and just depends not only on the potential solution itself but the particular biophysical and societal context in which it might occur (Section 17.5; Gorddard et al., 2016; Wise et al., 2014). Solutions can also be space and time dependent because the biophysical and societal context can change over space and time (Section 18.1.4). In addition, the large gap that exists between current climate action and that needed to meet policy goals suggests that decision-makers may not only seek to implement available solutions but seek to actively expand the set of solutions (Chapters 17, 18). Finally, as used in this report the concept of solution does not fully engage with questions of "by whom?" and "for whom?" In many cases solutions would necessarily be implemented by multiple, independent actors interacting with varying degrees of cooperation and competition (Sections 1.4.2, 1.5.2).

[START BOX 1.2 HERE]

Box 1.2: Financing as an Example of Enabler

According to the UNFCCC, adaptation finance includes public, private and alternative sources of finance for supporting adaptation actions, whereby adaptation and resilience are often used interchangeably in this context. Adaptation finance constitutes a crucial enabling condition and shaper of the solution space, depending on other enabling conditions such as proper planning, implementation and governance which are also the triggers for investments and finance to flow and to ensure that positive adaptation outcomes. Details of adaptation finance can be found in Chapter 17 (Cross-Chapter Box FINANCE in Chapter 17, Section 17.4). The adaptation and resilience options offer multiple benefits including avoiding risks and losses, economic growth, wellbeing as well as social and environmental benefits (Agrawal and Lemos, 2015; Bayleyegn et al., 2018; Global Commission on Adaptation, 2019). Hence, the rate of return on adaptation is large, for example, there is a huge potential of net benefits i.e. $7.1 trillion while investing $1.8 trillion globally in climate resilience and adaptation options such as early warning systems, climate-resilient infrastructure, improved dryland agriculture crop production, global mangrove protection, and resilience of water resources (Global Commission on Adaptation, 2019). These net benefits resulted primarily from reducing future losses and risk, increasing productivity and innovation, and social and environmental benefits. Despite strong uncertainty associated with benefit-cost estimates, and concerns on focusing efficiency (monetary) ignore important issues of non-economic values, effectiveness of risk reduction and climate justice (procedural/distributional).

The current public and private financial flows to adaptation are much smaller than needed (Cross-Chapter Box FINANCE in Chapter 17). Only a small portion of overall adaptation finance needs is likely to be covered by public sector finance. Private sector investment thus needs to play a crucial role. Hence, tracking adaptation finance flows is important for enabling effective planning and prioritisation of investments, assessing whether needs are being met, and ensuring accountability towards funding commitments, such as the 100 billion USD promised to developing countries per year by 2020 under the Paris Agreement (Donner et al., 2016). Since AR5, significant progress has been made in tracking adaptation finance flows through UNFCCC channels, multilateral development banks and bilateral finance (Cross-Chapter Box FINANCE in Chapter 17), but large information gaps on adaptation finance via national public finance, commercial lenders, investors, asset managers and insurers, company finance, and individuals and households remain. That these financial flows do not occur suggests misaligned incentives and other governance challenges that could be addressed as part of a response to climate change (Chapter 17). Across regions and sectors, financial constraints have identified most significant which leading to limits to adaptation (Chapter 16).

[END BOX 1.2 HERE]

[START BOX 1.3 HERE]

Box 1.3: Nature-Based Solutions

Nature-based solutions (NbS) (Section 2.6 and Cross-Chapter Box NATURAL in Chapter 2) provides an example of how innovative ideas can expand the climate solution space (IPCC, 2018b; Seddon et al., 2019). A commonly-used definition of Nature-based solutions (NbS) is that of IUCN (The World Conservation Union) which defines it as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016); in the context of IPCC, it focuses on NbS which deliver climate change adaptation and / or mitigation benefits. NbS generally benefits biodiversity and supports its role in both climate mitigation and adaptation. While the carbon sequestering mitigation role of increasing forest and tree cover has dominated much of the earlier discussions, the role of

NbS in promoting adaptation of natural ecosystems and human societies to climate change is being increasingly emphasized. The details of different categories of ecosystem services in the ocean or on land including biodiversity, food provision, other provisioning services e.g., medicinal and commercial products, regulating and cultural services have been described in Chapters 2 and 3.

Forest restoration would certainly contribute substantially towards climate-proofing and achievement of several Sustainable Development Goals as well as the Paris Agreement. There is increasing evidence that diverse, native tree species plantations are more likely to be resilient to climate change in contrast to fast-growing monocultures, (Hulvey et al., 2013) often of exotic species. At the same time, other natural ecosystems such as savannas, grasslands, peatlands, wetlands and mangroves have considerable value in acting as carbon sinks as well as providing other ecosystem services such as hydrological regulation, coastal protection, maintaining biodiversity and contributing to human livelihoods especially pastoralists and fishermen (Conant et al., 2017; Leifeld and Menichetti, 2018; Seddon et al., 2019; Veldman et al., 2015). Coastal and marine ecosystems including wetlands and mangroves have featured prominently in studies of NbS in climate adaptation and mitigation potential for "blue carbon" sequestration (Inoue, 2019; Sections 3.6.2.1; 6.3.3; Cross-Chapter Paper 2.3.2.3). Agroecological practices such as agroforestry, intercropping, rotational grazing, organic manuring, and integrating livestock production with cropping etc can also consider as NbS which contribute to both climate mitigation and adaptation (Altieri and Nicholls, 2017; Bezner Kerr et al., 2019; Leakey, 2020; Webb et al., 2017; Box 5.10).

There are concerns about large-scale conversion of non-forest land into forest plantations for the sole purpose of increasing carbon sinks through bioenergy with carbon capture and storage (BECCS) (Hanssen et al., 2020; Heck et al., 2018; Cross-Chapter Box in Chapter 2), which may actually result in negative carbon sink (Jackson et al., 2002; Mureva et al., 2018) and significant loss of overall biodiversity (Abreu et al., 2017). Such large-scale afforestation may also lead to the dispossession of previous users, such as smallholders and pastoralists. Hence, when NBS includes forest plantations or other large-scale conversion of land-use, there is a risk that it results in maladaptation and malmitigation including climate injustice (Cousins, 2021; Seddon et al., 2019).

Much of the conceptual framework for NbS has come from initiatives to bring environmental, social and economic dimensions to the same level of importance particularly in the context of a highly urbanized society (Faivre et al., 2017; Nesshöver et al., 2017; Section 6.3.3). Emphasis has been given on urban storm water management (Section 2.6.5.2) and heat mitigation using measures such as sustainable drainage systems, urban forests, parks and green roof-tops apart from coastal defences using NbS (Section 13.6.2.3) This has triggered much debate on how distinct the concept of NbS is in relation to other similar concepts such as ecosystem-based adaptation (EbA) approaches (Section 9.11.4.2), and call for an assessment framework for proving the "effectiveness and efficiency" of NbS in providing superior ecosystem and societal benefits (Calliari et al., 2019). Instead, EbA can be treated as a subset of NbS (Chapter 2). However, the time frame of ecosystem-based adaptation is also an important consideration; thus, grassland and forest restoration would operate at different time scales, while mangrove restoration can promote adaptation only at local to national scales, depending on the extent and nature of coastlines (Taillardat et al., 2018). Given the complex nature of plant and animal species adapting to climate change through dispersal and migration to more suitable habitat, this also means that landscape-scale approaches, as opposed to purely protected areas, are needed to promote adaptation, conserve and sustainably use biodiversity, and sustain livelihoods (Sukumar et al., 2016; Vos et al., 2008).

[END BOX 1.3 HERE]

1.4.2.2 Governing Adaptation

Governance and governing refer to the structures, processes, and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local. Governance systems and the specific societal institutions through which they are organized are crucial to the feasibility and success of climate change adaptation, both in terms of its effectiveness in reducing climate risk and vulnerability as well as equity (including climate justice), and with respect to incremental as well as transformational adaptation. This is why AR6 WGII pays even more attention than previous assessments to governance as an important enabling condition, and to the wide range of new actors beyond governments involved in planning, implementing, and monitoring and evaluating adaptation action. The assessments in subsequent chapters of AR6 WGII show that successful and equitable collective adaptation efforts at different levels and scales, and based on key principles of iterative risk management, require strong, usually multi-level governance systems. Multi-level governance refers to the dispersion of governance across multiple levels of jurisdiction and decision-making, including, global, regional, national and local, as well as trans-regional and trans-national levels (see also WG III Chapter 1). The concept emphasises that modern governance generally consists of, and is more flexible, when there are linkages of governance processes across different scales and levels. Multi-level governance is widely regarded as crucial particularly for transformational adaptation, defined as "adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices including approaches that enable new ways of decision-making on adaptation" (IPCC SR1.5, see also Section 1.5). The assessment in subsequent chapters also shows that public governance arrangements and institutions support the majority of adaptation for addressing the most important climate risks, though the importance of the private sector and community organizations in adaptation is increasing. It also shows that polycentric governance tends to benefit adaptation.

The empirical literature on adaptation governance has advanced strongly since AR5. It shows that stronger general governance capabilities are usually associated with more ambitious adaptation plans and more effective implementation of such plans (Chen et al., 2016; Keskitalo and Preston, 2019b: 24; ND-GAIN, 2019; Oberlack, 2017; Oberlack and Eisenack, 2018; UNEP, 2014; UNEP, 2018; UNEP et al., 2021; Woodruff and Regan, 2019). Governance capabilities are, to a significant degree, but not exclusively, a function of available financial resources and technology, but also a function of social capital and societal institutions, including well-functioning local, regional, and national governments and collaboration among these governmental actors and non-governmental stakeholders, including civil society and the private sector. The literature also points to governance conditions that are likely to enable transformational adaptation (Maor et al., 2017; see also Sections 1.4.4 and 1.5, Chapter 17).

Existing comparative data for adaptive capacity worldwide is at a rather coarse level of temporal and spatial resolution. It can, nonetheless, provide a very general picture of rates of change in adaptive capacity at the national scale, and differences between countries. Further empirical research is needed to identify the most important predictors of variation across countries and time, though the available data suggests that differing national income and education levels play a major role in accounting for differences in adaptive capacity (Andrijevic et al., 2020). Spatially more resolved (subnational) data is needed because a large body of case study research suggests that there is strong variation also within countries, particularly the large ones (e.g. India, China, Brazil, United States) (Chapter 16, see also Nalau and Verrall, 2021 and Cross-Chapter Box ADAPT). Moreover, higher degrees of adaptive capacity do not mean that adaptation action will follow automatically, nor that it will succeed in terms of equity and effectiveness in reducing vulnerability to climate change and enhancing well-being. How differences across and within countries in climate risk exposure translate into adaptation action, contingent on differences in adaptive capacity, can to some extent be inferred from case studies, but remains to be studied at a larger, comparable and generalizable scale.

Governance capacity constitutes an important enabling condition not only because it facilitates the (efficient) organization and implementation of adaptation action, but also because it contributes to learning. The latter is central to the process of adaptation as information regarding current and future climate conditions continues to evolve, as does understanding of appropriate response options and the actors involved. In addition, norms, values and practices may change in response to changing conditions (Jones et al., 2014). Much learning by individuals, communities and organisations is unplanned (National Research Council, 2009) as is much current adaptation (Berrang-Ford, 2020), which can reduce near-term costs and administrative complexity, but may prove maladaptive (Section 1.4.2.4). Iterative risk management (Section 1.2.1.1) and related concepts such as risk governance (Renn, 2008) describe a planned learning process of ongoing assessment, action and reassessment. Iterative risk management can be as simple as scheduling future updates of assessments and plans, as with the five-year updates of the global stocktake after 2023 called for in the Paris Agreement or encompass more elaborate learning processes, such as dynamic adaptive pathways (Haasnoot et al., 2019b; Cross-Chapter Box DEEP in Chapter 17) which include specific near-term actions, specific trends to monitor and specific contingency actions to take depending on the future conditions observed. While often more effective at meeting goals, such planned learning processes may pose implementation and governance challenges (Metzger et al., 2021)

Mainstreaming adaptation into existing governance structures and associated organisations and their investments, policies and practices can contribute to expanding the solution space and support efforts at transformative adaptation. For instance, urban planning can support adaptation by mainstreaming adaptation into city plans, such as land-use planning, procuring resilient infrastructure and transportation, supporting health and social services, promoting community-based adaptation, and protecting and integrating biodiversity and ecosystem services into city planning (Section 17.4.3). Mainstreaming adaptation also shows many shortcomings, such as, diminish the visibility of dedicated, stand-alone adaptation approaches (Persson et al., 2016), unequal distribution of adaptation efforts; dilute responsibilities for implementation (Nalau et al., 2016; Reckien et al., 2019); exhibit disconnects between planning, investment and implementation and limited policy coherence (Bizikova et al., 2015; England et al., 2018; Friend et al., 2014; Koch, 2018); and fail to adequately balance overlapping and/or competing policy objectives (Vij et al., 2018).

Finally, governing adaptation in ways that maximize the solution space and facilitate learning can help avoid maladaptation. Maladaptation refers to potentially adverse effects of certain forms of adaptation action, such as increased GHG emissions, or increased vulnerability to climate change and diminished welfare of certain parts of a population now or in the future (Anguelovski et al., 2016; Benzie et al., 2018; IPCC, 2018b; Keskitalo and Pettersson, 2016; Munia et al., 2018; Nadin and Roberts, 2018; Prabhakar et al., 2018; Veldkamp et al., 2017; Zimmermann et al., 2018). Maladaptation is an example of response risk, which is increasingly highlighted in both AR6 WGII and WGIII (Section 1.3.1.2, see also IPCC Risk Guidance). One example is that adaptation action may set paths that limit the choices of future generations to adapt. This last characteristic refers to the lock-in effects of improperly designed and costly infrastructures that affect the ability of future generations to amend.

Maladaptation can result from many potential barriers, including administrative, human, financial and technical resource constraints (Hassanali, 2017; Pardoe et al., 2018; Singh et al., 2018); lack of transparency and/or capacity in governance (Friend et al., 2014); unreliable information on climate impacts and the lack of key policy guidelines (Pilato et al., 2018); entrenched institutional, legal and technical obstacles (Gao, 2018) and low literacy, including environmental and scientific literacy (Wright et al., 2014); and exclusion of vulnerable groups (Forsyth, 2018); governance fragmentation (that is, a fragmentation of laws, regulations, and policy requirements); and limited cross-sectoral collaboration, meaning that there is limited coordination and that top-down planning approaches are not connected to local dynamics (Archer et al., 2014; Pardoe et al., 2018). This report draws attention to maladaptation challenges recognising that not all adaptation-related responses reduce risks (Chapter 16). Besides, maladaptation is the opposite of successful adaptation which is associated with reduction of climate risks and vulnerabilities for humans and ecosystems, increased well-being, and co-benefits with other sustainable development objectives. (Chapter 17)

1.4.3 Monitoring and Evaluation of Adaptation

Monitoring and evaluation (M&E) encompasses a broad range of activities serving multiple purposes, including tracking progress of adaptation efforts over time, understanding equity and effectiveness of adaptation options and outcomes, and informing ongoing adaptation processes (Section 17.5.2.1). While monitoring and evaluation are often referred to jointly as "M&E," monitoring usually refers to continuous information gathering whereas evaluation denotes more comprehensive assessments of effectiveness and equity, often resulting in recommendations for decision makers (Sections 17.5.1.1 and 17.5.1.7). In some literatures M&E refers solely to efforts undertaken after implementation. In other literatures, M&E refers both to efforts conducted before and after implementation. As shown in Figure 1.8, M&E is essential to the process of iterative risk management, both in terms of adaptation assessment prior to implementation and M&E of implemented adaptation measures. AR6 highlights that M&E after implementation is much less common than adaptation assessment prior to implementation (Section 17.5.2.1; Berrang-Ford, 2020).

Tracking adaptation planning and policies: Since AR5, interest in M&E for tracking progress in adaptation has grown substantially at the local, national and global level. I The Paris Agreement calls for a Global Stocktake every five years starting in 2023 (Cross-Chapter Box PROGRESS in Chapter 17). It also encourages states to monitor and evaluate their adaptation plans, policies, programmes and actions and provides guidance on communicating information about adaptation to the international community (UNFCCC, 2015b, Article 7.9d; UNFCCC, 2018a, Decision 9/CMA.1; UNFCCC, 2018b, Decision 18/CMA.1).

Since AR5, a large number of case studies on individual local to national level adaptation measures have been published (see Chambwera et al., 2014; Keskitalo and Preston, 2019b), as well as comparative studies across countries over multiple years (Biesbroek et al., 2018; Biesbroek and Delaney, 2020; Lesnikowski et al., 2016). The existing literature now allows for at least preliminary conclusions about where and why we observe adaptation efforts, as described in the sectoral, regional and synthesis chapters of this report.

While case studies provide context-specific insights, global inventories are essential for tracking global progress on adaptation (UNEP, 2018; UNEP et al., 2021; Cross-Chapter Box PROGRESS). Until recently, the dominant approach surveyed National Communications to the UNFCCC to measure the amount of adaptation planning activity worldwide (Gagnon-Lebrun and Agrawala, 2007; Lesnikowski et al., 2016). More recent assessments have focused also on the quality of local and national adaptation planning to better characterize its potential merits, shortcomings and effects (UNEP et al., 2021; Woodruff and Regan, 2019) and have compiled inventories of adaptation projects (Leiter, 2021) and local adaptation policies (Lesnikowski et al., 2019b; Olazabal et al., 2019; Reckien et al., 2018; see also Section 6.4.6). Chapters 16 and 17 of this report offer an initial synthesis, but efforts to compile a comprehensive global, empirical inventory of climate change adaptation remain in an early phase (e.g., Berrang-Ford et al., 2011; Fankhauser, 2017; Ford et al., 2015; GEF, 2014; Leiter, 2021; Lesnikowski et al., 2016; Tompkins et al., 2010; Tompkins et al., 2018).

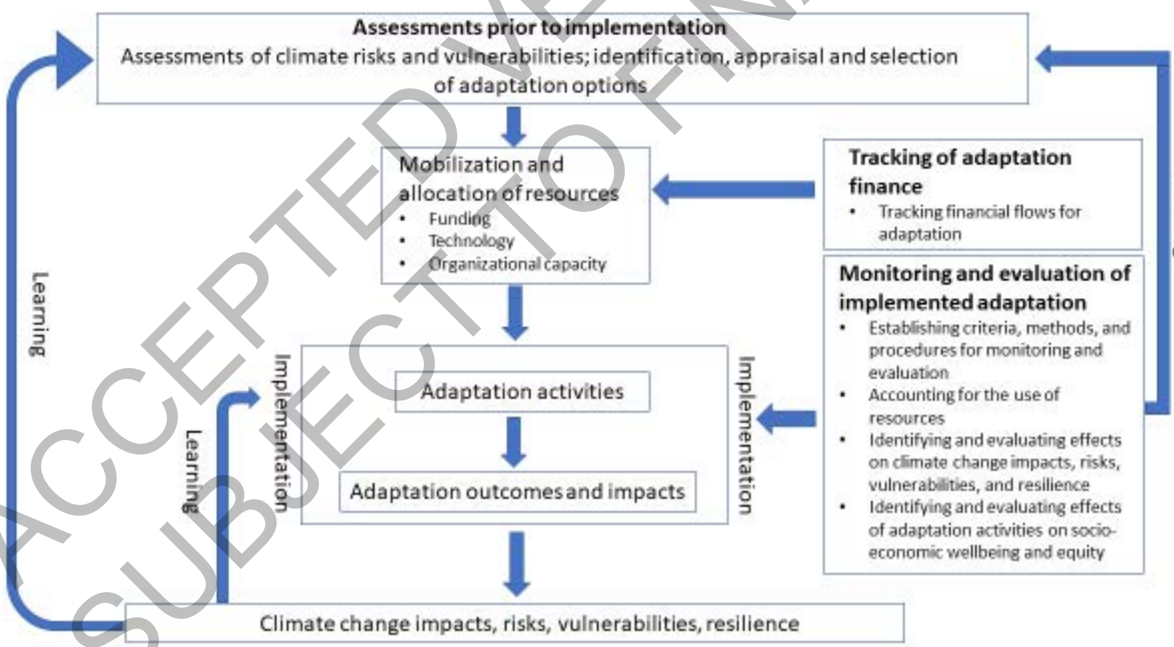


Figure 1.8: Adaptation assessment prior to implementation and M&E during and after implementation. Both systematic assessment of adaptation needs and options and M&E of implemented adaptation are key to iterative climate risk management, and to achieving effective and equitable adaptation. Most assessments to date have referred to aspects prior to implementation. There is much less systematic evidence on adaptation action, and even less evidence on adaptation outcomes and impacts and their implications for climate change impacts, risks, vulnerabilities and resilience. Figure 17.9 in Chapter 17 provides more detail on M&E.

Improving effectiveness: Information regarding the effectiveness of adaptation remains scarce (UNEP et al., 2021), which hinders efforts to improve adaptation practice. A recent comprehensive review found that only 2.3% of the close to 1,700 articles identified by the Global Adaptation Mapping Initiative as documenting implemented adaptation provide evidence of risk reduction (Chapter 16; Berrang-Ford, 2020). However, there exists limited but emerging evidence of the use of M&E by different actors to assess adaptation progress (Section 17.5.1).

Existing case studies use varying criteria for assessing effectiveness, complicating comparisons. Judgements regarding successful adaptation are contingent on the chosen scale and perspective (success for whom?) (Adger et al., 2005; Dilling et al., 2019) and on the level of risk, i.e., increasing climate risks may cause previously successful adaptation to become insufficient. Rather than a binary outcome (successful or unsuccessful), adaptation can be viewed on a continuum from successful adaptation to maladaptation (Section17.5.2). Assessments of adaptation success need to account for distributional effects and differential vulnerability, as well as consider connections across different scales and complex interactions with other change processes (Section 17.5.1). Recent literature has begun to identify how adaptation can better achieve its intended objectives (Eriksen et al., 2021). For instance, inclusive M&E can legitimize and validate M&E and foster commitment and learning.

Informing ongoing adaptation: Iterative risk management involves an ongoing cycle of assessment, action, learning and response in which M&E plays a central, enabling role (Section 1.2.1.1). Assessing the risk reduction provided by adaptation, both planned and implemented, often requires projections of anticipated future climate, socio-economic conditions, and the effectiveness and implications for justice of each option (Section 17.4.4). Understanding the potential for maladaptation may also require such assessments (Section 1.4.2). Processes, such as adaptive pathways, that involve anticipating future responses (Box 11.4; Box 11.6; Sections 11.7; 17.3) entail monitoring to detect early warning of approaching thresholds or changes in the solution space (e.g. more rapid than expected sea level rise or new social acceptance of managed retreat) that suggest the need or opportunity to adjust or expand current adaptation efforts (Haasnoot et al., 2021).

[START CROSS-CHAPTER BOX ADAPT HERE]

Cross-Chapter Box ADAPT: Adaptation Science

Authors: Johanna Nalau (Australia/Finland), Lauren Rickards (Australia), Tabea Lissner (Germany), Katharine J. Mach (USA), Lisa Schipper (Sweden/United Kingdom), Chandni Singh (India), William Solecki (USA), Adelle Thomas (Bahamas) and Edmond Totin (Benin)

High-level statements:

- Adaptation knowledge consists of a diverse set of sources including academic research, applied analysis and practice and experience with projects and policy on the ground.
- Adaptation science encompasses both research 'on adaptation', documenting and analysing experiences of adaptation, and 'for adaptation', aiming to advance the planning and implementation of adaptation.
- The nature of adaptation research is diversifying and examines different approaches from local case studies to more global, transboundary, comparative and interactive perspectives, although critical conceptual and empirical gaps remain in defining effectiveness in adaptation and measuring adaptation progress.

This cross-chapter box complements the reviews of specific adaptation knowledge, content and progress described throughout WG2 by providing a higher-level analysis of the shifting characteristics of and trends in **adaptation research** and its evolution over time.

The characteristics and diversity of adaptation knowledge

The knowledge base on adaptation has matured significantly since AR5. Whereas adaptation research was primarily academic during the 1990s and 2000s, it now includes a proliferation of on-the-ground experience of how to adapt to climate change, increasingly documented in reports and papers. Furthermore, academic research on adaptation has diversified significantly. Understanding the characteristics and diversity of this knowledge base is key for it to effectively inform decision making and action on adaptation.

Academic work on adaptation now spans an increasing number of disciplines and countries and is published across diverse academic outlets and disciplines, with 28.5% annual average increase in adaptation specific publications (Nalau and Verrall, 2021). This expands the range of considerations and perspectives within adaptation research and increases the challenge of identifying and synthesising all relevant research on adaptation in reviews or assessments (Berrang-Ford et al., 2015; Sietsma et al., 2021; Singh et al., 2020; Webber, 2016). Also, large bodies of research and knowledge exist that support climate adaptation ideas, theoretical development, and practical implementation, but are not explicitly framed as climate change adaptation (Biesbroek et al., 2018; Dupuis and Biesbroek, 2013; Keskitalo and Preston, 2019a). Therefore, debates still emerge about what actually counts as "adaptation" (Dupuis and Biesbroek, 2013), and what knowledge is being assessed and measured for this purpose.

IPCC assessment reports combine two complementary approaches to adaptation research: that which is 'on' or 'about' adaptation and that which is 'for adaptation'. Both are needed because research 'on adaptation' helpfully investigates the phenomenon and processes of adaptation (e.g., via analyses of others' adaptation practices and efforts) while research 'for adaptation' generates knowledge that can enable the planning and implementation of adaptation (e.g., action research as part of an adaptive capacity building process) (Swart et al., 2014).

One of the contributions of research 'on adaptation' is to track and debate the broader trends, core characteristics and overall assumptions embedded in adaptation knowledge. This reflexive turn about the foundational assumptions is itself one emerging trend in adaptation research (e.g., Atteridge and Remling, 2017; Juhola, 2016; Nalau et al., 2015; Preston et al., 2013). This signals the influence of more social science in adaptation research and increased awareness of the practical value of being transparent and critically reflective about the content, topics, frames and approaches that researchers use (Lacey et al., 2015; Nalau et al., 2021; Singh et al., 2021). For example, different conceptions of adaptation contribute to different definitions of "adaptation success", different ideas about what "effective" adaptation practice looks like and, thus, different conclusions about what is and is not working well (Berrang-Ford et al., 2019; Dilling et al., 2019; Eriksen et al., 2021; Magnan et al., 2020; Owen, 2020; Singh et al., 2021; Section 17.5.1.1). This diversity adds richness and options, but also poses challenges in constructing a conventional evidence base for decision- and policy making. Adaptation researchers are increasingly expected to offer clear and confident advice on adaptation success, yet are also increasingly aware of how context-specific and contested success is (see also Lacey et al., 2015 on ethics).

Grey literature on adaptation is also proliferating, typically authored by organisations funding and implementing adaptation. This literature often documents a range of adaptation strategies (Sections 9.8.3; 10.4.6.4; 14.4.3.3; 17.2.1.) and lived experiences of adaptation efforts, including helping give voice to marginalised groups, and highlighting the importance of Indigenous knowledge and local knowledge (Nunn et al., 2016; Section 4.7.5.4; Box 9.2; 15.6.4; Cross-Chapter Box INDIG in Chapter 18; Petzold et al., 2020). However, most of the lessons learned through implementation of adaptation projects and programmes are still not captured in academic or even grey literature and thus remains less systematically analysed. Crucially, the large gaps in documentation of adaptation knowledge mean that a lack of published evidence about a given issue does not necessarily reflect its absence in real life – a qualification about adaptation research that readers of AR6 need to appreciate.

The evolution of adaptation research trends

In the 1990s, climate change adaptation was constrained as a specific topic of inquiry by the dominant focus on mitigation of greenhouse gas emissions and the related assumption that successful mitigation would render unnecessary the need for adaptation beyond what human and natural systems could inherently manage (Pielke, 1998; Schipper, 2006; Schipper and Burton, 2009). Several key developments in the 1990s included the IPCC 2nd report (1996) and the establishment of several key journals including Climatic Change (1978), Mitigation and Adaptation Strategies to Global Change (1996), and the Global Environmental Change journal that strengthened more dedicated focus on climate change related research.
Many foundational papers on key concepts central to adaptation were published in 1990s and early 2000s onwards (Adger et al., 2005; Burton, 1992; Fankhauser et al., 1999; Klein, 2003; Parry and Carter, 1998; Pittock and Jones, 2000; Smit, 1993; Smit et al., 1999; Smithers and Smit, 1997) while adaptation began to gain more prominence in IPCC's 3rd assessment (2001) and 4th assessment (2007). For example, the Canada

Climate Program report (Smit, 1993) report set out many of the principles of adaptation, and was highly influential charting these concepts also in IPCC's 3rd Assessment Report (Schipper and Burton, 2009). These papers and IPCC reports remain key foundations of climate adaptation science literature (Nalau and Verrall, 2021).

Helping to differentiate adaptation from mitigation during this period was a focus on theoretical principles and a framing of adaptation as local and context-specific, in contrast to mitigation's global character (Nalau et al., 2015; Westoby et al., 2020), leading to locally oriented adaptation research and practice, including the rise of community-based adaptation (Kirkby et al., 2017). Since AR5, however, adaptation has extended beyond the local, recognising the 'borderless' character of many climate change risks and vulnerabilities (Benzie and Persson, 2019) and framing adaptation and global adaptation governance as a global public good (Persson, 2019a). Encompassing this expanded scale is challenging for adaptation research compared to treating adaptation as a local issue, which fits more easily with social research methods. Adaptation now works across scales (Biesbroek et al., 2013; Dzebo and Stripple, 2015; Keskitalo and Preston, 2019a) and attends simultaneously to both the opportunities and risks arising from climate change (Juhola, 2016; Keskitalo and Preston, 2019a). This suggests that empirical adaptation research should incorporate multi-scalar research designs and methods.

A strong focus has been and remains on case studies of adaptation practice, but adaptation science literature reviews have become common. Recent systematic reviews cover topics such as adaptation effectiveness (Owen, 2020), public participation and engagement (Hügel and Davies, 2020), role of local knowledge (Klenk et al., 2017), adaptive capacity (Mortreux and Barnett, 2017; Mortreux et al., 2020; Siders, 2019a), evolution of adaptation science (Nalau and Verrall, 2021), empirical adaptation research in the Global South (Vincent and Cundill, 2021), how cities are adapting (Reckien et al., 2018), how decisions can be made (Siders and Pierce, 2021), Indigenous knowledge (Petzold et al., 2020) and small island developing states (Robinson, 2020). Review papers have developed common methodologies for how to undertake robust reviews in adaptation research (Berrang-Ford et al., 2015; Biesbroek et al., 2018; Lesnikowski et al., 2019a; Singh et al., 2020), and noted an existing imbalance as the majority of the literature still originates from the Global North compared to Global South (Nalau and Verrall, 2021; Robinson, 2020; Sietsma et al., 2021).

At the same time, adaptation research is also challenged by increasing attention to transformational adaptation (TA), which refers to fundamental changes going beyond existing practices, including new approaches to adaptation decision-making (Section 1.5). Whereas AR5 noted TA as an area of future research (Klein et al., 2014b), it has continued to grow in profile since then. Rather than a future or fringe consideration - e.g., an extreme action necessitated by the limits of incremental adaptation - transformational adaptation is increasingly an option that decision-makers are considering today. This increasing attention on TA is driven by a growing recognition of climate risks and impacts as well as the need for urgent, systemic action as laid out in the IPCC's recent special reports (IPCC, 2018d). Yet what incremental and transformational adaptation look like, how they relate in practice, and how to appropriately choose incremental or transformational options, is uncertain and increasingly debated (Few et al., 2017; Magnan et al., 2020; Termeer et al., 2016; Vermeulen et al., 2018; Wilson et al., 2020; Section 17.2.2.3). One of the main challenges is now to generate empirical evidence and policy relevant insights on transformational adaptation (e.g., Jakku et al., 2016). Transformative approaches are especially being discussed in the context of COVID-19 (Schipper et al., 2020; Cross-Chapter Box COVID in Chapter 7).

Increasingly reflective adaptation research

Another characteristic of recent adaptation research is a stronger focus on ethics, justice and power (Byskov et al., 2021; Coggins et al., 2021; Eriksen et al., 2021; Singh et al., 2021). Researchers and practitioners are increasingly impatient to address the root causes of vulnerability and use inclusive climate adaptation processes to generate effective adaptation responses for marginalised and misrecognized groups (Eriksen et al., 2015; Gillard et al., 2016; Scoones et al., 2015; Tschakert et al., 2013; Wisner, 2016). Increasingly ambitious, normative adaptation research often challenges technological solutions that simply reinforce the existing *status quo* (Nightingale et al., 2019, p. 2) and calls for "socially-just pathways for change". Here work on adaptation overlaps with mitigation, transitions and other large-scale social change, encouraging the move towards more systemic, integrated approaches that discern between options according to multiple criteria (Goldman et al., 2018).

Fundamental questions about equity and justice in adaptation include gender and intersectionality (see Cross-Chapter Box GENDER in Chapter 18, Section 1.4.1.1 Chapter 18;) and broader critiques of who participates in processes of adaptation planning and implementation, who receives investments, who and what benefits from them, who makes key decisions regarding adjustments through time (Boeckmann and Zeeb, 2016; Byskov et al., 2021; Eriksen et al., 2021; Nightingale et al., 2019; Pelling and Garschagen, 2019; Taylor et al., 2014), and how climate justice intersects with other justice agendas. Attention is also turning to relations and tensions between different adaptation approaches, scales, constraints, limits, losses, enablers and outcomes (Barnett et al., 2015; Crichton and Esteban, 2017; Deshpande et al., 2018; Gharbaoui and Blocher, 2017; McNamara and Jackson, 2019; Mechler and Schinko, 2016; Pelling et al., 2015). Evident here is an ongoing, serious knowledge gap around the long-term repercussions of adaptation interventions. There is growing awareness of the need to address the potential for maladaptation (Sections 1.4.2.4; 5.13.3; 15.5.1, 17.5.2, Chapter 4 on Water). Concerns about maladaptation have led to renewed calls to open the “black box” of decision making to examine the influence of power relationships, politics and institutional culture(Biesbroek et al., 2013; Eriksen et al., 2015; Goldman et al., 2018), including the power-adaptation linkage itself (Woroniecki et al., 2019), external factors outside the decision-making process (Eisenack et al., 2014) and the influence of leadership on adaptation processes and outcomes (Meijerink et al., 2014; Vignola et al., 2017).

All of these developments indicate that adaptation research is not only more reflexive about some of its central assumptions, methodologies and tools (Biesbroek et al., 2013; Conway and Mustelin, 2014; Eriksen et al., 2015; Lubell and Niles, 2019; Nalau et al., 2015; Nightingale, 2015a; Porter et al., 2015; Singh et al., 2021; Woroniecki et al., 2019), but also cognisant of the need to critically consider its underpinning goals, purpose and impact in the world.

[END CROSS CHAPTER BOX ADAPT HERE]

1.4.4 Limits to Adaptation

The effectiveness of adaptation efforts also depends on the constraints and limits that human and natural systems face when confronted with increasingly higher levels of climate risks. The concept of adaptation limits strongly affects any appropriate balance among adaptation and mitigation actions in the sense that less mitigation makes adaptation harder or even infeasible. **Adaptation limits** refer to the point at which an actor’s objectives (or system needs) cannot be secured from intolerable risks through adaptive actions (WGII AR6 Glossary). Adaptation limits can be soft or hard. **Soft adaptation limits** occur when options may exist but are currently not available to avoid intolerable risks through adaptive actions and **hard adaptation limits** occur when no adaptive actions are possible to avoid intolerable risks. Intolerable risks are those which fundamentally threaten a private or social norm — threatening, for instance, public safety, continuity of traditions, a legal standard or a social contract -- despite adaptive action having been taken (Dow et. al. 2013). Intolerable risks threaten core social objectives associated with health, welfare, security, or sustainability (WGII AR5 Chapter 16). Through the lens of resilience, hard limits represent the range of change or disturbance beyond which a system cannot maintain its essential function, identity, and structure. Soft limits represent the range of change or disturbance of a system which can be sustained over time by innovation or policy changes. The level of greenhouse gas reduction, adaptation and risk management measures are the key factors determining if and when adaptation limits are reached.

1.4.4.1 Limits to Adaptation and Relation to Transformation

A species ability to adapt may be significantly impacted by the dynamics of interactions between the ecosystems and species, so that a species may reach its limit to adapt even in a gradually changing environment, leading to sudden changes in range fragmentation (Radchuk et al., 2019). As human interventions affect the ability of species and ecosystems to adapt, a deeper understanding on ecosystems and species interactions and evolution in response to climate change is important in order to reduce future biodiversity losses (Nadeau and Urban, 2019). Hard limits for ecological and natural systems are more proximate than for human systems (Chapter 16) (*medium confidence)*. Many terrestrial, freshwater, ocean and coastal ecosystems are currently near or beyond their hard adaptation limits (Chapters 2, 3 and 16).

Many human and natural systems are currently near or beyond their soft adaptation limits (Dow et al., 2013; Chapters 4, 5, 6, 7, 8, and 16). The concept of limits to adaptation is dynamic in terms of the temporal, spatial and contextual dimensions of climate change risks, impacts and responses (Chapter 17; Storch, 2018). Adaptation limits depend on a complex function of interactions between social, ecological, technological and climatic elements, which appear to have thresholds beyond which adaptation can be infeasible and represent limits to adaptation. Such thresholds are endogenous to society and hence contingent on ethics, knowledge, attitudes, culture, governance, institutions and policies (Abrahamson et al., 2009; Tschakert et al., 2017). Since AR5, the evidence on limits to adaptation has been advanced across regions and sectors. Many adaptation constraints (financial, governance, institutional and policy etc.) lead to soft adaptation limits (see Chapter 16 for detailed evidence on constraints and adaptation limits). The ability of actors to overcome these constraints including social constraints to behavioural changes, depends on additional adaptation implementation. (Abrahamson et al., 2009; Di Virgilio et al., 2019; Juan, 2011). Thus, socioeconomic, technological, governance and institutional systems or policies can be changed or transformed in responses to the different dimension of adaptation limits to climate change and extreme events.

When a soft limit is reached, then intolerable risks and impacts may occur, and additional adaptations (incremental or transformational) are required.to reduce or avoid these risks and impacts (Chapters 2, 3, 4, 5, 6, 7, 16 and 17). IPCC SR1.5 defined incremental adaptation that maintains the essence and integrity of a system or process at a given scale whereas transformational adaptation that changes the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts. When incremental adaptation is insufficient to avoid intolerable risks, transformational adaptation may be able to extend the potential to sustain human and natural systems (IPCC, 2018a; Cross-Chapter Box LOSS in Chapter 17; Klein et al., 2014b). Transformational adaptation can allow a system to extend beyond its soft limits and prevent soft limits from becoming hard limits. This report provides evidence of assessing transformational adaptation in terms of scope, depth, speed and limits to adaptation (Chapter 16).

This report assesses adaptation limits (soft and hard) and residual risks for some actors and systems (Chapter 16). **Residual risk** is the risk that remains following adaptation and risk reduction efforts (SROCC). Residual risk is also used as other terms such as 'residual impacts', 'residual loss and damage' and 'residual damage'. As noted in AR5 WGII, the residual risk is larger or smaller depending on a society's choices about the appropriate level of adaptation and its ability to achieve an appropriate level. The intersection of inequality and poverty presents significant adaptation limits, resulting in residual impacts for vulnerable groups, including women, youth, elderly, ethnic and religious minorities, Indigenous People and refugees (Section 8.4.5). An appropriate level of adaptation, which ideally reflects a balance between the desired level of risk and the actions needed to achieve that level of risk, depends on the solution space, the society's views on climate justice, the tolerance for climate-related risks, the society's tolerance for the costs and other impacts of the actions needed to reduce risk. IPCC'S special reports stated that residual risks rise with increasing global temperatures from 1.5°C to 2°C (SR 1.5) and emerge from irreversible forms of land degradation (SRCCL). Among other risks, this report is evidenced that at risk to coastal flooding from sea level rise, nature-based adaptation measures (e.g., coral reefs, mangroves, marshes) reach hard limits beginning at 1.5ºC of global warming (Chapter 16). Residual risks may lead to exceeding the limits of adaptation, hence, this report underscores on the role of decision-making on transformational adaptation for dealing with residual risk and soft as well as hard adaptation limits (Cross-Chapter Box LOSS in Chapter 17). Section 1.5 addresses transformational adaptation in the context of climate resilient development pathways, since such adaptation is inseparable from mitigation and sustainable development.

1.4.4.2 Emerging importance of loss and damage

The concept of **Loss and Damage** (with capitalized letters, L&D) refers to discussion point under the UNFCCC, which is to "address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change." Lowercase letters of **losses and damages** refer broadly to harm from (observed) impacts and (projected) risks (IPCC, 2018a). The IPCC report uses the latter for its assessment on loss and damage which may provide useful information for the former. L&D associated with climate change has gained importance supported by the robust scientific evidence on the anthropogenic climate change amplifying frequency, intensity and duration of climate-related hazards (Mechler et al., 2019). Loss and damage associated with those residual losses and damages that are felt beyond the adaptation actions taken implying a sense of limits to adaptation at a given time and spatial contexts (Tschakert et al., 2017). IPCC's special report on climate change and land also underlined the unavoidable loss and damage due to changes in tropical and extratropical cyclones and marine heatwaves where adaptation and resilience limits are being exceeded for the people and ecosystems (IPCC, 2019a; Cross-Chapter Box LOSS in Chapter 17).

Loss and damage has emerged as an important topic in international climate policy (Boyd et al., 2017; Roberts and Pelling, 2016; Surminski and Lopez, 2015) which originated from Small Island Developing States for compensation, related to sea level rise impacts. It has since become formalized under the UNFCCC, through the establishment of the Warsaw International Mechanism (UNFCCC, 2013) and Article 8 of the Paris Agreement (UNFCCC, 2015b). The WIM promotes the implementation of comprehensive risk management approaches, improves understanding of slow onset events, non-economic losses and human mobility (migration, displacement) and enhances action and support, including finance, technology and capacity-building to avert, minimize and address loss and damage associated with climate change impacts particularly vulnerable and developing countries (UNFCCC, 2021). Different actors have defined loss and damage differently in reference to climate change impacts and responses (Boyd et al., 2017; McNamara and Jackson, 2019; Roberts and Pelling, 2016; Surminski and Lopez, 2015). These understanding includes the following: i) an adaptation and mitigation perspective linking all human-induced climate change impacts to potential loss and damage and the mandate to avoid dangerous anthropogenic interference; ii) a risk management perspective emphasising interconnections among disaster risk reduction, climate change adaptation, and humanitarian efforts; iii) a limits to adaptation perspective focused on residual loss and damage beyond adaptation and mitigation; and iv) an existential perspective highlighting inevitable harm and unavoidable transformation for some people and systems. This report assesses the growing literature on loss and damage across sectors and regions linking with adaptation constraints and limits, global warming level and incremental and or transformational adaptation to climate risks (Section 8.3.4, Cross-Chapter Box LOSS in Chapter 17, Box 10.7).

For assessing the projected losses and damages, residual risks also need to be taken into account. The loss and damage associated with the future climate change impacts, beyond the limits to adaptation, is an area of increasing focus, although yet to be fully developed in terms of methods of assessing including non-economic losses and damages as well as identifying means to avoid and reduce both economic (loss of asset, infrastructure, land etc.) and non-economic (loss of societal beliefs and values, cultural heritage, biodiversity and ecosystem services) losses and damages (Andrei et al., 2015; Fankhauser and Dietz, 2014). There is an increasing evidence in economic and non-economic losses due to climate extremes and slow onset events under observed increases in global temperatures (Coronese et al., 2019; Section 8.3.4; Grinsted et al., 2019; Kahn et al., 2019), however assessing non-economic losses and damages is lacking and needs more attention (Serdeczny et al., 2016; Tschakert et al., 2019). The aggregate losses and damages would be higher if non-economic values are considered in such assessment (Laurila-Pant et al., 2015; McShane, 2017). Solutions to reduce or avoid loss and damage need a robust conceptual framework and analysis, focusing the future losses rather than past losses (Preston, 2017) and emphasis on avoiding versus addressing loss and damage, and the role of justice (Boyd et al., 2017), clarity on the detection and attribution (Section 8.2.1, Section 8.3.3), effectiveness of risk management and adaptation (Cross-Chapter Box FEASIB in Chapter 18, Section 1.4), the concepts of risk transfer, liability and financing (Cross-Chapter Box FINANCE in Chapter 17, Section 17.4.2), and the role of transformation (Section 1.5).

1.5 Facilitating Long-Term Transformation

This report highlights that transformative system change is required to meet sustainable development goals (Chapter 18). **Transformation** is defined as "a change in the fundamental attributes of a system including altered goals or values" (SR 1.5). The related concept of **transition** is defined as "the process of changing from one state or condition to another in a given period of time" (IPCC SR 1.5/SRCCL, also see Section 1.5.2).

Many timescales have been assessed that shape the context for any such transformations: including the present, 2030 and mid-century (Cross-Chapter Box CLIMATE in Chapter 1). In the present, significant changes in the climate system have already occurred in many places (WGI) while commensurate adaptation actions have in general been lacking (Chapter 16). By 2030, the SDGs call for significant societal changes, many of which would be more difficult to achieve without significant reductions in climate risk and impacts. By mid-century, global emissions pathways consistent with the Paris Agreement 1.5°C target drop to zero net greenhouse gas emissions with no overshoot and roughly a decade later with overshoot (Cross-Chapter Box CLIMATE in Chapter 1). Pathways consistent with the Paris 2°C target drop to zero net emissions in the latter half of the 21st century. Even in low emission scenarios temperatures, storm intensities, sea levels and other climate parameters are expected to continuing changing for decades (IPCC, 2021).

The concepts of transition and transformation help organize assessments of near and longer-term adaptation actions that may prove feasible and effective in achieving societal goals related to climate and sustainable development.

1.5.1 Understanding Transformation

Over the last two hundred years, human society has undergone a rapid and profound transformation, with population and income per capita expanding by an order of magnitude or more after many millennia of relative stasis in living standards (Dasgupta et al., 2018). The transformations associated with sustainable development and managing climate risk may be of similar scale as these historic transformations. In the past, changes in technologies and economies of this scale are not separate from, but are necessarily embedded alongside changes in political, religious and social relationships (Polanyi, 1957). Future transformation may similarly involve such interlinked social, cultural, economic, environmental, technical and political factors (Chapter 18; Section 1.5.2). Technology-led, market-led or state-led transitions aimed at meeting Paris Agreement and SDGs may fail without integrating dimensions of social justice and addressing the social and political exclusion that prevent the disadvantaged from accessing such improvements and increasing their incomes (Burkett et al., 2014; Scoones et al., 2015). (*medium confidence*)

As used in the global environmental change literature, transformation is a pluralistic concept embracing many interpretations (Box 18.3), but all focus on the general idea of fundamental change in society as opposed to change that is minor, marginal, or incremental. Uses of the term can differ with respect to: 1) how the system undergoing change is conceptualized, 2) the extent to which change is continuous or discontinuous and the time scales involved, 3) the extent to which transformation is guided towards desired goals or emerges without intent and 4) whether the usage focuses on descriptions of societal processes or includes normative judgements as to which outcomes should or should not occur (Feola, 2015) . The literature generally uses transformation as an analytic-descriptive concept, which aims to describe significant change in couple human-natural systems, or as solutions-oriented concept, which aims to inform or contribute to societal change.

The IPCC Fifth Assessment cycle, starting with its Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), first highlighted the concept of transformation, drawing primarily on the solutions-oriented approaches of O'Brien (2011) and Pelling (2011). This Sixth Assessment report also generally employs transformation as a solutions-oriented concept, with mention in almost all chapters and significant emphasis in the synthesis chapters.

The IPCC Sixth Assessment cycle also highlights the concept of transition, drawn from the sustainability transitions literature (Köhler et al., 2019). The 1.5 Special Report organizes its assessments of feasibility and potential policy actions around transitions in four socio-technical system: energy, land, urban and infrastructure and industrial system (IPCC, 2018b: Chapter 4). This report adds a fifth system transition -- a societal transition focused on attributes that drive innovation, the evolution of patterns of consumption and development and power relationships among societal actors (Section 18.1.4). The AR6 WGIII report is organized around six systems transitions: energy; agricultural, forestry, other land use; urban; buildings; transportation; and industry, which includes supply chains and the circular economy.

The literature offers multiple views on the relationships between transition and transformation (Box 18.3). The 1.5 Special Report suggests that transformation is needed to generate the four system transitions. In many literatures, transformation is considered a more expansive process than transition, with the former less exclusively focused on socio-technical systems and more engaged with questions of power, politics, capabilities, culture, identity and sense-making (Gillard et al., 2016; Hölscher et al., 2018; Linnér and

Wibeck, 2019). This report generally takes this more expansive view of transformation, often to engage with issues of equity, climate justice and large-scale institutional and societal change (Box 18.3).

This WGII report has a particular focus on **transformational adaptation** (Section 1.4.4.1), which it views as laying on a continuum from incremental and transformational with no sharp division between them (Sections 17.2.2.3, 1.5.2).

The IPCC first highlighted the concept of transformational adaptation in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). SREX generally used the phrase transformation to refer to fundamental societal changes that advance climate adaptation, disaster risk management and sustainable development. Transformation was seen as one part of the solution space alongside options such as reducing vulnerability and exposure and increasing resilience for managing risk. WGII of the IPCC Fifth Assessment Report used the phrase transformational adaptation to contrast with incremental adaptation. That report used the former term to refer to: 1) adaptation at large scope or scale, 2) as the type of adaptation that occurs once soft limits have been breached, or 3) change that addresses root causes of vulnerability as well as redressing long-standing inequities. The Fifth Assessment Report's WGIII employed the concepts of transformation and transformation pathways to assess the large-scale societal changes needed to meet greenhouse gas emission reduction goals.

This WGII report focuses on transformational adaptation as one component of climate resilient development in which adaptation, mitigation and development solutions are pursued together to exploit synergies and reduce trade-offs among these actions (Section 1.5.3; Chapter 18). Chapter 16 assesses the extent to which transformational adaptation is currently being implemented, using criteria including the scope, depth and speed of the adaptation actions as well as the extent to which limits to adaptation have been considered (Section 16.3.2.4). Chapter 17 ranks potential adaptation options by where they lie on the incremental to transformational continuum (Section 17.5.1.1.2).

Societal transformation can arise without explicit intent as, arguably, did the industrial revolution and some of the trends re-making today's society (See Section 1.1). In order to help policy-makers achieve societal goals this report seeks to identify the conditions for **deliberate transformations**, that is, those envisioned and intended by at least some societal actors (Linnér and Wibeck, 2019).

Figure 1.9 connects several key concepts that this report employs to help distinguish pathways that lead to deliberative and forced transformations. As shown in the figure, adaptation goals might imply a desired level of adaptation: 1) accessible by actions within the solution space of the existing system or 2) beyond the solution space of the existing system. In the former case, incremental adaptation may stay within soft limits and hold risks to tolerable levels that avoid threatening private or social norms (also see Fig 17.6). In the latter case, deliberate transformational adaptation is necessary to reach the goals. Alternatively, if deliberate transformation does not successfully occur or hard limits are exceeded, the system may nonetheless undergo some type of forced transformation which results in outcomes inconsistent with societal goals. While the figure shows single decision points, multiple actors are involved at each stage. Thus, some people may find themselves coping with what they regard as intolerable risks which are not otherwise avoided. Often such coping situations display significant inequities, with tolerable risks for powerful groups and intolerable ones for marginalized groups.

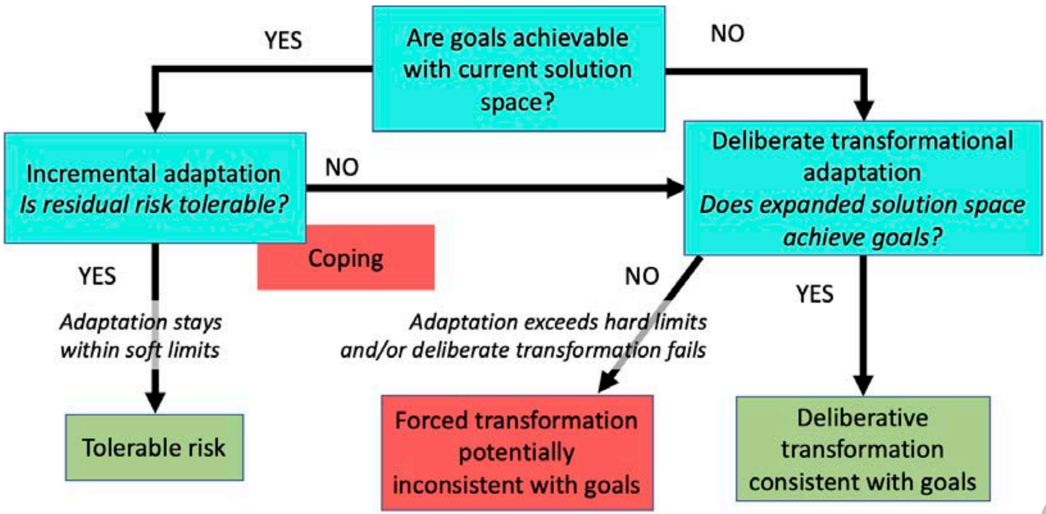


Figure 1.9: **Alternative Pathways to Transformation** Adaptation goals may be accessible by actions within or beyond the existing solution space. In the former case, incremental adaptation may stay within soft limits and hold risks to tolerable levels. In the latter case, deliberate transformational adaptation becomes necessary to achieve goals. If a successful deliberate transformation does not occur, the system may nonetheless undergo a forced transformation. Multiple actors are involved at each stage so that some people may nonetheless find themselves coping with what they regard as intolerable risks.

Multiple narratives describe pathways for pursuing deliberate transformations (Cavanagh and Benjaminsen, 2017). While building on the new "green economy" framing that emerged with the Rio+20 conference in 2012 (De Mello and Dutz, 2012; OECD, 2012; UNEP, 2011), these narratives reflect differing trade-offs among values and differing assumptions about the factors driving system change (see WGIII). The narratives range from "business-as-usual" scenarios focused on modernisation of sectors such as energy, agriculture and use of natural resources to more transformational propositions such as various green new deal proposals (European Commission, 2019), the new climate economy (Global Commission on the Economy and Climate, 2018), and "doughnut economics" (Raworth, 2017). Some literature suggests significant benefits from such new climate economy proposals, claiming tens of trillions in economic benefits, tens of millions of new jobs and close to a million fewer premature deaths from pollution over the coming decade (Global Commission on the Economy and Climate, 2018).

Two contrasting schools of thought, called ecomodernism and degrowth (D'Alisa et al., 2014), offer important bounding narratives for "green economy" approaches that aim achieve the SDGs and Paris Agreement goals.

Ecomodernism aims to decouple GHG emissions and other environmental impacts from GDP growth (Desrochers and Szurmak., 2020)(AR6 WGIII Sect 1.4.1) through three primary strategies: i) 'green' technological innovation, ii) resource efficiency or productivity improvements and iii) the sustainable intensification of land use in both rural and urban areas (Asafu-Adjaye et al., 2015; Isenhour, 2016). Such efforts to mobilize large-scale investment in climate change adaptation and to decouple GDP growth from environmental impacts could generate substantial employment opportunities and open up profitable investment frontiers (Adelman, 2018; Asafu-Adjaye et al., 2015), which could help achieve SDG 8, which calls for accelerated annual growth rates of at least 7 percent in least developed countries and achieve SDG 10, which calls for "income growth of the bottom 40 percent of the population at a rate higher than the national average".

Degrowth proponents question the feasibility of decoupling at a scale and rate sufficient for meeting Paris Agreement goals (Gómez-Baggethun, 2020; Hickel and Kallis, 2020; Kallis, 2017; Parrique et al., 2019). Using precautionary principle-rooted arguments (Latouche, 2001), degrowth aims for the intentional decreases in both GDP and coupled GHG emissions (Kallis, 2011) using policy mechanisms such a "cap and share" framework for distributing emissions permits on an annually declining basis with legislation to prohibit the overshoot of established carbon budgets (Douthwaite, 2012; Kallis et al., 2012). Degrowth thus seeks to minimize reliance on negative emissions technologies, such as the large-scale deployment of

BECCS (e.g., illustrative emissions reduction pathway labelled P4 in IPCC SR1.5, also WGIII Chapter 3) and aims to generate progress toward achieving the SDGs by prioritising redistribution rather than GDP growth. SDGs potentially addressed by degrowth include universal basic income (SDGs 1 and 10), work-sharing to guarantee full employment (SDGs 8 and 10) and shifting taxation burdens from income to resource and energy extraction (SDGs 8 and 12).

The contrasting premises of ecomodernism and degrowth have prompted a series of mutual counterarguments. Degrowth scholars emphasize that global absolute decoupling is currently not proceeding fast enough to meet Paris Agreement targets (Haberl et al., 2020; Moreau et al., 2019; Ward et al., 2016). Ecomodernists point to important progress towards achieving absolute decoupling at the national or regional scale – as shown by Le Quéré et al. (2019) in 18 developed countries – and the future potential of emerging technologies and policy reforms (Asafu-Adjaye et al., 2015)

1.5.2 Enabling Transformation

As one important theme, this Sixth Assessment report assesses who needs to take what actions and when in order that transformations unfold at sufficient speed and scale to meet Paris, SDG and other policy goals. A number of literatures inform these assessments.

Various literatures describe multiple, co-evolving societal elements which organize themselves into stable regimes that, under some circumstance, can undergo significant change. The sustainability transitions literature provides one central focus for understanding such processes and potential intervention points for actors seeking change (Köhler et al., 2019). This literature identifies three, interacting scales: the micro, meso and macro.(Geels, 2004; Köhler et al., 2019) The micro level reflects changing individual choices, attitudes and motivations. The meso reflects socio-technical systems, 'a cluster of elements, including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks' The macro reflects the cultures, institutions, norms, governance and other broad organising features of society. The sustainability transitions literature generally focuses on change that originates and occurs within the meso scale, while the transformation literature focuses on change within and among all scales. This Working Group II report often considers three interacting scales labelled personal, practical and political (O'Brien and Sygna, 2013). Working Group III often employs the multi-level perspectives framework (Geels, 2004) and the more actor-oriented three domains of decision-making framework (Grubb et al., 2014; WGIII Section 1.6.4) to describe related societal scales.

These literatures describe similar processes through which these interacting elements generate significant system change. In the sustainability transitions literature the process begins with a stable system of actors, technologies and institutions (Köhler et al., 2019). Radical innovations begin in niches or protected spaces, sometimes introduced by new entrants or outsiders. Successful innovations expand in scale, scope, and geographically, and ultimately help generate new regimes. Incumbent actors can support or resists innovations through combinations of government policies, economic forces and institutional and behavioural pressures. Such processes can, but need not, follow a common S-curve pattern of initial adoption, take-off, acceleration and stabilisation (Rotmans et al., 2001). The multi-level perspectives literature in WGIII similarly describes innovations as moving from niches to socio-technical regimes, at first mediated by and then potentially altering exogenous socio-technical landscapes (Smith et al., 2010; WGIII Section 1.6.4).

The socio-ecological systems literature, a main source of the resilience concept, focuses on the system elements of society and eco-systems, their interdependence and on how they change in response to shocks (Section 1.2.1.4). Coupled human and natural systems maintain their vital functions through what are called adaptive cycles that begin with growth, reach a period of stasis, experience a disruption, and then reorganize. This repeating cycle can leave the system unchanged or transition it to new states. Human agency can alter system characteristics so that after any disruption the system will reorganize into a different, more desired state; guide the reorganisation in desired directions after a system shock (such as a natural disaster); or provide the shock that catalyses a reorganisation.

These literatures view incremental and transformational change as linked processes. In the transformational adaptation literature, Park et al. (2012) consider incremental and transformational adaptation as two concentric and linked action-learning cycles with similar steps that include monitoring and learning. Systems generally reside in the incremental cycle but can temporarily jump to the transformational cycle before returning to the incremental, albeit in a state with fundamentally changed attributes. Shifts from the incremental to transformational cycle are made possible by knowledge and skills, as well as adjustments to vision, agendas and coalitions achieved through monitoring and learning. The incremental cycle is characterized by reactive responses to external drivers and performance evaluation relative to past performance. Shifts to the transformational cycle are characterized by more pro-active responses and more expansive problem framings.

The socio-ecological and sustainability transitions literature describes transitions as often non-linear, characterized by tipping point behaviour with periods of relative stability interspersed with periods of more rapid change as thresholds are crossed (van Ginkel et al., 2020). Actors seeking transformation may take incremental steps that aim to induce such tipping point behaviour (Otto et al., 2020b). For instance, full accounting of climate risk in insurance and financial lending decisions could similarly act as such social tipping point interventions for adaptation (Hill and Martinez-Diaz, 2019). Transformations need not, however, be equitable or smooth. Historical examples suggest the potential for rigidity traps, in which suppression of innovation and a high degree of connectivity in a system delay an eventual transformation which, when it eventually occurs, unfolds as exceptionally harsh (Hegmon et al., 2008).

Many actors can contribute to launching or blocking significant system change. Pelling et al (2015) highlights power relationships within and among activity spheres that influence the process of transformational adaptation and distribution of risks. In the sustainability transitions literature each set of actors --including those from academia, politics, industry, civil society and households -- brings their own resources, capabilities, beliefs, strategies and interests, which affects their interest, objectives, ability to affect the process and their ability to affect others (Kern and Rogge, 2018).

There is no consensus in the literature on the best means for actors to pursue deliberate transformation (Section 1.5.1) and the extent to which actors can guide the process. The transitions and some transformation literatures derive from a complex systems perspective (Köhler et al., 2019; Section 1.3.1.2; Linnér and Wibeck, 2019) in which behaviours can be understood but not predicted (Mitchell, 2009; Chapter 17). These literatures suggest that interventions in such systems will rarely result in them evolving along some pre-determined pathway. Rather, successful interventions more often resemble iterative processes of action, observation and response, which are described in the literature with terms such as iterative risk management (Section 17.2.1), clumsy solutions (Linnér and Wibeck, 2019; Thompson and Rayner, 1998), probe and response (Chapter 17; French, 2013) and what Young (2017) calls adaptive governance.

These literatures view transformation as a collective action challenge among actors with both common and differing values, interests and capabilities interacting over time with a mix of cooperation and competition (Dasgupta et al., 2018; Young, 2017). Concepts such as radical incremental transformation (Göpel, 2016), direct incrementalism (Grunwald 2007) and progressive incrementalism (Levin et al., 2012) envision strategies in which actors pursue incremental actions in one or more niches that move the current system towards tipping points which, once crossed, will drive the system to a new state (Tàbara et al., 2018). The incremental actions aim to promote learning, remove barriers to change (Baresi et al., 2020; Dasgupta et al., 2018), create a series of wins that generate momentum and generate positive feedbacks (e.g. by creating constituencies) such that the speed and scale of the climate action grows over time (Levin et al., 2012). But incremental strategies can fail to move fast enough; can succumb to path-dependency that locks in initially helpful but long-adverse responses (such as the well-known levee-effect) (Sadoff 2015; Haasnoot 2019); or can result in a transition that meets some goals (e.g., environmental) but not others (e.g., equity). (*high confidence*)

This report describes decision frameworks and tools that can help those involved in such a process – acting independently or collectively - identify, evaluate, seek compromise on, and then implement sequences of solutions that lead to pathways with more desirable outcomes and avoid pathways with less desirable outcomes (Section 17.3.1). For instance, adaptive (also called adaptation) pathways (Cross-Chapter Boxes SLR in Chapter 3 and DEEP in Chapter 17) explicitly chart alternative sequences of actions including near-term steps, indicators to monitor and contingency actions to take if pre-determined monitoring thresholds are breached. Employed in contexts with multiple actors and contested values, adaptive pathways frames deliberate transformation as both a near-term decision problem focused on physical, financial and natural resources as well as a social change process of co-evolving knowledge, policies, institutions, values, rules and norms (Fazey et al., 2016). Transition Management (Loorbach, 2010), rooted in the sustainability transitions literature, supports arenas of actors that co-produce visions of future change, plan pathways and recruit additional actors into the change process.

As a central feature, such frameworks and tools embrace: 1) multiple objectives and measures (Section 1.4.1.2) to help identify and consider trade-offs among parties with a diversity of interests, values and objectives and 2) multiple scenarios enable stress-testing of proposed actions to identify conditions in which they would fail to meet their goals and thus inform consideration of ways to make those actions more robust and resilient over multiple futures in the near- and longer-term (Chapter 17; Cross-Chapter Box DEEP in Chapter 17). A focus on single or overly aggregated measures (Section 1.4.1.2) and single scenarios can privilege some actors' views over others, reduce transparency, and make it more difficult to identify resilient and equitable solutions to complex, deeply uncertain, non-linear and contested problems (Jones et al., 2014; Lempert and Turner, 2020; Renn, 2008; Schoen and and Rein, 1994). (*medium confidence*)

Nonetheless, most concepts of deliberate transformation also emphasize the importance of common goals and principles within a process of goal setting, acting on those goals, monitoring and evaluation and readjustment. Such goals encourage proactive action; help align the activities of multiple, loosely co-ordinated actors (Dasgupta et al., 2018; Göpel, 2016); and provide benchmarks against which to measure progress (Young, 2017). The Paris Agreement and SDGs aim to provide such common goals for the world as a whole and implement what some have described as goal-based as opposed to rule-based governance for galvanising collection action (Kanie and Biermann, 2017; Sachs, 2015). As intended, many public sector, private sector and civil society actors have developed their own goals as that aim to align with the Paris Agreement and the SDGs (see Section 1.1). The existence of goals that helps people envision a future significantly different than present can be one often key difference between decision processes that pursue transformational as opposed to incremental change (Park et al., 2012; Chapter 17). Narratives that help explain where a community is, where it wants to go and how it intends to get there are an important enabler of transformation (Section 1.5.1; Section 1.2.3; Fazey et al., 2020; Linnér and Wibeck, 2019).

1.5.3 Climate-Resilient Development

Adaptation and mitigation can reduce climate-related risks. Implementing these two types of climate action together increases their effectiveness by exploiting synergies and reducing trade-offs among them. In addition, implementing adaptation and mitigation as an integral part of development can similarly make all three more effective (Section 18.2.3). The link between climate change and sustainable development has long been recognized and has been assessed in every Working Group 2 report since AR3. AR5 introduced the concept of climate resilient development to help assess development trajectories that include co-ordinated adaptation and mitigation actions aimed at reducing climate risk.

Building on AR5, this AR6 report expands the focus with increased attention to equity and the processes needed to follow such trajectories. AR6 thus defines **climate resilient development** as "a process of implementing greenhouse gas mitigation and adaptation solutions to support sustainable development for all" (Section 18.1.1). In AR6 WGII, some chapters have a section dedicated to climate resilient development, emphasizing the need for integrative and transformative solutions within a sector or region that address the uneven distribution of climate risks among different groups and geographies, as well as extend the goals of these solutions to more than reducing risk, such as in improving social, economic and ecological outcomes (Sections 2.6.7, 4.1, 5.14.4, 6.4.8, 7.4.3.5, 7.4.5, 10.6, 11.8, 15.7 and 17.6; Boxes 4.7, 13.3 and 8.10). Multiple chapters also employ the concept of climate resilient development to identify and balance trade-offs and make progress on achieving the SDGs (Sections 6.1.3, 7.4.5, 10.6, 13.11, 15.7 and 16.6.4.3; Box 4.7; Chapter 18).

Climate resilient development requires large and equitable changes in human and natural systems. As noted in Section 1.5.1, the SR1.5 finds that four transitions in socio-economic systems - energy, land and ecosystems, urban and infrastructure and industrial – must occur at large scale and rapid rate in order to achieve climate resilient development. This report notes that transitions of such scale, even when beneficial for many people, can also impose significant adverse impacts on others, in particular on marginal and vulnerable populations (Section 18.1.2). This report identifies a fifth socio-economic transition, that in societal systems that "drive innovation, preferences for alternative patterns of consumption and development, and the power relationships among different actors that engage in CRD" (Section 18.1.4). Such societal transitions are necessary to ensure the other four transitions unfold at sufficient speed and scale to meet Paris and Sustainable Development goals as well as to ensure equity in these transitions.

Introduced in the WGII AR5 (Olsson et al., 2014), and further addressed in SR1.5, climate resilient development pathways are trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities, while promoting fair and equitable reductions of GHG emissions, and serve to steer societies towards low-carbon, prosperous and ecologically safe futures. This report defines a **climate resilient development pathway** as a trajectory in time reflecting a particular sequence of actions and consequences against a background of autonomous developments leading to a specific future situation (Section 18.1.2). Such a pathway emerges from the spatially and temporally distributed choices of many different actors in government, business, civic organizations and households at the individual, community, national and international levels. As such, there exists no single or preferred pathway for climate resilient development and no single best combination of adaptation, mitigation and sustainable development strategies. All pathways involve complex trade-offs and synergies among different actions (Sections 18.1.4, 18.2.2). All pathways are subject to hard-to-predict shocks, both adverse, such as climate disasters, and beneficial, such as new technologies or shifts in public values. The pathway that emerges will represent the results of negotiation, cooperation and competition among actors at many scales whose differing values and objectives would favour differing trajectories (Section 18.1.4). Individual actors at various scales will determine the mix of adaptation, mitigation and development appropriate for their development context and goals, while also influenced by the desire for their collective actions to become consistent with the global policy goals such as those in the Paris Agreement and the SDGs (Section 18.1.2). The norms, institutions and power relationships that mediate such choices determine the extent to which the process unfolds consistent with principles of equity and social justice. (*high confidence*)

Enabling conditions that can accelerate climate resilient development include governance; finance; economy; and science, technology and information (Sections 18.4.2, 18.9.2). The pursuit of equity and justice are both an enabler and an outcome of climate resilient development (Section 18.1.4). Climate resilient development involves a process of action, learning and response (Section 1.5.2), so the capability for such monitoring and iterative risk management also represents an important enabling condition (Section 18.1.4.2). Governments have an important role to play in expanding the solution space, often focusing on technology, policy and finance. Expanding the solution space also requires a broader set of actors. Chapter 18 and other chapters in this report use the climate resilient development concept to highlight the role of citizens, civil society, knowledge institutions, media, investors and businesses and the importance of expanding the arenas of engagement in which they interact.

1.6 Structure of the Report

The IPCC mandate involves the provisioning of available scientific information and evidence to inform climate action by multiple actors, notably governments (including international alliances) in the context of UNFCCC. Increasingly, IPCC assessments also aim to provide valuable information to non-governmental organisations, small and large enterprises and citizens.

Figure 1.10 shows the structure of this report, organized into three sections comprising chapters and cross-chapter papers. This first chapter provides the point of departure for this assessment, defines key concepts, and describes the connections among them.

The next group of chapters assess risks, adaptation and sustainability for systems impacted by climate change from the vantage of seven sectoral chapters, The next group of chapters organizes the assessment from the vantage of seven regional chapters.

In contrast to previous assessments, the current report embeds adaptation in each regional and sectoral chapter rather than in separate adaptation chapters, in order to reflect the increasing prevalence of adaptation and the extent to which many current risk, impacts and vulnerability estimates incorporate adaptation actions already taken. In addition, cross-chapter papers (CCPs) integrate across chapter topics, sectors and regions in particular types of geographies or ecosystems, termed typological regions, such as mountains, cities by the sea, or tropical forests. CCPs are a new element in WGII AR6 included at the request of Governments to highlight and expand relevant material from chapters and beyond into one place to ensure the integrated treatment of particular systems or regions and to improve accessibility of the report to readers.

Finally, section three highlights sustainable development pathways of integrating adaptation and mitigation by three synthesis chapters. The synthesis chapters summarize findings across all the chapters, CCPs and literatures on key risks, decision making options, and climate resilient development pathways that can lead from the current situation to a future more consistent with the stated policy goals. This report also assesses the adaptation options available, the extent to which such options can reduce risk, the effectiveness of current adaptation efforts, and their interactions with mitigation and sustainable development.

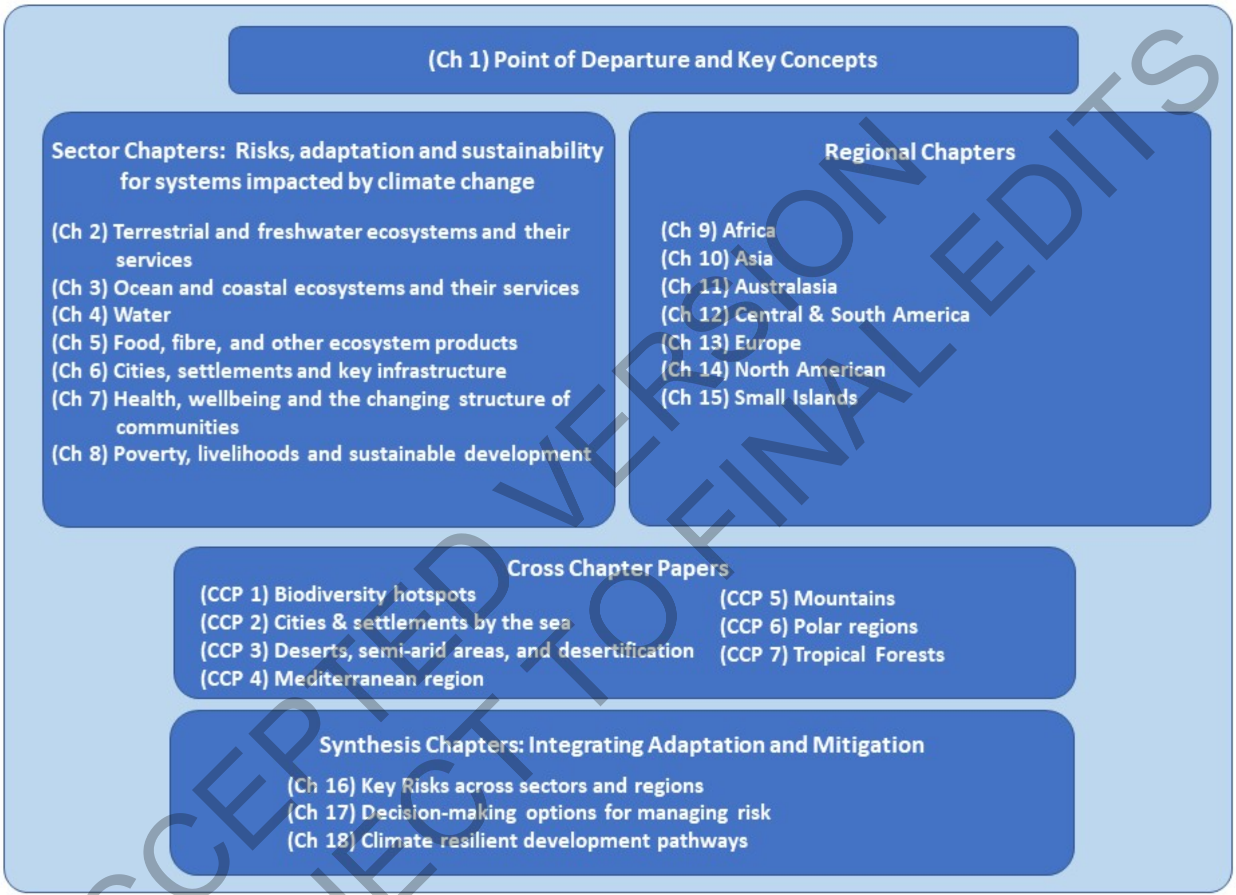


Figure 1.10: Key elements of the IPCC WGII report

[START FAQ1.1 HERE]

FAQ1.1: What are the goals of climate change adaptation?

The goals of climate change adaptation, as a broad concept, are to reduce risk and vulnerability to climate change, strengthen resilience, enhance well-being and the capacity to anticipate, and respond successfully to change. Existing international frameworks provide a high-level direction for coordinating, financing and assessing progress toward these goals. However, specifying the goals for specific adaptation actions is not straightforward because the impacts of climate change affect people and nature in many different ways requiring different adaptation actions. Thereby, goals that accompany these actions are diverse. Goals can relate to health, water or food security, jobs and employment, poverty eradication and social equity, biodiversity and ecosystem services at international, national, and local levels.

Climate change adaptation entails the process of adjustment to actual or expected climate change and its effects in order to moderate harm or exploit beneficial opportunities. At a high level, international frameworks, including the Paris Agreement and the Sustainable Development Goals (SDGs), have come to provide a direction for coordinating, financing and assessing global progress in these terms. The Paris Agreement calls for climate change adaptation actions, referring to these actions as those that reduce risk and vulnerability, strengthen resilience, enhance the capacity to anticipate and respond successfully, and ensure the availability of necessary financial resources, as these processes and outcomes relate to climate change. In addition, the Sustainable Development Goals include 17 targets (with a specific goal SDG 13 on climate action) to fulfil its mission to end extreme poverty by 2030, protect the planet, and build more peaceful, just, and inclusive societies. These goals are difficult to reach without successful adaptation to climate change. Other notable frameworks that identify climate change adaptation as important global priorities include the Sendai Framework for Disaster Risk Reduction, the finance-oriented Addis Ababa Action Agenda and the New Urban Agenda.

While vital for international finance, coordination and assessment, the global goals set forth by these frameworks and conventions do not necessarily provide sufficient guidance to plan, implement or evaluate specific adaptation efforts at the community level. Specifying goals of adaptation is harder than setting goals for reducing emissions of climate-warming greenhouse gas emissions. For instance, emission-reduction effort is ultimately measured by the total amount of greenhouse gases in the Earth's atmosphere. Instead, adaptation aims to reduce risk and vulnerability from climate change and helps to enhance well-being in each individual community worldwide.

Because the impacts of climate change affect people and nature in so many different ways, the specific goals of adaptation depend on the impact being managed and the action being taken . For human systems, adaptation includes actions aimed at reducing a specific risk, such as by hardening a building against flooding, or actions aimed at multiple risks, such as requiring climate risk assessments in financial reporting in anticipation of different kinds of risk. At the local level, communities can take actions that include updating building codes and land use plans, improving soil management, enhancing water use efficiency, supporting migrants and taking measures for poverty reduction. For natural systems, adaptation includes organisms changing behaviours, migrating to new locations and genetic modifications in response to changing climate conditions. The goals for these adaptation actions can relate to health, water or food security, jobs and employment, poverty eradication and social equity, biodiversity and ecosystem services, among others. Articulating the goals of adaptation thus requires engaging with the concepts of equity, justice, and effectiveness at the international, national, and local levels.

[END FAQ1.1 HERE]

[START FAQ1.2 HERE]

FAQ1.2: Is climate change adaptation urgent?

Climate impacts, such as stronger heat waves, longer droughts, more frequent floods, accelerating sea- level rise, and storm surges, are already being observed in some regions, and people around the world are increasingly perceiving changing climates, regarding these changes as significant and considering climate action as a matter of high urgency. Reducing climate risk to levels that avoid threatening private or social norms and ensuring sustainable development will require immediate and long-term adaptation efforts by governments, business, civil society, and individuals at a scale and speed significantly faster than the current trends.

Current observed climate impacts and expected future risks include stronger and longer heat waves, unprecedented droughts and floods, accelerating sea-level rise and storm surges affecting many geographies and communities. People around the world are increasingly perceiving changing climates, regarding these changes as significant and considering climate action as a matter of high urgency. Particularly, marginalised and poor people as well as island and coastal community experience relatively higher risks and vulnerability. The available evidence suggests that current adaptation efforts may be insufficient to help ensure sustainable development and other societal goals in many communities worldwide even under the most optimistic greenhouse gas emissions scenarios.

Climate change adaptation is, therefore, urgent to the extent that meeting important societal goals requires immediate and long-term action by governments, business, civil society, and individuals at a scale and speed significantly faster than that represented by current trends.

[END FAQ1.2 HERE]

[START FAQ1.3 HERE]

FAQ1.3: What constitutes successful adaptation to climate change?

Success of climate change adaptation is dependent on the extent to which relevant actions reduce risk and vulnerability, as well as achieve their respective goals. At a global scale, these goals are set and tracked according to international frameworks and conventions. At smaller scales, such as local and national, goals are dependent on the specific impacts being managed, the actions being taken, and the relevant scale. While success can take shape as uniquely as goals can, the degree to which an adaptation is feasible, effective, and conforms to principles of justice represents important attributes for measuring success across actions. Adaptation responses that lead to increased risk and impacts are considered maladaptation.

Altogether, adaptation success is dependent on the extent to which adaptation actions achieve their respective goals of reducing climate risk, increasing resilience, and pursuing other climate-related societal goals. Viewed globally, successful adaptation consists of actions anticipated to make significant contributions to meeting sustainable development goal such as ending extreme poverty, hunger, and discrimination and reduce risks to ecosystems, water, food systems, human settlements, and health and well-being. Viewed locally, successful adaptation consists of actions that help communities meet their diverse goals including reducing anticipated current and future risks, enhancing capacity to adapt and transform, avoiding maladaptation, yielding benefits greater than costs, serving vulnerable populations, and arising from an inclusive, evidence-based, and equitable decision process.

While success can be unique to an adaptation action, there are important attributes that constitute it as a successful solution. These include the extent to which an action is considered feasible, effective, and conforms to principles of justice.

The degree to which an action is **feasible** is the extent it is appraised as possible and desirable, taking into consideration barriers, enablers, synergies, and trade-offs. These considerations are based on financial or economic, political, physical, historical, and social factors, depending on what is required for an action to be implemented. The degree to which an action is **effective** depends on the extent it reduces climate risk, as well as the extent an action achieves its intended goals or outcomes. An adaptation action can sometimes – usually inadvertently – increase risk or vulnerability for some or all affected individuals or communities. In some cases, such risk increases will be sufficient to call the actions maladaptation. The degree to which an action is **just** is when its outcomes, the process of implementing the action, and the process of choosing the action respects principles of distributive, procedural, and recognitional justice. Distributive justice refers to the different distributions of benefits and burdens of an action across members of society; procedural justice refers to ensuring the opportunity for fairness, transparency, inclusion, and impartiality in the decision-making of an action; and recognitional justice insists on recognizing and including those who are or may be most affected by an action.

These attributes of adaptation success can be assessed throughout the adaptation process of planning, implementation, monitoring and evaluation, adjustment, and learning. However, at the same time, the success of many adaptation actions depend strongly on context and time. For instance, the effectiveness of adaptation will depend on the success of greenhouse gas mitigation efforts, as adaptation has strong synergies and trade-offs with mitigation efforts

[END FAQ1.3 HERE]

[START FAQ1.4 HERE]

FAQ1.4: What is transformational adaptation?

Continuing and expanding current adaptation efforts can reduce some climate risks. But even with emission reductions sufficient to meet the Paris Agreement goals, transformational adaptation will be necessary.

Over six assessment reports, the IPCC has documented transformative changes in the Earth's climate and ecosystems caused by human actions. These changes are now unequivocal and projected to become even more significant in the years and decades ahead. This AR6 report also highlights climate adaptation actions people are taking and can take in response to these significant changes in the climate system.

Some adaptation is incremental, which only modifies existing systems. Other actions are transformational, leading to changes in the fundamental characteristics of a system. For instance, building a seawall to protect a coastal community from flooding might exemplify incremental adaptation. Changing land use regulations in that community and establishing a program of managed retreat might exemplify transformational adaptation. There exists no bright line between incremental and transformational adaptation. Some incremental actions stay incremental. Others may expand the future space of solutions. For instance, including climate risk in mortgages and insurance might at first seem incremental but might lead to more transformational change over time.

Transformation can be deliberate, envisioned and intended by at least some societal actors, or forced, arising without explicit intent.

Deliberate transformational adaptation is not without risks because change can disturb existing power relationships and can unfold in difficult to predict and unintended ways. But transformational adaptation is important to consider because it may be needed to avoid intolerable risks from climate change and may be needed to help meet development goals as articulated in the SDGs. In addition, some type of societal transformation may be inevitable and deliberate rather than forced transformation may bring society closer to its goals.

Some type of transformation may be inevitable because the amount of transformational adaptation needed to avoid intolerable risks depends in part on the level of greenhouse gas mitigation. Low concentration pathways consistent with Paris Agreement goals require deliberate transformations that lead to significant and rapid change in energy, land, urban and infrastructure, and industrial systems. Even with low concentration pathways, some transformational adaptation will be necessary to limit intolerable risks. But with higher concentrations pathways, more extensive transformational adaptation would be required to limit (though not entirely avoid) intolerable risks. In such circumstance, insufficient deliberate transformation could lead to undesirable forced transformations.

[END FAQ1.4 HERE]

[START FAQ1.5 HERE]

FAQ1.5: What is new in this 6th IPCC report on impacts, adaptation and vulnerability?

Since IPCC Fifth Assessment Report, many new sources of knowledge have been employed to provide better understanding of climate change risks, impacts, vulnerability, and also societal responses through adaptation, mitigation and sustainable development. This new, more integrative assessment increasing focuses on risk and solutions, social justice, different forms of knowledge including Indigenous knowledge and local knowledge, role of transformation and the urgency of fast climate actions.

The IPCC Sixth Assessment Report (AR6) plays a prominent role in science-policy–society interactions on the climate issue since 1988, has advanced in important ways of interdisciplinary climate change assessment since AR5. Many new sources of knowledge have been employed to provide better understanding of climate change risks, impacts, vulnerability, and also societal responses through adaptation, mitigation and sustainable development.

This AR6 assessment has increasingly focus on risk and solutions. The risk framing for the first time spans all three working groups, includes risks from the responses to climate change, considers dynamic and cascading consequences, describes with more geographic detail risks to people and ecosystems, and assesses such risks over a range of scenarios. The solutions framing encompasses the interconnections among climate responses, sustainable development, and transformation—and the implications for governance across scales within the public and private sectors. The assessment therefore includes climate-related decision-making and risk management, climate-resilient development pathways, implementation and evaluation of adaptation, and also limits to adaptation and loss and damage.

The AR6 emphases the emergent issue on social justice and different forms of knowledge. As climate change impacts and implemented responses increasingly occur, there is heightened awareness of the ways that climate responses interact with issues of justice and social progress. In this report, there is expanded attention to inequity in climate vulnerability and responses, the role of power and participation in processes of implementation, unequal and differential impacts, and climate justice. The historic focus on scientific literature has also been increasingly accompanied by attention to and incorporation of Indigenous knowledge, local knowledge, and associated scholars.

The AR6 has a more extensive focus on the role of transformation and the urgency of fast climate actions in meeting societal goals. This report assesses extensive literatures with an increasing diversity of topics and geographical areas with more sectoral and regional details. The literature also increasingly evaluates the lived experiences of climate change—the physical changes underway, the impacts for people and ecosystems, the perceptions of the risks, and adaptation and mitigation responses planned and implemented.

The assessment in AR6 has increasingly become integrative across multiple disciplines and combine experts across working groups, chapters, papers and disciplines, such as natural and social sciences, medical and health sciences, engineering, humanities, law, and business administration etc. The emphasis on knowledge for action has also included the role of public communication, stories, and narratives within assessment and associated outreach.

[END FAQ1.5 HERE]

References

Abrahamson, V., Wolf, J., Lorenzoni, I., Fenn, B., Kovats, S., Wilkinson, P., Adger, W.N. and Raine, R., 2009. Perceptions of heatwave risks to health: interview-based study of older people in London and Norwich, UK. J. Public Health, 31: 119–126.

Abreu, R.C., Hoffmann, W.A., Vasconcelos, H.L., Pilon, N.A., Rossatto, D.R. and Durigan, G., 2017. The biodiversity cost of carbon sequestration in tropical savanna. Science advances, 3(8): e1701284.

Adelman, S., 2018. The sustainable development goals, anthropocentrism and neoliberalism, Sustainable Development Goals. Edward Elgar Publishing.

Adger, N., W.,, Arnell, N.W. and and Tompkins, E.L., 2005. Successful adaptation to climate change across scales. Global Environmental Change, 15(2): 77-86.

Adger, W.N., 2010. Climate Change, Human Well-Being and Insecurity. New Political Economy, 15(2): 275-292.

Adger, W.N., 2016. Place, well-being, and fairness shape priorities for adaptation to climate change. Global Environmental Change, 38: A1-A3.

Adger, W.N., Barnett, J., Brown, K., Marshall, N. and O'brien, K., 2013. Cultural dimensions of climate change impacts and adaptation. Nature climate change, 3(2): 112-117.

Adger, W.N., Benjaminsen, T.A., Brown, K. and Svarstad, H., 2001. Advancing a political ecology of global environmental discourses. Development and change, 32(4): 681-715.

Adger, W.N., Brown, I. and Surminski, S., 2018. Advances in risk assessment for climate change adaptation policy. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 376(2121).

Adler, M., 2012. Well-Being and Fair Distribution: Beyond Cost-Benefit Analysis. Oxford University Press.

Adler, M.D., Anthoff, D., Bosetti, V., Garner, G., Keller, K. and Treich, N., 2016. Priority for the Worse Off and the Social Cost of Carbon.

Agrawal, A. and Lemos, M.C., 2015. Adaptive development. Nature Climate Change, 5(3): 185.

Aldunce, P., Beilin, R., Howden, M. and Handmer, J., 2015. Resilience for disaster risk management in a changing climate: Practitioners' frames and practices. Global Environmental Change-Human and Policy Dimensions, 30: 1-11.

Allen, C.R. and Holling, C., 2010. Novelty, adaptive capacity, and resilience.

Allen, M., Dube, O.P., Solecki, W., Aragón–Durand, F., Cramer, W., Humphreys, S., Kainuma, M., Kala, J., Mahowald, N., Mulugetta, Y., Perez, R., Wairiu, M. and Zickfeld, K., 2018. Framing and Context. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Altieri, M.A. and Nicholls, C.I., 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. Climatic Change, 140(1): 33-45.

Anderegg, W.R., Callaway, E.S., Boykoff, M.T., Yohe, G. and Root, T.L., 2014. Awareness of Both Type 1 and 2 Errors in Climate Science and Assessment. Bulletin of the American Meteorological Society, 95(9): 1445-1451.

Anderson, D.G., Bissett, T.G., Yerka, S.J., Wells, J.J., Kansa, E.C., Kansa, S.W., Myers, K.N., DeMuth, R.C. and White, D.A., 2017. Sea-level rise and archaeological site destruction: An example from the southeastern United States using DINAA (Digital Index of North American Archaeology). PloS one, 12(11): e0188142-e0188142.

Andrei, S., Rabbani, G., Khan, H., Haque, M. and Ali, D., 2015. Non-economic loss and damage caused by climatic stressors in selected coastal districts of Bangladesh. Report for the Asian Development Bank.

Andrijevic, M., Crespo Cuaresma, J., Muttarak, R. and Schleussner, C.-F., 2020. Governance in socioeconomic pathways and its role for future adaptive capacity. Nature Sustainability, 3(1): 35-41.

Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K. and Teicher, H., 2016. Equity impacts of urban land use planning for climate adaptation: Critical perspectives from the global north and south. Journal of Planning Education and Research, 36(3): 333-348.

Archer, D., Almansi, F., DiGregorio, M., Roberts, D., Sharma, D. and Syam, D., 2014. Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. Climate and Development, 6(4): 345-356.

Arneth, A., Shin, Y.-J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., Midgley, G.F., Oberdorff, T., Palomo, I. and Saito, O., 2020. Post-2020 biodiversity targets need to embrace climate change. Proceedings of the National Academy of Sciences, 117(49): 30882-30891.

Asafu-Adjaye, J., Blomquist, L., Brand, S., Brook, B.W., DeFries, R., Ellis, E., Foreman, C., Keith, D., Lewis, M. and Lynas, M., 2015. An ecomodernist manifesto.

Atteridge, A. and Remling, E., 2017. Is adaptation reducing vulnerability or redistributing it? WIREs Climate Change, 9(1).

Aven, T., 2016. Risk assessment and risk management: Review of recent advances on their foundation. European Journal of Operational Research, 253(1): 1-13.

Banerjee, A., Fyfe, J.C., Polvani, L.M., Waugh, D. and Chang, K.-L., 2020. A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. Nature, 579(7800): 544-548.

Banerjee, S.B., 2003. Who sustains whose development? Sustainable development and the reinvention of nature. Organization studies, 24(1): 143-180.

Baresi, U., Vella, K.J. and Sipe, N.G., 2020. A limits-oriented adaptive approach for strategic environmental assessment. Environmental Science & Policy, 114: 128-139.
Barnes, D.K., Kuklinski, P., Jackson, J.A., Keel, G.W., Morley, S.A. and Winston, J.E., 2011. Scott's collections help reveal accelerating marine life growth in Antarctica. Curr Biol, 21(4): R147-8.
Barnett, J., Evans, L.S., Gross, C., Kiem, A.S., Kingsford, R.T., Palutikof, J.P., Pickering, C.M. and Smithers, S.G., 2015. From barriers to limits to climate change adaptation: path dependency and the speed of change. Ecology and Society, 20(3).
Barnosky, A.D., Hadly, E.A., Gonzalez, P., Head, J., Polly, P.D., Lawing, A.M., Eronen, J.T., Ackerly, D.D., Alex, K., Biber, E., Blois, J., Brashares, J., Ceballos, G., Davis, E., Dietl, G.P., Dirzo, R., Doremus, H., Fortelius, M., Greene, H.W., Hellmann, J., Hickler, T., Jackson, S.T., Kemp, M., Koch, P.L., Kremen, C., Lindsey, E.L., Looy, C., Marshall, C.R., Mendenhall, C., Mulch, A., Mychajliw, A.M., Nowak, C., Ramakrishnan, U., Schnitzler, J., Das Shrestha, K., Solari, K., Stegner, L., Stegner, M.A., Stenseth, N.C., Wake, M.H. and Zhang, Z., 2017. Merging paleobiology with conservation biology to guide the future of terrestrial ecosystems. Science, 355(6325).
Barragán, J.M. and de Andrés, M., 2015. Analysis and trends of the world's coastal cities and agglomerations. Ocean & Coastal Management, 114: 11-20.
Bawaka Country, Wright, S., Suchet-Pearson, S., Lloyd, K., Burarrwanga, L., Ganambarr, R., Ganambarr-Stubbs, M., Ganambarr, B., Maymuru, D. and Sweeney, J., 2015. Co-becoming Bawaka. Progress in Human Geography, 40(4): 455-475.
Bayleyegn, D., Ericksen, P. and Solomon, D., 2018. Climate Resilient Green Economy Strategy.
Beck, S. and Mahony, M., 2018. The IPCC and the new map of science and politics. Wiley Interdisciplinary Reviews: Climate Change, 9(6): e547.
Begum, R.A., Sarkar, M.S.K., Jaafar, A.H. and and Pereira, J.J., 2014. Toward Conceptual Framework for Linking Disaster Risk Reduction and Climate Change Adaptation. International Journal of Disaster Risk Reduction, 10: 362-373.
Béné, C., Evans, L., Mills, D., Ovie, S., Raji, A., Tafida, A., Kodio, A., Sinaba, F., Morand, P. and Lemoalle, J., 2011. Testing resilience thinking in a poverty context: experience from the Niger River basin. Global Environmental Change, 21(4): 1173-1184.
Benjaminsen, T.A., H. Svarstad and I. Shaw of Tordarroch, 2021. Recognising recognition in climate justice Ids Bulletin-Institute of Development Studies, 52.
Benton, M.J., 2018. Hyperthermal-driven mass extinctions: killing models during the Permian–Triassic mass extinction. Philosophical Transactions of the Royal Society A, 376(2130): 20170076.
Benzie, M., Adams, K.M., Roberts, E., Magnan, A.K., Persson, A., Nadin, R., Klein, J.T., Harris, K., Trever, S. and and Kirbyshire, A., 2018. Meeting the global challenge of adaptation by addressing transboundary climate risk.
Benzie, M. and Persson, Å., 2019. Governing borderless climate risks: moving beyond the territorial framing of adaptation. International Environmental Agreements: Politics, Law and Economics, 19(4-5): 369-393.
Bergstrand, K., Mayer, B., Brumback, B. and Zhang, Y., 2015. Assessing the Relationship Between Social Vulnerability and Community Resilience to Hazards. Social Indicators Research, 122(2): 391-409.
Berrang-Ford, L., 2020. Mapping evidence of human adaptation to climate change. Nature Climate Change.
Berrang-Ford, L., Biesbroek, R., Ford, J.D., Lesnikowski, A., Tanabe, A., Wang, F.M., Chen, C., Hsu, A., Hellmann, J.J. and Pringle, P., 2019. Tracking global climate change adaptation among governments. Nature Climate Change, 9(6): 440.
Berrang-Ford, L., Ford, J.D. and Paterson, J., 2011. Are we adapting to climate change? Global environmental change, 21(1): 25-33.
Berrang-Ford, L., Pearce, T. and Ford, J.D., 2015. Systematic review approaches for climate change adaptation research. Regional Environmental Change, 15(5): 755-769.
Berry, H.L., Bowen, K. and Kjellstrom, T., 2010. Climate change and mental health: a causal pathways framework. International Journal of Public Health, 55(2): 123-132.
Betti, L., Beyer, R.M., Jones, E.R., Eriksson, A., Tassi, F., Siska, V., Leonardi, M., Maisano Delser, P., Bentley, L.K., Nigst, P.R., Stock, J.T., Pinhasi, R. and Manica, A., 2020. Climate shaped how Neolithic farmers and European hunter-gatherers interacted after a major slowdown from 6,100 bce to 4,500 bce. Nature Human Behaviour, 4(10): 1004-1010.
Bezner Kerr, R., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L., Msachi, R., Boateng, G.O., Snapp, S.S., Chitaya, A., Maona, E., Gondwe, T., Nkhonjera, P. and Luginaah, I., 2019. Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. Agriculture, Ecosystems & Environment, 279: 109-121.
Biesbroek, G.R., Klostermann, J.E.M., Termeer, C.J.A.M. and Kabat, P., 2013. On the nature of barriers to climate change adaptation. Regional Environmental Change, 13(5): 1119-1129.
Biesbroek, R., Berrang-Ford, L., Ford, J.D., Tanabe, A., Austin, S.E. and Lesnikowski, A., 2018. Data, concepts and methods for large- n comparative climate change adaptation policy research: A systematic literature review. WIREs Climate Change, 9(6).
Biesbroek, R. and Delaney, A., 2020. Mapping the evidence of climate change adaptation policy instruments in Europe. Environmental Research Letters, 15(8): 083005.

Bindoff, N.L. and et al., 2014. Detection and Attribution of Climate Change: from Global to Regional. In: C. Intergovernmental Panel on Climate (Editor), Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 867-952.
Bizikova, L., Parry, J.-E., Karami, J. and Echeverria, D., 2015. Review of key initiatives and approaches to adaptation planning at the national level in semi-arid areas. Regional Environmental Change, 15(5): 837-850.
Boé, J., Terray, L., Moine, M.-P., Valcke, S., Bellucci, A., Drijfhout, S., Haarsma, R., Lohmann, K., Putrasahan, D.A., Roberts, C., Roberts, M., Scoccimarro, E., Seddon, J., Senan, R. and Wyser, K., 2020. Past long-term summer warming over western Europe in new generation climate models: role of large-scale atmospheric circulation. Environmental Research Letters, 15(8): 084038.
Boeckmann, M. and Zeeb, H., 2016. Justice and Equity Implications of Climate Change Adaptation: A Theoretical Evaluation Framework. Healthcare (Basel, Switzerland), 4(3): 65.
Bond, D.P.G. and Grasby, S.E., 2017. On the causes of mass extinctions. Palaeogeography, Palaeoclimatology, Palaeoecology, 478: 3-29.
Boonstra, W.J., 2016. Conceptualizing power to study social-ecological interactions. Ecology and Society, 21(1).
Booth, B.B.B., Harris, G.R., Murphy, J.M., House, J.I., Jones, C.D., Sexton, D. and Sitch, S., 2017. Narrowing the Range of Future Climate Projections Using Historical Observations of Atmospheric CO2. Journal of Climate, 30(8): 3039-3053.
Boyd, E., James, R.A., Jones, R.G., Young, H.R. and Otto, F.E.L., 2017. A typology of loss and damage perspectives. Nature Climate Change, 7(10): 723-+.
Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R. and van der Sluijs, J., 2019. Toward a multi-faceted conception of co-production of climate services. Climate Services, 13: 42-50.
Brovkin, V., Brook, E., Williams, J.W., Bathiany, S., Lenton, T.M., Barton, M., DeConto, R.M., Donges, J.F., Ganopolski, A., McManus, J., Praetorius, S., de Vernal, A., Abe-Ouchi, A., Cheng, H., Claussen, M., Crucifix, M., Gallopín, G., Iglesias, V., Kaufman, D.S., Kleinen, T., Lambert, F., van der Leeuw, S., Liddy, H., Loutre, M.-F., McGee, D., Rehfeld, K., Rhodes, R., Seddon, A.W.R., Trauth, M.H., Vanderveken, L. and Yu, Z., 2021. Past abrupt changes, tipping points and cascading impacts in the Earth system. Nature Geoscience, 14(8): 550-558.
Brown, K., 2014. Global environmental change I: A social turn for resilience? Progress in human geography, 38(1): 107-117.
Brysse, K., Oreskes, N., O'Reilly, J. and Oppenheimer, M., 2013. Climate change prediction: Erring on the side of least drama? Global Environmental Change, 23(1): 327-337.
Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzig, F., Heussner, K.-U., Wanner, H., Luterbacher, J. and Esper, J., 2011. 2500 Years of European Climate Variability and Human Susceptibility. Science, 331(6017): 578-582.
Burke, A., Peros, M.C., Wren, C.D., Pausata, F.S.R., Riel-Salvatore, J., Moine, O., de Vernal, A., Kageyama, M. and Boisard, S., 2021. The archaeology of climate change: The case for cultural diversity. Proceedings of the National Academy of Sciences, 118(30): e2108537118.
Burkett, V.R., Suarez, A.G., Bindi, M., Conde, C., Mukerji, R., Prather, M.J., Clair, A.L.S. and Yohe, G.W., 2014. Point of departure. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169-194.
Burton, I., Dube, O.P., Campbell-Lendrum, D., Davis, I., Klein, R.J.T., Linnerooth-Bayer, J., Sanghi, A. and Toth, F., 2012. Managing the Risks: International Level and Integration across Scales. In: C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (Editors), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 393-435.
Butler, E.E., Mueller, N.D. and Huybers, P., 2018. Peculiarly pleasant weather for US maize. Proceedings of the National Academy of Sciences, 115(47): 11935-11940.
Byskov, M.F., Hyams, K., Satyal, P., Anguelovski, I., Benjamin, L., Blackburn, S., Borie, M., Caney, S., Chu, E., Edwards, G., Fourie, K., Fraser, A., Heyward, C., Jeans, H., McQuistan, C., Paavola, J., Page, E., Pelling, M., Priest, S., Swiderska, K., Tarazona, M., Thornton, T., Twigg, J. and Venn, A., 2021. An agenda for ethics and justice in adaptation to climate change. Climate and Development, 13(1): 1-9.
Callaghan, M., Schleussner, C.-F., Nath, S., Lejeune, Q., Knutson, T.R., Reichstein, M., Hansen, G., Theokritoff, E., Andrijevic, M. and Brecha, R.J., 2021. Machine learning-based evidence and attribution mapping of 100,000 climate impact studies. Nature Climate Change.
Calliari, E., Staccione, A. and Mysiak, J., 2019. An assessment framework for climate-proof nature-based solutions. Science of the Total Environment, 656: 691-700.

Calosi, P., Putnam, H.M., Twitchett, R.J. and Vermandele, F., 2019. Marine metazoan modern mass extinction: Improving predictions by integrating fossil, modern, and physiological data. Annual Review of Marine Science, 11: 369-390.
Campbell, B.M.S. and Ludlow, F., 2020. Climate, disease and society in late-medieval Ireland. Proceedings of the Royal Irish Academy: Archaeology, Culture, History, Literature, 120C: 159-252.
Caney, S., 2014. Two kinds of climate justice: avoiding harm and sharing burdens. Journal of Political Philosophy, 22(2): 125-149.
Cantin, N.E., Cohen, A.L., Karnauskas, K.B., Tarrant, A.M. and McCorkle, D.C., 2010. Ocean warming slows coral growth in the central Red Sea. Science, 329(5989): 322-325.
Capela Lourenço, T., Cruz, M.J., Dzebo, A., Carlsen, H., Dunn, M., Juhász-Horváth, L. and Pinter, L., 2019. Are European decision-makers preparing for high-end climate change? Regional Environmental Change, 19(3): 629-642.
Cardona, O.D., van Aalst, M.K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F. and Sinh, B.T., 2012. Determinants of Risk: Exposure and Vulnerability. In: C.B. Field, V.R. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (Editors), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 65-108.
Carolin, S.A., Walker, R.T., Day, C.C., Ersek, V., Sloan, R.A., Dee, M.W., Talebian, M. and Henderson, G.M., 2019. Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change. Proceedings of the National Academy of Sciences, 116(1): 67-72.
Carotenuto, F., Di Febbraro, M., Melchionna, M., Mondanaro, A., Castiglione, S., Serio, C., Rook, L., Loy, A., Lima-Ribeiro, M.S., Diniz-Filho, J.A.F. and Raia, P., 2018. The well-behaved killer: Late Pleistocene humans in Eurasia were significantly associated with living megafauna only. Palaeogeography, Palaeoclimatology, Palaeoecology, 500: 24-32.
Carr, E.R., 2019. Properties and projects: Reconciling resilience and transformation for adaptation and development. World Development, 122: 70-84.
Carr, E.R. and Thompson, M.C., 2014. Gender and climate change adaptation in agrarian settings: Current thinking, new directions, and research frontiers. Geography Compass, 8(3): 182-197.
Cavanagh, C.J. and Benjaminsen, T.A., 2017. Political ecology, variegated green economies, and the foreclosure of alternative sustainabilities. Journal of Political Ecology, 24: 200-216.
CBD, 2011. Strategic plan for biodiversity 2011–2020, including Aichi Biodiversity Targets. The Convention on Biological Diversity Nagoya, Japan.
Chambwera, M., Heal, G., Dubeux, C., Hallegatte, S., Leclerc, L., Markandya, A., McCarl, B.A., Mechler, R. and Neumann, J.E., 2014. Economics of adaptation. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977.
Chase-Dunn, C. and Almeida, P., 2020. Global Struggles and Social Change: From Prehistory to World Revolution in the Twenty-First Century. Johns Hopkins University Press.
Chatterton, P., Featherstone, D. and Routledge, P., 2013. Articulating climate justice in Copenhagen: Antagonism, the commons, and solidarity. Antipode, 45(3): 602-620.
Chen, C., Doherty, M., Coffee, J., Wong, T. and Hellmann, J., 2016. Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. Environmental Science & Policy, 66: 403-419.
Chiotis, E., 2018. Climate Changes in the Holocene: Impacts and Human Adaptation. CRC Press.
Chollet, A. and Felli, R., 2015. Le catastrophisme écologique contre la démocratie. VertigO(Volume 15 Numéro 2).
Chu, E. and Michael, K., 2018. Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. Environment and Urbanization, 31(1): 139-156.
Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., De Fries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S. and and Thornton, P., 2013. Carbon and Other Biogeochemical Cycle. In: D.Q. T.F. Stocker, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Editors) (Editor), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, pp. 465-570.
City of Santa Monica, 2018. The Well Being Project. In: https://wellbeing.smgov.net/about/project-resources (Editor).
Ciullo, A., Kwakkel, J.H., De Bruijn, K.M., Doorn, N. and Klijn, F., 2020. Efficient or Fair? Operationalizing Ethical Principles in Flood Risk Management: A Case Study on the Dutch-German Rhine. Risk Analysis.
Clapham, M.E. and Renne, P.R., 2019. Flood basalts and mass extinctions. Annual Review of Earth and Planetary Sciences, 47(1): 275-303.
Clark, G.A., Michael Barton, C. and Straus, L.G., 2019. Landscapes, climate change & forager mobility in the Upper Paleolithic of northern Spain. Quaternary International, 515: 176-187.

Clarke, L., L. Nichols, R. Vallario, M. Hejazi, J. Horing, A.C. Janetos, K. Mach, M. Mastrandrea, M. Orr, B.L. Preston, P. Reed, R.D. Sands and White, a.D.D., 2018. Sector Interactions, Multiple Stressors, and Complex Systems.

In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II, U.S. Global Change Research Program, Washington, DC, USA.

Climate & Development Knowledge Network, 2017. Annual Report.

Climate Change Cultural Heritage Working Group International, 2019. The Future of Our Pasts: Engaging cultural heritage in climate action Outline of Climate Change and Cultural Heritage. Technical Report, ICOMOS Paris, 62 pp.

Coates, K., 2004. A global history of indigenous peoples. Springer.

Coggins, S., Berrang-Ford, L., Hyams, K., Satyal, P., Ford, J., Paavola, J., Arotoma-Rojas, I. and Harper, S., 2021. Empirical assessment of equity and justice in climate adaptation literature: a systematic map. Environmental Research Letters, 16(7): 073003.

Cohen, J.M., Lajeunesse, M.J. and Rohr, J.R., 2018. A global synthesis of animal phenological responses to climate change. Nature Climate Change, 8(3): 224-228.

Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S., 2016. Nature-based solutions to address global societal challenges. IUCN: Gland, Switzerland, 97.

Conant, R.T., Cerri, C.E., Osborne, B.B. and Paustian, K., 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecological Applications, 27(2): 662-668.

Connelly, A., Carter, J., Handley, J. and Hincks, S., 2018. Enhancing the Practical Utility of Risk Assessments in Climate Change Adaptation. Sustainability, 10(5): 1399.

Conway, D. and Mustelin, J., 2014. Strategies for improving adaptation practice in developing countries. Nature Climate Change, 4(5): 339-342.

Cook, G.D., Jackson, S. and Williams, R.J., 2012. A revolution in northern Australian fire management: recognition of Indigenous knowledge, practice and management. Flammable Australia. Collingwood: CSIRO Publishing: 293-305.

Cookson, E., Hill, D.J. and Lawrence, D., 2019. Impacts of long term climate change during the collapse of the Akkadian Empire. Journal of Archaeological Science, 106: 1-9.

Coronese, M., Lamperti, F., Keller, K., Chiaromonte, F. and Roventini, A., 2019. Evidence for sharp increase in the economic damages of extreme natural disasters. Proceedings of the National Academy of Sciences, 116(43): 21450-21455.

Cote, M. and Nightingale, A.J., 2012. Resilience thinking meets social theory: situating social change in socio-ecological systems (SES) research. Progress in Human Geography, 36(4): 475-489.

Cousins, J.J., 2021. Justice in nature-based solutions: Research and pathways. Ecological Economics, 180: 106874.

Cramer, W., Yohe, G.W., Auffhammer, M., Huggel, C., Molau, U., Dias, M.A.F.S., Solow, A., Stone, D.A. and Tibig, L., 2014. Detection and attribution of observed impacts. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 979-1037.

Crichton, R. and Esteban, M., 2017. Limits to Coastal Adaptation in Samoa: Insights and Experiences, Climate Change Management. Springer International Publishing, pp. 283-300.

D'Alisa, G., Demaria, F. and Kallis, G., 2014. Degrowth: a vocabulary for a new era. Routledge.

d'Alpoim Guedes, J. and Bocinsky, R.K., 2018. Climate change stimulated agricultural innovation and exchange across Asia. Science Advances, 4(10): eaar4491.

D'Andrea, W.J., Huang, Y., Fritz, S.C. and Anderson, N.J., 2011. Abrupt Holocene climate change as an important factor for human migration in West Greenland. Proceedings of the National Academy of Sciences, 108(24): 9765-9769.

Dasgupta, P., Edenhofer, O., Amezquita, A.M.A., Bento, A., Caney, S., Croix, D.D.l., Fosu, A., Jakob, M., Saam, M., Shrader-Frechette, K., Weyant, J., You, L., Delgado-Ramos, G.C., Dorsch, M.J., Flachsland, C., Klenert, D., Lempert, R., Leroux, J., Lessmann, K., Liu, J., Mattauch, L., Perrings, C., Schwerhoff, G., Seyboth, K., Steckel, J., Strefler, J.a. and Seyboth, K., 2018. Economic Growth, Human Development, and Welfare., In IPSP (Ed.), Rethinking Society for the 21st Century: Report of the International Panel on Social Progress (pp. 141-186). Cambridge: Cambridge University Press.

David-Chavez, D.M. and Gavin, M.C., 2018. A global assessment of Indigenous community engagement in climate research. Environmental Research Letters, 13(12): 123005.

Dawson, R., 2015. Handling interdependencies in climate change risk assessment. Climate, 3(4): 1079-1096.

De Mello, L. and Dutz, M.A., 2012. Promoting inclusive growth: Challenges and policies. Paris: OECD and the World Bank.

Degorska, B. and Degorski, M., 2018. Influence of Climate Change on Environmental Hazards and Human Well-Being in the Urban Areas-Warsaw Case Study Versus General Problems. Climate Change, Extreme Events and Disaster Risk Reduction: Towards Sustainable Development Goals: 43-57.

Demortain, D., 2019. Une société (de l'analyse) du risque ? Natures Sciences Sociétés, 27(4): 390-398.

Deshpande, T., Michael, K. and Bhaskara, K., 2018. Barriers and enablers of local adaptive measures: a case study of Bengaluru's informal settlement dwellers. Local Environment, 24(3): 167-179.
Desrochers, P. and Szurmak., a.J., 2020. Seven Billion Solutions Strong: Why Markets, Growth, and Innovation Are the Antidote to Eco-Pessimism. Breakthrough Journal, 12.
Di Virgilio, G., Evans, J.P., Blake, S.A., Armstrong, M., Dowdy, A.J., Sharples, J. and McRae, R., 2019. Climate change increases the potential for extreme wildfires. Geophysical Research Letters.
Diffenbaugh, N.S. and Burke, M., 2019. Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences, 116(20): 9808-9813.
Dilling, L., Prakash, A., Zommers, Z., Ahmad, F., Singh, N., de Wit, S., Nalau, J., Daly, M. and Bowman, K., 2019. Is adaptation success a flawed concept? Nature Climate Change, 9(8): 572-574.
Donner, S.D., Kandlikar, M. and Webber, S., 2016. Measuring and tracking the flow of climate change adaptation aid to the developing world. Environmental Research Letters, 11(5): 054006.
Doppelt, B., 2017. Transformational Resilience. Routledge.
Douthwaite, R., 2012. Degrowth and the supply of money in an energy-scarce world. Ecological Economics, 84: 187-193.
Dow, K., Berkhout, F., Preston, B.L., Klein, R.J.T., Midgley, G. and Shaw, M.R., 2013. Limits to adaptation. Nature Climate Change, 3: 305.
Dryzek, J., Norgaard, R. and Schlosberg, D., 2013. Climate Challenged Society. Oxford University Press, Oxford.
Dupuis, J. and Biesbroek, R., 2013. Comparing apples and oranges: The dependent variable problem in comparing and evaluating climate change adaptation policies. Global Environmental Change, 23(6): 1476-1487.
Dzebo, A. and Stripple, J., 2015. Transnational adaptation governance: An emerging fourth era of adaptation. Global Environmental Change, 35: 423-435.
Easterling, D.R., Kunkel, K.E., Wehner, M.F. and Sun, L., 2016. Detection and attribution of climate extremes in the observed record. Weather and Climate Extremes, 11: 17-27.
Eisenack, K., Moser, S.C., Hoffmann, E., Klein, R.J.T., Oberlack, C., Pechan, A., Rotter, M. and Termeer, C.J.A.M., 2014. Explaining and overcoming barriers to climate change adaptation. Nature Climate Change, 4(10): 867-872.
Elliott, J., 2005. Using narrative in social research: Qualitative and quantitative approaches. Sage Publications.
England, M.I., Dougill, A.J., Stringer, L.C., Vincent, K.E., Pardoe, J., Kalaba, F.K., Mkwambisi, D.D., Namaganda, E. and Afionis, S., 2018. Climate change adaptation and cross-sectoral policy coherence in southern Africa. Regional environmental change, 18(7): 2059-2071.
Eriksen, S., Schipper, E.L.F., Scoville-Simonds, M., Vincent, K., Adam, H.N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C. and West, J.J., 2021. Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? World Development, 141: 105383.
Eriksen, S.H., Nightingale, A.J. and Eakin, H., 2015. Reframing adaptation: The political nature of climate change adaptation. Global Environmental Change, 35: 523-533.
European Commission, 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions–The European Green Deal. Document 52019DC0640, 640.
Fagan, M.a.H., C., 2019. A look at how people around the world view climate change, Pew Research Center.
Faivre, N., Fritz, M., Freitas, T., de Boissezon, B. and Vandewoestijne, S., 2017. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environmental research, 159: 509-518.
Fankhauser, S., 2017. Adaptation to climate change. Annual Review of Resource Economics, 9: 209-230.
Fankhauser, S. and Dietz, S., 2014. Non-economic losses in the context of the UNFCCC work programme on loss and damage.
Fanning, A.L. and O'Neill, D.W., 2019. The Wellbeing-Consumption paradox: Happiness, health, income, and carbon emissions in growing versus non-growing economies. Journal of Cleaner Production, 212: 810-821.
Fazey, I., Schäpke, N., Caniglia, G., Hodgson, A., Kendrick, I., Lyon, C., Page, G., Patterson, J., Riedy, C., Strasser, T., Verveen, S., Adams, D., Goldstein, B., Klaes, M., Leicester, G., Linyard, A., McCurdy, A., Ryan, P., Sharpe, B., Silvestri, G., Abdurrahim, A.Y., Abson, D., Adetunji, O.S., Aldunce, P., Alvarez-Pereira, C., Amparo, J.M., Amundsen, H., Anderson, L., Andersson, L., Asquith, M., Augenstein, K., Barrie, J., Bent, D., Bentz, J., Bergsten, A., Berzonsky, C., Bina, O., Blackstock, K., Boehnert, J., Bradbury, H., Brand, C., Böhme, J., Bøjer, M.M., Carmen, E., Charli-Joseph, L., Choudhury, S., Chunhachoti-ananta, S., Cockburn, J., Colvin, J., Connon, I.L.C., Cornforth, R., Cox, R.S., Cradock-Henry, N., Cramer, L., Cremaschi, A., Dannevig, H., Day, C.T., de Lima Hutchison, C., de Vrieze, A., Desai, V., Dolley, J., Duckett, D., Durrant, R.A., Egermann, M., Elsner, E., Fremantle, C., Fullwood-Thomas, J., Galafassi, D., Gobby, J., Golland, A., González-Padrón, S.K., Gram-Hanssen, I., Grandin, J., Grenni, S., Lauren Gunnell, J., Gusmao, F., Hamann, M., Harding, B., Harper, G., Hesselgren, M., Hestad, D., Heykoop, C.A., Holmén, J., Holstead, K., Hoolohan, C., Horcea-Milcu, A.-I., Horlings, L.G., Howden, S.M., Howell, R.A., Huque, S.I., Inturias Canedo, M.L., Iro, C.Y., Ives, C.D., John, B., Joshi, R., Juarez-Bourke, S., Juma, D.W., Karlsen, B.C., Kliem, L., Kläy, A., Kuenkel, P., Kunze, I., Lam, D.P.M., Lang, D.J., Larkin, A., Light, A., Luederitz, C., Luthe, T., Maguire, C., Mahecha-Groot, A.-M., Malcolm, J., Marshall, F., Maru, Y., McLachlan, C., Mmbando, P., Mohapatra, S., Moore, M.-L., Moriggi, A., Morley-

Fletcher, M., Moser, S., Mueller, K.M., Mukute, M., Mühlemeier, S., Naess, L.O., Nieto-Romero, M., Novo, P., O'Brien, K., O'Connell, D.A., O'Donnell, K., Olsson, P., Pearson, K.R., Pereira, L., Petridis, P., Peukert, D., Phear, N., Pisters, S.R., Polsky, M., Pound, D., Preiser, R., Rahman, M.S., Reed, M.S., Revell, P., Rodriguez, I., Rogers, B.C., Rohr, J., Nordbø Rosenberg, M., Ross, H., Russell, S., Ryan, M., Saha, P., Schleicher, K., Schneider, F., Scoville-Simonds, M., Searle, B., Sebhatu, S.P., Sesana, E., Silverman, H., Singh, C., Sterling, E., Stewart, S.-J., Tàbara, J.D., Taylor, D., Thornton, P., Tribaldos, T.M., Tschakert, P., Uribe-Calvo, N., Waddell, S., Waddock, S., van der Merwe, L., van Mierlo, B., van Zwanenberg, P., Velarde, S.J., Washbourne, C.-L., Waylen, K., Weiser, A., Wight, I., Williams, S., Woods, M., Wolstenholme, R., Wright, N., Wunder, S., Wyllie, A. and Young, H.R., 2020. Transforming knowledge systems for life on Earth: Visions of future systems and how to get there. Energy Research & Social Science, 70: 101724.
Fazey, I., Wise, R.M., Lyon, C., Câmpeanu, C., Moug, P. and Davies, T.E., 2016. Past and future adaptation pathways. Climate and Development, 8(1): 26-44.
Feola, G., 2015. Societal transformation in response to global environmental change: A review of emerging concepts. Ambio, 44(5): 376-390.
Fernández-Llamazares, Á., Garcia, R.A., Díaz-Reviriego, I., Cabeza, M., Pyhälä, A. and Reyes-García, V., 2017. An empirically tested overlap between indigenous and scientific knowledge of a changing climate in Bolivian Amazonia. Regional Environmental Change, 17(6): 1673-1685.
Few, R., Morchain, D., Spear, D., Mensah, A. and Bendapudi, R., 2017. Transformation, adaptation and development: relating concepts to practice. Palgrave Communications, 3(1): 17092.
Fisher, S., 2015. The emerging geographies of climate justice. The Geographical Journal, 181(1): 73-82.
Fisichelli, N.A., Schuurman, G.W. and Hoffman, C.H., 2016. Is 'Resilience' Maladaptive? Towards an Accurate Lexicon for Climate Change Adaptation. Environmental Management, 57(4): 753-758.
Fleurbaey, M., Kartha, S., Bolwig, S., Chee, Y.L., Chen, Y., Corbera, E., Lecocq, F., Lutz, W., Muylaert, M.S. and Norgaard, R.B., 2014. Sustainable development and equity.
Flood, S. and Schechtman, J., 2014. The rise of resilience: Evolution of a new concept in coastal planning in Ireland and the US. Ocean & Coastal Management, 102: 19-31.
Flynn, C., Yamasumi, E., Fisher, S., Snow, D., Grant, Z., Kirby, M., Browning, P., Rommerskirchen, M. and and Russell, I., 2021. The Peoples' Climate Vote, UNDP and University of Oxford.
Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Global environmental change, 16(3): 253-267.
Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T. and Rockström, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecology and society, 15(4).
Ford, J.D., Berrang-Ford, L., Biesbroek, R., Araos, M., Austin, S.E. and Lesnikowski, A., 2015. Adaptation tracking for a post-2015 climate agreement. Nature Climate Change, 5(11): 967-969.
Ford, J.D., Cameron, L., Rubis, J., Maillet, M., Nakashima, D., Willox, A.C. and Pearce, T., 2016. Including indigenous knowledge and experience in IPCC assessment reports. Nature Climate Change, 6(4): 349.
Ford, J.D., Pearce, T., McDowell, G., Berrang-Ford, L., Sayles, J.S. and Belfer, E., 2018. Vulnerability and its discontents: the past, present, and future of climate change vulnerability research. Climatic Change, 151(2): 189-203.
Fordham, D.A., Jackson, S.T., Brown, S.C., Huntley, B., Brook, B.W., Dahl-Jensen, D., Gilbert, M.T.P., Otto-Bliesner, B.L., Svensson, A., Theodoridis, S., Wilmshurst, J.M., Buettel, J.C., Canteri, E., McDowell, M., Orlando, L., Pilowsky, J., Rahbek, C. and Nogues-Bravo, D., 2020. Using paleo-archives to safeguard biodiversity under climate change. Science, 369(6507): eabc5654.
Forsyth, T., 2018. Is resilience to climate change socially inclusive? Investigating theories of change processes in Myanmar. World Development, 111: 13-26.
Foster, G.L., Hull, P., Lunt, D.J. and Zachos, J.C., 2018. Placing our current 'hyperthermal' in the context of rapid climate change in our geological past. Philosophical Transactions of the Royal Society A, 376(2130): 20170086.
Frame, D.J., Wehner, M.F., Noy, I. and Rosier, S.M., 2020. The economic costs of Hurricane Harvey attributable to climate change. Climatic Change, 160(2): 271-281.
Frank, T.D., Fielding, C.R., Winguth, A.M.E., Savatic, K., Tevyaw, A., Winguth, C., McLoughlin, S., Vajda, V., Mays, C., Nicoll, R., Bocking, M. and Crowley, J.L., 2021. Pace, magnitude, and nature of terrestrial climate change through the end-Permian extinction in southeastern Gondwana. Geology, $.
Fraser, D. and Lyons, S.K., 2020. Mammal Community Structure through the Paleocene-Eocene Thermal Maximum. The American Naturalist, 196(3): 271-290.
Fraser, N., 1999. Social Justice in the Age of Identity Politics: Redistribution, Recognition, and Participation. Culture and Economy After the Cultural Turn: 25.
French, S., 2013. Cynefin, statistics and decision analysis. Journal of the Operational Research Society, 64(4): 547-561.
Friend, R., Jarvie, J., Reed, S.O., Sutarto, R., Thinphanga, P. and Toan, V.C., 2014. Mainstreaming urban climate resilience into policy and planning; reflections from Asia. Urban Climate, 7: 6-19.
Gagnon-Lebrun, F. and Agrawala, S., 2007. Implementing adaptation in developed countries: an analysis of progress and trends. Climate Policy, 7(5): 392-408.
Gao, Q., 2018. Mainstreaming climate change into the EIA procedures: a perspective from China. International Journal of Climate Change Strategies and Management, 10(3): 342-358.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research policy, 33(6-7): 897-920.
GEF, 2014. Tracking tool for climate change adaptation projects. In: GEF (Editor).
Gelcich, S., Hughes, T.P., Olsson, P., Folke, C., Defeo, O., Fernández, M., Foale, S., Gunderson, L.H., Rodríguez-Sickert, C. and Scheffer, M., 2010. Navigating transformations in governance of Chilean marine coastal resources. Proceedings of the National Academy of Sciences, 107(39): 16794-16799.
Gerten, C., Fina, S. and Rusche, K., 2019. The sprawling planet: Simplifying the measurement of global urbanization trends. Frontiers in Environmental Science, 7: 140.
Gharbaoui, D. and Blocher, J., 2017. Limits to Adapting to Climate Change Through Relocations in Papua-New Guinea and Fiji, Climate Change Management. Springer International Publishing, pp. 359-379.
Gibbs, S.J., Bown, P.R., Ridgwell, A., Young, J.R., Poulton, A.J. and O'Dea, S.A., 2016. Ocean warming, not acidification, controlled coccolithophore response during past greenhouse climate change. Geology, 44(1): 59-62.
Gillard, R., Gouldson, A., Paavola, J. and Van Alstine, J., 2016. Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. Wiley Interdisciplinary Reviews: Climate Change, 7(2): 251-265.
Gillett, N.P., Kirchmeier-Young, M., Ribes, A., Shiogama, H., Hegerl, G.C., Knutti, R., Gastineau, G., John, J.G., Li, L., Nazarenko, L., Rosenbloom, N., Seland, Ø., Wu, T., Yukimoto, S. and Ziehn, T., 2021. Constraining human contributions to observed warming since the pre-industrial period. Nature Climate Change, 11(3): 207-212.
Giosan, L., Orsi, W.D., Coolen, M., Wuchter, C., Dunlea, A.G., Thirumalai, K., Munoz, S.E., Clift, P.D., Donnelly, J.P., Galy, V. and Fuller, D.Q., 2018. Neoglacial climate anomalies and the Harappan metamorphosis. Clim. Past, 14(11): 1669-1686.
Global Commission on Adaptation, 2019. Adapt Now: A global call for leadership on climate resilience, Global Commission on Adaptation.
Global Commission on the Economy and Climate, 2018. Unlocking the Inclusive Growth Story of the 21st Century: Accelerating Climate Action in Urgent Times, New Climate Economy, Washington, DC, USA.
Goldman, M.J., Turner, M.D. and Daly, M., 2018. A critical political ecology of human dimensions of climate change: Epistemology, ontology, and ethics. WIREs Climate Change, 9(4).
Gómez-Baggethun, E., 2020. More is more: Scaling political ecology within limits to growth. Political Geography, 76: 102095.
Göpel, M., 2016. The great mindshift: how a new economic paradigm and sustainability transformations go hand in hand. Springer Nature.
Gorddard, R., Colloff, M.J., Wise, R.M., Ware, D. and Dunlop, M., 2016. Values, rules and knowledge: Adaptation as change in the decision context. Environmental Science & Policy, 57: 60-69.
Gough, I., 2015. Climate change and sustainable welfare: the centrality of human needs. Cambridge Journal of Economics, 39(5): 1191-1214.
Grantham Research Institute on Climate Change and the Environment and Sabin Center for Climate Change Law, 2021. Climate Change Laws of the World database.
Green, D., Jackson, S. and Morrison, J., 2009. Risks from climate change to indigenous communities in the tropical north of Australia. Department of Climate Change, Commonwealth of Australia.
Grinsted, A., Ditlevsen, P. and Christensen, J.H., 2019. Normalized US hurricane damage estimates using area of total destruction, 1900−2018. Proceedings of the National Academy of Sciences, 116(48): 23942-23946.
Grose, M.R., Black, M.T., Wang, G., King, A.D., Hope, P. and Karoly, D.J., 2020. The warm and extremely dry spring in 2015 in Tasmania contained the fingerprint of human influence on the climate. Journal of Southern Hemisphere Earth Systems Science, 69(1): 183-195.
Grubb, M., Hourcade, J.-C. and and Neuhoff, K., 2014. Planetary economics: energy, climate change and the three domains of sustainable development. Routledge.
Gulev, S.K., Thorne, P.W., Ahn, J., Dentener, F.J., Domingues, C.M., Gerland, S., Gong, D., Kaufman, D.S., Nnamchi, H.C., Quaas, J., Rivera, J.A., Sathyendranath, S., Smith, S.L., Trewin, B., von Shuckmann, K. and Vose, R.S., 2021. Changing State of the Climate System. In: V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (Editors), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Gutmann, A. and Thompson, D.F., 2009. Why Deliberative Democracy? Princeton University Press.
Haasnoot, M., Biesbroek, R., Lawrence, J., Muccione, V., Lempert, R. and Glavovic, B., 2020. Defining the solution space to accelerate climate change adaptation. Regional Environmental Change, 20(2): 1-5.
Haasnoot, M., Brown, S., Scussolini, P., Jimenez, J.A., Vafeidis, A.T. and Nicholls, R.J., 2019a. Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. Environmental Research Communications, 1(7): 071006.
Haasnoot, M., Lawrence, J. and Magnan, A.K., 2021. Pathways to coastal retreat. Science, 372(6548): 1287-1290.
Haasnoot, M., Warren, A. and Kwakkel, J.H., 2019b. Dynamic adaptive policy pathways (DAPP), Decision Making under Deep Uncertainty. Springer, Cham, pp. 71-92.

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F. and Leon-Gruchalski, B., 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environmental Research Letters, 15(6): 065003.
Hale, T.N., Chan, S., Hsu, A., Clapper, A., Elliott, C., Faria, P., Kuramochi, T., McDaniel, S., Morgado, M., Roelfsema, M., Santaella, M., Singh, N., Tout, I., Weber, C., Weinfurter, A. and Widerberg, O., 2021. Sub- and non-state climate action: a framework to assess progress, implementation and impact. Climate Policy, 21(3): 406-420.
Hall, J.A., Weaver, C.P., Obeysekera, J., Crowell, M., Horton, R.M., Kopp, R.E., Marburger, J., Marcy, D.C., Parris, A. and Sweet, W.V., 2019. Rising sea levels: Helping decision-makers confront the inevitable. Coastal Management, 47(2): 127-150.
Hamborg, S., Meya, J.N., Eisenack, K. and Raabe, T., 2020. Rethinking resilience: A cross-epistemic resilience framework for interdisciplinary energy research. Energy Research & Social Science, 59: 101285.
Hansen, G., Stone, D., Auffhammer, M., Huggel, C. and Cramer, W., 2016. Linking local impacts to changes in climate: a guide to attribution. Regional Environmental Change, 16(2): 527-541.
Hansen, J., Sato, M., Russell, G. and Kharecha, P., 2013. Climate sensitivity, sea level and atmospheric carbon dioxide. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371(2001): 20120294.
Hanssen, S., Daioglou, V., Steinmann, Z., Doelman, J., Van Vuuren, D. and Huijbregts, M., 2020. The climate change mitigation potential of bioenergy with carbon capture and storage. Nature Climate Change: 1-7.
Hassanali, K., 2017. Challenges in mainstreaming climate change into productive coastal sectors in a Small Island State–The case of Trinidad and Tobago. Ocean & coastal management, 142: 136-142.
Hauser, M., Orth, R. and Seneviratne, S.I., 2016. Role of soil moisture versus recent climate change for the 2010 heat wave in western Russia. Geophysical Research Letters, 43(6): 2819-2826.
Hausfather, Z. and Peters, G.P., 2020. Emissions – the 'business as usual' story is misleading. Nature, 577(7792): 618-620.
Haywood, A.M., Valdes, P.J., Aze, T., Barlow, N., Burke, A., Dolan, A.M., von der Heydt, A.S., Hill, D.J., Jamieson, S.S.R., Otto-Bliesner, B.L., Salzmann, U., Saupe, E. and Voss, J., 2019. What can Palaeoclimate Modelling do for you? Earth Systems and Environment, 3(1): 1-18.
Heck, V., Gerten, D., Lucht, W. and Popp, A., 2018. Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nature climate change, 8(2): 151-155.
Hegerl, G.C., Hoegh-Guldberg, O., Casassa, G., Hoerling, M.P., Kovats, R., Parmesan, C., Pierce, D.W. and Stott, P.A., 2010. Good practice guidance paper on detection and attribution related to anthropogenic climate change, Meeting report of the intergovernmental panel on climate change expert meeting on detection and attribution of anthropogenic climate change. IPCC Working Group I Technical Support Unit, University of Bern, Bern ….
Hegmon, M., Peeples, M.A., Kinzig, A.P., Kulow, S., Meegan, C.M. and and Nelson, M.C., 2008. Social Transformation and Its Human Costs in the Prehispanic U.S. Southwest. American Anthropologist, 110(3): 313-324.
Heimhofer, U., Wucherpfennig, N., Adatte, T., Schouten, S., Schneebeli-Hermann, E., Gardin, S., Keller, G., Kentsch, S. and Kujau, A., 2018. Vegetation response to exceptional global warmth during Oceanic Anoxic Event 2. Nature Communications, 9(1): 3832.
Herrero, C., Martínez, R. and Villar, A., 2012. A Newer Human Development Index. Journal of Human Development and Capabilities, 13(2): 247-268.
Herring, S.C., Christidis, N., Hoell, A., Hoerling, M.P. and Stott, P.A., 2021. Explaining Extreme Events of 2019 from a Climate Perspective. Bulletin of the American Meteorological Society, 102(1): S1-S116.
Herrmann, J. and Guenther, E., 2017. Exploring a scale of organizational barriers for enterprises' climate change adaptation strategies. Journal of Cleaner Production, 160: 38-49.
Hickel, J. and Kallis, G., 2020. Is green growth possible? New Political Economy, 25(4): 469-486.
Hill, A.C. and Martinez-Diaz, L., 2019. Building a resilient tomorrow: How to prepare for the coming climate disruption. Oxford University Press, USA.
Hochman, Z., Gobbett, D.L. and Horan, H., 2017. Climate trends account for stalled wheat yields in Australia since 1990. Global Change Biology, 23(5): 2071-2081.
Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bolaños, T.G., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R. and Ebi, K., 2019. The human imperative of stabilizing global climate change at 1.5° C. Science, 365(6459): eaaw6974.
Hoekstra, R. and van den Bergh, J.C.J.M., 2003. Comparing structural decomposition analysis and index. Energy Economics, 25(1): 39-64.
Hollesen, J., Callanan, M., Dawson, T., Fenger-Nielsen, R., Friesen, T.M., Jensen, A.M., Markham, A., Martens, V.V., Pitulko, V.V. and Rockman, M., 2018. Climate change and the deteriorating archaeological and environmental archives of the Arctic. Antiquity, 92(363): 573-586.
Holling, C.S., 1973. Resilience and stability of ecological systems. Annual review of ecology and systematics, 4(1): 1-23.
Holman, I.P., Brown, C., Carter, T.R., Harrison, P.A. and Rounsevell, M., 2019. Improving the representation of adaptation in climate change impact models. Regional Environmental Change, 19(3): 711-721.

Hölscher, K., Wittmayer, J.M. and Loorbach, D., 2018. Transition versus transformation: what's the difference. Environmental innovation and societal transitions, 27: 1-3.
Hong, L. and Page, S.E., 2004. Groups of diverse problem solvers can outperform groups of high-ability problem solvers. Proceedings of the National Academy of Sciences, 101(46): 16385-16389.
Horton, R.M., de Sherbinin, A., Wrathall, D. and Oppenheimer, M., 2021. Assessing human habitability and migration. Science, 372(6548): 1279-1283.
Hourdequin, M., 2016. Justice, recognition and climate change. Climate justice and geoengineering: Ethics and policy in the atmospheric anthropocene: 33-48.
Hügel, S. and Davies, A.R., 2020. Public participation, engagement, and climate change adaptation: A review of the research literature. WIREs Climate Change, 11(4).
Huggel, C., Stone, D., Eicken, H. and Hansen, G., 2015. Potential and limitations of the attribution of climate change impacts for informing loss and damage discussions and policies. Climatic Change, 133(3): 453-467.
Hughes, T.P., Linares, C., Dakos, V., Van De Leemput, I.A. and Van Nes, E.H., 2013. Living dangerously on borrowed time during slow, unrecognized regime shifts. Trends in ecology & evolution, 28(3): 149-155.
Hulvey, K.B., Hobbs, R.J., Standish, R.J., Lindenmayer, D.B., Lach, L. and Perring, M.P., 2013. Benefits of tree mixes in carbon plantings. Nature Climate Change, 3(10): 869-874.
Huurdeman, E.P., Frieling, J., Reichgelt, T., Bijl, P.K., Bohaty, S.M., Holdgate, G.R., Gallagher, S.J., Peterse, F., Greenwood, D.R. and Pross, J., 2021. Rapid expansion of meso-megathermal rain forests into the southern high latitudes at the onset of the Paleocene-Eocene Thermal Maximum. Geology, 49(1): 40-44.
IAC, 2010. Climate change assessments. Review of the Processes and Procedures of the IPCC, Amsterdam, The Netherlands.
Iglesias, V., Whitlock, C., Krause, T.R. and Baker, R.G., 2018. Past vegetation dynamics in the Yellowstone region highlight the vulnerability of mountain systems to climate change. Journal of Biogeography, 45(8): 1768-1780.
Ignatowski, J.A. and Rosales, J., 2013. Identifying the exposure of two subsistence villages in Alaska to climate change using traditional ecological knowledge. Climatic change, 121(2): 285-299.
ILO, 1989. Convention on Indigenous and Tribal Peoples.
ILO, 2013. Understanding the Indigenous and Tribal people Convention, 1989 (No. 169): Handbook for ILO tripartite constituents. International Labour Office.
ILO, 2019. Indigenous and Tribal Peoples
Convention, 1989 (No. 169) Committee of Experts on the Application of Conventions and Recommendations. International Labour Organization, Geneva.
Inoue, T., 2019. Carbon Sequestration in Mangroves. In: T. Kuwae and M. Hori (Editors), Blue Carbon in Shallow Coastal Ecosystems: Carbon Dynamics, Policy, and Implementation. Springer Singapore, Singapore, pp. 73-99.
Inuit Tapiriit Kanatami, 2018. National Inuit Strategy on Research.
IPBES, 2018. The IPBES assessment report on land degradation and restoration, Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
IPBES, 2019a. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany.
IPBES, 2019b. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Secretariat, Bonn, Germany.
IPCC, 2005. Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties". Intergovernmental Panel on Climate Change.
IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). In: C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (Editors), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3-21.
IPCC, 2013. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge, United Kingdom and New York, NY, USA.
IPCC, 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.
IPCC, 2014b. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada,

R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.
IPCC, 2014c. Summary for Policymakers. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 1-32.
IPCC, 2018a. Annex I: Glossary [R. Matthews (ed.)]. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
IPCC, 2018b. Global warming of 1.5 C: An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
IPCC, 2018c. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, In press pp.
IPCC, 2018d. Summary for Policymakers, Global Warming of 1.5°C. In: V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (Editors), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, pp. 32 pp.
IPCC, 2019a. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL).
IPCC, 2019b. Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).
IPCC, 2019c. Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, In press.
IPCC, 2020. The concept of risk in the IPCC Sixth Assessment Report: A summary of cross-Working Group discussions.
IPCC, 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
Isenhour, C., 2016. Unearthing human progress? Ecomodernism and contrasting definitions of technological progress in the Anthropocene. Economic Anthropology, 3(2): 315-328.
Ivany, L.C., Pietsch, C., Handley, J.C., Lockwood, R., Allmon, W.D. and Sessa, J.A., 2018. Little lasting impact of the Paleocene-Eocene Thermal Maximum on shallow marine molluscan faunas. Science Advances, 4(9): eaat5528.
Jackson, R.B., Banner, J.L., Jobbágy, E.G., Pockman, W.T. and Wall, D.H., 2002. Ecosystem carbon loss with woody plant invasion of grasslands. Nature, 418(6898): 623-626.
Jafry, T., Mikulewicz, M. and Helwig, K., 2018. Introduction: Justice in the era of climate change, Routledge Handbook of Climate Justice. Routledge, pp. 1-9.
Jakku, E., Thorburn, P.J., Marshall, N.A., Dowd, A.M., Howden, S.M., Mendham, E., Moon, K. and Brandon, C., 2016. Learning the hard way: a case study of an attempt at agricultural transformation in response to climate change. Climatic Change, 137(3-4): 557-574.
Janif, S.Z., Nunn, P.D., Geraghty, P., Aalbersberg, W., Thomas, F.R. and Camailakeba, M., 2016. Value of traditional oral narratives in building climate-change resilience: insights from rural communities in Fiji. Ecology and Society, 21(2).
Jézéquel, A., Dépoues, V., Guillemot, H., Trolliet, M., Vanderlinden, J.-P. and Yiou, P., 2018. Behind the veil of extreme event attribution. Climatic Change, 149(3): 367-383.
Jonas, H., 1985. The imperative of responsibility: In search of an ethics for the technological age. University of Chicago press.
Jones, C., 2019. Climate Change and Farming Response in a Temperate Oceanic Zone—the Exploitation of a Karstic Region in Western Ireland in the Third and Second Millennia BC. The Journal of Island and Coastal Archaeology: 1-22.
Jones, C., Robertson, E., Arora, V., Friedlingstein, P., Shevliakova, E., Bopp, L., Brovkin, V., Hajima, T., Kato, E., Kawamiya, M., Liddicoat, S., Lindsay, K., Reick, C.H., Roelandt, C., Segschneider, J. and Tjiputra, J., 2013. Twenty-First-Century Compatible CO2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways. Journal of Climate, 26(13): 4398-4413.
Jones, L. and Boyd, E., 2011. Exploring social barriers to adaptation: insights from Western Nepal. Global Environmental Change, 21(4): 1262-1274.

Jones, R.N., Patwardhan, A., Cohen, S.J., Dessai, S., Lammel, A., Lempert, R.J., Mirza, M.M.Q. and von Storch, H., 2014. Foundations for decision making. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 195-228.

Jones, R.N. and Preston, B.L., 2011. Adaptation and risk management. WIREs Climate Change(2).

Jorgenson, A.K., Fiske, S., Hubacek, K., Li, J., McGovern, T., Rick, T., Schor, J.B., Solecki, W., York, R. and Zycherman, A., 2019. Social science perspectives on drivers of and responses to global climate change. WIREs Climate Change, 10(1): e554.

Juan, S., 2011. La transition écologique. Eres.

Juhola, S., 2016. Barriers to the implementation of climate change adaptation in land use planning. International Journal of Climate Change Strategies and Management, 8(3): 338-355.

Jurgilevich, A., Räsänen, A., Groundstroem, F. and Juhola, S., 2017. A systematic review of dynamics in climate risk and vulnerability assessments. Environmental Research Letters, 12(1): 013002.

Kahn, M.E., Mohaddes, K., Ng, R.N., Pesaran, M.H., Raissi, M. and Yang, J.-C., 2019. Long-term macroeconomic effects of climate change: A cross-country analysis, National Bureau of Economic Research.

Kallis, G., 2011. In defence of degrowth. Ecological economics, 70(5): 873-880.

Kallis, G., 2017. Radical dematerialization and degrowth. Philosophical transactions of the royal society a: mathematical, physical and engineering sciences, 375(2095): 20160383.

Kallis, G., Kerschner, C. and Martinez-Alier, J., 2012. The economics of degrowth. Elsevier.

Kanie, N. and Biermann, F., 2017. Governing through goals: Sustainable development goals as governance innovation. mit Press.

Kay, R. and and Adler, J., 2017. Coastal planning and management. CRC Press.

Kemp, D.B., Eichenseer, K. and Kiessling, W., 2015. Maximum rates of climate change are systematically underestimated in the geological record. Nature Communications, 6: 8890.

Kern, F. and Rogge, K.S., 2018. Harnessing theories of the policy process for analysing the politics of sustainability transitions: A critical survey. Environmental innovation and societal transitions, 27: 102-117.

Keskitalo, E. and Preston, B., 2019a. Research Handbook on Climate Change Adaptation Policy. Edward Elgar Publishing.

Keskitalo, E.C.H. and Pettersson, M., 2016. Can adaptation to climate change at all be mainstreamed in complex multi-level governance systems? A case study of forest-relevant policies at the EU and Swedish levels, Implementing climate change adaptation in cities and communities. Springer, pp. 53-74.

Keskitalo, E.C.H. and Preston, B.L., 2019b. Research handbook on climate change adaptation policy. Edward Elgar Publishing.

Kienberger, S., Blaschke, T. and Zaidi, R.Z., 2013. A framework for spatio-temporal scales and concepts from different disciplines: the 'vulnerability cube'. Natural Hazards, 68(3): 1343-1369.

Kiessling, W., Simpson, C., Beck, B., Mewis, H. and Pandolfi, J.M., 2012. Equatorial decline of reef corals during the last Pleistocene interglacial. Proceedings of the National Academy of Sciences of the United States of America, 109(52): 21378-21383.

Kirkby, P., Williams, C. and Huq, S., 2017. Community-based adaptation (CBA): adding conceptual clarity to the approach, and establishing its principles and challenges. Climate and Development, 10(7): 577-589.

Kitcher, P., 2011. Science in a democratic society. Brill Rodopi.

Klauer, B., 1999. Defining and achieving sustainable development. The International Journal of Sustainable Development & World Ecology, 6(2): 114-121.

Klein, J.A., Hopping, K.A., Yeh, E.T., Nyima, Y., Boone, R.B. and Galvin, K.A., 2014a. Unexpected climate impacts on the Tibetan Plateau: local and scientific knowledge in findings of delayed summer. Global Environmental Change, 28: 141-152.

Klein, R.J.T., Midgley, G.F., Preston, B.L., Alam, M., Berkhout, F.G.H., Dow, K. and Shaw, M.R., 2014b. Adaptation opportunities, constraints, and limits. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943.

Klenk, N., Fiume, A., Meehan, K. and Gibbes, C., 2017. Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co-production. WIREs Climate Change, 8(5).

Knapp, A.B. and Manning, S.W., 2016. Crisis in context: The end of the Late Bronze Age in the eastern Mediterranean. American Journal of Archaeology, 120(1): 99-149.

Koch, F., 2018. Mainstreaming adaptation: a content analysis of political agendas in Colombian cities. Climate and Development, 10(2): 179-192.

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A. and Boons, F., 2019. An agenda for sustainability transitions research: State of the art and future directions. Environmental Innovation and Societal Transitions, 31: 1-32.
Kohler, T.A., Ortman, S.G., Grundtisch, K.E., Fitzpatrick, C.M. and Cole, S.M., 2014. The Better Angels of their Nature: Declining Violence through Time Among Prehispanic Farmers of the Pueblo Southwest. American Antiquity, 79(3): 444-464.
Kopp, R.E., K. Hayhoe, D.R. Easterling, T. Hall, R.H., K.E. Kunkel and LeGrande, a.A.N., 2017. Potential surprises – compound extremes and tipping elements. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I, U.S. Global Change Research Program, Washington, DC, USA.
Koren, H.S. and Butler, C.D., 2006. The interconnection between the built environment ecology and health. Environmental Security and Environmental Management: The Role of Risk Assessment, 5: 111-+.
Kröger, B., 2017. Changes in the latitudinal diversity gradient during the Great Ordovician Biodiversification Event. Geology, 46(2): 127-130.
Kuil, L., Carr, G., Prskawetz, A., Salinas, J.L., Viglione, A. and Blöschl, G., 2019. Learning from the Ancient Maya: Exploring the Impact of Drought on Population Dynamics. Ecological Economics, 157: 1-16.
Kuruppu, N., 2009. Adapting water resources to climate change in Kiribati: the importance of cultural values and meanings. Environmental Science & Policy, 12(7): 799-809.
Lacey, J., Howden, S.M., Cvitanovic, C. and Dowd, A.-M., 2015. Informed adaptation: Ethical considerations for adaptation researchers and decision-makers. Global Environmental Change, 32: 200-210.
Lamb, W.F. and Steinberger, J.K., 2017. Human well-being and climate change mitigation. Wiley Interdisciplinary Reviews-Climate Change, 8(6).
Landemore, H., 2013. Deliberation, cognitive diversity, and democratic inclusiveness: an epistemic argument for the random selection of representatives. Synthese, 190(7): 1209-1231.
Latouche, S., 2001. La déraison de la raison économique. Albin Michel, Paris.
Laurila-Pant, M., Lehikoinen, A., Uusitalo, L. and Venesjärvi, R., 2015. How to value biodiversity in environmental management? Ecological indicators, 55: 1-11.
Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., Muir-Wood, R. and Myeong, S., 2012. Climate Change: New Dimensions in Disaster Risk, Exposure, Vulnerability, and Resilience. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. In: C.B. Field, V.R. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (Editors), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 25-64.
Lawrence, D., Palmisano, A. and de Gruchy, M.W., 2021. Collapse and continuity: A multi-proxy reconstruction of settlement organization and population trajectories in the Northern Fertile Crescent during the 4.2kya Rapid Climate Change event. PLOS ONE, 16(1): e0244871.
Le Quéré, C., Korsbakken, J.I., Wilson, C., Tosun, J., Andrew, R., Andres, R.J., Canadell, J.G., Jordan, A., Peters, G.P. and van Vuuren, D.P., 2019. Drivers of declining CO 2 emissions in 18 developed economies. Nature Climate Change, 9(3): 213-217.
Leakey, R.R.B., 2020. A re-boot of tropical agriculture benefits food production, rural economies, health, social justice and the environment. Nature Food, 1(5): 260-265.
Leal Filho, W., Azeiteiro, U., Alves, F., Pace, P., Mifsud, M., Brandli, L., Caeiro, S.S. and Disterheft, A., 2018. Reinvigorating the sustainable development research agenda: the role of the sustainable development goals (SDG). International Journal of Sustainable Development & World Ecology, 25(2): 131-142.
Lee, J.Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., Engelbrecht, F., Fischer, E., Fyfe, J.C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S. and Zhou, T., 2021. Future Global Climate: Scenario-Based Projections and Near-Term Information. In: V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (Editors), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Lee, S.J., Kim, Y. and Phillips, R. (Editors), 2015. Exploring the Intersection of Community Well-Being and Community Development. Community Well-Being and Community Development. Springer, Cham, SpringerBriefs in Well-Being and Quality of Life Research.
Lehmann, P., Brenck, M., Gebhardt, O., Schaller, S. and Süßbauer, E., 2015. Barriers and opportunities for urban adaptation planning: analytical framework and evidence from cities in Latin America and Germany. Mitigation and Adaptation Strategies for Global Change, 20(1): 75-97.
Leifeld, J. and Menichetti, L., 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. Nature communications, 9(1): 1-7.
Leiter, T., 2021. Progress in implementing adaptation: insights from project proposals and scientific literature. In: UNEP (Editor), The Adaptation Gap Report 2020. UNEP, pp. p. 33-40.
Lejeune, Q., Davin, E.L., Gudmundsson, L., Winckler, J. and Seneviratne, S.I., 2018. Historical deforestation locally increased the intensity of hot days in northern mid-latitudes. Nature Climate Change, 8(5): 386-390.

Lempert, R., Arnold, J.G., Pulwarty, R., Gordon, K., Greig, C., Hawkins Hoofman, C., Sands, D. and Werrell, C., 2018. Reducing Risks Through Adaptation Actions. In: D.R. Reidmiller, C.W. Avery, K.E. Easterling, K.L.M. Knkel, T.K. Maycock and B.C. Stewart (Editors), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Vol II. U.S. Global Change Research Program, Washington, DC.
Lempert, R.J. and Turner, S., 2020. Engaging Multiple Worldviews With Quantitative Decision Support: A Robust Decision-Making Demonstration Using the Lake Model. Risk Analysis.
Lesnikowski, A., Belfer, E., Rodman, E., Smith, J., Biesbroek, R., Wilkerson, J.D., Ford, J.D. and Berrang-Ford, L., 2019a. Frontiers in data analytics for adaptation research: Topic modeling. WIREs Climate Change, 10(3).
Lesnikowski, A., Ford, J., Biesbroek, R., Berrang-Ford, L., Maillet, M., Araos, M. and Austin, S.E., 2017. What does the Paris Agreement mean for adaptation? Climate Policy, 17(7): 825-831.
Lesnikowski, A., Ford, J.D., Biesbroek, R. and Berrang-Ford, L., 2019b. A policy mixes approach to conceptualizing and measuring climate change adaptation policy. Climatic Change: 1-23.
Lesnikowski, A.C., Ford, J.D., Biesbroek, R., Berrang-Ford, L. and Heymann, J., 2016. National level progress on adaptation. Nature Climate Change, 6: 261–264.
Levin, K., Cashore, B., Bernstein, S. and Auld, G., 2012. Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change. Policy sciences, 45(2): 123-152.
Lewis, S.C., King, A.D., Perkins-Kirkpatrick, S.E. and Wehner, M.F., 2019. Toward Calibrated Language for Effectively Communicating the Results of Extreme Event Attribution Studies. Earth's Future, 7(9): 1020-1026.
Lewis, S.L. and Maslin, M.A., 2015. Defining the Anthropocene. Nature, 519(7542): 171-180.
Lindström, S., 2016. Palynofloral patterns of terrestrial ecosystem change during the end-Triassic event – a review. Geological Magazine, 153(2): 223-251.
Linnér, B.-O. and Wibeck, V., 2019. Sustainability Transformations Across Societies: Agents and Drivers across Societies. Cambridge University Press.
Llavador, H., Roemer, J.E. and Silvestre, J., 2010. Intergenerational justice when future worlds are uncertain. Journal of Mathematical Economics, 46(5): 728-761.
Loorbach, D., 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. Governance, 23(1): 161-183.
Lövbrand, E., Beck, S., Chilvers, J., Forsyth, T., Hedrén, J., Hulme, M., Lidskog, R. and Vasileiadou, E., 2015. Who speaks for the future of Earth? How critical social science can
extend the conversation on the Anthropocene. Global Environmental Change 32: 211-218.
Lubell, M. and Niles, M.T., 2019. The limits of capacity building. Nature Climate Change, 9(8): 578-579.
MacDonald, J.P., Willox, A.C., Ford, J.D., Shiwak, I., Wood, M., Teami, I. and Govt, R.I.C., 2015. Protective factors for mental health and well-being in a changing climate: Perspectives from Inuit youth in Nunatsiavut, Labrador. Social Science & Medicine, 141: 133-141.
MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A. and Elkins, J., 2006. Law Dome CO2, CH4 and N2O ice core records extended to 2000 years BP. Geophysical Research Letters, 33(14).
Mach, K.J. and Field, C.B., 2017. Toward the Next Generation of Assessment. Annual Review of Environment and Resources, 42(1): 569-597.
Mach, K.J., Kraan, C.M., Adger, W.N., Buhaug, H., Burke, M., Fearon, J.D., Field, C.B., Hendrix, C.S., Maystadt, J.-F. and O'Loughlin, J., 2019. Climate as a risk factor for armed conflict. Nature: 1.
Mach, K.J., Mastrandrea, M.D., Bilir, T.E. and Field, C.B., 2016. Understanding and responding to danger from climate change: the role of key risks in the IPCC AR5. Climatic Change, 136(3-4): 427-444.
Mach, K.J., Mastrandrea, M.D., Freeman, P.T. and Field, C.B., 2017. Unleashing expert judgment in assessment. Global environmental change, 44: 1-14.
MacKinnon, D. and Derickson, K.D., 2013. From resilience to resourcefulness: A critique of resilience policy and activism. Progress in Human Geography, 37(2): 253-270.
Magnan, A.K., Schipper, E.L.F. and Duvat, V.K.E., 2020. Frontiers in Climate Change Adaptation Science: Advancing Guidelines to Design Adaptation Pathways. Current Climate Change Reports, 6(4): 166-177.
Malm, A. and Hornborg, A., 2014. The geology of mankind? A critique of the Anthropocene narrative. Anthropocene Review, 1(1): 62-69.
Maor, M., Tosun, J. and Jordan, A., 2017. Proportionate and disproportionate policy responses to climate change: core concepts and empirical applications. Journal of Environmental Policy & Planning, 19(6): 599-611.
Marjanac, S., Patton, L. and Thornton, J., 2017. Acts of God, human influence and litigation. Nature Geoscience, 10(9): 616-619.
Markhvida, M., Walsh, B., Hallegatte, S. and Baker, J., 2020. Quantification of disaster impacts through household well-being losses. Nature Sustainability: 1-10.
Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J. and Matschoss, P.R., 2010. Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties.
Mastrandrea, M.D. and Mach, K.J., 2011. Treatment of uncertainties in IPCC Assessment Reports: past approaches and considerations for the Fifth Assessment Report. Climatic Change, 108(4): 659.

Mathes, G.H., van Dijk, J., Kiessling, W. and Steinbauer, M.J., 2021. Extinction risk controlled by interaction of long-term and short-term climate change. Nature Ecology & Evolution, 5: 304-310.
Matthews, H.D., 2016. Quantifying historical carbon and climate debts among nations. Nature Climate Change, 6(1): 60-64.
Mavrodieva, A.V., Rachman, O.K., Harahap, V.B. and Shaw, R., 2019. Role of Social Media as a Soft Power Tool in Raising Public Awareness and Engagement in Addressing Climate Change. Climate, 7(10): 122.
McDowell, G., Ford, J. and Jones, J., 2016. Community-level climate change vulnerability research: trends, progress, and future directions. Environmental Research Letters, 11(3): 033001.
McNamara, K.E. and Jackson, G., 2019. Loss and damage: A review of the literature and directions for future research. Wiley Interdisciplinary Reviews-Climate Change, 10(2).
McShane, K., 2017. Values and harms in loss and damage. Ethics, Policy & Environment, 20(2): 129-142.
Mechler, R., Calliari, E., Bouwer, L.M., Schinko, T., Surminski, S., Linnerooth-Bayer, J., Aerts, J., Botzen, W., Boyd, E. and Deckard, N.D., 2019. Science for loss and damage. Findings and propositions, Loss and Damage from Climate Change. Springer, pp. 3-37.
Mechler, R. and Schinko, T., 2016. Identifying the policy space for climate loss and damage. Science, 354(6310): 290-292.
Meerow, S., Newell, J.P. and Stults, M., 2016. Defining urban resilience: A review. Landscape and Urban Planning, 147: 38-49.
Meijerink, S., Stiller, S., Keskitalo, E.C.H., Scholten, P., Smits, R. and van Lamoen, F., 2014. The role of leadership in regional climate change adaptation: a comparison of adaptation practices initiated by governmental and non-governmental actors. Journal of Water and Climate Change, 6(1): 25-37.
Mellegård, V. and Boonstra, W.J., 2020. Craftsmanship as a carrier of indigenous and local ecological knowledge: photographic insights from Sámi Duodji and archipelago fishing. Society & Natural Resources: 1-21.
Metzger, J., Carlsson Kanyama, A., Wikman-Svahn, P., Mossberg Sonnek, K., Carstens, C., Wester, M. and Wedebrand, C., 2021. The flexibility gamble: challenges for mainstreaming flexible approaches to climate change adaptation. Journal of Environmental Policy & Planning: 1-16.
Miller, C.A., O'Leary, J., Graffy, E., Stechel, E.B. and Dirks, G., 2015. Narrative futures and the governance of energy transitions. Futures, 70: 65-74.
Mimura, N., Pulwarty, R.S., Duc, D.M., Elshinnawy, I., Redsteer, M.H., Huang, H.Q., Nkem, J.N. and Rodriguez, R.A.S., 2014. Adaptation planning and implementation. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869-898.
Minx, J.C., Callaghan, M., Lamb, W.F., Garard, J. and Edenhofer, O., 2017. Learning about climate change solutions in the IPCC and beyond. Environmental Science & Policy, 77: 252-259.
Mistry, J., Bilbao, B.A. and Berardi, A., 2016. Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1696): 20150174.
Mitchell, R.B., Clark, W.C., Cash, D.W. and Dickson, N.M., 2006. Global environmental assessments: information and influence. MIT Press.
Mitchell, S.D., 2009. Unsimple truths: Science, complexity, and policy. University of Chicago Press.
Moreau, V., Neves, C.A.D.O. and Vuille, F., 2019. Is decoupling a red herring? The role of structural effects and energy policies in Europe. Energy Policy, 128: 243-252.
Morgan, M.G., 2014. Use (and abuse) of expert elicitation in support of decision making for public policy. Proceedings of the National Academy of Sciences, 111(20): 7176-7184.
Morgan, M.S. and Wise, M.N., 2017. Narrative science and narrative knowing. Introduction to special issue on narrative science. Studies in History and Philosophy of Science Part A, 62: 1-5.
Mortreux, C. and Barnett, J., 2017. Adaptive capacity: exploring the research frontier. WIREs Climate Change, 8(4).
Mortreux, C., O'Neill, S. and Barnett, J., 2020. Between adaptive capacity and action: new insights into climate change adaptation at the household scale. Environmental Research Letters, 15(7): 074035.
Moser, S., Meerow, S., Arnott, J. and Jack-Scott, E., 2019a. The turbulent world of resilience: interpretations and themes for transdisciplinary dialogue. Climatic Change, 153(1-2): 21-40.
Moser, S.C. and Boykoff, M.T., 2013. Successful adaptation to climate change: Linking science and policy in a rapidly changing world. Routledge.
Moser, S.C., Ekstrom, J.A., Kim, J. and Heitsch, S., 2019b. Adaptation finance archetypes: local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. Ecology and Society, 24(2).
Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. and Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature, 463(7282): 747-756.

Moss, R.H. and Schneider, S.H., 2000. Towards consistent assessment and reporting of uncertainties in the IPCC TAR: Initial recommendations for discussion by authors. New Delhi: TERI.
Muiderman, K., Gupta, A., Vervoort, J. and Biermann, F., 2020. Four approaches to anticipatory climate governance: Different conceptions of the future and implications for the present. Wiley Interdisciplinary Reviews: Climate Change, 11(6): e673.
Munia, H.A., Guillaume, J.H., Mirumachi, N., Wada, Y. and Kummu, M., 2018. How downstream sub-basins depend on upstream inflows to avoid scarcity: typology and global analysis of transboundary rivers. Hydrol. Earth Syst. Sci, 22: 2795-2809.
Mureva, A., Ward, D., Pillay, T., Chivenge, P. and Cramer, M., 2018. Soil organic carbon increases in Semi-arid regions while it decreases in humid regions due to Woody-Plant encroachment of grasslands in South Africa. Scientific reports, 8(1): 1-12.
Nadeau, C.P. and Urban, M.C., 2019. Eco-evolution on the edge during climate change. Ecography.
Nadin, R. and Roberts, a.E., 2018. Moving towards a growing global discourse on transboundary adaptation, ODI, London, UK.
Nagy, G., Azeiteiro, U., Heimfarth, J., Verocai, J. and Li, C., 2018. An assessment of the relationships between extreme weather events, vulnerability, and the impacts on human wellbeing in Latin America. International journal of environmental research and public health, 15(9): 1802.
Nalau, J., Handmer, J., Dalesa, M., Foster, H., Edwards, J., Kauhiona, H., Yates, L. and Welegtabit, S., 2016. The practice of integrating adaptation and disaster risk reduction in the south-west Pacific. Climate and Development, 8(4): 365-375.
Nalau, J., Preston, B.L. and Maloney, M.C., 2015. Is adaptation a local responsibility? Environmental Science & Policy, 48: 89-98.
Nalau, J., Torabi, E., Edwards, N., Howes, M. and Morgan, E., 2021. A critical exploration of adaptation heuristics. Climate Risk Management, 32: 100292.
Nalau, J. and Verrall, B., 2021. Mapping the evolution and current trends in climate change adaptation science. Climate Risk Management, 32: 100290.
National Academies of Sciences, Engineering,,and Medicine,, 2016. Attribution of Extreme Weather Events in the Context of Climate Change. The National Academies Press, Washington, DC, 186 pp.
National Research Council, 2009. Informing decisions in a changing climate. National Academies Press.
Nauels, A., Gütschow, J., Mengel, M., Meinshausen, M., Clark, P.U. and Schleussner, C.-F., 2019. Attributing long-term sea-level rise to Paris Agreement emission pledges. Proceedings of the National Academy of Sciences, 116(47): 23487-23492.
Naveau, P., Ribes, A.l., Zwiers, F., Hannart, A., Tuel, A. and Yiou, P., 2018. Revising Return Periods for Record Events in a Climate Event Attribution Context. Journal of Climate, 31(9): 3411-3422.
ND-GAIN, 2019. ND-GAIN Country Index. In: U.o.N. Dame (Editor).
NEAA, 2010. Assessing an IPCC Assessment: An Analysis of Statements on Projected Regional Impacts in the 2007 Report. Netherlands Environmental Assessment Agency.
Neaves, T.T. and Royer, G.A., 2017. The social construction of disasters in the United States: A historical and cultural phenomenon. Journal of emergency management, 15(3): 175-187.
Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., Lefebvre, P., Alencar, A., Prinz, E. and Fiske, G., 2006. Inhibition of Amazon deforestation and fire by parks and indigenous lands. Conservation biology, 20(1): 65-73.
Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H. and Kovacs, E., 2017. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Science of the Total Environment, 579: 1215-1227.
Nightingale, A.J., 2015a. Adaptive scholarship and situated knowledges? Hybrid methodologies and plural epistemologies in climate change adaptation research. Area, 48(1): 41-47.
Nightingale, A.J., 2015b. A socionature approach to adaptation, Climate change adaptation and development. ROUTLEDGE in association with GSE Research, pp. 219-234.
Nightingale, A.J., Eriksen, S., Taylor, M., Forsyth, T., Pelling, M., Newsham, A., Boyd, E., Brown, K., Harvey, B. and Jones, L., 2019. Beyond Technical Fixes: climate solutions and the great derangement. Climate and Development: 1-10.
Noble, I.R., Huq, S., Anokhin, Y.A., Carmin, J., Goudou, D., Lansigan, F.P., Osman-Elasha, B. and Villamizar, A., 2014. Adaptation needs and options. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 833-868.
Nogués-Bravo, D., Rodríguez-Sánchez, F., Orsini, L., de Boer, E., Jansson, R., Morlon, H., Fordham, D.A. and Jackson, S.T., 2018. Cracking the Code of Biodiversity Responses to Past Climate Change. Trends in Ecology & Evolution, 33(10): 765-776.

Nunn, P.D., Runman, J., Falanruw, M. and Kumar, R., 2016. Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. Regional Environmental Change, 17(4): 959-971.
Nursey-Bray, M., Palmer, R., Smith, T.F. and Rist, P., 2019. Old ways for new days: Australian Indigenous peoples and climate change. Local Environment, 24(5): 473-486.
O'Neill, B.C., Oppenheimer, M., Warren, R., Hallegatte, S., Kopp, R.E., Pörtner, H.O., Scholes, R., Birkmann, J., Foden, W. and Licker, R., 2017. IPCC reasons for concern regarding climate change risks. Nature Climate Change, 7(1): 28.
O'Brien, K., 2011. Global environmental change II: From adaptation to deliberate transformation. Progress in Human Geography, 36(5): 667-676.
O'Brien, K. and Sygna, L., 2013. Responding to climate change: the three spheres of transformation. Proceedings of transformation in a changing climate: 19-21.
O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J. and Kok, K., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change, 42: 169-180.
Oberlack, C., 2017. Diagnosing institutional barriers and opportunities for adaptation to climate change. Mitigation and Adaptation Strategies for Global Change, 22(5): 805-838.
Oberlack, C. and Eisenack, K., 2014. Alleviating barriers to urban climate change adaptation through international cooperation. Global Environmental Change, 24: 349-362.
Oberlack, C. and Eisenack, K., 2018. Archetypical barriers to adapting water governance in river basins to climate change. Journal of Institutional Economics, 14(3): 527-555.
OECD, 2012. Incorporating Green Growth and Sustainable Development Policies into Structural Reform Agendas. Organisation for Economic Co-operation and Development, 19.
Olazabal, M., Chu, E., Castán Broto, V. and Patterson, J., 2021. Subaltern forms of knowledge are required to boost local adaptation. One Earth, 4(6): 828-838.
Olazabal, M., Galarraga, I., Ford, J., Sainz De Murieta, E. and Lesnikowski, A., 2019. Are local climate adaptation policies credible? A conceptual and operational assessment framework. International Journal of Urban Sustainable Development, 11(3): 277-296.
Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B. and Takahashi, K., 2014. Emergent risks and key vulnerabilities. In: C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (Editors), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.
Oppenheimer, M., Oreskes, N., Jamieson, D., Brysse, K., O'Reilly, J., Shindell, M. and Wazeck, M., 2019. Discerning Experts: The Practices of Scientific Assessment for Environmental Policy. University of Chicago Press.
Orlove, B., Roncoli, C., Kabugo, M. and Majugu, A., 2010. Indigenous climate knowledge in southern Uganda: the multiple components of a dynamic regional system. Climatic Change, 100(2): 243-265.
Orlove, B., Shwom, R., Markowitz, E. and Cheong, S.-M., 2020. Climate Decision-Making. Annual Review of Environment and Resources, 45(1): 271-303.
Ortega-Rosas, C.I., Peñalba, M.C. and Guiot, J., 2008. Holocene altitudinal shifts in vegetation belts and environmental changes in the Sierra Madre Occidental, Northwestern Mexico, based on modern and fossil pollen data. Review of Palaeobotany and Palynology, 151(1): 1-20.
Otto, F.E., Skeie, R.B., Fuglestvedt, J.S., Berntsen, T. and Allen, M.R., 2017. Assigning historic responsibility for extreme weather events. Nature Climate Change, 7(11): 757.
Otto, F.E.L., Harrington, L.J., Frame, D., Boyd, E., Lauta, K.C., Wehner, M., Clarke, B., Raju, E., Boda, C., Hauser, M., James, R.A. and Jones, R.G., 2020a. Toward an Inventory of the Impacts of Human-Induced Climate Change. Bulletin of the American Meteorological Society, 101(11): E1972-E1979.
Otto, I.M., Donges, J.F., Cremades, R., Bhowmik, A., Hewitt, R.J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S.S.P., Lenferna, A., Morán, N., van Vuuren, D.P. and Schellnhuber, H.J., 2020b. Social tipping dynamics for stabilizing Earth's climate by 2050. Proceedings of the National Academy of Sciences, 117(5): 2354-2365.
Owen, G., 2020. What makes climate change adaptation effective? A systematic review of the literature. Global Environmental Change, 62: 102071.
Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q. and Dasgupta, P., 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Ipcc.
Palmisano, A., Lawrence, D., de Gruchy, M.W., Bevan, A. and Shennan, S., 2021. Holocene regional population dynamics and climatic trends in the Near East: A first comparison using archaeo-demographic proxies. Quaternary Science Reviews, 252: 106739.
Papathoma-Kohle, M., Promper, C. and Glade, T., 2016. A Common Methodology for Risk Assessment and Mapping of Climate Change Related Hazards-Implications for Climate Change Adaptation Policies. Climate, 4(1).

Pardoe, J., Vincent, K. and Conway, D., 2018. How do staff motivation and workplace environment affect capacity of governments to adapt to climate change in developing countries? Environmental Science & Policy, 90: 46-53.
Park, J., Park, J., Yi, S., Cheul Kim, J., Lee, E. and Choi, J., 2019. Abrupt Holocene climate shifts in coastal East Asia, including the 8.2 ka, 4.2 ka, and 2.8 ka BP events, and societal responses on the Korean peninsula. Scientific Reports, 9(1): 10806.
Park, S.E., Marshall, N.A., Jakku, E., Dowd, A.M., Howden, S.M., Mendham, E. and Fleming, A., 2012. Informing adaptation responses to climate change through theories of transformation. Global Environmental Change, 22(1): 115-126.
Parmesan, C., Burrows, M.T., Duarte, C.M., Poloczanska, E.S., Richardson, A.J., Schoeman, D.S. and Singer, M.C., 2013. Beyond climate change attribution in conservation and ecological research. Ecology Letters, 16(s1): 58-71.
Parmesan, C. and Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature, 421(6918): 37-42.
Parrique, T., Barth, J., Briens, F., Kuokkanen, A. and Spangenberg, J., 2019. Evidence and arguments against green growth as a sole strategy for sustainability.
Pasgaard, M., Van Hecken, G., Ehammer, A. and Strange, N., 2017. Unfolding scientific expertise and security in the changing governance of Ecosystem Services. Geoforum, 84: 354-367.
Pearce, W., Niederer, S., Özkula, S.M. and Sánchez Querubín, N., 2019. The social media life of climate change: Platforms, publics, and future imaginaries. WIREs Climate Change, 10(2): e569.
Pei, Q., Lee, H.F. and Zhang, D.D., 2018. Long-term association between climate change and agriculturalists' migration in historical China. The Holocene, 28(2): 208-216.
Pelling, M. and Garschagen, M., 2019. Put equity first in climate adaptation. Nature, 569(7756): 327-329.
Pelling, M. and Manuel-Navarrete, D., 2011. From resilience to transformation: the adaptive cycle in two Mexican urban centers. Ecology and Society, 16(2).
Pelling, M., O'Brien, K. and Matyas, D., 2015. Adaptation and transformation. Climatic Change, 133(1): 113-127.
Penn, J.L., Deutsch, C., Payne, J.L. and Sperling, E.A., 2018. Temperature-dependent hypoxia explains biogeography and severity of end-Permian marine mass extinction. Science, 362(6419): eaat1327.
Persson, Å., 2019a. Global adaptation governance: An emerging but contested domain. WIREs Climate Change, 10(6).
Persson, Å., 2019b. Global adaptation governance: An emerging but contested domain. Wiley Interdisciplinary Reviews: Climate Change, 10(6): e618.
Persson, Å., Eckerberg, K. and Nilsson, M., 2016. Institutionalization or wither away? Twenty-five years of environmental policy integration under shifting governance models in Sweden. Environment and Planning C: Government and Policy, 34(3): 478-495.
Pescaroli, G. and Alexander, D., 2018. Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework. Risk Analysis, 38(11): 2245-2257.
Petzold, J., Andrews, N., Ford, J.D., Hedemann, C. and Postigo, J.C., 2020. Indigenous knowledge on climate change adaptation: a global evidence map of academic literature. Environmental Research Letters, 15(11): 113007.
Philip, S., Kew, S., van Oldenborgh, G.J., Otto, F., Vautard, R., van der Wiel, K., King, A., Lott, F., Arrighi, J., Singh, R. and van Aalst, M., 2020. A protocol for probabilistic extreme event attribution analyses. Adv. Stat. Clim. Meteorol. Oceanogr., 6(2): 177-203.
Pielke, R.A., 1998. Rethinking the role of adaptation in climate policy. Global Environmental Change, 8(2): 159-170.
Pilato, G., Sallu, S. and Gaworek-Michalczenia, M., 2018. Assessing the integration of climate change and development strategies at local levels: Insights from Muheza District, Tanzania. Sustainability, 10(1): 174.
Pinsky, M.L., Eikeset, A.M., McCauley, D.J., Payne, J.L. and Sunday, J.M., 2019. Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature, 569(7754): 108-111.
Polanyi, K., 1957. The Great Transformation: The Political and Economic Origins of Our Time.
Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F., Thompson, S.A. and Richardson, A.J., 2013. Global imprint of climate change on marine life. Nature Climate Change, 3(10): 919-925.
Polsky, C., Neff, R. and Yarnal, B., 2007. Building comparable global change vulnerability assessments: The vulnerability scoping diagram. Global Environmental Change, 17(3-4): 472-485.
Porter, J.J., Demeritt, D. and Dessai, S., 2015. The right stuff? informing adaptation to climate change in British Local Government. Global Environmental Change, 35: 411-422.
Pörtner, H., Scholes, R., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L. and Cheung, W., 2021. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change.
Pörtner, H.-O., 2021. Climate impacts on organisms, ecosystems and human societies: integrating OCLTT into a wider context. The Journal of Experimental Biology, 224(Suppl 1): jeb238360.
Potts, R., 1998. Variability selection in hominid evolution. Evolutionary Anthropology: Issues, News, and Reviews, 7(3): 81-96.
Potts, R., Dommain, R., Moerman, J.W., Behrensmeyer, A.K., Deino, A.L., Riedl, S., Beverly, E.J., Brown, E.T., Deocampo, D., Kinyanjui, R., Lupien, R., Owen, R.B., Rabideaux, N., Russell, J.M., Stockhecke, M., deMenocal, P., Faith, J.T., Garcin, Y., Noren, A., Scott, J.J., Western, D., Bright, J., Clark, J.B., Cohen, A.S., Keller, C.B., King, J., Levin, N.E., Brady Shannon, K., Muiruri, V., Renaut, R.W., Rucina, S.M. and Uno, K., 2020. Increased

ecological resource variability during a critical transition in hominin evolution. Science Advances, 6(43): eabc8975.
Prabhakar, S.V.R.K., S.B. Raj and Corral, a.A.F., 2018. Transboundary Impacts of Climate Change in Asia: Making a Case for Regional Adaptation Planning and Cooperation, Institute for Global Environmental Strategies, Hayama, Japan.
Preston, B.L., Mustelin, J. and Maloney, M.C., 2013. Climate adaptation heuristics and the science/policy divide. Mitigation and Adaptation Strategies for Global Change, 20(3): 467-497.
Preston, C.J., 2017. Challenges and opportunities for understanding non-economic loss and damage. Ethics, Policy & Environment, 20(2): 143-155.
Radchuk, V., Reed, T., Teplitsky, C., van de Pol, M., Charmantier, A., Hassall, C., Adamík, P., Adriaensen, F., Ahola, M.P. and Arcese, P., 2019. Adaptive responses of animals to climate change are most likely insufficient. Nature communications, 10(1): 1-14.
Raia, P., Mondanaro, A., Melchionna, M., Di Febbraro, M., Diniz-Filho, J.A.F., Rangel, T.F., Holden, P.B., Carotenuto, F., Edwards, N.R., Lima-Ribeiro, M.S., Profico, A., Maiorano, L., Castiglione, S., Serio, C. and Rook, L., 2020. Past Extinctions of Homo Species Coincided with Increased Vulnerability to Climatic Change. One Earth, 3(4): 480-490.
Ran, M. and Chen, L., 2019. The 4.2 ka BP climatic event and its cultural responses. Quaternary International, 521: 158-167.
Rao, N.D. and Min, J., 2018. Decent Living Standards: Material Prerequisites for Human Wellbeing. Social Indicators Research, 138(1): 225-244.
Raupach, M.R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J.G., Klepper, G. and Field, C.B., 2007. Global and regional drivers of accelerating CO₂ emissions. Proceedings of the National Academy of Sciences, 104(24): 10288-10293.
Raworth, K., 2017. Doughnut economics: seven ways to think like a 21st-century economist. Chelsea Green Publishing.
Ray, D.K., Gerber, J.S., MacDonald, G.K. and West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nature Communications, 6(1): 5989.
Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., McEvoy, D. and Satterthwaite, D., 2017. Climate change, equity and the Sustainable Development Goals: an urban perspective. Environment and urbanization, 29(1): 159-182.
Reckien, D., Salvia, M., Heidrich, O., Church, J.M., Pietrapertosa, F., de Gregorio-Hurtado, S., d'Alonzo, V., Foley, A., Simoes, S.G. and Lorencová, E.K., 2018. How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. Journal of cleaner production, 191: 207-219.
Reckien, D., Salvia, M., Pietrapertosa, F., Simoes, S.G., Olazabal, M., De Gregorio Hurtado, S., Geneletti, D., Krkoška Lorencová, E., D'Alonzo, V., Krook-Riekkola, A., Fokaides, P.A., Ioannou, B.I., Foley, A., Orru, H., Orru, K., Wejs, A., Flacke, J., Church, J.M., Feliu, E., Vasilie, S., Nador, C., Matosović, M., Flamos, A., Spyridaki, N.A., Balzan, M.V., Fülöp, O., Grafakos, S., Paspaldzhiev, I. and Heidrich, O., 2019. Dedicated versus mainstreaming approaches in local climate plans in Europe. Renewable and Sustainable Energy Reviews, 112: 948-959.
Redclift, M., 2005. An oxymoron comes of age sustainable development (1987–2005). Sustainable Development, 13: 212-227.
Reddin, C.J., Kocsis, Á.T. and Kiessling, W., 2018. Marine invertebrate migrations trace climate change over 450 million years. Global Ecology and Biogeography, 27(6): 704-713.
Reddin, C.J., Nätscher, P.S., Kocsis, Á.T., Pörtner, H.-O. and Kiessling, W., 2020. Marine clade sensitivities to climate change conform across timescales. Nature Climate Change, 10(3): 249-253.
Reghezza-Zitt, M., Rufat, S., Djament-Tran, G., Le Blanc, A. and Lhomme, S., 2012. What Resilience Is Not: Uses and Abuses. Cybergeo.
Rehdanz, K., Welsch, H., Narita, D. and Okubo, T., 2015. Well-being effects of a major natural disaster: The case of Fukushima. Journal of Economic Behavior & Organization, 116: 500-517.
Renn, O., 2008. Risk governance: coping with uncertainty in a complex world.
Ribes, A., Qasmi, S. and Gillett, N.P., 2021. Making climate projections conditional on historical observations. Science Advances, 7(4): eabc0671.
Richerson, P.J., Boyd, R. and Bettinger, R.L., 2001. Was Agriculture Impossible during the Pleistocene but Mandatory during the Holocene? A Climate Change Hypothesis. American Antiquity, 66(3): 387-411.
Riris, P. and Arroyo-Kalin, M., 2019. Widespread population decline in South America correlates with mid-Holocene climate change. Scientific Reports, 9(1): 6850.
Rittel, H. and Webber, M., 1973. Dilemmas in a General Theory of Planning. Policy Sciences, 4: 155-169.
Roberts, E. and Pelling, M., 2016. Climate change-related loss and damage. Climate and Development: 1-14.
Robinson, S.-a., 2020. Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. WIREs Climate Change, 11(4): e653.
Rockman, M. and Hritz, C., 2020. Expanding use of archaeology in climate change response by changing its social environment. Proceedings of the National Academy of Sciences, 117(15): 8295-8302.
Roe, E., 1994. Narrative policy analysis: Theory and practice. Duke University Press.
Roe, E., 2017. Except-Africa: Remaking development, rethinking power. Routledge.

Roe, E.M., 1991. Development narratives, or making the best of blueprint development. World development, 19(4): 287-300.
Roggero, M., 2015. Adapting institutions: exploring climate adaptation through institutional economics and set relations. Ecological Economics, 118: 114-122.
Rohling, E.J., Marino, G., Grant, K.M., Mayewski, P.A. and Weninger, B., 2019. A model for archaeologically relevant Holocene climate impacts in the Aegean-Levantine region (easternmost Mediterranean). Quaternary Science Reviews, 208: 38-53.
Rosa, E.A. and Dietz, T., 2012. Human drivers of national greenhouse-gas emissions. Nature Climate Change, 2(8): 581-586.
Rose, S. and and M. Scott, M., 2020. Review of 1.5˚C and Other Newer Global Emissions Scenarios: Insights for Company and Financial Climate Low-Carbon Transition Risk Assessment and Greenhouse Gas Goal Setting. EPRI, Palo Alto, CA, USA.
Rose, S. and Scott, a.M., 2018. Grounding Decisions: A Scientific Foundation for Companies Considering Global Climate Scenarios and Greenhouse Gas Goals. EPRI, Palo Alto, CA, USA.
Rotmans, J., Kemp, R. and Van Asselt, M., 2001. More evolution than revolution: transition management in public policy. foresight, 3(1): 15-31.
Rufat, S., Tate, E., Burton, C.G. and Maroof, A.S., 2015. Social vulnerability to floods: Review of case studies and implications for measurement. International Journal of Disaster Risk Reduction, 14: 470-486.
Russel, D., Castellari, S., Capriolo, A., Dessai, S., Hildén, M., Jensen, A., Karali, E., Mäkinen, K., Ørsted Nielsen, H., Weiland, S., den Uyl, R. and Tröltzsch, J., 2020. Policy Coordination for National Climate Change Adaptation in Europe: All Process, but Little Power. Sustainability, 12(13): 5393.
Sachs, J.D., 2015. Goal-based development and the SDGs: implications for development finance. Oxford Review of Economic Policy, 31(3-4): 268-278.
Saltré, F., Chadoeuf, J., Peters, K.J., McDowell, M.C., Friedrich, T., Timmermann, A., Ulm, S. and Bradshaw, C.J.A., 2019. Climate-human interaction associated with southeast Australian megafauna extinction patterns. Nature Communications, 10(1): 5311.
Sandom, C., Faurby, S., Sandel, B. and Svenning, J.-C., 2014. Global late Quaternary megafauna extinctions linked to humans, not climate change. Proceedings of the Royal Society B: Biological Sciences, 281(1787).
Sangha, K.K., Maynard, S., Pearson, J., Dobriyal, P., Badola, R. and Hussain, S.A., 2019. Recognising the role of local and Indigenous communities in managing natural resources for the greater public benefit: Case studies from Asia and Oceania region. Ecosystem Services, 39: 100991.
Santer, B.D., Fyfe, J.C., Solomon, S., Painter, J.F., Bonfils, C., Pallotta, G. and Zelinka, M.D., 2019. Quantifying stochastic uncertainty in detection time of human-caused climate signals. Proceedings of the National Academy of Sciences, 116(40): 19821-19827.
Sauer, I., Reese, R., Otto, C., Geiger, T., Willner, S.N., Guillod, B., Bresch, D. and Frieler, K., 2021. Climate Signals in River Flood Damages Emerge under Sound Regional Disaggregation. Nature Nature Portfolio.
Schaller, N., Kay, A.L., Lamb, R., Massey, N.R., van Oldenborgh, G.J., Otto, F.E.L., Sparrow, S.N., Vautard, R., Yiou, P., Ashpole, I., Bowery, A., Crooks, S.M., Haustein, K., Huntingford, C., Ingram, W.J., Jones, R.G., Legg, T., Miller, J., Skeggs, J., Wallom, D., Weisheimer, A., Wilson, S., Stott, P.A. and Allen, M.R., 2016. Human influence on climate in the 2014 southern England winter floods and their impacts. Nature Climate Change, 6(6): 627-634.
Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. and Walker, B., 2001. Catastrophic shifts in ecosystems. Nature, 413(6856): 591.
Scheffer, M., Carpenter, S.R., Dakos, V. and van Nes, E.H., 2015. Generic indicators of ecological resilience: inferring the chance of a critical transition. Annual Review of Ecology, Evolution, and Systematics, 46: 145-167.
Scheffer, M., Carpenter, S.R., Lenton, T.M., Bascompte, J., Brock, W., Dakos, V., Van de Koppel, J., Van de Leemput, I.A., Levin, S.A. and Van Nes, E.H., 2012. Anticipating critical transitions. science, 338(6105): 344-348.
Scheffer, M., van Nes, E.H., Bird, D., Bocinsky, R.K. and Kohler, T.A., 2021. Loss of resilience preceded transformations of pre-Hispanic Pueblo societies. Proceedings of the National Academy of Sciences, 118(18): e2024397118.
Schipper, E.L.F., 2006. Conceptual History of Adaptation in the UNFCCC Process. Review of European Community & International Environmental Law, 15(1): 82-92.
Schipper, E.L.F. and Burton, I., 2009. Understanding adaptation: origins, concepts, practice and policy. The earthscan reader on adaptation to climate change. London, UK and Sterling, VA, USA: 1-9.
Schipper, E.L.F., Eriksen, S.E., Fernandez Carril, L.R., Glavovic, B.C. and Shawoo, Z., 2020. Turbulent transformation: abrupt societal disruption and climate resilient development. Climate and Development, 13(6): 467-474.
Schipper, E.L.F., Thomalla, F., Vulturius, G., Davis, M. and Johnson, K., 2016. Linking disaster risk reduction, climate change and development. International Journal of Disaster Resilience in the Built Environment, 7(2): 216-228.
Schlosberg, D., 2003. The justice of environmental justice: reconciling equity, recognition, and participation in a political movement. In: *Moral and Political Reasoning in Environmental Practice*. Moral and political reasoning in environmental practice, 77: 106.
Schlosberg, D., 2009. Defining environmental justice: theories, movements, and nature. Oxford University Press.

Schlosberg, D., 2013. Theorising environmental justice: the expanding sphere of a discourse. Environmental politics, 22(1): 37-55.
Schoen, D. and and Rein, M., 1994. Reframing: Towards the resolution of intractable policy controversies. Basic Books, New York.
Schwab, K., 2017. The fourth industrial revolution. Currency.
Schwalm, C.R., Glendon, S. and Duffy, P.B., 2020. RCP8.5 tracks cumulative CO(2) emissions. Proceedings of the National Academy of Sciences of the United States of America, 117(33): 19656-19657.
Schwindt, D.M., Bocinsky, R.K., Ortman, S.G., Glowacki, D.M., Varien, M.D. and Kohler, T.A., 2016. The social consequences of climate change in the central Mesa Verde region. American Antiquity, 81(1): 74-96.
Scoones, I., Leach, M. and Newell, P., 2015. The politics of green transformations. Routledge.
Seddon, N., Turner, B., Berry, P., Chausson, A. and Girardin, C.A., 2019. Grounding nature-based climate solutions in sound biodiversity science. Nature Climate Change, 9(2): 84-87.
Sekulova, F. and van den Bergh, J.C.J.M., 2013. Climate change, income and happiness: An empirical study for Barcelona. Global Environmental Change-Human and Policy Dimensions, 23(6): 1467-1475.
Sen, A., 1985. Well-Being, Agency and Freedom: The Dewey Lectures 1984. The Journal of Philosophy, 82(4): 169-221.
Sengupta, T., Deshpande Mukherjee, A., Bhushan, R., Ram, F., Bera, M.K., Raj, H., Dabhi, A.J., Bisht, R.S., Rawat, Y.S., Bhattacharya, S.K., Juyal, N. and Sarkar, A., 2020. Did the Harappan settlement of Dholavira (India) collapse during the onset of Meghalayan stage drought? Journal of Quaternary Science, 35(3): 382-395.
Sera, F., Hashizume, M., Honda, Y., Lavigne, E., Schwartz, J., Zanobetti, A., Tobias, A., Iñiguez, C., Vicedo-Cabrera, A.M., Blangiardo, M., Armstrong, B. and Gasparrini, A., 2020. Air Conditioning and Heat-related Mortality: A Multi-country Longitudinal Study. Epidemiology, 31(6): 779-787.
Serdeczny, O., Waters, E. and Chan, S., 2016. Non-economic loss and damage in the context of climate change: understanding the challenges, German Development Institute/Deutsches Institut für Entwicklungspolitik (DIE).
Setzer, J. and Higham, C., 2021. Global trends in climate change litigation: 2021 snapshot, Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science, London.
Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., Fowler, H.J., James, R., Maraun, D. and Martius, O., 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Climatic change, 151(3-4): 555-571.
Siders, A.R., 2019a. Adaptive capacity to climate change: A synthesis of concepts, methods, and findings in a fragmented field. WIREs Climate Change, 10(3).
Siders, A.R., 2019b. Social justice implications of US managed retreat buyout programs. Climatic Change, 152(2): 239-257.
Siders, A.R. and Keenan, J.M., 2020. Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. Ocean & Coastal Management, 183: 105023.
Siders, A.R. and Pierce, A.L., 2021. Deciding how to make climate change adaptation decisions. Current Opinion in Environmental Sustainability, 52: 1-8.
Sieber, I.M., Biesbroek, R. and de Block, D., 2018. Mechanism-based explanations of impasses in the governance of ecosystem-based adaptation. Regional Environmental Change, 18(8): 2379-2390.
Sietsma, A.J., Ford, J.D., Callaghan, M.W. and Minx, J.C., 2021. Progress in climate change adaptation research. Environmental Research Letters, 16(5): 054038.
Simpson, e.a., In review. Assessing and responding to complex risk in a changing climate.
Singer, D.J., 2019. Diversity, not randomness, trumps ability. Philosophy of Science, 86(1): 178-191.
Singh, C., Ford, J., Ley, D., Bazaz, A. and Revi, A., 2020. Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. Climatic Change, 162(2): 255-277.
Singh, C., Iyer, S., New, M., Few, R., Kuchimanchi, B., Segnon, A.C. and and Morchain, D., 2021. Interrogating 'effectiveness' in climate change adaptation: 11 guiding principles for adaptation research and practice. Climate and Development.
Singh, N.P., Anand, B. and Khan, M.A., 2018. Micro-level perception to climate change and adaptation issues: A prelude to mainstreaming climate adaptation into developmental landscape in India. Natural Hazards, 92(3): 1287-1304.
Skeie, R.B., Fuglestvedt, J., Berntsen, T., Peters, G.P., Andrew, R., Allen, M. and Kallbekken, S., 2017. Perspective has a strong effect on the calculation of historical contributions to global warming. Environmental Research Letters, 12(2): 024022.
Slater, S.M., Twitchett, R.J., Danise, S. and Vajda, V., 2019. Substantial vegetation response to Early Jurassic global warming with impacts on oceanic anoxia. Nature Geoscience, 12(6): 462-467.
Smith, A., Voß, J.-P. and Grin, J., 2010. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. Research Policy, 39(4): 435-448.
Smith, R. and Botha, J., 2005. The recovery of terrestrial vertebrate diversity in the South African Karoo Basin after the end-Permian extinction. Comptes Rendus Palevol, 4(6): 623-636.

Smithers, J. and Smit, B., 1997. Human adaptation to climatic variability and change. Global Environmental Change, 7(2): 129-146.
Solecki, W., Pelling, M. and and Garschagen, M., 2017. A framework for urban risk management regime shifts. Ecology and Society, 22(2): 38.
Song, H., Kemp, D.B., Tian, L., Chu, D., Song, H. and Dai, X., 2021. Thresholds of temperature change for mass extinctions. Nature Communications, 12(1): 4694.
Spielman, S.E., Tuccillo, J., Folch, D.C., Schweikert, A., Davies, R., Wood, N. and Tate, E., 2020. Evaluating social vulnerability indicators: criteria and their application to the Social Vulnerability Index. Natural Hazards, 100(1): 417-436.
Stanley, S.M., 2016. Estimates of the magnitudes of major marine mass extinctions in earth history. Proceedings of the National Academy of Sciences, 113(42): E6325-E6334.
Stockholm Resilience Center, 2015. Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems. Cambridge University Press, Cambridge.
Stone, D., Auffhammer, M., Carey, M., Hansen, G., Huggel, C., Cramer, W., Lobell, D., Molau, U., Solow, A., Tibig, L. and Yohe, G., 2013. The challenge to detect and attribute effects of climate change on human and natural systems. Climatic Change, 121(2): 381-395.
Stone, D.A., Rosier, S.M. and Frame, D.J., 2021. The question of life, the universe and event attribution. Nature Climate Change, 11(4): 276-278.
Storch, H.V., 2018. The temporal dimension of coastal adaptation to climate change, The 9th Chinese-German Joint Symposium on Hydraulic and Ocean Engineering (CGJOINT 2018). National Cheng Kung University, Tainan, Taiwan, pp. 53-58.
Stott, P.A., Christidis, N., Otto, F.E.L., Sun, Y., Vanderlinden, J.-P., van Oldenborgh, G.J., Vautard, R., von Storch, H., Walton, P., Yiou, P. and Zwiers, F.W., 2016. Attribution of extreme weather and climate-related events. WIREs Climate Change, 7(1): 23-41.
Suding, K.N. and Hobbs, R.J., 2009. Threshold models in restoration and conservation: a developing framework. Trends in ecology & evolution, 24(5): 271-279.
Sukumar, R., Sharma, J.K., Chaturvedi, R.K. and Ravindranath, N., 2016. the impacts of climate change on Biodiversity and Ecosystems in India. Tropical Conservation: Perspectives on Local and Global Priorities, 89.
Sun, J. and Yang, K., 2016. The wicked problem of climate change: A new approach based on social mess and fragmentation. Sustainability, 8(12): 1312.
Surminski, S. and Lopez, A., 2015. Concept of loss and damage of climate change - a new challenge for climate decision-making? A climate science perspective. Climate and Development, 7(3): 267-277.
Sutton, R.T., 2018. ESD Ideas: A simple proposal to improve the contribution of IPCC WGI to the assessment and communication of climate change risks. Earth System Dynamics, 9(4): 1155-1158.
Svarstad, H. and Benjaminsen, T.A., 2020. Reading radical environmental justice through a political ecology lens. Geoforum, 108: 1-11.
Swart, R., Biesbroek, R. and LourenÃ§o, T.C., 2014. Science of adaptation to climate change and science for adaptation. Frontiers in Environmental Science, 2.
Tàbara, J.D., Frantzeskaki, N., Hölscher, K., Pedde, S., Kok, K., Lamperti, F., Christensen, J.H., Jäger, J. and Berry, P., 2018. Positive tipping points in a rapidly warming world. Current Opinion in Environmental Sustainability, 31: 120-129.
Taberna, A., Filatova, T., Roy, D. and Noll, B., 2020. Tracing resilience, social dynamics and behavioral change: a review of agent-based flood risk models. Socio-Environmental Systems Modelling, 2: 17938.
Taillardat, P., Friess, D.A. and Lupascu, M., 2018. Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. Biology letters, 14(10): 20180251.
Tanner, T., Lewis, D., Wrathall, D., Bronen, R., Cradock-Henry, N., Huq, S., Lawless, C., Nawrotzki, R., Prasad, V., Rahman, M.A., Alaniz, R., King, K., McNamara, K., Nadiruzzaman, M., Henly-Shepard, S. and Thomalla, F., 2015. Livelihood resilience in the face of climate change. Nature Climate Change, 5(1): 23-26.
Taylor, A.L., Dessai, S. and de Bruin, W.B., 2014. Public perception of climate risk and adaptation in the UK: a review of the literature. Climate Risk Management, 4: 1-16.
Termeer, C.J.A.M., Dewulf, A. and Biesbroek, G.R., 2016. Transformational change: governance interventions for climate change adaptation from a continuous change perspective. Journal of Environmental Planning and Management, 60(4): 558-576.
Thackeray, S.J., Robinson, S.A., Smith, P., Bruno, R., Kirschbaum, M.U.F., Bernacchi, C., Byrne, M., Cheung, W., Cotrufo, M.F., Gienapp, P., Hartley, S., Janssens, I., Hefin Jones, T., Kobayashi, K., Luo, Y., Penuelas, J., Sage, R., Suggett, D.J., Way, D. and Long, S., 2020. Civil disobedience movements such as School Strike for the Climate are raising public awareness of the climate change emergency. Global Change Biology, 26(3): 1042-1044.
Thaler, T., Attems, M.-S., Bonnefond, M., Clarke, D., Gatien-Tournat, A., Gralepois, M., Fournier, M., Murphy, C., Rauter, M. and Papathoma-Köhle, M., 2019. Drivers and barriers of adaptation initiatives–How societal transformation affects natural hazard management and risk mitigation in Europe. Science of the Total Environment, 650: 1073-1082.

Theys J. and Cornu, P., 2019. Temps de la nature, temps de la société, temps scientifique à l'heure du changement global. Pour une approche interdisciplinaire de la crise de la temporalité. Natures Sciences Sociétés, 27(4): 381-389.
Thiery, W., Visser, A.J., Fischer, E.M., Hauser, M., Hirsch, A.L., Lawrence, D.M., Lejeune, Q., Davin, E.L. and Seneviratne, S.I., 2020. Warming of hot extremes alleviated by expanding irrigation. Nature Communications, 11(1): 290.
Thompson, M. and Rayner, S., 1998. Risk and Governance Part I: The Discourses of Climate Change. Government and Opposition, 33(2): 139-166.
Tierney, J.E., deMenocal, P.B. and Zander, P.D., 2017. A climatic context for the out-of-Africa migration. Geology, 45(11): 1023-1026.
Timmermann, A. and Friedrich, T., 2016. Late Pleistocene climate drivers of early human migration. Nature, 538(7623): 92-95.
Tompkins, E.L., Adger, W.N., Boyd, E., Nicholson-Cole, S., Weatherhead, K. and Arnell, N., 2010. Observed adaptation to climate change: UK evidence of transition to a well-adapting society. Global environmental change, 20(4): 627-635.
Tompkins, E.L., Vincent, K., Nicholls, R.J. and Suckall, N., 2018. Documenting the state of adaptation for the global stocktake of the Paris Agreement. Wiley Interdisciplinary Reviews: Climate Change, 9(5): e545.
Tozier de la Poterie, A. and Baudoin, M.-A., 2015. From Yokohama to Sendai: Approaches to Participation in International Disaster Risk Reduction Frameworks. International Journal of Disaster Risk Science, 6(2): 128-139.
Tschakert, P., Barnett, J., Ellis, N., Lawrence, C., Tuana, N., New, M., Elrick-Barr, C., Pandit, R. and Pannell, D., 2017. Climate change and loss, as if people mattered: values, places, and experiences. Wiley Interdisciplinary Reviews: Climate Change, 8(5): e476.
Tschakert, P., Ellis, N.R., Anderson, C., Kelly, A. and Obeng, J., 2019. One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. Global Environmental Change-Human and Policy Dimensions, 55: 58-72.
Tschakert, P., van Oort, B., St. Clair, A.L. and LaMadrid, A., 2013. Inequality and transformation analyses: a complementary lens for addressing vulnerability to climate change. Climate and Development, 5(4): 340-350.
Turney, C.S.M. and Brown, H., 2007. Catastrophic early Holocene sea level rise, human migration and the Neolithic transition in Europe. Quaternary Science Reviews, 26(17): 2036-2041.
UN, 2007. United Nations Declaration on the Rights of Indigenous Peoples. UN Wash, 12: 1-18.
UN, 2015. Addis Ababa Action Agenda of the Third International Conference on Financing for Development. United Nations New York.
UN, 2017. New Urban Agenda, United Nations Conference on Housing and Sustainable Urban Development (Habitat III), pp. 1-66.
UN, 2020. Building an Inclusive, Sustainable and Resilient Future with Indigenous Peoples: A Call To Action. In: U.N.S.C.E.B.F.C. (CEB) (Editor). UNITED NATIONS SYSTEM CHIEF EXECUTIVES BOARD FOR COORDINATION (CEB).
UN Commission on Human Rights (50th sess. : 1994 : Geneva), 1992. Rio Declaration on Environment and Development.
UN Department of Economic and Social Affairs, 2020. World Social Report 2020: Inequality in a rapidly changing world, UN.
UN Inter-agency Task Force on Financing for Development 2019. Financing for Sustainable Development 2019, UN, New York, NY.
Undorf, S., Polson, D., Bollasina, M.A., Ming, Y., Schurer, A. and Hegerl, G.C., 2018. Detectable Impact of Local and Remote Anthropogenic Aerosols on the 20th Century Changes of West African and South Asian Monsoon Precipitation. Journal of Geophysical Research: Atmospheres, 123(10): 4871-4889.
UNDP, 2018. Inequality-adjusted Human Development Index (IHDI).
UNDRR, 2019. Integration between disaster risk reduction and national climate change adaptation strategies and plans, Global Assessment Report, pp. 335-362.
UNEP, 2011. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication.
UNEP, 2014. Adaptation Gap Report 2014, Nairobi.
UNEP, 2018. Adaptation Gap Report.
UNEP, UNEP DTU Partnership and (WASP), a.W.A.S.P., 2021. Adaptation Gap Report 2020.
UNESCO, 2018a. Local and Indigenous Knowledge Systems. United Nations Educational, Scientific and Cultural Organization.
UNESCO, 2018b. Report of the UNESCO Expert Meeting on Indigenous Knowledge and Climate Change in Africa, Nairobi, Kenya, 27-28 June 2018.
UNFCCC, 2013. Warsaw International Mechanism. In: UNFCCC (Editor), COP 19, Warsaw.
UNFCCC, 2015a. Decision 1/CP.21, Conference of the Parties, Paris.
UNFCCC, 2015b. Paris Agreement, COP 21, Paris.
UNFCCC, 2016. Paris Agreement, COP 21, Paris.

UNFCCC, 2018a. Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on the third part of its first session, held in Katowice from 2 to 15 December 2018. Addendum 1. Decisions 1-12., FCCC/PA/CMA/2018/3/Add.2.
UNFCCC, 2018b. Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on the third part of its first session, held in Katowice from 2 to 15 December 2018. Addendum 2. Decisions 13-20, FCCC/PA/CMA/2018/3/Add.2.
UNFCCC, 2021. Action for Climate Empowerment Guidelines.
UNISDR, 2015. Sendai Framework for Disaster Risk Reduction 2015–2030, Proceedings of the 3rd United Nations World Conference on DRR, Sendai, Japan, pp. 14-18.
United Nations; Department of Economic and Social Affairs; Population Division, 2019. World Population Prospects 2019: Highlights (ST/ESA/SER.A/423).
United Nations, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. In: United Nations (Editor).
USEPA, 2016. Climate Change Indicators in the United States 2016. (4).
USGCRP, 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, U.S. Global Change Research Program, Washington, DC, USA.
van Ginkel, K.C., Botzen, W.W., Haasnoot, M., Bachner, G., Steininger, K.W., Hinkel, J., Watkiss, P., Boere, E., Jeuken, A. and de Murieta, E.S., 2020. Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research. Environmental Research Letters, 15(2): 023001.
Van Valkengoed, A.M. and Steg, L., 2019. Meta-analyses of factors motivating climate change adaptation behaviour. Nature Climate Change, 9(2): 158.
van Vliet, J., Eitelberg, D.A. and Verburg, P.H., 2017. A global analysis of land take in cropland areas and production displacement from urbanization. Global environmental change, 43: 107-115.
Vautard, R., Christidis, N., Ciavarella, A., Alvarez-Castro, C., Bellprat, O., Christiansen, B., Colfescu, I., Cowan, T., Doblas-Reyes, F., Eden, J., Hauser, M., Hegerl, G., Hempelmann, N., Klehmet, K., Lott, F., Nangini, C., Orth, R., Radanovics, S., Seneviratne, S.I., van Oldenborgh, G.J., Stott, P., Tett, S., Wilcox, L. and Yiou, P., 2019. Evaluation of the HadGEM3-A simulations in view of detection and attribution of human influence on extreme events in Europe. Climate Dynamics, 52(1): 1187-1210.
Veldkamp, T., Wada, Y., Aerts, J., Döll, P., Gosling, S.N., Liu, J., Masaki, Y., Oki, T., Ostberg, S. and Pokhrel, Y., 2017. Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. Nature communications, 8(1): 1-12.
Veldman, J.W., Overbeck, G.E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G.W., Durigan, G., Buisson, E., Putz, F.E. and Bond, W.J., 2015. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. BioScience, 65(10): 1011-1018.
Vermeulen, S.J., Dinesh, D., Howden, S.M., Cramer, L. and Thornton, P.K., 2018. Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change. Frontiers in Sustainable Food Systems, 2.
Verschuur, J., Li, S., Wolski, P. and Otto, F.E.L., 2021. Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. Scientific Reports, 11(1): 3852.
Vervoort, J. and Gupta, A., 2018. Anticipating climate futures in a 1.5°C era: the link between foresight and governance. Current Opinion in Environmental Sustainability, 31: 104-111.
Vicedo-Cabrera, A.M., Sera, F., Guo, Y., Chung, Y., Arbuthnott, K., Tong, S., Tobias, A., Lavigne, E., de Sousa Zanotti Stagliorio Coelho, M., Hilario Nascimento Saldiva, P., Goodman, P.G., Zeka, A., Hashizume, M., Honda, Y., Kim, H., Ragettli, M.S., Röösli, M., Zanobetti, A., Schwartz, J., Armstrong, B. and Gasparrini, A., 2018. A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. Environment International, 111: 239-246.
Vignola, R., Leclerc, G., Morales, M. and Gonzalez, J., 2017. Leadership for moving the climate change adaptation agenda from planning to action. Current Opinion in Environmental Sustainability, 26-27: 84-89.
Vij, S., Biesbroek, R., Groot, A. and Termeer, K., 2018. Changing climate policy paradigms in Bangladesh and Nepal. Environmental science & policy, 81: 77-85.
Vincent, K. and Cundill, G., 2021. The evolution of empirical adaptation research in the global South from 2010 to 2020. Climate and Development: 1-14.
Viner, D., Ekstrom, M., Hulbert, M., Warner, N.K., Wreford, A. and Zommers, Z., 2020. Understanding the dynamic nature of risk in climate change assessments—A new starting point for discussion. Atmospheric Science Letters, 21(4).
Vogel, M.M., Zscheischler, J., Wartenburger, R., Dee, D. and Seneviratne, S.I., 2019. Concurrent 2018 Hot Extremes Across Northern Hemisphere Due to Human-Induced Climate Change. Earth's Future, 7(7): 692-703.
Vos, C.C., Berry, P., Opdam, P., Baveco, H., Nijhof, B., O'Hanley, J., Bell, C., Kuipers, H. and Nijho, B., 2008. Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. Journal of Applied Ecology: 1722-1731.
Walker, B. and Meyers, J., 2004. Thresholds in ecological and social–ecological systems: a developing database. Ecology and society, 9(2).

Wan, X. and Zhang, Z., 2017. Climate warming and humans played different roles in triggering Late Quaternary extinctions in east and west Eurasia. Proceedings of the Royal Society B: Biological Sciences, 284(1851): 20162438.
Wang, H., Easter, R.C., Zhang, R., Ma, P.-L., Singh, B., Zhang, K., Ganguly, D., Rasch, P.J., Burrows, S.M., Ghan, S.J., Lou, S., Qian, Y., Yang, Y., Feng, Y., Flanner, M., Leung, L.R., Liu, X., Shrivastava, M., Sun, J., Tang, Q., Xie, S. and Yoon, J.-H., 2020. Aerosols in the E3SM Version 1: New Developments and Their Impacts on Radiative Forcing. Journal of Advances in Modeling Earth Systems, 12(1): e2019MS001851.
Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H. and Simmons, C.T., 2016. Is Decoupling GDP Growth from Environmental Impact Possible? Plos One, 11(10).
Watkiss, P., Hunt, A., Dyszynski, J. and Dyszynski, J., 2015. The use of new economic decision support tools for adaptation assessment: A review of methods and applications, towards guidance on applicability. Climatic Change, 132(3): 401-416.
Webb, N.P., Marshall, N.A., Stringer, L.C., Reed, M.S., Chappell, A. and Herrick, J.E., 2017. Land degradation and climate change: building climate resilience in agriculture. Frontiers in Ecology and the Environment, 15(8): 450-459.
Webber, S., 2016. Climate Change Adaptation as a Growing Development Priority: Towards Critical Adaptation Scholarship. Geography Compass, 10(10): 401-413.
Wehner, M.F., Zarzycki, C. and Patricola, C., 2019. Estimating the Human Influence on Tropical Cyclone Intensity as the Climate Changes. In: J.M. Collins and K. Walsh (Editors), Hurricane Risk. Springer International Publishing, Cham, pp. 235-260.
Weiss, H. (Editor), 2017. Megadrought and collapse: from early agriculture to Angkor. Oxford University Press.
Welch, J.R., Brondízio, E.S., Hetrick, S.S. and Coimbra Jr, C.E., 2013. Indigenous burning as conservation practice: Neotropical savanna recovery amid agribusiness deforestation in Central Brazil. PloS one, 8(12): e81226.
Westaway, M.C., Olley, J. and Grün, R., 2017. At least 17,000 years of coexistence: Modern humans and megafauna at the Willandra Lakes, South-Eastern Australia. Quaternary Science Reviews, 157: 206-211.
Westoby, R., McNamara, K.E., Kumar, R. and Nunn, P.D., 2020. From community-based to locally led adaptation: Evidence from Vanuatu. Ambio, 49(9): 1466-1473.
Williams, A.N., Ulm, S., Sapienza, T., Lewis, S. and Turney, C.S.M., 2018. Sea-level change and demography during the last glacial termination and early Holocene across the Australian continent. Quaternary Science Reviews, 182: 144-154.
Willox, A.C., Stephenson, E., Allen, J., Bourque, F., Drossos, A., Elgaroy, S., Kral, M.J., Mauro, I., Moses, J., Pearce, T., MacDonald, J.P. and Wexler, L., 2015. Examining relationships between climate change and mental health in the Circumpolar North. Regional Environmental Change, 15(1): 169-182.
Wilson, A.J. and Orlove, B., 2019. What do we mean when we say climate change is urgent?
Wilson, R.S., Herziger, A., Hamilton, M. and Brooks, J.S., 2020. From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. Nature Climate Change, 10(3): 200-208.
Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer Van Garderen, E.R.M. and Campbell, B., 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Global Environmental Change, 28: 325-336.
Wisner, B., 2016. Vulnerability as Concept, Model, Metric, and Tool, Oxford Research Encyclopedia of Natural Hazard Science. Oxford University Press.
Woodruff, S.C., Meerow, S., Stults, M. and Wilkins, C., 2018. Adaptation to Resilience Planning: Alternative Pathways to Prepare for Climate Change. Journal of Planning Education and Research: 0739456X1880105.
Woodruff, S.C. and Regan, P., 2019. Quality of national adaptation plans and opportunities for improvement. Mitigation and adaptation strategies for global change, 24(1): 53-71.
World Economic Forum, 2021. The Global Risks Report 2021: Insight Report.
Woroniecki, S., Krüger, R., Rau, A.L., Preuss, M.S., Baumgartner, N., Raggers, S., Niessen, L., Holländer, L., Beyers, F., Rathgens, J., Wagner, K.C., Habigt, L., Krause, T., Wamsler, C., von Wehrden, H. and Abson, D., 2019. The framing of power in climate change adaptation research. WIREs Climate Change, 10(6).
Wright, H., Vermeulen, S., Laganda, G., Olupot, M., Ampaire, E. and Jat, M.L., 2014. Farmers, food and climate change: ensuring community-based adaptation is mainstreamed into agricultural programmes. Climate and development, 6(4): 318-328.
Xu, C., Kohler, T.A., Lenton, T.M., Svenning, J.-C. and Scheffer, M., 2020. Future of the human climate niche. Proceedings of the National Academy of Sciences, 117(21): 11350-11355.
Yasuhara, M., Wei, C.-L., Kucera, M., Costello, M.J., Tittensor, D.P., Kiessling, W., Bonebrake, T.C., Tabor, C.R., Feng, R., Baselga, A., Kretschmer, K., Kusumoto, B. and Kubota, Y., 2020. Past and future decline of tropical pelagic biodiversity. Proceedings of the National Academy of Sciences, 117(23): 12891-12896.
Yeh, E.T., 2016. 'How can experience of local residents be "knowledge"?'Challenges in interdisciplinary climate change research. Area, 48(1): 34-40.
Yokohata, T., Tanaka, K., Nishina, K., Takahashi, K., Emori, S., Kiguchi, M., Iseri, Y., Honda, Y., Okada, M. and Masaki, Y., 2019. Visualizing the interconnections among climate risks. Earth's Future, 7(2): 85-100.
Young, O.R., 2017. Beyond regulation: Innovative strategies for governing large complex systems. Sustainability, 9(6): 938.

Yu, J., Broutin, J., Chen, Z.-Q., Shi, X., Li, H., Chu, D. and Huang, Q., 2015. Vegetation changeover across the Permian–Triassic Boundary in Southwest China: Extinction, survival, recovery and palaeoclimate: A critical review. Earth-Science Reviews, 149: 203-224.
Yumagulova, L., Phibbs, S., Kenney, C.M., Yellow Old Woman-Munro, D., Christianson, A.C., McGee, T.K. and Whitehair, R., 2019. The role of disaster volunteering in Indigenous communities. Environmental Hazards: 1-18.
Zimmermann, A., J. Benda, H. Webber and Jafari, a.Y., 2018. Trade, food security, and climate change: conceptual linkages and policy implications, Food and Agricultural Organization, Rome, Italy.
Zommers, Z., Marbaix, P., Fischlin, A., Ibrahim, Z.Z., Grant, S., Magnan, A.K., Pörtner, H.-O., Howden, M., Calvin, K., Warner, K., Thiery, W., Sebesvari, Z., Davin, E.L., Evans, J.P., Rosenzweig, C., O'Neill, B.C., Patwardhan, A., Warren, R., van Aalst, M.K. and Hulbert, M., 2020. Burning embers: towards more transparent and robust climate-change risk assessments. Nature Reviews Earth & Environment, 1(10): 516-529.

Chapter 2: Terrestrial and Freshwater Ecosystems and their Services

Coordinating Lead Authors: Camille Parmesan (France/USA/United Kingdom), Mike D. Morecroft (United Kingdom), Yongyut Trisurat (Thailand)

Lead Authors: Rita Adrian (Germany), Gusti Zakaria Anshari (Indonesia), Almut Arneth (Germany), Qingzhu Gao (China), Patrick Gonzalez (USA), Rebecca Harris (Australia), Jeff Price (United Kingdom), Nicola Stevens (South Africa), Gautam Hirak Talukdar (India)

Contributing Authors: David D Ackerly (USA), Elizabeth Anderson (USA), Vanessa Bremerich (Germany), Lluís Brotons (Spain), Yu-Yun Chen (Taiwan, Province of China), Meghnath Dhimal (Nepal), Sami Domisch (Germany), Errol Douwes (South Africa), Alexander Flecker (USA), Wendy Foden (South Africa), Rachael V. Gallagher (Australia), Michael Goulding (USA), Aurora Gaxiola (Chile), Kerry-Anne Grey (South Africa), Susan Harrison (USA), David A. Keith (Australia), Benjamin M. Kraemer (USA/Germany), Simone Langhans (Switzerland), Andrew Latimer (USA), Julie Loisel (Canada, USA), James Pearce-Higgins (United Kingdom), Guy Midgley (South Africa), Erin Mordecai (USA), Francisco Moreira (Portugal), Isla Myers-Smith (United Kingdom/USA), A. Townsend Peterson (USA), Julio C. Postigo (Peru/USA), Joacim Rocklöv (Sweden), Angela Gallego-Sala (Spain/United Kingdom), Nathalie Seddon (United Kingdom), Michael C. Singer (France/United Kingdom), Jasper Slingsby (South Africa), Stavana E. Strutz (USA), Merritt Turetsky (USA), Beth Turner (Canada), Kenneth Young (USA).

Review Editors: Carol Franco Billini (Dominican Republic/USA), Yakiv Didukh (Ukraine), Andreas Fischlin (Switzerland)

Chapter Scientists: Stavana E. Strutz (USA), Dalila Mezzi-Booth (France)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Chapter 2, building upon prior assessments[1] provides a global assessment of observed impacts and projected risks of climate change to terrestrial and freshwater ecosystems, including their component species and the services they provide to people. Where possible, differences among regions, taxonomic groups and ecosystems types are presented. Adaptation options to reduce risks to ecosystems and people are assessed.

Observed Impacts

Multiple lines of evidence, combined with strong and consistent trends observed on every continent, make it *very likely*[2] that many observed changes in ranges, phenology, physiology and morphology of terrestrial and freshwater species can be attributed to regional and global climate changes, particularly increases in frequency and severity of extreme events *(very high confidence[3])* {2.3.1; 2.3.3.5; 2.4.2; 2.4.5; Table 2.2; Table 2.3; Table 2.S.1; Cross-Chapter Box EXTREMES this Chapter}. The most severe impacts are occurring in the most vulnerable species and ecosystems, characterized by inherent physiological, ecological or behavioural traits that limit their abilities to adapt and those most exposed to climatic hazards *(high confidence)* {2.4.2.2; 2.4.2.6; 2.4.2.8; 2.4.5; 2.6.1; Cross-Chapter Box EXTREMES this Chapter}.

New studies since AR5 and SR1.5 (now >12,000 species globally) show changes consistent with climate-change. Where attribution was assessed (>4,000 species globally) approximately half of species had shifted their ranges to higher latitudes or elevations and two-thirds of spring phenology had advanced, driven by regional climate changes *(very high confidence).* Shifts in species ranges are altering community make-up, with exotic species exhibiting greater ability to adapt to climate change than natives, especially in more northern latitudes, potentially leading to newly invasive species {2.4.2.3.3}. New analyses demonstrate that prior reports underestimated impacts due to complex biological responses to climate change *(high confidence).* {2.4.2.1; 2.4.2.3; 2.4.2.4; 2.4.2.5; 2.4.5; Table 2.2; Table SM2.1; Table 2.3}

Responses in freshwater species are strongly related to changes in the physical environment *(high confidence)* {2.3.3; 2.4.2.3.2}. Global coverage of quantitative observations in freshwater ecosystems has increased since AR5. Water temperature has increased in rivers (up to 1°C decade^{-1}) and lakes (up to 0.45°C decade^{-1}) {2.3.3.1; Figure 2.2}. Extent of ice cover has declined by 25% and duration by >2 weeks {2.3.3.4; Figure 2.4}. Changes in flow have led to reduced connectivity in rivers (*high confidence*) {2.3.3.2; Figure 2.3}. Indirect changes include alterations in river morphology, substrate composition, oxygen concentrations and thermal regime in lakes (*very high confidence*) {2.3.3.2; 2.3.3.3}. Dissolved oxygen concentrations have typically declined and primary productivity increased with warming. Warming and browning (increase in organic matter) have occurred in boreal freshwaters with both positive and negative repercussions on water temperature profiles (lower vs. upper water)*(high confidence)* and primary productivity (*medium confidence*) and reduced water quality *(high confidence)* {2.4.4.1; Figure 2.5}.

---

[1] Previous IPCC assessments include the IPCC Fifth Assessment Report (AR5) (IPCC, 2013; IPCC, 2014c; IPCC, 2014d; IPCC, 2014a), the Special Report on Global Warming of 1.5°C (SR1.5) (IPCC, 2014b), the Special Report on Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2019b) and the IPCC Sixth Assessment Report Working Group I (AR6 WGI).

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

[3] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Climate change has increased wildlife diseases *(high confidence).* Experimental studies provide *high confidence* in attribution of observed increased disease severity, outbreak frequency and emergence of novel vectors and their diseases into new areas to recent trends in climate and extreme events. Many vector-borne diseases, and those caused by ticks, helminth worms and Bd (chytrid) fungus, have shifted poleward, upward, and are emerging in new regions *(high confidence).*In the high Arctic and high elevations of Nepal, there is *high confidence* that climate change has driven expansion of vector-borne diseases that infect humans. {2.4.2.7, 7.2.2.1, 9.8.2.4, 10.4.7.1, 12.3.1.4, 13.7.1.2, 14.4.6.4, Cross-Chapter Box ILLNESS this Chapter}

Forest insect pests have expanded northward and severity and outbreak extent has increased in northern North America, northern Eurasia, due to warmer winters reducing mortality and longer growing seasons favouring more generations per year *(high confidence)* {2.4.2.1}

Climate-caused local population extinctions have been widespread among plants and animals, detected in 47% of 976 species examined and associated with increases in hottest yearly temperatures *(very high confidence)* {2.4.2.2}. Climate-driven population extinctions have been higher in tropical (55%), than temperate habitats (39%), higher in freshwater (74%), than in marine (51%) or terrestrial (46%) habitats and higher in animals (50%) than in plants (39%). Extreme heat waves has led to local fish kills in lakes {2.3.3.5}. Intensification of droughts contributes to disappearance of small or ephemeral ponds, which often hold rare and endemic species. {2.4.2.2; Cross-Chapter Box EXTREMES this Chapter}

Global extinctions or near-extinctions have been linked to regional climate change in three documented cases {2.4.2.2}**.** The cloud-forest-restricted Golden toad (*Incilius periglenes*) was extinct by 1990 in a nature preserve in Costa Rica following successive extreme droughts *(medium confidence)*. The white sub-species of the lemuroid ringtail possum (*Hemibelideus lemuroides*) in Queensland, Australia, disappeared after heatwaves in 2005 *(high confidence)*: intensive censuses found only 2 individuals in 2009. The Bramble Cays Melomys (*Melomys rubicola),* was not seen after 2009 and declared extinct in 2016, with SLR and increased storm surge, associated with climate change, the most probable drivers *(high confidence).* The interaction of climate change and chytrid fungus (Bd) has driven many of the observed global amphibian declines and species' extinctions *(robust evidence, high agreement)* {2.4.2.7.1}.

A growing number of studies document genetic evolution within populations in response to recent climate change *(very high confidence).* To date, genetic changes remain within the limits of known variation for species *(high confidence)*. **Controlled selection experiments and field observations indicate that evolution would not prevent a species becoming extinct if its climate space disappears globally *(high confidence).*** Climate hazards outside those to which species are adapted are occurring on all continents (*high confidence*). More frequent and intense extreme events, superimposed on longer-term climate trends, have pushed sensitive species and ecosystems towards tipping points, beyond ecological and evolutionary capacity to adapt, causing abrupt and possibly irreversible changes *(medium confidence)*. {2.3.1; 2.3.3; 2.4.2.6; 2.4.2.8; 2.6.1; Cross-Chapter Box ILNESS this Chapter, Cross-Chapter Box EXTREMES this Chapter}

Since AR5, biome shifts and structural changes within ecosystems have been detected at an increasing number of locations, consistent with climate change and increasing atmospheric CO_2 *(high confidence).* New studies document changes that were projected in prior reports, including upward shifts in the forest/alpine tundra ecotone, northward shifts in the deciduous/boreal forest ecotones, increased woody vegetation in sub-Arctic tundra, and shifts in thermal habitat in lakes. A combination of changes in grazing, browsing, fire, climate, and atmospheric CO_2 are leading to observed woody encroachment into grasslands and savannas, consistent with projections from process-based models driven by precipitation, atmospheric CO_2 and wildfire *(high confidence)*. {2.4.3; Table 2.3; Table 2.S.1; Box 2.1; Figure Box 2.1.1; Table Box 2.1.1} There is high agreement between projected changes in earlier reports and recent observed trends for areas of increased tree death in temperate and boreal forests and of woody encroachment in savannas, grasslands and tundra {2.5.4; Box 2.1; Figure Box 2.1.1; Table Box 2.1.1}. Observed changes impact structure, functioning and resilience of ecosystems, and ecosystem services such as climate regulation (*high confidence*). {2.3; 2.4.2; 2.4.3; 2.4.4, 2.5.4, Figure 2.11, Table 2.5, Box 2.1; Figure Box 2.1.1; Table Box 2.1.1}

Regional increases in area burned by wildfires (up to double natural levels), tree mortality up to 20%, and biome shifts up to 20 km latitudinally and 300 m upslope, have been attributed to anthropogenic climate change in tropical, temperate and boreal ecosystems around the world (*high confidence*), damaging key aspects of ecological integrity. This degrades vegetation survival, habitat for biodiversity, water supplies, carbon sequestration, and other key aspects of the integrity of ecosystems and their ability to provide services for people (*high confidence*). {2.4.3.1, 2.4.4.2, 2.4.4.3, 2.4.4.4; Table 2.3; Table 2.S.1}

B.11 Fire seasons have lengthened on one-quarter of vegetated area since 1979 as a result of increasing temperature, aridity, and drought *(medium confidence)*. **Field evidence shows that anthropogenic climate change has increased the area burned by wildfire above natural levels in western North America from 1984–2017 by double for the Western USA and 11 time higher than natural in one extreme year in British Columbia *(high confidence).*** Burned area has increased in the Amazon, the Arctic, Australia, and parts of Africa and Asia, consistent with, but not formally attributed to anthropogenic climate change. Wildfires generate up to one-third of global ecosystem carbon emissions, a feedback that exacerbates climate change (*high confidence*). Deforestation, peat draining, agricultural expansion or abandonment, fire suppression, and inter-decadal cycles such as the El Niño-Southern Oscillation, can exert a stronger influence than climate change on increasing or decreasing wildfire. {2.4.4.2; Table 2.3; Table 2.S.1; FAQ2.1}. Increases in wildfire from levels to which ecosystems are adapted degrades vegetation, habitat for biodiversity, water supplies, and other key aspects of the integrity of ecosystems and their ability to provide services for people (*high confidence*). {2.4.3.1, 2.4.4.2, 2.4.4.3, 2.4.4.4; Table 2.3; Table 2.S.1}

Anthropogenic climate change has caused drought-induced tree mortality of up to 20% in the period 1945–2007 in three regions in Africa and North America. It has also potentially contributed to over 100 other cases of drought-induced tree mortality across Africa, Asia, Australia, Europe, and North and South America *(high confidence).* Field observations document post-mortality vegetation shifts *(high confidence).* Timber cutting, agricultural expansion, air pollution, and other non-climate factors also contribute to tree death. Climate-change driven increases in forest insect pests have contributed to mortality and changes in carbon dynamics in many temperate and boreal forest areas (*very high confidence*). The direction of changes in carbon balance and wildfires following insect outbreaks depends on the local forest-insect communities (*medium confidence*). {2.4.4.3; Table 2.3; Table 2.S.1}.

Terrestrial ecosystems currently remove more carbon from the atmosphere, 2.5–4.3 Gt y^{-1}, than they emit. Intact tropical rainforests, Arctic permafrost, and other healthy high carbon ecosystems provide a vital global ecosystem service of preventing release of stored carbon *(high confidence).* Terrestrial ecosystems contain stocks of ~3500 GtC in vegetation, permafrost, and soils, three to five times the amount of carbon in unextracted fossil fuels (*high confidence*), and >4 times the carbon currently in the atmosphere (*high confidence*). Tropical forests and Arctic permafrost contain the highest ecosystem carbon, with peatlands following (*high confidence*). Deforestation, draining and burning of peatlands, and thawing of Arctic permafrost due to climate change shifts these ecosystems from carbon-sinks to carbon-sources *(high confidence)*. {2.4.3.6; 2.4.3.8; 2.4.3.9. 2.4.4.4}

Evidence indicates that climate change is affecting many species, ecosystems, and ecological processes that provide ecosystem services connected to human health, livelihoods, and well-being *(medium confidence).* These services include climate regulation, water and food provisioning, pollination of crops, tourism and recreation. It is difficult establish end-to-end attribution from climatic changes to changes in a given ecosystem service and to identify the location and timing of impacts. This limits specific adaptation planning, but protection and restoration of ecosystems could build resilience of service provision.{2.2; 2.3; 2.4.2.7; 2.4.5; 2.6.3; 2.6.4; 2.6.5; 2.6.6; 2.6.7; Cross-Chapter Box NATURAL this Chapter; Cross-Chapter Box ILLNESS this Chapter; Cross-Chapter Box EXTREMES this Chapter; Cross-Chapter Box COVID in Chapter 7; Cross-Chapter Box MOVING PLATE in Chapter 5}

Projected Risks

Climate change increases risks to fundamental aspects of terrestrial and freshwater ecosystems, with the potential for species' extinctions to reach 60% at 5°C GSAT warming (*high confidence*), biome shifts (changes in the major vegetation form of an ecosystem) on 15% (at 2ºC warming) to 35% (at 4ºC warming) of global land (*medium confidence*), and increases in the area burned by wildfire of 35%

(at 2ºC warming) to 40% (at 4ºC warming) of global land (*medium confidence*). {2.5.1; 2.5.2; 2.5.3; 2.5.4; Figure 2.6; Figure 2.7; Figure 2.8; Figure 2.9; Figure 2.11; Table 2.5; Table 2.S.2; Table 2.S.4; Cross-Chapter Box DEEP in Chapter 1; Cross-Chapter Paper 1}

Extinction of species is an irreversible impact of climate change, the risk of which increases steeply with rises in global temperature. It is *likely* that the percentage of species at high risk of extinction (median and maximum estimates) will be 9% (max 14%) at 1.5°C, 10% (max 18%) at 2°C, 12% (max 29%) at 3.0°C, 13% (max 39%) at 4°C and 15% (max 48%) at 5°C (Figure 2.7). Among groups containing largest numbers of species at high risk of extinctions for mid-levels of warming (3.2°C) are: invertebrates (15%), specifically pollinators (12%), amphibians (11%, but salamanders are at 24%) and flowering plants (10%). All groups fare substantially better at 2°C, with extinction projections reducing to <3% for all groups, except salamanders at 7% *(medium confidence)* (Figure 2.8a). Even the lowest estimates of species' extinctions (9%) are 1000x natural background rates. Projected species' extinctions at future global warming levels are consistent with projections from AR4, but assessed on many more species with much greater geographic coverage and a broader range of climate models. {2.5.1.3; Figure 2.6; Figure 2.7; Figure 2.8; Cross-Chapter Box DEEP in Chapter1; Cross-Chapter Paper 1}

Species are the fundamental unit of ecosystems, and increasing risk to species increases risk to ecosystem integrity, functioning and resilience with increasing warming *(high confidence)*. As species become rare, their roles in the functioning of the ecosystem diminishes *(high confidence)*. Loss of species reduces the ability of an ecosystem to provide services and lowers its resilience to climate change *(high confidence)*. At 1.58°C (median estimate), >10% of species are projected to become endangered (sensu IUCN); at 2.07°C (median) >20% of species are projected to become endangered, representing high and very high biodiversity risk, respectively *(medium confidence)*{2.5.4; Figure 2.8b, Figure 2.11; Table 2.5, Table 2.S.4}. Biodiversity loss is projected for more regions with increasing warming, and to be worst in northern South America, southern Africa, most of Australia, and northern high latitudes *(medium confidence)*{2.5.1.3; Figure 2.6}.

Climate change increases risks of biome shifts on up to 35% of global land at ≥4ºC warming, that emissions reductions could limit to <15% for <2ºC warming (*medium confidence*). Under high warming scenarios, models indicate shifts of extensive parts of the Amazon rainforest to drier and lower-biomass vegetation (*medium confidence*), poleward shifts of boreal forest into treeless tundra across the Arctic, and upslope shifts of montane forests into alpine grassland (*high confidence*). Area at high risk of biome shifts from climate change and land use change combined can double or triple compared to climate change alone (*medium confidence*). Novel ecosystems, with no historical analogue, are expected to become increasingly common in future *(medium confidence)*. {2.3, 2.4.2.3.3, 2.5.2; 2.5.4, Figure 2.11; Table 2.5; Table 2.S.4}

Risk of wildfires increases with global temperature *(high confidence)*. With 4ºC warming by 2100 wildfire frequency is projected to have a net increase of ~30% *(medium confidence)*. Increased wildfire, combined with soil erosion due to deforestation, could degrade water supplies *(medium confidence)*. For ecosystems with historically low fire frequencies, a projected 4ºC global temperature rise increases risks of fire, with potential increases in tree mortality and conversion of extensive parts of Amazon rainforest to drier and lower-biomass vegetation *(medium confidence)*. {2.5.3.2; 2.5.3.3}

Continued climate change substantially increases risk of carbon stored in the biosphere being released into the atmosphere due to increases in processes such as wildfires, tree mortality, insect pest outbreaks, peatland drying and permafrost thaw (*high confidence*). These phenomena exacerbate self-reinforcing feedbacks between emissions from high-carbon ecosystems (that currently store ~3030–4090 GtC) and increasing global temperatures. Complex interactions of climate change, land use change, carbon dioxide fluxes, and vegetation changes, combined with insect outbreaks and other disturbances, will regulate the future carbon balance of the biosphere, processes incompletely represented in current earth system models. The exact timing and magnitude of climate-biosphere feedbacks and potential tipping points of carbon loss are characterized by large uncertainty, but studies of feedbacks indicate increased ecosystem carbon losses can cause large future temperature increases *(medium confidence)*. {AR6 WGI 5.4, Table 5.4, Figure 5.29; 2.5.2.7; 2.5.2.8; 2.5.2.9; 2.5.3.2; 2.5.3.3; 2.5.3.4; 2.5.3.5; Figure 2.10; Figure 2.11; Table 2.4; Table 2.5; Table 2.S.2; Table 2.S.4}

Contributions of Adaptation Measures to Solutions

The resilience of biodiversity and ecosystem services to climate change can be increased by human adaptation actions including ecosystem protection and restoration *(high confidence)*. Ecological theory and observations show that a wide range of actions can reduce risks to species and ecosystem integrity. This includes minimising additional stresses or disturbances, reducing fragmentation, increasing natural habitat extent, connectivity and heterogeneity, maintaining taxonomic, phylogenetic and functional diversity and redundancy; and protecting small-scale refugia where microclimate conditions can allow species to persist *(high confidence).* Adaptation also includes actions to aid the recovery of ecosystems following extreme events. Understanding the characteristics of vulnerable species can assist in early warning systems to minimise negative impacts and inform management intervention. {2.3; Figure 2.1; 2.5.3.1, 2.6.2, Table 2.6, 2.6.5, 2.6.7, 2.6.8}.

There is new evidence that species can persist in refugia where conditions are locally cooler, when they are declining elsewhere *(high confidence)* {2.6.2}. Protecting refugia, for example where soils remain wet during drought or fire risk is reduced, and in some cases creating cooler microclimates, are promising adaptation measures {2.6.3; 2.6.5; CCP1; CCP5.2.1}. There is also new evidence that species can persist locally because of plasticity, including changes in phenology or behavioural changes that move an individual into cooler micro-climates, and genetic adaptation may allow species to persist for longer than might be expected from local climatic changes *(high confidence)* {2.4.2.6; 2.4.2.8, 2.6.1}. There is no evidence to indicate that these mechanisms will prevent global extinctions of rare, very localised species at their climatic limits or species inhabiting climate/habitat zones that are disappearing *(high confidence)*. {2.4.2.8, 2.5.1, 2.5.3.1, 2.5.4, 2.6.1, 2.6.2, 2.6.5}

Since AR5, many adaptation plans and strategies have been developed to protect ecosystems and biodiversity but there is limited evidence of the extent to which adaptation is taking place and virtually no evaluation of the effectiveness of adaptation measures in the scientific literature *(medium confidence)*. This is an important evidence gap that needs to be addressed to ensure a baseline is available against which to judge effectiveness and develop and refine adaptation in future. Many proposed adaptation measures have not been implemented (*low confidence*) {2.6.2; 2.6.3; 2.6.4; 2.6.5; 2.6.6; 2.6.8; 2.7}

Ecosystem restoration and resilience building cannot prevent all impacts of climate change, and adaptation planning needs to manage inevitable changes to species distributions, ecosystem structure and processes (*very high confidence*). Actions to manage inevitable change include local modification of microclimate or hydrology, adjustment of site management plans and facilitating the dispersal of vulnerable species to new locations, both by increasing habitat connectivity or by active translocations of species. Adaptation can reduce risks but cannot prevent all damaging impacts so is not a substitute for reductions in greenhouse gas emissions (*high confidence*). {2.2; 2.3; 2.3.1; 2.3.2; 2.4.5; 2.5.1.3; 2.5.1.4; 2.5.2; 2.5.3.1; 2.5.3.5; 2.5.4; 2.6.1; 2.6.2; 2.6.3; 2.6.4; 2.6.5; 2.6.6; 2.6.8; Cross-Chapter Box NATURAL this Chapter}.

Ecosystem-base Adaptation (EbA)can deliver climate change adaptation for people with multiple additional benefits, including for biodiversity (*high confidence*). An increasing body of evidence demonstrates that climatic risks to people, including from flood, drought, fire and over-heating, can be lowered by a range of Ecosystem-based Adaptation techniques in urban and rural areas (*medium confidence*). EbA forms part of a wider range Nature-based Solutions (NbS) actions and some have mitigation co-benefits, including the protection and restoration of forests and other high-carbon ecosystems, as well as agroecological farming practices {2.6.3; 2.6.5; Cross-Chapter Box NATURAL this Chapter}. However, EbA and other NbS are still not widely implemented. {2.2; 2.5.3.1; 2.6.2; 2.6.3; 2.6.4; 2.6.5; 2.6.6, 2.6.7; Table 2.7; Cross-Chapter Box NATURAL this Chapter; Cross-Chapter Paper 1}.

To realise potential benefits and avoid harm, it is essential that EbA is deployed in the right places and with the right approaches for that area, with inclusive governance *(high confidence)*. Interdisciplinary scientific information and practical expertise, including local and Indigenous knowledge, are essential to effectiveness (*high confidence*). There is a large risk of maladaptation where this does not happen (*high confidence*). {1.4.2; 2.2; 2.6; Table 2.7; Box 2.2; Figure Box 2.2.1; Cross-Chapter Box NATURAL this Chapter; Cross-Chapter Paper1; 5.14.2}.

Ecosystem-based Adaptation and other Nature-based Solutions are themselves vulnerable to climate change impacts. They need to take account of climate change adaptation if they are to remain effective and will increasingly be under threat at higher warming levels. Nature-based Solutions cannot be regarded as an alternative to, or a reason to delay, deep cuts in greenhouse gas emissions (high confidence). {2.6.3, 2.6.5; 2.6.7; Cross-Chapter Box NATURAL this Chapter}

Climate Resilient Development

Protection and restoration of natural and semi-natural ecosystems are key adaptation measures in light of clear evidence that damage and degradation of ecosystems exacerbates the impacts of climate change on biodiversity and people (*high confidence*). Ecosystem services that are at threat from a combination of climate change and other anthropogenic pressures include climate change mitigation, flood risk management, food provisioning and water supply (*high confidence*). Adaptation strategies that treat climate, biodiversity and human society as coupled systems will be most effective. {2.3; Figure 2.1; 2.5.4; 2.6.2; 2.6.3; 2.6.7; Cross-Chapter Box NATURAL and Cross-Chapter Box ILLNESS this Chapter}

A range of analyses have concluded that ~30% of Earth's surface needs to be effectively conserved to maintain biodiversity and ecosystem services *(medium confidence)*. Climate change places additional stress on ecosystem integrity and functioning, adding urgency for taking action. Low intensity, sustainable management, including by Indigenous peoples, is an integral part of some protected areas and can support effective adaptation and maintain ecosystem health. Food and fibre production in other areas will need to be efficient, sustainable and adapted to climate change to meet the needs of the human population *(high confidence).* {Figure 2.1; 2.5.4; 2.6.2; 2.6.3; 2.6.7}

Natural ecosystems can provide carbon storage and sequestration at the same time as providing multiple other ecosystem services, including EbA *(high confidence)* but there are risks of maladaptation and environmental damage from some approaches to land-based mitigation (*high confidence*). Plantation forests in areas which would not naturally support forest, including savannas, natural grasslands and temperate peatlands, or replacing native tropical forests on peat soils, have destroyed local biodiversity and created a range of problems, including for water supply, food supply, fire risk and greenhouse gas emissions. Large scale deployment of bioenergy, including Bioenergy with Carbon Capture and Storage (BECCS) through dedicated herbaceous or woody bioenergy crops and non-native production forests can damage ecosystems directly or through increasing competition for land. {2.6.3, 2.6.5, 2.6.6, 2.6.7; Box 2.2; Cross-Chapter Box NATURAL this Chapter; CCP7.3.2; Cross-Working Group Box BIOECONOMY in Chapter 5}.

Terrestrial and aquatic ecosystems and species are often less degraded in lands managed by Indigenous Peoples and local communities than in other lands *(medium confidence).* Including indigenous and local institutions is a key element in developing successful adaptation strategies. Indigenous and local knowledge contain a wide variety of resource-use practices and ecosystem stewardship strategies that conserve and enhance both wild and domestic biodiversity**.** {2.6.5; 2.6.7; Cross-Chapter Box NATURAL this Chapter}

Extreme events are compressing the timeline available for natural systems to adapt and impeding our ability to identify, develop and implement solutions (*medium confidence*). There is now an urgent need to build resilience and assist recovery following extreme events. This, combined with long-term changes in baseline conditions means that implementation of adaptation and mitigation measures cannot be delayed if they are to be fully effective. {2.3; Cross-Chapter Box EXTREMES this Chapter}

2.1 Introduction

2.1.1 *Overview*

Chapter 2: We provide assessments of observed and projected impacts of climate change across species, biomes (vegetation types), ecosystems and ecosystem services, highlighting processes emerging on a global scale. Where sufficient evidence exists, differences in biological responses among regions, taxonomic groups or types of ecosystems are presented, particularly when such differences provide meaningful insights into current or potential future autonomous or human-mediated adaptations. Human interventions that might build resilience of ecosystems and minimise negative impacts of climate change on biodiversity and ecosystem functioning are assessed. Such interventions include adaptation strategies and programmes to support biodiversity conservation and Ecosystem-based Adaptation (EbA). The assessments were done in the context of the Convention on Biological Diversity (CBD) and Sustainable Development Goals (SDGs), whose contributions to climate-resilient development pathways are assessed. This chapter highlights both successes and failures of adaptation attempts and considers potential synergies and conflicts with land-based climate change mitigation. Knowledge gaps and sources of uncertainty are included to encourage additional research.

The Working Group II Summary for Policy Makers of the 5th Assessment Report (WGII AR5 SPM) stated that "many terrestrial and freshwater species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change" (IPCC, 2014e). Based on long-term observed changes across the regions, it was estimated that approximately 20–30% of plant and animal species are at risk of extinction when global mean temperatures rise 2–3°C above preindustrial levels (Fischlin et al., 2007). In addition, WGII AR5 (IPCC, 2014f) broadly suggested that autonomous adaptation by ecosystems and wild species might occur, and proposed human-assisted adaptation to minimise negative climate change impacts.

Risk assessments for species, communities, key ecosystems and their services were based on the Risk Assessment Framework introduced in the IPCC AR5 (IPCC, 2014). Assessments of observed changes in biological systems emphasise detection and attribution of climate change on ecological and evolutionary processes with an emphasis on freshwater ecosystems, and assess ecosystem processes that were lightly assessed in previous reports, such as wildfire. Where appropriate, assessment of interactions between climate change and other human activities is provided.

Land-use and land cover change (LULCC), and unsustainable exploitation of resources from terrestrial and freshwater systems continue to be a major factor of natural ecosystem and biodiversity loss (*high confidence*). Fertiliser input, pollution of waterways, dam construction and extraction of freshwater for irrigation put additional pressure on biodiversity and alter ecosystem function (Shin et al., 2019). Likewise, for biodiversity, invasive alien species have been identified as a major threat, especially in freshwater systems, islands and coastal regions (*high confidence*) (IPBES, 2018b; IPBES, 2018e; IPBES, 2018c; IPBES, 2018d; IPBES, 2019). Climate change and CO_2 are expected to become increasingly important as drivers of change over the coming decades (Ciais et al., 2013; Settele et al., 2014; IPBES, 2019; IPCC, 2019c).

2.1.2 *Points of Departure*

Species diversity and ecosystem function influence each other reciprocally, while ecosystem function forms the necessary basis for ecosystem services (Hooper et al., 2012; Mokany et al., 2016). Drivers of impacts on biodiversity, ecosystem function and ecosystem services have been assessed in reports from IPCC, Food and Agriculture Organization (FAO), IPBES and the Global Environmental Outlook (Settele et al., 2014; FAO, 2018; IPBES, 2018b; IPBES, 2018e; IPBES, 2018c; IPBES, 2018d; IPBES, 2019; UNEP, 2019; Diversity, 2020). Most recently, the IPCC SRCCL provided an assessment on land degradation and desertification, greenhouse gas emissions and food security in the context of global warming (IPCC, 2019c), and the IPBES-IPCC joint report on Biodiversity and Climate Change provided a synthesis of current understanding of the interactions, synergies and feedbacks between biodiversity and climate change (Pörtner et al., 2021). This chapter builds on and expands the results from these assessments.

Assessment of impacts of climate change on freshwater systems has been limited in previous assessments, and interlinkages between terrestrial and freshwater processes have not been fully explored (Settele et al., 2014; IPBES, 2019). Improved treatment of impacts on terrestrial and freshwater systems is critical considering the revisions of international sustainability Goals and Targets, especially the conclusion that many of the proposed post-2020 Biodiversity-targets of the Convention on Biological Diversity (CBD) cannot be met due to climate change impacts (Arneth et al., 2020).

Previous reports highlighted the possibility of new ecosystem states stemming from shifts in thermal regimes, species composition, and energy and matter flows (Settele et al., 2014; Shin et al., 2019). Projecting such "tipping points" (see glossary) has been identified in previous reports as a challenge since neither monitoring programmes nor field studies, nor ecosystem and biodiversity modelling tools capture the underlying species-species and species-climate interactions sufficiently well to identify how biological interactions within and across trophic levels may amplify or dampen shifts in ecosystem states (Settele et al., 2014; Shin et al., 2019). Building on these previous analyses and recent literature, Chapter 2 in this AR6 provides new insights compared to previous assessments by (i) emphasising freshwater aspects, and the interlinkages between freshwater and terrestrial systems, (ii) assessing more clearly the link between biodiversity and ecosystem functioning, (iii) assessing impacts associated with climate change mitigation scenarios versus impacts of climate change, including interactions with adaptation, and (iv) where possible, places findings in context of the United Nations Sustainable Development Goals (SDGs) 2030, and services for human societies.

2.1.3 Guide to Attribution and Traceability of Uncertainty Assessments

For biological systems we use the framework for detection and attribution outlined in AR5 in which attribution of observed biological changes is made not to global, but to local or regional climate changes, (Parmesan et al., 2013; Cramer et al., 2014). However, global distribution of regional responses is desirable to achieve generality, and data in prior reports were concentrated from the northern hemisphere. The critique of "global" studies by (Feeley et al., 2017) argues that their naming is misleading, that most of them are far from global and that considerable geographic and taxonomic bias remains. This bias is diminishing, as data from southern hemisphere regions are added and there is now representation from every continent.

Overall confidence in climate change attribution of a biological change can be increased in multiple ways (Parmesan et al., 2013), of which we list four here. First, confidence rises when the time span of biological records is long, such that decadal trends in climate can be compared with decadal trends in biological response and long-term trends can be statistically distinguished from natural variability. Secondly, confidence can be increased by examining a large geographic area, which tends to diminish the effects of local confounding factors (Parmesan et al., 2013; Daskalova et al., 2020). Third, confidence is increased when there is experimental or empirical evidence of a mechanistic link between particular climate metrics and biological response. Fourth, confidence is increased when particular fingerprints of climate change are documented that uniquely implicate climate change as the causal driver of the biological change (Parmesan and Yohe, 2003). These conditions constitute multiple lines of evidence which, when they converge, can provide *very high confidence* that climate change is the causal driver of an observed change in a particular biological species or system (Parmesan et al., 2013).

Important factors that may confound or obscure effects of climate change are presence of invasive species, changes in land use (LULCC), and, in freshwater systems, eutrophication (IPCC, 2019a). Temporal and spatial scale of the study also affect estimates of impacts. The most extreme published estimates of biological change tend to be derived from smaller areas and/or shorter timeframes (Daskalova et al., 2020), and a recent large global analysis of data for 12,415 species found that differences in study methodology accounted for most of the explained variance in reported range shifts (Lenoir et al., 2020). The importance of land-use change is frequently stressed, but there is a paucity of studies that actually quantify the relative effects of climate change and land-use change on species and communities. Sirami et al. (2017) found only 13 such studies, among which four concluded that effects of land-use change over-rode those of climate change, four found that the two drivers independently affected different species and five found that they acted in synergy.

2.2 Connections of Ecosystem Services to Climate Change

Ecosystems provide services essential for human survival and well-being. The Millennium Ecosystem Assessment defined ecosystem services as "the benefits people obtain from ecosystems" including "provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious, and other nonmaterial benefits" (Assessment, 2005).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) re-named the concept "nature's contributions to people" and broadened the definition to "the contributions, both positive and negative, of living nature (i.e. diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life for people. Beneficial contributions from nature include such things as food provision, water purification, flood control, and artistic inspiration, whereas detrimental contributions include disease transmission and predation that damages people or their assets" (IPBES, 2019). IPBES modified the concept to include more social viewpoints and broaden analyses beyond narrow economic stock-and-flow valuation approaches (Díaz et al., 2018). IPBES developed a classification of 18 categories of ecosystem services (see Table 2.1).

When anthropogenic climate change affects ecosystems, it can also affect ecosystem services for people. Climate change connects to ecosystem services through three links: climate change—species—ecosystems—ecosystem services. This IPCC chapter assesses these connections through all three links when end-to-end published scientific analyses are available for terrestrial and freshwater ecosystems. This type of robust evidence exists for some key ecosystem services (Section 2.5.4), and is assessed in specific report sections: biodiversity habitat creation and maintenance (Sections 2.4, 2.5), regulation of detrimental organisms and biological processes (Sections 2.4.2.3, 2.4.2.7, 2.4.4, 2.5.3, 2.6.4, Cross-Chapter Box ILLNESS this Chapter), regulation of climate through ecosystem feedbacks in terms of carbon storage (Sections 2.4.4.4, 2.5.2.10, 2.5.3.4, 2.5.3.5) and albedo (Section 2.5.3.5), and provision of freshwater from ecosystems to people (Section 2.5.3.6).

For ecosystem services that do not have published scientific information to establish unambiguous links to climate change, the climate—species—ecosystem links are assessed. Global ecological assessments, including the Global Biodiversity Assessment (Programme, 1995), the Millennium Ecosystem Assessment (Assessment, 2005), and the IPBES Global Assessment Report (IPBES, 2019) have synthesised scientific information on the ecosystem—ecosystem services link, but full assessment from climate change to ecosystem services is often impeded by limited quantitative studies that span this entire spectrum, see (Mengist et al., 2020) for a review of this gap in montane regions.

IPCC and IPBES are collaborating to address gaps in knowledge on the effects of climate change on ecosystem services (Services and Ecosystem, 2021). Table 2.1 provides a guide for finding information on climate change and individual ecosystem services in the IPCC Sixth Assessment Report.

Table 2.1: Connections of ecosystem services to climate change, indicating the 18 categories of nature's contributions to people of the IPBES (IPBES, 2019), the most relevant sections in the IPCC Sixth Assessment Report, and the level of evidence in this report for attribution to anthropogenic climate change of observed impacts on ecosystem services. The order of services in the table follows the order presented by IPBES and does not denote importance or priority. Connections denote observed impacts, future risks, and adaptation. The order of connections follows the relevance or the order of sections.

Ecosystem service	Connections to climate change
Habitat creation and maintenance	Species extinctions (2.4.2.2, 2.5.1.3), Species range shifts (2.4.2.1, 2.4.2.5), Ecological changes in freshwater ecosystems (2.3.3, 2.4.2.3.2, 2.4.4.1, 2.4.4.5.2, 2.5.1.3.2, 2.5.3.5, 2.5.4, 2.5.3.6, 2.5.5.8), Vegetation changes (2.4.3, 2.4.4.2.5, 2.4.4.3, 2.4.4.4, 2.4.4.5.1, 2.5.2, 2.5.3.3), Biome shifts (2.4.3.2, 2.5.4), Wildfire (2.4.4.2, 2.5.3.2), Tree mortality (2.4.4.3, 2.5.3.3) (*robust evidence*)

Pollination and dispersal of seeds and other propagules	Species extinctions (2.4.2.2, 2.5.1.3), Species range shifts (2.4.2.1, 2.4.2.5), Phenology changes (2.4.2.4, 2.4.2.5) (*medium evidence*)
Regulation of air quality	Wildfire (2.4.4.2, 2.5.3.2, Chapter 7), Tree mortality (2.4.4.3, 2.5.3.3) (*medium evidence*)
Regulation of climate	Ecosystem carbon stocks, emissions, and removals (2.4.4.4, 2.5.3.4, IPCC AR6 Working Group I, Chapter 5), Amazon rainforest dieback (2.4.3.6, 2.4.4.3.2, 2.4.4.4.2, 2.5.2.6, 2.5.2.10, 2.5.3.3), Tundra permafrost thaw (2.4.4.4.4, 2.5.2.8, 2.5.3.5, 2.5.4), biome shifts (2.4.3, 2.5.2, 2.5.3.2.2), Wildfire (2.4.4.2, 2.5.3.2), Tree mortality (2.4.4.3, 2.5.3.3), Primary productivity changes (2.4.4.5, 2.5.3.5) (*robust evidence*)
Regulation of ocean acidification	Ocean acidification (IPCC AR6 Working Group I, Chapter 5), Changes in marine species distribution and abundance (Chapter 3) (*robust evidence*)
Regulation of freshwater quantity, location, and timing	Physical changes in freshwater systems (2.3.3), Ecological changes in freshwater ecosystems (2.4.2.3.2, 2.4.4.1, 2.4.4.5.2, 2.5.1.3.2, 2.5.3.7), Tree mortality (2.4.4.3, 2.5.3.3), Freshwater supply from ecosystems (2.5.3.6) (*medium evidence*)
Regulation of freshwater and coastal water quality	Coastal ecosystem changes (Chapter 3), Physical changes in freshwater systems (2.3.3), Ecological changes in freshwater ecosystems (2.4.2.3.2; 2.4.4.1, 2.4.4.5.2, 2.5.1.3.2, 2.5.3.7) (*robust evidence*)
Formation, protection, and decontamination of soils and sediments	Agricultural ecosystem changes (Chapter 5), Physical changes in freshwater systems (2.3.1), Vegetation changes (2.4.3, 2.5.4), Wildfire (2.4.4.2, 2.5.3.2) (*medium evidence*)
Regulation of hazards and extreme events	Coastal ecosystem changes (Chapter 3), Vegetation changes (2.4.3, 2.5.2), Wildfire (2.4.4.2, 2.5.5.2), Summary of hazards (2.3), Cross-Chapter Box EXTREMES this Chapter (*medium evidence*)
Regulation of detrimental organisms and biological processes	Inter-species interactions (2.4.2), Control of disease vectors (2.4.2.7, 2.5.1, 2.6.4), Insect pest infestations (2.4.4.3), Cross-Chapter Box ILLNESS this Chapter (*medium evidence*)
Energy	Forestry plantation changes (Chapter 5), Biomass changes in natural ecosystems (2.4.4.4), Bioeconomy (Cross-Working Group Box BIOECONOMY in Chapter 5), Tree mortality (2.4.4.3, 2.5.3.3) (*limited evidence*)
Food and feed	Agricultural ecosystem changes (Chapter 5), Species extinctions (2.4.2.2, 2.5.1.3), Species range shifts (2.4.2.1), Nature-based services from natural ecosystems (Cross-Chapter Box NATURAL this chapter), shifts in commercial food species Cross-Chapter Box Moving Plate in Chapter 5) (*medium evidence*)
Materials, companionship, and labour	Forestry plantation changes (Chapter 5), Species extinctions (2.4.2.2, 2.5.1.3), Species range shifts (2.4.2.1), Tree mortality (2.4.4.3, 2.5.3.3) (*limited evidence*)
Medicinal, biochemical, and genetic resources	Species extinctions (2.4.2.2, 2.5.1.3), Species range shifts (2.4.2.1) (*limited evidence*)
Learning and inspiration	All observed impacts (2.4) and future risks (2.5) in terrestrial and freshwater ecosystems (*limited evidence*)

Physical and psychological experiences	All observed impacts (2.4) and future risks (2.5) in terrestrial and freshwater ecosystems (*limited evidence*)
Supporting identities	All observed impacts (2.4) and future risks (2.5) in terrestrial and freshwater ecosystems (*limited evidence*)
Maintenance of options	All observed impacts (2.4) and future risks (2.5) in terrestrial and freshwater ecosystems, Nature-based services from natural ecosystems (Cross-Chapter Box NATURAL this Chapter, Cross-Chapter Box DEEP in Chapter 17 *(limited evidence)*

2.3 Hazards and Exposure

In AR6, WGI describes changes in physical climate systems using the term 'climatic impact-drivers' (CIDs), which can have detrimental, beneficial or neutral effects on a system. In contrast, the literature on natural systems tends to focus on hazards, which include natural or human-induced physical events, impacts or trends with the potential to cause negative effects on ecosystems and environmental resources. Hazards are affected by current and future changes in climate, including altered climate variability and extreme events (WGI Chapter 12). Hazards can occur suddenly (e.g., a heat wave or heavy rain event), or more slowly (e.g., land loss, degradation and erosion linked to multiple climate hazards compounding). Observed exposure and risks to protected areas is assessed in Section 2.5.3.1.1. See also Cross-Chapter Box EXTREMES this Chapter.

Non-climatic hazards such as land use change, habitat fragmentation, pollution and invasive species have been the primary drivers of change in terrestrial and freshwater ecosystems in the past (*high confidence*) (Figure 2.1). These impacts have been extensively documented in reports by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2021). However, whilst climate change has not been the predominant influence to date, its relative impact is increasing (IPCC Special Report on Climate Change and Land (SRCCL)), with greater interactive effects of non-climate and climate hazards now occurring (Birk et al., 2020).

2.3.1 Observed Changes to Hazards and Extreme Events

The major climate hazards at the global level are generally well understood (WGI AR6 Chapter 12; WGI AR6 Interactive Atlas). Increased temperatures and changes to rainfall and runoff patterns; greater variability in temperature, rainfall, river flow and water levels; rising sea-levels and increased frequency of extreme events means that greater areas of the world are being exposed to climate hazards outside those to which they are adapted (*high confidence*) (Lange et al., 2020).

Extreme events are a natural and important part of many ecosystems and many organisms have adapted to cope with long-term and short-term climate variability, within the disturbance regime experienced during their evolutionary history (*high confidence*). However, climate changes, disturbance regimes change and the magnitude and frequency of extreme events such as floods, droughts, cyclones, heatwaves and fire have increased in many regions (*high confidence*). These disturbances affect ecosystem functioning, biodiversity and ecosystem services (*high confidence*) but are, in general, poorly captured in impact models (Albrich et al., 2020b), although this should improve as higher-resolution climate models that better capture smaller-scale processes and extreme events become available (WGI AR6, Chapter 11). Extreme events pose large challenges for Ecosystem-based Adaptation (IPCC Special Reports on Extremes, Section 2.6.3). Ecosystem functionality on which such adaptation measures rely may be altered or destroyed by extreme episodic events (Handmer et al., 2012; Lal et al., 2012; Pol et al., 2017).

There is *high confidence* that the combination of internal variability, superimposed on longer-term climate trends, is pushing ecosystems to tipping points, beyond which abrupt and possibly irreversible changes are occurring (Harris et al., 2018a; Jones et al., 2018; Hoffmann et al., 2019b; Prober et al., 2019; Berdugo et al., 2020; Bergstrom et al., 2021). Increases in the frequency and severity of heatwaves, droughts and aridity, floods, fires and extreme storms have been observed in many regions (Seneviratne et al., 2012; Ummenhofer and Meehl, 2017) and these trends are projected to continue (*high confidence*) (Section 3.2.2.1, Cross-Chapter Box EXTREMES this Chapter, AR6 WGI Chapter 11;, SR1.5, Hoegh-Guldberg et al., 2018b).

While the major climate hazards at the global level are generally well described with high confidence, there is less understanding about the importance of hazards on ecosystems when they are superimposed (Allen et al., 2010; Anderegg et al., 2015; Seidl et al., 2017; Dean et al., 2018), and the outcomes are difficult to quantify in future projections (Handmer et al., 2012). Simultaneous or sequential events (coincident or compounding events) can lead to an extreme event or impact, even if each event is not in themselves extreme (Denny et al., 2009; Hinojosa et al., 2019). For example, the compounding effects of sea-level rise, extreme coastal high tide, storm surge, and river flow can substantially increase flooding hazard and impacts on freshwater systems (Moftakhari et al., 2017). On land, changing rainfall patterns and repeated heat waves may interact with biological factors such as altered plant growth and nutrient allocation under elevated CO_2, affecting herbivory rates and insect outbreaks leading to widespread dieback of some forests (e.g. in Australian *Eucalypt* forests) (Gherlenda et al., 2016; Hoffmann et al., 2019a). Risk assessments typically only consider a single climate hazard without changing variability, potentially underestimating actual risk (Milly et al., 2008; Sadegh et al., 2018; Zscheischler et al., 2018; Terzi et al., 2019; Stockwell et al., 2020;).

Understanding impacts associated with the rapid rate of climate change is less developed and more uncertain than changes in mean climate. High climate velocity (Loarie et al., 2009) is expected to be associated with distribution shifts, incomplete range filling and species extinctions (*high confidence*) (Sandel et al., 2011; Burrows et al., 2014), although not all species are equally at risk from high velocity (see Sections 2.4.2.2, 2.5.1.3). It is generally assumed that the more rapid the rate of change, the greater the impact on species and ecosystems, but responses are taxonomically and geographically variable (*high confidence*) (Kling et al., 2020).

For example, strong dispersers are less at risk, while species with low dispersal ability, small ranges and long lifespans (e.g. many plants, especially trees, many amphibians and some small mammals) are more at risk (Hamann et al., 2015) (IPCC, 2014). This is likely to favour generalist and invasive species, altering species composition, ecosystem structure and function (Clavel et al., 2011; Büchi and Vuilleumier, 2014). The ability to track suitable climates is substantially reduced by habitat fragmentation and human modifications of the landscape such as dams on rivers and urbanisation (*high confidence*). Freshwater systems are particularly at risk of rapid warming given their naturally fragmented distribution. Velocity of change in surface temperature of inland standing waters globally has been estimated as 3.5 ± 2.3 km per decade from 1861 to 2005. This is projected to increase from 2006 to 2099 from between 8.7 ± 5.5 km per decade (RCP 2.6) to 57.0 ± 17.0 km per decade (RCP 8.5) (Woolway and Maberly, 2020). Although the dispersal of aerial adult stage of some aquatic insects can surpass these climate velocities, rates of change under mid- and high emissions scenarios (RCP4.5, RCP6.0, RCP8.5) are substantially higher than known rates of active dispersal of many species (Woolway and Maberly, 2020). Many species, both terrestrial and freshwater, are not expected to be able to disperse fast enough to track suitable climates under mid- and high emissions scenarios (*medium confidence*) (RCP4.5, RCP6.0, RCP8.5; Brito-Morales et al., 2018).

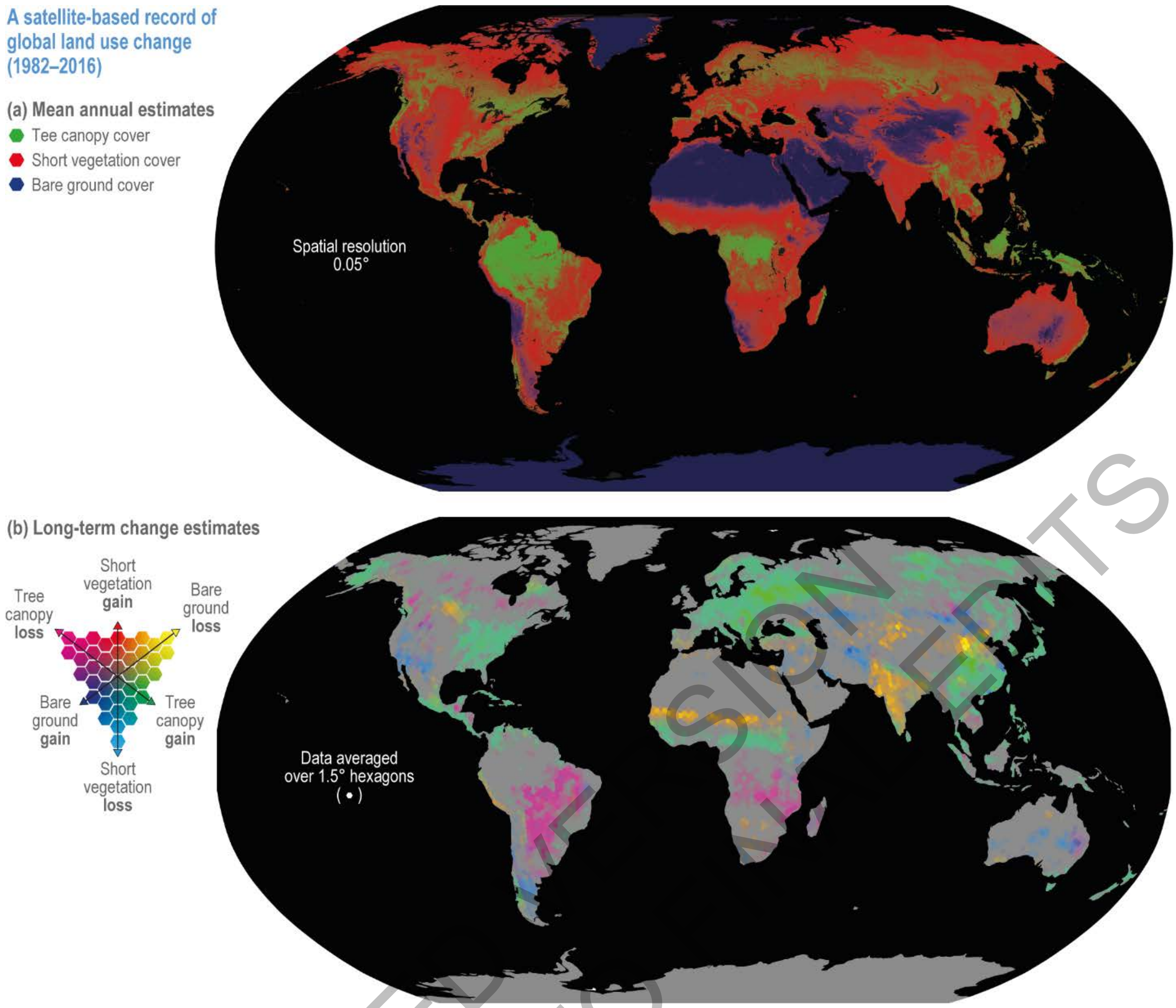


Figure 2.1: Map of global land use change from 1982–2016. Based on satellite records of global tree canopy (TC), short vegetation (SV) and bare ground (BG) cover (from Song et al., 2018). a) Mean annual estimates of cover (% of pixel area at 0.05° resolution). b) Long-term change estimates (% of pixel area at 1.5° resolution), with pixels showing a statistically significant trend (n = 35 years, two-sided Mann–Kendall test, P < 0.05) in TC, SV or BG. The dominant changes are Tree canopy gain with Short vegetation loss; Bare Ground gain with Short vegetation loss; Tree canopy gain with Bare Ground loss; Bare Ground gain with Tree canopy loss; 5, Short vegetation gain with Bare Ground loss; and Short vegetation gain with TC loss. Grey indicates areas with no significant change between 1982–2016.

2.3.2 Projected Impacts of Extreme Events

Understanding of the large-scale drivers and the local to regional feedback processes that lead to extreme events is still limited and projections of extremes and coincident or compounding events remain uncertain (Prudhomme et al., 2014; Sillmann et al., 2017; Hao et al., 2018; Miralles et al., 2019). Extreme events are challenging to model because they are by definition rare and often occur at spatial and temporal scales much finer than the resolution of climate models (Sillmann et al., 2017; Zscheischler et al., 2018). Additionally, the processes that cause extreme events often interact, as is the case for drought and heat events, and are spatially and temporally dependent, for example, as is the case in soil moisture and temperature (Vogel et al., 2017). Understanding feedbacks between land and atmosphere also remains limited. For example, positive feedbacks between soil and vegetation, or between evaporation, radiation and precipitation are important in the preconditioning of extreme events such as heatwaves and droughts, increasing the severity and impact of extreme events (Miralles et al., 2019).

Despite recent improvements in observational studies and climate modelling (Santanello et al., 2015; Stegehuis et al., 2015; PaiMazumder and Done, 2016; Basara and Christian, 2018; Knelman et al., 2019), the potential to quantify or infer formal causal relationships between multiple drivers and/or hazards remains limited, for several reasons (Zscheischler and Seneviratne, 2017; Kleinman et al., 2019; Miralles et al., 2019; Yokohata et al., 2019; Harris et al., 2020). The mechanisms underlying the response are difficult to identify (e.g., response to heat stress, drought, insects), effects vary among species and at different life stages, and an initial stress may influence the response to further stress (Nolet and Kneeshaw, 2018). Additionally, hazards such as drought are often exacerbated by societal, industrial and agricultural water demands, requiring more sophisticated modelling of the physical and human systems (Mehran et al., 2017; Wan et al., 2017). Observations of past compound events may not provide reliable guides to how future events may evolve, because human activity and recent climate change continue to interact to influence both system functioning and the climate state that have not been experienced in the past (see Chapter 11, WGI AR6).

2.3.3 Biologically Important Physical Changes in Freshwater Systems

Physical changes are fundamental drivers of change at all levels of biological organisation, from individual species to communities to whole ecosystems and climate hazards specific to freshwater systems which are not documented elsewhere in AR6 are summarised here.

2.3.3.1 Observed Change in Thermal Habitat and Oxygen Availability

Since AR5, evidence for changes in temperatures of lakes and rivers has continued to increase. Global warming rates for lake surface waters were estimated as 0.21°C to 0.45°C per decade between 1970-2010, exceeding SST trends of 0.09°C per decade between 1980–2017 (*robust evidence, high agreement*) (Figure 2.2; Schneider and Hook, 2010; Kraemer et al., 2015; O'Reilly et al., 2015; Woolway et al., 2020b). Warming of lake surface water temperatures was variable within regions (O'Reilly et al., 2015) but more homogeneous than changes of deep water temperature (Pilla et al., 2020). Because temperature trends in lakes can vary vertically, horizontally, and seasonally, complex changes have occurred in the amounts of habitat available to aquatic organisms at particular depths and temperatures (Kraemer et al., 2021).

Changes in river water temperatures ranged from -1.21 to +1.076 °C per decade between 1901–2010 (*medium evidence, medium agreement*) (Figure 2.2; Hari et al., 2006; Kaushal et al., 2010; Jurgelėnaitė et al., 2012; Li et al., 2012; Latkovska and Apsīte, 2016; Marszelewski and Pius, 2016). The more rapid increase in surface water temperature in lakes and rivers in regions with cold winters (O'Reilly et al., 2015) can in part be attributed to the amplified warming in polar and high latitude regions (*robust evidence, high agreement*) (Figure 2.2b; Screen and Simmonds, 2010; Stuecker et al., 2018).

Shifts in thermal regime: Since AR5 the trend that lake waters mix less frequently continues (Butcher et al., 2015; Adrian et al., 2016; Richardson et al., 2017; Woolway et al., 2017). This results from greater warming of surface temperatures relative to deep water temperatures and the loss of ice during winter which prevents inverse thermal stratification in north temperate lakes *(robust evidence, high agreement)* (Adrian et al., 2009; Winslow et al., 2015; Adrian et al., 2016; Schwefel et al., 2016; Richardson et al., 2017).

Oxygen availability: Increased water temperature and reduced mixing cause a decrease in dissolved oxygen. In 400 lakes, dissolved oxygen in surface and deep waters declined by 4.1 and 16.8%, respectively between 1980 and 2017 (Jane et al., 2021). The deepest water layers are expected to experience an increase in hypoxic conditions by more than 25% due to reduced winter mixing and fewer complete mixing events, with strong repercussions on nutrient dynamics and loss of thermal habitat (*robust evidence, high agreement*) (Straile et al., 2010; Zhang et al., 2015; Schwefel et al., 2016; Adrian et al., 2016; Kraemer et al., 2021).

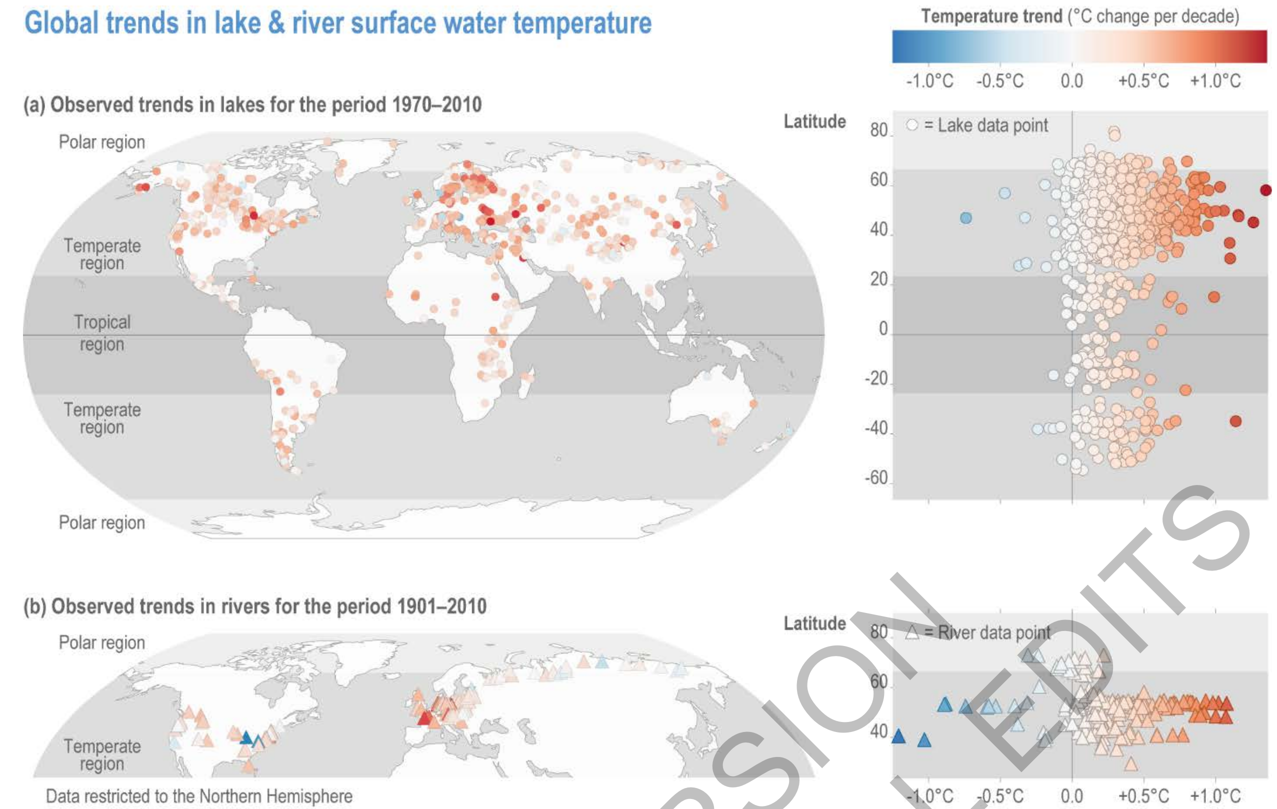


Figure 2.2: Observed global trends in lake and river surface water temperature. a) Left panel: Map of temperatures of lakes (1970-2010). b) Left panel: Map of temperatures of rivers (1901–2010). Note that the trends of river water temperatures are not directly comparable within rivers or directly comparable to lakes since time periods are not consistent across river studies. Right panels in a) and b) depict water temperature trends along a latitudinal gradient highlighting the above average warming rates in northern Polar Regions (polar amplification). Data sources for lakes: (O'Reilly et al., 2015; Carrea and Merchant, 2019; Woolway et al., 2020a; Woolway et al., 2020b). Data sources for rivers: (Webb and Walling, 1992; Langan et al., 2001; Daufresne et al., 2004; Moatar and Gailhard, 2006; Lammers et al., 2007; Patterson et al., 2007; Webb and Nobilis, 2007; Durance and Ormerod, 2009; Kaushal et al., 2010; Pekárová et al., 2011; Jurgelėnaitė et al., 2012; Markovic et al., 2013; Arora et al., 2016; Latkovska and Apsīte, 2016; Marszelewski and Pius, 2016; Jurgelėnaitė et al., 2017).

2.3.3.2 Observed Changes in Water Level

Depending on how the intensification of the global water cycle affects individual lake water budgets, the amount of water stored in specific lakes may increase, decrease, or have no substantial cumulative effect (Notaro et al., 2015; Pekel et al., 2016; Rodell et al., 2018; Busker et al., 2019; Woolway et al., 2020b). The magnitude of hydrological changes that can be assuredly attributed to climate change remains uncertain (Hegerl et al., 2015; Gronewold and Rood, 2019; Kraemer et al., 2020). Attribution of water storage variation in lakes due to climate change is facilitated when such variations occur coherently across broad geographic regions and long timescales, preferably absent other anthropogenic hydrological influences (Watras et al., 2014; Kraemer et al., 2020). There is increasing awareness that climate change contributes to the loss of small temporary ponds, which cover a greater global area than lakes (Bagella et al., 2016).

Lakes fed by glacial meltwater are growing in response to climate change and glacier retreat (*robust evidence*, *high agreement*) (Shugar et al., 2020). Water storage increases on the Tibetan Plateau (Figure 2.3a) have been attributed to changes in glacier melt, permafrost thaw, precipitation and runoff, in part as a result of climate change (Huang et al., 2011; Meng et al., 2019; Wang et al., 2020a). *High confidence* in attribution of these trends to climate change is supported by long-term ground survey data and observations from the GRACE satellite mission (Ma et al., 2010; Rodell et al., 2018; Kraemer et al., 2020).

In the Arctic, lake area has increased in regions with continuous permafrost and decreased in regions where permafrost is thinner and discontinuous *(robust evidence, high agreement)* (see Chapter 4; Smith et al., 2005; Andresen and Lougheed, 2015; Nitze et al., 2018; Mekonnen et al., 2021).

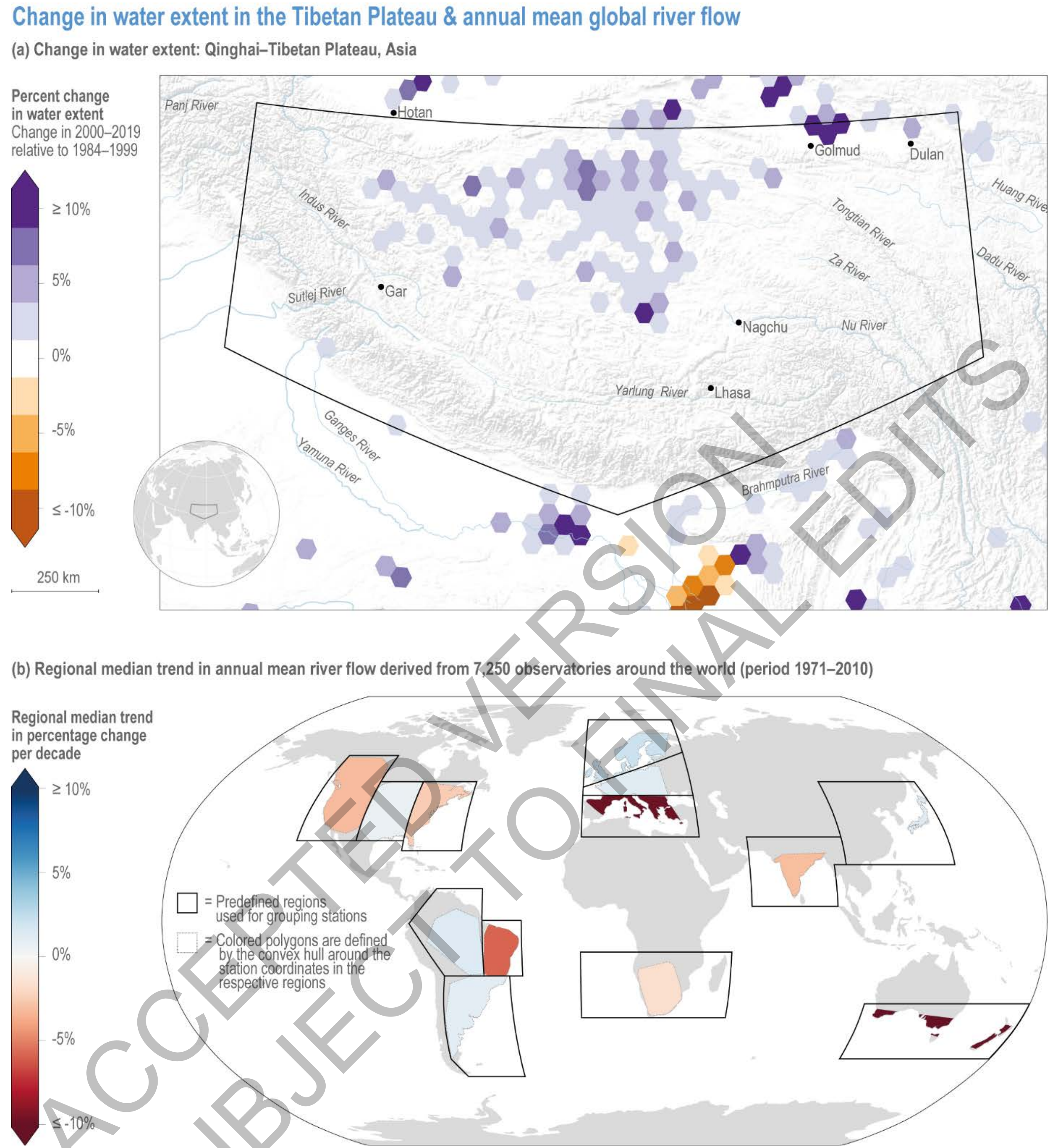


Figure 2.3: Change in water extent in the Tibetan Plateau and annual mean global river flow. a) Changes in water storage on the Tibetan Plateau. Map of the Qinghai-Tibetan Plateau, Asia showing the percent change in surface water extent from 1984-2019 based on LANDSAT imagery. Increases in surface water extent in this region are mainly caused by climate-change mediated increases in precipitation and glacial melt (Source: EC JRC/Google; (Pekel et al., 2016). b) Global map of the median trend in annual mean river flow derived from 7250 observatories around the world (period 1971–2010). Some regions are drying (northeast Brazil, southern Australia, and the Mediterranean) and others are wetting (northern Europe) mainly caused by large-scale shifts in precipitation, changes in factors that influence evapotranspiration and alterations of the timing of snow accumulation and melt driven by rising temperatures (Source: Gudmundsson et al., 2021).

2.3.3.3 Observed Changes in Discharge

Analysis of river flows from 7,250 observatories around the world covering the years 1971 to 2010 and identified spatially complex patterns, with reductions in northeastern Brazil, southern Australia and the

Mediterranean and increases in northern Europe (*medium evidence, medium agreement*) (Figure 2.3b; Gudmundsson et al., 2021). More than half of global rivers undergo periodic drying that reduces river connectivity (*medium evidence, medium agreement*). Increased frequency and intensity of droughts may cause perennial rivers to become intermittent and intermittent rivers to disappear (*medium evidence, medium agreement*), threatening freshwater fish in habitats already characterised by heat and droughts (Datry et al., 2016; Schneider et al., 2017; Jaric et al., 2019). In high altitude/latitude streams, reduced glacier and snowpack extent, earlier snowmelt and altered precipitation patterns, attributed to climate change, have increased flow intermittency (Vorosmarty et al., 2010; Siebers et al., 2019; Gudmundsson et al., 2021) Patterns in flow regimes can be directly linked to a variety of processes shaping freshwater biodiversity, hence any climate-change induced changes on flow regimes and river connectivity are expected to alter species composition, as well as having societal impacts (See Chapter 3 of IPCC SR1.5; Bunn and Arthington, 2002; Thomson et al., 2012; Chessman, 2015; Kakouei et al., 2018)

2.3.3.4 Observed Loss of Ice

Studies since AR5 have confirmed ongoing and accelerating loss of lake and river ice in the northern hemisphere (*robust evidence, high agreement)* (Figure 2.4). In recent decades, systems have been freezing later in winter and thawing earlier in spring, reducing ice duration by >2 weeks per year and leading to increasing numbers of years with loss of perennial ice cover, leading to intermittent ice-cover or even absence of ice (Adrian et al., 2009; Kirillin et al., 2012; Paquette et al., 2015; Adrian et al., 2016; Park et al., 2016; Roberts et al., 2017; Sharma et al., 2019). The global extent of river ice declined by 25% between 1984 and 2018 (Yang et al., 2020). This trend has been more pronounced at higher latitudes, consistent with enhanced polar warming (large geographic coverage) (Du et al., 2017). Empirical long-term and remote sensing data gathered in an increasingly large number of freshwater systems supports *very high confidence* in attribution of these trends to climate change. For declines of glaciers, snow and permafrost see AR6 WGII Chapter 4 and SROCC report.

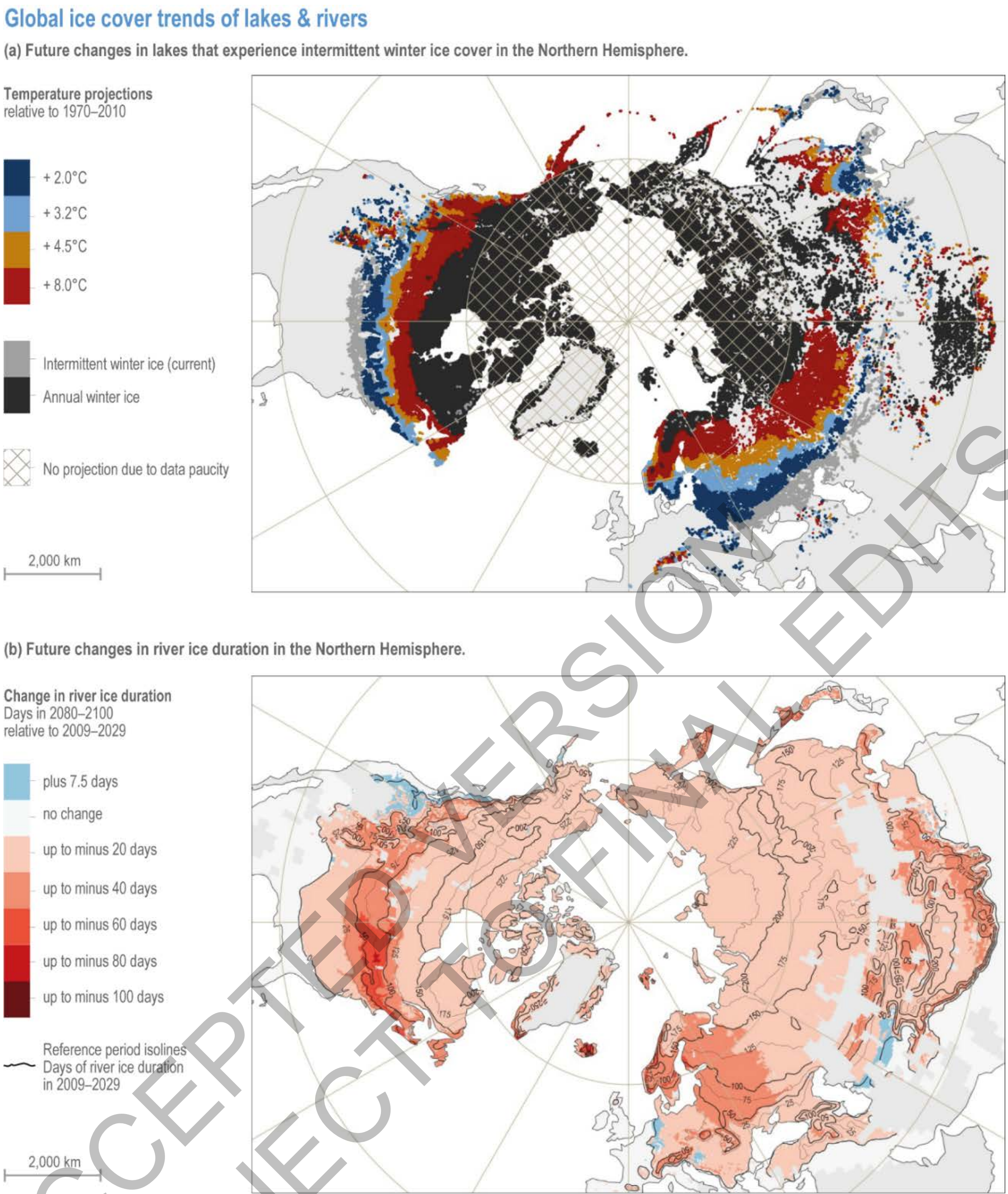


Figure 2.4: Global ice cover trends of lakes and rivers. a) Spatial distribution of current (light grey areas) and future (coloured areas) Northern Hemisphere lakes that may experience intermittent winter ice cover with climate warming. Projections were based on current conditions (1970-2010) and four established air temperature projections (Data source: (Sharma et al., 2019). b) Spatial distribution of projected change in Northern Hemisphere river ice duration under the RCP 4.5 emission scenario by 2080-2100 relative to the period 2009-2029. White areas refer to rivers without ice cover in the period 2009-2029 (zero days). Reference period isolines indicate river ice duration in the period 2009-2029. Coloured areas depict loss of ice duration in days. Blue areas depict a projected increase in river ice duration. Grey land areas indicate a lack of Landsat-observable rivers (Data source: Yang et al., 2020).

2.3.3.5 Extreme Weather Events and Freshwater Systems

Since AR5, numerous drastic short-term responses have been observed in lakes and rivers, both to expected seasonal extreme events and to unexpected supra-seasonal extremes extending over multiple seasons. Consequences for ecosystem functioning are not well understood (Bogan et al., 2015; Death et al., 2015; Stockwell et al., 2020). Increasing frequencies of severe floods and droughts attributed to climate change are major threats for river ecosystems (Peters et al., 2016; Alfieri et al., 2017). While extreme floods cause massive physical disturbance, moderate floods can have positive effects, providing woody debris that contributes to habitat complexity and diversity, flush fine sediments, dissolving organic carbon and providing important food sources from terrestrial origins (Peters et al., 2016; Talbot et al., 2018). Droughts reduce river habitat diversity and connectivity, threatening aquatic species, especially in deserts and arid regions (Bogan et al., 2015; Death et al., 2015; Ledger and Milner, 2015; Jaric et al., 2019).

Rivers already stressed by human activities such as urban development and farming on floodplains are prone to reduced resilience to future extreme events (*medium confidence*) (Woodward et al., 2016; Talbot et al., 2018). Thus, potential for floods to become catastrophic for ecosystem services are exacerbated by land-use changes (Peters et al., 2016; Talbot et al., 2018). However, biota can recover rapidly from extreme flood events if river geomorphology is not reformed. If instream habitat is strongly affected, recovery, if it occurs, takes much longer, resulting in decline in biodiversity (*medium confidence*) (Thorp et al., 2010; Death et al., 2015; Poff et al., 2018).

However, not all extreme events will have a biological impact, depending in particular on the timing, magnitude, frequency of events and the antecedent conditions (Bailey and van de Pol, 2016; Stockwell et al., 2020; Jennings et al., 2021; Thayne et al., 2021). For instance, an extreme wind event may have little impact on phytoplankton in a lake, which was fully mixed prior to the event. Conversely, storm effects on phytoplankton communities may compound when lakes are not yet recovered from a previous storm or if periods of drought alternate with periods of intense precipitation (*limited evidence*) (Leonard, 2014; Stockwell et al., 2020).

In summary, extreme events (heat waves, storms, loss of ice) affect lakes in terms of water temperature, water level, light, oxygen concentrations and nutrient dynamics, that in turn affect primary production, fish communities and greenhouse gas emissions *(high confidence)*. These impacts are modified by levels of solar radiation, wind speed and precipitation (Woolway et al., 2020a). Droughts have negative impact on water quality in streams and lakes by increasing water temperature, salinity, the frequency of algal blooms and contaminant concentrations, and reducing concentrations of nutrients and dissolved oxygen (*medium confidence*) (Peters et al., 2016; Alfieri et al., 2017) (Woolway et al., 2020a). Understanding how these pressures subsequently cascade through freshwater ecosystems will be essential for future projections of their resistance and resilience towards extreme events (Leonard, 2014; Stockwell et al., 2020). See Table SM2.1 for specific examples of observed changes.

2.3.3.6 Projected Changes in Physical Characteristics of Lakes and Rivers

Given the strength of relationship between past GAST and warming trends at lake surfaces (Figure 2.2; section 2.3.3.1), and projected increases in heatwaves, surface water temperatures are projected to continue to increase (Woolway et al., 2021). Mean May to October lake surface temperatures in 46,557 European lakes were projected to be 2.9°, 4.5°, and 6.5°C warmer by 2081-2099 compared to historic (1981-1999) under RCPs 2.0, 6.0, and 8.5, respectively (Woolway et al., 2020a). Under RCP 2.6, average lake heatwave intensity increases from 3.7° to 4.0°C and average duration from 7.7 to 27.0 days, relative to the historical period (1970-1999). For RCP 8.5, warming increases to 5.4°C and duration increases dramatically to 95.5 days (*medium confidence*) (Woolway et al., 2021).

Worldwide alteration of lake mixing regimes in response to climate change are projected (Kirillin, 2010). Most prominently, monomictic lakes–undergoing one mixing event in most years–will become permanently stratified, while lakes that are currently dimictic–mixing twice per year–will become monomictic by 2080-2100 (*medium confidence*) (Woolway and Merchant, 2019). Nevertheless, predicting mixing behavior remains an important challenge and attribution to climate change remains difficult (Schwefel et al., 2016; Bruce et al., 2018).

Under climate projections of 3.2°C warming, 4.6% of the ice covered lakes in the northern hemisphere could switch to intermittent winter ice cover (Figure 2.4a; Sharma et al., 2019). Unfrozen and warmer lakes lose more water to evaporation (Wang et al., 2018b). By 2100, global annual lake evaporation will increase by 16%, relative to 2006-2015, under RCP 8.5 (Woolway et al., 2020b). Moreover, melting of ice decreases the ratio of sensible to latent heat flux, thus channelling more energy into evaporation (*medium confidence*)

(Wang et al., 2018b). Between 2009-2029 and 2080-2100, average river ice duration is projected to decline by 7.3 and 16.7 days under the RCP 4.5 and RCP 8.5 (Figure 2.4b; Yang et al., 2020).

Projections of lake water are limited by the absence of reliable, long-term, homogenous, and spatially resolved hydrologic observations (Hegerl et al., 2015). This uncertainty is reflected in the widely divergent projections for lake water storage in response to future climate changes in individual lakes (Angel and Kunkel, 2010; Malsy et al., 2012) (MacKay and Seglenieks, 2012; Notaro et al., 2015). Selecting models that perform well when comparing hindcasted to observed past water storage variation often does little to reduce water storage projection uncertainty (Angel and Kunkel, 2010). This wide range of potential changes complicates lake management. For information on observed and projected changes in the global water cycle and hydrological regimes for streams, lakes, wetland, groundwater and their implications on water quality and societies, see Chapter 4 of WGII and Chapter 8 of WGI. For the role of weather and climate extremes on the global water cycle, see Chapter 11 of WGI.

In summary, with ongoing climate warming and an increase in the frequency and intensity of extreme events, observed increases in water temperature, losses of ice and shifts in thermal regime, are projected to continue (*high confidence*).

[START CROSS-CHAPTER BOX EXTREMES HERE]

Cross-Chapter Box EXTREMES: Ramifications of Climatic Extremes for Marine, Terrestrial, Freshwater and Polar Natural Systems

Authors: Rebecca Harris (Australia, Chapter 2, CCP3), Philip Boyd (Australia, Chapter 3), Rita Adrian (Germany, Chapter 2), Jörn Birkmann (Germany, Chapter 8), Sarah Cooley (USA, Chapter 3), Simon Donner (Canada, Chapter 3), Mette Mauritzen (Norway, Chapter 3), Guy Midgley (South Africa, Chapter 16); Camille Parmesan (France/USA/United Kingdom, Chapter 2), Dieter Piepenburg (Germany, Chapter 13, CCP6), Marie-Fanny Racault (United Kingdom/France, Chapter 3), Björn Rost (Germany, Chapter 3, CCP6), David Schoeman (Australia, Chapter 3), Maarten van Aalst (The Netherlands, Chapter 16).

Introduction

Extreme events are now causing profound negative effects across all realms of the world (marine, terrestrial, freshwater and polar) (*medium confidence*) (WGI, Chapter 9, 11; WGII AR6 Section 2.3.1, 2.3.2, 2.3.3.5, Chapter 3, Chapters 9–12). Changes to population abundance, species distributions, local extirpations and extinctions are leading to long-term, potentially irreversible shifts in the composition, structure and function of natural systems (*medium confidence*) (Frolicher and Laufkotter, 2018; Harris et al., 2018a; Maxwell et al., 2019; Smale et al., 2019). These effects have widespread ramifications for ecosystems and the services they provide – physical habitat, erosion control, carbon storage, nutrient cycling and water quality, with knock-on effects on tourism, fisheries, forestry and other natural resources (Kaushal et al., 2018; Heinze et al., 2021; Pörtner et al., 2021).

Increasingly, the magnitude of extreme events is exceeding values projected for mean conditions for 2100, regardless of emissions scenario (Figure Cross-Chapter Box EXTREMES.1). This has collapsed the timeline organisms and natural communities have to acclimate or adapt to climate change (*medium confidence)*. Consequently, rather than having decades to identify, develop and adopt solutions, there is now an urgent need to build resilience and assist recovery following extreme events.

Recent extremes highlight characteristics that enable natural systems to resist or recover from events, helping natural resource managers to develop solutions to improve resilience of natural communities and identify limits to adaptation (Bergstrom et al., 2021).

Marine Heatwaves

Consensus is emerging that anthropogenic climate change has significantly increased the likelihood of recent marine heat waves (MHWs) (*medium confidence*) (WGI AR6, Chapter 9; Oliver et al., 2018). A widespread

MHW occurred in the NE Pacific between 2013–2015, with upper ocean temperature anomalies of up to 6.2°C relative to 2002-2012 (Gentemann et al., 2017). This event, termed the "Blob", enhanced surface water stratification, decreasing nutrient supply, primary and community production, leading to widespread changes to open ocean and coastal ecosystems, with geographical shifts of key species across trophic levels, mass strandings of marine mammals, seabird mortalities and closures of commercially important fisheries (Cavole et al., 2016; Piatt et al., 2020). The heatwave reappeared in 2019 ("Blob 2.0") (Amaya et al., 2020), with similarly high temperature anomalies extending from Alaska to California, but the ecological effects of this event are expected to differ because the Blob originated in winter, and Blob2.0 intensified in summer (Amaya et al., 2020). Modelling suggests rapid shifts in the geographic distributions of important fish species in response to MHWs (Cheung & Frölicher, 2020), with projected decreased biomass and distributional shifts of fish at least four times faster and larger than the effects of decadal-scale mean changes throughout the 21st century under RCP8.5 *(high confidence*) (Cheung & Frölicher, 2020). Marine heatwaves can also dramatically increase CH4 emissions from oceans, a significant positive feedback on global warming (See also Chapter 3; Borges et al., 2019).

The Arctic region is warming more than twice as fast as the global mean, and polar organisms and ecosystems are likely to be particularly vulnerable to heatwaves due to their specific thermal niches and physiological thresholds and the lack of poleward 'refugia' (*high confidence*). The consequences of MHWs are exacerbated by concomitant sea-ice melting and freshening of surface waters, leading to secondary effects due to osmotic stress and failing pH homeostasis. Since sea-ice associated organisms are often critical components of polar food chains, cascading effects up to top predators are expected. In 2015–2016 a MHW occurred in the Gulf of Alaska/Bering Sea (Walsh et al., 2018) which was unprecedented in terms of surface temperatures and ocean heat content, geographical extent, depth range and persistence, impacting the entire marine food web. Persistent warming favoured some phytoplankton species and triggered one of the largest algal blooms recorded in this region, with concomitant oyster farm closures due to uncommon paralytic shellfish poisoning events (Walsh et al., 2018). There were also massive die-offs of common murres (*Uria aalge*) and puffins (*Fratercula cirrhata)*, attributed to starvation resulting from warming-induced effects on food supply (Jones et al., 2019). A 2017 survey found a 71% decline in abundance of Pacific cod (*Gadus macrocephalus*) since 2015, likely due to an increase in metabolic demand and reduced prey supply during the MHWs (Barbeaux et al., 2020).

Terrestrial Heatwaves

Heatwaves are now regularly occurring that exceed the physiological thresholds of some species, including birds and other small endotherms such as flying-foxes (*high confidence)* (Sections 2.4.2.2, 2.4.2.6). Heatwaves in Australia, North America and southern Africa have caused mass mortality events due to lethal hyperthermia and dehydration (Saunders et al., 2011; Conradie et al., 2020; McKechnie et al., 2021), reducing fitness (du Plessis et al., 2012; Andrew et al., 2017; Sharpe et al., 2019; van de Ven et al., 2019; van de Ven et al., 2020), breeding success and recruitment (Kennedy et al., 2013; Wiley and Ridley, 2016; Ratnayake et al., 2019) and affecting daily activity and geographic distributions (Albright et al., 2017). They also place enormous demands on wildlife management agencies and pose human health risks (Welbergen et al., 2008).

Recent mortality events affected 14 species of bird and fruit bats (*Epomophorus wahlbergi*) in South Africa when maximum air temperatures exceeded 43–45°C in 2020 (McKechnie et al., 2021). Passerine birds seem more vulnerable to lethal hyperthermia due to the relative inefficiency of panting to lose heat (McKechnie et al., 2021) and their small size, as heat tolerance generally increases with body mass (McKechnie et al., 2017). Several mass mortality events of flying-foxes (*Pteropus poliocephalus, P. alecto*) have occurred in eastern Australia when maximum air temperatures exceeded 42℃ (Welbergen et al., 2008). Nineteen such events occurred between 1994 and 2008, compared to three events prior to 1994. In January 2002, maximum temperatures exceeded the 30-year average mean daily maximum by up to 16.5℃ and killed more than 3500 individuals (Welbergen et al., 2008). In 2014, an estimated 45,500 flying-foxes died in a single day, when average maximum temperatures were 8°C or more above average (Meteorology, 2014). Drought compounds the impacts, as mortality increases when water availability is low (Welbergen et al., 2008; Mo and Roache, 2020; McKechnie et al., 2021).

Antarctica encountered its first recorded heatwave in 2020. Record-high temperatures occurred in East Antarctica (Robinson et al., 2020), with a maximum (9.2°C) temperature ~7°C above the mean maximum, and minimum temperatures > 0°C. Record-high temperatures (18.3°C) were also recorded in West Antarctica (Robinson et al., 2020). It is too soon to know the impacts on polar life, but such abrupt heating is expected to have wide-ranging effects on biota, from flash-flooding and dislodgement of plants, to excess melt waters supplying moisture to arid polar ecosystems (CCP Polar). Heatwaves in Siberia in 2016, 2018 and 2020, with air temperature anomalies >6°C, were associated with extensive wildfires, pest infestations and melting permafrost (Overland and Wang, 2021).

Freshwater Extremes

Heatwaves, storms and floods affect the thermal regime and biogeochemical functioning of lakes and rivers (Woolway and Merchant, 2017; Vicente-Serrano et al., 2020). Extreme heatwaves lead to abnormally high water temperatures (Till et al., 2019) and reduce mixing of lakes (Woolway et al., 2021), causing a decrease in oxygen and deep-water oxygen renewal (Zhang et al., 2015). Ectotherms such as fish and invertebrates are particularly susceptible to such temperature and oxygen stress (Stoks et al., 2014). Their metabolic demands increase with rising temperature and suitable habitat is eroded due to both high temperatures and lower oxygen concentrations in lakes and rivers. Till et al. (2019) attributed 502 fish kill events in Wisconsin lakes (USA) to warmer summers in lakes that experienced abnormally high water temperatures. Such events are predicted to double by 2041–2059 and increase fourfold by 2081–2099 compared to historical levels (Till et al., 2019). This anticipated increase in die-offs may facilitate warm-water fish species displacing cool-water species (Hansen et al., 2017; Jennings et al., 2021). Floods mobilise nutrients and sediment, and aid dispersal of invasive species in rivers (Death et al., 2015), while drought extremes reduce river connectivity, threatening biodiversity in rivers (Section 2.3.3.5; Tickner et al., 2020).

Learnings from Recent Extremes

These examples show that the impact of an extreme event is a function of its characteristics and those of the exposed ecosystem. The timing, frequency, absolute magnitude and geographic extent of the extreme event, relative to antecedent conditions, the life-cycle, resistance and resilience of the natural community, all determine the biological response (Figure Cross-Chapter Box EXTREMES.2; Hillebrand et al., 2018; Gruber et al., 2020). Impacts appear to be greater when extreme events occur more frequently, particularly when the interval between events is insufficient to allow recovery to previous population sizes (e.g. frequent fire, coral bleaching), or coincides with vulnerable life cycle stages, even when populations are adapted to cope with such disturbances. Events occurring over large spatial areas reduce the potential for recolonisation from nearby populations (e.g. regional droughts causing widespread declines). Often the magnitude of extreme events exceeds historical levels, so organisms are less likely to be adapted to them, particularly when several extremes coincide (e.g. high water temperatures, drought) (Duke et al., 2017). When hazards occur simultaneously (compound events), impacts of extremes can be substantially aggravated, triggering cascading effects in ecosystems (Gruber et al., 2020).

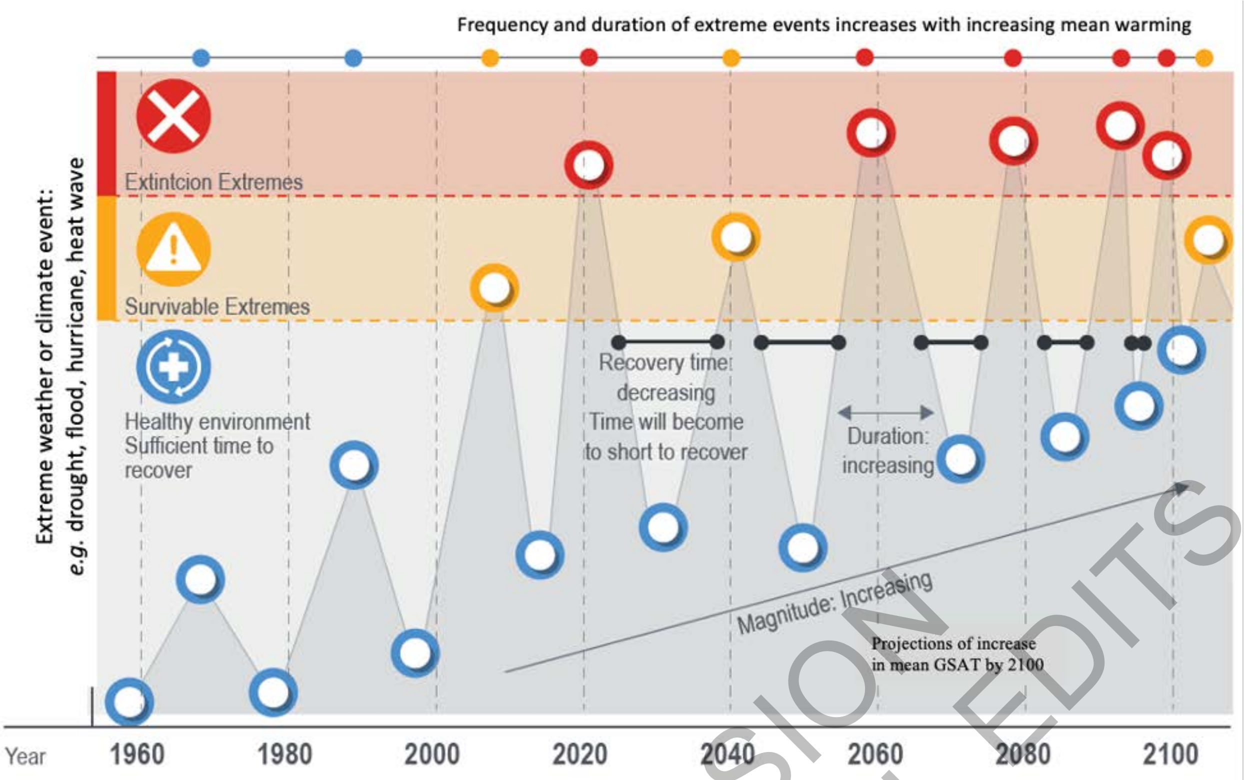


Figure Cross-Chapter Box EXTRMES.1: A conceptual illustration of how extinction risk is affected by changes in the frequency, duration and magnitude of extreme weather or climate events (e.g,. drought, fire, flood, heatwaves). Many organisms have adapted to cope with long-term and short-term climate variability, but as the magnitude and frequency of extreme events increases, superimposed on the long-term climate trend, the threshold between survivable extreme weather events (yellow) and extremes that have high risk of causing population or species extinctions (red) is crossed more frequently. This can lead to local extinction events with insufficient time between to enable recovery, resulting in long-term, irreversible changes to the composition, structure and function of natural systems. When the extreme event occurs over a large area relative to the distribution of a species (e.g., a hurricane impacting an island which is the only place a given species occurs), a single extreme event can drive the global extinction of a species.

Several characteristics of natural systems are associated with greater vulnerability to extreme events (Figure Cross-Chapter Box EXTREMES.2), knowledge of which can inform solutions to build resilience and aid recovery (Robinson et al., 2020). Resilience can be built prior to an event by minimising additional disturbances, such as water extraction from river systems, pollution of aquatic systems, land-use change and fragmentation. Managing landscapes to reduce fragmentation and increase habitat extent, connectivity and heterogeneity, by increasing the number and extent of reserves, may provide local refugia from extreme events and enhance post-event recolonisation, but may be less effective for marine systems (Chapter 3, Section 3.6). Maintaining taxonomic, phylogenetic and functional diversity is important, as more diverse systems may be more stable in the face of disturbance (Pimm, 1984; García-Palacios et al., 2018).

Several characteristics increase vulnerability: low or narrow thermal tolerances, high habitat specificity, low dispersal ability, long generation times, low competitive ability and lifecycle constraints that limit recovery or recolonisation. Populations living close to one or more limiting factors near range edges are also vulnerable (Arafeh-Dalmau et al., 2019). Understanding these characteristics can inform management intervention to aid recovery following an extreme event. For instance, knowledge of the flying-fox's physiological temperature threshold led to successful interventions, including misting of populations to reduce mortality (Mo and Roache, 2020) and the development of a 'heat stress forecaster', an online tool which uses weather forecasts to identify roosts at risk of extreme heat events (Ratnayake et al., 2019). This early-warning system increases the preparedness of wildlife management and conservation agencies, enabling efficient allocation of management resources towards locations that are likely to be most affected. Monitoring following extreme events can help identify immediate impacts and the potential for cascading interactions, such as changes to competitive interactions following range shifts, impacts on freshwater ecosystems following wildfires and the spread of invasive species. Ongoing monitoring of recovery and effectiveness of management intervention is important, focussing on habitat-forming species (eg. kelp, corals, dominant tree species) and keystone species (eg. filter feeders, macrophytes, top predators), as the loss of these species can lead to ecosystem tipping points, beyond which the system may not recover (Section 2.5.3; SROCC Chapter 6, Section 3.4.4.1; AR6 sectoral chapters, Chapter 3 section 3.4.4.1.4). The acute impacts of extreme events, in addition to the chronic stress of changing mean conditions, are accelerating and amplifying the biological effects of climate change. This amplification is being observed globally and in all realms where life exists. Extreme events are compressing the timeline available for natural systems to adapt and impeding our ability to identify, develop and adopt solutions. Recent events highlight the urgent need to mitigate global greenhouse gas emissions and identify solutions to halt accelerating impacts on natural systems (Díaz et al., 2020).

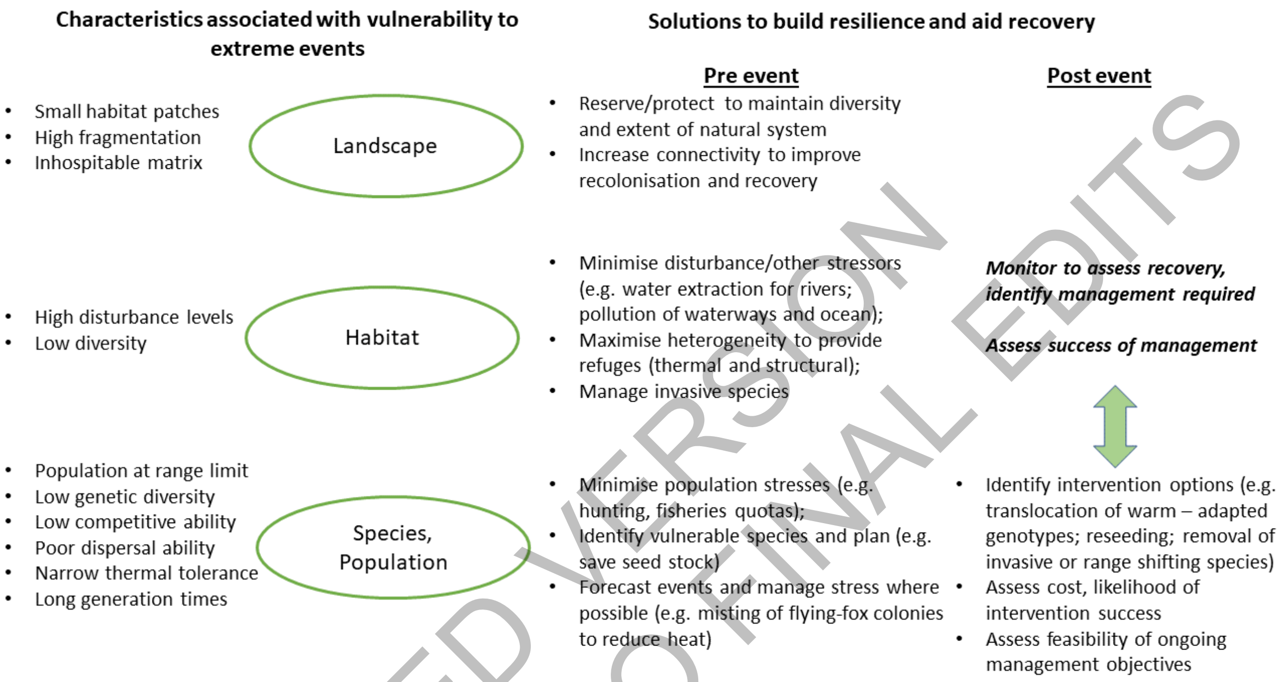


Figure Cross-Chapter Box EXTREMES.2: Characteristics of natural systems that affect vulnerability and help identify solutions – both prior to and after extreme events - to build resistance, resilience and recovery.

[END CROSS-CHAPTER BOX EXTREMES HERE]

2.4 Observed Impacts of Climate Change on Species, Communities, Biomes, Key Ecosystems and their Services

2.4.1 Overview

Global meta-analyses of terrestrial systems in AR3 and AR4 concentrated on long time frames (>20 years) and findings from relatively undisturbed areas, where confidence in attributing observed changes to climate change is high. Recent global and regional meta-analyses (AR5 and later) have been broader, including data from degraded and disturbed areas and studies with shorter time frames (Tables 2.2a,b).

By the time of AR5, >4000 species with long-term observational data had been studied in the context of climate change (Parmesan, 2006; Parmesan and Hanley, 2015). Since then, hundreds of new studies have been added, leading to higher confidence in climate change attribution (Table 2.2; Scheffers et al., 2016; Wiens, 2016; Cohen et al., 2018; Feeley et al., 2020). Freshwater habitats have been under-represented in prior reports, but new long-term data sets, coupled with laboratory and field experiments, are improving our understanding and this assessment stresses observations from lakes and streams. As numbers of studies increase and data is increasingly extracted from areas with high LULCC, attribution is more difficult as habitat loss and fragmentation are known major drivers of changes in terrestrial and freshwater species (IPBES) (Gardner and Finlayson, 2018; Grill et al., 2019; Zarfl et al., 2019; Tickner et al., 2020).

2.4.2 Observed Responses to Climate Change by Species and Communities (Freshwater and Terrestrial)

2.4.2.1 Observed Range Shifts Driven by Climate Change

Poleward and upward range shifts were already attributable to climate warming with *high confidence* in AR5. Publication of observed range shifts in accord with climate change have accelerated since AR5 and strengthened attribution. Ongoing latitudinal and elevational range shifts driven by regional climate trends are now well-established globally across many groups of organisms, and attributable to climate change with *very high confidence* due to very high consistency across a now very large body of species and studies and in-depth understanding of mechanisms underlying physiological and ecological responses to climate drivers (Table 2.2; Table 2.3, Table SM2.1;Pöyry et al., 2009; Chen et al., 2011; Grewe et al., 2013; Gibson-Reinemer and Rahel, 2015; MacLean and Beissinger, 2017; Pacifici et al., 2017; Anderegg et al., 2019b). Range shifts stem from local extinctions along warm-range-boundaries (Anderegg et al., 2019b), as well as from colonisation of new regions at cold-range-boundaries (Ralston et al., 2017).

Many studies since AR4 have tended not to be designed as attribution studies, particularly recent large scale, multispecies meta-analyses. That is, all data available were included in such studies (from both undisturbed and from highly degraded lands, and including very short term datasets of <20 years) with little attempt to design the studies to differentiate effects of climate change from effects of other potential confounding variables. These studies tended to find greater lag and lower proportion of species changing in directions expected from climate change, with authors concluding that LULCC, particularly habitat loss and fragmentation, was impeding wild species from effectively tracking climate change (Lenoir and Svenning, 2015; Rumpf et al., 2019; Lenoir et al., 2020).

Unprecedented outbreaks of spruce beetles occurring from Alaska to Utah in the 1990s were attributed to warm weather that, in Alaska, facilitated a halving of the insect's life cycle from two years to one (Logan et al., 2003). Milder winters and warmer growing seasons were likewise implicated in poleward range expansions and increasing outbreaks of several forest pests (Weed et al., 2013), leading to the current prediction that 41% of major insect pest species will increase their damage further as climate warms, and only 4% will reduce their impacts, while the rest will show mixed responses (Lehmann et al., 2020).

During their range shifts, forest pests remain climate-sensitive. For example, the distribution of Western Spruce Budworm is limited at its warm range edges by adverse effects of mild winters on overwinter survival, and at its cool range limits by ability to arrive at a cold-resistant stage before winter arrives (Régnière and Nealis, 2019). We might therefore expect tree mortality from insect outbreaks to be most severe in sites climatically less suitable for the plants, where plants would be under more stress. However, (Jaime et al., 2019), using separate SDMs (MaxEnt) for the insects and plants, found that mortality of Scots Pine from bark beetles was highest in sites most climatically suitable for the trees as well as for the insects. In a study of tree mortality in California, bark beetles selectively killed highly-stressed fir trees but killed pines according to their size, irrespective of stress status (Stephenson et al., 2019).

Range shifts in a poleward and upward direction, following expected trajectories given the local and regional climate trends, are strongly occurring in freshwater fish populations in North America (Lynch et al., 2016b), Europe (Comte and Grenouillet, 2013; Gozlan et al., 2019) and Central Asia (Gozlan et al., 2019). Cold water fish, such as coregonids and smelt have been negatively affected at the equatorial borders of their distributions (Jeppesen et al., 2012). Upward elevational range shifts in rivers and streams have been observed. Systematic shifts towards higher elevation and upstream were found for 32 stream fish species in France following regional variation in climate change (Comte and Grenouillet, 2013). Bull trout (*Salvelinus confluentus*) in Idaho (USA), were estimated to have lost 11–20% (8–16% decade^{-1}) of the headwater stream lengths necessary for cold water spawning and early juvenile rearing, with the largest losses occurring in the coldest habitats (Isaak et al., 2010). Range contractions of the same species have been found in the Rocky Mountain watershed (Eby et al., 2014). Likewise, the distribution of the stonefly *Zapada glacier*, endemic to alpine streams of Glacier National Park in Montana (USA), has been reduced over several decades by upstream retreat to higher, cooler sites as water temperatures have increased and glacial masses decreased (Giersch et al., 2015).

The melting of glaciers has led to a change in water discharge associated with community turnover in glacier-fed streams (Cauvy-Fraunié and Dangles, 2019). For instance, glacier-obligate macroinvertebrates have started disappearing when glacial cover drops below approximately 50% (*robust agreement, high confidence)*, reviewed in (Hotaling et al., 2017). For freshwater invertebrates, no meaningful trends have been detected in geographic extent or population size for most species (Gozlan et al., 2019).

An invasive freshwater cyanobacterium in lakes*, Cylindrospermopsis raciborskii,* originating from the tropics, has spread to temperate zones over the last few decades due to climate change-induced earlier increase of water temperature in spring (Wiedner et al., 2007), aided by a competitive advantage in eutrophic systems (Ekvall et al., 2013; Urrutia-Cordero et al., 2016).

2.4.2.2 Observed Local Population and Global Species' Extinctions Driven by Climate Change

Disappearances of local populations within a species range are more frequent and better documented than whole species' extinctions, and attribution to climate change is possible for sites with minimal confounding non-climatic stressors. Changes of temperature extremes are often more important to these local extinction rates than changes of mean annual temperature (see Sections 2.3.1, 2.3.2, 2.3.3.5, 2.4.2.6, Cross-chapter Box EXTREMES this Chapter; Parmesan et al., 2013). In a study of 538 plant and animal species, sites with local extinctions were associated with smaller changes of mean annual temperature but larger and faster changes of hottest yearly temperatures than sites where populations persisted (Román-Palacios and Wiens, 2020). Near warm range limits, 44% of species had suffered local extinctions. In both temperate and tropical regions, sites with local extinction had greater increases in maximum temperatures than those without (T_{max} increased 0.456°C and 0.316°C vs. T_{mean} increase of 0.153 °C and 0.061 °C for temperate (n=505 sites) and tropical (n=76 sites), respectively, $P < 0.001$) (Román-Palacios and Wiens, 2020).

Wiens (2016) assumed that population extinctions were primarily driven by climate change when they occurred at elevational or latitudinal "warm edge" range limits, and were in relatively undisturbed sites that were stated by authors to be under increasing climatic stress. By this criterion, climate-caused local extinctions were widespread among plants and animals, detected in 47% of 976 species examined. The percentage of species suffering these extinctions was higher in the tropics (55%), than in temperate habitats (39%), higher in freshwater (74%), than in marine (51%) or terrestrial (46%) habitats and higher in animals (50%) than in plants (39%). The difference between plants and animals varied with latitude: in the temperate zone a much higher proportion of animals than plants suffered range-limit extinctions (38.6% of 207 animal species versus 8.6% of 105 plants, $p < 0.0001$) while at tropical sites local extinction rates were (nonsignificantly) higher in plants (59% of 155 species) than in animals (52% of 349 species), the reverse of their temperate zone relationship. Rates varied among animal groups, from 35% in mammals through 43% in birds to 56% in insects and 59% in fish (Wiens, 2016).

Freshwater population extinctions are mainly due to habitat loss, introduction of alien species, pollution, over-harvesting (Gozlan et al., 2019; IPBES, 2019) and climate change induced epidemic diseases (Pounds et al., 2006)(see Section 2.4.2.7.1). Climate warming particularly through intensification and severity of droughts, contributes to the disappearance of small ponds, which hold rare and endemic species (Bagella et al., 2016). Systematic data on the extent and biology of small ponds is, however, lacking at a global scale. Extreme heat waves can lead to large local fish kills in lakes (see Section 2.3.3.5), when water temperature and oxygen concentrations surpass critical thresholds, threatening cold water fish and amphibians (Thompson et al., 2012). Evidence for a local extinction of some invertebrate species with a 1.4°–1.7°C rise in mean annual stream winter temperature from 1981–2005 was reported in (Abrahams et al., 2013). Population declines of specialist species in glacier-fed streams, such as the non-biting midge *Diamesa davisi* (Chironomidae), can be attributed to glacier retreat given climate change (Cauvy-Fraunié and Dangles, 2019), and the flatworm *Crenobia alpina* (Planariidae) has been reported as locally extinct in the Welsh Llyn Brianne river (Durance and Ormerod, 2010; Larsen et al., 2018).

Many high montane possums in Australia have low physiological tolerance to heatwaves, with death occuring due to heat-driven dehydration at temperatures exceeding 29°–30°C for >4–5 hours over several days (Meade et al., 2018; Turner, 2020), with major declines recorded for several species, and population extinctions at lower elevations, since the early 2000s (Chandler, 2014; Weber et al., 2021).

Two terrestrial and freshwater species have gone extinct, with climate change implicated as a key driver. The cloud-forest-restricted Golden toad (*Incilius periglenes*) was extinct by 1990 in a nature preserve in Costa Rica, driven by successive extreme droughts. This occurred in the absence of chytridiomycosis infection, caused by the fungal pathogen *Batrachochytrium dendrobatidis* (BD), verified during field censuses of golden toad populations in the process of extinction and through genetic analyses of museum specimens, although Bd was present in other frog species in the region *(medium evidence, high agreement)* (Pounds et al., 1999; Pounds et al., 2006; Puschendorf et al., 2006; Richards-Hrdlicka, 2013). The interaction between expansion of chytrid fungus globally and local climate change is implicated in the extinction of a wide range of tropical amphibians (see Section 2.4.2.7.1 Case study 2 *Chytrid fungus and climate change*).

The Bramble Cay Melomys *(Melomys rubicola)*, the only mammal endemic to the Great Barrier Reef, inhabited a small (five hectare) low-lying (<3m high) cay in the Torres Strait Islands, Australia. Recorded having a population size of several hundred in 1978, this mammal has not been seen since 2009 and was declared extinct in 2016 (Gynther et al., 2016). SLR, documented increases in storm surge and in tropical cyclones, driven by climate change, led to multiple inundations of the island in the 2000s. Between 1998 and 2014, herbacious vegetation, the food resource for the BC Melomys, declined by 97% in area (from 2.2 ha down to 0.065 ha), and from 11 plant species down to two (Gynther et al., 2016; Watson, 2016; Woinarski, 2016; Woinarski et al., 2017). The island was unihabited with few non-climatic threats, providing *high confidence* in attribution of extinction of the BC Melomys to climate change-driven increases in frequency and duration of island inundation (Turner and Batianoff, 2007; Woinarski et al., 2014; Gynther et al., 2016; Watson, 2016; Woinarski et al., 2017).

In the IUCN Red List (IUCN, 2019), 16.2% of terrestrial and freshwater species (n=3,777 species) that are listed as endangered, critically endangered or extinct in the wild (n=23,251 species) list climate change or severe weather as one of their threats.

[START FAQ2.1 HERE]

FAQ2.1: Will species go extinct with climate change and is there anything we can do to prevent it?

Climate change is already posing major threats to biodiversity and the most vulnerable plants and animals are likely to go extinct. If climate change continues to worsen, it is expected to cause many more species to go extinct unless we take actions to improve the resilience of natural areas, through protection, connection and restoration. We can also help individual species that we care most about by reducing the stress they are under from other human activities, and even helping them move to new places as their climate space shifts and they need to shift to keep up.

Climate change has already caused some species to go extinct, and is likely to drive more species to extinction. Species have always gone extinct in the history of our planet but human activities causing climate change are accelerating this process. For instance, recent research predicts that one-third of all plant and animal species could be extinct by 2070 if climate change continues as it is. Species can adapt to some extent to these rapidly changing climate patterns. We are seeing changes in behaviour, dispersal to new areas as the climate becomes more suitable, and genetic evolution. However, these changes are small, and adaptations are limited. Species that cannot adapt beyond their basic climate tolerances (ability to survive extremes of temperature or rainfall) or successfully reproduce in a different climate environment from what they have evolved in, will simply disappear. In the Arctic for example, sea ice is melting and will likely disappear in summer time within a century. This means that the animals that have evolved to live on sea ice - polar bears and some seals and sea lions - will go extinct.

Fortunately, there are some things we can do to help. We can take actions to assist, protect and conserve natural ecosystems and prevent the loss of our planet's endangered wildlife, such as:

"Assisting" species' migration: This has many names, "assisted colonisation", "assisted translocation", "assisted migration", "assisted movement". In effect, it is about helping endangered species to move to a new area with a good habitat for them to survive. "Passive" assisted colonisation focuses on helping species move themselves, whilst the most "active" form implies picking up individuals and transporting them to a new location. This is different from re-introductions that are already a normal part of conservation programs. Climate-driven translocations are moving plants or animals to an area where they have never lived historically, a new location that is now suitable for them due to climate change.

This active form of "assisted colonisation" has been controversial, because exotic species can become invasive when they are moved between continents or oceans. For example, no one would advocate moving polar bears to Antarctica, as they would likely fest on native penguins, thus causing another conservation problem. However, moving species only a few hundred kilometers avoids most adverse outcomes, and that is often all that is needed to help a wild plant or animal cope with climate change. In extreme cases, another type of assisted adaptation is to preserve species until we get climate change under control and can reintroduce them to the wild. This might include moving them into zoos or into seed or frozen embryo banks.

Extending protected zones and their connectivity: Species' ability to move to new locations and track climate change are very limited – in particular, when a habitat has been turned into a crop field or a city. To help them move between their natural habitats, we can increase the connectedness of protected areas or simply create small patches or corridors of semi-wild nature within a largely agricultural or inhabited region, that encourages wildlife to move through an area, and in which they are protected from hunting and poisons. Those semi-wild protected areas can be very small, like the hedgerows between fields in England, that provide both habitats for many flowers, birds, insects and corridors to move between larger protected areas. Alternatively, it can just be an abandoned field that is now growing "weeds" without pesticides, hunting or farming. For instance, in the United States of America, private landowners get a tax break by making their land a "wildlife conservation" area using no pesticide, not cutting weeds too often, putting up brush piles and bird boxes for nesting, and providing a water source.

Assisting, protecting and conserving natural ecosystems would help enhance biodiversity overall as well as already endangered species. Diverse plant and animal communities are more resilient to disturbances, including climate change. A healthy ecosystem also recovers more quickly from extreme events, such as floods, droughts and heat waves that are a part of human-driven climate change. Healthy ecosystems are critical to prevent species' extinctions from climate change, but are also important for human health and well-being, providing clean, plentiful water, cleaning the air, providing recreation and holiday adventures, and making people feel happier, calmer and more contented.

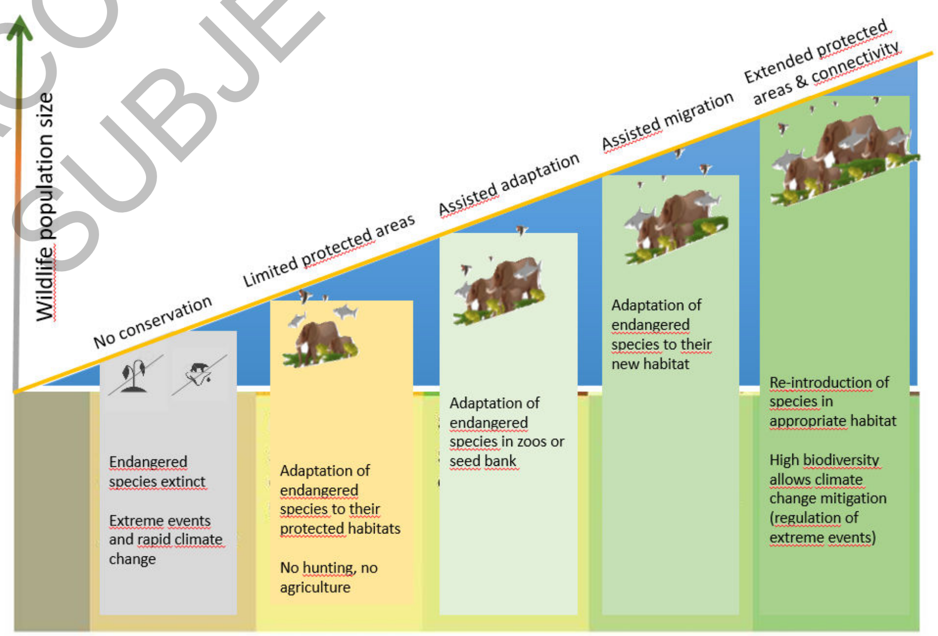


Figure FAQ2.1.1: Possible actions to assist protect and conserve natural ecosystems and prevent the loss of our planet's endangered wildlife in the face of continued climate change. *(Inspired by Natural Alliance website © Chris Heward/GWCT)*

[END FAQ2.1 HERE]

2.4.2.3 Observed Changes in Community Composition Driven by Climate Change

2.4.2.3.1 Overall patterns of community change

The most common type of community change takes the form of in situ decreases of cold-adapted species and increases of warm-adapted species (Bowler et al., 2017; Hughes et al., 2018; Kuhn and Gégout, 2019; Feeley et al., 2020). This process has lead to increases of species richness on mountaintops and decreased richness at adjacent lower elevations *(medium evidence, high agreement)* (Forister et al., 2010; Steinbauer et al., 2018). Observed shifts in community composition have consequences for species' interactions. Such indirect effects of climate change have been shown to often have greater impacts on species than direct effects of climate itself, particularly for higher level consumers (Ockendon et al., 2014).

Like other responses, analyses indicated responses were lagging behind the change expected from regional warming, and thereby accumulating 'climate debt.' Examples of climate debt, measured from community composition changes, come from birds and butterflies in Europe (Devictor et al., 2012) and from lowland forest herbaceous plants in France (Bertrand et al., 2011). The French study found that larger debts occurred in communities with warmer baseline conditions and that some of the apparent debt stemmed from species' ability to tolerate warming in situ. Geothermal streams have provided evidence about community structure and ecosystem function in high temperatures. A study of 14 such habitats reported simplified the food-web structures and shortened pathways of energy flux between consumers and resources (*high confidence*) (O'Gorman et al., 2019).

Prominent changes in freshwater community composition, such as increases in cyanobacteria and warm tolerant zooplankton species, loss of cold water fish, gain in thermo-tolerant fish and macroinvertebrates and gain in floating macrophytes, are occurring (*medium evidence, high agreement*, *medium confidence)* (Adrian et al., 2016; Hossain et al., 2016; Short et al., 2016; Huisman et al., 2018; Gozlan et al., 2019). Changes in relative species abundances, species composition and biodiversity due to warming trends and non-climate driven changes are to be expected in lakes and rivers globally. However, thus far empirical evidence and mechanistic understanding to inform modelling is too limited to draw general conclusions about the nature of current and future climate change driven changes within entire food webs on a global scale (Urban et al., 2016).

2.4.2.3.2 Freshwater mechanistic drivers and responses

Physical changes in lakes (see Section 2.3.3) have affected primary production (see Section 2.4.4.5.2), algal bloom formation and composition, zooplankton and fish size distribution and species composition (Urrutia-Cordero et al., 2017; Gozlan et al., 2019; Seltmann et al., 2019). Declines in abundance of cold-stenothermal species (particularly Arctic charr, *Salvelinus alpinus, coregonids* and smelt) and increases in eurythermal fish (e.g. the thermo-tolerant carp *Cyprinus carpio*, common bream, pike perch, roach and shad) have been observed in northern temperate lakes associated with warming trends (*high agreement*, *medium confidence*) (Jeppesen et al., 2012; Jeppesen et al., 2014). These changes increase predation pressure on zooplankton and reduce grazing pressure on phytoplankton, which may result in higher phytoplankton biomass (De Senerpont Domis et al., 2013; Jeppesen et al., 2014; Adrian et al., 2016). Reduction in lake mixing lowers the concentration of nutrients in the epilimnion and may lead to higher silicon to phosphorous ratios negatively affecting diatom growth (Yankova et al., 2017) or overall primary productivity (see Section 2.4.4.5.2).

In as study of 1,567 lakes across Europe and North America, (Kakouei, 2021) identified climate change as the major driver of increases in phytoplankton biomass in remote areas with minimal LULCC. Greater temperature variability can be more important than long-term temperature trends as a driver of zooplankton biodiversity (Shurin et al. (2010). Reductions of winter severity attributed to anthropogenic climate change are increasing winter algal biomass, and motile and phototropic species at the expense of mixotrophic species (Özkundakci et al., 2016; Hampton et al., 2017).

Tropical lakes are prone to loss of deep-water oxygen due to lake warming with negative consequences for their fisheries and their biodiversity (Lewis Jr, 2000; Van Bocxlaer et al., 2012). Many ancient tropical lakes (Malawi, Tanganyika, Victoria, Titicaca, Towuti and Matano) hold thousands of endemic animal species (Vadeboncoeur et al., 2011).

Observed climate-change effects on freshwater invertebrates are variable (Knouft and Ficklin, 2017). In glacier-fed streams globally, climate change has caused community turnover and changes in abundances in terms of increased generalist and decreased specialist species abundances (Lencioni, 2018; Cauvy-Fraunié and Dangles, 2019). In turn, dragonflies in flowing waters, monitored during the warming period from 1988 through 2006 in Europe, did not show consistent changes in their distribution (Grewe et al., 2013), reviewed in (Knouft and Ficklin, 2017). Long-term trends in species composition and community structure of stream macroinvertebrates, specifically a general trend for decreases in species characteristic of cold, fast-flowing waters and increases of thermophilic species typical of stagnant or slow-moving waters, have been attributed to climate change (*high agreement, high confidence*) (Daufresne et al., 2007; Chessman, 2015). A study of 14 geothermal streams reported simplified food-web structures and shortened pathways of energy flux between consumers and resources (O'Gorman et al., 2019). Macrophytes benefit from rising water temperatures, but increased shading from increased phytoplankton biomass could offset this (see 2.5.3.6.2 for projections; Hossain et al., 2016; Short et al., 2016;Zhang et al., 2017a).

2.4.2.3.3 Emergence of novel communities and invasive species

As climate change is increasing the movements of species into new areas, there is concern about how exotic species are being impacted, either by becoming invasive or by already invasive species gaining even more advantage over native species. Modeling predicts that effects of climate warming on food web structure and stability favour success of invading species (Sentis et al., 2021). Both simulated warming experiments (Zettlemoyer et al., 2019) and long-term observations (Losos et al., 2010) have found phenologies of exotic species to respond more adaptively to warming than those of natives, and in the long-term observations the success of exotics was attributed to their greater phenological responsiveness. In an expert assessment of the future relative importance of different drivers of the impacts of biological invasions, climate change was named as the most important driver in polar regions, the second most important in temperate regions (after trade/transport) and the third most important in the tropics (after trade/transport and human demography/migration) (Essl et al., 2020).

However, not all exotic species become invasive. As novel climate conditions develop, novel communities made up of new combinations of species are emerging as populations and species adapt and shift ranges differentially, not always with negative consequences (*high confidence*) (Dornelas et al., 2014; Evers et al., 2018; Teixeira and Fernandes, 2020). Novel communities differ in composition, structure, function and evolutionary trajectories, as the proportion of specialists and generalists, native, introduced and range shifting species changes and species interactions are altered, ultimately affecting ecosystem dynamics and functioning (Lurgi et al., 2012; Hobbs et al., 2014; Heger and van Andel, 2019 Towards an Integrative). The exact nature of novel communities is difficult to predict because species-level uncertainties propagate at the community level due to ecological interactions (Williams and Jackson, 2007), but observations, experimental mesocosms (Bastazini et al., 2021); and theoretical models (Lurgi et al., 2012; Sentis et al., 2021) provide support that they will continue to emerge with climate change.

2.4.2.4 Observed Phenological Responses to Climate Change

With advances in remote sensing, quality and quantity of phenological data are rapidly increasing (Piao et al., 2019). Since AR5, numbers of studies have increased substantially with consistent conclusions in response to warming, including advancement of spring events and lengthening of growing seasons in temperate regions (through a combination of advancement of spring events and to a lesser extent, retardation of autumn events) *(robust evidence, high agreement)* (Table 2.2, Table 2.3, Table SM2.1; Menzel et al., 2020). In the tropics, by contrast, precipitation changes have more strongly influenced phenology than temperature changes (Cohen et al., 2018). A meta-analysis comparing observed phenological advances in birds with expectations from warming of local climates concluded that the advances fell short of expectation and that substantial phenological climate debt had been generated (Radchuk et al., 2019).

Taxonomic groups have differed in their responses (Parmesan, 2007; Thackeray et al., 2010), and a few have completely abstained from the general trends—for example, seabirds continue to breed with their pre-climate-change phenologies (Keogan et al., 2018). Newer reviews and analyses reveal differences in responses among continents and across time intervals (Piao et al., 2019). Mean advance in days per decade was 5.5 in China, and 3.0–4.2 in Europe but only 0.9 in North America (Piao et al., 2019). Mean values for retardation of autumn leaf fall, which can be more influenced by photoperiod and less by temperature than spring leaf-out, were 0.36 days per decade in Europe (Menzel et al., 2020), 2.6 days per decade in China and around 3 days per decade in the USA *(medium evidence, high agreement)* (Piao et al., 2019).

The rapid rates of advance of spring events in the 1990s slowed down in the 2000s and stalled or even reversed in some regions (Menzel et al., 2020). Wang et al. (2019) noted, from remote sensing, that during the 'global warming hiatus' from 1998–2012, there were no global trends in either Spring green-up or autumn colouring. Annual crops, for which timing is determined by farmers, were an exception. When natural systems were advancing fast prior to 1998, farmers advanced more slowly, but during the natural 'hiatus', farmed crops advanced faster than wild plants and cultivated trees (Menzel et al., 2020). In a long (67 year) European time series (Menzel et al., 2020), autumn leaf colouring showed delays attributed to winter & spring warming in 57% of observations (mean delay 0.36 days per decade); spring & summer phenologies advanced in 89% of wild plants despite decreased winter chilling, with c.60% of trends significant and 'strongly attributable' to winter & spring warming; and growing season length increased in 84% of cases (mean lengthening 0.26 days yr^{-1}) (Table 2.2).

Changes in freshwater systems are consistent with changes in terrestrial systems: earlier timing of spring phytoplankton and zooplankton development and earlier spawning by fish, as well as extension of the growing season are occurring *(robust evidence, high agreement)* (Adrian et al., 2009; De Senerpont Domis et al., 2013; Adrian et al., 2016; Thackeray et al., 2016). Phenological changes in lakes have been related to rising water temperatures, reductions of ice cover and prolongation of thermal stratification (increasing evidence and agreement since AR5; *very high confidence*). Crozier and Hutchings (2014) reviewed phenological changes in fish and documented that changes in the timing of migration and reproduction, age at maturity, age at juvenile migration, growth, survival and fecundity were associated primarily with changes in temperature. The median return time of Atlantic salmon among rivers in Newfoundland and Labrador advanced by 12 to 21 days over the past decades, associated with overall warmer conditions (Dempson et al., 2017).

2.4.2.5 Observed Complex Phenological and Range Shift Responses

Early meta-analyses tested the straightforward hypotheses that warming should shift timing earlier and ranges poleward. Once these trends had been established, exceptions to them became foci of study. For example, some plants in northern regions of the northern hemisphere were retarding their spring flowering instead of advancing it as expected with warming. These turned out to be species requiring vernalisation (winter chilling) to speed spring development. For these plants, phenological changes result from combined effects of advancement caused by spring warming and retardation caused by winter warming. Incorporating this level of complexity into analyses revealed that a greater proportion of species were responding to climate change than estimated under the simple expectation that warming should always cause advancement (92% responding vs 72% from earlier analyses) (Cook et al., 2012).

Animal species can show vernalisation equivalent to that in plants (Stålhandske et al., 2017). However, a semi-global meta-analysis across terrestrial animals failed to detect delaying effects of warming winters (Cohen et al., 2018). The same animal-based meta-analysis contrasted phenological changes in temperate-zone animals, which are principally explained by changes of temperature, with those at lower latitudes, which follow changes of precipitation (Cohen et al., 2018).

Vitasse et al. (2018), working with Alpine trees, found that phenological delay with increasing elevation had declined from 34 days per 1,000 m in the 1960s to 22 days per 1,000 m, greatly reducing the differences in timing between trees growing at different elevations. This reduction was greatest after warmer winters, suggesting winter warming as a principal cause of the overall trend.

Lian et al. (2020) observed that earlier spring leaf-out in the Northern Hemisphere is causing increases in evapotranspiration that are not fully compensated by increased precipitation. The consequence is increased soil moisture deficit in summer, expected to exacerbate impacts of heatwaves as well as drought stress. In Arctic freshwater ecosystems, Heim et al. (2015) demonstrated the importance of seasonal cues for fish migration, which can be impacted by climate change due to reduced stream connectivity and fragmentation, earlier peak flows, and increased evapotranspiration.

Precipitation has also been implicated in exceptions to the rule that ranges should be shifting to higher elevations. In dry climates, increases of precipitation accompanying climate warming can facilitate downslope range shifts (Tingley et al., 2012).

Multiple responses can co-occur. Hällfors et al (Hällfors et al., 2021), in a study of 289 lepidoptera in Finland, found 45% had either shifted their ranges northward or advanced their flight season with warming. The 15% of species that did both (shifting northward by 113.1 km and advancing flight period by 2.7 days per decade, on average, over a 20 year period) had the largest population increases, and the 40% of species that showed no response had the largest population declines.

Table 2.2: Global Fingerprints of Climate Change Impacts across Wild Species. Updated from (Parmesan and Hanley, 2015). For each dataset, a response for an individual species or functional group was classified as (1) no response (no significant change in the measured trait over time), (2) if a significant change was found, the response was classified as either consistent or not consistent with expectations from local or regional climate trends. Percentages are approximate and estimated for the studies as a whole. Individual analyses within the studies may differ. The specific metrics of climate change analysed for associations with biological change vary somewhat across studies, but most use changes in local or regional temperatures (e.g. mean monthly T or mean annual T), with some using precipitation metrics (e.g. total annual rainfall). For example, a consistent response would be poleward range shifts in areas that are warming. Probability (P) of getting the observed ratio of consistent: not consistent responses by chance was <10-13 for (Parmesan and Yohe, 2003; Root et al., 2003; Root et al., 2005; Poloczanska et al., 2013) and was <0.001 for Rosenzweig 2008 (source=publication) (Parmesan and Yohe, 2003; Root et al., 2003; Root et al., 2005; Rosenzweig et al., 2008; Poloczanska et al., 2013). Test were all binomial tests against p=0.5, performed by Parmesan.

[INSERT TABLE 2.2 HERE.]

2.4.2.6 Observed Changes to Physiology and Morphology Driven by Climate Change

Impacts on species physiology in terrestrial and freshwater systems have been observed and attributed to climate change (*medium confidence*), including changes in tolerances to high temperatures (Healy and Schulte, 2012; Gunderson and Stillman, 2015; Deery et al., 2021), increased metabolic costs of living under elevated temperatures (Scheffers et al., 2016) and shifts in sex ratios in species with temperature-dependent sex determination (e.g. masculinisation of lizard populations (Schwanz and Janzen, 2008; Schwanz, 2016; Edmands, 2021) and feminisation of turtle populations (Telemeco et al., 2009)). Skewed sex ratios can lead to mate shortages, reduced population growth and adaptive potential, and increased extinction risk, because genetic diversity decreases as fewer individuals mate and heterozygosity is lost (Mitchell and Janzen, 2010; Edmands, 2021).

Behavioural plasticity such as nest-site selection can provide a partial buffer from the effects of increasing temperature, but there are environmental and physical limits to this plasticity (*medium confidence*) (Refsnider and Janzen, 2016; Telemeco et al., 2017). Plasticity in heat tolerance (e.g. due to reversible acclimation or acclimatisation) can also potentially compensate for rising temperatures (Angilletta Jr, 2009), but ectotherms have relatively low acclimation in thermal tolerance and acclimation is expected to only slightly reduce overheating risk in even the most plastic taxa (*low confidence*) (Gunderson and Stillman, 2015).

Geographic variation in thermal tolerance plasticity is expected to influence species vulnerability and range shifts in response to climate change (Gunderson and Stillman, 2015; Sun et al., 2021). In many ectotherms, plasticity in thermal tolerance increases towards the poles, as thermal seasonality increases (Chown et al., 2004), contributing to higher vulnerability to warming in tropical organisms (*low confidence*) (Huey et al., 2009; Campos et al., 2021). Some species have evolved extreme upper thermal limits at the expense of plasticity, reflecting an evolutionary trade-off between these traits (Angilletta et al., 2003; Stillman, 2003). The most heat-tolerant species, such as those from extreme environments, may therefore be at greater risk of warming because of an inability to physiologically adjust to thermal change (*low confidence*) (Bozinovic et al., 2011; Overgaard et al., 2014; Magozzi and Calosi, 2015).

Physiological changes have observable impacts on morphology, such as changes to body size (and length of appendages) and colour changes in butterflies, dragonflies, and birds (*medium confidence*) (Galeotti et al., 2009; Karell et al., 2011), but trends are not always linear or consistent across realms, taxonomic groups or geographic regions (Gotanda et al., 2015). Some morphological changes arise in response to environmental changes rather than as the result of genetic adaptation or selection for an optimum body type. For example, dietary changes associated with climate change have led to changes in chipmunk skull morphology (Walsh et al., 2016).

Decreased body size has been suggested as a general response of species to climate change in freshwater species given the temperature related constraints of metabolism with increasing body size. Reduced body size in response to global warming has been documented for freshwater bacteria, plankton and fish, as well as a shift towards smaller species (*low confidence*) (Daufresne et al., 2009; Winder et al., 2009; Jeppesen et al., 2010; Crozier and Hutchings, 2014; Jeppesen et al., 2014; Farmer et al., 2015; Rasconi et al., 2015; Woodward et al., 2016). However, the lack of systematic empirical evidence in freshwaters and confounding effects such as interactions between temperature, nutrient availability and predation limit generalisations about body size effects (Pomati et al., 2020 Nutrients).

Evidence is weak for a consistent reduction in body size across taxonomic groups in terrestrial animals (*low confidence*) (Siepielski et al., 2019). Decreased body size in warmer climates (as higher surface area to volume ratios maximise heat loss) is expected based on biogeographic patterns such as Bergmann's Rule, but both increases and decreases have been documented in mammals, birds, lizards and invertebrates and attributed to climate change (Teplitsky and Millien, 2014; Gotanda et al., 2015; Gardner et al., 2019; Hill et al., 2021). Contrasting patterns (increased body size) may be due to short-term modifications in selection pressures (e.g. changes to predation and competition), variation in life histories or a result of interactions with climate variables other than temperature (e.g. changes to food availability with rainfall changes) and other disturbances (Yom-Tov and Yom-Tov, 2004; Gardner et al., 2019; Wilson et al., 2019) or body size measurements (linear vs. volumetric dimensions) (Salewski et al., 2014).

Several lines of evidence suggest evolution of melanism in response to climate change (*low confidence*), with colour changes associated with thermoregulation being demonstrated in butterflies (Zeuss et al., 2014; MacLean et al., 2016; MacLean et al., 2019a), beetles (de Jong and Brakefield, 1998; Brakefield and de Jong, 2011; Zvereva et al., 2019), dragonflies (Zeuss et al., 2014) and phasmids (Nosil et al., 2018). Such changes may represent decreased phenotypic diversity and, potentially, genetic diversity (*low confidence*), but the consequences of climate change on the genetic structure and diversity of populations have not been widely assessed (Pauls et al., 2013). Simplistically, the thermal melanism hypothesis suggests that lighter (higher reflectance) individuals should have increased fitness and therefore be selected for in a warmer climate (Clusella-Trullas et al., 2007). However, several biotic (e.g thermoregulatory requirements, predator avoidance, signalling) and abiotic (e.g. UV, moisture, interannual variability) factors interact to influence changes in colour, making attribution to climate change across species and broad geographic regions difficult (Kingsolver and Buckley, 2015; Stuart-Fox et al., 2017; Clusella-Trullas and Nielsen, 2020).

Interactions between morphological changes and changes to phenology may facilitate or constrain adaptation to climate change (*medium confidence*) (Hedrick et al., 2021). For example, advancing phenology in migratory species may impose selection on morphological traits (e.g. wing length) to increase migration speed. If advancing spring phenology results in earlier breeding, this may offset the effect of rising temperatures in the breeding range and reduce the effect of increasing temperature on body size (Zimova et al., 2021). A study of 52 species of North American migratory birds, based on more than 70,000 specimens, showed that spring migration phenology has advanced over the past 40 years, concurrent with widespread shifts in morphology (reduced body size and increased wing length), perhaps to compensate for the increased metabolic cost of flight as body size decreases (Weeks et al., 2020).

A lack of understanding of physiological constraints and mechanisms remains a barrier to predicting many of the ecological effects of climate change (Bozinovic et al., 2011; Vázquez et al., 2017; González-Tokman et al., 2020). Many behavioural, morphological and physiological responses are highly species and context specific, making generalisations difficult (Bodensteiner et al., 2021). Recent advances in mechanistic understanding (from experiments), in process-based modeling that includes microclimates and developmental processes (Carter and Janzen, 2021) and in sophistication of niche models (Kearney et al., 2009) have improved projections, but comprehensive tests of geographic patterns and processes in thermal tolerance and plasticity are still lacking, with studies limited to a few phylogenetically restricted analyses showing mixed results (Gunderson and Stillman, 2015). Improved understanding of the mechanistic basis for observed geographic patterns in thermal tolerance and plasticity is needed to identify species' physiological limits, the potential for adaptation and the presence of evolutionary trade-offs, which will strongly influence population declines, species range shifts, invasive interactions and success of conservation interventions (Cooke et al., 2021; Ryan and Gunderson, 2021).

2.4.2.7 Observed Impacts of Climate Change on Diseases of Wildlife and Associated Impacts on Humans

Assessment of changes in diseases of terrestrial and freshwater wild organisms was scarce in WGII AR4, AR5, IPCC SR1.5 and IPCC SRCCL. Most emerging infectious diseases (EIDs) are zoonoses, that is, transmissible between humans and animals, and climate sensitive (Woolhouse et al., 2001; Woolhouse and Gowtage-Sequeria, 2005; McIntyre et al., 2017; Salyer et al., 2017). WGII AR4 found weak to moderate evidence that disease vectors and their diseases had changed their distributions in concert with climate change, but attribution studies were lacking. In WGII AR5 Chapter 11, geographic expansion of a few vector borne diseases (VBDs) to higher latitudes and elevations had been detected and associated with regional climate trends, but non-climatic drivers were not assessed well, leading to only a *medium confidence* in attribution) (IPCC, 2014). Here we build upon previous assessments by focusing on changes in population dynamics and geographic distributions of diseases of wildlife, and those of humans and domestic animals that are also harbored, amplified, and transmitted by wild animal reservoir hosts and vectors.

Increased disease incidence is correlated with regional climatic changes and is expected from underlying biology of relationships between temperature, precipitation, and disease ecology (*robust evidence, high agreement*) (Norwegian Polar Institute, 2009; Tersago et al., 2009; Tabachnick, 2010; Paz, 2015; Dewage et al., 2019; Deksne et al., 2020; Shocket et al., 2020; Couper et al., 2021). Whether increases in diseases in wild and domestic animals correspond to increased disease risk in nearby human populations is complicated by potential buffering effects of the local medical system, healthcare access, socio-economic status, education, behaviours and general health of the human population (see also Chapter 7 and Cross-Chapter Box ILLNESS this Chapter).

2.4.2.7.1 Direct effects of climate on reproduction, seasonality, growing season length and transmission of pathogens, vectors, and hosts

VBDs require arthropod vector hosts (e.g., insects or ticks), while other infectious diseases (e.g., fungi, bacteria, and helminths) have free-living life stages and/or complex life cycles that require intermediate hosts (e.g., snails), all of which have temperature-driven rates of development and replication/reproduction *(robust evidence, high agreement)* (Mordecai et al., 2013; Liu-Helmersson et al., 2014; Moran and Alexander, 2014; Bernstein, 2015; Marcogliese, 2016; Ogden and Lindsay, 2016; Mordecai et al., 2017; Short et al., 2017; Caminade et al., 2019; Cavicchioli et al., 2019; Mordecai et al., 2019; Liu et al., 2020; Rocklöv and Dubrow, 2020). Additionally, microbes such as bacteria thermally adapt to temperature changes through multiple mechanisms, indicating that warming will not reduce antibiotic resistance (MacFadden et al., 2018; Pärnänen et al., 2019; Shukla, 2019; McGough et al., 2020; Rodriguez-Verdugo et al., 2020).

There is increasing evidence for a role of extreme events in disease outbreaks (Tjaden et al., 2018; Bryson et al., 2020). Heat waves have been associated with outbreaks of helminth pathogens, especially in subarctic and Arctic areas. For example, a severe outbreak of microfilaremia, a vector-borne disease spread by mosquitoes and flies, plagued reindeer in northern Europe following extreme high temperatures (Laaksonen et al., 2010). More frequent and severe extreme events such as floods, droughts, heat waves, and storms can either increase or decrease outbreaks, depending upon the region and disease (*robust evidence, high agreement*) (Anyamba et al., 2001; Marcheggiani et al., 2010; Brown and Murray, 2013; Paz, 2015; Boyce et al., 2016; Wu et al., 2016b; Wilcox et al., 2019; Nosrat et al., 2021). Heavy precipitation events have been shown to increase some infectious diseases with aquatic life cycle components such as mosquito-borne, helminth, and rodent-borne diseases (*robust evidence, high agreement*) (Anyamba et al., 2001; Zhou et al., 2005; Wu et al., 2008; Brown and Murray, 2013; Anyamba et al., 2014; Boyce et al., 2016). Conversely, flooding also increases flow rate and decreases parasite load and diversity in other aquatic wildlife (Hallett and Bartholomew, 2008; Bjork and Bartholomew, 2009; Marcogliese, 2016; Marcogliese et al., 2016) and can reduce mosquito abundance by flushing them out of the system (Paaijmans et al., 2007; Paz, 2015).

Droughts reduce aquatic habitat of some mosquito species while simultaneously increasing the availability of stagnant standing pools of water that are ideal breeding habitats for other species, such as dengue vector *Aedes* mosquitos *(medium evidence, medium agreement)* (Chareonviriyaphap et al., 2003; Chretien et al., 2007; Padmanabha et al., 2010; Trewin et al., 2013; Paz, 2015). Extreme drought has been associated with an increase in bluetongue virus haemorrhagic disease in wildlife in eastern North America, though mechanisms were not identified (Christensen et al., 2020). Heatwaves in some regions, especially coastal regions, increased parasitism and decreased host richness and abundance leading to population crashes (Larsen and Mouritsen, 2014; Mouritsen et al., 2018). Changes in temperature and precipitation, especially extreme events, can alter community structure (Larsen et al., 2011) by increasing or decreasing parasites and their host organisms and even altering host behavior in ways advantageous to parasites (Macnab and Barber, 2012).

Climate change not only affects the occurrence of pathogens and their hosts in geographic space but also the temporal patterns of disease transmission. Warmer winters allow greater overwinter survival of arthropod vectors which, coupled with lengthened tranmission seasons, drive increases in vector population sizes, pathogen prevalence, and hence proportion of vectors infected *(robust evidence, high agreement)* (Laaksonen et al., 2009; Molnár et al., 2013; Waits et al., 2018). For example, a parasitic nematode lung worm (*Umingmakstrongylus pallikuukensis)* has shortened its larval development time in half (from two years to one year), which has increased infection rates in North American muskoxen (Norwegian Polar Institute, 2009).

Case study 1: Climate change impacts on pathogenic helminths in Europe

Parasitic helminth worms can reduce growth and yield, or kill livestock, and infect humans and wildlife, leading to health, agricultural and economic losses (Fairweather, 2011; Charlier et al., 2016; Charlier, 2020). Attribution of increased helminth disease incidence and risk to climate change is stronger than for most human diseases because of long-term records and careful analysis of other anthropogenic drivers (e.g. land use change, agricultural/livestock intensification, and antihelminthic intervention and resistance) (van Dijk et al., 2008; van Dijk et al., 2010; Fox et al., 2011b; Martínez-Valladares et al., 2013; Charlier et al., 2016; Innocent et al., 2017; Mehmood et al., 2017).

In Europe, evidence from laboratory studies, long term surveillance, statistical analyses, and modelling shows that multiple helminth pathogens and their host snails have extended their transmission windows and have increased survival, fecundity, growth and abundances (*robust evidence, high agreement)*. Furthermore, they have expanded or shifted their ranges poleward due to increases in temperature, precipitation and humidity (*robust evidence, high agreement*) (Lee et al., 1995; Pritchard et al., 2005; Poulin, 2006; van Dijk et al., 2008; van Dijk et al., 2010; Fairweather, 2011; Fox et al., 2011b; Martínez-Valladares et al., 2013; Bosco et al., 2015; Caminade et al., 2015; Caminade et al., 2019). These documented changes in climate, hosts and pathogens have been linked to higher disease incidence and more frequent outbreaks in livestock across Europe (*high confidence*) (Bosco et al., 2015).

Case study 2: Chytrid fungus and climate change

Infection by the chytrid fungus, *Batrachochytrium dendrobatidis* (Bd), can cause chytridiomycosis in amphibians. Bd is widely distributed globally and has caused catastrophic disease in amphibians, associated with declines of 501 species and extinctions of a further 90 species, primarily in tropical regions of the Americas and Australia (Scheele et al., 2019; Fisher and Garner, 2020). Bd successfully travelled with high-elevation Andean frog species as they expanded their elevational ranges upward, driven by regional warming, to > 5200 m (Seimon et al., 2017).

New findings since AR5 from controlled laboratory experiments (manipulating temperature, humidity and water availability), intensive analyses of observed patterns of infection and disease in nature, and modeling studies have led to an emerging consensus that interactions between chytrids and amphibians are climate-sensitive, and that the interaction of climate change and Bd has driven many of the observed global amphibian declines and species' extinctions *(robust evidence, high agreement)* (Rohr and Raffel, 2010; Puschendorf et al., 2011; Rowley and Alford, 2013; Raffel et al., 2015; Sauer et al., 2018; Cohen et al., 2019a; Sauer et al., 2020; Turner et al., 2021).

The "thermal mismatch hypothesis" posits that vulnerability to disease should be higher at warm temperatures in cool-adapted species and higher at cool temperatures in warm-adapted species and is generally supported. However, the most recent studies reveal more complex mechanisms underlying amphibian-disease-climate change dynamics, including variation in thermal preferences among individuals in a single amphibian population *(robust evidence, high agreement)* (Zumbado-Ulate et al., 2014; Sauer et al., 2018; Cohen et al., 2019b; Neely et al., 2020; Sauer et al., 2020).

Bd is not universally harmful—it has been recorded as endemic in frog populations that did not suffer disease, where it may be commensal rather than parasitic (Puschendorf et al., 2006; Puschendorf et al., 2011; Rowley and Alford, 2013). Projections of future impacts are difficult, as the virulence of Bd is variable across Bd populations and dependent upon the evolutionary and ecological histories, and evolutionary potentials, of both the local amphibian populations and the endemic or invading Bd *(robust evidence, high agreement)* (Retallick et al., 2004; Daskin et al., 2011; Puschendorf et al., 2011; Phillips and Puschendorf, 2013; Rowley and Alford, 2013; Zumbado-Ulate et al., 2014; Sapsford et al., 2015; Voyles et al., 2018; Bradley et al., 2019; Fisher and Garner, 2020; McMillan et al., 2020). Further, specific local habitats might serve as regional climate refugia from chytrid infection (e.g. hot and dry) *(medium evidence, high agreement)* (Zumbado-Ulate et al., 2014; Cohen et al., 2019b; Neely et al., 2020; Turner et al., 2021).

2.4.2.7.2 Effects on geographic distribution and connectivity patterns of pathogens

As species' geographic ranges and migration patterns are modified by climate change (Section 2.4.2.1, Table 2.2), pathogens accompany them. Diverse vectors and associated parasites, pests, and pathogens of plants and animals are being recorded at higher latitudes and elevations in conjunction with regional temperature increases and precipitation changes *(robust evidence, high agreement),* although analysis of realized disease incidence often lacks inclusion of non-climatic vs climate drivers, compromising attribution (Ollerenshaw and Rowlands, 1959; Purse et al., 2005; Laaksonen et al., 2010; van Dijk et al., 2010; Alonso et al., 2011; Genchi et al., 2011; Pinault and Hunter, 2011; Jaenson et al., 2012; Loiseau et al., 2012; Kweka et al., 2013; Medlock et al., 2013; Dhimal et al., 2014a; Dhimal et al., 2014b seasonal; Siraj et al., 2014; Khatchikian et al., 2015; Hotez, 2016a; Hotez, 2016b; Bett et al., 2017; Mallory and Boyce, 2017; Strutz, 2017; Booth, 2018; Dumic and Severnini, 2018; Carignan et al., 2019; Gorris et al., 2019; Le et al., 2019; Stensgaard et al., 2019b snails and; Brugueras et al., 2020; Gilbert, 2021).

At least six major VBDs affected by climate drivers have recently emerged in Nepal and are now considered endemic, with climate change implicated as a primary driver as LULCC has been assessed to have a minimal influence on these diseases (*high confidence*) (Table SM2.1). There is *increasing evidence* that climate warming has extended the elevational distribution of *Anopheles, Culex* and *Aedes* mosquito vectors above 2,000 m in Nepal *(limited evidence, high agreement)* (Dahal, 2008; Dhimal et al., 2014a; Dhimal et al., 2014b; Dhimal et al., 2015) with similar trends being recorded in neighboring Himalayan regions *(medium evidence, high agreement)* (Phuyal et al., 2020; Dhimal et al., 2021). Host animals in novel areas may be immunologically naive, and therefore more vulnerable to severe illness (Bradley et al., 2005; Hall et al., 2016).

Case study 3: Arctic and subarctic disease expansion and intensification

High Arctic regions have warmed by more than double the global average, >2°C in most areas (see Sections 2.3.1.1.2, Figure 2.11, and Atlas 11.2.1.2, in WGI). Experimental, field ecology studies and computational models in Arctic and subarctic regions indicate that milder winters have reduced mortality of vectors and reservoir hosts and increased their habitat as forested taiga expands into previously treeless tundra (Table SM2.1; Parkinson et al., 2014). Warmer temperatures and longer seasonal windows have allowed faster reproduction/replication, accelerated development, and increased the number of generations per year of pathogens, vectors and some host animals, that in turn increase the populations of disease organisms and disease transmission (Sections 2.4.2.4, 2.4.4.3.3). Ticks, mosquitos, culicoides biting midges, deer flies, horseflies, and simuliid black flies that transmit a variety of pathogens are being documented in high-latitude regions at higher numbers or where they have been historically absent (*robust evidence, high agreement*) (Waits et al., 2018; Caminade et al., 2019; Gilbert, 2021). In concert with these poleward shifts of hosts and vectors, pathogens, particularly tick-borne pathogens and helminth infections, have increased dramatically in incidence and severity from once rare occurrences and have appeared in new regions (*robust evidence, high agreement, very high confidence*) (Caminade et al., 2019; Gilbert, 2021).

Zoonoses and VBDs that have been historically rare or never documented in Arctic and subarctic regions of Europe, Asia, and North America, such as anthrax, cryptosporidiosis, elaphostrongylosis, filariasis (Huber et al., 2020), tick-borne encephalitis, and tularemia (Evander and Ahlm, 2009; Parkinson et al., 2014; Pauchard et al., 2016), are spreading poleward and increasing in incidence *(robust evidence, high agreement, very high confidence)* (Table SM2.1; Omazic et al., 2019). Recent anthrax outbreaks and mass mortality events among humans and reindeer, respectively, have been linked to abnormally hot summer temperatures that caused permafrost to melt and exposed diseased animal carcasses, releasing thawed, highly infectious, *Bacillus anthracis* spores *(medium evidence, medium agreement)* (Ezhova et al., 2019; Hueffer et al., 2020; Ezhova et al., 2021). Multiple contributing factors conspired over different time scales to compound a 2016 anthrax outbreak occurring on the Yamal peninsula: (i) rapid permafrost thawing for 5 years preceding the outbreak; (ii) thick snow cover the year before the outbreak insulated the warmed permafrost and kept it from re-freezing; and (iii) anthrax vaccination rates had decreased or ceased in the region (Ezhova et al., 2019; Ezhova et al., 2021). These precursors converged with an unusually dry and hot summer that: (i) melted permafrost, creating an anthrax exposure hazard; (ii) increased the vector insect population; and (iii) weakened the immune systems of reindeer thus increasing their susceptibility (Waits et al., 2018; Hueffer et al., 2020).

Warmer temperatures have increased blood-feeding insect harassment of reindeer with compounding consequences: (1) increased insect bite rates lead to higher parasite loads, (2) time spent by raindeer in trying to escape biting flies reduces foraging while simulataneously increasing energy expenditure, (3) the combination of (1) and (2) lead to poor body condition, that subsequently leads to (4) reduced winter survival and fecundity (Mallory and Boyce, 2017). As temperatures warm and connectivity increases between the Arctic and the rest of the world, tourism, resource extraction, and increased commercial transport will create additional risks of biological invasion by infectious agents and their hosts (Pauchard et al., 2016). These increases in introduction risk compounded with climate change have already begun to harm indigenous peoples dependent on hunting and herding livestock (horses and reindeer) that are suffering increased pathogen infection (Deksne et al., 2020; Stammler and Ivanova, 2020).

2.4.2.7.3 Biodiversity-disease links

Anthropogenic impacts, such as disturbances caused by climate change, can reduce biodiversity through multiple mechanisms and increase disease risk to humans *(limited evidence, low agreement)* but more research is needed to understand the underlying mechanisms (Civitello et al., 2015; Young et al., 2017b; Halliday et al., 2020; Rohr et al., 2020; Glidden et al., 2021). Known wildlife hosts of human-shared pathogens and parasites overall comprise a greater proportion of local species richness (18–72% higher) and abundance (21–144% higher) in sites under substantial human use (agricultural and urban lands) compared with nearby undisturbed habitats (Gibb et al., 2020).

Exploitation of wildlife and degradation of natural habitats have increased opportunities for ‘spill over’ of pathogens from wildlife to human populations and increased emergence of zoonotic disease epidemics and pandemics *(robust evidence, high agreement)*; animal and human migrations driven by climate change have added to this increased risk *(medium evidence, medium agreement)* (see Section 2.4.2.1, Chapter 8, Cross-Chapter Box MOVING PLATE in Chapter 5; Patz et al., 2004; Cleaveland et al., 2007; Karesh et al., 2012; Altizer et al., 2013; Allen et al., 2017; Plowright et al., 2017; Olivero et al., 2017; Faust et al., 2018; Carlson et al., 2020; Gibb et al., 2020; Hockings et al., 2020; IPBES, 2020; Volpato et al., 2020; Glidden et al., 2021). Agricultural losses and subsequent food scarcity, that is increasing due to climate change, can also lead to an increase in the use of bushmeat, and, hence increase risk of diseases jumping from wild animals to humans *(medium evidence, high agreement)* (Brashares et al., 2004; Leroy et al., 2004; Wolfe et al., 2004;

Rosen and Smith, 2010; Kurpiers et al., 2016).

2.4.2.7.4 Implications for humans of changes in diseases in wild animals

Changes in temperature, precipitation, humidity, and extreme events have been associated with more frequent disease outbreaks, increases in disease incidence and severity, and novel disease and vector emergence into new areas for wild animals, with a mechanistic understanding of the roles of these drivers from experimental studies providing *high confidence* for the role of climate change. However, attribution of how this has impacted human infectious diseases remains difficult, and definitive attribution studies are lacking. The specific role of recent climate change is difficult to examine in isolation for most regions where human disease incidence has also been affected by land use change (particularly agricultural and urban expansion), changes in public health access and measures, socio-economic changes, increased global movements of people, and changes in vector and rodent control programs, supporting *medium confidence* in the role of climate change driving observed changes in human diseases globally. Exceptions are in areas noted above (Arctic, subarctic, and high elevation regions), in which climate change fingerprints are strong and/or concurrent changes in non-climatic drivers are less pronounced than in other regions (*high confidence* for climate change attribution) (see Table SM2.1, Sections 5.5.1.3, 7.2.2.1, Cross-Chapter Box ILLNESS this Chapter; Harvell et al., 2002; Norwegian Polar Institute, 2009; Tersago et al., 2009; Tabachnick, 2010; Altizer et al., 2013; Garrett et al., 2013; Paz, 2015; Wu et al., 2016b; Caminade et al., 2019; Dewage et al., 2019; Coates and Norton, 2020; Deksne et al., 2020; Shocket et al., 2020; Couper et al., 2021; Gilbert, 2021).

[START FAQ2.2 HERE]

FAQ2.2: How does climate change increase the risk of diseases?

Climate change is contributing to the spread of diseases in both wildlife and humans. Increased contact between wildlife and human populations increases disease risk and climate change is altering where pathogens that cause diseases and the animals that carry them live. Disease risk can often be reduced by improving health care and sanitation systems, training the medical community to recognize and treat potential new diseases in their region, limiting human encroachment into natural areas, limiting wildlife trade, and promoting sustainable and equitable socioeconomic development.

Diseases spread between humans and animals are called zoonoses. Zoonoses comprise nearly two-thirds of known human infectious diseases and the majority of newly emerging infectious diseases (EIDs). COVID-19 is the most recent zoonosis and has killed millions of people globally while devastating economies. The risk posed by EIDs has increased because of: (1) movement of wild animals and their parasites into new areas via climate change, global trade, and travel; (2) human intrusion into and conversion of natural areas for agriculture, livestock, industrial/raw materials extraction, and housing; (3) increased wildlife trade and consumption; (4) increased human mobility resulting from global trade, war/conflicts, and migration made faster and farther by fossil fuel powered travel; and (5) widespread antimicrobial use, which can promote antibiotic resistant infections (Figure FAQ2.3.1).

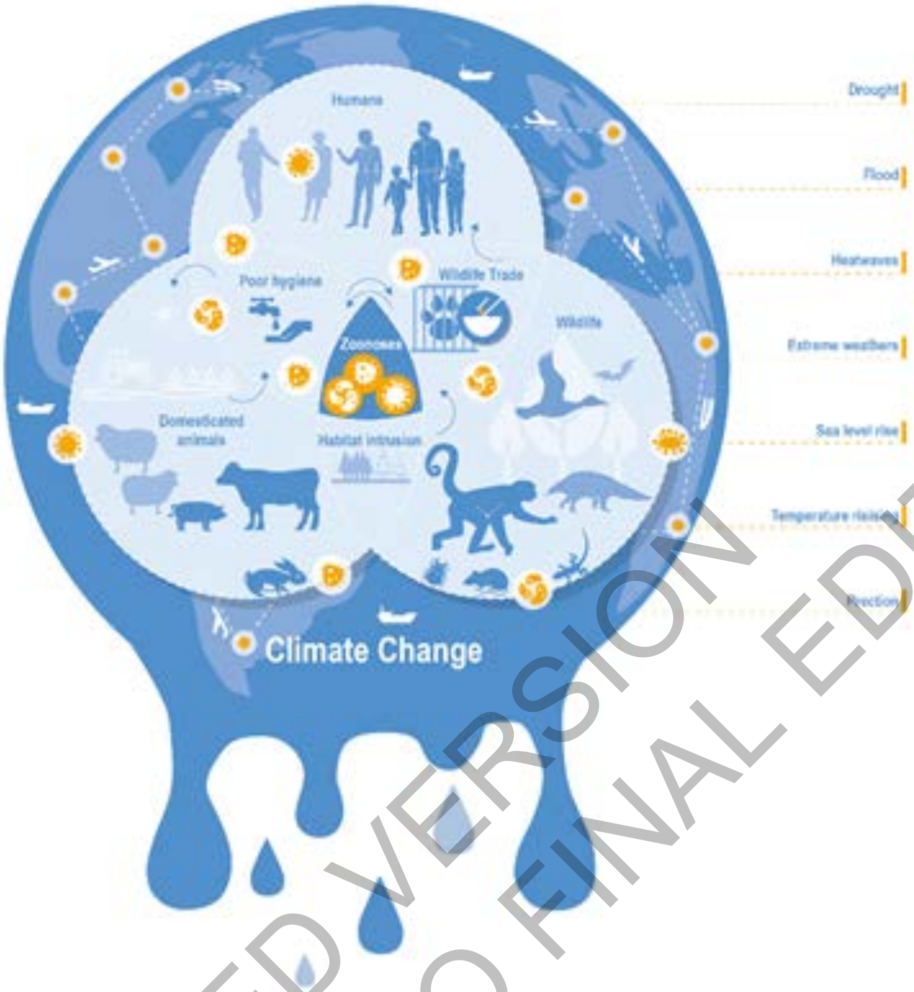


Figure FAQ2.2.1: How diseases move from the wild into human populations. Climate change may increase diseases in nature, but whether or not this leads to an increase in disease risk for humans depends upon a range of societal, infrastructure and medical buffers that form a shield protecting humans.

Climate change further increases risk by altering pathogen and host animal (1) geographic ranges and habitats; (2) survival, growth, and development; (3) reproduction and replication; (4) transmission and exposure (5) behavior; and (6) access to immunologically naïve animals and people who lack infection resistance. This can lead to novel disease emergence in new places, more frequent and larger outbreaks, and longer or shifted seasons of transmission. Climate change is making it possible for many EIDs to colonize historically colder areas that are becoming warmer and wetter in temperate and polar regions and in mountains. Vector-borne diseases (VBDs) are diseases spread by vectors such as mosquitoes, sand flies, kissing bugs, and ticks. For example, ticks that carry the virus that causes tick-borne encephalitis have moved into northern subarctic regions of Asia and Europe. Viruses like dengue, chikungunya, and Japanese encephalitis are emerging in Nepal in hilly and mountainous areas. Novel outbreaks of *Vibrio* bacteria seafood poisoning are being traved to the the Baltic States and Alaska where they were never documented before. Many scientific studies show that infectious disease transmission and the number of individuals infected depends on rainfall and temperature; climate change often makes these conditions more favourable for disease transmission.

Climate change can also have complicated, compounding, and contradictory effects on pathogens and vectors. Increased rainfall creates more habitat for mosquitoes that transmit diseases like malaria but too much rain washes away the habitat. Decreased rainfall also increases disease risk when people without reliable water access use containers to store water in that mosquitos, such as the vectors of dengue fever, *Aedes aegypti* and *Ae. albopictus,* use for egg laying. Hotter temperatures also increase mosquito bite rate, parasite development, and viral replication! Certain species of snails are intermediate hosts for many helminth worm parasites that make humans, livestock, and wild animals sick. When it gets hot, the snails can produce two to three times as many infective larvae but if it becomes too hot many pathogens and their vectors cannot survive or reproduce.

Humans also contract zoonoses directly through their skin, mucus membranes, and lungs when eating or butchering animals, or coming into contact with pathogen shed in the air, urine, or faeces that contaminates water, food, clothing, and other surfaces. Any activity that increases contact with wildlife, especially in high biodiversity regions like the tropics and subtropics, increases disease risk. Climate change-related disease emergence events are often rare but may become more frequent. Fortunately, there are ways to reduce risks and protect our health, as described below.

Habitat and biodiversity protection: Encroachment of humans into natural areas, due to expansion of agriculture and livestock, timber harvests, resource extraction, and urban development has increased human contact with wild animals, and creates more opportunities for disease spillover (transmission from an animal to a new species, including humans). By conserving, protecting, and restoring wild habitats, we can build healthier ecosystems that provide other services, such as clean air, clean and abundant water, recreation, spiritual value, and well-being, as well as reduced disease spillover. If humans must go into wild areas or hunt, they should take appropriate precautions such as wearing protective clothing, using insect repellant, performing body checks for vectors like ticks, and washing hands and clothing well.

Food resilience: Investing in sustainable agroecological farming will alleviate the pressure to hunt wild animals and reduce the conversion of more land to agriculture/livestock use. Stopping illegal animal trading and poaching and decreasing reliance on wild meats and products made from animal parts will reduce direct contact with potentially infected animals. This has the added benefit of increasing food security, nutrition, improving soil, reducing erosion, preserving biodiversity, and mitigating climate change.

Disease prevention and response: The level of protection against infection is linked directly to the level of development and wealth of a country. Improved education, high-quality medical and veterinary systems, high food security, proper sanitation of water and waste, high housing quality, and disease surveillance and alarm systems dramatically reduce disease risk and improve health. Utilizing a One Biosecurity or One Health framework further improves resilience. Sharing knowledge within communities, municipalities, regional, and between national health authorities globally is important to assessing, preventing and responding to outbreaks and pandemics more efficiently and economically.

Humans are facing many direct or indirect challenges because of climate change. Increasing EIDs is one of our greatest challenges, due to our ever-growing interactions with wildlife and the climatic changes creating new disease transmission patterns. COVID-19 is a current crisis, and follows other recent EIDs: SARS, HIV/AIDS, H1N1 influenza, Ebola, Zika, and West Nile fever. EIDs have accelerated in recent decades, making it clear that new societal and environmental approaches to wildlife interactions, climate change, and health are urgently needed to protect our current and future well-being as a species.

[END FAQ2.2 HERE]

2.4.2.8 Observed Evolutionary Responses to Climate Change

Prior sections document species' tendencies to retain their climate envelopes by some combination of range shift and phenological change. However, this tracking of climate change can be incomplete, causing species or populations to experience hotter conditions than those to which they are adapted and thereby incur 'climate debts' (Devictor et al., 2012). The importance of population-level debt is illustrated by a study in which estimated debt values were correlated with population dynamic trends in a North American migratory songbird, the Yellow Warbler, *Setophaga petechia.* Populations that were genetic outliers for their local climate space had larger population declines (greater debt) than populations with genotypes closer to the average values for that particular climate space. Debt values were estimated from genomic analyses independent of the population trends, and were distributed across the species' range in a mosaic, not simply concentrated at range margins, rendering the results robust to being confounded by broad-scale geographical trends (Bay et al., 2018).

In the absence of evolutionary constraints, climate debts can be cancelled by genetically-based increases in thermal tolerance and ability to perform in high ambient temperatures. In species already showing local adaptation to climate, populations currently living at relatively cool sites should be able to evolve to adopt traits of populations currently at warmer sites, as their local experience of climate changes (Singer, 2017; Socolar et al., 2017).

An increasing number of studies document evolutionary responses to climate change in populations not at warm range limits (Franks and Hoffmann, 2012). Organisms with short generation times should have higher capacity to genetically track climate change than species with long generation times, such as mammals (Boutin and Lane, 2014). Indeed, observed evolutionary impacts have been mainly documented in insects, especially at expanding range margins (Chuang and Peterson, 2016) where evolutionary changes have been documented of dispersal ability (Thomas et al., 2001) and host specialisation (Bridle et al., 2014; Lancaster, 2020).

Away from range margins, individual populations experiencing regional warming have evolved diverse traits related to climate adaptation. For example, pitcher-plant mosquitos (*Wyeomyia smithii)* in Pacific NW America have evolved to wait for shorter day lengths before initiating diapause. This adaptation to lengthening summers enables them to delay overwintering until later and add an extra generation each year (Bradshaw and Holzapfel, 2001). Among 26 populations of *Drosophila subobscura* studied on three continents, 22 experienced climate warming across two or more decades, and 21 of those 22 showed increasing frequencies of chromosome inversions characteristic of populations adapted to hot climates (Balanya et al., 2006).

However, for populations already at their warm range limits, their ability to track climate change in situ would require evolving to survive and reproduce outside their species' historical climate envelope, which is not supported by experimental or observational evidence *(medium evidence, high agreement)* (Singer, 2017). Whether or not they can do so depends on the level of 'niche conservatism' operating at the species level (Lavergne et al., 2010). If a species' whose range limits are determined by climate finds itself completely outside of its traditional climate envelope, extinction is expected in the absence of 'evolutionary rescue' (Bell and Gonzalez, 2009; Bell et al., 2019). To investigate the evolutionary potential enabling a species to survive in a novel climate entirely outside its traditional climate envelope, experiments have been carried out on ectotherms testing thermal performances, thermal tolerances, and their evolvabilities (Castaneda et al., 2019; Xue et al., 2019). Tests of thermal performance have been complicated as both long-term acclimation and transgenerational effects occur (Sgro et al., 2016). However, the results to date have been consistent: despite widespread local adaptation to climate across species' ranges, substantial constraints exist to the evolution of greater stress tolerance (e.g. high temperatures and drought) at warm range limits *(medium evidence, high agreement)* (Hoffmann and Sgro, 2011; MacLean et al., 2019b). For example, as temperature was experimentally increased, the amount of genetic variance in fitness of *Drosophila melanogaster* decreased: in hot environments, flies had low evolvability (Kristensen et al., 2015). The hypothesis that heat stress tolerance is evolutionarily constrained is further supported by experiments in which 22 Drosophila species drawn from tropical and temperate climes were subjected to extremes of heat and cold. They differed as expected in cold tolerances, but not in heat tolerances nor in temperatures at which optimal performances were observed (MacLean et al., 2019b).

Plasticity in acclimating to thermal regimes helps organisms adapt to environmental change. The form and extent of plasticity can vary among populations experiencing different climates (Kelly, 2019) and generate phenotypic values outside the prior range for the species, but plasticity itself has not yet been observed to evolve in response to climate change (Kelly, 2019). Relevant genetic changes in nature (e.g. affecting heat tolerance) have not yet been shown to alter the boundaries of existing genetic variation for any species. Evolutionary rescue of entire species has not yet been observed in nature, nor is it expected based upon experimental and theoretical studies *(medium evidence, high agreement)*.

Hybridisation between closely related species has increased in recent decades as one species shifts its range boundaries and positions itself more closely to the other—hybrids between polar bears and brown bears have been documented in northern Canada (Kelly et al., 2010). In North American rivers, hybridisation between invasive rainbow trout and native cutthroat trout has increased in frequency as the rainbow trout expanded into warming waters (Muhlfeld et al., 2014). Whether climate-changed induced hybridisations can generate novel climate adaptations remains to be seen.

In summary, with present knowledge, evolution is not expected to be sufficient to prevent whole species' extinctions if a species' climate space disappears *(high confidence)*.

2.4.3 Observed Changes in Key Biomes, Ecosystems and their Services

2.4.3.1 Detection and Attribution for Observed Biome Shifts

Attribution for biome (major vegetation form of an ecosystem) shifts is complex because of their extensive, sometimes continental, spatial scale (Whittaker, 1975; Olson et al., 2001; Woodward et al., 2004); and therefore, non-climatic factors strongly influence biome spatial distributions (Ellis and Ramankutty, 2008).

The most robust attribution studies use data from individual locations with minimal confounding factors, particularly recent land use change, and scale up by analysing multiple locations across a long zone between biomes. As with individual species, multiple lines of evidence increase confidence (Hegerl et al., 2010; Parmesan et al., 2013). Multivariate statistical analyses aid attribution studies by allowing the assessment of relative weights among multiple factors, including variables related to climate change (Gonzalez et al., 2012). However, drivers often have strong, significant interactions with one another, complicating quantitative assessment of the strength of individual drivers (Parmesan et al., 2013). In these cases, manipulative experiments are critical in assessing attribution to climate change drivers.

Certain biomes exhibit a relatively stronger relationship to climate; for example, Arctic tundra generally has a distinct ecotone with boreal conifer forest (Whittaker, 1975). In these areas, attribution of biome shifts to climate change are relatively straightforward, if human land use change is minimal. However, other biomes, such as many grassland systems, are not at equilibrium with climate (Bond et al., 2005). In these systems their evolutionary history (Keeley et al., 2011; Strömberg, 2011; Charles-Dominique et al., 2016), distribution, structure and function have been shaped by climate and natural disturbances, such as fire and herbivory (Staver et al., 2011; Lehmann et al., 2014; Pausas, 2015; Bakker et al., 2016; Malhi et al., 2016). Disturbance variability is an inherent characteristic of grassland systems and suitable “control” conditions are seldom available in nature. Furthermore, due to the integral role of disturbance, these biomes have been widely affected by long-term and widespread shifts in grazing regimes, large-scale losses of mega-herbivores and fire suppression policies (Archibald et al., 2013; Malhi et al., 2016; Hempson et al., 2017). It is necessary to conduct climate change attribution on a case-by-case basis for grasslands; such assessments are complex as direct climate change impacts from either inherent variation within disturbance regimes or directional changes in background disturbances are difficult to separate (detailed in Sections 2.4.3.2.1; 2.4.3.2.2; 2.4.3.5). Confidence in assessments is increased when observed trends are supported by mechanistic understanding of responses identified by physiological studies, manipulative field experiments, greenhouse studies and lab experiments (Table SM2.1).

2.4.3.2 Global Patterns of Observed Biome Shifts Driven by Climate Change

2.4.3.2.1 Observed biome shifts predominantly driven by climate change

Th IPCC Fifth Assessment Report and a meta-analysis found that vegetation at the biome level shifted poleward latitudinally and upward altitudinally due to anthropogenic climate change at 19 sites in boreal, temperate, and tropical ecosystems from 1700 to 2007 (Gonzalez et al., 2010a; Settele et al., 2014). In these areas, temperature increased 0.4° to 1.6ºC above the pre-industrial period (Gonzalez et al., 2010a; Settele et al., 2014). Field research since the IPCC Fifth Assessment Report detected additional poleward and upslope biome shifts over periods of 24 to 210 years at numerous sites (described below) but were not directly attributed to anthropogenic climate change as the studies were not designed nor conducted properly for attribution.

Many of the recently detected shifts were nevertheless consistent with climate change temperature increases and observed in areas lacking agriculture, livestock grazing, timber harvesting, or other anthropogenic land uses. For example, in the Andes Mountains in Ecuador, a biome shift was detected by comparing a survey by Alexander von Humboldt in 1802 to a re-survey in 2012, making this the longest time span in the world for this type of data (Morueta-Holme et al., 2015) and 2017 (Moret et al., 2019). During 210 years, temperature increased 1.7ºC (Morueta-Holme et al., 2015) and the upper edge of alpine grassland shifted upslope 100–450 m (Moret et al., 2019).

Other biome shifts consistent with climate change and not substantially affected by local land use include northward shifts of deciduous forest into boreal conifer forest in Canada (5 km between 1970–2012, (Sittaro et al., 2017) and 20 km between 1970–2014, (Boisvert-Marsh et al., 2019)) and northward shifts of temperate conifer into boreal conifer forest in Canada (21 km between 1970–2015, (Boisvert-Marsh and de Blois, 2021)). Research detected upslope shifts of boreal and sub-alpine conifer forest into alpine grassland at 143 sites on four continents (41 m, 1901–2018, (Lu et al., 2021)) and individual sites in Canada (54 m, 1900–2010, (Davis et al., 2020)), China (300 m, 1910–2000 (Liang et al., 2016); 33 m, 1985–2014, (Du et al., 2018)), Nepal (50 m, 1860–2000, (Sigdel et al., 2018)), Russia (150 m, 1954–2006, (Gatti et al., 2019)) and the United States (19 m, 1950–2016, (Smithers et al., 2018); 38 m, 1953–2015, (Terskaia et al., 2020)). Other upslope cases include shifts of temperate conifer forest in Canada (Jackson et al., 2016) and the United States (Lubetkin et al., 2017), temperate deciduous forest in Switzerland (Rigling et al., 2013) and temperate shrubland in the United States (Donato et al., 2016).

In summary, anthropogenic climate change has caused latitudinal and elevational biome shifts in at least 19 sites in boreal, temperate, and tropical ecosystems between 1700 and 2007, where temperature increased 0.4° to 1.6ºC above the pre-industrial period (*robust evidence, high agreement*). Additional cases of 5 to 20 km northward and 20 to 300 m upslope biome shifts between 1860 and 2016, under approximately 0.9ºC mean global temperature increase above the pre-industrial period, are consistent with climate change (*medium evidence, high agreement*).

2.4.3.2.2 Observed biome shifts from combined land use change and climate change

Research has detected biome shifts in areas where agriculture, fire use or suppression, livestock grazing, timber and fuelwood harvesting, or other local land use actions substantially altered vegetation, in addition to changes in climatic factors and CO_2 fertilisation. These studies were not designed or conducted in a manner to make climate change attribution possible, although vegetation changes are consistent with climate change: for example, a global review of observed changes in treelines found that 2/3 of treelines globally have shifted upslope in elevation over the past 50 years or more (Hansson, 2021, a review of).

Upslope and poleward forest shifts have occurred where timber harvesting or livestock grazing was abandoned, allowing regeneration of trees at sites in Canada (Brice et al., 2019; Wang et al., 2020b), France (Feuillet et al., 2020), Italy (Vitali et al., 2017), Spain (Ameztegui et al., 2016), the United States (Wang et al., 2020b) and mountain areas across Europe (Cudlin et al., 2017). Intentional use of fire drove an upslope forest shift in Peru (Bush et al., 2015) while mainly human-ignited fires drove conversion of shrubland to grassland in a drought-affected area of the United States (Syphard et al., 2019b). In eastern Canada, timber harvesting and wildfire drove conversion of mixed conifer-broadleaf forests to broadleaf-dominated forests (Brice et al., 2020; Wang et al., 2020b).

Shrub encroachment onto savanna has occurred at numerous sites, particularly across the Southern Hemisphere, mainly between 1992 and 2010 (Criado et al., 2020). Globally, overgrazing initiates shrub encroachment by reducing grasses more than woody plants, while fire exclusion maintains the shrub cover (D'Odorico et al., 2012; Caracciolo et al., 2016; Bestelmeyer et al., 2018). The magnitude of woody cover change in savannas is not correlated to mean annual temperature change (Criado et al., 2020), however, higher atmospheric CO_2 increases shrub growth in savannas (Nackley et al., 2018; Manea and Leishman, 2019). A global remote sensing analysis of biome changes from all causes, including agricultural and grazing expansion and deforestation, estimated that 14% of pixels changed between 1981 and 2012, although this approach can overestimate global changes since it uses a new biome classification system, which doubles the conventional biome classifications (Higgins et al., 2016). In addition to climate change, land use change causes vegetation changes at the biome level (*robust evidence, high agreement*).

2.4.3.3 Observed Changes in Deserts and Arid Shrublands

Divergent responses to anthropogenic climate change are occurring within and across arid regions, depending on time period, location, detection methodology and vegetation type (see Cross-Chapter Paper 3). Emerging shifts in ecosystem structure, functioning and biodiversity are supported by evidence from modelled impacts of projected climate and CO_2 levels. While observed responsiveness of arid vegetation productivity to rising atmospheric CO_2 (Fensholt et al., 2012b) may offset risks from reduced water availability (Fang et al., 2017), climate- and CO_2 driven changes are key risks in arid regions, interacting with habitat degradation, wildfire, and invasive species (Hurlbert et al., 2019).

Widespread vegetation greening, as projected in AR4, is occurring in arid shrublands (Zhang et al., 2019a; Maestre et al., 2021) as a result of increases in leaf area, woody cover and herbaceous production at desert-grassland interfaces (Gonsamo et al., 2021). Plant productivity in arid regions has increased (Fensholt et al., 2012b) because of improved water use efficiency associated with elevated CO_2 (Norby and Zak, 2011; Donohue et al., 2013; Burrell et al., 2020; Gonsamo et al., 2021) *(medium evidence, high agreement)*, altered rainfall seasonality and amount (Rohde et al., 2019; Zhang et al., 2019a) *(robust evidence, high agreement),* increases in temperature (Ratajczak et al., 2014; Wilcox et al., 2018)*(robust evidence, high agreement)* and heavy grazing (*robust evidence, high agreement*) with relative importance differing among locations (Donohue et al., 2013; Caracciolo et al., 2016; Archer et al., 2017; Hoffmann et al., 2019b; Rohde et al., 2019). Woody plant encroachment into arid shrublands is occurring in North America (Caracciolo et al., 2016; Archer et al., 2017), southern Africa (du Toit and O'Connor, 2014; Ward et al., 2014; Masubelele et al., 2015a; Hoffman et al., 2019; Rohde et al., 2019) (*high confidence*) and Central Asia (Li et al., 2015) (*low confidence*). In North America, sagebrush steppe changes have been attributed to increases in temperature and earlier snowpack melt (Wuebbles et al., 2017; Mote et al., 2018; Snyder et al., 2019).

Non-native grasses are invading the sagebrush steppes (cold deserts) in North America (Chambers et al., 2014) attributed to warming (Bradley et al., 2016; Hufft and Zelikova, 2016). In the eastern semi-desert (Karoo) of South Africa, annual rainfall increases and a rainfall seasonality shift (du Toit and O'Connor, 2014) are increasing grassiness as arid grasslands expand into semi-desert shrublands (du Toit et al., 2015; Masubelele et al., 2015b; Masubelele et al., 2015a) causing fire in areas seldom burned (Coates et al., 2016).

Drought, warming, and land management interactions have caused vegetation mortality (see section 2.4.4.3) and reduced vegetation cover in shrublands as projected by AR4 (Burrell et al., 2020). Increased heat and drought are causing succulent species health and abundance to decline (Musil et al., 2009; Schmiedel et al., 2012; Aragón-Gastélum et al., 2014; Koźmińska et al., 2019). Hot droughts especially reduce population resilience (*medium confidence*) (Koźmińska et al., 2019).

2.4.3.4 Observed Changes in Mediterranean-Type Ecosystems

Since AR5, Settele et al. (2014) found that all five Mediterranean-Type Ecosystems (MTEs) of the world experienced extreme droughts within the past decade, with South Africa and California reporting the worst on record (*robust evidence, high agreement*) (Diffenbaugh et al., 2015; Williams et al., 2015a; Garreaud et al., 2017; Otto et al., 2018; Sousa et al., 2018). Climate change is causing these droughts to become more frequent and severe (*medium evidence, medium agreement*) (AghaKouchak et al., 2014, Garreaud et al 2017 The 2010-2015 megadrought , AR6 WGI Chpt 11; Otto et al., 2018).

MTEs show a range of direct responses to various forms of water deficit, but have also been affected by increasing fire activity linked to drought (Abatzoglou and Williams, 2016), and interactions between drought or extreme weather and fire, affecting post-fire ecosystem recovery (Slingsby et al., 2017). Responses include shifts in functional composition (Acácio et al., 2017; Syphard et al., 2019a), decline in vegetation health (Hope et al., 2014; Asner et al., 2016a), decline or loss of characteristic species (White et al., 2016; Stephenson et al., 2019), shifts in composition towards more drought- or heat-adapted species and declining diversity (also see Section 2.4.4.3; Slingsby et al., 2017.; Harrison et al., 2018).

Declines in plant health and increased mortality in MTEs associated with drought have been widely documented (*robust evidence, high agreement*) (Section 2.4.4.3). Remote sensing studies show drought associated mortality in postfire vegetation regrowth in the Fynbos of South Africa (Slingsby et al., 2020b), reduced canopy health in forests within MTE zones of South Africa (Hope et al., 2014), and declines in canopy water content in forests of California (Asner et al., 2016a). Several studies reported climate-associated responses of dominant or charismatic species. High mortality in the Clanwilliam Cedar between 1931 to 2013 occurred at lower, hotter elevations in the Fynbos of South Africa (White et al., 2016). Drought reduced growth and increased mortality of the holm oak, *Quercus ilex,* in the Iberian Peninsula of Spain, Natalini et al. (2016). Portuguese shrublands experienced losses of many deciduous and evergreen oak species, and increasing dominance of to pyrophytic xeric trees (Acácio et al., 2017). The 2012–2015 drought in California caused: high canopy foliage die-back of the Giant Sequoia (*Sequoiadendron giganteum*) (Stephenson et al., 2019), increased the dominance of oaks relative to pines resulting from increased water deficit, and large-scale mortality from drought and insect pest outbreak interactions (McIntyre et al., 2015; Fettig et al., 2019).

Species distribution or community composition changes have contributed to declines in diversity and/or shifts towards more drought- or heat-adapted species (*medium evidence, high agreement*). Two conifer species (*Pinus longaeva*, *P. flexilis*) shifted upslope 19 m from 1950 to 2016 in the Great Basin, USA, (Smithers et al., 2018). Reduced winter precipitation caused native annual forbs to recede resulting in long-lasting and potentially unidirectional reductions in diversity in a Californian grassland (Harrison et al., 2018). More frequent extreme hot and dry weather between 1966 and 2010 caused declines in diversity during the post-fire regeneration phase in the Fynbos of South Africa (Slingsby et al., 2017) resulting in shifts towards species with higher temperature preferences (Slingsby et al., 2017). In Italy, Del Vecchio et al. (2015) observed increases in plant cover and thermophilic species in coastal foredune habitats between 1989 and 2012.

In southern California, USA, areas of forest and woody shrublands are shifting to grasslands, driven by a combination of climate and land use factors such as increased drought, fire ignition frequency and increases in nitrogen deposition (*robust evidence, high agreement*) (Jacobsen and Pratt, 2018; Park et al., 2018; Park and Jenerette, 2019; Syphard et al., 2019b).

The effects of climate change on heat, fuel, and wildfire ignition limitations show spatial and temporal variation globally (see Section 2.3.6.1), but there have been a number of observed impacts in MTEs (*medium evidence, high agreement*). Climate change has caused increases in fuel aridity and area burned by wildfire across the western United States from 1985 to 2015 (Abatzoglou and Williams, 2016). Local and global climatic variability led to a 4 year decrease in the average fire return time in Fynbos, South Africa when comparing fires recorded between 1951 to 1975 and 1976 to 2000 (Wilson et al., 2010). For Chile, González et al. (2018) reported a significant increase in the number, size, duration and simultaneity of large fires during the 2010 to 2015 "megadrought" when compared to the 1990 to 2009 baseline.

2.4.3.5 Observed Changes in Savanna and Grasslands

Savannas consist of coexisting trees and grasses in the tropics and temperate regions (Archibald et al., 2019). The global trend of woody encroachment reported in AR5 (Settele et al., 2014) is continuing *(robust evidence, high agreement, very high confidence)* (see Table 2.S.1), with increases occurring in: temperate savannas in North America (10-20% per decade) (Archer et al., 2017), tropical savannas in South America (8% per decade), Africa (2.4% per decade) and Australia (1% per decade) (O'Connor et al., 2014; Espírito-Santo et al., 2016; Skowno et al., 2017; Stevens et al., 2017; McNicol et al., 2018; Venter et al., 2018; Rosan et al., 2019). Additionally, forest expansion into mesic savannas reported in AR5 (Settele et al., 2014), is continuing in Africa, South America and Southeastern Asia (Marimon et al., 2014; Keenan et al., 2015; Baccini et al., 2017; Ondei et al., 2017; Stevens et al., 2017; Aleman et al., 2018; Rosan et al., 2019). Extreme high rainfall anomalies also contributed to an increase in herbaceous and foliar production in the Sahel (Brandt et al., 2019; Zhang et al., 2019a).

New studies since AR5, using multiple study designs (experimental manipulations in lab and field, meta-analyses and modelling), attribute climate change increases in woody cover to elevated atmospheric CO_2 (Donohue et al., 2013; Nackley et al., 2018; Quirk et al., 2019) and increased rainfall amount and intensity *(robust evidence, high agreement)* (Venter et al., 2018; Xu et al., 2018b; Zhang et al., 2019a). Direct quantification of climate change drivers is confounded with local land use changes such as fire suppression (Archibald, 2016; Venter et al., 2018), heavy grazing (du Toit and O'Connor, 2014; Archer et al., 2017), removal of native browsers, and specifically loss of mega-herbivores in Africa *(medium evidence, medium agreement)* (Asner et al., 2016b; Daskin et al., 2016; Stevens et al., 2016; Davies et al., 2018). The relative importance of the climate- and non-climate-related causes of woody plant vary between regions, but there is general agreement that climate change impacts, specifically, increasing rainfall and rising CO_2, are frequent and strong contributing factors of woody cover increase *(robust evidence, high agreement*).

Extensive woody cover increases in non-forested biomes is reducing grazing potential (Smit and Prins, 2015), and changing the carbon stored per unit land area (González-Roglich et al., 2014; Puttock et al., 2014; Pellegrini et al., 2016; Mureva et al., 2018) and hydrological characteristics (Honda and Durigan, 2016; Schreiner-McGraw et al., 2020). Woody cover encroachment also reduces biodiversity by threatening fauna and flora adapted to open ecosystems (Ratajczak et al., 2012; Smit and Prins, 2015; Pellegrini et al., 2016; Andersen and Steidl, 2019).

The global extent of grasslands is declining significantly because of climate change *(medium confidence)*. In temperate and boreal zones, where about half of treelines are shifting, they are overwhelmingly expanding poleward and upward, with accompanying loss of montane grassland (*robust evidence, high agreement*); whereas tropical treelines have been generally stable *(medium evidence, medium agreement)* (Harsch et al., 2009; Rehm & Feeley 2015; Silva et al., 2016; Andela et al., 2017; Song et al., 2018; Aide et al., 2019; Gibson and Newman, 2019). The Eurasian steppes experienced a 1% increase in woody cover per decade since 2000 (Liu et al., 2021) and Inner Mongolian grasslands in China experienced broad encroachment as well (Chen et al., 2015). Climatic drivers of woody expansion in temperature limited grasslands, particularly alpine grasslands, are most frequently attributed to warming (*robust evidence, high agreement, high confidence*) (D'Odorico et al., 2012; Hagedorn et al., 2014), increases in water and nutrient availability from thawing permafrost (*medium evidence, high agreement*) (Zhou et al., 2015b; Silva et al., 2016) and rising CO_2 (*medium evidence, medium agreement*) (Frank et al., 2015; Aide et al., 2019). Interactions between land use changes: land abandonment, grazing management shifts, and fire suppression, and climate change are contributing factors (Liu et al., 2021)

Remote sensing shows overall increasing trends in both the annual maximum NDVI and annual mean NDVI in global grasslands ecosystems between 1982 and 2011 (Gao et al., 2016). Multiple lines of evidence indicate that changes in grassland productivity are positively correlated with increases in mean annual precipitation (Hoover et al., 2014; Brookshire and Weaver, 2015; Gang et al., 2015; Gao et al., 2016; Wilcox et al., 2017; Wan et al., 2018). Increasing temperatures positively impact grassland production and biomass, especially in temperature limited regions (Piao et al., 2014; Gao et al., 2016). However, grasslands in hot areas are expected to decrease production with increases in temperature *(limited evidence, low agreement)* (Gang et al., 2015). Nevertheless, grassland responses to warming and drought are being ameliorated by increasing CO_2 and associated improved water use efficiency (Roy et al., 2016). For example, in a cool temperate grassland experiment, warming led to a longer growing season and elevated CO_2 further extended growing by conserving water, which enabled most species to remain active longer (*medium evidence, medium agreement)* (Reyes-Fox et al., 2014).

2.4.3.6 Observed Changes in Tropical Forest

Overall declines of tropical forest cover (Kohl et al., 2015; Liu et al., 2015; Baccini et al., 2017; Harris et al., 2021), with declines more than triple the gains (Harris et al., 2021) have been driven primarily by deforestation and land conversion (*robust evidence, high agreement*) (Lewis et al., 2015; Curtis et al., 2018; Espaciais, 2021). In opposition to this general trend, expansion of tropical forest cover into savannas and grasslands has occurred in Africa, South America, and Australia (Baccini et al., 2017; Aleman et al., 2018; Staver, 2018) (Marimon et al., 2014; Ondei et al., 2017; Stevens et al., 2017; Rosan et al., 2019).

Specific examples of climate-change driven range shifts of tropical deciduous forests upslope into alpine grasslands have been documented in the Americas (Chacón-Moreno et al., 2021; Jiménez-García et al., 2021) and in Asia (Sigdel et al., 2018). However, treeline behaviours are diverse. A study in Nepal recorded that treeline fomed by *Abies spectabilis* had been stable for more than a century, while the upper limit of large shrubs (*Rhododendron campanulatum*) had been advancing (Mainali et al., 2020). In both the Andes (Harsch et al., 2009) and Himalaya (Singh et al., 2021) most treelines have been stable, leading (Rehm & Feeley 2015) to postulate a "grass ceiling" that has been difficult for trees to penetrate. The treeline shifts that have occurred are probably driven by interactions between changing land-use, such as fire suppression, and climate changes such as increased rainfall, warming and elevated CO_2 either through CO_2 fertilisation or increases in water-use efficiency (*medium evidence, medium agreement)* (Cernusak et al., 2013; Huang et al., 2013; Van Der Sleen et al., 2015; Yang et al., 2016).

Increases in productivity of tropical forests (Gatti et al., 2014; Brienen et al., 2015; Baccini et al., 2017), Africa and SE Asia (Qie et al., 2017) have been attributed to elevated CO_2 *(robust evidence, medium agreement)* (Ballantyne et al., 2012; Brienen et al., 2015; Sitch et al., 2015; Yang et al., 2016; Mitchard, 2018). The rates of these increases have been slowing down in the central Amazon (Brienen et al., 2015; de Meira Junior et al., 2020) and SE Asia (Qie et al., 2017). In contrast, the carbon sink (and hence rate of biomass gain) in intact African forests was stable until 2010 and has only recently started to decline, indicating asynchronous carbon sink saturation in Amazonia and Africa, the difference driven by rates of tree mortality (Hubau et al. 2020). At a global level (Hubau et al 2020) argue that the carbon sink associated with intact tropical forests peaked in the 1990s and is now in decline.

Declines in productivity are most strongly associated with warming (Sullivan et al., 2020), reduced growth rates during droughts (Bennett et al., 2015; Bonai et al., 2016; Corlett, 2016), drought related mortality (Brando et al., 2014; Zhou et al., 2014; Brienen et al., 2015; Corlett, 2016; McDowell et al., 2018), fire (Liu et al., 2017), and cloud-induced radiation-limitation *(robust evidence, high agreement)* (Deb Burman et al., 2020). Increases in frequency and severity of droughts and shorter tree residence times due to increases in growth rates caused by elevated CO_2 may be additional interactive factors increasing tree mortality (Malhi et al., 2014; Brienen et al., 2015). Vulnerability to drought varies between tree species and sizes with large, long-lived trees at highest risk of mortality (McDowell et al., 2018; Meakem et al., 2018). Mortality risk also varies between forest types with seasonal rainforests appearing most vulnerable to drought (Corlett, 2016).

Lianas (long-stemmed woody vines) generally negatively impact trees, significantly reducing the growth of heavily infested trees (Reis et al., 2020). They would benefit from climate change and disturbance (LingZi et al., 2014; Hodgkins et al., 2018). The extent of their suitable niche can increase (Taylor and Kumar, 2016), thereby decreasing forest biomass accumulation *(robust evidence, high agreement*) (van der Heijden et al., 2013; Fauset et al., 2015; Estrada-Villegas et al., 2020).

Climate change continues to degrade forests by reducing resilience to pests and diseases, increasing species invasion, facilitating pathogen spread (Malhi et al., 2014; Deb et al., 2018) and intensifying fire risk and potential die-back (Lapola et al., 2018; Marengo et al., 2018). Drought, temperature increases and forest fragmentation interact to increase the prevalence of fires in tropical forests (*robust evidence, high agreement*). Warming increases water stress in trees (Corlett, 2016) and together with forest fragmentation, dramatically increases desiccation of forest canopies—resulting in deforestation that then leads to even hotter and drier regional climates (Malhi et al., 2014; Lewis et al., 2015). Warming and drought increase invasion of grasses into forest edges and increase fire risk (*robust evidence, high agreement*) (Brando et al., 2014; Balch et al., 2015; Lewis et al., 2015). Droughts and fires additively increase mortality and, consequently, reduce canopy cover and aboveground biomass (Cross-Chapter Paper 7; Brando et al., 2014, 2020; Balch et al., 2015; Lewis et al., 2015).

2.4.3.7 Observed Changes in Boreal and Temperate Forests

The IPCC Fifth Assessment Report found increased tree mortality, wildfire and plant phenology changes in boreal and temperate forests (Settele et al., 2014). Expanding on those conclusions, this Assessment, using analyses of causal factors, attributes to anthropogenic climate change the following observed changes in boreal and temperate forests in the 20th and 21st centuries: upslope and poleward biome shifts at sites in Asia, Europe, and North America (Section 2.4.3.2.1); range shifts of plants (Section 2.4.2.1); earlier blooming and leafing of plants (Section 2.4.2.4); poleward shifts in tree-feeding insects (Section 2.4.2.1); increases in insect pest outbreaks (Section 2.4.4.3.3); increases in area burned by wildfire in western North America (Section 2.4.4.2.1); increased drought-induced tree mortality in western North America (Section 2.4.4.3.1); and thawing of permafrost that underlies extensive areas of boreal forest (IPCC Sixth Assessment Report, Working Group I, Chapter 2, Section 2.4.3.9). Atmospheric CO_2 from anthropogenic sources has also increased net primary productivity (Section 2.4.4.5.1). In summary, anthropogenic climate change has caused substantial changes to temperate and boreal forest ecosystems, including biome shifts and increases in wildfire, insect pest outbreaks, and tree mortality, at a global mean surface temperature increase of 0.9º C above the pre-industrial period (*robust evidence, high agreement*).

Other changes detected in boreal forests and consistent with, but not formally attributed to climate change, include increased wildfire in Siberia (Section 2.4.4.2.3), long-lasting smoldering belowground fires in Canada and the United States (Scholten et al., 2021), tree mortality in Europe (Section 2.4.4.3.3), and post-fire shifts of boreal conifer to deciduous broadleaf tree species in Alaska (Mack et al., 2021). From 1930 to 1960, boreal forest growth became limited more by precipitation than temperature in the Northern Hemisphere (Babst et al., 2019).

For some vegetation changes, land use and land management changes have exerted more influence than climate change. These include upslope and poleward forest shifts in Europe following abandonment of timber harvesting or livestock grazing (Section 2.4.3.2.2), changes in wildfire in Europe affected by fire suppression, fire prevention, and agricultural abandonment (Section 2.4.4.2.3), and forest species composition changes in Scotland due to nitrogen deposition from air pollution (Hester et al., 2019). Remote sensing suggests that the area of temperate and boreal forests increased in Asia and Europe between 1982 and 2016 (Song et al., 2018) and in Canada between 1984 and 2015 (Guindon et al., 2018), but forest plantations and regrowth are probable drivers (Song et al., 2018).

2.4.3.8 Observed Changes in Peatlands

Globally, peatland ecosystems store approximately 25% (600±100 GtC) of the world's soil organic carbon (Yu et al., 2010; Page et al., 2011; Hugelius et al., 2020) and 10% of the world's freshwater resources (Joosten and Clarke, 2002), despite only occupying 3% of the global land area (Xu et al., 2018a). The long-term role of northern peatlands in the carbon cycle was mentioned for the first time in IPCC AR4 (IPCC, 2007b), while SR1.5 briefly mentioned the combined effects of climate and land-use change on peatlands (IPCC, 2018b). New evidence confirms that climate change, including extreme weather events (e.g., droughts; Section 8.3.1.6), permafrost degradation (Section 2.3.2.5), sea-level rise (Section 2.3.3.3), and fire (Section 5.4.3.2) (Henman and Poulter, 2008; Kirwan and Mudd, 2012; Turetsky et al., 2015; Page and Hooijer, 2016; Swindles et al., 2019; Hoyt et al., 2020; Hugelius et al., 2020; Jovani-Sancho et al., 2021; Veraverbeke et al., 2021), superimposed on anthropogenic disturbances (for example, draining for agriculture or mining; Section 5.2.1.1), has led to rapid losses of peatland carbon across the world (*robust evidence, high agreement*) (Page et al., 2011; Leifeld et al., 2019; Hoyt et al., 2020; Turetsky et al., 2020; Loisel et al., 2021). Other essential peatland ecosystem services, such as water storage and biodiversity, are also being lost worldwide (*robust evidence, high agreement*) (Bonn et al., 2014; Martin-Ortega et al., 2014; Tiemeyer et al., 2017).

The switch from carbon sink to source in peatlands globally is mainly attributable to changes in water table depth, regardless of management or status (*robust evidence, high agreement*) (Lafleur et al., 2005; Dommain et al., 2011; Lund et al., 2012; Cobb et al., 2017; Evans et al., 2021; Novita et al., 2021). Across the temperate and tropical biomes, extensive drainage and deforestation have caused widespread water table drawdowns and/or peat subsidence, as well as large CO_2 emissions (*medium evidence, high agreement*). Climate change is compounding these impacts (*medium evidence, medium agreement*). For example, in Indonesia, the highest emissions from drained tropical peatlands were reported in the extremely dry year of the 1997 El Niño (810–2570 TgC yr^{-1}) (Page et al., 2002) and the 2015 fire season (380 TgC yr^{-1}) (Field et al., 2016). These prolonged dry seasons have also led to tree die-offs and fires, which are relatively new phenomena in these latitudes (*medium evidence, high agreement*) (Cole et al., 2015; Mezbahuddin et al., 2015; Fanin and van der Werf, 2017; Taufik et al., 2017; Cole et al., 2019). Low soil moisture contributes to increased fire propagation (see Cross-Chapter Box 5, and Section 12.4.2.2; Dadap et al., 2019), causing long-lasting fires responsible for smoke and haze pollution (*robust evidence, high agreement*) (Ballhorn et al., 2009; Page et al., 2009; Gaveau et al., 2014; Huijnen et al., 2016; Page and Hooijer, 2016; Hu et al., 2018; Vadrevu et al., 2019; Niwa et al., 2021). Increases in fires and smoke lead to habitat loss and negatively impact regional faunal populations (*limited evidence, high agreement*) (Neoh et al., 2015; Erb et al., 2018b; Thornton et al., 2018).

In large lowland tropical peatland basins that are less impacted by anthropogenic activities (i.e., Amazon and Congo river basins), the direct impact of climate change is that of a decreased carbon sink (*limited evidence,* *medium agreement*) (Roucoux et al., 2013; Gallego-Sala et al., 2018; Wang et al., 2018a; Dargie et al., 2019; Ribeiro et al., 2021). As for the temperate and boreal regions, climatic drying also tends to promote peat oxidation and carbon loss to the atmosphere (*medium evidence, medium agreement*) (section 2.3.1.3.4) (Helbig et al., 2020; Zhang et al., 2020). In Europe, increasing mean annual temperatures in the Baltic, Scandinavia, and Continental Europe (Section 12.4.5.1) have led to widespread lowering of peatland water tables at intact sites (Swindles et al., 2019), *Sphagnum* moss desiccation and die off (Bragazza, 2008; Lees et al., 2019), and increased fire intensity and frequency resulting in rapid carbon loss (Davies et al., 2013; Veraverbeke et al., 2021). Nevertheless, longer growing seasons and warmer, wetter climates have increased carbon accumulation and promoted thick deposits regionally, as reported for some North American sites (*limited evidence, medium agreement*) (Cai and Yu, 2011; Shiller et al., 2014; Ott and Chimner, 2016).

In high-latitude peatlands, the net effect of climate change on the permafrost peatland carbon sink capacity remains uncertain (Abbott et al., 2016; McGuire et al., 2018b; Laamrani et al., 2020; Loisel et al., 2021; Sim et al., 2021; Väliranta et al., 2021). Increasing air temperatures have been linked to permafrost degradation and altered hydrological regimes (Section 2.3.3.2, Figure 2.4a, 2.4.3.9, and Box 5.1), which have led to rapid changes in plant communities and biogeochemical cycling (*robust evidence, high agreement*) (Liljedahl et al., 2016; Swindles et al., 2016; Voigt et al., 2017; Zhang et al., 2017b; Voigt et al., 2020; Sim et al., 2021). In many instances, permafrost degradation triggers thermokarst land subsidence associated with local wetting (*robust evidence, high agreement*) (Jones et al., 2013; Borge et al., 2017; Olvmo et al., 2020; Olefeldt et al., 2021). Permafrost thaw in peatland-rich landscapes can also cause local drying through increased hydrological connectivity and runoff (Connon et al., 2014). In the first decades following thaw, increases in methane, CO_2, and nitrous oxide emissions have been recorded from peatland sites, depending on surface moisture conditions (Schuur et al., 2009; O'Donnell et al., 2012; Elberling et al., 2013; Matveev et al., 2016; Euskirchen et al., 2020; Hugelius et al., 2020). Conversely, some evidence suggests increased peat accumulation after thaw (Jones et al., 2013; Estop-Aragonés et al., 2018; Väliranta et al., 2021). There is also a need to consider the impact of wildfire on permafrost thaw, due to its effect on soil temperature regime (Gibson et al., 2018), wildfire as a}, as fire intensity and frequency have increased across the boreal and Arctic biomes (*limited evidence, high agreement*) (Kasischke et al., 2010; Scholten et al., 2021).

Unfortunately, the CO_2 emissions from degrading peatlands is contributing to climate change in a positive feedback loop (*robust evidence, high agreement)*. In the midlatitudes, widespread anthropogenic disturbance led to large historical GHG emissions and current legacy emissions of 0.15 PgC yr^{-1} between 1990 and 2000 (*limited evidence, high agreement*) (Maljanen et al., 2010; Tiemeyer et al., 2016; Drexler et al., 2018; Qiu et al., 2021). About 80 million ha of peatlands have been converted to agriculture, equivalent to 72 PgC emissions between 850–2010 CE (Leifeld et al., 2019; Qiu et al., 2021). In southeast Asia, an estimated 20–25 Mha of peatlands have been converted to agriculture with carbon currently being lost at a rate of ~155 ± 30 MtC yr^{-1} (Miettinen et al., 2016; Leifeld et al., 2019; Hoyt et al., 2020). Extensive deforestation and drainage have caused widespread peat subsidence and large CO_2 emissions at a current average of ~10 ± 2 t ha^{-1} yr^{-1} (excluding fires, (Hoyt et al., 2020)), with values estimated from point subsidence measurements being as high as 30–90 t CO_2 ha^{-1} yr^{-1} locally (*robust evidence, high agreement*) (Wösten et al., 1997; Matysek et al., 2018; Swails et al., 2018; Evans et al., 2019; Conchedda and Tubiello, 2020; Anshari et al., 2021). On balance, at the global scale, increases in GHG emissions from peatlands have primarily come from the compounded effects of land-use change, drought, and fire, with emissions from some thawing permafrost peatlands (*robust evidence, high agreement*).

2.4.3.9 Observed Changes in Polar Tundra

Warming at high latitudes, documented in both AR4 and AR5, is leading to earlier snow and sea ice melt and longer growing seasons (WGI AR6) which are continuing to alter tundra plant communities (*medium evidence, high agreement)* (Post et al., 2009; Gauthier et al., 2013). Woody encroachment and increases in vegetation productivity observed in both AR4 and AR5 are widespread and continuing. Both experiments and monitoring indicate that climate warming is causing increases in shrub, grass and sedge abundance, density, frequency and height, with decreases in mosses and/or lichens *(robust evidence, high agreement)* (Myers-Smith et al., 2011; Bjorkman et al., 2018; Bjorkman et al., 2019). Shrub growth is climate-sensitive and greater in years with warmer growing seasons (Myers-Smith et al., 2015). Plant species that prefer warmer conditions are increasing (Elmendorf et al., 2015; Bjorkman et al., 2018), plant cover is increasing and bare ground is decreasing in long-term monitoring plots (Bjorkman et al., 2019; Myers-Smith et al., 2019). Animals such as moose, beavers and songbirds may already be responding to these vegetation changes by expanding their ranges northward or upslope into shrub tundra (Boelman et al., 2015; Tape et al., 2016a; Tape et al., 2016b; Tape et al., 2018).

In addition to direct warming, indirect effects of climate change such as thawed permafrost, altered hydrology and enhanced nutrient cycling (as observed in AR4 and AR5) continue and are causing pronounced vegetation changes *(medium evidence, medium agreement)* (Schuur et al., 2009; Natali et al., 2012). Soil moisture status influences temperature sensitivity of plant growth and canopy heights (Myers-Smith et al., 2015; Ackerman et al., 2017; Bjorkman et al., 2018). In tundra ecosystems permafrost thawing can decouple below-ground plant growth dynamics from above-ground dynamics, with below-ground root growth continuing until soils refreeze in autumn (Cross-Chapter Paper 6; Iversen et al., 2015; Blume-Werry et al., 2016; Radville et al., 2016).

2.4.4 Observed Changes in Ecosystem Processes and Services

2.4.4.1 Observed Browning of Rivers and Lakes

In boreal coniferous areas there has been an increase in terrestrial derived dissolved organic carbon (DOC) transport into rivers and lakes, which has caused increased opacity and shift toward a brown colour (browning). This process was not given much attention in AR5 even though it is a consequence of climate change: hydrological intensification, greening of the Northern Hemisphere, and degradation of carbon sinks in peatlands *(robust evidence, high agreement*) (Solomon et al., 2015; Catalán et al., 2016; Crowther et al., 2016; de Wit et al., 2016; Finstad et al., 2016; Creed et al., 2018; Hayden et al., 2019) factors that enhance terrestrial productivity, alter vegetation communities, and affect the hydrological control on production and transport of DOC (Weyhenmeyer et al., 2016). Non climate-related drivers of browning are: declining atmospheric sulphur deposition, forestry practices and land-use changes (see Table 2.S.1 for detail).

Browning creates a positive feedback by absorbing photosynthetically active radiation accelerating upper water (epilimnetic) warming (Solomon et al., 2015). Browning of lakes leads to shallower and more stable thermoclines and thus, overall deep water cooling (Solomon et al., 2015; Williamson et al., 2015) and can provoke a transition of the seasonal mixing regime from a mixed lake (polymictic) to one that is seasonally stratified (Kirillin and Shatwell, 2016).

The ecological responses of browning need to be considered as concomitant effects of climate change and nutrient status. Results from long-term, large-scale lake experiments were variable, showing both strong synergistic effects (Urrutia-Cordero et al., 2016) and no significant effects of browning on plankton community food webs (Rasconi et al., 2015). Browning has driven a shift from auto- to heterotrophic/mixotrophic-based production (Wilken et al., 2013; Urrutia-Cordero et al., 2017) and supports heterotrophic metabolism of the bacterial community (Zwart et al., 2016). Browning may also accelerate primary production through input of nutrients associated with DOM in nutrient poor lakes and increase cyanobacteria, which better cope with low light intensities (Huisman et al., 2018) and toxin levels (Urrutia-Cordero et al., 2016). However, the synergistic impacts of browning and climate change on aquatic communities depends on regional precipitation patterns (Weyhenmeyer et al., 2016), watershed type (de Wit et al., 2016), and food chain length (Hansson et al., 2013). Quantitative attribution of browning to climate change remains difficult (*medium evidence, medium confidence*).

In summary, new studies since AR5 have explicitly estimated the effects of warming and browning on freshwaters in boreal areas with complex positive and negative repercussions on water temperature profiles (lower vs upper water) (*high confidence*) and primary production (*medium confidence*).

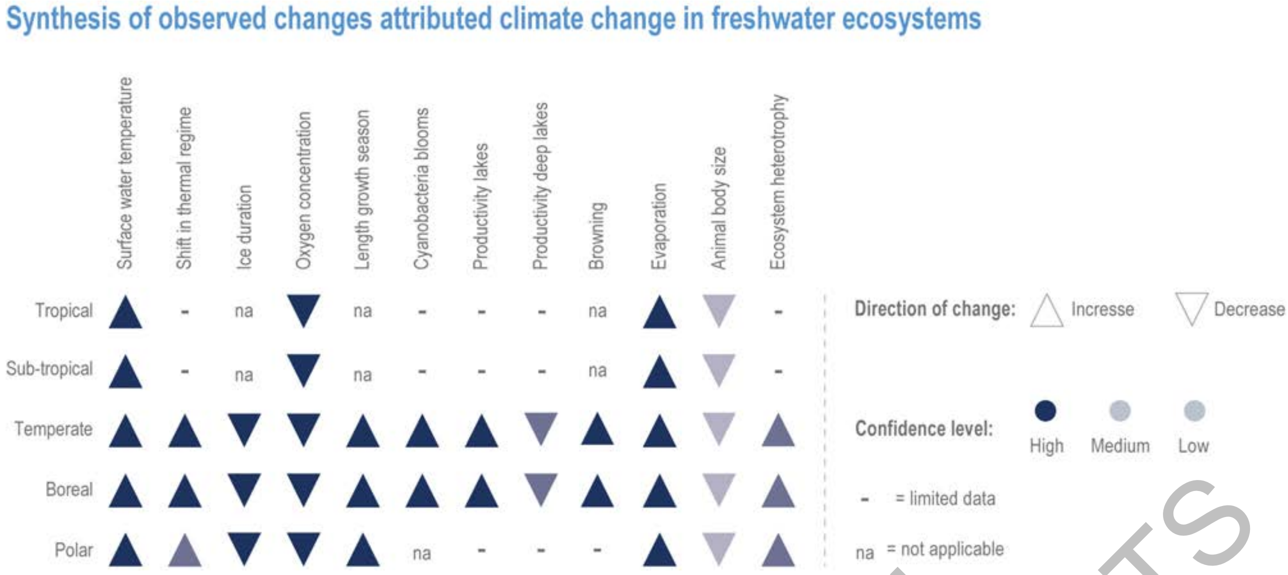


Figure 2.5: Large scale observed changes in freshwater ecosystems attributed to climate change over more than four decades. For description and references, see 2.3.3, 2.4.2, and 2.5.3.6.2.

2.4.4.2 Observed Changes in Wildfire

2.4.4.2.1 Detection and attribution of observed changes in wildfire

Wildfire is a natural and essential component of many forest and other terrestrial ecosystems. Excessive wildfire, however, can kill people, cause respiratory disease, destroy houses, emit carbon dioxide, and damage ecosystem integrity (see Section 2.4.4.2, 2.4.4.4). Anthropogenic climate change increases wildfire by exacerbating its three principal driving factors—heat, fuel, and ignition (Moritz et al., 2012; Jolly et al., 2015). Non-climatic factors also contribute to wildfires—in tropical areas fires are set intentionally to clear forest for agricultural fields and livestock pastures (Bowman et al., 2020b). Urban areas and roads create ignition hazards. Governments in many temperate zone countries implement policies to suppress fires, even natural ones, producing unnatural accumulations of fuel in the form of coarse woody debris and high densities of small trees (Ruffault and Mouillot, 2015; Hessburg et al., 2016; Andela et al., 2017; Balch et al., 2017; Lasslop and Kloster, 2017; Aragao et al., 2018, (Kelley et al., 2019). Globally, 4.2 million km^2 of land per year burned on average from 2002 to 2016 (Giglio et al., 2018) with the highest fire frequencies in the Amazon rainforest, deciduous forests and savannas in Africa, and deciduous forests in northern Australia (Earl and Simmonds, 2018; Andela et al., 2019).

Since the IPCC Fifth Assessment Report and the IPCC Special Report on Land, published research has detected increases in the area burned by wildfire, analysed relative contributions of climate and non-climate factors, and attributed burned area increases above natural levels to anthropogenic climate change in one part of the world – western North America (*robust evidence, high agreement)* (Abatzoglou and Williams, 2016; Partain et al., 2016; Kirchmeier-Young et al., 2019; Mansuy et al., 2019; Bowman et al., 2020b). Across the western United States, increases in vegetation aridity due to higher temperatures from anthropogenic climate change doubled burned area from 1984 to 2015 over what would have burned due to non-climate factors, including unnatural fuel accumulation from fire suppression, with the burned area attributed to climate change accounting for 49% (32–76%, 95% confidence interval) of cumulative burned area (Abatzoglou and Williams, 2016). Anthropogenic climate change has doubled the severity of a southwest North American drought from 2000 to 2020 that has reduced soil moisture to its lowest levels since the 1500s (Williams et al., 2020), driving half of the increase in burned area (Abatzoglou and Williams, 2016; Holden et al., 2018; Williams et al., 2019). In British Columbia, Canada, the increased maximum temperatures due to anthropogenic climate change increased burned area in 2017 to its highest extent in the 1950–2017 record, seven to eleven times the area that would have burned without climate change (Kirchmeier-Young et al., 2019). In Alaska, USA, the high maximum temperatures and extremely low relative humidity due to anthropogenic climate change accounted for 33–60% of the probability of wildfire in 2015, when the area burned was the second highest in the 1940–2015 record (Partain et al., 2016). In protected areas of Canada and the United States, climate factors (temperature, precipitation, relative humidity, evapotranspiration) accounted for 60% of burned area from local human and natural ignitions from 1984 to 2014, outweighing local human factors (population density, roads, and built area) (Mansuy et al., 2019).

In summary, field evidence shows that anthropogenic climate change has increased the area burned by wildfire above natural levels across western North America in the period 1984–2017, at global mean surface temperature increases of 0.6ºC –0.9ºC, increasing burned area up to 11 times in one extreme year and doubling burned area over natural levels in a 32 year period (*high confidence*).

2.4.4.2.2 Observed changes in wildfire globally

For global terrestrial area as a whole, wildfire trends vary depending on the time period of analysis. From 1900 to 2000, global average fire frequency, based on field data, increased 0.4% but the change was not statistically significant, (Mouillot and Field, 2005; Gonzalez et al., 2010b). Fire frequency increased on one-third of global land, mainly from burning for agricultural clearing in Africa, Asia, and South America, slightly less than the area of fire frequency decrease, mainly from fire suppression across Australia, North America, and Russia (Gonzalez et al., 2010b). Analyses of the Global Fire Emissions Database document that from 1996 to 2015, global burned area decreased at a rate of –0.7% y^{-1} (Forkel et al., 2019) but the change was not statistically significant, (Giglio et al., 2013). From 1998 to 2015, global burned area decreased at a rate of $-1.4 \pm 0.5\%\ y^{-1}$ (Giglio et al., 2013; Andela et al., 2017). The area of fire increases was a third of the area of decreases, due to reduction of vegetation cover from agricultural expansion and intensification (Andela et al., 2017) and increased precipitation (Forkel et al., 2019). Furthermore, much of the decreasing trend derives from two years: 1998 with high burned area and 2013 with low burned area (Forkel et al., 2019). Wildfire does not show a clear long-term trend for the world as a whole because of increases and decreases in different regions (*medium evidence, medium agreement*).

Where global average burned area has decreased in the past two decades, higher correlations of rates of change in burning to human population density, cropland area, and livestock density than to precipitation indicate that agricultural expansion and intensification were main causes (Andela et al., 2017). The global decrease of fire frequency from 2000 to 2010 is correlated to increasing human population density (Knorr et al., 2014). The fire-reduction effect of reduced vegetation cover following expansion of agriculture and livestock herding can counteract the fire-increasing effect of increased heat of climate change (Lasslop and Kloster, 2017; Arora and Melton, 2018; Forkel et al., 2019). The reduction of burning needed after the initial clearing for agricultural expansion drives much of the decline in fire in the tropics (Andela et al., 2017; Earl and Simmonds, 2018; Forkel et al., 2019). The human influence on fire ignition can be seen through the decrease documented on holy days (Sundays and Fridays), traditional religious days of rest (Earl et al., 2015). Overall, human land use exerts an influence on wildfire trends for global terrestrial area as a whole that can be stronger than climate change (*medium confidence*).

2.4.4.2.3 Observed changes in wildfire in individual regions

While burned area has increased in parts of Asia, Australia, Europe, and South America, published research has not yet attributed the increases to anthropogenic climate change (*medium evidence, high agreement*).

In the Amazon, deforestation for agricultural expansion and the degradation of forests adjacent to deforested areas cause wildfire in moist humid tropical forests not adapted to fire (*robust evidence, high agreement*) (Fonseca et al., 2017; van Marle et al., 2017; da Silva et al., 2018; da Silva et al., 2021; dos Reis et al., 2021; Libonati et al., 2021). Roads facilitate deforestation, fragmenting the rainforest and increasing the dryness and flammability of vegetation (Alencar et al., 2015). Extreme droughts that occur during warm phases of the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation combine with the degradation of vegetation to cause extreme fire events (*robust evidence, high agreement*) (Fonseca et al., 2017; Aragao et al., 2018; da Silva et al., 2018; Burton et al., 2020; dos Reis et al., 2021; Libonati et al., 2021). In the State of Roraima, Brazil, distance to roads, infrastructure that enables deforestation, and ENSO were the two factors most explaining fire occurrence in the extreme 2015–2016 fire season (Fonseca et al., 2017). From 1973 to 2014, burned area increased in the Amazon, coinciding with increased deforestation (van Marle et al., 2017). In the State of Acre, Brazil, burned area increased 36-fold from 1984 to 2016, with 43% burned area in agricultural and livestock settlement areas (da Silva et al., 2018). In 2019, the extreme fire year 2019, 85% of the area burned in the Amazon occurred in areas deforested in 2018 (Cardil et al., 2020). Even though relatively higher moisture in 2019 led to burning below the 2002–2019 average across most of South America, burning in areas of recent deforestation in the Amazon were above the 2002-2019 average, indicating that deforestation, not meteorological conditions, triggered the 2019 fires (Kelley et al., 2021; Libonati et al., 2021). Furthermore, from 1981 to 2018, deforestation in the Amazon reduced moisture inputs to the lower atmosphere, increasing drought and fire in a self-reinforcing feedback (Xu et al., 2020). In the Amazon, deforestation exerts an influence on wildfire that can be stronger than climate change (*robust evidence, high agreement*).

In Australia, burned area increased significantly between the periods 1950–2002 and 2003–2020 in the southeast state of Victoria, with the area burned in the 2019–2020 bushfires the highest on record (Lindenmayer and Taylor, 2020). In addition to the deaths of dozens of people and destruction of thousands of houses, the 2019–2020 Australia bushfires burned almost half of the area protected for conservation in Victoria and two-thirds of forests allocated for timber harvesting (Lindenmayer and Taylor, 2020), wildlife, and extensive areas of habitat for threatened plant and animal species (Geary et al., 2021). Generally, past timber harvesting did not lead to more severe fire canopy damage (Bowman et al., 2021). Across Southeastern Australia, the fraction of vegetated area that burned increased significantly in eight of the 32 bioregions from 1975 to 2009 but decreased significantly in three bioregions (Bradstock et al., 2014). Increases in four bioregions were correlated to increasing temperature and decreasing precipitation. Decreases in burned area occurred despite increased temperature and decreased precipitation. Analyses of climate across Australia from 1950 to 2017 (Dowdy, 2018; Harris and Lucas, 2019) and during periods with extensive fires in 2017 in eastern Australia (Hope et al., 2019), in 2018 in Northeastern Australia (Lewis et al., 2020), and in period 2019-2020 in Southeastern Australia (Abram et al., 2021; van Oldenborgh et al., 2021) indicate that temperature and drought extremes due to the El Niño-Southern Oscillation, Southern Annular Mode, and other natural interdecadal cycles drive interannual variability of fire weather. While the effects of interdecadal climate cycles on fire are superimposed on long-term climate change, the relative importance of anthropogenic climate change in explaining changes in burned area in Australia remains unquantified (*medium evidence, high agreement*).

In Africa, the rate of change of burned area for the continent as a whole ranged from a non-statistically significant –0.45% y^{-1} from 2002 to 2016 (Zubkova et al., 2019) to a significant –1.9% y^{-1} from 2001 to 2016 (Wei et al., 2020). Burned area decreases coincided with areas of agricultural expansion or areas where drought reduced fuel loads (Zubkova et al., 2019; Wei et al., 2020). It is possible, however, that the 500 m spatial resolution of Modis remote sensing fire data underestimates burned area in Africa by half by missing small fires (Ramo et al., 2021). In the Serengeti-Mara savanna of east Africa, burned area showed no significant change from 2001 to 2014, although an increase in domestic livestock would tend to reduce the grass cover that fuels savanna fires (Probert et al., 2019).

In Mediterranean Europe, burned area for the region as a whole decreased from 1985 to 2011 (Turco et al., 2016), although burned area for Spain did not show a significant long-term increase from 1968 to 2010 (Moreno et al., 2014) while burned area for Portugal in 2017 was the highest in the period 1980–2017 (Turco et al., 2019). Increased summer maximum temperature and decreased soil moisture explained most of observed burned area, suggesting a contribution of climate change, but fire suppression, fire prevention, agricultural abandonment, and reforestation, and reduction of forest area exerted even stronger influences on burned area than climate across Mediterranean Europe (*robust evidence, high agreement*) (Moreno et al., 2014; Turco et al., 2017; Viedma et al., 2018; Turco et al., 2019).

In the Arctic tundra and boreal forest, where wildfire has naturally been infrequent, burned area showed statistically significant increases of ~50% y^{-1} across Siberia, Russia, from 1996 to 2015 (Ponomarev et al., 2016) and 2% y^{-1} across Canada from 1959 to 2015 (Hanes et al., 2019). Wildfire burned ~ 6% of the area of four extensive Arctic permafrost regions in Alaska, USA, eastern Canada, and Siberia from 1999 to 2014 (Nitze et al., 2018). In boreal forest in the Northwest Territories, Canada, and Alaska, USA, the area burned by wildfire increased at a statistically significant rate of 6.8% y^{-1} in the period 1975–2015, (Veraverbeke et al., 2017), with smouldering belowground fires that lasted through the winter covering ~1% of burned area in the period 2002-2016 (Scholten et al., 2021). While burned area was correlated to temperature and reduced precipitation in Siberia (Ponomarev et al., 2016; Masrur et al., 2018) and to lightning, correlated with temperature and precipitation in the Northwest Territories and Alaska (Veraverbeke et al., 2017), no attribution analyses have examined relative influences of climate and non-climate factors.

In Indonesia, deforestation and draining of peat swamp forests dries out the peat, providing substantial fuel for fires (Page and Hooijer, 2016). Extreme fire years in Indonesia, including 1997, 2006, and 2015, coincide with extreme heat and aridity during the warm phase of the El Niño-Southern Oscillation (Field et al., 2016). Fire-resistant forest in 2019 covered only 3% of peatlands and 4.5% of non-peatlands on Sumatra and Kalimantan (Nikonovas et al., 2020).

In Chile, burned area in the summer of 2016–2017 was 14 times the mean for the period 1985–2016 and the highest on record (Bowman et al., 2019). While that extreme fire year coincided with the highest daily mean maximum temperature in the period 1979–2017 (Bowman et al., 2019), in central Chile, the area of highest fire activity, burned area from 1976 to 2013 showed highest correlation to precipitation cycles of the El Niño-Southern Oscillation and temperature cycles of the Antarctic Oscillation (Urrutia-Jalabert et al., 2018).

Overall, burned area has increased in the Amazon, the Arctic, Australia, and parts of Africa and Asia, consistent with, but not formally attributed to anthropogenic climate change (*medium evidence, high agreement*). Deforestation, peat draining, agricultural expansion or abandonment, fire suppression, and interdecadal cycles such as the El Niño-Southern Oscillation exert a stronger influence than climate change on wildfire trends in numerous regions outside of North America (*high confidence*).

2.4.4.2.4 Observed changes in fire seasons globally

IPCC AR6 Working Group 1, Chapter 12, has assessed fire weather, while this chapter assesses burned area and fire frequency. The global increases in temperature of anthropogenic climate change have increased aridity and drought, lengthening the fire weather season (annual period with a heat and aridity index greater than half of its annual range) on one-quarter of global vegetated area and increasing average fire season length by one-fifth, from 1979 to 2013 (Jolly et al., 2015). Climate change has contributed to increases in the fire weather season or the probability of fire weather conditions in the Amazon (Jolly et al., 2015), Australia (Dowdy, 2018; Abram et al., 2021; van Oldenborgh et al., 2021), Canada (Hanes et al., 2019), central Asia (Jolly et al., 2015), East Africa (Jolly et al., 2015), and North America (Jain et al., 2017; Williams et al., 2019; Goss et al., 2020). In forest areas, the burned area is correlated to fuel aridity, a function of temperature; in non-forest areas, the burned area is correlated to high precipitation in the previous year, which can produce high grass fuel loads (Abatzoglou et al., 2018). Fire use in agriculture and livestock raising or other factors have generated a second fire season on approximately one-quarter of global land where fire is present, despite sub-optimal fire weather in the second fire season (Benali et al., 2017). In summary, anthropogenic climate change, through a 0.9ºC surface temperature increase since the pre-industrial period, has lengthened or increased the frequency of periods with heat and aridity that favour wildfire on up to one-quarter of vegetated area, since 1979 (*robust evidence, high agreement*).

2.4.4.2.5 Observed changes in post-fire vegetation

Globally, fire has contributed to biome shifts (Section 2.4.3.2) and tree mortality (Section 2.4.4.2, 2.4.4.3) attributed to anthropogenic climate change. Research since the IPCC Fifth Assessment Report has also found vegetation changes from wildfire due to climate change. Through increased temperature and aridity, anthropogenic climate change has driven post-fire changes in plant regeneration and species composition in South Africa (Slingsby et al., 2017) and tree regeneration in the western United States (Davis et al., 2019b). In the Fynbos vegetation of the Cape Floristic Region, South Africa, post-fire heat and drought and legacy effects of exotic plant species reduced native plant species regeneration, decreasing species richness 12% from 1966 to 2010 and shifting the average temperature tolerance of species upward by 0.5ºC (Slingsby et al., 2017). In burned areas across the western United States, the increasing heat and aridity of anthropogenic climate change from 1979 to 2015 pushed low-elevation ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) forests across critical thresholds of heat and aridity that reduced post-fire tree regeneration by half (Davis et al., 2019b). In the Southwestern United States of America, where anthropogenic climate change has caused drought (Williams et al., 2019) and increased wildfire (Abatzoglou and Williams, 2016), high-severity fires have converted some forest patches to shrublands (Barton and Poulos, 2018). Field evidence shows that anthropogenic climate change and wildfire together have altered vegetation species composition in the Southwestern USA and in the Cape floristic region, South Africa, reducing post-fire natural regeneration and species richness of tree and other plant species, between 1966 and 2015, at global mean surface temperature increases of 0.3-0.9ºC (*medium evidence, high agreement*).

[START FAQ2.3 HERE]

FAQ2.3: Is climate change increasing wildfire?

In the Amazon, Australia, North America, Siberia, and other regions, wildfires are burning wider areas than in the past. Analyses show that human-caused climate change has driven the increases in burned area in the forests of western North America. Elsewhere, deforestation, fire suppression, agricultural burning, and short-term cycles like El Niño can exert a stronger influence than climate change. Many forests and grasslands naturally require fire for ecosystem health but excessive wildfire can kill people, destroy homes, and damage ecosystems.

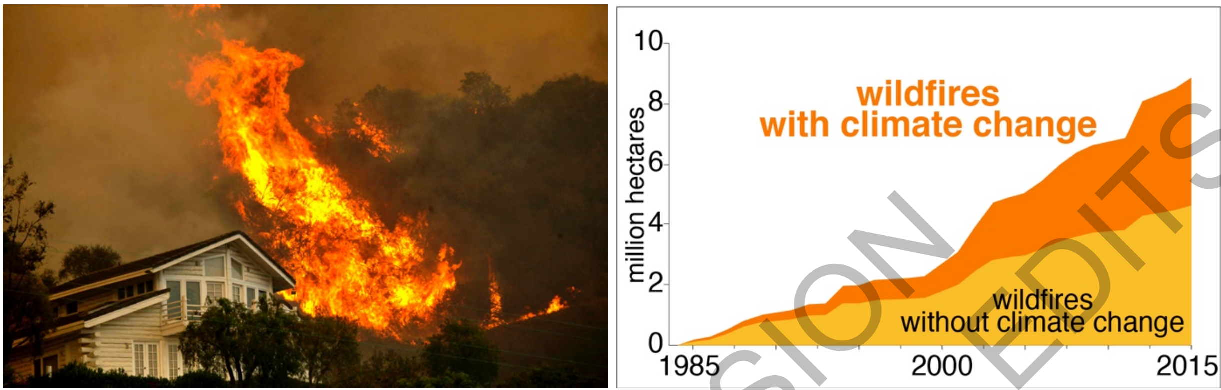


Figure FAQ2.3.1: (a) Springs Fire, May 2, 2013, Thousand Oaks, California, USA (photo by Michael Robinson Chávez, Los Angeles Times). (b) Cumulative area burned by wildfire in the western U.S., with (orange) and without (yellow) the increased heat and aridity of climate change (Abatzoglou and Williams, 2016).

Wildfire is a natural and essential part of many forest, woodland, and grassland ecosystems, killing pests, releasing plant seeds to sprout, thinning out small trees, and serving other functions essential for ecosystem health. Excessive wildfire, however, can kill people, cause breathing illnesses from the smoke, destroy homes (Figure FAQ2.1a), and damage ecosystems.

Human-caused climate change increases wildfire by intensifying its principal driving factor – heat. The heat of climate change dries out vegetation and accelerates burning. Non-climate factors also cause wildfires. Agricultural companies, small farmers, and livestock herders in many tropical areas cut down forests and intentionally set fires to clear fields and pastures. Cities, towns, and roads increase the number of fires that people ignite. Governments in many countries suppress fires, even natural ones, producing unnatural accumulations of fuel in the form of coarse woody debris and dense stands of small trees. The fuel accumulations cause particularly severe fires that burn into tree crowns.

Evidence shows that human-caused climate change has driven increases in the area burned by wildfire in the forests of western North America. Across the western U.S., the higher temperatures of human-caused climate change doubled burned area from 1984 to 2015, compared with what would have burned without climate change (Figure FAQ2.1b). The additional area burned, 4.9 million hectares, is greater than the land area of Switzerland. In this region, human-caused climate change has driven a drought from 2000 to 2020 that is the most severe since the 1500s, severely increasing the aridity of vegetation. In British Columbia, Canada, the higher maximum temperatures of human-caused climate change increased burned area in 2017 to its widest extent in the 1950–2017 record, seven to eleven times the area that would have burned without climate change. Moreover, in national parks and other protected areas of Canada and the U.S., climate factors explained the majority of burned area from 1984 to 2014, with climate factors (temperature, rainfall, aridity) outweighing local human factors (population density, roads, and urban area).

In other regions, wildfires are also burning wider areas and occurring more often. This is consistent with climate change but analyses have not yet shown if climate change is more important than other factors. In the Amazon, deforestation by companies, farmers, and herders who cut down and intentionally burn rainforests to expand agricultural fields and pastures causes wildfires even in relatively moister years. Drought exacerbates these fires. In Australia, much of the southeastern part of the continent has experienced extreme wildfire years, but analyses suggest that El Niño, a heat phenomenon that cycles up and down periodically, is more important than long-term climate change. In Indonesia, intentional burning of rainforests for oil palm plantations and El Niño seem to be more important than long-term climate change. In Mediterranean Europe, fire suppression seems to have prevented any increasing trend in burned area but suppression and abandonment of agricultural lands have allowed fuel to build up in some areas and contribute to major fires in years of extreme heat. In Canada and Siberia, wildfires are now burning more often in permafrost areas where fire had been rare, but analyses are lacking on the relative influence of climate change. For the world as a whole, satellite data indicate that the vast amount of land that converted from forest to farmland from 1998 to 2015 actually decreased total burned area. Nevertheless, the evidence from the forests of western North America shows that human-caused climate change has, on one continent, clearly driven increases in wildfire.

[END FAQ2.3 HERE]-

2.4.4.3 Observed Changes in Tree Mortality

2.4.4.3.1 Observed tree mortality globally

Anthropogenic climate change can cause tree mortality directly through increased aridity or drought (Section 2.4.4.3.3) or indirectly through wildfire (Section 2.4.4.2.1) and insect pests (Section 2.4.4.3.3). Catastrophic failure of the plant hydraulic system, in which a lack of water causes the xylem to lose hydraulic conductance, is the principal mechanism of drought-induced tree death (Anderegg et al., 2016; Adams et al., 2017; Anderegg et al., 2018; Choat et al., 2018; Menezes-Silva et al., 2019; Brodribb et al., 2020).

Up through the IPCC Fifth Assessment Report (Settele et al., 2014), detection and attribution analyses had found that anthropogenic climate change, with global temperature increases of 0.3°-0.9ºC above the pre-industrial period and increases in aridity exceeding the effects of local non-climate change factors, caused three cases of drought-induced tree mortality of up to 20% in the period 1945-2007, in western North America (van Mantgem et al., 2009), the African Sahel (Gonzalez et al., 2012), and North Africa (le Polain de Waroux and Lambin, 2012). Increased wildfire and pest infestations, driven by climate change, also contributed to the North American tree mortality (van Mantgem et al., 2009). In addition, a meta-analysis of published cases found that drought consistent with, but not formally attributed, to climate change, had caused tree mortality at 88 sites in boreal, temperate and tropical ecosystems (Allen et al., 2010), with 49 additional cases found by the IPCC Fifth Assessment report (Settele et al., 2014).

Since the IPCC Fifth Assessment Report (Settele et al., 2014), global meta-analyses have found at least 15 (Allen et al., 2015) and 25 (Hartmann et al., 2018) additional sites of drought-induced tree mortality around the world. These and other global analyses found more rapid mortality than previously (Allen et al., 2015), rising background mortality (Allen et al., 2015), mortality increasing with drought severity (Greenwood et al., 2017), mortality of tropical trees increasing with temperature (Locosselli et al., 2020), mortality increasing with tree size for many species (Bennett et al., 2015), mortality predominantly at the dry edge of species ranges (Anderegg et al., 2019a), and three-fourths of drought-induced mortality cases leading to a change in the dominant species (Batllori et al., 2020). Multiple non-climate factors contribute to tree mortality, including timber cutting, livestock grazing, and air pollution (Martinez-Vilalta and Lloret, 2016). Globally, tropical dry forests lost, from all causes, 95,000 km^2, 8% of their total area, from 1982 to 2016, the most extensive area of mortality of any biome (Song et al., 2018).

In summary, anthropogenic climate change has caused drought-induced tree mortality up to 20% in the period 1945-2007 in western North America, the African Sahel, and North Africa, through global temperature increases of 0.3°–0.9ºC above the pre-industrial period and increases in aridity, and contributed to over 100 other cases of drought-induced tree mortality in Africa, Asia, Australia, Europe, and North and South America (*high confidence*). Field observations document accelerating mortality rates, rising background mortality, and post-mortality vegetation shifts (*high confidence*). Water stress, leading to plant hydraulic failure, is the principal mechanism of drought-induced tree mortality. Timber cutting, agricultural expansion, air pollution, and other non-climate factors also contribute to tree death.

2.4.4.3.2 Observed tree mortality in tropical ecosystems

In the Brazilian Amazon, deforestation to clear agricultural land comprises the principal cause of tree mortality, reducing forest cover an average of 13,900 km^2 y^{-1} from 1988 to 2020 (Espaciais, 2021). In addition, an annual average temperature increase of 1.2ºC from 1950 to 2018 (Marengo et al., 2018) contributed to mortality in a set of 310 Amazon field plots of ~40% from 1983 to 2011 (Brienen et al., 2015). In another set of plots, mortality among newly recruited trees of mesic genera increased and drought-tolerant genera became more abundant from 1985 to 2015 (Esquivel-Muelbert et al., 2019). In other plots, tree mortality did not show a statistically significant change from 1965 to 2016 but rose abruptly in severe drought years, mainly during warm phases of the El Niño-Southern Oscillation (ENSO) (Aleixo et al., 2019). Nearly half the area of the Amazon has experienced extremely dry conditions during ENSO warm phases, which can cause extensive wildfire (Section 2.4.4.2.3). Wildfire can increase tree mortality rates by >600% above rates in non-burned areas, with the higher mortality persisting up to a decade after a fire (Silva et al., 2018; Berenguer et al., 2021). Climate change has contributed to tree mortality in Amazon rainforest (*medium evidence, medium agreement*).

In the African Sahel field research has continued to detect tree mortality, ranging from 20% to 90% in the period 1965-2018 (Kusserow, 2017; Trichon et al., 2018; Dendoncker et al., 2020), and declines in tree biodiversity, with local losses of tree species up to 80% in the period 1970-2014 (Hanke et al., 2016; Kusserow, 2017; Ibrahim et al., 2018; Dendoncker et al., 2020), consistent with, but not formally attributed to climate change. In Algeria, mortality of Atlas cedar (*Cedrus atlantica*) increased from 1980 to 2006, coinciding with a ~1ºC spring temperature increase, but non-climate factors were not examined (Navarro-Cerrillo et al., 2019). Across southern Africa, nine of the 13 oldest known baobab trees (*Adansonia digitata*), 1100–2500 years old, have died since 2005, although the causes are unknown (Patrut et al., 2018). In South Africa, savanna trees experienced an order of magnitude increase in mortality, related, but not formally attributed to decreased rainfall (Case et al., 2019). In Tunisia, insect infestations related, but not formally attributed to, hotter temperatures led to mortality of cork oaks (*Quercus suber*) (Bellahirech et al., 2019).

2.4.4.3.3 Observed tree mortality in boreal and temperate ecosystems

The most extensive research on tree mortality since the IPCC Fifth Assessment Report has occurred in the western United States, where anthropogenic climate change accounts for half the magnitude of a drought from 2000 to 2020 that has been the most severe since the 1500s (Williams et al., 2020) and for one-tenth to one-quarter of the magnitude of the 2012-2014 period of the severe 2012-2016 drought in California (Williams et al., 2015a). Across the western United States, anthropogenic climate change doubled tree mortality between 1955 and 2007 (van Mantgem et al., 2009). Lodgepole pine (*Pinus contorta*) mortality increased 700% from 2000 to 2013 (Anderegg et al., 2015) and piñon pine (*Pinus edulis*) experienced over 50% mortality from 2002 to 2014 (Redmond et al., 2018). In California montane conifer forest, anthropogenic climate change increased tree mortality one-quarter (Goulden and Bales, 2019). One-quarter of trees died in some areas with mortality rates of ponderosa pine (*Pinus ponderosa*) and sugar pine (*Pinus lambertiana*) increasing up to 700% of pre-drought rates (Stephenson et al., 2019; Stovall et al., 2019). Substantial field evidence shows that anthropogenic climate change has caused extensive tree mortality in North America (*robust evidence, high agreement*).

In western North America, increased infestations of bark beetles and other tree-feeding insects that benefit from increased winter temperatures (IPCC AR6 WGI 3.3.1.1) and longer growing seasons (IPCC AR6 WGI 2.3.4.3.1) have killed drought-stressed trees (Section 2.4.2.1; Anderegg et al., 2015; Kolb et al., 2016; Lloret and Kitzberger, 2018; Redmond et al., 2018; Stephens et al., 2018; Fettig et al., 2019; Restaino et al., 2019; Stephenson et al., 2019). Increasing temperatures have allowed bark beetles to move further north and higher in elevation, survive through the winter at sites where they would previously have died, and reproduce more often (Raffa et al., 2008; Bentz et al., 2010; Jewett et al., 2011; Macfarlane et al., 2013; Raffa et al., 2013; Hart et al., 2017; Stephenson et al., 2019; Teshome et al., 2020; Koontz et al., 2021). Under warmer conditions, some insects that were previously innocuous have become important agents of tree mortality (Stephenson et al., 2019; Trugman et al., 2021). Field observations show mixed effects of bark beetle-induced tree mortality on subsequent fire-caused tree mortality (Andrus et al., 2016; Meigs et al., 2016; Candau et al., 2018; Lucash et al., 2018; Talucci and Krawchuk, 2019; Wayman and Safford, 2021). From 1997 to 2018, ~5% of western U.S. forest area died from bark beetle infestations (Hicke et al., 2020). In most circumstances, trees that have been weakened by drought are more vulnerable to being killed by bark beetles (Anderegg et al., 2015; Kolb et al., 2016; Lloret and Kitzberger, 2018; Redmond et al., 2018;

Stephens et al., 2018; Fettig et al., 2019; Restaino et al., 2019; Stephenson et al., 2019; Koontz et al., 2021). Climate change has contributed to bark beetle infestations that have caused much of the tree mortality in North America (*robust evidence, high agreement*) (Section 2.4.2.1).

Across Europe, rates of tree mortality in field inventories from 2000 to 2012 were highest in Spain, Bulgaria, Sweden, and Finland, positively correlated to maximum winter temperature and inversely correlated to spring precipitation (Neumann et al., 2017). Tree mortality in Austria, the Czech Republic, Germany, Poland, Slovakia, and Switzerland doubled from 1984 to 2016, correlated to intensified logging and increased temperatures (Senf et al., 2018). Drought-related tree mortality rates from 1987 to 2016 were highest in Ukraine, Moldova, southern France, and Spain (Senf et al., 2020). Climate contributed to tree mortality across Europe from 1958 to 2001 (Seidl et al., 2011). In addition, insect infestations related to higher temperatures (Okland et al., 2019) have caused extensive mortality of Norway spruce (*Picea abies*) across nine European countries (Marini et al., 2017; Mezei et al., 2017). Across the Mediterranean Basin, a combination of drought, wildfire, pest infestations, and livestock grazing has driven tree mortality (Penuelas and Sardans, 2021). Climate change has contributed to tree mortality in Europe (*high agreement, medium confidence*). (Section 2.4.2.1)

2.4.4.3.4 Tree mortality and fauna

A global meta-analysis of 631 cases of bird and mammal abundance changes in areas of tree mortality found increasing abundance in a set of 186 bird species with increasing mortality and no trend in mammal abundance (Fleming et al., 2021). Ground-nesting, ground foraging, tree hole nesting, and bark foraging increased most, while nectar-feeding and foliage-gleaning birds declined. Invertebrates, especially ground-foraging predators and detritivores, decreased.

2.4.4.4 Observed Terrestrial Ecosystem Carbon

2.4.4.4.1 Observed terrestrial ecosystem carbon globally

Terrestrial ecosystems contain stocks of 450 Gt (380–540 Gt) carbon in vegetation, 1700 Gt ± 250 Gt carbon in soils, and 1400 Gt ± 200 Gt carbon in permafrost (Hugelius et al., 2014; Batjes, 2016; Jackson et al., 2017; Strauss et al., 2017; Erb et al., 2018a; Xu et al., 2021). Ecosystem carbon stocks, totaling 3030–4090 GtC (from lowest and highest estimates above) substantially exceed the ~900 Gt carbon in unextracted fossil fuels (see Chapter 5 of WGI).

Deforestation, draining of peatlands, expansion of agricultural fields, livestock pastures, and human settlements, and other land use changes emitted carbon at a rate of 1.6 ± 0.7 Gt y^{-1} from 2010 to 2019, (Friedlingstein et al., 2020), of which wildfires and peat burning emitted 0.4 ± 0.2 Gt y^{-1} from 1997 to 2016 (van der Werf et al., 2017). Anthropogenic climate change has caused a portion of these emissions through increases in wildfire (Section 2.4.4.2.1) and tree mortality (Section 2.4.4.3.1) but the fraction of the total remains unquantified. Land use change produced ~15% of global anthropogenic emissions, from fossil fuels and land (Friedlingstein et al., 2020). Terrestrial ecosystems removed carbon from the atmosphere through plant growth at a rate of -3.4 ± 0.9 Gt y^{-1} from 2010 to 2019 (Friedlingstein et al., 2020).

Tropical deforestation and draining and burning of peatlands produce almost all of the carbon emissions from land use change (Houghton and Nassikas, 2017; Friedlingstein et al., 2020), while forest growth accounts for two-thirds of ecosystem carbon removals from the atmosphere (Pugh et al., 2019b). Global terrestrial ecosystems comprised a net sink of -1.9 ± 1.1 Gt y^{-1} from 2010 to 2019 (Friedlingstein et al., 2020), mainly due to growth in forests (Harris et al., 2021; Xu et al., 2021), mitigating ~31% of global emissions from fossil-fuel burning and land use change (Friedlingstein et al., 2020).

In summary, terrestrial ecosystems contain 3000-4000 Gt carbon in vegetation, permafrost, and soils, three to five times the amount of carbon in unextracted fossil fuels, and 4.4 times the carbon currently in the atmosphere (*robust evidence, high agreement*). Tropical deforestation, draining and burning of peatlands and other land use changes emit 0.9-2.3 Gt y^{-1} of carbon, ~15% of global emissions from fossil fuel and ecosystems (*robust evidence, high agreement*). Terrestrial ecosystems currently remove more carbon from the atmosphere, 2.5-4.3 Gt y^{-1}, than they emit, so tropical rainforests, Arctic permafrost, and other ecosystems provide the global ecosystem service of naturally preventing carbon from contributing to climate change (*high confidence*).

2.4.4.4.2 Observed stocks in high-carbon terrestrial ecosystems

The ecosystem that attains the highest aboveground carbon density in the world is coast redwood (*Sequoia sempervirens*) forest, in California, USA, with 2600 ± 100 t ha^{-1} carbon (Van Pelt et al., 2016). The ecosystem with the second highest documented carbon density in the world is mountain ash (*Eucalyptus regnans*) forest in Victoria, Australia, with ~1900 t ha^{-1} (Keith et al., 2009). Within the tropics, tropical evergreen broadleaf forests (rainforests) in the Amazon, the Congo, and Indonesia attain the highest carbon densities, reaching a maximum of 230 t ha^{-1} in the Amazon (Mitchard et al., 2014) and the Congo (Xu et al., 2017). Temperature increases reduce tropical rainforest aboveground carbon density 9.1 t ha^{-1} per degree Celsius, through reduced growth and increased mortality (Sullivan et al., 2020).

Tropical forests contain the largest vegetation carbon stock in the world, with 180–250 Gt of above- and belowground carbon (Saatchi et al., 2011; Baccini et al., 2012; Avitabile et al., 2016). The Amazon contains a carbon stock of 45–60 Gt (Baccini et al., 2012; Mitchard et al., 2014; Englund et al., 2017).

Ecosystems with high soil carbon densities include peat bogs in Ireland, with up to 3000 t ha^{-1} (Tomlinson, 2005), Cuvette Centrale swamp forest peatlands in Congo, with an average of ~2200 t ha^{-1} (Dargie et al., 2017), Arctic tundra, with an average of ~900 t ha^{-1} (Tarnocai et al., 2009), and mangrove peatlands in Kalimantan, Indonesia, with an average of 850 ± 320 t ha^{-1} (Murdiyarso et al., 2015). Arctic permafrost contains 1400 Gt ± 200 Gt to 3 m depth, the largest soil carbon stock in the world (Hugelius et al., 2014). Globally, peatlands contain 470–620 Gt carbon (Page et al., 2011; Hodgkins et al., 2018) of which boreal and temperate peatlands contain 415 ± 150 Gt (Hugelius et al., 2020) and tropical peatlands 80–350 Gt (Page et al., 2011; Dargie et al., 2017; Gumbricht et al., 2017; Ribeiro et al., 2021). Other analyses increase the upper estimates for boreal and temperate peatlands to 800-1200 Gt (Nichols and Peteet, 2019; Mishra et al., 2021b).

Tropical forests and Arctic permafrost contain the highest ecosystem carbon stocks in aboveground vegetation and soil, respectively, in the world (*robust evidence, high agreement*). These ecosystems form natural sinks that prevent the emission to the atmosphere of 1400-1800 Gt carbon that would otherwise increase the magnitude of climate change (*high confidence*).

2.4.4.4.3 Biodiversity and observed terrestrial ecosystem carbon

High biodiversity and ecosystem carbon generally occur together, with rainforests in the Amazon, the Congo, and Indonesia containing the largest aboveground vegetation carbon stocks (Saatchi et al., 2011; Baccini et al., 2012; Avitabile et al., 2016) and the highest vascular plant species richness (Kreft and Jetz, 2007) in the world. Aboveground ecosystem carbon and animal species richness show high correlation but also high spatial variability (Strassburg et al., 2010). Aboveground carbon is correlated to genus richness globally (Cavanaugh et al., 2014), but to species richness only in local areas (Poorter et al., 2015; Sullivan et al., 2017). Species richness generally increases vegetation productivity in the humid tropics while tree abundance increases productivity in drier conditions (Madrigal-Gonzalez et al., 2020). Across the Amazon, ~1% of tree species contain 50% of the aboveground carbon, due to abundance and maximum height (Fauset et al., 2015). Aboveground carbon in tropical forest shows positive correlations to vertebrate species richness (probability values not reported) (Deere et al., 2018; Di Marco et al., 2018). In logged and burned tropical forest in Brazil, species richness of plants, birds, and beetles increased with carbon density up to ~100 t ha^{-1} (Ferreira et al., 2018).

National parks and other protected areas, which, in June 2021, covered 15.7% of global terrestrial area (UNEP-WCMC, 2021), contain ~90 Gt carbon in vegetation and ~150 Gt carbon in soil (one-fifth and one-tenth, respectively, of global stocks) and remove carbon from the atmosphere at a rate of ~0.5 Gt y^{-1} (one-sixth of global removals) (Melillo et al., 2016). The most strictly protected areas contain carbon at higher densities, but illegal deforestation and fires in some protected areas emit 38 ± 17 Mt y^{-1} globally (Collins and Mitchard, 2017). In the Amazon, protected areas store more than half of the aboveground vegetation carbon stock of the region but account for only one-tenth of net emissions (Walker et al., 2020). Conservation of high biodiversity areas, particularly in protected areas, protects ecosystem carbon, prevents emissions to the atmosphere, and reduces the magnitude of climate change (*high confidence*).

2.4.4.4.4 Observed emissions and removals from high-carbon terrestrial ecosystems

Most global deforestation is occurring in tropical forests (Pan et al., 2011; Liu et al., 2015; Houghton and Nassikas, 2017; Erb et al., 2018a; Li et al., 2018; Harris et al., 2021), primarily for clearing of agricultural land (Hong et al., 2021), causing primary tropical forest to comprise a net source of carbon to the atmosphere from 2001 to 2019 (emissions to the atmosphere 0.6 Gt y^{-1}, removals from the atmosphere -0.5 Gt y^{-1}, net 0.1 Gt y^{-1}) (Harris et al., 2021). While wildfires emitted an average of 0.4 ± 0.2 Gt y^{-1} carbon from 1997 to 2016 (van der Werf et al., 2017), individual fire seasons can emit the same magnitude, such as the 0.4 Gt carbon from the Amazon fires of 2007 (Aragao et al., 2018), 0.5 Gt carbon from the Amazon fires of 2015-2016 (Berenguer et al., 2021) and 0.2 Gt from the Australia fires of 2019-2020 (Shiraishi and Hirata, 2021). So, wildfires account for up to one-third of annual average ecosystem carbon emissions, while major fire seasons can emit up to two-thirds of global ecosystem carbon emissions (*medium evidence, medium agreement*).

Primary boreal and temperate forests also comprised net sources in the period 2001-2019, but, when including all tree age classes, boreal, temperate, and tropical forests were net sinks, as growth exceeded permanent forest cover losses (Harris et al., 2021), though boreal and temperate forests are much stronger sinks (Pan et al., 2011; Liu et al., 2015; Houghton and Nassikas, 2017). Estimates of carbon removals from remote sensing may provide more accurate estimates of boreal forest carbon balances than earth system models, which overestimate regrowth after forest and timber (Wang et al., 2021a). Mortality of boreal forest in British Columbia from mountain pine beetle infestations converted 374 000 km^2 from a net carbon sink to a net carbon source (Kurz et al., 2008). Modeling suggests that a potential increase in water-use efficiency and regrowth could offset the losses in part of the forest mortality area (Giles-Hansen et al., 2021).

The Amazon as a whole was a net carbon emitter from 2003 to 2008 (Exbrayat and Williams, 2015; Yang et al., 2018b), primarily due to expansion of agricultural and livestock areas, which caused over two-thirds of deforestation from 1990 to 2005 (De Sy et al., 2015; De Sy et al., 2019). Four sites in the Amazon also showed net carbon emissions from 2010 to 2018, from deforestation and fire (Gatti et al., 2021). In the Amazon, deforestation emitted 0.17 ± 0.05 Gt y^{-1} carbon from 2001 to 2015 (Silva Junior et al., 2020) while fires emitted 0.12 ± 0.14 Gt y^{-1} carbon from 2003 to 2015 (Aragao et al., 2018). An analysis of the Amazon carbon loss from deforestation and degradation estimated a loss of 0.5 Gt y^{-1} from 2010 to 2019, with degradation accounting for three-fourths (Qin et al., 2021). Intact old-growth Amazon rainforest has been a net carbon sink (Hubau et al., 2020) but may have become a net carbon source from 2010 to 2019 (Qin et al., 2021).

In Indonesia and Malaysia, draining and burning of peat swamp forests for oil palm plantations emitted 60 – 260 Mt y^{-1} carbon from 1990 to 2015, converting peatlands in that period from a carbon sink to a source (Miettinen et al., 2017; Wijedasa et al., 2018; Cooper et al., 2020). Deforestation of mangrove forests emitted 10–30% of deforestation emissions in Indonesia from 1980 to 2005 (Donato et al., 2011; Murdiyarso et al., 2015), even though mangroves comprised only 3% of Indonesia primary forest area in 2000 (Margono et al., 2014; Murdiyarso et al., 2015).

In North America, wildfire emitted 0.1 ± 0.02 Gt y^{-1} of carbon from 1990 to 2012, but regrowth was slightly greater to produce a net sink (Chen et al., 2017). In California, USA, two-thirds of the 70 Mt carbon emissions from natural ecosystems from 2001 to 2010 came from the 6% of the area that burned (Gonzalez et al., 2015). Anthropogenic climate change caused up to half of the burned area (Section 2.4.4.2.1).

In the Arctic, anthropogenic climate change has thawed permafrost (Guo et al., 2020), leading to carbon emissions of 1.7 ± 0.8 Gt y^{-1} in the winter from 2003 to 2017 (Natali et al., 2019). Wildfires in Arctic tundra in Alaska from ~1930 to 2010 caused up to 0.5 m of permafrost thaw (Brown et al., 2015), exposing peatland carbon (Brown et al., 2015; Gibson et al., 2018), including soil carbon deposits up to 1600 years old (Walker et al., 2019).

Tropical deforestation, draining and burning of peatlands, and thawing of Arctic permafrost due to climate change have caused those ecosystems to emit more carbon to the atmosphere than they naturally remove through vegetation growth (*high confidence*).

2.4.4.5 Observed Changes in Primary Productivity

2.4.4.5.1 Observed changes in terrestrial primary productivity

The difference between photosynthesis by plants (gross primary productivity [GPP]) and plant energy use through respiration is the net growth of plants (net primary productivity [NPP]), which removes CO_2 from the atmosphere and mitigates emissions from deforestation and other land use changes (Section 2.4.4.4). Global terrestrial NPP has exceeded land use emissions since the early 2000s, making terrestrial ecosystems a net carbon sink (Friedlingstein et al., 2020).

Global terrestrial NPP increased 6% from 1982 to 1999, through increased temperature and increased solar radiation in the Amazon from decreased cloud cover (Nemani et al., 2003), then decreased 1% from 2000 to 2009, because of extensive droughts in the southern hemisphere (Zhao and Running, 2010). From 1999 to 2015, increased aridity caused extensive declines in the Normalized Difference Vegetation Index (NDVI) globally, particularly semi-arid ecosystems (Huang et al., 2016), indicating widespread decreases in NPP (Yuan et al., 2019).

Global terrestrial GPP increased 2% from 1951 to 2010 and continued increasing at least through 2016, with increased atmospheric CO_2 showing a greater influence than natural factors (Li et al., 2017; Fernandez-Martinez et al., 2019; Liu et al., 2019a; Cai and Prentice, 2020; Melnikova and Sasai, 2020). Global forest area increased 7% from 1982 to 2016, mainly from forest plantations and regrowth in boreal and temperate forests in Asia and Europe (Song et al., 2018), while regrowth in secondary forests > 20 years old, mainly in boreal, temperate, and sub-tropical regions, generated a net removal of 7.7 Gt y^{-1} CO_2 from the atmosphere from 2001 to 2019 (Harris et al., 2021). Vegetation growth that exceeds the modelled CO_2 fertilisation, gaps in field data, and incomplete knowledge of plant mortality and soil carbon responses introduce uncertainties into quantifying the magnitude of CO_2 fertilisation (Walker et al., 2021). A combination of CO_2 fertilisation of global vegetation and secondary forest regrowth has increased global vegetation productivity (*medium evidence, medium agreement*).

The relative increase in GPP per unit of atmospheric CO_2 increase declined from 1982 to 2015, indicating a weakening of any CO_2 fertilisation effect (Wang et al., 2020c). Increased growth from CO_2 fertilisation has begun to shorten the life span of trees due to a trade-off between growth rate and longevity, based on analyses of tree rings of 110 species around the world (Brienen et al., 2020). Furthermore, water availability controls the magnitude of NPP (Beer et al., 2010; Jung et al., 2017; Yu et al., 2017), including water from precipitation (Beer et al., 2010), soil moisture (Stocker et al., 2019), groundwater storage (Humphrey et al., 2018; Madani et al., 2020a), and atmospheric vapour (Novick et al., 2016; Madani et al., 2020b). Drought stress reduced NPP across tropical forests from 2000 to 2015 (Zhang et al., 2019b) and GPP in the tropics from 1982 to 2016 (Madani et al., 2020b). Drought stress has also reduced GPP in some semi-arid and arid lands (Huang et al., 2016; Liu et al., 2019a). In addition, nitrogen and phosphorus constrain CO_2 fertilisation (Terrer et al., 2019), though phosphorus limitation of tropical tree growth is species-specific (Alvarez-Clare et al., 2013; Thompson et al., 2019). NPP has decreased during some time periods and in some regions where drought stress has exerted a greater influence than increased atmospheric CO_2 (*medium evidence, high agreement*).

2.4.4.5.2 Observed changes in freshwater ecosystem productivity

Temperature affects primary productivity through moderating phytoplankton growth rates, ice cover, thermal stratification and growing season length (Rühland et al., 2015; Richardson et al., 2018). Global warming has reinforced eutrophication, especially cyanobacteria blooms (Wagner and Adrian, 2009; Kosten et al., 2012; O'Neil et al., 2012; De Senerpont Domis et al., 2013; Adrian et al., 2016; Visser et al., 2016; Huisman et al., 2018) (*very high confidence).* Conversely*,* warming can reduce cyanobacteria in hypertrophic lakes (Richardson et al., 2019). Freshwater cyanobacteria may benefit directly from elevated CO_2 concentrations (Visser et al., 2016; Ji et al., 2017; Huisman et al., 2018; Richardson et al., 2019).

Macrophyte growth in freshwaters is likely to increase with rising water temperatures, atmospheric CO_2 and precipitation (*robust evidence*, *high agreement*) (Dhir, 2015; Hossain et al., 2016; Short et al., 2016; Reitsema et al., 2018). Nonetheless, primary productivity in rivers is variable and unpredictable (Bernhardt et al., 2018) because seasonal variations in temperature and light are uncorrelated, frequent high flow events reduce biomass of autotrophs and droughts can strand and desiccate autotrophs.

In large, nutrient-poor lakes warming-induced prolonged thermal stratification can reduce primary production (*medium evidence*) (Kraemer et al., 2017). Warming may reduce phytoplankton concentrations when temperature-induced increases in consumption of phytoplankton outpace increases in phytoplankton production (De Senerpont Domis et al., 2013). These decreases in productivity may be under-recognised responses to climate change.

Summary: Evidence is *robust* for increase in primary production with warming trends, but increases or declines of algae cannot entirely be attributed to climate change; they are lake specific and modulated through weather conditions, lake morphology, salinity, land-use and restoration, and biotic interactions (*medium evidence*, *medium confidence*) (O'Beirne et al., 2017; Velthuis et al., 2017; Rusak, 2018; Ho et al., 2019).

2.4.5 Conclusions on Observed Impacts

The consistency of patterns of biological change with expectations from regional or global warming processes, coupled with an understanding of underlying processes, the coherence of these patterns at both regional and global scales, all form multiple lines of evidence (Parmesan et al., 2013) that it is *very likely* that observed range shifts and phenological changes in individual species can be attributed to regional and global climate changes *(very high confidence)* (Section 2.4.2, Table 2.2; Table 2.3; Table SM2.1; Parmesan et al., 2013).

Global and regional meta-analyses of diverse systems, habitats and taxonomic groupings document that approximately half of all species with long-term records have shifted their ranges poleward and/or upward in elevation and ~2/3 have advanced their timing of spring events (phenology) (Section 2.4.2, Table 2.2; Parmesan and Hanley, 2015; Parmesan, 2019). Changes in abundance tend to match predictions from climate warming, with warm-adapted species significantly out-performing cold-adapted species in warming habitats (Feeley et al., 2020) and the composition of local communities becoming more 'thermophilised' i.e., experiencing 'increase in relative abundance of heat-loving or heat-tolerant species' (Section 2.4.2.3; Cline et al., 2013; Feeley et al., 2020).

New studies since AR5, with more sophisticated analyses designed to capture complex responses, indicate that past estimates of the proportion of species impacted by recent climate change have been underestimates due to their unspoken assumptions that local or regional warming should lead solely to poleward/upward range shifts and advancements of spring timing (Duffy et al., 2019). More complex analyses have documented cases of winter warming driving delayed spring timing of northern temperate species due to chilling requirements, and increased precipitation driving species' range shifts downslope in elevation, and eastward and westward in arid regions *(high confidence).* Further new studies have shown that phenological changes have, in some cases, successfully compensated for local climate change and reduced degree of range shifts *(medium confidence).* Limited number of studies of this type make it difficult to estimate the generality of these effects globally (Section 2.4.2.5, Table 2.2).

Responses in freshwater species are consistent with responses in terrestrial species, including poleward and upward ranges shifts, earlier timing of spring plankton development, earlier spawning in fish, and extension of the growing season. Observed changes in freshwater species are strongly related to anthropogenic climate change driven changes in the physical environment (e.g. increased water temperature, reduced ice cover, reduced mixing in lakes, loss of oxygen, reduction in river connectivity). While evidence is high for an increase in primary production in nutrient rich lakes with warming trends (*high confidence*), increasing or declining algal formations are lake specific and modulated through variability in weather conditions, lake morphology, changes in salinity, stoichiometry, land-use and restoration measures, and food web interactions. In boreal coniferous forest, there has been an increase in terrestrial derived dissolved organic matter transported into rivers and lakes as a consequence of climate change (that has induced increases in run-off and greening of the northern hemisphere), as well as to changes in forestry practices. This has caused waters to become brown resulting in an acceleration of upper water warming and an overall cooling of deep water *(high confidence).* Browning may accelerate primary production through input of nutrients associated with DOM in nutrient poor lakes and increase cyanobacteria growth, which better cope with low light intensities (*medium confidence*) (Sections 2.4.2.1, 2.4.2.2, 2.4.2.3, 2.4.2.4).

Field research since the IPCC Fifth Assessment Report has detected biome shifts at numerous sites, poleward and upslope, that are consistent with increased temperatures and altered precipitation patterns driven by climate change, and support prior studies that attributed such shifts to anthropogenic climate change *(high confidence).* These new studies help fill prior geographic and habitat gaps, for example documenting upward shifts in the forest/alpine tundra ecotone in the Andes, Tibet and Nepal, and northward shifts in the deciduous/boreal forest ecotones in Canada. Globally, woody encroachment into open areas (grasslands, arid regions and tundra) is *likely* being driven by climate change and increased CO_2 in concert with changes in grazing and fire regime *(medium confidence)* (Section 2.4.3).

Climate change has driven or is contributing to increased tree mortality directly through increased aridity or drought and indirectly through increased wildfire and insect pests in many locations *(high confidence).* Analyses of causal factors have attributed increasing tree mortality at sites in Africa and North America to anthropogenic climate change and field evidence has detected tree mortality from drought, wildfire, and insect pests in temperate and tropical forests around the world *(high confidence)*. Water stress, leading to plant hydraulic failure, is ~~the~~ a principal mechanism of drought-induced tree mortality, along with indirect effects of climate change mediated through community interactions *(high confidence)* (Section 2.4.4.3).

Terrestrial ecosystems sequester and store globally critical stocks of carbon but these stocks are at risk from deforestation and climate change (*high confidence*). Tropical deforestation, draining, and burning of peatlands produce almost all of the carbon emissions from land use change. In the Arctic, increased temperatures have thawed permafrost at numerous sites, dried some areas, and increased fire, causing net emissions of carbon from soils *(high confidence)* (Sections 2.4.4.4, 2.5.3.4).

Globally, increases in temperature, aridity, and drought have increased the length of fire seasons and doubled potentially burnable area *(medium confidence)*. Increases in burnt area have been attributed to anthropogenic climate change in North America *(high confidence).* In parts of Africa, Asia, Australia, and South America, area burned have also increased, consistent with anthropogenic climate change. Deforestation, peat burning, agricultural expansion or abandonment, fire suppression, and inter-decadal cycles, strongly influence fire occurrence. Areas with the greatest increases in fire season length include the Amazon, western North America, western Asia, and East Africa. (Section 2.4.4.2)

The changes we have observed, and project to continue, in biodiversity and ecosystem health pose a risk of declines in human health and well-being: e.g. tourism, recreation, food, livelihoods and quality of life *(medium confidence).* Clear attribution of these impacts is often not possible, but inference can be made by comparison of observed changes in biodiversity / ecosystem health and known services from those particular ecosystems.

Table 2.3: Confidence in detecting and attributing observed changes in terrestrial and freshwater species and systems to climate change. Lines of evidence for attribution of observed changes to climate change and increased CO2 are used to support stated confidence in attribution of key statements on observed biological changes to climate change and increased atmospheric CO2. Icons represent lines of evidence. This is a summary table that is fully detailed in Table SM2.1 in Supplementary Material.

Lines of evidence:

Paleo data	Experiment	Long-term observations
Fingerprint of climate change response	Models	Complex statistical analysis

Key statement	Region	Period	Lines of evidence	Climate change attribution

About half of all species where land use change has been minimal have shifted their ranges, with 80–90% of movements being in the direction expected from regional warming trends – i.e. poleward and upward.	Global	Range 20 - 260 years		*robust evidence high agreement very high confidence*
Downslope elevational shifts and east-west shifts (shown for trees and birds) have been associated with regional increases in precipitation where precipitation has been shown to be the principal driver of a range boundary	USA	~ 40–60 years		*limited evidence, high agreement, medium confidence*
About two- thirds of all species with long-term (>20 years) records have shifted the timing of spring events in directions expected from regional winter and spring warming.	Global	Varies by study. Range: 20–400 years		*robust evidence high agreement very high confidence*
Winter chilling-depending species have delayed or not changed spring events despite spring warming countered by winter warming. When these species are taken into account, it is estimated that 92% of species in these studies have responded to regional warming trends	Northern Europe and USA	Varies by study. Range = 26–46 years		*medium evidence high agreement high confidence*
Anthropogenic climate change, acting through increased heat and aridity at global mean surface temperature increases of 0.6-0.9ºC, has increased the area burned by wildfire over natural levels, increasing burned area up to 11 times in one extreme year and doubling over natural levels in a 32-year period	western north America	1984–2017		*robust evidence high agreement high confidence*
Anthropogenic climate change has caused drought-induced tree mortality of up to 20% in three regions, through global mean surface temperature increases of 0.3-0.9ºC above the pre-industrial period and increases in aridity, more than non-climate change factors	North America and Africa	ca. 1945–2007		*medium evidence high agreement medium confidence*
Anthropogenic climate change has caused latitudinal and elevational vegetation biome shifts in at least 19 sites in boreal, temperate, and tropical ecosystems, between 1700 and 2007, through local temperature increases of 0.4 to 1.6ºC above the pre-industrial period more than non-climate change factors	Global	1500–2007		*robust evidence high agreement high confidence*
Anthropogenic climate change and wildfire together have altered vegetation species composition in at least two regions, reducing post-fire natural regeneration and species richness of tree and other plant species, at global mean surface temperature increases of 0.3-0.9ºC	western North America, Africa	1966–2015		*medium evidence high agreement medium confidence*

Beetles & moths shifting poleward and upward has brought new pest species into some forests; warming winters and longer growing season has increased destructive outbreaks of beetles and moths in temperate and boreal forests	North America, Europe	Varies by study		*medium-high confidence*
Exotic species are responding differently from native species in both abundance changes and phenological changes, but not in a consistent fashion	North America			*low/medium evidence low agreement*
The most cold-adapted species are generally declining in population abundances and contracting their ranges poleward and upward: (e.g. sea-ice dependent, mountain-top restricted, upper headwaters, coldest lakes)	Arctic, Himalayas , Antarctic, Alps			*medium confidence*
Diseases of both wildlife and humans have emerged into new areas they have not been in historically	Global	past 20–100 years		*medium confidence*
Warming has amplified the trophic state lakes are already in. Eutrophic lakes have become more productive while oligotrophic lakes tend to become more nutrient limited	Global	Past 20–50 years		*robust evidence high agreement high/medium confidence*
Woody encroachment into open (grassland, desert) systems has occurred, with climate change as one of the drivers, along with changes in grazing and other land uses	Global			*medium confidence*
In boreal, coniferous areas changes in forestry practices and climate change have caused an increase in terrestrial derived dissolved organic matter (DOM) transport into rivers and lakes leading to their browning	Boreal	Past decades		*robust evidence high agreement high confidence*
Climate change induced warming leads to shifts in thermal regime of lakes	Global	Past decades		*robust evidence high agreement high confidence*
Climate change causes gains and losses in freshwater water level	Global	Past decades		*limited evidence low confidence*
Greenhouse gas emissions from freshwater ecosystems are equivalent to around 20% of global burning fossil-fuel CO_2 emission	Global	Past decades		*medium evidence medium agreement medium/low confidence*
In lakes weather extremes in wind, temperature, precipitation and loss of ice foremost affect the thermal regime with repercussions on water temperature, transparency, oxygen and nutrient dynamics, affecting ecosystem functionality	North America, Europe	Varies by study		*medium/limited evidence high agreement medium/low confidence*

Climate change induced warming leads to shifts in thermal regime of rivers and streams; lowland rivers show a stronger thermal response than high-altitude, cold-water receiving streams	North America, Europe	Past decades		*robust evidence medium agreement high confidence*
Loss of biodiversity in streams can be directly attributed to climate change through increased water temperatures, hydrological changes such as increased peak discharges, flow alteration and droughts	Global	Past decades		*high agreement very high confidence*
Climate change is causing range shifts of freshwater fish	North America Europe	Past decades		*high agreement, high confidence*

2.5 Projected Impacts and Risk for Species, Communities, Biomes, Key Ecosystems and their Services

Under the Risk Assessment Framework that was introduced in AR5 (2014), risk means the probability of harmful consequences resulting from climate change. It results from the interaction of vulnerability, exposure, and hazard (see Chapter 1) and can be represented as the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur (IPCC, 2014). The Framework defines vulnerability as a pre-existing condition, incorporating the extent to which species or ecosystems are susceptible to, or unable to cope with, adverse effects of climate change. Vulnerable species have limited adaptive capacity stemming from physiological and behavioural constraints, limited dispersal abilities and restricted resource requirements or capacities for distributional and genetic changes (Foden et al., 2019) (Foden et al., 2013; Cizauskas et al., 2017). Traits that render entire ecosystems vulnerable are harder to define, but it is clear that vulnerabilities are high in the coldest habitats, in those with limited geographic ranges such as low-lying islands, and in specialized, restricted habitats such as serpentine outcrops in California (Anacker and Harrison, 2012) and dry meadows in Fennoscandia and Tibet (Yang et al., 2018a). Ecosystem vulnerability can depend critically on the fates of plants that function as 'foundation species,' providing community biomass aboveground and below, structuring habitat for fauna and providing ecosystem services such as erosion control (Camac et al., 2021).

2.5.1 Projected Changes at Species and Community Levels

2.5.1.1 Assessment of Models and Sources of Uncertainties

Methods for projecting impacts of climate change on biodiversity can be classified into three types: 1) statistical models such as species distribution models (Elith and Leathwick, 2009); 2) mechanistic or process–based models (Chuine and Régnière, 2017) and 3) trait–based models (Pacifici et al., 2015). It is only recently that models have been developed looking at smaller levels of warming. such as 1.5°C (Hoegh-Guldberg et al., 2018a; Warren et al., 2018).

Species distribution models (SDMs) or niche-based models assess potential geographic areas of suitable climate for the species in current conditions and then project them into future conditions (Trisurat, 2018; Vieira et al., 2018). There are limitations in all models and it is critical that modellers understand the assumptions, proper parameterization, and limitations of each model technique, including differences among climate models, emission scenarios or representative concentration pathways, and baselines (Araujo et al., 2019). Several systems automate development of SDMs, including R-packages (e.g., (Beaumont et al., 2016; Hallgren et al., 2016), development of other model types (Foden et al., 2019) and aid in use of climate model data (Suggitt et al., 2017), including allowing for connectivity constraints (Peterson et al., 2013). Buisson et al. (2010) found most variation in model outputs stem from differences in design, followed by GCMs.

Mechanistic approaches, also known as process-based models, project species' responses to climate changes by explicitly incorporating known biological processes, thresholds and interactions (Morin and Thuiller, 2009; Maino et al., 2016). Mechanistic models are able to accommodate a broad range of climate change impact mechanisms and include species-specific characteristics such as dispersal distances, longevity, fecundity, genetic evolution, phenotypic plasticity. However, sufficient knowledge is available for only a few well-studied species. Species traits have been used to more broadly estimate potential climate change impacts (Foden et al., 2013; Cizauskas et al., 2017).

Most models are at large scales (20 km–50 km), and so cannot capture micro-climatic refugia generated by diversities of slope aspect, elevation or shade (Suggitt et al., 2015; Suggitt et al., 2018). In analyzing records of 430 climate-threatened and range-declining species in England, (Suggitt et al., 2015; Suggitt et al., 2018) showed that topographic diversity reduced population declines most strongly in areas experiencing the most local warming and in species most sensitive to warming. In these circumstances topographic diversity reduced population extinction risk by 22% for plants and by 9% for insects.

None of the modelling techniques are predictions of the future; they are projections of possible futures. To date, few studies have validated model performance against observations, and many of these have been on islands, reducing ability to generalize (Fordham et al., 2018). Species' models should be considered as hypotheses of what a future world might look like if the climate projections came to pass. Suggestions have been made on how to start bringing more biotic interactions into species distribution models (Early and Keith, 2019), but limited basic ecological understandings of interactions, along with limits on computation and funding, constrain how far and how fast these modelling techniques can advance.

2.5.1.2 Risk Assessment and non-modelling approaches

In order to add realism and reliability to risk assessments at the species and community levels, non-modelling approaches based on known biological traits or processes, as well as on expert opinion (Camac et al., 2021), are used to temper model outputs with ground-based validation. Trait-based assessment approaches use species' biological characteristics as predictors of sensitivity, adaptive capacity and extinction risk due to climate change. Climate exposure can be estimated using GIS-based modelling, statistical programs or expert judgment (Chin et al., 2010). These trait-based approaches are widely applied to predict responses of biodiversity to climate change because they do not require modelling expertise nor detailed distibutional data (Pacifici et al., 2015; Willis et al., 2015). Most of these methods have not been independently validated and do not allow direct comparison of vulnerability and risk among taxonomic groups.

Some studies have combined two or three approaches for climate change risk assessment of biodiversity in order to capture the advantages of each and avoid their limitations. Warren et al. (2013) used combinations of SDMs and trait-based approaches to estimate the proportions of species losing their climatically suitable ranges under the various future scenarios of climate and dispersal rate. Similarly, spatial projections of climate change exposure were combined with traits to assess vulnerability of sub-Saharan amphibians (Garcia et al., 2014). Laurance et al. (2012) combined 31 functional groups of species and 21 potential drivers of environmental change to assess both the ecological integrity and threats for tropical protected areas on a global scale. Keith et al. (2014) used a combination of three approaches (SDMs-trait-mechanistic) to determine how long before extinction a species would become eligible for listing as threatened based on the IUCN Red List criteria.

2.5.1.3 Risk of Species' Extinctions

2.5.1.3.1 Overview

This assessment of current findings is of studies across a range of taxa and modelling techniques. Extinction risk estimates whether or not a particular species may be at risk of extinction over the coming decades if climatic trends continue and usually does not take into account other human-induced stressors (e.g. invasive species or pollution). It is not a prediction that a species will definitely go extinct, because even complete loss of a species' range is projected, the scale of the model cannot estimate persistence in micro-climatic refugia (Suggitt et al., 2015; Suggitt et al., 2018). Individuals and populations can survive after conditions for successful reproduction are gone, leading to a lagged decline, called 'extinction debt' (Alexander et al., 2018). Therefore, range loss is an established criterion for assessing endangerment status and risk of extinction. As a species range becomes smaller and occupied habitats become more isolated, the likelihood of a single stochastic event causing extinction increases. It is this combination of projected loss of climatically suitable space and additional stressors (especially LULCC of critical habitat) that is expected to drive future extinctions.

The IUCN Red List Criteria (IUCN, 2019) classifies a species as 'critically endangered' if it has suffered a range loss of ≥80%, with a resulting likelihood of extinction of >50% in the near term (10-100 years, depending upon generation time). A species is classified as 'endangered' if it has suffered a range loss of ≥50%, with a resulting likelihood of extinction of >20% in the near term (10-100 years).

2.5.1.3.2 Projections for freshwater biodiversity

Lakes, rivers and freshwater wetlands cover approximately 7.7–9.1 % of global land surface area; (Lehner et al., 2008; Fluet-Chouinard et al., 2015; Allen and Pavelsky, 2018), and hold 9.5% of the Earth's described animals (Balian et al., 2008), with climate change indicated as a threat for 50–75% of fish (Xenopoulos et al., 2005; Darwall and Freyhof, 2015 who). Climate change is cited as a primary factor in species' extinction risk, through changes in water temperatures, stream flow, loss of cold water habitat, increased variability of precipitation, and increased disease risk from warming temperatures (*high evidence, high agreement, high confidence*) (Knouft and Ficklin, 2017; Pletterbauer et al., 2018; Reid et al., 2019; Jaric et al., 2019), adding to stress from overexploitation and LULCC (Craig et al., 2017; IPBES, 2019 Global assessment report).

Increased frequency of stream drying events, reducing hydrologic connectivity and limiting access of native fishes to spawning habitats is projected for RCP 8.5 in Colorado, USA (*medium evidence, medium agreement*) (Jaeger et al., 2014). Cold-water habitats and associated obligate species are particularly vulnerable and losses in these habitats have been both documented and projected, for example in salmonids (Santiago et al., 2016; Fullerton et al., 2017; Merriam et al., 2017). River networks are projected to lose connections to cold tributary refugia, that are important thermal refuges for cold water species *(robust evidence, high agreement)* (Isaak et al., 2016) during low flows (Merriam et al., 2017).

Community turnovers are expected in freshwaters as cold-adapted species lose and warm-adapted species gain climatically suitable habitat (Domisch et al., 2011; Domisch et al., 2013; Shah et al., 2014). While a number of warm-adapted species may experience range expansions, the majority of species are predicted to lose climatically suitable areas by on average 38–44%, depending on the emission scenario (A2a and B2a) (*medium evidence*) (Domisch et al., 2013).

Molluscs are projected to be the most at risk group, given their limited dispersal capability (Woodward et al., 2010). Mediterranean freshwater fish are especially susceptible to climate change due to increasing flood and drought events and risks of surpassing critical temperature thresholds (Santiago et al., 2016; Jaric et al., 2019). In southern Europe, aquatic insects (Ephemeroptera, Plecoptera, and Trichoptera) are endangered by climate change (Conti et al., 2014). European protected areas are not expected to be sufficient under warming to provide habitat for the majority of rare molluscs and fish (Markovic et al., 2014). Observed trends agree with model projections in direction, but magnitude remains uncertain (*medium evidence, medium agreement, medium confidence*). (see Figure 2.8 for extinction risk globally for dragonflies, amphibians and turtles).

Regional threats from climate change have been reported for 40% of amphibians in China, (Wu, 2020), 33% of European freshwater fish species (Janssen et al., 2016) and 56-69% of Odonates in Australia, (Bush et al., 2014b). Assessment of site-specific extirpation likelihoods for 88 aquatic insect taxa projected that climate-change induced hydrological alteration would result in a 30–40% loss of taxa in warmer, drier ecoregions and 10–20% loss in cooler, wetter ecoregions (*medium evidence*) (Pyne and Poff, 2017). In Africa's Albertine Rift, 51% (n=551) of fish are expected to be impacted by climate change, with 5.5% at high risk due to their sensitivity and poor adaptative capability (*high agreement*) (Carr et al., 2013).

The GLOBIO-Aquatic model (Janse et al., 2015 a) links models for demography, economy, land use changes, climate change, nutrient emissions, a global hydrological model and a global map of water bodies. It projects that changes in both water quality (eutrophication) and quantity (flow) will generate negative relations in freshwater ecosystems between persistence of species originally present in each community and a constellation of stressors, including harmful algal blooms. Under 4°C rise by 2050, mean abundance of species is projected to decline by 70% in running water and 80% in standing water (*medium evidence, high agreement, medium confidence*) (Janse et al., 2015 a).

2.5.1.3.3 Global projections of extinction risk

In prior reports, risk assessed from the literature was generally based on estimates of overall range contractions with climate change. In AR4, extinction risk was carefully quantified: 'There is *medium confidence* that approximately 20–30% of species assessed so far are *likely* to be at increased risk of extinction if increases in global average warming exceed 1.5–2.5°C (relative to 1980 to 1999). As global average temperature increase exceeds about 3.5°C, model projections suggest significant extinctions (40–70% of species assessed) around the globe.' These estimates approximately correspond to 50% reductions in range size (IPCC, 2007a). AR5 stated 'a large fraction of terrestrial and freshwater species face increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures ... (*high confidence*)' (Field et al., 2014). A series of multi-species and global analyses have been published since AR5, using both statistical models and trait-based approaches.

In this Chapter, risk to species, with implications for ecosystems, is assessed using three different approaches. First is an assessment of the geographic distributions of species' losses at different levels of GAST warming, termed 'biodiversity loss, measured as the proportion of species within a given location becoming classified as 'endangered' or 'critically endangered' (sensu IUCN). This measure provides estimates of which sites are at most risk of losing substantial numbers of species locally, leading to degradation of that ecosystems' ability to function. Second is an assessment of risk of proportions of species' becoming extinct globally at different levels of GAST warming, measured using the IUCN criteria for 'critically endangered', and termed 'species' extinction risk'. This measure is closest to assessing the complete loss of a species in the wild, and can be used to compare to past (paleo) extinction rates. Third is an assessment of proportions of species becoming rare or endangered globally (not just locally), and is the foundation for the Burning Embers on biodiversity risk in Figure 2.11. These three approaches provide complementary information of the overall risks to biodiversity and ecosystem integrity under different warming levels.

Biodiversity risk, estimated as the proportion of species in a given area projected to become endangered (sensu IUCN), is projected to affect a greater number of regions with increasing warming, with about one-third of land area risking loss of >50% of species currently inhabiting those ecosystems. Species' losses are projected to be worst in the northern South America, southern Africa, most of Australia, and northern high latitudes *(medium confidence)* (Figure 2.6).

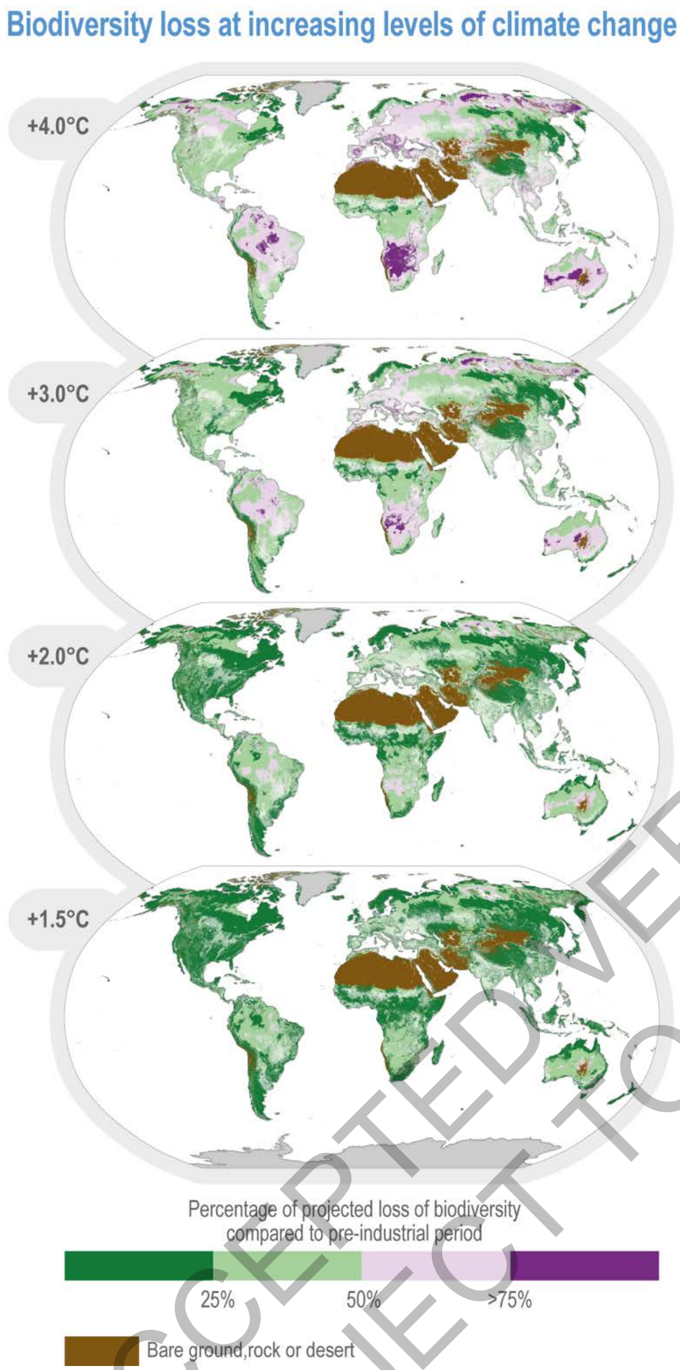


Figure 2.6: Biodiversity loss at increasing levels of climate change. The higher the percent of species projected to lose suitable climate in a given area, the higher the risk to ecosystem integrity, functioning and resilience to climate change. Warming levels are based on global levels (GSAT) above pre-industrial temperatures. Colour shading represent proportion of species for which the climate is projected to become unsuitable within a given pixel across their current distributions at a given GSAT warming level, based on the data underpinning (Warren et al., 2018) (modelled n=119,813 species globally, with no dispersal, averaged over 21 CMIP5 climate models). Areas shaded in green are above the 50% biodiversity loss threshold, meaning that <50% of species in that area are projected to go locally extinct. Areas shaded in pink and purple represent significant risk of biodiversity loss (areas where climates become unsuitable, rendering them locally extinct, for >50% and >75% of species, respectively). The maps of species richness remaining have been overlaid with a landcover layer (2015) from the European Space Agency Climate Change Initiative. This landcover layer leaves habitats classified by the ESA as natural as being transparent, cities as black, water as blue, permanent snow/ice as white and bare/rock as dark brown. Areas with a landcover identified as agriculture are 5% transparent, such that potential species richness remaining if the land had not been converted to agricultural shows as pale shading of the legend colours (very pale pink or very pale green). These paler areas represent biodiversity loss due to habitat destruction, but with a potential to be restored, with green shading having potential for restoration to higher species richness than pink and purple shadings.

Risk of species' becoming extinct globally was estimated as the probability of loss of suitable climate space rendering it critically endangered (sensu IUCN). It is *likely* that the percentage of species at high risk of extinction (median and maximum estimates) will be 9% (max 14%) at 1.5°C, 10% (max 18%) at 2°C, 12% (max 29%) at 3.0°C, 13% (max 39%) at 4°C and 15% (max 48%) at 5°C (Figure 2.7). Among groups containing largest numbers of species at high risk of extinctions for mid-levels of projected warming (3.2°C) are: invertebrates (15%), specifically pollinators (12%), amphibians (11%, but salamanders are at 24%) and flowering plants (10%) (Figure 2.8a). All groups fare substantially better at 2°C, with extinction projectionsreducing to <3% for all groups, except salamanders at 7% *(medium confidence)* (Figure 2.8a). Even the lowest estimates of species' extinctions (9%) are 1000x natural background rates (Section 2.5.4; De Vos et al., 2015). Projected species' extinctions at future global warming levels are in accord with projections from AR4, assessed on much larger numbers of species with much greater geographic coverage and a broader range of climate models. (Figure 2.7; Figure 2.8)

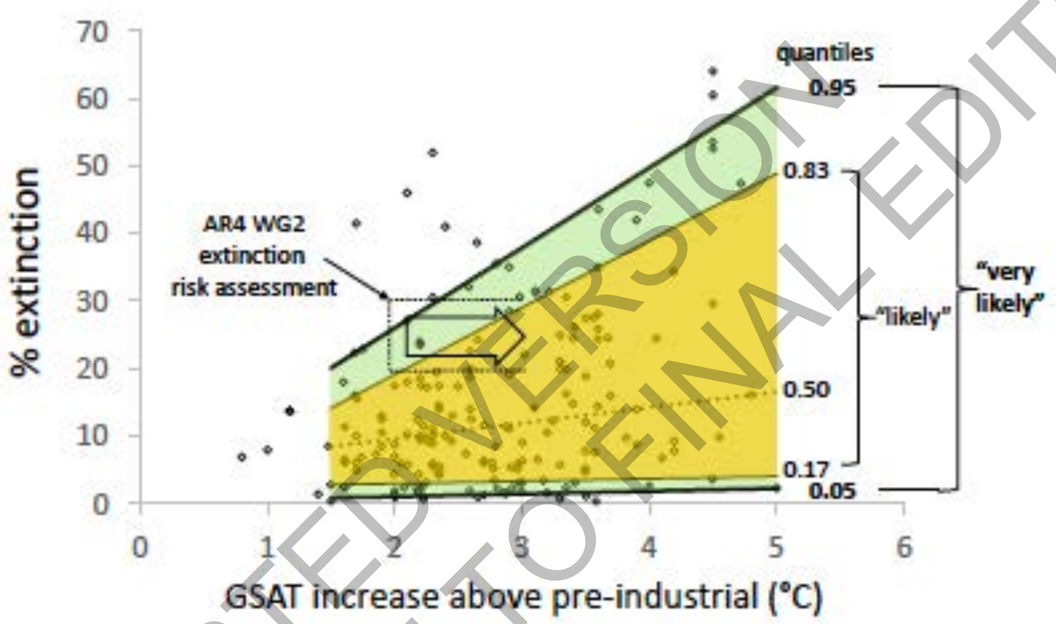


Figure 2.7: Synthesis of modelled climate-driven extinction risk studies. The relationship between modelled projections of extinction (expressed as a proportion of species at risk of extinction assessed in individual studies) and GSAT increase above the pre-industrial average. Data (global sample size n = 178 modelled estimates) were sourced from a number of sources, including digitization of data points in Figure 2 in the synthetic analysis of (Urban, 2015), note: unweighted for sample size, n = 126); Table 4.1 of the AR4 WG2 chapter 2 (Fischlin et al., 2007), n = 40; (Hannah et al., 2020) n = 6); and (Warren et al., 2018) n = 6). The. Quantile regression (which is robust to the non-normal distribution of the response variable, and less sensitive to data outliers) was used to fit quantile estimates for levels relevant to informing *"likely"* (between the 0.17 and 0.83 quantiles, shaded in orange) and "very likely" ranges (between the 0.05 and 0.95 quantiles, shaded in green) relating extinction risk to GSAT increase (Quantile regression implemented using the Barrodale and Roberts algorithm in XLSTAT). The roughly equivalent estimate of this risk as expressed in AR4 (Fischlin et al., 2007) is indicated by the dotted block indicating the medium confidence statement "Approximately 20 to 30% of plant and animal species assessed so far (in an unbiased sample) are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above preindustrial levels *(medium confidence)."* This box is open on the right-side because AR4 estimates stipulated temperatures at or exceeding given levels.

Projections of extinction risk by taxa are presented both for risk of becoming critically endangered (losing ≥80% of suitable climate habitat, Figure 2.8a) and endangered (losing ≥50% of suitable climate habitat, Figure 2.8b). The percentages of species projected at risk of becoming endangered (or worse) was 49% for insects, 44% for plants, and 26% for vertebrates at ~3°C global rise in temperature (Warren et al., 2018). Those estimates dropped considerably at lower levels of warming, down to 18%, 16%, and 8% at 2°C; and 6%, 8% and 4% at 1.5°C (Warren et al., 2018); thus not entirely dis-similar to the numbers in AR4 (Figure 2.7). Figure 2.8 shows the benefits of dispersal in offsetting extinction risk in birds, mammals, butterflies, moths and dragonflies. While dispersal may benefit individual species, it poses additional risks to communities and ecosystems as interactions between species are changed or eliminated.

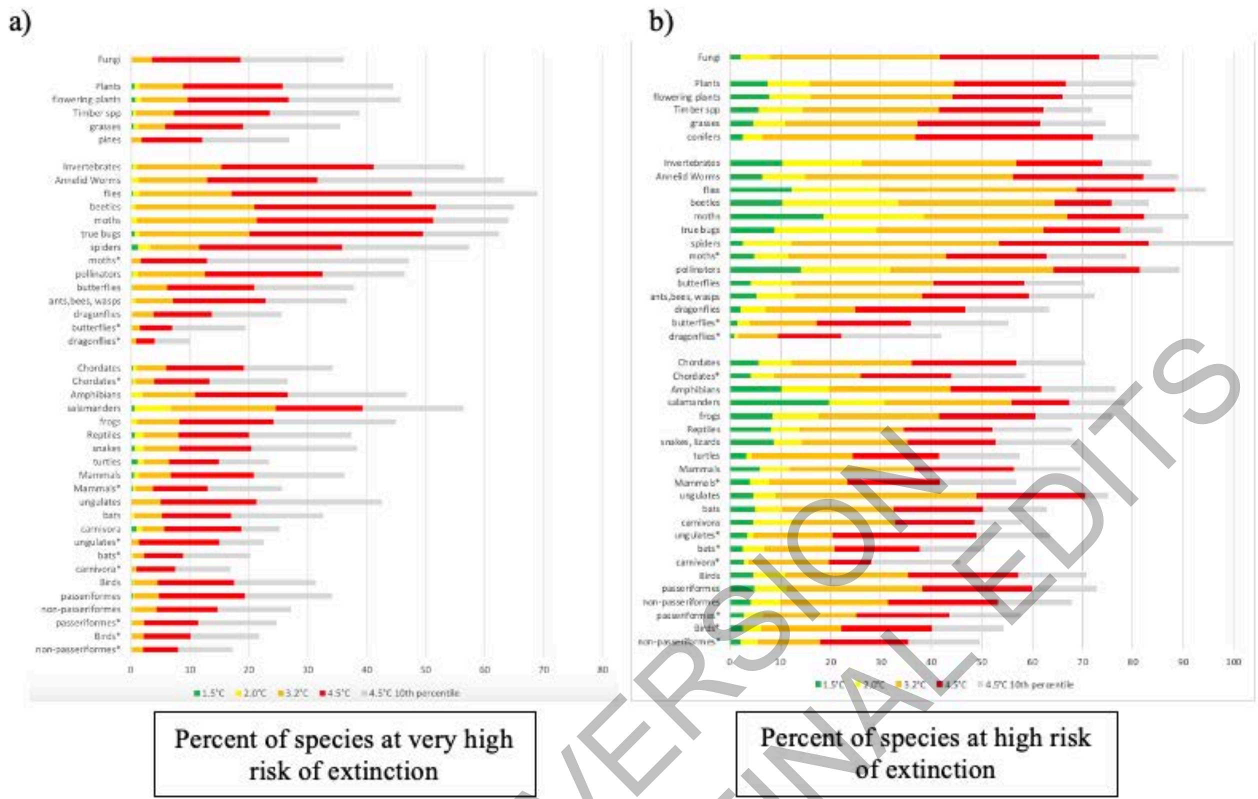


Figure 2.8: Percent of species of different groups classified as being under risk of extinction. a) Percent of the species group listed projected to be at very high risk of extinction, corresponding to the IUCN Red List criteria for a species classified as "critically endangered" (version 3.1) through losing >80% of its climatically suitable range area. b) Percent of the species group listed projected to be at high risk of extinction, corresponding to the IUCN Red List criteria for a species classified as "endangered" (version 3.1) through losing >50% of its climatically suitable range area. For a) and b), values calculated from the underlying data underpinning (Warren et al., 2018). Values for each temperature are the mean values across 21 CMIP5 models. The grey band represents the high-end of extinction risk from the 10th percentile of the climate models to show the maximum range of values while the low end (90th percentile, 1.5°C) is not shown as it is too small to appear on the plots. Taxa marked with * represent potential benefits from adaptation, specifically dispersal at realistic rates (Warren et al., 2018); those with no * have dispersal rates that are essentially not detected in the spatial resolution of the models (20 km). See (Warren et al., 2018) for caveats and more details. Sample size for each group is as follows: Invertebrates (33949), Annelid Worms (155), Butterflies (1684), Moths (6910), Dragonflies (599), Pollinators (1755), Spiders (2212), Beetles (7630), True Bugs (1728), Bees/Ants/Wasps (5914), Flies (4809), Plants (72399), Flowering Plants (52310), Conifers (340), Timber spp (1328), Grasses (3389), Fungi (16187), Vertebrates (12642), Mammals (1769), Carnivores (107), Ungulates (80), Bats (500), Birds (7968), Passeriformes (4744), Non-passeriformes (3224), Amphibians (1055), Frogs (887), Salamanders (163), Reptiles (1850), Snakes (1741), Turtles (94).

For local biodiversity loss, at 1.58°C (median estimate), >10% of species are projected to become endangered (sensu IUCN); at 2.07°C (median) >20% of species are projected to become endangered, representing high and very high biodiversity risk, respectively *(medium confidence)* (see Section 2.5.4; Figure 2.11; Table 2.5, Table 2.S.4).

Using data from geological time scales, Song et al. (2021) predicted that a warming of 5.2 °C above pre-industrial would result in mass extinction comparable to that of the five mass extinctions over the past 540 My, on the order of 70–85% of species going extinct, in the absence of non-climatic stressor. Mathes et al. (2021) found evidence in the geological record that short-term rapid warming, on top of long-term warming trends, increases extinction risk by up to 40% over that expected from the long-term trend alone, with a biodiversity 'memory' up to 60 Myr, indicating an additonal risk of multi-decadal overshoot.

Most of the large-scale studies that have been performed are for losses based on climate alone (Figures 2.6, 2.7, 2.8). However, climate is rarely the only stressor affecting species survival. Habitat loss is currently the largest driver of range loss and extinction risk for most species (IUCN). Communities in different regions are becoming more similar to each other as species tolerant of human activities prosper and spread, with many rare and endemic species already having been driven extinct, primarily by LULCC (Pimm et al., 2006). Thus, it will likely be the interaction of climate change and habitat conversion (often also being driven by climate change) that will ultimately determine the risk and ability to survive of many species.

2.5.1.4 Changing Risks of Diseases

Multiple studies predict increases in disease incidence or geographic and phenological changes of pathogens, vectors, and reservoir host species due to climate change with or without other non-climatic variables (González et al., 2010; Moo-Llanes et al., 2013; Roy-Dufresne et al., 2013; Liu-Helmersson et al., 2014; Laporta et al., 2015; Ryan et al., 2015; Haydock et al., 2016; Hoover and Barker, 2016; Prist et al., 2017; Blum and Hotez, 2018; Dumic and Severnini, 2018; Hundessa et al., 2018; Ryan et al., 2019; Ryan et al., 2021). However, models predicting changes in infectious disease risk are complex and sometimes produce conflicting results and lack consensus (Caminade et al., 2014; Giesen et al., 2020). For example, malaria is projected to increase in some regions of Africa, Asia, and South America by the end of the 21st century if public health interventions are not sufficient, but malaria is also forecasted to decrease in some of the higher risk areas (Peterson, 2009; Caminade et al., 2014; Ryan et al., 2015; Khormi and Kumar, 2016; Leedale et al., 2016; Murdock et al., 2016; Endo and Eltahir, 2020; Mordecai et al., 2020).

While malaria risk is predicted to decrease in some lowland tropical areas as temperatures become too hot for vector or parasite development, other, warmer-adapted diseases like dengue and Zika, transmitted by *Aedes aegypti*, are predicted to increase (Ryan et al., 2019; Ryan et al., 2021). In more temperate regions, arboviruses and other vector-borne diseases with wider thermal breadths, such as West Nile fever, Ross River fever, and Lyme disease, are predicted to increase with climate warming (Ogden et al., 2008; Leighton et al., 2012; Shocket et al., 2018; Shocket et al., 2020; Couper et al., 2021), and drought can exacerbate these effects of temperature (Paull et al., 2017).

A global analysis of 7346 wildlife populations and 2021 host-parasite combinations found that organisms adapted to cool and mild climates are likely to experience increased risks of outbreaks with climate warming while warm-adapted organisms may experience lower disease risk, providing further support for predictions that climate change will increase infectious disease transmission in higher latitude regions across a taxonomically diverse array of pathogens (*robust evidence, high confidence*) (Cohen et al., 2020). A study examining the future risk of arboviruses (chikungunya, dengue, yellow fever, and Zika viruses) spread by *Aedes aegypti* and *Ae. albopictus* projected increased disease risk due to interactions of multiple variables, including increased human connectivity, urbanisation and climate change (Kraemer et al., 2019), although vector species' ranges broaden only slightly (Campbell et al., 2015).

In sum, climate change is expected to expand and redistribute the burden of vector-borne and other environmentally-transmitted diseases by shifting many regions toward the thermal optima of vector-borne disease transmission for multiple parasites, increasing transmission, while pushing temperatures above optima and toward upper thermal limits for other vectors and pathogens, decreasing transmission (Mordecai et al., 2019; Mordecai et al., 2020). These effects are mediated by other human impacts such as land use change, mobility, socio-economic conditions, and vector and pathogen control measures (Parham et al., 2015; Tjaden et al., 2018).

2.5.2 Projected Changes at Level of Biomes and Whole Ecosystems

2.5.2.1 Global Overview, Assessment of Ecosystem-level Models, and Sources of Uncertainties

Shifts in terrestrial biome and changes in ecosystem processes in response to climate change are most frequently projected with dynamic global vegetation models (DGVMs), or land-surface models that form part of Earth System Models, which use gridded climate variables, atmospheric CO_2 concentration and information on soil properties as input variables. Since AR5, most of DGVMs have been upgraded to capture carbon-nitrogen cycle interactions (e.g. Le Quéré et al., 2018), many also include a representation of wildfire, and fire-vegetation interactions (Rabin et al., 2017), and a small number now also accounts for land management (such as wood removal from forests, crop fertilisation harvest of irrigation (Arneth et al., 2017). Other forms of disturbance, such as tree mortality in response to, for example, episodic weather extremes or insect pest outbreaks, are relatively poorly represented, or not at all, although they demonstrably impact calculated carbon cycling (Pugh et al., 2019a). Simulated biome shifts are generally in agreement in projecting broad patterns at the global scales, but vary greatly regarding the simulated trends in historical and future carbon uptake or losses, both regionally and globally (WGI, Chapter 5 AR6; Chang et al., 2017).

Similar to other models, models to project large-scale changes in vegetation and ecosystem processes have to deal with structural uncertainty (associated with the choice and the representation of processes in models), input-data uncertainty (associated with variability in initial conditions and parameter values) and error propagation (associated with coupling models) (Rounsevell et al., 2019). The IPBES methodological assessment report on scenarios and models of biodiversity and ecosystem services provides a comprehensive overview over the relevant issues (Ferrier et al., 2016).

In order to assess the model's performance, most models have been individually evaluated against a range of observations. Moreover, in the annual updates of the global carbon budgets a model has to meet a small set of basis criteria to have its output included (Le Quéré et al., 2018). More systematic benchmarking approaches have also been proposed that utilise a range of different data sets (Kelley et al., 2013; Chang et al., 2017), in order to assess multiple simulated processes. These methods in principle allow to assign quality scores to models based on their overall performance (Kelley et al., 2013). So far, this scoring does not yet allow a clear quality ranking of models since the individual DGVMs tend to score well for some variables and badly for others. A recent comparison of global fire-vegetation model outputs was also able to clearly identify outliers when using a formalised benchmarking and scoring approach (Hantson et al., 2020). However, benchmarking does not address sources of uncertainty and it would be advisable to perform "perturbed-physics" experiments, in which multiple model parameters are varied in parallel more frequently, as a means to test parameter-value uncertainty (Wramneby et al., 2008; Booth et al., 2012; Lienert and Joos, 2018).

Species diversity impact ecosystem functioning and hence ecosystem services (Hooper et al., 2012; Mokany et al., 2016). So far, however, integrated modelling of ecosystem processes and biodiversity across multiple trophic levels and food webs is in its infancy (Harfoot et al., 2014). Whether or not enhanced integration of state, function, and functional diversity across multiple trophic levels in models will markedly alter projections of how ecosystems respond to climate change thus remains an open research question.

Beyond simulating dynamically biome shifts and carbon cycling, which are important aspects of climate regulation, DGVMs can also provide information on a number of variables closely linked to other ecosystem services, such as water availability, air quality or food provisioning (Krause et al., 2017; Rabin et al., 2020). However, they are not intended to provide a comprehensive assessment of ecosystem services. For these, other approaches applied, but to date these are mostly applied on regional scales and are only weakly dynamic (Ferrier et al., 2016).

2.5.2.2 Projected Changes Globally at the Biome Level

Climate change and the associated change in atmospheric CO_2 levels already exacerbate other human-caused impacts on structure and composition of land and freshwater ecosystems, such as land-use change, nitrogen deposition, of pollution. The relative importance of these drivers for ecosystems over the coming decades will likely differ between biomes, but climate change and atmospheric CO_2 will be pervasive unless we manage to rapidly limit fossil-fuel emissions and warming (*high confidence*) (Pereira et al., 2010; Warren, 2011; Ostberg et al., 2013; Davies-Barnard et al., 2015; Pecl et al., 2017; Ostberg et al., 2018). Global vegetation and Earth system models agree on climate-change driven shifts of biome boundaries potentially of hundreds of km over this century, combined with several substantial alterations that take place within biomes (e.g., changes in phenology, canopy structure and functional diversity, etc.). Large discrepancies exist between models and between scenarios regarding the region and the speed of change (Gonzalez et al., 2010b; Pereira et al., 2010; Pecl et al., 2017), but robust understanding is emerging in that the degree of impact increases in high emission and warming scenarios (*high confidence)* (Figure 2.9).

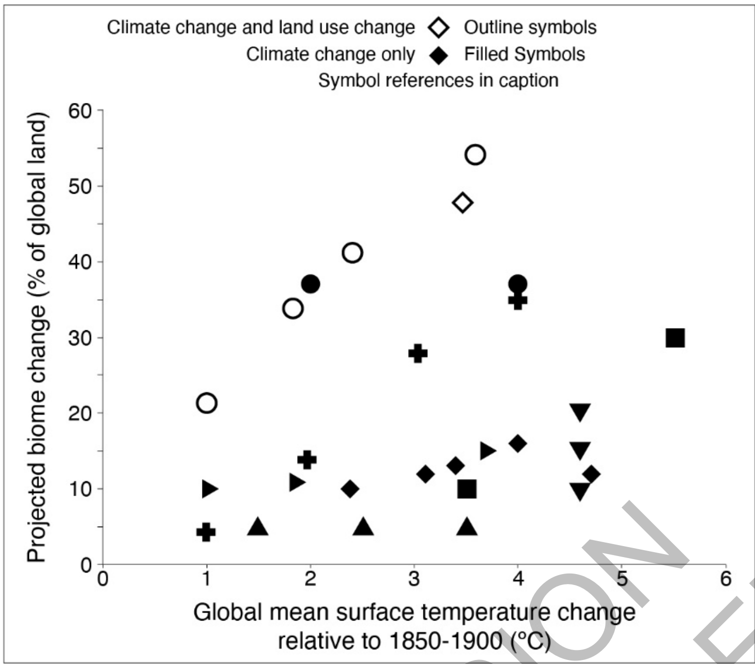


Figure 2.9: Projected fraction of global terrestrial area that could experience a biome shift by 2100, due to climate change (filled symbols) or a combination of climate change and land use change (outline symbols), from publications in Supplementary Table 2.S.3 (Projected vulnerabilities and risks of ecosystems to biome shifts). Circle filled (Bergengren et al., 2011), square filled (Alo and Wang, 2008), diamond filled (Gonzalez et al., 2010b), triangle up filled (Scholze et al., 2006), triangle down filled (Sitch et al., 2008), triangle on side filled (Li et al., 2018), cross filled (Warszawski et al., 2013), circle outline (Ostberg et al., 2018), diamond outline (Eigenbrod et al., 2015).

Substantial changes in vegetation structure and ecosystem processes are already happening (see section 2.4). Many of these observations have already been projected to take place as early as at least IPCC AR3 (Rosenzweig et al., 2007), and can they now be increasingly tested for their robustness with observational evidence. These multiple changes in response to warming (and changes in precipitation and increasing atmospheric CO_2 levels that go hand-in-hand with the warming) are further expected for already relatively small additional temperature increases, in particular in cold (boreal, tundra) regions, as well as in dry regions (*high confidence*): alterations of 2–47% of the areal extent of terrestrial ecosystems in scenarios of <2°C warming above pre-industrial have been projected, increasing drastically with higher-warming scenarios (Warren, 2011; Wårlind et al., 2014). More recent work, applying also probabilistic methods confirm the risk of drastic changes in vegetation cover (e.g. forest to non-forest or vice versa) at the end of the 21st century even for ca. 2°C warming scenarios, especially in tundra, and in tropical forest and savannah regions, with more subtle changes (within a given biome types) likely to occur in all regions (Ostberg et al., 2013; Ostberg et al., 2018). Model studies have found 5–20% of terrestrial ecosystems affected by warming ca. 2–3ºC, increasing to above one-third at a warming of 4–5ºC (Ostberg et al., 2013; Warszawski et al., 2013).

In general, vegetation types are projected to be moving into their 'neighbouring' climates, depending on whether temperature or precipitation is expected to be the predominant factor, and how vegetation interacts with the increasing CO_2 levels in the atmosphere (Wårlind et al., 2014; Scheiter et al., 2015; Schimel et al., 2015; Huntzinger et al., 2017). For instance, boreal or temperate forest vegetation is simulated to migrate polewards, closed tropical (moist) forest is expected to transition towards dry tropical forest types, while climate-driven degradation might expand arid vegetation cover (Sections 2.5.4.2.1-2.5.4.2.5) However, 'novel ecosystems', that is, communities with no current or historical equivalent because of the novel combinations of abiotic conditions under climate change, are expected to be increasingly common in the future (*medium confidence)* although the regions where these novel ecosystems might emerge are still disputed (Reu et al., 2014; Radeloff et al., 2015; Ordonez et al., 2016). The possibility of these novel ecosystems and the communities that live within them poses challenges to current modelling of ecosystem shifts, and will require new approaches to conservation that are designed to adapt to rapid changes in species composition and ensuing conservation challenges.

2.5.2.3 Risk to Arid Regions

Shifts in arid system structure and functioning that have been observed to date (section 2.4.3.3) are projected to continue and include widespread woody plant encroachment, notably in savanna systems in Africa, Australia and South America, and attributed to interacting land use change, climate change, and CO_2 fertilisation effects (Fensholt et al., 2012a; Fang et al., 2017; Stevens et al., 2017). Arid Mongolian Steppe grassland did not respond to experimentally elevated CO_2 (Song et al., 2019). Woody encroachment is projected to continue or not reverse in North American drylands (Caracciolo et al., 2016), and in southern African arid ecosystems (Moncrieff et al., 2014b). Dryland woody encroachment may increase carbon stocks, depending on emissions scenario (Martens et al., 2021), but reduce soil water and biodiversity of grassland-dependent species diversity (Archer et al., 2017). Warm season (C4) grass expansion into arid shrublands risks sudden ecosystem transformation due to introduced wildfire (Bradley et al., 2016), a risk anticipated for grass-invaded desert ecosystems of Australia and south-western United States (Horn and St. Clair, 2017). Novel fire regimes in grassy shrublands have enhanced grass cover locally in southern African Nama-Karoo (du Toit et al., 2015).

Range retractions are projected for endemic plants in southern Africa (Young et al., 2016) and dry woodlands in Morocco (Alba-Sánchez et al., 2015). Increasing thermal stress is projected to increase woody plant mortality in Sonoran Desert ecosystems (Munson et al., 2016), and facilitate perennial grass replacement by xeric shrubs in the south-western USA (Bestelmeyer et al., 2018). Ecological effects may occur rapidly when extreme events compound long-term trends (Hoover et al., 2015), but evolve more slowly as opportunity costs accumulate due to warming (Cross-Chapter Paper 3; Cunningham et al., 2021).

2.5.2.4 Risk to Mediterranean-type Systems

All Mediterranean Type Ecosystems (MTEs) show *high confidence* in projected increases in the intensity and frequency of hot extremes and decreases in the intensity and frequency of cold extremes and *medium confidence* in increasing ecological drought due to increased evapotranspiration (all regions) and reduced rainfall (excluding California, where model agreement is low) (see Chapter 11 of WG1). Projections also show a robust increase in the intensity and frequency of heavy precipitation in the event of 2° C warming or more for MTEs in South Africa, the Mediterranean Basin and California, but are less clear for Australia and Chile (see Chapter 11 of WG1).

MTEs are characterised by the distinctive seasonal timing of precipitation and temperature and disruption of this regime is likely to be critical for their maintenance. Unfortunately, projections of changes in rainfall seasonality have received less attention and are far more uncertain than many other aspects of climate change (Pascale et al., 2016; Breinl et al., 2020), limiting our ability to predict the ecological consequences of climate change in MTEs. Responses to experimental manipulation of rainfall seasonality show potential for shifts in plant functional composition and diversity loss, but results vary with soil type (van Blerk et al., 2021).

Unfortunately, global and regional scale dynamic vegetation models show poor performance for large areas of MTEs, because they do not characterise shrub and CAM-photosynthetic plant functional types well (Moncrieff et al., 2015). Furthermore, the grain of these models are too coarse for quantifying impacts to many vegetation formations which are patchy or of limited extent (e.g. forests). There is *high confidence* that observations of high mortality in trees and other growth forms, reduced reproductive and recruitment success, range shifts, community shifts towards more thermophilic species, and type conversions are set to continue, either due to direct climate impacts through drought and other extreme weather events, or their interaction with factors like fire and pathogens (Sections 2.4.3.6; 2.4.4.2; 2.4.4.3; 2.5.4.2.4; 2.5.5.2).

Fire is a key driver across most MTEs due to summer-dry conditions. Climate projections for the MTEs translate into high confidence that periods of low fuel moisture will become more severe and prolonged and that episodes of extreme fire weather will become more frequent and severe (see Chapter 11, Section 8.3 WGI). This will lead to the birth of novel fire regimes in MTEs characterised by an increase in the probability of greater burned area and extreme wildfire events (e.g. megafires), with associated loss of human life and property, and long-term impacts on ecosystems and accelerating the possible loss of resilience and capacity to recover (Abatzoglou and Williams, 2016; González et al., 2018; Boer et al., 2020; Moreira et al., 2020; Nolan et al., 2020; Duane et al., 2021; Gallagher et al., 2021).

Fire is virtually certain to have additional impacts through compound events (AR6 WGI Chapter 11.8). Extreme postfire weather is extremely likely to continue to impact diversity (Slingsby et al., 2017), retard vegetation regrowth (Slingsby et al., 2020a) and accelerate vegetation shifts (Batllori et al., 2019). Any increases in the intensity and frequency of heavy precipitation are highly likely to compromise soil stability in recently burnt areas (Morán-Ordóñez et al., 2020). The impacts of fire often depend on interactions with non-climatic factors such as habitat fragmentation (Slingsby et al., 2020b), management (Steel et al., 2015) or the spread of flammable exotic plantation forestry and invasive species (Kraaij et al., 2018; McWethy et al., 2018). Managing these factors provides opportunities for adaptation and mitigation (Moreira et al., 2020).

Human adaptation and mitigation responses to climate change may create additional threats to MTEs. MTEs have dry summers by definition, posing a challenge for the year-round supply of water to growing human populations and agriculture. With recent major droughts in all MTEs (Section 2.4.3.6), there is increasing reliance on groundwater for bulk water supply (Kaiser and Macleod, 2018). The majority of groundwater systems have exceeded or are rapidly approaching their environmental flow limits (de Graaf et al., 2019), threatening human populations and ecosystems that depend on these systems for their persistence through unfavourable climatic conditions (McLaughlin et al., 2017 Plants). Similarly, much of the MTEs are open shrublands and grasslands and proposed extensive tree-planting to sequester atmospheric CO_2 could result in loss of biodiversity and threaten water security (Doblas-Miranda et al., 2017; Bond et al., 2019).

2.5.2.5 Risk to Grasslands and Savannas

Worldwide, woody cover is increasing in savannas (Buitenwerf et al., 2012; Donohue et al., 2013; Stevens et al., 2017), as a result interactions of elevated CO_2 combined with altered fire and herbivory impacts (i.e. from land-use change; see Section 2.4.3.5; CCP3.2; Venter et al., 2018; Wu et al., 2021). In some regions, altered climate may also contribute (CCP3.2). Elevated CO_2 benefits plants with C3 photosynthesis (often woody plants), more than C4 species (Moncrieff et al., 2014a; Scheiter et al., 2015; Knorr et al., 2016a). Increases in woody vegetation in grassy ecosystems could provide some carbon increase (*medium confidence*) (Zhou et al., 2017; Mureva et al., 2018), but is expected to decrease biodiversity (Smit and Prins, 2015; Abreu et al., 2017; Andersen and Steidl, 2019), decrease water availability (Honda and Durigan, 2016; Stafford et al., 2017) and alter ecosystem services like grazing and wood provision (*high confidence*) (Anadon et al., 2014).

The relative importance of climate, disturbance (e.g. fire/herbivory) and plant feedbacks in shaping present and future savanna distribution vary between continents (Lehmann et al., 2014), which makes projections of changing biome extent challenging (Moncrieff et al., 2016). It has been shown that simulation studies that do not account of CO_2 interactions and only consider climate change impacts do not realistically capture the future distribution of savannas (*high confidence)* (Higgins and Scheiter, 2012; Moncrieff et al., 2016; Scheiter et al., 2020). Due to the continued strong effect of CO_2 on tree (and shrub) to grass ratios in future, models suggest a loss of savanna extent and conversion into closed canopy forest/thicket and an expansion of savanna-type vegetation into arid grasslands (Wårlind et al., 2014; Moncrieff et al., 2016). In arid savannas and their interface to grasslands, survival of woody vegetation (which may be stimulated to grow by increasing CO_2) will depend l on their capacity to survive potentially more severe and frequent droughts (Sankaran and Staver, 2019). Across a range of models, for RCP4.5 future climate change and CO_2 concentrations, savanna expanse declined by around 50% (converting to closed canopy systems) by 2070 in Africa and South America, 25% in Asia with small changes in Australia (Moncrieff et al., 2016; Kumar et al., 2021). Future fire spread is expected to be reduced with increased woody-dominance (Scheiter et al., 2015; Knorr et al., 2016b; Scheiter et al., 2020), feeding back to further increase tree to grass ratios (*high confidence)*.

Like the tropical forest biome, savannas are at large risk, given the projected climate changes in combination with land-use change (see Cross Chapter Paper 3). About 50% of Brazilian Cerrado has been transformed to agriculture and pastures (Lehman and Parr, 2016), and African savannas have been proposed to follow a similar tropical agricultural revolution pathway in order to enhance agronomical prosperity (Ryan et al., 2016). In fact, indirect climate change impacts arising from mitigation efforts on land may be particularly perilous to savannas: extensive tree-planting to restore ecosystems and remove CO_2 from the atmosphere, as pledged, for example, under the African Forest Restoration Initiative, could lead to carbon losses, loss of biodiversity and damage ecosystem's water balance if trees are planted in what naturally are grasslands or savannas (Box 2.2, FAQ2.6; Bond et al., 2019).

2.5.2.6 Risk to Tropical Forest

Key factors affecting the future distribution of tropical humid and dry forests are amounts and seasonalities of precipitation, increased temperatures, prolonged droughts and droughted-moderated fires (*robust evidence, high agreement*) (Bonai et al., 2016; Corlett, 2016; Lyra et al., 2017; Anderson et al., 2018; da Silva et al., 2018; Fontes et al., 2018; O'Connell et al., 2018; Aguirre-Gutiérrez et al., 2019; Bartlett et al., 2019; Brando et al., 2019; Stan and Sanchez-Azofeifa, 2019). Probability of severe drought is projected to quadruple in natural areas in Brazil with above 2°C warming (Barbosa and Lakshmi Kumar, 2016; Marengo et al., 2020). Most multi-model studies assuming rapid economic growth/business-as-usual scenarios (A2, A1B, RCP8.5) show an increase in future woody biomass and areas of woody cover towards the end of the 21st century in the temperate regions (Boit et al., 2016; Nabuurs et al., 2017) and in tropical forests in East Africa (Ross et al., 2021) but decrease in the remaining tropical regions (Anadón et al., 2014; Boit et al., 2016; Lyra et al., 2017; Nabuurs et al., 2017; Maia et al., 2020). Terrestrial species are predicted to shift to cooler temperatures and higher elevations (Pecl et al., 2017). Tropical species are more susceptible to climate warming than temperate species (Rehm and Feeley, 2016; Sentinella et al., 2020). This susceptibility will be exacerbated by road-building increasing ease of access into forests (Brinck et al., 2017; Taubert et al., 2018; Bovendorp et al., 2019; Senior et al., 2019). Furthermore, most tropical cloud forest species are unable to invade grasslands and this will increase risk of extinctions in tropical cloud forests (Rehm and Feeley, 2015).

Sea level rise as the result of climate change is likely to influence mangroves in all regions, with greater impact on North and Central America, Asia, Australia, and East Africa than West Africa and South America (*robust evidence, high agreement*) (Alongi, 2015; Ward et al., 2016). On a small scale, mangroves are potentially moving landward (Di Nitto et al., 2014), while on a large scale they will continue to expand poleward (Alongi, 2015).

Most simulations predict a significant geographical shifts of transition areas between tropical forests and savanna in the tropical and subtropical Americas and Himalayas (Anadón et al., 2014) (Rashid et al., 2015). Forest die-back, as postulated for the Amazon region, does not occur in the majority of simulations (Malhi et al., 2009; Poulter et al., 2010; Rammig et al., 2010; Higgins and Scheiter, 2012; Huntingford et al., 2013; Davies-Barnard et al., 2015; Sakschewski et al., 2016; Wu et al., 2016a). Model projections of future biodiversity in tropical forests are rare. Arguably, species are most vulnerable to climate change effects in higher altitudes or at the dry end of tropical forest occurrence (*medium evidence, medium agreement*) (Krupnick, 2013; Nobre et al., 2016; Trisurat, 2018). Tropical lowlands are expected to lose plant species as temperatures rise above species' heat tolerance but could also generate novel communities of heat tolerant species (*robust evidence, high agreement*) (Colwell et al., 2008; Trisurat et al., 2009; Trisurat et al., 2011; Krupnick, 2013; Zomer et al., 2014a; Zomer et al., 2014b; Sullivan et al., 2020; Pomoim et al., 2021).

Statistical models that correlate data on species abundance with information on human pressures (such as land-use change (Srichaichana et al., 2019), population density (Leclère et al., 2020) hunting (Mockrin et al., 2011) found for tropical and sub-tropical forests that birds, invertebrates, mammals and reptiles show a decline in their probability of presence with declining forest cover, which is particularly pronounced in forest specialists or narrow-ranged species (Newbold et al., 2014). Different soil fauna groups showed different responses in abundance and diversity to climate change conditions (Coyle et al., 2017; Facey et al., 2017) but these changes can impact decomposition rates and biogeochemical cycles (*medium evidence, low agreement*).

Invasive plant species are predicted to expand upward by 500-1,500m in the Western Himalaya (Thapa et al., 2018), and by 6-35% per year from the current extent in South America (*robust evidence, high agreement*) (Bhattarai and Cronin, 2014). Global assessment (Wang et al., 2017) also revealed that ecoregions of high elevation tropical forests and sub-tropical coniferous forests have high risk of invasive plant expansion in the low CO_2 emission scenarios, with negative impacts on ecosystem functioning and local livelihoods (Shrestha et al., 2019).

The impact of unsustainable land use on tropical forests continues in all regions (see Cross-Chapter Paper 7). Projected climate changes will not only cause impacts on biodiversity but also on the livelihoods of affected people (*robust evidence, high agreement*). Increased drought drives crop failures that cause local communities to expand agricultural area by further clearing native forests (Desbureaux and Damania, 2018). Climate change is projected to enlarge the area of suitability for booming tree crops such as oil palm, acacia, Eucalyptus, and rubber (Koninck et al., 2011; Cramb et al., 2015; Nath, 2016; Hurni et al., 2017; Li et al., 2017; Varkkey et al., 2018). An increase of 8% in area of rubber plantations in Yunnan province, China, between 2002–2010 to higher altitude due to decreased environmental limits, potentially increases pressure on remaining biodiversity both within and outside of protected areas (Zomer et al., 2014a). As a consequence, the suitable area for mammals is projected to be reduced by 47.7% (RCP 2.6) and 67.7% (RCP8.5) by 2070, with large variability depending on the different species (See also Cross-Chapter Paper 7; Brodie, 2016).

2.5.2.7 Risk to Boreal and Temperate Forests

As in the Arctic, warming substantially exceeding the global average has already been observed for the northern parts of the temperate and boreal forest zone (Gauthier et al., 2015), and is projected to continue (see Chapter 4 of WGI, see Cross-Chapter Paper 6). As a consequence, boreal tree species are expected to move northwards (or in mountain regions: upwards) into regions dominated by tundra, unless constrained by edaphic features, and temperate species are projected to grow in regions currently occupied by southern boreal forest (*high confidence)*. In both biomes, deciduous trees are simulated to increasingly grow in regions currently dominated by conifers (Wårlind et al., 2014; Boulanger et al., 2017). These simulation results have been supported by observational examples. In Eastern Siberia, fire disturbance of larch-dominated forest was followed by recovery to birch-dominated forest (Stuenzi and Schaepman-Strub, 2020). In Alberta Lodgepole Pine (*Pinus contorta*) lost its dominant status after attacks by Mountain Pine Beetles (*Dendroctonus ponderosae*) caused the canopy to switch to non-pine conifers and broadleaved trees (Axelson et al., 2018). In contrast to the examples above, some boreal forests have proven resilient to disturbances, including to recent unprecedented spates of insect attacks (Campbell et al., 2019a; Prendin et al., 2020).

Reforestation, either natural or anthropogenic, leads to summer cooling and winter warming of the ground, while forest thinning or removal by fire has the reverse effects and deepens the upper layer free of permafrost (Stuenzi et al., 2021a). Interactions between permafrost and vegetation are important. For example, trees in East Siberian taiga obtained water mostly from rain in wet summers and mostly from permafrost meltwater in dry summers (Sugimoto et al., 2002), suggesting that these forests will be particularly vulnerable to combination of drought with retraction further underground of permafrost under climate warming.

2.5.2.8 Risk to Peatland Systems

The overall effect of climate change on the extent of northern peatlands is still debated (*limited evidence, low agreement*). It is expected that climate change will drive high-latitude peatland expansion poleward of their present distribution due to warming, permafrost degradation, and glacier retreat, which could provide new land and conditions favourable for peat development (*limited evidence, medium agreement*) (Zhang et al., 2017b), as seen during the last deglacial warming (*robust evidence, high agreement)* (MacDonald et al., 2006; Jones and Yu, 2010; Ratcliffe et al., 2018). Peatland area loss (shrinking) near the southern limit of their current distribution or in areas where the climate becomes unsuitable is also expected (*medium evidence, medium agreement*) (Section 2.3.4.3.2; Finkelstein and Cowling, 2011 temperature, and; Gallego-Sala and Colin Prentice, 2013; Schneider et al., 2016; Müller and Joos, 2020), though these peatlands could persist if moisture is maintained via peatlands' self-regulating capacity. In Western Canada, a study suggests that peatlands may persist until 2100, even though the climate will be less suitable (Schneider et al., 2016). Simulations suggest that climate change driven increases in temperature and atmospheric CO_2 could drive reductions in the northern peatland area up to 18% (SSP1-2.6), 41% (SSP2-4.5), and 61% (SSP5-8.5) by 2300 (Müller and Joos, 2020). This is in contrast with findings of northern peatland persistence and expansion under RCP2.6 and RCP6.0 scenarios during 1861–2099 by another modelling study (Qiu et al., 2020). In the tropics, the only available study suggests peatland area will increase until 2300, mainly due to the CO_2 fertilisation effect (Müller and Joos, 2020).

The combination of climate and land-use change represents a substantial risk to peatland carbon stocks, but full assessment is impeded because peatlands are yet to be included in Earth System models (*limited evidence, high agreement)* (Loisel et al., 2021). It is expected that the carbon balance of peatlands globally will switch from sink to source in the near future (2020–2100), mainly because tropical peatland emissions, together with those from climate change -driven permafrost thaw, will likely surpass the carbon gain expected from climate change-driven enhanced plant productivity in the northern high latitudes (Gallego-Sala et al., 2018; Chaudhary et al., 2020; Turetsky et al., 2020; Loisel et al., 2021), mainly because of groundwater drawdown *(robust evidence, medium agreement)* (Hirano et al., 2014; Brouns et al., 2015; Cobb et al., 2017; Itoh et al., 2017; Evans et al., 2021). The overall northern peatland carbon sink has been simulated to persist for at least 300 years under RCP2.6, but not under RCP8.5 (Qiu et al., 2020).

Increases in fire extent, severity, and duration are expected in all peatland regions in the future due to temperature increases (Section 4.3.1.1), changes in precipitation patterns (section 4.3.1.2), and increases in ignition sources (such as lightning) (Section 5.4.3.2), with associated rapid carbon losses to the atmosphere *(medium evidence, high agreement)* (Dadap et al., 2019; Chen et al., 2021a; Nelson et al., 2021). For example, drought has been linked to fires in SE Asian peatlands (Field et al., 2009) and there are predicted decreases in mean summer precipitation (10-30%) for high and low RCPs, particularly over the Indonesian region by mid and late twenty-first century (Section 12.4.2.2; Tangang et al., 2020; Taufik et al., 2020). During wet years, the fire probability in Indonesian peatlands also significantly increases (+15-40 %) when July-October temperatures surpass 0.5°C anomalies compared to a 1995-2015 baseline (Fernandes et al., 2017). Overall, current evidence suggests that peat carbon losses via fire have the potential to be equal to, or greater than, losses due to human peatland drainage and disturbance (*limited evidence, high agreement*) (Turetsky et al., 2015).

In permafrost peatlands, studies differ, with some projecting net loss ~~or~~ and others net gain of carbon (*medium evidence, low agreement*) (Estop-Aragonés et al., 2018; Hugelius et al., 2020; Loisel et al., 2021; Väliranta et al., 2021). In some permafrost peatlands, prolonged and warmer growing seasons due to climate change (section 2.3.4.3.1), along with increases in nitrogen deposition since 1850 (Lamarque et al., 2013), are promoting plant primary productivity. Other studies indicate increased nitrogen-mediated sequestration could be exceeded by increased decomposition due to climate-change-driven warming and fire (*medium evidence, low agreement*) (Natali et al., 2012; Vonk et al., 2015; Keuper et al., 2017; Burd et al., 2018; Estop-Aragonés et al., 2018; Gallego-Sala et al., 2018; Serikova et al., 2018; Wild et al., 2019; Chaudhary et al., 2020; Hugelius et al., 2020).

Any climate change or human-driven degradation of peatlands will also entail losses in water storage (*limited evidence, high agreement*) (Wooster et al., 2012 drought and; Hirano et al., 2015; Cole et al., 2019; Taufik et al., 2019) and biodiversity (Harrison, 2013; Lampela et al., 2017; Renou-Wilson et al., 2019). The environmental archive contained in peat that preserves records of vegetation, hydrology, climate change, pollution and/or human disturbances is also lost as the peatlands degrade (Greiser and Joosten, 2018). (Kasischke and Turetsky, 2006; MacDonald et al., 2006; Turunen, 2008; Field et al., 2009; Flannigan et al., 2009; Jones and Yu, 2010; Kasischke et al., 2010; Peterson et al., 2010; Finkelstein and Cowling, 2011 temperature, and; Rooney et al., 2012; Gallego-Sala and Colin Prentice, 2013; Lamarque et al., 2013; Hirano et al., 2014; Brouns et al., 2015; Turetsky et al., 2015; Miettinen et al., 2016; Schneider et al., 2016; Cobb et al., 2017; Fernandes et al., 2017; Itoh et al., 2017; Gallego-Sala et al., 2018; Greiser and Joosten, 2018; Ratcliffe et al., 2018; Dadap et al., 2019; Leifeld et al., 2019; Chaudhary et al., 2020; Hoyt et al., 2020; Müller and Joos, 2020; Qiu et al., 2020; Tangang et al., 2020; Taufik et al., 2020; Turetsky et al., 2020; Chen et al., 2021a; Evans et al., 2021; Loisel et al., 2021; Nelson et al., 2021; Qiu et al., 2021)

2.5.2.9 Risk to Polar Tundra Ecosystems

For boreal-tundra systems, AR5 projected transformation of species composition, land cover and permafrost extent, decreasing albedo and increasing greenhouse gases emission *(medium confidence)*. The Special Report on Global Warming of 1.5°C classified tundra and boreal forests as particularly vulnerable to degradation and encroachment of woody shrubs *(high confidence)*. The Special Report on Oceans and Cryosphere (SROCC) projected climate-related changes to arctic hydrology, wildfire and abrupt thaw, *(high confidence)* and broad disappearance of arctic near-surface permafrost in this century, with important consequences for global climate *(very high confidence).* Chapter 2 of AR6 has focused on new key findings about observed and projected changes in tundra vegetation and related hydrology, with implications for feedbacks to the climate system.

Due to the rapid warming in high northern latitudes, Arctic tundra is one of the terrestrial biomes where climate change impacts are already clearly visible (Settele et al., 2014; Uboni et al., 2016). Climate models project that warming for the Arctic is likely to continue at more than double the global rate. Compared to the period 1995–2014, mean annual surface air temperatures in Arctic tundra are projected to increase by 7.9°–10°C by the end of the century for scenarios of high greenhouse gas emissions (RCP 7.0 and 8.5). For scenarios of low greenhouse gas emissions (RCP 1.9 and 2.6), the projected increase is 2.6°–3.2°C (see Chapter 4 pf WGI). The Arctic is also projected to have among the largest increases in precipitation globally, although there is high uncertainty in these projections. In contrast to climate change, land use change is projected to be very low in Arctic tundra systems (van Asselen and Verburg, 2013).

Models of vegetation response to climate project acceleration in coming decades of observed increases in shrub dominance and boreal forest encroachment that have been driven by recent warming (Settele et al., 2014), leading to a shrinking of the area of tundra globally (*medium confidence)* (Mod and Luoto, 2016; Gang et al., 2017). Simulating changes in tundra vegetation is complicated by permafrost dynamics (e.g. formation of thaw ponds), changes in precipitation, or low nutrient availability, which may promote abundance of graminoids (van der Kolk et al., 2016). The changes in vegetation, when combined with warming and increased precipitation effects on soil thawing and carbon cycling, are projected to modify greenhouse gas emissions and have biophysical feedbacks to regional and global climate. Large uncertainty in modelled carbon cycle changes arises from differences between the vegetation models (Nishina et al., 2015; Ito et al., 2016). In addition, climate change is expected to strongly interact with other factors, such as fire, to further increase uncertainty in projections of tundra ecosystem function (Jiang et al., 2017).

2.5.2.10 Committed Impacts of Climate Change on Terrestrial Ecosystems and Implications of Overshoot

Projections point to potentially large changes of canopy structure and composition within and across the terrestrial biomes in response to climate change and changes in atmospheric CO_2. These changes will contribute to altered ecosystem carbon uptake and losses, biophysical climate feedbacks (Sections 2.3.2; 2.4.4; 2.5.3.2; 2.5.3.3. 2.5.3.4, 2.5.3.5, Figure 2.10, Table 2.4), and multiple other ecosystem services (Sections 2.5.3, 2.5.4), as well as for biodiversity (Sections 2.4.2, 2.4.3, 2.4.4, 2.4.5, 2.5.1.3, 2.5.1.4, 2.5.2, Figure Box 2.1.1, Table Box 2.1.1, Table SM2.4). Until now, most studies project changes over next decades until the end of this century.

However, there is an increasing body of literature that has found continued, longer-term responses of ecosystems to climate change, so-called 'committed changes,' that arise from lags that exist in many systems. Many processes in ecosystems take more than a few decades to quasi-equilibrate to environmental changes. Therefore, trends of changing vegetation cover identified in simulations of transient warming continue to show up in simulations that hold climate change at low levels of warming (*medium confidence)* (Boulton et al., 2017; Pugh et al., 2018; Scheiter et al., 2020). Such changes, which could tip ecosystems into an alternative state, could also be triggered by a ‘warming overshoot’ – if global warming were to exceed a certain threshold, even if mean temperatures afterwards decline again (Albrich et al., 2020a).

For instance, even if warming achieved by 2100 remained constant after 2100, such committed responses continue to occur. These include: (1) continued Amazon forest loss (Boulton et al., 2017), consistent with results in (Pugh et al., 2018) that found continued tropical forest cover loss across a range of models and simulation set-ups, and (2) across Africa, an increased shift towards woody C3 vegetation was found in equilibrium state, the overall response depending on the atmospheric CO_2 concentration (Scheiter et al., 2020). In Pugh et al. (2018), the opposite was found for boreal forest cover, which showed a strong committed increase. The committed changes in vegetation composition correspond to large committed changes in terrestrial carbon uptake and losses (Boulton et al., 2017; Pugh et al., 2018; Scheiter et al., 2020), and would plausibly also appear in other ecosystem functioning and services. These studies point to the importance of having not only a multi-decadal but also a multi-century perspective when exploring the impacts of political decisions on climate change mitigation taken now. Even if climate-warming targets are met, published evidence so far suggests that fundamental changes in some ecosystems are *likely* as these correspond to well-understood ecosystem physiological responses that trigger long-term changes in composition.

[START BOX 2.1 HERE]

Box 2.1: Assessing Past Projections of Ecosystem Change Against Observations

To assess future climate change impacts on ecosystems we use models to project their future distribution. Comparing the trends in the observed changes against the projections can help assess the strength of the model projections. In this box, we compare observed trends of changes in ecosystem structure to projections highlighted in previous IPCC reports (specifically AR3 (IPCC, 2001), AR4 (Fischlin et al., 2007) and AR5 (Settele et al., 2014). We use this to assess how well the projections are matching up with observed changes. The map represents studies documenting observed changes in common plant functional groups (e.g. trees, grasses, shrubs). Studies, documenting changes in plant functional groups, were collated from published papers in natural and semi-natural areas. Studies were included if climate change, or interactions between climate change and land use showed a causal link to the observed change. Studies were excluded if the changes only from landscape/land use transformation (e.g. deforestation). In each paper, we recorded the geographical location, the type of functional change and noted the causes. Observed changes are plotted onto a biome map derived from the WWF ecoregions database (Olson et al., 2001). Trends in changing plant functional types are good indicators of potential biome shifts and are used to assess how observations match up with projections.

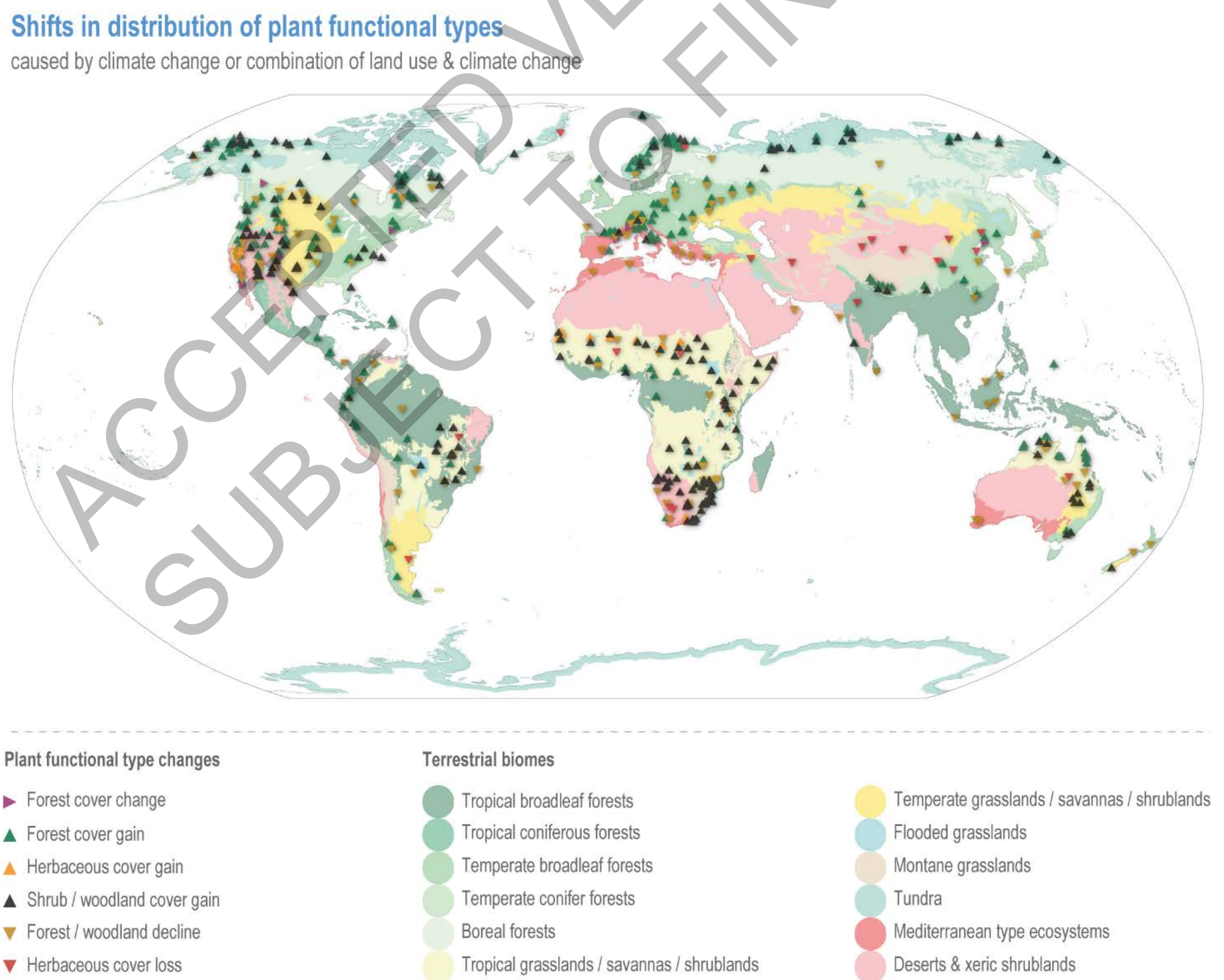


Figure Box 2.1.1: Observed changes in the distribution of plant functional types that are caused by climate change or combination of land use and climate change. Shifts in plant functional types are indicative of shift in biome function and structure

Table Box 2.1.1: Comparison of projections on biome change from the Third, Fourth and Fifth assessment report (IPCC, 2001; Fischlin et al., 2007; Settele et al., 2014) with observed changes in ecosystems as assessed in this current report (see section 2.4 and Fig Box 2.1.1). Observed changes marked in bold show good agreement with past projections, those in red show mismatch with observations and projections.

Biome	AR3	AR4	AR5	Observed trends 1990–2021
Mediterranean Type ecosystems	Increased disturbance by fire and warming will cause a loss of unique habitats	Loss of 65% of area due to warming. Increased fire frequencies will favor resprouting plants. An increase in grass dominance. Forest expansion within MTE's systems due to elevated CO_2.	Range contractions of all species	Increased in water deficit **and fire activity** (sections 2.4.3.6, *2.4.4.2*) **causing declines in diversity**, tree mortality (Fig Box 2.1.1) with resprouting trees worst affected. **Increasing dominance of grasses (often alien).** Increasing dominance of deciduous over evergreen species (Fig Box 2.1.1).
Tundra	Tree and shrub encroachment into tundra.	Increased woody plant growth due to longer and warmer growing seasons and replacement of dwarf tundra by shrub tundra Poleward expansion of tundra into polar desert and encroachment of coniferous trees into tundra	Continued woody expansion in tundra regions with reduced surface albedo due to less snow and more woody cover	**Increase in woody shrub cover in tundra and expansion of boreal forest into tundra**. (Fig Box 2.1.1, 2.4.3.4)
Boreal forest	Reduced productivity due to weather related disturbances (e.g. increase fire risk). Deciduous broadleaf tree encroachment into boreal forest	Extensive boreal tree spread into tundra. Boreal forest dieback within boreal zone and contraction of boreal forest at southern ecotone with continental grasslands		**Expansion into Tundra and upslope tree line advance** (Section 2.4.3.8 and Fig Box 2.1.1). **Increased mortality due to drought, fire, beetle infestations** (Sections 2.4.3.8, 2.4.42.1, 2.4.4.3.1)
Tropical forest	Increasing CO_2 concentration would increase net primary productivity	Increases in forest productivity and biomass through increased CO_2 with localised decreases in the Amazon. Shift in forest species composition. Expansion of forest area into mesic savanna.	Shift in the climate envelope of moist tropical forests but forests are less likely to undergo major retractions or expansions than suggested in AR4	**Expansion of tropical forest into savannas in Africa, Asia, South America** (Section 2.4.3.7, Fig Box 2.1.1) **Forest biomass increases (though slowing). (**Section 2.4.4.4) Forest degradation from drought, warming x fire and shorter residence time of trees. (Section 2.4.3.7) **Shift in species composition** towards species with more arid adapted trait (Section 2.4.3.7)
Temperate forest	Forest decline and increased mortality	Increase in tree mortality from drought related declines. A general increase of deciduous at the expense of evergreen vegetation is predicted at all latitudes		Map indicates a shift towards deciduous species in W N America (Fig Box 2.1.1) **Tree death due to interactions with drought x pest outbreaks x fire** (2.4.3.8, 2.4.42.1., 2.4.4.3.1)

Grasslands and savannas	Increasing CO_2 concentration will increase net primary productivity	Increased tree dominance in savannas and grasslands (from elevated CO_2). With C3 plants benefiting more than C4 plants	Rising CO_2 will increase the likelihood woodier states (but the transition will vary in different environments)	**Greening and encroachment across tropical and temperate savannas in Africa, Asia, Australia and N America** (Section 2.4.3.5) **Expansion of trees into grasslands and advancement of tree lines** Signs of increased C4 grass productivity in drought conditions. Increased C3 grass productivity (Section 2.4.3.5).
Desert/ arid shrublands		An increase in desert vegetation productivity was projected in southern Africa, the Sahel, central Australia, the Arabian Peninsula and parts of central Asia due to a positive impact of rising atmospheric CO_2.		**Greening** (increased LAI, woody cover) and increased herbaceous production is occurring at desert grassland interfaces (Chapter – Cross-Chapter Paper 3).

Assessment: There is a high agreement between observations and projections of tree death in temperate and boreal forests, with current projections (AR6) indicating this trend will continue (Section 2.5.4). Forest death is most widely recorded in central Europe and Westerns North America (Fig Box 2.1.1). There is also very high agreement between observations and projections of woody encroachment in savannas, grasslands and tundra, with projections also indicating that this trend is likely to continue (Section 2.5.4). Observations of desert greening show good agreement with earlier projections. Patterns of desertification are also occurring although the geographical match between projections and observations shows moderate agreement, likely due to the strong role of land use in this process. Projections of tropical forest expansion into mesic savannas and boreal forest expansion into tundra also shows agreement with observations.

Projections on the future of Mediterranean shrublands, deserts, xeric shrublands and temperate grassy systems are limited making assessment of this relationship less clear. It is also unclear, due to limited observations, how widespread a shift from deciduous forest species to evergreen forest species is. Some observations suggest this is occurring although it is not clear how widespread this change is and if the geographical pattern is as projected.

[END BOX 2.1 HERE]

2.5.3 Risk Assessment of Ecosystems and Related Services

2.5.3.1 Risks in Protected Areas

National parks and other protected areas, which, in June 2021, covered 15.7% of global terrestrial area (UNEP-WCMC, 2021), conserve higher biodiversity than adjacent unprotected areas (Gray et al., 2016), and protect one-fifth of global vegetation carbon stocks and one-tenth of global soil carbon stocks (Section 2.4.4.4). This section assesses climate change specifically in protected areas. Even though it is in a part of the chapter on projected risks, this section includes both observed exposure and projected risks to gather the chapter information on protected areas in one place.

2.5.3.1.1 Observed exposure of protected areas

Deforestation, agricultural expansion, overgrazing, and urbanisation exposed to intense human pressure one-third of global protected area (6 million km^2) in 2009, a 6% increase from 1993 (Venter et al., 2016; Jones et al., 2018). The observed change in exposure to climate change has not yet been quantified for protected areas globally but research has analysed spatial patterns and magnitudes of observed changes for the 360 000 km^2

system of U.S. national parks (Gonzalez et al., 2018), including the first national park in the world. From 1895 to 2010, mean annual temperature of the U.S. national park area increased at a rate of 1 ± 0.2ºC century^{-1}, double the rate of the U.S. as a whole, and precipitation decreased on 12% of the national park area, compared with 4% for the U.S. as a whole, due to a high fraction of U.S. national park area in the Arctic, at high elevations, and the arid Southwestern USA. (Gonzalez et al., 2018). In addition, analyses of weather station measurements in and near six South African National Parks found that maximum temperature increased at a rate of 0.024 ± 0.003ºC y^{-1} from 1960 to 2010 (Van Wilgen et al., 2016). While a substantial fraction of global protected area has been exposed to observed human land cover change, the global exposure to observed climate change is unquantified.

2.5.3.1.2 Projected risks in protected areas

Under a climate change scenario of ~3.5ºC temperature increase by 2070, current climate could disappear from individual protected areas that comprise half of global protected area and novel climates (climate conditions that are currently not present within an individual protected area) could expose half of global protected area (Hoffmann et al., 2019b). A lower emissions scenario of ~1.5ºC could reduce the climate disappearance to 40% and the exposure to novel climates to 41% (Hoffmann et al., 2019b). Models project the highest projected exposure in subtropical projected areas (Hoffmann and Beierkuhnlein, 2020). Projected disappearance of current climate conditions from protected areas is most extensive in Africa, Oceania, and North and South America (Elsen et al., 2020).

Projections indicate higher exposure to novel climates of tropical rainforests, shrublands, and grasslands, temperate conifer forests and grasslands, and tundra (Hoffmann et al., 2019b; Elsen et al., 2020). A climate change scenario of ~3.5ºC temperature increase by 2100 could expose 32% of protected area in humid tropical forests, 1.6 million km^2 in 2000, to climate that would be novel to humid tropical forest protected areas, while climate currently present in humid tropical forest protected areas could disappear from 0.6 million km^2, 12% of current total area by 2050 (Tabor et al., 2018). High deforestation and climate change combined could expose 2% of the humid tropical forest protected area (Tabor et al., 2018). Regional analyses under RCP8.5 also project substantial disappearance of current climate from protected areas in Bolivia, Chile, and Peru (Fuentes-Castillo et al., 2020), Canada, Mexico, and the U.S. (Batllori et al., 2017; Holsinger et al., 2019), China (Zomer et al., 2015), Europe (Nila et al., 2019), and Indonesia (Scriven et al., 2015). Projected climate change could expose an extensive part of global protected area to disappearing and novel climate conditions (*high confidence*) (Cross-Chapter Paper 1).

Continued climate change increases risks to individual species and vegetation types in protected areas. Under a climate change scenario of 4ºC temperature increase by 2100, suitable climate for two species of baobab trees (*Adansonia perrieri, A. suarezensis*) in Madagascar could shift entirely out of the protected areas network (Vieilledent et al., 2013). Other species and vegetation types at risk of partial disappearance of suitable climate from protected areas include Atlantic Forest amphibians in Brazil (Lemes et al., 2014), birds in Finland (Virkkala et al., 2013), birds and trees in Canada and Mexico (Stralberg et al., 2020), bog woodlands in Germany (Steinacker et al., 2019), butterflies and mammals in Egypt (Leach et al., 2013), and tropical dry forests in Mexico (Prieto-Torres et al., 2016). Projected disappearance of suitable climate conditions from protected areas increase risks to the survival of species and vegetation types of conservation concern in tropical, temperate, and boreal ecosystems (*high confidence*) (Cross-Chapter Paper 1).

Protected rivers, lakes, and other freshwater protected areas require inter-catchment connectivity to maintain species and population movements (Bush et al., 2014a; Hermoso et al., 2016; Thieme et al., 2016), but dams and other barriers interrupt connectivity (Grill et al., 2019). Climate change could also reduce freshwater connectivity (Section 2.3.3.3). Globally, over two-thirds of river reaches (by length) lack protected areas in their upstream catchments and nine-tenths of river reaches (by length) do not achieve full integrated protection (Abell et al., 2017).

Terrestrial and freshwater protected areas can also serve as climate change refugia, locations where suitable conditions may persist for the species into the future (e.g. Section 2.6.5.6). In Canada, Mexico, and the U.S., only a fraction of protected area is located in potential climate change refugia under a 4ºC temperature increase, estimated at 4% (Michalak et al., 2018) to 7% (Batllori et al., 2017). Potential refugia from biome shifts due to climate change under temperature increases of 1.8-3.4ºC cover <1% of the U.S. national park area (Gonzalez et al., 2010b), a fraction that reduces to near zero when climate change is combined with habitat fragmentation due to land use change (Eigenbrod et al., 2015). Protected areas in boreal ecosystems could serve as refugia for species shifting north in Canada (Berteaux et al., 2018) and Finland (Lehikoinen et al., 2019). Invasive species, habitat loss, and other disturbances in protected areas could be lower than in unprotected areas across Europe (Gallardo et al., 2017) and specifically in Spain (Regos et al., 2016) and in Sri Lanka (Kariyawasam et al., 2020). Protected areas conserve refugia from climate change under a temperature increase of 4ºC, important for biodiversity conservation but limited to <10% of current protected area (*medium confidence*).

2.5.3.2 Risks to Ecosystems and Services from Wildfire

2.5.3.2.1 Future projections of wildfire globally

Continued climate change under high emissions scenarios that increase global temperature ~4ºC by 2100 could increase global burned area 50% (Knorr et al., 2016b) to 70% (Kloster and Lasslop, 2017) and global mean fire frequency ~30% (Gonzalez et al., 2010b), with increases on one-third (Gonzalez et al., 2010b) to two-thirds (Moritz et al., 2012) of global land and decreases on one-fifth (Gonzalez et al., 2010b; Moritz et al., 2012). Lower emissions that would limit the global temperature increase to <2ºC would reduce projected increases of global burned area to 30% (Lange et al., 2020) to 35% (Kloster and Lasslop, 2017) and projected increases of fire frequency to ~20% (Gonzalez et al., 2010b; Huang et al., 2015). Continued climate change could further lengthen fire weather seasons (IPCC AR6 WGI Chapter 12). Models that combine projected climate change with potential agricultural expansion project decreases in total burned area (Huang et al., 2015; Knorr et al., 2016b; Park et al., 2021). The area of projected increases in burned area and fire frequency due solely to continued climate change is higher for the world as a whole than the area of projected decreases (*medium evidence, medium agreement*).

Increased wildfire due to continued climate change increases risks of tree mortality (Sections 2.5.2.6, 2.5.2.7, 2.5.3.2), biome shifts (Section 2.5.2.2), and carbon emissions (Sections 2.5.2.10, 2.5.3.4). Wildfire and biome shifts under projected climate change of 4º C above the pre-industrial period, combined with international trade and transport, cause high risks of invasive species across one-sixth of global area, including extensive high-biodiversity regions (Early et al., 2016).

Wildfire risks to people include death and destruction of homes, respiratory illnesses from smoke (Ford et al., 2018; Machado-Silva et al., 2020), post-fire flooding from areas exposed by vegetation loss, and degraded water quality through increases in sediment flows (Dahm et al., 2015) and chemical precursors of carcinogenic trihalomethanes when water is later chlorinated for drinking (Section 2.5.3.7; Uzun et al., 2020) . Under RCP8.5 and shared socio-economic pathway SSP3 (high population growth, slow urbanisation), the number of people living in fire-prone areas could increase by three-quarters, to 720 million people in 2100, in a projected global population of 12.4 billion people (Knorr et al., 2016b). Lower emissions under RCP4.5 could reduce the number of people at risk by 70 million people. In these projections, human population growth increases human exposure to wildfires more than increase in burned area (Knorr et al., 2016c). A global temperature increase <2ºC could increase global population exposure to wildfire by ~30% (Lange et al., 2020). Increased wildfire under continued climate change increases probabilities of human exposure to fire and risks to public health (*medium evidence, high agreement*).

2.5.3.2.2 Future projections of wildfire in high-risk areas

Regions identified at high risk of increased burned area, fire frequency, or fire weather by multiple global analyses include: Amazon (Gonzalez et al., 2010b; Huang et al., 2015; Knorr et al., 2016c; Burton et al., 2018; Abatzoglou et al., 2019), Mediterranean Europe (Gonzalez et al., 2010b; Burton et al., 2018; Abatzoglou et al., 2019), Arctic tundra (Moritz et al., 2012; Flannigan et al., 2013), western Australia (Gonzalez et al., 2010b; Burton et al., 2018; Abatzoglou et al., 2019), western United States (Gonzalez et al., 2010b; Moritz et al., 2012; Knorr et al., 2016c). Higher-resolution spatial projections indicate high risks of increased wildfire in the Amazon, Australia, boreal ecosystems, Mediterranean Europe, and the United States under climate change (*medium evidence, medium agreement*).

In the Amazon, climate change under RCP8.5, combined with high deforestation, could double the area of high fire probability (Fonseca et al., 2019), double burned area by 2050 (Brando et al., 2020) increase burned area 400–2800% by 2100 (Le Page et al., 2017), and increase fire intensity 90% (De Faria et al., 2017). Lower greenhouse gas emissions (RCP4.5) and reduced deforestation could reduce fire risk to a one-fifth increase in the area of high fire probability (Fonseca et al., 2019) and a 100–500% increase in burned area by 2100 (Le Page et al., 2017). Moreover, increased fire, deforestation, and drought, acting through vegetation-atmosphere feedbacks, increase risks of extensive forest dieback and potential biome shifts of up to half of Amazon rainforest to grassland, a tipping point that could release an amount of carbon that would substantially increase global emissions (Oyama and Nobre, 2003; Sampaio et al., 2007; Lenton et al., 2008; Nepstad et al., 2008; Malhi et al., 2009; Settele et al., 2014; Lyra et al., 2016; Zemp et al., 2017a; Zemp et al., 2017b; Brando et al., 2020). Continued climate change, combined with deforestation, increases risks of wildfire and extensive forest dieback in the Amazon rainforest (*robust evidence, high agreement*).

In Australia, climate change under RCP8.5 increases risks of pyroconvective fire by 20 to 40 days in rangelands of Western Australia, South Australia, and the Northern Territory (Dowdy et al., 2019). Pyroconvective fire conditions could reach more frequently into the more populated areas of New South Wales, particularly at the start of austral summer (Di Virgilio et al., 2019). General circulation models do not agree, however, on projected areas of fire increase in New South Wales (Clarke and Evans, 2019). Increases in heat and potential increases in wildfire threaten the existence of temperature montane rainforest in Tasmania, Australia (Mariani et al., 2019).

In Mediterranean Europe, climate change of 3ºC could double or triple burned area, while keeping the temperature increase to 1.5ºC could limit burned area increase to 40–50% (Turco et al., 2018). Under RCP8.5, the frequency of heat-induced fire weather could increase 30% (Ruffault et al., 2020). Severe fire followed by drought could cause biome shifts of forest to non-forest (Batllori et al., 2019) and tree mortality >50% (Dupire et al., 2019).

In Arctic tundra, boreal forests, northern peatlands, including permafrost areas, climate change under scenarios of 4ºC temperature increase could triple burned area in Canada (Boulanger et al., 2014), double the number of fires in Finland (Lehtonen et al., 2016), increase lightning-driven burned area 30 to 250% (Veraverbeke et al., 2017; Chen et al., 2021a), push half of the area of tundra and boreal forest in Alaska above the burning threshold temperature, and double burned area in Alaska (Young et al., 2017a). Thawing of Arctic permafrost from a projected temperature of 4ºC and resulting wildfire could release 11-200 Gt carbon that could substantially exacerbate climate change (Section 2.5.2.9).

In the United States, climate change under RCP8.5 could increase burned area 60−80% by 2049 (Buotte et al., 2019) and the number of fires with an area >50 km^2 by 300–400% by 2070 (Barbero et al., 2015). In montane forests in the U.S., climate change under RCP8.5 increases the risk of fire-facilitated conversion of ~7% of forest to non-forest by 2050 (Parks et al., 2019). In California, climate change under a scenario of 4ºC temperature increase could double fire frequency in some areas (Mann et al., 2016), but emissions reductions that limit the temperature increase to ~2ºC could keep fire frequency from increasing (Westerling et al., 2011). Carbon dioxide fertilisation and increased temperature under climate change could increase invasive grasses and wildfire in desert ecosystems of the Southwestern United States, where wildfire has historically been absent or infrequent, and increase mortality of the sparse tree cover (Horn and St. Clair, 2017; Klinger and Brooks, 2017; Syphard et al., 2017; Moloney et al., 2019; Sweet et al., 2019).

In summary, under a high emissions scenario that increases global temperature 4ºC by 2100, climate change could increase global burned area 50–70% and global mean fire frequency ~30% with increases on one-third to two-thirds of global land and decreases on one-fifth of global land (*medium confidence*). Lower emissions that would limit the global temperature increase to <2ºC would reduce projected increases of burned area to ~35% and projected increases of fire frequency to ~20% (*medium confidence*). Increased wildfire, combined with erosion due to deforestation, could degrade water supplies (*high confidence*). For ecosystems with historically low fire frequencies, a projected 4ºC global temperature increases risks of fire, contributing to potential tree mortality and conversion of over half of Amazon rainforest to grassland and thawing of Arctic permafrost that could release 11–200 Gt carbon that could substantially exacerbate climate change (*medium confidence*).

2.5.3.3 Risks to Ecosystems and Services from Tree Mortality

Under continued climate change, increased temperature, aridity, drought, wildfire (Section 2.5.3.2), and insect infestations (Section 2.4.4.3.3) will tend to increase tree mortality across wide parts of the world (McDowell et al., 2020). Boreal and temperate forest loss to fire, wind, and bark beetles could cause more negative than positive effects for most ecosystem services, including carbon storage to regulate climate change (Sections 2.4.4.3, 2.5.2.6, 2.5.2.7, 2.5.3.4), water supply for people (Section 2.5.3.6.1), timber production (Chapter 5), and hazard protection (Thom and Seidl, 2016). In addition, deforestation in tropical and temperate forests can increase local temperatures 0.3° to 2ºC (Hesslerová et al., 2018; Lejeune et al., 2018; Zeppetello et al., 2020) and this effect can extend up to 50 km (Cohn et al., 2019).

In Amazon rainforests, the relatively lower buffering capacity for plant moisture during drought increases the risk of tree mortality and, combined with increased heat from climate change and fire from deforestation, the possibility of a tipping point of extensive forest dieback and a biome shift to grassland (Oyama and Nobre, 2003; Sampaio et al., 2007; Lenton et al., 2008; Nepstad et al., 2008; Malhi et al., 2009; Salazar and Nobre, 2010; Settele et al., 2014; Lyra et al., 2016; Zemp et al., 2017b; Brando et al., 2020). This could occur at a 4-5ºC temperature increase above the pre-industrial period (Salazar and Nobre, 2010). Under RCP8.5, half of Amazon tropical evergreen forest could shift to grassland through drought-induced tree mortality and wildfire, but lower emissions (RCP4.5) could limit the loss to ~5% (Lyra et al., 2016). Precipitation declines from reduced evapotranspiration inputs after forest loss could cause additional Amazon forest loss of one-quarter to one-third (Zemp et al., 2017a). Similarly, in Guinean tropical deciduous forest in Africa, climate change under RCP8.5 could increase mortality 700% by 2100 or 400% under lower emissions (RCP4.5; Claeys et al., 2019). These projections indicate risks of climate change-induced tree mortality reducing tropical forest areas in Africa and South America up to half under a 4ºC increase above the pre-industrial period, but a lower projection of a 2ºC increase could limit the projected increases in tree mortality (*robust evidence, high agreement*).

Temperate and boreal forests possess greater diversity of physiological traits related to plant hydraulics, so they are more buffered against drought than tropical forests (Anderegg et al., 2018). Nevertheless, in temperate forests, drought-induced tree mortality under RCP8.5 could cause the loss of half of northern hemisphere conifer forest area by 2100 (McDowell et al., 2016). In the western United States, one-tenth of forest area is highly vulnerable to drought-induced mortality under RCP8.5 by 2050 (Buotte et al., 2019). In California, increased evapotranspiration in Sierra Nevada conifer forests increases the potential fraction of the area at risk of tree mortality 15–20% per degree Celsius (Goulden and Bales, 2019). In Alaska, fire-induced tree mortality from climate change under RCP8.5 could reduce the extent of spruce forest (*Picea sp.*) 8–44% by 2100 (Pastick et al., 2017). Under RCP8.5, tree mortality from drought, wildfire, and bark beetles could reduce timber productivity of boreal forests in Canada by 2100 below current levels (Boucher et al., 2018; Chaste et al., 2019; Brecka et al., 2020). In Tasmania, projected increases in wildfire (Fox-Hughes et al., 2014) increase risks of mortality in mesic vegetation (Harris et al., 2018b) and threaten ~~the~~ disappearance of the long-lived endemic pencil pine (*Athrotaxis cupressoides*) (Holz et al., 2015; Worth et al., 2016) and temperate montane rainforest (Mariani et al., 2019). These projections indicate risks of climate change-induced tree mortality reducing some temperate forest areas by half under emissions scenarios of 2.5-4ºC above the pre-industrial period (*medium evidence, high agreement*).

2.5.3.4 Risk to Terrestrial Ecosystem Carbon Stocks

Globally, increasing atmospheric CO_2 enhances the terrestrial sink but temperature increases constrain it, reflecting biological process understanding, highlighted in previous IPCC reports (*high confidence*). Analyses of atmospheric inversion model output and spatial climate data indicate a sensitivity of net ecosystem productivity to CO_2 fertilisation of 3.1 ± 0.1 to 8.1 ± 0.3 Gt per 100 ppm CO_2 (~1°C increase) and a sensitivity to temperature of -0.5 ± 0.2, to -1.1 ± 0.1 Gt per degree Celsius (Fernandez-Martinez et al., 2019). The future of the global land carbon sink (Section 2.4.4.4) nevertheless remains highly uncertain because (i) of regionally complex interactions of climate change and changes in atmospheric CO_2 with vegetation, soil and aquatic processes, (ii) episodic events such as heat-waves or droughts (and related impacts through mortality, wildfire or insects, pests and diseases, (Section 2.5.5.2, 2.5.5.3) so far are only incompletely captured in carbon cycle models, and (iii) legacy effects from historic land-use change and environmental changes are incompletely captured but likely to decline in future, and (iv) lateral carbon transport processes such as export of inland waters or erosion are incompletely understood and modelled (AR6 WGI Chapter 5; Pugh et al., 2019a; Friedlingstein et al., 2020; Krause et al., 2020). Enhanced carbon losses from terrestrial systems further limit the available carbon budget for global warming staying below 1.5ºC (Rogelj et al., 2018). Analyses of satellite remote sensing and ground-based observations has indicated that between 1982 and 2015 the CO_2 fertilisation effect has already declined, implying a negative climate system feedback (Wang et al., 2020c). Peatlands, permafrost regions and tropical ecosystems are particularly vulnerable due to their large carbon stocks in combination with over-proportional warming, increases in heatwaves and droughts and/or a complex interplay of climate change and increasing atmospheric CO_2 (Section 2.5.2.8, 2.5.2.9, 2.5.3.2).

Model projections suggest under all warming scenarios a reduction of permafrost extent and potentially large carbon losses (AR6 WGI Chapter 5). Already a mean temperature increase of 2ºC could reduce the total permafrost area extent by ca 5-20% by 2100 (Comyn-Platt et al., 2018; Yokohata et al., 2020). Associated CO_2 losses of order of 15 up to nearly 70 GtC by 2100 have been projected across a number of modelling studies (Schneider von Deimling et al., 2015; Comyn-Platt et al., 2018; Yokohata et al., 2020). Limiting the global temperature increase to 1.5ºC, compared to 2ºC could reduce projected permafrost CO_2 losses by 2100 by (median) 24.2 GtC (calculated for 3m depth (Comyn-Platt et al., 2018). Losses are possibly underestimated in those studies that consider only upper permafrost layers. Likewise, the actual committed carbon loss may well be larger (e.g., eventually a loss of ca. 40% of today's permafrost area extent if climate is stabilised at 2ºC above pre-industrial levels) due to the long time-scale of warming in deep permafrost layers (Chadburn et al., 2017). It is unknown at which level of global warming abrupt permafrost collapse estimated to enhance CO_2 emission by 40% in 2300 in a high emissions scenario, compared to gradual thaw emissions (Turetsky et al., 2020) would have to be considered an important additional risk. Large uncertainties arise also from interactions with changes in surface hydrology and/or northward migrating woody vegetation as climate warms, which could dampen or even reverse projected net carbon losses in some regions (McGuire et al., 2018a; Mekonnen et al., 2018; Pugh et al., 2018) so overall there is *low confidence* on how carbon-permafrost interactions will affect future carbon cycle and climate, although net carbon losses and thus positive (amplifying feedbacks) are *likely* (Sections 2.5.2.10, 2.5.3.5; Shukla et al., 2019). See also AR6 WGI (Chapter 5) for discussion of impacts of higher emission and warming scenarios.

Peatland carbon is estimated as ca. 550–1000 GtC in northern latitudes (many of these peatlands would be found in permafrost regions) (Turetsky et al., 2015; Nichols and Peteet, 2019) and > 100 GtC in tropical regions (Turetsky et al., 2015; Dargie et al., 2017). Both for northern mid- and high-latitude and for tropical peatlands a shift from contemporary CO_2 sinks to sources were simulated in high warming scenarios (Wang et al., 2018a; Qiu et al., 2020). Due to the lack of large-scale modelling studies, the confidence on climate change impacts on peat carbon uptake and emissions is low. The largest risk to tropical peatlands is expected to arise from drainage and conversion to forestry or agriculture, outpacing impacts of climate change (Page and Baird, 2016; Leifeld et al., 2019; Cooper et al., 2020) although the magnitude of possible carbon losses are uncertain and depend strongly on socio-economic scenarios. (Sections 2.4.3.8, 2.4.4.2; 2.4.4.4.2, 2.5.2.8)

For tropical and sub-tropical regions the interplay of atmospheric CO_2 with precipitation and temperature becomes of particular importance for future carbon uptake, since in warm and dry environments, elevated CO_2 fosters plants with C3 photosynthesis and enhances their water use efficiency relative to C4 species (Moncrieff et al., 2014a; Midgley and Bond, 2015; Knorr et al., 2016a). As a consequence, enhanced woody cover is expected to occur in future especially in mesic savannas, while in xeric savannas an increase in woody cover would occur in regions with enhanced precipitation (Criado et al., 2020). Even though semi-arid regions have dominated the recent decades' global trend in land CO_2 uptake (Ahlström et al., 2015), so far most studies that investigated future climate change impacts on savanna ecosystems have concentrated on changes in areal extent (2.5.2.5), rather than on carbon cycling, with *medium confidence* on increasing woody:grass ratios (Moncrieff et al., 2014a; Midgley and Bond, 2015; Moncrieff et al., 2016; Criado et al., 2020). Increases in woody vegetation in what is now grass-dominated would possibly come with a carbon benefit, for instance a broad range of future climate and CO_2 changes were found to enhance vegetation C storage in Australian savannas (Scheiter et al., 2015). Results from a number of field experiments indicate however, that impacts on total ecosystem carbon storage may be smaller, due to a loss in belowground carbon (Coetsee et al., 2013; Wigley et al., 2020). Nunez et al., 2021) critique existing incentives to promote invasion of non-native trees into treeless areas as a means of carbon sequestration, raising doubts about the effects on fire, albedo, biodiversity and water yield (see Box 2.2).

Substantial climate-change driven impacts on tropical tree cover and vegetation type are projected in all studies, irrespective of whether or not the degree amounts to a forest "dieback" (Sections 2.4.3.6, 2.4.4.3; 2.5.2.6, 2.5.3.3; AR6 WGI Chapter 5) (Davies-Barnard et al., 2015; Wu et al., 2016a; Zemp et al., 2017a). Accordingly, models also suggest a continuation of tropical forests acting as carbon sinks (Huntingford et al., 2013; Mercado et al., 2018). A recent study, combining field plot data with statistical models, (Hubau et al., 2020) indicates that in the Amazonian and possibly also in the African forest the carbon sink in aboveground biomass has already declined over the three decades to 2015. This trend is distinct in the Amazon, whereas data from Africa suggest a possible decline after 2010. the authors estimate the vegetation carbon sink in 2030-2040 to decline to zero (-0.5–0-46) Pg C a^{-1} in the Amazon and 0.26 (0.04–0.47, a loss of 14% compared to present) Pg C a^{-1} in Africa. Their results suggest that CO_2 fertilisation is over time outweighed by impacts of higher temperatures and drought, enhancing tree mortality and diminishing growth. The degree of thermal resilience of tropical forest still remains uncertain, however (Sullivan et al., 2020).

The lack of simulation studies that seek to quantify all important interacting factors (CO_2, drought and fire) for future carbon-cycling in savannas and tropical forests, and the apparent disagreement between trends projected in models compared to data-driven estimates results in *low confidence* regarding the direction or magnitude of carbon flux and pool size changes. Similar to tropical peatlands, given projected human population growth and socio-economic changes. the continued conversion of forests and savannas into agricultural or pasture systems *very likely* poses a significant risk of rapid carbon loss which will amplify climate change induced risks substantially (*high confidence*) (Sections 2.5.2.10, 2.5.3.5; Aragao et al., 2014; Searchinger et al., 2015; Aleman et al., 2016; Nobre et al., 2016).

The impacts of climate-induced altered animal composition and trophic cascades on global land ecosystem carbon cycling are as yet unquantified (Schmitz et al., 2018) even though climate change is expected to lead to shifts in consumer-resource interactions that also contribute to losses of top-predators or top herbivores (Sections 2.4.2.2, 2.5.1.3, 2.5.4; Lurgi et al., 2012; Damien and Tougeron, 2019). Cascading trophic effects triggered by top predators or the largest herbivores propagate through food webs and reverberate through to the functioning of whole ecosystems, altering notably productivity, carbon and nutrient turnover and net carbon storage (*medium confidence)* (Wilmers and Schmitz, 2016; Sobral et al., 2017; Stoner et al., 2018). Across different field experiments, the ecosystem consequences of the presence or absence of herbivores and carnivores have been found to be quantitatively as large as the effects of other environmental change drivers such as warming, enhanced CO_2, fire or variable nitrogen deposition (*medium confidence*) (Hooper et al., 2012; Smith et al., 2015). Some local and regional-scale modelling experiments have begun to explore animal impacts on vegetation dynamics and carbon and nutrient cycling (Pachzelt et al., 2015; Dangal et al., 2017; Berzaghi et al., 2019). Given that turnover rate is a chief factor that determines future land ecosystem carbon dynamics and hence carbon-climate feedbacks (Friend et al., 2014). To improve projections, it is imperative to better quantify the broader role of carnivores, grazers, browsers, and the way these interact in global studies of how ecosystems respond to climate change.

2.5.3.5 Feedbacks between Ecosystems and Climate

The possibility of feedbacks and interactions between climate drivers and biological systems or ecological processes was identified as a significant emerging issue in AR5, and has since also been highlighted in the CRCCL and the Special Report on 1.5ºC. It is virtually certain that land cover changes affect regional and global climate through changes to albedo, evapotranspiration and roughness (*very high confidence*) (Perugini et al., 2017). There is growing evidence that biosphere-related climate processes are being affected by climate change in combination with disturbance and land use change (*high confidence*) (Jia et al., 2019). It is virtually certain that land surface change caused by disturbances such as forest fire, hurricanes, phenological changes, insect outbreaks and deforestation affect carbon, water, and energy exchanges, thereby influencing weather and climate (*very high confidence*) (Table 2.4; Figure 2.10; Bright et al., 2013; Brovkin et al., 2013; Naudts et al., 2016; Prăvălie, 2018).

Table 2.4: Terrestrial and freshwater ecosystem feedbacks which affect the Earth's climate system dynamics, following (Prăvălie, 2018).

Perturbation	Implications for Warming/Feedback Mechanism the Earth's Climate System Dynamics
Phenological change	Increased primary productivity and plant growth with CO_2 fertilisation (Mao et al., 2016; Wang et al., 2018a); Increasing growing season length (Peñuelas et al., 2009; Barichivich et al., 2013); reduced diurnal temperature range through evapotranspiration (mid-latitudes) and albedo (high latitudes) caused by vegetation greening (Jeong et al., 2011); increased CO_2 storage in biomass (cooling) (Keenan et al., 2014); Reduced albedo in snow-covered regions as canopies become taller and darker (warming); increased evapotranspiration, a key component of the global water cycle and energy balance which influences global rainfall, temperature, and atmospheric motion (Zeng et al., 2017).
Insect outbreaks	Reduced carbon uptake and storage (warming); Increased surface albedo (cooling) (Landry et al., 2016); increased CO_2 emissions (warming); decreased leaf area index and gross primary productivity (Ghimire et al., 2015), leading to reduced evapotranspiration and increased land surface temperature (Bright et al., 2013).
Range shifts	Reduced albedo in snow-covered regions as trees expand poleward (warming) (Chae et al., 2015); enhanced permafrost thawing; expansion of insect outbreak range, increasing forest impact (Pureswaran et al., 2018); biome dependent changes in albedo and evapotranspiration regimes (Naudts et al., 2016). Reduction in snow and ice albedo in freshwater due to loss of ice (warming) (Lang et al., 2018).
Die-off and large-scale mortality events	Decreased Gross primary productivity (GPP); decline in carbon storage (warming); increased CO_2 emissions; increased solar radiation, reduced soil moisture, higher surface runoff; albedo effects (Lewis et al., 2011; Prăvălie, 2018)
Deforestation	Reduced carbon storage (warming) (Pugh et al., 2019a); increase in (regional) surface air temperature due to reduced evaporation (less cooling); increased albedo in high-latitude systems (regional radiative cooling) (Loranty et al., 2014); increased air temperature and diurnal temperature variation (Alkama and Cescatti, 2016), locally and globally (Winckler et al., 2019); reduced precipitation (Perugini et al., 2017); decreased biogenic volatile organic compounds (BVOC) and aerosol emissions (warming through direct and indirect aerosol effects; cooling associated with reduction in atmospheric methane (Jia et al., 2019)
Forest degradation	Reduced carbon storage (warming) (de Paula et al., 2015; Bustamante et al., 2016; de Andrade et al., 2017; Mitchard, 2018)
Fragmentation	Carbon losses because biomass is less developed in forest edges (Pütz et al., 2014; Chaplin-Kramer et al., 2015; Haddad et al., 2015)
Air pollution	Decreased plant productivity, transpiration and carbon sequestration in forest with lower biomass due to ozone toxicity (Sitch et al., 2007; Ainsworth et al., 2012); increased (regional) productivity due to increase in diffuse solar radiation caused by terrestrial aerosols (Xie et al., 2021)
Declining populations of megafauna	Changes to physical and chemical properties of organic matter, soils and sediments influence carbon uptake and storage (Schmitz et al., 2018); increased or decreased carbon storage biomass and carbon storage, with differences across biomes determined by floristic structure and animal size (Bello et al., 2015; Osuri et al., 2016; Peres et al., 2016; He et al., 2017; Berzaghi et al., 2018; Schmitz et al., 2018; He et al., 2019)
Fire	Increased carbon and aerosol emissions(van der Werf et al., 2017); surface warming (Liu et al., 2019b); albedo effect dependent on ecosystem and species-level traits (Rogers et al., 2015; Chen et al., 2018a) (initial albedo decrease post-fire; increased albedo where snow exposure is increased by canopy removal and species composition changes during recovery); black carbon deposition on snow and sea ice (short-term) (Randerson et al., 2006); indirect increases in carbon emissions due to soil erosion (Caon et al., 2014)
Change in forest composition	Reduced carbon storage due to decline in biomass (warming) (McIntyre et al., 2015)
Woody encroachment in non-forested ecosystems	Reduced production, increased water use, reduced albedo and altered land-atmosphere feedbacks; increased carbon storage in woody savannas (Zhou et al., 2017; Mureva et al., 2018); Uncertain feedbacks to C cycle (some suggest an increase, others a decrease)
Net Primary Productivity (NPP) shifts	Reduced albedo following high-latitude expansion of trees caused by photosynthetic enhancement of growth (cooling); increased photosynthesis and net ecosystem production (NEP) (Fernandez-Martinez et al., 2019); increased NPP in N-limited ecosystems due to increased nitrogen deposition from agriculture and combustion (Du and de Vries, 2018; Schulte-Uebbing and de Vries, 2018); Nutrient limited lakes are likely to become less productive, while nutrient rich lakes are likely to become more productive due to warming induced prolongation of stable stratification (Adrian et al., 2016; Kraemer et al., 2017).
Biogeochemical shifts	Decline in carbon storage due to nitrogen limitation in N limited systems (warming)(Reich et al., 2014; Wieder et al., 2015); increased carbon storage on land(Peñuelas et al., 2013) and in lakes (Heathcote et al., 2015; Mendonça et al., 2017); Increase in CO_2 and CH4 emissions from freshwater ecosystems due to increased eutrophication (DelSontro et al., 2018), the imbalance

between losses and gains of CO_2 by photosynthesis and respiration (metabolic theory of ecology), enhanced emissions from exposed river and lake sediments during droughts and re-wetting (Marcé et al., 2019; Keller et al., 2020), enhanced CH4 ebullition of seasonally hypoxic lakes (Aben et al., 2017; DelSontro et al., 2018; Bartosiewicz et al., 2019; Beaulieu et al., 2019; Sanches et al., 2019), increased transfer of organic carbon from land to water (particularly in permafrost areas) (Wauthy et al., 2018)

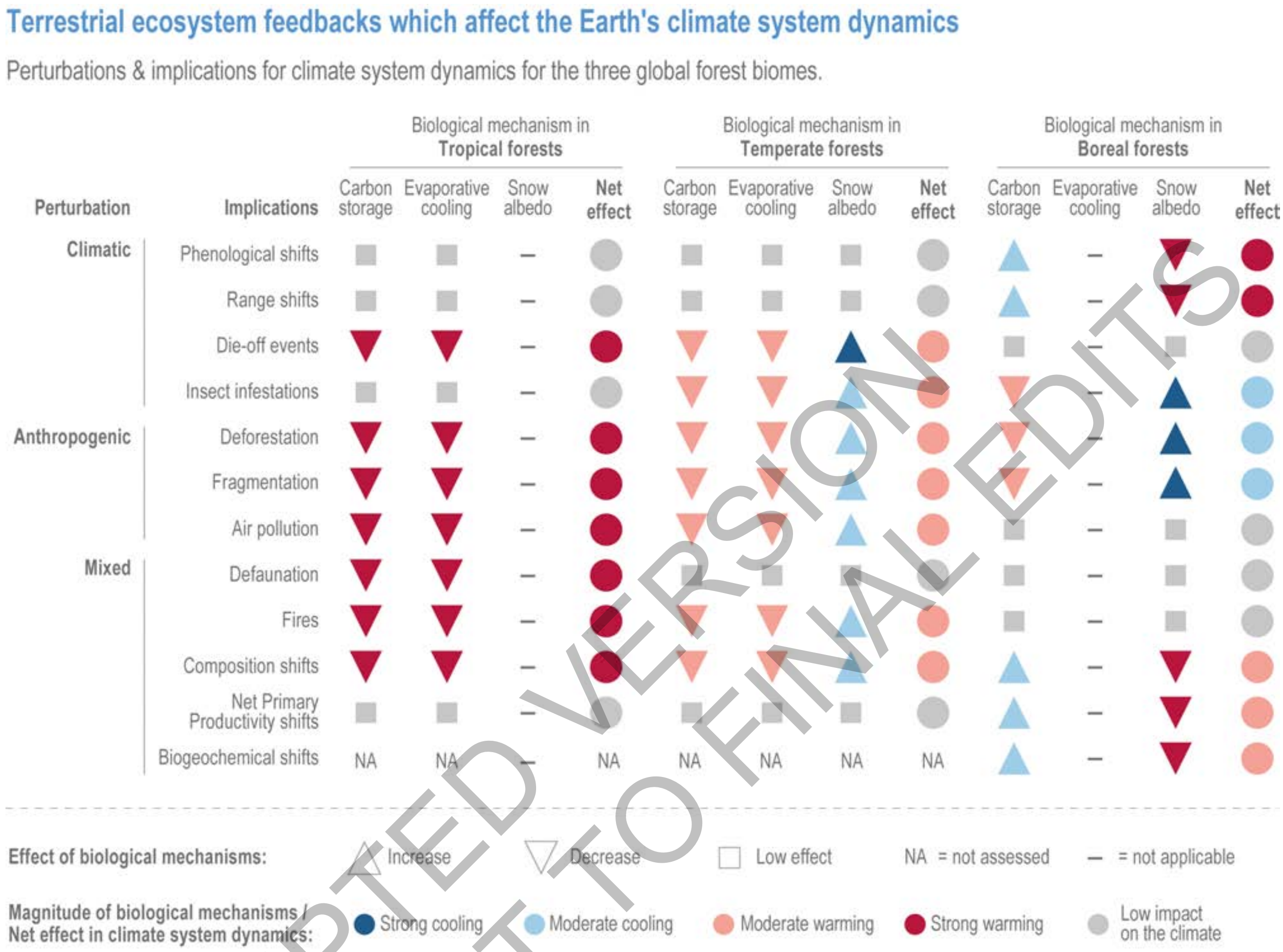


Figure 2.10: Terrestrial ecosystem feedbacks, which affect the Earth's climate system dynamics. Perturbations and implications for climate system dynamics (warming/cooling) are shown for the three global forest biomes (adapted from Figure 5, Prăvălie, 2018). The strength of the mechanism is estimated in general terms based on the magnitude of carbon storage and evaporative cooling processes that characterise each forest biome (Bonan, 2008). Carbon storage includes forest biomass, without accounting for carbon dynamics in soil, peat and underlying permafrost deposits. Implications of biogeochemical shifts were only estimated in relation to the intensification of the carbon cycle and increase in biomass at high latitudes, assuming N availability for the stoichiometric demands of forest vegetation).

Feedbacks can be positive or negative (i.e., amplify or dampen the original forcing), vary spatially and seasonally, and act over large geographic areas and long time periods (>decades), making them difficult to observe and quantify directly (AR6 WGI Chapter 5; Schimel et al., 2015). Due to the positive impacts of CO_2 on vegetation growth and ecosystem carbon storage (*high confidence*) (Sections 2.4.4.4; 2.5.5.4; AR6 WGI chapter 5), the associated climate feedback is negative (increased removal of atmospheric CO_2 and dampened warming, compared to absence of the feedback). By contrast, projected global losses of carbon in warmer climates (AR6 WGI Chapter 5) imply a positive climate feedback. Chapter 5 of WGI assesses an overall increase in land carbon uptake through the 21st century. However, the overall strength of the carbon cycle-climate feedback remains very uncertain. One of the underlying reasons may be complex interactions with ecosystem water balance and nitrogen and phosphorous availability, which are poorly constrained by observational evidence and incompletely captured in Earth System Models (AR6 WGI Chapter 5, Section 2.5.2.10; Huntzinger et al., 2017).

Land ecosystems contribute substantially to global emissions of nitrous-oxides and methane. As with CO_2, these emissions respond both directly and indirectly to atmospheric CO_2 concentration and climate change, which gives rise to potential additional biogeochemical feedbacks in the climate system. A large part of these emissions stem from land and water management, such as fertiliser application, rice production, aquaculture or animal husbandry (Jia et al., 2019). However, nearly 60% of total nitrous-oxide emissions (2007-2016) is estimated to stem from natural ecosystems, especially in the tropics (AR6 WGI Chapter 5; Tian et al., 2019), while freshwater wetlands and peatlands are estimated to contribute between 83% (top-down estimates) and 40% (bottom up estimates) of total natural CH_4 (and 31% or 20% of total methane emissions, respectively) for the period 2008-2017 (AR6 WGI Chapter 5). Median CH_4 emissions from northern latitude wetlands in 2100 were estimated to be 12.1 and 13.5 Pg C in emission scenarios leading to 1.5ºC and 2ºC warming, respectively (Comyn-Platt et al., 2018). Likewise, global warming was attributed to soil N_2O emission increases since the pre-industrial period of 0.8 (0.3–1.3) Tg N a^{-1} (Tian et al., 2020). Overall, climate feedbacks from future altered land ecosystem emissions of CH_4 or N_2O are uncertain, but expected to be small (AR6 WGI Chapter 5).

Changes in regional biodiversity are integral parts of ecosystem-climate feedback loops, including and beyond carbon-cycle processes (Figure 2.10; Table 2.4). For instance, the impacts of climate-induced altered animal composition and trophic cascades on ecosystem carbon turnover (see Sections 2.4.4.4; 2.5.3.4) could be a substantive contribution to carbon-climate feedbacks (*low confidence*). Additional surface-atmosphere feedbacks that arise from changes in vegetation cover and subsequently altered albedo, evapotranspiration or roughness (often summarised as biophysical feedbacks) can be regionally relevant and could amplify or dampen vegetation cover changes (Jia et al., 2019).

Climate-induced shifts towards forests in what is currently tundra would be expected to reduce regional albedo especially in spring but also during parts of winter when trees are snow-free (whereas tundra vegetation would be covered in snow), which amplifies warming regionally (*high confidence*) (Perugini et al., 2017; Jia et al., 2019). Trees would also enhance momentum absorption compared to low tundra vegetation thus impacting surface-atmosphere mixing of latent and sensible heat fluxes (Jia et al., 2019). Boreal forests insulate and stabilize permafrost and reduce fluctuations of ground temperature: the amplitude of variation of ground surface temperatures was 28°C in a forested site, compared to 60°C in nearby grassland (Section 2.5.2.7; Bonan, 1989; Stuenzi et al., 2021a; Stuenzi et al., 2021b). Likewise, a shift in moist tropical forests towards vegetation with drought-tolerant traits could possibly reduce evapotranspiration, increase albedo, alter heat transfer at the surface and lead to a negative feedback to precipitation (Section 2.5.2.6; Jia et al., 2019). In savannas, restoration of woody vegetation has been shown to enhance cloud formation and precipitation in response to enhanced transpiration and turbulent mixing, leading to a positive feedback on woody cover (Syktus and McAlpine, 2016). While this has not yet been systematically explored, similar feedbacks might also emerge from a CO_2-induced woody cover increase in savannas (*low confidence*) (Section 2.5.2.5).

Since biophysical feedbacks can contribute to both surface temperature warming or cooling, analyses so far suggest that, at global scale, the net impact on climate change is small (Perugini et al., 2017; Jia et al., 2019), unless these feedbacks also accelerate vegetation mortality and lead to substantive carbon losses (Zemp et al., 2017a; Lemordant and Gentine, 2019). More than one third of the Earth's land surface has at least 50% of its evapotranspiration regulated by vegetation, and in some regions between 40 and >80% of the land's evaporated water is returned to land as precipitation. Locally, both, direct human-mediated as well as climate change-mediated vegetation cover change can therefore notably affect annual average freshwater availability to human societies, especially if negative feedbacks amplify vegetation cover reduction, reduced evapotranspiration and reduced precipitation (*medium confidence*) (Keys et al., 2016; Keys and Wang-Erlandsson, 2018).

Since AR5, freshwater ecosystems (lakes, reservoirs, rivers, ponds) have been increasingly recognised as important sources of greenhouse gas emissions (CO_2, CH_4, N_2O) into the atmosphere. Key mechanisms which contribute to rising GHG emissions from freshwater ecosystems are the temperature imbalance between photosynthesis and respiration (respiration increases more than photosynthesis with rising temperature), CO_2 and CH_4 emissions from exposed sediments during droughts, increased matter transport from land to water, changes in water retention time in rivers and lakes, and temperature effects on lake stratification and anoxia, favouring CH_4 emissions.

DelSontro et al. (2018) assembled the largest global dataset to date on emission rates from lakes of CO_2, CH_4 and N_2O and found that they co-vary with lake size and trophic state. They estimated that moderate global increases in eutrophication of lakes could translate to 5–40% increases in the GHG effects in the atmosphere. Moreover, they estimated that greenhouse gas emissions from lakes and impoundments in past decades accounted for 1.25-2.30 Pg C-CO_2 yr^{-1} (DelSontro et al., 2018), thus around 20% of global burning fossil-fuel CO_2 emission (9.4 PgC-CO_2 yr^{-1} (Friedlingstein et al., 2020).

Global warming will strongly enhance freshwater CH_4 emissions through a disproportionate increase in ebullition (gas flux) by 6–20% per 1°C increase in water temperature (Aben et al., 2017). It can be expected that ongoing eutrophication enhanced by climate change-related increases in sediment nutrient release and organic carbon and nutrient loading from catchments will enhance CH_4 ebullition at a global scale (Aben et al., 2017; DelSontro et al., 2018; Bartosiewicz et al., 2019; Beaulieu et al., 2019; Sanches et al., 2019). The strongest increase in ebullition is expected in shallow waters where sediment temperatures are strongly related to atmospheric temperature (Aben et al., 2017). Given that small ponds and shallow lakes are the most abundant freshwater ecosystems globally they may become hot spots of CH_4 ebullition in the future (Aben et al., 2017). On average CH_4, CO_2, N_2O account for 75%, 23, and 2% of the total CO_2 equivalent emissions, respectively in lakes (DelSontro et al., 2018).

Further, the exposure of lake and river sediments during droughts activates decomposition of buried organic carbon. In dry river beds, mineralisation of buried organic matter is likely to increase with climate change as anoxic sediments are oxygenated downwards during drying along with pulses of microbial activity following rewetting of desiccated sediment. Conservative estimates indicate that adding emissions from exposed sediments of dry inland waters across diverse ecosystem types and climate zones to current global estimates of CO_2 emissions could result in a 6% (~0.12 Pg C y^{-1}) increase of total inland water CO_2 emission rates covering streams and rivers (334 mmol m^{-2} day^{-1}), lakes and reservoirs (320 mmol m^{-2} day^{-1}) and small ponds (148 mmol m^{-2} day^{-1}) (Marcé et al., 2019; Keller et al., 2020).

Overall, uncertainty in the quantity of carbon fluxes within freshwater ecosystems and between terrestrial and freshwater systems and subsequent emissions to the atmosphere remain very high (Raymond et al., 2013; Catalán et al., 2016; Stanley et al., 2016; Evans et al., 2017; Drake et al., 2018; Seekell et al., 2018; Sanches et al., 2019; Bodmer et al., 2020; Keller et al., 2020) (see Table 2.SM., see also Chapter 5 of WGI). Projections of carbon fluxes are e.g. challenged by the complex interaction between rising water temperature, loss of ice, changes in hydrology, ecosystem productivity, increase in extreme events, and variation in terrestrial matter transport. While we are still short in empirical data, particularly in the tropics (DelSontro et al., 2018), improvements in sensor technology (Eugster et al., 2011; Gonzalez-Valencia et al., 2014; Maeck et al., 2014; Delwiche et al., 2015) and the use of statistically robust survey designs (Beaulieu et al., 2016; Wik et al., 2016) have improved the accuracy of GHG emission rate measurements in freshwater ecosystems. Global networks such as GLEON (Global Lakes Ecological Observatory Network) increasingly allow a global view of carbon fluxes improving estimates of the contribution of freshwater ecosystems to global GHG emissions to the atmosphere.

In summary (Drake et al., 2018) aggregated contemporary estimates of CO_2 and CH_4 emissions from freshwater ecosystems with global estimates made by (Raymond et al., 2013) and arrived at an estimate of 3.9 Pg C yr^{-1}. Rivers and streams accounted for 85% of the emissions and lakes and reservoirs for 15% (Raymond et al., 2013). This trend will continue under scenarios of nutrient loading to inland waters over the next century where inland water increased CH_4 emission has an atmospheric impact of 1.7–2.6 Pg C-CO_2-eq y^{-1}, which is equivalent to 18–33% of annual CO_2 emissions from burning fossil fuels (*medium evidence, medium agreement, medium confidence*) (Beaulieu et al., 2019). For comparison, annual uptake of CO_2 in land ecosystems is estimated as 3.4 (± 0.9) PgC/yr (Friedlingstein et al., 2020). The freshwater numbers combine CO_2 and CH_4 and are thus not directly comparable. However, they are indicative for the importance to account better for freshwater systems in global carbon budgets.

2.5.3.6 Risks to Freshwater Ecosystem Services: Drinking Water, Fisheries and Hydropower

AR5 named water supply and biodiversity as freshwater ecosystem services vulnerable to climate change. We discuss risks to these and to additional services identified by model projections based both on climate-change scenarios (Schröter et al., 2005; Boithias et al., 2014; Huang et al., 2019; Jorda-Capdevila et al., 2019) and on the Common International Classification of Ecosystem Services (*high agreement, high confidence*) (CICES, 2018). Effects of floods, droughts, permafrost and glacier melting on global changes in water quality, particularly with respect to contamination with pollutants, are described in Section 4.2.6.

2.5.3.6.1 Risks to quantity and quality of drinking water

Forests and other vegetated ecosystems assist production of drinkable water by facilitating infiltration of rainfall and snowfall into the ground, where water either moves through the soil saturated zone to supply streams and other surface waters or infiltrates further to recharge groundwater aquifers (Ellison et al., 2012; Bonnesoeur et al., 2019). Globally, 4 billion people depend on forested watersheds for drinking water (Mekonnen and Hoekstra, 2016). Chapter 4 assesses the physical science of water supply, including precipitation, runoff, and hydrology, and social aspects of human water use. This section assesses ecological aspects of risks to freshwater supplies for people.

Reduction of vegetation cover following wildfires (Section 2.5.5.2) and tree mortality (Section 2.5.5.3) can reduce long-term water infiltration, increase soil erosion and flash floods, and release sediment that degrades drinking water quality. Widlfires increase impacts of extreme precipitation events due to climate change, which contribute to increased surface runoff and hence to increased risks of land erosion, landslides and flooding (Ebel et al., 2012; Robinne et al., 2020). Under current conditions, nearly half of global land area is at moderate to high risk of water scarcity due to wildfires (Robinne et al., 2018; Robinne et al., 2020). From 1984 to 2014 wildfires in the western USA affected 6-11% of stream and river length (Ball et al., 2021). Under a high emissions scenario of a 3.5ºC temperature increase post-fire erosion across the western USA could double sedimentation and degrade drinking water quality in one-third of watersheds by 2050 (Sankey et al., 2017). In Brazil, post-fire vegetation loss tends to increase runoff, reduce infiltration, and reduce groundwater recharge and flow of springs (Rodrigues et al., 2019). Runoff from wildfires can contain dissolved organic carbon precursors for the formation of carcinogenic trihalomethanes during water chlorination for drinking (Uzun et al., 2020), plus chromium, mercury, selenium, and other toxic trace metals (Burton et al., 2016; Burton et al., 2019).

Net effects of deforestation and afforestation on runoff and water supply depend on local factors, leading to conflicting evidence for effects of land cover change (Ellison et al., 2012; Chen et al., 2021b), but combinations of climate change and deforestation are projected to reduce water flows (Olivares et al., 2019). In southern Thailand, the combination of conversion of forest to rubber plantations and a one-third increase in rainfall could increase erosion and sediment load 15% (Trisurat et al., 2016). In the watershed that supplies São Paulo, Brazil, afforestation could increase water quantity and quality (Ferreira et al., 2019). In most regions with dry or Mediterranean subtropical climates, climate change reduces renewable surface water and groundwater resources significantly (Doell et al., 2015). In northeast Spain, reduced precipitation and vegetation cover under a high emissions scenario of a 3.5ºC temperature increase could reduce drinking water supplies by half by 2100 (Bangash et al., 2013).

Changes in algal biomass development and spread of cyanobacteria blooms, related to global warming, resemble those triggered by eutrophication with well-known negative effects on the services lakes provide, particularly for drinking water provision and recreation (*robust empirical evidence*, *high agreement, high confidence*) (Carvalho et al., 2013; Adrian et al., 2016; Gozlan et al., 2019).

Based on a 10% increase in precipitation, (de Wit et al., 2016) estimated increased mobilisation of organic carbon from soils to freshwaters by at least 30%, demonstrating the importance of climate wetting for the carbon cycle. Browning negatively affects the taste of drinking water and may be difficult to address (Kothawala et al., 2015; Mineau et al., 2016; Kritzberg et al., 2020). It also often reduces attractives for recreational purposes, especially swimming (Arthington and Hadwen, 2003; Keeler et al., 2015). Based on a worst-case climate scenario until 2030 (Weyhenmeyer et al., 2016) projected an increase in browning of lakes and rivers in boreal Sweden by a factor of 1.3. The chemical character of dissolved organic matter, as modified by climate change (Kellerman et al., 2014), determines its amenability to removal by water treatment (Ritson et al., 2014). Therefore, in order to provide safe and acceptable drinking water, more advanced, more expensive and more energy/resource intensive technical solutions may be required (Matilainen et al., 2010).

In summary, climate change increases risks to the integrity of watersheds and provision of safe, acceptable freshwater to people (*medium evidence, medium agreement*).

2.5.3.6.2 Risks to freshwater fisheries and biodiversity

Climate change will increase water temperatures and decrease dissolved oxygen levels (Section 2.3.1) impacting freshwater fisheries which form an important ecosystem service (Vári et al., 2021). People living in the vicinity of cold lakes will be affected by projected losses of ice. In a worst-case scenario (air temperatures increase of 8°C), 230,400 lakes and 656 million people in 50 countries will be impacted (Reid et al., 2019; Sharma et al., 2019). Winter ice fishing (Orru et al., 2014), transportation via ice roads (Prowse et al., 2011) and cultural activities (Magnuson and Lathrop, 2014) are ecosystem services at stake with ongoing loss of lake ice.

Eutrophication of central European lakes has wiped out a significant proportion of the endemic fish fauna (Vonlanthen et al., 2012), so climate-induced further eutrophication is expected to represent an additional threat to fish fauna and commercial fisheries (Ficke et al., 2007). Given that the ecological consequences of lake warming may be especially strong in the tropics (Section 2.3.1.1), ecosystem services may be most affected there. Tropical lakes support important fisheries (Lynch et al., 2016a economic; McIntyre et al., 2016) providing critical sources of nutrition to adjacent human populations. These lakes are especially prone to loss of deep-water oxygen due to warming, with adverse consequences for fisheries productivity and biodiversity (*medium evidence, medium confidence*) (Lewis Jr, 2000; Van Bocxlaer et al., 2012).

Tropical lakes tend to be hotspots of freshwater biodiversity (Vadeboncoeur et al., 2011; Brawand et al., 2014; Sterner et al., 2020); ancient tropical lakes such as Malawi, Tanganyika, Victoria, Titicaca, Towuti and Matano hold thousands of animal species found nowhere else (Vadeboncoeur et al., 2011). While biodiversity and several ecosystem services can be considered synergistic (food webs, tourism, aesthetical and spiritual value (Langhans et al., 2019), others can be considered antagonistic in case of a strong ecosystem service demand (such as water abstraction, water use, food security in terms of over-exploitation). Here the balance between biodiversity and ecosystem services is key (Langhans et al., 2019), where biodiversity can be integrated into water policy through Integrated Water Resource Management (IWRM) towards nature-based solutions (Ligtvoet et al., 2017)

2.5.3.6.3 Risks to hydro power and erosion control

River banks, riparian vegetation and macrophyte beds play important roles in erosion control through reducing current velocities, increasing sedimentation and reducing turbidity (Madsen et al., 2001). Rates of flow in rivers affect and inland navigation (Vári et al., 2021). Changing seasonality in snow-dominated basins is expected to enhance hydropower production in winter, but decrease it during summer (Doell et al., 2015). Glacier melt changes hydrological regimes, sediment transport, and biogeochemical and contaminant fluxes from rivers to oceans, profoundly influencing ecosystem services that glacier-fed rivers provide, particularly provision of water for agriculture, hydropower, and consumption (Milner et al., 2017). Loss of glacial mass and snowpack has already impacted flow rates, quantities and seasonality (Hock et al., 2019); see AR6 WGII, Chapter 4 Water). Meltwater yields from glacier ice are likely to increase in many regions during the next decades, but decrease thereafter as glaciers become smaller and smaller and finally disappear (Hock et al., 2019).

2.5.4 Key Risks to Terrestrial and Freshwater Ecosystems from Climate Change

Among numerous risks to terrestrial and freshwater ecosystems from climate change, this IPCC chapter identified five phenomena as the most fundamental risks of climate change to ecosystem integrity and the ecosystem services that support human well-being that are also quantified: species losses to ecosystems, increased wildfire, increased tree mortality, ecosystem carbon losses, and ecosystem structure change (Table 2.5, Table 2.S.4, Figure 2.11). These key risks form part of the overall assessment of key risks in Chapter 16. The IPCC Fifth Assessment Report chapter on terrestrial ecosystems (Settele et al., 2014) had also identified three of these key risks – species extinctions, tree mortality, ecosystem carbon losses – and a fourth – invasion by non-native species. This IPCC chater assesses impacts of climate change on invasive species in multiple sections with respect to different processes or systems (e.g. in Section 2.4.2.3.3), and here includes this aspect in a new broader key risk of ecosystem structure change. The IPCC Fifth Assessment Report had included wildfire as a mechanism of the ecosystem carbon loss key risk. Based on additional research and field experience with major wildfires since then, this IPCC chapter sets wildfire apart as a specific key risk to ecosystem integrity and human well-being. These different measures of risk are interconnected but approach assessment of risk to terrestrial and freshwater ecosytems from different angles, using complementary metrics.

Species are the fundamental unit of ecosystems. As species become rare, their roles in the functioning of the ecosystem diminishes, and disappears altogether if they go locally extinct *(high confidence)* (Isbell et al., 2015; Chen et al., 2018b; van der Plas, 2019; Wang et al., 2021b). Loss of species and functional groups reduces the ability of an ecosystem to provide services, and lowers its resilience to climate change *(high confidence)* (Section 2.6.7; Elmqvist et al., 2003; Cadotte et al., 2011; Harrison et al., 2014; Carlucci et al., 2020). For example, among crop systems, a key factor to succesful pollination is the phylogenetic diversity of bee species available, more than total abundances (Drossart and Gérard, 2020). Because many species have obligate interactions with, or are resources for, other species (e.g. predators and their prey, insects and their host plants, plants and their mycorrhizae symbionts), loss of one species affects risk to another species and, ultimately, ecosystem functioning (Mahoney and Bishop, 2017)

Global rates of species extinction are accelerating dramatically (Barnosky et al., 2011), with approximately 10% of species having been driven extinct by humans since the late Pleistocene, principally by over-exploitation and habitat destruction, a rate estimated to be 1000 times higher than pre-Anthropocene (natural) background extinction rates (De Vos et al., 2015). Therefore, this level—10%—of species becoming endangered (sensu IUCN) due to loss of suitable climate space (Figure 2.8b), is used here as a threshold moving risk to biodiversity from moderate to high, and twice that (20%) as the threshold from high to very high.

Key risks assessed here are interconnected. Extinction of species is an irreversible impact of climate change, has negative consequences on ecosystem integrity and functioning, and risk increases steeply with even small rises in global temperature (Section 2.5.1.3; Figure 2.6; Figure 2.7; Figure 2.8). Continued climate change substantially increases risks of carbon losses due to wildfires, tree mortality from drought and insect pest outbreaks, peatland drying, permafrost thaw, and ecosystem structure change which could exacerbate self-reinforcing feedbacks between emissions from high-carbon ecosystems and increasing global temperatures (*medium confidence*). Thawing of Arctic permafrost alone could release 11–200 Gt carbon *(medium confidence)*. Complex interactions of climate change, land use change, carbon dioxide fluxes, and vegetation changes will regulate the future carbon balance of the biosphere, processes incompletely represented in earth system models. The exact timing and magnitude of climate-biosphere feedbacks and potential tipping points of carbon loss are characterized by high ranges of the estimates, yet studies indicate increased ecosystem carbon losses could cause extreme future temperature increases (*medium confidence*) (Sections 2.5.2.7; 2.5.2.8; 2.5.2.9; 2.5.3.2; 2.5.3.3; 2.5.3.4; 2.5.3.5; Figure 2.10; Figure 2.11; Table 2.4; Table 2.5; Table 2.S.2; Table 2.S.4)

Table 2.5: Key risks to terrestrial and freshwater ecosystems from climate change. This IPCC chapter assesses these as the most fundamental risks of climate change to ecosystem integrity and the ecosystem services that support human well-being. Climate factors include the primary variables governing the risk. Non-climate factors include other phenomena that can dominate or contribute to the risk. Detection and attribution comprise cases of observed changes attributed predominantly or in part to anthropogenic climate change (Section 2.4.2, 2.4.3, 2.4.4, 2.4.5, Table 2.2, Table 2.3, Table 2.S.1). Adaptation includes options to address the risk (Section 2.6). Risk transitions (defined in Figure 2.11) indicate an approximate global mean surface temperature increase, relative to the pre-industrial period (1850-1900), to move from one level of risk to the other and confidence in the assessment. Table 2.S.4 provides details of the temperature levels for risk transitions. Both tables provides details for the key risk burning embers diagram (Figure 2.11).

Biodiversity Risk: Increasing high extinction risk (species projected loss of >50% of range) among increasing number of plant and animal species. The transition from non-detectable to moderate was based on the number of local population extinctions, major declines of sub-species and two global species extinctions and that are attributable to climate change. The transition from moderate to high is centred around 1.5°C based on a few taxa that are known from their basic biology and habitat requirements to be at risk of extinction (endangered) at 1.5°C and on the increasing number of taxa that are projected to have high extinction risk (losing >50% of their suitable climate space) affecting >10% of the species in that taxa (1000x natural background rates of extinction). The

transition to very high comes from the increasing number of taxa projected to have >20% of species at high risk of extinction. In the worst-case scenario (10th percentile of the models), some of the taxa show >50% of the species at high risk of extinction. These assessments are also weighted by role the species in the taxa play in performing ecosystem services (both to the ecosystems and to humans, e.g. pollinators, detritivores). Confidence for the moderate threshold is *high* because it is based on observed trends attributed to climate change. Confidence for future projections are is *medium* as these are based on one large study (covering more than 135,000 species) and primarily based on loss of suitable climate. Based on Sections 2.4.2, 2.5.1, 2.6.1, 2.6.6, Table 2.3, Figure 2.6, Table SM2.1 and Table SM2.2.

Climate factors	**Non-climate factors**	**Detection and attribution**	**Adaptation**	**Risk transitions (*confidence*)**
Shifts in geographic placements of climate space; loss of climate space globally; emergence of non-analogue climates, increases in extreme climate events	land use change, habitat degradation from pollution, fertilisation, invasive species	Observed D&A: many cases of population extinctions; two cases of species extinctions (2.4.2.2); species have tracked their climate niches raising confidence in SDM projections (2.4.2.1, 2.4.2.3, 2.4.2.5)	Habitat restoration, habitat creation, increased connectivity of habitats and protected areas, increase in protected areas, assisted colonisation	0.8ºC undetectable-moderate (*high confidence*) 1.58°C moderate-high (*medium confidence*) 2.07°C high-very high (*medium confidence*)

Wildfire: Increasing risk of wildfire that exceeds natural levels, damaging ecosystems, increasing illnesses and death of people, and increasing carbon emissions. Field evidence shows that anthropogenic climate change has increased the area burned by wildfire above natural levels across western North America in the period 1984–2017, increasing burned area up to 11 times in one extreme year and doubling burned area over natural levels in a 32-year period. Burned area has increased in the Amazon, the Arctic, Australia, and parts of Africa and Asia, consistent with, but not formally attributed to anthropogenic climate change. These changes have occurred at global mean surface temperature increases of 0.6-0.9ºC. Empirical and dynamic global vegetation models project increases in burned area and fire frequency above natural levels on all continents under continued climate change, emergence of an anthropogenic signal from natural variation in fire weather for a third of global area, and increases of burned area in regions where fire had been rare or absent, particularly Arctic tundra and Amazon rainforest, at global temperature increases of 1.5-2.5ºC. Models project up to a doubling of burned area globally and wildfire-induced conversion of up to half the area of Amazon rainforest to grassland at temperature increases of 3-4.5ºC. (Sections 2.4.4.2, 2.5.3.2)

Climate factors	**Non-climate factors**	**Detection and attribution**	**Adaptation**	**Risk transitions (*confidence*)**
Increase in magnitude and duration of high temperatures, decrease in precipitation, decrease in relative humidity	Deforestation, agricultural burning, peatland burning	Increased burned area in western North America above natural levels	Reduce deforestation, reduce use of fire in tropical forests, use prescribed burning and allow naturally ignited fires to burn in targeted areas to reduce fuel loads, encourage settlement in non-fire-prone areas	0.75°C undetectable-moderate (*high*) 2.0 °C moderate-high (*medium*) 4.0°C high-very high (*medium*)

Tree mortality: Tree mortality that exceeds natural levels degrades habitat for plant and animal species, increases carbon emissions, and reduces water supplies for people. Anthropogenic climate change caused three cases of drought-induced tree mortality in the period 1945–2007 in western North America, the African Sahel, and North Africa in temperate and tropical ecosystems. Pest infestations and wildfire due to climate change also caused much of the tree mortality in North America. These changes occurred at global mean surface temperature increases of 0.3–0.9ºC above the pre-industrial period. Models project increasingly extensive drought-induced tree mortality at continued temperature increases of 1–2ºC. Models project risks of mortality of up to half of forest area in different biomes at temperature increases of 2.5–4.5ºC. In Amazon rainforests, insufficient plant moisture reserves during drought increase the risk of tree mortality and, combined with increased fire from climate change and deforestation, the risk of a tipping point of massive forest dieback and a biome shift to grassland. (Sections 2.4.4.3, 2.5.2.6, 2.5.3.3, 2.5.3.5)

Climate factors	Non-climate factors	Detection and attribution	Adaptation	Risk transitions (*confidence*)
Increase in temperature, decrease in precipitation, increase in aridity, increase in frequency and severity of drought	Deforestation, land-use change	Tree mortality up to 20% in three regions in Africa and North America	Reduce deforestation, reduce habitat fragmentation, encourage natural regeneration, restore fragmented habitats	0.6°C undetectable-moderate (*high*) 1.5°C: moderate-high (*medium*) 3.0°C high-very high (*medium*)

Ecosystem carbon loss: Increasing risk of ecosystem carbon losses that could substantially raise the atmospheric carbon dioxide level. Measurements have detected emissions of carbon from boreal, temperate, and tropical ecosystems in places where increases in wildfire and tree mortality have been attributed to anthropogenic climate change, at global mean surface temperature increases of 0.6–0.9ºC above the pre-industrial period. Many factors govern the carbon balance of ecosystems, so changes have not been attributed to climate change. Tropical forests and Arctic permafrost contain the highest ecosystem stocks of aboveground and belowground carbon, respectively. Primary tropical forests currently emit more carbon to the atmosphere than they remove due to deforestation and forest degradation. Wildfires in the Arctic are contributing to permafrost thaw and soil carbon release. An emissions scenario of 2ºC increase could thaw ~15% of permafrost area and emit 20-100 Gt carbon by 2100, Under emissions scenarios of a 4ºC global temperature increase, models project possible tipping points of conversion of half of Amazon rainforest to grasslands and thawing of Arctic permafrost that could release 11–200 Gt carbon that could substantially exacerbate climate change. (Sections 2.4.3, 2.4.4.3, 2.4.4.4, 2.5.2.7–10; 2.5.3.2–5; Figure 2.9; Figure 2.10; Figure 2.11; Table 2.4; Table 2.5; Table 2.S.2; Table 2.S.3; Table 2.S.4)

Climate factors	Non-climate factors	Detection and attribution	Adaptation	Risk transitions (*confidence*)
Increase in temperature, increase in aridity, increase in frequency and severity of drought	Deforestation, road and infrastructure expansion, agricultural expansion	Losses of carbon detected in boreal, temperate, and tropical ecosystems, due to wildfire and tree mortality, not formally attributed to climate change	Reduce deforestation, especially in tropical forests, reduce road and infrastructure expansion, especially in the Arctic, reduce use of fire to clear agricultural land, increase protected areas	0.75°C undetectable-moderate (*medium*) 2°C: moderate-high (*medium*) 4°C high-very high (*low*)

Ecosystem Structure Change: Increasing risk of large-scale changes in ecosystem structure. Ecosystem structural change with most information derived for tropical forest, boreal forest, savannas, and tundra for both observations and future projections. The transition from non-detectable to moderate is based on detected changes attributable to climate change, or interactions between changing disturbance regime, climate and rising CO_2, already observed at 0.5°C above pre-industrial, with shifts initially detected in boreal forests, tundra, and tropical grassy ecosystems. Transition from moderate to high is centred around 1.5°C based on widespread global observations (at current GSAT of 1.09°C above pre-industrial) that agree with projected future impacts with at least 10% area of key ecosystems being affected (Box 2.1). Overall confidence in projections is *medium*, based on existing observations and projections giving *high* confidence of risk for several ecosystems but because data and projections are not available for all biomes, overall confidence lowers to *medium*. Transition from high to very high occurs when more than 50% of multiple ecosystems are projected to experience shifts in structure. (Sections 2.4.2.3, 2.4.3, 2.4.5, 2.5.2, Box 2.1, Figure Box 2.1.1, Table Box 2.1.1, Table 2.S.2, Table 2.S.2, Table 2.S.3, Table 2.S.5)

Climate factors	**Non-climate factors**	**Detection and attribution**	**Adaptation**	**Risk transitions (*confidence*)**
Increases in average and extreme temperatures, changes in precipitation amount and timing, increased atmospheric CO_2	Land use change, livestock grazing, deforestation, fire suppression, loss of native herbivores, food, fiber, or wood production	Individual species ranges shifts, biome shifts	Conservation of potential refugia, habitat restoration, increasing connectivity of habitats and protected areas, increase in protected areas, changes in grazing and fire management	0.5°C undetectable-moderate (*high*) 1.5°C moderate-high (*medium*) 2.5°C high-very high (*medium*)

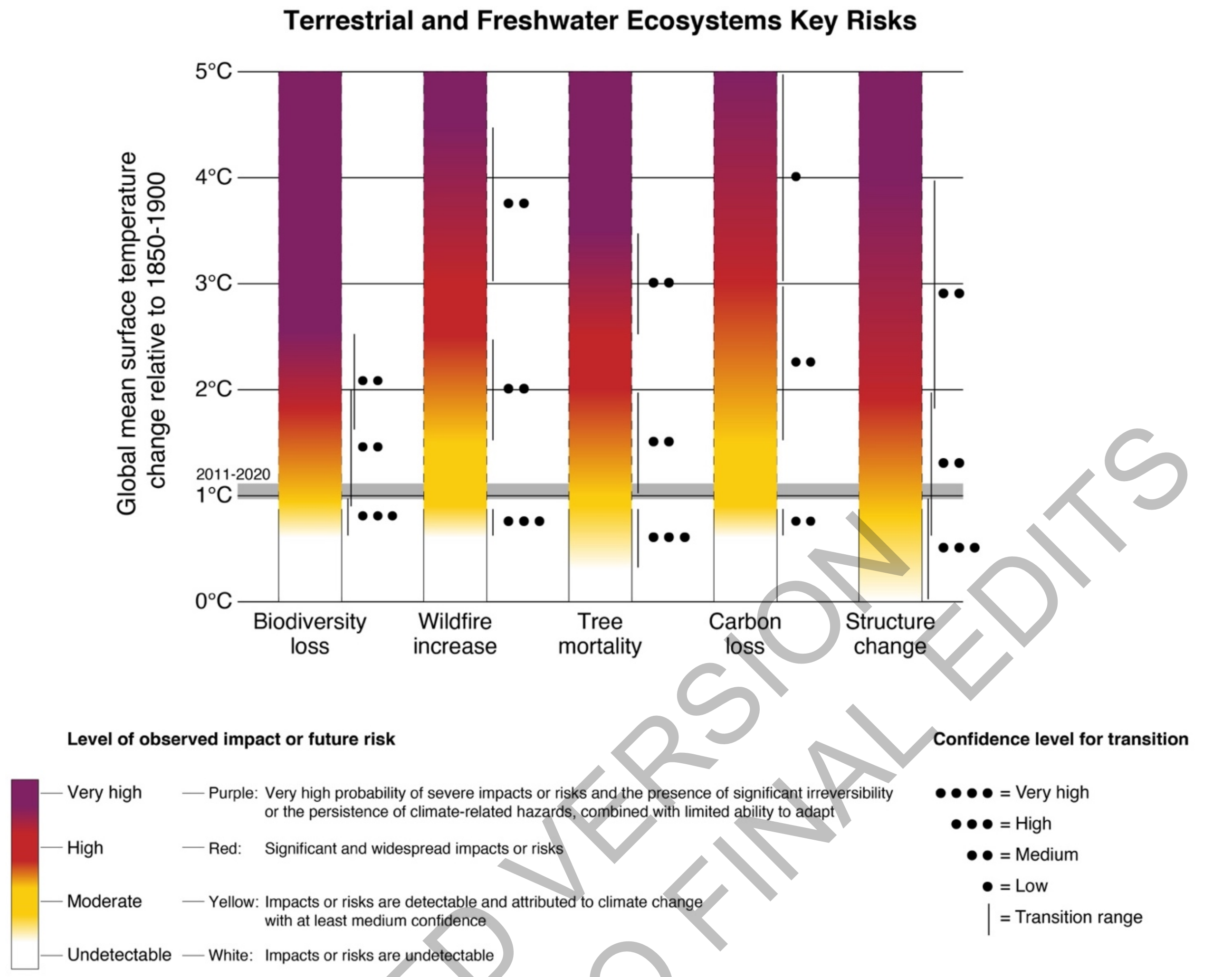


Figure 2.11: Key risks to terrestrial and freshwater ecosystems from climate change. This IPCC chapter assesses these as the most fundamental risks of climate change to ecosystem integrity and the ecosystem services that support human well-being, based on observed impacts and future risks of: (far left) Losses of animal and plant species from different ecosystems globally with resulting declines in ecosystem integrity, functioning and resilience (Section 2.4.2.1, 2.4.2.2, 2.5.1.3.3); (middle left) wildfire exceeding natural levels (Section 2.4.4.2, 2.5.3.2); (middle) tree mortality exceeding natural levels (Chapter 2.4.4.3, 2.5.3.3), (middle right) ecosystem carbon losses that could occur abruptly and substantially raise atmospheric carbon dioxide (Sections 2.4.3.6—2.4.3.9, 2.4.4.4, 2.5.2.6—2.5.2.10, 2.5.3.4, 2.5.3.5); (far right) major changes occurring in ecosystem structure (Sections 2.4.3, Box 2.1, 2.5.2, Figure 2.9, Figure Box 2.1.1, Table Box 2.1.1, Table 2.S.5). This burning embers diagram shows impacts and risks in relation to changes in global mean surface temperature, relative to the pre-industrial period (1850−1900). Risk levels reflect current levels of adaptation and do not include more interventions that could lower risk. The compound effects of climate change combined with deforestation, agricultural expansion, urbanisation, air, water, and soil pollution, and other non-climate hazards could increase risks. Tables 2.5 and 2.S.4 provide details of the key risks and temperature levels for the risk transitions.

[START FAQ2.4 HERE]

FAQ2.4: How does nature benefit human health and well-being and how does climate change affect this?

Human health and well-being are highly dependent on the "health" of nature. Nature provides material and economic services that are essential for human health and productive livelihoods, but studies also show that being in "direct contact with natural environments" has direct positive effects on well-being, health and socio-cognitive abilities. Therefore, the loss of species and biodiversity under climate change will reduce natural space, decrease biodiversity and in turn, decrease human-well-being and health worldwide.

Human health and well-being are highly dependent on the "health" of nature. Biodiversity – the variety of genes, species, communities and ecosystems – provides services that are essential for human health and productive livelihoods, such as breathable air, drinkable water, productive oceans and fertile soils for growing food and fuels. Natural ecosystems also help store carbon and regulate climate, floods, disease, pollution and water quality. The loss of species, leading to reduced biodiversity, has direct and measurable negative effects on all of these essential services, and therefore, on humankind. A recent demonstration of this is the decline of pollinator species, with potential negative effects on crop pollination, a fundamental ecosystem function crucial for agriculture. The loss of wild relatives of the domesticated varieties humans rely on for agriculture reduces the genetic variability that may be needed to support the adaptation of crops to future environmental and social challenges.

The number of species that can be lost before negative impacts occur is not known and is likely to differ in different systems. However, in general, more diverse systems are more resilient to disturbances and able to recover from extreme events more quickly. Biodiversity loss means there are fewer connections within an ecosystem. A simpler food web with fewer interactions means less redundancy in the system, reducing the stability and ability of plants and animal communities to recover from disturbances and extreme weather events such as floods and drought.

In addition to "material" and economic services such as eco-tourism, nature also provides cultural services such as recreation, spirituality and well-being. Specifically, being in "direct contact with natural environments" (versus urban environment) has a high positive and causal impact on human well-being (e.g. mood, happiness), psychological and physical health (energy, vitality, heart rate, depression) and socio-cognitive abilities (attention, memory, hyperactivity, altruism, cooperation). Therefore, the loss of species and biodiversity under climate change and urbanisation will reduce natural space, decrease biodiversity and in turn, decrease human-well-being and health worldwide.

Finally, the extent to which humans consider themselves as part of the natural world – known as human-nature connectedness – has been demonstrated to be closely associated with human health and well-being. Individuals who are more connected to nature are not only happier and healthier but also tend to engage more in pro-nature behaviours, making the enhancement of human-nature connectedness worldwide a valuable win-win solution for humans and nature to face environmental challenges.

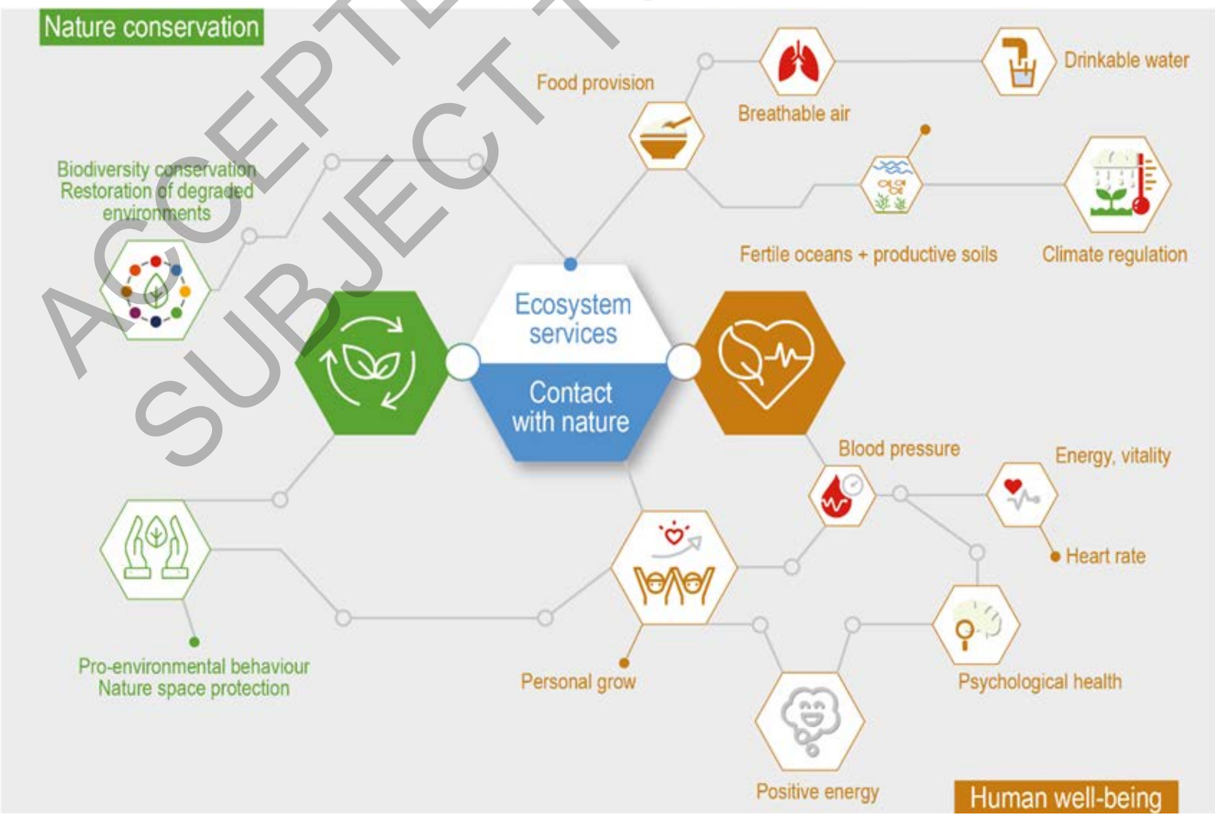


Figure FAQ2.4.1: Positive relationship between human health and well-being and nature conservation. Nature provides essential services to humans including material and economic services (i.e. ecosystem services) as well as cultural, experiential and recreational services, which, in turn enhance human psychological and physical health, and well-being. People who are more connected to nature are not only happier and healthier but are also more likely to engage in pro-nature behaviours, making the enhancement of human-nature connectedness worldwide a valuable win-win solution for humans and nature to face environmental challenges.

[END FAQ2.4 HERE]

2.6 Climate Change Adaptation for Terrestrial and Freshwater Ecosystems

Adaptation to reduce vulnerability of ecosystems and their services to climate change has been addressed in previous IPCC Reports, with AR4 and AR5 recognising both autonomous adaptation and human assisted adaptation to protect natural species and ecosystems. In AR5, Ecosystem-based Adaptation (EbA), adaptation for people, based on better protection, restoration and management of the natural environment, was identified as an area of emerging opportunity, with a dedicated Cross Chapter Box on the topic. In the SRCCL report, conservation, EbA and related concepts were integrated throughout the report; SR1.5 also noted the role of EbA. Since the last assessment report the scientific literature has expanded considerably, with growing interest in the concept of Nature-based Solutions (NbS). This section assesses this new literature and its implications for the implementation of climate change adaptation.

Previous sections of this chapter have set out the vulnerability of natural and semi-natural ecosystems to climate change and the risks this poses both to biodiversity and ecosystem services (also sometimes described as 'Nature's Contributions to People'). Natural systems respond to climatic and other environmental changes in variety of ways. Individual organisms can respond through growth, movement and developmental processes. Species and populations genetically adapt to changing conditions and evolve over successive generations. Geomorphological features, such as the path of watercourses, can also change naturally in response to climate change. However, there is a limit to which these natural processes can maintain biodiversity and the benefits people derive from nature, partly because of intrinsic limits, but also because of the pressures that people exert on the natural environment. Most of this section therefore focuses on human interventions to build the resilience of ecosystems, enable species to survive or to adjust management to climate change. Vulnerability is in many cases exacerbated by the degraded state of many ecosystems as a result of human exploitation and land use change, leading to fragmentation of habitats, loss of species and impaired ecosystem function. This interaction between climate change and environmental degradation means that protecting ecosystems in a natural or near-natural state will be an important pre-requisite for maintaining resilience and give many species the best chance of persisting in a changed climate (Belote et al., 2017; Arneth et al., 2020; Ferrier et al., 2020; França et al., 2020). Protection from degradation, deforestation and exploitation is also essential to maintain critical ecosystem services, including carbon storage and sequestration and water supply (Dinerstein et al., 2020; Pörtner, 2021).

It is worth briefly considering some key concepts that are relevant to adaptation in ecosystems. Adaptation for biodiversity and ecosystems can encompass both managing change and building resilience. We use the definition of 'resilience' set out Chapter 1: 'the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation', It includes the concept of 'resistance', which is used in some ecological literature to distinguish systems which a resistant to change from those that recover quickly from change. We consider both interventions designed primarily to protect biodiversity and those intended to reduce the risks of climate change to people.

A variety of terms are used to describe using environmental management reduce the impacts of climate change on people in ways that also benefit biodiversity in the scientific literature, particularly Ecosystem based Adaptation (EbA) and Nature-based Solutions (NbS) (see also Section 1.4). EbA is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to climate change (CBD, 2009). EbA aims to maintain and increase the resilience and reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change (Vignola et al., 2009). NbS is a broader term which is not restricted to climate change and is also often used to refer to climate change mitigation; it has been defined by the International Union for the Conservation of Nature (IUCN) as 'Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (Cohen-Shacham et al., 2016). This widely accepted definition excludes actions, which use the natural environment to solve human problems but do not provide benefits for biodiversity and is closely linked to the concept of the Ecosystem Approach. NbS is not a universally accepted term but it is increasingly used in the scientific literature. It is a concept which recognises the importance of biodiversity in ecosystem service provision and offers the opportunity to address climate change and loss of biodiversity together in an efficient integrated way (Chong, 2014; Seddon et al., 2020a; Ortiz et al., 2021). Given the focus of this chapter is on adaptation we primary use the term EbA as it is more specific, but we do so understanding that it can be regarded as a subset of NbS. The wider concept of NbS for climate change adaptation and mitigation is covered in a Cross-Chapter Box on the topic (see Cross-Chapter Box NATURAL this Chapter).

Whilst we distinguish between adaptation for biodiversity and EbA, it is important to recognise that the two are linked in that if ecosystems themselves are not resilient to climate change, they will not be able to provide adaptation benefits for people. The case for resourcing biodiversity conservation and building the resilience of ecosystems is also strengthened when there are direct benefits for people in addition to the more general benefits of biodiversity.

Ecosystems are specifically included in the adaptation goals set out in the Paris Agreement and are addressed in most national adaptation plans (Seddon et al., 2020b). There is also now a large number of adaptation programmes and plans for local governments and governmental and non-governmental conservation organisations. Adaptation for and by ecosystems needs to be understood and developed in the wider contexts of conservation, Climate Resilient Development and Sustainable Development: there is significant potential synergies, but also conflicts between different objectives, which require an integrated approach (covered further in 2.6.7).

2.6.1 Limits to Autonomous (Natural) Adaptation

Natural ecosystems often have a high degree of resilience and can to some extent adjust to change. Species can adjust through evolutionary adaptation, distribution change, behavioural change, developmental plasticity and ecophysiological adjustment. There are, however, limits to autonomous adaptation, because of intrinsic limitations, the rate at which the climate is changing and the degraded state of many ecosystems.

None of the evolutionary changes either documented or theorised would enable a species to survive and reproduce in climate spaces that it does not already inhabit. Evolutionary responses are *very unlikely* to prevent species extinctions in the case of that species losing its climate space entirely on a regional or global scale (Parmesan and Hanley, 2015). At highest risk are the world's most cold-adapted species (whose habitats are restricted to polar and high mountaintop areas). Examples include the polar bear (Regehr et al., 2016), "sky-island" plants in the tropics (Kidane et al., 2019), mountain-top amphibians in Spain (Enriquez-Urzelai et al., 2019), mountain-top lichens in the Appalachians (USA) (Allen and Lendemer, 2016), and silverswords in Hawaii (Krushelnycky et al., 2013). However, there is potential for using evolutionary changes to enhance the adaptive capacity of target species, as is being done in the Great Barrier reef by translocating symbionts and corals that have survived recent intense heat-induced bleaching events into areas that have had large die-off (Rinkevich, 2019). Multiple studies assessed when and how evolution might be able to help wild species adapt to climate change (Ratnam et al., 2011; Sgro et al., 2011).

Some of the reasons cited in the literature as limits to autonomous adaptation are:

1) Genetic changes in populations require many generations and for many species operate on longer time scales than those, on which the climate is currently changing.

2) Many species are moving to higher latitudes as the climate warms, but not all are keeping pace with changes in suitable climate space (Valladares et al., 2014; Mason et al., 2015). Such climate debt indicates an inability for non-genetic autonomous adaptation (e.g. evidence-limited ability for plastic responses, such as stemming from dispersal limitations, or behavioural restrictions, or physiological constraints).

3) Some species have low capacity for dispersal, which, combined with increased fragmentation of habitats, creates barriers to range shifts to match climate warming. Studies have shown that changes in distribution of species and composition of communities are limited by the presence of intensively managed agricultural land fragmenting natural habitats (Oliver et al., 2017).

There are a variety of mechanisms which promote the resilience of ecosystems through persistence, recovery, and reorganisation (Falk et al., 2019). Changes in the balance of different plant species within a community can maintain the persistence of the community itself, maintaining its value as a habitat for other species and providing ecosystem services (add reference?). In some cases there are negative feedback mechanisms between biological and physical processes, for example in peatlands, lowered water tables resulting from drier conditions can lead to reduced permeability of peat, increasing rates of water loss (Page and Baird, 2016). There are limits to this resilience and the concept of tipping points beyond which ecosystems change state and returning to the original state has been subject of much recent research (van Nes et al., 2016). There is clear evidence that the degradation of ecosystems has reduced their resilience and restoration can help to reduce risks to biodiversity and ecosystem services, discussed below (see Section 2.6.2, 2.6.3). However, as rates of climate change increase, the limits of this approach will start to be reached and losses, including some with potentially catastrophic consequences, cannot be prevented; this is discussed further in Section 2.6.6.

2.6.2 Adaptation for Biodiversity Conservation

A variety of approaches have been identified as potential adaptation measures which people can take to reduce the risks of climate change to biodiversity. (Heller and Zavaleta, 2009) (quoted in AR5) identified 113 categories of recommendation for adaptation from a survey of 112 papers and reports. Since this time the literature has greatly expanded, with thousands of relevant publications. Whilst there is increasing interest in adaptation for biodiversity conservation and a wide range of plans and strategies, there is less evidence of these plans being implemented. Since AR5 a number of studies, predominantly from Europe and North America, have investigated the extent to which adaptation has been integrated into conservation planning and is being implemented at site and regional scale (Macgregor and van Dijk, 2014; Delach et al., 2019; Prober et al., 2019; Clifford et al., 2020; Barr et al., 2021; Duffield et al., 2021). A common pattern in these studies is that vulnerability has been assessed and potential adaptation actions identified, but implementation has been limited beyond actions to improve ecological condition, which may increase resilience at a local scale.

To date most scientific literature on adaptation to reduce risk to biodiversity from climate change has been based on ecological theory rather than observations or practical experience. A recent review (Prober et al., 2019) concluded that out of 473 papers on adaptation, only 16% presented new empirical evidence and very few assessed the effectiveness of actual adaptation actions. It is also the case that relatively little research is focussed on local-scale management interventions rather than larger scale strategies (Ledee et al., 2021), although there are some exceptions (Duffield et al., 2021).

Although direct assessments of the effectiveness of adaptation actions are rare, since AR5 there has been an increasing number of empirical analyses of how different land use and management influences the vulnerability of species and habitats. As climate change often interacts with other factors including ecosystem degradation and fragmentation (Oliver et al., 2015a), actions to address these other interacting factors is expected to build resilience to climate change. Table 2.6 summarises evidence that supports the main categories of proposed adaptation measures. We have taken an inclusive approach and included studies that address extreme weather events such as droughts, which may be exacerbated by climate change as well as long-term changes in climate variables. We have not distinguished between studies in which climate change adaptation was an explicit focus and those in which lessons for adaptation can be learnt from studies conducted for other reasons but inform the assessment of the impacts of actions identified as potential adaptation measures.

Table 2.6: Evidence to support proposed climate change adaptation measures for biodiversity. Highlights that adaptation for biodiversity is a broad concept, encompassing a wide range of actions. It includes targeted interventions to change the microclimate for particular species (for example by shading); through to changing national conservation objectives to take account of changing distributions of species and communities. It includes targeted actions addressing

both climate change and protection and restoration of ecosystems, with multiple additional benefits including reducing vulnerability to climate change. Most of the studies are not direct tests of the impacts of adaptation actions, which, as noted above, is an important evidence gap. There is also a major limitation in that reported studies are predominantly from Europe, North America and Australasia, with little research in other regions.

Proposed Adaptation Measures for Biodiversity	Confidence Assessment	Comment	Selected References
Protect large areas of natural and semi-natural habitat	*Robust evidence, high agreement*	Considerable evidence that intact systems provide better quality and quantity of ecosystem services; that larger intact areas provide better ecosystem services; that species' extinction risk with disturbances, including climate change, are reduced by having large, connected populations; that more biodiverse systems provide higher levels of ecosystem services and are more resilient to climate change than degraded systems that have lost species	Dinerstein et al. (2019); Woodley et al. (2019); Brooks et al. (2020); Zhao et al. (2020); Sala et al. (2021); Pimm et al. (2018); Hannah et al. (2020); Luther et al. (2020)
Increase connectivity in terrestrial habitats – corridors, stepping stones	*Medium evidence, Medium agreement*	Good evidence that some species move more quickly in more connected landscapes. However, not all species do and some species that benefit are invasive / pest / disease species and there is limited empirical evidence showing connectivity has reduced climate change impacts on species to date.	Keeley et al. (2018); Stralberg et al. (2019); von Holle et al. (2020)
Increase connectivity in river networks	*Limited evidence, High agreement*	Connectivity is needed to maintain species and population movements, but river reaches and catchments lack integrated protection.	Hermoso et al. (2016); Thieme et al. (2016); Abell et al. (2017); Brooks et al. (2018)
Increase habitat patch size site and expand protected areas	*Limited evidence High agreement*	Generally increase resilience because of functioning natural processes, large species populations and refugial areas	Eigenbrod et al. (2015); Oliver et al. (2015a)
Increase replication and representation of protected areas	*Limited evidence, High agreement*	Various benefits inferred, including, wider range of climatic and other conditions, less risk of extreme events affecting many rather than few areas. More sites available for colonisation by range expanding species and better conditions to maintain species in situ under range contraction.	Mawdsley et al. (2009); Thomas et al. (2012a); Virkkala et al. (2014); Gillingham et al. (2015); Pavón-Jordán et al. (2020b)
Protect microclimatic refugia	*Medium evidence, High agreement*	Locally cool areas can be identified and there is evidence species can survive better in such areas.	Haslem et al. (2015); Suggitt et al. (2015); Isaak et al. (2016); Morelli et al. (2016); Merriam et al. (2017); Bramer et al. (2018); Suggitt et al. (2018); Massimino et al. (2020)
Creating shade to lower temperatures for vulnerable species	*Limited evidence, High agreement*	Creating shade has been used as an adaptation strategy, for example by watercourses but improvements in species survival under warming conditions have yet to be demonstrated.	Broadmeadow et al. (2011); Lagarde et al. (2012); Patino-Martinez et al. (2012); Thomas et al. (2016)
Restoring hydrological processes of wetlands, rivers and catchments, including by raising water tables and restoring original channels of watercourses,	*Medium evidence, High agreement*	Wetland restoration is well established as a conservation measure in some countries. Can reduce vulnerability to drought with climate change but evidence to demonstrate effectiveness as an adaptation measure is limited and requires long-term monitoring of a range of sites. Little restoration of degraded tropical peatlands to date	Carroll et al. (2011); Hossack et al. (2013); Dokulil (2016); Timpane-Padgham et al. (2017); Moomaw et al. (2018)
Restoration of natural vegetation dynamics	*Medium evidence,*	Includes reintroduction of native herbivores and reversing woody encroachment of	Coffman et al. (2014); Valkó et al. (2014);

	Medium agreement	savannas. Benefits for biodiversity are well established in a wide range of different regions	Batáry et al. (2015); Smit et al. (2016); Stevens et al. (2016); Hempson et al. (2017); Bakker and Svenning (2018); Cromsigt et al. (2018); Fulbright et al. (2018); Olofsson and Post (2018)
Reduce non-climatic stressors to increase resilience of ecosystems	*Limited evidence, Medium agreement*	As a general principal climate change is recognised as a 'threat multiplier' but specific details are often unclear	Oliver et al. (2017); Pearce-Higgins et al. (2019)
Assisted translocation and migration of species	*Limited evidence, Medium agreement*	Assisted translocation has been commonly suggested as an adaptation measure, but there have been very few examples of this being trialed. Translocations have been carried out for other reasons and lessons for climate change adaptation have been inferred	Willis et al. (2009); Brooker et al. (2018); Skikne et al. (2020)
Intensive management for specific species	*Medium Evidence, Medium Agreement*	A variety of approaches including manipulating microclimate and competition between species to improve chances of survival under climate change.	Angerbjörn et al. (2013); Greenwood et al. (2016); Pearce-Higgins et al. (2019)
Ex-situ conservation (seedbanks/genetic stores, etc.)	Not possible to assess at present time	Seed banks have been established but long-term effectiveness could only be evaluated at a later point.	Christmas et al. (2016)
Adjusting conservation strategies and site objectives to reflect changing species distributions and habitat characteristics	*Robust evidence, High Agreement*	Conservation management will need to take account of changes that cannot be prevented, for example in the distribution of species and composition of communities, in order to protect and manage biodiversity as effectively as possible in a changing climate.	Stein et al. (2013); Rannow et al. (2014); Oliver et al. (2016); Stralberg et al. (2019); Duffield et al. (2021)
Softening the matrix of unsuitable habitats between patches to increase permeability for species movement in response to climate change	*Limited evidence*	Potential for agri-environment schemes to do this in hostile farmed landscapes.	Donald and Evans (2006); Stouffer et al. (2011)

Many climate adaptation actions for biodiversity operate at the landscape scale (von Holle et al., 2020). The total area of habitat, how fragmented it is, the size of habitat patches and the connectivity between them are interlinked properties at this scale. A growing number of studies have investigated how these properties affect species ability to persist *in situ* and colonise new areas. Overall, larger areas of semi-natural habitat are associated with increased resilience to ongoing climate change and extreme events and the capacity to colonise new areas (Haslem et al., 2015; Oliver et al., 2017; Papanikolaou et al., 2017). Larger habitat patches can support larger populations, which are more likely to maintain themselves and recover from periods of adverse conditions. A large patch size has been found to increase resilience of some populations of species to extreme events such as droughts (Oliver et al., 2015b). They are also more likely to provide a range of different resources and microclimate conditions, which may increase chances of species persistence under climate change. A larger area of habitat may also enables greater connectivity between patches and increases the chances of species colonising new areas as they track climate change. (Oliver et al., 2015b)Protecting and restoring natural processes is a general principle for maintain and building resilience to climate change for biodiversity (Timpane-Padgham et al., 2017). One element of this is ensuring naturally functioning hydrology for wetlands and river systems (Table 6), which is particularly important in a context of changing rainfall patterns and increased evapo-transpiration. An important development in approaches to conservation over recent decades has been the concept of re-wilding (Schulte To Bühne et al., 2021); this encompasses a number of elements of restoring natural processes, including the reintroduction of top predators, larger conservation areas and less prescriptive outcomes than much previous conservation. There are elements of re-wilding which may well contribute to building resilience to climate change but it will be increasingly important to factor climate change adaptation into the planning of rewilding schemes (Carroll and Noss, 2021).

The most consistently cited climate change adaptation measure for species is increasing connectivity to facilitate colonisation of new areas. This reflects the fact that many species' habitats are highly fragmented in areas with more intensive land management, which prevents them naturally changing their range to track changing climatic conditions. Advances and innovations in modelling techniques can support decision making on connectivity (Littlefield et al., 2019). There is evidence from empirical as well as modelling studies that species can disperse more effectively in better connected areas in terrestrial habitats (Keeley et al., 2018). The issues are different in more natural landscapes—species may still be threatened in intrinsically isolated habitats, such as mountain top, but connectivity cannot be created in the same way. Evidence suggests that increased connectivity will only benefit a subset of species, probably those which are intermediate habitat specialists that are able to disperse (Pearce-Higgins et al., 2014). Generalists do not require corridors or stepping stones whilst many corridors or stepping stones will not be of sufficient quality to be used by the most habitat specialists. There should also be a caveat to the general principle that increasing connectivity is a benefit for climate change adaptation. It can increase the spread of invasive, pest and disease-causing species into newly suitable regions. In some places isolated refugia may better allow vulnerable species and biological communities to survive.

There are many different approaches to increasing connectivity, ranging from increasing overall area of suitable habitat through to 'corridors' and 'stepping stones', with different strategies likely to be more effective for different species and circumstances (Keeley et al., 2018). Connectivity can also be important in increasing resilience of populations to extreme climatic events (Newson et al., 2014; Oliver et al., 2015b). Within freshwater environments, connectivity of watercourses is essential. Fluvial corridors are necessary to ensure migrating fish population survival, even without climate change; with climate change, connectivity becomes crucial for relatively cold-adapted organisms to migrate upstream to colder areas. Connectivity is also important for the larvae of benthic invertebrates to be able to drift downstream and hence to disperse (Brooks et al., 2018); for adult benthic invertebrates, riparian and terrestrial habitat features can potentially affect dispersal. Connectivity within river and wetland systems for some species can also mediated by more mobile animal species such as fish and birds (Martín-Vélez et al., 2020) Which factors are the most important in either promoting their colonisation of new sites or persisting *in situ* will differ between species and locations. Some general principle have been recognised and can guide conservation policy and practice (England and RSPB, 2020; Stralberg et al., 2020) but this will often require additional investigation and planning based on understanding individual the niche of specific species.

Managed, translocation by moving species from areas where the climate is becoming unsuitable to places where there persistence under climate change is more likely has been discussed as an adaptation option for many years. So far there have been very few examples of this and it is likely to be a last resort in most cases as in many cases it requires a large investment of resources, the outcome is uncertain and there may be adverse impacts on receiving sites. Nevertheless there are cases where it may be a be a viable option (Stralberg et al., 2019). This is discussed in more detail as a case study in section 2.6.5.1.

The evidence that species can persist in microclimatic refugia where suitable conditions for them are maintained locally (for example, because of variations in topography) has increased in recent years. This has opened up the potential to include refugia in conservation plans and strategies to facilitate local survival of species (Jones et al., 2016; Morelli et al., 2016; Morelli et al., 2020). For example, in targeting management actions (Sweet et al., 2019) aimed at supporting populations of species and is likely to become an important aspect of climate change adaptation for biodiversity conservation in future. It is also possible to manipulate microclimate for example by creating shelters for birds' nests (see case study of African Penguins 2.6.5.5) (Patino-Martinez et al., 2012). One specific approach of this sort is planting or retention of trees and wooded corridors to shade water courses (see also case study 2.6.4.5 below; Thomas et al., 2016). In the latter case, riparian shading can also possibly help to reduce phytoplankton and benthic diatom growth in smaller streams and rivers (Halliday et al., 2016).

Refugia often refer to locally places in a landscape, such as on shaded slopes or high elevations, but they can also include places where water supply may continue during dry periods (Morelli et al., 2016) Monitoring can reveal which streams, wetlands, springs, and other aquatic resources retain suitable discharges, water quality, wetland area, and ecological integrity, especially during dry years (Cartwright et al., 2020). Measures to conserve drought refugia may include protecting springs and other groundwater-fed systems from groundwater extraction, contamination, salinisation, surface-water diversion, channelisation of streams, livestock trampling, recreation and invasive species, as well as effects from surrounding landscape disturbances (Cartwright et al., 2020; Krawchuk et al., 2020). Restoration of degraded aquatic ecosystems can include removal of flow-diversion infrastructure, exclusion of livestock, reduction of other human impacts, geomorphic restructuring, invasive species removal, and planting of native riparian vegetation.

In fire prone areas, fire suppression and management is a key element of protecting refugia (Section 2.6.5.8 below). In ecosystems in which a natural fire regime has been suppressed restoration practices such as prescribed fires, thinning trees, and allowing some wildfires where it benefits the ecosystem can be introduced to reduce increasing risks from severe wildfires (Meigs et al., 2020).

Protected areas—areas of land set aside for species and habitat protection with legal protection from development or exploitation—have been a cornerstone of nature conservation for many years. Their effectiveness under a changing climate has been the subject of debate and investigation. There is now a large body of evidence demonstrating that colonisations by range shifting species are more likely to occur on protected sites compared to non-protected sites for a wide range of taxa (e.g. Thomas et al., 2012b; Gillingham et al., 2015), including across continents (Pavón-Jordán et al., 2020a). This is probably because by protecting large areas of natural and semi-natural habitats they provide suitable places for colonising species (Hiley et al., 2013) which may not be available in the surrounding landscape. Although the evidence for protected areas being associated with reduced extinctions is weaker, the finding in Gillingham et al. (2015) that protected sites were associated with reduced extinction rates at low latitudes and elevations is strongly suggestive that they can help species' persistence in the face of climate change.

It is intrinsically difficult to assess the effectiveness of climate change adaptation measures, the benefit of which will be realised in years and decades ahead (Morecroft, 2019, Measuring success). Nevertheless, taking account of the wide range of evidence reported above, including theory, modelling and observations of climate change impacts in contrasting circumstances, it is possible to make an overarching assessment that appropriate adaptation measures can reduce the vulnerability of many aspects of biodiversity to climate change (*robust evidence, high agreement*). It is also however clear that to be most effective and avoid unintended consequences, measures need to be carefully implemented taking account of specific local circumstances *(robust evidence, high agreement)* and include the management of inevitable changes (*robust evidence, high agreement*). It is also clear that whilst there are now many plans and strategies for adapting biodiversity conservation to climate change, many have yet to be implemented fully (*medium evidence, high agreement*).

2.6.3 Nature-based Solutions: Ecosystem-based Adaptation

Ecosystem-based Adaptation is an increasingly important element of Nature-based Solutions (see 2.6 above). A study published in 2020 found that out of 162 Intended Nationally Determined Contributions (covering 189 countries) submitted to the United Nations Framework Convention on Climate Change, as commitments to action under the Paris Agreement, 109 indicated 'ecosystem-orientated visions' for adaptation, although only 23 use the term 'Ecosystem-based Adaptation' (Seddon et al., 2020b).

EbA includes a range of different approaches. Examples include restoring coastal and river systems to reduce flood risk and improve water quality and the creation of natural areas within urban areas to reduce temperatures through shading and evaporative cooling. EbA is closely linked with a variety of other concepts such as ecosystem services, natural capital and Disaster Risk Reduction (DRR). EbA was becoming a well-recognised concept at the time of AR5 but implementation was still at an early stage in many cases. Since then pilot studies have been assessed and EbA projects have been initiated around the world. The evidence base continues to grow (Table 2.7) and this has led to increasing confidence in approaches which have been shown to work leading to further expansion in some countries (Table 2.7). However, this is not uniform and there is relatively little synthesis across disciplines and regions (Seddon et al., 2020a). Chausson et al. (2020) used a systematic mapping methodology to characterise 386 published studies. They found that interventions in natural or semi-natural ecosystems ameliorated adverse climate change impacts in 66% of cases, with fewer trade-offs than for more artificial systems such as plantation forest. However, the evidence base has substantial gaps. Most of the evidence has been collected in the Global North and there is a lack of robust, site-specific investigations of the effectiveness of interventions compared to alternatives and of more holistic appraisals accounting for broader social and ecological outcomes.

Table 2.7: Examples of key Ecosystem- based Adaptation measures with assessments of confidence. Note only adaptation related services are shown – many measures also provide a range of other benefits to people. All also provide benefits for biodiversity.

Ecosystem Based Adaptation Measures	Confidence Assessment	Ecosystem Services for climate change adaptation	Climate Change Impact addressed	Social Benefits from adaptation	Relevant Ecosystems and contexts	Selected References
Natural Flood risk management in river systems –restoring natural river courses (removing canalisation), restoring and protecting wetlands and riparian vegetation	*Medium evidence Medium agreement*	Flood regulation; sediment retention; water storage; water purification	Increased rainfall intensity	Reduction of flood damage Increased water security (quality and supply)	Multiple	Iacob et al. (2014); Meli et al. (2014); Burgess-Gamble et al. (2017); Dadson et al. (2017); Rowiński et al. (2018)
Shade rivers and streams by restoration of riparian vegetation or trees.	*Medium evidence High agreement*	Provision of fish stocks	Warmer water temperatures	Food security income benefits	Multiple	Broadmeadow et al. (2011); Isaak et al. (2015); Williams et al. (2015b); Thomas et al. (2016)
Managed realignment of coastlines; re-establishing and protecting coastal habitats including mangroves, salt marsh,	*Robust evidence High agreement*	Coastal storm and flood protection Coastal erosion control Salt water intrusion prevention	Rising sea level Increasing storm energy	Protection of life, property and livelihoods Water security	Coastal	Høye et al. (2013); Spalding et al. (2014); Narayan et al. (2016); Morris et al. (2018); Chowdhury et al. (2019); Powell et al. (2019)
Agroforestry and other agro-ecological/conservation agricultural practices on agricultural land	*Medium evidence Medium agreement*	Local climate regulation; soil conservation; soil nutrient regulation; water conservation; pest control; food provisioning	High temperature or changing temperature regimes Changing precipitation regimes	Food security income benefits	Multiple	Vignola et al. (2015); Torralba et al. (2016); Paul et al. (2017); Blaser et al. (2018); Nesper et al. (2019); Verburg et al. (2019); Aguilera et al. (2020); Tamburini et al. (2020)
Restore and maintain urban and peri-urban green space – trees, parks, local nature reserves, created wetlands	*Robust evidence High agreement*	Local climate regulation Flood regulation Water purification Water storage	Higher temperatures and heatwaves Increased rainfall intensity or	Cooler microclimate Reduced flood damage, water security	Urban areas	Norton et al. (2015); Liquete et al. (2016); Liu (2016); Bowler et al. (2017); Aram et al. (2019);

		Erosion control	reduced rainfall intensity			Stefanakis (2019); Ziter et al. (2019)
Ecological restoration for fire risk reduction through restoration of natural vegetation and herbivory and by re-instating natural fire regimes	*Medium evidence High agreement*	Regulation of wildfires	Mega-fires from increases in drought and heat	Reduce deaths and infrastructure damage from fires	Fire-adapted ecosystems	Waldram et al. (2008); Stephens et al. (2010); van Mantgem et al. (2016); Boisramé et al. (2017); Johnson et al. (2018); Parisien et al. (2020a); Parisien et al. (2020b); Stephens et al. (2020)
Invasive non-native aquatic plant control to improve water security	*Robust evidence High agreement*	Water provision	Increasing droughts	water security	Water scarce regions prone to an increase in droughts	van Wilgen and Wannenburgh (2016)
Woody plant control (of encroaching biomass) in open grassy ecosystems to restore and maintain grassy vegetation (see 2.4.3.5)	*Medium evidence Medium agreement*	Fodder biomass production	Elevated CO_2 increasing tree growth/ increases in rainfall promoting tree growth	income through bush clearing, fuelwood supplies, restore grazing	Savanna and grasslands	Haussmann et al. (2016)
Rangeland rehabilitation and management such as through livestock enclosures, appropriate grazing management, re-introducing native grassland species	*Medium evidence Medium agreement*	Fodder biomass production; soil erosion control; soil formation; nutrient cycling; water retention	Changing precipitation and temperature regimes including prolonged dry seasons and increased drought frequency	Food security Water security, income benefits	Rangelands	Descheemaeker et al. (2010); Wairore et al. (2016); Kimiti et al. (2017)
Sustainable forestry of biodiverse managed forests, maintaining forest cover and protecting soils	*Medium evidence Medium agreement*	Timber production	Increased frequency and severity of storms Higher temperatures Changing precipitation regimes (more intensive wet and dry periods) Increased incidents of wildfire, pest, and disease outbreaks	Livelihood and income benefits	Boreal, temperate, subtropical, tropical forests	Gyenge et al. (2011); Barsoum et al. (2016); Jactel et al. (2017); Cabon et al. (2018)

Watershed reforestation and conservation for hydrological services	*Medium evidence Medium agreement*	Flood control; erosion control; water provisioning; water purification	Changing precipitation regimes	Food security; Water security; Flood Protection	Boreal, temperate, subtropical, tropical forests	Filoso et al. (2017); Bonnesoeur et al. (2019)
Multifunctional forest management and conservation to provide climate resilient sources of food and livelihoods and protect water sources	*Medium evidence Medium agreement*	Timber and non-timber forest production; fuel wood production; water provisioning; water purification	Multiple	Food security; Water security; income benefits	Boreal, temperate, subtropical, tropical forests	Lunga and Musarurwa (2016); Strauch et al. (2016); Adhikari et al. (2018)
Slope revegetation for landslide prevention and erosion control	*Robust evidence High agreement*	Soil retention; slope stabilisation	Increased rain frequency	Reduced landslide damage; prevention of loss of life	Montane and other steep sloped regions	Fox et al. (2011a); Krautzer et al. (2011); Leal Filho et al. (2013); Bedelian and Ogutu (2017); Getzner et al. (2017); de Jesús Arce-Mojica et al. (2019)

Restoring coasts, rivers and wetlands to reduce flood risk have probably seen the largest investment in EbA and it is becoming an increasingly accepted approach in some places (e.g. case studies in Sections 2.6.5.2, 2.6.5.7) although significant social, economic and technical barriers remain (Wells et al., 2020; Bark et al., 2021; Hagedoorn et al., 2021). Natural flood management encompasses a wide range of techniques in river systems and at the coast and have been used in varied locations around the world. In tropical and sub-tropical areas, the restoration of mangroves to reduce the risk of coastal flooding is widely advocated, evidence-based approach (for example (Høye et al., 2013; Sierra-Correa and Kintz, 2015; Powell et al., 2019)). In temperate regions salt marsh is a similarly important habitat (Spalding et al., 2014). Both provide buffering against rising sea levels and storm surges. Managed realignment of the coast, by creating new habitats can lead to a loss of terrestrial and freshwater ecosystems, but it can protect them and the services they provide by reducing the risks of catastrophic failure from hard-engineered sea defences. In river systems (Iacob et al., 2014) management of both catchments and the channel itself is important: restoring natural meanders in canalised water courses and allowing the build-up of woody debris can slow flows rates; restoring upstream wetlands or creating them in urban and peri-urban situations can store water during flood events if they are in the right place in a catchment (Acreman and Holden, 2013; Ameli and Creed, 2019; Wu et al., 2020). There is less data on the potential for natural flood management in tropical compared to temperate catchments, however (Ogden et al., 2013) showed that flooding was reduced from a secondary forested catchment compared to those which were pasture or a mosaic of forest, pasture and subsistence agriculture. EbA approaches to reduce flooding can be applied within urban areas, as well as in rural catchments, as in Durban (Section 2.6.5.7), although its effectiveness will depend on its being implemented at a sufficient scale and in the right locations (Hobbie and Grimm, 2020; Costa et al., 2021). which may in turn provide protection to downstream urban communities.

Protecting and restoring natural river systems, natural vegetation cover within catchments and integrating agro-ecological techniques into agricultural systems can also help to maintain and manage water supplies for human use, under climate change, including during drought periods, by storing water in catchments and improving water quality (Taffarello et al., 2018; Agol et al., 2021; Khaniya et al., 2021) (Lara et al., 2021) showed that replacing a non-native *Eucalyptus* plantation in Chile with native forest caused base flow increased by 28% to 87% during the restoration period compared to pre-treatment, and found it remained during periods with low summer precipitation

EbA can operate at a range of different scales, from local to catchment to region. At the local scale, there is a variety of circumstances in which microclimates can be managed and local temperatures lowered by the presence of vegetation (Table 2.7), and these EbA techniques are now being used more widely. In both urban and agricultural situations, shade trees are a traditional technique, which can be applied to contemporary climate change adaptation. Shading of water courses can lower temperatures, as reported in Section 2.6.2, above, which can allow species to survive locally, as well as supporting diversity it can help to maintain are important fisheries, including of Salmonid fish (O'Briain et al., 2020). Within cities, green spaces, including parks, local nature reserves and green roofs and walls can also provide cooling as a result of evapo-transpiration (Bowler et al., 2010a; Aram et al., 2019; Hobbie and Grimm, 2020), although this may be reduced in drought conditions.

Wildfire is an increasing risk for people as well as to ecosystems, in many parts of the world. As discussed in Section 2.4.4.2, this is the result not just of climate change but also past management practices, including fire suppression. Better fire management including reinstating more natural fire regimes can reduce risks.

EbA is usually a place-specific approach and a number of studies have documented how attempts to implement it without an understanding of local circumstances and full engagement of local communities have been unsuccessful (Nalau et al., 2018). Since AR5, a number of studies have considered the factors that are important for environment adaptation programmes and projects (UNFCCC, 2015; Nalau et al., 2018; Duncan et al., 2020; Network and ENCA, 2020; Townsend et al., 2020). Considering these sources, others described above and the case studies presented, in 2.6.5, a number of requirements for effective implementation of EbA can be identified, including the following:

- Targeting of the right EbA measure in the right location
- Decision-making at the appropriate level of governance with participation from all affected communities
- Integration of Local Knowledge and Indigenous Knowledge & capacity into decision-making and management of project
- Involvement of government and non-government stakeholders
- Full integration of EbA with other policy areas, including agriculture, water resources and natural resource protection
- Protection and if possible improvement of incomes of local people.
- Effective institutional support to manage finances and implementation of projects and programmes.
- Time -many EbA interventions take time to establish e.g. trees to grow, wetlands recover
- Monitoring of intended outcomes and other impacts and communication of results

Whilst it is essential to develop place-specific EbA measures, with full engagement of local communities, it is worth noting that new opportunities may emerge that would not have been possible in the past. As the climate changes, novel ecosystems may emerge with no present day analogue which have the potential to provide different adaptation benefits and societies may be more willing to adopt transformative approaches (Colloff et al., 2017; Lavorel et al., 2020).

Increasingly it is essential to integrate adaptation and the protection of biodiversity with land based climate change mitigation initiatives; this is discussed in more detail in Cross-Chapter Box NATURAL, this Chapter. The new IUCN standard (IUCN, 2020, Global standard) offers a basis for assessing whether actions are true Nature-based Solutions and take account of the wider factors necessary for success.

Whilst policy interest is growing and there is an increasing deployment of EbA there is still a long way to go in delivering it full potential (Huq and Stubbings, 2015) and significant institutional and cultural barriers remain(Huq et al., 2017; Nalau et al., 2018). Nevertheless it is increasingly clear that EbA can offer a portfolio of effective measures to reduce risks from climate change to people at the same time as benefiting biodiversity (*robust evidence, high agreement*), providing they are deployed with careful planning in a way that is appropriate local ecological and societal contexts (*robust evidence, high agreement*).

2.6.4 Adaptation for Increased Risk of Disease

Low-probability events can be very high impact (for example, the transmission of the SARS-CoV-2 from wild animals to humans). A robust disease risk reduction policy would include utilizing a One Biosecurity approach (Hulme, 2020) with actions to reduce disease risk across multiple sectors and from a variety of anthropogenic drivers, including climate change, even if there is high uncertainty in projected risk (see Cross-Chapter Boxes: ILLNESS, COVID, DEEP). Kraemer et al. (2019) found that vector importation was a key risk factor and focus should be on preventing invasive species introductions. Further, many neglected tropical diseases (NTDs) are also VBDs, and the UN SDG of good health and well-being explicitly calls for increased control and intervention with a focus on emergency preparedness and response (Stensgaard et al., 2019a). Online tools are being developed to warn conservation biologists when species of conservation concern are at greater risk of disease outbreaks due to environmental changes (e.g., for Hawaiian Honeycreepers and avian malaria (Berio Fortini et al., 2020) and for coral diseases (Caldwell et al., 2016)). Forecasting models to warn of human disease outbreaks like malaria and dengue are also now available, with findings that multiple model ensemble forecasts outperform individual models (Lowe et al., 2013; Lowe et al., 2014; Lowe et al., 2018; Zhai et al., 2018; Johansson et al., 2019; Tompkins et al., 2019; Muñoz et al., 2020; Colón-González et al., 2021; Petrova et al., 2021). Improving vector-borne disease and NTD public health responses will require multi-disciplinary teams capable of interpreting, analyzing, and synthesizing diverse components of complex ecosystem-based studies for effective intervention (Mills James et al., 2010; Rubin et al., 2014; Valenzuela and Aksoy, 2018), broad epidemiological and entomological surveillance (Depaquit et al., 2010; Lindgren et al., 2012; Springer et al., 2016), and community-based disease control programs that build local capacity (Andersson et al., 2015; Jones et al., 2020b).

[START CROSS-CHAPTER BOX ILLNESS HERE]

Cross-Chapter Box ILLNESS: Infectious Diseases, Biodiversity and Climate: Serious Risks Posed by Vector- and Water-borne Diseases

Authors: Marie-Fanny Racault (United Kingdom/France, Chapter 3), Stavana E. Strutz (USA, Chapter 2), Camille Parmesan (France/United Kingdom /USA, Chapter 2), Rita Adrian (Germany, Chapter 2), Guéladio Cissé (Mauritania/Switzerland/France, Chapter 7), Sarah Cooley (USA, Chapter 3), Adugna Gemeda (Ethiopia, Chapter 9), Nathalie Jeanne Marie Hilmi (Monaco/France, Chapter 18), Salvador E. Lluch-Cota (Mexico, Chapter 5), Gretta Pecl (Australia, Chapter 11), David Schoeman (Australia, Chapter 3), Jan C. Semenza (Italy, Chapter 7), Maria Cristina Tirado (USA/Spain, Chapter 7), Gautam Hirak Talukdar (India, Chapter 2), Yongyut Trisurat (Thailand, Chapter 2), Meghnath Dhimal (Nepal, CA), Luis E. Escobar (Guatemala/Columbia/USA, CA), Erin Mordecai (USA, CA), A. Townsend Peterson (USA, CA), Joacim Rocklöv (Sweden, CA), Marina Romanello (United Kingdom, CA)

Climate change is altering the life cycles of many pathogenic organisms and changing the risk of vector- and water-borne infectious diseases transmission to humans (high confidence). Re-arrangement and emergence of some diseases are already observed in temperate-zone and high-elevation areas, and coastal areas (medium to high confidence). Shifts in the geographic and seasonal range suitability of pathogens and vectors are related to climatic-impact drivers (warming, extreme events, precipitation, humidity) (high to very high confidence), but there are substantial non-climatic drivers (land use change, wildlife exploitation, habitat degradation, public health and socio-economic conditions) that affects the attribution of the overall impacts on prevalence or severity of some vector- and water-borne infectious diseases over recent decades (high confidence). Adaptation options that involve sustained and rapid surveillance systems, and the preservation and restoration of natural habitats, with their associated higher levels of biodiversity, both marine and terrestrial, will be key to reducing risk of epidemics and large-scale disease transmissions (medium confidence).

Since AR5, further evidence is showing that climate-related changes in the geographic and seasonal range suitability of pathogens and vectors and in the prevalence or new emergence of vector- and water-borne infectious diseases have continued across many regions worldwide and are sustained over decadal time scales (*medium to high confidence*) (WGII Sections 2.4.2.5, 3.5.5.3, 7.2, 7.3, 9.10.1.2.1; Harvell et al., 2009; Garrett et al., 2013; Burge et al., 2014; Guzman and Harris, 2015; Baker-Austin et al., 2018; Watts et al., 2019; Semenza, 2020; Watts et al., 2021) . Ecosystem-mediated infectious diseases at risk of increase from climate change include water-borne diseases associated with pathogenic *Vibrio* species (e.g., those causing cholera and vibriosis), and harmful algal blooms (e.g., ciguatera-fish poisoning) (SROCC 5.4.2.1.1, Box 5.4, AR6 WGII 3.5, Table 3.S.3, 5.12; Baker-Austin et al., 2013; Levy, 2015; Trtanj et al., 2016; Ebi Kristie et al., 2017; Mantzouki et al., 2018; Nichols et al., 2018), and vector-borne diseases associated with arthropods (e.g., malaria, dengue, chikungunya, Zika virus, West Nile virus, and Lyme disease), helminths (e.g., schistosomiasis) and zoonotic diseases associated with cattle and wildlife (e.g., leptospirosis) (*medium to high confidence*) (Sections 2.4.2.7, 3.5, 7.2, 7.3, 9.10.1.1.1, 13.7.1.2, 14.4.6, Cross-Chapter Box COVID in Chapter 7; Table Cross-Chapter Box ILLNESS.1; SR1.5 3.4.7.1; Ebi et al., 2021) .

The attribution of observed changes in disease incidence partly or fully to climatic-impact drivers remains challenging because of the difficulty of accurately capturing the contributions of multiple, interacting, and often nonlinear underlying responses of host, pathogen, and vector, which can be influenced further by non-climate stressors and the long history of anthropogenic disturbance. Disease emergence in new areas requires independent drivers to coincide (i.e., increasing climate suitability for pathogen or vector survival and competence/capacity, and introduction of the pathogen via mobility of human populations). Further, the extent to which changes in ecosystem-mediated diseases impact human health is highly dependent upon local socio-economic status, sanitation, medical systems, and practices (Section 2.4.2.5; Figure FAQ2.3.1; Gething et al., 2010; Lindgren et al., 2012; Mordecai et al., 2013; Liu-Helmersson et al., 2014; Bhatt et al., 2015; Morin et al., 2015; Ryan et al., 2015; Wesolowski et al., 2015; Stanaway et al., 2016; Yamana et al., 2016; Mordecai et al., 2017; Tesla et al., 2018; Ryan et al., 2019; Shah et al., 2019; Iwamura et al., 2020; Mordecai et al., 2020; Colón-González et al., 2021; Ryan et al., 2021).Thus, the links between climate change, ecosystem change, health and adaptation need to be considered concurrently (AR6 WGII 2.4, 3.5.3, 7.2, 7.3, 4.3.3, 6.2.2.3, Table 2.S.1).

Table Cross-Chapter Box ILLNESS.1: Observed climate change impacts on cholera, dengue, and malaria. 1) Cholera: Endemicity based on Ali et al., 2015. Changes (2003-2018) in suitability for coastal *Vibrio cholerae* estimated from model observations driven by sea-surface temperature (SST) and chlorophyll-a (CHL) concentration (Escobar et al., 2015; Watts et al., 2019). Vulnerabilities based on Sigudu et al., 2015, Agtini et al., 2005, and Sack et al., 2003. 2) Dengue: Endemicity based on Guzmen et al., 2015. 3) Malaria: Endemicity based on Phillips et al. 2017, and WHO Global Malaria Programme. Impacts of climate change on diseases and their vectors are most evident at the margins of current distributions. However, climate change is difficult to implicate in areas with extensive existing transmission and vector/pathogen abundance, and in particular is difficult to separate from concurrent directional trends in disease control, changes in land use, water access, socioeconomic and public health conditions. As a result, while many studies indicate increasing climate suitability of some areas for cholera, dengue, and malaria, the degree to which these changes can be attributed to climate change remains challenging. For these cases, confidence statements of *low, medium*, or *high* reflect confidence that variation in the disease and/or vector/pathogen is associated with variation in climate drivers, rather than with directional climate change *per se*. Acronyms: ONI (Oceanic Niño Index), Tmin (minimum temperature), SPI (Standardised Precipitation Index), LST Land-surface temperature. Full references for this table can be seen in supplemental table 6 (see Table 2.S.6).

	Cholera	Dengue	Malaria
Africa			
Endemicity	Endemic	Endemic in sub-Saharan Africa but not S South Africa	Endemic
Climate drivers	Disease incidence: NE Africa, Central Africa & Madagascar: Rainfall (*medium confidence*) SE Africa: Rainfall, LST, SST, Plankton (*medium to high confidence*) ES Africa: SST, CHL (*low* confidence due to *limited evidence*) W Africa: Rainfall (floods), LST, SST (*medium to high confidence*)		W Africa: Temp (*medium to high confidence)* E Africa: Temp *medium to high confidence)*
Change and Confidence	Area of coastline suitable for outbreak: N&W Africa: Increase (*low to medium confidence)* C & E Africa: No change (*low to medium confidence)* S Africa: Decrease (*low to medium confidence)*	Potentially expanding *(low confidence)* Dengue and *Ae. aegypti* present but underdetected in climatically suitable areas.	E Africa: Upward shift and increase in malaria & *Anopheles* spp. in highland areas *(medium to high confidence)* Widespread decreases due to malaria control *(medium confidence)* and warming climate *(low confidence)*

Vulnerabilities	ES Africa: women of all ages more affected than men by outbreaks		
Asia			
Endemicity	Endemic	Endemic in S Asia, SE Asia, and E Asia	Endemic in S Asia, SE Asia, Partially endemic in E Asia
Climate drivers	Disease incidence: E Asia: SST, CHL, Sea Level (medium to high confidence) S Asia: SST, CHL, LST, Rainfall(floods) (high to very high conficende)	S Asia: Rainfall, Temp, Humidity *(medium confidence)* SE Asia: Rainfall, Temp *medium confidence)* E Asia: Rainfall, Temp, Typhoons *(low confidence)*	S Asia: Rainfall, Temp *(*medium to high confidence*)* SE Asia: Rainfall, Temp *(medium confidence)*
Change and Confidence	Area of coastline suitable for outbreak: Increase (*low to medium confidence*)	SE Asia: Increase (*low confidence)* S Asia: Increase (*medium confidence)* E Asia: Increase (*low confidence)*	S Asia: Increase *(medium confidence)*
Vulnerabilities	SE Asia: infants (<9 years) with highest incidences of cholera S Asia: older children and young adults (16-20 years old) more frequently reported with cholera than non-cholera diarrhoea		
Australasia			
Endemicity	Not endemic	Partially endemic in N Australia	Not endemic
Climate drivers	No evidence for disease incidence	Rainfall, Temp *(low confidence)*	
Change and Confidence	Area of coastline suitable for outbreak: No change (*low to medium confidence*)	Increase in sporadic outbreaks due to climate change (*low confidence)*	No change
Central America			
Endemicity	Not endemic	Endemic	Partially endemic
Climate drivers	No evidence for disease incidence	ONI, SST, Tmin, Temp, Rainfall, Drought (*low confidence)*	
Change and Confidence	Areas of coastline suitable for outbreak: Decrease (*low to medium confidence)*	Increasing due to climate (*low confidence)* Upward expansion of *Ae. aegypti (low confidence)*	Overall decrease not linked to climate change. Focal increases due to human activities.
South America			
Endemicity	Epidemic	Endemic in all regions except S South America	Endemic
Climate drivers	Abundance of coastal *V. cholerae*: NW South America: SST, Plankton (*low to medium confidence*)	Temp, Prec, Drought	N South America: Temp (*low confidence)* N SE South America: Tmax, Tmin, humidity *(low confidence)*
Change and Confidence	Area of coastline suitable for outbreak: No change (*low to medium confidence*)	Increasing due to urbanization and decreased vector control programmes, not strongly linked to climate	Higher elevation regions: Increase (*low confidence)*
Europe			
Endemicity	Not endemic	S Europe: focal outbreaks	Not endemic
Climate drivers	No evidence for disease incidence Abundance of coastal *V. cholerae*: N Europe: SST, Plankton (medium confidence)		
Change and Confidence	Area of coastline suitable for outbreak: Increase (*low to medium confidence*)	Mediterranean regions of S Europe: Outbreaks *(low confidence)*	No change
North America			
Endemicity	Not endemic	Partially endemic in S North America	Not endemic
Climate drivers	Area of coastline suitable for outbreak: Increase (*low to medium confidence*)	Winter minT *(Low)*	

Change and Confidence	No evidence for disease incidence Abundance of coastal *V. cholerae*: EN America: SST (*Low* due to *limited evidence*)	Declining	No change
Small Islands			
Endemicity	Epidemic	Endemic in many small islands in the Tropics	Endemic in many small islands in the Tropics
Climate drivers	Disease incidence: Caribbean: SST, LST, Rainfall (low to medium confidence)	Caribbean: SPI, Tmin *(low confidence)*	
Change and Confidence	Area of coastline suitable for outbreak: Caribbean & Pacific Small Island: Decrease (low to medium confidence)	Increasing (*low confidence)*	Decrease in Caribbean not linked to climate

Observed and projected changes

In aquatic systems, at least 30 human pathogens with water infection-routes (freshwater and marine) are affected by climate change (Section 3.5.3 Table SM3.G; Nichols et al., 2018) . Warming, acidification, hypoxia, sea-level rise, and increases in extreme weather and climate events (*e.g.* marine heatwaves, storm surges, flooding, and drought), which are projected to intensify in the 21st century (*high confidence*) (AR6 WGI SPM B2.2, B.3.2), are driving species' geographic range shifts and global rearrangements in the location and extent of areas with suitable conditions for many harmful pathogens, including viruses, bacteria, algae, protozoa, and, helminths (*high confidence*) (Sections 2.3, 2.4.2.7, 3.5.5.3, SROCC 5.4.2.1.1, Box 5.4; Trtanj et al., 2016; Ebi Kristie et al., 2017; Manning and Nobles, 2017; Pecl et al., 2017; Mantzouki et al., 2018; Nichols et al., 2018; Bindoff et al., 2019; Kubickova et al., 2019; Watts et al., 2019; Watts et al., 2020; Watts et al., 2021).

Incidence of cholera and *Vibrio*-related disease outbreaks has been shown to originate primarily in coastal regions, and then spread inland via human transportation. Our understanding of impacts of climate drivers on the dynamics of *Vibrio*-related infections have been strengthened through improved observations from long-term monitoring programs (e.g., (Vezzulli et al., 2016)), and statistical modelling supported by large-scale and high-resolution satellite observations of climate drivers (*high confidence*) (e.g., Baker-Austin et al., 2013; Escobar et al., 2015; Jutla et al., 2015; Martinez et al., 2017; Semenza et al., 2017; Racault et al., 2019; Campbell et al., 2020).

The coastal area suitable for *V. cholerae* (the causative agent for cholera) has increased by 9.9% globally compared to a 2000s baseline (Escobar et al., 2015; Watts et al., 2019). The poleward expansion of the distribution of *Vibrio* spp. has increased the risk of vibriosis outbreaks in northern latitudes. Specifically, the coastal area suitable for *Vibrio* infections in the past 5 years has increased by 50.6% compared with a 1980s baseline at latitudes of 40–70°N; in the Baltic region, the highest-risk season has been extended by 6.5 weeks over the same periods (Watts et al., 2021). Already, studies have noted greater numbers of *Vibrio*-related human infections, and most notably disease outbreaks linked to extreme weather events such as heat waves in temperate regions such as Northern Europe (Baker-Austin et al., 2013; Baker-Austin et al., 2017; Baker-Austin et al., 2018) (*high confidence*). By the end of the 21^{st} century, under RCP6.0, the number of months of risk of *Vibrio* illness is projected to increase in Chesapeake Bay by 10.4±2.4%, with largest increases during May and September, which are the months of strong recreational and occupational use, compared to a 1985-2000 baseline (Jacobs et al., 2015; Davis et al., 2019a). In the Gulf of Alaska, the coastal area suitable for *Vibrio* spp. is projected to increase on average by 58%±17.2% in summer under RCP6.0 by the 2090s, compared to a 1971-2000 baseline (*low to medium confidence*) (Jacobs et al., 2015).

On land, increased global connectivity and mobility, unsustainable exploitation of wild areas and species, land conversion (agricultural expansion, intensification of farming, deforestation, infrastructure development), together with climate-change-driven range shifts of species and human migration (Cross-Chapter Box MOVING PLATE in Chapter 5), have modified interfaces between people and natural systems (IPBES, 2018a). Climate-driven increase in temperature, frequency and intensity of extreme events, and changes in precipitation and relative humidity, have provided opportunities for re-arrangements of disease geography and seasonality, and emergence into new areas (*high confidence*) (Section 2.4.2.7). In particular, malaria has expanded into higher elevations in recent decades and although climate change attribute remains challenging (Hay et al., 2002; Pascual et al., 2006; Alonso et al., 2011; Campbell et al., 2019c), evidence that the elevational distribution of malaria has tracked warmer temperatures is compelling for some regions (Siraj et al., 2014). Models based on both empirical relationships between temperature and the *Anopheles* mosquito and *Plasmodium* parasite traits that drive transmission (Mordecai et al., 2013; Yamana Teresa and Eltahir Elfatih, 2013; Johnson et al., 2015) and existing mosquito distributions (Peterson, 2009) predict that warming will increase the risk of malaria in highland East Africa and Southern Africa, while decreasing the risk in some lowland areas of Africa, as temperatures exceed the thermal optimum and upper thermal limit for transmission (Peterson, 2009; Yamana Teresa and Eltahir Elfatih, 2013; Ryan et al., 2015; Watts et al., 2021).

In contrast to malaria, dengue has expanded globally since 1990, particularly in Latin America and the Caribbean, South Asia, and sub-Saharan Africa (Stanaway et al., 2016). While urbanization, changes in vector control, and human mobility play roles in this expansion (Gubler, 2002; Åström et al., 2012; Wesolowski et al., 2015), the physiological suitability of temperatures for dengue transmission is also expected to have increased as climates have warmed (Colón-González et al., 2013; Liu-Helmersson et al., 2014; Mordecai et al., 2017; Rocklöv and Tozan, 2019). Models predict that dengue transmission risk will expand across many tropical, subtropical, and seasonal temperate environments with future warming (Åström et al., 2012; Colón-González et al., 2013; Ryan et al., 2019; Iwamura et al., 2020; Watts et al., 2021)).

Adaptation options

During the 21st century, public health adaptation measures (Figure Cross-Chapter Box ILLNESS.2) have been put in place in attempts to control or eradicate a variety of infectious diseases by improving surveillance and early detection systems; constraining pathogen, vector, and/or reservoir host distributions and abundances; reducing likelihood of transmission to humans; and improving treatment and vaccination programs and strategies (*medium to robust evidence, medium to high agreement*) (Chinain et al., 2014; Adrian et al., 2016; Friedman et al., 2017; Konrad et al., 2017; Semenza et al., 2017; Borbor-Córdova et al., 2018; Rocklöv and Dubrow, 2020). In addition, effective management and treatment of domestic and wastewater effluent, through better infrastructure and preservation of aquatic systems acting as natural water purifiers, have been key to securing the integrity of the surrounding water bodies, such as groundwater, reservoirs and lakes, and agricultural watersheds, as well as protecting public health (*high confidence*) (Okeyo et al., 2018; Guerrero-Latorre et al., 2020; Kitajima et al., 2020; Sunkari et al., 2021). The preservation and restoration of natural ecosystems, with their associated higher levels of biodiversity, have been reported as significant buffers against epidemics and large-scale pathogen transmission (*medium confidence*) (Johnson and Thieltges, 2010; Ostfeld and Keesing, 2017; Keesing and Ostfeld, 2021). Further, the timely allocation of financial resources and sufficient political will in support of a "One Health" scientific research approach, recognising the health of humans, animals and ecosystems as interconnected (Rubin et al., 2014; Whitmee et al., 2015; Zinsstag et al., 2018), holds potential for improving surveillance and prevention strategies that may help to reduce the risks of further spread, and new emergence of pathogens and vectors (*medium confidence*) (Destoumieux-Garzón et al., 2018; Hockings et al., 2020; Volpato et al., 2020; Hopkins et al., 2021; Services and Ecosystem, 2021).

Adaptation measures to reduce risks of ecosystem-mediated diseases under climate change

Type	Description of adaptation options			Climate impact	Confidence
Warning systems	Early surveillance in wildlife & humans	Seasonal & dynamic forecasts of disease outbreaks; detailed risk mapping	Early Warning systems targeted locally		+++
Diagnostic abilities	Technology & trained personnel to permit rapid diagnosis and awareness of cases	Reporting in near-real time, for efficient response & resources mobilization for mitigation	Rapid response to disease emergence events, with public health and medical resources		+++
Capacity building	Training health & environmental officials to respond to new disease emergent risks	Awareness of local populations of the health risks from pathogens & vectors	Robust healthcare systems with good facilities, access & epidemic protocols		++
Public policy	Policy-making and international cooperation within a One Health framework	Large-scale public health programs for diseases/vectors eradication	Herd-immunity level vaccination for pathogens with few host species		++
Financing	Green recovery funds to tackling biodiversity loss & climate change	National funds for nature-based projects for forest conservation, water services	Funds to provide jobs for tribal groups in plantation work, forest & water management		+
Technology	Non-insecticide-based controls of vectors	Other control alternatives (avoiding use of antibiotics & chemical drugs)	Genetic surveillance & control of disease vectors & pathogens		++
Management	Planning aligned with climate targets	Long-term observing & monitoring systems	Environmental regulations & sustainable agriculture, livestock & fisheries farming practice		++
Infrastructure	Urban forests & green spaces, standing water removal	Drinking water access, sewage & drainage maintenance	Better homes keeping mosquitoes out of habited-indoor areas		+++
Nature-based solutions	Natural habitats restoration, reforestation	Reducing habitats fragmentation & limiting human proximity to risky environments	Ecosystem-based management to regulate pathogens & vectors population		++
Practice change	Diets diversification, more resilient food systems	Reduction of wildlife trade	Alternatives to reduce reliance on bushmeat and usage of wild animals		++
Co-benefits from mitigation	Reducing local emission from energy systems	Clean transport systems	Better access to food, water & energy		++

Figure Cross-Capter Box ILLNESS.1: Adaptation measures to reduce risks of climate change impact on water- and vector-borne diseases. Impacts are identified at three levels: 1) impact on pathogen, host/vector distributions and abundance; 2) impact on pathogen-host transmission cycle occurrence and efficiency; and 3) impact on likelihood of transmission to humans. Adaptation typology is based on (Biagini et al., 2014; Pecl et al., 2019). For each type of adaptation, examples are provided with their level of evidence and agreement.

[END CROSS-CHAPTER BOX ILLNESS HERE]

2.6.5 Adaptation in Practice: Case Studies and Lessons Learned

Adaptation plans for biodiversity and EbA have been adopted in many places and different scales but it is difficult to get a systematic overview of adaptation in practice. We have therefore reviewed a series of contrasting case studies to illustrate the some key issues. There is a pressing need for more thorough monitoring and evaluation of adaptation to assess effectiveness. Climate change adaptation is conceptually difficult to measure but it is possible to test which techniques work in reducing vulnerability and monitor their deployment (Morecroft et al., 2019).

Adaptation can take place at a range of scales with specific projects nested within overarching national strategies. Small scale projects can be adaptation focused, but in larger scale adaptation is often integrated with wider objectives. Within an urban or peri-urban context, the benefits of natural and semi-natural areas for health and well- help to justify support for EbA. Economic wellbeing is also an important factor in many cases, whether as, in Durban (Section 2.6.5.7), by providing new job opportunities or, in the Andes (Section 2.6.5.4) by supporting long-established agricultural practice. Action on the ground often depends on factors at a range of scales, for example, a local plan, a national strategy and international funding. Within Durban, partnership between local communities, local authorities and the academic community were essential, together with an international context. Nevertheless, there are examples of communities using traditional or local knowledge to adapt to changing circumstances, with little or no external input, (Section 2.6.5.4). They are, however, limited in their scope to adapt by factors beyond their direct control.

Specific interventions to protect species from climate change, such as the case of South African penguins(Section 2.6.5.5) and the Tasmanian Wilderness World Heritage Area (Section 2.6.5.8), are rare. However, in countries where nature reserves are actively managed or where ecosystem restoration projects are progressing, local practitioners may use local knowledge to adapt to weather conditions and their associated effects (fire or water shortage for example). This is good practice, but it may not be sufficiently to address likely future changes in climate (Duffield et al., 2021). Training and resources to support conservation practitioners are becoming available to help address this. Examples include the Climate Change Adaptation Manual in England (Section 2.6.5.2), and The Alliance for Freshwater Life (https://allianceforfreshwaterlife.org), that provide expertise for the sustainable management of freshwater biodiversity (Darwall et al., 2018).

Adaptation is widely recognised as important for national conservation policy and is being considered in a variety of countries (Section 2.6.5.2, 2.6.5.3). Adaptation in this strategic context includes decisions about the selection and objectives for protected areas, for example identifying places which can act as refugia. It can also mean recognising where protected areas remains important but will support a changing range of species and ecosystems. This is important for directing resources effectively and ensuring that site management remains appropriate. There are however often major uncertainties and the extent to which there will be a need for more radical measures will depend on success in reducing greenhouse gas emissions globally. A global rise of 1.5–2°C would require relatively incremental adjustments to conservation management in many parts of the world, but a 3–4°C rise would require radical, transformational changes to maintain many species and ecosystem services (Morecroft et al., 2012).

Whilst adaptation strategies for conservation are relatively common, at least at an outline level, implementation is slow in most places. This may partly reflect lack of resources for conservation in many parts of the world; however, another barrier is that people often value protected sites in their present form. Actions, which might jeopardise this, are inevitably a last resort. Initiatives to engage wider communities in discussions are likely to be essential in gaining support for such changing approaches.

EbA and adaptation for biodiversity are intrinsically linked and the largest scale interventions for adaptation in ecosystem have tended to bring together both elements. For example adaptation to reduce flood risk by habitat creation and using natural processes, (Section 2.6.5.2, Cross-Chapter Box SLR in Chapter 3), such as by re-naturalising straightened river systems or creating wetlands for water storage, offers the potential to meet multiple objectivesand has increased overall funding available for ecosystem restoration.

2.6.5.1 Case study: Assisted Colonisation / Managed Relocation in Practice

Scale: Global
Issue: Helping species move to track shifting climate space

Managed relocation (assisted migration, assisted colonisation) is the movement of species, populations, or genotypes to places outside the areas of their historical distributions (Hoegh-Guldberg et al., 2008) and may be an option where they are not able to disperse and colonise naturally. It requires careful consideration of scientific, ethical, economic and legal issues between the object of relocation and the receiving ecosystem (Hoegh-Guldberg et al., 2008; Richardson et al., 2009; Schwartz et al., 2012).

Individual cases show that assisted migration can be successful. Anich & Ward (2017) extended the geographic breeding range of a rare bird, Kirtland's warbler, *Setophaga kirtlandii*, by 225km by using song playbacks to attract migrating individuals. Wadgymar (2015) successfully transplanted an annual legume, *Chamaecrista fasciculata,* to sites beyond its current poleward range limit, while Liu (2012) found that all but one of 20 orchid species survived when transplanted to higher elevations than their current range limits. After introducing two British butterfly species to sites ~65 and ~35 km beyond their poleward range margins, Willis (2009) observed that both introduced populations grew, expanded their ranges and survived for at least 8 years.

Butterflies have been favoured subjects for assisted migration in response to regional climate warming, since they are easy to move and their range dynamics have been extensively studied. The Chequered Skipper butterfly, *Carterocephalus palaemon,* became locally extinct in England in the 1970's, in an area not close to either the species' poleward or equatorial range limits. Nonetheless, Maes (2019) consider climate a crucial parameter for re-introduction, using SDMs both for choosing the source population in Belgium and introduction site.

Success of assisted migration for conservation purposes has been variable. Bellis (2019), identified 56 successes and 33 failures among 107 translocations of insects that had been undertaken explicitly for conservation purposes. They concluded failure was most strongly associated with low numbers of individuals released. Another potential source of failure is local adaptation: there is *good evidence* that adaptive differences among potential source populations can be important. For example, the transplants of *C. fasciculata* were more successful when sourced from the most poleward existing sites, while individuals from more equatorial habitats performed poorly even when artificially warmed (Wadgymar et al., 2015).

2.6.5.2 Case study: Adaptation for conservation and Natural Flood Management in England, United Kingdom

Scale: National
Issue: National approach to adaptation in the natural environment

Climate change threats to biodiversity in England include range retraction of cold adapted species and effects of more frequent extreme weather events such as droughts. These threats are exacerbated by land use and management: with habitats fragmented, land often drained and rivers straightened. There are also risks to people, which are exacerbated by environmental factors, including flooding and over-heating in urban areas. A National Adaptation Programme, provides a broad policy framework for England and includes a chapter on the natural environment. There are also adaptation plans produced by public bodies such as Natural England, the conservation agency and the Environment Agency, with a wide range of responsibilities including flood defence. The principles of climate change adaptation are well established in the UK conservation community and resources are available. Natural England has published a Climate Change Adaptation Manual jointly with the Royal Society for the Protection of Birds–a major conservation NGO (England and RSPB, 2020) and spatial mapping tool for climate change vulnerability (Taylor et al., 2014).

(Duffield et al., 2021) found that awareness of the need for adaptation was common amongst nature reserve managers and that they were implementing actions that might building resilience to climate change, such as restoring ecosystem processes and reducing fragmentation. . There is a recognition that it will be necessary to change management objectives of protected sites to adjust to changing circumstances but there was little implementation of such changes (Duffield et al., 2021). The main examples of managing change, was at the coast where rising sea level is causing transitions from terrestrial and freshwater systems to coastal and marine ones.

A range of EbA approaches are starting to contribute to adaptation in England but the best developed is Natural Flood Management (NFM): restoring natural processes and natural habitats to reduce flood risk (Wingfield et al., 2019). Over the last decade, a series of NFM projects have been established in local areas. The Environment Agency collated the evidence base on NFM (Burgess-Gamble et al., 2017) and was able to draw on 65 case studies (Ngai et al., 2017), covering river and floodplain management, woodland management, run-off management and coast and estuary management.

NFM includes a broad range of techniques, some of which, deliver real benefits for biodiversity and allow natural ecological process to re-establish. Others, such as creating 'woody debris dams' – barriers artificially constructed from tree trunks and branches in water courses to slow flow of water –will have fewer benefits, although they may benefit some species. Dadson et al. (2017) concluded that 'the hazard associated with small floods in small catchments may be significantly reduced' by natural flood management techniques.

However, they noted that the most extreme flood events may overwhelm any risk management measures and failed to find clear evidence of NFM in reducing flood risk downstream in large catchments.

There remain challenges in deploying NFM at larger scales, partly reflecting the time necessary to demonstrate the effectiveness of pilot studies and build confidence and building stakeholder support is important (Huq et al., 2017). There are now a number of examples of where collaborative initiatives between local communities, land owners and government agencies have been successful in establishing effective NFM schemes (Short et al., 2019).

2.6.5.3 Case Study: Protected Areas Planning in Response to Climate Change in Thailand

Scale: National
Issue: Protected area network planning

Many countries in the Association of South East Asian Nations (ASEAN) are expanding protected area networks to meet the Aichi target 11 of at least 17% of terrestrial area protected and it is important to take the effects of climate change into account. Existing protected areas in Thailand cover approximately 21% of the land area, and it is one of the few tropical countries that passes the Aichi Target 11. Most protected areas in Thailand were established on an ad hoc basis to protect remaining forest cover, and as a result do not represent diverse habitats and their associated species (Chutipong et al., 2014; Tantipisanuh, 2016) and may not be resilient to the interacting impacts of future land use and climate change (Klorvuttimontara et al., 2011; Trisurat, 2018).

Recent research conducted in northern Thailand indicated that the existing protected areas (31% of the region area) cannot secure viability of many medium- size and large mammals. Most species climate space would substantially shift, bringing a risk of extinction. The model results based on the spatial distribution model and network flow determined there was a need for expansion areas of 5,200 km^2 or 3% of the region to substantially minimise the high-risk level and increase the average coping capacity of the protection of suitable habitats from 82% as the current plan to 90%. These results were adopted by the Thailand's Department of National Parks, Wildlife and Plant Conservation and included in the National Wildlife Administration and Conservation Plan (2021-2031).

2.6.5.4 Case Study: Effects of Climate Change on Tropical High Andean Social Ecological Systems

Scale: Regional
Issue: Complex ramifications of glacial retreat on vegetation, animals, herders and urban populations

Accelerated warming is shrinking tropical glaciers at rates unseen since the middle of the Little Ice Age (Rabatel et al., 2013; Zemp et al., 2015). Climate-driven upward migration of species associated with warming and glacier retreat has modified species distribution and richness, and community composition along the Andes altitudinal gradient (Seimon et al., 2017; Carilla et al., 2018; Zimmer et al., 2018; Moret et al., 2019). Climate-driven glacier retreat alters hydrological regimes, impacting Andean pastoralists directly (López-i-Gelats et al., 2016; Postigo, 2020; Thompson et al., 2021), and water provisioning to lowland regions (Vuille et al., 2018; Hock et al., 2019; Orlove et al., 2019; Rasul and Molden, 2019). Drying wetlands has modified alpine plant communities, which are relevant to storing carbon, regulating water, and providing food for local livestock, leading to negative impacts on herders' livelihoods (Dangles et al., 2017; Polk et al., 2017; Postigo, 2020) and differently affecting the wild vicuña and the domesticated alpaca and llama. Vicuña (*Vicugna vicugna*) and alpaca (*Vicugna pacos)* wool are important income sources for indigenous communities and Llama (*Lama glama*) is the main source of meat. Vicuña is adjusting its feeding behaviour and spatial distribution as vegetation migrates upwards (Reider and Schmidt, 2020), causing them to roam outside protected areas and become vulnerable to illegal poaching.

Andean herders have responded to drying of grasslands by increasing livestock mobility, accessing new grazing areas through kinship and leases, creating and expanding wetlands through building long irrigation canals (of several km), limiting allocation of wetlands to new households, and sometimes cultivating grasses (Postigo, 2013; López-i-Gelats et al., 2015; Postigo, 2020). These adaptive responses to regional climate change are enabled by deeply-embedded indigenous institutions that have traditionally governed Andean pastoralists, but have become severely compromised by national socio-economic pressures (Valdivia et al., 2010; Postigo, 2019; Postigo, 2020). For instance, water quality, access and control by local pastoralists has declined due to new mining concessions in headwaters of Andean watersheds (Bebbington and Bury, 2009) and diversion of water to lowland coastal desert for agricultural irrigation (Mark et al., 2017).

Glacier mass and runoff in the tropics are projected to reduce >70% and >10%, respectively, by 2100 under RCP 2.6, RCP 4.5 and RCP 8.5 (Huss and Hock, 2018; Hock et al., 2019). In Peru, montane ice-field melt-water provides 80% of the water resources for the arid coast where half the population lives (Thompson et al., 2021). Increasing variability of precipitation has compromised rain-fed agriculture and power generation, particularly in the dry season, exacerbating pressures for new water sources (Bradley et al., 2006; Bury et al., 2013; Buytaert et al., 2017). Thus, there is risk of increasing conflicts between climate change adaptation to benefit high Andean human and natural communities and adaptation to maintain water provisioning for lowland agricultural and urban areas.

2.6.5.5 Case Study: Helping African Penguins Adapt to Climate Change

Scale: Regional / local
Issue: Adaptation for a threatened species

The African penguin, *Spheniscus demersus,* is the only resident penguin species on mainland Africa and breeds in a handful of colonies in South Africa and Namibia. In 2017, penguins in Cape Town's Boulders Beach colony attracted almost one million visitors, providing 885 jobs and $18.9m revenue (Van Zyl and Kinghorn, 2018).Ninety-six percent of the population has been lost since 1900, with a 77% decline in the last two decades (Sherley et al., 2018) and by 2019 only 17,700 pairs remained (Sherley et al., 2020). The species is listed as Endangered on the IUCN Red List (IUCN, 2018) and if this trajectory persists the African penguin will become functionally extinct in the near future (Sherley et al., 2018).

Historically, hunting, egg and guano collection were the species' main threats, but three aspects of climate change now predominate. Firstly, a several-hundred-kilometre eastward shift in distributions of their main prey species, anchovies and sardines, has reduced food availability (Roy et al., 2007; Crawford et al., 2011). While adult penguins typically forage up to 400 km from their colonies, they are restricted to a ~20 km radius from their colonies during breeding months (Ludynia et al., 2012; Pichegru et al., 2012). The resulting food shortage at this critical time is compounded by competition with commercial fisheries and environmental fluctuations (Crawford et al., 2011; Pichegru et al., 2012; Sherley et al., 2018). This has impacted adults' survival and their ability to raise high-quality offspring (Crawford et al., 2006; Crawford et al., 2011; Sherley et al., 2013; Sherley et al., 2014).

Increasing heat wave frequency and intensity recorded in recent decades presents a second threat (van Wilgen and Wannenburgh, 2016; Van Wilgen et al., 2016; Mbokodo et al., 2020). Nests were historically built in insulated guano burrows, but are now frequently sited on open ground (Kemper et al., 2007; Pichegru et al., 2012; Sherley et al., 2012). High temperatures frequently expose the birds to severe heat stress, causing adults to abandon nests and resulting in mortality of eggs and chicks (Frost et al., 1976; Shannon and Crawford, 1999; Pichegru et al., 2012).Intensifying storm surges and greater wave heights can cause nest flooding (Randall et al., 1986; de Villiers, 2002).

The African penguin's survival in the wild is dependent on the success of adaptation action. Increasing access to food resources is a management priority (IUCN, 2018). One approach is to reduce fishing pressure immediately around breeding colonies. An experiment excluding fishing around colonies since 2008 has demonstrated positive effects (Pichegru et al., 2010; Pichegru et al., 2012; Sherley et al., 2015; Sherley et al., 2018; Campbell et al., 2019b). A second approach is to establish breeding colonies closer to their prey. An ongoing translocation initiative aims to entice birds eastwards to recolonise an extinct breeding colony and potentially to establish a new one (Schwitzer et al., 2013; Sherley et al., 2014; International, 2018). Penguin "look-alikes" or decoys, constructed from rubber and concrete, have been placed at the extinct colony site and, along with call play-backs, give the illusion of an established penguin colony (Morris and Hagen, 2018). This approach has not yet proven successful.

To promote on-site adaptation to heat extremes and flooding, initiatives are underway to provide cooler nesting sites that also provide storm protection and are sufficiently above the high water level (Extinction, 2018; International, 2018). Artificial nest boxes of various designs and constructed from a range of materials have been explored in combination with use of natural vegetation. Some designs have proven successful, increasing breeding success (Kemper et al., 2007; Sherley et al., 2012), but the same designs have had less success at other locations (Pichegru, 2013; Lei et al., 2014).

Hand-rearing and releasing African penguin chicks, including from eggs, has long proven valuable because moulting parents, being shore-bound, are unable to feed late-hatching chicks. Since 2006, over 7,000-orphaned chicks have been released into the wild as part of the Chick Bolstering Project with a success rate of 77% (Schwitzer et al., 2013; Sherley et al., 2014; Klusener et al., 2018; SANCCOB, 2018). A new project at Boulders Beach aims to use real-time weather station data, within-nest temperatures and known thresholds of penguin heat stress as triggers for implementing a Heat Wave Response Plan. Drawing on well-established chick-rearing facilities and a large body of expertise, this includes removing heat-stressed eggs and birds, hand rearing and/or rehabilitation and release. It is hoped that such birds may be released at the proposed new colony site.

2.6.5.6 Case study: Conserving Climate Change Refugia for the Joshua tree in Joshua Tree National Park, California, United States of America

Scale: Local
Issue: Possible extirpation of a plant species from a national park

Joshua Tree National Park conserves 3200 km2 of Mojave and Sonoran Desert ecosystems. The climate of the national park is arid, with a 1971-2000 average summer temperature of 27.3ºC ± 0.7ºC and average annual precipitation of 170 ± 80 mm y^{-1} (Gonzalez et al., 2018). From 1895 to 2017, average annual temperature increased at a significant ($p < 0.0001$) rate of 1.5 ± 0.1ºC $century^{-1}$ and average annual precipitation decreased at a significant ($p = 0.0174$) rate of -32 ± 12% $century^{-1}$ (Gonzalez et al., 2018). Anthropogenic climate change accounts for half the magnitude of a 2000–2020 drought in the Southwestern USA, the most severe since the 1500s (Williams et al., 2020).

The national park was established to protect ecosystems and cultural features unique to the region, particularly the Joshua tree (*Yucca brevifolia*), a tall, tree-like yucca that provides habitat for birds and other small animals and holds cultural significance. The national park protects the southernmost populations of the Joshua tree. Paleobiological data from packrat (*Neotoma spp.*) middens and fossil dung of the extinct Shasta ground sloth (*Nothrotheriops shastensis*) show that Joshua trees grew 13 000–22 000 thousand years before present a across a wider range, extending as far as 300 km south into what is now México (Holmgren et al., 2010; Cole et al., 2011). A major retraction of the range began ~11 700 thousand years before present, coinciding with a warming in the region of 4ºC, caused by Milankovitch cycles, that marked the end of the Pleistocene and beginning of the Holocene (Cole et al., 2011), suggesting a sensitivity of Joshua trees of 300 km latitude per 4ºC.

Under an emissions scenario that could increase park temperatures over 4ºC by 2100, suitable climate for the Joshua tree could shift north and the species become extirpated from the park (Sweet et al., 2019). Plant mortality would increase from drought stress and wildfires, which have been rare or absent in the Mojave, but which invasive grasses have and may continue to fuel (Brooks and Matchett, 2006; DeFalco et al., 2010; Abatzoglou and Kolden, 2011; Hegeman et al., 2014).

The national park had been trying to conserve the species wherever in the park it was found. The future risk of extirpation prompted them to adapt conservation to focus on protecting potential refugia, where suitable conditions may persist for the species into the future (Barrows et al., 2020). The national park used spatial analyses of suitable climate to identify potential refugia under all emissions scenarios except for the highest (Barrows and Murphy-Mariscal, 2012; Sweet et al., 2019). The park prioritises the refugia for removal of invasive grasses and fire control (Barrows et al., 2020)and works to restore refugia that have burned in fires, using native plants, including nursery-grown Joshua tree seedlings. The park and its partners are monitoring plant species composition and abundance in the refugia for early warning of any changes (Barrows et al., 2014).

2.6.5.7 Case Study: Ecosystem based Adaptation in Durban, South Africa

Scale: Local
Issue: Ecosystem based adaptation (EbA) in a city and surrounding area

Durban was an early pioneer of EbA in a city context, establishing a Municipal Climate Protection Programme (MCPP) in 2004 (Roberts et al., 2012). The City, situated in a global biodiversity hotspot (Bank, 2016), has a rapidly growing population (approximately 3.5 million) and is highly fragmented (Roberts et al., 2013). High levels of development, particularly in peri-urban areas, have encroached into natural habitats (Bank, 2016). Degradation of the natural resource base in this way has direct economic and financial costs, is threatening the City's long-term sustainability, and is exacerbated by climate change (Bank, 2016; Municipality, 2020). The impacts of climate change are anticipated to increase unless appropriate mitigation and adaptation interventions are prioritised (Municipality, 2020). High rates of poverty, unemployment and health problems have pushed Durban to explore a climate change adaptation work stream within its MCPP (Roberts et al., 2013; Roberts et al., 2020b).

A single approach to adaptation is likely to be insufficient (Archer et al., 2014), and community-based adaptation should be integrated as part of a package of tools applied at the city level. Durban's climate change adaptation work stream is composed of three separate components: municipal adaptation (adaptation activities linked to the key functions of local government); community-based adaptation (focused on improving the adaptive capacity of local communities); and a series of urban management interventions (addressing specific challenges such as the urban heat island, increased storm water runoff, water conservation and sea level rise) (Roberts et al., 2013).

Lessons learnt from Duban's experience include the importance of meaningful partnerships, long-term financial commitments (Douwes et al., 2015) and significant political and administrative will (Roberts et al., 2012; Roberts et al., 2020b). Securing these requires strong leadership (Douwes et al., 2015), including from local champions (Archer et al., 2014), even if EbA is considered cost-effective (Roberts et al., 2012). Natural habitat restoration projects are seen as an ideal tool, as they combine mitigation outcomes with increased adaptation capacity that not only reduces vulnerability of ecosystems and communities (Douwes et al., 2016), but creates economic opportunities. These include direct job creation (Diederichs and Roberts, 2016; Douwes and Buthelezi, 2016) with various spinoffs such as better education for schoolchildren (Douwes et al., 2015). Indirect benefits, include better water quality and reduced flooding, are generated as a result of improved ecosystem service delivery (Douwes and Buthelezi, 2016). In areas that are already developed, opportunities for green roof infrastructure can yield reductions in roof storm water run-off (by approximately 60 ml/m^2/minute during a rainfall event), slow release of water over time, and reduced temperatures on roof surfaces (Roberts et al., 2012).

2.6.5.8 Case Study: Protecting Gondwanan refugia against fire in Tasmania, Australia

Scale: Local
Issue: Protection of rare endemic species

The Tasmanian Wilderness World Heritage Area (TWWHA) has a high concentration of 'paleo-endemic' plant species restricted to cool, wet climates and fire free environments, but recent wildfires have burnt substantial stands, which are unlikely to recover (Harris et al., 2018b, Bowman et al., 2021, The 2016 Tasmanian). The fires led to government inquiries and a fire-fighting review, which have suggested changes to management as that climate change will make such fires more likely in the future (Council, 2016; Press, 2016; Council, 2019).

The majority of the TWWHA is managed as a Wilderness Zone, where management is currently carried out in a manner that allows natural processes to predominate. The exclusion of fire from stands of fire-sensitive trees such as the Pencil pine, *Athrotaxis cupressoides,* is part of this management strategy, possible in the past due to the moisture differential and lower flammability of these areas. However, in recent years, the threat posed by extensive and repeated wildfires, and an increasing awareness that fire risk is likely to increase (Fox-Hughes et al., 2014; Love et al., 2017; Love et al., 2019) have meant that more direct management intervention has been implemented. There has been a realisation that a "hands off" approach to managing the threat will not be sufficient to protect the paleo-endemics. Not only is fire-fighting difficult in the remote wilderness area, but limited resources mean that fire managers must prioritise where fires will be fought when many fires are threatening towns and lives across the state simultaneously.

After wildfires in 2016 caused extensive damage (Bowman et al., 2020a), significant effort and resources were spent trying to protect the remaining stands of Pencil pine during the 2019 fires, using new approaches including the strategic application of long-term fire retardant and the installation of kilometres of sprinkler lines (Council, 2019). These approaches are thought to have been effective at halting the fire and protecting the high value vegetation in some situations. Impact reports are currently being finalised to quantify the extent of fire-sensitive vegetation communities that have been affected. However, there is concern that these interventions may have adverse effects on the values of the TWWHA if applied widely, so while research is ongoing, these will only be applied in strategic areas (e.g., fire retardant is not being applied to some areas).

The TWWHA Management Plan (2016) emphasises Aboriginal fire management as an important value of the area, along with their knowledge of plants, animals, marine resources, minerals (ochre and rock sources), and their connection with the area as a living and dynamic landscape. Fire management planning aims to protect important sites from fire and ensure that management does not impact Aboriginal cultural values (DPIPWE, 2016). Increasingly, there is an acknowledgment that the cessation of traditional fire uses has led to changes in vegetation and calls to incorporate Aboriginal burning knowledge into fire management of the TWWHA.

2.6.5.9 Case Study: Bhojtal Lake, Bhopal, India

Scale: Local
Issue: Protection of water resources and biodiversity

The city of Bhopal, the capital of Madhya Pradesh state in central India, is dependent on Bhojtal, a large man-made lake bordering the city, for its water supply (Everard et al., 2020). It is also an important conservation site with wetlands protected under the Ramsar convention and diverse flora and fauna (WWF, 2006). Bhojtal also provides a wide range of other benefits to people, including tourism, recreation, navigation, and subsistence and commercial fisheries, supporting the livelihoods of many families (Verma, 2001).

Climate change in Bhopal may pose ecological and socio-economic stresses due to changes in rainfall and weather patterns (Anonymous, 2019), exacerbated by a series of problems such as wastewater discharge, illegal digging of bore wells and unsustainable water extraction/exploitation (Everard et al., 2020). Ecosystem service provision at Bhojtal was assessed using the Rapid Assessment of Wetland Ecosystem Services (RAWES) approach, including water quality analysis from the lake. Information on the geology, hydrology and catchment ecology of the lake was collected and a Baseline Biodiversity Assessment was conducted.

The Lake Bhopal Conservation and Management Project (JICA, 2007) was developed with the following actions:

1. Desilting and dredging; deepening and widening of spill channel; prevention of pollution (sewerage scheme); management of shoreline and fringe area; improvement and management of water quality

2. Soil and water conservation measures using vegetative and engineering structures particularly at upper ridges of watersheds; construction of small check dams or percolation tanks for recharge purposes in areas marked for 'drainage line recharge measures'.

3. Afforestation initiatives.

Implementation of these measures with the help of local communities improved the lake's health. Nature-based solutions are more resilient adaptation measures towards climate change. Restoration not only reduced water stress but also provides multiple societal benefits in the urban area (Kabisch et al., 2016).

2.6.5.10 Case Study: Addressing Vulnerability of Peat Swamp Forests in South East Asia (SEA)

Scale: Regional
Issue: Protecting peatland biodiversity, carbon and ecosystem services from climate change and land degradation

SEA peatlands have undergone extensive logging, drainage and land-use conversion that have caused habitat loss for endemic species, i.e., orangutan (*Pongo* spp) (Gregory et al., 2012; Struebig et al., 2015). Prolonged droughts associated with El Niño (Section 4.4.3.2) compound the effects of drainage, leading to large recurrent fires (Langner and Siegert, 2009; Gaveau et al., 2014; Putra et al., 2019). Under RCP 8.5, it is projected that by the end of the century, the annual rainfall will significantly decrease (30%) over SEA, and the number of consecutive dry days will significantly increase (60%) over Indonesia and Malaysia (Supari et al., 2020). Peat degradation and losses to fire result in large GHG emissions (Miettinen et al., 2016) as well as haze pollution that is a trans-boundary problem in the region (Heil et al., 2007).

Improving resilience to fire and climate change in SEA peatlands through restoration is extremely difficult and presents many challenges. The Indonesian government has tasked the Badan Restorasi Gambut (Peatland Restoration Agency) to restore peatlands (Darusman et al., 2021; Giesen, 2021). Other local initiatives exist, such as fire management programmes and restoration projects (Puspitaloka et al., 2020). Since 2016, the Government of Indonesia has rewetted ~380,000 hectares of degraded peatlands mainly through canal blocking and flooding, but less than 2000 hectares were successfully restored to native plant species common to peat swamp forests (Giesen, 2021).Replanting native trees has had relatively low success (Lampela et al., 2017) because they have a low tolerance to prolonged inundation and a lack of fire adaptation strategies (Page et al., 2009; Roucoux et al., 2013; Dohong et al., 2018; Cole et al., 2019; Luom, 2020; Giesen, 2021). Barriers to successful management are complex, and include the disparity in timeframes between ecological restoration and political/socioeconomic needs (Harrison et al., 2020) and an over-focus on fire-fighting rather than fire prevention (Mishra et al., 2021a). Early protection of peat forests has been highlighted as a more effective management strategy than restoration, not only in insular SEA but also in areas like Papua New Guinea, which may be targeted for expansion of estate crop plantations (Neuzil et al., 1997; Dennis, 1999; Anshari et al., 2001; Anshari et al., 2004; Hooijer et al., 2006 Assessment of; Heil et al., 2007; Page et al., 2009; Page et al., 2011; Posa et al., 2011; International, 2012; Miettinen et al., 2012; Biagioni et al., 2015; Miettinen et al., 2016; Rieley and Page, 2016; Adila et al., 2017; Cole et al., 2019; Vetrita and Cochrane, 2019; Harrison et al., 2020; Hoyt et al., 2020; Ruwaimana et al., 2020; Ward et al., 2020; Cole et al., 2021).

2.6.6 Limits to Adaptation Actions by People

The evidence summarised above (Sections 2.6.2 - 2.6.4) shows that by restoring ecosystems it is possible to increase their resilience to climate change, including the resilience of the populations of species they support and of human communities. However, changes to healthy ecosystems and biodiversity are already happening as described in this chapter *(robust evidence, high agreement)* and further changes are inevitable even under low greenhouse gas emissions scenarios (*robust evidence, high agreement*). Planning to manage the consequences of inevitable changes and prioritise investments in conservation actions where they have best chance of succeeding (e.g. Section 2.6.4.6) will be an increasingly necessary component of adaptation (*robust evidence, high agreement*) (Table 2.6).

It is possible to help species survive by active interventions such as translocation but as described above (Section 2.6.4.1) it is not a straightforward process, is not suitable for all species and is resource intensive. Modifying local microclimate or hydrological conditions can work for some species (Sections 2.6.2, 2.6.4.5), but is likely to be less effective at higher levels of climate change. It will also be less successful for larger species and more mobile ones. The microclimate of a tree is much more closely coupled with wider atmospheric conditions than that of a small plant or animal in the boundary layer and mobile species such birds and large mammals range over large areas rather than being confined to discrete locations where conditions can be manipulated. There is potential for using evolutionary changes to enhance the adaptive capacity for target species, such as is being done in the Great Barrier reef by translocating symbionts and corals that have survived recent intense heat-induced bleaching events into areas that have had large die-off.

However, known limitations to genetic adaptation preclude species-level adaptation to climates beyond their ecological and evolutionary history (Sections 2.2.4.6; 2.6.1). All of these interventionist approaches are constrained by requiring significant financial resources and expertise, they also require a high level of understanding of individual species autecology, which can take years to acquire, even if resources were available. Ex situ conservation (for example in seed banks may be the only option to conserve some species, especially as levels of warming increase and this will not be feasible for all.

While the science of restoration has generated many successes, some habitats are very difficult to restore, making certain decisions effectively irreversible. For example, *Acacia nilotica* was introduced into Indonesia in the 1850s for gum arabic with planting expanded for fire breaks in the 1960s. This tree became invasive and has already replaced >50% of savanna habitat in Baluran National Park, with complete replacement expected in the near future. This shift from savanna to Acacia forest is causing large declines in native species, including the charismatic wild banteng, *Bos javanicus* and wild dog (dhole, *Cuon alpinus)*, (Caesariantika et al., 2011; Padmanaba et al., 2017; Zahra et al., 2020). Multiple approaches to controlling the spread of this Acacia have been ineffective, highlighting the difficulty of reversing the decision to plant this tree (Zahra et al., 2020). Another example is the difficulties in restoring tropical peat forests of South East Asia (Section 6.5.10).

EbA when implemented well can reduce risks to people but there are limits, for example, an extreme flood event may exceed the capacity of natural catchments to hold water or slow its flow (Dadson et al., 2017), urban shade trees and green space can make a few degrees difference to temperatures experienced by people but that may not be enough in the hottest conditions.

In general adaptation measures can substantially reduce the adverse impacts of 1-2°C of global temperature rise, but beyond this losses will increase (IPCC, 2018b), including species extinctions and changes, such as major biome shifts which are cannot be reversed on human timescales. Some adaptation measures will also become less effective at higher temperatures. Whilst adaptation is essential to reduce risks, it cannot be regarded as a substitute for effective climate change mitigation (*robust evidence, high agreement*).

2.6.7 Climate Resilient Development

Climate Resilient Development (CRD) is the subject of Chapter 18. This section briefly assesses some of the fundamental issues for CRD relating to ecosystems; an overview of the importance of specific ecosystem services for CRD is presented in Box 18.7 in Chapter 18. A large body of evidence has demonstrated the extent to which human life, well-being and economies are dependent on healthy ecosystems and the range of threats they are under (*high confidence*) (IPBES, 2019; Dasgupta, 2021; Pörtner et al., 2021). An analysis of 64 studies found a strong positive synergy among eight critical regulating services of healthy ecosystems, including climate regulation, water provisioning, pest and disease control and adjacent crop pollination (Lee and Lautenbach, 2016). Health of ecosystems is, in turn, reliant upon maintenance of natural levels of species' richness and functional diversity (*high confidence*) (Lavorel et al., 2020) (see Section 2.5.4). A meta-analysis of 74 studies documented the mechanism for increased ecosystem stability was increased asynchrony among species, that itself was a product of higher species diversity (Xu, 2021, consistently positive effect). Responding to these threats requires the protection and restoration of natural and semi-natural ecosystems, together with sustainable management of other areas.

The Convention on Biological Diversity set the Aichi 2020 target of 17% of each country to be protected for biodiversity. Analyses suggest that 30% or even 50% of land and sea needs to be protected or restored to confer adequate protection for species and ecosystem services (*high confidence*) (Pimm et al., 2018; Dinerstein et al., 2019) (Woodley et al., 2019; Brooks et al., 2020; Hannah et al., 2020; Luther et al., 2020; Zhao et al., 2020; Sala et al., 2021). Hannah (2020) estimated that limiting warming to 2°C and protecting 30% of high biodiversity regions (Africa, Asia and Latin America) reduced risk of species' extinctions in half (*medium confidence*). Placement of protected areas is as important as total area (Pimm et al., 2018), and quality of protection (strictness and enforcement) is as important as the official land designation (Shah et al., 2021). Pimm et al. (Pimm et al., 2018) found that many small protected areas are successful because they are in areas of very high biodiversity containing species of small ranges size, while many large regions identified as wild often are of low biodiversity value, though they may have high mitigation value (e.g. high Arctic tundra). Finally, a global meta-analysis of 89 restoration projects, biodiversity increased by 44% and ecosystem services by 25% after restoration, but values remained lower than in intact reference systems (Benayas José et al., 2009).

There is also increasing evidence, reported in this chapter, that the loss and degradation of natural and semi-natural habitats exacerbates the impacts of climate change and climatic extreme events on biodiversity and ecosystem services (*high confidence*); example references include: (Ogden et al., 2013; Eigenbrod et al., 2015; Struebig et al., 2015; Stevens et al., 2016; Oliver et al., 2017; McAlpine et al., 2018; Taffarello et al., 2018; Lehikoinen et al., 2019; Birk et al., 2020; Chapman et al., 2020; Agol et al., 2021; Khaniya et al., 2021; Lara et al., 2021; Lehikoinen et al., 2021). Considering these two sets of evidence together, it is clear that climate change adaptation and ecosystem degradation both need to be addressed if either is to be tackled successfully (*robust evidence, high agreement*) as a number of recent publications have concluded (Haddad et al., 2015; Hannah et al., 2020; Arneth et al., 2021; Pörtner, 2021). Taking this combined body of evidence together, this assessment is that the protection and restoration of natural and semi-natural ecosystems are key adaptation measures (*robust evidence, high agreement*) (Section 2.5.4).

Large scale protection and restoration of ecosystems can also make a significant contribution to climate change mitigation (Dinerstein et al., 2020; Roberts et al., 2020a; Soto-Navarro et al., 2020). Globally, there is a 38% overlap between areas of high carbon storage and high intact biodiversity (mainly in the peatland tropical forests of Asia, Western Amazon and the high Arctic), but only 12% of that is protected (*high confidence*) (Soto-Navarro et al., 2020). Peatlands are particularly important carbon stores but are threatened human disturbance, land use change (Leifeld et al., 2019) and fire (Turetsky et al., 2015). Restoration of peatlands is not only an efficient nature climate solution in terms of GHG (Nugent et al., 2019), but it may also increase ecosystem resilience (Glenk et al., 2021). Global restoration efforts are ongoing to target degraded temperate peatlands in the American and Europe (Chimner et al., 2017), as a result of their importance for climate change mitigation being recognised (Paustian et al., 2016; Bossio et al., 2020; Humpenöder et al., 2020; Drever et al., 2021; Tanneberger et al., 2021). It has been estimated that the global GHG saving potential of peatland restoration is similar to the most optimistic sequestration potential from all agricultural soils (Leifeld and Menichetti, 2018). However the pressure on peatlands from human activity remains high in many parts of the world (Humpenöder et al., 2020; Tanneberger et al., 2021). Currently, the rapid destruction of tropical peatlands overshadows any current restoration efforts in temperate peatlands or any potential carbon gain from natural high-latitude peatlands (Roucoux et al., 2017; Wijedasa et al., 2017; Leifeld et al., 2019). (Sections 2.4.3.8, 2.4.4.4.2, 2.4.4.4.4, 2.5.2.8, 2.5.3.4)

Recent studies have highlighted the importance of ensuring that ecosystem protection is not implemented in a way which disadvantages those who live in or depend on the most intact ecosystems (Mehrabi et al., 2018; Schleicher et al., 2019) or risk food security. The actual area of land to be protected and the balance between sustainable use and protection will need careful planning and targeting to where it can have most benefit (Pimm et al., 2018); it will also be important to ensure that protection measures are effective in preventing damage (Shah et al., 2021).

At a local level, EbA can often provide a wide range of additional benefits for sustainable development in both rural and urban areas (Wilbanks, 2003; Nelson et al., 2007; Cohen-Shacham et al., 2016; Hobbie and Grimm, 2020; Martín et al., 2020). A number of the case studies above, such as those in Durban and at Bhojtal Lake illustrate this (2.6.5). A key element of Climate Resilient Development is ensuring that actions taken to mitigate climate change do not compromise adaptation, biodiversity and human needs. This depends on choosing appropriate actions for different locations (Box 2.2, Cross-Chapter Box NATURAL this Chapter). A particularly notable case of this is woodland creation as described in Box 2.2: re-afforestation of previously forested areas can provide multiple benefits (Lee et al., 2018; Lee et al., 2020) including for climate change mitigation, adaptation and biodiversity. However planting trees where they would not naturally grow can create multiple problems include the loss of native biodiversity and disruption of hydrology (Box 2.2). It is also the case that protection of existing natural forest ecosystems is the highest priority for reducing greenhouse gas emissions (Moomaw et al., 2019) and restoration may not always be practical (see Section 2.6.4.10). (Sections 2.4.3.6, 2.4.3.7, 2.4.4.3, 2.4.4.4, 2.5.2.6, 2.5.2.7, 2.5.3.3, Box 2.2, Cross-Chapter Box NATURAL this Chapter)

In some cases actions supported by international donors and presented as addressing climate change adaptation and mitigation in the natural environment can have damaging consequences for people and nature as well as failing to deliver adaptation and mitigation. One example of this was presented by (Work et al., 2019) who reviewed three climate change mitigation and adaptation projects in Cambodia: an irrigation project, a protected-area forest management project, and a reforestation project. In each case they found evidence of local communities rights being violated, maladaptation and destruction of biodiverse habitats. They concluded that the potential for maladaptation and adverse social and environmental impacts had been ignored by international donors as well as national authorities and that there was a need for much strict accountability mechanisms. Moyo et al. (Moyo et al., 2021), using case studies from South Africa, documented higher success of ecosystem restoration projects when they embraced broader SDGs, particularly enhancement of people's livelihoods. Better assessment of the impacts of adaptation and mitigation measures on people and ecosystems, before they are implemented, will be increasingly necessary to avoid unintended and damaging consequences as their deployment is scaled up (Larsen, 2014; Enríquez-de-Salamanca et al., 2017; Pour et al., 2017). This applies to ostensibly nature-based approaches as well as more engineering-based ones.

Another aspect of the benefits to people from ecosystems that needs to be taken into account in Climate Resilient Development is increasingly strong evidence of the benefits of natural environments for human health and well-being beyond the provision of basic necessities, such as food and water (Bratman et al., 2019; Marselle et al., 2021). Meta-analyses of 162 studies across 51,738 people documented that individuals with high levels of contact with nature through their lives felt significantly happier, healthier and more satisfied with their lives, and engage in more pro-nature behaviours, than those with little or no contact with nature *(high confidence)* (Capaldi et al., 2014; Mackay and Schmitt, 2019; Pritchard et al., 2020; Whitburn et al., 2020). Meta-analyses of manipulative human trials across 65 studies document a significant increase in positive feelings and attitudes, and declines in negative feelings, after experimental treatments involving nature *(medium confidence)* (Bowler et al., 2010b; McMahan and Estes, 2015; Soga et al., 2017). Within the context of CRD improving *the extent to which humans see themselves as part of the natural world* – known as human-nature connectedness (HNC) – by increasing access to natural areas, particularly within urban areas, can provide additional health, cultural and recreation benefits of NbS as well as increasing public engagement and support *(robust evidence, high agreement)* (Wilbanks, 2003; Nelson et al., 2007; Bowler et al., 2010b; Capaldi et al., 2014; McMahan and Estes, 2015; Cohen-Shacham et al., 2016; Soga et al., 2017; Mackay and Schmitt, 2019; Work et al., 2019; Hobbie and Grimm, 2020; Pritchard et al., 2020; Whitburn et al., 2020).

[START CCB NATURAL HERE]

Cross-Chapter Box NATURAL: Nature-Based Solutions for Climate Change Mitigation and Adaptation

Authors: Camille Parmesan (Chapter 2), Gusti Anshari (Chapter 2, CCP7), Polly Buotte (Chapter 4), Donovan Campbell (Chapter 15), Edwin Castellanos (Chapter 12), Annette Cowie (WGIII Chapter 12), Marta Rivera Ferre (Chapter 8), Patrick Gonzalez (Chapter 2, CCP3), Elena López Gunn (ch4), Rebecca Harris (ch2, CCP3), Jeff Hicke (Chapter 14), Rachel Bezner Kerr (Chapter 5), Rodel Lasco (Chapter 5), Robert Lempert (Chapter 1), Brendan Mackey (Chapter 11), Paulina Martinetto (Chapter 3), Robert Matthews (WGIII, Chapter 3), Timon McPhearson (Chapter 6), Mike Morecroft (Chapter 2, CCP5), Aditi Mukherji (Chapter 4), Gert-Jan Nabuurs (WGIII Chapter 7), Henry Neufeldt (Chapter 5), Roque Pedace (WGIII Chapter 3), Julio Postigo (Chapter 12), Jeff Price (Chapter 2, CCP1), Juan Pulhin (Chapter 10), Joeri Rogelj (WGI Chapter 5), Daniela Schmidt (Chapter 13), Dave Schoeman (Chapter 3), Pramod Kumar Singh (Chapter 18), Pete Smith (WGIII Chapter 12), Nicola Stevens (Chapter 2, CCP3), Stavana E. Strutz (ch2), Raman Sukumar (Chapter 1), Gautam Talukdar (Chapter 2, CCP1), Maria Cristina Tirado (Chapter 7), Chapter ris Trisos (Chapter 9)

Nature-based Solutions provide adaptation and mitigation benefits for climate change as well as contributing to other sustainable development goals (high confidence). Effective nature-based climate mitigation stems from inclusive decision-making and adaptive management pathways that deliver climate-resilient systems serving multiple sustainable development goals. Robust decision-making adjusts management pathways as systems are impacted by on-going climate change. Poorly conceived and designed nature-based mitigation efforts have the potential for multiple negative impacts, including

competing for land and water with other sectors, reducing human well-being and failing to provide mitigation that is sustainable in the long-term (high confidence).

The concept of Nature-based Solutions (NbS) is broad and debated but has become prominent in both the scientific literature and policy since AR5, including earlier concepts, including Ecosystem based Adaptation (EbA). The key point is that these are actions benefiting both people and biodiversity (IUCN 2020; WGII Glossary). In the context of climate change, NbS provide adaptation and mitigation benefits for climate change in ways that support wild species and habitats, often contributing to other sustainable development goals *(robust evidence, high agreement)* (Keesstra et al., 2018; Lavorel et al., 2020; Malhi et al., 2020) (Griscom et al., 2017; Hoegh-Guldberg et al., 2019; IPCC, 2019a; Lewis et al., 2019; Seddon et al., 2020b)(AR6 WGIII Chapter 12, see Sections 2.2, 2.5.4, 2.6.3, 2.6.5, 2.6.7). Well-designed and implemented NbS mitigation schemes can increase carbon uptake or reduce greenhouse gases emissions at the same time as protecting or restoring biodiversity and incorporating elements of food provisioning (Mehrabi et al., 2018). A variety of measures can be part of NbS, ranging from the protection of natural terrestrial, freshwater and marine ecosystems, the restoration of degraded ones (this Cross-Chapter Box; Section 13.3), to more sustainable management of naturally regenerating ecosystems used for food, fibre and energy production (Figure Cross-Chapter Box NATURAL 1, Chapter 5, Cross-Working Group Box BIOECONOMY in Chapter 5). Agroecological practices mitigate and adapt to climate change and can promote native biodiversity (*high confidence*) (Sinclair et al., 2019; Snapp et al., 2021).

The role of restoration in NbS

Where natural ecosystems have been degraded or destroyed, re-establishing them and restoring natural processes can be a key action for adaptation and mitigation, and the science of restoration is well-established (de los Santos et al., 2019; Duarte et al., 2020) (Section 13.4.1). Such restoration activities need to adapt to on-going climate change risks for the landscape and ocean scape and the species composition of biological communities. Indeed, climate-change impacts may overwhelm attempts at restoration/conservation of previous or existing ecosystems, particularly when the ecosystem is already near its tipping point, as are tropical coral reefs (Bates et al., 2019; Bruno et al., 2019).

Lands (e.g.forests) and oceans (e.g. fisheries) managed for products using sustainable practices (whether applied by private, state, or indigenous peoples) can also be carbon- and biodiversity-rich, and so effective NbS (Paneque-Gálvez et al., 2018; Soto-Navarro et al., 2020). Indigenous people and private forest owners manage, use or occupy at least one-quarter of global land area, over one-third of which overlaps with protected areas, thus combining both protection and production (Jepsen et al., 2015; Garnett et al., 2018; IPBES, 2019; Santopuoli et al., 2019).

Protection/restoration of natural systems, including reducing non-climate stressors, and sustainable management of semi-natural areas emerge as necessary actions for adaptation to minimise extinctions of species, reaching tipping points that cause regime shifts in natural systems, loss of whole ecosystems, and their associated benefits for humans (Scheffer et al., 2001; Folke et al., 2005; Luther et al., 2020) (Chapters 2 and 3, AR6 WGIII Chapter 7). Such measures are critical for conservation of biodiversity and the provision of ecosystem goods and services in the face of projected climate change (Duarte et al., 2020). Supporting local livelihoods and providing benefits to indigenous, local communities and millions of private landowners, together with their active engagement in decision-making, is critical to ensuring support for NbS and its successfully delivery *(high confidence)* (Chapter 05; Figure Cross-Chapter Box NATURAL 1; Ceddia et al., 2015; Blackman et al., 2017; Nabuurs et al., 2017; Smith et al., 2019a; Smith et al., 2019b; Jones et al., 2020a; McElwee et al., 2020; Cao et al., 2021).

Forests

Intact natural forest ecosystems are major stores of carbon and support large numbers of species that cannot survive in degraded habitats *(very high confidence)*. Extensive areas of natural forest ecosystems remain in tropical, boreal and (to a lesser extent) temperate biomes regions, but in many regions, they are managed (sustainably and unsustainably) or have been degraded or cleared. Deforestation and degradation continue to be a source of global greenhouse gas emissions *(very high confidence)* (Friedlingstein et al., 2019). Protecting existing natural forests and sustainable management of semi natural forests providing goods and services is a highly effective NbS (Bauhus et al., 2009) *(high confidence).* Natural forests and sustainably managed diverse forests play important roles for climate change mitigation and adaptation while providing many other ecosystem goods and services *(very high confidence)* (Bradshaw and Warkentin, 2015; Favero et al., 2020; Mackey et al., 2020). Contributions to climate change mitigation are estimated at medians of 5-7 Gt CO_2/y (Roe et al., 2019). Forests influence the water cycle at local, regional and global scales (Creed and van Noordwijk, 2018) reducing surface runoff, increasing infiltration to groundwater and improving water quality (Bruijnzeel, 2004; Zhou et al., 2015a; Ellison et al., 2017; Alvarez-Garreton et al., 2019). Recent evidence shows that downwind precipitation is also influenced by evapo-transpiration from forests (Keys et al., 2016; Ellison et al., 2017). Protecting existing natural forest and sustainably managing production forests, in a holistic manner, can optimise the provision of the many functions forests fulfil for owners, conservation, mitigation and for society as a whole (Bauhus et al., 2009; Nabuurs et al., 2013).

Reforestation of formerly forested land can help to protect and recover biodiversity and can be one of the most practical and cost effective ways of sequestering and storing carbon *(high confidence)* (Nabuurs et al., 2017; Hoegh-Guldberg et al., 2018b; Paneque-Gálvez et al., 2018; Smith et al., 2018; Cook-Patton et al., 2020; Cowie et al., 2021; Drever et al., 2021). This can be achieved through planting or by allowing natural colonisation by tree and shrub species. The most effective method to employ depends upon local circumstances (such as the presence of remnant forest cover) or socio-cultural and management objectives. Reforestation with climate-resilient native or geographically near species restores biodiversity at the same time as sequestering large amounts of carbon (Lewis et al., 2019; Rozendaal et al., 2019). It can also restore hydrological processes, improving water supply and quality (Ellison et al., 2017) and reducing risks of soil erosion and floods *(high confidence)* (Locatelli et al., 2015).

Climate change may mean that in any given location, different species will be able to survive and become dominant, and restoring the former composition of forests may not be possible (Sections 2.4; 2.5). Severe disturbances such as insect/pathogen outbreaks, wildfires, and droughts, which are an increasing risk, can cause widespread tree mortality resulting in sequestered forest carbon being returned to the atmosphere (Anderegg et al., 2020; Senf and Seidl, 2021) thus suggesting we need to adapt (Sections 2.4, 2.5, 13.3 14.4.1, Box 14.1). Adaptation measures, such as increasing the diversity of forest stands through ecological restoration rather than monoculture plantations can help to reduce these risks (*confidence*). When plantations are established without effective landscape planning and meaningful engagement including free prior and informed consent, they can present risks to biodiversity and the rights, well-being and livelihoods of Indigenous and local communities, as well as being less climate-resilient than natural forests *(very high confidence)* (Section 5.6; Corbera et al., 2017; Mori et al., 2021).

Afforesting areas such as savannahs and many temperate peatlands, which would not naturally be forested, damages biodiversity and increase vulnerability to climate change *(high confidence)* so is not a Nature-based Solution and can exacerbate greenhouse gas emissions (Sections 2.4.3.5, 2.5.2.5, Box 2.2 this Chapter). Remote sensing based assessments of suitability for tree planting can over-estimate potential, due to failure to adequately distinguish between degraded forest and naturally open areas (Bastin et al., 2019; Veldman et al., 2019; Bastin et al., 2020; Sullivan et al., 2020).

Peatlands

Peatlands are naturally high-carbon ecosystems, which have built up over millennia. Draining, cutting and burning peat lead to oxidation and the release of CO_2 (*very high confidence*). Rewetting by blocking drainage, preventing cutting and burning can reverse this process on temperate peatlands (*medium confidence*) although can take many years (Bonn et al., 2016). Trees are naturally found on many tropical peatlands and restoration can involve removing non-native species such as oil palm and re-establishing natural forest. However, peatland tropical forest is difficult to fully restore, and native pond fish, that are vital as a local food, often do not return. Protection of intact peat forests, rather than attempting to restore cleared forest, is by far the more effective pathway both in terms of cost, CO_2 mitigation, and protection of food sources (Kreft and Jetz, 2007). Naturally treeless temperate and boreal peatlands have in some cases been drained to enable trees to be planted, which leads to CO_2 emissions, and restoration requires removal of trees as well as re-blocking drainage. *(high confidence*) (Sections 2.4.3.8; 2.5.4.8; 2.6.5.10).

Blue Carbon

Blue Carbon ecosystems (mangroves, saltmarshes and seagrass meadows; see glossary) often have high rates of carbon accumulation and sequestration (Section 3.5.5.5; Macreadie et al., 2019). However, quantification of their overall mitigation value is difficult due to variable production of CH_4 and N_2O (Adams et al., 2012; Rosentreter et al., 2018; MacLean et al., 2019b), uncertainties regarding the provenance of carbon accumulated (Macreadie et al., 2019), and the release of CO_2 by biogenic carbonate formation in seagrass ecosystems (Saderne et al., 2019). Therefore, blue carbon strategies, referring to climate change mitigation and adaptation actions based on conservation and restoration of blue carbon ecosystems, can be effective NbS, with evidence of recovery in carbon stocks following restoration, although their global or regional carbon sequestration potential and net mitigation potential may be limited *(medium confidence)* (Sections 3.6.3.1.6; 13.4.3, AR6 WGI 5.6.2.2.2; Duarte et al., 2020). They can also significantly attenuate wave energy, raise the seafloor thus counteracting sea level rise effects, and buffer storm surges and flooding erosion *(high confidence)* (Sections 13.2.2; 13.10.2). Additionally, they provide a suite of cultural (for example, tourism, livelihood and well-being for native and local communities), provision (e.g. mangrove woods, edible fish and shellfish) and regulation (e.g. nutrient cycling) services *(high confidence)* (Section 3.5.5.5). These services have motivated the implementation of management and conservation strategies of these ecosystems (Sections 3.6.3.1.6; 13.4.2). Blue carbon strategies are relatively new, with many of them experimental and small scale; therefore there is *limited evidence* of their long-term effectiveness. There is also limited information on the potential emission of other GHGs from restored blue carbon ecosystems, although reconnecting hydrological flow in mangroves and saltmarsh restoration are effective interventions to reduce CH_4 and CO_2 (*limited evidence, medium agreement*) (Kroeger et al., 2017; Al-Haj and Fulweiler, 2020).

Urban NbS

Nature-based Solutions can be a key part of urban climate adaptation efforts. Direct human adaptation benefit may stem from the cooling effects of urban forests and green spaces (parks and green roofs), from coastal wetlands and mangroves reducing storm surge and flooding, and from sustainable drainage systems designed to reduce surface flooding from extreme rainfall, as well as general benefits to human health and well-being *(high confidence)* (Sections 2.2; 2.6; Chapter 6; Frantzeskaki et al., 2019; Keeler et al., 2019) (Kowarik, 2011). Not all green schemes are considered "Nature Based Solutions" if they do not benefit biodiversity, but carefully designed urban greening can be effective NbS. Careful planning also helps limit negative equity consequences, benefiting wealthy neighbourhoods more than poor (Geneletti et al., 2016; Pasimeni et al., 2019; Grafakos et al., 2020). Effective planning should also consider what is appropriate for the climate and conditions of each city. For example, some trees emit volatiles (e.g. isoprene) that, in the presence of certain atmospheric pollutants, can increase surface ozone that in turn can cause human respiratory problems (Kreft and Jetz, 2007). Wetlands restoration close to human settlements needs to be paired with mosquito control to prevent negative impacts on human health and well-being (Stewart-Sinclair et al., 2020), but has been shown to provide better filtration and toxicity reduction with lower environmental impact than other forms of waste-water treatment (Vymazal et al., 2021), including "green roofs" and "green walls" (Chapter 06; Addo-Bankas et al., 2021).

Agroecological Farming

Agroecological farming (AF) is a holistic approach that incorporates ecologic and socio-economic principles. It strives to enhance biodiversity, soil health and synergies between agroecosystem components, reduce reliance on synthetic inputs (e.g., pesticides), builds on Indigenous knowledge and local knowledge, and fosters social equity (e.g., supporting fair, local markets (HLPE, 2019; Wezel et al., 2020). AF practices include intercropping, mobility of livestock grazing across landscapes, organic agriculture, integration of livestock, fish and cropping, cover crops and agroforestry. (Sections 5.14; FAQ 12.5, 13.5.)

Agroforestry, cover crops and other practices that increase vegetation cover and enhance soil organic matter, carefully management and varying by agroecosystem, mitigate climate change (*high confidence*) (Zomer et al., 2016; Aryal et al., 2019; Nadège et al., 2019). Global meta-analyses demonstrate agroforestry storing 20 -33% more soil carbon than conventional agriculture (De Stefano and Jacobson, 2018; Shi et al., 2018) and reducing the spread of fire (Sections 5.6, 13.5.2, 7.4.3, Box 7.7). Minimising synthetic inputs such as N-based fertilisers reduces emissions (Gerber et al., 2016). Cover crops can reduce N_2O emissions and increase soil organic carbon (Abdalla et al., 2019). Conservation farming (no-till with residue retention and crop rotation) increases soil organic carbon particularly in arid regions (Sun et al., 2020). Silvo-pastoral systems (pastures with trees), and other practices that increase vegetation cover and enhance soil organic matter increase sequestered carbon in vegetation and soils (Zomer et al., 2016; Aryal et al., 2019; Nadège et al., 2019; Ryan et al. 2019). Agroecologically improved cropland and grazing land management have significant mitigation potential, estimated at 2.8- 4.1 $GtCO_2e$ per year (Smith et al., 2020). (Sectiond 5.10, 5.14, Box 5.10, Cross Working-Group Box BIOECONOMY in Chapter 5; WGIII 7.4.3; Box 7.7).

AF enhances adaptation to climate change, including resilience to extreme events. Building organic matter improves soil water-holding capacity and buffers against drought; increased perenniality and high levels of ground cover reduce soil erosion during storms; agroforestry shelters stock and crops in heat waves; landscape complexity and agrobiodiversity increase resilience to disease and pests and stabilise livestock production and restoration of oyster reefs provides thermal refugia and storm surge protection (Allred et al., 2014; Henry et al., 2018; Kremen and Merenlender, 2018; Beillouin et al. 2019; ; Kuyah et al. 2019; Gilby et al., 2020; Niether et al. 2020; Richard et al. 2020; Howie and Bishop, 2021; Snapp et al. 2021) (;) . Livestock mobility enables adjusting to increased climatic variability while maintaining pastoral systems' productivity (Turner and Schlecht, 2019; Scoones, 2020). Thus, adoption of agroecology principles and practices will be highly beneficial to maintaining healthy, productive food systems under climate change (*high confidence*) (Sections 5.4.4; 13.5.2; FAQ 12.4).

AF practices such as hedgerows and polycultures maintain habitat and connectivity for biodiversity and support ecosystem functioning under climate stress compared to conventional agriculture (*high confidence*), Section 5.4.4.4; Buechley et al., 2015; Kremen and Merenlender, 2018; Albrecht et al., 2020). Increasing farm biodiversity benefits pollination, pest control, nutrient cycling, water regulation and soil fertility (Snapp et al. 2021; Beillouin et al. 2019; Tamburini et al. 2020). Biodiverse agroforestry systems increase ecosystem services and biodiversity benefits compared to simple agroforestry and conventional agriculture (*high confidence);* up to 45% more biodiversity and 65% more ecosystem services compared to conventional timber, crop or livestock production in the Brazilian Atlantic Forest (Santos et al., 2019), including for birds (M. Greenler and Ebersole, 2015; Karp et al., 2019), local tree species (Braga et al., 2019) and fewer invasive exotic plants species (Cordeiro et al., 2018). AF includes conservation of semi-natural woodlands, which can conserve bird predators of insect pests (Gonthier et al., 2019). Organic production increases insect species richness and abundance in and around the farm, including essential pollinators (Sections 5.10, 12.6; Kennedy et al., 2013; Haggar et al., 2015; Lichtenberg et al., 2017).

AF significantly improves food security and nutrition by increasing access to healthy, diverse diets and rising incomes for food producers, through increased biodiversity of crops, animals, and landscapes (*high confidence)* (Garibaldi et al., 2016; D'Annolfo et al., 2017; Isbell et al., 2017; Dainese et al., 2019; Bezner Kerr et al. 2021). Livestock mobility improves the site-specific matching of animals' needs with food availability (Damonte et al., 2019; Mijiddorj et al., 2020; Postigo, 2021), and can generate a form of rewilding that restores lost ecosystem functioning (Gordon et al., 2021). Conservation of crop wild relatives in situ supports genetic diversity in crops for the range of future climate scenarios (Redden et al., 2015).

System-level agroecological transitions require policy support for farmer experimentation and knowledge exchange, community-based participatory methodologies and market and policy measures e.g. public procurement, local and regional market support, regulation or payments for environmental services (HLPE 2019; Snapp et al. 2021; Mier y Teran et al. 2018). Scientific consensus about the food security and environmental implications of agroecological transitions at a global scale is lacking. Yields in agroforestry and organic can be lower than high-input agricultural systems, but conversely, AF can boost productivity and profit, varying by timeframe, socio-economic, political and ecosystem context (*medium confidence)* (Section 5.14; Muller et al., 2017; LaCanne, 2018; Barbieri et al., 2019; Rosa-Schleich et al. 2019; Smith et al., 2019b; Smith et al., 2020). ;. Such contrasting results and the limited investment in agroecological research to date make paramount assessing the global and regional impacts of agroecological transitions on food production, ecosystems and economy (Section 5.14; DeLonge et al., 2016; Muller et al., 2017; Barbieri et al., 2019).

Conclusions

Nature–based Solutions provide adaptation and mitigation benefits for climate change as well as contributing to other sustainable development goals *(high confidence)*. NbS avoid further emissions and promote CO_2 removal using approaches that yield long-lasting mitigation benefits and avoid negative outcomes for other sustainable development goals. Poorly conceived and designed mitigation efforts have the potential for multiple negative impacts: (1) They can have cascading negative effects on long-term mitigation by promoting short term sequestration over existing long-term accumulated carbon stocks, (2) They can be detrimental to biodiversity, undermining conservation adaptation, and (3) They can erode other ecosystem services important for human health and well-being *(high confidence)*. Conversely, well-designed and implemented mitigation efforts have the potential to provide co-benefits in terms of climate-change adaptation, as well as multiple goods and services, including conservation of biodiversity, clean and abundant water resources, flood mitigation, sustainable livelihoods, food and fibre security, and human health and well-being *(high confidence)*. A key aspect to such 'smart' climate mitigation is implementation of inclusive and adaptive management pathways (Section 1.4.2). These entail acceptance of the inherent uncertainty in projections of future climate change, especially at a regional or local level, and using decision making processes that keep open as many options as possible, for as long as possible, with periodic re-evaluation to aid in choosing pathways forward even as systems are being impacted by on-going climate change (Figure Cross-Chapter Box NATURAL 1; Cross-Chapter Box DEEP in Chapter 17; Section 1.4.2).

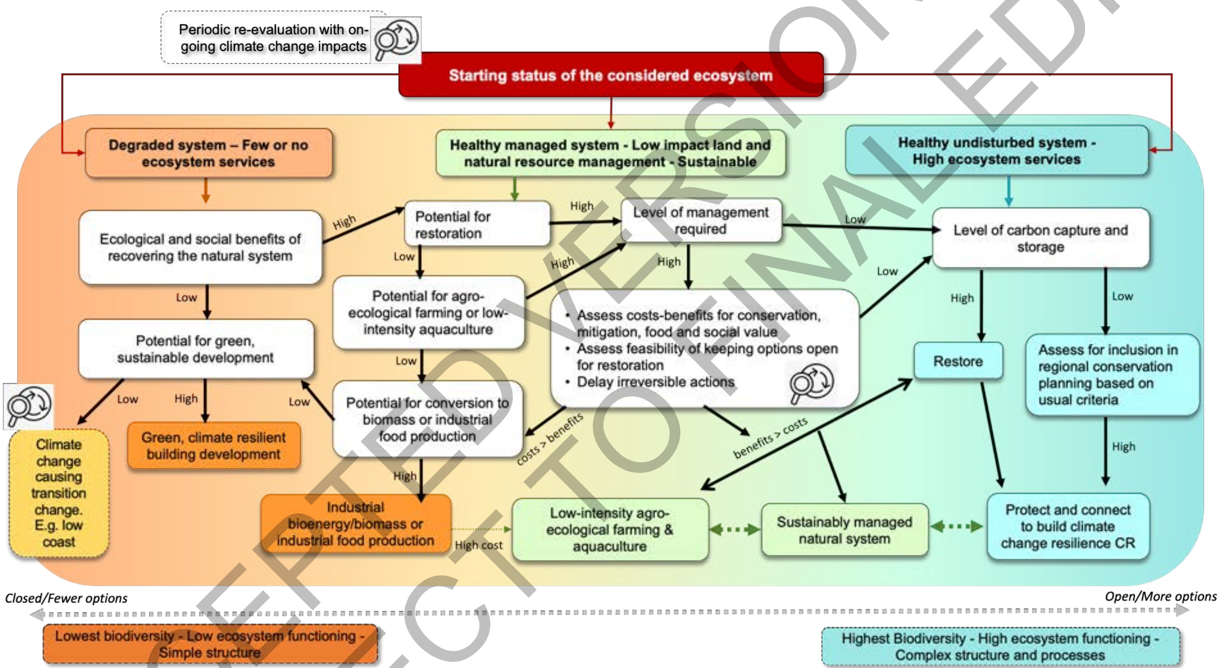


Figure Cross-Chapter Box NATURAL.1: Decision-making framework to co-maximise adaptation and mitigation benefits from natural systems. Decision-making pathways are designed to add robustness in the face of uncertainties in future climate change and its impacts. Emphasis is on keeping open as many options as possible, for as long as possible, with periodic re-evaluation to aid in choosing pathways forward even as systems are being impacted by on-going climate change

Table Cross-Chapter Box NATURAL.1: Assessment of benefits and tradeoffs between mitigation and strategies for both biodiversity and human adaptation to future climate change. Best practices highlight approaches that lead to maximal positive synergies between mitigation and adaptation; worst practices are those most likely to lead to negative tradeoffs for adaptation. Many best practices have additional societal benefits beyond adaptation, such as food provisioning, recreation and improved water quality. Mitigation Potential (Mit. Pot.) and Restoration Potential (Rest. Pot.) are considered.

System	Mit. Pot.	Rest. Pot.	Best practices and adaptation benefits	Worst practices and negative adaptation tradeoffs	Additional societal benefits	References
Forests						

Boreal Forests	Medium	Medium	Maintain or restore species and structural diversity, reduce fire risk, spatially separate wood production, and sustainably intensify management in some regions	Very large scale clear cuts, aiming for one or few tree species, although boreal is characterised by few tree species and a natural fire risk	Providing goods and services, improved air quality, improved hydrology, jobs	Drever et al. (2021)
Temperate forests	Very high	High	Maintain or restore natural species and structural diversity, leading to more biodiverse and resilient system	Planting large scale non-native monocultures which would lead to loss of biodiversity and poor climate change resilience	Providing goods and services, jobs, improved hydrology and biodiversity	Sections 2.4.3; 2.5; Box 2.2 ; Nabuurs et al. (2017); Roe et al. (2019); Favero et al. (2020)
Tropical wet forests	High	Moderate	Maintain or restore natural species and structural diversity, high biodiversity, more resilient to climate change	Planting non-native monocultures, loss of biodiversity, poor climate change resilience, soil erosion	Indiginous foods, medicines and other forest products, including sustainable selective logging	Section 2.4.3 Edwards et al. (2014)
Tropical dry forests	High	Moderate	Integrated landscape management	Planting non-native monocultures, Loss of biodiversity, poor climate change resilience, soil erosion		Foli et al. (2018)
Tropical peatland forests	Very high	Low	Integrated landscape management	Cutting native rainforest and planting palm oil for biodiesel results in very high carbon emissions from exposed peat soils	Forest pond fish are major food for local communities	Section 2.4.3; 2.5; Smith et al. (2019b)
Blue Carbon						AR6 WGI 5.6.2.2.2
Mangroves	Moderate	High	Conservation, restoration of hydrological flows, revegetation with native plants, livelihoods diversification, landscape planning for landward and upstream migration	Potential NH4 emissions	Improved fisheries and biodiversity, coastal protection against SLR and storm surges, recreation and cultural benefits	Sections 3.4.2.5; 3.5.5.5; 3.6.3.1 ; Macreadie et al. (2019); Duarte et al. (2020); Sasmito et al. (2020)
Saltmarshes	Moderate	High	Conservation, reduce nutrient loads, restoration of hydrological flows and sediment delivery, revegetation with native plants, landscape planning for landward and upstream migration	Potential NH4 emissions	Improved fisheries and biodiversity, protection against SLR and storm surges, recreational and cultural benefits	Sections 3.4.2.5; 3.5.5.5; 3.6.3.1 ; Macreadie et al. (2019); Duarte et al. (2020)
Seagrasses	Moderate	High	Conservation; restoration; improve water quality and reduce local stressors (reduction of industrial sewage, anchoring and trawling regulation)	Potential NH4 emissions	Improved fisheries and biodiversity; protection from shoreline erosion; recreational benefits	Section 3.4.2.5; 3.5.5.5; 3.6.3.1 ; de los Santos et al. (2019); Macreadie et al. (2019); Duarte et al. (2020)
Urban Ecosystems						
Urban forests	Moderate to High*	Moderate	Integrated landscape management. Species richness (including exotics) can be high	monoculture of an exotic tree lowers resilience and reduces biodiversity	Recreation & aesthetics; stormwater absorption benefits;	WGII Chapter 06

					heat mitigation, air quality improvements	
Urban wetlands	Moderate*	Moderate	Integrated landscape management.		Recreation & aesthetics; stormwater absorption; heat mitigation; coastal flood protection	WGII Chapter 06
Urban grasslands	Moderate*	Moderate	Integrated landscape management	fertilized commercial grass monocultures often require irrigation and are less resilient to droughts than native, mixed grasses and forbs	Recreation & aesthetics; stormwater absorption; heat mitigation	WGII Chapter 06
Open grasslands & savanna						
Boreal & Temperate Peatlands	High	Moderate	Blocking drainage channels; Raise water level to natural condition; remove planted trees; revegetation of bare peat; No burns; Increases biodiversity resilience; Reduce flood risk	Inappropriate hydrological restoration, e.g., flood surface depth greater than natural depth leading to methane emissions	Improved water quality in some conditions.	Sections 2.4.3; 2.5 ; Bonn et al. (2016); Nugent (2019); Taillardat et al. (2020)
Tropical savannas and grasslands (including rangelands)	Moderate	High	Control of feral herbivores; Reintroduce indigenous burns; reintroduce native Herbivores, controlled grazing; strategic design of water-holes; Community-based natural resource management, grass reseeding, clearing of invasive and encroaching woody plants	Afforestation,over-grazing/stocking; No burns; inappropriate placement and design of watering points. All leads to loss of biodiversity, and resilience; soil erosion; water insecurity	Improved grazing potential for livestock and dairy production, sustainable wildlife harvests, Increased water security, income from eco-tourism, medicanal plants, fuel wood. Enhanced food security.	Sections 2.4.3; 2.5; Box 2.1 ; Stafford et al. (2017); Moura et al. (2019); Shackelford et al. (2021); Stringer et al. (2021); Wilsey (2021)
Temperate Grasslands and rangelands	Moderate to High	Moderate to High	Integrated landscape management; sustainable grazing; Community-based natural resource management; Native grassland species more resistant to drought than introduced species	Monoculture of introduced species; over-fertilising with chemical or organic amendments; Failure to manage human-wildlife clashes; Failure to distribute income equitably; inadequate enabling policy to facilitate integrated landscape management	Sustainable harvest of wildlife, livestock and dairy production, wild fruits, medicinal plants, construction material, fuelwood; income from ecotourism	Sections 2.4.3; 2.5, Box 2.1; Farai, (2017); Baker et al. (2018); Homewood et al. (2020) Wilsey (2021)
Agroecologial farming and aquaculture	High	High (context specific)	Biodiverse systems at landscape scale; participatory adaptation to context; Short value chains; Farmer incentives; Biodiversity synergies; reduced climate risk	Poorly chosen species, practices and amendments can lead to low yields; Simplified agroforestry systems or industrial scale organic agriculture lacks holistic system-wide approach. Over-fertilising with organic amendments	Food security, human health, livelihoods, socio-cultural benefits e.g. culturally-appropriate foods.	Sections 5.4, 5.10, 5.12, 5.14 ; Coulibaly et al. (2017); HLPE (2019); Quandt et al. (2019); Sinclair et al. (2019); Smith et al. (2019b); Muchane et al. (2020); Reppin et al. (2020)

[END CROSS-CHAPTER BOX NbS-NATURAL HERE]

[INSERT FAQ2.5 HERE]

FAQ2.5: How can we reduce the risk of climate change to people by protecting and managing nature better?

Damage to our natural environment can increase the risk climate change poses to people. Protecting and restoring nature can be a way to adapt to climate change, with benefits for both humans and biodiversity. Examples include reducing flood risk by restoring catchments and coastal habitats, the cooling effects of natural vegetation and shade from trees and reducing the risk of extreme wildfires by better managing of natural fires.

Protecting and restoring natural environments, such as forests and wetlands can reduce the risks climate change poses to people, as well as supporting biodiversity, storing carbon and providing many other benefits for human health and wellbeing. Climate change is bringing an increasing number of threats to people, including flooding, droughts, wildfire, heat waves and rising sea levels. These threats can however be reduced or aggravated, depending on how land, sea and freshwater are managed or protected. There is now clear evidence that 'Nature-based Solutions' (NbS) can reduce the risks that climate change presents to people. This is sometimes called 'Ecosystem-based Adaptation (EbA) and includes::

- *Natural flood management*: As warm air holds more water, and in some places, because of changing seasonal rainfall patterns, we are seeing more heavy downpours in many parts of the world. This can create serious flooding problems, with loss of life, homes and livelihoods. The risk of flooding is higher where natural vegetation has been removed, wetlands drained or channels straightened. In these circumstances, water flows quicker and the risk of flood defenses being breached is increased. Restoring the natural hydrology of upstream catchments, including by restoring vegetation, creating wetlands and re-naturalising watercourse channels and reinstating connections with the flood plain can reduce this risk. In a natural catchment with trees or other vegetation, water flows slowly overland and much of it soaks into the soil. When the water reaches a watercourse, it moves slowly down the channel, both because of the longer distance it travels when the channel bends and because vegetation and fallen trees slow the flow. Wetlands, ponds and lakes can also hold water back and slowly release it into river systems.

- *Restoring natural coastal defences:* Rising sea levels as a result of climate change, mean that coasts are eroding at a fast rate and storm surges are more likely to cause damaging coastal flooding. Natural coastal vegetation, such as saltmarsh and mangrove swamps can, in the right places, stabilise the shoreline and act as a buffer, absorbing the force of waves. On a natural coast, the shoreline will move inland and as sea level rises, the coastal vegetation will gradually move inland with it. This contrasts with hard coastal defences such as sea walls and banks, which can be overwhelmed and fail. In many places however, coastal habitats have been cleared and where there are hard sea defences behind the coastal zone, the vegetation disappears as the coast erodes rather than moving inland. This is often referred to as 'coastal squeeze' as the vegetation is squeezed between the sea and the sea wall. Restoring coastal habitats and removing hard sea defences, can help reduce the risks of catastrophic flooding.

- *Providing local cooling:* Climate change is bringing higher temperatures globally, which can result in heatwaves affecting people's health, comfort and agriculture. In cities, this can be a particular problem for health as temperatures are typically higher than in the countryside. Trees give shade, which people, in both rural and urban areas, have long used to provide cool places for themselves and for crops such as coffee and livestock. Planting trees in the right place can be a valuable, low-cost Natural-based Solution to reduce the effects of increasing heat, including in reducing water temperatures in streams and rivers, which can help to maintain fisheries. Trees and other vegetation also have a cooling effect as a result of water being lost from their leaves through evaporation and transpiration (loss of water through pores in the leaves, known as stomata). Natural areas, parks, gardens in urban areas can help reduce air temperatures by up to a few degrees.

- *Restoring natural fire regimes:* Some natural ecosystems are adapted to burning, such as savannas and boreal forests. Where fire has been suppressed or non-native species of trees planted in more open habitats, there is a risk that potential fuel accumulates, which can result in larger and hotter fires. Solutions can include restoring natural fire regimes and removing non-native species to decrease people and ecosystems' vulnerability to the exacerbated fire risk climate change is bringing through higher temperatures and in some places changing rainfall patterns.

Nature-based Solutions, including protecting and restoring mangroves, forests and peatlands, also play an important part in reducing greenhouse gas emissions and taking carbon dioxide out of the atmosphere. They can also help people in a wide range of other ways, including through providing food, materials and providing opportunities for recreation. There is increasing evidence that spending time in natural surroundings is good for physical and mental health.

It is important that the right adaptation actions are carried out in the right place and that local communities play an active part in making decisions about their local environment if Nature-based Solutions are to be effective. When they are not part of the process, conflicts can emerge and benefits can be lost.

Whilst Nature-based Solutions help us to adapt to climate change and reduce the amount of greenhouse gases in the atmosphere, it is important to note that there are limits to what they can do. To provide a safe environment for both people and nature, it will be essential to radically reduce greenhouse gas emissions, especially from fossil-fuel burning in the near future.

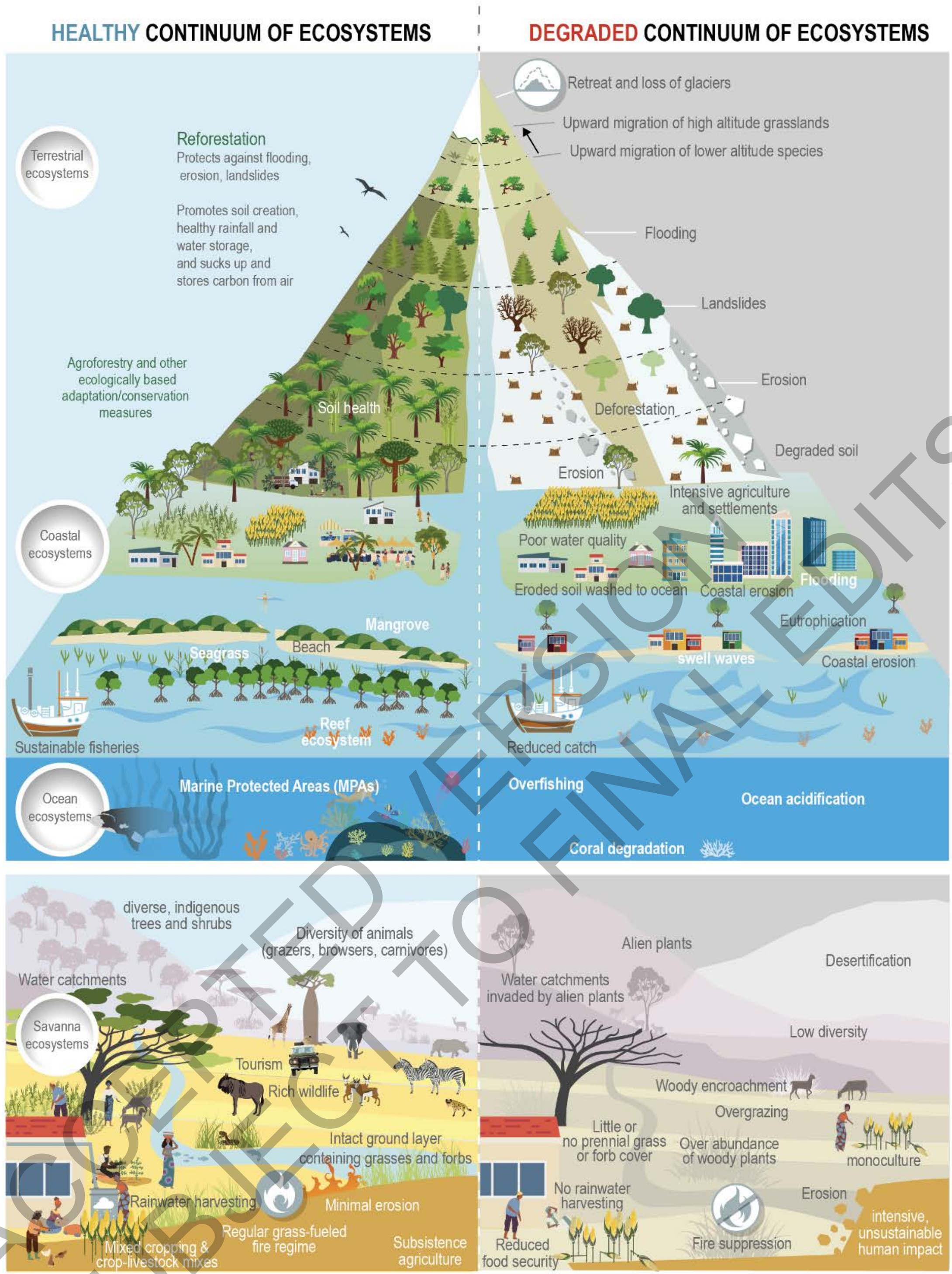


Figure FAQ2.5.1: Different Nature-based Solutions strategies.

[END FAQ2.5 HERE]

2.6.8 Feasibility of Adaptation Options

IPCC (2018a) defined feasibility as "the degree to which climate goals and response options are considered possible and/or desirable" (IPCC 2018) and set out an approach to assessing feasibility of pathways to limit global temperature rise to 1.5 °C. (Singh et al., 2020) have developed this approach for adaptation, recognising 6 different dimensions of feasibility: economic, technological, institutional, socio-cultural, environmental / ecological and geophysical (Table 2.9). Feasibility is considered more fully in other chapters of this report, including Cross-Chapter Box FEASIB in Chapter 18. Adaptation for biodiversity conservation and EbA encompasses a large range of approaches and techniques (Sections 2.6.2, 2.6.3) and will vary in different contexts globally, as illustrated by the range of case studies (Section 2.6.5). It is important to take account of specific regional and local circumstances as well as the type of adaptation action that envisaged before making a feasibility assessment. It is also important to note that what is a feasible adaptation response may change with the level of warming experienced – some techniques will be become less effective at higher levels of warming. With global temperature rises of less than 2°C, in many cases it will be realistic to build resilience and maintain species and ecosystems *in situ*, but at higher levels of warming, this will become increasingly difficult and managing inevitable change, including the consequences of loss and damage will be important (Prober et al., 2019). Similarly to be effective at higher levels of warming may require the adaptation of EbA approaches themselves (Calliari et al., 2019; Martín et al., 2021; Ossola and Lin, 2021). We have therefore not attempted a global scale assessment of the feasibility of adaptation options, but rather present some key cross cutting considerations in assessing feasibility for adaptation for and through ecosystems.

Many of the necessary techniques for climate change adaptation for biodiversity and EbA have been demonstrated and shown to provide a wide range of additional benefits. This does however depend on deploying the right techniques in the right place (Box 2.2) and the engagement of local communities (see Section 2.6.6). There is also a challenge where there is high demand for land for other purposes, especially for agriculture and urban developments. Table 2.8 summarise the main feasibility considerations, drawing on previous sections. An assessment of constraints on EbA by Nalau et al. (2018) addressed similar issues.

Table 2.8: Considerations in assessing feasibility of ecosystem restoration for climate change adaptation, following Singh et al. (2020)

Feasibility characteristics	Feasibility indicators	Factors relevant to ecosystem restoration
Economic	Micro-economic viability Macro-economic viability Socio-economic vulnerability reduction potential Employment & productivity enhancement potential	Costs are highly variable, depending on techniques and whether land purchase is required. Costs will depend on local rates for labour and materials. Economic benefits to local communities where employment is created and where loss from extreme events are avoided. (Section 2.6.4; De Groot et al., 2013)
Technological	Technical resource availability Risks mitigation potential (stranded Assets, unforeseen Impacts)	Techniques are available for restoration of most ecosystems (Sections 2.6.2; 2.6.3) although it can be very difficult to achieve in some circumstances and take a long time, e.g. the restoration of peat swamp forests (Section 2.6.5.10). Successful implementation may also require skills which are in short supply and training may be required.
Institutional	Political acceptability Legal, Regulatory feasibility Institutional capacity & Administrative feasibility Transparency & accountability potential	This will vary according to local factors. It should however be noted that EbA and adaptation for conservation has been implemented in wide range of different countries, including ones (see case studies in Section 2.6.5). In many cases EbA can meet multiple policy objectives but fall between different decision makers responsibilities.
Socio-cultural	Social co-benefits (Health, education) Socio-Cultural acceptability Social & Regional Inclusiveness Benefits for gender equity Intergenerational equity	Multiple benefits to local communities are possible but full engagement and/or leadership of affected members of communities has been shown to be critical. Local Knowledge and Indigenous Knowledge can provide important insights. (Section 2.6.6)
	Ecological capacity	

Environmental/ ecological	Adaptive capacity/potential	It is important to assess the benefits for ecosystems in relation to other potential options. In particular for some EbA approaches, it may be possible to achieve a range of different outcomes for biodiversity.
Geophysical	Physical Feasibility Land use change enhancement potential Hazard risk reduction potential	Appropriate measures need to be designed to take account of local geophysical conditions, for example catchment characteristics which define where some habitats can occur. This is also critical for ensuring the effectiveness of EbA in reducing natural hazards.

A key element of economic feasibility is the cost of adaptation options. Costs of adaptation vary greatly depending on the actions taken, the location, the methods used, the need for ongoing maintenance and whether land purchase is necessary. At its simplest adaptation may be a matter of taking account of actual or potential climate change impacts in the course of conservation planning and have little or no additional cost. For example, if a species of conservation concern colonises or starts to use a new area as a result of climate change (for example, migrant waterfowl shifting the locations where they overwinter (Pavón-Jordán et al., 2020b), protection or habitat management may be re-directed there. At the other extreme large scale restoration can incur significant costs, for example between 1993 and 2015, the EU-LIFE nature programme invested 167.6M € in 80 projects, which aim to restore over 913 km^2 of peatland habitats in Western European countries (Andersen et al., 2017). This is equivalent to less than 2% of the remaining peatland area, much of which has been affected to at least some extent by human pressures and restoring the total areas will cost considerably more. De Groot et al. (2013) analysed 94 restoration projects globally and found costs varied by several orders of magnitude but terrestrial and freshwater ecosystems mostly in the range of 100–10,000 USD per ha. They did however estimate that the majority of these projects provided net benefits and should be considered as high yield investments. Some methods can however be much cheaper than others even in the same type of ecosystems in the same Country: estimated cost of restoring forest cover in Brazil varied between a mean of 49 USD using natural regeneration compared to a mean of 2041 USD per hectare using planting (Brancalion et al., 2019). In assessing costs it is also important to take account of the benefits delivered by different options, both in economic terms and other wider benefits.

The 'technological' dimension of feasibility in the context of ecosystems can be regarded as the range of techniques available and the capacity to implement them. As described in Sections 2.6.2 and 2.6.3, above, a wide range of techniques have been developed and are starting to be implemented. There is good evidence to support adaptation for biodiversity and EbA in general terms and in many cases adaptation draws on techniques for habitat creation and restoration which have been develop to mee other objectives. However, feasibility needs to be assessed alongside likely effectiveness: a feasible but ineffective scheme is of no value and the evaluation of success for specific interventions remains poorly developed (Morecroft et al., 2019). It is often therefore important to proceed with the use of pilot studies and good monitoring and evaluation of outcomes to build confidence before wider deployment of approaches. A linked technical area is the availability of specialist skills and knowledge to implement adaptation which can vary considerably according to the type of adaptation measure.

Institutional dimensions are dealt with more fully in other chapters, but in the specific context of the natural environment, it is notable that EbA is relevant to a wide range of organisations and policy objectives, in addition to environmental departments, NGOs and agencies, which conservation has traditionally been delivered by. Upscaling implementation is likely to be dependent on this wider range of interests. There can however be problems in that appropriate geographies for decision making on ecosystems (such as a catchment) may not directly map onto governance arrangements

Socio-cultural factors are important in adaptation of the natural environment, in reviewing constraints on EbA Nalau et al. (2018) found that risk perceptions and cultural preferences for particular types of management approaches were frequently identified in studies.

In the IPCC feasibility assessment framework, one integral dimension is 'Environmental / ecological'. In this respect adaptation by and for ecosystems should perform well and this may be a reason to prefer EbA to other approaches when there is an alternative. It should however be noted that sometimes apparently environmentally positive approaches such as forest creation can be done in ways which are damaging (Section 2.6.7 and Box 2.2) and impacts need to be critically assessed for local circumstances.

Geophysical dimensions are important for ecosystems as they have typically shaped which ecosystems can occur where and feasibility will depend on implementing adaptation options in places where they are appropriate. Paleoecological studies can help inform potential options (Wingard et al., 2017)

[START BOX 2.2 HERE]

Box 2.2: Risks of Maladaptive Mitigation

To hold global temperature rise to well below 2°C and pursue efforts to limit it to 1.5°C as required by the Paris Agreement requires major changes in land use and management. There are many opportunities for Nature-based Solutions, which can provide climate change mitigation and adaptation in ways, which protect and restore biodiversity and provide a wide range of benefits to people (Cross Chapter Box NATURAL this Chapter). There are also new technologies and approaches to develop the bioeconomy in ways, which provide many benefits (Cross-Working Group Box BIOECONOMY in Chapter 5). Nevertheless, renewable energy is a large and essential element of the climate change mitigation and there are adverse impacts on biodiversity associated with some renewable energy, including wind and solar technologies (Rehbein et al., 2020) However, of the most serious emerging conflicts are between land-based approaches to mitigation and the protection of biodiversity, particularly as a result of afforestation strategies and potentially large areas devoted to bioenergy, including bioenergy with carbon capture and storage (BECCS). It is important to recognise the impacts of climate change mitigation at the same time as assessing the direct impacts of climate change and ensure that adaptation and mitigation are joined up.

BECCS is an integral part of all widely accepted pathways to holding global temperature rise to 1.5°C (IPCC, 2018b). This requires large areas of land which can conflict with the need to produce food and protect biodiversity (Smith et al., 2018). One study that examined the combined impacts of climate change and land use change for bioenergy and found severe impacts on species were likely if bioenergy were a major component of climate change mitigation strategies (Hof et al., 2018). A study on the potential impacts of bioenergy production and climate change on European birds found that land conversion for biodiversity to meet a 2°C target would have greater impacts on species range loss than a global temperature increase of 4°C, if bioenergy were the only mitigation option (Meller et al., 2015). To avoid the worst impacts of BECCS, it will need to be carefully targeted, according to context and local conditions (and other mitigation strategies prioritised so its use can be minimised IPCC, 2019, Special Report on Land; Ohashi, 2019, Biodiversity can benefit).

Reforestation of formerly forested areas can bring multiple benefits, but planting trees in places where they do not naturally grow can have serious environmental impacts, including potentially exacerbating the effects of climate change. Savannas, are at amongst those that are at risk from afforestation programmes. Savannas are grass dominated, high diversity ecosystems with endemic species adapted to high light environments, herbivory and fire (Staver et al., 2011; Murphy et al., 2016). Interactions between climate change, elevated CO_2 and the disruption of natural disturbance regimes have led to widespread woody plant encroachment (Stevens et al., 2016) causing a fundamental shift in ecosystem structure and function with loss of grass, reduced fire frequency (Archibald et al., 2009) and streamflow (Honda and Durigan, 2016). Afforestation exacerbates this degradation (Bremer and Farley, 2010; Veldman et al., 2015; Abreu et al., 2017). Global-scale analyses aimed at identifying degraded forest areas suitable for afforestation (Veldman et al., 2019) cannot reliably separate grassy ecosystems with sparse tree cover from degraded forests and local knowledge is essential to ensure tree planting is targeted where it can most benefit and avoid harm. Figure Box 2.2.1 indicates where these issues are most likely to arise.

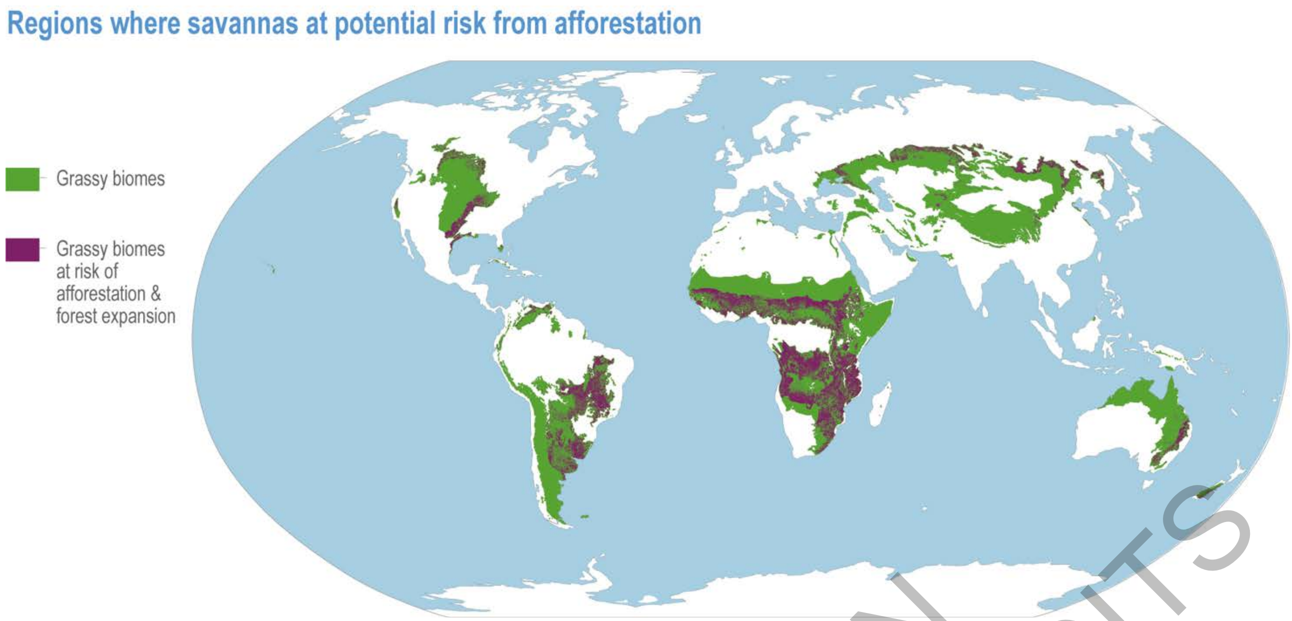


Figure Box 2.2.1: Regions where savannas at potential risk from afforestation. Based on (Veldman et al., 2015)

A similar issue can occur in naturally treeless peatlands which can be afforested if they are drained, but this leads to the loss of distinctive peatland species and communities as well as high greenhouse gas emissions (Wilson et al., 2014). Mitigation benefits of growing timber are reduced or become negative in these conditions by CO_2 emissions from the oxidation of the drained peat - they can be a net sources rather than a sinks (Simola et al., 2012; Crump, 2017; Goldstein et al., 2020).

[END BOX 2.2 HERE]

[START FAQ2.6 HERE]

FAQ2.6: Can tree planting tackle climate change?

Restoring and preventing further loss of native forests is essential for combating climate change. Planting trees in historically unforested areas (grasslands, shrublands, savannas, some peatlands) can reduce biodiversity and increase the risks of damage from climate change. It is therefore essential to target tree planting to the appropriate locations and use appropriate species. Restoring and protecting forests reduces human vulnerability to climate change, reduces air pollution, stores carbon and builds natural systems resilience.

Like all living plants, trees remove carbon dioxide from the atmosphere through the process of photosynthesis. In trees, this carbon uptake is relatively long-term, since much of it is stored in the trees' woody stems and roots. Therefore, tree planting can be a valuable contribution to reducing climate change. Besides capturing carbon, planting trees can reduce some negative impacts of climate change by providing shade and cooling. It can also help prevent erosion and reduce flood risk by slowing water flow. Restoring forest in degraded areas supports biodiversity and can provide benefits to people, ranging from timber to food and recreation.

There are some areas where replacing lost trees is useful. These include forest that has been recently cut down, and where reforestation is usually practical. However, it is very important to identify correctly areas of forest that are degraded or have definitely been deforested. Reforesting places, especially where existing native forest patches occur, brings benefits both in sucking up carbon from the atmosphere and helping us adapt to climate change. Plantations of a non-native species, although offering economic benefits, do not usually provide the same range of positive impacts and generally have lower biodiversity and carbon uptake and storage.

Reforestation options include the natural regeneration of the forest, assisted restoration, enrichment planting, native tree plantations, commercial plantations and directed tree planting can occur in agroforestry systems and urban areas. Reforestation with native species, usually contributes to a wide range of sustainability goals, including biodiversity recovery, improved water filtration and groundwater recharge. It can reduce the risks of soil erosion and flood risk. In cities, planting trees can support climate change adaptation by reducing the heat of the area and can promote a wide range of social benefits such as providing shade and benefiting outdoor recreation. Urban trees can also lower energy costs by reducing demand for conventional sources of cooling like air-conditioning, especially during peak-demand periods. It is therefore important to recognise that there are a wide range of different planting and forest management strategies. The choice will depend on the objectives and the location.

Not everywhere is suitable for tree planting. It is particularly problematic in native non-forested ecosystems. These natural ecosystems are not deforested and degraded but are instead naturally occurring non-forested ecosystems. These areas vary from being open grasslands to densely wooded savannas and shrublands. Here restoring the natural ecosystems instead of afforesting them will better contribute to increasing carbon storage and increasing the areas resilience. It is important to remember, just because a tree can grow somewhere, it does not mean that it should. These systems are very important in their own right, storing carbon in soils, supporting a rich biodiversity and providing people with important ecosystem services such as grazing. Planting trees in these areas destroys the ecosystem and threatens the biodiversity, which is adapted to these environments. They can also impact on ecosystem services such as forage for livestock, on which many people rely.

Many of these open areas also occur in low rainfall areas. Planting trees there uses a lot of water, can cause reductions in stream flow and groundwater. Many of these locations also burn regularly and planting trees threatens both the establishing trees but can also increase the intensity of the fires from that of a grass-fuelled fire to that of a woody-fuelled fire. Swapping grassy ecosystems for forests may contribute to warming, as forests absorb more incoming radiation (warmth) than grasslands. Aside from the negative impacts to adaptation, it is also questionable just how much carbon can be sequestered in these landscapes asplanting trees in grassy ecosystems can reduce carbon gains. Furthermore, a high belowground carbon store prevents carbon loss to fire in these fire-prone environments.

Another example is with peatlands. Peats store an incredible amount of carbon within them and are therefore important in maintaining and restoring to reduce atmospheric carbon. However, the restoration actions depend on what type of peatland it is and where it is located. Many temperate and boreal peatlands are naturally treeless. Here planting trees is often only possible following drainage, but draining and planting (especially with non-native species) destroys native biodiversity and releases greenhouse gases. Yet many peatlands, especially in the tropics, are naturally forested and restoring these peatlands requires re-wetting and restoring natural tree cover (see Figure FAQ2.2.1) which will increase carbon storage.

There are actions we can do instead of planting trees in non-forested ecosystems, and these include:

- Address the causes of deforestation, forest degradation and widespread ecosystem loss;
- Reduce carbon emissions from fossil fuels;
- Focus on ecosystem restoration over tree planting. For example, in restoring tropical grassy ecosystems, we can look at actions that cut down trees, enhance grass regrowth, and restore natural fire regimes. We have then a much better chance of both enhancing carbon capture and reducing some of the harmful effects of climate change.

In between the two extremes of where planting trees is highly suitable and areas where it is not, it is important to remember that the context matters and decisions to (re)forest should look beyond simply the act of planting trees. We can consider **what the ecological, social and economic goals are of tree planting**. It is then important to verify the local context and then decide **what restoration action will be most effective**. It is also very important to conserve forests before worrying about reforesting.

Figure FAQ2.6.1: Some places are more appropriate for tree planting than others and caution needs to be applied when planting in different biomes with some biomes being more suitable than others. This figure highlights some basic biome specific guidelines when planting in natural and semi-natural vegetation.

[END FAQ2.6 HERE]

2.7 Reducing Scientific Uncertainties to Inform Policy and Management Decisions

Research since the IPCC Fifth Assessment Report (Settele et al., 2014) has increased understanding of climate change impacts and vulnerability in ecosystems. Evidence gaps remain and geographic coverage of research is uneven. This section assesses gaps in ecosystem science where research is necessary for environmental policies and natural resource management, including under the UN Framework Convention on Climate Change and the Convention on Biological Diversity.

2.7.1 Observed impacts

Detection and attribution efforts have yet to give robust assessments of the roles of climate change in wildfires, tree mortality and human infectious diseases. Only one fire impact – the increase of the area burned by wildfire in western North America in the period 1984–2017 (Section 2.4.4.2.1) and just a few cases of tree mortality (Section 2.4.4.3) have been formally attributed to anthropogenic climate change. Global changes in soil and freshwater ecosystem carbon over time remain uncertainties in global carbon stocks and changes (Section 2.4.4.4); due to physical inabilities to conduct repeat monitoring and the lack of remote sensing to scale up point measurements, no global methods can yet produce repeating spatial estimates of soil carbon stock changes.

Despite the growing understanding of the importance of ecosystem services this assessment found limited research on observed impacts of climate change on ecosystem services for 14 of 18 ecosystem services (Table 2.1)

2.7.2 Projected risks

A challenge for future projections that continues from previous IPCC reports is accurately characterising and quantifying interactions among climate change and other factors causing ecological change, including deforestation, agricultural expansion, urbanisation, and air and water pollution. Interactions can be particularly complex for invasive species, pests and pathogens, and human infectious diseases. Modelling of risks at the species level requires comprehensive databases of physiological, life-history, and functional traits relevant to ecosystem resilience to climate change. Taxa that particularly lack this basis for model projections include fungi and bacteria. For numerous plant and animal species, research on genotypic and phenotypic diversity as a source of ecosystem resilience would inform projections of risk.

Soil plays a vital role in ecosystem function, is the habitat of a large number of species and is a large carbon store which is currently a major source of greenhouse gas emissions, it is therefore a priority for climate change research (Hashimoto et al., 2015). Major uncertainties remain in our understanding of soil functions. Earth System Models (ESMs) predict soil respiration to increase with rising temperature (Friedlingstein et al., 2014). However, there is evidence of acclimation post-increase (Carey et al., 2016) as the opposite response of decrease in respiration with warming (Li et al., 2013; Reynolds et al., 2015). Long-term, large scale field observations combined with a better conceptual understanding of factors governing soil process responses to climate change is needed. A better understanding of plant water relations is also necessary, including the response of plant transpiration to increased CO_2, climate warming and changes in soil moisture and groundwater elevation.

2.7.3 Adaptation and Climate Resilient Development

There are significant evidence gaps in developing adaptation, both for biodiversity conservation and EbA. In particular, whilst many adaptation measures have been proposed and implementation is starting, there are very few evaluations of success in the scientific literature (Morecroft et al., 2019; Prober et al., 2019). As detailed in Section 2.6.2, there is a strong literature on conceptual approaches to climate change adaptation for biodiversity, but very little empirical testing of which approaches actual work best. Going forward it is important put in place good monitoring and evaluation of adaptation strategies. For EbA, there are good examples of measuring changes in response to new adaptation measures, but these remain relatively rare globally.

Human factors which promote or hinder adaptation are important as well as the technical issues. There are few studies incorporating climate change and ecosystem services in integrated decision making, and even fewer aimed to identify solutions robust to uncertainty (Runting et al., 2017).
Over the last decades, losses from natural disasters including those from events related to extreme weather have strongly increased (Mechler and Bouwer, 2015). There is a need for better assessment of global adaptation costs, funding and investment (Micale et al., 2018). Potential synergies between international finance for disaster risk management and adaptation have not yet been fully realised. Research has almost exclusively focused on normalising losses for changes in exposure, yet not for vulnerability, a major gap given the dynamic nature of vulnerability (Mechler and Bouwer, 2015).

References

Abatzoglou, J. T. and C. A. Kolden, 2011: Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangeland Ecology & Management*, **64**(5), 471-478, doi:10.2111/rem-d-09-00151.1.

Abatzoglou, J. T. and A. P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, **113**(42), 11770-11775, doi:10.1073/pnas.1607171113.

Abatzoglou, J. T., A. P. Williams and R. Barbero, 2019: Global emergence of anthropogenic climate change in fire weather indices. *Geophysical Research Letters*, **46**(1), 326-336, doi:10.1029/2018GL080959.

Abatzoglou, J. T. et al., 2018: Global patterns of interannual climate-fire relationships. *Global Change Biology*, **24**(11), 5164-5175, doi:10.1111/gcb.14405.

Abbott, B. W. et al., 2016: Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment. *Environmental Research Letters*, **11**(3), 034014, doi:10.1088/1748-9326/11/3/034014.

Abdalla, M. et al., 2019: A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology*, **25**(8), 2530-2543, doi:10.1111/gcb.14644.

Abell, R., B. Lehner, M. Thieme and S. Linke, 2017: Looking Beyond the Fenceline: Assessing Protection Gaps for the World's Rivers. *Conservation Letters*, **10**(4), 384-394, doi:10.1111/conl.12312.

Aben, R. C. H. et al., 2017: Cross continental increase in methane ebullition under climate change. *Nature Communications*, **8**, doi:10.1038/s41467-017-01535-y.

Abrahams, C. et al., 2013: *The Impact of Extreme Events on Freshwater Ecosystems* [Jones, I. (ed.)]. Ecological Issues, British Ecological Society, 1-67 pp. Available at: http://irep.ntu.ac.uk/id/eprint/29446/1/PubSub6803_Abrahams2.pdf.

Abram, N. J. et al., 2021: Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment*, **2**(1), 8, doi:10.1038/s43247-020-00065-8.

Abreu, R. C. R. et al., 2017: The biodiversity cost of carbon sequestration in tropical savanna. *Science advances*, **3**(8), e1701284, doi:https://doi.org/10.1126/sciadv.1701284.

Acácio, V. et al., 2017: Landscape dynamics in Mediterranean oak forests under global change: understanding the role of anthropogenic and environmental drivers across forest types. *Global Change Biology*, **23**(3), 1199-1217.

Ackerman, D., D. Griffin, S. E. Hobbie and J. C. Finlay, 2017: Arctic shrub growth trajectories differ across soil moisture levels. *Global change biology*, **23**(10), 4294-4302.

Acreman, M. and J. Holden, 2013: How wetlands affect floods. *Wetlands*, **33**(5), 773-786.

Adams, C., J. Andrews and T. Jickells, 2012: Nitrous oxide and methane fluxes vs. carbon, nitrogen and phosphorous burial in new intertidal and saltmarsh sediments. *Science of the Total Environment*, **434**, 240-251.

Adams, H. D. et al., 2017: A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. *Nature Ecology & Evolution*, **1**(9), 1285-1291, doi:10.1038/s41559-017-0248-x.

Addo-Bankas, O. et al., 2021: Green walls: A form of constructed wetland in green buildings. *Ecological Engineering*, **169**, 106321, doi:https://doi.org/10.1016/j.ecoleng.2021.106321.

Adhikari, S., H. Baral and C. Nitschke, 2018: Adaptation to climate change in Panchase Mountain ecological regions of Nepal. *Environments*, **5**(3), 42, doi:10.3390/environments5030042.

Adila, N. et al., 2017: Effects of peat swamp logging and agricultural expansion on species richness of native mammals in Peninsular Malaysia. *Basic and Applied Ecology*, **22**, 1-10, doi:10.1016/j.baae.2017.04.002.

Adrian, R. et al., 2016: Environmental impacts—Lake ecosystems. In: *North Sea Region Climate Change Assessment*. Springer, Cham, pp. 315-340.

Adrian, R. et al., 2009: Lakes as sentinels of climate change. *Limnology and Oceanography*, **54**(6), 2283-2297, doi:10.4319/lo.2009.54.6_part_2.2283.

AghaKouchak, A., L. Y. Cheng, O. Mazdiyasni and A. Farahmand, 2014: Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. *Geophysical Research Letters*, **41**(24), 8847-8852, doi:10.1002/2014gl062308.

Agol, D., H. Reid, F. Crick and H. Wendo, 2021: Ecosystem-based adaptation in Lake Victoria Basin; synergies and trade-offs. *Royal Society Open Science*, **8**(6), 201847, doi:10.1098/rsos.201847.

Aguilera, E. et al., 2020: Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. *Agricultural Systems*, **181**, 102809.

Aguirre-Gutiérrez, J. et al., 2019: Drier tropical forests are susceptible to functional changes in response to a long-term drought. *Ecology Letters*, **22**(5), 855-865, doi:10.1111/ele.13243.

Ahlström, A. et al., 2015: The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink. *Science*, **348**(6237), 895-899, doi:10.1126/science.aaa1668.

Aide, T. M. et al., 2019: Woody vegetation dynamics in the tropical and subtropical Andes from 2001 to 2014: Satellite image interpretation and expert validation. *Global change biology*, **25**(6), 2112-2126, doi:10.1111/gcb.14618.

Ainsworth, E. A. et al., 2012: The Effects of Tropospheric Ozone on Net Primary Productivity and Implications for Climate Change. *Annual Review of Plant Biology*, **63**, 637-661, doi:10.1146/annurev-arplant-042110-103829.

Al-Haj, A. N. and R. W. Fulweiler, 2020: A synthesis of methane emissions from shallow vegetated coastal ecosystems. *Global Change Biology*, **26**(5), 2988-3005, doi:10.1111/gcb.15046.

Alba-Sánchez, F., J. A. López-Sáez, D. Nieto-Lugilde and J.-C. Svenning, 2015: Long-term climate forcings to assess vulnerability in North Africa dry argan woodlands. *Applied Vegetation Science*, **18**(2), 283-296, doi:https://doi.org/10.1111/avsc.12133.
Albrecht, M. et al., 2020: The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: a quantitative synthesis. *Ecology Letters*, **23**(10), 1488-1498, doi:10.1111/ele.13576.
Albrich, K., W. Rammer and R. Seidl, 2020a: Climate change causes critical transitions and irreversible alterations of mountain forests. *Global Change Biology*, **26**(7), 4013-4027, doi:https://doi.org/10.1111/gcb.15118.
Albrich, K. et al., 2020b: Simulating forest resilience: A review. *Global Ecology and Biogeography*, **29**(12), 2082-2096, doi:https://doi.org/10.1111/geb.13197.
Albright, T. P. et al., 2017: Mapping evaporative water loss in desert passerines reveals an expanding threat of lethal dehydration. *Proceedings of the National Academy of Sciences*, **114**(9), 2283, doi:10.1073/pnas.1613625114.
Aleixo, I. et al., 2019: Amazonian rainforest tree mortality driven by climate and functional traits. *Nature Climate Change*, **9**(5), 384-+, doi:10.1038/s41558-019-0458-0.
Aleman, J. C., O. Blarquez and C. A. Staver, 2016: Land-use change outweighs projected effects of changing rainfall on tree cover in sub-Saharan Africa. *Global Change Biology*, **22**(9), 3013-3025, doi:10.1111/gcb.13299.
Aleman, J. C., M. A. Jarzyna and A. C. Staver, 2018: Forest extent and deforestation in tropical Africa since 1900. *Nature ecology & evolution*, **2**(1), 26.
Alencar, A. A., P. M. Brando, G. P. Asner and F. E. Putz, 2015: Landscape fragmentation, severe drought, and the new Amazon forest fire regime. *Ecological Applications*, **25**(6), 1493-1505, doi:10.1890/14-1528.1.
Alexander, J. M. et al., 2018: Lags in the response of mountain plant communities to climate change. *Global Change Biology*, **24**(2), 563-579, doi:https://doi.org/10.1111/gcb.13976.
Alfieri, L. et al., 2017: Global projections of river flood risk in a warmer world. *Earths Future*, **5**(2), 171-182, doi:10.1002/2016ef000485.
Alkama, R. and A. Cescatti, 2016: Biophysical climate impacts of recent changes in global forest cover. *Science*, **351**(6273), 600-604, doi:10.1126/science.aac8083.
Allen, C. D., D. D. Breshears and N. G. McDowell, 2015: On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, **6**(8), 1-55.
Allen, C. D. et al., 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259**(4), 660-684, doi:10.1016/j.foreco.2009.09.001.
Allen, G. H. and T. M. Pavelsky, 2018: Global extent of rivers and streams. *Science*, doi:10.1126/science.aat0636.
Allen, J. L. and J. C. Lendemer, 2016: Climate change impacts on endemic, high-elevation lichens in a biodiversity hotspot. *Biodiversity and Conservation*, **25**(3), 555-568, doi:10.1007/s10531-016-1071-4.
Allen, T. et al., 2017: Global hotspots and correlates of emerging zoonotic diseases. *Nature Communications*, **8**(1), 1124, doi:10.1038/s41467-017-00923-8.
Alo, C. A. and G. Wang, 2008: Potential future changes of the terrestrial ecosystem based on climate projections by eight general circulation models. *Journal of Geophysical Research: Biogeosciences*, **113**(G1), doi:10.1029/2007JG000528.
Alongi, D. M., 2015: The impact of climate change on mangrove forests. *Current Climate Change Reports*, **1**(1), 30-39.
Alonso, D., M. J. Bouma and M. Pascual, 2011: Epidemic malaria and warmer temperatures in recent decades in an East African highland. *Proceedings of the Royal Society B: Biological Sciences*, **278**(1712), 1661-1669, doi:10.1098/rspb.2010.2020.
Altizer, S. et al., 2013: Climate Change and Infectious Diseases: From Evidence to a Predictive Framework. *Science*, **341**(6145), 514-519, doi:10.1126/science.1239401.
Alvarez-Clare, S., M. C. Mack and M. Brooks, 2013: A direct test of nitrogen and phosphorus limitation to net primary productivity in a lowland tropical wet forest. *Ecology*, **94**(7), 1540-1551, doi:10.1890/12-2128.1.
Alvarez-Garreton, C., A. Lara, J. P. Boisier and M. Galleguillos, 2019: The Impacts of Native Forests and Forest Plantation on Water Supply in Chile. *Forests*, **10**(6), 473.
Ameli, A. A. and I. F. Creed, 2019: Does wetland location matter when managing wetlands for watershed-scale flood and drought resilience? *JAWRA Journal of the American Water Resources Association*, **55**(3), 529-542.
Ameztegui, A., L. Coll, L. Brotons and J. M. Ninot, 2016: Land-use legacies rather than climate change are driving the recent upward shift of the mountain tree line in the Pyrenees. *Global Ecology and Biogeography*, **25**(3), 263-273, doi:10.1111/geb.12407.
Anacker, B. L. and S. P. Harrison, 2012: Climate and the evolution of serpentine endemism in California. *Evolutionary Ecology*, **26**(4), 1011-1023, doi:10.1007/s10682-011-9532-4.
Anadón, J. D., O. E. Sala and F. T. Maestre, 2014: Climate change will increase savannas at the expense of forests and treeless vegetation in tropical and subtropical Americas. *Journal of Ecology*, **102**(6), 1363-1373, doi:10.1111/1365-2745.12325.
Anadon, J. D., O. E. Sala, B. L. Turner and E. M. Bennett, 2014: Effect of woody-plant encroachment on livestock production in North and South America. *Proceedings of the National Academy of Sciences*, **111**(35), 12948-12953, doi:10.1073/pnas.1320585111.
Andela, N. et al., 2017: A human-driven decline in global burned area. *Science*, **356**(6345), 1356-1361, doi:10.1126/science.aal4108.

Andela, N. et al., 2019: The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth System Science Data*, **11**(2), 529-552, doi:10.5194/essd-11-529-2019.
Anderegg, W. R., L. D. Anderegg, K. L. Kerr and A. T. Trugman, 2019a: Widespread drought-induced tree mortality at dry range edges indicates that climate stress exceeds species' compensating mechanisms. *Global change biology*, **25**(11), 3793-3802.
Anderegg, W. R. et al., 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368**(6497).
Anderegg, W. R. L., L. D. L. Anderegg, K. L. Kerr and A. T. Trugman, 2019b: Widespread drought-induced tree mortality at dry range edges indicates that climate stress exceeds species' compensating mechanisms. *Global Change Biology*, **25**(11), 3793-3802, doi:10.1111/gcb.14771.
Anderegg, W. R. L. et al., 2015: Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytologist*, **208**(3), 674-683, doi:10.1111/nph.13477.
Anderegg, W. R. L. et al., 2016: Meta-analysis reveals that hydraulic traits explain cross-species patterns of drought-induced tree mortality across the globe. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(18), 5024-5029, doi:10.1073/pnas.1525678113.
Anderegg, W. R. L. et al., 2018: Hydraulic diversity of forests regulates ecosystem resilience during drought. *Nature*, **561**(7724), 538-+, doi:10.1038/s41586-018-0539-7.
Andersen, E. M. and R. J. Steidl, 2019: Woody plant encroachment restructures bird communities in semiarid grasslands. *Biological Conservation*, **240**, 108276.
Andersen, R. et al., 2017: An overview of the progress and challenges of peatland restoration in Western Europe. *Restoration Ecology*, **25**(2), 271-282.
Anderson, L. O. et al., 2018: Vulnerability of Amazonian forests to repeated droughts. *Philos Trans R Soc Lond B Biol Sci*, **373**(1760), doi:10.1098/rstb.2017.0411.
Andersson, N. et al., 2015: Evidence based community mobilization for dengue prevention in Nicaragua and Mexico (Camino Verde, the Green Way): cluster randomized controlled trial. *BMJ : British Medical Journal*, **351**, h3267, doi:10.1136/bmj.h3267.
Andresen, C. G. and V. L. Lougheed, 2015: Disappearing Arctic tundra ponds: Fine-scale analysis of surface hydrology in drained thaw lake basins over a 65 year period (1948–2013). *Journal of Geophysical Research: Biogeosciences*, **120**(3), 466-479, doi:https://doi.org/10.1002/2014JG002778
Andrew, S. C., L. L. Hurley, M. M. Mariette and S. C. Griffith, 2017: Higher temperatures during development reduce body size in the zebra finch in the laboratory and in the wild. *J. Evol. Biol.*, **30**(12), 2156-2164, doi:https://doi.org/10.1111/jeb.13181.
Andrus, R. A., T. T. Veblen, B. J. Harvey and S. J. Hart, 2016: Fire severity unaffected by spruce beetle outbreak in spruce-fir forests in southwestern Colorado. *Ecological Applications*, **26**(3), 700-711, doi:10.1890/15-1121.
Angel, J. R. and K. E. Kunkel, 2010: The response of Great Lakes water levels to future climate scenarios with an emphasis on Lake Michigan-Huron. *Journal of Great Lakes Research*, **36**, 51-58.
Angerbjörn, A. et al., 2013: Carnivore conservation in practice: replicated management actions on a large spatial scale. *Journal of Applied Ecology*, **50**(1), 59-67.
Angilletta Jr, M. J., 2009: *Thermal Adaptation: A Theoretical and Empirical Synthesis*. Oxford University Press, Oxford, 302 pp. ISBN 978-0-19-857087-5.
Angilletta, M. J., R. S. Wilson, C. A. Navas and R. S. James, 2003: Tradeoffs and the evolution of thermal reaction norms. *Trends in Ecology & Evolution*, **18**(5), 234-240, doi:https://doi.org/10.1016/S0169-5347(03)00087-9.
Anich, N. M. and M. P. Ward, 2017: Using audio playback to expand the geographic breeding range of an endangered species. *Diversity and Distributions*, **23**(12), 1499-1508, doi:10.1111/ddi.12635.
Anonymous, 2019: *Madhya Pradesh climate change vulnerabilities and response strategies*. State Knowledge Management Centre on Climate Change, Madhya Pradesh. Available at: http://climatechange.mp.gov.in/sites/default/files/resources/Madhya%20Pradesh%20Climate%20Change%20Vulnerabilities%20&%20Response%20Strategies.pdf.
Anshari, G., A. Peter Kershaw and S. van der Kaars, 2001: A Late Pleistocene and Holocene pollen and charcoal record from peat swamp forest, Lake Sentarum Wildlife Reserve, West Kalimantan, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **171**(3-4), 213-228, doi:10.1016/S0031-0182(01)00246-2.
Anshari, G., A. Peter Kershaw, S. Van Der Kaars and G. Jacobsen, 2004: Environmental change and peatland forest dynamics in the Lake Sentarum area, West Kalimantan, Indonesia. *Journal of Quaternary Science*, **19**(7), 637-655, doi:10.1002/jqs.879.
Anshari, G. Z., E. Gusmayanti and N. Novita, 2021: The Use of Subsidence to Estimate Carbon Loss from Deforested and Drained Tropical Peatlands in Indonesia. *Forests*, **12**(6), 732, doi:10.3390/f12060732.
Anyamba, A., K. J. Linthicum and C. J. Tucker, 2001: Climate-disease connections: Rift Valley Fever in Kenya. *Cad Saude Publica*, **17 Suppl**, 133-140, doi:10.1590/s0102-311x2001000700022.
Anyamba, A. et al., 2014: Recent Weather Extremes and Impacts on Agricultural Production and Vector-Borne Disease Outbreak Patterns. *PLOS ONE*, **9**(3), e92538, doi:10.1371/journal.pone.0092538.
Arafeh-Dalmau, N. et al., 2019: Extreme Marine Heatwaves Alter Kelp Forest Community Near Its Equatorward Distribution Limit. *Frontiers in Marine Science*, **6**, doi:10.3389/fmars.2019.00499.
Aragao, L. E. O. C. et al., 2018: 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, **9**, doi:10.1038/s41467-017-02771-y.

Aragao, L. E. O. C. et al., 2014: Environmental change and the carbon balance of Amazonian forests. *Biological Reviews*, **89**(4), 913-931, doi:10.1111/brv.12088.
Aragón-Gastélum, J. L. et al., 2014: Induced climate change impairs photosynthetic performance in Echinocactus platyacanthus, an especially protected Mexican cactus species. *Flora - Morphology, Distribution, Functional Ecology of Plants*, **209**(9), 499-503, doi:10.1016/j.flora.2014.06.002.
Aram, F., E. Higueras García, E. Solgi and S. Mansournia, 2019: Urban green space cooling effect in cities. *Heliyon*, **5**(4), e01339, doi:10.1016/j.heliyon.2019.e01339.
Araujo, M. et al., 2019: Standards for distribution models in biodiversity assessments. *Science Advances*, **5**(1), doi:10.1126/sciadv.aat4858.
Archer, D. et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Climate and Development*, **6**(4), 345-356.
Archer, S. R. et al., 2017: Woody plant encroachment: causes and consequences. In: *Rangeland systems*. Springer, Cham, pp. 25–84.
Archibald, S., 2016: Managing the human component of fire regimes: lessons from Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1696), 20150346, doi:10.1098/rstb.2015.0346.
Archibald, S. et al., 2019: Distribution and determinants of savannas. *Savanna woody plants and large herbivores*, 1-24.
Archibald, S., C. E. R. Lehmann, J. L. Gómez-Dans and R. A. Bradstock, 2013: Defining pyromes and global syndromes of fire regimes. *Proceedings of the National Academy of Sciences*, **110**(16), 6442-6447, doi:10.1073/pnas.1211466110.
Archibald, S., D. P. Roy, B. W. van Wilgen and R. J. Scholes, 2009: What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology*, **15**(3), 613-630.
Arneth, A. et al., 2021: Restoring Degraded Lands. *Annual Review of Environment and Resources*, doi:10.1146/annurev-environ-012320-054809.
Arneth, A. et al., 2020: Post-2020 biodiversity targets need to embrace climate change. *Proceedings of the National Academy of Sciences*, **117**(49), 30882, doi:10.1073/pnas.2009584117.
Arneth, A. et al., 2017: Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. *Nature Geoscience*, **10**(2), 79-84, doi:10.1038/ngeo2882.
Arora, R., K. Tockner and M. Venohr, 2016: Changing river temperatures in northern Germany: trends and drivers of change. *Hydrological Processes*, **30**(17), 3084-3096, doi:10.1002/hyp.10849.
Arora, V. K. and J. R. Melton, 2018: Reduction in global area burned and wildfire emissions since 1930s enhances carbon uptake by land. *Nature Communications*, **9**, doi:10.1038/s41467-018-03838-0.
Arthington, A. H. and W. L. Hadwen, 2003: The significance and management implications of perched dune lakes as swimming and recreation sites on Fraser Island, Australia. *Journal of Tourism Studies*, **14**(2), 35.
Aryal, D. R., R. R. Gómez-González, R. Hernández-Nuriasmú and D. E. Morales-Ruiz, 2019: Carbon stocks and tree diversity in scattered tree silvopastoral systems in Chiapas, Mexico. *Agroforestry Systems*, **93**(1), 213-227, doi:10.1007/s10457-018-0310-y.
Asner, G. P. et al., 2016a: Progressive forest canopy water loss during the 2012–2015 California drought. *Proceedings of the National Academy of Sciences*, **113**(2), E249–E255.
Asner, G. P., N. Vaughn, I. P. Smit and S. Levick, 2016b: Ecosystem-scale effects of megafauna in African savannas. *Ecography*, **39**(2), 240–252.
Assessment, M. E., 2005: Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
Åström, C. et al., 2012: Potential Distribution of Dengue Fever Under Scenarios of Climate Change and Economic Development. *EcoHealth*, **9**(4), 448-454, doi:10.1007/s10393-012-0808-0.
Avitabile, V. et al., 2016: An integrated pan-tropical biomass map using multiple reference datasets. *Global Change Biology*, **22**(4), 1406-1420, doi:10.1111/gcb.13139.
Axelson, J. N., B. C. Hawkes, L. van Akker and R. I. Alfaro, 2018: Stand dynamics and the mountain pine beetle-30 years of forest change in Waterton Lakes National Park, Alberta, Canada. *Canadian Journal of Forest Research*, **48**(10), 1159-1170, doi:10.1139/cjfr-2018-0161.
Babst, F. et al., 2019: Twentieth century redistribution in climatic drivers of global tree growth. *Science Advances*, **5**(1), doi:10.1126/sciadv.aat4313.
Baccini, A. et al., 2012: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, **2**(3), 182-185, doi:10.1038/nclimate1354.
Baccini, A. et al., 2017: Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science*, **358**(6360), 230-234.
Bagella, S. et al., 2016: Mediterranean Temporary Ponds: new challenges from a neglected habitat. *Hydrobiologia*, **782**(1), 1-10, doi:10.1007/s10750-016-2962-9.
Bailey, L. and M. van de Pol, 2016: Tackling extremes: challenges for ecological and evolutionary research on extreme climatic events. *Journal of Animal Ecology*, **85**(1), 85-96, doi:10.1111/1365-2656.12451.
Baker-Austin, C. et al., 2018: Vibrio spp. infections. *Nature Reviews Disease Primers*, **4**(1), 1-19, doi:10.1038/s41572-018-0005-8.
Baker-Austin, C., J. Trinanes, N. Gonzalez-Escalona and J. Martinez-Urtaza, 2017: Non-cholera *Vibrios*: the microbial barometer of climate change. *Trends in Microbiology*, **25**(1), 76-84, doi:10.1016/j.tim.2016.09.008.

Baker-Austin, C. et al., 2013: Emerging Vibrio risk at high latitudes in response to ocean warming. *Nature Climate Change*, **3**(1), 73-77, doi:10.1038/nclimate1628.
Baker, D. M., G. Murray and A. K. Agyare, 2018: Governance and the making and breaking of social-ecological traps. *Ecology and Society*, **23**(1).
Bakker, E. S. et al., 2016: Combining paleo-data and modern exclosure experiments to assess the impact of megafauna extinctions on woody vegetation. *Proceedings of the National Academy of Sciences*, **113**(4), 847-855.
Bakker, E. S. and J.-C. Svenning, 2018: Trophic rewilding: impact on ecosystems under global change. *Philosophical Transactions of the Royal Society B*, doi:10.1098/rstb.2017.0432.
Balanya, J. et al., 2006: Global genetic change tracks global climate warming in Drosophila subobscura. *Science*, **313**(5794), 1773-1775, doi:10.1126/science.1131002.
Balch, J. K. et al., 2017: Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(11), 2946-2951, doi:10.1073/pnas.1617394114.
Balch, J. K. et al., 2015: The susceptibility of southeastern Amazon forests to fire: insights from a large-scale burn experiment. *BioScience*, **65**(9), 893-905.
Balian, E., H. Segers, C. Leveque and K. Martens, 2008: An introduction to the freshwater animal diversity assessment (FADA) project. *Hydrobiologia*, **595**, 3-8, doi:10.1007/s10750-007-9235-6.
Ball, G. et al., 2021: Wildfires increasingly impact western US fluvial networks. *Nature Communications*, **12**(1), 8, doi:10.1038/s41467-021-22747-3.
Ballantyne, A. P. et al., 2012: Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature*, **488**(7409), 70.
Ballhorn, U., F. Siegert, M. Mason and S. Limin, 2009: Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. *Proceedings of the National Academy of Sciences*, **106**(50), 21213-21218, doi:10.1073/pnas.0906457106.
Bangash, R. F. et al., 2013: Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control. *Science of The Total Environment*, **458-460**, 246-255, doi:https://doi.org/10.1016/j.scitotenv.2013.04.025.
Bank, W., 2016: *Urbanization, Climate Change Threaten eThekwini Municipality's Long-Term Sustainability*. Bank, W. Available at: https://www.worldbank.org/en/country/southafrica/publication/urbanization-climate-change-threaten-ethekwini-municipalitys-long-term-sustainability.
Barbeaux, S. J., K. Holsman and S. Zador, 2020: Marine Heatwave Stress Test of Ecosystem-Based Fisheries Management in the Gulf of Alaska Pacific Cod Fishery. *Frontiers in Marine Science*, **7**, doi:10.3389/fmars.2020.00703.
Barbero, R. et al., 2015: Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*, **24**(7), 892–899.
Barbieri, P., S. Pellerin, V. Seufert and T. Nesme, 2019: Changes in crop rotations would impact food production in an organically farmed world. *Nature Sustainability*, **2**(5), 378-385, doi:10.1038/s41893-019-0259-5.
Barbosa, H. A. and T. V. Lakshmi Kumar, 2016: Influence of rainfall variability on the vegetation dynamics over Northeastern Brazil. *Journal of Arid Environments*, **124**, 377-387, doi:https://doi.org/10.1016/j.jaridenv.2015.08.015.
Barichivich, J. et al., 2013: Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO2 at high northern latitudes from 1950 to 2011. *Global Change Biology*, **19**(10), 3167-3183, doi:10.1111/gcb.12283.
Bark, R. H., J. Martin-Ortega and K. A. Waylen, 2021: Stakeholders' views on natural flood management: Implications for the nature-based solutions paradigm shift? *Environmental Science & Policy*, **115**, 91-98.
Barnosky, A. D. et al., 2011: Has the Earth's sixth mass extinction already arrived? *Nature*, **471**(7336), 51-57.
Barr, S. L., B. M. Larson, T. J. Beechey and D. J. Scott, 2021: Assessing climate change adaptation progress in Canada's protected areas. *The Canadian Geographer/Le Géographe canadien*, **65**(2), 152-165.
Barrows, C. W. et al., 2014: Designing a sustainable monitoring framework for assessing impacts of climate change at Joshua Tree National Park, USA. *Biodiversity and Conservation*, **23**(13), 3263-3285, doi:10.1007/s10531-014-0779-2.
Barrows, C. W. and M. L. Murphy-Mariscal, 2012: Modeling impacts of climate change on Joshua trees at their southern boundary: How scale impacts predictions. *Biological Conservation*, **152**, 29-36, doi:10.1016/j.biocon.2012.03.028.
Barrows, C. W. et al., 2020: Validating climate-change refugia: empirical bottom-up approaches to support management actions. *Frontiers in Ecology and the Environment*, **18**(5), 298-306, doi:10.1002/fee.2205.
Barsoum, N. et al., 2016: Diversity, functional structure and functional redundancy of woodland plant communities: How do mixed tree species plantations compare with monocultures? *Forest Ecology and Management*, **382**, 244-256.
Bartlett, M. K., M. Detto and S. W. Pacala, 2019: Predicting shifts in the functional composition of tropical forests under increased drought and CO. *Ecology Letters*, **22**(1), 67-77, doi:10.1111/ele.13168.

Barton, A. M. and H. M. Poulos, 2018: Pine vs. oaks revisited: Conversion of Madrean pine-oak forest to oak shrubland after high-severity wildfire in the Sky Islands of Arizona. *Forest Ecology and Management*, **414**, 28-40, doi:10.1016/j.foreco.2018.02.011.
Bartosiewicz, M. et al., 2019: Hot tops, cold bottoms: Synergistic climate warming and shielding effects increase carbon burial in lakes. *Limnology and Oceanography Letters*, **0**(0), doi:10.1002/lol2.10117.
Basara, J. B. and J. I. Christian, 2018: Seasonal and interannual variability of land-atmosphere coupling across the Southern Great Plains of North America using the North American regional reanalysis. *International Journal of Climatology*, **38**(2), 964-978, doi:10.1002/joc.5223.
Bastazini, V. A. G. et al., 2021: The impact of climate warming on species diversity across scales: Lessons from experimental meta-ecosystems. *Global Ecology and Biogeography*, **30**(7), 1545-1554, doi:https://doi.org/10.1111/geb.13308.
Bastin, J.-F. et al., 2019: The global tree restoration potential. *Science*, **365**(6448), 76-79, doi:10.1126/science.aax0848.
Bastin, J. F. et al., 2020: Erratum for the Report: "The global tree restoration potential" by J.-F. Bastin, Y. Finegold, C. Garcia, D. Mollicone, M. Rezende, D. Routh, C. M. Zohner, T. W. Crowther and for the Technical Response "Response to Comments on 'The global tree restoration potential'" by J.-F. Bastin, Y. Finegold, C. Garcia, N. Gellie, A. Lowe, D. Mollicone, M. Rezende, D. Routh, M. Sacande, B. Sparrow, C. M. Zohner, T. W. Crowther. *Science*, **368**(6494), doi:10.1126/science.abc8905.
Batáry, P., L. V. Dicks, D. Kleijn and W. J. Sutherland, 2015: The role of agri-environment schemes in conservation and environmental management. *Conservation Biology*, **29**(4), 1006-1016.
Bates, A. E. et al., 2019: Climate resilience in marine protected areas and the 'Protection Paradox'. *Biological Conservation*, **236**, 305-314, doi:10.1016/j.biocon.2019.05.005.
Batjes, N. H., 2016: Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. *Geoderma*, **269**, 61-68, doi:10.1016/j.geoderma.2016.01.034.
Batllori, E. et al., 2019: Compound fire-drought regimes promote ecosystem transitions in Mediterranean ecosystems. *Journal of Ecology*, **107**(3), 1187-1198, doi:10.1111/1365-2745.13115.
Batllori, E. et al., 2020: Forest and woodland replacement patterns following drought-related mortality. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(47), 29720-29729, doi:10.1073/pnas.2002314117.
Batllori, E. et al., 2017: Potential relocation of climatic environments suggests high rates of climate displacement within the North American protection network. *Global Change Biology*, **23**(8), 3219-3230, doi:10.1111/gcb.13663.
Bauhus, J., K. Puettmann and C. Messier, 2009: Silviculture for old-growth attributes. *Forest Ecology and Management*, **258**(4), 525-537, doi:https://doi.org/10.1016/j.foreco.2009.01.053.
Bay, R. A. et al., 2018: Genomic signals of selection predict climate-driven population declines in a migratory bird. *Science*, **359**(6371), 83-86, doi:10.1126/science.aan4380.
Beaulieu, J. J., T. DelSontro and J. A. Downing, 2019: Eutrophication will increase methane emissions from lakes and impoundments during the 21st century. *Nature Communications*, **10**, doi:10.1038/s41467-019-09100-5.
Beaulieu, J. J., M. G. McManus and C. T. Nietch, 2016: Estimates of reservoir methane emissions based on a spatially balanced probabilistic-survey. *Limnology and Oceanography*, **61**(S1), S27-S40.
Beaumont, L. et al., 2016: Which species distribution models are more (or less) likely to project broad-scale, climate-induced shifts in species ranges? *Ecological Modelling*, **342**, 135-146, doi:10.1016/j.ecolmodel.2016.10.004.
Bebbington, A. J. and J. T. Bury, 2009: Institutional challenges for mining and sustainability in Peru. *Proceedings of the National Academy of Sciences*, **106**(41), 17296-17301, doi:10.1073/pnas.0906057106.
Bedelian, C. and J. O. Ogutu, 2017: Trade-offs for climate-resilient pastoral livelihoods in wildlife conservancies in the Mara ecosystem, Kenya. *Pastoralism*, **7**(1), 10.
Beer, C. et al., 2010: Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. *Science*, **329**(5993), 834-838, doi:10.1126/science.1184984.
Bell, G. et al., 2019: Trophic structure modulates community rescue following acidification. *Proceedings of the Royal Society B: Biological Sciences*, **286**(1904), 9, doi:10.1098/rspb.2019.0856.
Bell, G. and A. Gonzalez, 2009: Evolutionary rescue can prevent extinction following environmental change. *Ecology Letters*, **12**(9), 942-948, doi:10.1111/j.1461-0248.2009.01350.x.
Bellahirech, A. et al., 2019: Site- and tree-related factors affecting colonization of cork oaks Quercus suber L. by ambrosia beetles in Tunisia. *Annals of Forest Science*, **76**(2), doi:10.1007/s13595-019-0815-1.
Bellis, J., D. Bourke, C. Williams and S. Dalrymple, 2019: Identifying factors associated with the success and failure of terrestrial insect translocations. *Biological Conservation*, **236**, 29-36, doi:10.1016/j.biocon.2019.05.008.
Bello, C. et al., 2015: Defaunation affects carbon storage in tropical forests. *Science Advances*, **1**(11), doi:10.1126/sciadv.1501105.
Belote, R. T. et al., 2017: Wild, connected, and diverse: building a more resilient system of protected areas. *Ecological Applications*, **27**(4), 1050-1056, doi:https://doi.org/10.1002/eap.1527.
Benali, A. et al., 2017: Bimodal fire regimes unveil a global-scale anthropogenic fingerprint. *Global Ecology and Biogeography*, **26**(7), 799-811, doi:10.1111/geb.12586.
Benayas José, M. R., C. Newton Adrian, A. Diaz and M. Bullock James, 2009: Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis. *Science*, **325**(5944), 1121-1124, doi:10.1126/science.1172460.

Bennett, A. C., N. G. McDowell, C. D. Allen and K. J. Anderson-Teixeira, 2015: Larger trees suffer most during drought in forests worldwide. *Nature Plants*, **1**(10), 15139.
Bentz, B. J. et al., 2010: Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *BioScience*, **60**(8), 602-613, doi:10.1525/bio.2010.60.8.6.
Berdugo, M. et al., 2020: Global ecosystem thresholds driven by aridity. *Science*, **367**(6479), 787, doi:10.1126/science.aay5958.
Berenguer, E. et al., 2021: Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. *Proceedings of the National Academy of Sciences*, **118**(30), e2019377118, doi:10.1073/pnas.2019377118.
Bergengren, J. C., D. E. Waliser and Y. L. Yung, 2011: Ecological sensitivity: a biospheric view of climate change. *Climatic Change*, **107**(3-4), 433, doi:10.1007/s10584-011-0065-1.
Bergstrom, D. M. et al., 2021: Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology*, **27**(9), 1692-1703, doi:https://doi.org/10.1111/gcb.15539.
Berio Fortini, L., L. R. Kaiser and D. A. LaPointe, 2020: Fostering real-time climate adaptation: Analyzing past, current, and forecast temperature to understand the dynamic risk to Hawaiian honeycreepers from avian malaria. *Global Ecology and Conservation*, **23**, e01069, doi:10.1016/j.gecco.2020.e01069.
Bernhardt, E. et al., 2018: The metabolic regimes of flowing waters. *Limnology and Oceanography*, **63**, S99-S118, doi:10.1002/lno.10726.
Bernstein, A., 2015: Climate Change and the Crystal Ball of Vector-Borne Disease Forecasts. *Current Climate Change Reports*, **1**(4), 217-223, doi:10.1007/s40641-015-0022-6.
Berteaux, D. et al., 2018: Northern protected areas will become important refuges for biodiversity tracking suitable climates. *Scientific Reports*, **8**, doi:10.1038/s41598-018-23050-w.
Bertrand, R. et al., 2011: Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, **479**(7374), 517-520.
Berzaghi, F. et al., 2019: Carbon stocks in central African forests enhanced by elephant disturbance. *Nature Geoscience*, **12**(9), 725-+, doi:10.1038/s41561-019-0395-6.
Berzaghi, F. et al., 2018: Assessing the role of megafauna in tropical forest ecosystems and biogeochemical cycles - the potential of vegetation models. *Ecography*, **41**(12), 1934-1954, doi:10.1111/ecog.03309.
Bestelmeyer, B. T. et al., 2018: The Grassland-Shrubland Regime Shift in the Southwestern United States: Misconceptions and Their Implications for Management. *Bioscience*, **68**(9), 678-690, doi:10.1093/biosci/biy065.
Bett, B. et al., 2017: Effects of climate change on the occurrence and distribution of livestock diseases. *Preventive Veterinary Medicine*, **137**, 119-129, doi:10.1016/j.prevetmed.2016.11.019.
Bhatt, S. et al., 2015: The effect of malaria control on Plasmodium falciparum in Africa between 2000 and 2015. *Nature*, **526**(7572), 207-211, doi:10.1038/nature15535.
Bhattarai, G. P. and J. T. Cronin, 2014: Hurricane activity and the large-scale pattern of spread of an invasive plant species. *PLoS One*, **9**(5), e98478.
Biagini, B. et al., 2014: A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. *Global Environmental Change*, **25**, 97-108, doi:10.1016/j.gloenvcha.2014.01.003.
Biagioni, S. et al., 2015: 8000 years of vegetation dynamics and environmental changes of a unique inland peat ecosystem of the Jambi Province in Central Sumatra, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **440**, 813-829, doi:10.1016/j.palaeo.2015.09.048.
Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Birk, S. et al., 2020: Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. *Nature Ecology & Evolution*, **4**(8), 1060-1068, doi:10.1038/s41559-020-1216-4.
Bjork, S. J. and J. L. Bartholomew, 2009: The effects of water velocity on the Ceratomyxa shasta infectious cycle. *Journal of Fish Diseases*, **32**(2), 131-142, doi:https://doi.org/10.1111/j.1365-2761.2008.00964.x.
Bjorkman, A. D. et al., 2019: Status and trends in Arctic vegetation: Evidence from experimental warming and long-term monitoring. *Ambio*, 1-15.
Bjorkman, A. D. et al., 2018: Plant functional trait change across a warming tundra biome. *Nature*, **562**(7725), 57.
Blackman, A., L. Corral, E. S. Lima and G. P. Asner, 2017: Titling indigenous communities protects forests in the Peruvian Amazon. *Proceedings of the National Academy of Sciences*, **114**(16), 4123-4128, doi:10.1073/pnas.1603290114.
Blaser, W. J. et al., 2018: Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nature Sustainability*, **1**(5), 234.
Blum, A. J. and P. J. Hotez, 2018: Global “worming”: Climate change and its projected general impact on human helminth infections. *PLoS Neglected Tropical Diseases*, **12**(7), doi:10.1371/journal.pntd.0006370.
Blume-Werry, G., S. D. Wilson, J. Kreyling and A. Milbau, 2016: The hidden season: growing season is 50% longer below than above ground along an arctic elevation gradient. *New Phytologist*, **209**(3), 978-986.

Bodensteiner, B. L. et al., 2021: Thermal adaptation revisited: How conserved are thermal traits of reptiles and amphibians? *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, **335**(1), 173-194, doi:https://doi.org/10.1002/jez.2414.
Bodmer, P., J. Wilkinson and A. Lorke, 2020: Sediment Properties Drive Spatial Variability of Potential Methane Production and Oxidation in Small Streams. *Journal of Geophysical Research: Biogeosciences*, **125**(1), doi:10.1029/2019jg005213.
Boelman, N. T. et al., 2015: Greater shrub dominance alters breeding habitat and food resources for migratory songbirds in Alaskan arctic tundra. *Global Change Biology*, **21**(4), 1508-1520.
Boer, M. M., V. R. de Dios and R. A. Bradstock, 2020: Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, **10**(3), 171-172.
Bogan, M. T., K. S. Boersma and D. A. Lytle, 2015: Resistance and resilience of invertebrate communities to seasonal and supraseasonal drought in arid-land headwater streams. *Freshwater Biology*, **60**(12), 2547-2558, doi:10.1111/fwb.12522

Boisramé, G., S. Thompson, B. Collins and S. Stephens, 2017: Managed Wildfire Effects on Forest Resilience and Water in the Sierra Nevada. *Ecosystems*, **20**(4), 717-732, doi:10.1007/s10021-016-0048-1.
Boisvert-Marsh, L. and S. de Blois, 2021: Unravelling potential northward migration pathways for tree species under climate change. *Journal of Biogeography*, **48**(5), 1088-1100, doi:10.1111/jbi.14060.
Boisvert-Marsh, L., C. Perie and S. de Blois, 2019: Divergent responses to climate change and disturbance drive recruitment patterns underlying latitudinal shifts of tree species. *Journal of Ecology*, **107**(4), 1956-1969, doi:10.1111/1365-2745.13149.
Boit, A. et al., 2016: Large-scale impact of climate change vs. land-use change on future biome shifts in Latin America. *Global Change Biology*, **22**(11), 3689-3701, doi:10.1111/gcb.13355.
Boithias, L. et al., 2014: Assessment of the water supply:demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. *Science of The Total Environment*, **470-471**, 567-577, doi:https://doi.org/10.1016/j.scitotenv.2013.10.003.
Bonai, D. et al., 2016: The response of tropical rainforests to drought-lessons from recent research and future prospects. *Annals of Forest Science*, **73**, 27-44, doi:10.1007/s13595-015-0522-5.
Bonan, G. B., 1989: Environmental Factors and Ecological Processes in Boreal Forests. 28.
Bonan, G. B., 2008: Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science*, **320**(5882), 1444-1449, doi:10.1126/science.1155121.
Bond, W. J., N. Stevens, G. F. Midgley and C. E. R. Lehmann, 2019: The Trouble with Trees: Afforestation Plans for Africa. *Trends in ecology & evolution*.
Bond, W. J., F. I. Woodward and G. F. Midgley, 2005: The global distribution of ecosystems in a world without fire. *New phytologist*, **165**(2), 525-538.
Bonn, A. et al., 2016: Peatland restoration and ecosystem services: science, policy and practice. *Peatland restoration and ecosystem services: science, policy and practice.*
Bonn, A. et al., 2014: Investing in nature: Developing ecosystem service markets for peatland restoration. *Ecosystem Services*, **9**, 54-65, doi:10.1016/j.ecoser.2014.06.011.
Bonnesoeur, V. et al., 2019: Impacts of forests and forestation on hydrological services in the Andes: A systematic review. *Forest Ecology and Management*, **433**, 569-584, doi:10.1016/j.foreco.2018.11.033.
Booth, B. B. B. et al., 2012: High sensitivity of future global warming to land carbon cycle uncertainties. *Environmental Research Letters*, **7**, doi:10.1088/1748-9326/7/2/024002.
Booth, M., 2018: Chapter Three - Climate Change and the Neglected Tropical Diseases. In: *Advances in Parasitology* [Rollinson, D. and J. R. Stothard (eds.)]. Academic Press, pp. 39-126.
Borbor-Córdova, M. J. et al., 2018: Risk Perception of Coastal Communities and Authorities on Harmful Algal Blooms in Ecuador. *Frontiers in Marine Science*, **5**, doi:10.3389/fmars.2018.00365.
Borge, A. F., S. Westermann, I. Solheim and B. Etzelmüller, 2017: Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years. *The Cryosphere*, **11**(1), 1-16, doi:10.5194/tc-11-1-2017.
Borges, A. V. et al., 2019: Response of marine methane dissolved concentrations and emissions in the Southern North Sea to the European 2018 heatwave. *Continental Shelf Research*, **190**, 104004, doi:https://doi.org/10.1016/j.csr.2019.104004.
Bosco, A. et al., 2015: Outbreak of acute fasciolosis in sheep farms in a Mediterranean area arising as a possible consequence of climate change. *Geospat Health*, **9**(2), 319-324, doi:10.4081/gh.2015.354.
Bossio, D. A. et al., 2020: The role of soil carbon in natural climate solutions. *Nature Sustainability*, **3**(5), 391-398, doi:10.1038/s41893-020-0491-z.
Boucher, D. et al., 2018: Current and projected cumulative impacts of fire, drought, and insects on timber volumes across Canada. *Ecological Applications*, **28**(5), 1245-1259, doi:10.1002/eap.1724.
Boulanger, Y., S. Gauthier and P. J. Burton, 2014: A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. *Canadian Journal of Forest Research*, **44**(4), 365-376, doi:10.1139/cjfr-2013-0372.
Boulanger, Y. et al., 2017: Climate change impacts on forest landscapes along the Canadian southern boreal forest transition zone. *Landscape Ecology*, **32**(7), 1415-1431, doi:10.1007/s10980-016-0421-7.

Boulton, C. A., B. B. B. Booth and P. Good, 2017: Exploring uncertainty of Amazon dieback in a perturbed parameter Earth system ensemble. *Global Change Biology*, **23**(12), 5032-5044, doi:10.1111/gcb.13733.
Boutin, S. and J. Lane, 2014: Climate change and mammals: evolutionary versus plastic responses. *Evolutionary Applications*, **7**(1), 29-41, doi:10.1111/eva.12121.
Bovendorp, R. S. et al., 2019: Defaunation and fragmentation erode small mammal diversity dimensions in tropical forests. *Ecography*, **42**(1), 23-35.
Bowler, D. E., L. Buyung-Ali, T. M. Knight and A. S. Pullin, 2010a: Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, **97**(3), 147-155, doi:https://doi.org/10.1016/j.landurbplan.2010.05.006.
Bowler, D. E., L. M. Buyung-Ali, T. M. Knight and A. S. Pullin, 2010b: A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC public health*, **10**(1), 456.
Bowler, D. E. et al., 2017: Cross-realm assessment of climate change impacts on species' abundance trends. *Nat Ecol Evol*, **1**(3), 67, doi:10.1038/s41559-016-0067.
Bowman, D., D. Dario Rodriguez-Cubillo and L. Prior, 2020a: The 2016 Tasmanian Wilderness fires: Fire regime shifts and climate change in a Gondwanan biogeographic refugium. In: *Ecosystem Collapse and Climate Change, Ecological Studies* [Jackson, C. J. G. a. R. B. (ed.)]. Springer Nature, Switzerland AG.
Bowman, D. et al., 2020b: Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment*, **1**(10), 500-515, doi:10.1038/s43017-020-0085-3.
Bowman, D. et al., 2021: The severity and extent of the Australia 2019-20 Eucalyptus forest fires are not the legacy of forest management. *Nature Ecology & Evolution*, **5**(7), 1003-+, doi:10.1038/s41559-021-01464-6.
Bowman, D. M. J. S. et al., 2019: Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires. *Ambio; Stockholm*, **48**(4), 350-362, doi:http://dx.doi.org.ezproxy.lib.utexas.edu/10.1007/s13280-018-1084-1.
Boyce, R. et al., 2016: Severe Flooding and Malaria Transmission in the Western Ugandan Highlands: Implications for Disease Control in an Era of Global Climate Change. *J Infect Dis*, **214**(9), 1403-1410, doi:10.1093/infdis/jiw363.
Bozinovic, F., P. Calosi and J. I. Spicer, 2011: Physiological Correlates of Geographic Range in Animals. *Annual Review of Ecology, Evolution, and Systematics*, **42**(1), 155-179, doi:10.1146/annurev-ecolsys-102710-145055.
Bradley, B. A., C. A. Curtis and J. C. Chambers, 2016: Bromus response to climate and projected changes with climate change. In: *Exotic brome-grasses in arid and semiarid ecosystems of the western US*. Springer, pp. 257–274.
Bradley, M. J., S. J. Kutz, E. Jenkins and T. M. O'Hara, 2005: The potential impact of climate change on infectious diseases of Arctic fauna. *International Journal of Circumpolar Health*, **64**(5), 468-477, doi:10.3402/ijch.v64i5.18028.
Bradley, P. W. et al., 2019: Shifts in temperature influence how Batrachochytrium dendrobatidis infects amphibian larvae. *PLoS ONE*, **14**(9), 1-13, doi:10.1371/journal.pone.0222237.
Bradley, R. S., M. Vuille, H. F. Diaz and W. Vergara, 2006: Threats to water supplies in the tropical Andes. *Science*, **312**(5781), 1755-1756.
Bradshaw, C. J. A. and I. G. Warkentin, 2015: Global estimates of boreal forest carbon stocks and flux. *Global and Planetary Change*, **128**, 24-30, doi:10.1016/j.gloplacha.2015.02.004.
Bradshaw, W. E. and C. M. Holzapfel, 2001: Genetic shift in photoperiodic response correlated with global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **98**(25), 14509-14511, doi:10.1073/pnas.241391498.
Bradstock, R. et al., 2014: Divergent responses of fire to recent warming and drying across south-eastern Australia. *Global Change Biology*, **20**(5), 1412-1428, doi:10.1111/gcb.12449.
Braga, D. P. P., F. Domene and F. B. Gandara, 2019: Shade trees composition and diversity in cacao agroforestry systems of southern Pará, Brazilian Amazon. *Agroforestry Systems*, **93**(4), 1409-1421, doi:10.1007/s10457-018-0250-6.
Bragazza, L., 2008: A climatic threshold triggers the die-off of peat mosses during an extreme heat wave: SURVIVAL OF PEAT MOSSES DURING AN EXTREME DROUGHT. *Global Change Biology*, **14**(11), 2688-2695, doi:10.1111/j.1365-2486.2008.01699.x.
Brakefield, P. M. and P. W. de Jong, 2011: A steep cline in ladybird melanism has decayed over 25 years: a genetic response to climate change? *Heredity*, **107**(6), 574-578, doi:10.1038/hdy.2011.49.
Bramer, I. et al., 2018: Chapter Three - Advances in Monitoring and Modelling Climate at Ecologically Relevant Scales. In: *Advances in Ecological Research* [Bohan, D. A., A. J. Dumbrell, G. Woodward and M. Jackson (eds.)]. Academic Press, pp. 101-161.
Brancalion, P. H. et al., 2019: What makes ecosystem restoration expensive? A systematic cost assessment of projects in Brazil. *Biological Conservation*, **240**, 108274.
Brando, P. M. et al., 2014: Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proceedings of the National Academy of Sciences*, **111**(17), 6347-6352.
Brando, P. M. et al., 2019: Droughts, wildfires, and forest carbon cycling: A pantropical synthesis. *Annual Review of Earth and Planetary Sciences*, **47**, 555-581.
Brando, P. M. et al., 2020: The gathering firestorm in southern Amazonia. *Science Advances*, **6**(2), doi:10.1126/sciadv.aay1632.

Brandt, M. et al., 2019: Changes in rainfall distribution promote woody foliage production in the Sahel. *Communications Biology*, **2**(1), 133.
Brashares, J. S. et al., 2004: Bushmeat Hunting, Wildlife Declines, and Fish Supply in West Africa. *Science*, **306**, 1180-1183, doi:10.1126/science.1102425.
Bratman, G. N. et al., 2019: Nature and mental health: An ecosystem service perspective. *Science Advances*, **5**(7), eaax0903, doi:10.1126/sciadv.aax0903.
Brawand, D. et al., 2014: The genomic substrate for adaptive radiation in African cichlid fish. *Nature*, **513**(7518), 375-381.
Brecka, A. F. J. et al., 2020: Sustainability of Canada's forestry sector may be compromised by impending climate change. *Forest Ecology and Management*, **474**, 10, doi:10.1016/j.foreco.2020.118352.
Breinl, K. et al., 2020: Extreme dry and wet spells face changes in their duration and timing. *Environmental Research Letters*, **15**(7), 074040.
Bremer, L. L. and K. A. Farley, 2010: Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. *Biodiversity and Conservation*, **19**(14), 3893-3915.
Brice, M. H., K. Cazelles, P. Legendre and M. J. Fortin, 2019: Disturbances amplify tree community responses to climate change in the temperate-boreal ecotone. *Global Ecology and Biogeography*, **28**(11), 1668-1681, doi:10.1111/geb.12971.
Brice, M. H. et al., 2020: Moderate disturbances accelerate forest transition dynamics under climate change in the temperate-boreal ecotone of eastern North America. *Global Change Biology*, **26**(8), 4418-4435, doi:10.1111/gcb.15143.
Bridle, J. R., J. Buckley, E. J. Bodsworth and C. D. Thomas, 2014: Evolution on the move: specialization on widespread resources associated with rapid range expansion in response to climate change. *Proceedings of the Royal Society B: Biological Sciences*, **281**(1776), 7, doi:10.1098/rspb.2013.1800.
Brienen, R. J. W. et al., 2020: Forest carbon sink neutralized by pervasive growth-lifespan trade-offs. *Nature Communications*, **11**(1), 4241, doi:10.1038/s41467-020-17966-z.
Brienen, R. J. W. et al., 2015: Long-term decline of the Amazon carbon sink. *Nature*, **519**(7543), 344.
Bright, B. C., J. A. Hicke and A. J. H. Meddens, 2013: Effects of bark beetle-caused tree mortality on biogeochemical and biogeophysical MODIS products. *Journal of Geophysical Research-Biogeosciences*, **118**(3), 974-982, doi:10.1002/jgrg.20078.
Brinck, K. et al., 2017: High resolution analysis of tropical forest fragmentation and its impact on the global carbon cycle. *Nature Communications*, **8**(1), 1-6.
Brito-Morales, I. et al., 2018: Climate Velocity Can Inform Conservation in a Warming World. *Trends in Ecology & Evolution*, **33**(6), 441-457, doi:https://doi.org/10.1016/j.tree.2018.03.009.
Broadmeadow, S. et al., 2011: The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. *River Research and Applications*, **27**(2), 226-237.
Brodie, J. F., 2016: Synergistic effects of climate change and agricultural land use on mammals. *Frontiers in Ecology and the Environment*, **14**(1), 20-26, doi:10.1002/16-0110.1.
Brodribb, T. J., J. Powers, H. Cochard and B. Choat, 2020: Hanging by a thread? Forests and drought. *Science*, **368**(6488), 261-+, doi:10.1126/science.aat7631.
Brooker, R. W. et al., 2018: Tiny niches and translocations: The challenge of identifying suitable recipient sites for small and immobile species. *Journal of applied ecology*, **55**(2), 621-630.
Brooks, A. J., B. Wolfenden, B. J. Downes and J. Lancaster, 2018: Barriers to dispersal: The effect of a weir on stream insect drift. *River research and applications*, **34**(10), 1244-1253.
Brooks, C. M. et al., 2020: Progress towards a representative network of Southern Ocean protected areas. *PLOS ONE*, **15**(4), e0231361, doi:10.1371/journal.pone.0231361.
Brooks, M. L. and J. R. Matchett, 2006: Spatial and temporal patterns of wildfires in the Mojave Desert, 1980-2004. *Journal of Arid Environments*, **67**, 148-164, doi:10.1016/j.jaridenv.2006.09.027.
Brookshire, E. N. J. and T. Weaver, 2015: Long-term decline in grassland productivity driven by increasing dryness. *Nature communications*, **6**, 7148.
Brouns, K. et al., 2015: Spatial Analysis of Soil Subsidence in Peat Meadow Areas in Friesland in Relation to Land and Water Management, Climate Change, and Adaptation. *Environmental Management*, **55**(2), 360-372, doi:10.1007/s00267-014-0392-x.
Brovkin, V. et al., 2013: Effect of Anthropogenic Land-Use and Land-Cover Changes on Climate and Land Carbon Storage in CMIP5 Projections for the Twenty-First Century. *Journal of Climate*, **26**(18), 6859-6881, doi:10.1175/jcli-d-12-00623.1.
Brown, D. R. N. et al., 2015: Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. *Journal of Geophysical Research-Biogeosciences*, **120**(8), 1619-1637, doi:10.1002/2015jg003033.
Brown, L. and V. Murray, 2013: Examining the relationship between infectious diseases and flooding in Europe. *Disaster Health*, **1**(2), 117-127, doi:10.4161/dish.25216.
Bruce, L. C. et al., 2018: A multi-lake comparative analysis of the General Lake Model (GLM): Stress-testing across a global observatory network. *Environmental Modelling & Software*, **102**, 274-291, doi:10.1016/j.envsoft.2017.11.016.

Brugueras, S. et al., 2020: Environmental drivers, climate change and emergent diseases transmitted by mosquitoes and their vectors in southern Europe: A systematic review. *Environmental Research*, **191**, 110038, doi:10.1016/j.envres.2020.110038.
Bruijnzeel, L. A., 2004: Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment*, **104**(1), 185-228.
Bruno, J. F., I. M. Côté and L. T. Toth, 2019: Climate change, coral loss, and the curious case of the parrotfish paradigm: Why don't marine protected areas improve reef resilience? *Annual review of marine science*, **11**, 307-334.
Bryson, J. M. et al., 2020: Neglected Tropical Diseases in the Context of Climate Change in East Africa: A Systematic Scoping Review. *The American Journal of Tropical Medicine and Hygiene*, **102**(6), 1443-1454, doi:10.4269/ajtmh.19-0380.
Büchi, L. and S. Vuilleumier, 2014: Coexistence of Specialist and Generalist Species Is Shaped by Dispersal and Environmental Factors. *The American Naturalist*, **183**(5), 612-624, doi:10.1086/675756.
Buechley, E. R. et al., 2015: Importance of Ethiopian shade coffee farms for forest bird conservation. *Biological Conservation*, **188**, 50-60, doi:10.1016/j.biocon.2015.01.011.
Buisson, L. et al., 2010: Uncertainty in ensemble forecasting of species distribution. *Global Change Biology*, **16**(4), 1145-1157, doi:10.1111/j.1365-2486.2009.02000.x.
Buitenwerf, R., W. J. Bond, N. Stevens and W. S. W. Trollope, 2012: Increased tree densities in South African savannas: > 50 years of data suggests CO2 as a driver. *Global Change Biology*, **18**(2), 675-684, doi:10.1111/j.1365-2486.2011.02561.x.
Bunn, S. E. and A. H. Arthington, 2002: Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ Manage*, **30**(4), 492-507, doi:10.1007/s00267-002-2737-0.
Buotte, P. C. et al., 2019: Near-future forest vulnerability to drought and fire varies across the western United States. *Global change biology*, **25**(1), 290–303.
Burd, K. et al., 2018: Seasonal shifts in export of DOC and nutrients from burned and unburned peatland-rich catchments, Northwest Territories, Canada. *Hydrology and Earth System Sciences*, **22**(8), 4455-4472, doi:10.5194/hess-22-4455-2018.
Burge, C. A. et al., 2014: Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society. *Annual Review of Marine Science*, **6**(1), 249-277, doi:10.1146/annurev-marine-010213-135029.
Burgess-Gamble, L. et al., 2017: Working with natural processes–evidence directory. *Environmental Agency, Report No. SC150005*.
Burrell, A. L., J. P. Evans and M. G. De Kauwe, 2020: Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. *Nature Communications*, **11**(1), 3853, doi:10.1038/s41467-020-17710-7.
Burrows, M. T. et al., 2014: Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**(7493), 492-+, doi:10.1038/nature12976.
Burton, C. et al., 2020: El Nino Driven Changes in Global Fire 2015/16. *Frontiers in Earth Science*, **8**, 12, doi:10.3389/feart.2020.00199.
Burton, C., R. A. Betts, C. D. Jones and K. Williams, 2018: Will Fire Danger Be Reduced by Using Solar Radiation Management to Limit Global Warming to 1.5 degrees C Compared to 2.0 degrees C? *Geophysical Research Letters*, **45**(8), 3644-3652, doi:10.1002/2018gl077848.
Burton, C. A. et al., 2016: Trace Elements in Stormflow, Ash, and Burned Soil following the 2009 Station Fire in Southern California. *Plos One*, **11**(5), 26, doi:10.1371/journal.pone.0153372.
Burton, E. D., G. Choppala, N. Karimian and S. G. Johnston, 2019: A new pathway for hexavalent chromium formation in soil: Fire-induced alteration of iron oxides. *Environmental Pollution*, **247**, 618-625, doi:10.1016/j.envpol.2019.01.094.
Bury, J. et al., 2013: New geographies of water and climate change in Peru: Coupled natural and social transformations in the Santa River watershed. *Annals of the Association of American Geographers*, **103**(2), 363-374.
Bush, A. et al., 2014a: Freshwater conservation planning under climate change: demonstrating proactive approaches for Australian Odonata. *Journal of Applied Ecology*, **51**(5), 1273-1281, doi:10.1111/1365-2664.12295.
Bush, A. A. et al., 2014b: Continental-scale assessment of risk to the Australian odonata from climate change. *PLoS ONE*, **9**(2), e88958, doi:10.1371/journal.pone.0088958.
Bush, M. B. et al., 2015: Anthropogenic influence on Amazonian forests in pre-history: An ecological perspective. *Journal of Biogeography*, **42**(12), 2277-2288, doi:10.1111/jbi.12638.
Busker, T. et al., 2019: A global lake and reservoir volume analysis using a surface water dataset and satellite altimetry. *Hydrology and Earth System Sciences*, **23**(2), 669-690, doi:10.5194/hess-23-669-2019.
Bustamante, M. M. C. et al., 2016: Toward an integrated monitoring framework to assess the effects of tropical forest degradation and recovery on carbon stocks and biodiversity. *Global Change Biology*, **22**(1), 92-109, doi:10.1111/gcb.13087.
Butcher, J. B., D. Nover, T. E. Johnson and C. M. Clark, 2015: Sensitivity of lake thermal and mixing dynamics to climate change. *Climatic Change*, **129**(1-2), 295-305.
Buytaert, W. et al., 2017: Glacial melt content of water use in the tropical Andes. *Environmental Research Letters*, **12**(11), 8, doi:10.1088/1748-9326/aa926c.

Cabon, A. et al., 2018: Thinning increases tree growth by delaying drought-induced growth cessation in a Mediterranean evergreen oak coppice. *Forest Ecology and Management*, **409**, 333-342.
Cadotte, M. W., K. Carscadden and N. Mirotchnick, 2011: Beyond species: functional diversity and the maintenance of ecological processes and services. *Journal of Applied Ecology*, **48**(5), 1079-1087, doi:https://doi.org/10.1111/j.1365-2664.2011.02048.x.
Caesariantika, E., T. Kondo and N. Nakagoshi, 2011: Impact of Acacia nilotica (L.) Willd. ex Del invasion on plant species diversity in the Bekol Savanna, Baluran National Park, East Java, Indonesia. *Tropics*, **20**(2), 45-53, doi:10.3759/tropics.20.45.
Cai, S. and Z. Yu, 2011: Response of a warm temperate peatland to Holocene climate change in northeastern Pennsylvania. *Quaternary Research*, **75**(3), 531-540, doi:10.1016/j.yqres.2011.01.003.
Cai, W. and I. C. Prentice, 2020: Recent trends in gross primary production and their drivers: analysis and modelling at flux-site and global scales. *Environmental Research Letters*, **15**(12), 124050, doi:10.1088/1748-9326/abc64e.
Caldwell, J. M., S. F. Heron, C. M. Eakin and M. J. Donahue, 2016: Satellite SST-Based Coral Disease Outbreak Predictions for the Hawaiian Archipelago. *Remote Sensing*, **8**(2), doi:10.3390/rs8020093.
Calliari, E., A. Staccione and J. Mysiak, 2019: An assessment framework for climate-proof nature-based solutions. *Science of the Total Environment*, **656**, 691-700.
Camac, J. S. et al., 2021: Predicting species and community responses to global change using structured expert judgement: An Australian mountain ecosystems case study. *Glob Chang Biol*, **27**(18), 4420-4434, doi:10.1111/gcb.15750.
Caminade, C. et al., 2014: Impact of climate change on global malaria distribution. *Proceedings of the National Academy of Sciences*, **111**(9), 3286-3291, doi:10.1073/pnas.1302089111.
Caminade, C., K. M. McIntyre and A. E. Jones, 2019: Impact of recent and future climate change on vector-borne diseases. *Annals of the New York Academy of Sciences*, **1436**(1), 157-173, doi:10.1111/nyas.13950.
Caminade, C., J. Van Dijk, M. Baylis and D. Williams, 2015: Modelling recent and future climatic suitability for fasciolosis in Europe. *Geospat Health*, **9**(2), 301, doi:10.4081/gh.2015.352.
Campbell, A. M., M.-F. Racault, S. Goult and A. Laurenson, 2020: Cholera Risk: A Machine Learning Approach Applied to Essential Climate Variables. *International Journal of Environmental Research and Public Health*, **17**(24), doi:10.3390/ijerph17249378.
Campbell, E. M., J. A. Antos and L. vanAkker, 2019a: Resilience of southern Yukon boreal forests to spruce beetle outbreaks. *Forest Ecology and Management*, **433**, 52-63, doi:10.1016/j.foreco.2018.10.037.
Campbell, K. J. et al., 2019b: Local forage fish abundance influences foraging effort and offspring condition in an endangered marine predator. *Journal of Applied Ecology*, **56**(7), 1751-1760.
Campbell, L. P. et al., 2015: Climate change influences on global distributions of dengue and chikungunya virus vectors. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**(1665), 20140135, doi:10.1098/rstb.2014.0135.
Campbell, L. P., A. T. Peterson, A. M. Samy and C. Y. Arenas, 2019c: CHAPTER TWENTY-ONE: Climate Change and Disease. [Lovejoy, T. E. and L. Hannah (eds.)]. Yale University Press, pp. 278-288.
Campos, D. F., R. D. Amanajás, V. M. F. Almeida-Val and A. L. Val, 2021: Climate vulnerability of South American freshwater fish: Thermal tolerance and acclimation. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, **n/a**(n/a), doi:https://doi.org/10.1002/jez.2452.
Candau, J. N., R. A. Fleming and X. L. Wang, 2018: Ecoregional Patterns of Spruce Budworm-Wildfire Interactions in Central Canada's Forests. *Forests*, **9**(3), 17, doi:10.3390/f9030137.
Cao, S., C. Xia, W. Li and J. Xian, 2021: Win–win path for ecological restoration. *Land Degradation & Development*, **32**(1), 430-438, doi:https://doi.org/10.1002/ldr.3739.
Caon, L., V. R. Vallejo, C. J. Ritsema and V. Geissen, 2014: Effects of wildfire on soil nutrients in Mediterranean ecosystems. *Earth-Science Reviews*, **139**, 47-58, doi:10.1016/j.earscirev.2014.09.001.
Capaldi, C. A., R. L. Dopko and J. M. Zelenski, 2014: The relationship between nature connectedness and happiness: a meta-analysis. *Frontiers in psychology*, **5**, 976.
Caracciolo, D., E. Istanbulluoglu, L. V. Noto and S. L. Collins, 2016: Mechanisms of shrub encroachment into Northern Chihuahuan Desert grasslands and impacts of climate change investigated using a cellular automata model. *Advances in water resources*, **91**, 46–62.
Cardil, A. et al., 2020: Recent deforestation drove the spike in Amazonian fires. *Environmental Research Letters*, **15**(12), 5, doi:10.1088/1748-9326/abcac7.
Carignan, A., L. Valiquette and K. B. Laupland, 2019: Impact of climate change on emerging infectious diseases: Implications for Canada. *Official Journal of the Association of Medical Microbiology and Infectious Disease Canada*, **4**(2), 55-59, doi:10.3138/jammi.2018-12-10.
Carilla, J. et al., 2018: Vegetation trends over eleven years on mountain summits in NW Argentina. *Ecology and Evolution*, **8**(23), 11554-11567.
Carlson, C. J. et al., 2020: Climate change will drive novel cross-species viral transmission. *bioRxiv*, 2020.2001.2024.918755, doi:10.1101/2020.01.24.918755.
Carlucci, M. B. et al., 2020: Functional traits and ecosystem services in ecological restoration. *Restoration Ecology*, **28**(6), 1372-1383, doi:https://doi.org/10.1111/rec.13279.

Carr, J. A. et al., 2013: *Vital but vulnerable: Climate change vulnerability and human use of wildlife in Africa's Albertine Rift* [IUCN, O. P. o. t. I. S. S. C. N. (ed.)]. Gland, Switzerland and Cambridge, UK, xii + 224pp pp.
Carrea, L. and C. Merchant, 2019: GloboLakes: Lake Surface Water Temperature (LSWT) v4.0 (1995-2016). *Centre for Environmental Data Analysis*, doi:doi:10.5285/76a29c5b55204b66a40308fc2ba9cdb3.
Carroll, C. and R. F. Noss, 2021: Rewilding in the face of climate change. *Conservation Biology*, **35**(1), 155-167, doi:https://doi.org/10.1111/cobi.13531.
Carroll, M. J., P. Dennis, J. W. PEARCE-HIGGINS and C. D. Thomas, 2011: Maintaining northern peatland ecosystems in a changing climate: effects of soil moisture, drainage and drain blocking on craneflies. *Global Change Biology*, **17**(9), 2991-3001.
Carter, A. L. and F. J. Janzen, 2021: Predicting the effects of climate change on incubation in reptiles: methodological advances and new directions. *Journal of Experimental Biology*, **224**(Suppl_1), doi:10.1242/jeb.236018.
Cartwright, J. M. et al., 2020: Oases of the future? Springs as potential hydrologic refugia in drying climates. *Frontiers in Ecology and the Environment*, **18**(5), 245-253, doi:https://doi.org/10.1002/fee.2191.
Carvalho, L. et al., 2013: Sustaining recreational quality of European lakes: minimizing the health risks from algal blooms through phosphorus control. *Journal of Applied Ecology*, **50**(2), 315-323.
Case, M. F. et al., 2019: Severe drought limits trees in a semi-arid savanna. *Ecology*, doi:10.1002/ecy.2842.
Castaneda, L. E. et al., 2019: Evolutionary potential of thermal preference and heat tolerance in Drosophila subobscura. *J. Evol. Biol.*, **32**(8), 818-824, doi:10.1111/jeb.13483.
Catalán, N., R. Marcé, D. N. Kothawala and L. J. Tranvik, 2016: Organic carbon decomposition rates controlled by water retention time across inland waters. *Nature Geoscience*, **9**(7), 501-504, doi:10.1038/ngeo2720.
Cauvy-Fraunié, S. and O. Dangles, 2019: A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, **3**(12), 1675-1685, doi:10.1038/s41559-019-1042-8.
Cavanaugh, K. C. et al., 2014: Carbon storage in tropical forests correlates with taxonomic diversity and functional dominance on a global scale. *Global Ecology and Biogeography*, **23**(5), 563-573, doi:10.1111/geb.12143.
Cavicchioli, R. et al., 2019: Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, **17**(9), 569-586, doi:10.1038/s41579-019-0222-5.
Cavole, L. M. et al., 2016: Biological Impacts of the 2013-2015 Warm-Water Anomaly in the Northeast Pacific. *Oceanography*, **29**(2), 273-285, doi:10.5670/oceanog.2016.32.
Ceddia, M. G., U. Gunter and A. Corriveau-Bourque, 2015: Land tenure and agricultural expansion in Latin America: The role of Indigenous Peoples' and local communities' forest rights. *Global Environmental Change*, **35**, 316-322, doi:10.1016/j.gloenvcha.2015.09.010.
Cernusak, L. A. et al., 2013: Tropical forest responses to increasing atmospheric CO2: current knowledge and opportunities for future research. *Functional plant biology*, **40**(6), 531-551.
Chacón-Moreno, E. et al., 2021: Impacts of Global Change on the Spatial Dynamics of Treeline in Venezuelan Andes. *Frontiers in Ecology and Evolution*, **9**(74), doi:10.3389/fevo.2021.615223.
Chadburn, S. E. et al., 2017: An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, **7**(5), 340-+, doi:10.1038/nclimate3262.
Chae, Y. et al., 2015: Arctic greening can cause earlier seasonality of Arctic amplification. *Geophysical Research Letters*, **42**(2), 536-541, doi:10.1002/2014gl061841.
Chambers, J. C. et al., 2014: Resilience to stress and disturbance, and resistance to Bromus tectorum L. invasion in cold desert shrublands of western North America. *Ecosystems*, **17**(2), 360–375.
Chandler, J., 2014: Ghosts of the rainforest. *New Scientist*, **223**(2980), 42-45, doi:https://doi.org/10.1016/S0262-4079(14)61493-7.
Chang, J. et al., 2017: Benchmarking carbon fluxes of the ISIMIP2a biome models. *Environmental Research Letters*, **12**(4), doi:045002 10.1088/1748-9326/aa63fa.
Chaplin-Kramer, R. et al., 2015: Degradation in carbon stocks near tropical forest edges. *Nature Communications*, **6**, doi:10.1038/ncomms10158.
Chapman, S. et al., 2020: Compounding impact of deforestation on Borneo's climate during El Niño events. *Environmental Research Letters*, **15**(8), 084006, doi:10.1088/1748-9326/ab86f5.
Chareonviriyaphap, T., P. Akratanakul, S. Nettanomsak and S. Huntamai, 2003: LARVAL HABITATS AND DISTRIBUTION PATTERNS OF AEDES AEGYPTI (LINNAEUS) AND AEDES ALBOPICTUS (SKUSE), IN THAILAND. *SOUTHEAST ASIAN J TROP MED PUBLIC HEALTH*, **34**(3), 7.
Charles-Dominique, T. et al., 2016: Spiny plants, mammal browsers, and the origin of African savannas. *Proceedings of the National Academy of Sciences*, **113**(38), E5572-E5579.
Charlier, J., 2020: Initial assessment of the economic burden of major parasitic helminth infections to the ruminant livestock industry in Europe. *Preventive Veterinary Medicine*, 12.
Charlier, J. et al., 2016: Climate-driven longitudinal trends in pasture-borne helminth infections of dairy cattle. *International Journal for Parasitology*, **46**(13), 881-888, doi:10.1016/j.ijpara.2016.09.001.
Chaste, E. et al., 2019: Increases in heat-induced tree mortality could drive reductions of biomass resources in Canada's managed boreal forest. *Landscape Ecology*, **34**(2), 403-426, doi:10.1007/s10980-019-00780-4.
Chaudhary, N. et al., 2020: Modelling past and future peatland carbon dynamics across the pan-Arctic. *Global Change Biology*, **26**(7), 4119-4133, doi:10.1111/gcb.15099.

Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*.
Chen, D. et al., 2018a: Strong cooling induced by stand-replacing fires through albedo in Siberian larch forests. *Scientific Reports*, **8**, doi:10.1038/s41598-018-23253-1.
Chen, G., D. J. Hayes and A. D. McGuire, 2017: Contributions of wildland fire to terrestrial ecosystem carbon dynamics in North America from 1990 to 2012. *Global Biogeochemical Cycles*, **31**(5), 878–900, doi:https://doi.org/10.1002/2016GB005548.
Chen, I.-C. et al., 2011: Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science*, **333**(6045), 1024-1026, doi:10.1126/science.1206432.
Chen, L. et al., 2015: Climate and native grassland vegetation as drivers of the community structures of shrub-encroached grasslands in Inner Mongolia, China. *Landscape Ecology*, **30**(9), 1627-1641.
Chen, S. et al., 2018b: Plant diversity enhances productivity and soil carbon storage. *Proceedings of the National Academy of Sciences*, **115**(16), 4027, doi:10.1073/pnas.1700298114.
Chen, Y. et al., 2021a: Future increases in Arctic lightning and fire risk for permafrost carbon. *Nature Climate Change*, **11**(5), 404-+, doi:10.1038/s41558-021-01011-y.
Chen, Z. F., W. G. Wang, R. A. Woods and Q. X. Shao, 2021b: Hydrological effects of change in vegetation components across global catchments. *Journal of Hydrology*, **595**, 15, doi:10.1016/j.jhydrol.2020.125775.
Chessman, B. C., 2015: Relationships between lotic macroinvertebrate traits and responses to extreme drought. *Freshwater Biology*, **60**(1), 50-63, doi:https://doi.org/10.1111/fwb.12466.
Chimner, R. A., D. J. Cooper, F. C. Wurster and L. Rochefort, 2017: An overview of peatland restoration in North America: where are we after 25 years?: Peatland restoration in North America. *Restoration Ecology*, **25**(2), 283-292, doi:10.1111/rec.12434.
Chin, A., P. M. Kyne, T. I. Walker and R. B. McAULEY, 2010: An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change Biology*, **16**(7), 1936-1953, doi:10.1111/j.1365-2486.2009.02128.x.
Chinain, M. et al., 2014: The ecology, biology and toxicology of ciguatera. *Revue Francophone des Laboratoires*, **2014**(460), 27-39, doi:10.1016/S1773-035X(14)72403-7.
Choat, B. et al., 2018: Triggers of tree mortality under drought. *Nature*, **558**(7711), 531-539, doi:10.1038/s41586-018-0240-x.
Chong, J., 2014: Ecosystem-based approaches to climate change adaptation: progress and challenges. *International Environmental Agreements: Politics, Law and Economics*, **14**(4), 391-405.
Chowdhury, M. S. N. et al., 2019: Oyster breakwater reefs promote adjacent mudflat stability and salt marsh growth in a monsoon dominated subtropical coast. *Scientific reports*, **9**(1), 8549.
Chown, S. L., K. J. Gaston and D. Robinson, 2004: Macrophysiology: large-scale patterns in physiological traits and their ecological implications. *Functional Ecology*, **18**(2), 159-167, doi:https://doi.org/10.1111/j.0269-8463.2004.00825.x.
Chretien, J.-P. et al., 2007: Drought-associated chikungunya emergence along coastal East Africa. *American Journal of Tropical Medicine and Hygiene*, **76**(3), 405-407.
Christensen, S. A. et al., 2020: The role of drought as a determinant of hemorrhagic disease in the eastern United States. *Global Change Biology*, **26**(7), 3799-3808, doi:10.1111/gcb.15095.
Christmas, M. J., M. F. Breed and A. J. Lowe, 2016: Constraints to and conservation implications for climate change adaptation in plants. *Conservation Genetics*, **17**(2), 305-320.
Chuang, A. and C. R. Peterson, 2016: Expanding population edges: theories, traits, and trade-offs. *Global Change Biology*, **22**(2), 494-512, doi:10.1111/gcb.13107.
Chuine, I. and J. Régnière, 2017: Process-Based Models of Phenology for Plants and Animals. *Annual Review of Ecology, Evolution, and Systematics*, **48**(1), 159-182, doi:10.1146/annurev-ecolsys-110316-022706.
Chutipong, W. et al., 2014: Current distribution and conservation status of small carnivores in Thailand: a baseline review. *Small Carnivore Conservation*, **51**, 96-136.
Ciais, P. et al., 2013: Carbon and Other Biogeochemical Cycles. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T. F., D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom.
CICES, 2021: CICES Version 5.1. Available at: https://cices.eu/.
Civitello, D. J. et al., 2015: Biodiversity inhibits parasites: Broad evidence for the dilution effect. *Proceedings of the National Academy of Sciences*, **112**(28), 8667, doi:10.1073/pnas.1506279112.
Cizauskas, C. et al., 2017: Parasite vulnerability to climate change: an evidence- based functional trait approach. *Royal Society Open Science*, **4**(1), doi:10.1098/rsos.160535.
Claeys, F. et al., 2019: Climate change would lead to a sharp acceleration of Central African forests dynamics by the end of the century. *Environmental Research Letters*, **14**(4), doi:10.1088/1748-9326/aafb81.
Clarke, H. and J. P. Evans, 2019: Exploring the future change space for fire weather in southeast Australia. *Theoretical and Applied Climatology*, **136**(1-2), 513-527, doi:10.1007/s00704-018-2507-4.
Clavel, J., R. Julliard and V. Devictor, 2011: Worldwide decline of specialist species: toward a global functional homogenization? *Frontiers in Ecology and the Environment*, **9**(4), 222-228, doi:https://doi.org/10.1890/080216.

Cleaveland, S., D. T. Haydon and L. Taylor, 2007: Overviews of Pathogen Emergence: Which Pathogens Emerge, When and Why? In: *Wildlife and Emerging Zoonotic Diseases: The Biology, Circumstances and Consequences of Cross-Species Transmission* [Childs, J. E., J. S. Mackenzie and J. A. Richt (eds.)]. Springer, Berlin, Heidelberg, pp. 85-111. ISBN 978-3-540-70962-6.
Clifford, K. R. et al., 2020: Navigating Climate Adaptation on Public Lands: How Views on Ecosystem Change and Scale Interact with Management Approaches. *Environmental Management*, doi:10.1007/s00267-020-01336-y.
Cline, T., V. Bennington and J. Kitchell, 2013: Climate Change Expands the Spatial Extent and Duration of Preferred Thermal Habitat for Lake Superior Fishes. *PLoS ONE*, **8**(4), doi:10.1371/journal.pone.0062279.
Clusella-Trullas, S. and M. Nielsen, 2020: The evolution of insect body coloration under changing climates. *Current Opinion in Insect Science*, **41**, 25-32, doi:https://doi.org/10.1016/j.cois.2020.05.007.
Clusella-Trullas, S., J. H. van Wyk and J. R. Spotila, 2007: Thermal melanism in ectotherms. *Journal of Thermal Biology*, **32**(5), 235-245, doi:https://doi.org/10.1016/j.jtherbio.2007.01.013.
Coates, P. S. et al., 2016: Wildfire, climate, and invasive grass interactions negatively impact an indicator species by reshaping sagebrush ecosystems. *Proceedings of the National Academy of Sciences*, **113**(45), 12745, doi:10.1073/pnas.1606898113.
Coates, S. J. and S. A. Norton, 2020: The effects of climate change on infectious diseases with cutaneous manifestations. *Int J Womens Dermatol*, doi:10.1016/j.ijwd.2020.07.005.
Cobb, A. R. et al., 2017: How temporal patterns in rainfall determine the geomorphology and carbon fluxes of tropical peatlands. *Proceedings of the National Academy of Sciences*, **114**(26), E5187-E5196, doi:10.1073/pnas.1701090114.
Coetsee, C. et al., 2013: Low gains in ecosystem carbon with woody plant encroachment in a South African savanna. *Journal of Tropical Ecology*, **29**, 49-60, doi:10.1017/s0266467412000697.
Coffman, J. M. et al., 2014: Restoration practices have positive effects on breeding bird species of concern in the Chihuahuan Desert. *Restoration Ecology*, **22**(3), 336-344.
Cohen-Shacham, E., G. Walters, C. Janzen and S. Maginnis, 2016: Nature-based solutions to address global societal challenges. *IUCN: Gland, Switzerland*, **97**.
Cohen, J. M. et al., 2019a: An interaction between climate change and infectious disease drove widespread amphibian declines. *Global Change Biology*, **25**(3), 927-937, doi:10.1111/gcb.14489.
Cohen, J. M., M. J. Lajeunesse and J. R. Rohr, 2018: A global synthesis of animal phenological responses to climate change. *Nature Climate Change*, **8**(3), 224, doi:10.1038/s41558-018-0067-3.
Cohen, J. M. et al., 2019b: Impacts of thermal mismatches on chytrid fungus Batrachochytrium dendrobatidis prevalence are moderated by life stage, body size, elevation and latitude. *Ecology Letters*, **22**(5), 817-825, doi:10.1111/ele.13239.
Cohen, J. M. et al., 2020: Divergent impacts of warming weather on wildlife disease risk across climates. *Science*, **370**(6519), eabb1702, doi:10.1126/science.abb1702.
Cohn, A. S. et al., 2019: Forest loss in Brazil increases maximum temperatures within 50 km. *Environmental Research Letters*, **14**(8), doi:10.1088/1748-9326/ab31fb.
Cole, K. L. et al., 2011: Past and ongoing shifts in Joshua tree distribution support future modeled range contraction. *Ecological Applications*, **21**(1), 137-149, doi:10.1890/09-1800.1.
Cole, L. E. S., S. A. Bhagwat and K. J. Willis, 2015: Long-term disturbance dynamics and resilience of tropical peat swamp forests. *Journal of Ecology*, **103**(1), 16-30, doi:10.1111/1365-2745.12329.
Cole, L. E. S., S. A. Bhagwat and K. J. Willis, 2019: Fire in the Swamp Forest: Palaeoecological Insights Into Natural and Human-Induced Burning in Intact Tropical Peatlands. *Frontiers in Forests and Global Change*, **2**, doi:10.3389/ffgc.2019.00048.
Cole, L. E. S., K. J. Willis and S. A. Bhagwat, 2021: The future of Southeast Asia's tropical peatlands: Local and global perspectives. *Anthropocene*, **34**, 100292, doi:10.1016/j.ancene.2021.100292.
Collins, M. B. and E. T. A. Mitchard, 2017: A small subset of protected areas are a highly significant source of carbon emissions. *Scientific Reports*, **7**, doi:10.1038/srep41902.
Colloff, M. J. et al., 2017: An integrative research framework for enabling transformative adaptation. *Environmental Science & Policy*, **68**, 87-96, doi:https://doi.org/10.1016/j.envsci.2016.11.007.
Colón-González, F. J., C. Fezzi, I. R. Lake and P. R. Hunter, 2013: The Effects of Weather and Climate Change on Dengue. *PLOS Neglected Tropical Diseases*, **7**(11), e2503, doi:10.1371/journal.pntd.0002503.
Colón-González, F. J. et al., 2021: Projecting the risk of mosquito-borne diseases in a warmer and more populated world: a multi-model, multi-scenario intercomparison modelling study. *The Lancet Planetary Health*, **5**(7), e404-e414, doi:https://doi.org/10.1016/S2542-5196(21)00132-7.
Colwell, R. K. et al., 2008: Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, **322**(5899), 258-261, doi:10.1126/science.1162547.
Comte, L. and G. Grenouillet, 2013: Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography*, **36**(11), 1236-1246, doi:10.1111/j.1600-0587.2013.00282.x.
Comyn-Platt, E. et al., 2018: Carbon budgets for 1.5 and 2 degrees C targets lowered by natural wetland and permafrost feedbacks. *Nature Geoscience*, **11**(8), 568-+, doi:10.1038/s41561-018-0174-9.
Conchedda, G. and F. N. Tubiello, 2020: Drainage of organic soils and GHG emissions: validation with country data. *Earth System Science Data*, **12**(4), 3113-3137, doi:10.5194/essd-12-3113-2020.

Connon, R. F., W. L. Quinton, J. R. Craig and M. Hayashi, 2014: Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada: CHANGING HYDROLOGIC CONNECTIVITY DUE TO PERMAFROST THAW. *Hydrological Processes*, **28**(14), 4163-4178, doi:10.1002/hyp.10206.
Conradie, S. R. et al., 2020: Avian mortality risk during heat waves will increase greatly in arid Australia during the 21st century. *Conservation Physiology*, **8**(1), doi:10.1093/conphys/coaa048.
Conti, L., A. Schmidt-Kloiber, G. Grenouillet and W. Graf, 2014: A trait-based approach to assess the vulnerability of European aquatic insects to climate change. *Hydrobiologia*, **721**(1), 297-315, doi:10.1007/s10750-013-1690-7.
Cook-Patton, S. C. et al., 2020: Mapping carbon accumulation potential from global natural forest regrowth. *Nature*, **585**(7826), 545-550, doi:10.1038/s41586-020-2686-x.
Cook, B. I., E. M. Wolkovich and C. Parmesan, 2012: Divergent responses to spring and winter warming drive community level flowering trends. *Proceedings of the National Academy of Sciences*, **109**(23), 9000-9005, doi:10.1073/pnas.1118364109.
Cooke, S. J. et al., 2021: One hundred research questions in conservation physiology for generating actionable evidence to inform conservation policy and practice. *Conservation Physiology*, **9**(1), doi:10.1093/conphys/coab009.
Cooper, H. V. et al., 2020: Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. *Nature Communications*, **11**(1), doi:10.1038/s41467-020-14298-w.
Corbera, E., C. Hunsberger and C. Vaddhanaphuti, 2017: Climate change policies, land grabbing and conflict: perspectives from Southeast Asia. *Canadian Journal of Development Studies/Revue canadienne d'études du développement*, **38**(3), 297-304.
Cordeiro, A. d. A. C., S. D. Coelho, N. C. Ramos and J. A. A. Meira-Neto, 2018: Agroforestry systems reduce invasive species richness and diversity in the surroundings of protected areas. *Agroforestry systems*, **92**(6), 1495-1505.
Corlett, R. T., 2016: The impacts of droughts in tropical forests. *Trends in plant science*, **21**(7), 584-593.
Costa, S. et al., 2021: Effectiveness of nature-based solutions on pluvial flood hazard mitigation: The case study of the city of eindhoven (the netherlands). *Resources*, **10**(3), 24.
Coulibaly, J. Y., B. Chiputwa, T. Nakelse and G. Kundhlande, 2017: Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agricultural Systems*, **155**, 52-69, doi:10.1016/j.agsy.2017.03.017.
Council, A. F. a. E. S. A., 2016: *AFAC Independent Operational Review: a review of the management of the Tasmanian fire January 2016*, Limited, A. F. a. E. S. A. C., Australasian Fire and Emergency Service Authorities Council Limited, Victoria, Australia. Available at: http://www.fire.tas.gov.au/userfiles/AFAC/AFAC_Review.pdf.
Council, A. F. a. E. S. A., 2019: *AFAC Independent Operational Review: A review of the management of the Tasmanian fires of December 2018 – March 2019*, Limited, A. F. a. E. S. A. C., Australasian Fire and Emergency Service Authorities Council Limited, Victoria, Australia. Available at: http://www.fire.tas.gov.au/userfiles/AFAC/AFAC_Review.pdf.
Couper, L. I., A. J. MacDonald and E. A. Mordecai, 2021: Impact of prior and projected climate change on US Lyme disease incidence. *Global Change Biology*, **27**(4), 738-754, doi:https://doi.org/10.1111/gcb.15435.
Cowie, A. L. et al., 2021: Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *GCB Bioenergy*, **13**(8), 1210-1231, doi:https://doi.org/10.1111/gcbb.12844.
Coyle, D. R. et al., 2017: Soil fauna responses to natural disturbances, invasive species, and global climate change: Current state of the science and a call to action. *Soil Biology and Biochemistry*, **110**, 116-133.
Craig, L. S. et al., 2017: Meeting the challenge of interacting threats in freshwater ecosystems: A call to scientists and managers. *ELEMENTA: Science of the Anthropocene*, **5**(0), 72, doi:10.1525/elementa.256.
Cramb, R. A., J. F. McCarthy and NUS Press, 2015: The oil palm complex : smallholders, agribusiness, and the state in Indonesia and Malaysia. *Recherche en sciences humaines sur l'Asie du Sud-Est*, 335-338, doi:10.4000/moussons.3860.
Cramer, W. et al., 2014: Detection and attribution of observed impacts. In: *Climate Climate Change 2014: Impacts, Adaptation, and Vulnerability,*. Cambridge University Press, pp. 979-1038.
Crawford, R. et al., 2011: Collapse of South Africa's penguins in the early 21st century. *African Journal of Marine Science*, **33**(1), 139-156.
Crawford, R. J. et al., 2006: The influence of food availability on breeding success of African penguins Spheniscus demersus at Robben Island, South Africa. *Biological Conservation*, **132**(1), 119-125.
Creed, I. et al., 2018: Global change-driven effects on dissolved organic matter composition: Implications for food webs of northern lakes. *Global Change Biology*, **24**(8), 3692-3714, doi:10.1111/gcb.14129.
Creed, I. F. and M. van Noordwijk, 2018: *Forest and Water on a Changing Planet: Vulnerability, Adaptation and Governance Opportunities: A Global Assessment Report*. IUFRO World Series, **38**, International Union of Forest Research Organizations (IUFRO), 190 pp. Available at: https://www.iufro.org/science/gfep/forests-and-water-panel/report/.
Criado, M. G. et al., 2020: Woody plant encroachment intensifies under climate change across tundra and savanna biomes. *Global Ecology and Biogeography*, doi:10.1111/geb.13072.
Cromsigt, J. P. et al., 2018: Trophic rewilding as a climate change mitigation strategy? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **373**(1761), 20170440.
Crowther, T. W. et al., 2016: Quantifying global soil carbon losses in response to warming. *Nature*, **540**(7631), 104.

Crozier, L. G. and J. A. Hutchings, 2014: Plastic and evolutionary responses to climate change in fish. *Evolutionary Applications*, **7**(1), 68-87.
Crump, J., 2017: *Smoke on Water: Countering Global Threats From Peatland Loss and Degradation*. Unep, Grida, Gpi, 72 pp. ISBN 978-82-7701-168-4.
Cudlin, P. et al., 2017: Drivers of treeline shift in different European mountains. *Climate Research*, **73**(1-2), 135-150, doi:10.3354/cr01465.
Cunningham, S. J., J. L. Gardner and R. O. Martin, 2021: Opportunity costs and the response of birds and mammals to climate warming. *Frontiers in Ecology and the Environment*, **19**(5), 300-307, doi:10.1002/fee.2324.
Curtis, P. G. et al., 2018: Classifying drivers of global forest loss. *Science*, **361**(6407), 1108-1111, doi:10.1126/science.aau3445.
D'Annolfo, R., B. Gemmill-Herren, B. Graeub and L. A. Garibaldi, 2017: A review of social and economic performance of agroecology. *International Journal of Agricultural Sustainability*, **15**(6), 632-644, doi:10.1080/14735903.2017.1398123.
D'Odorico, P., G. S. Okin and B. T. Bestelmeyer, 2012: A synthetic review of feedbacks and drivers of shrub encroachment in arid grasslands. *Ecohydrology*, **5**(5), 520-530, doi:10.1002/eco.259.
da Silva, S. S. et al., 2018: Dynamics of forest fires in the southwestern Amazon. *Forest Ecology and Management*, **424**, 312-322, doi:10.1016/j.foreco.2018.04.041.
da Silva, S. S. et al., 2021: Burning in southwestern Brazilian Amazonia, 2016?2019. *Journal of Environmental Management*, **286**, 10, doi:10.1016/j.jenvman.2021.112189.
Dadap, N. C. et al., 2019: Satellite soil moisture observations predict burned area in Southeast Asian peatlands. *Environmental Research Letters*, **14**(9), 094014, doi:10.1088/1748-9326/ab3891.
Dadson, S. J. et al., 2017: A restatement of the natural science evidence concerning catchment-based 'natural'flood management in the UK. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **473**(2199), 20160706.
Dahal, S., 2008: Climatic determinants of malaria and kala-azar in Nepal. *Special Issue on World Health Day 2008 theme: Protecting Health from Climate Change*, **12**(1), 32-37.
Dahm, C. N. et al., 2015: Extreme water quality degradation following a catastrophic forest fire. *Freshwater Biology*, **60**(12), 2584-2599, doi:10.1111/fwb.12548.
Dainese, M. et al., 2019: A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*, **5**(10), eaax0121-eaax0121, doi:10.1126/sciadv.aax0121.
Damien, M. and K. Tougeron, 2019: Prey-predator phenological mismatch under climate change. *Current Opinion in Insect Science*, **35**, 60-68, doi:10.1016/j.cois.2019.07.002.
Dangal, S. R. S. et al., 2017: Integrating Herbivore Population Dynamics Into a Global Land Biosphere Model: Plugging Animals Into the Earth System. *Journal of Advances in Modeling Earth Systems*, **9**(8), 2920-2945, doi:10.1002/2016ms000904.
Dangles, O. et al., 2017: Ecosystem sentinels for climate change? Evidence of wetland cover changes over the last 30 years in the tropical Andes. *PLoS ONE*, **12**(5), e0175814, doi:10.1371/journal.pone.0175814.
Dargie, G. C. et al., 2019: Congo Basin peatlands: threats and conservation priorities. *Mitigation and Adaptation Strategies for Global Change*, **24**(4), 669-686, doi:10.1007/s11027-017-9774-8.
Dargie, G. C. et al., 2017: Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature*, **542**(7639), 86-+, doi:10.1038/nature21048.
Darusman, T., D. P. Lestari and D. Arriyadi, 2021: Management Practice and Restoration of the Peat Swamp Forest in Katingan-Mentaya, Indonesia. In: *Tropical Peatland Eco-management* [Osaki, M., N. Tsuji, N. Foead and J. Rieley (eds.)]. Springer, Singapore, pp. 381-409. ISBN 978-981-334-654-3.
Darwall, W. et al., 2018: The Alliance for Freshwater Life: A global call to unite efforts for freshwater biodiversity science and conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **28**(4), 1015-1022, doi:10.1002/aqc.2958.
Darwall, W. R. T. and J. Freyhof, 2015: Lost fishes, who is counting? The extent of the threat to freshwater fish biodiversity. In: *Conservation of Freshwater Fishes* [Closs, G. P., J. D. Olden and M. Krkosek (eds.)]. Cambridge University Press, Cambridge, pp. 1-36. ISBN 978-1-107-04011-3.
Dasgupta, P., 2021: *The Economics of Biodiversity : the Dasgupta Review*. HM Treasury. ISBN 978-1-911680-29-1.
Daskalova, G. N., I. Myers-Smith and A. Phillimore, 2020: Accounting for year effects and sampling error in temporal analyses of population and biodiversity change-Response to Seibold et al. 2019 "Arthropod decline in grasslands and forests is associated with landscape-level drivers". *EcoEvoRxiv*, doi:10.32942/osf.io/cg3zs.
Daskin, J. H., R. A. Alford and R. Puschendorf, 2011: Short-Term Exposure to Warm Microhabitats Could Explain Amphibian Persistence with Batrachochytrium dendrobatidis. *PLoS ONE*, **6**(10), doi:10.1371/journal.pone.0026215.
Daskin, J. H., M. Stalmans and R. M. Pringle, 2016: Ecological legacies of civil war: 35-year increase in savanna tree cover following wholesale large-mammal declines. *Journal of Ecology*, **104**(1), 79–89.
Datry, T., K. Fritz and C. Leigh, 2016: Challenges, developments and perspectives in intermittent river ecology. *Freshwater Biology*, **61**(8), 1171-1180, doi:10.1111/fwb.12789.

Daufresne, M., P. Bady and J. F. Fruget, 2007: Impacts of global changes and extreme hydroclimatic events on macroinvertebrate community structures in the French Rhone River. *Oecologia*, **151**(3), 544-559, doi:10.1007/s00442-006-0655-1.
Daufresne, M., K. Lengfellner and U. Sommer, 2009: Global warming benefits the small in aquatic ecosystems. *Proceedings of the National Academy of Sciences*, **106**(31), 12788-12793, doi:10.1073/pnas.0902080106.
Daufresne, M., M. C. Roger, H. Capra and N. Lamouroux, 2004: Long-term changes within the invertebrate and fish communities of the Upper Rhône River: effects of climatic factors. *Global Change Biology*, **10**(1), 124-140, doi:https://doi.org/10.1046/j.1529-8817.2003.00720.x.
Davies-Barnard, T. et al., 2015: Quantifying the relative importance of land cover change from climate and land-use in the representative concentration pathways. *Global Biogechemical Cycles*, doi:10.1002/2014gb004949.
Davies, A. B., A. Gaylard and G. P. Asner, 2018: Megafaunal effects on vegetation structure throughout a densely wooded African landscape. *Ecological applications*, **28**(2), 398–408.
Davies, G. M., A. Gray, G. Rein and C. J. Legg, 2013: Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland. *Forest Ecology and Management*, **308**, 169-177, doi:10.1016/j.foreco.2013.07.051.
Davis, B. J. K. et al., 2019a: Vibrio parahaemolyticus in the Chesapeake Bay: Operational In Situ Prediction and Forecast Models Can Benefit from Inclusion of Lagged Water Quality Measurements. *Applied and Environmental Microbiology*, **85**(17), e01007-01019, doi:10.1128/AEM.01007-19.
Davis, E. L. et al., 2020: Regional variability in the response of alpine treelines to climate change. *Climatic Change*, **162**(3), 1365-1384, doi:10.1007/s10584-020-02743-0.
Davis, K. T. et al., 2019b: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, **116**(13), 6193–6198.
de Andrade, R. B. et al., 2017: Scenarios in tropical forest degradation: carbon stock trajectories for REDD+. *Carbon Balance and Management*, **12**(1), 6, doi:10.1186/s13021-017-0074-0.
De Faria, B. L. et al., 2017: Current and future patterns of fire-induced forest degradation in Amazonia. *Environmental Research Letters*, **12**(9), 095005.
de Graaf, I. E. M. et al., 2019: Environmental flow limits to global groundwater pumping. *Nature*, **574**(7776), 90-94.
De Groot, R. S. et al., 2013: Benefits of investing in ecosystem restoration. *Conservation Biology*, **27**(6), 1286-1293.
de Jesús Arce-Mojica, T. et al., 2019: Nature-based solutions (NbS) for reducing the risk of shallow landslides: Where do we stand? *International Journal of Disaster Risk Reduction*, **41**, 101293.
de Jong, P. W. and P. M. Brakefield, 1998: Climate and change in clines for melanism in the two–spot ladybird, Adalia bipunctata (Coleoptera: Coccinellidae). *Proceedings of the Royal Society of London. Series B: Biological Sciences*, **265**(1390), 39-43, doi:10.1098/rspb.1998.0261.
de los Santos, C. B. et al., 2019: Recent trend reversal for declining European seagrass meadows. *Nature Communications*, **10**(1), 3356, doi:10.1038/s41467-019-11340-4.
de Meira Junior, M. S. et al., 2020: The impact of long dry periods on the aboveground biomass in a tropical forests: 20 years of monitoring. *Carbon Balance and Management*, **15**, 12, doi:10.1186/s13021-020-00147-2.
de Paula, M. D., J. Groeneveld and A. Huth, 2015: Tropical forest degradation and recovery in fragmented landscapes - Simulating changes in tree community, forest hydrology and carbon balance. *Global Ecology and Conservation*, **3**, 664-677, doi:10.1016/j.gecco.2015.03.004.
De Senerpont Domis, L. E., JJ Gsell, AS
Huszar, VLM et al., 2013: Plankton dynamics under different climatic conditions in space and time. *Freshwater Biology*, **58**, 463-482.
De Stefano, A. and M. G. Jacobson, 2018: Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry systems*, **92**(2), 285-299.
De Sy, V. et al., 2019: Tropical deforestation drivers and associated carbon emission factors derived from remote sensing data. *Environmental Research Letters*, **14**(9), doi:10.1088/1748-9326/ab3dc6.
De Sy, V. et al., 2015: Land use patterns and related carbon losses following deforestation in South America. *Environmental Research Letters*, **10**(12), doi:10.1088/1748-9326/10/12/124004.
de Villiers, M., 2002: Effect of a storm on breeding African Penguins Spheniscus demersus at Foxy Beach, Boulders Penguin Colony, Simon's Town. *Bird Numbers*, **11**, 7-9.
De Vos, J. M. et al., 2015: Estimating the normal background rate of species extinction. *Conservation biology*, **29**(2), 452-462.
de Wit, H. A. et al., 2016: Current browning of surface waters will be further promoted by wetter climate. *Environmental Science & Technology Letters*, **3**(12), 430-435.
Dean, J. F. et al., 2018: Methane feedbacks to the global climate system in a warmer world. *Reviews of Geophysics*, **56**(1), 207-250.
Death, R. G., I. C. Fuller and M. G. Macklin, 2015: Resetting the river template: the potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshwater Biology*, **60**(12), 2477-2496, doi:https://doi.org/10.1111/fwb.12639.
Deb Burman, P. K. et al., 2020: The effect of Indian summer monsoon on the seasonal variation of carbon sequestration by a forest ecosystem over North-East India. *SN Applied Sciences*, **2**(2), 154, doi:10.1007/s42452-019-1934-x.
Deb, J., S. Phinn, N. Butt and C. McAlpine, 2018: Climate change impacts on tropical forests: identifying risks for tropical Asia. *Journal of Tropical Forest Science*, **30**(2), 182-194.

Deere, N. J. et al., 2018: High Carbon Stock forests provide co-benefits for tropical biodiversity. *Journal of Applied Ecology*, **55**(2), 997-1008, doi:10.1111/1365-2664.13023.
Deery, S. W., J. E. Rej, D. Haro and A. R. Gunderson, 2021: Heat hardening in a pair of Anolis lizards: constraints, dynamics and ecological consequences. *Journal of Experimental Biology*, **224**(7), doi:10.1242/jeb.240994.
DeFalco, L. A., T. C. Esque, S. J. Scoles-Sciulla and J. Rodgers, 2010: DESERT WILDFIRE AND SEVERE DROUGHT DIMINISH SURVIVORSHIP OF THE LONG-LIVED JOSHUA TREE (YUCCA BREVIFOLIA; AGAVACEAE). *American Journal of Botany*, **97**(2), 243-250, doi:10.3732/ajb.0900032.
Deksne, G. et al., 2020: Parasites in the changing world – Ten timely examples from the Nordic-Baltic region. *Parasite Epidemiology and Control*, **10**, e00150, doi:https://doi.org/10.1016/j.parepi.2020.e00150.
Del Vecchio, S., I. Prisco, A. T. R. Acosta and A. Stanisci, 2015: Changes in plant species composition of coastal dune habitats over a 20-year period. *AoB Plants*, **7**.
Delach, A. et al., 2019: Agency plans are inadequate to conserve US endangered species under climate change. *Nature Climate Change*, **9**(12), 999-1004.
DeLonge, M. S., A. Miles and L. Carlisle, 2016: Investing in the transition to sustainable agriculture. *Environmental Science & Policy*, **55**, 266-273, doi:10.1016/j.envsci.2015.09.013.
DelSontro, T., J. J. Beaulieu and J. A. Downing, 2018: Greenhouse gas emissions from lakes and impoundments: Upscaling in the face of global change. *Limnology and Oceanography Letters*, **3**(3), 64-75, doi:10.1002/lol2.10073.
Delwiche, K., S. Senft-Grupp and H. Hemond, 2015: A novel optical sensor designed to measure methane bubble sizes in situ. *Limnology and Oceanography: Methods*, **13**(12), 712-721.
Dempson, B. et al., 2017: Influence of climate and abundance on migration timing of adult Atlantic salmon (S almo salar) among rivers in N ewfoundland and L abrador. *Ecology of Freshwater Fish*, **26**(2), 247-259.
Dendoncker, M. et al., 2020: 50 years of woody vegetation changes in the Ferlo (Senegal) assessed by high-resolution imagery and field surveys. *Regional Environmental Change*, **20**(4), doi:10.1007/s10113-020-01724-4.
Dennis, R., 1999: *A review of fire projects in Indonesia, 1982-1998*. Center for International Forestry Research, Bogor, Indonesia, 105 pp. ISBN 978-979-8764-30-1.
Denny, M. W., L. J. H. Hunt, L. P. Miller and C. D. G. Harley, 2009: On the prediction of extreme ecological events. *Ecological Monographs*, **79**(3), 397-421, doi:https://doi.org/10.1890/08-0579.1.
Depaquit, J. et al., 2010: Arthropod-borne viruses transmitted by Phlebotomine sandflies in Europe: A review. *Euro surveillance : bulletin européen sur les maladies transmissibles = European communicable disease bulletin*, **15**, 19507.
Desbureaux, S. and R. Damania, 2018: Rain, forests and farmers: Evidence of drought induced deforestation in Madagascar and its consequences for biodiversity conservation. *Biological Conservation*, **221**, 357-364, doi:10.1016/j.biocon.2018.03.005.
Descheemaeker, K., E. Mapedza, T. Amede and W. Ayalneh, 2010: Effects of integrated watershed management on livestock water productivity in water scarce areas in Ethiopia. *Physics and Chemistry of the Earth, Parts A/B/C*, **35**(13-14), 723-729.
Destoumieux-Garzón, D. et al., 2018: The One Health Concept: 10 Years Old and a Long Road Ahead. *Frontiers in Veterinary Science*, **5**(14), doi:10.3389/fvets.2018.00014.
Devictor, V. et al., 2012: Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change*, **2**(2), 121-124, doi:10.1038/nclimate1347.
Dewage, B. G. et al., 2019: Trends in canine seroprevalence to Borrelia burgdorferi and Anaplasma spp. in the eastern USA, 2010–2017. *Parasites & Vectors*, **12**(1), 476, doi:10.1186/s13071-019-3735-x.
Dhimal, M., B. Ahrens and U. Kuch, 2014a: Altitudinal shift of malaria vectors and malaria elimination in Nepal. *Malaria Journal*, **13**(1), P26, doi:10.1186/1475-2875-13-S1-P26.
Dhimal, M., B. Ahrens and U. Kuch, 2014b: Species composition, seasonal occurrence, habitat preference and altitudinal distribution of malaria and other disease vectors in eastern Nepal. *Parasites & Vectors*, **7**(1), 540, doi:10.1186/s13071-014-0540-4.
Dhimal, M. et al., 2015: Risk factors for the presence of chikungunya and dengue vectors (Aedes aegypti and Aedes albopictus), their altitudinal distribution and climatic determinants of their abundance in central Nepal. *PLoS Neglected Tropical Diseases*, **9**(3), e0003545, doi:10.1371/journal.pntd.0003545.
Dhimal, M. et al., 2021: Climate change and its association with the expansion of vectors and vector-borne diseases in the Hindu Kush Himalayan region: A systematic synthesis of the literature. *Advances in Climate Change Research*, **12**(3), 421-429, doi:https://doi.org/10.1016/j.accre.2021.05.003.
Dhir, B., 2015: Status of aquatic macrophytes in changing climate: A perspective. *Journal of Environmental Science and Technology*, **8**(4), 139.
Di Marco, M. et al., 2018: The extent and predictability of the biodiversity-carbon correlation. *Ecology Letters*, **21**(3), 365-375, doi:10.1111/ele.12903.
Di Nitto, D. et al., 2014: Mangroves facing climate change: landward migration potential in response to projected scenarios of sea level rise. *Biogeosciences*, **11**(3), 857-871.
Di Virgilio, G. et al., 2019: Climate Change Increases the Potential for Extreme Wildfires. *Geophysical Research Letters*, **46**(14), 8517-8526, doi:10.1029/2019gl083699.

Díaz, S. et al., 2018: Assessing nature's contributions to people. *Science*, **359**(6373), 270-272, doi:10.1126/science.aap8826.
Díaz, S. et al., 2020: Set ambitious goals for biodiversity and sustainability. *Science*, **370**(6515), 411-413, doi:10.1126/science.abe1530.
Diederichs, N. and D. Roberts, 2016: Climate protection in mega-event greening: the 2010 FIFA™ World Cup and COP17/CMP7 experiences in Durban, South Africa. *Climate and Development*, **8**(4), 376-384, doi:10.1080/17565529.2015.1085361.
Diffenbaugh, N. S., D. L. Swain and D. Touma, 2015: Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(13), 3931-3936, doi:10.1073/pnas.1422385112.
Dinerstein, E. et al., 2020: A "Global Safety Net" to reverse biodiversity loss and stabilize Earth's climate. *Science Advances*, **6**, doi:10.1126/sciadv.abb2824.
Dinerstein, E. et al., 2019: A Global Deal For Nature: Guiding principles, milestones, and targets. *Science Advances*, **5**(4), eaaw2869, doi:10.1126/sciadv.aaw2869.
Diversity, S. o. t. C. o. B., 2020: *Global Biodiversity Outlook 5 – Summary for Policy Makers*. Montréal. Available at: www.cbd.int/GBO5.
Doblas-Miranda, E. et al., 2017: A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: Beyond drought effects. *Global and Planetary Change*, **148**, 42-54.
Doell, P. et al., 2015: Integrating risks of climate change into water management. *Hydrological Sciences Journal*, **60**(1), 4-13.
Dohong, A., A. A. Aziz and P. Dargusch, 2018: A review of techniques for effective tropical peatland restoration. *Wetlands*, **38**(2), 275-292, doi:10.1007/s13157-018-1017-6.
Dokulil, M. T., 2016: Climate impacts on ecohydrological processes in aquatic systems. *Ecohydrology & Hydrobiology*, **16**(1), 66-70, doi:https://doi.org/10.1016/j.ecohyd.2015.08.001.
Domisch, S. et al., 2013: Modelling distribution in European stream macroinvertebrates under future climates. *Glob Chang Biol*, **19**(3), 752-762, doi:10.1111/gcb.12107.
Domisch, S., S. C. JÄHnig and P. Haase, 2011: Climate-change winners and losers: stream macroinvertebrates of a submontane region in Central Europe. *Freshwater Biology*, **56**(10), 2009-2020, doi:10.1111/j.1365-2427.2011.02631.x.
Dommain, R., J. Couwenberg and H. Joosten, 2011: Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability. *Quaternary Science Reviews*, **30**(7), 999-1010, doi:10.1016/j.quascirev.2011.01.018.
Donald, P. F. and A. D. Evans, 2006: Habitat connectivity and matrix restoration: the wider implications of agri-environment schemes. *Journal of Applied Ecology*, **43**(2), 209-218, doi:https://doi.org/10.1111/j.1365-2664.2006.01146.x.
Donato, D. C., B. J. Harvey and M. G. Turner, 2016: Regeneration of montane forests 24 years after the 1988 Yellowstone fires: A fire-catalyzed shift in lower treelines? *Ecosphere*, **7**(8), doi:10.1002/ecs2.1410.
Donato, D. C. et al., 2011: Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, **4**(5), 293-297, doi:10.1038/ngeo1123.
Donohue, R. J., M. L. Roderick, T. R. McVicar and G. D. Farquhar, 2013: Impact of CO2 fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters*, **40**(12), 3031-3035, doi:10.1002/grl.50563.
Dornelas, M. et al., 2014: Assemblage Time Series Reveal Biodiversity Change but Not Systematic Loss. *Science*, **344**(6181), 296, doi:10.1126/science.1248484.
dos Reis, M. et al., 2021: Forest fires and deforestation in the central Amazon: Effects of landscape and climate on spatial and temporal dynamics. *Journal of Environmental Management*, **288**, 12, doi:10.1016/j.jenvman.2021.112310.
Douwes, E. and N. Buthelezi, 2016: Growing Forests and Communities. *Thola*, **18**, 58-61.
Douwes, E., N. Buthelezi, K. Mavundla and D. Roberts, 2015: *EThekwini Municipality's Community Reforestation Programme: A Model of Ecosystem-Based Adaptation (Policy Brief 4)*.
Douwes, E. et al., 2016: The Buffelsdraai Landfill Site Community Reforestation Project. *Unasylva*, **67**, 12-19.
Dowdy, A. J., 2018: Climatological Variability of Fire Weather in Australia. *Journal of Applied Meteorology and Climatology*, **57**(2), 221-234, doi:10.1175/jamc-d-17-0167.1.
Dowdy, A. J. et al., 2019: Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Scientific Reports*, **9**, doi:10.1038/s41598-019-46362-x.
DPIPWE, 2016: *Tasmanian Wilderness World Heritage Area Management Plan 2016. Department of Primary Industries, Parks, Water and Environment*, ISBN 978-0-7246-6806-9, Hobart, Australia.
Drake, T. W., P. A. Raymond and R. G. M. Spencer, 2018: Terrestrial carbon inputs to inland waters: A current synthesis of estimates and uncertainty. *Limnology and Oceanography Letters*, **3**(3), 132-142, doi:10.1002/lol2.10055.
Drever, C. R. et al., 2021: Natural climate solutions for Canada. *Science Advances*, **7**(23), eabd6034, doi:10.1126/sciadv.abd6034.

Drexler, J. Z., S. Khanna, D. H. Schoellhamer and J. Orlando, 2018: The Fate of Blue Carbon in the Sacramento-San Joaquin Delta of California, USA. In: *A Blue Carbon Primer*. CRC Press. ISBN 978-0-429-43536-2.
Drossart, M. and M. Gérard, 2020: Beyond the Decline of Wild Bees: Optimizing Conservation Measures and Bringing Together the Actors. *Insects*, **11**(9), doi:10.3390/insects11090649.
Du, E. and W. de Vries, 2018: Nitrogen-induced new net primary production and carbon sequestration in global forests. *Environmental Pollution*, **242**, 1476-1487, doi:10.1016/j.envpol.2018.08.041.
Du, H. B. et al., 2018: Warming-induced upward migration of the alpine treeline in the Changbai Mountains, northeast China. *Global Change Biology*, **24**(3), 1256-1266, doi:10.1111/gcb.13963.
Du, J. Y. et al., 2017: Satellite microwave assessment of Northern Hemisphere lake ice phenology from 2002 to 2015. *Cryosphere*, **11**(1), 47-63, doi:10.5194/tc-11-47-2017.
du Plessis, K. L. et al., 2012: The costs of keeping cool in a warming world: implications of high temperatures for foraging, thermoregulation and body condition of an arid-zone bird. *Global Change Biology*, **18**(10), 3063-3070, doi:https://doi.org/10.1111/j.1365-2486.2012.02778.x.
du Toit, J. C. O., T. G. O'Connor and L. Van den Berg, 2015: Photographic evidence of fire-induced shifts from dwarf-shrub-to grass-dominated vegetation in Nama-Karoo. *South African Journal of Botany*, **101**, 148-152.
du Toit, J. C. O. and T. G. O'Connor, 2014: Changes in rainfall pattern in the eastern Karoo, South Africa, over the past 123 years. *Water SA*, **40**(3), 453-460, doi:10.4314/wsa.v40i3.8.
Duane, A., M. Castellnou and L. Brotons, 2021: Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change*, **165**(3), 1-21.
Duarte, C. M. et al., 2020: Rebuilding marine life. *Nature*, **580**(7801), 39-51, doi:10.1038/s41586-020-2146-7.
Duffield, S. J., B. Le Bas and M. D. Morecroft, 2021: Climate change vulnerability and the state of adaptation on England's National Nature Reserves. *Biological Conservation*, **254**, 108938, doi:https://doi.org/10.1016/j.biocon.2020.108938.
Duffy, P. B. et al., 2019: Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases. *Science*, **363**(6427), eaat5982, doi:10.1126/science.aat5982.
Duke, N. C. et al., 2017: Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. *Marine and Freshwater Research*, **68**(10), 1816-1829, doi:10.1071/MF16322.
Dumic, I. and E. Severnini, 2018: "Ticking Bomb": The Impact of Climate Change on the Incidence of Lyme Disease. *Canadian Journal of Infectious Diseases and Medical Microbiology*.
Duncan, J. M. A. et al., 2020: Managing multifunctional landscapes: Local insights from a Pacific Island Country context. *Journal of Environmental Management*, **260**, doi:10.1016/j.jenvman.2019.109692.
Dupire, S., T. Curt, S. Bigot and T. Frejaville, 2019: Vulnerability of forest ecosystems to fire in the French Alps. *European Journal of Forest Research*, **138**(5), 813-830, doi:10.1007/s10342-019-01206-1.
Durance, I. and S. J. Ormerod, 2009: Trends in water quality and discharge confound long-term warming effects on river macroinvertebrates. *Freshwater Biology*, **54**(2), 388-405, doi:10.1111/j.1365-2427.2008.02112.x.
Durance, I. and S. J. Ormerod, 2010: Evidence for the role of climate in the local extinction of a cool-water triclad. *Journal of the North American Benthological Society*, **29**(4), 1367-1378, doi:10.1899/09-159.1.
Earl, N. and I. Simmonds, 2018: Spatial and Temporal Variability and Trends in 2001-2016 Global Fire Activity. *Journal of Geophysical Research (Atmospheres)*, **123**, 2524-2536, doi:10.1002/2017JD027749.
Earl, N., I. Simmonds and N. Tapper, 2015: Weekly cycles of global fires-Associations with religion, wealth and culture, and insights into anthropogenic influences on global climate. *Geophysical Research Letters*, **42**(21), 9579-9589, doi:10.1002/2015gl066383.
Early, R. et al., 2016: Global threats from invasive alien species in the twenty-first century and national response capacities. *Nature Communications*, **7**, doi:10.1038/ncomms12485.
Early, R. and S. Keith, 2019: Geographically variable biotic interactions and implications for species ranges. *Global Ecology and Biogeography*, **28**(1), 42-53, doi:10.1111/geb.12861.
Ebel, B. A., J. A. Moody and D. A. Martin, 2012: Hydrologic conditions controlling runoff generation immediately after wildfire. *Water Resources Research*, **48**(3), doi:https://doi.org/10.1029/2011WR011470.
Ebi, K. L. et al., 2021: Burning embers: synthesis of the health risks of climate change. *Environmental Research Letters*, **16**(4), 044042, doi:10.1088/1748-9326/abeadd.
Ebi Kristie, L., H. Ogden Nicholas, C. Semenza Jan and A. Woodward, 2017: Detecting and Attributing Health Burdens to Climate Change. *Environmental Health Perspectives*, **125**(8), 085004, doi:10.1289/EHP1509.
Eby, L. A., O. Helmy, L. M. Holsinger and M. K. Young, 2014: Evidence of climate-induced range contractions in bull trout Salvelinus confluentus in a Rocky Mountain watershed, USA. *PLoS ONE*, **9**(6).
Edmands, S., 2021: Sex Ratios in a Warming World: Thermal Effects on Sex-Biased Survival, Sex Determination, and Sex Reversal. *Journal of Heredity*, **112**(2), 155-164, doi:10.1093/jhered/esab006.
Edwards, D. P. et al., 2014: Maintaining ecosystem function and services in logged tropical forests. *Trends in Ecology & Evolution*, **29**(9), 511-520, doi:https://doi.org/10.1016/j.tree.2014.07.003.
Eigenbrod, F., P. Gonzalez, J. Dash and I. Steyl, 2015: Vulnerability of ecosystems to climate change moderated by habitat intactness. *Global Change Biology*, **21**(1), 275-286, doi:10.1111/gcb.12669.
Ekvall, M. K. et al., 2013: Synergistic and species-specific effects of climate change and water colour on cyanobacterial toxicity and bloom formation. *Freshwater Biology*, **58**(11), 2414-2422.

Elberling, B. et al., 2013: Long-term CO2 production following permafrost thaw. *Nature Climate Change*, **3**(10), 890-894, doi:10.1038/nclimate1955.
Elith, J. and J. R. Leathwick, 2009: Species Distribution Models: Ecological Explanation and Prediction Across Space and Time. *Annual Review of Ecology, Evolution, and Systematics*, **40**, 677-697, doi:10.1146/annurev.ecolsys.110308.120159.
Ellis, E. C. and N. Ramankutty, 2008: Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, **6**(8), 439-447, doi:10.1890/070062.
Ellison, D., M. N. Futter and K. Bishop, 2012: On the forest cover-water yield debate: From demand- to supply-side thinking, 806-820 pp.
Ellison, D. et al., 2017: Trees, forests and water: Cool insights for a hot world. *Global Environmental Change-Human and Policy Dimensions*, **43**, 51-61, doi:10.1016/j.gloenvcha.2017.01.002.
Elmendorf, S. C. et al., 2015: Experiment, monitoring, and gradient methods used to infer climate change effects on plant communities yield consistent patterns. *Proceedings of the National Academy of Sciences*, **112**(2), 448-452.
Elmqvist, T. et al., 2003: Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, **1**(9), 488-494, doi:https://doi.org/10.1890/1540-9295(2003)001[0488:RDECAR]2.0.CO;2.
Elsen, P. R., W. B. Monahan, E. R. Dougherty and A. M. Merenlender, 2020: Keeping pace with climate change in global terrestrial protected areas. *Science Advances*, **6**(25), eaay0814, doi:10.1126/sciadv.aay0814.
Endo, N. and E. A. B. Eltahir, 2020: Increased risk of malaria transmission with warming temperature in the Ethiopian Highlands. *Environmental Research Letters*, **15**(5), 054006, doi:10.1088/1748-9326/ab7520.
England, N. and RSPB, 2020: Climate Change Adaptation Manual. Natural England York.
Englund, O. et al., 2017: A new high-resolution nationwide aboveground carbon map for Brazil. *Geo-Geography and Environment*, **4**(2), doi:10.1002/geo2.45.
Enríquez-de-Salamanca, Á., R. Díaz-Sierra, R. M. Martín-Aranda and M. J. Santos, 2017: Environmental impacts of climate change adaptation. *Environmental Impact Assessment Review*, **64**, 87-96, doi:https://doi.org/10.1016/j.eiar.2017.03.005.
Enriquez-Urzelai, U. et al., 2019: Are amphibians tracking their climatic niches in response to climate warming? A test with Iberian amphibians. *Climatic Change*, **154**(1-2), 289-301, doi:10.1007/s10584-019-02422-9.
Erb, K. H. et al., 2018a: Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, **553**(7686), 73-+, doi:10.1038/nature25138.
Erb, W. M. et al., 2018b: Wildfire smoke impacts activity and energetics of wild Bornean orangutans. *Scientific reports*, **8**(1), 7606-7606, doi:10.1038/s41598-018-25847-1.
Escobar, L. E. et al., 2015: A global map of suitability for coastal *Vibrio cholerae* under current and future climate conditions. *Acta Tropica*, **149**, 202-211, doi:10.1016/j.actatropica.2015.05.028.
Espaciais, I. N. d. P., Portal TerraBrasilis. Available at: http://terrabrasilis.dpi.inpe.br.
Espírito-Santo, M. M. et al., 2016: Understanding patterns of land-cover change in the Brazilian Cerrado from 2000 to 2015. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150435, doi:10.1098/rstb.2015.0435.
Esquivel-Muelbert, A. et al., 2019: Compositional response of Amazon forests to climate change. *Global Change Biology*, **25**(1), 39-56, doi:10.1111/gcb.14413.
Essl, F. et al., 2020: Drivers of future alien species impacts: An expert-based assessment. *Global Change Biology*, **26**(9), 4880-4893, doi:https://doi.org/10.1111/gcb.15199.
Estop-Aragonés, C. et al., 2018: Limited release of previously-frozen C and increased new peat formation after thaw in permafrost peatlands. *Soil Biology and Biochemistry*, **118**, 115-129, doi:10.1016/j.soilbio.2017.12.010.
Estrada-Villegas, S., J. S. Hall, M. van Breugel and S. A. Schnitzer, 2020: Lianas reduce biomass accumulation in early successional tropical forests. *Ecology*, **101**(5), e02989, doi:https://doi.org/10.1002/ecy.2989.
Eugster, W., T. DelSontro and S. Sobek, 2011: Eddy covariance flux measurements confirm extreme CH (4) emissions from a Swiss hydropower reservoir and resolve their short-term variability. *Biogeosciences*, **8**(9), 2815-2831.
Euskirchen, E. S., E. S. Kane, C. W. Edgar and M. R. Turetsky, 2020: When the Source of Flooding Matters: Divergent Responses in Carbon Fluxes in an Alaskan Rich Fen to Two Types of Inundation. *Ecosystems*, **23**(6), 1138-1153, doi:10.1007/s10021-019-00460-z.
Evander, M. and C. Ahlm, 2009: Milder winters in northern Scandinavia may contribute to larger outbreaks of haemorrhagic fever virus. *Global Health Action*, **2**(1), 2020, doi:10.3402/gha.v2i0.2020.
Evans, C. D. et al., 2017: Variability in organic carbon reactivity across lake residence time and trophic gradients. *Nature Geoscience*, **10**(11), 832-835, doi:10.1038/ngeo3051.
Evans, C. D. et al., 2021: Overriding water table control on managed peatland greenhouse gas emissions. *Nature*, **593**(7860), 548-552, doi:10.1038/s41586-021-03523-1.
Evans, C. D. et al., 2019: Rates and spatial variability of peat subsidence in Acacia plantation and forest landscapes in Sumatra, Indonesia. *Geoderma*, **338**, 410-421.
Everard, M. et al., 2020: Can nature-based solutions contribute to water security in Bhopal? *Science of The Total Environment*, **723**, 138061, doi:https://doi.org/10.1016/j.scitotenv.2020.138061.
Evers, C. R. et al., 2018: The ecosystem services and biodiversity of novel ecosystems: A literature review. *Global Ecology and Conservation*, **13**, e00362, doi:https://doi.org/10.1016/j.gecco.2017.e00362.

Exbrayat, J. F. and M. Williams, 2015: Quantifying the net contribution of the historical Amazonian deforestation to climate change. *Geophysical Research Letters*, **42**(8), 2968-2976, doi:10.1002/2015gl063497.
Extinction, S. A. F., 2018: *Annual Report: Growing the Movement*. Silver Spring, MD, USA, 28 pp.
Ezhova, E. et al. (eds.), Potential Links between Precipitation and Anthrax Outbreak at North-West Siberia. 16 th International Conference on Environmental Science and Technology, 2019, Rhodes, Greece.
Ezhova, E. et al., 2021: Climatic Factors Influencing the Anthrax Outbreak of 2016 in Siberia, Russia. *EcoHealth*, doi:10.1007/s10393-021-01549-5.
Facey, S. L. et al., 2017: Atmospheric change causes declines in woodland arthropods and impacts specific trophic groups. *Agricultural and Forest Entomology*, **19**(1), 101-112.
Fairweather, I., 2011: Reducing the future threat from (liver) fluke: realistic prospect or quixotic fantasy? *Veterinary Parasitology*, **180**(1), 133-143, doi:10.1016/j.vetpar.2011.05.034.
Falk, D. A., A. C. Watts and A. E. Thode, 2019: Scaling ecological resilience. *Frontiers in Ecology and Evolution*, **7**, 275.
Fang, X. et al., 2017: Isolating and Quantifying the Effects of Climate and CO2 Changes (1980–2014) on the Net Primary Productivity in Arid and Semiarid China. *Forests*, **8**(3), doi:10.3390/f8030060.
Fanin, T. and G. R. van der Werf, 2017: Precipitation–fire linkages in Indonesia (1997–2015). *Biogeosciences*, **14**(18), 3995-4008, doi:10.5194/bg-14-3995-2017.
FAO, 2018: *The state of the World´s forests 2018 - Forest pathways to sustainable development*. Food and Agriculture Organization of the United Nations (FAO), FAO, Rome, 118 pp. Available at: http://www.fao.org/3/I9535EN/i9535en.pdf.
Farai, M., 2017: Challenges for the sustainability of community based natural resources management programmes (CBRM) such as campfire in Zimbabwe'. *International Journal of Research in Social Sciences*, **7**(5), 8-16.
Farmer, T., E. Marschall, K. Dabrowski and S. Ludsin, 2015: Short winters threaten temperate fish populations. *Nature Communications*, **6**, doi:10.1038/ncomms8724.
Fauset, S. et al., 2015: Hyperdominance in Amazonian forest carbon cycling. *Nature Communications*, **6**, doi:10.1038/ncomms7857.
Faust, C. L. et al., 2018: Pathogen spillover during land conversion. *Ecology Letters*, **21**(4), 471-483, doi:10.1111/ele.12904.
Favero, A., A. Daigneault and B. Sohngen, 2020: Forests: Carbon sequestration, biomass energy, or both? *Science Advances*, **6**(13), eaay6792, doi:10.1126/sciadv.aay6792.
Feeley, K. et al., 2020: Climate-driven changes in the composition of New World plant communities. *Nature Climate Change*, 1-6.
Feeley, K. J., J. T. Stroud and T. M. Perez, 2017: Most 'global' reviews of species' responses to climate change are not truly global. *Diversity and Distributions*, **23**(3), 231-234, doi:10.1111/ddi.12517.
Fensholt, R. et al., 2012a: Greenness in semi-arid areas across the globe 1981–2007 — an Earth Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment*, **121**, 144–158, doi:10.1016/j.rse.2012.01.017.
Fensholt, R. et al., 2012b: Greenness in semi-arid areas across the globe 1981–2007 — an Earth Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment*, **121**, 144-158, doi:https://doi.org/10.1016/j.rse.2012.01.017.
Fernandes, K. et al., 2017: Heightened fire probability in Indonesia in non-drought conditions: the effect of increasing temperatures. *Environmental Research Letters*, **12**(5), 054002, doi:10.1088/1748-9326/aa6884.
Fernandez-Martinez, M. et al., 2019: Global trends in carbon sinks and their relationships with CO2 and temperature. *Nature Climate Change*, **9**(1), 73-+, doi:10.1038/s41558-018-0367-7.
Ferreira, J. et al., 2018: Carbon-focused conservation may fail to protect the most biodiverse tropical forests. *Nature Climate Change*, **8**(8), 744, doi:10.1038/s41558-018-0225-7.
Ferreira, P. et al., 2019: Can forests buffer negative impacts of land-use and climate changes on water ecosystem services? The case of a Brazilian megalopolis. *Science of the Total Environment*, **685**, 248-258, doi:10.1016/j.scitotenv.2019.05.065.
Ferrier, S., T. D. Harwood, C. Ware and A. J. Hoskins, 2020: A globally applicable indicator of the capacity of terrestrial ecosystems to retain biological diversity under climate change: The bioclimatic ecosystem resilience index. *Ecological Indicators*, **117**, 106554, doi:https://doi.org/10.1016/j.ecolind.2020.106554.
Ferrier, S. et al., 2016: *The methodological assessment report on scenarios and models of biodiversity and ecosystem services* [Rondinini, C. and B. Wintle (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 348 pp. Available at: https://ipbes.net/sites/default/files/downloads/pdf/2016.methodological_assessment_report_scenarios_models.pdf.
Fettig, C. J., L. A. Mortenson, B. M. Bulaon and P. B. Foulk, 2019: Tree mortality following drought in the central and southern Sierra Nevada, California, US. *Forest Ecology and Management*, **432**, 164-178, doi:10.1016/j.foreco.2018.09.006.
Feuillet, T. et al., 2020: Spatial dynamics of alpine tree lines under global warming: What explains the mismatch between tree densification and elevational upward shifts at the tree line ecotone? *Journal of Biogeography*, **47**(5), 1056-1068, doi:10.1111/jbi.13779.

Ficetola, G. F. and L. Maiorano, 2016: Contrasting effects of temperature and precipitation change on amphibian phenology, abundance and performance. *Oecologia*, **181**(3), 683-693, doi:10.1007/s00442-016-3610-9.
Ficke, A. D., C. A. Myrick and L. J. Hansen, 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*, **17**(4), 581-613.
Field, C. B. et al., 2014: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation and Vulnerability - Contributions of the Working Group II to the Fifth Assessment Report.* Cambridge University Press, Cambridge and New York, pp. 1-32.
Field, R. D. et al., 2016: Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Nino-induced drought. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(33), 9204-9209, doi:10.1073/pnas.1524888113.
Field, R. D., G. R. van der Werf and S. S. P. Shen, 2009: Human amplification of drought-induced biomass burning in Indonesia since 1960. *Nature Geoscience*, **2**(3), 185-188, doi:10.1038/ngeo443.
Filoso, S., M. O. Bezerra, K. C. Weiss and M. A. Palmer, 2017: Impacts of forest restoration on water yield: A systematic review. *PloS one*, **12**(8), e0183210.
Finkelstein, S. A. and S. A. Cowling, 2011: Wetlands, temperature, and atmospheric CO2 and CH4 coupling over the past two millennia. *Global Biogeochemical Cycles*, **25**(1), doi:10.1029/2010GB003887.
Finstad, A. et al., 2016: From greening to browning: Catchment vegetation development and reduced S-deposition promote organic carbon load on decadal time scales in Nordic lakes. *Scientific Reports*, **6**, doi:10.1038/srep31944.
Fischlin, A. et al., 2007: Ecosystems, their properties, goods, and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutifok, P. Van der Linden and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, pp. 211-272.
Fisher, M. C. and T. W. J. Garner, 2020: Chytrid fungi and global amphibian declines. *Nature Reviews Microbiology*, **18**(6), 332-343, doi:10.1038/s41579-020-0335-x.
Flannigan, M. et al., 2013: Global wildland fire season severity in the 21st century. *Forest Ecology and Management*, **294**, 54-61, doi:10.1016/j.foreco.2012.10.022.
Flannigan, M., B. Stocks, M. Turetsky and M. Wotton, 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology*, **15**(3), 549-560, doi:10.1111/j.1365-2486.2008.01660.x.
Fleming, P. A. et al., 2021: Global meta-analysis of tree decline impacts on fauna. *Biological Reviews*, **96**(5), 1744-1768, doi:https://doi.org/10.1111/brv.12725.
Fluet-Chouinard, E. et al., 2015: Development of a global inundation map at high spatial resolution from topographic downscaling of coarse-scale remote sensing data. *Remote Sensing of Environment*, **158**, 348-361, doi:https://doi.org/10.1016/j.rse.2014.10.015.
Foden, W. B. et al., 2013: Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. *PLoS ONE*, **8**(6), e65427, doi:10.1371/journal.pone.0065427.
Foden, W. B. et al., 2019: Climate change vulnerability assessment of species. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(1), e551, doi:10.1002/wcc.551.
Foli, S., M. A. F. Ros-Tonen, J. Reed and T. Sunderland, 2018: Natural Resource Management Schemes as Entry Points for Integrated Landscape Approaches: Evidence from Ghana and Burkina Faso. *Environmental Management*, **62**(1), 82-97, doi:10.1007/s00267-017-0866-8.
Folke, C. et al., 2005: Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, **35**, 557-581.
Fonseca, M. G. et al., 2019: Effects of climate and land-use change scenarios on fire probability during the 21st century in the Brazilian Amazon. *Global Change Biology*, **25**(9), 2931-2946, doi:10.1111/gcb.14709.
Fonseca, M. G. et al., 2017: Climatic and anthropogenic drivers of northern Amazon fires during the 2015-2016 El Nino event. *Ecological Applications*, **27**(8), 2514-2527, doi:10.1002/eap.1628.
Fontes, C. G. et al., 2018: Dry and hot: the hydraulic consequences of a climate change-type drought for Amazonian trees. *Philos Trans R Soc Lond B Biol Sci*, **373**(1760), doi:10.1098/rstb.2018.0209.
Ford, B. et al., 2018: Future Fire Impacts on Smoke Concentrations, Visibility, and Health in the Contiguous United States. *Geohealth*, **2**(8), 229-247, doi:10.1029/2018gh000144.
Fordham, D. et al., 2018: How complex should models be? Comparing correlative and mechanistic range dynamics models. *Global Change Biology*, **24**(3), 1357-1370, doi:10.1111/gcb.13935.
Forister, M. L. et al., 2010: Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proceedings of the National Academy of Sciences*, **107**(5), 2088, doi:10.1073/pnas.0909686107.
Forkel, M. et al., 2019: Recent global and regional trends in burned area and their compensating environmental controls. *Environmental Research Communications*, **1**(5), 051005, doi:10.1088/2515-7620/ab25d2.
Fox-Hughes, P. et al., 2014: Future fire danger climatology for Tasmania, Australia, using a dynamically downscaled regional climate model. *International Journal of Wildland Fire*, **23**(3), 309-321, doi:10.1071/wf13126.
Fox, J., S. P. Bhattarai and Y. Gyasi-Agyei, 2011a: Evaluation of different seed mixtures for grass establishment to mitigate soil erosion on steep slopes of railway batters. *Journal of irrigation and drainage engineering*, **137**(9), 624-631.

Fox, N. J. et al., 2011b: Predicting Impacts of Climate Change on Fasciola hepatica Risk. *PLoS ONE*, **6**(1), e16126, doi:10.1371/journal.pone.0016126.
França, F. M. et al., 2020: Climatic and local stressor interactions threaten tropical forests and coral reefs. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190116, doi:10.1098/rstb.2019.0116.
Frank, D. C. et al., 2015: Water-use efficiency and transpiration across European forests during the Anthropocene. *Nature Climate Change*, **5**(6), 579.
Franks, S. J. and A. A. Hoffmann, 2012: Genetics of Climate Change Adaptation. *Annual Review of Genetics*, **46**, 185-208, doi:10.1146/annurev-genet-110711-155511.
Frantzeskaki, N. et al., 2019: Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making. *BioScience*, **69**(6), 455-466, doi:10.1093/biosci/biz042.
Freeman, B. G., J. A. Lee-Yaw, J. M. Sunday and A. L. Hargreaves, 2018: Expanding, shifting and shrinking: The impact of global warming on species' elevational distributions. *Global Ecology and Biogeography*, **27**(11), 1268-1276, doi:https://doi.org/10.1111/geb.12774.
Friedlingstein, P. et al., 2019: Global Carbon Budget 2019. *Earth System Science Data*, **11**(4), 1783-1838, doi:10.5194/essd-11-1783-2019.
Friedlingstein, P. et al., 2020: Global Carbon Budget 2020. *Earth System Science Data*, **12**(4), 3269-3340, doi:10.5194/essd-12-3269-2020.
Friedman, A. M. et al., 2017: An updated review of ciguatera fish poisoning: clinical, epidemiological, environmental, and public health management. *Marine Drugs*, **15**(3), 72, doi:10.3390/md15030072.
Friend, A. D. et al., 2014: Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO2. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(9), 3280-3285, doi:10.1073/pnas.1222477110.
Frost, P., W. Siegfried and J. Cooper, 1976: Conservation of the jackass penguin (Spheniscus demersus (L.)). *Biological Conservation*, **9**(2), 79-99.
Fuentes-Castillo, T., H. J. Hernandez and P. Pliscoff, 2020: Hotspots and ecoregion vulnerability driven by climate change velocity in Southern South America. *Regional Environmental Change*, **20**(1), 15, doi:10.1007/s10113-020-01595-9.
Fulbright, T. E., K. W. Davies and S. R. Archer, 2018: Wildlife responses to brush management: a contemporary evaluation. *Rangeland Ecology & Management*, **71**(1), 35-44.
Fullerton, A. H. et al., 2017: Longitudinal thermal heterogeneity in rivers and refugia for coldwater species: effects of scale and climate change. *Aquatic Sciences*, **80**(1), 3, doi:10.1007/s00027-017-0557-9.
Galeotti, P., D. Rubolini, R. Sacchi and M. Fasola, 2009: Global changes and animal phenotypic responses: melanin-based plumage redness of scops owls increased with temperature and rainfall during the last century. *Biology Letters*, **5**(4), 532-534, doi:10.1098/rsbl.2009.0207.
Gallagher, R. V. et al., 2021: High fire frequency and the impact of the 2019–2020 megafires on Australian plant diversity. *Diversity and Distributions*, **27**(7), 1166-1179.
Gallardo, B. et al., 2017: Protected areas offer refuge from invasive species spreading under climate change. *Global Change Biology*, **23**(12), 5331-5343, doi:10.1111/gcb.13798.
Gallego-Sala, A. V. et al., 2018: Latitudinal limits to the predicted increase of the peatland carbon sink with warming. *Nature Climate Change*, **8**(10), 907-913, doi:10.1038/s41558-018-0271-1.
Gallego-Sala, A. V. and I. Colin Prentice, 2013: Blanket peat biome endangered by climate change. *Nature Climate Change*, **3**(2), 152-155, doi:10.1038/nclimate1672.
Gang, C. et al., 2017: Modeling the dynamics of distribution, extent, and NPP of global terrestrial ecosystems in response to future climate change. *Global and Planetary Change*, **148**, 153-165, doi:10.1016/j.gloplacha.2016.12.007.
Gang, C. et al., 2015: Comparative assessment of grassland NPP dynamics in response to climate change in China, North America, Europe and Australia from 1981 to 2010. *Journal of Agronomy and Crop Science*, **201**(1), 57-68.
Gao, Q. Z. et al., 2016: Changes in Global Grassland Productivity during 1982 to 2011 Attributable to Climatic Factors. *Remote Sensing*, **8**(5), doi:10.3390/rs8050384.
García-Palacios, P., N. Gross, J. Gaitán and F. T. Maestre, 2018: Climate mediates the biodiversity–ecosystem stability relationship globally. *Proceedings of the National Academy of Sciences*, **115**(33), 8400-8405, doi:10.1073/pnas.1800425115.
Garcia, R. et al., 2014: Matching species traits to projected threats and opportunities from climate change. *Journal of Biogeography*, **41**(4), 724-735, doi:10.1111/jbi.12257.
Gardner, J. L. et al., 2019: Australian songbird body size tracks climate variation: 82 species over 50 years. *Proceedings of the Royal Society B: Biological Sciences*, **286**(1916), 20192258, doi:10.1098/rspb.2019.2258.
Gardner, R. C. and C. Finlayson (eds.), Global wetland outlook: state of the World's wetlands and their services to people. Ramsar Convention Secretariat.
Garibaldi, L. A. et al., 2016: Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science*, **351**, 388-391, doi:10.1126/science.aac7287.
Garnett, S. T. et al., 2018: A spatial overview of the global importance of Indigenous lands for conservation. *Nature Sustainability*, **1**(7), 369.

Garreaud, R. D. et al., 2017: The 2010–2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation. *Hydrology and earth system sciences*, **21**(12), 6307-6327.
Garrett, K. A. et al., 2013: The effects of climate variability and the color of weather time series on agricultural diseases and pests, and on decisions for their management. *Agricultural and Forest Meteorology*, **170**, 216-227, doi:10.1016/j.agrformet.2012.04.018.
Gatti, L. V. et al., 2021: Amazonia as a carbon source linked to deforestation and climate change. *Nature*, **595**(7867), 388-+, doi:10.1038/s41586-021-03629-6.
Gatti, L. V. et al., 2014: Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. *Nature*, **506**(7486), 76.
Gatti, R. C. et al., 2019: Accelerating upward treeline shift in the Altai Mountains under last-century climate change. *Scientific Reports*, **9**, doi:10.1038/s41598-019-44188-1.
Gauthier, G. et al., 2013: Long-term monitoring at multiple trophic levels suggests heterogeneity in responses to climate change in the Canadian Arctic tundra. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **368**(1624), 20120482.
Gauthier, S. et al., 2015: Boreal Forest Health and Global Change. *Science*, **349**, 819–822, doi:doi:10.1126/science.aaa9092.
Gaveau, D. L. A. et al., 2014: Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: Evidence from the 2013 Sumatran fires. *Scientific Reports*, **4**, doi:10.1038/srep06112.
Geary, W. L. et al., 2021: Responding to the biodiversity impacts of a megafire: A case study from south-eastern Australia's Black Summer. *Diversity and Distributions*, 16, doi:10.1111/ddi.13292.
Genchi, C. et al., 2011: Changing climate and changing vector-borne disease distribution: The example of Dirofilaria in Europe. *Veterinary Parasitology*, **176**(4), 295-299, doi:10.1016/j.vetpar.2011.01.012.
Geneletti, D., L. Zardo and C. Cortinovis, 2016: Promoting nature-based solutions for climate adaptation in cities through impact assessment. *Handbook on Biodiversity and Ecosystem Services in Impact Assessment*.
Gerber, J. S. et al., 2016: Spatially explicit estimates of N 2 O emissions from croplands suggest climate mitigation opportunities from improved fertilizer management. *Global Change Biology*, **22**(10), 3383-3394, doi:10.1111/gcb.13341.
Gething, P. W. et al., 2010: Climate change and the global malaria recession. *Nature*, **465**(7296), 342-345, doi:10.1038/nature09098.
Getzner, M. et al., 2017: Gravitational natural hazards: Valuing the protective function of Alpine forests. *Forest Policy and Economics*, **80**, 150-159.
Gherlenda, A. N. et al., 2016: Boom and bust: rapid feedback responses between insect outbreak dynamics and canopy leaf area impacted by rainfall and CO2. *Global Change Biology*, **22**(11), 3632-3641, doi:https://doi.org/10.1111/gcb.13334.
Ghimire, B. et al., 2015: Large carbon release legacy from bark beetle outbreaks across Western United States. *Global Change Biology*, **21**(8), 3087-3101, doi:10.1111/gcb.12933.
Gibb, R. et al., 2020: Zoonotic host diversity increases in human-dominated ecosystems. *Nature*, **584**(7821), 398-402, doi:10.1038/s41586-020-2562-8.
Gibson-Reinemer, D. K. and F. J. Rahel, 2015: Inconsistent range shifts within species highlight idiosyncratic responses to climate warming. *PloS one*, **10**(7), e0132103.
Gibson, C. M. et al., 2018: Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nature Communications*, **9**, doi:10.1038/s41467-018-05457-1.
Gibson, D. J. and J. A. Newman, 2019: *Grasslands and climate change*. Cambridge University Press.
Giersch, J. et al., 2015: Climate-induced range contraction of a rare alpine aquatic invertebrate. *Freshwater Science*, **34**(1), 53-65, doi:10.1086/679490.
Giesen, C. et al., 2020: The impact of climate change on mosquito-borne diseases in Africa. *Pathogens and Global Health*, **114**(6), 287-301, doi:10.1080/20477724.2020.1783865.
Giesen, W., 2021: Tropical Peatland Restoration in Indonesia by Replanting with Useful Indigenous Peat Swamp Species: Paludiculture. In: *Tropical Peatland Eco-management* [Osaki, M., N. Tsuji, N. Foead and J. Rieley (eds.)]. Springer, Singapore, pp. 411-441. ISBN 978-981-334-654-3.
Giglio, L. et al., 2018: The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sensing of Environment*, **217**, 72-85, doi:10.1016/j.rse.2018.08.005.
Giglio, L., J. T. Randerson and G. R. van der Werf, 2013: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research-Biogeosciences*, **118**(1), 317-328, doi:10.1002/jgrg.20042.
Gilbert, L., 2021: The Impacts of Climate Change on Ticks and Tick-Borne Disease Risk. *Annual Review of Entomology*, **66**, 373-388, doi:10.1146/annurev-ento-052720-094533.
Gilby, B. L. et al., 2020: Identifying restoration hotspots that deliver multiple ecological benefits. *Restoration Ecology*, **28**(1), 222-232, doi:https://doi.org/10.1111/rec.13046.
Giles-Hansen, K., X. H. Wei and Y. P. Hou, 2021: Dramatic increase in water use efficiency with cumulative forest disturbance at the large forested watershed scale. *Carbon Balance and Management*, **16**(1), 15, doi:10.1186/s13021-021-00169-4.

Gill, A. L. et al., 2015: Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies. *Annals of botany*, **116**(6), 875-888.
Gillingham, P. K. et al., 2015: The effectiveness of protected areas in the conservation of species with changing geographical ranges. *Biological Journal of the Linnean Society*, **115**(3), 707-717, doi:10.1111/bij.12506.
Glenk, K. et al., 2021: The opportunity cost of delaying climate action: Peatland restoration and resilience to climate change. *Global Environmental Change*, **70**, 102323, doi:https://doi.org/10.1016/j.gloenvcha.2021.102323.
Glidden, C. et al., 2021: Impacts of anthropogenic change on biodiversity affects disease spillover risk. Authorea Preprints.
Goldstein, A. et al., 2020: Protecting irrecoverable carbon in Earth's ecosystems. *Nature Climate Change*, **10**(4), 287-295, doi:10.1038/s41558-020-0738-8.
Gonsamo, A. et al., 2021: Greening drylands despite warming consistent with carbon dioxide fertilization effect. *Global Change Biology*, **27**(14), 3336-3349, doi:https://doi.org/10.1111/gcb.15658.
Gonthier, D. J. et al., 2019: Bird services and disservices to strawberry farming in Californian agricultural landscapes. *Journal of Applied Ecology*, 1365-2664.13422, doi:10.1111/1365-2664.13422.
González-Roglich, M., J. J. Swenson, E. G. Jobbágy and R. B. Jackson, 2014: Shifting carbon pools along a plant cover gradient in woody encroached savannas of central Argentina. *Forest Ecology and Management*, **331**, 71-78.
González-Tokman, D. et al., 2020: Insect responses to heat: physiological mechanisms, evolution and ecological implications in a warming world. *Biological Reviews*, **95**(3), 802-821, doi:https://doi.org/10.1111/brv.12588.
Gonzalez-Valencia, R. et al., 2014: In situ measurement of dissolved methane and carbon dioxide in freshwater ecosystems by off-axis integrated cavity output spectroscopy. *Environmental science & technology*, **48**(19), 11421-11428.
Gonzalez, C. et al., 2010a: Climate Change and Risk of Leishmaniasis in North America: Predictions from Ecological Niche Models of Vector and Reservoir Species. *PLoS Neglected Tropical Diseases*, **4**(1), doi:10.1371/journal.pntd.0000585.
González, C. et al., 2010: Climate Change and Risk of Leishmaniasis in North America: Predictions from Ecological Niche Models of Vector and Reservoir Species. *PLoS Negl Trop Dis*, **4**(1), e585, doi:10.1371/journal.pntd.0000585.
González, M. E. et al., 2018: The 2010–2015 Megadrought and its influence on the fire regime in central and south-central Chile. *Ecosphere*, **9**(8), e02300.
Gonzalez, P. et al., 2015: Aboveground live carbon stock changes of California wildland ecosystems, 2001–2010. *Forest Ecology and Management*, **348**, 68-77, doi:10.1016/j.foreco.2015.03.040.
Gonzalez, P., R. P. Neilson, J. M. Lenihan and R. J. Drapek, 2010b: Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, **19**(6), 755-768, doi:10.1111/j.1466-8238.2010.00558.x.
Gonzalez, P., C. Tucker and H. Sy, 2012: Tree density and species decline in the African Sahel attributable to climate. *Journal of Arid Environments*, **78**, 55-64, doi:10.1016/j.jaridenv.2011.11.001.
Gonzalez, P. et al., 2018: Disproportionate magnitude of climate change in United States national parks. *Environmental Research Letters*, **13**(10), doi:10.1088/1748-9326/aade09.
Gordon, I. J., F. J. Pérez-Barbería and A. D. Manning, 2021: Rewilding Lite: Using Traditional Domestic Livestock to Achieve Rewilding Outcomes. *Sustainability*, **13**(6), doi:10.3390/su13063347.
Gorris, M. E., K. K. Treseder, C. S. Zender and J. T. Randerson, 2019: Expansion of Coccidioidomycosis Endemic Regions in the United States in Response to Climate Change. *GeoHealth*, **3**(10), 308-327, doi:10.1029/2019GH000209.
Goss, M. et al., 2020: Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, **15**(9), 14, doi:10.1088/1748-9326/ab83a7.
Gotanda, K. M. et al., 2015: Linking macrotrends and microrates: Re-evaluating microevolutionary support for Cope's rule. *Evolution*, **69**(5), 1345-1354, doi:10.1111/evo.12653.
Goulden, M. L. and R. C. Bales, 2019: California forest die-off linked to multi-year deep soil drying in 2012-2015 drought. *Nature Geoscience*, **12**(8), 632-+, doi:10.1038/s41561-019-0388-5.
Gozlan, R. E. et al., 2019: Status, trends, and future dynamics of freshwater ecosystems in Europe and Central Asia. *Inland Waters*, **9**(1), 78-94, doi:10.1080/20442041.2018.1510271.
Grafakos, S. et al., 2020: Integration of mitigation and adaptation in urban climate change action plans in Europe: A systematic assessment. *Renewable and Sustainable Energy Reviews*, **121**, 109623, doi:10.1016/j.rser.2019.109623.
Gray, C. L. et al., 2016: Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nature Communications*, **7**, doi:10.1038/ncomms12306.
Greenwood, O. et al., 2016: Using in situ management to conserve biodiversity under climate change. *Journal of Applied Ecology*, **53**(3), 885-894, doi:10.1111/1365-2664.12602.
Greenwood, S. et al., 2017: Tree mortality across biomes is promoted by drought intensity, lower wood density and higher specific leaf area. *Ecology Letters*, **20**(4), 539-553, doi:10.1111/ele.12748.
Gregory, S. D. et al., 2012: Long-Term Field Data and Climate-Habitat Models Show That Orangutan Persistence Depends on Effective Forest Management and Greenhouse Gas Mitigation. *PLOS ONE*, **7**(9), e43846, doi:10.1371/journal.pone.0043846.

Greiser, C. and H. Joosten, 2018: Archive value: measuring the palaeo-information content of peatlands in a conservation and compensation perspective. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **14**(1), 209-220, doi:10.1080/21513732.2018.1523229.
Grewe, Y. et al., 2013: Recent range shifts of E uropean dragonflies provide support for an inverse relationship between habitat predictability and dispersal. *Global Ecology and Biogeography*, **22**(4), 403-409.
Grill, G. et al., 2019: Mapping the world's free-flowing rivers. *Nature*, **569**(7755), 215-221, doi:10.1038/s41586-019-1111-9.
Griscom, B. W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114**(44), 11645-11650, doi:10.1073/pnas.1710465114.
Gronewold, A. D. and R. B. Rood, 2019: Recent water level changes across Earth's largest lake system and implications for future variability. *Journal of Great Lakes Research*, **45**(1), 1-3, doi:10.1016/j.jglr.2018.10.012.
Gruber, N., T. L. Frölicher and P. W. Boyd, 2020: Ocean extremes: From marine heatwaves to compound events and their threats to ocean life. *Nature*.
Gubler, D. J., 2002: Epidemic dengue/dengue hemorrhagic fever as a public health, social and economic problem in the 21st century. *Trends Microbiol*, **10**(2), 100-103, doi:10.1016/s0966-842x(01)02288-0.
Gudmundsson, L. et al., 2021: Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, **371**(6534), 1159-1162.
Guerrero-Latorre, L. et al., 2020: SARS-CoV-2 in river water: Implications in low sanitation countries. *The Science of the Total Environment*, **743**, 140832, doi:10.1016/j.scitotenv.2020.140832.
Guindon, L. et al., 2018: Missing forest cover gains in boreal forests explained. *Ecosphere*, **9**(1), 9, doi:10.1002/ecs2.2094.
Gumbricht, T. et al., 2017: An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. *Global Change Biology*, **23**(9), 3581-3599, doi:10.1111/gcb.13689.
Gunderson, A. R. and J. H. Stillman, 2015: Plasticity in thermal tolerance has limited potential to buffer ectotherms from global warming. *Proceedings of the Royal Society B: Biological Sciences*, **282**(1808), 20150401, doi:10.1098/rspb.2015.0401.
Guo, D. L. et al., 2020: Attribution of historical near-surface permafrost degradation to anthropogenic greenhouse gas warming. *Environmental Research Letters*, **15**(8), doi:10.1088/1748-9326/ab926f.
Guzman, M. G. and E. Harris, 2015: Dengue. *The Lancet*, **385**(9966), 453-465, doi:10.1016/S0140-6736(14)60572-9.
Gyenge, J., M. E. Fernández, M. Sarasola and T. Schlichter, 2011: Stand density and drought interaction on water relations of Nothofagus antarctica: contribution of forest management to climate change adaptability. *Trees*, **25**(6), 1111-1120.
Gynther, I., N. Waller and L. K.-P. Leung, 2016: *Confirmation of the extinction of the Bramble Cay melomys Melomys rubicola on Bramble Cay, Torres Strait: results and conclusions from a comprehensive survey in August-September 2014*. Queensland Government.
Haddad, N. M. et al., 2015: Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science advances*, **1**(2), e1500052.
Hagedoorn, L. C. et al., 2021: Preferences of vulnerable social groups for ecosystem-based adaptation to flood risk in Central Vietnam. *World Development*, **148**, 105650, doi:https://doi.org/10.1016/j.worlddev.2021.105650.
Hagedorn, F. et al., 2014: Treeline advances along the Urals mountain range–driven by improved winter conditions? *Global change biology*, **20**(11), 3530-3543.
Haggar, J. et al., 2015: Tree diversity on sustainably certified and conventional coffee farms in Central America. *Biodiversity and Conservation*, **24**(5), 1175-1194, doi:10.1007/s10531-014-0851-y.
Hall, R. J., L. M. Brown and S. Altizer, 2016: Modeling vector-borne disease risk in migratory animals under climate change. *Integrative and Comparative Biology*, **56**(2), 353-364, doi:10.1093/icb/icw049.
Hallett, S. L. and J. L. Bartholomew, 2008: Effects of water flow on the infection dynamics of Myxobolus cerebralis. *Parasitology*, **135**(3), 371-384, doi:10.1017/S0031182007003976.
Hällfors, M. H. et al., 2021: Combining range and phenology shifts offers a winning strategy for boreal Lepidoptera. *Ecology Letters*.
Hallgren, W. et al., 2016: The Biodiversity and Climate Change Virtual Laboratory: Where ecology meets big data. *Environmental Modelling & Software*, **76**, 182-186, doi:10.1016/j.envsoft.2015.10.025.
Halliday, F. W., J. R. Rohr and A.-L. Laine, 2020: Biodiversity loss underlies the dilution effect of biodiversity. *Ecology Letters*, **23**(11), 1611-1622, doi:10.1111/ele.13590.
Halupka, L. and K. Halupka, 2017: The effect of climate change on the duration of avian breeding seasons: a meta-analysis. *Proceedings of the Royal Society B: Biological Sciences*, **284**(1867), doi:10.1098/rspb.2017.1710.
Hamann, A. et al., 2015: Velocity of climate change algorithms for guiding conservation and management. *Global Change Biology*, **21**(2), 997-1004, doi:10.1111/gcb.12736.
Hampton, S. et al., 2017: Ecology under lake ice. *Ecology Letters*, **20**(1), 98-111, doi:10.1111/ele.12699.
Handmer, J., Y. et al., 2012: Changes in impacts of climate extremes: human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C. B., C. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, C. D. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge and New York, pp. 231-290.

Hanes, C. C. et al., 2019: Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, **49**(3), 256-269, doi:10.1139/cjfr-2018-0293.
Hanke, H., L. Borjeson, K. Hylander and E. Enfors-Kautsky, 2016: Drought tolerant species dominate as rainfall and tree cover returns in the West African Sahel. *Land Use Policy*, **59**, 111-120, doi:10.1016/j.landusepol.2016.08.023.
Hannah, L. et al., 2020: 30% land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography*, **43**(7), 943-953, doi:https://doi.org/10.1111/ecog.05166.
Hansen, G. J., J. S. Read, J. F. Hansen and L. A. Winslow, 2017: Projected shifts in fish species dominance in Wisconsin lakes under climate change. *Global change biology*, **23**(4), 1463-1476.
Hansson A, Dargusch P, Shulmeister J (2021) A review of modern treeline migration, the factors controlling it and the implications for carbon storage. Journal of Mountain Science 18(2). https://doi.org/10.1007/s11629-020-6221-1
Hansson, L.-A. et al., 2013: Food-chain length alters community responses to global change in aquatic systems. *Nature Climate Change*, **3**(3), 228-233.
Hantson, S. et al., 2020: *Quantitative assessment of fire and vegetation properties in historical simulations with fire-enabled vegetation models from the Fire Model Intercomparison Project*. Biogeosciences. Available at: https://gmd.copernicus.org/preprints/gmd-2019-261/gmd-2019-261.pdf (accessed 2020/11/07/03:03:45).
Hao, Z., F. Hao, V. P. Singh and X. Zhang, 2018: Quantifying the relationship between compound dry and hot events and El Niño–southern Oscillation (ENSO) at the global scale. *Journal of Hydrology*, **567**, 332-338, doi:https://doi.org/10.1016/j.jhydrol.2018.10.022.
Harfoot, M. B. J. et al., 2014: Emergent Global Patterns of Ecosystem Structure and Function from a Mechanistic General Ecosystem Model. *PLoS Biology*, **12**(4), doi:e1001841 10.1371/journal.pbio.1001841.
Hari, R. E. et al., 2006: Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams. *Global Change Biology*, **12**(1), 10-26.
Harris, N. L. et al., 2021: Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change*, **11**(3), 22, doi:10.1038/s41558-020-00976-6.
Harris, R. M. B. et al., 2018a: Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, **8**(7), 579-587, doi:10.1038/s41558-018-0187-9.
Harris, R. M. B. et al., 2020: Biological responses to extreme weather events are detectable but difficult to formally attribute to anthropogenic climate change. *Scientific Reports*, **10**(1), doi:10.1038/s41598-020-70901-6.
Harris, R. M. B. et al., 2018b: Exploring the Future of Fuel Loads in Tasmania, Australia: Shifts in Vegetation in Response to Changing Fire Weather, Productivity, and Fire Frequency. *Forests*, **9**(4), doi:10.3390/f9040210.
Harris, S. and C. Lucas, 2019: Understanding the variability of Australian fire weather between 1973 and 2017. *PLoS ONE*, **14**(9), doi:10.1371/journal.pone.0222328.
Harrison, M. E., 2013: Using Conceptual Models to Understand Ecosystem Function and Impacts of Human Activities in Tropical Peat-swamp Forests. *Wetlands*, **33**(2), 257-267, doi:10.1007/s13157-013-0378-0.
Harrison, M. E. et al., 2020: Tropical forest and peatland conservation in Indonesia: Challenges and directions. *People and Nature*, **2**(1), 4-28, doi:10.1002/pan3.10060.
Harrison, P. et al., 2014: Linkages between biodiversity attributes and ecosystem services: a systematic review. Ecosyst. Serv. 9, 191–203.
Harrison, S. P., M. L. LaForgia and A. M. Latimer, 2018: Climate-driven diversity change in annual grasslands: Drought plus deluge does not equal normal. *Global change biology*, **24**(4), 1782-1792.
Harsch, M. A., P. E. Hulme, M. S. McGlone and R. P. Duncan, 2009: Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology Letters*, **12**(10), 1040-1049, doi:https://doi.org/10.1111/j.1461-0248.2009.01355.x.
Hart, S. J., T. T. Veblen, D. Schneider and N. P. Molotch, 2017: Summer and winter drought drive the initiation and spread of spruce beetle outbreak. *Ecology*, **98**(10), 2698-2707, doi:10.1002/ecy.1963.
Hartmann, H. et al., 2018: Research frontiers for improving our understanding of drought-induced tree and forest mortality. *New Phytologist*, **218**(1), 15-28, doi:10.1111/nph.15048.
Harvell, C. D. et al., 2002: Climate Warming and Disease Risks for Terrestrial and Marine Biota. *Science*, **296**(5576), 2158-2162.
Harvell, D. et al., 2009: Climate change and wildlife diseases: When does the host matter the most? *Ecology*, **90**(4), 912-920, doi:10.1890/08-0616.1.
Haslem, A., D. G. Nimmo, J. Q. Radford and A. F. Bennett, 2015: Landscape properties mediate the homogenization of bird assemblages during climatic extremes. *Ecology*, **96**(12), 3165-3174.
Haussmann, N. S., J. M. Kalwij and S. Bezuidenhout, 2016: Some ecological side-effects of chemical and physical bush clearing in a southern African rangeland ecosystem. *South African Journal of Botany*, **102**, 234-239.
Hay, S. I. et al., 2002: Hot topic or hot air? Climate change and malaria resurgence in East African highlands. *Trends in Parasitology*, **18**(12), 530-534, doi:https://doi.org/10.1016/S1471-4922(02)02374-7.
Hayden, B. et al., 2019: From clear lakes to murky waters - tracing the functional response of high-latitude lake communities to concurrent 'greening' and 'browning'. *Ecology Letters*, **22**(5), 807-816, doi:10.1111/ele.13238.
Haydock, L. A. J., W. E. Pomroy, M. A. Stevenson and K. E. Lawrence, 2016: A growing degree-day model for determination of Fasciola hepatica infection risk in New Zealand with future predictions using climate change models. *Veterinary Parasitology*, **228**, 52-59, doi:10.1016/j.vetpar.2016.05.033.

He, C., L. Zhou, W. Ma and Y. Wang, 2019: Spatial Assessment of Urban Climate Change Vulnerability during Different Urbanization Phases. *Sustainability*, **11**(8), 2406.
He, F. et al., 2017: Disappearing giants: a review of threats to freshwater megafauna. *Wiley Interdisciplinary Reviews: Water*, **4**(3), e1208.
Healy, T. M. and P. M. Schulte, 2012: Factors affecting plasticity in whole-organism thermal tolerance in common killifish (Fundulus heteroclitus). *Journal of Comparative Physiology B*, **182**(1), 49-62, doi:10.1007/s00360-011-0595-x.
Heathcote, A. J. et al., 2015: Large increases in carbon burial in northern lakes during the Anthropocene. *Nature Communications*, **6**(1), 10016, doi:10.1038/ncomms10016.
Hedrick, A. R. et al., 2021: Climate effects on nesting phenology in Nebraska turtles. *Ecology and Evolution*, **11**(3), 1225-1239, doi:https://doi.org/10.1002/ece3.7105.
Hegeman, E. E., B. G. Dickson and L. J. Zachmann, 2014: Probabilistic models of fire occurrence across National Park Service units within the Mojave Desert Network, USA. *Landscape Ecology*, **29**(9), 1587-1600, doi:10.1007/s10980-014-0078-z.
Heger, W. T. and T. van Andel, 2019: A social-ecological perspective on ecosystem vulnerability for the invasive creeper coralita (Antigonon leptopus) in the Caribbean: A review. *Global Ecology and Conservation*, **18**, e00605, doi:https://doi.org/10.1016/j.gecco.2019.e00605.
Hegerl, G. C. et al., 2015: Challenges in quantifying changes in the global water cycle. *Bulletin of the American Meteorological Society*, **96**(7), 1097-1115.
Hegerl, G. C. et al. (eds.), Good practice guidance paper on detection and attribution related to anthropogenic climate change. Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change, IPCC Working Group I Technical Support Unit, University of Bern, Bern ….
Heil, A., B. Langmann and E. Aldrian, 2007: Indonesian peat and vegetation fire emissions: Study on factors influencing large-scale smoke haze pollution using a regional atmospheric chemistry model. *Mitigation and Adaptation Strategies for Global Change*, **12**(1), 113-133, doi:10.1007/s11027-006-9045-6.
Heim, K. C. et al., 2015: Seasonal cues of Arctic grayling movement in a small Arctic stream: the importance of surface water connectivity. *Environmental Biology of Fishes*, **99**(1), 49-65, doi:10.1007/s10641-015-0453-x.
Heinze, C. et al., 2021: The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences*, **118**(9), e2008478118, doi:10.1073/pnas.2008478118.
Helbig, M. et al., 2020: Increasing contribution of peatlands to boreal evapotranspiration in a warming climate. *Nature Climate Change*, **10**(6), 555-560, doi:10.1038/s41558-020-0763-7.
Heller, N. E. and E. S. Zavaleta, 2009: Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological conservation*, **142**(1), 14-32.
Hempson, G. P., S. Archibald and W. J. Bond, 2017: The consequences of replacing wildlife with livestock in Africa. *Scientific reports*, **7**(1), 17196.
Henman, J. and B. Poulter, 2008: Inundation of freshwater peatlands by sea level rise: Uncertainty and potential carbon cycle feedbacks. *Journal of Geophysical Research: Biogeosciences*, **113**(G1), n/a-n/a, doi:10.1029/2006jg000395.
Henry, B., B. Murphy and A. L. Cowie, 2018: *Sustainable land management for environmental benefits and food security. A Synthesis Report for the GEF (Global Environmental Facility)*. Washington, DC.
Hermoso, V., R. Abell, S. Linke and P. Boon, 2016: The role of protected areas for freshwater biodiversity conservation: challenges and opportunities in a rapidly changing world. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **26**(S1), 3-11, doi:10.1002/aqc.2681.
Hessburg, P. F. et al., 2016: Tamm Review: Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. *Forest Ecology and Management*, **366**, 221-250, doi:10.1016/j.foreco.2016.01.034.
Hesslerová, P., H. Huryna, J. Pokorny and J. Prochazka, 2018: The effect of forest disturbance on landscape temperature. *Ecological Engineering*, **120**, 345-354, doi:10.1016/j.ecoleng.2018.06.011.
Hester, A. J. et al., 2019: Long-term vegetation change in Scotland's native forests. *Biological Conservation*, **235**, 136-146, doi:10.1016/j.biocon.2019.04.018.
Hicke, J. A., B. Xu, A. J. H. Meddens and J. M. Egan, 2020: Characterizing recent bark beetle-caused tree mortality in the western United States from aerial surveys. *Forest Ecology and Management*, **475**, 118402, doi:https://doi.org/10.1016/j.foreco.2020.118402.
Higgins, S. I., R. Buitenwerf and G. R. Moncrieff, 2016: Defining functional biomes and monitoring their change globally. *Global Change Biology*, **22**(11), 3583-3593, doi:10.1111/gcb.13367.
Higgins, S. I. and S. Scheiter, 2012: Atmospheric CO2 forces abrupt vegetation shifts locally, but not globally. *Nature*, **advance online publication**, 10.1038/nature11238, doi:http://www.nature.com/nature/journal/vaop/ncurrent/abs/nature11238.html#supplementary-information.
Hiley, J. R., R. B. Bradbury, M. Holling and C. D. Thomas, 2013: Protected areas act as establishment centres for species colonizing the UK. *Proceedings of the Royal Society B: Biological Sciences*, **280**(1760), 20122310, doi:10.1098/rspb.2012.2310.
Hill, G. M. et al., 2021: Climate change effects on animal ecology: butterflies and moths as a case study. *Biological Reviews*, **n/a**(n/a), doi:https://doi.org/10.1111/brv.12746.

Hillebrand, H. et al., 2018: Decomposing multiple dimensions of stability in global change experiments. *Ecology Letters*, **21**(1), 21-30, doi:10.1111/ele.12867.
Hinojosa, M. B. et al., 2019: Drought and its legacy modulate the post-fire recovery of soil functionality and microbial community structure in a Mediterranean shrubland. *Global Change Biology*, **25**(4), 1409-1427, doi:https://doi.org/10.1111/gcb.14575.
Hirano, T., K. Kusin, S. Limin and M. Osaki, 2014: Carbon dioxide emissions through oxidative peat decomposition on a burnt tropical peatland. *Global change biology*, **20**(2), 555-565.
Hirano, T., K. Kusin, S. Limin and M. Osaki, 2015: Evapotranspiration of tropical peat swamp forests. *Global change biology*, **21**(5), 1914-1927.
HLPE, 2019: *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security*. HLPE Report Series, Security, C. o. W. F., Rome, 162 pp. Available at: http://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-14_EN.pdf.
Ho, J. C., A. M. Michalak and N. Pahlevan, 2019: Widespread global increase in intense lake phytoplankton blooms since the 1980s. *Nature*, **574**(7780), 667-670.
Hobbie, S. E. and N. B. Grimm, 2020: Nature-based approaches to managing climate change impacts in cities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190124, doi:10.1098/rstb.2019.0124.
Hobbs, R. J. et al., 2014: Managing the whole landscape: historical, hybrid, and novel ecosystems. *Frontiers in Ecology and the Environment*, **12**(10), 557-564, doi:https://doi.org/10.1890/130300.
Hock, R. et al., 2019: High Mountain Areas. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Hockings, M. et al., 2020: Editorial Essay: COVID-19 and Protected and Conserved Areas. 18.
Hodgkins, S. B. et al., 2018: Tropical peatland carbon storage linked to global latitudinal trends in peat recalcitrance. *Nature Communications*, **9**(1), doi:10.1038/s41467-018-06050-2.
Hoegh-Guldberg, O. et al., 2008: Assisted colonization and rapid climate change. *Science*, **321**(5887), 345-346, doi:DOI: 10.1126/science.1157897.
Hoegh-Guldberg, O. et al., 2018a: Impacts of 1.5ºC global warming on natural and human systems. In: *IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*. http://www.ipcc.ch/report/sr15/.
Hoegh-Guldberg, O. et al., 2018b: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
Hoegh-Guldberg, O., E. Northrop and J. Lubchenco, 2019: The ocean is key to achieving climate and societal goals. *Science*, doi:10.1126/science.aaz4390.
Hof, C. et al., 2018: Bioenergy cropland expansion may offset positive effects of climate change mitigation for global vertebrate diversity. *Proceedings of the National Academy of Sciences*, **115**(52), 13294-13299, doi:10.1073/pnas.1807745115.
Hoffman, M. T., R. F. Rohde and L. Gillson, 2019: Rethinking catastrophe? Historical trajectories and modelled future vegetation change in southern Africa. *Anthropocene*, **25**, 100189, doi:10.1016/j.ancene.2018.12.003.
Hoffmann, A. A. et al., 2019a: Impacts of recent climate change on terrestrial flora and fauna: Some emerging Australian examples. *Austral Ecology*, **44**(1), 3-27, doi:10.1111/aec.12674.
Hoffmann, A. A. and C. M. Sgro, 2011: Climate change and evolutionary adaptation. *Nature*, **470**(7335), 479-485, doi:10.1038/nature09670.
Hoffmann, S. and C. Beierkuhnlein, 2020: Climate change exposure and vulnerability of the global protected area estate from an international perspective. *Diversity and Distributions*, **26**(11), 1496-1509, doi:10.1111/ddi.13136.
Hoffmann, S., S. D. H. Irl and C. Beierkuhnlein, 2019b: Predicted climate shifts within terrestrial protected areas worldwide. *Nature Communications*, **10**, doi:10.1038/s41467-019-12603-w.
Holden, Z. A. et al., 2018: Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences*, **115**(36), E8349-E8357, doi:10.1073/pnas.1802316115.
Holmgren, C. A., J. L. Betancourt and K. A. Rylander, 2010: A long-term vegetation history of the Mojave-Colorado Desert ecotone at Joshua Tree National Park. *Journal of Quaternary Science*, **25**(2), 222-236, doi:10.1002/jqs.1313.
Holsinger, L. et al., 2019: Climate change likely to reshape vegetation in North America's largest protected areas. *Conservation Science and Practice*, **1**(7), e50, doi:10.1111/csp2.50.

Holz, A., S. W. Wood, T. T. Veblen and D. Bowman, 2015: Effects of high-severity fire drove the population collapse of the subalpine Tasmanian endemic conifer Athrotaxis cupressoides. *Global Change Biology*, **21**(1), 445-458, doi:10.1111/gcb.12674.
Homewood, K., M. R. Nielsen and A. Keane, 2020: Women, wellbeing and Wildlife Management Areas in Tanzania. *The Journal of Peasant Studies*, **0**(0), 1-28, doi:10.1080/03066150.2020.1726323.
Honda, E. A. and G. Durigan, 2016: Woody encroachment and its consequences on hydrological processes in the savannah. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150313.
Hong, C. P. et al., 2021: Global and regional drivers of land-use emissions in 1961-2017. *Nature*, **589**(7843), 554-+, doi:10.1038/s41586-020-03138-y.
Hooijer, A., M. Silvius, H. Woesten and S. Page, 2006: *PEAT-CO2 Assessment of CO2 emissions from drained peatlands in SE Asia*. Delft Hydraulics, Netherlands, 41 pp. Available at: http://inis.iaea.org/search/search.aspx?orig_q=RN:42022627.
Hooper, D. U. et al., 2012: A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature*, **486**, 105, doi:10.1038/nature11118 https://www.nature.com/articles/nature11118#supplementary-information.
Hoover, D. L., M. C. Duniway and J. Belnap, 2015: Pulse-drought atop press-drought: unexpected plant responses and implications for dryland ecosystems. *Oecologia*, **179**(4), 1211-1221, doi:10.1007/s00442-015-3414-3.
Hoover, D. L., A. K. Knapp and M. D. Smith, 2014: Resistance and resilience of a grassland ecosystem to climate extremes. *Ecology*, **95**(9), 2646-2656.
Hoover, K. C. and C. M. Barker, 2016: West Nile virus, climate change, and circumpolar vulnerability. *WIREs Climate Change*, **7**(2), 283-300, doi:10.1002/wcc.382.
Hope, A., G. Fouad and Y. Granovskaya, 2014: Evaluating drought response of southern Cape Indigenous Forests, South Africa, using MODIS data. *International journal of remote sensing*, **35**(13), 4852-4864.
Hope, P. et al., 2019: ON DETERMINING THE IMPACT OF INCREASING ATMOSPHERIC CO2 ON THE RECORD FIRE WEATHER IN EASTERN AUSTRALIA IN FEBRUARY 2017. *Bulletin of the American Meteorological Society*, **100**(1), S111-S117, doi:10.1175/bams-d-18-0135.1.
Hopkins, S. R. et al., 2021: How to identify win–win interventions that benefit human health and conservation. *Nature Sustainability*, **4**(4), 298-304, doi:10.1038/s41893-020-00640-z.
Horn, K. J. and S. B. St. Clair, 2017: Wildfire and exotic grass invasion alter plant productivity in response to climate variability in the Mojave Desert. *Landscape Ecology*, **32**(3), 635-646, doi:10.1007/s10980-016-0466-7.
Hossack, B. R. et al., 2013: Roles of patch characteristics, drought frequency, and restoration in long-term trends of a widespread amphibian. *Conservation Biology*, **27**(6), 1410-1420.
Hossain, K. et al., 2016: Vulnerabilities of macrophytes distribution due to climate change. *Theoretical and Applied Climatology*, **129**(3-4), 1123-1132, doi:10.1007/s00704-016-1837-3.
Hotaling, S. et al., 2017: Climate change and alpine stream biology: progress, challenges, and opportunities for the future. *Biol Rev Camb Philos Soc*, **92**(4), 2024-2045, doi:10.1111/brv.12319.
Hotez, P. J., 2016a: Neglected Tropical Diseases in the Anthropocene: The Cases of Zika, Ebola, and Other Infections. *PLOS Neglected Tropical Diseases*, **10**(4), e0004648, doi:10.1371/journal.pntd.0004648.
Hotez, P. J., 2016b: Southern Europe's Coming Plagues: Vector-Borne Neglected Tropical Diseases. *PLoS Neglected Tropical Diseases*, **10**(6), doi:10.1371/journal.pntd.0004243.
Houghton, R. A. and A. A. Nassikas, 2017: Global and regional fluxes of carbon from land use and land cover change 1850–2015. *Global Biogeochemical Cycles*, **31**(3), 456-472, doi:10.1002/2016GB005546.
Howie, A. H. and M. J. Bishop, 2021: Contemporary oyster reef restoration: responding to a changing world. *Frontiers in Ecology and Evolution*, **9**(689915), 1-15, doi:10.3389/fevo.2021.689915.
Høye, T. T. et al., 2013: Shorter flowering seasons and declining abundance of flower visitors in a warmer Arctic. *Nature Climate Change*, **3**(8), 759.
Hoyt, A. M., E. Chaussard, S. S. Seppalainen and C. F. Harvey, 2020: Widespread subsidence and carbon emissions across Southeast Asian peatlands. *Nature Geoscience*, **13**(6), 435-440, doi:10.1038/s41561-020-0575-4.
Hu, Y., N. Fernandez-Anez, T. E. L. Smith and G. Rein, 2018: Review of emissions from smouldering peat fires and their contribution to regional haze episodes. *International Journal of Wildland Fire*, **27**(5), 293, doi:10.1071/wf17084.
Huang, L. et al., 2016: Drought dominates the interannual variability in global terrestrial net primary production by controlling semi-arid ecosystems. *Scientific Reports*, **6**, doi:10.1038/srep24639.
Huang, L. et al., 2019: Land conservation can mitigate freshwater ecosystem services degradation due to climate change in a semiarid catchment: The case of the Portneuf River catchment, Idaho, USA. *Science of The Total Environment*, **651**, 1796-1809, doi:https://doi.org/10.1016/j.scitotenv.2018.09.260.
Huang, L., J. Liu, Q. Shao and R. Liu, 2011: Changing inland lakes responding to climate warming in Northeastern Tibetan Plateau. *Climatic Change*, **109**(3-4), 479-502, doi:10.1007/s10584-011-0032-x.
Huang, P. et al., 2013: Patterns of the seasonal response of tropical rainfall to global warming. *Nature Geoscience*, **6**(5), 357-361.
Huang, Y. X., S. L. Wu and J. O. Kaplan, 2015: Sensitivity of global wildfire occurrences to various factors in the context of global change. *Atmospheric Environment*, **121**, 86-92, doi:10.1016/j.atmosenv.2015.06.002.
Hubau, W. et al., 2020: Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, **579**(7797), 80-87, doi:10.1038/s41586-020-2035-0.

Huber, I. et al., 2020: Symposium report: emerging threats for human health – impact of socioeconomic and climate change on zoonotic diseases in the Republic of Sakha (Yakutia), Russia. *International Journal of Circumpolar Health*, **79**(1), 1715698, doi:10.1080/22423982.2020.1715698.
Hueffer, K., D. Drown, V. Romanovsky and T. Hennessy, 2020: Factors Contributing to Anthrax Outbreaks in the Circumpolar North. *EcoHealth*, **17**(1), 174-180, doi:10.1007/s10393-020-01474-z.
Huey, R. B. et al., 2009: Why tropical forest lizards are vulnerable to climate warming. *Proceedings of the Royal Society B: Biological Sciences*, **276**(1664), 1939-1948, doi:10.1098/rspb.2008.1957.
Hufft, R. A. and T. J. Zelikova, 2016: Ecological genetics, local adaptation, and phenotypic plasticity in Bromus tectorum in the context of a changing climate. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US*. Springer, pp. 133–154.
Hugelius, G. et al., 2020: Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Sciences*, **117**(34), 20438-20446, doi:10.1073/pnas.1916387117.
Hugelius, G. et al., 2014: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, **11**(23), 6573-6593, doi:10.5194/bg-11-6573-2014.
Hughes, T. P. et al., 2018: Global warming transforms coral reef assemblages. *Nature*, **556**(7702), 492-496, doi:10.1038/s41586-018-0041-2.
Huijnen, V. et al., 2016: Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. *Scientific Reports*, **6**(1), 26886, doi:10.1038/srep26886.
Huisman, J. et al., 2018: Cyanobacterial blooms. *Nature Reviews Microbiology*, **16**(8), 471-483.
Hulme, P. E., 2020: One Biosecurity: a unified concept to integrate human, animal, plant, and environmental health. *Emerging Topics in Life Sciences*, **4**(5), 539-549, doi:10.1042/ETLS20200067.
Humpenöder, F. et al., 2020: Peatland protection and restoration are key for climate change mitigation. *Environmental Research Letters*, **15**(10), 104093, doi:10.1088/1748-9326/abae2a.
Humphrey, V. et al., 2018: Sensitivity of atmospheric CO2 growth rate to observed changes in terrestrial water storage. *Nature*, **560**(7720), 628-+, doi:10.1038/s41586-018-0424-4.
Hundessa, S. et al., 2018: Projecting potential spatial and temporal changes in the distribution of Plasmodium vivax and Plasmodium falciparum malaria in China with climate change. *Science of The Total Environment*, **627**, 1285-1293, doi:10.1016/j.scitotenv.2018.01.300.
Huntingford, C. et al., 2013: Simulated resilience of tropical rainforests to CO2-induced climate change. *Nature Geoscience*, **6**(4), 268-273, doi:10.1038/ngeo1741.
Huntzinger, D. N. et al., 2017: Uncertainty in the response of terrestrial carbon sink to environmental drivers undermines carbon-climate feedback predictions. *Scientific Reports*, **7**, doi:10.1038/s41598-017-03818-2.
Huq, N., A. Bruns, L. Ribbe and S. Huq, 2017: Mainstreaming Ecosystem Services Based Climate Change Adaptation (EbA) in Bangladesh: Status, Challenges and Opportunities. *Sustainability*, **9**(6), doi:10.3390/su9060926.
Huq, N. and A. Stubbings, 2015: How is the role of ecosystem services considered in local level flood management policies: case study in Cumbria, England. *Journal of Environmental Assessment Policy and Management*, **17**(04), 1550032.
Hurlbert, M. et al., 2019: Risk management and decision-making in relation to sustainable development. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.
Hurni, K., A. Heinimann, S. A.M. and J. Fox, 2017: Mapping the Expansion of Boom Crops in Mainland Southeast Asia Using Dense Time Stacks of Landsat Data. *Remote Sensing*, **9**, 4, doi:doi:10.3390/rs9040320.
Huss, M. and R. Hock, 2018: Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, **8**(2), 135-140.
Iacob, O., J. S. Rowan, I. Brown and C. Ellis, 2014: Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective. *Hydrology Research*, **45**(6), 774-787.
Ibrahim, Y. Z., H. Balzter and J. Kaduk, 2018: Land degradation continues despite greening in the Nigeria-Niger border region. *Global Ecology and Conservation*, **16**, doi:10.1016/j.gecco.2018.e00505.
Innocent, G. T. et al., 2017: Combining Slaughterhouse Surveillance Data with Cattle Tracing Scheme and Environmental Data to Quantify Environmental Risk Factors for Liver Fluke in Cattle. *Frontiers in Veterinary Science*, **4**, doi:10.3389/fvets.2017.00065.
International, B., 2018: Spheniscus demersus. The IUCN Red List of Threatened Species 2018: e.T22697810A132604504. Retrieved September 22, 2020, from https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22697810A132604504.en.
International, W., 2012: *Peatlands: guidance for climate change mitigation through conservation, rehabilitation and sustainable use* [Tapio-Biström, M.-L., H. Joosten and S. Tol (eds.)]. Mitigation of climate change in agriculture series, Food and Agriculture Organization of the United Nations : Wetlands International, 2nd ed ed., Mitigation of Climate Change in Agriculture, P. and I. Wetlands, Rome, 12 pp.

IPBES, 2018a: *The IPBES assessment report on land degradation and restoration.* [Montanarella, L., R. Scholes and A. Brainich (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 744 pp.
IPBES, 2018b: *The IPBES regional assessment report on biodiversity and ecosystem services for Africa* [Archer, E. (ed.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 492 pp.
IPBES, 2018c: *The IPBES regional assessment report on biodiversity and ecosystem services for Asia and the Pacific* [Karki, M. (ed.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 612 pp.
IPBES, 2018d: *The IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia* [Rounsevell, M. (ed.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 892 pp.
IPBES, 2018e: *The IPBES regional assessment report on biodiversity and ecosystem services for the Americas* [Rice, J. (ed.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 656 pp.
IPBES, 2019: *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* [Brondizio, E. S., J. Settele, S. Díaz and H. T. Ngo (eds.)]. IPBES secretariat, Bonn, Germany.
IPBES, 2020: *Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)*. Zenodo, Services, I. P. O. B. E. Available at: https://zenodo.org/record/4147317 (accessed 2020/11/10/02:30:50).
IPCC, 2001: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J. J. (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1032 pp. ISBN 0521807689.
IPCC, 2007a: *Climate Change 2007 - Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC*. Cambridge University Press, 765 pp. ISBN 978-0-521-88010-7.
IPCC, 2007b: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L. (ed.)]. Cambridge University Press, Cambridge, United Kingdom, 976 pp. ISBN 9780521880107.
IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-30. ISBN 9781107057991.
IPCC, 2014a. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.
IPCC, 2014b: *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* [Hiraishi, T. (ed.)]. 354 pp. ISBN 9789291691395.
IPCC, 2014c: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B. (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp. ISBN 9781107058071.
IPCC, 2014d: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R. (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp. ISBN 9781107058163.
IPCC, 2014e: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32. ISBN 9781107058071.
IPCC, 2014f: Topic 3: Future Pathways for Adaption, Mitigation and Sustainable Development. In: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing, T., R. K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, pp. 75-112. ISBN 9789291691432.
IPCC, 2018a: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea,

P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
IPCC, 2018b: Global Warming of 1.5° C. An IPCC Special Report on the Impacts of Global Warming of 1.5° C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. IPCC-World Meteorol. Organ Geneva.
IPCC, 2019a: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R. (ed.)]. In press pp.
IPCC, 2019b: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. In press.
IPCC, 2019c: *Summary for Policy Makers: IPCC Special Report on Climate Change and Land* [Ipcc (ed.)]. International Panel on Climate Change, Geneva, in press pp.
Isaak, D. J. et al., 2010: Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecol Appl*, **20**(5), 1350-1371, doi:10.1890/09-0822.1.
Isaak, D. J. et al., 2016: Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(16), 4374-4379, doi:10.1073/pnas.1522429113.
Isaak, D. J. et al., 2015: The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. *Global Change Biology*, **21**(7), 2540-2553.
Isbell, F. et al., 2017: Benefits of increasing plant diversity in sustainable agroecosystems. *Journal of Ecology*, **105**(4), 871-879, doi:10.1111/1365-2745.12789.
Isbell, F. et al., 2015: Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, **526**(7574), 574-577, doi:10.1038/nature15374.
Ito, A., K. Nishina and H. M. Noda, 2016: Impacts of future climate change on the carbon budget of northern high-latitude terrestrial ecosystems: An analysis using ISI-MIP data. *Polar Science*, **10**(3), 346-355, doi:10.1016/j.polar.2015.11.002.
Itoh, M., Y. Okimoto, T. Hirano and K. Kusin, 2017: Factors affecting oxidative peat decomposition due to land use in tropical peat swamp forests in Indonesia. *Science of the Total Environment*, **609**, 906-915.
IUCN, 2019: International Union for Conservation of Nature. 2019. The IUCN Red List of Threatened Species, version 2019-1. IUCN. www.iucnredlist.org.
Iversen, C. M. et al., 2015: The unseen iceberg: plant roots in arctic tundra. *New Phytologist*, **205**(1), 34-58.
Iwamura, T., A. Guzman-Holst and K. A. Murray, 2020: Accelerating invasion potential of disease vector Aedes aegypti under climate change. *Nature Communications*, **11**(1), 2130, doi:10.1038/s41467-020-16010-4.
J. Halliday, S. et al., 2016: Riparian shading controls instream spring phytoplankton and benthic algal growth. *Environmental Science: Processes & Impacts*, **18**(6), 677-689, doi:10.1039/C6EM00179C.
Jackson, M. M. et al., 2016: Expansion of subalpine woody vegetation over 40 years on Vancouver Island, British Columbia, Canada. *Canadian Journal of Forest Research*, **46**(3), 437-443, doi:10.1139/cjfr-2015-0186.
Jackson, R. B. et al., 2017: The Ecology of Soil Carbon: Pools, Vulnerabilities, and Biotic and Abiotic Controls. *Annual Review of Ecology, Evolution, and Systematics*, **48**, 419-445, doi:10.1146/annurev-ecolsys-112414-054234.
Jacobs, J., S. K. Moore, K. E. Kunkel and L. Sun, 2015: A framework for examining climate-driven changes to the seasonality and geographical range of coastal pathogens and harmful algae. *Climate Risk Management*, **8**, 16-27, doi:10.1016/j.crm.2015.03.002.
Jacobsen, A. L. and R. B. Pratt, 2018: Extensive drought-associated plant mortality as an agent of type-conversion in chaparral shrublands. *New Phytologist*, **219**(2), 498-504.
Jactel, H. et al., 2017: Tree diversity drives forest stand resistance to natural disturbances. *Current Forestry Reports*, **3**(3), 223-243.
Jaeger, K. L., J. D. Olden and N. A. Pelland, 2014: Climate change poised to threaten hydrologic connectivity and endemic fishes in dryland streams. *Proc Natl Acad Sci U S A*, **111**(38), 13894-13899, doi:10.1073/pnas.1320890111.
Jaenson, T. G. T. et al., 2012: Changes in the geographical distribution and abundance of the tick Ixodes ricinus during the past 30 years in Sweden. *Parasites & Vectors*, **5**(1), 8, doi:10.1186/1756-3305-5-8.
Jaime, L. et al., 2019: Scots pine (Pinus sylvestris L.) mortality is explained by the climatic suitability of both host tree and bark beetle populations. *Forest Ecology and Management*, **448**, 119-129, doi:https://doi.org/10.1016/j.foreco.2019.05.070.
Jain, P., X. L. Wang and M. D. Flannigan, 2017: Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. *International Journal of Wildland Fire*, **26**(12), 1009-1020, doi:10.1071/wf17008.
Jane, S. F. et al., 2021: Widespread deoxygenation of temperate lakes. *Nature*, **594**(7861), 66-70.
Janse, J. et al., 2015: GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems. *Environmental Science & Policy*, **48**, 99-114.

Janssen, J. A. M. et al., 2016: *European Red List of Habitats. Part 2. Terrestrial and freshwater habitats*. Environment, Alterra Wageningen UR
IUCN
naturebureau
Susan Gubbay
John Rodwell Ecologist, Commission, E., 39 pp. Available at: https://ec.europa.eu/environment/nature/knowledge/pdf/terrestrial_EU_red_list_report.pdf (accessed 07/10/2019).
Jaric, I. et al., 2019: Susceptibility of European freshwater fish to climate change: Species profiling based on life-history and environmental characteristics. *Global Change Biology*, **25**(2), 448-458, doi:10.1111/gcb.14518.
Jennings, E. et al., 2021: Ecological Consequences of Climate Extremes for Lakes. *Earth Systems and Environmental Sciences*.
Jeong, S. J. et al., 2011: Impact of vegetation feedback on the temperature and its diurnal range over the Northern Hemisphere during summer in a 2 x CO2 climate. *Climate Dynamics*, **37**(3-4), 821-833, doi:10.1007/s00382-010-0827-x.
Jeppesen, E. et al., 2014: Climate change impacts on lakes: an integrated ecological perspective based on a multi-faceted approach, with special focus on shallow lakes.
Jeppesen, E. et al., 2010: Impacts of climate warming on lake fish community structure and potential effects on ecosystem function. *Hydrobiologia*, **646**(1), 73-90.
Jeppesen, E. et al., 2012: Impacts of climate warming on the long-term dynamics of key fish species in 24 European lakes. *Hydrobiologia*, **694**(1), 1-39, doi:10.1007/s10750-012-1182-1.
Jepsen, M. R. et al., 2015: Transitions in European land-management regimes between 1800 and 2010. *Land Use Policy*, **49**, 53-64, doi:https://doi.org/10.1016/j.landusepol.2015.07.003.
Jewett, J. T. et al., 2011: Spatiotemporal Relationships between Climate and Whitebark Pine Mortality in the Greater Yellowstone Ecosystem. *Forest Science*, **57**(4), 320-335.
Ji, X., J. M. Verspagen, M. Stomp and J. Huisman, 2017: Competition between cyanobacteria and green algae at low versus elevated CO2: who will win, and why? *Journal of experimental botany*, **68**(14), 3815-3828.
Jia, G. et al., 2019: *Chapter 2: Land-Climate Interactions*. IPCC Special REport Climate Change and Land, IPCC, Geneva, Switzerland.
Jiang, Y. et al., 2017: Modeling long-term changes in tundra carbon balance following wildfire, climate change, and potential nutrient addition. *Ecological Applications*, **27**(1), 105-117, doi:10.1002/eap.1413.
Jiménez-García, D., X. Li, A. Lira-Noriega and A. T. Peterson, 2021: Upward shifts in elevational limits of forest and grassland for Mexican volcanoes over three decades. *Biotropica*, **53**(3), 798-807, doi:https://doi.org/10.1111/btp.12942.
Johansson, M. A. et al., 2019: An open challenge to advance probabilistic forecasting for dengue epidemics. *Proceedings of the National Academy of Sciences*, **116**(48), 24268-24274, doi:10.1073/pnas.1909865116.
Johnson, C. N. et al., 2018: Can trophic rewilding reduce the impact of fire in a more flammable world? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **373**(1761), 20170443.
Johnson, L. R. et al., 2015: Understanding uncertainty in temperature effects on vector-borne disease: a Bayesian approach. *Ecology*, **96**(1), 203-213, doi:https://doi.org/10.1890/13-1964.1.
Johnson, P. T. J. and D. W. Thieltges, 2010: Diversity, decoys and the dilution effect: how ecological communities affect disease risk. *Journal of Experimental Biology*, **213**(6), 961-970, doi:10.1242/jeb.037721.
Jolly, W. M. et al., 2015: Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, **6**, doi:10.1038/ncomms8537.
Jones, H. P. et al., 2020a: Global hotspots for coastal ecosystem-based adaptation. *PLoS ONE*, **15**(5), e0233005, doi:10.1371/journal.pone.0233005.
Jones, I. J. et al., 2020b: Improving rural health care reduces illegal logging and conserves carbon in a tropical forest. *Proceedings of the National Academy of Sciences*, **117**(45), 28515, doi:10.1073/pnas.2009240117.
Jones, K. R. et al., 2018: One-third of global protected land is under intense human pressure. *Science*, **360**(6390), 788-791, doi:10.1126/science.aap9565.
Jones, K. R., J. E. M. Watson, H. P. Possingham and C. J. Klein, 2016: Incorporating climate change into spatial conservation prioritisation: A review. *Biological Conservation*, **194**, 121-130, doi:10.1016/j.biocon.2015.12.008.
Jones, M. C., R. K. Booth, Z. Yu and P. Ferry, 2013: A 2200-Year Record of Permafrost Dynamics and Carbon Cycling in a Collapse-Scar Bog, Interior Alaska. *Ecosystems*, **16**(1), 1-19.
Jones, M. C. and Z. Yu, 2010: Rapid deglacial and early Holocene expansion of peatlands in Alaska. *Proceedings of the National Academy of Sciences*, **107**(16), 7347-7352, doi:10.1073/pnas.0911387107.
Jones, T. et al., 2019: Unusual mortality of Tufted puffins (Fratercula cirrhata) in the eastern Bering Sea. *PLOS ONE*, **14**(5), e0216532, doi:10.1371/journal.pone.0216532.
Joosten, H. and D. Clarke, 2002: *Wise use of mires and peatlands: background and principles including a framework for decision-making*. International Peat Society ; International Mire Conservation Group, Jyväskylä] : [Greifswald, 304 pp. ISBN 978-951-97744-8-0.
Jorda-Capdevila, D. et al., 2019: Impact and mitigation of global change on freshwater-related ecosystem services in Southern Europe. *Science of The Total Environment*, **651**, 895-908, doi:https://doi.org/10.1016/j.scitotenv.2018.09.228.

Jovani-Sancho, A. J., T. Cummins and K. A. Byrne, 2021: Soil carbon balance of afforested peatlands in the maritime temperate climatic zone. *Global Change Biology*, doi:10.1111/gcb.15654.

Jung, M. et al., 2017: Compensatory water effects link yearly global land CO2 sink changes to temperature. *Nature*, **541**(7638), 516-520, doi:10.1038/nature20780.

Jurgelėnaitė, A. et al., 2017: Spatial distribution and temporal changes in river water temperature in the Baltic States. *Hydrology Research*, **49**(2), 318-331, doi:10.2166/nh.2017.289.

Jurgelėnaitė, A., J. Kriaučiūnienė and D. Šarauskienė, 2012: Spatial and temporal variation in the water temperature of Lithuanian rivers. *Baltica*, **25**(1), 65-76.

Jutla, A. et al., 2015: Satellite Based Assessment of Hydroclimatic Conditions Related to Cholera in Zimbabwe. *PLOS ONE*, **10**(9), e0137828, doi:10.1371/journal.pone.0137828.

Kabisch, N. et al., 2016: Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, **21**(2), doi:10.5751/es-08373-210239.

Kaiser, G. and N. Macleod, 2018: Cape Town–where we've been and where we want to go. *Civil Engineering= Siviele Ingenieurswese*, **2018**(9), 8-12.

Kakouei, K., 2021 : Phytoplankton and cyanobacteria abundances in mid-21st century lakes depend strongly on future land use and climate projections. *Global Change Biology*. https://doi.org/10.1111/gcb.15866

Kakouei, K. et al., 2018: Projected effects of Climate-change-induced flow alterations on stream macroinvertebrate abundances. *Ecology and Evolution*, **8**(6), 3393-3409, doi:10.1002/ece3.3907.

Karell, P. et al., 2011: Climate change drives microevolution in a wild bird. *Nature Communications*, **2**, doi:10.1038/ncomms1213.

Karesh, W. B. et al., 2012: Ecology of zoonoses: natural and unnatural histories. *The Lancet*, **380**(9857), 1936-1945, doi:10.1016/S0140-6736(12)61678-X.

Kariyawasam, C. S., L. Kumar and S. S. Ratnayake, 2020: Potential Risks of Plant Invasions in Protected Areas of Sri Lanka under Climate Change with Special Reference to Threatened Vertebrates. *Climate*, **8**(4), doi:10.3390/cli8040051.

Karp, D. S. et al., 2019: Remnant forest in Costa Rican working landscapes fosters bird communities that are indistinguishable from protected areas. *Journal of Applied Ecology*, **56**(7), 1839-1849, doi:10.1111/1365-2664.13419.

Kasischke, E. S. and M. R. Turetsky, 2006: Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters*, **33**(9), doi:10.1029/2006GL025677.

Kasischke, E. S. et al., 2010: Alaska's changing fire regime — implications for the vulnerability of its boreal forestsThis article is one of a selection of papers from The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming. *Canadian Journal of Forest Research*, **40**(7), 1313-1324, doi:10.1139/X10-098
10.1139/X10-098</p>.

Kaushal, S. S., A. J. Gold, S. Bernal and J. L. Tank, 2018: Diverse water quality responses to extreme climate events: an introduction. *Biogeochemistry*, **141**(3), 273-279, doi:10.1007/s10533-018-0527-x.

Kaushal, S. S. et al., 2010: Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment*, **8**(9), 461-466, doi:10.1890/090037.

Kearney, M. et al., 2009: Integrating biophysical models and evolutionary theory to predict climatic impacts on species' ranges: the dengue mosquito Aedes aegypti in Australia. *Functional Ecology*, **23**(3), 528-538, doi:https://doi.org/10.1111/j.1365-2435.2008.01538.x.

Keeler, B. L. et al., 2019: Social-ecological and technological factors moderate the value of urban nature. *Nature Sustainability*, **2**(1), 29-38, doi:10.1038/s41893-018-0202-1.

Keeler, B. L. et al., 2015: Recreational demand for clean water: evidence from geotagged photographs by visitors to lakes. *Frontiers in Ecology and the Environment*, **13**(2), 76-81.

Keeley, A. T. et al., 2018: New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters*, **13**(7), 073002.

Keeley, J. E. et al., 2011: Fire as an evolutionary pressure shaping plant traits. *Trends in plant science*, **16**(8), 406-411.

Keenan, R. J. et al., 2015: Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. *Forest Ecology and Management*, **352**, 9–20.

Keenan, T. F. et al., 2014: Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nature Climate Change*, **4**, 598, doi:10.1038/nclimate2253 https://www.nature.com/articles/nclimate2253#supplementary-information.

Keesing, F. and R. S. Ostfeld, 2021: Impacts of biodiversity and biodiversity loss on zoonotic diseases. *Proceedings of the National Academy of Sciences*, **118**(17), e2023540118, doi:10.1073/pnas.2023540118.

Keesstra, S. et al., 2018: The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of The Total Environment*, **610-611**, 997-1009, doi:https://doi.org/10.1016/j.scitotenv.2017.08.077.

Keith, D. A. et al., 2014: Detecting Extinction Risk from Climate Change by IUCN Red List Criteria. *Conservation Biology*, **28**(3), 810-819, doi:10.1111/cobi.12234.

Keith, H., B. G. Mackey and D. B. Lindenmayer, 2009: Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(28), 11635-11640, doi:10.1073/pnas.0901970106.
Keller, P. et al., 2020: Global CO 2 emissions from dry inland waters share common drivers across ecosystems. *Nature communications*, **11**(1), 1-8.
Kellerman, A. M., T. Dittmar, D. N. Kothawala and L. J. Tranvik, 2014: Chemodiversity of dissolved organic matter in lakes driven by climate and hydrology. *Nature communications*, **5**(1), 1-8.
Kelley, D. I. et al., 2019: How contemporary bioclimatic and human controls change global fire regimes. *Nature Climate Change*, **9**(9), 690-696, doi:10.1038/s41558-019-0540-7.
Kelley, D. I. et al., 2021: Technical note: Low meteorological influence found in 2019 Amazonia fires. *Biogeosciences*, **18**(3), 787-804, doi:10.5194/bg-18-787-2021.
Kelley, D. I. et al., 2013: A comprehensive benchmarking system for evaluating global vegetation models. *Biogeosciences*, **10**(5), 3313-3340, doi:10.5194/bg-10-3313-2013.
Kelly, B., A. Whiteley and D. Tallmon, 2010: The Arctic melting pot. *Nature*, **468**(7326), 891-891, doi:10.1038/468891a.
Kelly, M., 2019: Adaptation to climate change through genetic accommodation and assimilation of plastic phenotypes. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **374**(1768), 10, doi:10.1098/rstb.2018.0176.
Kemper, J., L. G. Underhill and J.-P. Roux, 2007: Artificial burrows for African Penguins on Halifax Island, Namibia: do they improve breeding success. *Final Report of the BCLME (Benguela Current Large Marine Ecosystem) Project on Top Predators as Biological Indicators of Ecosystem Change in the BCLME'.(Ed. SP Kirkman.) pp*, 101-106.
Kennedy, C. M. et al., 2013: A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters*, **16**(5), 584-599, doi:https://doi.org/10.1111/ele.12082.
Keogan, K. et al., 2018: Global phenological insensitivity to shifting ocean temperatures among seabirds. *Nature Climate Change*, **8**(4), 313-318.
Keuper, F. et al., 2017: Experimentally increased nutrient availability at the permafrost thaw front selectively enhances biomass production of deep-rooting subarctic peatland species. *Global change biology*, **23**(10), 4257-4266.
Keys, P. W., L. Wanf-Erlandsson and L. J. Gordon, 2016: Revealing invisible water: Moisture recycling as an ecosystem service, 1-16 pp.
Keys, P. W. and L. Wang-Erlandsson, 2018: On the social dynamics of moisture recycling. *Earth System Dynamics*, **9**(2), 829-847, doi:10.5194/esd-9-829-2018.
Khaniya, B., M. B. Gunathilake and U. Rathnayake, 2021: Ecosystem-Based Adaptation for the Impact of Climate Change and Variation in the Water Management Sector of Sri Lanka. *Mathematical Problems in Engineering*, **2021**, 8821329, doi:10.1155/2021/8821329.
Kharouba, H. M. et al., 2018: Global shifts in the phenological synchrony of species interactions over recent decades. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(20), 5211-5216, doi:10.1073/pnas.1714511115.
Khatchikian, C. E. et al., 2015: Recent and rapid population growth and range expansion of the Lyme disease tick vector, Ixodes scapularis, in North America. *Evolution*, **69**(7), 1678-1689, doi:10.1111/evo.12690.
Khormi, H. M. and L. Kumar, 2016: Future malaria spatial pattern based on the potential global warming impact in South and Southeast Asia. *Geospat Health*, **11**(3), doi:10.4081/gh.2016.416.
Kidane, Y. O., M. J. Steinbauer and C. Beierkuhnlein, 2019: Dead end for endemic plant species? A biodiversity hotspot under pressure. *Global Ecology and Conservation*, **19**, doi:10.1016/j.gecco.2019.e00670.
Kimiti, D. W., C. Riginos and J. Belnap, 2017: Low-cost grass restoration using erosion barriers in a degraded African rangeland. *Restoration Ecology*, **25**(3), 376-384.
Kingsolver, J. G. and L. B. Buckley, 2015: Climate variability slows evolutionary responses of Colias butterflies to recent climate change. *Proceedings of the Royal Society B: Biological Sciences*, **282**(1802), 20142470, doi:10.1098/rspb.2014.2470.
Kirchmeier-Young, M. C. et al., 2019: Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earth's Future*, **7**(1), 2-10, doi:10.1029/2018EF001050.
Kirillin, G., 2010: Modeling the impact of global warming on water temperature and seasonal mixing regimes in small temperate lakes. *Boreal Environment Research*, **15**(2), 279-293.
Kirillin, G. et al., 2012: Physics of seasonally ice-covered lakes: a review. *Aquatic Sciences*, **74**(4), 659-682, doi:10.1007/s00027-012-0279-y.
Kirillin, G. and T. Shatwell, 2016: Generalized scaling of seasonal thermal stratification in lakes. *Earth-Science Reviews*, **161**, 179-190, doi:10.1016/j.earscirev.2016.08.008.
Kirwan, M. L. and S. M. Mudd, 2012: Response of salt-marsh carbon accumulation to climate change. *Nature*, **489**(7417), 550-553, doi:10.1038/nature11440.
Kitajima, M. et al., 2020: SARS-CoV-2 in wastewater: State of the knowledge and research needs. *Science of The Total Environment*, **739**, 139076, doi:10.1016/j.scitotenv.2020.139076.
Kleinman, J. S., J. D. Goode, A. C. Fries and J. L. Hart, 2019: Ecological consequences of compound disturbances in forest ecosystems: a systematic review. *Ecosphere*, **10**(11), e02962, doi:https://doi.org/10.1002/ecs2.2962.

Kling, M. M. et al., 2020: Multiple axes of ecological vulnerability to climate change. *Global Change Biology*, **26**(5), 2798-2813, doi:10.1111/gcb.15008.
Klinger, R. and M. Brooks, 2017: Alternative pathways to landscape transformation: invasive grasses, burn severity and fire frequency in arid ecosystems. *Journal of Ecology*, **105**(6), 1521-1533, doi:10.1111/1365-2745.12863.
Klorvuttimontara, S., C. J. McClean and J. K. Hill, 2011: Evaluating the effectiveness of Protected Areas for conserving tropical forest butterflies of Thailand. *Biological Conservation*, **144**(10), 2534-2540, doi:10.1016/j.biocon.2011.07.012.
Kloster, S. and G. Lasslop, 2017: Historical and future fire occurrence (1850 to 2100) simulated in CMIP5 Earth System Models. *Global and Planetary Change*, **150**, 58-69, doi:10.1016/j.gloplacha.2016.12.017.
Klusener, R. et al., 2018: From incubation to release: Hand-rearing as a tool for the conservation of the endangered African penguin. *PLoS ONE*, **13**(11), e0205126.
Knelman, J. E. et al., 2019: Multiple, Compounding Disturbances in a Forest Ecosystem: Fire Increases Susceptibility of Soil Edaphic Properties, Bacterial Community Structure, and Function to Change with Extreme Precipitation Event. *Soil Systems*, **3**(2), doi:10.3390/soilsystems3020040.
Knorr, K., L. Jiang and A. Arneth, 2016a: Climate, CO2, and demographic impacts on global wildfire emissions. *Biogeosciences*, **13**, 267-282, doi:doi:10.5194/bg-13-267-2016.
Knorr, W., A. Arneth and L. Jiang, 2016b: Demographic controls of future fire risks. *Nature Climate Change*, doi:doi:10.1038/nclimate2999.
Knorr, W., A. Arneth and L. Jiang, 2016c: Demographic controls of future global fire risk. *Nature Climate Change*, **6**(8), 781-+, doi:10.1038/nclimate2999.
Knorr, W., T. Kaminski, A. Arneth and U. Weber, 2014: Impact of human population density on fire frequency at the global scale. *Biogeosciences*, **11**(4), 1085-1102, doi:10.5194/bg-11-1085-2014.
Knouft, J. H. and D. L. Ficklin, 2017: The Potential Impacts of Climate Change on Biodiversity in Flowing Freshwater Systems. *Annual Review of Ecology, Evolution, and Systematics*, **48**(1), 111-133, doi:10.1146/annurev-ecolsys-110316-022803.
Kohl, M. et al., 2015: Changes in forest production, biomass and carbon: Results from the 2015 UN FAO Global Forest Resource Assessment. *Forest Ecology and Management*, **352**, 21-34, doi:10.1016/j.foreco.2015.05.036.
Kolb, T. E. et al., 2016: Observed and anticipated impacts of drought on forest insects and diseases in the United States. *Forest Ecology and Management*, **380**, 321-334, doi:10.1016/j.foreco.2016.04.051.
Koninck, R. d., S. p. Bernard and J.-F. o. Bissonnette, 2011: *Borneo transformed : agricultural expansion on the Southeast Asian frontier*. Challenges of the agrarian transition in Southeast Asia, NUS Press, Singapore, ix, 216 p. pp. ISBN 9789971695446.
Konrad, S. et al., 2017: Remote sensing measurements of sea surface temperature as an indicator of *Vibrio parahaemolyticus* in oyster meat and human illnesses. *Environmental Health*, **16**(1), 92, doi:10.1186/s12940-017-0301-x.
Koontz, M. J. et al., 2021: Cross-scale interaction of host tree size and climatic water deficit governs bark beetle-induced tree mortality. *Nature Communications*, **12**(1), 13, doi:10.1038/s41467-020-20455-y.
Kosten, S. et al., 2012: Warmer climates boost cyanobacterial dominance in shallow lakes. *Global Change Biology*, **18**(1), 118-126.
Kothawala, D. N. et al., 2015: The relative influence of land cover, hydrology, and in-stream processing on the composition of dissolved organic matter in boreal streams. *Journal of Geophysical Research: Biogeosciences*, **120**(8), 1491-1505.
Kowarik, I., 2011: Novel urban ecosystems, biodiversity, and conservation. *Environmental Pollution*, **159**(8), 1974-1983, doi:https://doi.org/10.1016/j.envpol.2011.02.022.
Koźmińska, A. et al., 2019: Responses of succulents to drought: Comparative analysis of four Sedum (Crassulaceae) species. *Scientia Horticulturae*, **243**, 235-242, doi:10.1016/j.scienta.2018.08.028.
Kraaij, T. et al., 2018: An assessment of climate, weather, and fuel factors influencing a large, destructive wildfire in the Knysna region, South Africa. *Fire Ecology*, **14**(2), 4, doi:10.1186/s42408-018-0001-0.
Kraemer, B. et al., 2015: Morphometry and average temperature affect lake stratification responses to climate change. *Geophysical Research Letters*, **42**(12), 4981-4988, doi:10.1002/2015gl064097.
Kraemer, B., T. Mehner and R. Adrian, 2017: Reconciling the opposing effects of warming on phytoplankton biomass in 188 large lakes. *Scientific Reports*, **7**, doi:10.1038/s41598-017-11167-3.
Kraemer, B. M. et al., 2021: Climate change drives widespread shifts in lake thermal habitat. *Nature Climate Change*, 1-9.
Kraemer, B. M., A. Seimon, R. Adrian and P. B. McIntyre, 2020: Worldwide lake level trends and responses to background climate variation. *Hydrology and Earth System Sciences*, **24**(5), 2593-2608.
Kraemer, M. U. G. et al., 2019: Past and future spread of the arbovirus vectors Aedes aegypti and Aedes albopictus. *Nature Microbiology*, **4**(5), 854-863, doi:10.1038/s41564-019-0376-y.
Krause, A., A. Arneth, P. Anthoni and A. Rammig, 2020: Legacy Effects from Historical Environmental Changes Dominate Future Terrestrial Carbon Uptake. *Earth's Future*, **8**(10), e2020EF001674, doi:10.1029/2020EF001674.
Krause, A. et al., 2017: Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. *Biogeosciences*, **14**(21), 4829-4850, doi:10.5194/bg-14-4829-2017.

Krautzer, B. et al., 2011: The influence of recultivation technique and seed mixture on erosion stability after restoration in mountain environment. *Natural hazards*, **56**(2), 547-557.
Krawchuk, M. A. et al., 2020: Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. *Frontiers in Ecology and the Environment*, **18**(5), 235-244, doi:https://doi.org/10.1002/fee.2190.
Kreft, H. and W. Jetz, 2007: Global patterns and determinants of vascular plant diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(14), 5925-5930, doi:10.1073/pnas.0608361104.
Kremen, C. and A. M. Merenlender, 2018: Landscapes that work for biodiversity and people. *Science*, **362**(6412), eaau6020-eaau6020, doi:10.1126/science.aau6020.
Kristensen, T. N. et al., 2015: Low evolutionary potential for egg-to-adult viability in Drosophila melanogaster at high temperatures. *Evolution*, **69**(3), 803-814, doi:10.1111/evo.12617.
Kritzberg, E. S. et al., 2020: Browning of freshwaters: Consequences to ecosystem services, underlying drivers, and potential mitigation measures. *Ambio*, **49**(2), 375-390, doi:10.1007/s13280-019-01227-5.
Kroeger, K. D., S. Crooks, S. Moseman-Valtierra and J. Tang, 2017: Restoring tides to reduce methane emissions in impounded wetlands: A new and potent Blue Carbon climate change intervention. *Scientific reports*, **7**(1), 1-12.
Krupnick, G. A., 2013: Conservation of Tropical Plant Biodiversity: What Have We Done, Where Are We Going? *Biotropica*, **45**(6), 693-708, doi:10.1111/btp.12064.
Krushelnycky, P. D. et al., 2013: Climate-associated population declines reverse recovery and threaten future of an iconic high-elevation plant. *Global Change Biology*, **19**(3), 911-922, doi:10.1111/gcb.12111.
Kubickova, B., P. Babica, K. Hilscherová and L. Šindlerová, 2019: Effects of cyanobacterial toxins on the human gastrointestinal tract and the mucosal innate immune system. *Environ Sci Eur*, **31**(1), 31, doi:10.1186/s12302-019-0212-2.
Kuhn, E. and J. C. Gégout, 2019: Highlighting declines of cold-demanding plant species in lowlands under climate warming. *Ecography*, **42**(1), 36-44.
Kumar, D. et al., 2021: Climate change and elevated CO₂ favor forest over savanna under different future scenarios in South Asia. *Biogeosciences*, **18**(9), 2957-2979, doi:10.5194/bg-18-2957-2021.
Kurpiers, L. A., B. Schulte-Herbrüggen, I. Ejotre and D. M. Reeder, 2016: Bushmeat and Emerging Infectious Diseases: Lessons from Africa. In: *Problematic Wildlife: A Cross-Disciplinary Approach* [Angelici, F. M. (ed.)]. Springer International Publishing, Cham, pp. 507-551. ISBN 978-3-319-22246-2.
Kurz, W. A. et al., 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452**(7190), 987-990, doi:10.1038/nature06777.
Kusserow, H., 2017: Desertification, resilience, and re-greening in the African Sahel - a matter of the observation period? *Earth System Dynamics*, **8**(4), 1141-1170, doi:10.5194/esd-8-1141-2017.
Kweka, E. J. et al., 2013: A first report of Anopheles funestus sibling species in western Kenya highlands. *Acta Tropica*, **128**(1), 158-161, doi:10.1016/j.actatropica.2013.06.006.
Laaksonen, S. et al., 2010: Climate Change Promotes the Emergence of Serious Disease Outbreaks of Filarioid Nematodes. *EcoHealth*, **7**(1), 7-13, doi:10.1007/s10393-010-0308-z.
Laaksonen, S. et al., 2009: Vectors and transmission dynamics for Setaria tundra (Filarioidea; Onchocercidae), a parasite of reindeer in Finland. *Parasites & Vectors*, **2**(1), 3, doi:10.1186/1756-3305-2-3.
Laamrani, A., O. Valeria, A. Chehbouni and Y. Bergeron, 2020: Analysis of the Effect of Climate Warming on Paludification Processes: Will Soil Conditions Limit the Adaptation of Northern Boreal Forests to Climate Change? A Synthesis. *Forests*, **11**(11), 1176, doi:10.3390/f11111176.
Lafleur, P. M., R. A. Hember, S. W. Admiral and N. T. Roulet, 2005: Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. *Hydrological Processes*, **19**(18), 3533-3550, doi:10.1002/hyp.5842.
Lagarde, F. et al., 2012: Bushes protect tortoises from lethal overheating in arid areas of Morocco. *Environmental Conservation*, **39**(2), 172-182.
Lal, P. N., T. Mitchell, R. Mechler and S. Hochrainer-Stigler, 2012: National systems for managing the risks from climate extremes and disasters.
Lamarque, J. F. et al., 2013: Multi-model mean nitrogen and sulfur deposition from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): evaluation of historical and projected future changes. *Atmospheric Chemistry and Physics*, **13**(16), 7997-8018, doi:10.5194/acp-13-7997-2013.
Lammers, R. B., J. W. Pundsack and A. I. Shiklomanov, 2007: Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass. *Journal of Geophysical Research: Biogeosciences*, **112**(G4), doi:10.1029/2006jg000370.
Lampela, M., J. Jauhiainen, S. Sarkkola and H. Vasander, 2017: Promising native tree species for reforestation of degraded tropical peatlands. *Forest Ecology and Management*, **394**, 52-63, doi:10.1016/j.foreco.2016.12.004.
Lancaster, L. T., 2020: Host use diversification during range shifts shapes global variation in Lepidopteran dietary breadth. *Nature Ecology & Evolution*, **4**(7), 963-969, doi:10.1038/s41559-020-1199-1.
Landry, J. S. et al., 2016: Modelling long-term impacts of mountain pine beetle outbreaks on merchantable biomass, ecosystem carbon, albedo, and radiative forcing. *Biogeosciences*, **13**(18), 5277-5295, doi:10.5194/bg-13-5277-2016.
Lang, J. et al., 2018: An Investigation of Ice Surface Albedo and Its Influence on the High-Altitude Lakes of the Tibetan Plateau. *Remote Sensing*, **10**(2), 218.

Langan, S. J. et al., 2001: Variation in river water temperatures in an upland stream over a 30-year period. *Science of The Total Environment*, **265**(1), 195-207, doi:doi.org/10.1016/S0048-9697(00)00659-8.

Lange, S. et al., 2020: Projecting Exposure to Extreme Climate Impact Events Across Six Event Categories and Three Spatial Scales. *Earths Future*, **8**(12), 22, doi:10.1029/2020ef001616.

Langhans, S. D. et al., 2019: - Combining eight research areas to foster the uptake of ecosystem-based management in fresh waters. **- 0**(- 0).

Langner, A. and F. Siegert, 2009: Spatiotemporal fire occurrence in Borneo over a period of 10 years. *Global Change Biology*, **15**(1), 48-62, doi:10.1111/j.1365-2486.2008.01828.x.

Lapola, D. M. et al., 2018: Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proceedings of the National Academy of Sciences*, **115**(46), 11671-11679.

Laporta, G. Z. et al., 2015: Malaria vectors in South America: current and future scenarios. *Parasites & Vectors*, **8**(1), 426, doi:10.1186/s13071-015-1038-4.

Lara, A., J. Jones, C. Little and N. Vergara, 2021: Streamflow response to native forest restoration in former Eucalyptus plantations in south central Chile. *Hydrological Processes*, **35**(8), e14270, doi:https://doi.org/10.1002/hyp.14270.

Larsen, M., K. Jensen and K. Mouritsen, 2011: Climate influences parasite-mediated competitive release. *Parasitology*, **138**, 1436-1441, doi:10.1017/S0031182011001193.

Larsen, M. H. and K. N. Mouritsen, 2014: Temperature–parasitism synergy alters intertidal soft-bottom community structure. *Journal of Experimental Marine Biology and Ecology*, **460**, 109-119, doi:https://doi.org/10.1016/j.jembe.2014.06.011.

Larsen, S., J. M. Chase, I. Durance and S. J. Ormerod, 2018: Lifting the veil: richness measurements fail to detect systematic biodiversity change over three decades. *Ecology*, **99**(6), 1316-1326, doi:10.1002/ecy.2213.

Larsen, S. V., 2014: Is environmental impact assessment fulfilling its potential? The case of climate change in renewable energy projects. *Impact Assessment and Project Appraisal*, **32**(3), 234-240, doi:10.1080/14615517.2014.898386.

Lasslop, G. and S. Kloster, 2017: Human impact on wildfires varies between regions and with vegetation productivity. *Environmental Research Letters*, **12**(11), doi:10.1088/1748-9326/aa8c82.

Latkovska, I. and E. Apsīte (eds.), Long-term changes in the water temperature of rivers in Latvia. Proceedings of the Latvian Academy of Sciences. Section B. Natural, Exact, and Applied Sciences., Sciendo, 78-87 pp.

Laurance, W. F. et al., 2012: Averting biodiversity collapse in tropical forest protected areas. *Nature*, **489**(7415), 290-294, doi:10.1038/nature11318.

Lavergne, S., N. Mouquet, W. Thuiller and O. Ronce, 2010: Biodiversity and Climate Change: Integrating Evolutionary and Ecological Responses of Species and Communities. *Annual Review of Ecology, Evolution, and Systematics*, **41**, 321-350, doi:10.1146/annurev-ecolsys-102209-144628.

Lavorel, S., B. Locatelli, M. J. Colloff and E. Bruley, 2020: Co-producing ecosystem services for adapting to climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190119, doi:10.1098/rstb.2019.0119.

Le Page, Y. et al., 2017: Synergy between land use and climate change increases future fire risk in Amazon forests. *Earth System Dynamics*, **8**(4), 1237-1246, doi:10.5194/esd-8-1237-2017.

le Polain de Waroux, Y. and E. F. Lambin, 2012: Monitoring degradation in arid and semi-arid forests and woodlands: The case of the argan woodlands (Morocco). *Applied Geography*, **32**(2), 777-786, doi:10.1016/j.apgeog.2011.08.005.

Le, P. V. V. et al., 2019: Predicting the direct and indirect impacts of climate change on malaria in coastal Kenya. *PLoS ONE*, **14**(2), e0211258, doi:10.1371/journal.pone.0211258.

Le Quéré, C. et al., 2018: Global Carbon Budget 2018. *Earth Syst. Sci. Data*, **10**(4), 2141-2194, doi:10.5194/essd-10-2141-2018.

Leach, K., S. Zalat and F. Gilbert, 2013: Egypt's Protected Area network under future climate change. *Biological Conservation*, **159**, 490-500, doi:10.1016/j.biocon.2012.11.025.

Leal Filho, W. et al., 2013: Pastoralism and ecosystem-based adaptation in Kenyan Masailand. *International Journal of Climate Change Strategies and Management*.

Leclère, D. et al., 2020: Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, **585**(7826), 551-556.

Ledee, O. E. et al., 2021: Preparing Wildlife for Climate Change: How Far Have We Come? *The Journal of Wildlife Management*, **85**(1), 7-16, doi:https://doi.org/10.1002/jwmg.21969.

Ledger, M. E. and A. M. Milner, 2015: Extreme events in running waters. *Freshwater Biology*, **60**(12), 2455-2460, doi:10.1111/fwb.12673.

Lee, C. G., S. H. Cho and C. Y. Lee, 1995: Metacercarial production of Lymnaea viridis experimentally infected with Fasciola hepatica. *Veterinary Parasitology*, **58**(4), 313-318, doi:https://doi.org/10.1016/0304-4017(94)00725-R.

Lee, H. and S. Lautenbach, 2016: A quantitative review of relationships between ecosystem services. *Ecological Indicators*, **66**, 340-351, doi:https://doi.org/10.1016/j.ecolind.2016.02.004.

Lee, J. et al., 2020: Determining economically viable forest management option with consideration of ecosystem services in Korea: A strategy after successful national forestation. *Ecosystem Services*, **41**, 101053, doi:https://doi.org/10.1016/j.ecoser.2019.101053.

Lee, J. et al., 2018: Economic viability of the national-scale forestation program: The case of success in the Republic of Korea. *Ecosystem Services*, **29**, 40-46, doi:https://doi.org/10.1016/j.ecoser.2017.11.001.
Leedale, J. et al., 2016: Projecting malaria hazard from climate change in eastern Africa using large ensembles to estimate uncertainty. *Geospat Health*, doi:10.4081/gh.2016.393.
Lees, K. J. et al., 2019: Changes in carbon flux and spectral reflectance of Sphagnum mosses as a result of simulated drought. *Ecohydrology*, **12**(6), doi:10.1002/eco.2123.
Lehikoinen, P. et al., 2019: Protected areas act as a buffer against detrimental effects of climate change-Evidence from large-scale, long-term abundance data. *Global Change Biology*, **25**(1), 304-313, doi:10.1111/gcb.14461.
Lehikoinen, P. et al., 2021: Increasing protected area coverage mitigates climate-driven community changes. *Biological Conservation*, **253**, 108892, doi:https://doi.org/10.1016/j.biocon.2020.108892.
Lehman, C. E. R. and C. L. Parr, 2016: Tropical grassy biomes: linking ecology, human use and conservation. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **371**(1703), doi:20160329 10.1098/rstb.2016.0329.
Lehmann, C. E. R. et al., 2014: Savanna vegetation-fire-climate relationships differ among continents. *Science*, **343**(6170), 548-552.
Lehmann, P. et al., 2020: Complex responses of global insect pests to climate warming. *Frontiers in Ecology and the Environment*, **18**(3), 141-150, doi:https://doi.org/10.1002/fee.2160.
Lehner, B., K. Verdin and A. Jarvis, 2008: New Global Hydrography Derived From Spaceborne Elevation Data. *Eos, Transactions American Geophysical Union*, **89**(10), 93-94, doi:10.1029/2008EO100001.
Lehtonen, I. et al., 2016: Risk of large-scale fires in boreal forests of Finland under changing climate. *Natural Hazards and Earth System Sciences*, **16**(1), 239-253, doi:10.5194/nhess-16-239-2016.
Lei, B. R., J. A. Green and L. Pichegru, 2014: Extreme microclimate conditions in artificial nests for Endangered African Penguins. *Bird Conservation International*, **24**(2), 201-213.
Leifeld, J. and L. Menichetti, 2018: The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature communications*, **9**(1), 1071.
Leifeld, J., C. Wust-Galley and S. Page, 2019: Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. *Nature Climate Change*, **9**(12), 945-+, doi:10.1038/s41558-019-0615-5.
Leighton, P. A. et al., 2012: Predicting the speed of tick invasion: an empirical model of range expansion for the Lyme disease vector Ixodes scapularis in Canada. *Journal of Applied Ecology*, **49**(2), 457-464, doi:https://doi.org/10.1111/j.1365-2664.2012.02112.x.
Lejeune, Q. et al., 2018: Historical deforestation locally increased the intensity of hot days in northern mid-latitudes. *Nature Climate Change*, **8**(5), 386-+, doi:10.1038/s41558-018-0131-z.
Lemes, P., A. S. Melo and R. D. Loyola, 2014: Climate change threatens protected areas of the Atlantic Forest. *Biodiversity and Conservation*, **23**(2), 357-368, doi:10.1007/s10531-013-0605-2.
Lemordant, L. and P. Gentine, 2019: Vegetation Response to Rising CO2 Impacts Extreme Temperatures. *Geophysical Research Letters*, **46**(3), 1383-1392, doi:10.1029/2018gl080238.
Lencioni, V., 2018: Glacial influence and stream macroinvertebrate biodiversity under climate change: Lessons from the Southern Alps. *Science of The Total Environment*, **622-623**, 563-575, doi:https://doi.org/10.1016/j.scitotenv.2017.11.266.
Lenoir, J. et al., 2020: Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, **4**(8), 1044-1059, doi:10.1038/s41559-020-1198-2.
Lenoir, J. and J. C. Svenning, 2015: Climate-related range shifts–a global multidimensional synthesis and new research directions. *Ecography*, **38**(1), 15-28, doi:https://doi.org/10.1111/ecog.00967.
Lenton, T. M. et al., 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(6), 1786-1793, doi:10.1073/pnas.0705414105.
Leonard, 2014: A compound event framework for understanding extreme impacts. *Climate Change*, **5**, 113-128.
Leroy, E. et al., 2004: Multiple Ebola Virus Transmission Events and Rapid Decline of Central African Wildlife. *Science (New York, N.Y.)*, **303**, 387-390, doi:10.1126/science.1092528.
Levy, S., 2015: Warming Trend: How Climate Shapes Vibrio Ecology. *Environmental Health Perspectives*, **123**(4), A82-A89, doi:10.1289/ehp.123-A82.
Lewis Jr, W. M., 2000: Basis for the protection and management of tropical lakes. *Lakes & Reservoirs: Research & Management*, **5**(1), 35-48.
Lewis, S. C. et al., 2020: DECONSTRUCTING FACTORS CONTRIBUTING TO THE 2018 FIRE WEATHER IN QUEENSLAND, AUSTRALIA. *Bulletin of the American Meteorological Society*, **101**(1), S115-S121, doi:10.1175/bams-d-19-0144.1.
Lewis, S. L. et al., 2011: The 2010 Amazon Drought. *Science*, **331**(6017), 554-554, doi:10.1126/science.1200807.
Lewis, S. L., D. P. Edwards and D. Galbraith, 2015: Increasing human dominance of tropical forests. *Science*, **349**(6250), 827-832.
Lewis, S. L., C. E. Wheeler, E. T. A. Mitchard and A. Koch, 2019: *Restoring natural forests is the best way to remove atmospheric carbon*. Nature Publishing Group.
Li, B., Y. Chen, Z. Chen and W. Li, 2012: Trends in runoff versus climate change in typical rivers in the arid region of northwest China. *Quaternary International*, **282**, 87-95.

Li, P. et al., 2017: Quantification of the response of global terrestrial net primary production to multifactor global change. *Ecological Indicators*, **76**, 245-255, doi:10.1016/j.ecolind.2017.01.021.
Li, W. et al., 2018: Gross and net land cover changes in the main plant functional types derived from the annual ESA CCI land cover maps (1992-2015). *Earth System Science Data*, **10**(1), 219-234, doi:10.5194/essd-10-219-2018.
Li, Z. et al., 2015: Potential impacts of climate change on vegetation dynamics in Central Asia. *Journal of Geophysical Research: Atmospheres*, **120**(24), 12345-12356.
Lian, X. et al., 2020: Summer soil drying exacerbated by earlier spring greening of northern vegetation. *Science advances*, **6**(1), eaax0255.
Liang, J. J. et al., 2016: Positive biodiversity-productivity relationship predominant in global forests. *Science*, **354**(6309), doi:aaf8957 10.1126/science.aaf8957.
Libonati, R. et al., 2021: Twenty-first century droughts have not increasingly exacerbated fire season severity in the Brazilian Amazon. *Scientific Reports*, **11**(1), 4400, doi:10.1038/s41598-021-82158-8.
Lichtenberg, E. M. et al., 2017: A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. *Global Change Biology*, **23**(11), 4946-4957, doi:10.1111/gcb.13714.
Lienert, S. and F. Joos, 2018: A Bayesian ensemble data assimilation to constrain model parameters and land-use carbon emissions. *Biogeosciences*, **15**(9), 2909-2930, doi:10.5194/bg-15-2909-2018.
Ligtvoet, W. et al., 2017: Overcoming water challenges through nature-based solutions. *Water Policy*, **19**(5), 820-836, doi:10.2166/wp.2017.105.
Liljedahl, A. K. et al., 2016: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*, **9**(4), 312-318, doi:10.1038/ngeo2674.
Lindenmayer, D. B. and C. Taylor, 2020: New spatial analyses of Australian wildfires highlight the need for new fire, resource, and conservation policies. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(22), 12481-12485, doi:10.1073/pnas.2002269117.
Lindgren, E. et al., 2012: Monitoring EU Emerging Infectious Disease Risk Due to Climate Change. *Science*, **336**, 418-419, doi:10.1126/science.1215735.
LingZi, D., Y. Chen and J. Zhang, 2014: Leaf traits and their associations among liana species in tropical rainforest. *Plant Science Journal*, **32**(4), 362-370, doi:10.3724/SP.J.1142.2014.40362.
Liquete, C. et al., 2016: Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. *Ecosystem Services*, **22**, 392-401.
Littlefield, C. E., M. Krosby, J. L. Michalak and J. J. Lawler, 2019: Connectivity for species on the move: supporting climate-driven range shifts. *Frontiers in Ecology and the Environment*, **17**(5), 270-278.
Liu-Helmersson, J., H. Stenlund, A. Wilder-Smith and J. Rocklöv, 2014: Vectorial Capacity of Aedes aegypti: Effects of Temperature and Implications for Global Dengue Epidemic Potential. *PLoS ONE*, **9**(3), doi:10.1371/journal.pone.0089783.
Liu, D., 2016: Water supply: China's sponge cities to soak up rainwater. *Nature*, **537**(7620), 307.
Liu, H. et al., 2012: Overcoming extreme weather challenges: Successful but variable assisted colonization of wild orchids in southwestern China. *Biological Conservation*, **150**(1), 68-75, doi:10.1016/j.biocon.2012.02.018.
Liu, K. et al., 2020: Climate factors and the East Asian summer monsoon may drive large outbreaks of dengue in China. *Environmental Research*, **183**, 109190, doi:https://doi.org/10.1016/j.envres.2020.109190.
Liu, X., S. Feng, H. Liu and J. Ji, 2021: Patterns and determinants of woody encroachment in the eastern Eurasian steppe. *Land Degradation & Development*.
Liu, Y. J. et al., 2017: Do invasive alien plants benefit more from global environmental change than native plants? *Global Change Biology*, **23**(8), 3363-3370, doi:10.1111/gcb.13579.
Liu, Y. Y. et al., 2015: Recent reversal in loss of global terrestrial biomass. *Nature Climate Change*, **5**(5), 470.
Liu, Z. et al., 2019a: Global divergent responses of primary productivity to water, energy, and CO2. *Environmental Research Letters*, **14**(12), 124044, doi:10.1088/1748-9326/ab57c5.
Liu, Z. H., A. P. Ballantyne and L. A. Cooper, 2019b: Biophysical feedback of global forest fires on surface temperature. *Nature Communications*, **10**, doi:10.1038/s41467-018-08237-z.
Lloret, F. and T. Kitzberger, 2018: Historical and event-based bioclimatic suitability predicts regional forest vulnerability to compound effects of severe drought and bark beetle infestation. *Global Change Biology*, **24**(5), 1952-1964, doi:10.1111/gcb.14039.
Loarie, S. R. et al., 2009: The velocity of climate change. *Nature*, **462**(7276), 1052-1055, doi:10.1038/nature08649.
Locatelli, B. et al., 2015: Tropical reforestation and climate change: beyond carbon. *Restoration Ecology*, **23**(4), 337-343.
Locosselli, G. M. et al., 2020: Global tree-ring analysis reveals rapid decrease in tropical tree longevity with temperature. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(52), 33358-33364, doi:10.1073/pnas.2003873117.
Logan, J. A., J. Régnière and J. A. Powell, 2003: Assessing the impacts of global warming on forest pest dynamics. *Frontiers in Ecology and the Environment*, **1**(3), 130-137, doi:https://doi.org/10.1890/1540-9295(2003)001[0130:ATIOGW]2.0.CO;2.
Loiseau, C. et al., 2012: First Evidence and Predictions of Plasmodium Transmission in Alaskan Bird Populations. *PLoS ONE*, **7**(9), e44729, doi:10.1371/journal.pone.0044729.

Loisel, J. et al., 2021: Expert assessment of future vulnerability of the global peatland carbon sink. *Nature Climate Change*, **11**(1), 70-77, doi:10.1038/s41558-020-00944-0.
López-i-Gelats, F. et al., 2015: Adaptation Strategies of Andean Pastoralist Households to Both Climate and Non-Climate Changes. *Human Ecology*, **43**(2), 267-282.
López-i-Gelats, F., E. D. G. Fraser, J. F. Morton and M. G. Rivera-Ferre, 2016: What drives the vulnerability of pastoralists to global environmental change? A qualitative meta-analysis. *Global Environmental Change*, **39**, 258-274, doi:https://doi.org/10.1016/j.gloenvcha.2016.05.011.
Loranty, M. M. et al., 2014: Vegetation controls on northern high latitude snow-albedo feedback: observations and CMIP5 model simulations. *Global Change Biology*, **20**(2), 594-606, doi:10.1111/gcb.12391.
Losos, J. B. et al., 2010: Favorable Climate Change Response Explains Non-Native Species' Success in Thoreau's Woods.
Love, P. T. et al., 2017: Impact of climate change on weather related fire risk in the Tasmanian Wilderness World Heritage Area, Technical Report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
Love, P. T. et al., 2019: Tasmanian Wilderness World Heritage Area Climate Change and Bushfire Research Initiative, Technical Report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
Lowe, R. et al., 2013: The development of an early warning system for climate-sensitive disease risk with a focus on dengue epidemics in Southeast Brazil. *Statistics in Medicine*, **32**(5), 864-883, doi:https://doi.org/10.1002/sim.5549.
Lowe, R. et al., 2014: Dengue outlook for the World Cup in Brazil: an early warning model framework driven by real-time seasonal climate forecasts. *The Lancet Infectious Diseases*, **14**(7), 619-626, doi:10.1016/S1473-3099(14)70781-9.
Lowe, R. et al., 2018: Nonlinear and delayed impacts of climate on dengue risk in Barbados: A modelling study. *PLOS Medicine*, **15**(7), e1002613, doi:10.1371/journal.pmed.1002613.
Lu, X. M. et al., 2021: Mountain treelines climb slowly despite rapid climate warming. *Global Ecology and Biogeography*, **30**(1), 305-315, doi:10.1111/geb.13214.
Lubetkin, K., A. Westerling and L. Kueppers, 2017: Climate and landscape drive the pace and pattern of conifer encroachment into subalpine meadows. *Ecological Applications*, **27**(6), 1876-1887, doi:10.1002/eap.1574.
Lucash, M. S. et al., 2018: More than the sum of its parts: how disturbance interactions shape forest dynamics under climate change. *Ecosphere*, **9**(6), 22, doi:10.1002/ecs2.2293.
Ludynia, K., J. Kemper and J.-P. Roux, 2012: The Namibian Islands' Marine Protected Area: using seabird tracking data to define boundaries and assess their adequacy. *Biological Conservation*, **156**, 136-145.
Lund, M., T. R. Christensen, A. Lindroth and P. Schubert, 2012: Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland. *Environmental Research Letters*, **7**(4), 045704, doi:10.1088/1748-9326/7/4/045704.
Lunga, W. and C. Musarurwa, 2016: Exploiting indigenous knowledge commonwealth to mitigate disasters: from the archives of vulnerable communities in Zimbabwe.
Luom, T. T., 2020: Effect of flooding on peatland in U Minh Thuong National Park, Vietnam. *Journal of Soil Science and Environmental Management*, **11**(2), 57-64.
Lurgi, M., B. C. Lopez and J. M. Montoya, 2012: Novel communities from climate change. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **367**(1605), 2913-2922, doi:10.1098/rstb.2012.0238.
Luther, D. et al., 2020: Global assessment of critical forest and landscape restoration needs for threatened terrestrial vertebrate species. *Global Ecology and Conservation*, **24**, e01359, doi:https://doi.org/10.1016/j.gecco.2020.e01359.
Lynch, A. J. et al., 2016a: The social, economic, and environmental importance of inland fish and fisheries. *Environmental Reviews*, doi:10.1139/er-2015-0064.
Lynch, A. J. et al., 2016b: Climate Change Effects on North American Inland Fish Populations and Assemblages. *Fisheries*, **41**(7), 346-361, doi:10.1080/03632415.2016.1186016.
Lyra, A. et al., 2017: Projections of climate change impacts on central America tropical rainforest. *Climatic Change*, **141**(1), 93-105, doi:10.1007/s10584-016-1790-2.
Lyra, A. D., S. C. Chou and G. D. Sampaio, 2016: Sensitivity of the Amazon biome to high resolution climate change projections. *Acta Amazonica*, **46**(2), 175-187, doi:10.1590/1809-4392201502225.
M. Greenler, S. and J. J. Ebersole, 2015: Bird communities in tropical agroforestry ecosystems: an underappreciated conservation resource. *Agroforestry Systems*, **89**(4), 691-704, doi:10.1007/s10457-015-9805-y.
Ma, R. et al., 2010: A half-century of changes in China's lakes: Global warming or human influence? *Geophysical Research Letters*, **37**(24), n/a-n/a, doi:10.1029/2010gl045514.
MacDonald, G. M. et al., 2006: Rapid Early Development of Circumarctic Peatlands and Atmospheric CH4 and CO2 Variations. *Science*, **314**(5797), 285-288, doi:10.1126/science.1131722.
MacFadden, D. R. et al., 2018: Antibiotic resistance increases with local temperature. *Nature Climate Change*, **8**(6), 510-514, doi:10.1038/s41558-018-0161-6.
Macfarlane, W. W., J. A. Logan and W. R. Kern, 2013: An innovative aerial assessment of Greater Yellowstone Ecosystem mountain pine beetle-caused whitebark pine mortality. *Ecological Applications*, **23**(2), 421-437, doi:10.1890/11-1982.1.

Macgregor, N. A. and N. van Dijk, 2014: Adaptation in practice: how managers of nature conservation areas in eastern England are responding to climate change. *Environmental management*, **54**(4), 700-719.
Machado-Silva, F. et al., 2020: Drought and fires influence the respiratory diseases hospitalizations in the Amazon. *Ecological Indicators*, **109**, 13, doi:10.1016/j.ecolind.2019.105817.
Mack, M. C. et al., 2021: Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees. *Science*, **372**(6539), 280-+, doi:10.1126/science.abf3903.
Mackay, C. M. and M. T. Schmitt, 2019: Do people who feel connected to nature do more to protect it? A meta-analysis. *Journal of Environmental Psychology*, **65**, 101323.
MacKay, M. and F. Seglenieks, 2012: On the simulation of Laurentian Great Lakes water levels under projections of global climate change. *Climatic Change*, **117**(1-2), 55-67, doi:10.1007/s10584-012-0560-z.
Mackey, B. et al., 2020: Understanding the importance of primary tropical forest protection as a mitigation strategy. *Mitigation and Adaptation Strategies for Global Change*, **25**(5), 763-787, doi:10.1007/s11027-019-09891-4.
MacLean, H. J., J. G. Kingsolver and L. B. Buckley, 2016: Historical changes in thermoregulatory traits of alpine butterflies reveal complex ecological and evolutionary responses to recent climate change. *Climate Change Responses*, **3**(1), 13, doi:10.1186/s40665-016-0028-x.
MacLean, H. J., M. E. Nielsen, J. G. Kingsolver and L. B. Buckley, 2019a: Using museum specimens to track morphological shifts through climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **374**(1763), 20170404, doi:10.1098/rstb.2017.0404.
MacLean, H. J. et al., 2019b: Evolution and plasticity of thermal performance: an analysis of variation in thermal tolerance and fitness in 22 Drosophila species. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **374**(1778), 10, doi:10.1098/rstb.2018.0548.
MacLean, S. A. and S. R. Beissinger, 2017: Species' traits as predictors of range shifts under contemporary climate change: A review and meta-analysis. *Global Change Biology*, **23**(10), 4094-4105.
Macnab, V. and I. Barber, 2012: Some (worms) like it hot: fish parasites grow faster in warmer water, and alter host thermal preferences. *Global Change Biology*, **18**(5), 1540-1548, doi:https://doi.org/10.1111/j.1365-2486.2011.02595.x.
Macreadie, P. I. et al., 2019: The future of Blue Carbon science. *Nature Communications*, **10**(1), 3998, doi:10.1038/s41467-019-11693-w.
Madani, N. et al., 2020a: Below-surface water mediates the response of African forests to reduced rainfall. *Environmental Research Letters*, **15**(3), doi:10.1088/1748-9326/ab724a.
Madani, N. et al., 2020b: Recent Amplified Global Gross Primary Productivity Due to Temperature Increase Is Offset by Reduced Productivity Due to Water Constraints. *AGU Advances*, **1**(4), e2020AV000180, doi:https://doi.org/10.1029/2020AV000180.
Madrigal-Gonzalez, J. et al., 2020: Climate reverses directionality in the richness-abundance relationship across the World's main forest biomes. *Nature Communications*, **11**(1), 7, doi:10.1038/s41467-020-19460-y.
Madsen, J. D. et al., 2001: The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia*, **444**(1), 71-84, doi:10.1023/A:1017520800568.
Maeck, A., H. Hofmann and A. Lorke, 2014: Pumping methane out of aquatic sediments: Ebullition forcing mechanisms in an impounded river. *Biogeosciences*, **11**(11), 2925-2938.
Maes, D. et al., 2019: The potential of species distribution modelling for reintroduction projects: the case study of the Chequered Skipper in England. *Journal of Insect Conservation*, **23**(2), 419-431, doi:10.1007/s10841-019-00154-w.
Maestre, F. T. et al., 2021: Biogeography of global drylands. *New Phytologist*, **231**(2), 540-558, doi:https://doi.org/10.1111/nph.17395.
Magnuson, J. J. and R. C. Lathrop, 2014: Lake Ice: Winter, Beauty, Value, Changes, and a Threatened Future. *LAKELINE*,(Winter 2014), 18-27.
Magozzi, S. and P. Calosi, 2015: Integrating metabolic performance, thermal tolerance, and plasticity enables for more accurate predictions on species vulnerability to acute and chronic effects of global warming. *Global Change Biology*, **21**(1), 181-194, doi:https://doi.org/10.1111/gcb.12695.
Mahoney, P. C. and M. J. Bishop, 2017: Assessing risk of estuarine ecosystem collapse. *Ocean & Coastal Management*, **140**, 46-58, doi:https://doi.org/10.1016/j.ocecoaman.2017.02.021.
Maia, V. A. et al., 2020: Interactions between climate and soil shape tree community assembly and above-ground woody biomass of tropical dry forests. *Forest Ecology and Management*, **474**, 118348.
Mainali, K. et al., 2020: Contrasting responses to climate change at Himalayan treelines revealed by population demographics of two dominant species. *Ecology and Evolution*, **10**(3), 1209-1222, doi:https://doi.org/10.1002/ece3.5968.
Maino, J. L. et al., 2016: Mechanistic models for predicting insect responses to climate change. *Current Opinion in Insect Science*, **17**, 81-86, doi:10.1016/j.cois.2016.07.006.
Malhi, Y. et al., 2009: Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences*, **106**(49), 20610-20615, doi:10.1073/pnas.0804619106.
Malhi, Y. et al., 2016: Megafauna and ecosystem function from the Pleistocene to the Anthropocene. *Proceedings of the National Academy of Sciences*, **113**(4), 838-846.

Malhi, Y. et al., 2020: Climate change and ecosystems: threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190104, doi:10.1098/rstb.2019.0104.
Malhi, Y. et al., 2014: Tropical forests in the Anthropocene. *Annual Review of Environment and Resources*, **39**.
Maljanen, M. et al., 2010: Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. *Biogeosciences*, **7**(9), 2711-2738, doi:10.5194/bg-7-2711-2010.
Mallory, C. D. and M. S. Boyce, 2017: Observed and predicted effects of climate change on Arctic caribou and reindeer. *Environmental Reviews*, **26**(1), 13-25, doi:10.1139/er-2017-0032.
Malsy, M., T. Aus der Beek, S. Eisner and M. Flörke, 2012: Climate change impacts on Central Asian water resources. *Advances in Geosciences*, **32**, 77-83, doi:10.5194/adgeo-32-77-2012.
Manea, A. and M. R. Leishman, 2019: The resprouting response of co-occurring temperate woody plant and grass species to elevated CO2 : An insight into woody plant encroachment of grasslands. *Austral Ecology*, **44**(5), 917-926, doi:10.1111/aec.12760.
Mann, M. L. et al., 2016: Incorporating Anthropogenic Influences into Fire Probability Models: Effects of Human Activity and Climate Change on Fire Activity in California. *PLoS ONE*, **11**(4), e0153589, doi:10.1371/journal.pone.0153589.
Manning, S. R. and D. R. Nobles, 2017: Impact of global warming on water toxicity: cyanotoxins. *Current Opinion in Food Science*, **18**, 14-20, doi:10.1016/j.cofs.2017.09.013.
Mansuy, N. et al., 2019: Contrasting human influences and macro-environmental factors on fire activity inside and outside protected areas of North America. *Environmental Research Letters*, **14**(6), doi:10.1088/1748-9326/ab1bc5.
Mantzouki, E. et al., 2018: Temperature Effects Explain Continental Scale Distribution of Cyanobacterial Toxins. *Toxins*, **10**(4), doi:10.3390/toxins10040156.
Mao, J. F. et al., 2016: Human-induced greening of the northern extratropical land surface. *Nature Climate Change*, **6**(10), 959-+, doi:10.1038/nclimate3056.
Marcé, R. et al., 2019: Emissions from dry inland waters are a blind spot in the global carbon cycle. *Earth-Science Reviews*, **188**, 240-248, doi:10.1016/j.earscirev.2018.11.012.
Marcheggiani, S. et al., 2010: Risks of water-borne disease outbreaks after extreme events. *Toxicological & Environmental Chemistry*, **92**(3), 593-599, doi:10.1080/02772240903252140.
Marcogliese, D. J., 2016: The Distribution and Abundance of Parasites in Aquatic Ecosystems in a Changing Climate: More than Just Temperature. *Integrative and Comparative Biology*, **56**(4), 611-619, doi:10.1093/icb/icw036.
Marcogliese, D. J., S. A. Locke, M. Gélinas and A. D. Gendron, 2016: Variation in Parasite Communities in Spottail Shiners (Notropis hudsonius) Linked with Precipitation. *Journal of Parasitology*, **102**(1), 27-36, doi:10.1645/12-31.
Marengo, J. A. et al., 2020: Assessing drought in the drylands of northeast Brazil under regional warming exceeding 4 °C. *Natural Hazards*, **103**(2), 2589-2611, doi:10.1007/s11069-020-04097-3.
Marengo, J. A. et al., 2018: Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. *Frontiers in Earth Science*, **6**, doi:10.3389/feart.2018.00228.
Margono, B. A. et al., 2014: Primary forest cover loss in Indonesia over 2000-2012. *Nature Climate Change*, **4**(8), 730-735, doi:10.1038/nclimate2277.
Mariani, M. et al., 2019: Climate change reduces resilience to fire in subalpine rainforests. *Global Change Biology*, **25**(6), 2030-2042, doi:10.1111/gcb.14609.
Marimon, B. S. et al., 2014: Disequilibrium and hyperdynamic tree turnover at the forest–cerrado transition zone in southern Amazonia. *Plant Ecology & Diversity*, **7**(1-2), 281-292.
Marini, L. et al., 2017: Climate drivers of bark beetle outbreak dynamics in Norway spruce forests. *Ecography*, **40**(12), 1426-1435, doi:10.1111/ecog.02769.
Mark, B. G. et al., 2017: Glacier loss and hydro-social risks in the Peruvian Andes. *Global and Planetary Change*, **159**, 61-76, doi:10.1016/j.gloplacha.2017.10.003.
Markovic, D. et al., 2014: Europe's freshwater biodiversity under climate change: distribution shifts and conservation needs. *Diversity and Distributions*.
Markovic, D. et al., 2013: Variability and alterations of water temperatures across the Elbe and Danube River Basins. *Climatic Change*, **119**(2), 375-389, doi:10.1007/s10584-013-0725-4.
Marselle, M. R., M. Triguero Mas, M. J. Nieuwenhuijsen and A. Bonn, 2021: Pathways linking biodiversity to human health: A conceptual framework. doi:10.1016/j.envint.2021.106420.
Marszelewski, W. and B. Pius, 2016: Long-term changes in temperature of river waters in the transitional zone of the temperate climate: a case study of Polish rivers. *Hydrological Sciences Journal*, **61**(8), 1430-1442, doi:10.1080/02626667.2015.1040800.
Martens, C. et al., 2021: Large uncertainties in future biome changes in Africa call for flexible climate adaptation strategies. *Global Change Biology*, **27**(2), 340-358, doi:10.1111/gcb.15390.
Martin-Ortega, J., T. E. H. Allott, K. Glenk and M. Schaafsma, 2014: Valuing water quality improvements from peatland restoration: Evidence and challenges. *Ecosystem Services*, **9**, 34-43, doi:10.1016/j.ecoser.2014.06.007.
Martín-Vélez, V. et al., 2020: Functional connectivity network between terrestrial and aquatic habitats by a generalist waterbird, and implications for biovectoring. *Science of The Total Environment*, **705**, 135886, doi:https://doi.org/10.1016/j.scitotenv.2019.135886.

Martín, E. G., M. M. Costa, S. Egerer and U. Schneider, 2021: Assessing the long-term effectiveness of Nature-Based Solutions under different climate change scenarios. *Science of The Total Environment*, 148515.
Martín, E. G. et al., 2020: Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. *Science of the Total Environment*, **738**, 139693.
Martínez-Valladares, M. et al., 2013: Prevalence of gastrointestinal nematodes and Fasciola hepatica in sheep in the northwest of Spain: relation to climatic conditions and/or man-made environmental modifications. *Parasites & Vectors*, **6**(1), 282, doi:10.1186/1756-3305-6-282.
Martinez-Vilalta, J. and F. Lloret, 2016: Drought-induced vegetation shifts in terrestrial ecosystems: The key role of regeneration dynamics. *Global and Planetary Change*, **144**, 94-108, doi:10.1016/j.gloplacha.2016.07.009.
Martinez, P. P. et al., 2017: Cholera forecast for Dhaka, Bangladesh, with the 2015-2016 El Niño: Lessons learned. *PLOS ONE*, **12**(3), e0172355, doi:10.1371/journal.pone.0172355.
Mason, S. C. et al., 2015: Geographical range margins of many taxonomic groups continue to shift polewards. *Biological Journal of the Linnean Society*, **115**(3), 586-597.
Masrur, A., A. N. Petrov and J. DeGroote, 2018: Circumpolar spatio-temporal patterns and contributing climatic factors of wildfire activity in the Arctic tundra from 2001-2015. *Environmental Research Letters*, **13**(1), doi:10.1088/1748-9326/aa9a76.
Massimino, D. et al., 2020: Can microclimate offer refuge to an upland bird species under climate change? *Landscape Ecology*, **35**(9), 1907-1922.
Masubelele, M. L., M. T. Hoffman and W. J. Bond, 2015a: Biome stability and long-term vegetation change in the semi-arid, south-eastern interior of South Africa: a synthesis of repeat photo-monitoring studies. *South African Journal of Botany*, **101**, 139-147.
Masubelele, M. L., M. T. Hoffman and W. J. Bond, 2015b: A repeat photograph analysis of long-term vegetation change in semi-arid South Africa in response to land use and climate. *Journal of vegetation science*, **26**(5), 1013-1023.
Mathes, G. H., J. van Dijk, W. Kiessling and M. J. Steinbauer, 2021: Extinction risk controlled by interaction of long-term and short-term climate change. *Nature Ecology & Evolution*, **5**(3), 304-310, doi:10.1038/s41559-020-01377-w.
Matilainen, A., M. Vepsäläinen and M. Sillanpää, 2010: Natural organic matter removal by coagulation during drinking water treatment: A review. *Advances in colloid and interface science*, **159**(2), 189-197.
Matveev, A. et al., 2016: High methane emissions from thermokarst lakes in subarctic peatlands. *Limnology and Oceanography*, **61**(S1), S150-S164, doi:10.1002/lno.10311.
Matysek, M., S. Evers, M. K. Samuel and S. Sjogersten, 2018: High heterotrophic CO2 emissions from a Malaysian oil palm plantations during dry-season. *Wetlands Ecology and Management*, **26**(3), 415-424, doi:10.1007/s11273-017-9583-6.
Mawdsley, J. R., R. O'malley and D. S. Ojima, 2009: A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology*, **23**(5), 1080-1089.
Mbokodo, I. et al., 2020: Heatwaves in the future warmer climate of South Africa. *Atmosphere*, **11**(7), 712.
McAlpine, C. A. et al., 2018: Forest loss and Borneo's climate. *Environmental Research Letters*, **13**(4), 044009, doi:10.1088/1748-9326/aaa4ff.
McDowell, N. et al., 2018: Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, **219**(3), 851-869.
McDowell, N. G. et al., 2020: Pervasive shifts in forest dynamics in a changing world. *Science*, **368**(6494), doi:10.1126/science.aaz9463.
McDowell, N. G. et al., 2016: Multi-scale predictions of massive conifer mortality due to chronic temperature rise. *Nature Climate Change*, **6**(3), 295-300, doi:10.1038/nclimate2873.
McElwee, P. et al., 2020: The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. *Global Change Biology*, **26**(9), 4691-4721, doi:10.1111/gcb.15219.
McGough, S. F. et al., 2020: Rates of increase of antibiotic resistance and ambient temperature in Europe: a cross-national analysis of 28 countries between 2000 and 2016. *Eurosurveillance*, **25**(45), 1900414, doi:10.2807/1560-7917.ES.2020.25.45.1900414.
McGuire, A. D. et al., 2018a: Assessing historical and projected carbon balance of Alaska: A synthesis of results and policy/management implications. *Ecological Applications*, **28**(6), 1396-1412, doi:10.1002/eap.1768.
McGuire, A. D. et al., 2018b: Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proceedings of the National Academy of Sciences*, **115**(15), 3882-3887, doi:10.1073/pnas.1719903115.
McIntyre, K. M. et al., 2017: Systematic Assessment of the Climate Sensitivity of Important Human and Domestic Animals Pathogens in Europe. *Scientific Reports*, **7**(1), 7134, doi:10.1038/s41598-017-06948-9.
McIntyre, P. B., C. A. R. Liermann and C. Revenga, 2016: Linking freshwater fishery management to global food security and biodiversity conservation. *Proceedings of the National Academy of Sciences*, **113**(45), 12880-12885, doi:10.1073/pnas.1521540113.

McIntyre, P. J. et al., 2015: Twentieth-century shifts in forest structure in California: Denser forests, smaller trees, and increased dominance of oaks. *Proceedings of the National Academy of Sciences*, **112**(5), 1458-1463, doi:10.1073/pnas.1410186112.
McKechnie, A. E. et al., 2017: Avian thermoregulation in the heat: evaporative cooling in five Australian passerines reveals within-order biogeographic variation in heat tolerance. *Journal of Experimental Biology*, **220**(13), 2436-2444, doi:10.1242/jeb.155507.
McKechnie, A. E., A. R. Gerson and B. O. Wolf, 2021: Thermoregulation in desert birds: scaling and phylogenetic variation in heat tolerance and evaporative cooling. *Journal of Experimental Biology*, **224**(Suppl_1), doi:10.1242/jeb.229211.
McLaughlin, B. C. et al., 2017: Hydrologic refugia, plants, and climate change. *Global change biology*, **23**(8), 2941-2961.
McMahan, E. A. and D. Estes, 2015: The effect of contact with natural environments on positive and negative affect: A meta-analysis. *The Journal of Positive Psychology*, **10**(6), 507-519, doi:10.1080/17439760.2014.994224.
McMillan, K. M., D. Lesbarrères, X. A. Harrison and T. W. J. Garner, 2020: Spatiotemporal heterogeneity decouples infection parameters of amphibian chytridiomycosis. *Journal of Animal Ecology*, **89**(4), 1109-1121, doi:https://doi.org/10.1111/1365-2656.13170.
McNicol, I. M., C. M. Ryan and E. T. Mitchard, 2018: Carbon losses from deforestation and widespread degradation offset by extensive growth in African woodlands. *Nature communications*, **9**(1), 3045.
McWethy, D. B. et al., 2018: Landscape drivers of recent fire activity (2001-2017) in south-central Chile. *PloS one*, **13**(8), e0201195.
Meade, J. et al., 2018: Substantial reduction in thermo-suitable microhabitat for a rainforest marsupial under climate change. *Biology Letters*, **14**(12), 20180189, doi:10.1098/rsbl.2018.0189.
Meakem, V. et al., 2018: Role of tree size in moist tropical forest carbon cycling and water deficit responses. *New Phytologist*, **219**(3), 947-958.
Mechler, R. and L. M. Bouwer, 2015: Understanding trends and projections of disaster losses and climate change: is vulnerability the missing link? *Climatic Change*, **133**(1), 23-35.
Medlock, J. M. et al., 2013: Driving forces for changes in geographical distribution of Ixodes ricinus ticks in Europe. *Parasites & Vectors*, **6**(1), 1, doi:10.1186/1756-3305-6-1.
Mehmood, K. et al., 2017: A review on epidemiology, global prevalence and economical losses of fasciolosis in ruminants. *Microbial Pathogenesis*, **109**, 253-262, doi:10.1016/j.micpath.2017.06.006.
Mehrabi, Z., E. C. Ellis and N. Ramankutty, 2018: The challenge of feeding the world while conserving half the planet. *Nature Sustainability*, **1**(8), 409-412, doi:10.1038/s41893-018-0119-8.
Mehran, A. et al., 2017: Compounding Impacts of Human-Induced Water Stress and Climate Change on Water Availability. *Scientific Reports*, **7**, doi:10.1038/s41598-017-06765-0.
Meigs, G. W., C. J. Dunn, S. A. Parks and M. A. Krawchuk, 2020: Influence of topography and fuels on fire refugia probability under varying fire weather conditions in forests of the Pacific Northwest, USA. *Canadian Journal of Forest Research*, **50**(7), 636-647, doi:10.1139/cjfr-2019-0406.
Meigs, G. W. et al., 2016: Do insect outbreaks reduce the severity of subsequent forest fires? *Environmental Research Letters*, **11**(4), 10, doi:10.1088/1748-9326/11/4/045008.
Mekonnen, M. M. and A. Y. Hoekstra, 2016: Four billion people facing severe water scarcity. *Science Advances*, **2**(2), doi:10.1126/sciadv.1500323.
Mekonnen, Z. A., W. J. Riley and R. F. Grant, 2018: 21st century tundra shrubification could enhance net carbon uptake of North America Arctic tundra under an RCP8.5 climate trajectory. *Environmental Research Letters*, **13**(5), doi:10.1088/1748-9326/aabf28.
Meli, P., J. M. R. Benayas, P. Balvanera and M. M. Ramos, 2014: Restoration enhances wetland biodiversity and ecosystem service supply, but results are context-dependent: a meta-analysis. *PloS one*, **9**(4), e93507.
Melillo, J. M. et al., 2016: Protected areas' role in climate-change mitigation. *Ambio*, **45**(2), 133-145, doi:10.1007/s13280-015-0693-1.
Meller, L. et al., 2015: Balance between climate change mitigation benefits and land use impacts of bioenergy: conservation implications for European birds. *GCB Bioenergy*, **7**(4), 741-751, doi:10.1111/gcbb.12178.
Melnikova, I. and T. Sasai, 2020: Effects of Anthropogenic Activity on Global Terrestrial Gross Primary Production. *Journal of Geophysical Research-Biogeosciences*, **125**(3), doi:10.1029/2019jg005403.
Mendonça, R. et al., 2017: Organic carbon burial in global lakes and reservoirs. *Nature Communications*, **8**(1), 1694, doi:10.1038/s41467-017-01789-6.
Menezes-Silva, P. E. et al., 2019: Different ways to die in a changing world: Consequences of climate change for tree species performance and survival through an ecophysiological perspective. *Ecology and Evolution*, **9**(20), 11979-11999, doi:10.1002/ece3.5663.
Meng, F., F. Su, Y. Li and K. Tong, 2019: Changes in terrestrial water storage during 2003–2014 and possible causes in Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, **124**(6), 2909-2931.
Mengist, W., T. Soromessa and G. Legese, 2020: Ecosystem services research in mountainous regions: A systematic literature review on current knowledge and research gaps. *Science of The Total Environment*, **702**, 134581, doi:https://doi.org/10.1016/j.scitotenv.2019.134581.

Menzel, A. et al., 2006: European phenological response to climate change matches the warming pattern. *Global change biology*, **12**(10), 1969-1976.
Menzel, A. et al., 2020: Climate change fingerprints in recent European plant phenology. *Global Change Biology*, **26**(4), 2599-2612.
Mercado, L. M. et al., 2018: Large sensitivity in land carbon storage due to geographical and temporal variation in the thermal response of photosynthetic capacity. *New Phytologist*, **218**(4), 1462-1477, doi:10.1111/nph.15100.
Merriam, E. R., R. Fernandez, J. T. Petty and N. Zegre, 2017: Can brook trout survive climate change in large rivers? If it rains. *Science of The Total Environment*, **607-608**, 1225-1236, doi:https://doi.org/10.1016/j.scitotenv.2017.07.049.
Meteorology, B. o., 2014: *Special Climate Statement 47 - an intense heatwave in central and eastern Australia*, **http://www.bom.gov.au/climate/current/statements/scs47.pdf**.
Mezbahuddin, M., R. F. Grant and T. Hirano, 2015: How hydrology determines seasonal and interannual variations in water table depth, surface energy exchange, and water stress in a tropical peatland: Modeling versus measurements. *Journal of Geophysical Research: Biogeosciences*, **120**(11), 2132-2157, doi:10.1002/2015JG003005.
Mezei, P. et al., 2017: Storms, temperature maxima and the Eurasian spruce bark beetle Ips typographus-An infernal trio in Norway spruce forests of the Central European High Tatra Mountains. *Agricultural and Forest Meteorology*, **242**, 85-95, doi:10.1016/j.agrformet.2017.04.004.
Micale, V., B. Tonkonogy and F. Mazza, 2018: *Understanding and Increasing Finance for Climate Adaptation in Developing Countries*. Available at: https://climatepolicyinitiative.org/wp-content/uploads/2018/12/Understanding-and-Increasing-Finance-for-Climate-Adaptation-in-Developing-Countries-1.pdf.
Michalak, J., J. Lawler, D. Roberts and C. Carroll, 2018: Distribution and protection of climatic refugia in North America. *Conservation Biology*, **32**(6), 1414-1425, doi:10.1111/cobi.13130.
Midgley, G. F. and W. J. Bond, 2015: Future of African terrestrial biodiversity and ecosystems under anthropogenic climate change. *Nature Climate Change*, **5**(9), 823-829, doi:10.1038/nclimate2753.
Miettinen, J. et al., 2012: Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections. *GCB Bioenergy*, **4**(6), 908-918, doi:10.1111/j.1757-1707.2012.01172.x.
Miettinen, J. et al., 2017: From carbon sink to carbon source: Extensive peat oxidation in insular Southeast Asia since 1990. *Environmental Research Letters*, **12**(2), doi:10.1088/1748-9326/aa5b6f.
Miettinen, J., C. Shi and S. C. Liew, 2016: Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, **6**, 67-78, doi:10.1016/j.gecco.2016.02.004.
Mills James, N., L. Gage Kenneth and S. Khan Ali, 2010: Potential Influence of Climate Change on Vector-Borne and Zoonotic Diseases: A Review and Proposed Research Plan. *Environmental Health Perspectives*, **118**(11), 1507-1514, doi:10.1289/ehp.0901389.
Milly, P. C. D. et al., 2008: Stationarity Is Dead: Whither Water Management? *Science*, **319**(5863), 573-574, doi:10.1126/science.1151915.
Milner, A. M. et al., 2017: Glacier shrinkage driving global changes in downstream systems. *Proc Natl Acad Sci U S A*, **114**(37), 9770-9778, doi:10.1073/pnas.1619807114.
Mineau, M. M. et al., 2016: Dissolved organic carbon uptake in streams: A review and assessment of reach-scale measurements. *Journal of Geophysical Research: Biogeosciences*, **121**(8), 2019-2029.
Miralles, D. G., P. Gentine, S. I. Seneviratne and A. J. Teuling, 2019: Land-atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Annals of the New York Academy of Sciences*, **1436**(1), 19-35, doi:10.1111/nyas.13912.
Mishra, S. et al., 2021a: Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration. *Journal of Applied Ecology*, **58**(7), 1370-1387, doi:https://doi.org/10.1111/1365-2664.13905.
Mishra, U. et al., 2021b: Spatial heterogeneity and environmental predictors of permafrost region soil organic carbon stocks. *Science Advances*, **7**(9), 12, doi:10.1126/sciadv.aaz5236.
Mitchard, E. T. A., 2018: The tropical forest carbon cycle and climate change. *Nature*, **559**(7715), 527-534, doi:10.1038/s41586-018-0300-2.
Mitchard, E. T. A. et al., 2014: Markedly divergent estimates of Amazon forest carbon density from ground plots and satellites. *Global Ecology and Biogeography*, **23**(8), 935-946, doi:10.1111/geb.12168.
Mitchell, N. J. and F. J. Janzen, 2010: Temperature-Dependent Sex Determination and Contemporary Climate Change. *Sexual Development*, **4**(1-2), 129-140, doi:10.1159/000282494.
Mo, M. and M. Roache, 2020: A review of intervention methods used to reduce flying-fox mortalities in heat stress events. *Australian Mammalogy*, doi:10.1071/AM20038.
Moatar, F. and J. Gailhard, 2006: Water temperature behaviour in the River Loire since 1976 and 1881. *Comptes Rendus Geoscience*, **338**(5), 319-328, doi:doi.org/10.1016/j.crte.2006.02.011.

Mockrin, M. H., R. F. Rockwell, K. H. Redford and N. S. Keuler, 2011: Effects of Landscape Features on the Distribution and Sustainability of Ungulate Hunting in Northern Congo. *Conservation Biology*, **25**(3), 514-525, doi:https://doi.org/10.1111/j.1523-1739.2011.01660.x.
Mod, H. K. and M. Luoto, 2016: Arctic shrubification mediates the impacts of warming climate on changes to tundra vegetation. *Environmental Research Letters*, **11**(12), doi:124028 10.1088/1748-9326/11/12/124028.
Moftakhari, H. R. et al., 2017: Compounding effects of sea level rise and fluvial flooding. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(37), 9785-9790, doi:10.1073/pnas.1620325114.
Mokany, K. et al., 2016: Integrating modelling of biodiversity composition and ecosystem function. *Oikos*, **125**(1), 10-19, doi:10.1111/oik.02792.
Molnár, P. K., S. J. Kutz, B. M. Hoar and A. P. Dobson, 2013: Metabolic approaches to understanding climate change impacts on seasonal host-macroparasite dynamics. *Ecology Letters*, **16**(1), 9-21, doi:10.1111/ele.12022.
Moloney, K. A. et al., 2019: Increased fire risk in Mojave and Sonoran shrublands due to exotic species and extreme rainfall events. *Ecosphere*, **10**(2), doi:10.1002/ecs2.2592.
Moncrieff, G. R., S. Chamaille-Jammes and W. J. Bond, 2014a: Modelling direct and indirect impacts of browser consumption on woody plant growth: moving beyond biomass. *Oikos*, **123**(3), 315-322, doi:10.1111/j.1600-0706.2013.00904.x.
Moncrieff, G. R., S. Scheiter, W. J. Bond and S. I. Higgins, 2014b: Increasing atmospheric CO2 overrides the historical legacy of multiple stable biome states in Africa. *New Phytol*, **201**(3), 908-915, doi:10.1111/nph.12551.
Moncrieff, G. R. et al., 2016: The future distribution of the savannah biome: model-based and biogeographic contingency. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **371**(1703), doi:20150311 10.1098/rstb.2015.0311.
Moncrieff, G. R., S. Scheiter, J. A. Slingsby and S. I. Higgins, 2015: Understanding global change impacts on South African biomes using Dynamic Vegetation Models. *South African Journal of Botany*, **101**, 16-23, doi:10.1016/j.sajb.2015.02.004.
Moo-Llanes, D. et al., 2013: Current and Future Niche of North and Central American Sand Flies (Diptera: Psychodidae) in Climate Change Scenarios. *PLoS Negl Trop Dis*, **7**(9), e2421, doi:10.1371/journal.pntd.0002421.
Moomaw, W. R. et al., 2018: Wetlands In a Changing Climate: Science, Policy and Management. *Wetlands*, **38**(2), 183-205, doi:10.1007/s13157-018-1023-8.
Moomaw, W. R., S. A. Masino and E. K. Faison, 2019: Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good. *Frontiers in Forests and Global Change*, **2**(27), doi:10.3389/ffgc.2019.00027.
Morán-Ordóñez, A. et al., 2020: Future impact of climate extremes in the Mediterranean: Soil erosion projections when fire and extreme rainfall meet. *Land Degradation & Development*, **31**(18), 3040-3054.
Moran, E. V. and J. M. Alexander, 2014: Evolutionary responses to global change: lessons from invasive species. *Ecology Letters*, **17**(5), 637-649, doi:https://doi.org/10.1111/ele.12262.
Mordecai, E. A. et al., 2019: Thermal biology of mosquito-borne disease. *Ecology Letters*, **22**(10), 1690-1708, doi:10.1111/ele.13335.
Mordecai, E. A. et al., 2017: Detecting the impact of temperature on transmission of Zika, dengue, and chikungunya using mechanistic models. *PLOS Neglected Tropical Diseases*, **11**(4), e0005568, doi:10.1371/journal.pntd.0005568.
Mordecai, E. A. et al., 2013: Optimal temperature for malaria transmission is dramatically lower than previously predicted. *Ecology Letters*, **16**(1), 22-30, doi:https://doi.org/10.1111/ele.12015.
Mordecai, E. A. et al., 2020: Climate change could shift disease burden from malaria to arboviruses in Africa. *The Lancet Planetary Health*, **4**(9), e416-e423, doi:10.1016/S2542-5196(20)30178-9.
Morecroft, M. D., H. Q. Crick, S. J. Duffield and N. A. Macgregor, 2012: Resilience to climate change: translating principles into practice. *Journal of Applied Ecology*, **49**(3), 547-551.
Morecroft, M. D. et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366**(6471), doi:10.1126/science.aaw9256.
Moreira, F. et al., 2020: Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters*, **15**(1), 011001.
Morelli, T. L. et al., 2020: Climate-change refugia: biodiversity in the slow lane. *Frontiers in Ecology and the Environment*, **18**(5), 228-234, doi:10.1002/fee.2189.
Morelli, T. L. et al., 2016: Managing climate change refugia for climate adaptation. *PLoS ONE*, **11**(8), e0159909, doi:10.1371/journal.pone.0159909.
Moreno, M. V., M. Conedera, E. Chuvieco and G. B. Pezzatti, 2014: Fire regime changes and major driving forces in Spain from 1968 to 2010. *Environmental Science & Policy*, **37**, 11-22, doi:10.1016/j.envsci.2013.08.005.
Moret, P., P. Muriel, R. Jaramillo and O. Dangles, 2019: Humboldt's Tableau Physique revisited. *Proceedings of the National Academy of Sciences*, **116**(26), 12889-12894, doi:10.1073/pnas.1904585116.
Mori, A. S. et al., 2021: Biodiversity–productivity relationships are key to nature-based climate solutions. *Nature Climate Change*, **11**(6), 543-550, doi:10.1038/s41558-021-01062-1.
Morin, C. W. et al., 2015: Meteorologically Driven Simulations of Dengue Epidemics in San Juan, PR. *PLOS Neglected Tropical Diseases*, **9**(8), e0004002, doi:10.1371/journal.pntd.0004002.

Morin, X. and W. Thuiller, 2009: Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology*, **90**(5), 1301-1313, doi:10.1890/08-0134.1.
Moritz, M. A. et al., 2012: Climate change and disruptions to global fire activity. *Ecosphere*, **3**(6), doi:10.1890/es11-00345.1.
Morris, R. L., T. M. Konlechner, M. Ghisalberti and S. E. Swearer, 2018: From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Global change biology*, **24**(5), 1827-1842.
Morris, T. and C. Hagen, 2018: Conserving African penguins. *African Birdlife*, **March/April 2018**,, 62-63.
Morueta-Holme, N. et al., 2015: Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(41), 12741-12745, doi:10.1073/pnas.1509938112.
Mote, P. W. et al., 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1**(1), 2.
Mouillot, F. and C. B. Field, 2005: Fire history and the global carbon budget: a 1 degrees x 1 degrees fire history reconstruction for the 20th century. *Global Change Biology*, **11**(3), 398-420, doi:10.1111/j.1365-2486.2005.00920.x.
Moura, L. C. et al., 2019: The legacy of colonial fire management policies on traditional livelihoods and ecological sustainability in savannas: Impacts, consequences, new directions. *Journal of Environmental Management*, **232**, 600-606, doi:10.1016/j.jenvman.2018.11.057.
Mouritsen, K. N., M. M. Sørensen, R. Poulin and B. L. Fredensborg, 2018: Coastal ecosystems on a tipping point: Global warming and parasitism combine to alter community structure and function. *Global Change Biology*, **24**(9), 4340-4356, doi:https://doi.org/10.1111/gcb.14312.
Moyo, H. et al., 2021: Adaptive management in restoration initiatives: Lessons learned from some of South Africa's projects. *South African Journal of Botany*, **139**, 352-361, doi:https://doi.org/10.1016/j.sajb.2021.03.016.
Muchane, M. N. et al., 2020: Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. *Agriculture, Ecosystems & Environment*, **295**, 106899-106899, doi:10.1016/j.agee.2020.106899.
Muhlfeld, C. et al., 2014: Invasive hybridization in a threatened species is accelerated by climate change. *Nature Climate Change*, **4**(7), 620-624, doi:10.1038/nclimate2252.
Muller, A. et al., 2017: Strategies for feeding the world more sustainably with organic agriculture. *Nature Communications*, **8**(1), 1290-1290, doi:10.1038/s41467-017-01410-w.
Müller, J. and F. Joos, 2020: Global peatland area and carbon dynamics from the Last Glacial Maximum to the present – a process-based model investigation. *Biogeosciences*, **17**(21), 5285-5308, doi:10.5194/bg-17-5285-2020.
Municipality, e., 2020: *Durban Strategic Environmental Assessment - Environmental Analysis Phase: Environmental Status Quo Summary Document*, eThekwini Municipa.
Muñoz, Á. G. et al., 2020: AeDES: a next-generation monitoring and forecasting system for environmental suitability of Aedes-borne disease transmission. *Scientific Reports*, **10**(1), 12640, doi:10.1038/s41598-020-69625-4.
Munson, S. M. et al., 2016: Decadal shifts in grass and woody plant cover are driven by prolonged drying and modified by topo-edaphic properties. *Ecological Applications*, **26**(8), 2480-2494, doi:https://doi.org/10.1002/eap.1389.
Murdiyarso, D. et al., 2015: The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, **5**(12), 1089-1092, doi:10.1038/nclimate2734.
Murdock, C. C., E. D. Sternberg and M. B. Thomas, 2016: Malaria transmission potential could be reduced with current and future climate change. *Scientific Reports*, **6**(1), 27771, doi:10.1038/srep27771.
Mureva, A. et al., 2018: Soil organic carbon increases in Semi-arid regions while it decreases in humid regions due to Woody-Plant encroachment of grasslands in South Africa. *Scientific reports*, **8**(1), 1-12.
Murphy, B. P., A. N. Andersen and C. L. Parr, 2016: The underestimated biodiversity of tropical grassy biomes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150319.
Musil, C. F., P. D. R. Van Heerden, C. D. Cilliers and U. Schmiedel, 2009: Mild experimental climate warming induces metabolic impairment and massive mortalities in southern African quartz field succulents. *Environmental and Experimental Botany*, **66**(1), 79-87, doi:10.1016/j.envexpbot.2008.11.008.
Myers-Smith, I. H. et al., 2015: Climate sensitivity of shrub growth across the tundra biome. *Nature Climate Change*, **5**(9), 887.
Myers-Smith, I. H. et al., 2011: Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental Research Letters*, **6**(4), 045509, doi:10.1088/1748-9326/6/4/045509.
Myers-Smith, I. H. et al., 2019: Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change. *Ecological Monographs*, **89**(2), e01351.
Nabuurs, G.-J. et al., 2017: By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. *Forests*, **8**(12), 484.
Nabuurs, G.-J. et al., 2013: First signs of carbon sink saturation in European forest biomass. *Nature Climate Change*, **3**(9), 792-796, doi:10.1038/nclimate1853.
Nackley, L. L. et al., 2018: CO2 enrichment does not entirely ameliorate Vachellia karroo drought inhibition: A missing mechanism explaining savanna bush encroachment. *Environmental and Experimental Botany*, **155**, 98–106.
Nadège, M. T. et al., 2019: Carbon storage potential of cacao agroforestry systems of different age and management intensity. *Climate and Development*, **11**(7), 543-554, doi:10.1080/17565529.2018.1456895.

Nalau, J., S. Becken and B. Mackey, 2018: Ecosystem-based Adaptation: A review of the constraints. *Environmental science & policy*, **89**, 357-364.
Narayan, S. et al., 2016: The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PloS one*, **11**(5), e0154735.
Natali, S. M., E. A. G. Schuur and R. L. Rubin, 2012: Increased plant productivity in Alaskan tundra as a result of experimental warming of soil and permafrost. *Journal of Ecology*, **100**(2), 488-498, doi:10.1111/j.1365-2745.2011.01925.x.
Natali, S. M. et al., 2019: Large loss of CO2 in winter observed across the northern permafrost region. *Nature Climate Change*, **9**(11), 852-+, doi:10.1038/s41558-019-0592-8.
Natalini, F. et al., 2016: The role of climate change in the widespread mortality of holm oak in open woodlands of Southwestern Spain. *Dendrochronologia*, **38**, 51-60.
Nath, T. K., 2016: *Monoculture farming : global practices, ecological impact and benefits/drawbacks*. Global agriculture developments, Nova Science Publishers, Hauppauge, New York, xi, 184 pages pp. ISBN 9781634851664 (hardcover).
Naudts, K. et al., 2016: Europe's forest management did not mitigate climate warming. *Science*, **351**(6273), 597-600, doi:10.1126/science.aad7270.
Navarro-Cerrillo, R. M. et al., 2019: The decline of Algerian Cedrus atlantica forests is driven by a climate shift towards drier conditions. *Dendrochronologia*, **55**, 60-70, doi:10.1016/j.dendro.2019.04.003.
Neely, W. J. et al., 2020: Synergistic effects of warming and disease linked to high mortality in cool-adapted terrestrial frogs. *Biological Conservation*, **245**, 108521, doi:10.1016/j.biocon.2020.108521.
Nelson, D. R., W. N. Adger and K. Brown, 2007: Adaptation to Environmental Change: Contributions of a Resilience Framework. *Annual Review of Environment and Resources*, **32**(1), 395-419, doi:10.1146/annurev.energy.32.051807.090348.
Nelson, K. et al., 2021: Peatland-fire interactions: A review of wildland fire feedbacks and interactions in Canadian boreal peatlands. *Science of The Total Environment*, **769**, 145212, doi:10.1016/j.scitotenv.2021.145212.
Nemani, R. R. et al., 2003: Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, **300**(5625), 1560-1563, doi:10.1126/science.1082750.
Neoh, K.-B. et al., 2015: Understanding the impact of fire on termites in degraded tropical peatlands and the mechanisms for their ecological success: current knowledge and research needs. *Ecological Research*, **30**(5), 759-769, doi:10.1007/s11284-015-1289-8.
Nepstad, D. C., C. M. Stickler, B. Soares and F. Merry, 2008: Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363**(1498), 1737-1746, doi:10.1098/rstb.2007.0036.
Nesper, M. et al., 2019: Simplification of shade tree diversity reduces nutrient cycling resilience in coffee agroforestry. *Journal of applied ecology*, **56**(1), 119-131.
Network, E. and ENCA, 2020: Recommendations for overcoming barriers to mainstreaming the deliver of Nature-based Solutions.Discussion paper from the Climate Change Interest Groups of the European Network of the Heads of Environment Protection Agencies (EPA Network) and Heads of European Nature Conservation Agencies (ENCA). EPA Network.
Neumann, M. et al., 2017: Climate variability drives recent tree mortality in Europe. *Global Change Biology*, **23**(11), 4788-4797, doi:10.1111/gcb.13724.
Neuzil, S. G., J. Rieley and S. Page, 1997: Onset and Rate of Peat and Carbon Accumulation in Four Domed Ombrogenous Peat Deposits, Indonesia, in Proceedings of the International Symposium of Biodiversity, Environmental Importance and Sustainability of Tropical Peat and Peatlands. Samara Pub., Cardigan, UK, pp. 55-72. ISBN 1-873692-10-2 978-1-873692-10-3.
Newbold, T. et al., 2014: A global model of the response of tropical and sub-tropical forest biodiversity to anthropogenic pressures. *Proceedings of the Royal Society B: Biological Sciences*, **281**(1792), doi:20141371 10.1098/rspb.2014.1371.
Newson, S. E. et al., 2014: Can site and landscape-scale environmental attributes buffer bird populations against weather events? *Ecography*, **37**(9), 872-882, doi:10.1111/ecog.00575.
Ngai, R. et al., 2017: Working with natural processes - evidence directory. Appendix 2: literature review. Environment Agency, Bristol, UK.
Nichols, G., I. Lake and C. Heaviside, 2018: Climate change and water-related infectious diseases. *Atmosphere*, **9**(10), 385, doi:10.3390/atmos9100385.
Nichols, J. E. and D. M. Peteet, 2019: Rapid expansion of northern peatlands and doubled estimate of carbon storage. *Nature Geoscience*, **12**(11), 917-921, doi:10.1038/s41561-019-0454-z.
Nikonovas, T. et al., 2020: Near-complete loss of fire-resistant primary tropical forest cover in Sumatra and Kalimantan. *Communications Earth & Environment*, **1**(1), 65, doi:10.1038/s43247-020-00069-4.
Nila, M. U. S. et al., 2019: Predicting the effectiveness of protected areas of Natura 2000 under climate change (vol 8, 13, 2019). *Ecological Processes*, **8**, doi:10.1186/s13717-019-0182-8.
Nishina, K. et al., 2015: Decomposing uncertainties in the future terrestrial carbon budget associated with emission scenarios, climate projections, and ecosystem simulations using the ISI-MIP results. *Earth System Dynamics*, **6**(2), 435-445, doi:10.5194/esd-6-435-2015.

Nitze, I. et al., 2018: Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. *Nature Communications*, **9**, doi:10.1038/s41467-018-07663-3.

Niwa, Y. et al., 2021: Estimation of fire-induced carbon emissions from Equatorial Asia in 2015 using in situ aircraft and ship observations. *Atmospheric Chemistry and Physics*, **21**(12), 9455-9473, doi:10.5194/acp-21-9455-2021.

Nobre, C. A. et al., 2016: Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(39), 10759-10768, doi:10.1073/pnas.1605516113.

Nolan, R. H. et al., 2020: Causes and consequences of eastern Australia's 2019-20 season of mega-fires. *Global change biology*.

Nolet, P. and D. Kneeshaw, 2018: Extreme events and subtle ecological effects: lessons from a long-term sugar maple–American beech comparison. *Ecosphere*, **9**(7), e02336, doi:https://doi.org/10.1002/ecs2.2336.

Norby, R. J. and D. R. Zak, 2011: Ecological Lessons from Free-Air CO ₂ Enrichment (FACE) Experiments. *Annual Review of Ecology, Evolution, and Systematics*, **42**(1), 181-203, doi:10.1146/annurev-ecolsys-102209-144647.

Norton, B. A. et al., 2015: Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and urban planning*, **134**, 127-138.

Norwegian Polar Institute, 2009: *Impact of climate change on infectious diseases of animals in the Norwegian Arctic* [Tryland, M., J. Godfroid and P. Arneberg (eds.)]. **10**, Norwegian Polar Institute Tromsø, Norway, 1-26 pp. Available at: https://brage.npolar.no/npolar-xmlui/bitstream/handle/11250/172981/Kortrapport10.pdf?sequence=1.

Nosil, P. et al., 2018: Natural selection and the predictability of evolution in Timema stick insects. *Science*, **359**(6377), 765, doi:10.1126/science.aap9125.

Nosrat, C. et al., 2021: Impact of recent climate extremes on mosquito-borne disease transmission in Kenya. *PLOS Neglected Tropical Diseases*, **15**(3), e0009182, doi:10.1371/journal.pntd.0009182.

Notaro, M., V. Bennington and B. Lofgren, 2015: Dynamical downscaling–based projections of Great Lakes water levels. *Journal of Climate*, **28**(24), 9721-9745.

Novick, K. A. et al., 2016: The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change*, **6**(11), 1023-1027, doi:10.1038/nclimate3114.

Novita, N. et al., 2021: Geographic Setting and Groundwater Table Control Carbon Emission from Indonesian Peatland: A Meta-Analysis. *Forests*, **12**(7), 832, doi:10.3390/f12070832.

Nugent, K. A., 2019: Carbon cycling at a post-extraction restored peatland: Small-scale processes to global climate impacts. Ph. D. McGill University, Montreal, Canada, 159 pp.

Nugent, K. A. et al., 2019: Prompt active restoration of peatlands substantially reduces climate impact. *Environmental Research Letters*, **14**(12), 124030, doi:10.1088/1748-9326/ab56e6.

Nunez, M. A. et al., 2021: Should tree invasions be used in treeless ecosystems to mitigate climate change? *Frontiers in Ecology and the Environment*, **19**(6), 334-341, doi:10.1002/fee.2346.

O'Briain, R. et al., 2020: The efficacy of riparian tree cover as a climate change adaptation tool is affected by hydromorphological alterations. *Hydrological Processes*, **34**(11), 2433-2449, doi:10.1002/hyp.13739.

O'Connell, C. S., L. Ruan and W. L. Silver, 2018: Drought drives rapid shifts in tropical rainforest soil biogeochemistry and greenhouse gas emissions. *Nat Commun*, **9**(1), 1348, doi:10.1038/s41467-018-03352-3.

O'Connor, T. G., J. R. Puttick and M. T. Hoffman, 2014: Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science*, **31**(2), 67–88.

O'Reilly, C. et al., 2015: Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, **42**(24), 10773-10781, doi:10.1002/2015gl066235.

O'Beirne, M. et al., 2017: Anthropogenic climate change has altered primary productivity in Lake Superior. *Nature communications*, **8**(1), 1-8.

O'Donnell, J. A. et al., 2012: The Effects of Permafrost Thaw on Soil Hydrologic, Thermal, and Carbon Dynamics in an Alaskan Peatland. *Ecosystems*, **15**(2), 213-229, doi:10.1007/s10021-011-9504-0.

O'Gorman, E. J. et al., 2019: A simple model predicts how warming simplifies wild food webs. *Nature Climate Change*, **9**(8), 611-616, doi:10.1038/s41558-019-0513-x.

O'Neil, J. M., T. W. Davis, M. A. Burford and C. J. Gobler, 2012: The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change. *Harmful Algae*, **14**, 313-334, doi:10.1016/j.hal.2011.10.027.

Ockendon, N. et al., 2014: Mechanisms underpinning climatic impacts on natural populations: altered species interactions are more important than direct effects. *Global Change Biology*, **20**(7), 2221-2229, doi:https://doi.org/10.1111/gcb.12559.

Ogden, F. L., T. D. Crouch, R. F. Stallard and J. S. Hall, 2013: Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama. *Water Resources Research*, **49**(12), 8443-8462, doi:https://doi.org/10.1002/2013WR013956.

Ogden, N. H. and L. R. Lindsay, 2016: Effects of Climate and Climate Change on Vectors and Vector-Borne Diseases: Ticks Are Different. *Trends in Parasitology*, **32**(8), 646-656, doi:10.1016/j.pt.2016.04.015.

Ogden, N. H. et al., 2008: Risk maps for range expansion of the Lyme disease vector, Ixodes scapularis, in Canada now and with climate change. *International Journal of Health Geographics*, **7**(1), 24, doi:10.1186/1476-072X-7-24.

Okeyo, A. N., N. Nontongana, T. O. Fadare and A. I. Okoh, 2018: Vibrio Species in Wastewater Final Effluents and Receiving Watershed in South Africa: Implications for Public Health. *International Journal of Environmental Research and Public Health*, **15**(6), doi:10.3390/ijerph15061266.

Okland, B. et al., 2019: Range expansion of the small spruce bark beetle Ips amitinus: a newcomer in northern Europe. *Agricultural and Forest Entomology*, **21**(3), 286-298, doi:10.1111/afe.12331.

Olefeldt, D. et al., 2021: Permafrost Thaw in Northern Peatlands: Rapid Changes in Ecosystem and Landscape Functions. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 27-67. ISBN 978-3-030-71330-0.

Olivares, E. A. O. et al., 2019: Climate Change, Land Use/Land Cover Change, and Population Growth as Drivers of Groundwater Depletion in the Central Valleys, Oaxaca, Mexico. *Remote Sensing*, **11**(11), doi:10.3390/rs11111290.

Oliver, T. H. et al., 2017: Large extents of intensive land use limit community reorganization during climate warming. *Global change biology*, **23**(6), 2272-2283.

Oliver, T. H. et al., 2015a: Biodiversity and resilience of ecosystem functions. *Trends in ecology & evolution*, **30**(11), 673-684.

Oliver, T. H. et al., 2015b: Interacting effects of climate change and habitat fragmentation on drought-sensitive butterflies. *Nature Climate Change*, **5**(10), 941.

Oliver, T. H., R. J. Smithers, C. M. Beale and K. Watts, 2016: Are existing biodiversity conservation strategies appropriate in a changing climate? *Biological Conservation*, **193**, 17-26, doi:https://doi.org/10.1016/j.biocon.2015.10.024.

Olivero, J. et al., 2017: Recent loss of closed forests is associated with Ebola virus disease outbreaks. *Scientific Reports*, **7**(1), 14291, doi:10.1038/s41598-017-14727-9.

Ollerenshaw, C. B. and W. T. Rowlands, 1959: A method of forecasting the incidence of fascioliasis in Anglesey. *Veterinary Record*, **71**(29), 591-598.

Olofsson, J. and E. Post, 2018: Effects of large herbivores on tundra vegetation in a changing climate, and implications for rewilding. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **373**(1761), 20170437.

Olson, D. M. et al., 2001: Terrestrial ecoregions of the worlds: A new map of life on Earth. *BioScience*, **51**(11), 933-938, doi:10.1641/0006-3568(2001)051[0933:teotwa]2.0.co;2.

Olvmo, M. et al., 2020: Sub-arctic palsa degradation and the role of climatic drivers in the largest coherent palsa mire complex in Sweden (Vissátvuopmi), 1955–2016. *Scientific Reports*, **10**(1), 8937, doi:10.1038/s41598-020-65719-1.

Omazic, A. et al., 2019: Identifying climate-sensitive infectious diseases in animals and humans in Northern regions. *Acta Vet Scand*, **61**(1), 53, doi:10.1186/s13028-019-0490-0.

Ondei, S., L. D. Prior, T. Vigilante and D. M. J. S. Bowman, 2017: Fire and cattle disturbance affects vegetation structure and rain forest expansion into savanna in the Australian monsoon tropics. *Journal of biogeography*, **44**(10), 2331-2342.

Ordonez, A., J. W. Williams and J. C. Svenning, 2016: Mapping climatic mechanisms likely to favour the emergence of novel communities. *Nature Climate Change*, **6**(12), 1104-1109, doi:10.1038/nclimate3127.

Orlove, B. et al., 2019: Framing climate change in frontline communities: anthropological insights on how mountain dwellers in the USA, Peru, and Italy adapt to glacier retreat. *Regional Environmental Change*, **19**(5), 1295-1309.

Orru, K. et al., 2014: Recreational ice fishing on the large Lake Peipsi: socioeconomic importance, variability of ice-cover period, and possible implications for fish stocks. *Estonian Journal of Ecology*, **63**(4).

Ortiz, A. M. D., C. L. Outhwaite, C. Dalin and T. Newbold, 2021: A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. *One Earth*, **4**(1), 88-101, doi:https://doi.org/10.1016/j.oneear.2020.12.008.

Ossola, A. and B. B. Lin, 2021: Making nature-based solutions climate-ready for the 50° C world. *Environmental Science & Policy*, **123**, 151-159.

Ostberg, S. et al., 2018: The Biosphere Under Potential Paris Outcomes. *Earth's Future*, **6**(1), 23-39, doi:10.1002/2017EF000628.

Ostberg, S., W. Lucht, S. Schaphoff and D. Gerten, 2013: Critical impacts of global warming on land ecosystems. *Earth Syst. Dynam.*, **4**(2), 347-357, doi:10.5194/esd-4-347-2013.

Ostfeld, R. S. and F. Keesing, 2017: Is biodiversity bad for your health? *Ecosphere*, **8**(3), e01676, doi:https://doi.org/10.1002/ecs2.1676.

Osuri, A. M. et al., 2016: Contrasting effects of defaunation on aboveground carbon storage across the global tropics. *Nature Communications*, **7**, 11351.

Ott, C. A. and R. A. Chimner, 2016: Long-term peat accumulation in temperate forested peatlands (Thuja occidentalis swamps) in the Great Lakes region of North America. *Mires and Peat*,(18), 1-9, doi:10.19189/MaP.2015.OMB.182.

Otto, F. E. L. et al., 2018: Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. *Environmental Research Letters*, **13**(12), 124010, doi:10.1088/1748-9326/aae9f9.

Overgaard, J., M. R. Kearney and A. A. Hoffmann, 2014: Sensitivity to thermal extremes in Australian Drosophila implies similar impacts of climate change on the distribution of widespread and tropical species. *Global Change Biology*, **20**(6), 1738-1750, doi:https://doi.org/10.1111/gcb.12521.

Overland, J. E. and M. Wang, 2021: The 2020 Siberian heat wave. *International Journal of Climatology*, **41**(S1), E2341-E2346, doi:https://doi.org/10.1002/joc.6850.
Oyama, M. D. and C. A. Nobre, 2003: A new climate-vegetation equilibrium state for tropical South America. *Geophysical Research Letters*, **30**(23), doi:10.1029/2003gl018600.
Özkundakci, D. et al., 2016: Winter severity determines functional trait composition of phytoplankton in seasonally ice-covered lakes. *Global change biology*, **22**(1), 284-298, doi:10.1111/gcb.13085
Paaijmans, K. P., M. O. Wandago, A. K. Githeko and W. Takken, 2007: Unexpected High Losses of Anopheles gambiae Larvae Due to Rainfall. *PLOS ONE*, **2**(11), e1146, doi:10.1371/journal.pone.0001146.
Pachzelt, A. et al., 2015: Potential impact of large ungulate grazers on African vegetation, carbon storage and fire regimes. *Global Ecology and Biogeography*, **24**(9), 991-1002, doi:10.1111/geb.12313.
Pacifici, M. et al., 2015: Assessing species vulnerability to climate change. *Nature Climate Change*, **5**(3), 215-225, doi:10.1038/NCLIMATE2448.
Pacifici, M. et al., 2017: Species' traits influenced their response to recent climate change. *Nature Climate Change*, **7**(3), 205-208, doi:10.1038/nclimate3223.
Padmanaba, M., K. W. Tomlinson, A. C. Hughes and R. T. Corlett, 2017: Alien plant invasions of protected areas in Java, Indonesia. *Scientific Reports*, **7**, doi:10.1038/s41598-017-09768-z.
Padmanabha, H. et al., 2010: Ecological Links Between Water Storage Behaviors and Aedes aegypti Production: Implications for Dengue Vector Control in Variable Climates. *EcoHealth*, **7**(1), 78-90, doi:10.1007/s10393-010-0301-6.
Page, S. et al., 2009: Tropical peatland fires in Southeast Asia. In: *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics* [Cochrane, M. A. (ed.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 263-287. ISBN 978-3-540-77381-8.
Page, S. E. and A. J. Baird, 2016: Peatlands and Global Change: Response and Resilience. *Annual Review of Environment and Resources*, **41**, 35-57, doi:10.1146/annurev-environ-110615-085520.
Page, S. E. and A. Hooijer, 2016: In the line of fire: the peatlands of Southeast Asia. *Philos Trans R Soc Lond B Biol Sci*, **371**(1696), 20150176, doi:10.1098/rstb.2015.0176.
Page, S. E., J. O. Rieley and C. J. Banks, 2011: Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, **17**(2), 798-818, doi:10.1111/j.1365-2486.2010.02279.x.
Page, S. E. et al., 2002: The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420**(6911), 61-65.
PaiMazumder, D. and J. M. Done, 2016: Potential predictability sources of the 2012 US drought in observations and a regional model ensemble. *Journal of Geophysical Research-Atmospheres*, **121**(21), 12581-12592, doi:10.1002/2016jd025322.
Pan, Y. et al., 2011: A large and persistent carbon sink in the world's forests. *Science*, **333**(6045), 988-993.
Paneque-Gálvez, J. et al., 2018: High overlap between traditional ecological knowledge and forest conservation found in the Bolivian Amazon. *Ambio*, **47**(8), 908-923.
Papanikolaou, A. D., I. Kühn, M. Frenzel and O. Schweiger, 2017: Semi-natural habitats mitigate the effects of temperature rise on wild bees. *Journal of Applied Ecology*, **54**(2), 527-536.
Paquette, M. et al., 2015: Rapid disappearance of perennial ice on Canada's most northern lake. *Geophysical Research Letters*, **42**(5), 1433-1440, doi:10.1002/2014gl062960.
Parham, P. E. et al., 2015: Climate, environmental and socio-economic change: weighing up the balance in vector-borne disease transmission. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**(1665), 20130551, doi:10.1098/rstb.2013.0551.
Parisien, M.-A. et al., 2020a: Author Correction: Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nature Communications*, **11**(1), 3855, doi:10.1038/s41467-020-17650-2.
Parisien, M.-A. et al., 2020b: Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nature Communications*, **11**(1), 2121, doi:10.1038/s41467-020-15961-y.
Park, C. Y. et al., 2021: How Will Deforestation and Vegetation Degradation Affect Global Fire Activity? *Earths Future*, **9**(5), 20, doi:10.1029/2020ef001786.
Park, H. et al., 2016: Quantification of warming climate-induced changes in terrestrial arctic river ice thickness and phenology. *Journal of Climate*, **29**(5), 1733-1754.
Park, I. W., J. Hooper, J. M. Flegal and G. D. Jenerette, 2018: Impacts of climate, disturbance and topography on distribution of herbaceous cover in Southern California chaparral: Insights from a remote-sensing method. *Diversity and Distributions*, **24**(4), 497-508, doi:10.1111/ddi.12693.
Park, I. W. and G. D. Jenerette, 2019: Causes and feedbacks to widespread grass invasion into chaparral shrub dominated landscapes. *Landscape Ecology*, **34**(3), 459-471.
Parkinson, A. J. et al., 2014: Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group. *International Journal of Circumpolar Health*, **73**(1), 25163, doi:10.3402/ijch.v73.25163.
Parks, S. A., S. Z. Dobrowski, J. D. Shaw and C. Miller, 2019: Living on the edge: trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere*, **10**(3), doi:10.1002/ecs2.2651.
Parmesan, C., 2006: Ecological and Evolutionary Responses to Recent Climate Change. *Annual Review of Ecology, Evolution, and Systematics*, **37**(1), 637-669, doi:10.1146/annurev.ecolsys.37.091305.110100.

Parmesan, C., 2007: Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology*, **13**(9), 1860-1872.
Parmesan, C., 2019: Chapter 3: Range and Abundance Changes. In: *Biodiversity and Climate Change: Transforming the Biosphere*. Yale University Press. ISBN 978-0-300-20611-1.
Parmesan, C. et al., 2013: Beyond climate change attribution in conservation and ecological research. *Ecology Letters*, **16**(s1), 58-71, doi:10.1111/ele.12098.
Parmesan, C. and M. E. Hanley, 2015: Plants and climate change: complexities and surprises. *Annals of Botany*, **116**(6), 849-864, doi:10.1093/aob/mcv169.
Parmesan, C. and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**(6918), 37-42, doi:10.1038/nature01286.
Pärnänen, K. M. M. et al., 2019: Antibiotic resistance in European wastewater treatment plants mirrors the pattern of clinical antibiotic resistance prevalence. *Science Advances*, **5**(3), eaau9124, doi:10.1126/sciadv.aau9124.
Partain, J. L. et al., 2016: AN ASSESSMENT OF THE ROLE OF ANTHROPOGENIC CLIMATE CHANGE IN THE ALASKA FIRE SEASON OF 2015. *Bulletin of the American Meteorological Society*, **97**(12), S14-S18, doi:10.1175/bams-d-16-0149.1.
Pascale, S. et al., 2016: Projected changes of rainfall seasonality and dry spells in a high greenhouse gas emissions scenario. *Climate Dynamics*, **46**(3-4), 1331-1350.
Pascual, M. et al., 2006: Malaria resurgence in the East African highlands: Temperature trends revisited. *Proceedings of the National Academy of Sciences*, **103**(15), 5829, doi:10.1073/pnas.0508929103.
Pasimeni, M. R., D. Valente, G. Zurlini and I. Petrosillo, 2019: The interplay between urban mitigation and adaptation strategies to face climate change in two European countries. *Environmental Science & Policy*, **95**, 20-27, doi:10.1016/j.envsci.2019.02.002.
Pastick, N. J. et al., 2017: Historical and projected trends in landscape drivers affecting carbon dynamics in Alaska. *Ecological Applications*, **27**(5), 1383-1402, doi:10.1002/eap.1538/full.
Patino-Martinez, J., A. Marco, L. Quiñones and L. Hawkes, 2012: A potential tool to mitigate the impacts of climate change to the Caribbean leatherback sea turtle. *Global Change Biology*, **18**(2), 401-411.
Patrut, A. et al., 2018: The demise of the largest and oldest African baobabs. *Nature Plants*, **4**(7), 423-426, doi:10.1038/s41477-018-0170-5.
Patterson, D. et al., 2007: Reconstructing the summer thermal history for the lower Fraser River, 1941 to 2006, and implications for adult sockeye salmon (Oncorhynchus nerka) spawning migration. *Canadian Technical Report of Fisheries and Aquatic Sciences*, **2724**, 1-51.
Patz, J., A. et al., 2004: Unhealthy Landscapes: Policy Recommendations on Land Use Change and Infectious Disease Emergence. *Environmental Health Perspectives*, **112**(10), 1092-1098, doi:10.1289/ehp.6877.
Pauchard, A. et al., 2016: Non-native and native organisms moving into high elevation and high latitude ecosystems in an era of climate change: new challenges for ecology and conservation. *Biological Invasions*, **18**(2), 345-353, doi:10.1007/s10530-015-1025-x.
Paul, C., M. Weber and T. Knoke, 2017: Agroforestry versus farm mosaic systems–Comparing land-use efficiency, economic returns and risks under climate change effects. *Science of the Total Environment*, **587**, 22-35.
Paull, S. H. et al., 2017: Drought and immunity determine the intensity of West Nile virus epidemics and climate change impacts. *Proceedings of the Royal Society B: Biological Sciences*, **284**(1848), 20162078, doi:10.1098/rspb.2016.2078.
Pauls, S. U., C. Nowak, M. Bálint and M. Pfenninger, 2013: The impact of global climate change on genetic diversity within populations and species. *Molecular Ecology*, **22**(4), 925-946, doi:https://doi.org/10.1111/mec.12152.
Pausas, J. G., 2015: Alternative fire-driven vegetation states. *Journal of Vegetation Science*, **26**(1), 4-6.
Paustian, K. et al., 2016: Climate-smart soils. *Nature*, **532**(7597), 49-57, doi:10.1038/nature17174.
Pavón-Jordán, D. et al., 2020a: Positive impacts of important bird and biodiversity areas on wintering waterbirds under changing temperatures throughout Europe and North Africa. *Biological Conservation*, **246**, 108549, doi:https://doi.org/10.1016/j.biocon.2020.108549.
Pavón-Jordán, D. et al., 2020b: Positive impacts of important bird and biodiversity areas on wintering waterbirds under changing temperatures throughout Europe and North Africa. *Biological Conservation*, **246**, 108549.
Paz, S., 2015: Climate change impacts on West Nile virus transmission in a global context. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**(1665), 20130561, doi:10.1098/rstb.2013.0561.
Pearce-Higgins, J. W., R. E. Green and R. Green, 2014: *Birds and Climate Change: Impacts and Conservation Responses*. Cambridge University Press, 481 pp. ISBN 978-0-521-11428-8.
Pearce-Higgins, J. W. et al., 2019: Site-based adaptation reduces the negative effects of weather upon a southern range margin Welsh black grouse Tetrao tetrix population that is vulnerable to climate change. *Climatic Change*, **153**(1-2), 253-265.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355**(6332), doi:10.1126/science.aai9214.
Pecl, G. T. et al., 2019: Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot. *Ambio*, 1-18, doi:10.1007/s13280-019-01186-x.
Pekárová, P. et al., 2011: Long-term trend and multi-annual variability of water temperature in the pristine Bela River basin (Slovakia). *Journal of Hydrology*, **400**(3), 333-340, doi:doi.org/10.1016/j.jhydrol.2011.01.048.

Pekel, J., A. Cottam, N. Gorelick and A. Belward, 2016: High-resolution mapping of global surface water and its long-term changes. *Nature*, **540**(7633), 418-+, doi:10.1038/nature20584.
Pellegrini, A. F. A., J. B. Socolar, P. R. Elsen and X. Giam, 2016: Trade-offs between savanna woody plant diversity and carbon storage in the Brazilian Cerrado. *Global change biology*, **22**(10), 3373-3382.
Peñuelas, J. et al., 2013: Human-induced nitrogen–phosphorus imbalances alter natural and managed ecosystems across the globe. *Nature Communications*, **4**, 2934, doi:10.1038/ncomms3934.
Peñuelas, J., T. Rutishauser and I. Filella, 2009: Phenology Feedbacks on Climate Change. *Science*, **324**(5929), 887-888, doi:10.1126/science.1173004.
Penuelas, J. and J. Sardans, 2021: Global Change and Forest Disturbances in the Mediterranean Basin: Breakthroughs, Knowledge Gaps, and Recommendations. *Forests*, **12**(5), 27, doi:10.3390/f12050603.
Pereira, H. M. et al., 2010: Scenarios for Global Biodiversity in the 21st Century. *Science*, **330**(6010), 1496-1501, doi:10.1126/science.1196624.
Peres, C. A. et al., 2016: Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(4), 892-897, doi:10.1073/pnas.1516525113.
Perugini, L. et al., 2017: Biophysical effects on temperature and precipitation due to land cover change. *Environmental Research Letters*, **12**(5), doi:10.1088/1748-9326/aa6b3f.
Peters, D. L. et al., 2016: An ecological perspective on floods in Canada. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, **41**(1-2), 288-306, doi:10.1080/07011784.2015.1070694.
Peterson, A. T., 2009: Shifting suitability for malaria vectors across Africa with warming climates. *BMC Infectious Diseases*, **9**(1), 59, doi:10.1186/1471-2334-9-59.
Peterson, D., J. Wang, C. Ichoku and L. A. Remer, 2010: Effects of lightning and other meteorological factors on fire activity in the North American boreal forest: implications for fire weather forecasting. *Atmospheric Chemistry and Physics*, **10**(14), 6873-6888, doi:10.5194/acp-10-6873-2010.
Peterson, E. E. et al., 2013: Modelling dendritic ecological networks in space: an integrated network perspective. *Ecology Letters*, **16**(5), 707-719, doi:10.1111/ele.12084.
Petrova, D. et al., 2021: The 2018–2019 weak El Niño: Predicting the risk of a dengue outbreak in Machala, Ecuador. *International Journal of Climatology*, **41**(7), 3813-3823, doi:https://doi.org/10.1002/joc.6744.
Phillips, B. L. and R. Puschendorf, 2013: Do pathogens become more virulent as they spread? Evidence from the amphibian declines in Central America. *Proceedings of the Royal Society B-Biological Sciences*, **280**(1766), doi:10.1098/rspb.2013.1290.
Phuyal, P. et al., 2020: Spatiotemporal Distribution of Dengue and Chikungunya in the Hindu Kush Himalayan Region: A Systematic Review. *International Journal of Environmental Research and Public Health*, **17**(18), 6656, doi:http://dx.doi.org.ezproxy.lib.utexas.edu/10.3390/ijerph17186656.
Piao, S. et al., 2019: Plant phenology and global climate change: Current progresses and challenges. *Global change biology*, **25**(6), 1922-1940.
Piao, S. et al., 2014: Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity. *Nature communications*, **5**, 5018.
Piatt, J. F. et al., 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. *PLoS ONE*, **15**(1), e0226087, doi:10.1371/journal.pone.0226087.
Pichegru, L., 2013: Increasing breeding success of an Endangered penguin: artificial nests or culling predatory gulls? *Bird Conservation International*, **23**(3), 296-308.
Pichegru, L., D. Grémillet, R. Crawford and P. Ryan, 2010: Marine no-take zone rapidly benefits endangered penguin. *Biology letters*, **6**(4), 498-501.
Pichegru, L. et al., 2012: Industrial fishing, no-take zones and endangered penguins. *Biological Conservation*, **156**, 117-125.
Pilla, R. M. et al., 2020: Deeper waters are changing less consistently than surface waters in a global analysis of 102 lakes. *Scientific reports*, **10**(1), 1-15.
Pimm, S., C. Jenkins and B. Li, 2018: How to protect half of Earth to ensure it protects sufficient biodiversity. *Science Advances*, **4**, eaat2616, doi:10.1126/sciadv.aat2616.
Pimm, S. et al., 2006: Human impacts on the rates of recent, present, and future bird extinctions. *Proceedings of the National Academy of Sciences of the United States of America*, **103**(29), 10941-10946, doi:10.1073/pnas.0604181103.
Pimm, S. L., 1984: The complexity and stability of ecosystems. *Nature*, **307**(5949), 321-326, doi:10.1038/307321a0.
Pinault, L. L. and F. F. Hunter, 2011: New highland distribution records of multiple Anopheles species in the Ecuadorian Andes. *Malaria Journal*, **10**, 236, doi:10.1186/1475-2875-10-236.
Pletterbauer, F., A. Melcher and W. Graf, 2018: Climate Change Impacts in Riverine Ecosystems. In: *Riverine Ecosystem Management. Science for Governing Towards a Sustainable Future*, 8 ed. [Schmutz, S. and J. Sendzimir (eds.)]. Springer.
Plowright, R. K. et al., 2017: Pathways to zoonotic spillover. *Nature Reviews Microbiology*, **15**(8), 502-510, doi:10.1038/nrmicro.2017.45.
Poff, N. L. et al., 2018: Extreme streams: species persistence and genomic change in montane insect populations across a flooding gradient. *Ecology letters*, **21**(4), 525-535.

Pol, M. v. d., S. Jenouvrier, J. H. C. Cornelissen and M. E. Visser, 2017: Behavioural, ecological and evolutionary responses to extreme climatic events: challenges and directions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **372**(1723), 20160134, doi:doi:10.1098/rstb.2016.0134.
Polk, M. H. et al., 2017: Exploring hydrologic connections between tropical mountain wetlands and glacier recession in Peru's Cordillera Blanca. *Applied Geography*, **78**, 94-103.
Poloczanska, E. S. et al., 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3**(10), 919-925, doi:10.1038/nclimate1958.
Pomati, F. et al., 2020: Interacting Temperature, Nutrients and Zooplankton Grazing Control Phytoplankton Size-Abundance Relationships in Eight Swiss Lakes. *Frontiers in Microbiology*, **10**(3155), doi:10.3389/fmicb.2019.03155.
Pomoim, N., R. J. Zomer, A. C. Hughes and R. T. Corlett, 2021: The Sustainability of Thailand's Protected-Area System under Climate Change. *Sustainability*, **13**(5), 2868.
Ponomarev, E. I., V. I. Kharuk and K. J. Ranson, 2016: Wildfires Dynamics in Siberian Larch Forests. *Forests*, **7**(6), doi:10.3390/f7060125.
Poorter, L. et al., 2015: Diversity enhances carbon storage in tropical forests. *Global Ecology and Biogeography*, **24**(11), 1314-1328, doi:10.1111/geb.12364.
Pörtner, H.-O., 2021: Climate impacts on organisms, ecosystems and human societies: integrating OCLTT into a wider context. *Journal of Experimental Biology*, **224**(Suppl_1), doi:10.1242/jeb.238360.
Pörtner, H. O. et al., 2021: IPBES-IPCC co-sponsored workshop report on biodiversity and climate change.
Posa, M. R. C., L. S. Wijedasa and R. T. Corlett, 2011: Biodiversity and conservation of tropical peat swamp forests. *BioScience*, **61**(1), 49-57, doi:10.1525/bio.2011.61.1.10.
Post, E. et al., 2009: Ecological dynamics across the Arctic associated with recent climate change. *science*, **325**(5946), 1355-1358.
Postigo, J. C., 2013: Adaptation of Andean Herders to Political and Climatic Changes. In: *Continuity and Change in Cultural Adaptation to Mountain Environments* [Lozny, L. R. (ed.)]. Springer New York, pp. 229-258. ISBN 978-1-4614-5701-5.
Postigo, J. C., 2019: Multi-temporal adatations to change in the Cetral Andes. In: *Climate and Culture* [Feola, G., H. Geoghegan and A. Arnall (eds.)]. Cambridge University Press, Cambridge, UK, pp. 117-140.
Postigo, J. C., 2020: The Role of Social Institutions in Indigenous Andean Pastoralists' Adaptation to Climate-Related Water Hazards. *Climate and Development*, doi:10.1080/17565529.2020.1850409.
Poulin, R., 2006: Global warming and temperature-mediated increases in cercarial emergence in trematode parasites. *Parasitology*, doi:10.1017/S0031182005008693.
Poulter, B. et al., 2010: Net biome production of the Amazon Basin in the 21st century. *Global Change Biology*, **16**(7), 2062-2075, doi:10.1111/j.1365-2486.2009.02064.x.
Pounds, J. et al., 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, **439**(7073), 161-167, doi:10.1038/nature04246.
Pounds, J. A., M. P. L. Fogden and J. H. Campbell, 1999: Biological response to climate change on a tropical mountain. *Nature*, **398**(6728), 611-615, doi:10.1038/19297.
Pour, N., P. A. Webley and P. J. Cook, 2017: A Sustainability Framework for Bioenergy with Carbon Capture and Storage (BECCS) Technologies. *Energy Procedia*, **114**, 6044-6056, doi:https://doi.org/10.1016/j.egypro.2017.03.1741.
Powell, E. J. et al., 2019: A review of coastal management approaches to support the integration of ecological and human community planning for climate change. *Journal of coastal conservation*, **23**(1), 1-18.
Pöyry, J. et al., 2009: Species traits explain recent range shifts of Finnish butterflies. *Global Change Biology*, **15**(3), 732-743.
Prăvălie, R., 2018: Major perturbations in the Earth's forest ecosystems. Possible implications for global warming. *Earth-Science Reviews*, **185**, 544-571, doi:https://doi.org/10.1016/j.earscirev.2018.06.010.
Prendin, A. L. et al., 2020: Immediate and carry-over effects of insect outbreaks on vegetation growth in West Greenland assessed from cells to satellite. *Journal of Biogeography*, **47**(1), 87-100, doi:10.1111/jbi.13644.
Press, A., 2016: *Tasmanian Wilderness World Heritage Area Bushfire and Climate Change Research Project*, Cabinet, D. o. P. a., Tasmanian Government, Hobart.
Prieto-Torres, D. A., A. G. Navarro-Siguenza, D. Santiago-Alarcon and O. R. Rojas-Soto, 2016: Response of the endangered tropical dry forests to climate change and the role of Mexican Protected Areas for their conservation. *Global Change Biology*, **22**(1), 364-379, doi:10.1111/gcb.13090.
Prist, P. R., M. Uriarte, K. Fernandes and J. P. Metzger, 2017: Climate change and sugarcane expansion increase Hantavirus infection risk. *PLOS Neglected Tropical Diseases*, **11**(7), e0005705, doi:10.1371/journal.pntd.0005705.
Pritchard, A., M. Richardson, D. Sheffield and K. McEwan, 2020: The relationship between nature connectedness and eudaimonic well-being: A meta-analysis. *Journal of Happiness Studies*, **21**(3), 1145-1167.
Pritchard, G. C. et al., 2005: Emergence of fasciolosis in cattle in East Anglia. *Veterinary Record*, **157**(19), 578-582, doi:https://doi.org/10.1136/vr.157.19.578.
Prober, S. M. et al., 2019: Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. *Ecological Monographs*, **89**(1), e01333, doi:https://doi.org/10.1002/ecm.1333.

Probert, J. R. et al., 2019: Anthropogenic modifications to fire regimes in the wider Serengeti-Mara ecosystem. *Global Change Biology*, **25**, 3406-3423, doi:10.1111/gcb.14711.
Programme, U. N. E., 1995: Global Biodiversity Assessment. Cambridge University Press, Cambridge, UK.
Prowse, T. et al., 2011: Effects of changes in arctic lake and river ice. *Ambio*, **40**(1), 63-74.
Prudhomme, C. et al., 2014: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(9), 3262-3267, doi:10.1073/pnas.1222473110.
Pugh, T. A. M. et al., 2019a: Important role of forest disturbances in the global biomass turnover and carbon sinks. *Nature Geoscience*, doi:10.1038/s41561-019-0427-2.
Pugh, T. A. M. et al., 2018: A Large Committed Long-Term Sink of Carbon due to Vegetation Dynamics. *Earth's Future*, **6**(10), 1413-1432, doi:doi:10.1029/2018EF000935.
Pugh, T. A. M. et al., 2019b: Role of forest regrowth in global carbon sink dynamics. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(10), 4382-4387, doi:10.1073/pnas.1810512116.
Pureswaran, D. S., A. Roques and A. Battisti, 2018: Forest Insects and Climate Change. *Current Forestry Reports*, **4**(2), 35-50, doi:10.1007/s40725-018-0075-6.
Purse, B. V. et al., 2005: Climate change and the recent emergence of bluetongue in Europe. *Nature Reviews Microbiology*, **3**(2), 171-181, doi:10.1038/nrmicro1090.
Puschendorf, R., F. Bolanos and G. Chaves, 2006: The amphibian chytrid fungus along an altitudinal transect before the first reported declines in Costa Rica. *Biological Conservation*, **132**(1), 136-142, doi:10.1016/j.biocon.2006.03.010.
Puschendorf, R. et al., 2011: Environmental Refuge from Disease-Driven Amphibian Extinction. *Conservation Biology*, **25**(5), 956-964, doi:10.1111/j.1523-1739.2011.01728.x.
Puspitaloka, D., Y.-S. Kim, H. Purnomo and P. Z. Fulé, 2020: Defining ecological restoration of peatlands in Central Kalimantan, Indonesia. *Restoration Ecology*, **28**(2), 435-446, doi:https://doi.org/10.1111/rec.13097.
Putra, E. I. et al., 2019: Developing better understanding on tropical peat fire occurrences and dynamics. *IOP Conf. Ser.: Earth Environ. Sci.*, **394**, 012044, doi:10.1088/1755-1315/394/1/012044.
Puttock, A. et al., 2014: Woody plant encroachment into grasslands leads to accelerated erosion of previously stable organic carbon from dryland soils. *Journal of Geophysical Research: Biogeosciences*, **119**(12), 2345-2357.
Pütz, S. et al., 2014: Long-term carbon loss in fragmented Neotropical forests. *Nature Communications*, **5**, 5037, doi:10.1038/ncomms6037 https://www.nature.com/articles/ncomms6037#supplementary-information.
Pyne, M. I. and N. L. Poff, 2017: Vulnerability of stream community composition and function to projected thermal warming and hydrologic change across ecoregions in the western United States. *Glob Chang Biol*, **23**(1), 77-93, doi:10.1111/gcb.13437.
Qie, L. et al., 2017: Long-term carbon sink in Borneo's forests halted by drought and vulnerable to edge effects. *Nature communications*, **8**(1), 1966.
Qin, Y. W. et al., 2021: Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nature Climate Change*, **11**(5), 442-+, doi:10.1038/s41558-021-01026-5.
Qiu, C. et al., 2021: Large historical carbon emissions from cultivated northern peatlands. *Science Advances*, **7**(23), eabf1332, doi:10.1126/sciadv.abf1332.
Qiu, C. J. et al., 2020: The role of northern peatlands in the global carbon cycle for the 21st century. *Global Ecology and Biogeography*, doi:10.1111/geb.13081.
Quandt, A., H. Neufeldt and J. T. McCabe, 2019: Building livelihood resilience: what role does agroforestry play? *Climate and Development*, **11**(6), 485-500, doi:10.1080/17565529.2018.1447903.
Quirk, J., C. Bellasio, D. Johnson and D. Beerling, 2019: Response of photosynthesis, growth and water relations of a savannah-adapted tree and grass grown across high to low CO2. *Annals of botany*, **124**, 77-90, doi:10.1093/aob/mcz048.
Rabatel, A. et al., 2013: Current state of glacier in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *The Cryosphere*, **7**(1), 81-102.
Rabin, S. S. et al., 2020: Impacts of future agricultural change on ecosystem service indicators. *Earth Syst. Dynam.*, **11**(2), 357-376, doi:10.5194/esd-11-357-2020.
Rabin, S. S. et al., 2017: The Fire Modeling Intercomparison Project (FireMIP), phase 1: experimental and analytical protocols with detailed model descriptions. *Geoscientific Model Development*, **10**(3), 1175-1197, doi:10.5194/gmd-10-1175-2017.
Racault, M.-F. et al., 2019: Environmental Reservoirs of Vibrio cholerae: Challenges and Opportunities for Ocean-Color Remote Sensing. *Remote Sensing*, **11**(23), doi:10.3390/rs11232763.
Radchuk, V. et al., 2019: Adaptive responses of animals to climate change are most likely insufficient. *Nature communications*, **10**(1), 1-14.
Radeloff, V. C. et al., 2015: The rise of novelty in ecosystems. *Ecological Applications*, **25**(8), 2051-2068.
Radville, L., M. L. McCormack, E. Post and D. M. Eissenstat, 2016: Root phenology in a changing climate. *Journal of Experimental Botany*, **67**(12), 3617-3628.
Raffa, K. F. et al., 2008: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. *BioScience*, **58**(6), 501-517, doi:10.1641/b580607.

Raffa, K. F., E. N. Powell and P. A. Townsend, 2013: Temperature-driven range expansion of an irruptive insect heightened by weakly coevolved plant defenses. *Proceedings of the National Academy of Sciences of the United States of America*, **110**(6), 2193-2198, doi:10.1073/pnas.1216666110.
Raffel, T. R. et al., 2015: Temperature variability and moisture synergistically interact to exacerbate an epizootic disease. *Proceedings of the Royal Society B: Biological Sciences*, **282**(1801), 20142039, doi:10.1098/rspb.2014.2039.
Ralston, J., W. V. DeLuca, R. E. Feldman and D. I. King, 2017: Population trends influence species ability to track climate change. *Global change biology*, **23**(4), 1390-1399.
Rammig, A. et al., 2010: Estimating the risk of Amazonian forest dieback. *New Phytologist*, **187**(3), 694-706, doi:10.1111/j.1469-8137.2010.03318.x.
Ramo, R. et al., 2021: African burned area and fire carbon emissions are strongly impacted by small fires undetected by coarse resolution satellite data. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(9), 7, doi:10.1073/pnas.2011160118.
Randall, R., B. Randall and T. Erasmus, 1986: Rain-related breeding failures in Jackass Penguins. *Le Gerfaut*, **76**(4), 281-288.
Randerson, J. T. et al., 2006: The impact of boreal forest fire on climate warming. *Science*, **314**(5802), 1130-1132, doi:10.1126/science.1132075.
Rannow, S. et al., 2014: Managing Protected Areas Under Climate Change: Challenges and Priorities. *Environmental Management*, **54**(4), 732-743, doi:10.1007/s00267-014-0271-5.
Rasconi, S., A. Gall, K. Winter and M. J. Kainz, 2015: Increasing water temperature triggers dominance of small freshwater plankton. *PLoS ONE*, **10**(10), e0140449.
Rashid, I. et al., 2015: Projected climate change impacts on vegetation distribution over Kashmir Himalayas. *Climatic Change*, **132**(4), 601-613.
Rasul, G. and D. Molden, 2019: The global social and economic consequences of mountain cryospheric change. *Frontiers in Environmental Science*, **7**(91), doi:10.3389/fenvs.2019.00091.
Ratajczak, Z., J. B. Nippert and S. L. Collins, 2012: Woody encroachment decreases diversity across North American grasslands and savannas. *Ecology*, **93**(4), 697-703.
Ratajczak, Z., J. B. Nippert and T. W. Ocheltree, 2014: Abrupt transition of mesic grassland to shrubland: evidence for thresholds, alternative attractors, and regime shifts. *Ecology*, **95**(9), 2633-2645, doi:10.1890/13-1369.1.
Ratcliffe, J. L. et al., 2018: Holocene carbon accumulation in the peatlands of northern Scotland. *Mires and Peat*,(23), 1-30, doi:10.19189/MaP.2018.OMB.347.
Ratnam, J. et al., 2011: When is a 'forest' a savanna, and why does it matter? *Global Ecology and Biogeography*, **20**(5), 653-660, doi:10.1111/j.1466-8238.2010.00634.x.
Ratnayake, H. U. et al., 2019: Forecasting wildlife die-offs from extreme heat events. *Animal Conservation*, **22**(4), 386-395, doi:10.1111/acv.12476.
Raymond, P. A. et al., 2013: Global carbon dioxide emissions from inland waters. *Nature*, **503**(7476), 355-359.
Redden, R. J. et al., 2015: *Crop wild relatives and climate change*. John Wiley & Sons, Ltd Chichester, UK.
Redmond, M. D., P. J. Weisberg, N. S. Cobb and M. J. Clifford, 2018: Woodland resilience to regional drought: Dominant controls on tree regeneration following overstorey mortality. *Journal of Ecology*, **106**(2), 625-639, doi:10.1111/1365-2745.12880.
Refsnider, J. M. and F. J. Janzen, 2016: Temperature-Dependent Sex Determination under Rapid Anthropogenic Environmental Change: Evolution at a Turtle's Pace? *Journal of Heredity*, **107**(1), 61-70, doi:10.1093/jhered/esv053.
Regehr, E. V. et al., 2016: Conservation status of polar bears (Ursus maritimus) in relation to projected sea-ice declines. *Biology Letters*, **12**(12), doi:10.1098/rsbl.2016.0556.
Régnière, J. and V. G. Nealis, 2019: Influence of temperature on historic and future population fitness of the western spruce budworm, Choristoneura occidentalis. *International Journal of Pest Management*, **65**(3), 228-243, doi:10.1080/09670874.2018.1541113.
Regos, A. et al., 2016: Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios. *Diversity and Distributions*, **22**(1), 83-96, doi:10.1111/ddi.12375.
Rehbein, J. A. et al., 2020: Renewable energy development threatens many globally important biodiversity areas. *Global Change Biology*, **26**(5), 3040-3051, doi:https://doi.org/10.1111/gcb.15067.
Rehm, E. and K. J. Feeley, 2016: Many species risk mountain top extinction long before they reach the top. *Frontiers of biogeography*, **8**(1).
Rehm, E. M. and K. J. Feeley, 2015: The inability of tropical cloud forest species to invade grasslands above treeline during climate change: potential explanations and consequences. *Ecography*, **38**(12), 1167-1175.
Reich, P. B., S. E. Hobbie and T. D. Lee, 2014: Plant growth enhancement by elevated CO2 eliminated by joint water and nitrogen limitation. *Nature Geoscience*, **7**(12), 920-924, doi:10.1038/ngeo2284.
Reid, A. J. et al., 2019: Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, **94**(3), 849-873, doi:10.1111/brv.12480.
Reider, K. and S. Schmidt, 2020: Vicuña dung gardens at the edge of the cryosphere. *Ecology*, **102**, doi:10.1002/ecy.3228.

Reis, S. M. et al., 2020: Causes and consequences of liana infestation in southern Amazonia. *Journal of Ecology*, **108**(6), 2184-2197.
Reitsema, R. E., P. Meire and J. Schoelynck, 2018: The future of freshwater macrophytes in a changing world: dissolved organic carbon quantity and quality and its interactions with macrophytes. *Frontiers in plant science*, **9**, 629.
Renou-Wilson, F. et al., 2019: Rewetting degraded peatlands for climate and biodiversity benefits: Results from two raised bogs. *Ecological Engineering*, **127**, 547-560, doi:10.1016/j.ecoleng.2018.02.014.
Reppin, S. et al., 2020: Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. *Agroforestry Systems*, **94**(1), 203-220, doi:10.1007/s10457-019-00383-7.
Restaino, C. et al., 2019: Forest structure and climate mediate drought-induced tree mortality in forests of the Sierra Nevada, USA. *Ecological Applications*, **29**(4), doi:10.1002/eap.1902.
Retallick, R. W. R., H. McCallum and R. Speare, 2004: Endemic infection of the amphibian chytrid fungus in a frog community post-decline. *PLoS Biology*, **2**(11), 1965-1971, doi:10.1371/journal.pbio.0020351.
Reu, B. et al., 2014: Future no-analogue vegetation produced by no-analogue combinations of temperature and insolation. *Global Ecology and Biogeography*, **23**(2), 156-167, doi:10.1111/geb.12110.
Reyes-Fox, M. et al., 2014: Elevated CO2 further lengthens growing season under warming conditions. *Nature*, **510**, doi:10.1038/nature13207.
Ribeiro, K. et al., 2021: Tropical peatlands and their contribution to the global carbon cycle and climate change. *Global Change Biology*, **27**(3), 489-505, doi:10.1111/gcb.15408.
Richards-Hrdlicka, K. L., 2013: Preserved Specimens of the Extinct Golden Toad of Monteverde (Cranopsis periglenes) Tested Negative for the Amphibian Chytrid Fungus (Batrachochytrium dendrobatidis). *Journal of Herpetology*, **47**(3), 456-458, doi:10.1670/11-243.
Richardson, D. et al., 2017: Transparency, Geomorphology and Mixing Regime Explain Variability in Trends in Lake Temperature and Stratification across Northeastern North America (1975–2014). *Water*, **9**(6), doi:10.3390/w9060442.
Richardson, D. M. et al., 2009: Multidimensional evaluation of managed relocation. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(24), 9721-9724, doi:10.1073/pnas.0902327106.
Richardson, J. et al., 2019: Response of cyanobacteria and phytoplankton abundance to warming, extreme rainfall events and nutrient enrichment. *Global change biology*, **25**(10), 3365-3380.
Richardson, J. et al., 2018: Effects of multiple stressors on cyanobacteria abundance vary with lake type. *Global change biology*, **24**(11), 5044-5055.
Rieley, J. and S. Page, 2016: Tropical Peatland of the World. In: *Tropical Peatland Ecosystems* [Osaki, M. and N. Tsuji (eds.)]. Springer Japan, Tokyo, pp. 3-32. ISBN 978-4-431-55681-7.
Rigling, A. et al., 2013: Driving factors of a vegetation shift from Scots pine to pubescent oak in dry Alpine forests. *Global Change Biology*, **19**(1), 229-240, doi:10.1111/gcb.12038.
Rinkevich, B., 2019: The Active Reef Restoration Toolbox is a Vehicle for Coral Resilience and Adaptation in a Changing World. *Journal of Marine Science and Engineering*, **7**(7), doi:10.3390/jmse7070201.
Ritson, J. et al., 2014: The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: a UK perspective. *Science of the Total Environment*, **473**, 714-730.
Roberts, C. M., B. C. O'Leary and J. P. Hawkins, 2020a: Climate change mitigation and nature conservation both require higher protected area targets. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190121, doi:10.1098/rstb.2019.0121.
Roberts, D. et al., 2012: Exploring ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face. *Environment and Urbanization*, **24**(1), 167-195, doi:10.1177/0956247811431412.
Roberts, D., J. Douwes, C. Sutherland and V. Sim, 2020b: Durban's 100 resilient cities journey: Governing resilience from within. *Environment and Urbanization*, **32**(2), 547-568.
Roberts, D. A. et al., 2013: Ocean acidification increases the toxicity of contaminated sediments. *Global Change Biology*, **19**(2), 340-351, doi:10.1111/gcb.12048.
Roberts, J. J., K. D. Fausch, T. S. Schmidt and D. M. Walters, 2017: Thermal regimes of Rocky Mountain lakes warm with climate change. *PloS one*, **12**(7), e0179498.
Robinne, F. N. et al., 2018: A spatial evaluation of global wildfire-water risks to human and natural systems. *Science of the Total Environment*, **610**, 1193-1206, doi:10.1016/j.scitotenv.2017.08.112.
Robinne, F. N., D. W. Hallema, K. D. Bladon and J. M. Buttle, 2020: Wildfire impacts on hydrologic ecosystem services in North American high-latitude forests: A scoping review. *Journal of Hydrology*, **581**, 15, doi:10.1016/j.jhydrol.2019.124360.
Robinson, S. A. et al., 2020: The 2019/2020 summer of Antarctic heatwaves. *Global Change Biology*, **26**(6), 3178-3180, doi:10.1111/gcb.15083.
Rocklöv, J. and R. Dubrow, 2020: Climate change: an enduring challenge for vector-borne disease prevention and control. *Nature Immunology*, **21**(5), 479-483, doi:10.1038/s41590-020-0648-y.
Rocklöv, J. and Y. Tozan, 2019: Climate change and the rising infectiousness of dengue. *Emerging Topics in Life Sciences*, **3**(2), 133-142, doi:10.1042/ETLS20180123.
Rodell, M. et al., 2018: Emerging trends in global freshwater availability. *Nature*, **557**(7707), 651-659, doi:10.1038/s41586-018-0123-1

Rodrigues, E. L., C. M. Jacobi and J. E. C. Figueira, 2019: Wildfires and their impact on the water supply of a large neotropical metropolis: A simulation approach. *Science of the Total Environment*, **651**, 1261-1271, doi:10.1016/j.scitotenv.2018.09.289.

Rodriguez-Verdugo, A. et al., 2020: Compounding Effects of Climate Warming and Antibiotic Resistance. *iScience*, **23**(4), UNSP-101024, doi:10.1016/j.isci.2020.101024.

Roe, S. et al., 2019: Contribution of the land sector to a 1.5 °C world. *Nature Climate Change*, **9**(11), 817-828, doi:10.1038/s41558-019-0591-9.

Rogelj, J. et al., 2018: Mitigation pathways compatible with 1.5°C in the context of sustainable development.

Rogers, B. M., A. J. Soja, M. L. Goulden and J. T. Randerson, 2015: Influence of tree species on continental differences in boreal fires and climate feedbacks. *Nature Geoscience*, **8**, 228, doi:10.1038/ngeo2352 https://www.nature.com/articles/ngeo2352#supplementary-information.

Rohde, R. F. et al., 2019: Vegetation and climate change in the Pro-Namib and Namib Desert based on repeat photography: Insights into climate trends. *Journal of Arid Environments*.

Rohr, J. R. et al., 2020: Towards common ground in the biodiversity–disease debate. *Nature Ecology & Evolution*, **4**(1), 24-33, doi:10.1038/s41559-019-1060-6.

Rohr, J. R. and T. R. Raffel, 2010: Linking global climate and temperature variability to widespread amphibian declines putatively caused by disease. *Proceedings of the National Academy of Sciences*, **107**(18), 8269, doi:10.1073/pnas.0912883107.

Román-Palacios, C. and J. J. Wiens, 2020: Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences*, **117**(8), 4211-4217.

Rooney, R. C., S. E. Bayley and D. W. Schindler, 2012: Oil sands mining and reclamation cause massive loss of peatland and stored carbon. *Proceedings of the National Academy of Sciences*, **109**(13), 4933-4937, doi:10.1073/pnas.1117693108.

Root, T. L., D. P. MacMynowski, M. D. Mastrandrea and S. H. Schneider, 2005: Human-modified temperatures induce species changes: Joint attribution. *Proceedings of the National Academy of Sciences of the United States of America*, **102**(21), 7465-7469, doi:10.1073/pnas.0502286102.

Root, T. L. et al., 2003: Fingerprints of global warming on wild animals and plants. *Nature*, **421**(6918), 57, doi:10.1038/nature01333.

Rosan, T. M. et al., 2019: Extensive twenty-first century woody encroachment in South America's savanna. *Geophysical Research Letters*.

Rosen, G. E. and K. F. Smith, 2010: Summarizing the Evidence on the International Trade in Illegal Wildlife. *EcoHealth*, **7**(1), 24-32, doi:10.1007/s10393-010-0317-y.

Rosentreter, J. A. et al., 2018: Methane emissions partially offset "blue carbon" burial in mangroves. *Science Advances*, **4**(6), eaao4985, doi:10.1126/sciadv.aao4985.

Rosenzweig, C. et al., 2007: Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 79-131. ISBN 9780521880107.

Rosenzweig, C. et al., 2008: Attributing physical and biological impacts to anthropogenic climate change. *Nature*, **453**(7193), 353-357, doi:10.1038/nature06937.

Ross, C. W. et al., 2021: Woody-biomass projections and drivers of change in sub-Saharan Africa. *Nature Climate Change*, **11**(5), 449-455.

Roucoux, K. H. et al., 2017: Threats to intact tropical peatlands and opportunities for their conservation. *Conservation Biology*, **31**(6), 1283-1292, doi:10.1111/cobi.12925.

Roucoux, K. H. et al., 2013: Vegetation development in an Amazonian peatland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **374**, 242-255, doi:10.1016/j.palaeo.2013.01.023.

Rounsevell, M. et al., 2019: Cross-Chapter Box 1: Scenarios and other methods to characterise the future of land In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.

Rowiński, P. M. et al., 2018: How vegetation can aid in coping with river management challenges: A brief review. *Ecohydrology & Hydrobiology*, **18**(4), 345-354.

Rowley, J. J. L. and R. A. Alford, 2013: Hot bodies protect amphibians against chytrid infection in nature. *Scientific Reports*, **3**(1), 1515, doi:10.1038/srep01515.

Roy-Dufresne, E. et al., 2013: Poleward Expansion of the White-Footed Mouse (Peromyscus leucopus) under Climate Change: Implications for the Spread of Lyme Disease. *PLoS ONE*, **8**(11), e80724, doi:10.1371/journal.pone.0080724.

Roy, C., C. D. Van der Lingen, J. C. Coetzee and J. R. E. Lutjeharms, 2007: Abrupt environmental shift associated with changes in the distribution of Cape anchovy Engraulis encrasicolus spawners in the southern Benguela. *African Journal of Marine Science*, **29**(3), 309-319.

Roy, J. et al., 2016: Elevated CO2 maintains grassland net carbon uptake under a future heat and drought extreme. *Proceedings of the National Academy of Sciences*, **113**(22), 6224-6229.
Rozendaal, D. M. A. et al., 2019: Biodiversity recovery of Neotropical secondary forests. *Science Advances*, **5**(3), eaau3114, doi:10.1126/sciadv.aau3114.
Rubin, C., B. Dunham and J. Sleeman, 2014: Making One Health a Reality—Crossing Bureaucratic Boundaries. In: *One Health*. John Wiley & Sons, Ltd, pp. 269-283. ISBN 978-1-68367-104-6.
Ruffault, J. et al., 2020: Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *Scientific Reports*, **10**(1), 13790, doi:10.1038/s41598-020-70069-z.
Ruffault, J. and F. Mouillot, 2015: How a new fire-suppression policy can abruptly reshape the fire-weather relationship. *Ecosphere*, **6**(10), doi:10.1890/es15-00182.1.
Rühland, K. M., A. M. Paterson and J. P. Smol, 2015: Lake diatom responses to warming: reviewing the evidence. *Journal of paleolimnology*, **54**(1), 1-35.
Rumpf, S. B., K. Hülber, N. E. Zimmermann and S. Dullinger, 2019: Elevational rear edges shifted at least as much as leading edges over the last century. *Global Ecology and Biogeography*, **28**(4), 533-543, doi:https://doi.org/10.1111/geb.12865.
Runting, R. K. et al., 2017: Incorporating climate change into ecosystem service assessments and decisions: a review. *Global Change Biology*, **23**(1), 28-41, doi:https://doi.org/10.1111/gcb.13457.
Rusak, 2018: Wind and trophic status explain within and among lake variability of algal biomass. *Limnology and Oceanography letters*.
Ruwaimana, M., G. Z. Anshari, L. C. R. Silva and D. G. Gavin, 2020: The oldest extant tropical peatland in the world: a major carbon reservoir for at least 47\hspace0.167em000 years. *Environmental Research Letters*, **15**(11), 114027, doi:10.1088/1748-9326/abb853.
Ryan, C. M. et al., 2016: Ecosystem services from southern African woodlands and their future under global change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150312.
Ryan, L. M. and A. R. Gunderson, 2021: Competing native and invasive Anolis lizards exhibit thermal preference plasticity in opposite directions. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, **335**(1), 118-125, doi:https://doi.org/10.1002/jez.2420.
Ryan, S. J., C. J. Carlson, E. A. Mordecai and L. R. Johnson, 2019: Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *PLOS Neglected Tropical Diseases*, **13**(3), e0007213, doi:10.1371/journal.pntd.0007213.
Ryan, S. J. et al., 2021: Warming temperatures could expose more than 1.3 billion new people to Zika virus risk by 2050. *Global Change Biology*, **27**(1), 84-93, doi:https://doi.org/10.1111/gcb.15384.
Ryan, S. J. et al., 2015: Mapping Physiological Suitability Limits for Malaria in Africa Under Climate Change. *Vector-Borne and Zoonotic Diseases*, **15**(12), 718-725, doi:10.1089/vbz.2015.1822.
Saatchi, S. S. et al., 2011: Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences of the United States of America*, **108**(24), 9899-9904, doi:10.1073/pnas.1019576108.
Sadegh, M. et al., 2018: Multihazard Scenarios for Analysis of Compound Extreme Events. *Geophysical Research Letters*, **45**(11), 5470-5480, doi:10.1029/2018gl077317.
Saderne, V. et al., 2019: Role of carbonate burial in Blue Carbon budgets. *Nature Communications*, **10**, doi:10.1038/s41467-019-08842-6.
Sakschewski, B. et al., 2016: Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change*, **6**(11), 1032-1036.
Sala, E. et al., 2021: Protecting the global ocean for biodiversity, food and climate. *Nature*, **592**(7854), 397-402, doi:10.1038/s41586-021-03371-z.
Salazar, L. F. and C. A. Nobre, 2010: Climate change and thresholds of biome shifts in Amazonia. *Geophysical Research Letters*, **37**, doi:10.1029/2010gl043538.
Salewski, V. et al., 2014: Morphological Change to Birds over 120 Years Is Not Explained by Thermal Adaptation to Climate Change. *PLOS ONE*, **9**(7), e101927, doi:10.1371/journal.pone.0101927.
Salyer, S. J., R. Silver, K. Simone and C. Barton Behravesh, 2017: Prioritizing Zoonoses for Global Health Capacity Building—Themes from One Health Zoonotic Disease Workshops in 7 Countries, 2014–2016. *Emerg Infect Dis. 23(Suppl 1):S55-S64.*, **23**.
Sampaio, G. et al., 2007: Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. *Geophysical Research Letters*, **34**(17), doi:10.1029/2007gl030612.
SANCCOB, 2018: *SANCCOB Annual Report*. SANCCOB, Cape Town.
Sanches, L. et al., 2019: Global regulation of methane emission from natural lakes. *Scientific Reports*, **9**, doi:10.1038/s41598-018-36519-5.
Sandel, B. et al., 2011: The Influence of Late Quaternary Climate-Change Velocity on Species Endemism. *Science*, **334**(6056), 660-664, doi:10.1126/science.1210173.
Sankaran, M. and C. Staver, 2019: Droughts and the ecological future of tropical savanna vegetation. *Journal of Ecology*, **107**(4), 1531-1549, doi:10.1111/1365-2745.13195.
Sankey, J. B. et al., 2017: Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, **44**(17), 8884-8892, doi:10.1002/2017gl073979.

Santanello, J. A., J. Roundy and P. A. Dirmeyer, 2015: Quantifying the Land-Atmosphere Coupling Behavior in Modern Reanalysis Products over the U.S. Southern Great Plains. *Journal of Climate*, **28**(14), 5813-5829, doi:10.1175/jcli-d-14-00680.1.
Santiago, J. M. et al., 2016: Brown trout thermal niche and climate change: expected changes in the distribution of cold-water fish in central Spain. *Ecohydrology*, **9**(3), 514-528, doi:10.1002/eco.1653.
Santopuoli, G. et al., 2019: Biodiversity conservation and wood production in a Natura 2000 Mediterranean forest. A trade-off evaluation focused on the occurrence of microhabitats. *iForest - Biogeosciences and Forestry*, **12**(1), 76-84.
Santos, P. Z. F., R. Crouzeilles and J. B. B. Sansevero, 2019: Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest. *Forest ecology and management*, **433**, 140-145.
Sapsford, S. J., M. J. Voordouw, R. A. Alford and L. Schwarzkopf, 2015: Infection dynamics in frog populations with different histories of decline caused by a deadly disease. *Oecologia*, **179**(4), 1099-1110, doi:10.1007/s00442-015-3422-3.
Sasmito, S. D. et al., 2020: Mangrove blue carbon stocks and dynamics are controlled by hydrogeomorphic settings and land-use change. *Global Change Biology*, **26**(5), 3028-3039, doi:https://doi.org/10.1111/gcb.15056.
Sauer, E. L. et al., 2020: A meta-analysis reveals temperature, dose, life stage, and taxonomy influence host susceptibility to a fungal parasite. *Ecology*, **101**(4), e02979, doi:10.1002/ecy.2979.
Sauer, E. L. et al., 2018: Variation in individual temperature preferences, not behavioural fever, affects susceptibility to chytridiomycosis in amphibians. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1885), 20181111, doi:10.1098/rspb.2018.1111.
Saunders, D. A., P. Mawson and R. Dawson, 2011: The impact of two extreme weather events and other causes of death on Carnaby’s Black Cockatoo: a promise of things to come for a threatened species? *Pacific Conservation Biology*, **17**(2), 141-148.
Scheele, B. C. et al., 2019: Amphibian fungal panzootic causes catastrophic and ongoing loss of biodiversity. *1463*, doi:10.1126/science.aav0379.
Scheffer, M. et al., 2001: Catastrophic shifts in ecosystems. *Nature*, **413**(6856), 591-596, doi:10.1038/35098000.
Scheffers, B. R. et al., 2016: The broad footprint of climate change from genes to biomes to people. *Science*, **354**(6313), aaf7671, doi:10.1126/science.aaf7671.
Scheiter, S., S. I. Higgins, J. Beringer and L. B. Hutley, 2015: Climate change and long-term fire management impacts on Australian savannas. *New Phytologist*, **205**(3), 1211-1226, doi:10.1111/nph.13130.
Scheiter, S., G. R. Moncrieff, M. Pfeiffer and S. I. Higgins, 2020: African biomes are most sensitive to changes in CO2 under recent and near-future CO2 conditions. *Biogeosciences*, **17**(4), 1147-1167, doi:10.5194/bg-17-1147-2020.
Schimel, D., B. B. Stephens and J. B. Fisher, 2015: Effect of increasing CO2 on the terrestrial carbon cycle. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(2), 436-441, doi:10.1073/pnas.1407302112/-/DCSupplemental.
Schleicher, J. et al., 2019: Protecting half of the planet could directly affect over one billion people. *Nature Sustainability*, **2**(12), 1094-1096, doi:10.1038/s41893-019-0423-y.
Schmiedel, U., J. Dengler and S. Etzold, 2012: Vegetation dynamics of endemic-rich quartz fields in the Succulent Karoo, South Africa, in response to recent climatic trends. *Journal of Vegetation Science*, **23**(2), 292-303, doi:10.1111/j.1654-1103.2011.01346.x.
Schmitz, O. J. et al., 2018: Animals and the zoogeochemistry of the carbon cycle. *Science*, **362**(6419), doi:10.1126/science.aar3213.
Schneider, A. et al., 2017: Global-scale river network extraction based on high-resolution topography and constrained by lithology, climate, slope, and observed drainage density. *Geophysical Research Letters*, **44**(6), 2773-2781, doi:https://doi.org/10.1002/2016GL071844.
Schneider, P. and S. Hook, 2010: Space observations of inland water bodies show rapid surface warming since 1985. *Geophysical Research Letters*, **37**, doi:10.1029/2010gl045059.
Schneider, R. R., K. Devito, N. Kettridge and E. Bayne, 2016: Moving beyond bioclimatic envelope models: integrating upland forest and peatland processes to predict ecosystem transitions under climate change in the western Canadian boreal plain: Western boreal ecosystem transitions under climate change. *Ecohydrology*, **9**(6), 899-908, doi:10.1002/eco.1707.
Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12**(11), 3469-3488, doi:10.5194/bg-12-3469-2015.
Scholten, R. C. et al., 2021: Overwintering fires in boreal forests. *Nature*, **593**(7859), 399-+, doi:10.1038/s41586-021-03437-y.
Scholze, M., W. Knorr, N. W. Arnell and I. C. Prentice, 2006: A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences*, **103**(35), 13116-13120, doi:10.1073/pnas.0601816103.
Schreiner-McGraw, A. P. et al., 2020: Woody Plant Encroachment has a Larger Impact than Climate Change on Dryland Water Budgets. *Scientific Reports*, **10**(1), 8112, doi:10.1038/s41598-020-65094-x.
Schröter, D. et al., 2005: Ecosystem Service Supply and Vulnerability to Global Change in Europe. *Science*, **310**(5752), 1333-1337, doi:10.1126/science.1115233.

Schulte-Uebbing, L. and W. de Vries, 2018: Global-scale impacts of nitrogen deposition on tree carbon sequestration in tropical, temperate, and boreal forests: A meta-analysis. *Global Change Biology*, **24**(2), E416-E431, doi:10.1111/gcb.13862.
Schulte To Bühne, H., N. Pettorelli and M. Hoffmann, 2021: The policy consequences of defining rewilding. *Ambio*, doi:10.1007/s13280-021-01560-8.
Schuur, E. A. G. et al., 2009: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, **459**(7246), 556.
Schwanz, L. E., 2016: Parental thermal environment alters offspring sex ratio and fitness in an oviparous lizard. *Journal of Experimental Biology*, **219**(15), 2349-2357, doi:10.1242/jeb.139972.
Schwanz, Lisa E. and Fredric J. Janzen, 2008: Climate Change and Temperature-Dependent Sex Determination: Can Individual Plasticity in Nesting Phenology Prevent Extreme Sex Ratios? *Physiological and Biochemical Zoology*, **81**(6), 826-834, doi:10.1086/590220.
Schwartz, M. W. et al., 2012: Managed Relocation: Integrating the Scientific, Regulatory, and Ethical Challenges. *Bioscience*, **62**(8), 732-743, doi:10.1525/bio.2012.62.8.6.
Schwefel, R., A. Gaudard, A. Wüest and D. Bouffard, 2016: Effects of climate change on deepwater oxygen and winter mixing in a deep lake (Lake Geneva): Comparing observational findings and modeling. *Water Resources Research*, **52**(11), 8811-8826, doi:10.1002/2016wr019194.
Schwitzer, C., N. Simpson, M. Roestorf and R. Sherley, 2013: The African Penguin Chick Bolstering Project: a One Plan approach to integrated species conservation. *WAZA Mag*, **14**, 23-26.
Screen, J. A. and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, **464**(7293), 1334-1337, doi:10.1038/nature09051.
Scriven, S. A., J. A. Hodgson, C. J. McClean and J. K. Hill, 2015: Protected areas in Borneo may fail to conserve tropical forest biodiversity under climate change. *Biological Conservation*, **184**, 414-423, doi:10.1016/j.biocon.2015.02.018.
Searchinger, T. D. et al., 2015: High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. *Nature Climate Change*, **5**(5), 481-486, doi:10.1038/nclimate2584.
Seddon, N. et al., 2020a: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190120, doi:10.1098/rstb.2019.0120.
Seddon, N. et al., 2020b: Global recognition of the importance of nature-based solutions to the impacts of climate change. *Global Sustainability*, **3**.
Seekell, D., P. Bystrom and J. Karlsson, 2018: Lake morphometry moderates the relationship between water color and fish biomass in small boreal lakes. *Limnology and Oceanography*, **63**(5), 2171-2178, doi:10.1002/lno.10931.
Seidl, R., M. J. Schelhaas and M. J. Lexer, 2011: Unraveling the drivers of intensifying forest disturbance regimes in Europe. *Global Change Biology*, **17**(9), 2842-2852, doi:10.1111/j.1365-2486.2011.02452.x.
Seidl, R. et al., 2017: Forest disturbances under climate change. *Nature Climate Change*, **7**(6), 395-402, doi:10.1038/nclimate3303.
Seimon, T. A. et al., 2017: Long-term monitoring of tropical alpine habitat change, Andean anurans, and chytrid fungus in the Cordillera Vilcanota, Peru: Results from a decade of study. *Ecology and Evolution*, **7**(5), 1527-1540, doi:10.1002/ece3.2779.
Seltmann, C. T., B. M. Kraemer and R. Adrian, 2019: The importance of nonrandom and random trait patterns in phytoplankton communities: a case study from Lake Müggelsee, Germany. *Theoretical Ecology*, **12**(4), 501-512.
Semenza, J. C., 2020: Cascading risks of waterborne diseases from climate change. *Nature Immunology*, **21**(5), 484-487, doi:10.1038/s41590-020-0631-7.
Semenza, J. C. et al., 2017: Environmental suitability of *Vibrio* infections in a warming climate: an early warning system. *Environmental Health Perspectives*, **125**(10), 107004, doi:10.1289/EHP2198.
Seneviratne, S. I. et al., 2012: Changes in climate extremes and their impacts on the natural physical environment [Field, C. B. V. B. T. F. S. D. Q. D. J. D. K. L. E. M. D. M. K. J. M. G. K. (ed.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.
Senf, C. et al., 2020: Excess forest mortality is consistently linked to drought across Europe. *Nature Communications*, **11**(1), 8, doi:10.1038/s41467-020-19924-1.
Senf, C. et al., 2018: Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nature Communications*, **9**, doi:10.1038/s41467-018-07539-6.
Senf, C. and R. Seidl, 2021: Mapping the forest disturbance regimes of Europe. *Nature Sustainability*, **4**(1), 63-70, doi:10.1038/s41893-020-00609-y.
Senior, R. A., J. K. Hill and D. P. Edwards, 2019: Global loss of climate connectivity in tropical forests. *Nature Climate Change*, **9**(8), 623-626.
Sentinella, A. T. et al., 2020: Tropical plants do not have narrower temperature tolerances, but are more at risk from warming because they are close to their upper thermal limits. *Global Ecology and Biogeography*, **29**(8), 1387-1398.
Sentis, A., J. M. Montoya and M. Lurgi, 2021: Warming indirectly increases invasion success in food webs. *Proceedings of the Royal Society B: Biological Sciences*, **288**(1947), 20202622, doi:10.1098/rspb.2020.2622.

Serikova, S. et al., 2018: High riverine CO2 emissions at the permafrost boundary of Western Siberia. *Nature Geoscience*, **11**(11), 825-829, doi:10.1038/s41561-018-0218-1.

Services, I. S.-P. P. o. B. and Ecosystem, 2021: *Scientific Outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change*. IPBES, Bonn, Germany.

Settele, J. et al., 2014: Terrestrial and inland water systems. In: *Climate Change 2014: Impacts, Adaptation, Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the IPCC* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, pp. 271-359.

Sgro, C. M., A. J. Lowe and A. A. Hoffmann, 2011: Building evolutionary resilience for conserving biodiversity under climate change. *Evolutionary Applications*, **4**(2), 326-337, doi:10.1111/j.1752-4571.2010.00157.x.

Sgro, C. M., J. S. Terblanche and A. A. Hoffmann, 2016: What Can Plasticity Contribute to Insect Responses to Climate Change? *Annual Review of Entomology*, **61**, 433-451, doi:10.1146/annurev-ento-010715-023859.

Shackelford, N. et al., 2021: Drivers of seedling establishment success in dryland restoration efforts. *Nature Ecology & Evolution*, **5**(9), 1283-1290, doi:10.1038/s41559-021-01510-3.

Shah, D. N. et al., 2014: Current and future latitudinal gradients in stream macroinvertebrate richness across North America. *Freshwater Science*, **33**(4), 1136-1147, doi:10.1086/678492.

Shah, M. M. et al., 2019: Malaria smear positivity among Kenyan children peaks at intermediate temperatures as predicted by ecological models. *Parasites & Vectors*, **12**(1), 288, doi:10.1186/s13071-019-3547-z.

Shah, P., K. Baylis, J. Busch and J. Engelmann, 2021: What determines the effectiveness of national protected area networks? *Environmental Research Letters*, **16**(7), 074017, doi:10.1088/1748-9326/ac05ed.

Shannon, L. and R. Crawford, 1999: MANAGEMENT OF THE AFRICAN PENGUIN SPHENISCUS DEMERSUS _ INSIGHTS FROM MODELLING. *Marine Ornithology*, **27**, 119-128.

Sharma, S. et al., 2019: Widespread loss of lake ice around the Northern Hemisphere in a warming world. *Nature Climate Change*, **9**(3), 227-+, doi:10.1038/s41558-018-0393-5.

Sharpe, L., B. Cale and J. L. Gardner, 2019: Weighing the cost: the impact of serial heatwaves on body mass in a small Australian passerine. *Journal of Avian Biology*, **50**(11), doi:https://doi.org/10.1111/jav.02355.

Sherley, R. B. et al., 2018: Bayesian inference reveals positive but subtle effects of experimental fishery closures on marine predator demographics. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1871), 20172443.

Sherley, R. B. et al., 2012: Artificial nests enhance the breeding productivity of African Penguins (Spheniscus demersus) on Robben Island, South Africa. *Emu-Austral Ornithology*, **112**(2), 97-106.

Sherley, R. B. et al., 2020: The conservation status and population decline of the African penguin deconstructed in space and time. *bioRxiv*.

Sherley, R. B. et al., 2013: Influence of local and regional prey availability on breeding performance of African penguins Spheniscus demersus. *Marine Ecology Progress Series*, **473**, 291-301.

Sherley, R. B. et al., 2014: Hand-rearing, release and survival of African penguin chicks abandoned before independence by moulting parents. *PLoS ONE*, **9**(10), e110794.

Sherley, R. B. et al., 2015: Bottom-up effects of a no-take zone on endangered penguin demographics. *Biology letters*, **11**(7), 20150237.

Shi, L., W. Feng, J. Xu and Y. Kuzyakov, 2018: Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes, and future potentials. *Land degradation & development*, **29**(11), 3886-3897.

Shiller, J. A., S. A. Finkelstein and S. A. Cowling, 2014: Relative importance of climatic and autogenic controls on Holocene carbon accumulation in a temperate bog in southern Ontario, Canada. *The Holocene*, **24**(9), 1105-1116, doi:10.1177/0959683614538070.

Shin, Y.-J. et al., 2019: *IPBES Global Assessment on Biodiversity and Ecosystem Services, Chapter 4: Plausible futures of nature, its contributions to people and their good quality of life*. Bonn, GErmany, in press pp.

Shiraishi, T. and R. Hirata, 2021: Estimation of carbon dioxide emissions from the megafires of Australia in 2019-2020. *Scientific Reports*, **11**(1), 10, doi:10.1038/s41598-021-87721-x.

Shocket, M. S., S. J. Ryan and E. A. Mordecai, 2018: Temperature explains broad patterns of Ross River virus transmission. *eLife*, **7**, e37762, doi:10.7554/eLife.37762.

Shocket, M. S. et al., 2020: Transmission of West Nile and five other temperate mosquito-borne viruses peaks at temperatures between 23°C and 26°C. *eLife*, **9**, e58511, doi:10.7554/eLife.58511.

Short, C. et al., 2019: Capturing the multiple benefits associated with nature-based solutions: Lessons from a natural flood management project in the C otswolds, UK. *Land degradation & development*, **30**(3), 241-252.

Short, E. E., C. Caminade and B. N. Thomas, 2017: Climate Change Contribution to the Emergence or Re-Emergence of Parasitic Diseases. *Infect Dis (Auckl)*, **10**, 1178633617732296, doi:10.1177/1178633617732296.

Short, F. T. et al., 2016: Impacts of climate change on submerged and emergent wetland plants. *Aquatic Botany*, **135**, 3-17.

Shrestha, B. B. et al., 2019: Community perception and prioritization of invasive alien plants in Chitwan-Annapurna Landscape, Nepal. *Journal of environmental management*, **229**, 38-47.

Shukla, A. K., 2019: Emerging Infectious Diseases Caused by Fungi in Animals and Their Prevention. In: *Recent Developments in Fungal Diseases of Laboratory Animals* [Gupta, A. and N. P. Singh (eds.)]. Springer International Publishing, Cham, pp. 1-5. ISBN 978-3-030-18586-2.

Shukla, P. R. et al., 2019: Technical Summary. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.
Shurin, J. B. et al., 2010: Environmental stability and lake zooplankton diversity–contrasting effects of chemical and thermal variability. *Ecology Letters*, **13**(4), 453-463.
Siebers, A. R., A. Paillex and C. T. Robinson, 2019: Flow intermittency influences the trophic base, but not the overall diversity of alpine stream food webs. *Ecography*, **42**(9), 1523-1535, doi:10.1111/ecog.04597.
Siepielski, A. M. et al., 2019: No evidence that warmer temperatures are associated with selection for smaller body sizes. *Proceedings of the Royal Society B: Biological Sciences*, **286: 20191332**, doi:http://dx.doi.org/10.1098/rspb.2019.1332.
Sierra-Correa, P. C. and J. R. C. Kintz, 2015: Ecosystem-based adaptation for improving coastal planning for sea-level rise: A systematic review for mangrove coasts. *Marine Policy*, **51**, 385-393.
Sigdel, S. R. et al., 2018: Moisture-mediated responsiveness of treeline shifts to global warming in the Himalayas. *Global Change Biology*, **24**(11), 5549-5559, doi:10.1111/gcb.14428.
Sillmann, J. et al., 2017: Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities. *Weather and climate extremes*, **18**, 65-74, doi:doi: 10.1016/j.wace.2017.10.003.
Silva, C. V. J. et al., 2018: Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **373**(1760), doi:10.1098/rstb.2018.0043.
Silva Junior, C. H. L. et al., 2020: Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses. *Science Advances*, **6**(40), eaaz8360, doi:10.1126/sciadv.aaz8360.
Silva, L. C. R. et al., 2016: Tree growth acceleration and expansion of alpine forests: The synergistic effect of atmospheric and edaphic change. *Science advances*, **2**(8), e1501302.
Sim, T. G. et al., 2021: Divergent responses of permafrost peatlands to recent climate change. *Environmental Research Letters*, **16**(3), 034001, doi:10.1088/1748-9326/abe00b.
Simola, H., A. Pitkänen and J. Turunen, 2012: Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. *European Journal of Soil Science*, **63**(6), 798-807.
Sinclair, F. et al., 2019: *The Contribution of Agroecological Approaches to Realizing Climate-Resilient Agriculture*. Rotterdam and Washington, DC, 46 p.-46 p. pp.
Singer, M. C., 2017: Shifts in time and space interact as climate warms. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(49), 12848-12850, doi:10.1073/pnas.1718334114.
Singh, C. et al., 2020: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Climatic Change*, **162**(2), 255-277, doi:10.1007/s10584-020-02762-x.
Singh, S. P. et al., 2021: Indian Himalayan timberline ecotone in response to climate change -- initial findings. *Current Science (00113891)*, **120**(5), 859-871, doi:10.18520/cs/v120/i5/859-871.
Siraj, A. S. et al., 2014: Altitudinal Changes in Malaria Incidence in Highlands of Ethiopia and Colombia. *Science*, **343**(6175), 1154-1158, doi:10.1126/science.1244325.
Sirami, C. et al., 2017: Impacts of global change on species distributions: obstacles and solutions to integrate climate and land use. *Global Ecology and Biogeography*, **26**(4), 385-394.
Sitch, S., P. M. Cox, W. J. Collins and C. Huntingford, 2007: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, **448**(7155), 791-U794, doi:10.1038/nature06059.
Sitch, S. et al., 2015: Recent trends and drivers of regional sources and sinks of carbon dioxide. *Biogeosciences*, **12**(3), 653-679, doi:10.5194/bg-12-653-2015.
Sitch, S. et al., 2008: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*, **14**(9), 2015-2039, doi:10.1111/j.1365-2486.2008.01626.x.
Sittaro, F., A. Paquette, C. Messier and C. A. Nock, 2017: Tree range expansion in eastern North America fails to keep pace with climate warming at northern range limits. *Global Change Biology*, **23**(8), 3292-3301, doi:10.1111/gcb.13622.
Skikne, S. A., A. L. Borker, R. S. Terrill and E. Zavaleta, 2020: Predictors of past avian translocation outcomes inform feasibility of future efforts under climate change. *Biological Conservation*, **247**, 108597.
Skowno, A. L. et al., 2017: Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers. *Global change biology*, **23**(6), 2358–2369.
Slingsby, J. et al., 2017: Intensifying postfire weather and biological invasion drive species loss in a Mediterranean-type biodiversity hotspot. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(18), 4697-4702, doi:10.1073/pnas.1619014114.
Slingsby, J. A., G. R. Moncrieff, A. J. Rogers and E. C. February, 2020a: Altered ignition catchments threaten a hyperdiverse fire-dependent ecosystem. *Global change biology*, **26**(2), 616-628.
Slingsby, J. A., G. R. Moncrieff and A. M. Wilson, 2020b: Near-real time forecasting and change detection for an open ecosystem with complex natural dynamics. *ISPRS Journal of Photogrammetry and Remote Sensing*, **166**, 15-25.

Smit, I. P. et al., 2016: An examination of the potential efficacy of high-intensity fires for reversing woody encroachment in savannas. *Journal of applied ecology*, **53**(5), 1623-1633.
Smit, I. P. J. and H. H. T. Prins, 2015: Predicting the effects of woody encroachment on mammal communities, grazing biomass and fire frequency in African savannas. *PloS one*, **10**(9), e0137857.
Smith, L. C., Y. Sheng, G. M. MacDonald and L. D. Hinzman, 2005: Disappearing Arctic lakes. *Science*, **308**(5727), 1429, doi:10.1126/science.1108142.
Smith, P. et al., 2019a: Impacts of land-based greenhouse gas removal options on ecosystem services and the United Nations sustainable development goals. *Annual Review of Environment and Resources*, **44**.
Smith, P. et al., 2020: Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Global Change Biology*, **26**(3), 1532-1575, doi:10.1111/gcb.14878.
Smith, P. et al., 2019b: Chapter 6: Interlinkages Between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Abdulla, A., I. Noble and T. Zatari (eds.)]. Cambridge University Press, pp. 551-672.
Smith, P. et al., 2018: Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. *Philosophical Transactions of the Royal Society A*, **376**.
Smith, S. W. et al., 2015: Combination of herbivore removal and nitrogen deposition increases upland carbon storage. *Global Change Biology*, **21**(8), 3036-3048, doi:10.1111/gcb.12902.
Smithers, B. V., M. P. North, C. I. Millar and A. M. Latimer, 2018: Leap frog in slow motion: Divergent responses of tree species and life stages to climatic warming in Great Basin subalpine forests. *Global Change Biology*, **24**(2), E442-E457, doi:10.1111/gcb.13881.
Snapp, S. et al., 2021: *Agroecology and climate change rapid evidence review: Performance of agroecological approaches in low- and middle- income countries*. CGIAR Research Program on Climate Change, Agriculture and Food Security. Available at: https://cgspace.cgiar.org/handle/10568/113487 (accessed 2021/09/08/03:49:15).
Snyder, K. A. et al., 2019: Effects of changing climate on the hydrological cycle in cold desert ecosystems of the Great Basin and Columbia Plateau. *Rangeland Ecology & Management*, **72**(1), 1–12.
Sobral, M. et al., 2017: Mammal diversity influences the carbon cycle through trophic interactions in the Amazon. *Nature Ecology & Evolution*, doi:10.1038/s41559-017-0334-0.
Socolar, J. B., P. N. Epanchin, S. R. Beissinger and M. W. Tingley, 2017: Phenological shifts conserve thermal niches in North American birds and reshape expectations for climate-driven range shifts. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(49), 12976-12981, doi:10.1073/pnas.1705897114.
Soga, M., K. J. Gaston and Y. Yamaura, 2017: Gardening is beneficial for health: A meta-analysis. *Preventive Medicine Reports*, **5**, 92-99, doi:10.1016/j.pmedr.2016.11.007.
Solomon, C. T. et al., 2015: Ecosystem consequences of changing inputs of terrestrial dissolved organic matter to lakes: current knowledge and future challenges. *Ecosystems*, **18**(3), 376-389.
Song, H. et al., 2021: Thresholds of temperature change for mass extinctions. *Nature Communications*, **12**(1), 4694, doi:10.1038/s41467-021-25019-2.
Song, J. et al., 2019: Elevated CO2 does not stimulate carbon sink in a semi-arid grassland. *Ecology Letters*, **22**(3), 458-468, doi:10.1111/ele.13202.
Song, X.-P. et al., 2018: Global land change from 1982 to 2016. *Nature*, **560**(7720), 639.
Soto-Navarro, C. et al., 2020: Mapping co-benefits for carbon storage and biodiversity to inform conservation policy and action. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190128, doi:10.1098/rstb.2019.0128.
Sousa, P. M. et al., 2018: The 'Day Zero'Cape Town drought and the poleward migration of moisture corridors. *Environmental Research Letters*, **13**(12), 124025.
Spalding, M. D. et al., 2014: The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean & Coastal Management*, **90**, 50-57, doi:10.1016/j.ocecoaman.2013.09.007.
Springer, Y. P. et al., 2016: Tick-, mosquito-, and rodent-borne parasite sampling designs for the National Ecological Observatory Network. *Ecosphere*, **7**(5), e01271, doi:https://doi.org/10.1002/ecs2.1271.
Srichaichana, J., Y. Trisurat and S. Ongsomwang, 2019: Land Use and Land Cover Scenarios for Optimum Water Yield and Sediment Retention Ecosystem Services in Klong U-Tapao Watershed, Songkhla, Thailand. *Sustainability*, **11**(10), doi:10.3390/su11102895.
Stafford, W. et al., 2017: The economics of landscape restoration: Benefits of controlling bush encroachment and invasive plant species in South Africa and Namibia. *Ecosystem Services*, **27**, 193-202, doi:10.1016/j.ecoser.2016.11.021.
Stålhandske, S., K. Gotthard and O. Leimar, 2017: Winter chilling speeds spring development of temperate butterflies. *Journal of Animal Ecology*, **86**(4), 718-729, doi:10.1111/1365-2656.12673.
Stammler, F. M. and A. Ivanova, 2020: From spirits to conspiracy? Nomadic perceptions of climate change, pandemics and disease. *Anthropology Today*, **36**(4), 8-12, doi:10.1111/1467-8322.12589.
Stan, K. and A. Sanchez-Azofeifa, 2019: Tropical dry forest diversity, climatic response, and resilience in a changing climate. *Forests*, **10**(5), 1-19, doi:10.3390/f10050443.

Stanaway, J. D. et al., 2016: The global burden of dengue: an analysis from the Global Burden of Disease Study 2013. *The Lancet Infectious Diseases*, **16**(6), 712-723, doi:https://doi.org/10.1016/S1473-3099(16)00026-8.
Stanley, E. H. et al., 2016: The ecology of methane in streams and rivers: patterns, controls, and global significance. *Ecological Monographs*, **86**(2), 146-171.
Staver, A. C., 2018: Prediction and scale in savanna ecosystems. *New Phytologist*, **219**(1), 52-57, doi:https://doi.org/10.1111/nph.14829.
Staver, A. C., S. Archibald and S. A. Levin, 2011: The global extent and determinants of savanna and forest as alternative biome states. *Science*, **334**(6053), 230-232.
Steel, Z. L., H. D. Safford and J. H. Viers, 2015: The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere*, **6**(1), 1-23.
Stefanakis, A., 2019: The Role of Constructed Wetlands as Green Infrastructure for Sustainable Urban Water Management. *Sustainability*, **11**, 6981, doi:10.3390/su11246981.
Stegehuis, A. I. et al., 2015: An observation-constrained multi-physics WRF ensemble for simulating European mega heat waves. *Geoscientific Model Development*, **8**(7), 2285-2298, doi:10.5194/gmd-8-2285-2015.
Stein, B. A. et al., 2013: Preparing for and managing change: climate adaptation for biodiversity and ecosystems. *Frontiers in Ecology and the Environment*, **11**(9), 502-510, doi:https://doi.org/10.1890/120277.
Steinacker, C., C. Beierkuhnlein and A. Jaeschke, 2019: Assessing the exposure of forest habitat types to projected climate change-Implications for Bavarian protected areas. *Ecology and Evolution*, **9**(24), 14417-14429, doi:10.1002/ece3.5877.
Steinbauer, M. J. et al., 2018: Accelerated increase in plant species richness on mountain summits is linked to warming. *Nature*, **556**(7700), 231-234.
Stensgaard, A.-S., L. Rinaldi and R. Bergquist, 2019a: The future is now: New United Nations' Sustainable Development Goals report provides a perspective on vector-borne diseases. *Geospat Health*, **14**(2), doi:10.4081/gh.2019.828.
Stensgaard, A.-S., P. Vounatsou, M. E. Sengupta and J. Utzinger, 2019b: Schistosomes, snails and climate change: Current trends and future expectations. *Acta Tropica*, **190**, 257-268, doi:10.1016/j.actatropica.2018.09.013.
Stephens, S. L. et al., 2018: Drought, Tree Mortality, and Wildfire in Forests Adapted to Frequent Fire. *BioScience*, **68**(2), 77-88, doi:10.1093/biosci/bix146.
Stephens, S. L., C. I. Millar and B. M. Collins, 2010: Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. *Environmental Research Letters*, **5**(2), 024003, doi:10.1088/1748-9326/5/2/024003.
Stephens, S. L. et al., 2020: Fire and climate change: conserving seasonally dry forests is still possible. *Frontiers in Ecology and the Environment*, **18**(6), 354-360, doi:https://doi.org/10.1002/fee.2218.
Stephenson, N. L. et al., 2019: Which trees die during drought? The key role of insect host-tree selection. *Journal of Ecology*, **107**(5), 2383-2401, doi:10.1111/1365-2745.13176.
Sterner, R. W. et al., 2020: Ecosystem services of Earth's largest freshwater lakes. *Ecosystem Services*, **41**, 101046.
Stevens, N., B. Erasmus, S. Archibald and W. Bond, 2016: Woody encroachment over 70 years in South African savannahs: overgrazing, global change or extinction aftershock? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150437.
Stevens, N., C. E. Lehmann, B. P. Murphy and G. Durigan, 2017: Savanna woody encroachment is widespread across three continents. *Global change biology*, **23**(1), 235–244.
Stewart-Sinclair, P. J. et al., 2020: Blue Restoration – Building Confidence and Overcoming Barriers. *Frontiers in Marine Science*, **7**, doi:10.3389/fmars.2020.541700.
Stillman, J. H., 2003: Acclimation Capacity Underlies Susceptibility to Climate Change. *Science*, **301**(5629), 65, doi:10.1126/science.1083073.
Stocker, B. D. et al., 2019: Drought impacts on terrestrial primary production underestimated by satellite monitoring. *Nature Geoscience*, **12**(4), 264-+, doi:10.1038/s41561-019-0318-6.
Stockwell, J. D. et al., 2020: Storm impacts on phytoplankton community dynamics in lakes. *Global Change Biology*, **26**(5), 2756-2784, doi:10.1111/gcb.15033.
Stoks, R., A. N. Geerts and L. De Meester, 2014: Evolutionary and plastic responses of freshwater invertebrates to climate change: realized patterns and future potential. *Evolutionary applications*, **7**(1), 42-55.
Stoner, D. C. et al., 2018: Climatically driven changes in primary production propagate through trophic levels. *Global Change Biology*, **24**(10), 4453-4463, doi:10.1111/gcb.14364.
Stouffer, P. C., E. I. Johnson, R. O. B. Jr and T. E. Lovejoy, 2011: Understory Bird Communities in Amazonian Rainforest Fragments: Species Turnover through 25 Years Post-Isolation in Recovering Landscapes. *PLoS ONE*, **6**(6), e20543, doi:10.1371/journal.pone.0020543.
Stovall, A. E. L., H. Shugart and X. Yang, 2019: Tree height explains mortality risk during an intense drought. *Nature Communications*, **10**, doi:10.1038/s41467-019-12380-6.
Straile, D. et al., 2010: Effects of a half a millennium winter on a deep lake - a shape of things to come? *Global Change Biology*, **16**(10), 2844-2856, doi:10.1111/j.1365-2486.2009.02158.x.
Stralberg, D. et al., 2019: Conservation planning for boreal birds in a changing climate: a framework for action. *Avian Conservation and Ecology*, **14**(1), doi:10.5751/ACE-01363-140113.

Stralberg, D., C. Carroll and S. E. Nielsen, 2020: Toward a climate-informed North American protected areas network: Incorporating climate-change refugia and corridors in conservation planning. *Conservation Letters*, **13**(4), 10, doi:10.1111/conl.12712.
Strassburg, B. B. N. et al., 2010: Global congruence of carbon storage and biodiversity in terrestrial ecosystems. *Conservation Letters*, **3**(2), 98-105, doi:10.1111/j.1755-263X.2009.00092.x.
Strauch, A. M., M. T. Rurai and A. M. Almedom, 2016: Influence of forest management systems on natural resource use and provision of ecosystem services in Tanzania. *Journal of environmental management*, **180**, 35-44.
Strauss, J. et al., 2017: Deep Yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability. *Earth-Science Reviews*, **172**, 75-86, doi:10.1016/j.earscirev.2017.07.007.
Stringer, L. C. et al., 2021: Climate change impacts on water security in global drylands. *One Earth*.
Strömberg, C. A. E., 2011: Evolution of grasses and grassland ecosystems. *Annual Review of Earth and Planetary Sciences*, **39**, 517-544.
Struebig, M. J. et al., 2015: Anticipated climate and land-cover changes reveal refuge areas for Borneo's orang-utans. *Global Change Biology*, **21**(8), 2891-2904, doi:https://doi.org/10.1111/gcb.12814.
Strutz, S. E., 2017: Cutaneous Leishmaniasis Emergence in Texas: Changing Patterns of Disease and Hosts. Ph. D. University of Texas at Austin, Austin, Texas, USA, 99 pp.
Stuart-Fox, D., E. Newton and S. Clusella-Trullas, 2017: Thermal consequences of colour and near-infrared reflectance. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **372**(1724), 20160345, doi:10.1098/rstb.2016.0345.
Stuecker, M. F. et al., 2018: Polar amplification dominated by local forcing and feedbacks. *Nature Climate Change*, **8**(12), 1076-1081, doi:10.1038/s41558-018-0339-y.
Stuenzi, S. M. et al., 2021a: Variability of the surface energy balance in permafrost-underlain boreal forest. *Biogeosciences*, **18**(2), 343-365, doi:10.5194/bg-18-343-2021.
Stuenzi, S. M. et al., 2021b: Sensitivity of ecosystem-protected permafrost under changing boreal forest structures. *Environmental Research Letters*, **16**(8), 084045, doi:10.1088/1748-9326/ac153d.
Stuenzi, S. M. and G. Schaepman-Strub, 2020: Vegetation Trajectories and Shortwave Radiative Forcing Following Boreal Forest Disturbance in Eastern Siberia. *Journal of Geophysical Research-Biogeosciences*, **125**(6), 13, doi:10.1029/2019jg005395.
Suggitt, A. et al., 2017: Conducting robust ecological analyses with climate data. *Oikos*, **126**(11), 1533-1541, doi:10.1111/oik.04203.
Suggitt, A. et al., 2015: Microclimate affects landscape level persistence in the British Lepidoptera. *Journal of Insect Conservation*, **19**(2), 237-253, doi:10.1007/s10841-014-9749-y.
Suggitt, A. J. et al., 2018: Extinction risk from climate change is reduced by microclimatic buffering. *Nature Climate Change*, **8**(8), 713-717, doi:10.1038/s41558-018-0231-9.
Sugimoto, A. et al., 2002: Importance of permafrost as a source of water for plants in east Siberian taiga. *Ecological Research*, **17**(4), 493-503, doi:10.1046/j.1440-1703.2002.00506.x.
Sullivan, M. J. P. et al., 2020: Long-term thermal sensitivity of Earth's tropical forests. *Science*, **368**(6493), 869-+, doi:10.1126/science.aaw7578.
Sullivan, M. J. P. et al., 2017: Diversity and carbon storage across the tropical forest biome. *Scientific Reports*, **7**, doi:10.1038/srep39102.
Sun, B.-j. et al., 2021: Latitudinal embryonic thermal tolerance and plasticity shape the vulnerability of oviparous species to climate change. *Ecological Monographs*, **91**(3), e01468, doi:https://doi.org/10.1002/ecm.1468.
Sun, W. et al., 2020: Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. *Global Change Biology*, **26**(6), 3325-3335, doi:10.1111/gcb.15001.
Sunkari, E. D., H. M. Korboe, M. Abu and T. Kizildeniz, 2021: Sources and routes of SARS-CoV-2 transmission in water systems in Africa: Are there any sustainable remedies? *Science of The Total Environment*, **753**, 142298, doi:10.1016/j.scitotenv.2020.142298.
Supari et al., 2020: Multi-model projections of precipitation extremes in Southeast Asia based on CORDEX-Southeast Asia simulations. *Environmental Research*, **184**, 109350, doi:10.1016/j.envres.2020.109350.
Swails, E. et al., 2018: Will CO2 Emissions from Drained Tropical Peatlands Decline Over Time? Links Between Soil Organic Matter Quality, Nutrients, and C Mineralization Rates. *Ecosystems*, **21**(5), 868-885, doi:10.1007/s10021-017-0190-4.
Sweet, L. C. et al., 2019: Congruence between future distribution models and empirical data for an iconic species at Joshua Tree National Park. *Ecosphere*, **10**(6), doi:10.1002/ecs2.2763.
Swindles, G. et al., 2019: Widespread drying of European peatlands in recent centuries. *Nature Geoscience*, **12**(11), 922-+, doi:10.1038/s41561-019-0462-z.
Swindles, G. T. et al., 2016: The long-term fate of permafrost peatlands under rapid climate warming. *Scientific Reports*, **5**(1), 17951, doi:10.1038/srep17951.
Syktus, J. I. and C. A. McAlpine, 2016: More than carbon sequestration: Biophysical climate benefits of restored savanna woodlands. *Scientific Reports*, **6**, doi:10.1038/srep29194.
Syphard, A. D., T. J. Brennan and J. E. Keeley, 2019a: Drivers of chaparral type conversion to herbaceous vegetation in coastal Southern California. *Diversity and Distributions*, **25**(1), 90-101.

Syphard, A. D., T. J. Brennan and J. E. Keeley, 2019b: Extent and drivers of vegetation type conversion in Southern California chaparral. *Ecosphere*, **10**(7), doi:10.1002/ecs2.2796.
Syphard, A. D., J. E. Keeley and J. T. Abatzoglou, 2017: Trends and drivers of fire activity vary across California aridland ecosystems. *Journal of Arid Environments*, **144**, 110-122, doi:10.1016/j.jaridenv.2017.03.017.
Tabachnick, W. J., 2010: Challenges in predicting climate and environmental effects on vector-borne disease episystems in a changing world. *J Exp Biol*, **213**(6), 946-954, doi:10.1242/jeb.037564.
Tabor, K. et al., 2018: Tropical Protected Areas Under Increasing Threats from Climate Change and Deforestation. *Land*, **7**(3), doi:10.3390/land7030090.
Taffarello, D. et al., 2018: Modeling freshwater quality scenarios with ecosystem-based adaptation in the headwaters of the Cantareira system, Brazil. *Hydrol. Earth Syst. Sci.*, **22**(9), 4699-4723, doi:10.5194/hess-22-4699-2018.
Taillardat, P. et al., 2020: Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. *Interface Focus.*, **10**(5), 20190129, doi:10.1098/rsfs.2019.0129.
Talbot, C. J. et al., 2018: The impact of flooding on aquatic ecosystem services. *Biogeochemistry*, **141**(3), 439-461, doi:10.1007/s10533-018-0449-7.
Talucci, A. C. and M. A. Krawchuk, 2019: Dead forests burning: the influence of beetle outbreaks on fire severity and legacy structure in sub-boreal forests. *Ecosphere*, **10**(5), 17, doi:10.1002/ecs2.2744.
Tamburini, G. et al., 2020: Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, **6**, eaba1715, doi:10.1126/sciadv.aba1715.
Tangang, F. et al., 2020: Projected future changes in rainfall in Southeast Asia based on CORDEX–SEA multi-model simulations. *Climate Dynamics*, **55**(5-6), 1247-1267, doi:10.1007/s00382-020-05322-2.
Tanneberger, F. et al., 2021: The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives. *Adv. Sustainable Syst.*, **5**(1), 2000146, doi:10.1002/adsu.202000146.
Tantipisanuh, N., 2016: Locality and Hotspot Areas of Globally Threatened Vertebrates in Thailand. *旭硝子財団助成研究成果報告 Reports of research assisted by the Asahi Glass Foundation*, 1-11.
Tape, K. D., K. Christie, G. Carroll and J. A. O'Donnell, 2016a: Novel wildlife in the Arctic: the influence of changing riparian ecosystems and shrub habitat expansion on snowshoe hares. *Global Change Biology*, **22**(1), 208-219.
Tape, K. D. et al., 2016b: Range expansion of moose in Arctic Alaska linked to warming and increased shrub habitat. *PLoS ONE*, **11**(4), e0152636.
Tape, K. D. et al., 2018: Tundra be dammed: Beaver colonization of the Arctic. *Global change biology*, **24**(10), 4478-4488.
Tarnocai, C. et al., 2009: Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, **23**, doi:10.1029/2008gb003327.
Taubert, F. et al., 2018: Global patterns of tropical forest fragmentation. *Nature*, **554**(7693), 519-522.
Taufik, M. et al., 2020: Human-induced changes in Indonesian peatlands increase drought severity. *Environmental Research Letters*, **15**(8), 084013, doi:10.1088/1748-9326/ab96d4.
Taufik, M. et al., 2017: Amplification of wildfire area burnt by hydrological drought in the humid tropics. *Nature Climate Change*, **7**(6), 428-431, doi:10.1038/nclimate3280.
Taufik, M., A. A. Veldhuizen, J. H. M. Wösten and H. A. J. van Lanen, 2019: Exploration of the importance of physical properties of Indonesian peatlands to assess critical groundwater table depths, associated drought and fire hazard. *Geoderma*, **347**, 160-169, doi:10.1016/j.geoderma.2019.04.001.
Taylor, S., M. Knight and A. Harfoot, 2014: *National biodiversity climate change vulnerability model. Natural England Research Report NERR054*. Natural England, York, UK.
Taylor, S. and L. Kumar, 2016: Will climate change impact the potential distribution of a native vine (Merremia peltata) which is behaving invasively in the Pacific region? *Ecology and Evolution*, **6**(3), 742-754.
Teixeira, C. P. and C. O. Fernandes, 2020: Novel ecosystems: a review of the concept in non-urban and urban contexts. *Landscape Ecology*, **35**(1), 23-39, doi:10.1007/s10980-019-00934-4.
Telemeco, R. S., M. J. Elphick and R. Shine, 2009: Nesting lizards (Bassiana duperreyi) compensate partly, but not completely, for climate change. *Ecology*, **90**(1), 17-22, doi:https://doi.org/10.1890/08-1452.1.
Telemeco, R. S. et al., 2017: Lizards fail to plastically adjust nesting behavior or thermal tolerance as needed to buffer populations from climate warming. *Global Change Biology*, **23**(3), 1075-1084, doi:https://doi.org/10.1111/gcb.13476.
Teplitsky, C. and V. Millien, 2014: Climate warming and Bergmann's rule through time: is there any evidence? *Evolutionary applications*, **7**(1), 156-168, doi:10.1111/eva.12129.
Terrer, C. et al., 2019: Nitrogen and phosphorus constrain the CO2 fertilization of global plant biomass. *Nature Climate Change*, **9**(9), 684-+, doi:10.1038/s41558-019-0545-2.
Tersago, K. et al., 2009: Hantavirus disease (nephropathia epidemica) in Belgium: effects of tree seed production and climate. *Epidemiol. Infect.*, **137**(2), 250-256, doi:10.1017/S0950268808000940.
Terskaia, A., R. J. Dial and P. F. Sullivan, 2020: Pathways of tundra encroachment by trees and tall shrubs in the western Brooks Range of Alaska. *Ecography*, **43**(5), 769-778, doi:10.1111/ecog.05015.
Terzi, S. et al., 2019: Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation. *Journal of Environmental Management*, **232**, 759-771, doi:https://doi.org/10.1016/j.jenvman.2018.11.100.

Teshome, D. T., G. E. Zharare and S. Naidoo, 2020: The Threat of the Combined Effect of Biotic and Abiotic Stress Factors in Forestry Under a Changing Climate. *Frontiers in Plant Science*, **11**, 19, doi:10.3389/fpls.2020.601009.
Tesla, B. et al., 2018: Temperature drives Zika virus transmission: evidence from empirical and mathematical models. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1884), 20180795, doi:10.1098/rspb.2018.0795.
Thackeray, S. et al., 2010: Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **16**(12), 3304-3313, doi:10.1111/j.1365-2486.2010.02165.x.
Thackeray, S. J. et al., 2016: Phenological sensitivity to climate across taxa and trophic levels. *Nature*, **535**(7611), 241-245, doi:10.1038/nature18608
Thapa, S. et al., 2018: Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. *PLoS ONE*, **13**(4), e0195752.
Thayne, M. W. et al., 2021: Antecedent lake conditions shape resistance and resilience of a shallow lake ecosystem following extreme wind storms. *Limnology and Oceanography*.
Thieme, M. L. et al., 2016: Freshwater conservation potential of protected areas in the Tennessee and Cumberland River Basins, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **26**(S1), 60-77, doi:10.1002/aqc.2644.
Thom, D. and R. Seidl, 2016: Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biological Reviews*, **91**(3), 760-781, doi:10.1111/brv.12193.
Thomas, C. D. et al., 2001: Ecological and evolutionary processes at expanding range margins. *Nature*, **411**(6837), 577-581, doi:10.1038/35079066.
Thomas, C. D. et al., 2012a: Protected areas facilitate species' range expansions. *Proceedings of the National Academy of Sciences*, **109**(35), 14063-14068.
Thomas, C. D. et al., 2012b: Protected areas facilitate species' range expansions. *Proceedings of the National Academy of Sciences*, **109**(35), 14063, doi:10.1073/pnas.1210251109.
Thomas, S. M., S. W. Griffiths and S. J. Ormerod, 2016: Beyond cool: adapting upland streams for climate change using riparian woodlands. *Global change biology*, **22**(1), 310-324.
Thompson, J. B. et al., 2019: Species-specific effects of phosphorus addition on tropical tree seedling response to elevated CO2. *Functional Ecology*, **33**(10), 1871-1881, doi:10.1111/1365-2435.13421.
Thompson, L. C. et al., 2012: Water management adaptations to prevent loss of spring-run Chinook salmon in California under climate change. *Journal of Water Resources Planning and Management*, **138**(5), 465-478.
Thompson, L. G. et al., 2021: The impacts of warming on rapidly retreating high-altitude, low-latitude glaciers and ice core-derived climate records. *Global and Planetary Change*, **203**, 103538, doi:https://doi.org/10.1016/j.gloplacha.2021.103538.
Thomson, J. R. et al., 2012: The influences of climatic variation and vegetation on stream biota: lessons from the Big Dry in southeastern Australia. *Global Change Biology*, **18**(5), 1582-1596.
Thornton, S. et al., 2018: Peatland fish of Sebangau, Borneo: Diversity, monitoring and conservation. *Mires and Peat*, **22**, 1-25, doi:10.19189/MaP.2017.OMB.313.
Thorp, J. H. et al., 2010: Linking Ecosystem Services, Rehabilitation, and River Hydrogeomorphology. *BioScience*, **60**(1), 67-74, doi:10.1525/bio.2010.60.1.11.
Tian, H. et al., 2020: A comprehensive quantification of global nitrous oxide sources and sinks. *Nature*, **586**(7828), 248-256, doi:10.1038/s41586-020-2780-0.
Tian, H. et al., 2019: Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty. *Global Change Biology*, **25**(2), 640-659, doi:10.1111/gcb.14514.
Tickner, D. et al., 2020: Bending the Curve of Global Freshwater Biodiversity Loss: An Emergency Recovery Plan. *BioScience*, doi:10.1093/biosci/biaa002.
Tiemeyer, B. et al., 2016: High emissions of greenhouse gases from grasslands on peat and other organic soils. *Global Change Biology*, **22**(12), 4134-4149, doi:10.1111/gcb.13303.
Tiemeyer, B. et al., 2017: Moor protection in Germany - Optimization of moor management with regard to the protection of biodiversity of ecosystem services: evaluation tools and survey of indicators. *Federal Agency for Nature Conservation*, **462**, doi:10.19217/skr462.
Till, A., A. L. Rypel, A. Bray and S. B. Fey, 2019: Fish die-offs are concurrent with thermal extremes in north temperate lakes. *Nature Climate Change*, **9**(8), 637-641.
Timpane-Padgham, B. L., T. Beechie and T. Klinger, 2017: A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. *PLoS ONE*, **12**(3), e0173812.
Tingley, M. W. et al., 2012: The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. *Global Change Biology*, **18**(11), 3279-3290, doi:10.1111/j.1365-2486.2012.02784.x.
Tingley, M. W., W. B. Monahan, S. R. Beissinger and C. Moritz, 2009: Birds track their Grinnellian niche through a century of climate change. *Proceedings of the National Academy of Sciences*, **106**(Supplement 2), 19637, doi:10.1073/pnas.0901562106.
Tjaden, N. B., C. Caminade, C. Beierkuhnlein and S. M. Thomas, 2018: Mosquito-Borne Diseases: Advances in Modelling Climate-Change Impacts. *Trends in Parasitology*, **34**(3), 227-245, doi:10.1016/j.pt.2017.11.006.
Tomlinson, R. W., 2005: Soil carbon stocks and changes in the Republic of Ireland. *Journal of Environmental Management*, **76**(1), 77-93, doi:10.1016/j.jenvman.2005.02.001.

Tompkins, A. M., F. J. Colón-González, F. D. Giuseppe and D. B. Namanya, 2019: Dynamical Malaria Forecasts Are Skillful at Regional and Local Scales in Uganda up to 4 Months Ahead. *GeoHealth*, **3**(3), 58-66, doi:10.1029/2018GH000157.
Torralba, M. et al., 2016: Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agriculture, ecosystems & environment*, **230**, 150-161.
Townsend, J., F. Moola and M.-K. Craig, 2020: Indigenous Peoples are critical to the success of nature-based solutions to climate change. *FACETS*, doi:10.1139/facets-2019-0058.
Trewin, B. J., B. H. Kay, J. M. Darbro and T. P. Hurst, 2013: Increased container-breeding mosquito risk owing to drought-induced changes in water harvesting and storage in Brisbane, Australia. *International Health*, **5**(4), 251-258, doi:10.1093/inthealth/iht023.
Trichon, V., P. Hiernaux, R. Walcker and E. Mougin, 2018: The persistent decline of patterned woody vegetation: The tiger bush in the context of the regional Sahel greening trend. *Global Change Biology*, **24**(6), 2633-2648, doi:10.1111/gcb.14059.
Trisurat, Y., 2018: Planning Thailand's Protected Areas in Response to Future Land Use and Climate Change. *International Journal of Conservation Science*, **9**(4), 805-820.
Trisurat, Y., J. Alkemade and E. Arets, 2009: Projecting forest tree distributions and adaptation to climate change in northern Thailand. *Journal of ecology and the natural environment*, **1**(3), 55-63.
Trisurat, Y., P. Eawpanich and R. Kalliola, 2016: Integrating land use and climate change scenarios and models into assessment of forested watershed services in Southern Thailand. *Environmental research*, **147**, 611-620.
Trisurat, Y., R. P. Shrestha and R. Kjelgren, 2011: Plant species vulnerability to climate change in Peninsular Thailand. *Applied Geography*, **31**(3), 1106-1114.
Trtanj, J. et al., 2016: *Climate Impacts on Water-Related Illness*. The Impacts of Climate Change on Human Health in the United States: A Scientific Asssessment, U.S. Global Change Research Program, Washington, D.C., 157-188 pp.
Trugman, A. T. et al., 2021: Why is Tree Drought Mortality so Hard to Predict? *Trends in Ecology & Evolution*, **36**(6), 520-532, doi:10.1016/j.tree.2021.02.001.
Turco, M. et al., 2016: Decreasing Fires in Mediterranean Europe. *PLoS ONE*, **11**(3), doi:10.1371/journal.pone.0150663.
Turco, M. et al., 2019: Climate drivers of the 2017 devastating fires in Portugal. *Scientific Reports*, **9**, doi:10.1038/s41598-019-50281-2.
Turco, M. et al., 2018: Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nature Communications*, **9**(1), 3821, doi:10.1038/s41467-018-06358-z.
Turco, M. et al., 2017: On the key role of droughts in the dynamics of summer fires in Mediterranean Europe. *Scientific Reports*, **7**, doi:10.1038/s41598-017-00116-9.
Turetsky, M. R. et al., 2020: Carbon release through abrupt permafrost thaw. *Nature Geoscience*, **13**(2), 138-143, doi:10.1038/s41561-019-0526-0.
Turetsky, M. R. et al., 2015: Global vulnerability of peatlands to fire and carbon loss. *Nature Geoscience*, **8**(1), 11-14, doi:10.1038/ngeo2325.
Turner, A., S. Wassens, G. Heard and A. Peters, 2021: TEMPERATURE AS A DRIVER OF THE PATHOGENICITY AND VIRULENCE OF AMPHIBIAN CHYTRID FUNGUS BATRACHOCHYTRIUM DENDROBATIDIS: A SYSTEMATIC REVIEW. *Journal of Wildlife Diseases*, **57**(3), 477-494, doi:10.7589/jwd-d-20-00105.
Turner, J. M., 2020: Facultative hyperthermia during a heatwave delays injurious dehydration of an arboreal marsupial. *Journal of Experimental Biology*, **223**(5), doi:10.1242/jeb.219378.
Turner, M. and G. N. Batianoff, 2007: *Chapter 20: Vulnerability of island flora and fauna in the Great Barrier Reef to climate change*. The Great Barrier Reef Marine Park Authority. ISBN 978-1-876945-61-9.
Turunen, J., 2008: Development of Finnish peatland area and carbon storage 1950–2000. *Boreal Environment Research*, **13**, 319-334.
Uboni, A. et al., 2016: Long-Term Trends and Role of Climate in the Population Dynamics of Eurasian Reindeer. *PLoS ONE*, **11**(6), doi:e0158359 10.1371/journal.pone.0158359.
Ummenhofer, C. C. and G. A. Meehl, 2017: Extreme weather and climate events with ecological relevance: a review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **372**(1723), doi:10.1098/rstb.2016.0135.
UNEP-WCMC, 2021: *Protected Planet Report 2020*. Iucn, U.-W. a., Cambridge, UK.
UNEP, 2019: *Global Environment Outlook 6*. United Nations Environment Programme, Nairobi, Kenya. Available at: https://www.unenvironment.org/resources/global-environment-outlook-6.
UNFCCC, 2015: Good practices and lessons learned in adaptation planning processes addressing ecosystems, human settlements, water resources and health, and in processes and structures for
linking national and local adaptation planning: a synthesis of case studies. FCCC/SBSTA/2015/4. Accessed 19 October 2020.
Urban, M., 2015: Accelerating extinction risk from climate change. *Science*, **348**(6234), 571-573, doi:10.1126/science.aaa4984.
Urban, M. C. et al., 2016: Improving the forecast for biodiversity under climate change. *Science*, **353**(6304).
Urrutia-Cordero, P., M. K. Ekvall and L.-A. Hansson, 2016: Local food web management increases resilience and buffers against global change effects on freshwaters. *Scientific reports*, **6**, 29542.

Urrutia-Cordero, P. et al., 2017: Phytoplankton diversity loss along a gradient of future warming and brownification in freshwater mesocosms. *Freshwater Biology*, **62**(11), 1869-1878, doi:10.1111/fwb.13027.
Urrutia-Jalabert, R. et al., 2018: Climate variability and forest fires in central and south-central Chile. *Ecosphere*, **9**(4), 17, doi:10.1002/ecs2.2171.
Uzun, H. et al., 2020: Two years of post-wildfire impacts on dissolved organic matter, nitrogen, and precursors of disinfection by-products in California stream waters. *Water Research*, **181**, 115891, doi:https://doi.org/10.1016/j.watres.2020.115891.
Vadeboncoeur, Y., P. B. McIntyre and M. J. Vander Zanden, 2011: Borders of biodiversity: life at the edge of the world's large lakes. *BioScience*, **61**(7), 526-537.
Vadrevu, K. P. et al., 2019: Trends in Vegetation fires in South and Southeast Asian Countries. *Scientific Reports*, **9**(1), 7422, doi:10.1038/s41598-019-43940-x.
Valdivia, C. et al., 2010: Adapting to Climate Change in Andean Ecosystems: Landscapes, Capitals, and Perceptions Shaping Rural Livelihood Strategies and Linking Knowledge Systems. *Annals of the Association of American Geographers*, **100**(4), 818-834.
Valenzuela, J. G. and S. Aksoy, 2018: Impact of vector biology research on old and emerging neglected tropical diseases. *PLOS Neglected Tropical Diseases*, **12**(5), e0006365, doi:10.1371/journal.pntd.0006365.
Väliranta, M. et al., 2021: Warming climate forcing impact from a sub-arctic peatland as a result of late Holocene permafrost aggradation and initiation of bare peat surfaces. *Quaternary Science Reviews*, **264**, 107022, doi:10.1016/j.quascirev.2021.107022.
Valkó, O., P. Török, B. Deák and B. Tóthmérész, 2014: Prospects and limitations of prescribed burning as a management tool in European grasslands. *Basic and Applied Ecology*, **15**(1), 26-33.
Valladares, F. et al., 2014: The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. *Ecology letters*, **17**(11), 1351-1364.
van Asselen, S. and P. H. Verburg, 2013: Land cover change or land use intensification: simulating land system change with a global-scale land change model. *Global Change Biology*, n/a-n/a, doi:10.1111/gcb.12331.
van Blerk, J. J., A. G. West, R. Altwegg and M. T. Hoffman, 2021: Does a trade-off between growth plasticity and resource conservatism mediate post-fire shrubland responses to rainfall seasonality? *New Phytologist*, **230**(4), 1407-1420.
Van Bocxlaer, B., R. SCHULTHEIß, P. D. PLISNIER and C. Albrecht, 2012: Does the decline of gastropods in deep water herald ecosystem change in Lakes Malawi and Tanganyika? *Freshwater Biology*, **57**(8), 1733-1744.
van de Ven, T. M. F. N., A. E. McKechnie and S. J. Cunningham, 2019: The costs of keeping cool: behavioural trade-offs between foraging and thermoregulation are associated with significant mass losses in an arid-zone bird. *Oecologia*, **191**(1), 205-215, doi:10.1007/s00442-019-04486-x.
van de Ven, T. M. F. N., A. E. McKechnie, S. Er and S. J. Cunningham, 2020: High temperatures are associated with substantial reductions in breeding success and offspring quality in an arid-zone bird. *Oecologia*, **193**(1), 225-235, doi:10.1007/s00442-020-04644-6.
van der Heijden, G. M., S. A. Schnitzer, J. S. Powers and O. L. Phillips, 2013: Liana Impacts on Carbon Cycling, Storage and Sequestration in Tropical Forests. *Biotropica*, **45**(6), 682-692, doi:https://doi.org/10.1111/btp.12060.
van der Kolk, H.-J. et al., 2016: Potential Arctic tundra vegetation shifts in response to changing temperature, precipitation and permafrost thaw. *Biogeosciences*, **13**(22), 6229-6245, doi:10.5194/bg-13-6229-2016.
van der Plas, F., 2019: Biodiversity and ecosystem functioning in naturally assembled communities. *Biological Reviews*, **94**(4), 1220-1245, doi:https://doi.org/10.1111/brv.12499.
Van Der Sleen, P. et al., 2015: No growth stimulation of tropical trees by 150 years of CO 2 fertilization but water-use efficiency increased. *Nature geoscience*, **8**(1), 24.
van der Werf, G. R. et al., 2017: Global fire emissions estimates during 1997–2016. *Earth System Science Data*, **9**(2), 697-720, doi:10.5194/essd-9-697-2017.
van Dijk, J., G. P. David, G. Baird and E. R. Morgan, 2008: Back to the future: Developing hypotheses on the effects of climate change on ovine parasitic gastroenteritis from historical data. *Veterinary Parasitology*, **158**(1), 73-84, doi:10.1016/j.vetpar.2008.08.006.
van Dijk, J., N. D. Sargison, F. Kenyon and P. J. Skuce, 2010: Climate change and infectious disease: helminthological challenges to farmed ruminants in temperate regions. *Animal: an International Journal of Animal Bioscience; Cambridge*, **4**(3), 377-392, doi:http://dx.doi.org.ezproxy.lib.utexas.edu/10.1017/S1751731109990991.
van Mantgem, P. et al., 2009: Widespread Increase of Tree Mortality Rates in the Western United States. *Science*, **323**(5913), 521-524, doi:10.1126/science.1165000.
van Mantgem, P. J., A. C. Caprio, N. L. Stephenson and A. J. Das, 2016: Does Prescribed Fire Promote Resistance to Drought in Low Elevation Forests of the Sierra Nevada, California, USA? *Fire Ecology*, **12**(1), 13-25, doi:10.4996/fireecology.1201013.
van Marle, M. J. E. et al., 2017: Fire and deforestation dynamics in Amazonia (1973-2014): Fire Dynamics in Amazonia (1973-2014). *Global Biogeochemical Cycles*, **31**(1), 24-38, doi:10.1002/2016GB005445.
van Nes, E. H. et al., 2016: What do you mean,'tipping point'? *Trends in ecology & evolution*, **31**(12), 902-904.
van Oldenborgh, G. J. et al., 2021: Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences*, **21**(3), 941-960, doi:10.5194/nhess-21-941-2021.

Van Pelt, R. et al., 2016: Emergent crowns and light-use complementarity lead to global maximum biomass and leaf area in Sequoia sempervirens forests. *Forest Ecology and Management*, **375**, 279-308, doi:10.1016/j.foreco.2016.05.018.
van Wilgen, B. W. and A. Wannenburgh, 2016: Co-facilitating invasive species control, water conservation and poverty relief: achievements and challenges in South Africa's Working for Water programme. *Current Opinion in Environmental Sustainability*, **19**, 7-17.
Van Wilgen, N. J. et al., 2016: Rising temperatures and changing rainfall patterns in South Africa's national parks. *International Journal of Climatology*, **36**(2), 706-721.
Van Zyl, H. and J. Kinghorn, 2018: *The Economic Value and Contributrion of the Simon's Town Penguin Colony*. **10**, Independent Economic Researchers, Cape Town, South Africa. Available at: https://www.capebirdclub.org.za/wp-content/uploads/2020/04/cbc-simons-town-penguin-colony-economic-assessment-report.pdf.
Vári, Á. et al., 2021: Freshwater systems and ecosystem services: Challenges and chances for cross-fertilization of disciplines. *Ambio*, 1-17.
Varkkey, H., A. Tyson, S. Al and B. Choiruzzad, 2018: Forest Policy and Economics Palm oil intensification and expansion in Indonesia and Malaysia : Environmental and socio-political factors influencing policy. **92**(September 2017), 148-159, doi:10.1016/j.forpol.2018.05.002.
Vázquez, D. P., E. Gianoli, W. F. Morris and F. Bozinovic, 2017: Ecological and evolutionary impacts of changing climatic variability. *Biological Reviews*, **92**(1), 22-42, doi:https://doi.org/10.1111/brv.12216.
Veldman, J. W. et al., 2019: Comment on "The global tree restoration potential". *Science*, **366**(6463), eaay7976.
Veldman, J. W. et al., 2015: Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience*, **65**(10), 1011-1018.
Velthuis, M. et al., 2017: Warming advances top-down control and reduces producer biomass in a freshwater plankton community. *Ecosphere*, **8**(1), e01651.
Venter, O. et al., 2016: Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications*, **7**, doi:10.1038/ncomms12558.
Venter, Z. S., M. D. Cramer and H.-J. Hawkins, 2018: Drivers of woody plant encroachment over Africa. *Nature communications*, **9**(1), 2272.
Veraverbeke, S. et al., 2021: Direct and longer-term carbon emissions from arctic-boreal fires: A short review of recent advances. *Current Opinion in Environmental Science & Health*, **23**, 100277, doi:10.1016/j.coesh.2021.100277.
Veraverbeke, S. et al., 2017: Lightning as a major driver of recent large fire years in North American boreal forests. *Nature Climate Change*, **7**(7), 529-+, doi:10.1038/nclimate3329.
Verburg, R. et al., 2019: An innovation perspective to climate change adaptation in coffee systems. *Environmental science & policy*, **97**, 16-24.
Vetrita, Y. and M. A. Cochrane, 2019: Fire Frequency and Related Land-Use and Land-Cover Changes in Indonesia's Peatlands. *Remote Sensing*, **12**(1), 5, doi:10.3390/rs12010005.
Vezzulli, L. et al., 2016: Climate influence on *Vibrio* and associated human diseases during the past half-century in the coastal North Atlantic. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(34), E5062-E5071, doi:10.1073/pnas.1609157113.
Vicente-Serrano, S. M. et al., 2020: A review of environmental droughts: Increased risk under global warming? *Earth-Science Reviews*, **201**, 102953.
Viedma, O., I. R. Urbieta and J. M. Moreno, 2018: Wildfires and the role of their drivers are changing over time in a large rural area of west-central Spain. *Scientific Reports*, **8**(1), 17797, doi:10.1038/s41598-018-36134-4.
Vieilledent, G. et al., 2013: Vulnerability of baobab species to climate change and effectiveness of the protected area network in Madagascar: Towards new conservation priorities. *Biological Conservation*, **166**, 11-22, doi:10.1016/j.biocon.2013.06.007.
Vieira, K. S., P. F. G. Montenegro, G. G. Santana and W. L. d. S. Vieira, 2018: Effect of climate change on distribution of species of common horned frogs in South America. *PLoS ONE*, **13**(9), e0202813, doi:10.1371/journal.pone.0202813.
Vignola, R. et al., 2015: Ecosystem-based adaptation for smallholder farmers: Definitions, opportunities and constraints. *Agriculture, Ecosystems & Environment*, **211**, 126-132.
Vignola, R., B. Locatelli, C. Martinez and P. Imbach, 2009: Ecosystem-based adaptation to climate change: what role for policy-makers, society and scientists? *Mitigation and Adaptation Strategies for Global Change*, **14**(8), 691, doi:10.1007/s11027-009-9193-6.
Virkkala, R. et al., 2013: Does the protected area network preserve bird species of conservation concern in a rapidly changing climate? *Biodiversity and Conservation*, **22**(2), 459-482, doi:10.1007/s10531-012-0423-y.
Virkkala, R. et al., 2014: Protected areas alleviate climate change effects on northern bird species of conservation concern. *Ecology and Evolution*, **4**(15), 2991-3003.
Visser, P. M. et al., 2016: How rising CO2 and global warming may stimulate harmful cyanobacterial blooms. *Harmful Algae*, **54**, 145-159.
Vitali, A. et al., 2017: Deconstructing human-shaped treelines: Microsite topography and distance to seed source control Pinus nigra colonization of treeless areas in the Italian Apennines. *Forest Ecology and Management*, **406**, 37-45, doi:10.1016/j.foreco.2017.10.004.

Vitasse, Y., C. Signarbieux and Y. H. Fu, 2018: Global warming leads to more uniform spring phenology across elevations. *Proceedings of the National Academy of Sciences*, **115**(5), 1004-1008.
Vogel, M. M. et al., 2017: Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks. *Geophysical Research Letters*, **44**(3), 1511-1519, doi:10.1002/2016gl071235.
Voigt, C. et al., 2020: Nitrous oxide emissions from permafrost-affected soils. *Nature Reviews Earth & Environment*, **1**(8), 420-434, doi:10.1038/s43017-020-0063-9.
Voigt, C. et al., 2017: Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw. *Proceedings of the National Academy of Sciences*, **114**(24), 6238, doi:10.1073/pnas.1702902114.
Volpato, G. et al., 2020: Baby pangolins on my plate: possible lessons to learn from the COVID-19 pandemic. *Journal of Ethnobiology and Ethnomedicine*, **16**(1).
von Holle, B., S. Yelenik and E. S. Gornish, 2020: Restoration at the landscape scale as a means of mitigation and adaptation to climate change. *Current Landscape Ecology Reports*, **5**(3), 85-97, doi:10.1007/s40823-020-00056-7.
Vonk, J. E. et al., 2015: Reviews and syntheses: Effects of permafrost thaw on Arctic aquatic ecosystems. *Biogeosciences*, **12**(23), 7129-7167, doi:10.5194/bg-12-7129-2015.
Vonlanthen, P. et al., 2012: Eutrophication causes speciation reversal in whitefish adaptive radiations. *Nature*, **482**(7385), 357-U1500, doi:10.1038/nature10824.
Vorosmarty, C. J. et al., 2010: Global threats to human water security and river biodiversity. *Nature*, **467**(7315), 555-561, doi:10.1038/nature09440.
Voyles, J. et al., 2018: Shifts in disease dynamics in a tropical amphibian assemblage are not due to pathogen attenuation. *Science*, **359**, 1517-1519, doi:10.1126/science.aao4806.
Vuille, M. et al., 2018: Rapid decline of snow and ice in the tropical Andes – Impacts, uncertainties and challenges ahead. *Earth-Science Reviews*, **176**, 195-213, doi:https://doi.org/10.1016/j.earscirev.2017.09.019.
Vymazal, J., Y. Zhao and Ü. Mander, 2021: Recent research challenges in constructed wetlands for wastewater treatment: A review. *Ecological Engineering*, **169**, 106318, doi:https://doi.org/10.1016/j.ecoleng.2021.106318.
Wadgymar, S. M., M. N. Cumming and A. E. Weis, 2015: The success of assisted colonization and assisted gene flow depends on phenology. *Global Change Biology*, **21**(10), 3786-3799, doi:10.1111/gcb.12988.
Wagner, C. and R. Adrian, 2009: Cyanobacteria dominance: quantifying the effects of climate change. *Limnology and Oceanography*, **54**(6part2), 2460-2468.
Wairore, J. N., S. M. Mureithi, O. V. Wasonga and G. Nyberg, 2016: Benefits Derived from Rehabilitating a Degraded Semi-Arid Rangeland in Private Enclosures in West Pokot County, Kenya. *Land Degradation & Development*, **27**(3), 532-541.
Waits, A. et al., 2018: Human infectious diseases and the changing climate in the Arctic. *Environment International*, **121**, 703-713, doi:https://doi.org/10.1016/j.envint.2018.09.042.
Waldram, M. S., W. J. Bond and W. D. Stock, 2008: Ecological engineering by a mega-grazer: white rhino impacts on a South African savanna. *Ecosystems*, **11**(1), 101-112.
Walker, A. P. et al., 2021: Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. *New Phytologist*, **229**(5), 2413-2445, doi:10.1111/nph.16866.
Walker, W. S. et al., 2020: The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(6), 3015-3025, doi:10.1073/pnas.1913321117.
Walsh, J. E. et al., 2018: The High Latitude Marine Heat Wave of 2016 and Its Impacts on Alaska. *Bulletin of the American Meteorological Society*, **99**(1), S39-S43, doi:10.1175/bams-d-17-0105.1.
Walsh, R. E. et al., 2016: Morphological and dietary responses of chipmunks to a century of climate change. *Global Change Biology*, **22**(9), 3233-3252, doi:https://doi.org/10.1111/gcb.13216.
Wan, W. H. et al., 2017: Hydrological Drought in the Anthropocene: Impacts of Local Water Extraction and Reservoir Regulation in the US. *Journal of Geophysical Research-Atmospheres*, **122**(21), 11313-11328, doi:10.1002/2017jd026899.
Wan, Z. et al., 2018: Ecological responses of Stipa steppe in Inner Mongolia to experimentally increased temperature and precipitation. 2: Plant species diversity and sward characteristics. *The Rangeland Journal*, **40**(2), 147-152.
Wang, C.-J., J.-Z. Wan and Z.-X. Zhang, 2017: Expansion potential of invasive tree plants in ecoregions under climate change scenarios: an assessment of 54 species at a global scale. *Scandinavian Journal of Forest Research*, **32**(8), 663-670.
Wang, J., X. Chen, Q. Hu and J. Liu, 2020a: Responses of terrestrial water storage to climate variation in the Tibetan Plateau. *Journal of Hydrology*, **584**, 124652.
Wang, J. A. et al., 2021a: Disturbance suppresses the aboveground carbon sink in North American boreal forests. *Nature Climate Change*, **11**(5), 435-+, doi:10.1038/s41558-021-01027-4.
Wang, J. A. et al., 2020b: Extensive land cover change across Arctic–Boreal Northwestern North America from disturbance and climate forcing. *Global Change Biology*, **26**(2), 807-822, doi:10.1111/gcb.14804.
Wang, S. et al., 2021b: Biotic homogenization destabilizes ecosystem functioning by decreasing spatial asynchrony. *Ecology*, **102**(6), e03332, doi:https://doi.org/10.1002/ecy.3332.
Wang, S. H. et al., 2020c: Recent global decline of CO2 fertilization effects on vegetation photosynthesis. *Science*, **370**(6522), 1295-+, doi:10.1126/science.abb7772.

Wang, S. R. et al., 2018a: Potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(49), 12407-12412, doi:10.1073/pnas.1801317115.
Wang, W. et al., 2018b: Global lake evaporation accelerated by changes in surface energy allocation in a warmer climate. *Nature Geoscience*, **11**(6), 410-+, doi:10.1038/s41561-018-0114-8.
Wang, X. et al., 2019: No trends in spring and autumn phenology during the global warming hiatus. *Nature communications*, **10**(1), 1-10.
Ward, C. et al., 2020: Wading through the swamp: what does tropical peatland restoration mean to national-level stakeholders in Indonesia? *Restoration Ecology*, **28**(4), 817-827, doi:10.1111/rec.13133.
Ward, D., M. T. Hoffman and S. J. Collocott, 2014: A century of woody plant encroachment in the dry Kimberley savanna of South Africa. *African Journal of Range & Forage Science*, **31**(2), 107-121.
Ward, R. D., D. A. Friess, R. H. Day and R. A. MacKenzie, 2016: Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and Sustainability*, **2**(4), e01211.
Wårlind, D., B. Smith, T. Hickler and A. Arneth, 2014: Nitrogen feedbacks increase future terrestrial ecosystem carbon uptake in an individual-based dynamic vegetation model. *Biogeosciences*, **11**(21), 6131-6146, doi:10.5194/bg-11-6131-2014.
Warren, R., 2011: The role of interactions in a world implementing adaptation and mitigation solutions to climate change. *Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci.*, **369**(1934), 217-241, doi:10.1098/rsta.2010.0271.
Warren, R. et al., 2018: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5 degrees C rather than 2 degrees C. *Science*, **360**(6390), 791-+, doi:10.1126/science.aar3646.
Warren, R. et al., 2013: Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*, **3**(7), 678-682, doi:10.1038/nclimate1887.
Warszawski, L. et al., 2013: A multi-model analysis of risk of ecosystem shifts under climate change. *Environmental Research Letters*, **8**(4), doi:10.1088/1748-9326/8/4/044018.
Watras, C. J. et al., 2014: Decadal oscillation of lakes and aquifers in the upper Great Lakes region of North America: Hydroclimatic implications. *Geophysical Research Letters*, **41**(2), 456-462, doi:10.1002/2013gl058679.
Watson, J., 2016: Bring climate change back from the future. *Nature*, **534**(7608), 437-437, doi:10.1038/534437a.
Watts, M. J. et al., 2020: Influence of socio-economic, demographic and climate factors on the regional distribution of dengue in the United States and Mexico. *International Journal of Health Geographics*, **19**(1), 1-15, doi:10.1186/s12942-020-00241-1.
Watts, N. et al., 2021: The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *The Lancet*, **397**(10269), 129-170, doi:https://doi.org/10.1016/S0140-6736(20)32290-X.
Watts, N. et al., 2019: The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *The Lancet*, **394**(10211), 1836-1878, doi:10.1016/S0140-6736(19)32596-6.
Wauthy, M. et al., 2018: Increasing dominance of terrigenous organic matter in circumpolar freshwaters due to permafrost thaw. *Limnology and Oceanography Letters*, **3**(3), 186-198, doi:https://doi.org/10.1002/lol2.10063.
Wayman, R. B. and H. D. Safford, 2021: Recent bark beetle outbreaks influence wildfire severity in mixed-conifer forests of the Sierra Nevada, California, USA. *Ecological Applications*, **31**(3), 19, doi:10.1002/eap.2287.
Webb, B. W. and F. Nobilis, 2007: Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal*, **52**(1), 74-85, doi:doi.org/10.1623/hysj.52.1.74.
Webb, B. W. and D. E. Walling, 1992: Long term water temperature behaviour and trends in a Devon, UK, river system. *Hydrological Sciences Journal*, **37**(6), 567-580, doi:10.1080/02626669209492624.
Weber, E. T. et al., 2021: Managing a World Heritage Site in the Face of Climate Change: A Case Study of the Wet Tropics in Northern Queensland. *Earth*, **2**(2), doi:10.3390/earth2020015.
Weed, A. S., M. P. Ayres and J. A. Hicke, 2013: Consequences of climate change for biotic disturbances in North American forests. *Ecological Monographs*, **83**(4), 441-470, doi:https://doi.org/10.1890/13-0160.1.
Weeks, B. C. et al., 2020: Shared morphological consequences of global warming in North American migratory birds. *Ecology Letters*, **23**(2), 316-325, doi:https://doi.org/10.1111/ele.13434.
Wei, F. L. et al., 2020: Nonlinear dynamics of fires in Africa over recent decades controlled by precipitation. *Global Change Biology*, **26**(8), 4495-4505, doi:10.1111/gcb.15190.
Welbergen, J. A., S. M. Klose, N. Markus and P. Eby, 2008: Climate change and the effects of temperature extremes on Australian flying-foxes. *Proceedings of the Royal Society B: Biological Sciences*, **275**(1633), 419-425, doi:10.1098/rspb.2007.1385.
Wells, J., J. C. Labadz, A. Smith and M. M. Islam, 2020: Barriers to the uptake and implementation of natural flood management: A social-ecological analysis. *Journal of flood risk management*, **13**, e12561.
Wesolowski, A. et al., 2015: Impact of human mobility on the emergence of dengue epidemics in Pakistan. *Proceedings of the National Academy of Sciences*, **112**(38), 11887, doi:10.1073/pnas.1504964112.
Westerling, A. L. et al., 2011: Climate change and growth scenarios for California wildfire. *Climatic Change*, **109**, 445-463, doi:10.1007/s10584-011-0329-9.
Weyhenmeyer, G. A., R. A. Müller, M. Norman and L. J. Tranvik, 2016: Sensitivity of freshwaters to browning in response to future climate change. *Climatic Change*, **134**(1-2), 225-239.

Wezel, A. et al., 2020: Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, **40**, 1-13, doi:10.1007/s13593-020-00646-z.
While, G. M. and T. Uller, 2014: Quo vadis amphibia? Global warming and breeding phenology in frogs, toads and salamanders. *Ecography*, **37**(10), 921-929.
Whitburn, J., W. Linklater and W. Abrahamse, 2020: Meta-analysis of human connection to nature and proenvironmental behavior. *Conservation Biology*, **34**(1), 180-193.
White, J. D. M. et al., 2016: Collapse of an iconic conifer: long-term changes in the demography of Widdringtonia cedarbergensis using repeat photography. *BMC ecology*, **16**(1), 1-11.
Whitmee, S. et al., 2015: Safeguarding human health in the Anthropocene epoch: Report of the Rockefeller Foundation-Lancet Commission on planetary health. *The Lancet*, **386**(10007), 1973-2028, doi:10.1016/S0140-6736(15)60901-1.
Whittaker, R. H., 1975: *Community and Ecosystems*. McMillan, New York, NY.
Wieder, W. R., C. C. Cleveland, W. K. Smith and K. Todd-Brown, 2015: Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience*, **8**, 441, doi:10.1038/ngeo2413 https://www.nature.com/articles/ngeo2413#supplementary-information.
Wiedner, C., J. Rücker, R. Brüggemann and B. Nixdorf, 2007: Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. *Oecologia*, **152**(3), 473-484, doi:10.1007/s00442-007-0683-5.
Wiens, J., 2016: Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLoS Biology*, **14**(12), doi:10.1371/journal.pbio.2001104.
Wigley, B. J. et al., 2020: Grasses continue to trump trees at soil carbon sequestration following herbivore exclusion in a semiarid African savanna. *Ecology*, doi:10.1002/ecy.3008.
Wijedasa, L. S. et al., 2018: Carbon emissions from South-East Asian peatlands will increase despite emission-reduction schemes. *Glob Chang Biol*, **24**(10), 4598-4613, doi:10.1111/gcb.14340.
Wijedasa, L. S. L. S. et al., 2017: Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences. *Global Change Biology*, **23**(3), 977-982, doi:10.1111/gcb.13516.
Wik, M. et al., 2016: Biased sampling of methane release from northern lakes: A problem for extrapolation. *Geophysical Research Letters*, **43**(3), 1256-1262.
Wilbanks, T. J., 2003: Integrating climate change and sustainable development in a place-based context. *Climate Policy*, **3**(sup1), S147-S154, doi:10.1016/j.clipol.2003.10.013.
Wilcox, B. A., P. Echaubard, M. d. Garine-Wichatitsky and B. Ramirez, 2019: Vector-borne disease and climate change adaptation in African dryland social-ecological systems. *Infectious Diseases of Poverty*, **8**(1), 1-12, doi:10.1186/s40249-019-0539-3.
Wilcox, B. P., A. Birt, S. D. Fuhlendorf and S. R. Archer, 2018: Emerging frameworks for understanding and mitigating woody plant encroachment in grassy biomes. *Current Opinion in Environmental Sustainability*, **32**, 46-52, doi:10.1016/j.cosust.2018.04.005.
Wilcox, K. R. et al., 2017: Asymmetric responses of primary productivity to precipitation extremes: a synthesis of grassland precipitation manipulation experiments. *Global change biology*, **23**(10), 4376-4385.
Wild, B. et al., 2019: Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. *Proceedings of the National Academy of Sciences*, **116**(21), 10280-10285, doi:10.1073/pnas.1811797116.
Wiley, E. M. and A. R. Ridley, 2016: The effects of temperature on offspring provisioning in a cooperative breeder. *Animal Behaviour*, **117**, 187-195, doi:https://doi.org/10.1016/j.anbehav.2016.05.009.
Wilken, S., J. Huisman, S. Naus-Wiezer and E. Van Donk, 2013: Mixotrophic organisms become more heterotrophic with rising temperature. *Ecology letters*, **16**(2), 225-233.
Williams, A. P. et al., 2019: Observed Impacts of Anthropogenic Climate Change on Wildfire in California. *Earth's Future*, **7**(8), 892-910, doi:10.1029/2019ef001210.
Williams, A. P. et al., 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368**(6488), 314-+, doi:10.1126/science.aaz9600.
Williams, A. P. et al., 2015a: Contribution of anthropogenic warming to California drought during 2012-2014. *Geophysical Research Letters*, **42**(16), 6819-6828, doi:10.1002/2015gl064924.
Williams, J. E. et al., 2015b: Climate change adaptation and restoration of western trout streams: opportunities and strategies. *Fisheries*, **40**(7), 304-317.
Williams, J. W. and S. T. Jackson, 2007: Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, **5**(9), 475-482, doi:https://doi.org/10.1890/070037.
Williamson, C. et al., 2015: Ecological consequences of long-term browning in lakes. *Scientific Reports*, **5**, doi:10.1038/srep18666.
Willis, S. G. et al., 2015: Integrating climate change vulnerability assessments from species distribution models and trait-based approaches. *Biological Conservation*, **190**, 167-178, doi:10.1016/j.biocon.2015.05.001.
Willis, S. G. et al., 2009: Assisted colonization in a changing climate: a test-study using two UK butterflies. *Conservation Letters*, **2**(1), 46-52.
Wilmers, C. C. and O. J. Schmitz, 2016: Effects of gray wolf-induced trophic cascades on ecosystem carbon cycling. *Ecosphere*, **7**(10), e01501, doi:doi:10.1002/ecs2.1501.
Wilsey, B., 2021: Restoration in the face of changing climate: importance of persistence, priority effects, and species diversity. *Restoration Ecology*, **29**(S1), e13132, doi:https://doi.org/10.1111/rec.13132.

Wilson, A. M. et al., 2010: A hierarchical Bayesian model of wildfire in a Mediterranean biodiversity hotspot: implications of weather variability and global circulation. *Ecological Modelling*, **221**(1), 106-112.
Wilson, J. D. et al., 2014: Modelling edge effects of mature forest plantations on peatland waders informs landscape-scale conservation. *Journal of Applied Ecology*, **51**(1), 204-213.
Wilson, R. J., S. J. Brooks and P. B. Fenberg, 2019: The influence of ecological and life history factors on ectothermic temperature–size responses: Analysis of three Lycaenidae butterflies (Lepidoptera). *Ecology and Evolution*, **9**(18), 10305-10316, doi:https://doi.org/10.1002/ece3.5550.
Winckler, J., Q. Lejeune, C. H. Reick and J. Pongratz, 2019: Nonlocal Effects Dominate the Global Mean Surface Temperature Response to the Biogeophysical Effects of Deforestation. *Geophysical Research Letters*, **46**(2), 745-755, doi:10.1029/2018gl080211.
Winder, M., J. Reuter and S. Schladow, 2009: Lake warming favours small-sized planktonic diatom species. *Proceedings of the Royal Society B: Biological Sciences*, **276**(1656), 427-435, doi:10.1098/rspb.2008.1200.
Wingard, G. L., C. E. Bernhardt and A. H. Wachnicka, 2017: The Role of Paleoecology in Restoration and Resource Management—The Past As a Guide to Future Decision-Making: Review and Example from the Greater Everglades Ecosystem, U.S.A. *Frontiers in Ecology and Evolution*, **5**(11), doi:10.3389/fevo.2017.00011.
Wingfield, T. et al., 2019: Natural flood management: Beyond the evidence debate. *Area*, **51**(4), 743-751.
Winslow, L., J. Read, G. Hansen and P. Hanson, 2015: Small lakes show muted climate change signal in deepwater temperatures. *Geophysical Research Letters*, **42**(2), 355-361, doi:10.1002/2014gl062325.
Woinarski, J., A. Burbidge and P. Harrison, 2014: *The action plan for Australian mammals 2012*. Commonwealth Scientific and Industrial Research Organization Publishing (CSIRO Publishing). ISBN 978-0-643-10873-8.
Woinarski, J. C. Z., 2016: A very preventable mammal extinction. *Nature*, **535**(7613), 493-493, doi:10.1038/535493e.
Woinarski, J. C. Z., S. T. Garnett, S. M. Legge and D. B. Lindenmayer, 2017: The contribution of policy, law, management, research, and advocacy failings to the recent extinctions of three Australian vertebrate species. *Conservation Biology*, **31**(1), 13-23, doi:https://doi.org/10.1111/cobi.12852.
Wolfe, N. D. et al., 2004: Naturally acquired simian retrovirus infections in central African hunters. *The Lancet*, **363**(9413), 932-937, doi:10.1016/S0140-6736(04)15787-5.
Woodley, S. et al., 2019: A review of evidence for area-based conservation targets for the post-2020 global biodiversity framework. *Parks*, **25**, 31-46, doi:10.2305/IUCN.CH.2019.PARKAS-25-2SW2.en.
Woodward, F. I., M. R. Lomas and C. K. Kelly, 2004: Global climate and the distribution of plant biomes. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, **359**(1450), 1465-1476, doi:10.1098/rstb.2004.1525.
Woodward, G. et al., 2016: The effects of climatic fluctuations and extreme events on running water ecosystems. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **371**(1694), doi:ARTN 20150274 10.1098/rstb.2015.0274.
Woodward, G., D. M. Perkins and L. E. Brown, 2010: Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **365**(1549), 2093-2106, doi:DOI 10.1098/rstb.2010.0055.
Woolhouse, M. E. J. et al., 2001: Risk factors for human disease emergence. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, **356**(1411), 983-989, doi:10.1098/rstb.2001.0888.
Woolhouse, M. E. J. and S. Gowtage-Sequeria, 2005: Host Range and Emerging and Reemerging Pathogens - Volume 11, Number 12—December 2005 - Emerging Infectious Diseases journal - CDC. doi:10.3201/eid1112.050997.
Woolway, R. I., E. Jennings and L. Carrea, 2020a: Impact of the 2018 European heatwave on lake surface water temperature. *Inland Waters*, **10**(3), 322-332, doi:10.1080/20442041.2020.1712180.
Woolway, R. I. et al., 2021: Lake heatwaves under climate change. *Nature*, **589**(7842), 402-407.
Woolway, R. I. et al., 2020b: Global lake responses to climate change. *Nature Reviews Earth & Environment*, **1**(8), 388-403, doi:10.1038/s43017-020-0067-5.
Woolway, R. I. and S. C. Maberly, 2020: Climate velocity in inland standing waters. *Nature Climate Change*, doi:10.1038/s41558-020-0889-7.
Woolway, R. I. et al., 2017: Atmospheric stilling leads to prolonged thermal stratification in a large shallow polymictic lake. *Climatic Change*, **141**(4), 759-773, doi:10.1007/s10584-017-1909-0.
Woolway, R. I. and C. J. Merchant, 2017: Amplified surface temperature response of cold, deep lakes to inter-annual air temperature variability. *Scientific reports*, **7**(1), 4130, doi:10.1038/s41598-017-04058-0.
Woolway, R. I. and C. J. Merchant, 2019: Worldwide alteration of lake mixing regimes in response to climate change. *Nature Geoscience*, **12**(4), 271-276.
Wooster, M. J., G. L. W. Perry and A. Zoumas, 2012: Fire, drought and El Niño relationships on Borneo (Southeast Asia) in the pre-MODIS era (1980–2000). *Biogeosciences*, **9**(1), 317-340, doi:10.5194/bg-9-317-2012.
Work, C., V. Rong, D. Song and A. Scheidel, 2019: Maladaptation and development as usual? Investigating climate change mitigation and adaptation projects in Cambodia. *Climate Policy*, **19**(sup1), S47-S62.
Worth, J. R. P. et al., 2016: Gondwanan conifer clones imperilled by bushfire. *Scientific Reports*, **6**, doi:10.1038/srep33930.
Wösten, J. H. M., A. B. Ismail and A. L. M. van Wijk, 1997: Peat subsidence and its practical implications: a case study in Malaysia. *Geoderma*, **78**(1), 25-36, doi:10.1016/S0016-7061(97)00013-X.

Wramneby, A., B. Smith, S. Zaehle and M. T. Sykes, 2008: Parameter uncertainties in the modelling of vegetation dynamics - effects on tree community structure and ecosystem functioning in European forest biomes. *Ecological Modelling*, **216**, 277-290.
Wu, C. et al., 2021: Historical and future global burned area with changing climate and human demography. *One Earth*, **4**(4), 517-530.
Wu, J., 2020: The hazard and unsureness of reducing habitat ranges in response to climate warming for 91 amphibian species in China. *Acta Oecologica*, **108**, doi:10.1016/j.actao.2020.103640.
Wu, M. et al., 2016a: Vegetation-climate feedbacks modulate rainfall patterns in Africa under future climate change. *Earth System Dynamics*, **7**(3), 627-647, doi:10.5194/esd-7-627-2016.
Wu, X.-H. et al., 2008: Effect of floods on the transmission of schistosomiasis in the Yangtze River valley, People's Republic of China. *Parasitology International*, **57**(3), 271-276, doi:10.1016/j.parint.2008.04.004.
Wu, X. et al., 2016b: Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. *Environment International*, **86**, 14-23, doi:10.1016/j.envint.2015.09.007.
Wu, Y. et al., 2020: On how wetlands can provide flood resilience in a large river basin: A case study in Nenjiang river Basin, China. *Journal of Hydrology*, 125012.
Wuebbles, D. J., D. W. Fahey and K. A. Hibbard, 2017: Climate science special report: fourth national climate assessment, volume I.
Xenopoulos, M. A. et al., 2005: Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, **11**(10), 1557-1564, doi:10.1111/j.1365-2486.2005.001008.x.
Xie, H., J. Zhao, K. Wang and H. Peng, 2021: Long-term variations in solar radiation, diffuse radiation, and diffuse radiation fraction caused by aerosols in China during 1961–2016. *PLOS ONE*, **16**(5), e0250376, doi:10.1371/journal.pone.0250376.
Xu, J., P. J. Morris, J. Liu and J. Holden, 2018a: PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *CATENA*, **160**, 134-140, doi:10.1016/j.catena.2017.09.010.
Xu, L. et al., 2017: Spatial Distribution of Carbon Stored in Forests of the Democratic Republic of Congo. *Scientific Reports*, **7**, doi:10.1038/s41598-017-15050-z.
Xu, L. et al., 2021: Changes in global terrestrial live biomass over the 21st century. *Science Advances*, **7**(27), 18, doi:10.1126/sciadv.abe9829.
Xu, X. et al., 2018b: Tree cover shows strong sensitivity to precipitation variability across the global tropics. *Global ecology and biogeography*, **27**(4), 450–460.
Xu, X. Y. et al., 2020: Climate regime shift and forest loss amplify fire in Amazonian forests. *Global Change Biology*, **26**(10), 5874-5885, doi:10.1111/gcb.15279.
Xue, Q., M. Z. Majeed, W. Zhang and C. S. Ma, 2019: Adaptation of Drosophila species to climate change - A literature review since 2003. *J. Integr. Agric.*, **18**(4), 805-814, doi:10.1016/s2095-3119(18)62042-8.
Xu Q, Yang X, Yan Y, Wang S, Loreau M, Jiang L. Consistently positive effect of species diversity on ecosystem, but not population, temporal stability. Ecology Letters. 2021;24:2256–2266. https://doi.org/10.1111/ele.13777
Yamana Teresa, K. and A. B. Eltahir Elfatih, 2013: Projected Impacts of Climate Change on Environmental Suitability for Malaria Transmission in West Africa. *Environmental Health Perspectives*, **121**(10), 1179-1186, doi:10.1289/ehp.1206174.
Yamana, T. K., A. Bomblies and E. A. B. Eltahir, 2016: Climate change unlikely to increase malaria burden in West Africa. *Nature Climate Change*, **6**(11), 1009-1013, doi:10.1038/nclimate3085.
Yang, X., T. M. Pavelsky and G. H. Allen, 2020: The past and future of global river ice. *Nature*, **577**(7788), 69-73.
Yang, Y. et al., 2016: Long-term CO2 fertilization increases vegetation productivity and has little effect on hydrological partitioning in tropical rainforests. *Journal of Geophysical Research: Biogeosciences*, **121**(8), 2125-2140.
Yang, Y. et al., 2018a: Permafrost and drought regulate vulnerability of Tibetan Plateau grasslands to warming. *Ecosphere*, **9**(5), e02233, doi:https://doi.org/10.1002/ecs2.2233.
Yang, Y. et al., 2018b: Post-drought decline of the Amazon carbon sink. *Nature Communications*, **9**, doi:10.1038/s41467-018-05668-6.
Yankova, Y., S. Neuenschwander, O. Köster and T. Posch, 2017: Abrupt stop of deep water turnover with lake warming: drastic consequences for algal primary producers. *Scientific reports*, **7**(1), 1-9.
Yokohata, T. et al., 2020: Model improvement and future projection of permafrost processes in a global land surface model. *Progress in Earth and Planetary Science*, **7**(1), 69, doi:10.1186/s40645-020-00380-w.
Yokohata, T. et al., 2019: Visualizing the Interconnections Among Climate Risks. *Earths Future*, **7**(2), 85-100, doi:10.1029/2018ef000945.
Yom-Tov, Y. and S. Yom-Tov, 2004: Climatic Change and Body Size in Two Species of Japanese Rodents. *Biological Journal of the Linnean Society*, **82**(2), 263-267.
Young, A. J., D. Guo, P. G. Desmet and G. F. Midgley, 2016: Biodiversity and climate change: Risks to dwarf succulents in Southern Africa. *Journal of Arid Environments*, **129**, 16-24, doi:https://doi.org/10.1016/j.jaridenv.2016.02.005.
Young, A. M., P. E. Higuera, P. A. Duffy and F. S. Hu, 2017a: Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography*, **40**(5), 606-617, doi:10.1111/ecog.02205.
Young, H. S. et al., 2017b: Introduced Species, Disease Ecology, and Biodiversity–Disease Relationships. *Trends in Ecology & Evolution*, **32**(1), 41-54, doi:https://doi.org/10.1016/j.tree.2016.09.008.

Yu, Z. et al., 2010: Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, **37**(13), doi:10.1029/2010GL043584.
Yu, Z. et al., 2017: Global gross primary productivity and water use efficiency changes under drought stress. *Environmental Research Letters*, **12**(1), 014016, doi:10.1088/1748-9326/aa5258.
Yuan, W. P. et al., 2019: Increased atmospheric vapor pressure deficit reduces global vegetation growth. *Science Advances*, **5**(8), doi:10.1126/sciadv.aax1396.
Zahra, S., R. W. Hofstetter, K. M. Waring and C. Gehring, 2020: The invasion of Acacia nilotica in Baluran National Park, Indonesia, and potential future control strategies. *Biodiversitas Journal of Biological Diversity*, **21**(1).
Zarfl, C. et al., 2019: Future large hydropower dams impact global freshwater megafauna. *Scientific Reports*, **9**(1), 18531, doi:10.1038/s41598-019-54980-8.
Zemp, D. C. et al., 2017a: Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications*, **8**, doi:10.1038/ncomms14681.
Zemp, D. C., C. F. Schleussner, H. M. J. Barbosa and A. Rammig, 2017b: Deforestation effects on Amazon forest resilience. *Geophysical Research Letters*, **44**(12), 6182-6190, doi:https://doi.org/10.1002/2017GL072955.
Zemp, M. et al., 2015: Historically unprecedented global glacier decline in the early 21st century. *Journal of glaciology*, **61**(228), 745-762.
Zeng, Z. et al., 2017: Climate mitigation from vegetation biophysical feedbacks during the past three decades. *Nature Climate Change*, **7**, 432, doi:10.1038/nclimate3299 https://www.nature.com/articles/nclimate3299#supplementary-information.
Zeppetello, L. R. V. et al., 2020: Large scale tropical deforestation drives extreme warming. *Environmental Research Letters*, **15**(8), 7, doi:10.1088/1748-9326/ab96d2.
Zettlemoyer, M. A., E. H. Schultheis and J. A. Lau, 2019: Phenology in a warming world: differences between native and non-native plant species. *Ecology Letters*, **22**(8), 1253-1263, doi:https://doi.org/10.1111/ele.13290.
Zeuss, D. et al., 2014: Global warming favours light-coloured insects in Europe. *Nature Communications*, **5**(1), 3874, doi:10.1038/ncomms4874.
Zhai, J. X. et al., 2018: Development of an empirical model to predict malaria outbreaks based on monthly case reports and climate variables in Hefei, China, 1990–2011. *Acta Tropica*, **178**, 148-154, doi:10.1016/j.actatropica.2017.11.001.
Zhang, H. et al., 2020: Decreased carbon accumulation feedback driven by climate-induced drying of two southern boreal bogs over recent centuries. *Global Change Biology*, **26**(4), 2435-2448, doi:10.1111/gcb.15005.
Zhang, W. et al., 2019a: Ecosystem structural changes controlled by altered rainfall climatology in tropical savannas. *Nature communications*, **10**(1), 671.
Zhang, Y. et al., 2017a: Global loss of aquatic vegetation in lakes. *Earth-Science Reviews*, **173**, 259-265.
Zhang, Y. et al., 2015: Dissolved oxygen stratification and response to thermal structure and long-term climate change in a large and deep subtropical reservoir (Lake Qiandaohu, China). *Water Research*, **75**, 249-258.
Zhang, Y. L., C. H. Song, L. E. Band and G. Sun, 2019b: No Proportional Increase of Terrestrial Gross Carbon Sequestration From the Greening Earth. *Journal of Geophysical Research-Biogeosciences*, **124**(8), 2540-2553, doi:10.1029/2018jg004917.
Zhang, Z. et al., 2017b: Emerging role of wetland methane emissions in driving 21st century climate change. *Proceedings of the National Academy of Sciences*, **114**(36), 9647-9652.
Zhao, M. S. and S. W. Running, 2010: Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009. *Science*, **329**(5994), 940-943, doi:10.1126/science.1192666.
Zhao, Q. et al., 2020: Where Marine Protected Areas would best represent 30% of ocean biodiversity. *Biological Conservation*, **244**, 108536, doi:https://doi.org/10.1016/j.biocon.2020.108536.
Zhou, G. et al., 2015a: Global pattern for the effect of climate and land cover on water yield. *Nature Communications*, **6**, 5918, doi:10.1038/ncomms6918.
Zhou, L. et al., 2014: Widespread decline of Congo rainforest greenness in the past decade. *Nature*, **509**(7498), 86.
Zhou, X.-N. et al., 2005: The public health significance and control of schistosomiasis in China—then and now. *Acta Tropica*, **96**(2-3), 97-105, doi:10.1016/j.actatropica.2005.07.005.
Zhou, Y., T. W. Boutton and X. B. Wu, 2017: Soil carbon response to woody plant encroachment: importance of spatial heterogeneity and deep soil storage. *Journal of Ecology*, **105**(6), 1738-1749, doi:https://doi.org/10.1111/1365-2745.12770.
Zhou, Z. et al., 2015b: Responses of alpine grassland to climate warming and permafrost thawing in two basins with different precipitation regimes on the Qinghai-Tibetan Plateaus. *Arctic Antarctic and Alpine Research*, **47**(1), 125-131.
Zimmer, A. et al., 2018: Time lag between glacial retreat and upward migration alters tropical alpine communities. *Perspectives in Plant Ecology, Evolution and Systematics*, **30**, 89-102, doi:https://doi.org/10.1016/j.ppees.2017.05.003.
Zimova, M., D. E. Willard, B. M. Winger and B. C. Weeks, 2021: Widespread shifts in bird migration phenology are decoupled from parallel shifts in morphology. *Journal of Animal Ecology*, **n/a**(n/a), doi:https://doi.org/10.1111/1365-2656.13543.
Zinsstag, J. et al., 2018: Climate change and One Health. *FEMS Microbiology Letters*, **365**(11), doi:10.1093/femsle/fny085.

Ziter, C. D., E. J. Pedersen, C. J. Kucharik and M. G. Turner, 2019: Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences*, **116**(15), 7575-7580.
Zomer, R. J. et al., 2016: Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, **6**(1), 29987-29987, doi:10.1038/srep29987.
Zomer, R. J. et al., 2014a: Projected climate change impacts on spatial distribution of bioclimatic zones and ecoregions within the Kailash Sacred Landscape of China, India, Nepal. *Climatic Change*, **125**(3-4), 445-460.
Zomer, R. J. et al., 2014b: Environmental stratification to model climate change impacts on biodiversity and rubber production in Xishuangbanna, Yunnan, China. *Biological Conservation*, **170**, 264-273, doi:10.1016/j.biocon.2013.11.028.
Zomer, R. J. et al., 2015: Projected impact of climate change on the effectiveness of the existing protected area network for biodiversity conservation within Yunnan Province, China. *Biological Conservation*, **184**, 335-345, doi:10.1016/j.biocon.2015.01.031.
Zscheischler, J. and S. I. Seneviratne, 2017: Dependence of drivers affects risks associated with compound events. *Science Advances*, **3**(6), doi:10.1126/sciadv.1700263.
Zscheischler, J. et al., 2018: Future climate risk from compound events. *Nature Climate Change*, **8**(6), 469-477, doi:10.1038/s41558-018-0156-3.
Zubkova, M., L. Boschetti, J. T. Abatzoglou and L. Giglio, 2019: Changes in Fire Activity in Africa from 2002 to 2016 and Their Potential Drivers. *Geophysical Research Letters*, **46**(13), 7643-7653, doi:10.1029/2019gl083469.
Zumbado-Ulate, H., F. Bolanos, G. Gutierrez-Espeleta and R. Puschendorf, 2014: Extremely Low Prevalence of Batrachochytrium dendrobatidis in Frog Populations from Neotropical Dry Forest of Costa Rica Supports the Existence of a Climatic Refuge from Disease. *EcoHealth*, **11**(4), 593-602, doi:10.1007/s10393-014-0967-2.
Zvereva, E. L. et al., 2019: Climate warming leads to decline in frequencies of melanic individuals in subarctic leaf beetle populations. *Science of The Total Environment*, **673**, 237-244, doi:https://doi.org/10.1016/j.scitotenv.2019.03.458.
Zwart, J. A. et al., 2016: Metabolic and physiochemical responses to a whole-lake experimental increase in dissolved organic carbon in a north-temperate lake. *Limnology and Oceanography*, **61**(2), 723-734.

Large Tables

Table 2.2: Global Fingerprints of Climate Change Impacts across Wild Species. Updated from (Parmesan and Hanley, 2015). For each dataset, a response for an individual species or functional group was classified as (1) no response (no significant change in the measured trait over time), (2) if a significant change was found, the response was classified as either consistent or not consistent with expectations from local or regional climate trends. Percentages are approximate and estimated for the studies as a whole. Individual analyses within the studies may differ. The specific metrics of climate change analysed for associations with biological change vary somewhat across studies, but most use changes in local or regional temperatures (e.g. mean monthly T or mean annual T), with some using precipitation metrics (e.g. total annual rainfall). For example, a consistent response would be poleward range shifts in areas that are warming. Probability (P) of getting the observed ratio of consistent: not consistent responses by chance was <10-13 for (Parmesan and Yohe, 2003; Root et al., 2003; Root et al., 2005; Poloczanska et al., 2013) and was <0.001 for Rosenzweig 2008 (source=publication) (Parmesan and Yohe, 2003; Root et al., 2003; Root et al., 2005; Rosenzweig et al., 2008; Poloczanska et al., 2013). Test were all binomial tests against p=0.5, performed by Parmesan.

Study	N: total numbers of species, functional groups or studies	Species in given system: Terrestrial (T) Marine (M) Freshwater (F)	Types of change	Changes documented	Geographical region	Study allows for attribution to climate change
2.2a Observed Phenological changes						
Parmesan and Yohe (2003)	677 species	461 plants, 168 birds, 35 insects, 9 amphibians, 2 fish	spring phenology	Overall: 9% delay; 27% no trend; 62% advance Mean change 2.3 days per decade advance	global	yes
Menzel et al. (2006)	agricultural crops, fruit trees, wild plants	T	spring and fall phenology	From 1971-2000 48% responding as expected; spring advance 2.5 days per decade; Mean fall delay = 0.2 days per decade fruit ripening 2.4 days per decade advance; farmer's activities 0.4 days per decade advance	Europe	yes
Parmesan (2007)	200 species		spring phenology	Overall advance 2.8 days per decade 20 changes delay, 153 advance, 8 no change; Significantly more advance at higher latitudes	global	yes
Rosenzweig et al. (2008)	55 studies (~100-200 species)	1T: 65% 1M: 13% 1F: 22%	various	90% of changes consistent with local/regional climate change	global	yes
Thackeray et al. (2010)	726 taxa	M,T&F; birds, moths, aphids, terrestrial plants, marine & FW phytoplankton	spring phenology	83.5 % of "trends" were advances; mean overall advance 3.9 days per decade. Terrestrial plants 93% advancing, mean 5.8 days per decade; FW plants 62% advancing, mean 2.3 days per decade secondary consumers advanced less than primary consumers & producers	UK	no
While and Uller (2014)	59 populations, 17 studies	amphibia	phenology	35% statistically significant change; mean advance 6.1±1.65 days per decade; range 17.5 days delay to 41.9 days advance; 65% (n=47 populations) found	global	no

				significant relationship between breeding phenology and temperature; higher latitudes advanced more.		
Gill et al. (2015)	64 studies	T: 100% trees	delay of autumn senescence	Delay averaged 0.33 days yr^{-1} and 1.20 days per degree warming; more delay at low latitudes across N-hemisphere; High latitude species driven more by photoperiod than low latitude species	global	no
Ficetola and Maiorano (2016)	n= 66 studies of temperature effects; 15 of precipitation	T/F 100% (amphibians)	phenology and abundances	Population dynamics driven by precipitation while breeding phenology driven by temperature	global	no
Halupka and Halupka (2017)	28 spp multi- brooded, 27 spp single-brooded, some spp. several pops	T 100% (birds)	phenology: Length of breeding season	Shows differences in sign of response between single & multi-broods & migrant vs resident; Season extended by 4 days per decade for multi-brooded, shortened by 2 days per decade for single-brooded; Multi: 26 species; 15 of 34 pops sig extended, none sig reduced	northern hemisphere	yes
Kharouba et al. (2018)	88 species in 54 pair-wise interactions	Not given	T: changes in relative phenologies of consumers and their resources	Asynchrony between consumer and resource has increased in some cases and decreased in others, with no significant trend; the prediction that asynchronies should be increasing in general is not supported.	global	no
Cohen et al. (2018)	127 studies	T 100% (animals)	phenological trends	81% of 127 studies of animals show phenological change in direction of earlier spring. Some studies were multi-species. Mean advance since 1950: 2.88 days per decade	Europe North America Australia Japan	no
Keogan et al. (2018)	145 populations, 209 time series	seabirds - terrestrial breeding sites	phenological trends	No change in breeding dates between 1952 and 2015	global	yes
Radchuk et al. (2019)	4835 studies, 1413 species	non-aquatic animals	phenological trends	Greatest phenological advancements in amphibians, followed by insects and birds in that order	global but most in N hemisphere	no
Piao et al. (2019)	Review	plants	spring and autumn phenologies	Rate of advance slowing down across northern hemisphere and reversed in parts of western N America in response to regional cooling since 1980s	Global	no
Menzel et al. (2020)	53 species in Germany, 37 in Austria, 21 in Switzerland (includes overlaps)	plants	spring and autumn phenologies	Long time series 1951–2018. Autumn leaf colouring: mean delay 0.36 days per decade. Spring phenology (leaf infolding) mean advance 0.24 days per decade. Summer phenology (fruit ripening)	Europe	yes

				mean advance 0.26 days per decade. Growing season length mean increase 0.26 days yr^{-1} but farming season length decreased by 0.02 days yr^{-1}		
2.2b. Observed Changes in distributions, abundances and local population extinctions						
Parmesan and Yohe (2003)	920 species	T: 85.2% M: 13.5% F: 1.3%	Distibutions and abundances	50% of species (n=460/920) showed changes in distribution or abundances consistent with local or regional climate change	global	yes
Root et al. (2003)	n=926 species	T: 94% M: 5.4% F: 0.6%	Distibutions and abundances	52 % of species (n=483/926) showed changes in distribution or abundances consistent with local or regional climate change	global	yes
Rosenzweig et al. (2008)	n=18 studies	T: 65% M: 13% F: 22%	Distibutions and abundances	90% of studies showed changes in distribution or abundances consistent with local or regional climate change	global	yes
Pöyry et al. (2009)	48 species	T, butterflies	range shifts	From 1992-2004 37 ranges shifted poleward; 9 shifted equatorial; 2 no change. Non-threatened species expanded poleward by 84.5 km, threatened species showed no significant change (-2.1 km)	Finland	yes
Tingley et al. (2009)	53 species	T, birds	elevational range shifts	Resurvery (2003—2008) of historical elevational transects (1911—1929). 90.6% of species track their climate niche (temperature and/or precipitation) with regional climate change. Lower elevation species (mean range centroid = 916m) tracked only precipitation; high elevation species (mean range centroid = 1,944m) tracked only temperature; Species that tracked both T and P had mid-elevation range centroids (1,374—1,841)	California	yes
Chen et al. (2011)	24 taxonomic group x region combinations for latitude, 31 for elevation	T >264 M>10 F >34	range shifts: elevation and latitude	Mean upward elevation shift 11.0 m per decade Poleward shift 16.9 km per decade	pseudo-global	no
Grewe et al. (2013)	90 species	dragonflies	shifts of northern range boundaries	48 poleward shifts; 26 equatorial; 16 no change from 1988 to2006	Europe	no

				southern lentic (standing water) species expanded 116 km polewards; southern lotic (running water) & all northern species stable.		
Mason et al. (2015)	21 animal groups, 1573 species	T: Birds, Lepidoptera F: Odonates	range shifts in 3 time periods	Northward shifts 23 km per decade (1966–1975) and 18 km per decade(1986–1995), with significant differences among taxa in rates of change	UK	yes
Gibson-Reinemer and Rahel (2015)	13 studies, 273 species: plants birds mammals marine inverts	T M	Range shifts in 2 or 3 areas for each species. shift measured as change of limit OR centroid	50% shifts of cold limit inconsistent with each other in within species despite similar warming. Percent species showing inconsistent shifts (including stable vs directional or different directions) = 47% plants,; 54% birds; 46% marine invert; 60% mammals. Large difference in magnitude of range shifts when in same direction (mean difference 8.8x);	global	no
Ficetola and Maiorano (2016)	n= 66 studies temperature effects; 15 precipitation	T/F 100% (amphibians)	phenology and abundances	Population dynamics driven by precipitation, breeding phenology driven by temperature	global	no
Scheffers et al. (2016)	n= 94 ecological processes	all	all possible types and levels of ecological change	82% of ecological processes affected by climate change	global	no
Wiens (2016)	976 species	all	population extinction rates near warm latitudinal and elevational range limits	47% of species suffered climate-related local extinctions: fish 59%; insects 56%; birds 44%; plants 39%; amphibians 37%; mammals 35%	global	yes
Bowler et al. (2017)	1,167 populations, 22 communities	T: 48% M: 61% F: 35%	abundance; population trends	Terrestrial species with warm temperature preference performed better than cool preferers; Freshwater and marine species: no effect of temperature preference on performance. 47% of species with significant abundance changes: 61%M, 48%T, 35% FW	Europe	yes
Pacifici et al. (2017)	873 mammals; 1272 birds	T 100% (birds and mammals)	multiple: range change, abundance, reproductive rate, survival, body mass	Estimated negative impacts (range contraction, reduced reproductive rates, or other measures of fitness estimates) for IUCN threatened species based on actual observed change in more common, related species. 47% threatened mammals and 23% birds	global for bird; mammals N America	unclear - complex methods

				negatively impacted by climate change in part of their ranges		
MacLean and Beissinger (2017)	21studies 26 assemblages of taxonomically related species	plants and animals	Range shifts in latitude and altitude related to species' traits: dispersal, body size, habitat, diet specialization & historic range limit.	High latitude/altitude range boundaries shifted less than lower laatitude/altitude boundaries. Author explanation is that habitat limits being reached (eg mountain top). Magnitudes of shifts positively related to dispersal traits and habitat breadth.	global	no
Ralston et al. (2017)	46 species	birds	Shifts in climate niche breadth, filling of climate space and overall abundance.	Species increasing in abundance were also increasing breeding climate niche breadth and niche filling. Declining species were opposite: niche breadths narrowing and greater climate debt.	north America	no
Rumpf et al. (2019)	1,026 species	terrestrial plants, invertebrates, vertebrates	Comparison of rates of range limit shift at leading & trailing elevational edges.	No difference in mean rate of shift of leading and trailing edges; elevational range sizes not changing systematically. Greater lags in regions with faster warming.	global	no
Freeman et al. (2018)	975 species, 32 elevational gradients	terrestrial plants, endotherms, ectotherms	Comparison of rates of range limit shift at leading & trailing elevational edges.	Mean change at warm limit 92±455 m per °C; cool limit 131±465 m per °C; (± SD, not significantly different from each other. Available area and range sizes decreased for mountaintop species.	global	no
Anderegg et al. (2019b)	meta-analysis 50 studies >100 species	T: 100% woody plants	mortality at dry range edges	100 indiv. species + a community of 828 species mortality at range edges due to drought was 33% greater than for core populations	apparently global	yes; drought not warming
Román-Palacios and Wiens (2020)	10 studies, 538 species, 581 sites	terrestrial plants and animals	analysis for drivers of population extinctions at warm range edges	44% of species had suffered local population extinctions near warm range limits. In temperate regions sites with local extinction had greater increases in maixmum temperature than those without (0.456°C vs. 0.153°C, $P < 0.001$, $n = 505$ sites) and smaller increases in mean temperatures (0.412°C vs 1.231°C, $P < 0.001$). In tropical regions, range edges with local extinction also had greater increases in maximum temperatures (0.316°C vs 0.061°C $P < 0.001$, $n = 76$) but changes	global	yes

				in mean temperatures were similar between edges with and without extinctions (0.415°C vs 0.406°C, P = 0.9		

Chapter 3: Oceans and Coastal Ecosystems and their Services

Coordinating Lead Authors: Sarah Cooley (USA) and David Schoeman (Australia)

Lead Authors: Laurent Bopp (France), Philip Boyd (Australia/United Kingdom), Simon Donner (Canada), Shin-Ichi Ito (Japan), Wolfgang Kiessling (Germany), Paulina Martinetto (Argentina), Elena Ojea (Spain), Marie-Fanny Racault (United Kingdom /France), Björn Rost (Germany), Mette Skern-Mauritzen (Norway), Dawit Yemane Ghebrehiwet (South Africa/Eritrea)

Contributing Authors: Johann D. Bell (Australia), Julia Blanchard (Australia), Jessica Bolin (Australia), William W. L. Cheung (Canada), Andrés Cisneros-Montemayor (Canada/Mexico), Sam Dupont (Sweden/Belgium), Stephanie Dutkiewicz (USA), Thomas Frölicher (Switzerland), Juan Diego Gaitán-Espitia (Hong Kong, Special Administrative Region, China/Colombia), Jorge García Molinos (Japan/Spain), Helen Gurney-Smith (Canada), Stephanie Henson (United Kingdom), Manuel Hidalgo (Spain), Elisabeth Holland (Fiji), Robert Kopp (USA), Rebecca Kordas (United Kingdom/USA), Lester Kwiatkowski (France/United Kingdom), Nadine Le Bris (France), Salvador E. Lluch-Cota (Mexico), Cheryl Logan (USA), Felix Mark (Germany), Yunus Mgaya (Tanzania), Coleen Moloney (South Africa), Norma Patricia Muñoz Sevilla (Mexico), Gregoire Randin (Fiji/France/Switzerland), Nussaibah B. Raja (Germany/Mauritius), Anusha Rajkaran (South Africa), Anthony Richardson (Australia), Stephanie Roe (Philippines/USA), Raquel Ruiz Diaz (Spain), Diana Salili (Vanuatu), Jean-Baptiste Sallée (France), Kylie Scales (Australia/United Kingdom), Michelle Scobie (Trinidad and Tobago), Craig T. Simmons (Australia), Olivier Torres (France), Andrew Yool (United Kingdom)

Review Editors: Karim Hilmi (Morocco) and Lisa Levin (USA)

Chapter Scientist: Jessica Bolin (Australia)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Ocean and coastal ecosystems support life on Earth and many aspects of human well-being. Covering two-thirds of the planet, the ocean hosts vast biodiversity and modulates the global climate system by regulating cycles of heat, water, and elements including carbon. Marine systems are central to many cultures, and they also provide food, minerals, energy and employment to people. Since previous assessments[1], new laboratory studies, field observations and process studies, a wider range of model simulations, Indigenous Knowledge, and local knowledge provide increasing evidence on the impacts of climate change on ocean and coastal systems, how human communities are experiencing these impacts, and the potential solutions for ecological and human adaptation.

Observations: vulnerabilities and impacts

Anthropogenic climate change has exposed ocean and coastal ecosystems to conditions that are unprecedented over millennia (*high confidence*[2]), and this has greatly impacted life in the ocean and along its coasts (*very high confidence*). Fundamental changes in the physical and chemical characteristics of the ocean acting individually and together are changing the timing of seasonal activities (*very high confidence*), distribution (*very high confidence*), and abundance (*very high confidence*) of oceanic and coastal organisms, from microbes to mammals and from individuals to ecosystems, in every region. Evidence of these changes is apparent from multi-decadal observations, laboratory studies and mesocosms, as well as meta-analyses of published data. Geographic range shifts of marine species generally follow the pace and direction of climate warming (*high confidence*): surface warming since the 1950s has shifted marine taxa and communities poleward at an average (mean ± *very likely* range) of 59.2 ± 15.5 km per decade (*high confidence*), with substantial variation in responses among taxa and regions. Seasonal events occur 4.3 ± 1.8 to 7.5 ± 1.5 days earlier per decade among planktonic organisms (*very high confidence*) and on average 3 ± 2.1 days earlier per decade for fish (*very high confidence*). Warming, acidification and deoxygenation are altering ecological communities by increasing the spread of physiologically sub-optimal conditions for many marine fish and invertebrates (*medium confidence*). These and other responses have subsequently driven habitat loss (*very high confidence*), population declines (*high confidence*), increased risks of species extirpations and extinctions (*medium confidence*) and rearrangement of marine food webs (*medium* to *high confidence*, depending on ecosystem). {3.2, 3.3, 3.3.2, 3.3.3, 3.3.3.2, 3.4.2.1, 3.4.2.3–3.4.2.8, 3.4.2.10, 3.4.3.1, 3.4.3.2, 3.4.3.3, Box 3.2}

Marine heatwaves lasting weeks to several months are exposing species and ecosystems to environmental conditions beyond their tolerance and acclimation limits (*very high confidence*). WGI AR6 concluded that marine heatwaves are more frequent (*high confidence*), more intense and longer (*medium confidence*) since the 1980s, and since at least 2006, *very likely*[3] attributable to anthropogenic climate change. Open-ocean, coastal and shelf-sea ecosystems, including coral reefs, rocky shores, kelp forests, seagrasses, mangroves, the Arctic Ocean and semi-enclosed seas, have recently undergone mass mortalities from marine heatwaves (*very high confidence*). Marine heatwaves, including well-documented events along the west coast of North America (2013–2016) and east coast of Australia (2015–2016, 2016–2017 and 2020), drive abrupt shifts in community composition that may persist for years (*very high confidence*), with associated biodiversity loss (*very high confidence*), collapse of regional fisheries and

[1] Previous IPCC assessments include the IPCC Fifth Assessment Report (AR5) (IPCC, 2013; IPCC, 2014c; IPCC, 2014b; IPCC, 2014d), the Special Report on Global Warming of 1.5°C (SR1.5) (IPCC, 2018), the Special Report on Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2019b) and the IPCC Sixth Assessment Report Working Group I (WGI AR6).

[2] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

[3] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33– 66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely: 95– 100%, more likely than not >50–100%, and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*.

aquaculture (*high confidence*) and reduced capacity of habitat-forming species to protect shorelines (*high confidence*). {WGI AR6 Chapter 9, 3.2.2.1, 3.4.2.1–3.4.2.5, 3.4.2.7, 3.4.2.10, 3.4.2.3, 3.4.3.3.3, 3.5.3}

At local to regional scales, climate change worsens the impacts on marine life of non-climate anthropogenic drivers, such as habitat degradation, marine pollution, overfishing and overharvesting, nutrient enrichment, and introduction of non-indigenous species (*very high confidence*). Although impacts of multiple climate and non-climate drivers can be beneficial or neutral to marine life, most are detrimental (*high confidence*). Warming exacerbates coastal eutrophication and associated hypoxia, causing 'dead zones' (*very high confidence*), which drive severe impacts on coastal and shelf-sea ecosystems (*very high confidence*), including mass mortalities, habitat reduction and fisheries disruptions (*medium confidence*). Overfishing exacerbates effects of multiple climate-impact drivers on predators at the top of the marine food chain (*medium confidence*). Urbanization and associated changes in freshwater and sediment dynamics increase the vulnerability of coastal ecosystems like sandy beaches, saltmarshes and mangrove forests to sea-level rise and changes in wave energy (*very high confidence*). Although these non-climate drivers confound attribution of impacts to climate change, adaptive, inclusive, and evidence-based management reduces the cumulative pressure on ocean and coastal ecosystems, which will decrease their vulnerability to climate change (*high confidence*). {3.3, 3.3.3, 3.4.2.4–3.4.2.8, 3.4.3.4, 3.5.3, 3.6.2, Cross-Chapter Box SLR in Chapter 3}

Climate-driven impacts on ocean and coastal environments have caused measurable changes in specific industries, economic losses, emotional harm, and altered cultural and recreational activities around the world (*high confidence*). Climate-driven movement of fish stocks is causing commercial, small-scale, artisanal, and recreational fishing activities to shift poleward and diversify harvests (*high confidence*). Climate change is increasing the geographic spread and risk of marine-borne pathogens like *Vibrio* sp. (*very high confidence*), which endanger human health and decrease provisioning and cultural ecosystem services (*high confidence*). Interacting climatic impact-drivers and non-climate drivers are enhancing movement and bioaccumulation of toxins and contaminants into marine food webs (*medium evidence, high agreement*), and increasing salinity of coastal waters, aquifers, and soils (*very high confidence*), which endangers human health (*very high confidence*). Combined climatic impact-drivers and non-climate drivers also expose densely populated coastal zones to flooding (*high confidence*) and decrease physical protection of people, property, and culturally important sites (*very high confidence*). {3.4.2.10, 3.5.3, 3.5.5, 3.5.5.3, 3.5.6, Cross-Chapter Box SLR in Chapter 3}

Projections: vulnerabilities, risks, and impacts

Ocean conditions are projected to continue diverging from a pre-industrial state (*virtually certain*), with the magnitude of warming, acidification, deoxygenation, sea-level rise and other climatic impact-drivers depending on the emission scenario (*very high confidence*), and to increase risk of regional extirpations and global extinctions of marine species (*medium confidence*). Marine species richness near the equator and in the Arctic is projected to continue declining, even with less than 2°C warming by the end of the century (*medium confidence*). In the deep ocean, all global warming levels will cause faster movements of temperature niches by 2100 than those that have driven extensive reorganisation of marine biodiversity at the ocean surface over the past 50 years (*medium confidence*). "At warming levels beyond 2°C by 2100, risks of extirpation, extinction and ecosystem collapse escalate rapidly (*high confidence*)." Paleorecords indicate that at extreme global warming levels (>5.2°C), mass extinction of marine species may occur (*medium confidence*). {Box 3.2, 3.2.2.1, 3.4.2.5, 3.4.2.10, 3.4.3.3, Cross-Chapter Box PALEO in Chapter 1}

Climate impacts on ocean and coastal ecosystems will be exacerbated by increases in intensity, reoccurrence and duration of marine heatwaves (*high confidence*), in some cases, leading to species extirpation, habitat collapse or surpassing ecological tipping points (*very high confidence*). Some habitat-forming coastal ecosystems including many coral reefs, kelp forests and seagrass meadows, will undergo irreversible phase shifts due to marine heatwaves with global warming levels >1.5°C and are at high risk this century even in <1.5°C scenarios that include periods of temperature overshoot beyond 1.5°C (*high confidence*). Under SSP1-2.6, coral reefs are at risk of widespread decline, loss of structural integrity and transitioning to net erosion by mid-century due to increasing intensity and frequency of marine heatwaves (*very high confidence*). Due to these impacts, the rate of sea-level rise is *very likely* to exceed that of reef growth by 2050, absent adaptation. Other coastal ecosystems, including kelp forests, mangroves and seagrasses, are vulnerable to phase shifts towards alternate states as marine heatwaves intensify (*high confidence*). Loss of kelp forests are expected to be greatest at the low-latitude warm edge of species' ranges (*high confidence*). {3.4.2.1, 3.4.2.3, 3.4.2.5, 3.4.4}

Escalating impacts of climate change on marine life will further alter biomass of marine animals (*medium confidence*), the timing of seasonal ecological events (*medium confidence*) and the geographic ranges of coastal and ocean taxa (*medium confidence*), disrupting life cycles (*medium confidence*), food webs (*medium confidence*) and ecological connectivity throughout the water column (*medium confidence*). Multiple lines of evidence suggest that climate-change responses are *very likely* to amplify up marine food webs over large regions of the ocean. Modest projected declines in global phytoplankton biomass translate into larger declines of total animal biomass (by 2080–2099 relative to 1995–2014) ranging from (mean ± *very likely* range) –5.7% ± 4.1% to –15.5% ± 8.5% under SSP1-2.6 and SSP5-8.5, respectively (*medium confidence*). Projected declines in upper-ocean nutrient concentrations, *likely* associated with increases in stratification, will reduce carbon export flux to the mesopelagic and deep-sea ecosystems (*medium confidence*). This will lead to a decline in the biomass of abyssal meio- and macrofauna (by 2081–2100 relative to 1995–2014) by –9.8% and –13.0% under SSP1-2.6 and SSP5-8.5, respectively (*limited evidence*). By 2100, 18.8% ± 19.0% to 38.9% ± 9.4% of the ocean will *very likely* undergo a change of more than 20 days (advances and delays) in the start of the phytoplankton growth period under SSP1-2.6 and SSP5-8.5, respectively (*low confidence*). This altered timing increases the risk of temporal mismatches between plankton blooms and fish spawning seasons (*medium* to *high confidence*) and increases the risk of fish recruitment failure for species with restricted spawning locations, especially in mid-to-high latitudes of the northern hemisphere (*low confidence*). Projected range shifts among marine species (*medium confidence*) suggest extirpations and strongly decreasing tropical biodiversity. At higher latitudes, range expansions will drive increased homogenisation of biodiversity. The projected loss of biodiversity ultimately threatens marine ecosystem resilience (*medium* to *high confidence*), with subsequent effects on service provisioning (*medium* to *high confidence*). {3.2.2.3, 3.4.2.10, 3.4.3.1–3.4.3.5, 3.5, WGI AR6 Section 2.3.4.2.3}

Risks from sea-level rise for coastal ecosystems and people are *very likely* to increase tenfold well before 2100 without adaptation and mitigation action as agreed by Parties to the Paris Agreement (*very high confidence*). Sea-level rise under emission scenarios that do not limit warming to 1.5°C will increase the risk of coastal erosion and submergence of coastal land (*high confidence*), loss of coastal habitat and ecosystems (*high confidence*) and worsen salinisation of groundwater (*high confidence*), compromising coastal ecosystems and livelihoods (*high confidence*). Under SSP1-2.6, most coral reefs (*very high confidence*), mangroves (*likely*, *medium confidence*) and saltmarshes (*likely*, *medium confidence*) will be unable to keep up with sea-level rise by 2050, with ecological impacts escalating rapidly beyond 2050, especially for scenarios coupling high emissions with aggressive coastal development (*very high confidence*). Resultant decreases in natural shoreline protection will place increasing numbers of people at risk (*very high confidence*). The ability to adapt to current coastal impacts, cope with future coastal risks, and prevent further acceleration of sea-level rise beyond 2050 depends on immediate implementation of mitigation and adaptation actions (*very high confidence*). {3.4.2.1, 3.4.2.4, 3.4.2.5, 3.4.2.6, 3.5.5.3, Cross-Chapter Box SLR in Chapter 3}

Climate change will alter many ecosystem services provided by marine systems (*high confidence*), but impacts to human communities will depend on people's overall vulnerability, which is strongly influenced by local context and development pathways (*very high confidence*). Catch composition and diversity of regional fisheries will change (*high confidence*), and fishers who are able to move, diversify, and leverage technology to sustain harvests decrease their own vulnerability (*medium confidence*). Management that eliminates overfishing facilitates successful future adaptation of fisheries to climate change (*very high confidence*). Marine-dependent communities, including Indigenous Peoples and local peoples, will be at increased risk of losing cultural heritage and traditional seafood-sourced nutrition (*medium confidence*). Without adaptation, seafood-dependent people face increased risk of exposure to toxins, pathogens, and contaminants (*high confidence*), and coastal communities face increasing risk from salinisation of groundwater and soil (*high confidence*). Early-warning systems and public education about environmental change, developed and implemented within the local and cultural context, can decrease those risks (*high confidence*). Coastal development and management informed by sea-level rise projections will reduce the number of people and amount of property at risk (*high confidence*), but historical coastal development and policies impede change (*high confidence*). Current financial flows are globally uneven and overall insufficient to meet the projected costs of climate impacts on coastal and marine socio-ecological systems (*very high confidence*). Inclusive governance that accommodates geographically shifting marine life; financially supports needed human transformations; provides effective public education; and incorporates scientific evidence, Indigenous knowledge, and local knowledge to manage resources sustainably shows greatest promise for decreasing human vulnerability to all of these projected changes in ocean and coastal ecosystem services (*very high confidence*). {3.5.3, 3.5.5, 3.5.6, 3.6.3, Box 3.4, Cross-Chapter Box ILLNESS in Chapter 2, Cross-Chapter Box SLR in Chapter 3}

Solutions, trade-offs, residual risk, decisions and governance

Humans are already adapting to climate-driven changes in marine systems, and while further adaptations are required even under low-emission scenarios (*high confidence*), transformative adaptation will be essential under high-emission scenarios (*high confidence*). Low-emission scenarios permit a wider array of feasible, effective and low-risk nature-based adaptation options (e.g., restoration, revegetation, conservation, early-warning systems for extreme events, and public education) (*high confidence*). Under high-emission scenarios, adaptation options (e.g., hard infrastructure for coastal protection, assisted migration or evolution, livelihood diversification, migration and relocation of people) are more uncertain and require transformative governance changes (*high confidence*). Transformative climate adaptation will reinvent institutions to overcome obstacles arising from historical precedents, reducing current barriers to climate adaptation in cultural, financial, and governance sectors (*high confidence*). Without transformation, global inequities will *likely* increase between regions (*high confidence*) and conflicts between jurisdictions may emerge and escalate. {3.5, 3.5.2, 3.5.5.3, 3.6, 3.6.2.1, 3.6.3.1, 3.6.3.2, 3.6.3.3, 3.6.4.1, 3.6.4.2, 3.6.5, Cross-Chapter Box SLR in Chapter 3, Cross-Chapter Box ILLNESS in Chapter 2}

Available adaptation options are unable to offset climate-change impacts on marine ecosystems and the services they provide (*high confidence*). Adaptation solutions implemented at appropriate scales, when combined with ambitious and urgent mitigation measures, can meaningfully reduce impacts (*high confidence*). Increasing evidence from implemented adaptations indicates that multi-level governance, early-warning systems for climate-associated marine hazards, seasonal and dynamic forecasts, habitat restoration, ecosystem-based management, climate-adaptive management, and sustainable harvesting tend to be both feasible and effective (*high confidence*). Marine protected areas, as currently implemented, do not confer resilience against warming and heatwaves (*medium confidence*) and are not expected to provide substantial protection against climate impacts past 2050 (*high confidence*). However, marine protected areas can contribute substantially to adaptation and mitigation if they are designed to address climate change, strategically implemented, and well governed (*high confidence*). Habitat restoration limits climate-change related loss of ecosystem services, including biodiversity, coastal protection, recreational use and tourism (*medium confidence*), provides mitigation benefits on local to regional scales (e.g., via carbon-storing 'blue carbon' ecosystems) (*high confidence*), and may safeguard fish stock production in a warmer climate (*limited evidence*). Ambitious and swift global mitigation offers more adaptation options and pathways to sustain ecosystems and their services (*high confidence*). {3.4.2, 3.4.3.3, 3.5, 3.5.2, 3.5.3, 3.5.5.4, 3.5.5.5, 3.6.2.1, 3.6.2.2, 3.6.2.3, 3.6.3.1, 3.6.3.2, 3.6.3.3, 3.6.5, Figure 3.24, Figure 3.25}

Nature-based solutions for adaptation of ocean and coastal ecosystems can achieve multiple benefits when well-designed and implemented (*high confidence*), but their effectiveness declines without ambitious and urgent mitigation (*high confidence*). Nature-based solutions such as ecosystem-based management, climate-smart conservation approaches (i.e., climate-adaptive fisheries and conservation) and coastal habitat restoration can be cost-effective and generate social, economic and cultural co-benefits, while contributing to the conservation of marine biodiversity and reducing cumulative anthropogenic drivers (*high confidence*). The effectiveness of nature-based solutions declines with warming; conservation and restoration will alone be insufficient to protect coral reefs beyond 2030 (*high confidence*) and to protect mangroves beyond the 2040s (*high confidence*). The multi-dimensionality of climate change impacts and their interactions with other anthropogenic stressors calls for integrated approaches that identify trade-offs and synergies across sectors and scales in space and time to build resilience of ocean and coastal ecosystems and the services they deliver (*high confidence*). {3.4.2, 3.5.2, 3.5.3, 3.5.5.3, 3.5.5.4, 3.5.5.5, 3.6.2.2, 3.6.3.2, 3.6.5, Figure 3.25, Table SM3.6}

Ocean-focused adaptations, especially those that employ nature-based solutions, address existing inequalities, and incorporate just and inclusive decision-making and implementation processes, support the UN Sustainable Development Goals (SDGs) (*high confidence*). There are predominantly positive synergies between adaptation options for Life Below Water (SDG14), Climate Action (SDG13), and social, economic and governance SDGs (SDG1–12, 16–17) (*high confidence*), but the ability of ocean adaptation to contribute to the Sustainable Development Goals is constrained by the degree of mitigation action (*high confidence*). Furthermore, existing inequalities and entrenched practices limit effective and just responses to climate change in coastal communities (*high confidence*). Momentum is growing towards transformative international and regional governance that will support comprehensive, equitable ocean and coastal adaptation while also achieving SDG14 (*robust evidence*), without compromising achievement of other SDGs. {3.6.4.0, 3.6.4.2, 3.6.4.3, Figure 3.26}.

3.1 Point of Departure

The ocean contains approximately 97% of Earth's water within a system of interconnected basins that cover 71% of its surface. Coastal systems mostly extend seaward from the high-water mark, or just beyond, to the edge of the continental shelf and include shores of soft sediments, rocky shores and reefs, embayments, estuaries, deltas and shelf systems. Oceanic systems comprise waters beyond the shelf edge, from ~200 m to nearly 11,000 m deep (Stewart and Jamieson, 2019), with an average depth of approximately 3700 m. The epipelagic zone, or upper 200 m of the ocean, is illuminated by sufficient sunlight to sustain photosynthesis that supports the rich marine food web. Below the epipelagic zone lies the barely-lit mesopelagic zone (200–1000 m), the perpetually dark bathypelagic zone (depth >1000 m) and the deep seafloor (benthic ecosystems at depths > 200 m), which spans rocky and sedimentary habitats on seamounts, mid-ocean ridges and canyons, abyssal plains and sedimented margins. Semi-enclosed seas (SES) include both coastal and oceanic systems.

The ocean sustains life on Earth by providing essential resources and modulating planetary flows of energy and materials. Together, harvests from the ocean and inland waters provide more than 20% of dietary animal protein for more than 3.3 billion people worldwide and livelihoods for about 60 million people (FAO, 2020b). The global ocean is centrally involved in sequestering anthropogenic atmospheric CO_2 and recycling many elements, and it regulates the global climate system by redistributing heat and water (WGI AR6 Chapter 9, Fox-Kemper et al., 2021). The ocean also provides a wealth of aesthetic and cultural resources (Barbier et al., 2011), contains vast biodiversity (Appeltans et al., 2012), supports more animal biomass than on land (Bar-On et al., 2018), and produces at least half the world's photosynthetic oxygen (Field et al., 1998). Ecosystem services (Annex II: Glossary) delivered by ocean and coastal ecosystems support humanity by protecting coastlines, providing nutrition and economic opportunities (Figure 3.1, Selig et al., 2019), and providing many intangible benefits. Even though ecosystem services and biodiversity underpin human well-being and support climate mitigation and adaptation (Pörtner et al., 2021b), there are also ethical arguments for preserving biodiversity and ecosystem functions regardless of the beneficiary (e.g., Taylor et al., 2020). This chapter assesses the impact of climate change on the full spectrum of ocean and coastal ecosystems, on their services and on related human activities, and it assesses marine-related opportunities within both ecological and social systems to adapt to climate change.

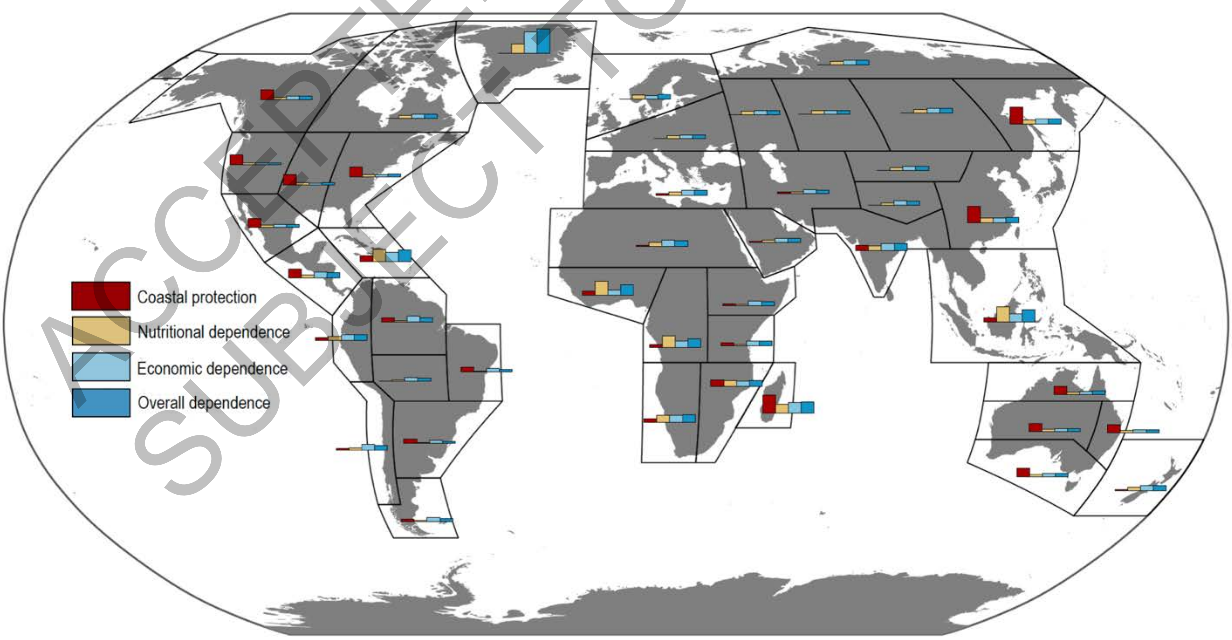


Figure 3.1: Estimated relative human dependence on marine ecosystems for coastal protection, nutrition, fisheries economic benefits and overall. Each bar represents an index value that semi-quantitatively integrates the magnitude, vulnerability to loss and substitutability of the benefit. Indices synthesize information on people's consumption of marine protein and nutritional status, gross domestic product, fishing revenues, unemployment, education, governance and coastal characteristics. Overall dependence is the mean of the three index values after standardization from 0–1 (Details are found in Table 1 and supplementary material of Selig et al. (2019)). This index does not include the

economic benefits from tourism or other ocean industries, and data limitations prevented including artisanal or recreational fisheries or the protective impact of saltmarshes (Selig et al., 2019). Values for reference regions established in the WGI AR6 Atlas (Gutiérrez et al., 2021) were computed as area-weighted means from original country-level data.

Previous IPCC Assessment Reports (IPCC, 2014c; IPCC, 2014b; IPCC, 2018; IPCC, 2019b) have expressed growing confidence in the detection of climate-change impacts in the ocean and their attribution to anthropogenic greenhouse gas emissions. Heat and CO_2 taken up by the ocean (*high* to *very high confidence*) (IPCC, 2021b) directly affect marine systems, and the resultant "climatic impact-drivers" (CIDs, e.g., ocean temperature and heatwaves, sea level, dissolved oxygen levels, acidification, Annex II: Glossary, WGI Figure SPM.9, IPCC, 2021b) also influence ocean and coastal systems (Section 3.2, Cross-Chapter Box SLR in Chapter 3, Cross-Chapter Box EXTREMES in Chapter 2, Figure SM3.1), from individual biophysical processes to dependent human activities. Several marine outcomes of CIDs are themselves drivers of ecological change (e.g., climate velocities, stratification, sea ice changes). This chapter updates and extends the assessment of SROCC (IPCC, 2019b) and WGI AR6 by assessing the ecosystem effects of the CIDs in WGI AR6 Figure SPM.9 (IPCC, 2021b) and their biologically relevant marine outcomes (detailed in Section 3.2), which are referred to collectively hereafter as "climate-impact drivers[4]".

[4] We henceforth use the term "climate-impact drivers" in reference to all drivers of ecological change that are related directly to climate change (CIDs, IPCC, 2021a) as well as those that emerge in response to CIDs.

Detrimental human impacts on ocean and coastal ecosystems are not only caused by climate. Other anthropogenic activities are increasingly affecting the physical, chemical, and biological conditions of the ocean (Doney, 2010; Halpern et al., 2019), and these "non-climate drivers[5]" also alter marine ecosystems and their services. Fishing and other extractive activities are major non-climate drivers in many ocean and coastal systems (Steneck and Pauly, 2019). Many activities, such as coastal development, shoreline hardening and habitat destruction, physically alter marine spaces (Suchley and Alvarez-Filip, 2018; Ducrotoy et al., 2019; Leo et al., 2019; Newton et al., 2020; Raw et al., 2020). Other human activities decrease water quality by overloading coastal water with terrestrial nutrients (eutrophication) and by releasing runoff containing chemical, biological and physical pollutants, toxins, and pathogens (Jambeck et al., 2015; Luek et al., 2017; Breitburg et al., 2018; Froelich and Daines, 2020) Some human activities disturb marine organisms by generating excess noise and light (Davies et al., 2014; Duarte et al., 2021), while others decrease natural light penetration into the ocean (Wollschläger et al., 2021). Several anthropogenic activities alter processes that span the land-sea interface by changing coastal hydrology or causing coastal subsidence (Michael et al., 2017; Phlips et al., 2020; Bagheri-Gavkosh et al., 2021). Atmospheric pollutants can harm marine systems or unbalance natural marine processes (Doney et al., 2007; Hagens et al., 2014; Lamborg et al., 2014; Ito et al., 2016). Organisms frequently experience non-climate drivers simultaneously with climate-impact drivers (Section 3.4), and feedbacks may exist between climate-impact drivers and non-climate drivers that enhance the effects of climate change (Rocha et al., 2015; Ortiz et al., 2018; Wolff et al., 2018; Cabral et al., 2019; Bowler et al., 2020; Gissi et al., 2021). SROCC assessed with *high confidence* that reduction of pollution and other stressors, along with protection, restoration, and precautionary management, supports ocean and coastal ecosystems and their services (IPCC, 2019b). This chapter examines the combined influence of climate-impact drivers and primary non-climate drivers on many ecosystems assessed.

Detecting changes and attributing them to specific drivers have been especially difficult in ocean and coastal ecosystems because drivers, responses and scales (temporal, spatial, organizational) often overlap and interact (IPCC, 2014c; IPCC, 2014b; Abram et al., 2019; Gissi et al., 2021). In addition, some marine systems have short, heterogeneous, or geographically biased observational records, which exacerbate the interpretation challenge (Beaulieu et al., 2013; Christian, 2014; Huggel et al., 2016; Benway et al., 2019). It is even more challenging to detect and attribute climate impacts on marine-dependent human systems, where culture, governance and society also strongly influence observed outcomes. To assess climate-driven change in natural and social systems robustly, IPCC reports rely on multiple lines of evidence, and the available types of evidence differ depending on the system under study (Section 1.3.2.1, Cross-Working Group Box ATTRIB). Lines of evidence used for ocean and coastal ecosystems for this and previous assessments include observed phenomena, laboratory and field experiments, long-term monitoring, empirical and dynamical model analyses, Indigenous knowledge (IK) and local knowledge (LK), and paleorecords (IPCC, 2014c; IPCC, 2014b; IPCC, 2019b). The growing body of climate research for ocean and coastal ecosystems and their services increasingly provides multiple independent lines of evidence whose conclusions support each other, raising the overall confidence in detection and attribution of impacts over time (Section 1.3.2.1, Cross-Working Group Box ATTRIB in Chapter 3).

[START FAQ3.1 HERE]

FAQ3.1: How do we know which changes to marine ecosystems are specifically caused by climate change?

To attribute changes in marine ecosystems to human-induced climate change, scientists use paleorecords (reconstructing the links between climate, evolutionary and ecological changes in the geological past), contemporary observations (assessing current climate and ecological responses in the field and through experiments) and models. We refer to these as multiple lines of evidence, meaning that the evidence comes from diverse approaches, as described below.

[5] We henceforth use the term "non-climate drivers" in reference to drivers of ecological change that are not caused by climate change.

Emissions of greenhouse gases like carbon dioxide from human activity cause ocean warming, acidification, oxygen loss, and other physical and chemical changes that are affecting marine ecosystems around the world. At the same time, natural climate variability and direct human impacts, such as overfishing and pollution, also affect marine ecosystems locally, regionally and globally. These climate and non-climate impact drivers counteract each other, add up or multiply to produce smaller or larger changes than expected from individual drivers. Attribution of changes in marine ecosystems requires evaluating the often-interacting roles of natural climate variability, non-climate drivers, and human-induced climate change. To do this work, scientists use

- paleorecords: reconstructing the links between climate and evolutionary and ecological changes of the past
- contemporary observations: assessing current climate and ecological responses,
- manipulation experiments: measuring responses of organisms and ecosystems to different climate conditions
- models: testing whether we understand how organisms and ecosystems are impacted by different stressors, and quantifying the relative importance of different stressors.

Paleorecords can be used to trace the correlation between past changes in climate and marine life. Paleoclimate is reconstructed from the chemical composition of shells and teeth or from sediments and ice cores. Changes to sea life signalled by changing biodiversity, extinction or distributional shifts are reconstructed from fossils. Using large datasets, we can infer the effects of climate change on sea life over relatively long timescales – usually hundreds to millions of years. The advantage of paleorecords is that they provide insights into how climate change affects life from organisms to ecosystems, without the complicating influence of direct human impacts. A key drawback is that the paleo and modern worlds do not have fully comparable paleoclimate regimes, dominant marine species, and rates of climate change. Nevertheless, the paleorecord can be used to derive fundamental rules by which organisms, ecosystems, environments and regions are typically most affected by climate change. For example, the paleorecord shows that coral reefs repeatedly underwent declines during past warming events, supporting the inference that corals may not be able to adapt to current climate warming.

Contemporary observations over recent decades allow scientists to relate the status of marine species and ecosystems to changes in climate or other factors. For example, scientists compile large datasets to determine whether species usually associated with warm water are appearing in traditionally cool-water areas that are rapidly warming. A similar pattern observed in multiple regions and over several decades (i.e., longer than timescales of natural variability) provides confidence that climate change is altering community structure. This evidence is weighed against findings from other approaches, such as manipulation experiments, to provide a robust picture of climate change impacts in the modern ocean.

In manipulation experiments, scientists expose organisms or communities of organisms to multiple stressors, for example, elevated CO_2, high temperature, or both, based on values drawn from future climate projections. Such experiments will involve multiple treatments (i.e., different aquarium tanks) in which organisms are exposed to different combinations of the stressors. This approach enables scientists to understand the effects of individual stressors as well as their interactions to explore physiological thresholds of marine organisms and communities. The scale of manipulation experiments can range from small tabletop tanks to large installations or natural ocean experiments involving tens of thousands of litres of water.

Ecological effects of climate change are also explored within models developed from fundamental scientific principles and observations. Using these numerical representations of marine ecosystems, scientists can explore how different levels of climate change and non-climate stressors influence species and ecosystems at scales not possible with experiments. Models are commonly used to simulate the ecological response to climate change over recent decades and centuries. Convergence between the model results and the observations suggests that our understanding of the key processes is sufficient to attribute the observed ecological changes to climate change, and to use the models to project future ecological changes. Differences between model results and observations indicate gaps in knowledge to be filled in order to better detect and attribute the impacts of climate change on marine life.

Using peer-reviewed research spanning the full range of scientific approaches (paleorecords, observations, experiments and models), we can assess the level of confidence in the impact of climate change on observed modifications in marine ecosystems. We refer to this as multiple lines of evidence, meaning that the evidence comes from the diverse approaches described above. This allows policy-makers and managers to address the specific actions needed to reduce climate change and other impacts.

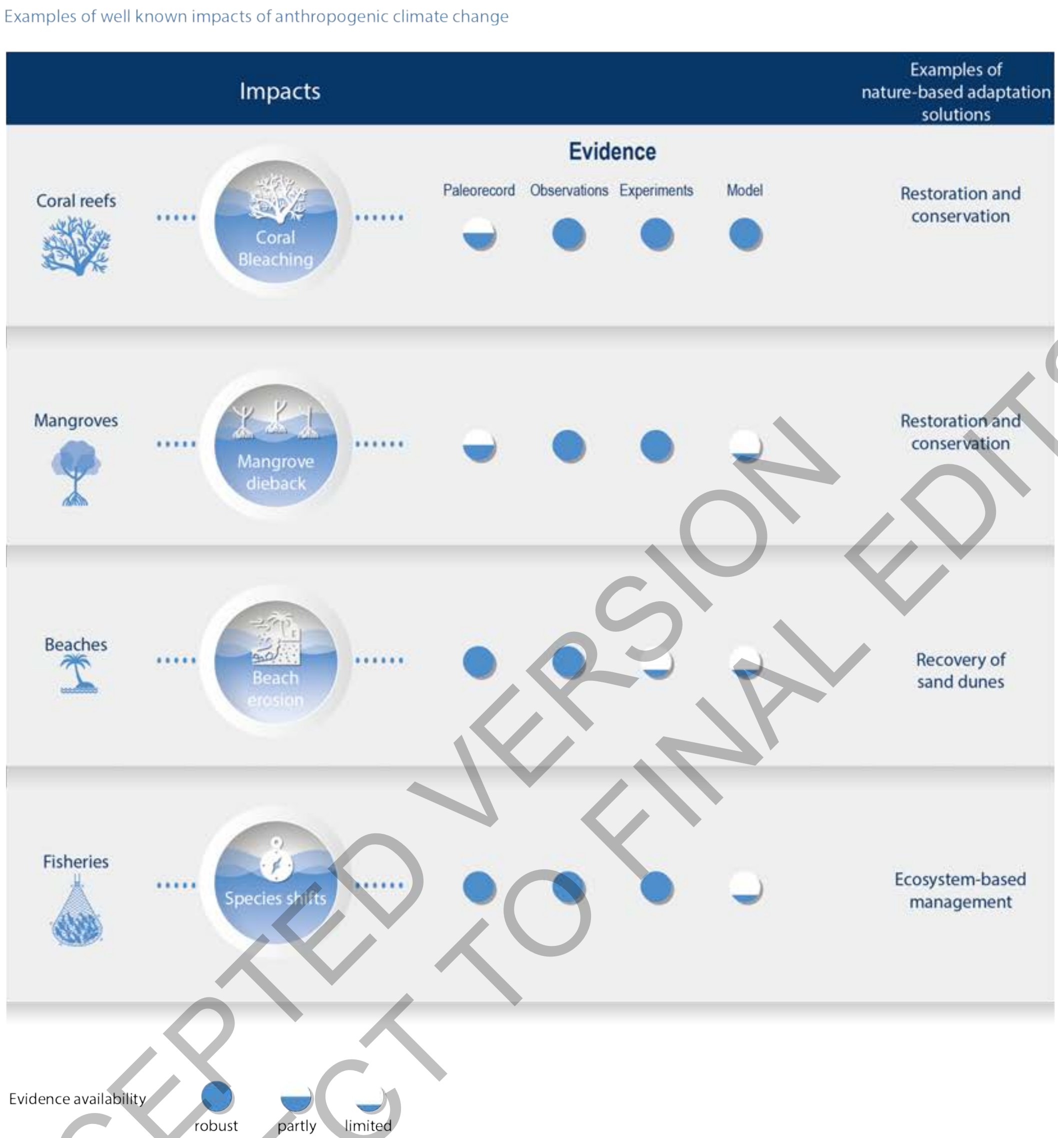


Figure FAQ3.1: Examples of well-known impacts of anthropogenic climate change and associated nature-based adaptation. To attribute changes in marine ecosystems to anthropogenic climate change, scientists use multiple lines of evidence including paleorecords, contemporary observations, manipulation experiments and models.

[END FAQ3.1 HERE]

Natural adaptation to climate change in ocean and coastal systems includes an array of responses taking place at scales from cells to ecosystems. Previous IPCC assessments have established that many marine species "have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to climate change," (*high confidence*) (IPCC, 2014c; IPCC, 2014b), which has had global impacts on species composition, abundance and biomass, and on ecosystem structure and function (*medium confidence*) (IPCC, 2019b). Warming and acidification have affected coastal ecosystems in concert with non-climate drivers (*high confidence*), which have affected habitat area, biodiversity, ecosystem function and services (*high confidence*) (IPCC, 2019b). Confidence has grown in these assessments over time as observational datasets have lengthened and other lines of evidence have corroborated observations. AR5 and SROCC assessed how physiological sensitivity to climate-impact drivers is the underlying cause of most marine organisms' vulnerability to climate (*high confidence*) (Pörtner et al., 2014; Bindoff et al., 2019). Since those assessments, more evidence supports the empirical physiological models of tolerance and plasticity (Sections 3.3.2, 3.3.4) and of interactions among multiple (climate and non-climate) drivers at individual to ecosystem scales (Sections 3.3.3, 3.4.5). New experimental evidence about evolutionary adaptation (Section 3.3.4) bolsters previous assessments that adaptation options to climate change are limited for eukaryotic organisms. Tools such as ecosystem models can now constrain probable ecosystem states (Sections 3.3.4–3.3.5 and 3.4). Observations have increased understanding of how extreme events affect individuals, populations and ecosystems, helping refine understanding of both ecological tolerance to climate impacts and ecological transformations (Section 3.4).

Human adaptation to climate impacts on ocean and coastal systems spans a variety of actions that change human activity to maintain marine ecosystem services. After AR5 concluded that coastal adaptation could reduce the effects of climate impacts on coastal human communities (*high agreement*, *limited evidence*) (Wong et al., 2014), SROCC confirmed that mostly risk-reducing ocean and coastal adaptation responses were underway (Bindoff et al., 2019). However, overlapping climate-impact and non-climate drivers confound implementation and assessment of the success of marine adaptation, revealing the complexity of attempting to maintain marine ecosystems and services through adaptation. SROCC assessed with *high confidence* that while the benefits of many locally implemented adaptations exceed their disadvantages, others are marginally effective and have large disadvantages, and overall, adaptation has a limited ability to reduce the probable risks from climate change, being at best a temporary solution (Bindoff et al., 2019). SROCC also concluded that a portfolio of many different types of adaptation actions, effective and inclusive governance, and mitigation must be combined for successful adaptation (Bindoff et al., 2019). The portfolio of adaptation measures has now been defined (Section 3.6.2), and individual and combined adaptation solutions have been implemented in several marine sectors (Section 3.6.3). Delays in marine adaptation have been partly attributed to the complexity of ocean governance (Section 3.6.4, Cross-Chapter Box 3 and Figure CB3.1 in Abram et al., 2019) and to the low priority accorded the ocean in international development goals (Nash et al., 2020), but in recent years the ocean is being increasingly incorporated in international climate policy and multilateral environmental agreements (Section 3.6.4).

This chapter assesses the current understanding of climate-impact drivers, ecological vulnerability and adaptability, risks to coastal and ocean ecosystems, and human vulnerability and adaptation to resulting changes in ocean benefits, now and in the future (Figure 3.2). It starts by assessing the biologically relevant outcomes of anthropogenic climate-impact drivers (Section 3.2). Next, it sets out the mechanisms that determine the responses of ocean and coastal organisms to individual and combined drivers from the genetic to the ecosystem level (Section 3.3). This supports a detailed assessment of the observed and projected responses of coastal and ocean ecosystems to these hazards, placing them in context using the paleo-record (Section 3.4). These observed and projected impacts are used to quantify consequent risks to delivery of ecosystem services and the socioeconomic sectors that depend on them, with attention to the vulnerability, resilience and adaptive capacity of social-ecological systems (Section 3.5). The chapter concludes by assessing the state of adaptation and governance actions available to address these emerging threats while also advancing human development (Section 3.6). Abbreviations used repeatedly in the chapter are defined in Table 3.1.

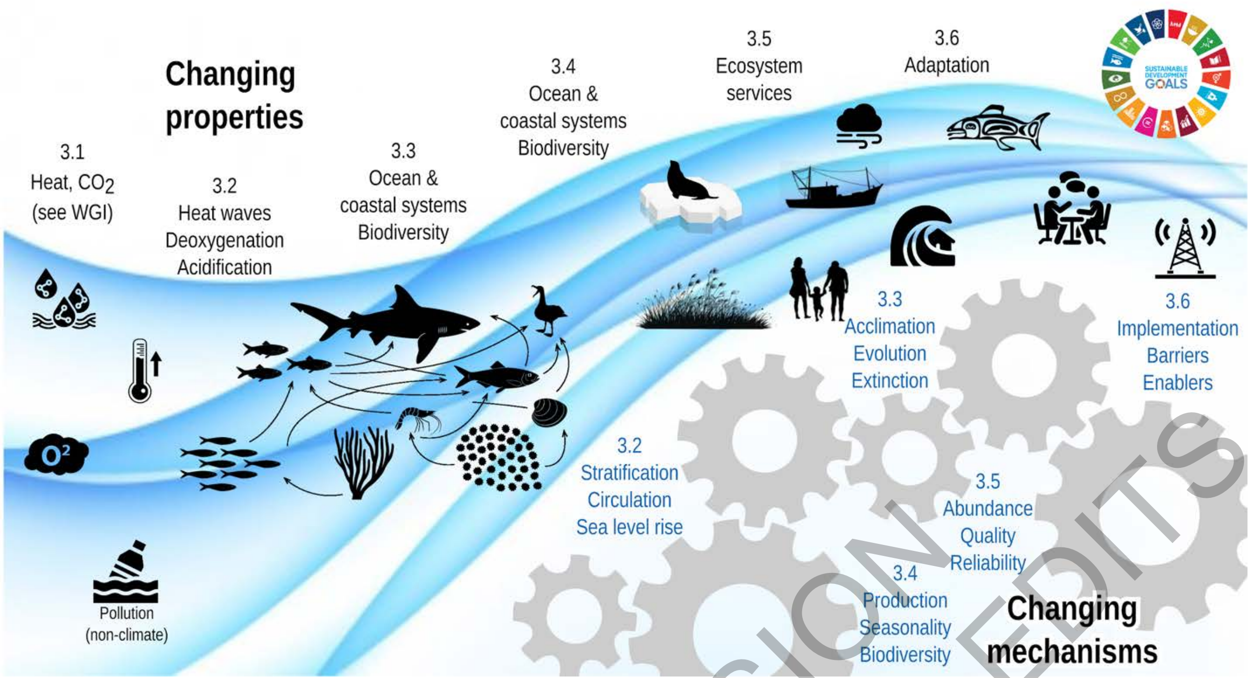


Figure 3.2: WGII AR6 Chapter 3 concept map. This chapter assesses how climate changes both the properties (top of wave, Sections 3.1–3.6) and the mechanisms (below wave, Sections 3.2–3.6) that influence the ocean and coastal social-ecological system. The Sustainable Development Goals (top right) represent ideal outcomes and achievement of equitable, healthy and sustainable ocean and coastal social-ecological systems.

Table 3.1: List of abbreviations frequently used in this chapter, with brief definitions for many of the abbreviations used.

Abbreviation	Definition
ABNJ	Areas beyond national jurisdiction. The water column beyond the exclusive economic zone called the high seas and the seabed beyond the limits of the continental shelf established in conformity with United Nations Convention on the Law of the Sea.
AMOC	Atlantic meridional overturning circulation (WGI AR6 Glossary, IPCC, 2021a).
AR5	The IPCC Fifth Assessment Report (IPCC, 2013; IPCC, 2014c; IPCC, 2014b; IPCC, 2014d).
CBD	Convention on Biological Diversity. An international legal instrument that has been ratified by 196 nations to conserve biological diversity, sustainably use its components and share its benefits fairly and equitably.
CE	Common era.
CID	Climatic Impact-Driver (WGI AR6 Glossary, IPCC, 2021a).
CMIP5, CMIP6	The Coupled Model Intercomparison Project, Phase 5 or 6 (WGI AR6 Glossary, IPCC, 2021a).
EbA	Ecosystem-based adaptation. The use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change.
EBUS	Eastern boundary upwelling system (WGI AR6 Glossary, IPCC, 2021a).
EBUE/EUS	Eastern boundary upwelling systems/equatorial upwelling systems. EBUEs are marine ecosystems in EBUS. EUSs

	are located on the equator, mostly on the eastern side of major ocean basins, where trade winds drive upwelling.
EEZ	Exclusive economic zone. The area from the coast to 200 nautical miles (370 km) off the coast, where a nation exercises its sovereign rights and exclusive management authority.
ESM	Earth-system model. A coupled atmosphere–ocean general circulation model (AOGCM, WGI AR6 Glossary, IPCC, 2021a) in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO_2 or compatible emissions.
Fish-MIP	The Fisheries and Marine Ecosystem Model Intercomparison Project. Fish-MIP is a component of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) that explores the long-term impacts of climate change on fisheries and marine ecosystems using scenarios from CMIP models.
GMSL/GMSLR	Global mean sea level/global mean sea-level rise (Sea-level change, WGI AR6 Glossary, IPCC, 2021a).
HAB	Harmful algal bloom. A HAB is an algal bloom composed of phytoplankton known to naturally produce bio-toxins that are harmful to the resident population, as well as humans.
ICZM	Integrated coastal zone management. ICZM is a dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones (European Environmental Agency).
IK and LK	Indigenous knowledge and Local knowledge (SROCC Glossary, IPCC, 2019a).
MHW	Marine heatwaves (WGI AR6 Glossary, IPCC, 2021a).
MPA	Marine protected area. MPA is an area-based management approach, commonly intended to conserve, preserve, or restore biodiversity and habitat, protect species, or manage resources (especially fisheries).
NbS	Nature-based Solution. Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN, 2016).
NDC	Nationally determined contribution by Parties to the Paris Agreement.
NPP	Net primary production. The difference between how much CO_2 vegetation takes in during photosynthesis (gross primary production) minus how much CO_2 the plants release during respiration.
OECM	Other effective area-based conservation measures. OECM is a conservation designation for areas that are achieving the effective *in situ* conservation of biodiversity outside of protected areas.
OMZ	Oxygen minimum zone (WGI AR6 Glossary, IPCC, 2021a).
pCO_2	Partial pressure of carbon dioxide. For seawater, pCO_2 is used to measure the amount of carbon dioxide dissolved in seawater.
pH	Potential of hydrogen (WGI AR6 Glossary, IPCC, 2021a).
POC	Particulate organic carbon. POC is a fraction of total organic carbon operationally defined as that which does

	not pass through a filter pore size that typically ranges in size from 0.053–2 mm.
SDG	Sustainable Development Goals. The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for Sustainable Development.
SES	Semi-enclosed sea. SES means a gulf, basin or sea surrounded by land and connected to another sea by a narrow outlet.
SIDS	Small Island Developing States (WGI AR6 Glossary, IPCC, 2021a).
SLR/RSLR/RSL	Sea-level rise/Relative rea-level rise/Relative Sea Level (Sea-level change, WGI AR6 Glossary, IPCC, 2021a).
SR15	The IPCC Special Report on 1.5 Degrees C (IPCC, 2018).
SROCC	The IPCC Special Report on the Ocean and Cryosphere (IPCC, 2019b).
SSP/RCP	Shared socio-economic pathways/Representative concentration pathways (Pathways, IPCC, 2021a).
SST	Sea-surface temperature (WGI AR6 Glossary, IPCC, 2021a).
$\Omega_{aragonite}$	Saturation state of seawater with respect to the calcium carbonate mineral aragonite, used as a proxy measurement for ocean acidification.

3.2 Observed Trends and Projections of Climatic Impact-Drivers in the Global Ocean

3.2.1 Introduction

Climate change exposes ocean and coastal ecosystems to changing environmental conditions, including ocean warming, SLR, acidification, deoxygenation and other climatic-impact drivers, which have distinct regional and temporal characteristics (Gruber, 2011; IPCC, 2018). This section aims to build on the WGI AR6 assessment (Table 3.2) to provide an ecosystem-oriented framing of climatic impact-drivers. Updating SROCC, projected trends assessed here are based on a new range of scenarios (Shared Socio-Economic Pathways, SSPs), as used in the Coupled Model Intercomparison Project Phase 6 (CMIP6, Section 1.2.2).

Table 3.2: Overview of the main global ocean Climatic Impact-Drivers and their observed and projected trends from WGI AR6, with corresponding confidence levels and links to WGI chapters, where these trends are assessed in detail.

Climatic-Impact Drivers (Hazards)	Observed trends over the historical period	WGI Section	Projected trends over the 21st century	WGI Section
Ocean Temperature				
Ocean Warming	At the ocean surface, temperature has on average increased by 0.88 [0.68–1.01] °C from 1850–1900 to 2011–2020.	2.3.3.1, 9.2.1 (Fox-Kemper et al., 2021; Gulev et al., 2021)	Ocean warming will continue over the 21st century (*virtually certain*), and with the rate of global ocean warming starting to be scenario-dependent from about the mid-21st century (*medium confidence*).	9.2.1 (Fox-Kemper et al., 2021)
Marine Heatwaves (MHW)	MHW have become more frequent (*high confidence*), more intense, and longer (*medium confidence*) over the 20th century.	Box 9.2 (Fox-Kemper et al., 2021)	MHW will become 4 [2–9, *likely* range] times more frequent in 2081–2100 compared to 1995–2014 under SSP1-2.6, and 8 [3–15, *likely* range] times more frequent under SSP5-8.5.	Box 9.2 (Fox-Kemper et al., 2021)
Climate Velocities	Not assessed in WGI.		Not assessed in WGI.	
Sea-Level				

Global Mean Sea Level (GMSL)	Since 1901, GMSL has risen by 0.20 [0.15–0.25] m, and the rate of rise is accelerating.	2.3.3, 9.6.1 (Fox-Kemper et al., 2021; Gulev et al., 2021)	There will be continued rise in GMSL through the 21st century under all assessed SSPs (*virtually certain*).	4.3.2.2, 9.6.3 (Fox-Kemper et al., 2021; Lee et al., 2021)
Extreme Sea Levels	Relative sea-level rise is driving a global increase in the frequency of extreme sea levels (*high confidence*).	9.6.4 (Fox-Kemper et al., 2021)	Rising mean relative sea level will continue to drive an increase in the frequency of extreme sea levels (*high confidence*).	9.6.4 (Fox-Kemper et al., 2021)
Ocean circulation				
Ocean Stratification	The upper ocean has become more stably stratified since at least 1970 (*virtually certain*).	9.2.1.3 (Fox-Kemper et al., 2021)	Upper-ocean stratification will continue to increase throughout the 21st century (*virtually certain*).	9.2.1.3 (Fox-Kemper et al., 2021)
Eastern Boundary Upwelling Systems	Only the California current system has experienced some large-scale upwelling-favourable wind intensification since the 1980s (*medium confidence*).	9.2.5 (Fox-Kemper et al., 2021)	Eastern boundary upwelling systems will change, with a dipole spatial pattern within each system of reduction at low latitude and enhancement at high latitude (*high confidence*).	9.2.5 (Fox-Kemper et al., 2021)
Atlantic Overturning Circulation (AMOC)	For the 20th century, there is *low confidence* in reconstructed and modelled AMOC changes.	2.3.3.4, 9.2.3 (Fox-Kemper et al., 2021; Gulev et al., 2021)	The AMOC will decline over the 21st century (*high confidence*, but *low confidence* for quantitative projections).	4.3.2.3, 9.2.3 (Fox-Kemper et al., 2021; Lee et al., 2021)
Sea-Ice				
Arctic Sea-Ice Changes	Current Arctic sea-ice coverage levels are the lowest since at least 1850 for both annual mean and late-summer values (*high confidence*).	2.3.2.1, 9.3.1 (Fox-Kemper et al., 2021; Gulev et al., 2021)	The Arctic will become practically ice-free in September by the end of the 21st century under SSP2-4.5, SSP3-7.0, and SSP5-8.5 (*high confidence*)	4.3.2.1, 9.3.1 (Fox-Kemper et al., 2021; Lee et al., 2021)
Antarctic Sea Ice Changes	There is no global significant trend in Antarctic sea-ice area from 1979 to 2020 (*high confidence*).	2.3.2.1, 9.3.2 (Fox-Kemper et al., 2021; Gulev et al., 2021)	There is *low confidence* in model simulations of future Antarctic sea ice.	9.3.2 (Fox-Kemper et al., 2021)
Ocean Chemistry				
Changes in Salinity	The large-scale, near-surface salinity contrasts have intensified since at least 1950 (*virtually certain*).	2.3.3.2, 9.2.2.2 (Fox-Kemper et al., 2021; Gulev et al., 2021)	Fresh ocean regions will continue to get fresher and salty ocean regions will continue to get saltier in the 21st century (*medium confidence*).	9.2.2.2 (Fox-Kemper et al., 2021)
Ocean Acidification	Ocean surface pH has declined globally over the past four decades (*virtually certain*).	2.3.3.5, 5.3.2.2 (Canadell et al., 2021; Gulev et al., 2021)	Ocean surface pH will continue to decrease through the 21st century, except for the lower-emission scenarios SSP1-1.9 and SSP1-2.6, (*high confidence*).	4.3.2.5, 4.5.2.2, 5.3.4.1 (Lee et al., 2021) (Canadell et al., 2021)
Ocean Deoxygenation	Deoxygenation has occurred in most open ocean regions since the mid 20th (*high confidence*).	2.3.3.6, 5.3.3.2 (Canadell et al., 2021; Gulev et al., 2021)	Subsurface oxygen content is projected to transition to historically unprecedented condition with decline over the 21st century (*medium confidence*).	5.3.3.2 (Canadell et al., 2021)
Changes in Nutrient Concentrations	Not assessed in WGI.		Not assessed in WGI.	

3.2.2 Physical Changes

3.2.2.1 Ocean Warming, Climate Velocities and Marine Heatwaves

Global mean SST has increased since the beginning of the 20th century by 0.88°C (*very likely* range: 0.68–1.01°C), and it is *virtually certain* that the global ocean has warmed since at least 1971 (WGI AR6 Section 9.2, Fox-Kemper et al., 2021). A key characteristic of ocean temperature change relevant for ecosystems is climate velocity, a measure of the speed and direction at which isotherms move under climate change (Burrows et al., 2011), which gives the rate at which species must migrate to maintain constant climate conditions. It has been shown to be a useful and simple predictor of species distribution shifts in marine ecosystems (Chen et al., 2011; Pinsky et al., 2013; Lenoir et al., 2020). Median climate velocity in the surface ocean has been 21.7 km per decade since 1960, with higher values in the Arctic/sub-Arctic and within 15° of the Equator (Figure 3.3, Burrows et al., 2011). While climate velocity has been slower in the mesopelagic layer (200–1000 m) than in the epipelagic layer (0–200 m) over the last 50 years, it has been shown to be faster in the bathypelagic (1000–4000 m) and abyssopelagic (>4000 m) layers (Figure 3.4, Brito-Morales et al., 2020), suggesting that deep-ocean species could be as exposed to effects of warming as species in the surface ocean (Brito-Morales et al., 2020).

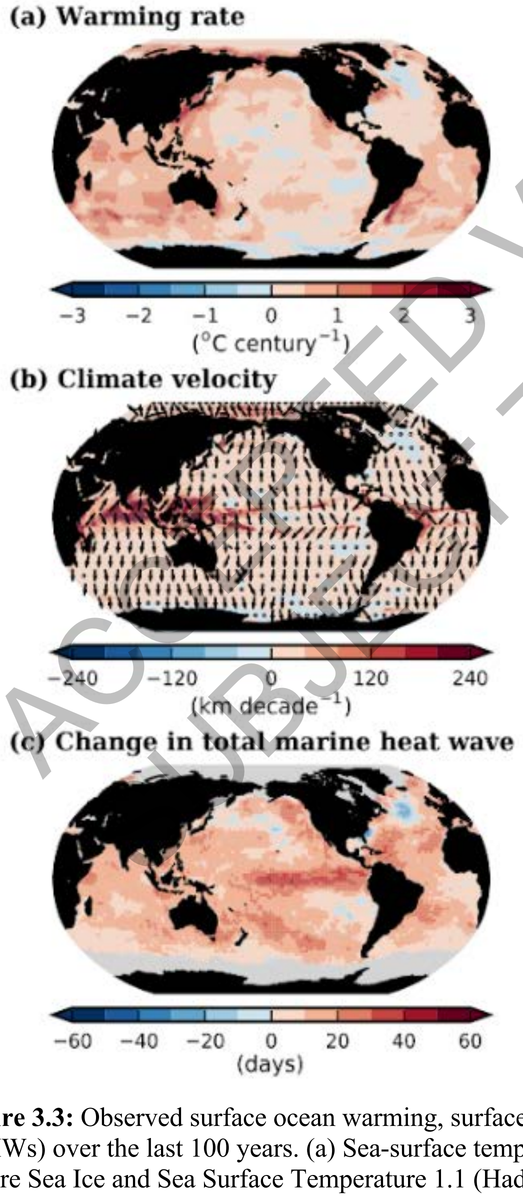


Figure 3.3: Observed surface ocean warming, surface climate velocity and reconstructed changes in marine heatwaves (MHWs) over the last 100 years. (a) Sea-surface temperature trend (°C per century) over 1925–2016 from Hadley Centre Sea Ice and Sea Surface Temperature 1.1 (HadISST1.1), (b) surface climate velocity (km per decade) over

1925–2016 computed from HadISST1.1, and (c) change in total MHW days for the surface ocean from 1925–1954 to 1987–2016 based on monthly proxies, from Oliver et al. (2018).

Marine heatwaves (MHW) are periods of extreme seawater temperature relative to the long-term mean seasonal cycle, that persist for days to months, and that may carry severe consequences for marine ecosystems and their services (WGI AR6 Box 9.2, Hobday et al., 2016a; Smale et al., 2019; Fox-Kemper et al., 2021). MHW have become more frequent over the 20th century (*high confidence*), approximately doubling in frequency (*high confidence*) and becoming more intense and longer since the 1980s (*medium confidence*) (WGI AR6 Box 9.2, Fox-Kemper et al., 2021). These trends in MHW are explained by an increase in ocean mean temperatures (Oliver et al., 2018), and human influence has *very likely* contributed to 84–90% of them since at least 2006 (WGI AR6 Box 9.2, Fox-Kemper et al., 2021). The probability of occurrence (as well as duration and intensity) of the largest and most impactful MHWs that have occurred in the past 30 years has increased more than 20-fold due to anthropogenic climate change (Laufkötter et al., 2020).

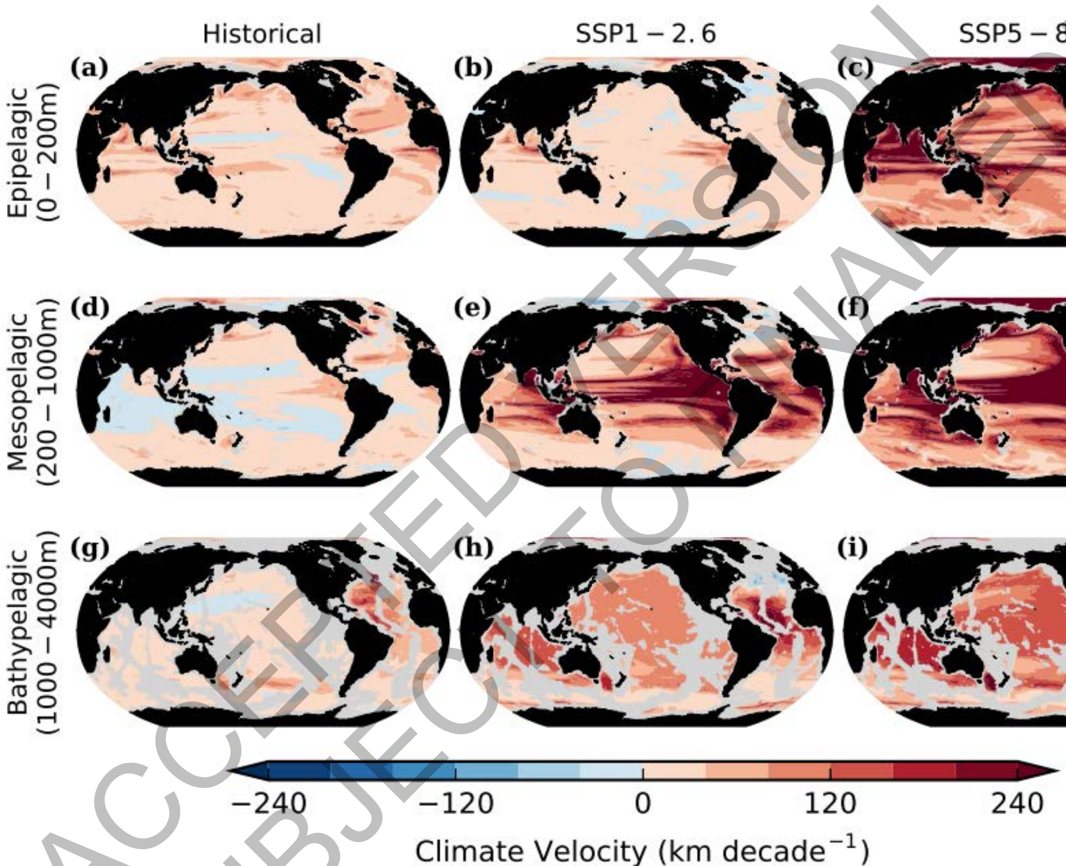


Figure 3.4: Historical and projected climate velocity. Climate velocities (in km per decade) for the (a,d,g) historical period (1965–2014), and for the last 50 years of the 21st century (2051–2100) under (b,e,h) SSP1-2.6 and (c,f,i) SSP5-8.5. Shown are the epipelagic (0–200 m), mesopelagic (200–1000 m) and bathypelagic (1000–4000 m) domains. Updated figure from Brito-Morales et al. (2020), with Coupled Model Intercomparison Project 6 models used in Kwiatkowski et al. (2020).

Ocean warming will continue over the 21st century (*virtually certain*), and with the rate of global ocean warming starting to be scenario-dependent from about the mid-21st century (*medium confidence*). At the ocean surface, it is *virtually certain* that SST will continue to increase throughout the 21st century, with increasing hazards to many marine ecosystems (WGI AR6 Box 9.2, Fox-Kemper et al., 2021). The future global mean SST increase projected by CMIP6 models for the period 1995–2014 to 2081–2100 is 0.86°C (*very likely* range: 0.43–1.47°C) under SSP1-2.6, 1.51 °C (1.02–2.19°C) under SSP2-4.5, 2.19°C (1.56–3.30°C) under SSP3-7.0, and 2.89°C (2.01–4.07°C) under SSP5-8.5 (WGI AR6 Section 9.2.1, Fox-Kemper et al., 2021). Stronger surface warming occurs in parts of the tropics, in the North Pacific, and in the Arctic

Ocean, where SST increases by >4°C in 2080–2099 under SSP5-8.5 (Kwiatkowski et al., 2020). The CMIP6 climate models also project ocean warming at the seafloor, with the magnitude of projected changes being less than that of surface waters but having larger uncertainties (Kwiatkowski et al., 2020). The projected end-of-the-century warming in CMIP6 as reported here is greater than assessed with Coupled Model Intercomparison Project 5 (CMIP5) models in AR5 and in SROCC for similar radiative forcing scenarios (Figure 3.5, Kwiatkowski et al., 2020), because of greater climate sensitivity in the CMIP6 model ensemble than in CMIP5 (WGI AR6 Chapter 4, Forster et al., 2020; Lee et al., 2021).

MHWs will continue to increase in frequency, with a *likely* global increase of 2–9 times in 2081–2100 compared to 1995–2014 under SSP1-2.6, and 3–15 times under SSP5-8.5, with the largest increases in tropical and Arctic oceans (WGI AR6 Box 9.2, Frölicher et al., 2018; Fox-Kemper et al., 2021).

3.2.2.2 Sea-Level Rise and Extreme Sea Levels

Global mean sea-level (GMSL, see also Cross-Chapter Box SLR in Chapter 3) has risen by about 0.20 m since 1901 and continues to accelerate (WGI AR6 Section 2.3.3.3, Church and White, 2011; Jevrejeva et al., 2014; Hay et al., 2015; Kopp et al., 2016; Dangendorf et al., 2017; Cazenave et al., 2018; Kemp et al., 2018; Ablain et al., 2019; Gulev et al., 2021).

Most coastal ecosystems (mangroves, sea grasses, saltmarshes, shallow coral reefs, rocky shores and sandy beaches) are affected by changes in relative sea-level (RSL, the change in the mean sea level relative to the land, Section 3.4.2). Regional rates of RSL rise differ from the global mean due to a range of factors, including local subsidence driven by anthropogenic activities such as groundwater and hydrocarbon extraction (WGI AR6 Box 9.1, Fox-Kemper et al., 2021). In many deltaic regions, anthropogenic subsidence is currently the dominant driver of RSL rise (WGI AR6 Section 9.6.3.2, Tessler et al., 2018; Fox-Kemper et al., 2021). RSL rise is driving a global increase in the frequency of extreme sea levels (*high confidence*) (WGI AR6 Section 9.6.4.1, Fox-Kemper et al., 2021).

GMSL rise through the middle of the 21st century exhibits limited dependence on emissions scenario; between 1995–2014 and 2050, GMSL is *likely* to rise by 0.15–0.23 m under SSP1-1.9 and 0.20–0.30 m under SSP5-8.5 (WGI AR6 Section 9.6.3, Fox-Kemper et al., 2021). Beyond 2050, GMSL and RSL projections are increasingly sensitive to the differences among emission scenarios. Considering only processes in which there is at least *medium confidence* (thermal expansion, land water storage, land ice surface mass balance, and some ice sheet dynamic processes), GMSL between 1995–2014 and 2100 is *likely* to rise by 0.28–0.55 m under SSP1-1.9, 0.33–0.61 m under SSP1-2.6, 0.44–0.76 m under SSP2-4.5, 0.55–0.90 m under SSP3-7.0, and 0.63–1.02 m under SSP5-8.5 (Figure 3.5). Under high-emission scenarios, ice-sheet processes in which there is *low confidence* and *deep uncertainty* might contribute more than one additional metre to GMSL rise by 2100 (WGI AR6 Chapter 9, Fox-Kemper et al., 2021).

Rising mean RSL will continue to drive an increase in the frequency of extreme sea levels (*high confidence*). The expected frequency of the current one-in-100-year extreme sea level is projected to increase by a median of 20–30 times across tide-gauge sites by 2050, regardless of emission scenario (*medium confidence*). In addition, extreme-sea-level frequency may be affected by changes in tropical cyclone climatology (*low confidence*), wave climatology (*low confidence*), and tides (*high confidence*) associated with climate change and sea-level change (WGI AR6 Section 9.6.4.2, Fox-Kemper et al., 2021).

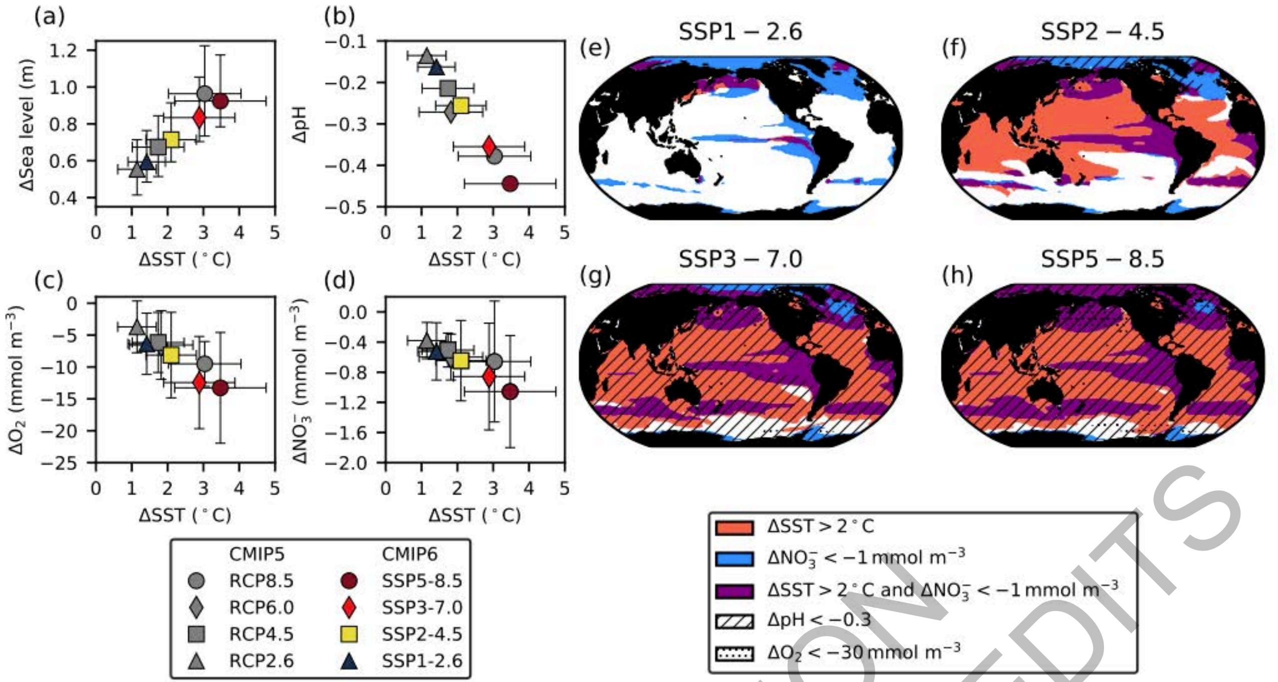


Figure 3.5: Projected trends in climatic-impact drivers for ocean ecosystems. Panels (a,b,c,d) represent Coupled Model Intercomparison Project 5 (CMIP5) Representative Concentration Pathway (RCP) and CMIP6 Shared Socioeconomic Pathway (SSP) end-of-century changes in (a) global sea-level rise (SLR), (b) average surface pH, (c) subsurface (100–600 m) dissolved oxygen concentration and (d) euphotic-zone (0–100 m) nitrate (NO_3) concentration against anomalies in sea surface temperature. All anomalies are model-ensemble averages over 2080–2099 relative to the 1870–1899 baseline period (from Kwiatkowski et al., 2020), except for SLR, which shows model-ensemble median in 2100 relative to 1901 (from AR6 WGI Chapter 9). Error bars represent *very likely* ranges, except for SLR where they represent *likely* ranges. *Very likely* ranges for pH changes are too narrow to appear on the figure (see text). Panels (e,f,g,h) show regions where end-of-century projected CMIP6 surface warming exceeds 2°C, where surface ocean pH decline exceeds 0.3, where subsurface dissolved oxygen decline exceeds 30 mmol m^{-3} and where euphotic-zone (0–100 m) nitrate decline exceeds 1 mmol m^{-3} in (e) SSP1-2.6, (f) SSP2-4.5, (g) SSP3-7.0 and (h) SSP5-8.5. All anomalies are 2080–2099 relative to the 1870–1899 baseline period (modified from Kwiatkowski et al., 2020).

3.2.2.3 *Changes in Ocean Circulation, Stratification and Coastal Upwelling*

Ocean circulation and its variations are key to the evolution of the physical, chemical and biological properties of the ocean. Vertical mixing and upwelling are critical factors affecting the supply of nutrients to the sunlit ocean and hence the magnitude of primary productivity. Ocean currents not only transport heat, salt, carbon, and nutrients, but they also control the dispersion of many organisms and the connectivity between distant populations.

Ocean stratification is an important factor controlling biogeochemical cycles and affecting marine ecosystems. WGI AR6 Section 9.2.1.3 (Fox-Kemper et al., 2021) assessed that it is *virtually certain* that stratification in the upper 200 m of the ocean has been increasing since 1970. Recent evidence has strengthened estimates of the rate of change (Yamaguchi and Suga, 2019; Li et al., 2020a; Sallée et al., 2021), with an estimated increase of 1.0 ± 0.3% (*very likely* range) per decade over the period 1970–2018 (*high confidence*) (WGI AR6 Section 9.2.1.3, Fox-Kemper et al., 2021), higher than assessed in SROCC. It is *very likely* that stratification in the upper few hundred metres of the ocean will increase substantially in the 21st century in all ocean basins, driven by intensified surface warming and near-surface freshening at high latitudes (WGI AR6 Section 9.2.1.3, Capotondi et al., 2012; Fu et al., 2016; Bindoff et al., 2019; Kwiatkowski et al., 2020; Fox-Kemper et al., 2021).

Contrasting changes among the major eastern boundary coastal upwelling systems (EBUS) were identified in AR5 (Hoegh-Guldberg et al., 2014). While SROCC assessed with *high confidence* that three (Benguela, Peru-Humboldt, California) out of the four major EBUS have experienced upwelling-favourable wind intensification in the past 60 years (Sydeman et al., 2014; Bindoff et al., 2019), WGI AR6 revisited this assessment based on evidence showing *low agreement* between studies that have investigated trends over past decades (Varela et al., 2015). WGI AR6 assessed that only the California Current system has undergone large-scale upwelling-favourable wind intensification since the 1980s (*medium confidence*) (WGI AR6 Section 9.2.1.5, García-Reyes and Largier, 2010; Seo et al., 2012; Fox-Kemper et al., 2021).

While no consistent pattern of contemporary changes in upwelling-favourable winds emerges from observation-based studies, numerical and theoretical work projects that summertime winds near poleward boundaries of upwelling zones will intensify, while winds near equatorward boundaries will weaken (*high confidence*) (WGI AR6 Section 9.2.3.5, García-Reyes et al., 2015; Rykaczewski et al., 2015; Wang et al., 2015; Aguirre et al., 2019; Fox-Kemper et al., 2021). Nevertheless, projected future annual cumulative upwelling wind changes at most locations and seasons remain within ±10–20% of present-day values (*medium confidence*) (WGI AR6 Section 9.2.3.5, Fox-Kemper et al., 2021).

Continuous observation of the Atlantic meridional overturning circulation (AMOC) has improved the understanding of its variability (Frajka-Williams et al., 2019), but there is *low confidence* in the quantification of AMOC changes in the 20th century because of *low agreement* in quantitative reconstructed and simulated trends (WGI AR6 Sections 2.3.3, 9.2.3.1, Fox-Kemper et al., 2021; Gulev et al., 2021). Direct observational records since the mid-2000s remain too short to determine the relative contributions of internal variability, natural forcing and anthropogenic forcing to AMOC change (*high confidence*) (WGI AR6 Sections 2.3.3, 9.2.3.1, Fox-Kemper et al., 2021; Gulev et al., 2021). Over the 21st century, AMOC will *very likely* decline for all SSP scenarios, but will not involve an abrupt collapse before 2100 (WGI AR6 Sections 4.3.2, 9.2.3.1, Fox-Kemper et al., 2021; Lee et al., 2021).

3.2.2.4 Sea Ice Changes

Sea ice is a key driver of polar marine life, hosting unique ecosystems and affecting diverse marine organisms and food webs through its impact on light penetration and supplies of nutrients and organic matter (Arrigo, 2014). Since the late 1970s, Arctic sea-ice area has decreased for all months, with an estimated decrease of two million km^2 (or 25%) for summer sea-ice (averaged for August, September, October) in 2010–2019 as compared to 1979–1988 (WGI AR6 Section 9.3.1.1, Fox-Kemper et al., 2021). For Antarctic sea-ice there is no significant global trend in satellite-observed sea-ice area from 1979 to 2020 in either winter or summer, due to regionally opposing trends and large internal variability (WGI AR6 Section 9.3.2.1, Maksym, 2019; Fox-Kemper et al., 2021).

CMIP6 simulations project that the Arctic Ocean will *likely* become practically sea-ice free (area below 1 million km^2) for the first time before 2050 and in the seasonal sea-ice minimum in each of the four emission scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, and SSP5-8.5 (Figure 3.7, WGI AR6 Section 9.3.2.2, SIMIP Community, 2020; Fox-Kemper et al., 2021). Antarctic sea-ice area is also projected to decrease during the 21st century, but due to mismatches between model simulations and observations, combined with a lack of understanding of reasons for substantial inter-model spread, there is *low confidence* in model projections of future Antarctic sea-ice changes, particularly at the regional level (WGI AR6 Section 9.3.2.2, Roach et al., 2020; Fox-Kemper et al., 2021).

3.2.3 Chemical Changes

3.2.3.1 Ocean Acidification

The ocean's uptake of anthropogenic carbon affects its chemistry in a process referred to as ocean acidification, which increases the concentrations of aqueous CO_2, bicarbonate and hydrogen ions, and decreases pH, carbonate ion concentrations and calcium carbonate mineral saturation states (Doney et al., 2009). Ocean acidification affects a variety of biological processes with, for example, lower calcium carbonate saturation states reducing net calcification rates for some shell-forming organisms and higher CO_2 concentrations increasing photosynthesis for some phytoplankton and macroalgal species (Section 3.3.2).

Direct measurements of ocean acidity from ocean time series, as well as pH changes determined from other shipboard studies, show consistent decreases in ocean surface pH over the past few decades (*virtually* *certain*) (WGI AR6 Section 5.3.2.2, Takahashi et al., 2014; Bindoff et al., 2019; Sutton et al., 2019; Canadell et al., 2021).

Since the 1980s, surface ocean pH has declined by a *very likely* rate of 0.016–0.020 per decade in the subtropics and 0.002–0.026 per decade in the subpolar and polar zones (WGI AR6 Section 5.3.2.2, Canadell et al., 2021). Typically, the pH of global surface waters has decreased from 8.2 to 8.1 since the pre-industrial era (1750 CE), a trend attributable to rising atmospheric CO_2 (*virtually certain*) (Orr et al., 2005; Jiang et al., 2019).

Ocean acidification is also developing in the ocean interior (*very high confidence*) due to the transport of anthropogenic CO_2 to depth by ocean currents and mixing (WGI AR6 Section 5.3.3.1, Canadell et al., 2021). There, it leads to the shoaling of saturation horizons of aragonite and calcite (*high confidence*) (WGI AR6 Section 5.3.3.1, Canadell et al., 2021), below which dissolution of these calcium carbonate minerals is thermodynamically favoured. The calcite or aragonite saturation horizons have migrated upwards in the North Pacific (1–2 m yr–1 over 1991–2006, Feely et al., 2012) and in the Irminger Sea (10–15 m yr–1 for the aragonite saturation horizon over 1991–2016, Perez et al., 2018). In some locations of the Western Atlantic Ocean, calcite saturation depth has risen by ~300 m since the pre-industrial due to increasing concentrations of deep-ocean dissolved inorganic carbon (Sulpis et al., 2018). In the Arctic, where some coastal surface waters are already undersaturated with respect to aragonite due to the degradation of terrestrial organic matter (Mathis et al., 2015; Semiletov et al., 2016), the deep aragonite saturation horizon has shoaled on average by 270 ± 60 m during 1765–2005 (Terhaar et al., 2020).

Detection and attribution of ocean acidification in coastal environments are more difficult than in the open ocean due to larger spatial and temporal variability of carbonate chemistry (Duarte et al., 2013; Laruelle et al., 2017; Torres et al., 2021), and to the influence of other natural acidification drivers such as freshwater and high-nutrient riverine inputs (Cai et al., 2011; Laurent et al., 2017; Fennel et al., 2019; Cai et al., 2020) or anthropogenic acidification drivers (Section 3.1) like atmospherically deposited nitrogen and sulphur (Doney et al., 2007; Hagens et al., 2014). Since AR5, the observing network in coastal oceans has expanded substantially, improving understanding of both the drivers and amplitude of observed variability (Sutton et al., 2016). Recent studies indicate that two more decades of observations may be required before anthropogenic ocean acidification emerges over natural variability in some coastal sites and regions (WGI AR6 Section 5.3.5.2, Sutton et al., 2019; Turk et al., 2019; Canadell et al., 2021).

Mean open-ocean surface pH is projected to decline by 0.08 ± 0.003 (*very likely range*), 0.17 ± 0.003, 0.27 ± 0.005 and 0.37 ± 0.007 pH units in 2081–2100 relative to 1995–2014, for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively (Figure 3.5, WGI AR6 Section 4.3.2, Kwiatkowski et al., 2020; Lee et al., 2021). Projected changes in surface pH are relatively uniform in contrast with those of other surface-ocean variables, but they are largest in the Arctic Ocean (Figure 3.6, WGI AR6 Section 5.3.4.1, Canadell et al., 2021). Similar declines in the concentration of carbonate ions are projected by Earth System Models (ESMs, Bopp et al., 2013; Gattuso et al., 2015; Kwiatkowski et al., 2020). The North Pacific, the Southern Ocean and Arctic Ocean regions will become undersaturated for calcium carbonate minerals first (Orr et al., 2005; Pörtner et al., 2014). Concurrent impacts on the seasonal amplitude of carbonate chemistry variables are anticipated (i.e., increased amplitude for pCO2 and hydrogen ions, decreased amplitude for carbonate ions, McNeil and Sasse, 2016; Kwiatkowski and Orr, 2018; Kwiatkowski et al., 2020).

Future declines in subsurface pH (Figure 3.6) will be modulated by changes in ocean overturning and water-mass subduction (Resplandy et al., 2013), and in organic matter remineralisation (Chen et al., 2017). In particular, decreases in pH will be less consistent at the seafloor than at the surface and will be linked to the transport of surface anomalies to depth. For example, >20% of the North Atlantic seafloor deeper than 500 m, including canyons and seamounts designated as marine protected areas (MPAs), will experience pH reductions >0.2 by 2100 under RCP8.5 (Gehlen et al., 2014). Changes in pH in the abyssal ocean (>3000 m deep) are greatest in the Atlantic and Arctic Oceans, with lesser impacts in the Southern and Pacific Oceans by 2100, mainly due to ventilation time scales (Sweetman et al., 2017).

3.2.3.2 Ocean Deoxygenation

Ocean deoxygenation, the loss of oxygen in the ocean, results from ocean warming, through a reduction in oxygen saturation, increased oxygen consumption, increased ocean stratification and ventilation changes (Keeling et al., 2010; IPCC, 2019a). In recent decades, anthropogenic inputs of nutrients and organic matter (Section 3.1) have increased the extent, duration, and intensity of coastal hypoxia events worldwide (Diaz and Rosenberg, 2008; Rabalais et al., 2010; Breitburg et al., 2018), while pollution-induced atmospheric deposition of soluble iron over the ocean has accelerated open-ocean deoxygenation (Ito et al., 2016). Dexoygenation and acidification often coincide because biological consumption of oxygen produces CO_2. Deoxygenation can have a range of detrimental effects on marine organisms and reduce the extent of marine habitats (Sections 3.3.2, 3.4.3.1, Vaquer-Sunyer and Duarte, 2008; Chu and Tunnicliffe, 2015).

Changes in ocean oxygen concentrations have been analysed from compilations of *in situ* data dating back to the 1960s (Helm et al., 2011; Ito et al., 2017; Schmidtko et al., 2017). SROCC concluded that a loss of oxygen had occurred in the upper 1000 m of the ocean (*medium confidence*), with a global mean decrease of 0.5–3.3% (*very likely range*) over 1970–2010 (Bindoff et al., 2019). Based on new regional assessments (Queste et al., 2018; Bronselaer et al., 2020; Cummins and Ross, 2020; Stramma et al., 2020). WGI AR6 assesses that ocean deoxygenation has occurred in most regions of the open ocean since the mid-20th century (*high confidence*), but is modified by climate variability on interannual and decadal time-scales (*medium confidence*) (WGI AR6 Sections 2.3.3.6, 5.3.3.2, Canadell et al., 2021; Gulev et al., 2021). New findings since SROCC also confirm that the volume of oxygen minimum zones (OMZs) are expanding at many locations (*high confidence*) (WGI AR6 Section 5.3.3.2, Canadell et al., 2021).

The most recent estimates of future oxygen loss in the subsurface ocean (100–600 m), using CMIP6 models, amount to –4.1 ± 4.2 (*very likely range*), –6.6 ± 5.7, –10.1 ± 6.7 and –11.2 ± 7.7% in 2081–2100 relative to 1995–2014 for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively (Figure 3.5, Kwiatkowski et al., 2020). Based on these CMIP6 projections, WGI AR6 concludes that the oxygen content of the subsurface ocean is projected to decline to historically unprecedented conditions over the 21st century (*medium confidence*) (WGI AR6 Section 5.3.3.2, Canadell et al., 2021). These declines are greater (by 31–72%) than simulated by the CMIP5 models in their Representative Concentration Pathway (RCP) analogues, a *likely* consequence of enhanced surface warming and stratification in CMIP6 models (Figure 3.5, Kwiatkowski et al., 2020). At the regional scale and for subsurface waters, projected changes are not spatially uniform, and there is *lower agreement* among models than they show for the global mean trend (Bopp et al., 2013; Kwiatkowski et al., 2020). In particular, large uncertainties remain for these future projections of ocean deoxygenation in the subsurface tropical oceans, where the major OMZs are located (Cabré et al., 2015; Bopp et al., 2017).

3.2.3.3 Changes in Nutrient Availability

The availability of nutrients in the surface ocean often limits primary productivity, with implications for marine food webs and the biological carbon pump. Nitrogen availability tends to limit phytoplankton productivity throughout most of the low-latitude ocean, whereas dissolved iron availability limits productivity in high-nutrient, low-chlorophyll regions, such as in the main upwelling region of the Southern Ocean and the Eastern Equatorial Pacific (*high confidence*) (Moore et al., 2013; IPCC, 2019b). Phosphorus, silicon, other micronutrients such as zinc, and vitamins can also co-limit marine phytoplankton productivity in some ocean regions (Moore et al., 2013). Whereas some studies have shown coupling between climate variability and nutrient trends in specific regions, such as in the North Atlantic (Hátún et al., 2016), North Pacific (Di Lorenzo et al., 2009; Yasunaka et al., 2014) and tropical (Stramma and Schmidtko, 2021) Oceans, very few studies have been able to detect long-term changes in ocean nutrient concentrations (but see Yasunaka et al., 2016).

Future changes in nutrient concentrations have been estimated using ESMs, with future increases in stratification generally leading to decreased nutrient levels in surface waters (IPCC, 2019b). CMIP6 models project a decline in the nitrate concentration of the upper 100 m in 2080–2099 relative to 1995–2014 of –0.46 ± 0.45 (*very likely range*), –0.60 ± 0.58, –0.80 ± 0.77 and –1.00 ± 0.78 mmol m^{-3} under SSP1-2.6, SSP2-4.5 and SSP5-8.5, respectively (Figure 3.5, Kwiatkowski et al., 2020). These declines in nitrate concentration are greater than simulated by the CMIP5 models in their RCP analogues, a *likely* consequence of enhanced surface warming and stratification in CMIP6 models (Figure 3.5, Kwiatkowski et al., 2020). It is concluded that the surface ocean will encounter reduced nitrate concentrations in the 21st century (*medium confidence*).

3.2.4 Global Synthesis on Multiple Climatic Impact Drivers

In the 21st century, ocean and coastal ecosystems are projected to face conditions unprecedented over past centuries to millennia (*high confidence*) (Section 3.2, WGI AR6 Chapters 4, 9, Fox-Kemper et al., 2021; Lee et al., 2021), with increased temperatures (*virtually certain*) and frequency and severity of MHWs (*very high confidence*), stronger upper-ocean stratification (*high confidence*), continued rise in GMSL through the 21st century (*high confidence*) and increased frequency of extreme sea levels (*high confidence*), further acidification (*virtually certain*), oxygen decline (*high confidence*), and decreased surface nitrate inventories (*medium confidence*).

The rates and magnitudes of these changes largely depend on the extent of future emissions (*very high confidence*), with surface ocean warming and acidification (*very likely range*) at +3.47°C ± 1.28°C and –0.44 pH units ± 0.008 in 2080–2099 (relative to 1870–1899) for SSP5-8.5 compared to +1.42°C ± 0.53°C and –0.16 ± 0.003 for SSP1-2.6 (Figure 3.5, Kwiatkowski et al., 2020).

3.2.4.1 Compound Changes in the 21st Century

ESMs project distinct regional evolutions of the different climatic-impact drivers over the 21st century (*very high confidence*) (Figures 3.5, 3.6, 3.7, Kwiatkowski et al., 2020). Tropical and subtropical oceans are characterized by projected warming and acidification, accompanied by declining nitrate concentrations in equatorial upwelling regions. The North Atlantic is characterized by a high exposure to acidification and declining nitrate concentrations. The North Pacific is characterized by high sensitivity to compound changes, with high rates of warming, acidification, deoxygenation and nutrient depletion. In contrast, the development of compound hazards is limited in the Southern Ocean, where rates of warming and nutrient depletion are lower. The Arctic Ocean is characterized by the highest rates of acidification and warming, strong nutrient depletion, and it will *likely* become practically sea-ice free in the September mean for the first time before the year 2050 in all SSP scenarios (*high confidence*) (Figures 3.5, 3.6, 3.7, Sections 3.2.2–3.2.3).

In general, the projected changes in climatic-impact drivers are less in absolute terms in the deep-sea (mesopelagic and bathypelagic domains and deep-sea habitats) than in the surface ocean and in shallow-waters habitats (kelp ecosystems, warm-water corals) (*very high confidence*) (Figures 3.6, 3.7, Mora et al., 2013; Sweetman et al., 2017). The mesopelagic domain will be nevertheless exposed to high rates of deoxygenation (Figure 3.6) and high climate velocities (Figure 3.4, Section 3.2.2.1), as well as impacted by the shoaling of aragonite or calcite saturation horizon (Section 3.2.3.2). Significant differences in projected trends between the SSPs show that mitigation strategies will limit exposure of deep-sea ecosystems to potential warming, acidification and deoxygenation during the 21st century (*very high confidence*) (Figure 3.6, Kwiatkowski et al., 2020).

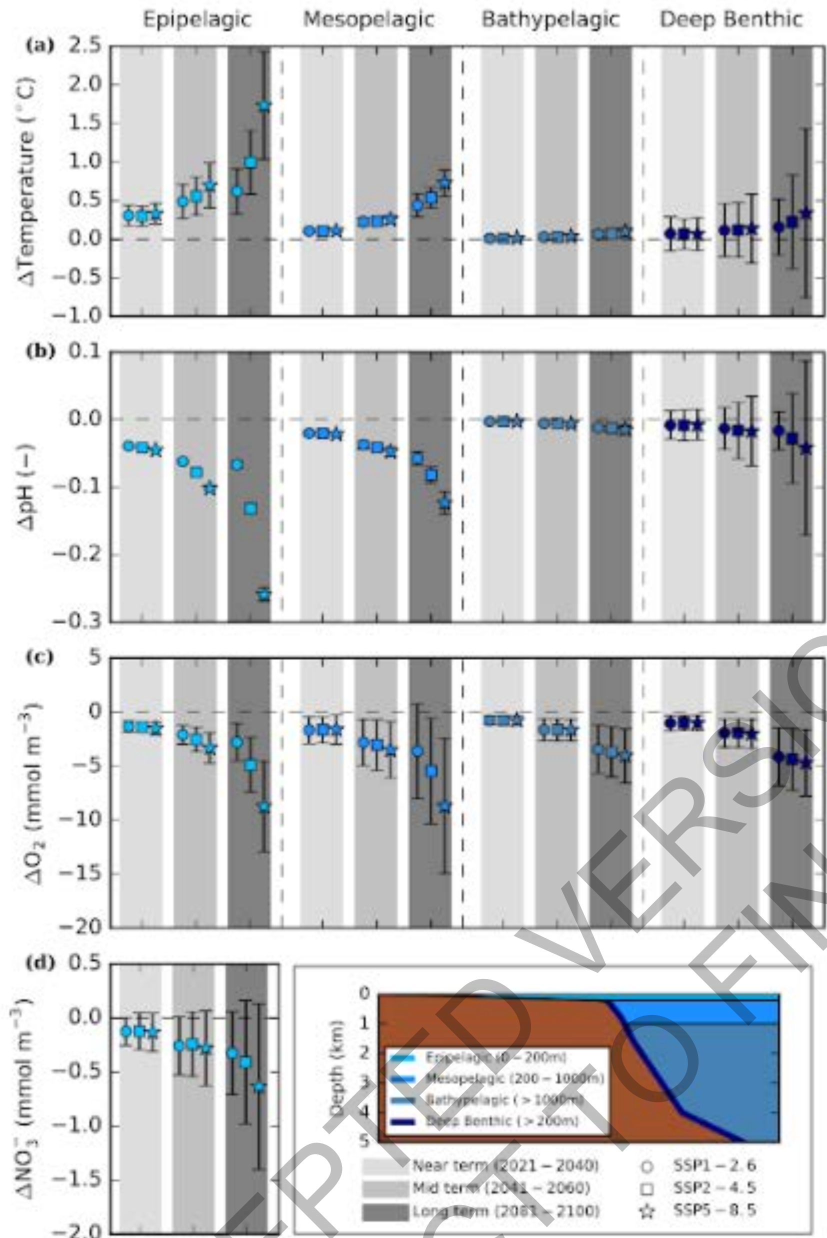


Figure 3.6: Projected trends across open-ocean systems. Projected annual and global (a) average warming, (b) acidification, (c) changes in dissolved oxygen concentrations and (d) changes in nitrate (NO_3) concentrations for four open-ocean systems, including the epipelagic (0–200 m depth), mesopelagic (200–1000 m), bathypelagic (>1000 m) domains, and deep benthic waters (>200 m). All projections are based on Coupled Model Intercomparison Project 6 models and for three Shared Socioeconomic Pathways (SSPs), SSP1-2.6, SSP2-4.5 and SSP5-8.5 (Kwiatkowski et al., 2020). Anomalies in the near-term (2020–2041), mid-term (2041–2060) and long-term (2081–2100) are all relative to 1985–2014. Error bars represent *very likely* ranges.

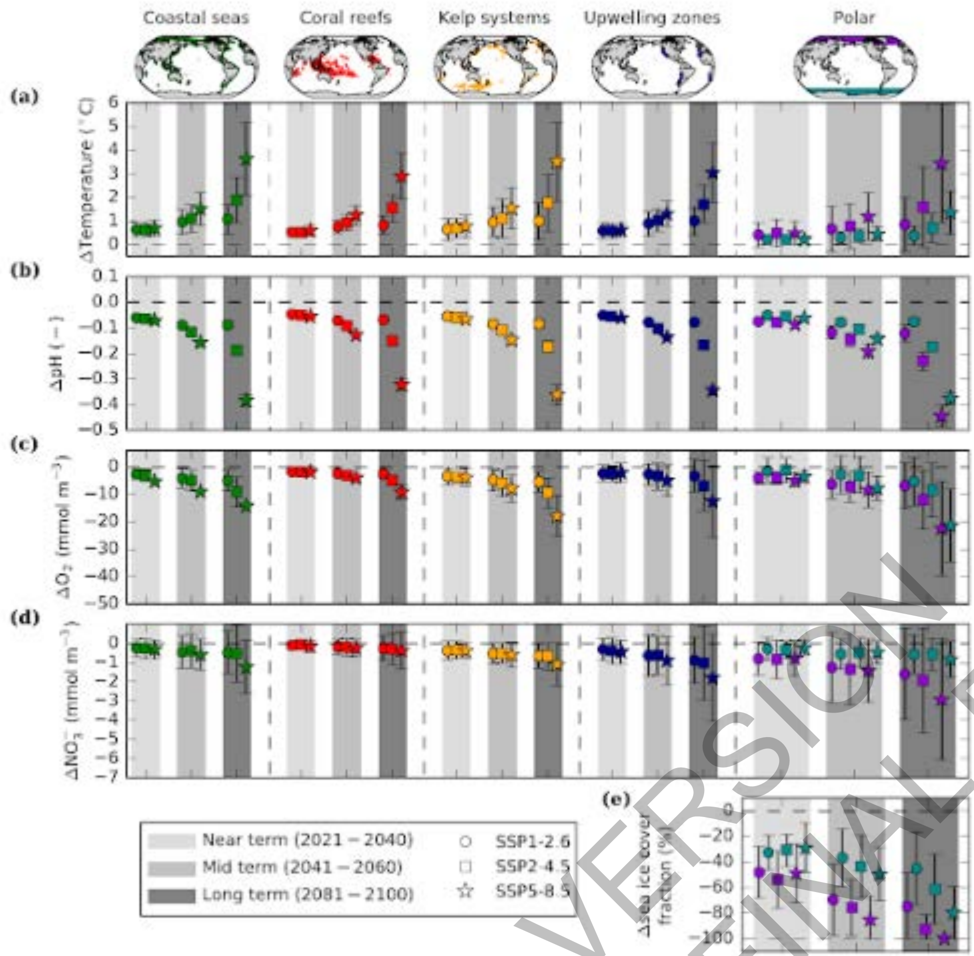


Figure 3.7: Projected trends across coastal-ocean ecosystems. Projected (a) warming, (b) acidification, (c) changes in dissolved oxygen concentrations, (d) changes in nitrate (NO_3) concentrations and (e) changes in summer sea ice cover fraction (September and north of 66°N for the Northern Polar Oceans, and March and south of 66°S for the Southern Polar Ocean) for five coastal-ocean ecosystems. All projected trends are for the surface ocean, except oxygen concentration changes that are computed for the subsurface ocean (100–600 m depth) for the upwelling ecosystems and the polar seas. All projections are based on Coupled Model Intercomparison Project 6 (CMIP6) models and for three Shared Socioeconomic Pathways (SSPs): SSP1-2.6, SSP2-4.5 and SSP5-8.5 (Kwiatkowski et al., 2020). Anomalies in the near-term (2020–2041), mid-term (2041–2060) and long-term (2081–2100) are all relative to 1985–2014. Error bars represent *very likely* ranges. Coastal seas are defined on a 1° × 1° grid when bathymetry is less than 200 m deep. Distribution of warm-water corals is from UNEP-WCMC et al. (2018). Distribution of kelp ecosystems is from OBIS (2020). Upwelling areas are defined according to Rykaczewski et al. (2015).

3.2.4.2 Time of Emergence

Anthropogenic changes in climatic impact-drivers assessed here exhibit vastly distinct times of emergence, which is the time scale over which an anthropogenic signal related to climate change is statistically detected to emerge from the background noise of natural climate for a specific region (Christensen et al., 2007; Hawkins and Sutton, 2012). SROCC concluded that for ocean properties, the time of emergence ranges from under a decade (e.g., surface ocean pH) to over a century (e.g., net primary production, see Section 3.4.3.3.4 for time of emergence of biological properties, Bindoff et al., 2019).

The literature assessed in SROCC mainly focused on surface ocean properties and gradual mean changes. Since then, the time of emergence has also been investigated for subsurface properties, ocean extreme events and particularly vulnerable regions, such as the Arctic Ocean (Hameau et al., 2019; Oliver et al., 2019; Burger et al., 2020; Landrum and Holland, 2020; Schlunegger et al., 2020), but subsequent assessments are *low confidence* due to *limited evidence*. Below the surface, changes in temperature typically emerge from internal variability prior to changes in oxygen. However in about a third of the global thermocline, deoxygenation emerges prior to warming (Hameau et al., 2019). Permanent MHW states, defined as when

SST exceeds the MHW threshold continuously over a full calendar year, will emerge during the 21st century in many parts of the surface ocean (Oliver et al., 2019). Ocean acidification extremes have already emerged from background natural internal variability during the 20th century in most of the surface ocean (Burger et al., 2020). In the Arctic, anthropogenic sea-ice changes have already emerged from the background internal variability, and anthropogenic alteration of air temperatures will emerge in the early- to mid-21st century (Landrum and Holland, 2020).

3.2.4.4 Perspectives from Paleo Data

Paleo observations are useful to assess multiple hazards of environmental change while excluding direct anthropogenic impacts (Section 3.4.3.3). Ancient intervals of rapid climate warming that occurred between 300 to 50 million years ago (Ma) were triggered by the release of greenhouse gases (*high confidence*). The sources of greenhouse gases varied but include volcanic degassing from continental flood basalts and methane hydrates stored in marine sediments and soils (Foster et al., 2018). Six extreme ancient hyperthermal events are known from the last 300 Ma, when tropical SSTs reached 1.5°C–10°C warmer than pre-industrial conditions, and with substantial impacts on ancient life (Cross-Chapter Box PALEO in Chapter 1). Warming and deoxygenation in the oceans were closely associated in hyperthermal events (*high confidence*), with anoxia reaching the photic zone and abyssal depths (Kaiho et al., 2014; Müller et al., 2017; Penn et al., 2018; Weissert, 2019), whereas ocean acidification has not been demonstrated consistently (*medium confidence*) (Hönisch et al., 2012; Penman et al., 2014; Clarkson et al., 2015; Harper et al., 2020a; Jurikova et al., 2020; Müller et al., 2020).

Greenhouse gases also contributed substantially to shaping the longer-term climate trends over the last 50 million years, although changes in continental configuration and ocean circulation as well as planetary orbital cycles were equally important (WGI AR6 Cross-Chapter Box 2.1, Westerhold et al., 2020; Gulev et al., 2021). There is little evidence for ocean acidification in the last 2.6 Ma (*low confidence*) (Hönisch et al., 2012), but ocean ventilation was highly sensitive to even modest warming such as observed in the last 10,000 years (*medium confidence*) (Jaccard and Galbraith, 2012; Lembke-Jene et al., 2018).

3.3 Linking Biological Responses to Climatic-Impact Drivers

3.3.1 Introduction

This section assesses new evidence since AR5 (Pörtner et al., 2014) and SROCC (Bindoff et al., 2019) regarding biotic responses to multiple environmental drivers. It assesses differential sensitivities among life stages within individual organisms, changing responses across scales of biological organisation and the potential for evolutionary adaptation to climate change (e.g., Przeslawski et al., 2015; Boyd et al., 2018; Reddin et al., 2020), providing examples and identifying key gaps and uncertainties that limit our ability to project the ecological impact of multiple climate-impact drivers (Figure 3.8a). The assessment includes physiological responses to single environmental drivers and their underlying mechanisms (Section 3.3.2), the characteristics of multiple drivers and organisms' responses to them (Section 3.3.3), short-term acclimation and longer-term evolutionary adaptation of populations (Section 3.3.4), and it concludes with an assessment of progress in upscaling laboratory findings to ecosystems within *in situ* settings (Figure 3.8b, Section 3.3.5).

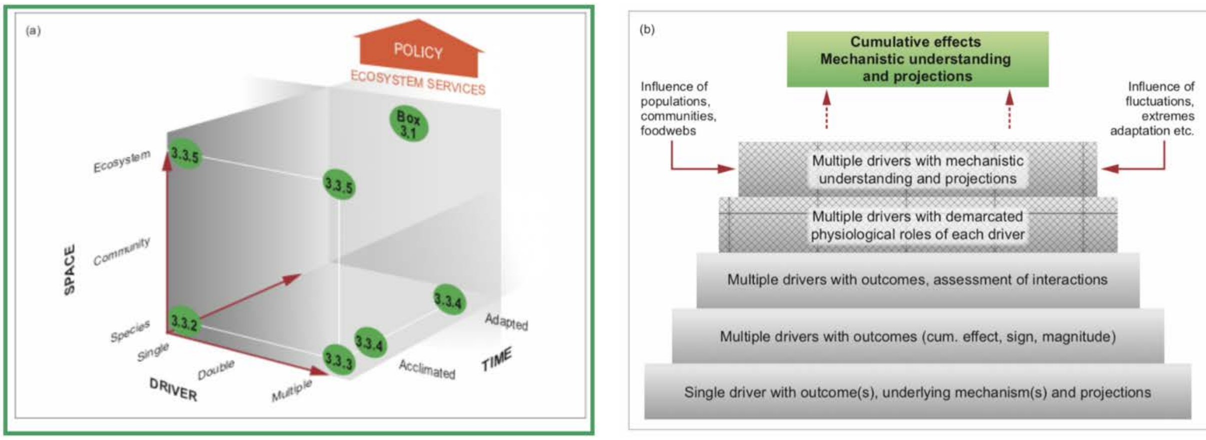


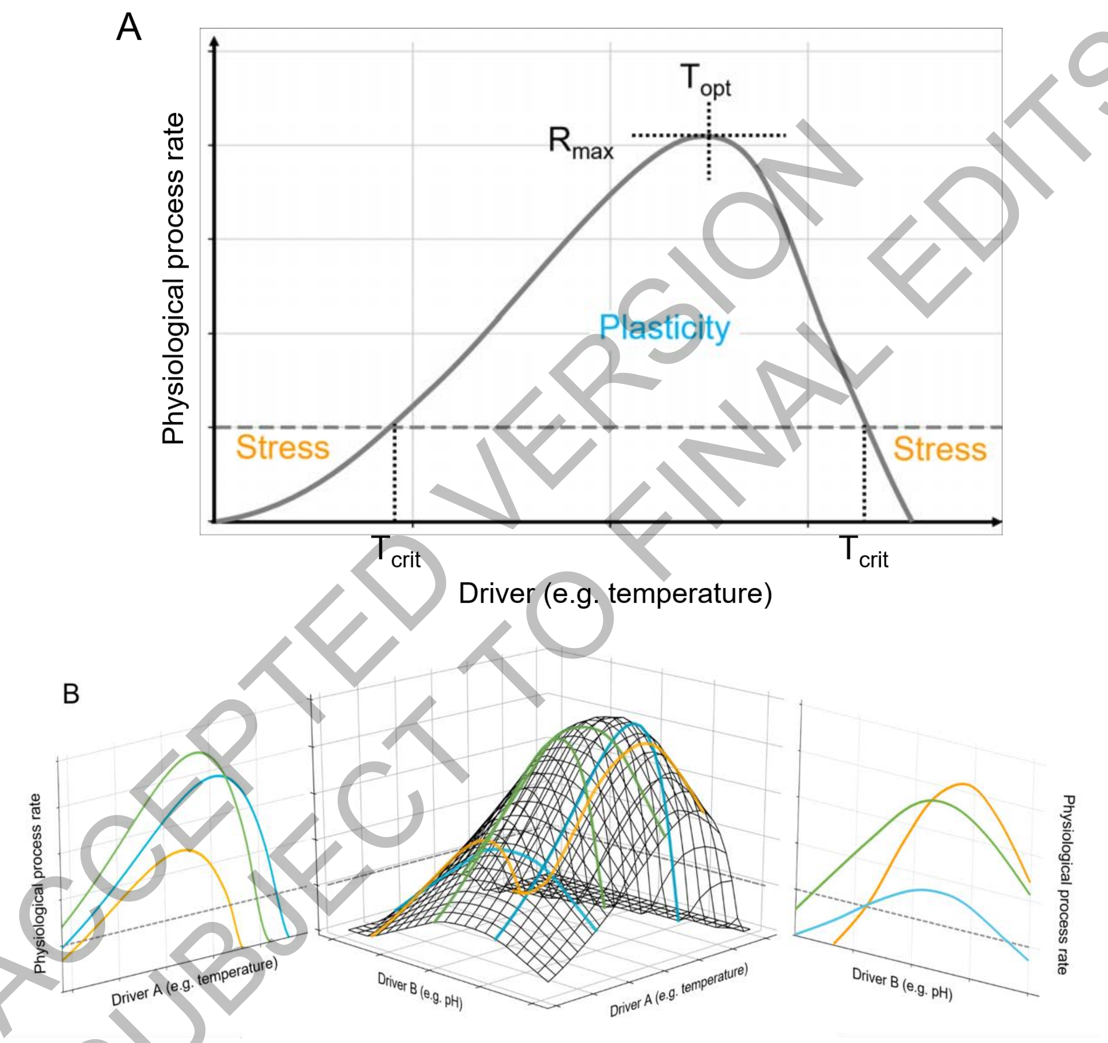
Figure 3.8: The state of knowledge regarding ecological responses to environmental drivers in experimental settings. (a) Schematic indicating where themes are discussed within Section 3.3, and how they jointly inform policy; adapted from Riebesell and Gattuso (2014). (b) The hierarchy of accumulating physiological knowledge (grey layers), from single (e.g., Pörtner et al., 2012) to multiple drivers, and from simple outcomes (e.g., Sciandra et al., 2003), interactions among drivers (e.g., Crain et al., 2008) and identification of physiological roles of drivers (e.g., Bach et al., 2015) to mechanistic understanding of drivers (e.g., Thomas et al., 2017). At present, the upper grey layer has been achieved, in full, for two drivers e.g., temperature and nutrient concentrations, with validation of dual controls on phytoplankton growth rate, Thomas et al. (2017). Hatched layers denote major advances since WGII AR5 Chapter 6 (Pörtner et al., 2014). The green layer indicates the level of understanding potentially needed to project the response of marine life subjected to multiple drivers. Red horizontal arrows indicate the influence of confounding factors on our current understanding, including population genetics, fluctuating oceanic conditions, or extreme events.

3.3.2 Responses to Single Drivers

Anthropogenic CO_2 emissions trigger a suite of changes that alter ocean temperature, pH and CO_2 concentration, oxygen concentration, and nutrient supply at global scales (Section 3.2). The response pathways of these climate-impact drivers have been investigated primarily as single variables.

Temperature affects the movement and transport of molecules and, thereby, the rates of all biochemical reactions. Thus, ongoing and projected warming (Section 3.2.2.1) that remains below an organism's physiological optimum will generally raise metabolic rates (*very high confidence*) (Pörtner et al., 2014). Beyond this optimum (T_{opt}, Figure 3.9), metabolism typically decreases sharply, finally reaching a critical threshold (T_{crit}) beyond which enzymes become thermally inactivated and cells undergo oxidative stress. Local and regional adaptation affect the heat tolerance thresholds of organisms. For example, organisms adapted to thermally-stable environments (e.g., tropical, polar, deep-sea) are often more sensitive to warming than those from thermally variable environments (e.g., estuaries) (*very high confidence*) (Section 3.4, Sunday et al., 2019; Collins et al., 2020). Heat tolerance also decreases with increasing organisational complexity (Storch et al., 2014; Pörtner and Gutt, 2016), and is lower in eggs, embryos and spawning fish than for their larval stages or adults outside the spawning season (*high confidence*) (Dahlke et al., 2020b). By altering physiological responses, projected changes in ocean warming (Section 3.2.2.1) will modify growth, migration, distribution, competition, survival and reproduction (*very high confidence*) (Messmer et al., 2017; Dahlke et al., 2018; Andrews et al., 2019; Pinsky et al., 2019; Anton et al., 2020).

Altered seawater carbonate chemistry (Section 3.2.3.1) affects specific processes to varying degrees. For example, higher CO_2 concentrations can increase photosynthesis and growth in some phytoplankton, macroalgal and seagrass species (*high confidence*) (Pörtner et al., 2014; Seifert et al., 2020; Zimmerman, 2021), while lower pH levels decrease calcification (*high confidence*) (Pörtner et al., 2014; Falkenberg et al., 2018; Doney et al., 2020; Fox et al., 2020; Reddin et al., 2020) or silicification (*low confidence*) (Petrou et al., 2019). Organisms' capacity to compensate for or resist acidification of internal fluids depends on their capacity for acid-base regulation, which differs due to organisms' wide-ranging biological complexity and adaptive abilities (*low* to *medium confidence*) (Vargas et al., 2017; Melzner et al., 2020). Detrimental impacts of acidification include decreased growth and survival, and altered development, especially in early life stages (*high confidence*) (Dahlke et al., 2018; Onitsuka et al., 2018; Hancock et al., 2020), along with lowered recruitment and altered behaviour in animals (Kroeker et al., 2013a; Wittmann and Pörtner, 2013; Clements and Hunt, 2015; Cattano et al., 2018; Esbaugh, 2018; Bednaršek et al., 2019; Reddin et al., 2020). For finfish, laboratory studies of behavioural and sensory consequences of ocean acidification showed mixed results (Rossi et al., 2018; Nagelkerken et al., 2019; Stiasny et al., 2019; Velez et al., 2019; Clark et al., 2020; Munday et al., 2020). Calcifiers are generally more sensitive to acidification (e.g., for growth and survival) than non-calcifying groups (*high confidence*) (Kroeker et al., 2013a; Wittmann and Pörtner, 2013; Clements and Hunt, 2015; Cattano et al., 2018; Bednaršek et al., 2019; Reddin et al., 2020; Seifert et al., 2020). For calcifying primary producers, including phytoplankton and coralline algae, ocean acidification has different, often opposing effects, for example, decreasing calcification while photosynthetic rates increase (*high confidence*) (Riebesell et al., 2000; Van de Waal et al., 2013; Bach et al., 2015; Cornwall et al., 2017b; Gafar et al., 2019).



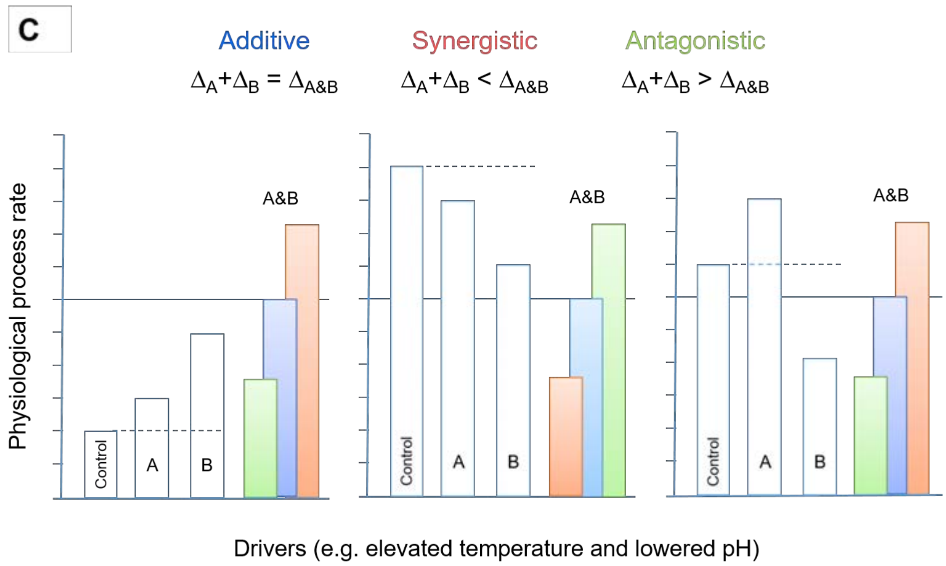


Figure 3.9: Organismal responses to single and multiple drivers. (a) The generic temperature-response curve describing physiological process rates as a nonlinear function of a particular driver (e.g., temperature) with maximum rates (R_{max}) and temperature optima (T_{opt}). The driver range that keeps physiological rates above a certain threshold represents the organism's range of phenotypic plasticity, while below that threshold, the critical temperature (T_{crit}), physiological performance is so low as to constitute stressful conditions. (b) The response curve for one driver can depend on other drivers, here exemplified for temperature and pH in the central panel. This interaction causes rates as well as optima to change with (left) pH and (right) temperature, indicated by the coloured lines. (c) Impacts of multiple drivers on processes can be (blue) additive, (red) synergistic or (green) antagonistic, that is, the cumulative effects of two (or more) drivers are equal to, larger than or smaller than the sum of their individual effects, respectively. Potential experimental outcomes affected by additive, synergistic, and antagonistic interactions are shown for scenarios where drivers (left) increase rates, (centre) decrease rates, or (right) cause opposite responses, showing how experimental outcomes can mask these mechanistic interactions. Adapted from Crain et al. (2008) and Piggott et al. (2015). For a quantitative analysis of effects of driver pairs on animals, see Figure SM3.2.

Oxygen concentrations affect aerobic and anaerobic processes, including energy metabolism and denitrification. Projected decreases in dissolved oxygen concentration (Section 3.2.3.2) will thus impact organisms and their biogeography in ways dependent upon their oxygen requirements (Deutsch et al., 2020), which are highest for large, multicellular organisms (Pörtner et al., 2014). The upper ocean generally contains high dissolved-oxygen concentrations due to air-sea exchange and photosynthesis, but in subsurface waters, deoxygenation may impair aerobic organisms in multiple ways (Oschlies et al., 2018; Galic et al., 2019; Thomas et al., 2019; Sampaio et al., 2021). Many processes contribute to lowered oxygen levels: altered ventilation and stratification; microbial respiration enhanced by nearshore eutrophication; and less oxygen solubility in warmer waters. For example, deoxygenation in highly eutrophic estuarine and coastal marine ecosystems (Section 3.4.2) can result from accelerated microbial activity, leading to acute organismal responses. Under hypoxia (oxygen concentrations ≤2 mg L–1, Limburg et al., 2020), physiological and ecological processes are impaired and communities undergo species migration, replacement and loss, transforming community composition (*very high confidence*) (Chu and Tunnicliffe, 2015; Gobler and Baumann, 2016; Sampaio et al., 2021). Hypoxia can lead to expanding OMZs which will favour specialised microbes and hypoxia-tolerant organisms (*medium confidence*) (Breitburg et al., 2018; Ramírez-Flandes et al., 2019). As respiration consumes oxygen and produces CO_2, lowered oxygen levels are often interlinked with acidification in coastal and tropical habitats (Rosa et al., 2013; Gobler and Baumann, 2016; Feely et al., 2018) and is an example of a compound hazard (Sections 3.2.4.1, 3.4.2.4).

Increased density stratification and mixed-layer shallowing, caused by warming, freshening and sea-ice decline, can alter light climate and nutrient availability within the surface mixed layer (*high confidence*) (Section 3.2.2.3). As light and nutrient levels drive photosynthesis, changes in these drivers directly affect primary producers, often in different directions (Matsumoto et al., 2014; Deppeler and Davidson, 2017). Decreased upward nutrient supply is expected to decrease primary production in the low-latitude ocean (*medium confidence*) (Section 3.4.4.2.1, Moore et al., 2018a; Kwiatkowski et al., 2019). Alternatively, higher mean underwater light levels resulting from changes in sea ice and/or mixed layer shallowing can increase primary production in high-latitude offshore regions, provided nutrient levels remain sufficiently high (*medium confidence*) (Section 3.4.4.2.1, Cross-Chapter Paper 6, Vancoppenolle et al., 2013; Deppeler and Davidson, 2017; Tedesco et al., 2019; Ardyna and Arrigo, 2020; Lannuzel et al., 2020). In some parts of the open Southern Ocean, where iron limitation largely controls primary productivity (Tagliabue et al., 2017), changes in wind fields will deepen the summer mixed-layer depth (Panassa et al., 2018), entrain more nutrients, and raise primary productivity in the future (*medium confidence*) (Cross-Chapter Paper 6, Hauck et al., 2015; Leung et al., 2015; Moore et al., 2018a; Kwiatkowski et al., 2020).

Climate-impact drivers fluctuate on time scales ranging from diurnal to annual, with potential consequences for organismal responses (Figure 3.10), but these fluctuations are commonly not incorporated experimentally. Experiments that simulate natural fluctuations in drivers, especially beyond tidal or diel cycles, can result in more detrimental impacts than those based on quasi-constant conditions (Eriander et al., 2015; Sunday et al., 2019), but can also ameliorate effects (Comeau et al., 2014; Laubenstein et al., 2020; Cabrerizo et al., 2021), confirming that the influence of environmental variability requires evaluation (Dowd et al., 2015). MHWs exacerbate the impacts of rising mean temperatures, with major ecological consequences (*very high confidence*) (Frölicher et al., 2018; IPCC, 2018; Arafeh-Dalmau et al., 2020; Laufkötter et al., 2020). Higher temperature variability decreased phytoplankton growth and calcification in *Emiliania huxleyi* relative to a stable warming regime (Wang et al., 2019b). Diel fluctuations (i.e., over 24 h) in carbonate chemistry superimposed on current and future pCO_2 levels influenced diatom species differently, depending on their habitat (Li et al., 2016). CO_2 fluctuations overlaid on changing mean values also altered phenotypic evolutionary outcomes of picoeukaryotic algae (Schaum et al., 2016). In the bivalve *Mytilus edulis*, fluctuating pH regimes exerted higher metabolic costs (Mangan et al., 2017), while salinity fluctuations might be more influential than pH fluctuations in other bivalves (Velez et al., 2016). The amplitude of diel and seasonal pH and CO_2 changes are projected to increase in the future due to lowered CO_2 seawater buffering capacity (*very high confidence*) (Section 3.2.3.1, Burger et al., 2020), which can impose additional stress on organisms.

3.3.3 Responses to Multiple Drivers

Each organism encounters a unique combination of local and climate-impact drivers, which vary in space and time. The contribution of these drivers to an organism's overall biological response, and thereby also potential risks for the organism, depends on the intensity and duration of its exposure to these drivers and associated sensitivities. Both geographical location (e.g., polar, tropical) and marine habitat (e.g., benthic, pelagic) strongly affect the combination of climate and non-climate drivers that organisms are exposed to. Non-climate drivers (Section 3.1) can dominate outcomes or amplify vulnerability to climate-impact drivers, with mostly detrimental effects such as extirpation (*very high confidence*) (Section 3.4, Boyd et al., 2018; Gissi et al., 2021), and unique feedbacks may exist between climate change and drivers like habitat loss or invasive species that further confound climate change effects (Ortiz et al., 2018; Wolff et al., 2018; Gissi et al., 2021). Individual responses are further influenced by an organism's behaviour, trophic level and life-history strategy (Figure 3.10, Przeslawski et al., 2015; Boyd et al., 2018). Evidence is increasing that some life-history stages are more sensitive to specific drivers than others (Dahlke et al., 2020b). To identify the most influential drivers for an organism requires targeting key traits (e.g., calcification, reproduction). The trophic level of the organism must also be considered, because autotrophs directly depend on light and nutrients while invertebrates are often more sensitive to changes in oxygen or altered prey, but temperature plays a key role for both groups (Figure 3.10b).

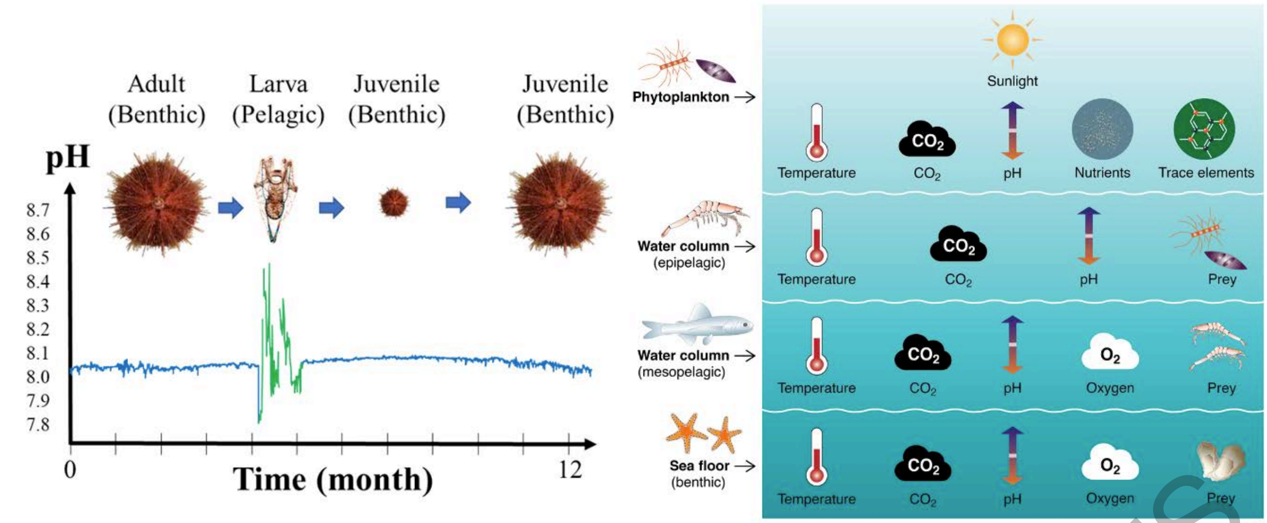


Figure 3.10: The effect of environmental drivers differs depending upon organisms' life history, and trophic strategy or habitat. (a) pH variability differs for benthic invertebrates, such as sea urchins (in blue), and their pelagic larvae (in green); pH fluctuations over the annual cycle can be much larger in the water column (due to primary production) relative to the seafloor. Variability associated with behaviour and life stage strongly defines organisms' niches and sensitivities to present and future conditions. (b) Examples of organisms that are influenced by different suites of drivers that are set jointly by their habitat (e.g., benthic versus epipelagic settings) and trophic strategy (e.g., nutrients for phytoplankton, prey characteristics for grazers).

Co-occurring environmental drivers often cause complex organismal responses (*high confidence*) (Pörtner et al., 2014). Individual drivers can have detrimental, neutral or beneficial effects, depending on the relationship between driver and physiological process (Section 3.3.2, Figure 3.9a). Multiple drivers can have interactive effects, where the response to one driver alters the sensitivity to another, and outcomes cannot be deduced from individual drivers' effects (Figure 3.9b). Impacts of multiple drivers can be additive, synergistic or antagonistic (Figure 3.9c, Crain et al., 2008; Piggott et al., 2015; Boyd et al., 2018; Bindoff et al., 2019). Well-controlled laboratory studies on multiple-driver effects have revealed insights into the mode of action of individual drivers and their interdependence (Kroeker et al., 2017; Gao et al., 2019; Reddin et al., 2020; Seifert et al., 2020; Green et al., 2021b; Sampaio et al., 2021). Understanding the outcomes of interactive drivers is important for robustly assessing risks to organisms under different climate-change scenarios.

3.3.3.1 *Effects of Multiple Drivers on Primary Producers*

Warming and rising CO_2 concentrations enhance growth and/or photosynthetic rates in many species of cyanobacteria, picoeukaryotes, coccolithophores, dinoflagellates and diatoms (*high confidence*) (Fu et al., 2007; Sett et al., 2014; Hoppe et al., 2018a; Wolf et al., 2018; Brandenburg et al., 2019), and the optimum pCO_2 for growth and/or primary production shifts upward under warming (*medium confidence*) (Sett et al., 2014; Hoppe et al., 2018a). Warming and ocean acidification appear to jointly favour the proliferation and toxicity of harmful algal bloom (HAB) species (*limited evidence, high agreement*) (Section 3.5.5.3, Bindoff et al., 2019; Brandenburg et al., 2019; Griffith et al., 2019a; Wells et al., 2020), but a 2021 analysis found no uniform global trend in HABs or their distribution over 1985–2018, once field data were adjusted for regional variations in monitoring effort (Hallegraeff et al., 2021). The predominantly detrimental impacts of ocean acidification on coccolithophores can partly be offset by warming (Seifert et al., 2020), but also be exacerbated, depending on the magnitudes of drivers (D'Amario et al., 2020). For non-calcifying macroalgae, responses are highly species-specific and often indicate synergistic interactions between warming and acidification (Kram et al., 2016; Falkenberg et al., 2018). Ocean acidification poses a large risk for coralline algae that is further amplified by warming (*medium confidence*) (Section 3.4.2.2, Cornwall et al., 2019). However, temperatures up to 5°C above ambient do not decrease calcification (Cornwall et al., 2019), and there is *limited evidence* that some species have the physiological capacity to resist acidification via pH upregulation at the calcification site (Cornwall et al., 2017a). For seagrass, warming beyond a species' thermal tolerance will limit growth and impact germination, but ocean acidification appears to increase thermal tolerance of some eelgrass species by increasing the photosynthesis-to-respiration ratio (*medium confidence*) (Egea et al., 2018; Scalpone et al., 2020; Zimmerman, 2021).

Thermal sensitivity of pelagic primary producers changes with nutrient supply (*high confidence*) (Thomas et al., 2017; Marañón et al., 2018; Fernández et al., 2020). Phosphorus limitation lowers the temperature optimum for growth of phytoplankton, making these organisms more prone to heat stress (Thomas et al., 2017; Bestion et al., 2018). This trend may hold for open-ocean phytoplankton, which are often iron-limited (*medium confidence*) (Boyd, 2019). Such temperature-nutrient interactions might be especially relevant during summer MHWs (Section 3.2.2.1, Cross-Chapter Box EXTREMES in Chapter 2, IPCC, 2018; Holbrook et al., 2019; DeCarlo et al., 2020; Hayashida et al., 2020), when primary producers are often nutrient-limited and near their thermal limits. Increasingly frequent and intense MHWs along with projected decreases in nutrient availability (Section 3.2.3.3) may push some primary producers beyond tolerance thresholds. Temperature-nutrient interactions can also alter the photosynthesis-to-respiration ratio in phytoplankton (Marañón et al., 2018). Overall, rising metabolic rates due to warming will be restricted to primary producers in high-nutrient regions (*medium confidence*) (Thomas et al., 2017; Marañón et al., 2018). For zooxanthellae-containing corals, nutrient supply from upwelling or from runoff can increase coral susceptibility to bleaching during warm-season MHWs (DeCarlo et al., 2020; Wooldridge, 2020).

The effects of ocean acidification on growth, metabolic rates or elemental composition of primary producers changes with nutrient availability and light conditions (*high confidence*) (Gao et al., 2019; Seifert et al., 2020). While interactions with nutrients are often additive in phytoplankton, diatoms revealed predominantly synergistic interactions (Seifert et al., 2020). Growth or photosynthesis of some diatom and HAB species, for instance, are stimulated by ocean acidification only if nutrients are replete (Hoppe et al., 2013; Boyd et al., 2015b; Eberlein et al., 2016; Griffith et al., 2019a). Interactions with light are more complex because relative effects of ocean acidification are larger under limiting irradiances, while saturating light levels decrease beneficial or detrimental effects on these processes (Kranz et al., 2010; Garcia et al., 2011; Rokitta and Rost, 2012; Heiden et al., 2016). For the coccolithophore *Emiliania huxleyi*, for example, the impacts of ocean acidification are less detrimental under high light availability, which could partly explain why this species is moving poleward (Winter et al., 2013; Kondrik et al., 2017; Neukermans et al., 2018), although acidification is more pronounced in polar waters (Section 3.2.3.1, Cross-Chapter Paper 6). Under excess light, however, the detrimental impacts of ocean acidification are amplified for many species (*high confidence*) (Gao et al., 2012; Li and Campbell, 2013; Zhang et al., 2015; Kottmeier et al., 2016; Gafar et al., 2019). Lowered photo-physiological capacity to cope with high-light stress and avoid photodamage (Gao et al., 2012; Li and Campbell, 2013; Hoppe et al., 2015; Kvernvik et al., 2020) is also consistent with observations that dynamic light regimes can become more stressful under ocean acidification (Jin et al., 2013; Hoppe et al., 2015). Given the expected mixed-layer shallowing in some regions (Section 3.2.2.3), the exposure to overall higher mean irradiances could shift the effects of acidification from beneficial to detrimental for some primary producers, depending on species and organismal traits (*medium confidence*) (Gao et al., 2019; Seifert et al., 2020).

Studies investigating two drivers provide most of the information on the wide range of interactive effects of drivers on phytoplankton (Gao et al., 2019; Seifert et al., 2020), although climate change alters several oceanic drivers concurrently (Section 3.2). The few experimental studies that have addressed three or more drivers (Xu et al., 2014; Boyd et al., 2015b; Brennan and Collins, 2015; Brennan et al., 2017; Hoppe et al., 2018b; Moreno-Marín et al., 2018) indicate that one or two drivers generally dominate the cumulative outcome, with others playing a subordinate role (*medium confidence*). In these studies, temperature had a disproportionately large influence, while other drivers differed in importance, depending on the type of primary producer, ecosystem characteristics and selected driver values.

3.3.3.2 Effects of Multiple Drivers on Animals

When changing CO_2 concentrations affect marine ectotherms, they typically combine additively or synergistically with warming (*medium confidence*) (e.g., Lefevre, 2016; Reddin et al., 2020; Sampaio et al., 2021), and their cumulative effects can lead to detrimental, neutral or beneficial effects (*high confidence*) (Figure 3.9a, Bennett et al., 2017; Büscher et al., 2017; Dahlke et al., 2017; Foo and Byrne, 2017; Johnson et al., 2017b; Cominassi et al., 2019). Higher ocean CO_2 influences the thermal tolerance of species adapted to extreme but stable habitats in tropical and polar regions, more than that of thermally tolerant generalists (*high confidence*) (Byrne et al., 2013; Schiffer et al., 2014; Flynn et al., 2015; Kunz et al., 2016; Pörtner et al., 2017; Kunz et al., 2018; Bindoff et al., 2019, but see) (Ern et al., 2017), especially in early life stages (Dahlke et al., 2020a). In thermal generalists from temperate and subtropical species, warming and ocean acidification generally have detrimental effects on growth and survival (e.g., Gao et al., 2020), but warming can also alleviate the detrimental effects of ocean acidification by increasing metabolic rate and/or growth (Garzke et al., 2020), provided that other conditions (e.g., thermal niche, food availability) are beneficial. For example, larval growth and survival of Australasian snapper (*Pagrus auratus*) appear to benefit from combined acidification and warming (but see Watson et al., 2018; McMahon et al., 2020), introducing major uncertainties to population modelling (Section 3.3.4, Parsons et al., 2020).

As with ocean acidification, reduced oxygen availability further alters the influence of warming on metabolic rates (*high confidence*). Acidification and hypoxia can contribute to a decrease or shift in thermal tolerance, while the magnitude of this effect depends on the duration of exposure (Tripp-Valdez et al., 2017; Cattano et al., 2018; Calderón-Liévanos et al., 2019; Schwieterman et al., 2019). Warming and hypoxia are mostly positively correlated and tolerance to both phenomena are often linked after long-term acclimation (e.g., Bouyoucos et al., 2020). Acute short-term heat shocks can impair hypoxia tolerance, for instance in intertidal fish (McArley et al., 2020). This is relevant for shallow waters, specifically for MHWs (Section 3.2.2.1, Hobday et al., 2016a; IPCC, 2018; Collins et al., 2019a). Ocean acidification can increase hypoxia tolerance in some cases, possibly by downregulating activity (Faleiro et al., 2015) and/or changing blood oxygenation (Montgomery et al., 2019). Other studies, however, reported additive negative effects of acidification and warming on hypoxia tolerance (Schwieterman et al., 2019; Götze et al., 2020), in line with the oxygen- and capacity-limited thermal tolerance (OCLTT) hypothesis presented in AR5 (Pörtner et al., 2014): warming causes increased metabolic rates and oxygen demand in ectotherms, which at some point exceed supply capacities (that also depend on environmental oxygen availability) and reduce aerobic scope. In consequence, expansion of OMZs and other regions where warming, hypoxia and acidification combine will further reduce habitat for many fish and invertebrates (*high confidence*) (Sections 3.4.3.2–3.4.3.3).

Food availability modulates, and may be more influential than, other driver responses by affecting the energetic and nutritional status of animals (Cole et al., 2016; Stiasny et al., 2019; Cominassi et al., 2020). Laboratory studies conducted under an excess of food risk underestimating the ecological effects of climate-impact drivers, because increased feeding rates may help mitigate adverse effects (Nowicki et al., 2012; Towle et al., 2015; Cominassi et al., 2020). Lowered food availability from reduced open-ocean primary production (Sections 3.2.3.3, 3.4.4.2.1) will act as an additional driver, amplifying the detrimental effects of other drivers. However, warming and higher CO_2 availability may increase primary productivity in some coastal areas (Section 3.4.4.1), ameliorating the adverse direct effects on animals (e.g., Sswat et al., 2018). Due to the few studies addressing food availability under multiple-driver scenarios (Thomsen et al., 2013; Pistevos et al., 2015; Towle et al., 2015; Ramajo et al., 2016; Brown et al., 2018a; Cominassi et al., 2020), there is *medium confidence* in its modulating effect on climate-impact driver responses.

Animal behaviour can be affected by ocean acidification, warming and hypoxia. While warming and hypoxia mostly induce avoidance behaviour, potentially leading to migration and habitat compression (Section 3.4, McCormick and Levin, 2017; Limburg et al., 2020), the effects of acidification appear more complex. Some studies reported that acidification dominates behavioural effects (Schmidt et al., 2017), although outcomes vary with experimental design and duration of exposure (*low confidence, low agreement*) (Maximino and de Brito, 2010; Munday et al., 2016; Laubenstein et al., 2018; Munday et al., 2019; Sundin et al., 2019; Clark et al., 2020; Munday et al., 2020; Williamson et al., 2021). Behaviour represents an integrated phenomenon that can be influenced both directly and indirectly by multiple drivers. For instance, increased pCO_2 can directly act on neuronal signalling pathways (e.g., Gamma-aminobutyric acid hypothesis, Nilsson et al., 2012; Thomas et al., 2020) and influence learning (Chivers et al., 2014), vision (Chung et al., 2014), and choice and escape behaviour (Watson et al., 2014; Wang et al., 2017b). There is further evidence that observed alterations in fish olfactory behaviour under ocean acidification may result from physiological and molecular changes of the olfactory epithelium, influencing olfactory receptors (Roggatz et al., 2016; Porteus et al., 2018; Velez et al., 2019; Mazurais et al., 2020). Temperature mainly drives metabolic processes and thus energetic requirements, which can indirectly influence behaviour, including increased risk-taking during feeding (Marangon et al., 2020). Ocean warming also accelerates the biochemical reactions and metabolic processes that are primarily influenced by acidification. It is therefore difficult to generalise to what extent co-occurring ocean warming ameliorates or exacerbates effects of acidification on behaviour (Laubenstein et al., 2019); outcomes depend upon species and life stage (Faleiro et al., 2015; Chan et al., 2016; Tills et al., 2016; Wang et al., 2018b; Jarrold et al., 2020), interactions between species (e.g., Paula et al., 2019) along with confounding factors including food availability and salinity (*medium confidence*) (Ferrari et al., 2015; Pistevos et al., 2015; Pimentel et al., 2016; Pistevos et al., 2017; Horwitz et al., 2020).

While hypoxia can dominate multiple-driver responses locally (Sampaio et al., 2021), warming is the fundamental physiological driver for most marine ectotherms, globally, as it directly affects their entire biochemistry and energy metabolism. Other influential drivers include ocean acidification, salinity (*high confidence*) (Lefevre, 2016; Whiteley et al., 2018; Reddin et al., 2020) or food availability/quality (*medium confidence*) (Nagelkerken and Munday, 2016; Gao et al., 2020). Fluctuating and decreasing salinity may aggravate the detrimental effects of warming and elevated CO_2, because dilution with freshwater lowers acid-base buffering capacity, resulting in lower pH and calcium carbonate saturation state (Dickinson et al., 2012; Shrivastava et al., 2019; Melzner et al., 2020).

3.3.4 Acclimation and Evolutionary Adaptation

Climate change is and will continue to be a major driver of natural selection, causing important changes in fitness-related (e.g., growth, reproduction, survival) and functional (e.g., body/cell size, morphology, physiology) traits, and in the genetic diversity of natural populations (*medium confidence*) (Pauls et al., 2013; Merilä and Hendry, 2014). Climate-change impacts will continue to be exacerbated by interactions with non-climate drivers such as habitat fragmentation or loss, pollution, or resource overexploitation, which limit the adaptive potential of populations to future conditions (Trathan et al., 2015; Gaitán-Espitia and Hobday, 2021). However the ultimate responses to complex change are conditioned by the rate and magnitude of environmental change, organisms' capacity for acclimation, the degree of local adaptation of natural populations, and populations' potential for adaptive evolution (Figure 3.11, Pespeni et al., 2013; Calosi et al., 2017; Vargas et al., 2017). These controlling factors are mainly determined by local environmental conditions encountered by populations across their geographical distribution (Boyd et al., 2016). In highly fluctuating environments (e.g., upwelling regions, coastal zones), multiple drivers can change and interact across temporal and spatial scales, generating geographical mosaics of tolerances and sensitivities to environmental and climate change in marine organisms (*medium confidence*) (Pespeni et al., 2013; Boyd et al., 2016; Vargas et al., 2017; Li et al., 2018a). A further challenge for marine life lies in its ability to cope with extreme events such as MHWs (Cross-Chapter Box EXTREMES in Chapter 2). The interplay between the abruptness, intensity, duration, magnitude and reoccurrence of extreme events may alter or prevent evolutionary responses (e.g., adaptation) to climate change and the potential for acclimation to extreme conditions such as MHWs (Cheung and Frölicher, 2020; Coleman et al., 2020a; Gurgel et al., 2020; Gruber et al., 2021).

Some studies have documented higher phenotypic plasticity and tolerance to ocean warming and acidification in marine invertebrates (Dam, 2013; Kelly et al., 2013; Pespeni et al., 2013; Gaitán-Espitia et al., 2017a; Vargas et al., 2017; Li et al., 2018a), seaweeds (Noisette et al., 2013; Padilla-Gamiño et al., 2016; Machado Monteiro et al., 2019), and fish (*medium confidence*) (Sandoval-Castillo et al., 2020; Enbody et al., 2021) living in coastal zones characterised by strong temporal fluctuations in temperature, pH, pCO_2, light and nutrients. For these populations, strong directional selection with intense and highly fluctuating conditions may have favoured local adaptation and increased tolerance to environmental stress (*low confidence, low evidence*) (Hong and Shurin, 2015; Gaitán-Espitia et al., 2017b; Li et al., 2018a).

Other mechanisms acting within and across generations can influence selection and inter-population tolerances to environmental and climate-impact drivers. For instance, transgenerational effects and/or developmental acclimation, both so-called "carry-over effects" (where the early-life environment affects the expression of traits in later life stages or generations), can influence within- and cross-generational changes in the tolerances of marine organisms (*medium confidence*) to ocean warming (Balogh and Byrne, 2020) and acidification (Parker et al., 2012). Over longer time scales, increasing tolerance to these drivers may be mediated by mechanisms such as transgenerational plasticity (Murray et al., 2014), leading to locally-adapted genotypes, as seen in bivalves (Thomsen et al., 2017), annelids (Rodríguez-Romero et al., 2016; Thibault et al., 2020), corals (Putnam et al., 2020), and coralline algae (Cornwall et al., 2020). However, transgenerational plasticity is species-specific (Byrne et al., 2020; Thibault et al., 2020) and, depending on the rate and magnitude of environmental change, it may either be insufficient for evolutionary rescue

(Morgan et al., 2020) or could induce maladaptive responses (i.e., reduced fitness) in marine organisms exposed to multiple drivers (*medium confidence, low evidence*) (Figure 3.11, Griffith and Gobler, 2017; Parker et al., 2017; Byrne et al., 2020).

Acclimation to environmental pressures and climate change via phenotypic plasticity (Section 3.3.3, Collins et al., 2020) enables species to undergo niche shifts, such that their present-day climatic niche is altered to incorporate new or shifted conditions (Fox et al., 2019). Although plasticity provides an adaptive mechanism, it is *unlikely* to provide a long-term solution for species undergoing sustained directional environmental change (e.g., global warming) (*medium confidence*) (Fox et al., 2019; Gaitán-Espitia and Hobday, 2021). Beyond the limits for plastic responses (Figure 3.9, DeWitt et al., 1998; Valladares et al., 2007), genetic adjustments are required to persist in a changing world (Figure 3.11, Fox et al., 2019). The ability of species and populations to undergo these adjustments (i.e., adaptive evolution) depends on extrinsic factors including the rate and magnitude of environmental change (important determinants of the strength and form of selection, Hoffmann and Sgrò, 2011; Munday et al., 2013), along with intrinsic factors such as generation times and standing genetic variation (Mitchell-Olds et al., 2007; Lohbeck et al., 2012). Accurately assessing the degree of acclimation and/or adaptation across space and time is difficult and constrains studying adaptive evolution in natural populations. There is a major gap in climate-change biology related to the study of evolutionary responses in complex and long-lived multicellular organisms. Insights on organismal acclimation, adaptation, and evolution rely on studies of small, short-lived marine organisms such as phytoplankton that divide rapidly and contain high genetic variation in large populations. (Schaum et al., 2016; Cavicchioli et al., 2019; Collins et al., 2020).

Experimental evolution suggests that microbial populations can rapidly adapt (i.e., over 1–2 years) to environmental changes mimicking projected effects of climate change (*medium confidence*). Phytoplankton adaptive mechanisms include intraspecific strain sorting and genetic changes (Bach et al., 2018; Hoppe et al., 2018b; Wolf et al., 2019). The evolutionary responses of microbes are conditioned by the number and characteristics of interacting drivers (*low confidence*) (Brennan et al., 2017). For example, in a high-salinity adapted strain of the phytoplankton *Chlamydomonas reinhardtii*, the selection intensity and the adaptation rate increased with the number of environmental drivers, accelerating the adaptive evolutionary response (Brennan et al., 2017). For this and other phytoplankton species, a few dominant drivers explain most of the phenotypic and evolutionary changes observed (Boyd et al., 2015a; Brennan and Collins, 2015; Brennan et al., 2017).

Adaptation can be impeded, delayed or constrained in eukaryotic microbial populations as a result of reduced genetic diversity, and/or the presence of functional and evolutionary trade-offs (Aranguren-Gassis et al., 2019; Lindberg and Collins, 2020; Walworth et al., 2020). In the marine diatom *Chaetoceros simplex*, a functional trade-off between high-temperature tolerance and increased nitrogen requirements underlies inhibited thermal adaptation under nitrogen-limited conditions (*low confidence*) (Aranguren-Gassis et al., 2019). When selection is strong due to unfavourable environmental conditions, microbial populations can encounter functional and evolutionary trade-offs evidenced by reducing growth rates while increasing tolerance and metabolism of reactive oxygen species (Lindberg and Collins, 2020). Other trade-offs can be observed in offspring quality and number (Lindberg and Collins, 2020). These findings contribute towards a mechanistic framework describing the range of evolutionary strategies in response to multiple drivers (Collins et al., 2020), but other hazards such as extreme events (e.g., MHWs) still need to be included because their characteristics may alter the potential for adaptation of species and populations to climate change (Gruber et al., 2021).

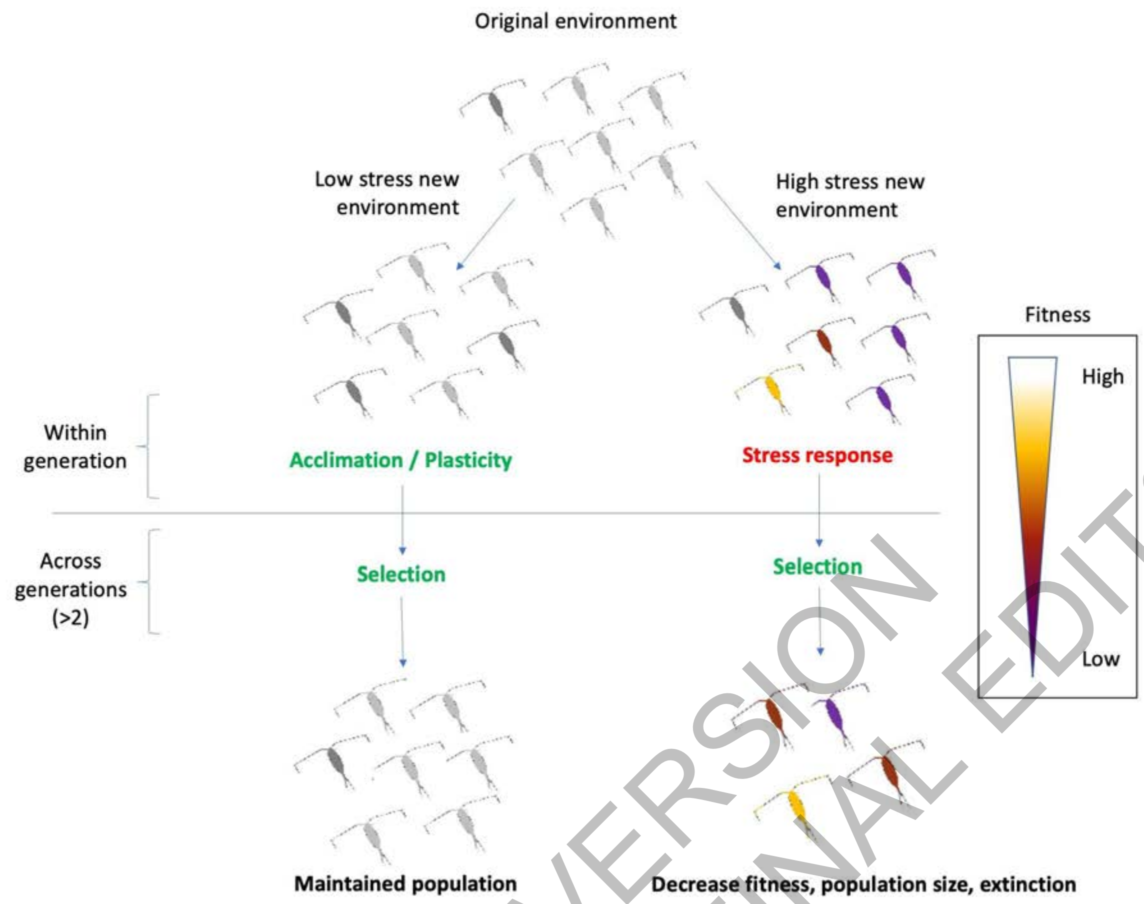


Figure 3.11: Micro-evolutionary dynamics in response to environmental change. Simplified conceptual framework shows two main eco-evolutionary trajectories for natural populations over time (vertical axis from top to bottom). If environmental stress is low, rapid responses (within a generation) through plastic phenotypic adjustments and selection (across generations) sustain fitness, enhancing maintenance of viable populations across generations. In contrast, if environmental stress is high, ongoing phenotypic plasticity and acclimation may be insufficient to buffer the negative effects, exacerbating the loss of fitness (change of colour to orange/yellow/red). Ultimately, very high stress conditions accelerate population decline, enhancing the risk of species extinction.

3.3.5 Ecological Response to Multiple Drivers

Assessing ecological responses to multiple climate-impact drivers requires a combination of approaches, including laboratory- and field-based experiments, field observations (e.g., natural gradients, climate analogues), study of paleo-analogues and the development of mechanistic and empirical models (Clapham, 2019; Gissi et al., 2021). Experimental studies of food-web responses are often limited to an individual driver, although recent manipulations have used a matrix of >1000-L mesocosms to explore ecological responses to both warming and acidification (Box 3.1, Nagelkerken et al., 2020). Hence, complementary approaches are needed to indirectly explore the mechanisms underlying ecosystem responses to global climate change (Parmesan et al., 2013). Observations from time series longer than modes of natural variability (i.e., decades) are essential for revealing and attributing ecological responses to climate change (e.g., Section 3.4, Barton et al., 2015b; Brun et al., 2019). Also, paleo records provide insights into the influence of multiple drivers on marine biota (Cross-Chapter Box PALEO in Chapter 1, Reddin et al., 2020). Specifically, associations between vulnerabilities and traits of marine ectotherms in laboratory experiments correspond with organismal responses to ancient hyperthermal events (*medium confidence*) (Reddin et al., 2020). This corroboration suggests that responses to multiple drivers inferred from the fossil record can help provide insights into the future status of functional groups and hence food webs under rapid climate change.

Multi-species and integrated end-to-end ecosystem models are powerful tools to explore and project outcomes to the often-interacting cumulative effects of climate change and other anthropogenic drivers (Section 3.1, Kaplan and Marshall, 2016; Koenigstein et al., 2016; Peck and Pinnegar, 2018; Tittensor et al., 2018; Gissi et al., 2021). These models can integrate some aspects of the knowledge accrued from manipulation experiments, paleo and contemporary observations, help test the relative importance of specific drivers and driver combinations, and identify synergistic or antagonistic responses (Koenigstein et al., 2016; Payne et al., 2016; Skogen et al., 2018; Tittensor et al., 2018). As these models are associated with wide-ranging uncertainties (SM3.2.2, Payne et al., 2016; Trolle et al., 2019; Heneghan et al., 2021) they cannot be expected to accurately project the trajectories of complex marine ecosystems under climate change. Hence, they are most useful for assessing overall trends and in particular for providing a plausible envelope of trajectories across a range of assumptions (Fulton et al., 2018; Peck et al., 2018; Tittensor et al., 2018). On a global scale, ecosystem models project a –5.7% ± 4.1% (*very likely range*) to –15.5% ± 8.5% decline in marine animal biomass with warming under SSP1-2.6 and SSP5-8.5, respectively, by 2080–2099 relative to 1995–2014, albeit with significant regional variation in both trends and uncertainties (*medium confidence*) (Section 3.4.34, Tittensor et al., 2021). Biological interactions may exacerbate or buffer the projected impacts. For instance, trophic amplification (strengthening of responses to climate-impact drivers at higher trophic levels), may result from combined direct and indirect food-web mediated effects (*medium confidence*) (Section 3.4.3.4, Lotze et al., 2019). Alternatively, compensatory species interactions can dampen strong impacts on species from ocean acidification, resulting in weaker responses at functional-group or community level than at species level (*medium confidence*) (Marshall et al., 2017; Hoppe et al., 2018b; Olsen et al., 2018; Gissi et al., 2021). Globally, the projected reduction of biomass due to climate-impact drivers is relatively unaffected by fishing pressure, indicating additive responses of fisheries and climate change (*low confidence*) (Lotze et al., 2019). Regionally, projected interactions of climate-impact drivers, fisheries and other regional non-climate drivers can be both synergistic and antagonistic, varying across regions, functional groups and species, and can cause non-linear dynamics with counterintuitive outcomes, underlining the importance of adaptations and associated trade-offs (*high confidence*) (Sections 3.5.3, 3.6.3.1.2, 4.5, 4.6, Weijerman et al., 2015; Fulton et al., 2018; Hansen et al., 2019; Trolle et al., 2019; Zeng et al., 2019; Holsman et al., 2020; Pethybridge et al., 2020; Gissi et al., 2021).

Given the limitations of individual ecological models discussed above, model intercomparisons, such as the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP, Tittensor et al., 2018) show promise in increasing the robustness of projected ecological outcomes (Tittensor et al., 2018). Model ensembles include a greater number of relevant processes and functional groups than any single model and thus capture a wider range of plausible responses. Among the global Fish-MIP models, there is *high* (temperate and tropical areas) to *medium agreement* (coastal and polar regions) on the direction of change, but *medium* (temperate and tropical regions) to *low agreement* (coastal and polar regions) on magnitude of change (Lotze et al., 2019; Heneghan et al., 2021). Although model outputs are validated relative to observations to assess model skills (Payne et al., 2016; Tittensor et al., 2018), the Fish-MIP models under-represent some sources of uncertainty, as they often do not include parameter uncertainties, and do not usually include impacts of ocean acidification, oxygen loss, or evolutionary responses because there remains high uncertainty regarding the influences of these processes across functional groups. Ensemble model investigations like Fish-MIP have also identified gaps in our mechanistic understanding of ecosystems and their responses to anthropogenic forcing, leading to model improvement and more rigorous benchmarking. These investigations could inspire future targeted observational and experimental research to test the validity of model assumptions (Payne et al., 2016; Lotze et al., 2019; Heneghan et al., 2021). The state-of-the-art in such experimental research is presented in Box 3.1.

[START BOX 3.1 HERE]

Box 3.1: Challenges for Multiple-Driver Research in Ecology and Evolution

The majority of the examples in Section 3.3 are from studies mimicking projected conditions in the year 2100 that report the responses of an individual species or strain to multiple drivers. This powerful generic experimental approach has largely been restricted to single species because it is logistically complex to conduct experiments that straddle multiple trophic levels, and that also include more than two drivers (Figure Box3.1.1b); the need for multiple replicates, drivers, and treatment levels greatly increase the work required

(Parmesan et al., 2013; Boyd et al., 2018). It is challenging to apply this experimental approach to communities or ecosystems (Figure Box 3.1.1). To date, most research on community or ecosystem response to climate-impact drivers has been in large-volume (>10,000 L) mesocosms (Riebesell and Gattuso, 2014), or at natural analogues such as CO_2 seeps, in which only one driver (ocean acidification) is altered (see (4) in Figure Box 3.1.1). Only very recently have two drivers been incorporated into climate-change manipulation studies examining responses of primary producers to secondary consumers ((5) in Figure Box3.1.1a, Nagelkerken et al., 2020). Therefore, 'natural experiments' from the geological past (Reddin et al., 2020) provide insights into how food webs and their constituents respond to complex change involving multiple drivers. Contemporary observations are occasionally long enough (>5 decades) to capture community responses to complex climate change. For example, Brun et al. (2019) reported a shift in zooplankton community structure in the North Atlantic (1960–2014), with major biogeochemical ramifications.

Conducting sufficiently long manipulation experiments to study the effect of adaptation on organisms is equally difficult (Figure Box3.1.1b), with much research restricted to multi-year studies of the microevolution of fast-growing (>one division day^{-1}) phytoplankton species responding to single drivers (Lohbeck et al., 2012; Schaum et al., 2016). In a few experimental evolution studies, ((7) in Figure Box3.1.1a, Brennan et al., 2017), multiple drivers have been used, but none have used communities or ecosystems (Figure Box3.1.1b). Nevertheless, the fossil record provides *limited evidence* of adaptations to less rapid (relative to present-day) climate change (Jackson et al., 2018). Despite the need to explore ecological or biogeochemical responses to projected future ocean conditions, logistical challenges require that assessments of climate-change impacts at scales larger than mesocosms use large-scale, long-term *in situ* observational studies (as documented within Section 3.4).

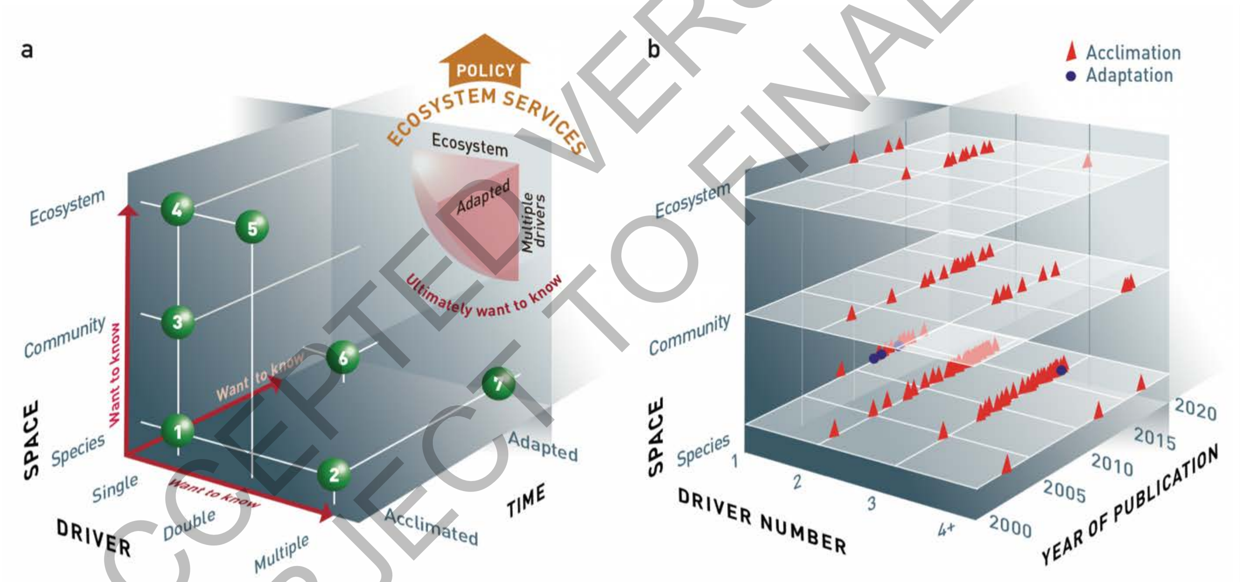


Figure Box 3.1.1: Knowledge gaps between current scientific understanding and that needed to inform policy. The conceptual space relating driver number, (Driver axis), ecological organisation (Space axis) and evolutionary acclimation state (Time axis), modified from Riebesell and Gattuso (2014). (a) Spheres indicate suites of studies that illustrate the progress of research, including multiple drivers (Sphere (1) one species and one driver, Hutchins et al. (2013) and (2) (one species and multiple drivers five, Boyd et al. (2015a)); ecology (Sphere (1) (one driver, one species), (3) (one driver, planktonic community, Moustaka-Gouni et al., 2016), (4) one driver (high-CO2 seep) and (benthic) ecosystem, Fabricius et al. (2014), and (5) two drivers and nearshore ecosystem, Nagelkerken et al. (2020)); and evolution (Sphere (1) (acclimated organism and one driver), (6) adapted organisms and one driver, Listmann et al. (2016) and (7) adapted organism and multiple drivers Brennan et al. (2017)). (b) Trends in research trajectories since 2000 from a survey of 171 studies, Boyd et al. (2018). Note the dominance of multiple-driver experiments at the species level (lower left cluster); the focus on acclimation (red triangle) rather than adaptation (blue dot); the focus of investigation on ≤3 drivers. Redrawn from Boyd et al. (2018).

[END BOX 3.1 HERE]

3.4 Observed and Projected Impacts of Climate Change on Marine Systems

3.4.1 Introduction

Ocean and coastal ecosystems and their resident species are under increasing pressure from a multitude of climate-impact drivers and non-climate drivers (Section 3.1, Figure 3.12, Bindoff et al., 2019). This section builds from the assessment of biological responses to climate-impact drivers (Section 3.3) to examine the new evidence about climate-change impacts at the level of marine ecosystems. It focuses on detection and attribution of observed changes to marine ecosystems and the projected changes under different future climate scenarios. This assessment considers emerging evidence on the effects of multiple non-climate drivers and physiological acclimation and/or evolutionary adaptation on these observations and projections.

The section focuses first on coastal ecosystems and seas (Section 3.4.2), which have high spatial variability in physical and chemical characteristics, are affected by many non-climate drivers (Section 3.1, Figure 3.12) and support rich fisheries, high biodiversity and high levels of species endemism. The assessment begins with warm-water coral reefs (Section 3.4.2.1) because these highly threatened systems are at the vanguard of research on acclimation and evolutionary adaptation among coastal ecosystems. It follows with the other shallow, nearshore ecosystems dominated by habitat-forming species (rocky shores, kelp systems) and then nearshore sedimentary systems (estuaries, deltas, coastal wetlands, and sandy beaches), before moving on to semi-enclosed seas, shelf seas, upwelling zones, and polar seas.

The section continues on to oceanic and cross-cutting changes (Section 3.4.3), which influence large areas of the epipelagic zone (<200 m depth), while also affecting the mesopelagic (200–1000 m), the perpetually dark bathypelagic (depth >1000 m) and the deep seafloor (benthic ecosystems at depths >200 m) zones. Assessed in this section are species range shifts (Section 3.4.3.1), phenological shifts and trophic mismatches (Section 3.4.3.2), changes in communities and biodiversity (Section 3.4.3.3.2), time of emergence of climate-impact signals in ecological systems from background natural variability (Section 3.4.3.3.4), and changes in biomass, primary productivity, and carbon export (Sections 3.4.3.4–3.4.3.6).

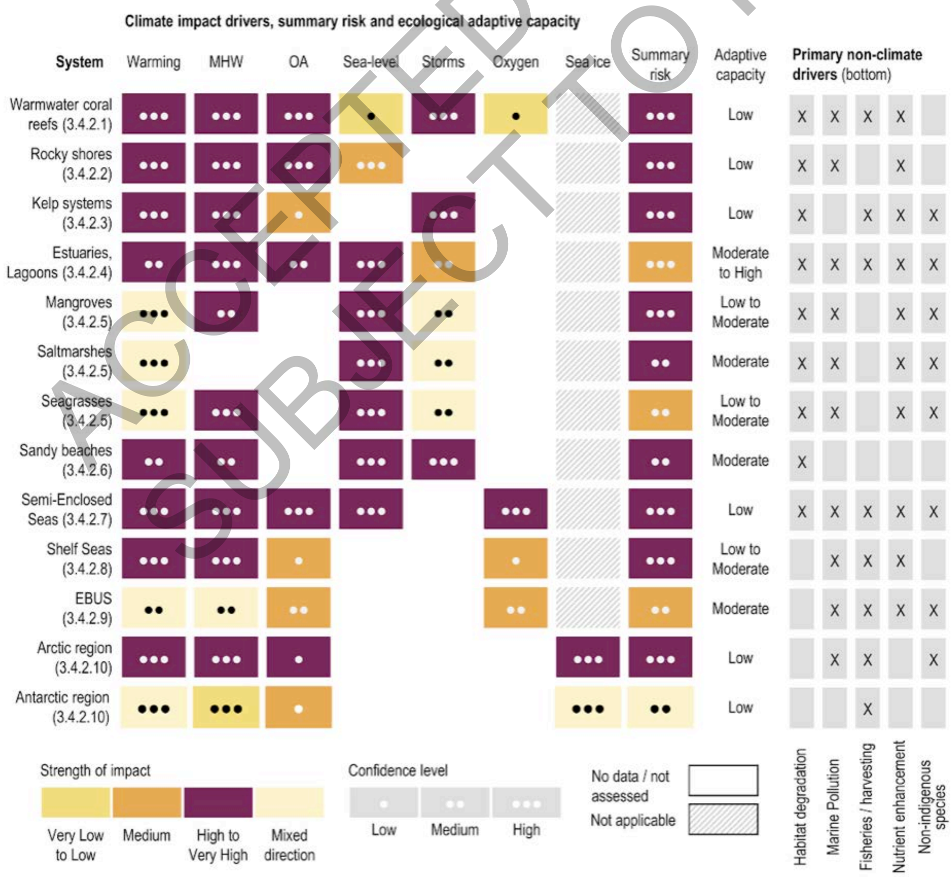


Figure 3.12: Summary assessment of observed hazards to coastal ecosystems and seas as assessed in Section 3.4.2.

3.4.2 Coastal Ecosystems and Seas

3.4.2.1 Warm-Water Coral Reefs

Warm-water coral reef ecosystems house one-quarter of the marine biodiversity and provide services in the form of food, income and shoreline protection to coastal communities around the world. These ecosystems are threatened by climate and non-climate drivers, especially ocean warming, MHWs, ocean acidification, SLR, tropical cyclones, fisheries/overharvesting, land-based pollution, disease spread and destructive shoreline practices (Hoegh-Guldberg et al., 2018a; Bindoff et al., 2019; Hughes et al., 2020). Warm-water coral reefs face near-term threats to their survival (Table 3.3), but research on observed and projected impacts is very advanced.

Table 3.3: Summary of previous IPCC assessments of coral reefs.

Observations	Projections
AR5 (Hoegh-Guldberg et al., 2014; Wong et al., 2014)	
Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*), and more than half of the world's reefs are under medium or high risk of degradation. Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change. Ocean acidification reduces biodiversity and the calcification rate of corals (*high confidence*) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*). In summary, ocean warming is the primary cause of mass coral bleaching and mortality (*very high confidence*), which, together with ocean acidification, deteriorates the balance between coral reef construction and erosion (*high confidence*).	Coral bleaching and mortality will increase in frequency and magnitude over the next decades (*very high confidence*). Analysis of the Coupled Model Intercomparison Project 5 ensemble projects the loss of coral reefs from most sites globally by 2050 under mid to high rates of warming (*very likely*). Under the A1B scenario, 99% of the reef locations will experience at least one severe bleaching event between 2090 and 2099, with *limited evidence* and *low agreement* that coral acclimation and/or adaptation will limit this trend. The onset of global dissolution of coral reefs is at an atmospheric CO_2 of 560 ppm (*medium confidence*) and dissolution will be widespread in 2100 (Representative Concentration Pathway (RCP)8.5, *medium confidence*). A number of coral reefs could keep up with the maximum rate of sea-level rise (SLR) of 15.1 mm yr^{-1} projected for the end of the century, but lower net accretion and increased turbidity will weaken this capability (*very high confidence*).
SR15 (Hoegh-Guldberg et al., 2018a; IPCC, 2019c)	
Climate change has emerged as the greatest threat to coral reefs, with temperatures of just 1°C above the 1985–1993 long-term summer maximum for an area over 4–6 weeks being enough to cause mass coral bleaching and mortality (*very high confidence*). Predictions of back-to-back bleaching events have become reality over 2015-2017 as have projections of declining coral abundance (*high confidence*).	Multiple lines of evidence indicate that the majority (70–90%) of warm water (tropical) coral reefs that exist today will disappear even if global warming is constrained to 1.5°C (*very high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2ºC (*very high confidence*).
SROCC (Bindoff et al., 2019)	
New evidence since AR5 and SR15 confirms the impacts of ocean warming and acidification on coral reefs (*high confidence*), enhancing reef dissolution and bioerosion (*high confidence*), affecting coral species distribution, and leading to community changes (*high confidence*). The rate	Coral reefs will face very high risk at temperatures 1.5ºC of global sea surface warming (*very high confidence*). Almost all coral reefs will degrade from their current state, even if global warming remains below 2ºC (*very high confidence*), and the remaining shallow coral reef

of SLR (primarily noticed in small reef islands) may outpace the growth of reefs to keep up, although there is *low agreement* in the literature (*low confidence*). Reefs are further exposed to other increased impacts, such as enhanced storm intensity, turbidity and increased runoff from the land (*high confidence*). Recovery of coral reefs resulting from repeated disturbance events is slow (*high confidence*). Only few coral reef areas show some resilience to global change drivers (*low confidence*).	communities will differ in species composition and diversity from present reefs (*very high confidence*). This will greatly diminish the services they provide to society, such as food provision (*high confidence*), coastal protection (*high confidence*) and tourism (*medium confidence*). The very high vulnerability of coral reefs to warming, ocean acidification, increasing storm intensity and SLR under climate, including enhanced bioerosion (*high confidence*), points to the importance of considering both mitigation and adaptation.

Global analyses published since AR5 show that mass coral bleaching events and disease outbreaks have increased due to more frequent and severe heat stress associated with ocean warming (*very high confidence, virtually certain*) (Donner et al., 2017; Hughes et al., 2018a; DeCarlo et al., 2019; Sully et al., 2019; Tracy et al., 2019). The mass coral bleaching, which occurred continuously across different parts of the tropics from 2014–2016, is considered the longest and most severe global coral bleaching event on record (Section 10.4.3, Box 15.2, Eakin et al., 2019). The Great Barrier Reef underwent mass bleaching three times between 2016–2020 (Box 11.2, Pratchett et al., 2021), validating past model projections that some warm-water coral reefs would encounter bleaching-level heat stress multiple times per decade by the 2020s (Hoegh-Guldberg, 1999; Donner, 2009).

Heat stress and mass bleaching events caused decreases in live coral cover (*virtually certain*) (Graham et al., 2014; Hughes et al., 2018b), loss of sensitive species (*extremely likely*) (Donner and Carilli, 2019; Lange and Perry, 2019; Toth et al., 2019; Courtney et al., 2020), vulnerability to disease (*extremely likely*) (van Woesik and Randall, 2017; Hadaidi et al., 2018; Brodnicke et al., 2019; Howells et al., 2020) and declines in coral recruitment in the tropics (*medium confidence*) (Hughes et al., 2019; Price et al., 2019). Recent observations also suggest that excess nutrients can increase the susceptibility of corals to heat stress (DeCarlo et al., 2020). Changes in coral community structure due to bleaching have caused declines in reef carbonate production (*high confidence*) (Perry and Morgan, 2017; Lange and Perry, 2019; Perry and Alvarez-Filip, 2019; Courtney et al., 2020; van Woesik and Cacciapaglia, 2021) and in reef structural complexity (*high confidence, very likely*) (Couch et al., 2017; Leggat et al., 2019; Magel et al., 2019), which increases water depth, reduces wave attenuation and increases coastal flood risk (Yates et al., 2017; Beck et al., 2018). Corals may also lose reproductive synchrony through climate change (Shlesinger and Loya, 2019), adding to their vulnerability. Bleaching and other drivers promote phase shifts to ecosystems dominated by macroalgae or other stress-tolerant species (*very high confidence*) (Graham et al., 2015; Stuart-Smith et al., 2018), leading to changes in reef-fish species assemblages (*high confidence*) (Richardson et al., 2018; Robinson et al., 2019a; Stuart-Smith et al., 2021).

Ocean acidification and associated declines in aragonite saturation state ($\Omega_{aragonite}$) decrease rates of calcification by corals and other calcifying reef organisms (*very high confidence*), reduce coral settlement (*medium confidence*) and increase bioerosion and dissolution of reef substrates (*high confidence*) (Hoegh-Guldberg et al., 2018a; Bindoff et al., 2019; Kline et al., 2019; Pitts et al., 2020). Warming can exacerbate the coral response to ocean acidification (Kornder et al., 2018) and accelerate the decrease in coral skeletal density (Guo et al., 2020). In addition, reefs with lower coral cover and a higher proportion of slow-growing species, because of bleaching, are more sensitive to acidification (net dissolution occurs $\Omega_{aragonite} = 2.3$ for 100% coral cover, and $\Omega_{aragonite} > 3.5$ for 30% coral cover, (Kline et al., 2019)). However, experimental evidence suggests that coral responses to ocean acidification are species-specific (*medium confidence*) (Fabricius et al., 2011; DeCarlo et al., 2018; Comeau et al., 2019). Evidence from experiments suggests that crustose coralline algae, which contribute to reef structure and integrity and may be resistant to warming at the RCP8.5 level by 2100 (Cornwall et al., 2019), are also sensitive to declines in $\Omega_{aragonite}$ (*high confidence*) (Section 3.4.2.3, Fabricius et al., 2015; Smith et al., 2020). The integrated effect of acidification, bleaching, storms and other non-climate drivers on corals, coralline algae and other calcifiers can further compromise reef integrity and ecosystem services (Rivest et al., 2017; Cornwall et al., 2018; Perry and Alvarez-Filip, 2019).

Since SROCC, there have been advances in experimental, field and modelling research on the projected response of coral cover and reef growth to bleaching and ocean acidification (Cziesielski et al., 2019; Morikawa and Palumbi, 2019; Cornwall et al., 2021; Klein et al., 2021; Logan et al., 2021; McManus et al., 2021), and on the effect of possible human interventions like assisted evolution on coral resilience (Section 3.6.3.2.2, Condie et al., 2021; Hafezi et al., 2021; Kleypas et al., 2021). New model projections incorporating physiological acclimation, larval dispersal, and evolutionary processes find limited ability to adapt this century at rates of warming at or exceeding that in RCP4.5 (*high confidence, very likely*) (Bay et al., 2017; Kubicek et al., 2019; Matz et al., 2020; McManus et al., 2020; Logan et al., 2021; McManus et al., 2021). For example, a global analysis (Logan et al., 2021) finds that increased thermal tolerance via evolution or switching to more stress-tolerant algal symbionts enable most (73–81%) coral to survive through 2100 under RCP2.6, but coral-dominated communities with a historical mix of coral taxa still disappear (0–8% coral survival) under RCP6.0 in simulations with adaptive mechanisms (Figure 3.13). Due to the impacts of warming, and to a lesser extent ocean acidification, global reef carbonate production is estimated to decline 71% by 2050 in SSP1-2.6, and the rate of SLR is estimated to exceed that of reef growth for 97% of reefs assessed, absent adaptation by corals and their symbionts (WGI AR6 Table 9.9, Cornwall et al., 2021; Fox-Kemper et al., 2021). The increased water depth due to coral loss and reef erosion, as well as reduced structural complexity, will limit wave attenuation and exacerbate the risk of flooding from SLR on reef-fringed shorelines and reef islands (Yates et al., 2017; Beck et al., 2018; Harris et al., 2018). Local coral reef fish species richness is projected to decline due to the impacts of warming on coral cover and diversity (*high confidence*), with declines up to 40% by 2060 in SSP5-8.5 (Strona et al., 2021).

These observed and projected impacts are supported by geological and paleo-ecological evidence showing a decline in coral reef extent and species richness under previous episodes of climate change and ocean acidification (Kiessling and Simpson, 2011; Pandolfi et al., 2011; Kiessling et al., 2012; Pandolfi and Kiessling, 2014; Kiessling and Kocsis, 2015). Major reef crises in the past 300 million years were governed by hyperthermal events (*medium confidence*) (Section 3.2.4.4, Cross-Chapter Box PALEO in Chapter 1) longer in timescale than anthropogenic climate change, during which net coral reef accretion was more strongly affected than biodiversity (*medium confidence*).

In response to the global-scale decline in coral reefs and high future risk, recent literature focuses on finding thermal refuges and identifying uniquely resilient species, populations or reefs for targeted restoration and management (Hoegh-Guldberg et al., 2018b). Reefs exposed to internal waves (Storlazzi et al., 2020), turbidity (Sully and van Woesik, 2020) or warm-season cloudiness (Gonzalez-Espinosa and Donner, 2021) are expected to be less sensitive to thermal stress. Mesophotic reefs (30–150 m) have also been proposed as thermal refugia (Bongaerts et al., 2010), although evidence from recent bleaching events, subsurface temperature records, and species overlap is mixed (Frade et al., 2018; Rocha et al., 2018b; Eakin et al., 2019; Venegas et al., 2019; Wyatt et al., 2020). A study of 2584 reef sites across the Indian and Pacific Oceans estimated that 17% had sufficient cover of framework-building corals to warrant protection, 54% required recovery efforts, and 28% were on a path to net erosion (Darling et al., 2019). There is *medium evidence* for greater bleaching resistance among reefs subject to temperature variability or frequent heat stress (Barkley et al., 2018; Gintert et al., 2018; Hughes et al., 2018a; Morikawa and Palumbi, 2019), but with trade-offs in terms of diversity and structural complexity (Donner and Carilli, 2019; Magel et al., 2019). There is *limited agreement* about the persistence of thermal tolerance in response to severe heat stress (Le Nohaïc et al., 2017; DeCarlo et al., 2019; Fordyce et al., 2019; Leggat et al., 2019; Schoepf et al., 2020). Recovery and restoration efforts that target heat-resistant coral populations and culture heat-tolerant algal symbionts have the greatest potential of effectiveness under future warming (*high confidence*) (Box 5.5 in SROCC Chapter 5, Bay et al., 2017; Darling and Côté, 2018; Baums et al., 2019; Bindoff et al., 2019; Howells et al., 2021); however, there is *low confidence* that enhanced thermal tolerance can be sustained over time (Section 3.6.3.3.2, Buerger et al., 2020). The effectiveness of active restoration and other specific interventions (e.g., reef shading) are further assessed in Section 3.6.3.3.2.

In sum, additional evidence since SROCC and SR15 (Table 3.3) finds that living coral and reef growth are declining due to warming and MHWs (*very high confidence*). Coral reefs are under threat of transitioning to net erosion with >1.5ºC of global warming (*high confidence*), with impacts expected to occur fastest in the Atlantic Ocean. The effectiveness of conservation efforts to sustain living coral area, coral diversity, and reef growth is limited for the majority of the world's reefs with >1.5ºC of global warming (*high confidence*) (Section 3.6.3.3.2, Hoegh-Guldberg et al., 2018b; Bruno et al., 2019; Darling et al., 2019).

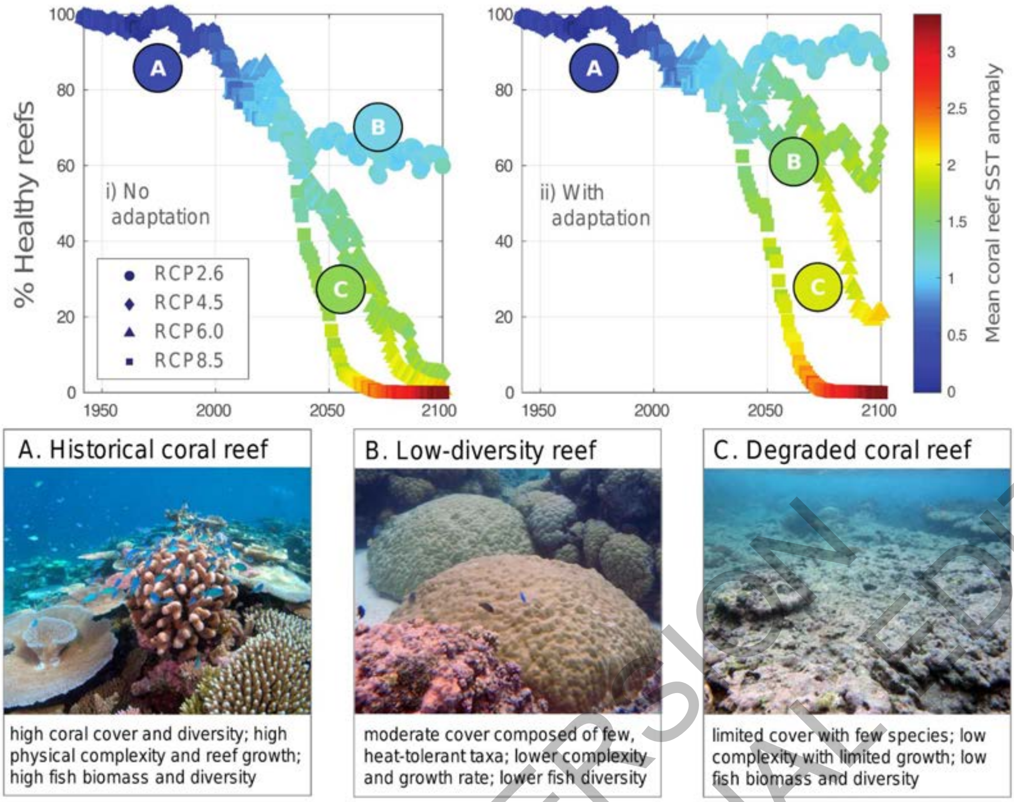


Figure 3.13: Coral reef futures, with and without adaptation. Graphs are based on a model of coral-symbiont evolutionary dynamics from (Logan et al., 2021), which simulates two coral types and symbiont populations for 1925 reef cells worldwide, from 1950–2100 drawn from simulations with National Oceanic and Atmospheric Administration-Geophysical Fluid Dynamics Laboratory Earth System Model (ESM2M) under four RCPs. Top panels show the simulated fraction of cells with healthy reefs, when both coral types are not in a state of severe bleaching or mortality, (i) without adaptive responses and (ii) with adaptive responses (symbiont evolution). Colours indicate maximum monthly sea-surface temperature increase across all reef cells, versus a 1861–2010 baseline. Panels (a,b,c) depict snapshots of coral reef conditions at time-points in the future each with different levels of warming, drawn from the model-projected cover of the two coral types, and from a literature assessment (Section 3.4.2.1, Hughes et al., 2018b; Bindoff et al., 2019; Darling et al., 2019; Leggat et al., 2019; Cornwall et al., 2021).

3.4.2.2 Rocky Shores

Rocky shore ecosystems refer to a range of temperate intertidal and shallow coastal ecosystems that are dominated by different foundational organisms, including mussels, oysters, fleshy macroalgae, hard and soft corals, coralline algae, bryozoans and sponges, which create habitat for species-rich assemblages of invertebrates, fish, marine mammals and other organisms. Rocky shores provide services including wave attenuation, habitat provision and food resources, and these support commercial, recreational, and Indigenous fisheries and shellfish aquaculture.

Observations since AR5 and SROCC (Table 3.4) find increased impacts of ocean warming on rocky shores. This includes extirpation of species at the warm edge of their ranges (Yeruham et al., 2015; Martínez et al., 2018), extension of poleward range boundaries (Sanford et al., 2019), mortality from climate extremes (Seuront et al., 2019), reduction in survival at shallower depths (Sorte et al., 2019; Wallingford and Sorte, 2019) and reorganisation of communities (Wilson et al., 2019; Mulders and Wernberg, 2020; Albano et al., 2021). Data collected after MHWs find ecological phase shifts (*moderate evidence, high agreement*) (e.g., California (Rogers-Bennett and Catton, 2019; McPherson et al., 2021)) and homogenisation of communities (*limited evidence*) (e.g., Alaska, (Weitzman et al., 2021)). For example, the collapse of sea star populations in the Northeast Pacific due to a MHW-related disease outbreak (Hewson et al., 2014; Menge et al., 2016; Miner et al., 2018; Schiebelhut et al., 2018), including 80–100% loss of the common predatory sunflower star, *Pycnopodia helianthoides* (*very high confidence*) (Harvell et al., 2019), triggered shifts from kelp- to urchin-dominated ecosystems (Schultz et al., 2016; Gravem and Morgan, 2017; McPherson et al., 2021).

Table 3.4: Summary of previous IPCC assessments of rocky shores.

Observations	Projections
AR5: (Wong et al., 2014)	
Rocky shores are among the better-understood coastal ecosystems in terms of potential impacts of climate variability and change. The most prominent effects are range shifts of species in response to ocean warming (*high confidence*) and changes in species distribution and abundance (*high confidence*) mostly in relation to ocean warming and acidification.	The abundance and distribution of rocky shore species will continue to change in a warming world (*high confidence*). For example, the long-term consequences of ocean warming on mussel beds of the northeast Pacific are both positive (increased growth) and negative (increased susceptibility to stress and of exposure to predation) (*medium confidence*).
The dramatic decline of biodiversity in mussel beds of the Californian coast has been attributed to large-scale processes associated with climate-related drivers (*high confidence*).	Observations performed near natural CO_2 vents in the Mediterranean Sea show that diversity, biomass, and trophic complexity of rocky shore communities will decrease at future pH levels (*high confidence*).
SR15 (Hoegh-Guldberg et al., 2018a)	
Changes in ocean circulation can have profound impacts on temperate marine ecosystems by connecting regions and facilitating the entry and establishment of species in areas where they were unknown before ('tropicalization') as well as the arrival of novel disease agents (*medium agreement, limited evidence*).	In the transition to 1.5°C, changes to water temperatures will drive some species (e.g., plankton, fish) to relocate to higher latitudes and for novel ecosystems to appear (*high confidence*). Other ecosystems (e.g., kelp forests, coral reefs) are relatively less able to move, however, and are projected to experience high rates of mortality and loss (*very high confidence*).
	In the case of 'less mobile' ecosystems (e.g., coral reefs, kelp forests, intertidal communities), shifts in biogeographical ranges may be limited, with mass mortalities and disease outbreaks increasing in frequency as the exposure to extreme temperatures have increased (*high agreement, robust evidence*)
SROCC (Bindoff et al., 2019)	
Intertidal rocky shores ecosystems are highly sensitive to ocean warming, acidification and extreme heat exposure during low tide emersion (*high confidence*).	Intertidal rocky shores are also expected to be at very high risk (transition above 3ºC) under the RCP8.5 scenario (*medium confidence*). These ecosystems have low to moderate adaptive capacity, as they are highly sensitive to ocean temperatures and acidification.
Sessile calcified organisms (e.g., barnacles and mussels) in intertidal rocky shores are highly sensitive to extreme temperature events and acidification (*high confidence*), a reduction in their biodiversity and abundance have been observed in naturally acidified rocky reef ecosystems (*medium confidence*).	Benthic species will continue to relocate in the intertidal zones and experience mass mortality events due to warming (*high confidence*). Interactive effects between acidification and warming will exacerbate the negative impacts on rocky shore communities, causing a shift towards a less diverse ecosystem in terms of species richness and complexity, increasingly dominated by macroalgae (*high confidence*).

Multiple lines of evidence find that foundational calcifying organisms such as mussels are at high risk of decline due to both the individual and synergistic effects of warming, acidification and hypoxia (*high confidence*) (Sunday et al., 2016; Sorte et al., 2017; Sorte et al., 2019; Newcomb et al., 2020). Warmer temperatures reduce mussel and barnacle recruitment (e.g., NW Atlantic (Petraitis and Dudgeon, 2020)) and the upper vertical limit of mussels (e.g., NE Pacific (Harley, 2011)) and (SW Pacific (Sorte et al., 2019)). Experiments show that ocean acidification negatively impacts mussel physiology (*very high confidence*), with evidence of reduced growth (Gazeau et al., 2010), attachment (Newcomb et al., 2020), biomineralisation (Fitzer et al., 2014) and shell thickness (Pfister et al., 2016; McCoy et al., 2018). Net calcification and abundance of mussels and other foundational species including oysters are expected to decline due to ocean acidification (*very high confidence*) (Kwiatkowski et al., 2016; Sunday et al., 2016; McCoy et al., 2018; Meng et al., 2018), causing the reorganisation of communities (*high confidence*) (Kroeker et al., 2013b; Linares et al., 2015; Brown et al., 2016; Sunday et al., 2016; Agostini et al., 2018; Teixidó et al., 2018). Experiments indicate that acidification can interact with warming and hypoxia to increase the detrimental effects on mussels (Gu et al., 2019; Newcomb et al., 2020). In regions where food is readily available to mussels, detrimental effects of ocean acidification may be dampened (Kroeker et al., 2016); however, recent findings are inconclusive (Brown et al., 2018a).

Coralline algae, foundational taxa that create habitat for sea urchins and abalone, form rhodolith beds in temperate to Arctic habitats, and bind together substrates, are expected to be highly susceptible to ocean acidification because they precipitate soluble magnesium calcite (Kuffner et al., 2008; Williams et al., 2021). Damage from acidification varies among species and regions, and can be due to direct physiological stress (Marchini et al., 2019) or interactions with non-calcifying competitors such as fleshy macroalgae (Smith et al., 2020). Experiments indicate that warming reduces calcification by coralline algae (*high confidence*) (Cornwall et al., 2019) and exacerbates the effect of acidification (Kim et al., 2020; Williams et al., 2021).

In contrast to warm-water coral reefs, there are no regional or global numerical models of rocky shore ecosystem response to projected climate change and acidification. Experiments suggest that existing genetic variation could be sufficient for some mussels (Bitter et al., 2019) and coralline algae (Cornwall et al., 2020) to adapt over generations to ocean acidification. Populations exposed to variable environments often have a greater capacity for phenotypic plasticity and resilience to environmental change (e.g., urchins (Gaitán-Espitia et al., 2017b) and coralline algae (Section 3.3.2, Rivest et al., 2017; Cornwall et al., 2018)). Although parental conditioning within and across generations is an acclimatisation mechanism to global change, there is *limited evidence* from experimental studies that this is applicable for marine invertebrates on rocky shores (Byrne et al., 2020).

This assessment concludes that MHWs, attributable to climate change (Section 3.2.2.1), can cause fatal disease outbreaks or mass mortality among some key foundational species (*high confidence*) and contribute to ecological phase shifts (*medium confidence*). The upper vertical limits of some species will also be constrained by climate change (*high confidence*). Experimental evidence since previous assessments further indicates that acidification decreases abundance and richness of calcifying species (*high confidence*), although there is *limited evidence* for acclimation in some species. Synergistic effects of warming and acidification will promote shifts toward macroalgal dominance in some ecosystems (*medium confidence*) and lead to reorganisation of communities (*medium confidence*).

3.4.2.3 Kelp Ecosystems

Kelp are temperate, habitat-forming marine macroalgae or seaweeds, mostly of the order *Laminariales*, which extend across one quarter of the world's coastlines (Assis et al., 2020; Jayathilake and Costello, 2020). The perennial species form dense underwater forest canopies and three-dimensional habitat that provides refuge for fish, crustaceans, invertebrates and marine mammals (Filbee-Dexter et al., 2016; Wernberg et al., 2019). Kelp ecosystems support fisheries, aquaculture, fertiliser, and food provision, including for local and Indigenous Peoples, along with regulating services in the form of wave attenuation and habitat provision. Kelp aquaculture can also buffer against local acidification (Xiao et al., 2021) and contribute to carbon storage (Froehlich et al., 2019).

Recent research (Straub et al., 2019; Butler et al., 2020; Filbee-Dexter et al., 2020b; Tait et al., 2021) supports the findings of previous assessments (Table 3.5) that kelp and other seaweeds in most regions are undergoing mass mortalities from high temperature extremes and range shifts from warming (*very high confidence*). Kelp are highly sensitive to the direct effect of high temperature on survival (Nepper-Davidsen et al., 2019) and indirect impact of temperature on herbivorous species (Ling, 2008; Vergés et al., 2016), upwelling and nutrient availability (Carr and Reed, 2015; Schiel and Foster, 2015). Synergies between warming, storms, pollution and intensified herbivory (due to removal or loss of predators including sea stars and otters that constrain herbivory by fish and urchin populations) can also cause physiological stress and physical damage in kelp, reducing productivity and reproduction (Rogers-Bennett and Catton, 2019; Beas-Luna et al., 2020; McPherson et al., 2021).

Table 3.5: Summary of previous IPCC assessments of kelp ecosystems.

Observations	Projections
AR5: (Wong et al., 2014)	
Kelp forests have been reported to decline in temperate areas in both hemispheres, a loss involving climate change (*high confidence*). Decline in kelp populations attributed to ocean warming has been reported in southern Australia and the North Coast of Spain.	Kelp ecosystems will decline with the increased frequency of heatwaves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*). Climate change will contribute to the continued decline in the extent of kelps in the temperate zone (*medium confidence*) and the range of kelp in the Northern Hemisphere will expand poleward (*high confidence*).
SR15 (Hoegh-Guldberg et al., 2018a) Observed movement of kelp ecosystems not assessed.	In the transition to 1.5°C, changes to water temperatures will drive some species (e.g., plankton, fish) to relocate to higher latitudes and for novel ecosystems to appear (*high confidence*). Other ecosystems (e.g., kelp forests, coral reefs) are relatively less able to move, however, and will experience high rates of mortality and loss (*very high confidence*).
SROCC (Bindoff et al., 2019)	
Kelp forests have experienced large-scale habitat loss and degradation of ecosystem structure and functioning over the past half century, implying a moderate to high level of risk at present conditions of global warming (*high confidence*). The abundance of kelp forests has decreased at a rate of ~2% yr^{-1} over the past half century, mainly due to ocean warming and marine heatwaves, as well as from other human stressors (*high confidence*). Changes in ocean currents have facilitated the entry of tropical herbivorous fish into temperate kelp forests decreasing their distribution and abundance (*medium confidence*). The loss of kelp forests is followed by the colonisation of turfs, which contributes to the reduction in habitat complexity, carbon storage and diversity (*high confidence*).	Kelp forests will face moderate to high risk at temperatures above 1.5ºC global sea surface warming (*high confidence*). Due to their low capacity to relocate and high sensitivity to warming, kelp forests are projected to experience higher frequency of mass mortality events as the exposure to extreme temperature rises (*very high confidence*). Changes in ocean currents have facilitated the entry of tropical herbivorous fish into temperate kelp forests decreasing their distribution and abundance (*medium confidence*). Kelp forests at low latitudes will continue to retreat due to intensified extreme temperatures, and their low dispersal ability will elevate the risk of local extinction under RCP8.5 (*high confidence*).

Trends in kelp abundance since 1950 are uneven globally (Krumhansl et al., 2016; Wernberg et al., 2019), with population declines (e.g., giant kelp *Macrocystis pyrifera* in Tasmania, (Butler et al., 2020), sugar kelp *Saccharina latissima* in the North Atlantic (Filbee-Dexter et al., 2020b)), more common than increases or no change (e.g., giant kelp *Macrocystis pyrifera* in southern Chile (Friedlander et al., 2020). Warming is driving range contraction and extirpation at the warm edge of species' ranges, and expansions at the cold range edge (*very high confidence*) (Smale, 2019; Filbee-Dexter et al., 2020b). Local declines in populations of kelp and other canopy-forming seaweeds driven by MHWs and other stressors have caused irreversible shifts to turf- or urchin-dominated ecosystems, with lower productivity and biodiversity (*high confidence*) (Filbee-Dexter and Scheibling, 2014; Filbee-Dexter and Wernberg, 2018; Rogers-Bennett and Catton, 2019; Beas-Luna et al., 2020; Stuart-Smith et al., 2021), ecosystems dominated by warm-affinity seaweeds or coral (*high confidence*) (Vergés et al., 2019), and loss of genetic diversity (Coleman et al., 2020a; Gurgel et al., 2020).

Species distribution models of kelp project range shifts and local extirpations with increasing levels of warming (Japan (Takao et al., 2015; Sudo et al., 2020)), (Australia (Table 11.6, Assis et al., 2018; Martínez et al., 2018; Castro et al., 2020)), (Europe (de la Hoz et al., 2019)), (North America (Wilson et al., 2019)), (South America (Figure 12.3)). There is *high agreement* on the direction but not the magnitude of change (Martínez et al., 2018; Castro et al., 2020), but effects of MHWs are not simulated. Where the length of higher-latitude coastlines is limited, range contractions are projected to occur, even with 2°C of global warming (i.e., SSP1-2.6) due to loss of habitat at the warm edge of species' ranges (Martínez et al., 2018). Poleward expansion of warm-affinity herbivores including urchins could further reduce warm-edge kelp populations (Castro et al., 2020; Mulders and Wernberg, 2020). Evidence from natural temperate CO_2 seeps suggests that ocean acidification at levels above those in RCP4.5 in 2100 could offset the increase in urchin abundance (Coni et al., 2021). Genetic analyses suggest that kelp populations at the midpoint of species' ranges will have lower tolerance of warming than implied by species distribution models, without assisted gene flow from warm-edge populations (King et al., 2019; Wood et al., 2021).

While reducing non-climate drivers can help prevent kelp loss from warming and MHWs, there is limited potential for restoration of kelp ecosystems after transition to urchin-dominant ecosystems (*high confidence*). Current restoration efforts are generally small-scale (<0.1 km^2) and less advanced than those in ecosystems like coral reefs (Coleman et al., 2020b; Eger et al., 2020; Layton et al., 2020). Although abundance of herbivores limits kelp populations, there is *limited evidence* that restoring predators of herbivores by creating marine reserves, or directly removing grazing species, will increase kelp forest resilience to warming and extremes (Vergés et al., 2019; Wernberg et al., 2019). Active reseeding of wild kelp populations through transplantation and propagation of warm-tolerant genotypes (Coleman et al., 2020b; Alsuwaiyan et al., 2021) can overcome low dispersal rates of many kelp species and facilitate effective restoration (*medium confidence*) (Morris et al., 2020c).

Building on the conclusions of SROCC, this assessment finds that kelp ecosystems are expected to decline and undergo changes in community structure in the future due to warming and increasing frequency and intensity of MHWs (*high confidence*). Risk of loss of kelp ecosystems and shifts to turf- or urchin-dominated ecosystems are highest at the warm edge of species' ranges (*high confidence*) and risks increase under RCP6.0 and RCP8.5 by the end of the century (*high confidence*).

3.4.2.4 Estuaries, Deltas and Coastal Lagoons

Estuaries, deltas and lagoons encounter environmental gradients over small spatial scales, generating diverse habitats that support myriad ecosystem services, including food provision, regulation of erosion, nutrient recycling, carbon sequestration, recreation and tourism, and cultural significance (D'Alelio et al., 2021; Keyes et al., 2021). Although these coastal ecosystems have historically been sensitive to erosion-accretion cycles driven by sea level, drought and storms (*high confidence*) (Peteet et al., 2018; Wang et al., 2018c; Jones et al., 2019b; Urrego et al., 2019; Hapsari et al., 2020; Zhao et al., 2020b), they were impacted for much of the 20th century primarily by non-climate drivers (*very high confidence*) (Brown et al., 2018b; Ducrotoy et al., 2019; Elliott et al., 2019; He and Silliman, 2019; Andersen et al., 2020; Newton et al., 2020; Stein et al., 2020). Nevertheless, the influence of climate-impact drivers has become more apparent over recent decades (*medium confidence*) (Table 3.6).

Table 3.6: Summary of previous IPCC assessments of estuaries, deltas and coastal lagoons.

Observations	Projections
AR5: (Wong et al., 2014)	
Humans have impacted lagoons, estuaries and deltas (*high to very high confidence*), but non-climate drivers have been the primary agents of change (*very high confidence*). In estuaries and lagoons, nutrient inputs have driven eutrophication, which has modified food-web structures (*high confidence*) and caused more-intense and longer-lasting hypoxia, more-frequent occurrence of harmful algal blooms, and enhanced emissions of nitrous oxide (*high confidence*).	Future changes in climate-impact drivers such as warming, acidification, waves, storms, sea-level rise (SLR), and runoff will have consequences for ecosystem function and services in lagoons and estuaries (*high confidence*), but with regional differences in magnitude of change in impact drivers and ecosystem response. Warming, changes in precipitation and changes in wind strength can interact to alter water-column salinity and

In deltas, land-use changes and associated disruption of sediment dynamics and land subsidence have driven changes that have been exacerbated by relative sea-level rise and episodic events including river floods and oceanic storm surges (*very high confidence*). Increased coastal flooding, erosion and saltwater intrusions have led to degradation of ecosystems (*very high confidence*).	stratification (*medium confidence*), which could impact water column oxygen content (*medium confidence*). Land-use change, SLR and intensifying storms will alter deposition-erosion dynamics, impacting shoreline vegetation and altering turbidity (*medium confidence*). Together with warming, these drivers will alter the seasonal pattern of primary production and the distribution of biota throughout the ecosystems (*medium to high confidence*), impacting associated ecosystem services. The projected impacts of climate change on deltas are associated mainly with pluvial floods and SLR, which will amplify observed impacts of interacting climate and non-climate drivers (*high confidence*).
SR15 (Hoegh-Guldberg et al., 2018a)	
Estuaries, deltas, and lagoons were not assessed in this report.	Under both a 1.5°C and 2°C of warming, relative to pre-industrial, deltas are expected to be highly threatened by SLR and localised subsidence (*high confidence*). The slower rate of SLR associated with 1.5°C of warming poses smaller risks of flooding and salinisation (*high confidence*), and facilitates greater opportunities for adaptation, including managing and restoring natural coastal ecosystems and infrastructure reinforcement (*medium confidence*). Intact coastal ecosystems may be effective in reducing the adverse impacts of rising sea levels and intensifying storms by protecting coastal and deltaic regions (*medium confidence*). Natural sedimentation rates are expected to be able to offset the effect of rising sea levels, given the slower rates of SLR associated with 1.5°C of warming (*medium confidence*). Other feedbacks, such as landward migration and the adaptation of infrastructure, remain important (*medium confidence*).
SROCC (Bindoff et al., 2019)	
Increased seawater intrusion caused by SLR has driven upstream redistribution of marine biotic communities in estuaries (*medium confidence*) where physical barriers such as the availability of benthic substrates do not limit availability of suitable habitats (*medium confidence*). Warming has driven poleward range shifts in species' distributions among estuaries (*medium confidence*). Interactions between warming, eutrophication and hypoxia have increased the incidence of harmful algal blooms (*high confidence*), pathogenic bacteria such as *Vibrio* species (*low confidence*), and mortalities of invertebrates and fish communities (*medium confidence*).	Salinisation and expansion of hypoxic conditions will intensify in eutrophic estuaries, especially in mid and high latitudes with microtidal regimes (*high confidence*). The effects of warming will be more pronounced in high-latitude and temperate shallow estuaries characterised by limited exchange with the open ocean and strong seasonality that already leads to development of dead zones (*medium confidence*). Interaction between SLR and changes in precipitation will have greater impacts on shallow than deep estuaries (*medium confidence*). Estuaries characterised by large tidal exchanges and associated well-developed sediments will be more resilient to projected SLR and changes in river flow (*medium confidence*). Human activities that inhibit sediment dynamics in coastal deltas increase their vulnerability to SLR (*medium confidence*).

Estuarine biota are sensitive to warming (*high confidence*), with recent responses including changes in abundance of some fish stocks (Erickson et al., 2021; Woodland et al., 2021), poleward shifts in distributions of fish species, communities and associated biogeographic transition zones (Table 12.3, Franco et al., 2020; Troast et al., 2020), recruits of warm-affinity species persisting into winter (Kimball et al., 2020), and changes in seasonal timing of peaks in species abundance (Kimball et al., 2020). MHWs can be more severe in estuaries than in adjacent coastal seas (Lonhart et al., 2019), causing conspicuous impacts (*very high confidence*), including mass mortality of intertidal vegetation (Section 3.4.2.5), range shifts in algae and animals (Lonhart et al., 2019), and reduced spawning success among invertebrates (Shanks et al., 2020).

RSLR extends the upstream limit of saline waters (*high confidence*) (Harvey et al., 2020; Jiang et al., 2020) and alters tidal ranges (*high confidence*) (Idier et al., 2019; Talke et al., 2020). Elevated water levels also alter submergence patterns for intertidal habitat (*high confidence*) (Andres et al., 2019), moving high-water levels inland (*high confidence*) (Peteet et al., 2018; Appeaning Addo et al., 2020; Liu et al., 2020e) and increasing the salinity of coastal water tables and soils (*high confidence*) (Eswar et al., 2021). These processes favour inland and/or upstream migration of intertidal habitat, where it is unconstrained by infrastructure, topography or other environmental features (*high confidence*) (Kirwan and Gedan, 2019; Parker and Boyer, 2019; Langston et al., 2020; Magolan and Halls, 2020; Saintilan et al., 2020). The spread of "ghost forests" along the North American east coast (Kirwan and Gedan, 2019) and elsewhere (Grieger et al., 2020) illustrates this phenomenon. Along estuarine shorelines, changing submergence patterns and upstream penetration of saline waters interact synergistically to stress intertidal plants, changing species composition and reducing above-ground biomass, in some cases favouring invasive species (Xue et al., 2018; Buffington et al., 2020; Gallego-Tévar et al., 2020). Overall, changing salinity and submergence patterns decrease the ability of shoreline vegetation to trap sediment (Xue et al., 2018), reducing accretion rates and increasing the vulnerability of estuarine shorelines to submergence by SLR and erosion by wave action (*medium confidence*) (Zhu et al., 2020b).

Drought and freshwater abstraction can reduce freshwater inflows to estuaries and lagoons, increasing salinity, reducing water quality (Brooker and Scharler, 2020) and depleting resident macrophyte communities (Scanes et al., 2020b). Changes in freshwater input and SLR, combined with land-use change, can alter inputs of land-based sediments, causing expansion (Suyadi et al., 2019; Magolan and Halls, 2020) or contraction (Andres et al., 2019; Appeaning Addo et al., 2020; Li et al., 2020b) of intertidal habitats. The same phenomena alter salinity gradients, which are the primary drivers of estuarine species distributions (*high confidence*) (Douglass et al., 2020; Lauchlan and Nagelkerken, 2020). Extreme reduction of freshwater input can extend residence time of estuarine water, leading to persistent HABs (Lehman et al., 2020) and converting estuaries to lagoons if the mouth clogs with sediment (Thom et al., 2020).

Acidification of estuarine water is a growing hazard (*medium confidence*) (Doney et al., 2020; Scanes et al., 2020a; Cai et al., 2021), and resident organisms display sensitivity to altered pH in laboratory settings (*medium confidence*) (Young et al., 2019a; Morrell and Gobler, 2020; Pardo and Costa, 2021). However, attribution of the biological effects of acidification is difficult because many biogeochemical processes affect estuarine carbon chemistry (Sections 3.2.3.1, 3.3.2). Warming can exacerbate the impacts of both acidification and hypoxia on estuarine organisms (Baumann and Smith, 2018; Collins et al., 2019b; Ni et al., 2020). These effects are further complicated by eutrophication, with high nitrogen loads associated with lower pH (Rheuban et al., 2019). Warming (including MHWs) and eutrophication interact to decrease estuarine oxygen content and pH, increasing the vulnerability of animals to MHWs (Brauko et al., 2020), and exacerbating the incidence and impact of dead zones (*medium confidence*) (Altieri and Gedan, 2015). The impacts of storms on estuaries are variable and are described in SM3.3.1.

All these impacts are projected to escalate under future climate change, but their magnitude depends on the amount of warming, the socio-economic development pathway, and implementation of adaptation strategies (*medium confidence*). Modelling studies (Lopes et al., 2019; Rodrigues et al., 2019; White et al., 2019; Zhang and Li, 2019; Hong et al., 2020; Krvavica and Ružić, 2020; Liu et al., 2020e; Shalby et al., 2020) suggest that responses of estuaries to SLR will be complex and context dependent (Khojasteh et al., 2021), but project that salinity, tidal range, storm-surge amplitude, depth and stratification will increase with SLR (*medium confidence*), and that marine-dominated waters will penetrate farther upstream (*high confidence*). Without careful management of freshwater inputs, sediment augmentation and/or the restoration of shorelines to more natural states, transformation and loss of intertidal areas and wetland vegetation will increase with SLR (*high confidence*) (Doughty et al., 2019; Leuven et al., 2019; Yu et al., 2019; Raw et al., 2020; Shih, 2020; Stein et al., 2020), with small, shallow microtidal estuaries being more vulnerable to impacts than deeper estuaries with well-developed sediments (*medium confidence*) (Leuven et al., 2019; Williamson and Guinder, 2021). Warming and MHWs will enhance stratification and deoxygenation in shallow lagoons (*medium confidence*) (Derolez et al., 2020) and will continue to drive range shifts among estuarine biota (*medium confidence*) (Veldkornet and Rajkaran, 2019; Zhang et al., 2020c), resulting in extirpations where thermal habitat is lost and potentially generating new habitat for warm-affinity species (*limited evidence, medium agreement*) (Veldkornet and Rajkaran, 2019).

3.4.2.5 Vegetated Blue Carbon Ecosystems

Mangroves, saltmarshes and seagrass beds (wetland ecosystems) are considered "blue carbon" ecosystems due to their capacity to accumulate and store organic-carbon rich sediments (Box 3.4, Macreadie et al., 2019; Rogers et al., 2019) and provide an extensive range of other ecosystem services (Box 3.4). Because these ecosystems are often found within estuaries and along sheltered coastlines, they share vulnerabilities, climate-impact (Table 3.7) and non-climate drivers with estuaries and coastal lagoons (Section 3.4.2.4).

Table 3.7: Summary of previous IPCC assessments of mangroves, saltmarshes and seagrass beds.

Observations	Projections
AR5: (Wong et al., 2014)	
Seagrasses occurring close to their upper thermal limits are already stressed by climate change (*high confidence*). Increased CO_2 concentrations have increased seagrass photosynthetic rates by 20% (*limited evidence, high agreement*).	Climate change will drive ongoing declines in the extent of seagrasses in temperate waters (*medium confidence*) as well as poleward range expansions of seagrasses and mangroves, especially in the Northern Hemisphere (*high confidence*). Beneficial effects of elevated CO_2 will increase seagrass productivity and carbon burial rates in salt marshes during the first half of the 21st century, but there is *limited evidence* that this will improve their survival or resistance to warming. As a result, interactions between climate change and non-climate drivers will continue to cause declines in estuarine vegetated systems (*very high confidence*).
SR15 (Hoegh-Guldberg et al., 2018a)	
Vegetated blue carbon systems were not assessed in this report.	Intact wetland ecosystems can reduce the adverse impacts of rising sea levels and intensifying storms by protecting shorelines (*medium confidence*) and their degradation could reduce remaining carbon budgets by up to 100 $GtCO_2$. Under 1.5°C of warming, natural sedimentation rates are projected to outpace SLR (*medium confidence*), but other feedbacks, such as landward migration of wetlands and the adaptation of infrastructure, remain important (*medium confidence*).
SROCC (Bindoff et al., 2019; Oppenheimer et al., 2019)	
Coastal ecosystems, including saltmarshes, mangroves, vegetated dunes and sandy beaches, can build vertically and expand laterally in response to SLR, though this capacity varies across sites (*high confidence*). These ecosystems provide important services that include coastal protection and habitat for diverse biota. However, because of human actions that fragment wetland habitats and	Seagrass meadows (*high confidence*) will face moderate to high risk at temperature above 1.5°C global sea surface warming. The transition from undetectable to moderate risk in salt marshes takes place between 0.7°C–1.2°C of global sea surface warming (*medium* to *high confidence*), and

restrict landward migration, coastal ecosystems progressively lose their ability to adapt to climate-induced changes and provide ecosystem services, including acting as protective barriers (*high confidence*).

Warming and SLR-driven salinisation of wetlands are causing shifts in the distribution of plant species inland and poleward. Examples include mangrove encroachment into subtropical salt marshes (*high confidence*) and contraction in extent of low-latitude seagrass meadows (*high confidence*).

Plants with low tolerance to flooding and extreme temperatures are particularly vulnerable, increasing the risk of extirpation (*medium confidence*).

Extreme weather events, including heatwaves, droughts and storms, are causing mass mortalities and changes in community composition in coastal wetlands (*high confidence*).

Severe disturbance of wetlands or transitions among wetland community types can favour invasive species (*medium confidence*).

The degradation or loss of vegetated coastal ecosystems reduces carbon storage, with positive feedbacks to the climate system (*high confidence*).

between 0.9°C–1.8°C (*medium confidence*) in sandy beaches, estuaries and mangrove forests.

The ecosystems at moderate to high risk under future emission scenarios are mangrove forests (transition from moderate to high risk at 2.5°C–2.7°C of global sea surface warming), estuaries and sandy beaches (2.3°C–3.0°C) and salt marshes (transition from moderate to high risk at 1.8°C–2.7°C and from high to very high risk at 3.0°C–3.4°C) (*medium confidence*).

Global coastal wetlands will lose between 20–90% of their area depending on emissions scenario with impacts on their contributions to carbon sequestration and coastal protection (*high confidence*).

Estuarine wetlands will remain resilient to modest rates of SLR where their sediment dynamics are unconstrained. But SLR and warming are projected to drive global loss of up to 90% of vegetated wetlands by the end of the century under the RCP8.5 (*medium confidence*), especially if landward migration and sediment supply are limited by human modification of shorelines and river flows (*medium confidence*).

Moreover, pervasive coastal squeeze and human-driven habitat deterioration will reduce the natural capacity of these ecosystems to adapt to climate impacts (*high confidence*).

Since AR5 and SROCC, syntheses have emphasised that the vulnerability of rooted wetland ecosystems to climate-impact drivers is exacerbated by non-climate drivers (*high confidence*) (Elliott et al., 2019; Ostrowski et al., 2021; Williamson and Guinder, 2021) and climate variability (*high confidence*) (Day and Rybczyk, 2019; Kendrick et al., 2019; Shields et al., 2019). Global rates of mangrove loss have been extensive but are slowing (*high confidence*) at least partially due to management interventions (Friess et al., 2020b; Goldberg et al., 2020). From 2000 to 2010 mangrove loss averaged 0.16% yr^{-1}, globally, but with greatest loss in Southeast Asia (*high confidence*) (Hamilton and Casey, 2016; Friess et al., 2019; Goldberg et al., 2020), and ubiquitous fragmentation leaving few mangroves intact (Bryan-Brown et al., 2020). Saltmarsh ecosystems have also suffered extensive losses (up to 60% in places, since the 1980s), especially in developed and rapidly developing countries (*medium confidence*) (Table 12.3, Gu et al., 2018; Stein et al., 2020). Similarly, 29% of seagrass meadows were lost from 1879–2006 due primarily to coastal development and degradation of water quality, with climate-change impacts escalating since 1990 (*medium confidence*) (Waycott et al., 2009; Sousa et al., 2019; Derolez et al., 2020; Green et al., 2021a). Local examples of habitat stability or growth (e.g., de los Santos et al., 2019; Laengner et al., 2019; Sousa et al., 2019; Suyadi et al., 2019; Derolez et al., 2020; Goldberg et al., 2020; McKenzie and Yoshida, 2020) indicate some resilience to climate change in the absence of non-climate drivers (*high confidence*). Nevertheless, previous declines have left wetland ecosystems more vulnerable to impacts from climate-impact and non-climate drivers (*high confidence*) (Friess et al., 2019; Williamson and Guinder, 2021).

Warming and MHWs have affected the range, species composition and survival of some wetland ecosystems. Warming is allowing some, but not all (Rogers and Krauss, 2018; Saintilan et al., 2018), mangrove species to expand their ranges poleward (*high confidence*) (Friess et al., 2019; Whitt et al., 2020). This expansion can affect species interactions (Guo et al., 2017; Friess et al., 2019), and enhance sediment accretion and carbon storage rates in some instances (*medium confidence*) (Guo et al., 2017; Kelleway et al., 2017; Chen et al., 2018b; Coldren et al., 2019; Raw et al., 2019). Drought, low sea levels and MHWs can cause significant die-offs among mangroves (*medium confidence*) (Lovelock et al., 2017b; Duke et al., 2021). Seagrasses are similarly vulnerable to warming (*high confidence*) (Repolho et al., 2017; Duarte et al., 2018; Jayathilake and Costello, 2018; Savva et al., 2018), which has been attributed as one cause of observed changes in distribution and community structure (*medium confidence*) (Hyndes et al., 2016; Nowicki et al., 2017). MHWs, together with storm-driven turbidity and structural damage, can cause seagrass die-offs (*high confidence*) (Arias-Ortiz et al., 2018; Kendrick et al., 2019; Smale et al., 2019; Strydom et al., 2020), shifts to small, fast-growing species (*high confidence*) (Kendrick et al., 2019; Shields et al., 2019; Strydom et al., 2020), and ecosystem collapse (Serrano et al., 2021).

The sensitivity of saltmarshes and mangroves to RSLR depends on whether they accrete inorganic sediment and/or organic material at rates equivalent to rising water levels (*very high confidence*) (Peteet et al., 2018; FitzGerald and Hughes, 2019; Friess et al., 2019; Gonneea et al., 2019; Leo et al., 2019; Marx et al., 2020; Saintilan et al., 2020). Otherwise, wetland ecosystems must migrate either inland or upstream, or face gradual submergence in deeper, increasingly saline water (*very high confidence*) (Section 3.4.2.4, Andres et al., 2019; Jones et al., 2019b; Cohen et al., 2020; Mafi-Gholami et al., 2020; Magolan and Halls, 2020; Sklar et al., 2021). Ability to migrate depends on local topography, the positioning of anthropogenic infrastructure, and structures placed to defend such infrastructure (Schuerch et al., 2018; Fagherazzi et al., 2020; Cahoon et al., 2021). Submergence drives changes in community structure (*high confidence*) (Jones et al., 2019b; Yu et al., 2019; Douglass et al., 2020; Langston et al., 2020) and functioning (*high confidence*) (Charles et al., 2019; Buffington et al., 2020; Stein et al., 2020), and will eventually lead to extirpation of the most sensitive vegetation (*medium confidence*) (Schepers et al., 2017; Scalpone et al., 2020) and associated animals (*low confidence*) (Rosencranz et al., 2018). The impacts of storms on wetlands are variable and are described in SM3.3.1.

As noted in SROCC, given the diversity of coastal wetlands as well as the dependence of their future vulnerability to climate change on adaptation pathways (Krauss, 2021; Rogers, 2021), projections of future impacts based on shoreline elevation estimated from satellite data and CMIP5 projections (Spencer et al., 2016; Schuerch et al., 2018) vary greatly. Although all approaches have individual strengths and weaknesses (Törnqvist et al., 2021), paleo-records provide some clarity because they yield estimates of wetland responses to changes in climate in the absence of other anthropogenic drivers and are therefore inherently conservative. On the basis of paleorecords (Table 3.8), we assess that mangroves and saltmarshes are *likely* at high risk from future SLR, even under SSP1-1.9, with impacts manifesting in the mid-term (*medium confidence*). Under SSP5-8.5, wetlands are *very likely* at high risk from SLR, with larger impacts manifesting before 2040 (*medium confidence*). By 2100, these ecosystems are at high risk of impacts under all scenarios except SSP1-1.9 (*high confidence*), with impacts most severe along coastlines with gently-sloping shorelines, limited sediment inputs, small tidal ranges and limited space for inland migration (*very high confidence*) (Cross-Chapter Box SLR in Chapter 3, Schuerch et al., 2018; FitzGerald and Hughes, 2019; Leo et al., 2019; Schuerch et al., 2019; Raw et al., 2020; Saintilan et al., 2020).

Table 3.8: Estimates of vulnerability of coastal wetlands to sea-level rise (SLR) on the basis of sediment cores.

Region	Habitat	Reference	Rates of SLR at which habitat loss is		WGI AR6 Table 9.9 estimate of SLR (Fox-Kemper et al., 2021)	
			Likely	*Very likely*	2040–2060	2090–2100
Global	Mangrove	(Saintilan et al., 2020)	4.2*	6.1	SSP1-1.9: 4.2 (2.9–6.1) mm yr^{-1}	4.3 (2.5–6.6) mm yr^{-1}
Southeastern USA	Saltmarsh	(Törnqvist et al., 2020)	3.5#	4.2#	SSP5-8.5: 7.3 (5.7–9.8) mm yr^{-1}	12.2 (8.8–17.7) mm yr^{-1}
UK	Saltmarsh	(Horton et al., 2018)	4.6*	7.1*		

* Estimate digitised from published figure
# Published figure digitised and remodelled as binomial generalised linear model (number drowned vs. not).

For seagrasses, recent projections for climate-change impacts vary by species and region. Warming is projected to increase the habitat available to *Zostera marina* on the east coast of the USA by 2100, but contract its southern range edge by 150–650 km under RCP2.6 and RCP8.5, respectively (Wilson and Lotze, 2019). Other species, such as *Posidonia oceanica* in the Mediterranean, might lose as much as 75% of their habitat by 2050 under RCP8.5 and become functionally extinct (*low confidence*) by 2100 (Chefaoui et al., 2018). Observed impacts of MHWs (Kendrick et al., 2019; Strydom et al., 2020; Serrano et al., 2021) indicate that increasing intensity and frequency of MHWs (Section 3.2.2.1) will have escalating impacts on seagrass ecosystems (*high confidence*). Habitat suitability can also be reduced by moderate RSLR, due to its impact on light attenuation (*medium confidence*) (Aoki et al., 2020; Ondiviela et al., 2020; Scalpone et al., 2020).

Overall, warming will drive range shifts in wetland species (*medium* to *high confidence*), but SLR poses greatest risk for mangroves and saltmarshes, with significant losses projected under all future scenarios by mid-century (*medium confidence*) and substantially greater losses by 2100 under all scenarios except SSP1-1.9 (*high confidence*). MHWs pose the greatest risk to seagrasses (*high confidence*). In all cases, losses will be greatest where accommodation space is constrained or where other non-climate drivers exacerbate risk from climate-impact drivers (*very high confidence*).

3.4.2.6 Sandy Beaches

Sandy beaches comprise unvegetated, fine- to medium-grained sediments in the intertidal zones that line roughly one-third of the length of the world's ice-free coastlines (Luijendijk et al., 2018). The amenity value of beaches as cultural, recreational and residential destinations has driven extensive urbanisation of beach-associated coastlines (Todd et al., 2019). Beaches also provide habitat for many resident species, nesting habitat for marine vertebrates, filtration of coastal waters and protection of the coastline from erosion (McLachlan and Defeo, 2018). These soft-sediment coastal ecosystems are particularly vulnerable to habitat loss caused by erosion, especially where landward transgression is inhibited by infrastructure (Table 3.9).

Table 3.9: Summary of previous IPCC assessments of sandy beaches.

Observations	Projections
AR5: (Wong et al., 2014)	
Globally, beaches and dunes have in general undergone net erosion over the past century or longer. Attributing shoreline changes to climate change is still difficult owing to the multiple natural and anthropogenic drivers contributing to coastal erosion.	In the absence of adaptation, beaches, sand dunes, and cliffs currently eroding will continue to do so under increasing sea level (*high confidence*). Coastal squeeze is expected to accelerate with sea-level rise (SLR). In many locations, finding sufficient sand to rebuild beaches and dunes artificially will become increasingly difficult and expensive as present supplies near project sites are depleted (*high confidence*). In the absence of adaptation measures, beaches and sand dunes currently affected by erosion will continue to be affected under SLR (*high confidence*).
SROCC (Bindoff et al., 2019)	
Coastal ecosystems are already impacted by the combination of SLR, other climate-related ocean changes, and adverse effects from human activities on ocean and land (*high confidence*). Attributing such impacts to SLR, however, remains challenging due to the influence of other climate-related and non-climate drivers such as infrastructure development and human-induced habitat degradation (*high confidence*). Coastal ecosystems, including saltmarshes, mangroves, vegetated dunes and sandy beaches, can build vertically and expand laterally in response to SLR, though this capacity varies across sites (*high confidence*) as a consequence of human actions that fragment wetland habitats and restrict landward migration, coastal ecosystems progressively lose their ability to adapt to climate-induced changes and	Sandy beach ecosystems will increasingly be at risk of eroding, reducing the habitable area for dependent organisms (*high confidence*). Sandy shorelines are expected to continue to reduce their area and change their topography due to SLR and increased extreme climatic erosive events. This will be especially important in low-lying coastal areas with high population and building densities (*medium confidence*). Assuming that the physiological underpinning of the relationship between body size and temperature can be applied to warming (*medium confidence*), the body size of sandy beach crustaceans is expected to decrease under warming (*low evidence, medium agreement*).

provide ecosystem services, including acting as protective barriers (*high confidence*). Loss of breeding substrate, including mostly coastal habitats such as sandy beaches, can reduce the available nesting or pupping habitat for land breeding marine turtles, lizards, seabirds and pinnipeds (*high confidence*). Overall, changes in sandy beach morphology have been observed from climate related events, such as storm surges, intensified offshore winds, and from coastal degradation caused by humans (*high confidence*), with impacts on beach habitats (e.g., benthic megafauna) (*medium confidence*).	Sandy beaches transition from undetectable to moderate risk between 0.9ºC–1.8ºC (*medium confidence*) of global sea surface warming and from moderate to high risk at 2.3ºC–3.0ºC of global sea surface warming (*medium confidence*). Projected changes in mean and extreme sea levels and warming under RCP8.5 are expected to result in high risk of impacts on sandy beach ecosystems by the end of the 21st century (*medium confidence*), taking account of the slow recovery rate of sandy beach vegetation, the direct loss of habitats and the high climatic sensitivity of some fauna. Under RCP2.6, the risk of impacts on sandy beaches is expected to be only slightly higher than the present-day level (*low confidence*). Coastal urbanisation lowers the buffering capacity and recovery potential of sandy beach ecosystems to impacts from SLR and warming and thus is expected to limit their resilience to climate change (*high confidence*). Coastal squeeze and human-driven habitat deterioration will reduce the natural capacity of these ecosystems to adapt to climate impacts (*high confidence*).

Since SROCC, observed trends in coastal erosion continue to be obscured by beach nourishment that replaces eroded sediment or by coastal protection of areas at risk of erosion (Section 3.6.3.1.1, Cross-Chapter Box SLR in Chapter 3). Nevertheless, RSLR, increases in wave energy and/or changes in wave direction, disruptions to sediment supplies (including sand mining), and other anthropogenic modifications of the coast have driven localised beach erosion (*very high confidence*) at rates up to 0.5–3 m yr^{-1} (Vitousek et al., 2017a; Vitousek et al., 2017b; Cambers and Wynne, 2019; Enríquez-de-Salamanca, 2020; Sharples et al., 2020). Corresponding analyses of coarse-scale (30-m resolution) global data estimate that 15% of tidal flats (including beaches) have been lost since 1984 (*medium confidence*) (Mentaschi et al., 2018; Murray et al., 2019) but with a corresponding number of the world's beaches accreting (28%) as eroding (24%) (*medium confidence*) (Luijendijk et al., 2018).

Progress is being made toward models that can project beach erosion under future scenarios despite inherent uncertainties and the presence of multiple confounding drivers in the coastal zone (Vitousek et al., 2017b; Le Cozannet et al., 2019; Cooper et al., 2020a; Vousdoukas et al., 2020b; Vousdoukas et al., 2020a). In the interim, models with varying levels of complexity estimate local loss of beach area to SLR by 2100 under RCP8.5-like scenarios, assuming minimal human intervention, ranging 30–70% (*low confidence*) (Vitousek et al., 2017b; Mori et al., 2018; Ritphring et al., 2018; Hallin et al., 2019; Kasmi et al., 2020). Within regions, projected impacts scale negatively with beach width and positively with the magnitude of projected SLR. None of these local studies, however, considered high-energy storm events, which are known to also impact sandy coasts (*high confidence*) (e.g., Burvingt et al., 2018; Garrote et al., 2018; Duvat et al., 2019; Sharples et al., 2020), and model structure often had more influence on projected shoreline responses than did physical drivers (Le Cozannet et al., 2019). Nevertheless, the most-advanced available models, which incorporate multiple coastal processes, including SLR, project that without anthropogenic barriers to erosion, 13.6–15.2% and 35.7–49.5% of the world's beaches *likely* risk undergoing at least 100 m of shoreline retreat (relative to 2010) by 2050 and 2100, respectively (*low confidence*) (Vousdoukas et al., 2020b). Aggregating these trends regionally suggests that relative rates of shoreline change under RCP4.5 and RCP8.5 diverge strongly after mid-century, with trends towards erosion escalating under RCP8.5 by 2100 (*medium confidence*) (Figure 3.14, Vousdoukas et al., 2020b). This trend supports the WGI AR6 assessment that projected SLR will contribute to erosion of sandy beaches, especially under high-emissions futures (*high confidence*) (WGI AR6 Technical Summary, Arias et al., 2021).

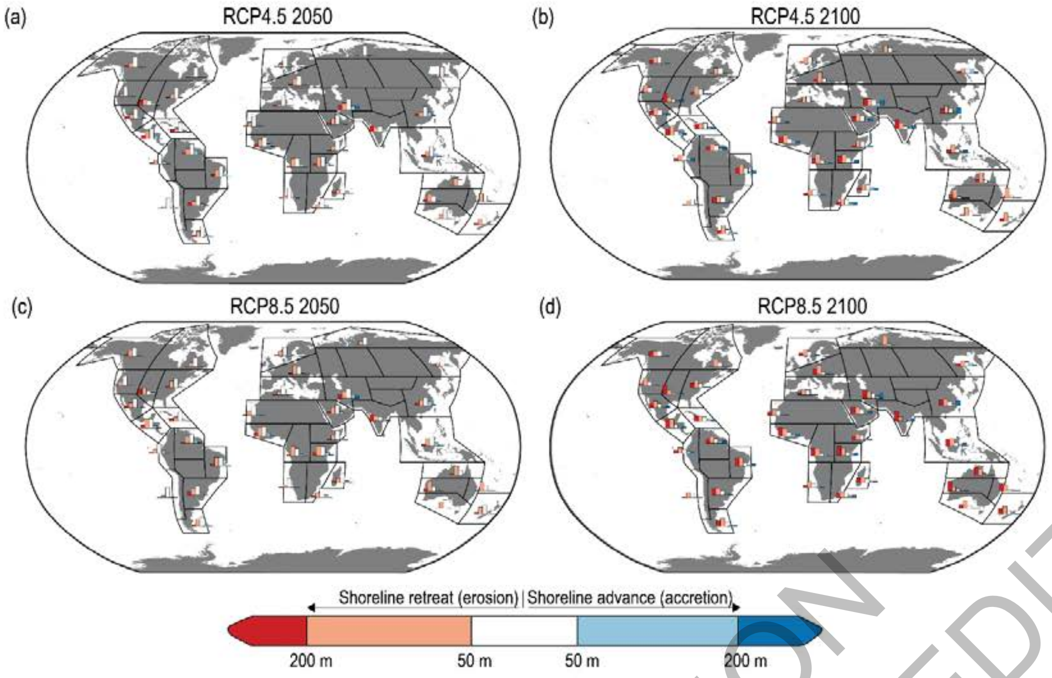


Figure 3.14: Relative trends in projected regional shoreline change (advance/retreat relative to 2010). Frequency distributions of median projected change by (a,c) 2050 and (b,d) 2100 under (a,b) RCP4.5 and (c,d) RCP8.5. Projections account for both long-term shoreline dynamics and sea-level rise and assume no impediment to inland transgression of sandy beaches. Data for small island states are aggregated and plotted in the Caribbean. Data from Vousdoukas et al. (2020b). Values for reference regions established in the WGI AR6 Atlas (Gutiérrez et al., 2021) were computed as area-weighted means from original country-level data. For model assumptions and associated debate, see Vousdoukas et al. (2020a) and Cooper et al. (2020a).

For beach fauna, *emerging evidence* links range shifts, increasing representation by warm-affinity species and mass mortalities to ocean warming (*limited evidence, high agreement*) (McLachlan and Defeo, 2018; Martin et al., 2019). But even amongst the best-studied taxa, such as turtles, vulnerability to warming (*high confidence*) and SLR (*medium confidence*) anticipated on the basis of theory (Poloczanska et al., 2009; Saba et al., 2012; Pike, 2013; Laloë et al., 2017; Tilley et al., 2019) yields only a few detected impacts in the field associated mainly with feminisation (female-skewed sex ratios driven by warmer nest temperatures) (Jensen et al., 2018; Colman et al., 2019; Tilley et al., 2019), phenology (Monsinjon et al., 2019), reproductive success (Bladow and Milton, 2019) and inter-nesting period (Valverde-Cantillo et al., 2019). Moreover, although established vulnerabilities imply high projected future risk for turtles (*high confidence*) (e.g., Almpanidou et al., 2019; Monsinjon et al., 2019; Patrício et al., 2019; Varela et al., 2019; Santidrián Tomillo et al., 2020), many populations remain resilient to change (Fuentes et al., 2019; Valverde-Cantillo et al., 2019; Laloë et al., 2020; Lamont et al., 2020), perhaps because variation in sand temperatures at nesting depth among beaches *very likely* exceeds the magnitude of warming anticipated by 2100, even under RCP8.5 (*medium confidence*) (Bentley et al., 2020a). As expected for a taxon with a long evolutionary history, turtles display natural adaptation, not only by virtue of broad geographic distributions that include natural climate-change refugia (Boissin et al., 2019; Jensen et al., 2019), but also because some initial responses to warming might counteract anticipated impacts. For example, although feminisation poses a significant long-term risk to turtle populations (*high confidence*), it might contribute to population growth in the near- to mid-term (*medium confidence*) (Patrício et al., 2019). Resilience to climate change might be further enhanced by range extensions, alterations in nesting phenology, and fine-scale nest-site selection (*medium confidence*) (Abella Perez et al., 2016; Santos et al., 2017; Almpanidou et al., 2018; Rivas et al., 2019; Laloë et al., 2020).

New literature since SROCC on climate impacts and risks has been scarce for most beach taxa besides turtles (the impacts of storms on beach fauna are variable and are described in SM3.3.1). Nevertheless, theoretical sensitivity to warming (Section 3.3.2), together with the projected loss of habitat under future climate scenarios, suggest substantial impacts for populations and communities of beach fauna into the future (*high confidence*). These impacts will be exacerbated by coastal squeeze along urbanised coastlines (*high* *confidence*), albeit with magnitudes that cannot yet be accurately projected (McLachlan and Defeo, 2018; Le Cozannet et al., 2019; Leo et al., 2019).

3.4.2.7 Semi-Enclosed Seas

This section assesses impacts on five SES, or seas larger than 200,000 km^2 with single entrances <120 km wide, including the Persian Gulf, the Red Sea, the Black Sea, the Baltic Sea and the Mediterranean Sea. These SES are largely landlocked and are thus heavily influenced by surrounding landscapes, local and global climate-impact drivers, as well as non-climate drivers (Section 3.1), making them highly vulnerable to cumulative threats. Key climate-impact drivers in SES are warming, increasing frequency and duration of MHWs, acidification, and the increasing in size and number of OMZs (Figure 3.12, Hoegh-Guldberg et al., 2014). In AR5, SES were recognised as regionally significant for fisheries and tourism, but highly exposed to both local and global stressors, offering limited options for organisms to migrate in response to climate change (Table 3.10).

Table 3.10: Summary of past IPCC assessments of semi-enclosed seas (SES).

Observations	Projections
AR5 (Hoegh-Guldberg et al., 2014)	
The surface waters of the SES exhibit significant warming from 1982 and most Coastal Boundary Systems show significant warming since 1950. Warming of the Mediterranean has led to the recent spread of tropical species invading from the Atlantic and Indian Oceans. SES are highly vulnerable to changes in global temperature on account of their small seawater volume and landlocked nature. Consequently, SES will respond faster than most other parts of the Ocean (*high confidence*). The impact of rising temperatures on SES is exacerbated by their vulnerability to other human influences such as over-exploitation, pollution, and enhanced runoff from modified coastlines. Due to a combination of global and local human stressors, key fisheries have undergone fundamental changes in their abundance and distribution over the past 50 years (*medium confidence*).	Projected warming increases the risk of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation of underlying waters and the formation of additional hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). Changing rainfall intensity can exert a strong influence on the physical and chemical conditions within SES, and in some cases will combine with other climatic changes to transform these areas. These changes are *likely* to increase the risk of reduced bottom-water O_2 levels for Baltic and Black Sea ecosystems (due to reduced solubility, increased stratification, and microbial respiration), which is *very likely* to affect fisheries. Persian Gulf, Red Sea: Extreme temperature events such as heatwaves are projected to increase (*high confidence*) and temperatures are *very likely* to increase above established thresholds for mass coral bleaching and mortality (*very high confidence*).
SROCC (Bindoff et al., 2019) *Semi-enclosed seas were not assessed in this report.*	
	Projections from distribution models for multiple fish species show hotspots of decreased species richness in the Indo-Pacific region, and semi-enclosed seas such as the Red Sea and Persian Gulf (*medium evidence, high agreement*). In addition, geographic barriers such as land boundaries or lower oxygen water in deeper waters are projected to limit species range shifts in semi-enclosed seas, resulting in larger relative decrease in species richness (*medium confidence*).

Since AR5, there is evidence for increasing frequency and duration of MHWs, extreme weather events and a diversity of threats across depth strata causing mass mortality events, local extirpations and coral reef decline (*high confidence*) (Section 3.4.2.1, SM3.3.2, Buchanan et al., 2016a; Shlesinger et al., 2018; Wabnitz et al., 2018b; Garrabou et al., 2019). In most SES, non-climate drivers, including pollution, habitat destruction, and especially overfishing are decreasing the local adaptive capacity of organisms and the ability of ecosystems to cope with climate change impacts (*high confidence*) (Cramer et al., 2018; Hidalgo et al., 2018; Ben-Hasan and Christensen, 2019). SLR is accelerating faster than expected (*high confidence*) (Kulp and Strauss, 2019), posing a key risk to SES' coastal ecosystems and the services they provide in urban areas, including drinking water provision, housing, recreational activities, among others (Hérivaux et al., 2018; Reimann et al., 2018).

The size and number of OMZs are increasing worldwide and in most SES (*high confidence*) (Global Ocean Oxygen Network, 2018), with growing impacts on fish species diversity and ecosystem functioning. In the Persian Gulf and Red Sea, increasing nutrient loads associated with coastal activities and warming has increased the size of OMZs (*high confidence*) (Al-Said et al., 2018; Lachkar et al., 2019). OMZs represent an even greater problem in the Black and Baltic Seas, with broad implications for ecosystem function and services (Levin et al., 2009), especially where actions to reduce nutrient loading from land have been unable to reduce the OMZ coverage (*high confidence*) (Carstensen et al., 2014; Miladinova et al., 2017; Global Ocean Oxygen Network, 2018). In the Baltic Sea, OMZs are affecting the extent of suitable spawning areas of cod, *Gadus morhua* (*high confidence*) (Hinrichsen et al., 2016), while in the Black Sea, the combined effect of OMZs and warming is influencing the distribution and physiology of fish species, and their migration and schooling behavior in their overwintering grounds (*medium confidence*) (Güraslan et al., 2017). Cascading effects on food webs have been reported in the Baltic, where detrimental effects of changing oxygen levels on zooplankton production, pelagic and piscivorous fish are influencing seasonal succession and species composition of phytoplankton (*high confidence*) (Viitasalo et al., 2015).

In the Mediterranean Sea (Cross-Chapter Paper 4), the increase in climate extremes and mass mortality events reported in AR5 has continued (*very high confidence*) (Gómez-Gras et al., 2021). Extreme weather events (including deep convection, González-Alemán et al., 2019) and MHWs have become more frequent (Darmaraki et al., 2019) and are associated with mass mortality of benthic sessile species across the basin (*high confidence*) (Garrabou et al., 2019; Gómez-Gras et al., 2021). Since AR5, in the Persian Gulf and Red Sea, extreme temperatures, together with disease and predation, have continued to cause bleaching-induced mortality of corals, along with declines in the average coral colony size (*high confidence*) (Burt et al., 2019). Poleward migration and tropicalisation of species (Section 3.4.2.3) has also continued in the Mediterranean, and these phenomena have also become an issue in the Black Sea (*high confidence*) (Boltachev and Karpova, 2014; Hidalgo et al., 2018). Climate impacts on phytoplankton production and phenology show high spatial heterogeneity across the Mediterranean Sea (*medium evidence*) (Marbà et al., 2015b; Salgado-Hernanz et al., 2019), with consequent effects on the diversity and abundance of zooplankton and fish species (*medium confidence*) (Peristeraki et al., 2019). Changes in primary production and a decrease in river runoff have also altered the optimum habitats for small pelagic fish in the Mediterranean, from local to the basin scale (Piroddi et al., 2017). Evidence of impacts from ocean acidification is increasing, with the rates of coral calcification showing major decline in the Red Sea (*medium confidence*) (Section 3.4.2.1, Steiner et al., 2018; Bindoff et al., 2019). In the Mediterranean Sea, evidence of acidification events have been reported at local scale (Hassoun et al., 2015), with impacts on bivalves and coralligenous species (*medium confidence*) (Lacoue-Labarthe et al., 2016).

Climate models project increasing frequency and intensity of MHWs (*high confidence*) (Section 3.2.2.1), which will exacerbate warming-driven impacts in the Red Sea and Persian Gulf regions, and erode the resilience of Red Sea coral reefs (*high confidence*) (Osman et al., 2018; Genevier et al., 2019; Kleinhaus et al., 2020). In the Persian Gulf region, extreme temperatures, >35ºC (Pal and Eltahir, 2016), have been linked with high rates of extirpation and a decrease in fisheries catch potential (*medium confidence*) (Wabnitz et al., 2018b). In the Mediterranean Sea, east-west gradients in rates of warming are projected to trigger spatially different changes in primary production, which combined with the increasing arrival of non-indigenous species, may trigger biogeographical changes in fish diversity, increasing in the eastern and decreasing in the western Mediterranean (*medium to high confidence*) (Albouy et al., 2013; Macias et al., 2015). Projections also show greater impacts from SLR than originally expected in the Mediterranean and Baltic (e.g., Dieterich et al., 2019; Thiéblemont et al., 2019). In the Baltic Sea, under high nutrient load and warming climate scenarios, eutrophication is projected to increase in the future (2069–2098) compared to historical (1976–2005) periods. In contrast, under continued nutrient load reductions following present management regulations, environmental conditions and ecological state will continue to improve independently of the climate warming scenarios (*low to medium confidence*) (Saraiva et al., 2019).

3.4.2.8 Shelf Seas

Shelf seas overlie the continental margin, often with maximum depths of <200 m, and represent 7% of the global ocean by area (Simpson and Sharples, 2012). These ecosystems are found offshore of every continent, generate 10–30% (Mackenzie et al., 2000; Andersson and Mackenzie, 2004) of global marine net primary production and play a key role in global biogeochemical cycling, including the export of land-borne carbon and nutrients (Johnson et al., 1999; Nishioka et al., 2011; Li et al., 2019) to the deep ocean and recycling of fixed nitrogen back to the atmosphere via denitrification (Devol, 2015). The shelf seas are home to several of the world's major industrial capture fisheries, such as those of the mid-Atlantic Bight, Scotian Shelf, Eastern Bering Sea Shelf and North Brazil Shelf (Barange et al., 2018), and support other marine industries, including aquaculture, extractive industries (oil, gas, and mining), shipping, and renewable-energy installations.

Similar to other coastal ecosystems, evidence since SROCC (Table 3.11) suggests shelf-sea ecosystems and the fisheries and aquaculture they support are sensitive to the interactive effects of climate-impact drivers, as well as non-climate drivers, including nutrient pollution, sedimentation, fishing pressure and resource extraction (Table 3.12, Figure 3.12). Changes in freshwater, nutrient and sediment inputs from rivers due to both climate and non-climate drivers can influence productivity and nutrient limitation, ecosystem structure, carbon export and species diversity and abundance (Balch et al., 2012; Picado et al., 2014), and can result in reduced water clarity and light penetration (Dupont and Aksnes, 2013; McGovern et al., 2019). Seasonal bottom-water hypoxia occurs in some shelf seas (e.g., northern Gulf of Mexico, Bohai Sea, East China Sea) due to riverine inputs of freshwater and nutrients, promoting stratification, enhanced primary production, and organic carbon export to bottom waters (*high confidence*) (Zhao et al., 2017; Wei et al., 2019; Del Giudice et al., 2020; Große et al., 2020; Jarvis et al., 2020; Rabalais and Baustian, 2020; Song et al., 2020a; Xiong et al., 2020; Zhang et al., 2020a).

Table 3.11: Summary of past IPCC assessments of shelf seas.

Observations	Projections
AR5 (Hoegh-Guldberg et al., 2014)	
Primary productivity, biomass yields, and fish capture rates have undergone large changes within the East China Sea over the past decades (*limited evidence, medium agreement, low confidence*). Changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod fisheries, and the size of demersal trawl catches in the northern South China Sea observed over the period 1976–2004 (*limited evidence, medium agreement*). Concurrent with the retreat of the "cold pool" on the northern Bering Sea shelf, bottom trawl surveys of fish and invertebrates show a significant community-wide northward distributional shift and a colonisation of the former cold pool areas by sub-Arctic fauna (*high confidence*). Observed changes in the phenology of plankton groups in the North Sea over the past 50 years are driven by climate forcing, in particular regional warming (*high confidence*).	Global warming will result in more frequent extreme events and greater associated risks to ocean ecosystems (*high confidence*). In some cases, projected increases will eliminate ecosystems, and increase the risks and vulnerabilities to coastal livelihoods and vulnerabilities for food security including Southeast Asia (*medium to high confidence*). Reducing stressors not related to climate change represents an opportunity to strengthen the ecological resilience within these regions, which may help biota survive some projected changes in ocean temperature and chemistry. Changes in eutrophication and hypoxia are *likely* to influence shelf seas, but there is *low confidence* in the understanding of the magnitude of potential changes and impacts on ecosystem functioning, fisheries and other industries.
SROCC (Bindoff et al., 2019)	
Species composition of fisheries catches since the 1970s in many shelf seas ecosystems of the world is increasingly dominated by warm water species (*medium confidence*). Estuaries, shelf seas and a wide range of other intertidal and shallow-water habitats play an important role in the	Direct anthropogenic impacts include coastal land-use change; indirect effects include increased nutrient delivery and other changes in river catchments, and marine resource exploitation in shelf seas. There is *high confidence* that these human-driven changes will continue, reflecting coastal settlement trends and global population growth.

global carbon cycle through their primary production by rooted plants, seaweeds (macroalgae) and phytoplankton, and also by processing riverine organic carbon. However, the natural carbon dynamics of these systems have been greatly changed by human activities (*high confidence*).

Table 3.12: Synthesis of interactive effects and their influence on shelf-sea ecosystems and the fisheries and aquaculture they support.

Factor	Example of effect	Example references
Temperature	Altered habitats for species, change in plankton, fish and macrofauna community structure, influence on species growth, thermal stress, altered diversity, altered productivity, altered phenology.	(Liang et al., 2018; Maharaj et al., 2018; Ma et al., 2019; Meyer and Kröncke, 2019; Yan et al., 2019; Bargahi et al., 2020; Bedford et al., 2020; Denechaud et al., 2020; Friedland et al., 2020b; Mérillet et al., 2020; Nohe et al., 2020)
pH	Acidification with hypoxia.	(Zhang and Wang, 2019)
Salinity	Change in species distribution due to altered salinity front distribution.	(Liu et al., 2020c)
Oxygen concentration	Deoxygenation.	(Wei et al., 2019; Del Giudice et al., 2020)
River discharge	Change in plankton community structure.	(Shi et al., 2020)
Nutrient pollution	Enhanced primary production, change in plankton community structure.	(Kong et al., 2019; Nohe et al., 2020)
Sedimentation	Modified ocean chemistry.	(Hallett et al., 2018)
Fishing pressure	Increased vulnerability leading to changes in community structure.	(Maharaj et al., 2018; Wang et al., 2019c; Hernvann and Gascuel, 2020)
Resource extraction	Contamination, change in benthic community structure.	(Hall, 2002)

Key risks to shelf seas include shifts or declines in marine micro- and macro-organism abundance and diversity driven by eutrophication, HABs and extreme events (storms and MHWs), and consequent effects on fisheries, resource extraction, transportation, tourism and marine renewable energy (Figure 3.12). The combined effects of deoxygenation and warming can affect the metabolism, growth, feeding behaviour and mobility of fish species (Section 3.3.3). The increasing availability of observations mean that ecosystem changes in shelf seas can be increasingly attributed to climate change (*high confidence*) (Liang et al., 2018; Maharaj et al., 2018; Ma et al., 2019; Meyer and Kröncke, 2019; Bargahi et al., 2020; Bedford et al., 2020; Friedland et al., 2020b; Mérillet et al., 2020). Eutrophication and seasonal bottom-water hypoxia in some shelf seas have been linked to warming (*high confidence*) (Wei et al., 2019; Del Giudice et al., 2020) and increased riverine nutrient loading (*high confidence*) (Wei et al., 2019; Del Giudice et al., 2020). Since SROCC, some severe HABs have been attributed to extreme events, such as MHWs (Section 14.4.2, Roberts et al., 2019; Trainer et al., 2019). However, a recent worldwide assessment of HABs attributed the increase in observed HABs to intensified monitoring associated with increased aquaculture production (*high confidence*) (Hallegraeff et al., 2021).

Since SROCC, changes in the community structure and diversity of plankton, macrofauna and infauna have been detected in some shelf seas, although attribution has been regionally specific (e.g., bottom-water warming or hypoxia) (Meyer and Kröncke, 2019; Rabalais and Baustian, 2020). Detection of the picoplankton *Synechococcus* spp. in the North Sea is potentially linked to a summer decrease in copepod stocks and declining food-web efficiency (*low confidence*) (Schmidt et al., 2020). The seasonally distinct phytoplankton assemblages in the North Sea have begun to appear concurrently and homogenise (Nohe et al., 2020). Changes in abundance, species composition, and size of zooplankton have been detected in some shelf seas (Yellow Sea, North Sea, Celtic Sea, and Tasman Sea), including a decline in stocks of larger copepods, increased abundances of gelatinous and meroplankton, and a shift to smaller species due to warming, increased river discharge, circulation change, and/or extreme events (*high confidence*) (Wang et al., 2018a; Bedford et al., 2020; Evans et al., 2020; Shi et al., 2020; Edwards et al., 2021).

Ocean warming has shifted distributions of fish (Free et al., 2019; Franco et al., 2020; Pinsky et al., 2020b; Fredston et al., 2021) and marine mammal species (Salvadeo et al., 2010; García-Aguilar et al., 2018; Davis et al., 2020) poleward (*high confidence*) or deeper (*low* to *medium confidence*) (Section 3.4.3.1, Nye et al., 2009; Pinsky et al., 2013; Pinsky et al., 2020b). Warming has also tropicalised the pelagic and demersal fish assemblages of mid- and high-latitude shelves (*high confidence*) (Montero-Serra et al., 2015; Liang et al., 2018; Maharaj et al., 2018; Ma et al., 2019; Friedland et al., 2020a; Kakehi et al., 2021; Punzón et al., 2021). Fisheries catch composition in many shelf-sea ecosystems has become increasingly dominated by warm-water species since the 1970s (*high confidence*) (Cheung et al., 2013; Leitão et al., 2018; Maharaj et al., 2018; McLean et al., 2019). Warming has taxonomically diversified fish communities along a latitudinal gradient in the North Sea, but homogenised functional diversity (McLean et al., 2019). However, in some regions, changing predator or prey distributions, temperature-dependent hypoxia, population changes, evolutionary adaptation, and other biotic or abiotic processes, including species' exploitation, confound responses to climate-impact drivers, which must therefore be interpreted with caution (Frank et al., 2018). For example, although, most species' range edges are tracking temperature change on the northeast shelf of the USA (*medium confidence*) (Fredston-Hermann et al., 2020; Fredston et al., 2021), range edges of others are not.

A wide range of responses by fish and invertebrate populations to warming have been observed. The majority of responses have been detrimental, with the direction and magnitude of the response depending on ecoregion, taxonomy, life history, and exploitation history (Free et al., 2019; Yati et al., 2020). For example, fisheries productivity has strongly decreased in the North Sea (Free et al., 2019), and fisheries yields have also decreased in the Celtic Sea, attributed primarily to warming and secondarily to long-term exploitation (Hernvann and Gascuel, 2020; Mérillet et al., 2020). Conversely, fish species diversity and overall productivity have increased in the Gulf of Maine, even with warming (Le Bris et al., 2018; Friedland et al., 2020a; Friedland et al., 2020b). Fisheries yields have decreased in the Yellow Sea, East China Sea and South China Sea due primarily to overexploitation (Ma et al., 2019; Wang et al., 2019c), with warming exerting more influence on the yield of cold-water species than on temperate- and warm-water groups (Ma et al., 2019). The combined effects of exploitation and multi-decadal climate fluctuations make it difficult to assess global climate-change impacts on fisheries yields (Chapter 5, Ma et al., 2019; Bentley et al., 2020b; Johnson et al., 2020).

Since AR5, increasing spatial and temporal extent of hypoxia has been projected due to enhanced benthic respiration and reduced oxygen solubility from warming (Del Giudice et al., 2020). Similar to the open ocean, large shifts in the phenology of phytoplankton blooms have been projected for shelf seas throughout subpolar and polar waters (*medium confidence*) (Henson et al., 2018a; Asch et al., 2019). Zooplankton, which are important prey for many fish species and sea birds, are expected to decrease in abundance on the northeast shelf of the USA (Grieve et al., 2017). However, responses vary by shelf ecosystem (Chust et al., 2014b). Trends towards tropicalisation will continue in the future (*high confidence*) (Cheung et al., 2015; Stortini et al., 2015; Allyn et al., 2020; Maltby et al., 2020; Costa et al., 2021), but uncertainty of future projections of fisheries production increases substantially beyond 2040 (Maltby et al., 2020). Nevertheless, shelf-sea fisheries at lower latitudes are most vulnerable to climate change (Monnereau et al., 2017). Under future climate change marked by more frequent and intense extreme events and the influences of multiple drivers, more flexible and adaptive management approaches could reduce climate impacts on species while also supporting industry adaptation (*high confidence*) (Section 3.6.3.1.2, Shackell et al., 2014; Stortini et al., 2015; Hare et al., 2016; Stortini et al., 2017; Greenan et al., 2019; Ocaña et al., 2019; Maltby et al., 2020).

3.4.2.9 Upwelling Zones

EBUS comprise four important social-ecological systems in the Pacific (California and Peru-Humboldt) and Atlantic (Canary and Benguela) ocean basins. Each is characterised by high primary production, sustained by wind-driven upwelling that draws cold, nutrient-rich, generally low-pH and low-oxygen water to the surface

(Bindoff et al., 2019). Despite their small relative size, the primary productivity in EBUS supports a vast biomass of marine consumers, including some of the world's most productive fisheries (Pauly and Zeller, 2016), along with many species of conservation significance (Bakun et al., 2015).

Although upwelling is important in many other oceanic regions, we focus here on the most documented examples provided by the EBUS. Yet even here, observed changes in upwelling, temperature, acidification and loss of oxygen (Seabra et al., 2019; Abrahams et al., 2021; Gallego et al., 2021; Varela et al., 2021) cannot be robustly attributed to anthropogenic climate change, and projected future changes in upwelling are expected to be relatively small and variable among and within EBUS (Section 3.2.2.3, WGI AR6 Chapter 9, Fox-Kemper et al., 2021). We therefore have few updates to assessments provided by AR5 and SROCC (Table 3.13) and restrict our brief assessment to the limited amount of new evidence (Figure 3.12).

Table 3.13: Summary of previous IPCC assessments of eastern boundary upwelling systems (EBUS).

Observations	Projections
AR5 (Hoegh-Guldberg et al., 2014; Lluch-Cota et al., 2014)	
EBUS are vulnerable to changes that influence the intensity of currents, upwelling, and mixing (and hence changes in sea-surface temperature, wind strength and direction), as well as O_2 content, carbonate chemistry, nutrient content, and the supply of organic carbon to deep offshore locations (*high confidence*). Climate-change-induced intensification of ocean upwelling in some EBUS, as observed in the last decades, may lead to regional cooling rather than warming of surface waters and cause enhanced productivity (*medium confidence*), but also enhanced hypoxia, acidification, and associated biomass reduction in fish and invertebrate stocks. Owing to contradictory observations there is currently uncertainty about the future trends of major upwelling systems and how their drivers will shape ecosystem characteristics (*low confidence*). Declining O_2 and shoaling of the aragonite saturation horizon through ocean acidification increase the risk of upwelling water being low in pH and O_2, with impacts on coastal ecosystems and fisheries. These risks and uncertainties are *likely* to involve significant challenges for fisheries and associated livelihoods along the west coasts of South America, Africa, and North America (*low to medium confidence*). There is *robust evidence* and *medium agreement* that the California Current has experienced an increase of the overall magnitude of upwelling events from 1967 to 2010 (*high confidence*). This is consistent with changes expected under climate change yet remains complicated by the influence of decadal-scale variability (*low confidence*). Declining oxygen concentrations and shoaling of the hypoxic boundary layer *likely* reduced the available habitat for key benthic communities as well as fish and other mobile species. Together with the shoaling of the saturation horizon, these changes have increased the incidence of low O_2 and low pH water flowing onto the continental shelf (*high confidence*; 40 to 120 m), causing problems for industries such as the shellfish aquaculture industry.	Like other ocean sub-regions, EBUS are projected to warm under climate change, with increased stratification and intensified winds as westerly winds shift poleward (*likely*). However, cooling has also been predicted for some EBUS, resulting from the intensification of wind-driven upwelling. There is *medium agreement*, despite *limited evidence*, that upwelling intensity and associated variables (e.g., temperature, nutrient, and O_2 concentrations) from the Benguela system will change as a result of climate change. Any projected increase in upwelling intensity has potential disadvantages. Elevated primary productivity may lead to decreasing trophic transfer efficiency, thus increasing the amount of organic carbon exported to the seabed, where it is *virtually certain* to increase microbial respiration and hence increase low O_2 stress.

Despite its apparent sensitivity to environmental variability, there is *limited evidence* of ecological changes in the Benguela Current EBUS due to climate change.

SROCC (Bindoff et al., 2019; IPCC, 2019c; IPCC, 2019d)

Increasing ocean acidification and oxygen loss are negatively impacting two of the four major upwelling systems: the California Current and Humboldt Current (*high confidence*). Ocean acidification and decrease in oxygen level in the California Current upwelling system have altered ecosystem structure, with direct negative impacts on biomass production and species composition (*medium confidence*).

Three out of the four major Eastern Boundary Upwelling Systems (EBUS) have shown large-scale wind intensification in the past 60 years (*high confidence*). However, the interaction of coastal warming and local winds may have affected upwelling strength, with the direction of changes varies between and within EBUS (*low confidence*). Increasing trends in ocean acidification in the California Current EBUS and deoxygenation in California Current and Humboldt Current EBUS are observed in the last few decades (*high confidence*), although there is *low confidence* to distinguish anthropogenic forcing from internal climate variability. The expanding California EBUS oxygen minimum zone has altered ecosystem structure and fisheries catches (*medium confidence*).

Overall, EBUS have been changing with intensification of winds that drives the upwelling, leading to changes in water temperature and other ocean biogeochemistry (*medium confidence*).

The direction and magnitude of observed changes vary among and within EBUS, with uncertainties regarding the driving mechanisms behind this variability. Moreover, the high natural variability of EBUS and their insufficient representation by global Earth System Models gives *low confidence* that these observed changes can be attributed to anthropogenic causes.

Anthropogenic changes in EBUS will emerge primarily in the second half of the 21st century (*medium confidence*). EBUS will be impacted by climate change in different ways, with strong regional variability with consequences for fisheries, recreation, and climate regulation (*medium confidence*). The Pacific EBUS are projected to have calcium carbonate undersaturation in surface waters within a few decades under Representative Concentration Pathway (RCP)8.5 (*high confidence*); combined with warming and decreasing oxygen levels, this will increase the impacts on shellfish larvae, benthic invertebrates, and demersal fishes (*high confidence*) and related fisheries and aquaculture (*medium confidence*).

The inherent natural variability of EBUS, together with uncertainties in present and future trends in the intensity and seasonality of upwelling, coastal warming and stratification, primary production and biogeochemistry of source waters poses large challenges in projecting the response of EBUS to climate change and to the adaptation of governance of biodiversity conservation and living marine resources in EBUS (*high confidence*).

Given the high sensitivity of the coupled human-natural EBUS to oceanographic changes, the future sustainable delivery of key ecosystem services from EBUS is at risk under climate change; those that are most at risk in the 21st century include fisheries (*high confidence*), aquaculture (*medium confidence*), coastal tourism (*low confidence*) and climate regulation (*low confidence*).

For vulnerable human communities with a strong dependence on EBUS services and low adaptive capacity, such as those along the Canary Current system, unmitigated climate change effects on EBUS (complicated by other non-climatic stresses such as social unrest) have a high risk of altering their development pathways (*high confidence*).

The California EBUS is arguably the best-studied of the four ecosystems in terms of robust projections of climate change, although even here, there is *limited evidence* and *low agreement* among projections. For example, trends in outputs from high-resolution, downscaled models in the California EBUS generally reflect those from underlying coarser-scale ESMs, but projections for physical variables are more convergent among modelling approaches than are those for biogeochemical variables (*high confidence*) (Howard et al., 2020a; Pozo Buil et al., 2021). Models agree on general warming in the California EBUS, with concomitant declines in oxygen content (*medium confidence*) (Howard et al., 2020b; Fiechter et al., 2021; Pozo Buil et al., 2021). But implications for the future spatial distribution of species, including for some fisheries resources (Howard et al., 2020b; Fiechter et al., 2021), are confounded by local-scale oceanographic process (Siedlecki et al., 2021) and by lateral input of anthropogenic land-based nutrients (Kessouri et al., 2021), suggesting that such projections should be accorded *low confidence*.

More generally, changes in upwelling intensity are observed to affect organismal metabolism, population productivity and recruitment, and food-web structure (*medium confidence*) (van der Sleen et al., 2018; Brodeur et al., 2019; Ramajo et al., 2020). But *low confidence* in projected trends in upwelling make it difficult to extrapolate these results to understand potential changes in the ecology of EBUS. Projected changes in fish biomass within EBUS (Carozza et al., 2019) are therefore accorded *low confidence*. Finally, although MHWs are an important emerging hazard in the global ocean, with intensity, frequency and duration increasing strongly (Section 3.2.2.1), the number of MHW days yr^{-1} within EBUS has been increasing more slowly (or decreasing faster, in the case of the Peru-Humboldt system) than in surrounding waters (Varela et al., 2021). Notwithstanding these trends, EBUS remain vulnerable both to MHWs (*high confidence*) (Sen Gupta et al., 2020) and to their long-lasting impacts (*high confidence*) (Arafeh-Dalmau et al., 2019; Harvell et al., 2019; McPherson et al., 2021). On this basis, the suggestion that EBUS may represent refugia from MHWs is accorded *low confidence*.

Despite *low confidence* in detailed projections for ecological changes in EBUS, the WGI assessment (WGI AR6 Chapter 9, Fox-Kemper et al., 2021) that upwelling-favourable winds will weaken (or be present for shorter durations) at low latitude but intensify at high latitude (*high confidence*), albeit by no more than 20% in either case (*medium confidence*), presents some key risks to associated EBUS ecosystems. These include potential decreases in provisioning services, including fisheries and marine aquaculture (Bertrand et al., 2018; Kifani et al., 2018; Lluch-Cota et al., 2018; van der Lingen and Hampton, 2018), and cultural services such as nature-based tourism (Section 3.5).

3.4.2.10 Polar Seas

The polar seas cover ~20% of the global ocean and include the deep Arctic Ocean and surrounding shelf seas as well as the Southern Ocean south of the polar front. They play a significant role in ocean circulation and absorption of anthropogenic CO_2 (Meredith et al., 2019). The Arctic is characterised by polar seas surrounded by land, while the Antarctic comprises continental Antarctica surrounded by the Southern Ocean. These high-latitude ecosystems share key properties, including strong seasonality in solar radiation and sea-ice coverage. Sea ice regulates water-column physics, chemistry and biology, air-sea exchange, and is a critical habitat for many species. In spring, when solar radiation returns and sea ice melts, intense phytoplankton blooms fuel food webs that include rich communities of both resident and summer-migrant species, with typically high dependency on a few key species for trophic transfer (Meredith et al., 2019; Rogers et al., 2020). Over the last two decades, Arctic Ocean surface temperature has increased in line with the global average, while there has been no uniform warming across the Antarctic (*high confidence*) (WGI AR6 Chapter 9, Fox-Kemper et al., 2021). Thus, the rate of change due to warming, and associated sea-ice loss, is greater in the Arctic than in the Antarctic (*high confidence*) (Section 3.2, Table 3.14, WGI AR6 Chapter 9, Fox-Kemper et al., 2021). Both Arctic and Antarctic regions have a long history of living resource extraction, including some of the largest fisheries on the globe in terms of catches. However, only the Arctic hosts human populations, holding a rich Indigenous knowledge and Local knowledge on these socio-ecological systems (Cross-Chapter Paper 6, Meredith et al., 2019).

Previous assessments of polar seas (Table 3.14) concluded that climate change has already profoundly influenced polar ecosystems, through changing species distributions and abundances from primary producers to top predators, including both ecologically and economically important species (*high confidence*) and that it will continue to do so (Table 3.14).

Table 3.14: Summary of previous IPCC assessments for polar seas.

Observations	Projections
AR5 (Wong et al., 2014)	
Poleward species distributional shifts are due to climate warming (*medium to high confidence*). Impacts of shifts in ocean conditions affect fish and shellfish abundances in the Arctic (*high confidence*). Changes in sea ice and the physical environment to the west of the Antarctic Peninsula are altering phytoplankton stocks and productivity, and krill (*high confidence*).	Some marine species will shift their ranges in response to changing ocean and sea ice conditions in the polar regions (*medium confidence*). Loss of sea ice in summer and increased ocean temperatures are expected to impact secondary pelagic production in some regions of the Arctic Ocean, with associated changes in the energy pathways within the marine ecosystem (*medium confidence*).

	Ocean acidification has the potential to inhibit embryo development and shell formation of some zooplankton and krill in the polar regions, with potentially far-reaching consequences to food webs in these regions (*medium confidence*). Shifts in the timing and magnitude of seasonal biomass production could disrupt coupled phenologies in the food webs, leading to decreased survival of dependent species (*medium confidence*).
SR15 (Hoegh-Guldberg et al., 2018a)	
A fundamental transformation is occurring in polar organisms and ecosystems, driven by climate change (*high confidence*).	The losses in sea ice at 1.5°C and 2°C of warming will result in habitat losses for organisms such as seals, polar bears, whales and seabirds. There is *high agreement* and *robust evidence* that phytoplankton species will change because of sea ice retreat and related changes in temperature and light penetration, and this is *very likely* to benefit fisheries productivity in the Arctic spring bloom system. 'Unique and threatened systems' (RFC1), including Arctic and coral reefs, display a transition from high to very high risk of transition at temperatures between 1.5°C and 2°C of global warming, as opposed to at 2.6°C of global warming in AR5 (*high confidence*).
SROCC (Bindoff et al., 2019)	
Climate-induced changes in seasonal sea ice extent and thickness and ocean stratification are altering marine primary production (*high confidence*), with impacts on ecosystems (*medium confidence*). Changes in the timing, duration and magnitude of primary production have occurred in both polar oceans, with marked regional or local variability (*high confidence*). In both polar regions, climate-induced changes in ocean and sea ice conditions have expanded the range of temperate species and contracted the range of polar fish and ice-associated species (*high confidence*). Ocean acidification will affect several key Arctic species (*medium confidence*).	Future climate-induced changes in the polar oceans, sea ice, snow and permafrost will drive habitat and biome shifts, with associated changes in the ranges and abundance of ecologically important species (*medium confidence*). Projected range expansion of subarctic marine species will increase pressure for high-Arctic species (*medium confidence*), with regionally variable impacts. Both polar oceans will be increasingly affected by CO_2 uptake, causing corrosive conditions for calcium carbonate shell-producing organisms (*high confidence*), with associated impacts on marine organisms and ecosystems (*medium confidence*). The projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial and subsistence fisheries with implications for regional economies, cultures and the global supply of fish, shellfish, and Antarctic krill (*high confidence*).

Since SROCC, evidence demonstrates that warmer oceans, less sea ice and increased advection results in increasing primary production in the Arctic, albeit with regional variation (*high confidence*), while trends remain spatially heterogeneous and less clear in the Antarctic (*medium confidence*) (Cross-Chapter Paper 6, Del Castillo et al., 2019; Lewis et al., 2020; Pinkerton et al., 2021; Song et al., 2021a). Furthermore, climate warming influences key mechanisms determining energy transfer between trophic levels including: (1) altered size spectra; (2) shifts in trophic pathways; (3) phenological mismatches; and (4) increased top-down trophic regulation (Table 3.15). However, the scale of impacts from changes in these mechanisms on ecosystem productivity in warming polar oceans remains unresolved and is hence assigned *low confidence*.

Table 3.15: Examples of mechanisms influencing transfer of energy between lower trophic levels in warmer polar oceans.

Mechanism	Examples	References
Altered size spectra	Shifts towards smaller algal cells and zooplankton in warmer and more stratified oceans results in longer and less-efficient food chains, with lower lipid content.	(Aarflot et al., 2018; Kimmel et al., 2018; Weydmann et al., 2018; Hop et al., 2019; Møller and Nielsen, 2020; Spear et al., 2020), but see Dong et al. (2021) and Vernet et al. (2017) for opposite trends.
Shifts in trophic pathways	Changes in microbial food-web interactions, including strengthening of microbial loop, may reduce overall productivity. Transitions from sea-ice algae to open-water phytoplankton production may reduce benthic-pelagic coupling and benthic production; transition from autotroph to heterotroph benthic production with increased water turbidity; shifts from krill-dominated to salp-dominated ecosystems in the Antarctic may have negative impacts on higher trophic levels.	(Cross-Chapter Paper 6, Fujiwara et al., 2016; Onda et al., 2017; Vernet et al., 2017; Grebmeier et al., 2018; Moore et al., 2018b; Cavan et al., 2019; Vaqué et al., 2019; Yurkowski et al., 2020)Braekcman et al 2021
Phenological mismatches	Mismatches in timing arise between spring phytoplankton blooms and zooplankton recruits.	(Søreide et al., 2010; Renaud et al., 2018; Dezutter et al., 2019)
Increased top-down trophic regulation	Increased predation efficiency and top-down regulation of zooplankton by zooplanktivorous fish (due to more light with less sea ice) disconnects zooplankton and phytoplankton production.	(Langbehn and Varpe, 2017; Kaartvedt and Titelman, 2018; Hobbs et al., 2021)

Major community shifts, both gradual and abrupt, are observed in polar oceans in response to warming trends and MHWs (Arctic only) (*high confidence*) (Cross-Chapter Paper 6, Figure 3.12, Beaugrand et al., 2019; Meredith et al., 2019; Huntington et al., 2020). In general, abundances and ranges of Arctic fish species are declining and contracting, while ranges of boreal fish species are expanding, both geographically and in terms of feeding interactions and ecological roles (*high confidence*) (Huserbråten et al., 2019; Meredith et al., 2019; Huntington et al., 2020; Pecuchet et al., 2020a), with variable outcomes for large commercial fish stocks (Cross-Chapter Paper 6, Kjesbu et al., 2014; Holsman et al., 2018; Free et al., 2019). The extreme seasonal solar radiation cycles of these high latitudes may both act as a barrier for species immigration and change predator-prey dynamics in previously ice-covered areas, factors not currently considered in projections (*limited evidence*) (Kaartvedt and Titelman, 2018; Ljungström et al., 2021). Responses by marine mammals and birds to the ongoing changes in polar ecosystems are both positive and negative (Meredith et al., 2019; Bestley et al., 2020). Phenological, behavioural, physiological, and distributional changes are observed in marine mammals and birds in response to altered ecological interactions and habitat degradation, especially to loss of sea ice (*high confidence*) (Box 3.2, Cross-Chapter Paper 6, Beltran et al., 2019; Cusset et al., 2019; Descamps et al., 2019; Meredith et al., 2019; Huntington et al., 2020). Reproductive failures and declining abundances attributed to warmer polar oceans and less sea-ice cover are observed in populations of polar bears, *Ursus maritimus*, seals, whales and marine birds (*high confidence*) (Box 3.2, Duffy-Anderson et al., 2019; Ropert-Coudert et al., 2019; Bestley et al., 2020; Chambault et al., 2020; Molnár et al., 2020; Stenson et al., 2020). The ongoing changes in polar marine ecosystems can lead to temporary increases in biodiversity and functional diversity (e.g., due to immigration of boreal species in the Arctic, *high confidence*), but reduced trophic-transfer efficiencies and functional redundancy, with uncertain consequences for ecosystem resilience and vulnerability (*limited evidence*, *low agreement*) (Griffith et al., 2019b; Alabia et al., 2020; du Pontavice et al., 2020; Alabia et al., 2021; Frainer et al., 2021).

Calcareous polar organisms are among the groups most sensitive to ocean acidification (*high confidence*) (Section 3.3.2). Niemi et al. (2021) reports that >80% of sampled sea snail, *Limacina helicina*, a key species in pelagic food webs, displayed signs of shell dissolution in the Amundsen Gulf. However, bacteria, phytoplankton, zooplankton and benthic communities are found to be detrimentally impacted, resilient, or even positively influenced by ocean acidification in observational and experimental studies (Section 3.3, Hildebrandt et al., 2016; Thor et al., 2018; Ericson et al., 2019; McLaskey et al., 2019; Meredith et al., 2019; Petrou et al., 2019; Renaud et al., 2019; Brown et al., 2020; Hancock et al., 2020; Henley et al., 2020; Johnson and Hofmann, 2020; Torstensson et al., 2021).While fish larval stages may be sensitive, adult fish are expected to have low vulnerability to projected acidification levels (Section 3.3.3, Hancock et al., 2020), although reduced swimming capacity in polar cod in an ocean acidification experiment has been observed (Kunz et al., 2018). Polar organisms' sensitivity to ocean acidification may increase with increasing light levels due to the loss of sea ice (algae, Donahue et al., 2019; Kvernvik et al., 2020), temperature stress (pteropods, Johnson and Hofmann, 2020), or indirectly via increased heterotrophic bacterial productivity (*limited evidence*) (Vaqué et al., 2019). Due to limited mechanistic understanding of observed effects, and mixed responses among Arctic species, future impacts of ocean acidification are assigned *medium confidence* for polar species, and *low confidence* for outcomes for polar ecosystems (Meredith et al., 2019; Green et al., 2021b).

While levels of pollutants in biota (e.g., persistent organic pollutants, mercury) have generally declined over the past decades, recent increasing levels are associated with release from reservoirs in ice, snow and permafrost, and through changing food webs and pathways for trophic amplification (*medium confidence*) (Box 3.2, Ma et al., 2016; Amélineau et al., 2019; Foster et al., 2019; Bourque et al., 2020; Kobusińska et al., 2020). Also, a warmer climate, altered ocean currents and increased human activities elevate the risk of invasive species in the Arctic (*medium confidence*), potentially changing ecosystems in this region (*high confidence*) (Chan et al., 2019; Goldsmit et al., 2020). In the remote Antarctic, there is a lower risk of invasive species (*limited evidence*) (McCarthy et al., 2019; Holland et al., 2021).

Fisheries are largely sustainably managed, yet are expanding polewards following sea-ice melt in the Arctic (*high confidence*) (Fauchald et al., 2021) and possibly in the Antarctic (*limited evidence*) (Santa Cruz et al., 2018). Tourism is increasing and expanding in both polar regions, while shipping and hydrocarbon exploration are growing in the Arctic, increasing the risks of compound effects on vulnerable and already stressed populations and ecosystems (*high confidence*) (Sections 3.6.3.1.3, 3.6.3.1.4, Cross-Chapter Paper 6, Hauser et al., 2018; Meredith et al., 2019; Helle et al., 2020; Rogers et al., 2020; Cavanagh et al., 2021).

Ensemble global model projections indicate future increases in primary production and total animal biomass towards 2100 under RCP2.6 (~ 5% and 50%, respectively) and RCP8.5 (~10% and 70%, respectively), in the Arctic (Bryndum-Buchholz et al., 2019; Lotze et al., 2019; Nakamura and Oka, 2019), highlighting opportunities for, and possibly conflicts over, new ecosystem services (Section 3.5). For the Southern Ocean, no overall trends are apparent, but greater variability in both primary production and total animal biomass are projected under RCP2.6, with a ~5% and 15% increase in primary production and total animal biomass under RCP8.5, respectively (Bryndum-Buchholz et al., 2019; Lotze et al., 2019; Nakamura and Oka, 2019). All projections presented exhibit high inter-model variability and hence uncertainty (Heneghan et al., 2021). Furthermore, regional models project significant distributional shifts and wide-ranging trends (i.e., relatively stable, increasing and declining) in productivity for key ecological and commercial species, and functional groups, with weak to strong dependence on emission scenarios, indicating *low confidence* in future outcomes for polar marine ecosystems and associated ecosystem services (Section 3.5, Piñones and Fedorov, 2016; Griffiths et al., 2017; Klein et al., 2018; Hansen et al., 2019; Meredith et al., 2019; Steiner et al., 2019; Tai et al., 2019; Alabia et al., 2020; Holsman et al., 2020; Reum et al., 2020; Veytia et al., 2020; Sandø et al., 2021). Potentially highly influential tipping points associated with Arctic sea-ice melt and Antarctic ocean circulation change adds to this uncertainty (Cross-Chapter Paper 6, Heinze et al., 2021). Nevertheless, increasing evidence supports that sustainable and adaptive ecosystem-based fisheries practices can reduce detrimental impacts of climate change on harvested populations (*medium confidence*) (Section 3.6.3.1.2, Klein et al., 2018; Free et al., 2019; Hansen et al., 2019; Holsman et al., 2020).

3.4.3 Oceanic Systems and Cross Cutting Changes

The oceanic zone, comprising >99% of the ocean's volume, is highly exposed to climate-impact drivers because of its proximity to the atmosphere (Section 3.2, Pörtner et al., 2014; Bindoff et al., 2019), while its relative distance from human settlements and coastal ecosystems decreases variability and interactions, and permits many phenomena to be detected clearly and attributed to climate change. This section assesses how climate-driven changes influence oceanic biological systems over very large spatial scales and notes how impacts on the epipelagic zone affect the mesopelagic, bathypelagic, and deep seafloor ecosystems.

3.4.3.1 Biogeography and Species Range Shifts

3.4.3.1.1 Observed species range shifts

Since previous assessments (Table 3.16), poleward range-shifts have remained a ubiquitous response to climate change (*high confidence*), moving species from warmer regions into higher-latitude ecosystems (Fossheim et al., 2015; Kumagai et al., 2018; Burrows et al., 2019; Lenoir et al., 2020).

Table 3.16: Summary of previous IPCC assessments of biogeography and species range shifts.

Observations	Projections
AR5: (Hoegh-Guldberg et al., 2014; Pörtner et al., 2014)	
The distribution and abundance of many fishes and invertebrates have shifted poleward and/or to deeper, cooler waters (*high confidence*). On average, species' distributions have shifted poleward by 72.0 ± 0.35 km per decade (*high confidence*).	Spatial shifts of marine species due to projected warming will cause high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas (*medium confidence*).
SROCC (Bindoff et al., 2019)	
Ocean warming has contributed to observed changes in biogeography of organisms ranging from phytoplankton to marine mammals (*high confidence*). The direction of the majority of the shifts of epipelagic organisms are consistent with a response to warming (*high confidence*) but are also shaped by oxygen concentrations and ocean currents across depth, latitudinal and longitudinal gradients (*high confidence*). Geographic ranges have shifted since the 1950s by 51.5 ± 33.3 km per decade (mean and *very likely* range) and 29.0 ± 15.5 km per decade for organisms in the epipelagic and seafloor ecosystems, respectively.	Recent model projections since AR5 and SR15 continue to support global-scale range shifts of marine fishes at rates of tens to hundreds of km per decade in the 21st century, with rate of shifts being substantially higher under RCP8.5 than RCP2.6.

Thermal tolerances of epipelagic populations drive biogeographic change (Figures 3.10, 3.15), but the strength and direction of range shifts tend to be modulated by both climate and non-climate drivers (Pinsky et al., 2020b), including: interactive effects of hypoxia and ocean acidification (Sampaio et al., 2021); oceanic dispersal barriers (Choo et al., 2021), food and critical habitat availability (Alabia et al., 2020; Tanaka et al., 2021), geographic position (including depth, Mardones et al., 2021), and ocean currents (Sunday et al., 2015; Chapman et al., 2020; Fuchs et al., 2020). The difference between physiological thermal tolerances (Section 3.3.2) and local environmental conditions determines safety margins against future climate warming in ectotherms (Pinsky et al., 2019). Acclimation and evolution (Section 3.3.4) and life-history stage (Section 3.3.3) also alter species' thermal tolerances. Biogeographic responses are further modulated by other interacting factors (Table 3.17).

A large global meta-analysis of range shifts across multiple levels of the marine food web (Lenoir et al., 2020) estimates that marine species are moving poleward at a rate of 59.2 km per decade (*very likely* range: 43.7–74.7 km per decade), closely matching the local climate velocity (*high confidence*). In some cases, warming-related distribution shifts were followed by density-dependent use of these areas, influencing associated fisheries (Baudron et al., 2020), and in others, warming influenced competitive interactions: in the Arctic-Boreal Barents Sea, warming-induced increases in cod (*Gadus morhua*) abundance reduces haddock (*Melanogrammus aeglefinus*) abundance (Durant et al., 2020).

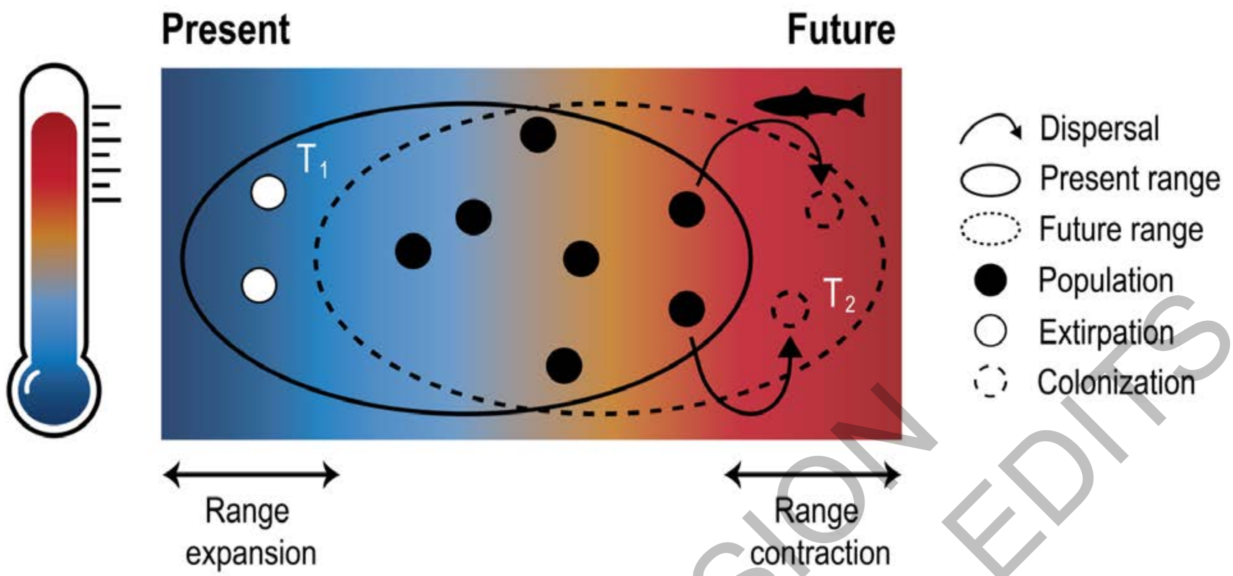


Figure 3.15: Schematic of range-shift dynamics in marine ectotherms in response to climate warming. As the ocean warms, conditions at the edge of the species' distribution may become warmer than the maximum thermal tolerance of the species (such as with T_2, see Figure 3.9), causing local populations to undergo a gradual decline in performance, a decreasing population size and ultimately their extirpation, resulting in a range contraction. Conversely, at the cool extreme of the distribution (such as with T_1), habitats beyond the current range of the species will become thermally suitable in the future (i.e., within the species' thermal tolerance range) and, providing the species can disperse to those locations, allow for the colonisation and consolidation of new populations and subsequent range expansion. These are processes conditioned by multiple drivers that interact with warming to ultimately define range shift responses; some of which are described in Table 3.17. Note that physiological thermal tolerances relate to body temperatures of the organism rather than ambient temperatures.

Table 3.17: Synthesis of selected processes conditioned by multiple environmental drivers that interact with warming to ultimately define range-shift responses.

Factor	Effect	Example references
Evolution and acclimation	Evolution of thermal tolerances and acclimation under local climatic conditions can increase resilience to future climate warming, slowing the loss of species at trailing (warm) range edges.	(Palumbi et al., 2014; Miller et al., 2020a)
Marine heatwaves (MHWs)	Influence the evolution of thermal tolerances by eliminating genotypes that are intolerant of elevated temperatures.	(Buckley and Huey, 2016; Sunday et al., 2019)
	MHWs can produce widespread die-offs of shallow-water benthic organisms triggering extensive contractions of their ranges.	(Smale and Wernberg, 2013)
	MHWs can facilitate range expansions by opening niches and/or enhancing recruitment of warm-affiliated species.	(Leriorato and Nakamura, 2019; Thomsen et al., 2019; Monaco et al., 2021)
	Cold-waves can halt or even reverse range expansions at leading edges.	(Leriorato and Nakamura, 2019)

Ocean currents	Influence range dynamics through their effect on dispersal, depending on their magnitude, direction and seasonal patterns.	(Hunt et al., 2016; Kumagai et al., 2018; Fuchs et al., 2020)
	Where currents align with spatial gradients of warming, range expansions track thermal changes more closely. Conversely, directional mismatches result in consistently slower expansion rates and larger response lags; an effect more acute for benthic organisms relying on passive dispersion of larvae and propagules.	(García Molinos et al., 2017)
	Rates of range contraction across taxa decreased (increased) under directional agreement (mismatch) with ocean currents, possibly associated with enhanced (reduced) flows of adaptive genes to warming in downstream (upstream) populations within the distributional range.	(García Molinos et al., 2017)
Climatic refugia	Areas of locally stable climatic conditions, such as deeper waters or regions with internal tides or localised upwelling, can buffer the effects of regional warming, facilitating species persistence and conserving genetic diversity at rear edge populations.	(Smith et al., 2014; Assis et al., 2016; Lourenço et al., 2016; Wyatt et al., 2020)
	Distributional shifts into deeper, cooler habitats can offer an effective alternative response to latitudinal shifts, because sharper thermal gradients mean vertical displacements, needed to compensate for the same amount of warming, are several orders of magnitude smaller than planar displacements.	(Smith et al., 2014; Assis et al., 2016; Lourenço et al., 2016)
Oxygen availability	Oxygen supersaturation may extend ectotherm survival to extreme temperatures and increase thermal tolerances by compensating for the increasing metabolic demand at high temperatures.	(Giomi et al., 2019)
	Oxygen deprivation increases metabolic demand and respiration rates. Shallowing of oxygen dead zones and subsequent hypoxic avoidance can render deep thermal refuges unsuitable for organisms.	(Brown and Thatje, 2015; Roman et al., 2019; Hughes et al., 2020)
Habitat availability and quality	The availability and quality of habitat (underwater light conditions, adequate substrate, nutrient and food supply) set limits to the distribution of organisms and range shift dynamics (e.g., resilience of populations to climate warming and the consolidation of range expansions).	(Krause-Jensen et al., 2019; Tamir et al., 2019)
Biotic interactions, including food availability	Species interactions can confer resilience to warming by retarding habitat degradation and buffering the impacts of warming on organisms.	(Falkenberg et al., 2015; Giomi et al., 2019)

	Changes in biotic interactions (e.g., altered predation rates, food availability, competition or trophic mismatches) induced by climate warming can modify range-shift dynamics.	(Selden et al., 2018; Westerbom et al., 2018; Figueira et al., 2019; Pinsky et al., 2020b; Monaco et al., 2021)

Biogeographic shifts lead to novel communities and biotic interactions (*high confidence*) (Zarco-Perello et al., 2017; Pecuchet et al., 2020b), with concomitant changes in ecosystem functioning and servicing (*high confidence*) (Vergés et al., 2019; Nagelkerken et al., 2020; Peleg et al., 2020). For instance, temperature-driven changes in distribution and abundance of copepods, the dominant zooplankton, were observed between 1960–2014 in the North Atlantic. These changes subsequently affect biogenic carbon cycling through alteration of microbial remineralisation and carbon sequestration in deep water (*medium confidence*) (Section 3.4.3.6, Pitois and Fox, 2006; Brun et al., 2019).

3.4.3.1.2 Observed vertical redistributions

Epipelagic isotherms have recently (1980–2015) deepened at an average of 6.6 ± 18.8 m per decade (Pinsky et al., 2019) but, there is *low agreement* on whether species move deeper in pursuit of thermal refuge. Prior studies suggested range shifts to depth (Dulvy et al., 2008; Pinsky et al., 2013; Yemane et al., 2014), but increasing evidence suggests that fish and planktonic communities across large parts of the North Atlantic, sub-Arctic and northeast Pacific Ocean redistribute horizontally with horizontal climate velocity, except where vertical temperature gradients are particularly steep. There is *low confidence* for temperature-driven depth shifts in the epipelagic zone (Burrows et al., 2019; Campana et al., 2020; Caves and Johnsen, 2021). At the same time, decreasing oxygen concentrations and the vertical expansion of OMZs have already decreased suitable habitat of pelagic fishes, including tuna and billfishes, by ~15% primarily due to vertical compression of environmental niches (Stramma et al., 2012; Deutsch et al., 2015).

3.4.3.1.3 Projected changes in species range shifts

Continued changes in the biogeography of marine predators and prey are anticipated under future climate change, with climate velocity in the epipelagic zone during 2050–2100 under RCP8.5 projected to be sevenfold faster than that during 1955–2005 (*medium confidence*) (Figure 3.4, Brito-Morales et al., 2020). This have substantial ecological implications, as projections suggest near-elimination of overlaps between the distributions of certain predator-prey pairs in the northeast Atlantic Ocean when their current joint distributions (1989–2014) are compared with those projected (2037–2062) under RCP8.5 (Sadykova et al., 2020).

Deepening of epipelagic isotherms is projected to accelerate over 2006–2100 to rates of 8.5 m per decade under RCP4.5 and 32 m per decade under RCP8.5 (Jorda et al., 2020). Although vertical redistribution of thermal niches is three to four orders of magnitude slower than horizontal displacement, maximum depth limits imposed by the seafloor and photic layer (both of which are projected to be reached in this century) will *likely* vertically compress suitable habitat for most marine organisms (*medium confidence*) (Dueri et al., 2014; Jorda et al., 2020).

Projections from coupled biogeochemical and ecosystem models suggest a general decline in mesopelagic biomass (Lefort et al., 2015), although this may vary among ocean basins. The volume of OMZs have been expanding at many locations (*high confidence*), and the oxygen content of the subsurface ocean is projected to decline to historically unprecedented conditions over the 21st century (*medium confidence*) (Section 3.2.3.2, WGI AR6 Section 5.3.3.2, Canadell et al., 2021) at a rate of 10–15 µM per decade in OMZs (Section 3.2.3.2, Breitburg et al., 2018). Oxygen availability and the effects of ocean acidification (Sections 3.3, 3.4.2) on zooplankton might become a dominant constraint in the upper ocean's metabolic index, which is projected to decrease globally by 20% by 2100 (Deutsch et al., 2015; Steinberg and Landry, 2017). In addition, extremely rapid acceleration of climate velocities projected in the mesopelagic under all emissions scenarios suggest that species in this ocean stratum will be even more exposed to future warming than species in the epipelagic (Figure 3.4, Brito-Morales et al., 2020). But projections also suggest that warming-related increases in trophic efficiency lead to a 17% increase in the biomass of the deep scattering layer (zooplankton and fish in the mesopelagic) by 2100 (low *confidence*) (Bindoff et al., 2019); observational studies appears to show that mesopelagic fishes adapted to warm water increased in abundance and distribution in the California Current associated with warming and the expansion of OMZ (Koslow et al., 2019), suggesting that some mesopelagic fish stocks might be resilient to a changing climate (*medium confidence*).

3.4.3.2 Phenological shifts & trophic mismatches

3.4.3.2.1 Observed changes

SROCC reported *high confidence* in phenological shifts towards earlier onset of biological events (Table 3.18), with phenological shifts among epipelagic species attributed to ocean warming (*high confidence*).

Table 3.18: Summary of previous IPCC assessments of phenological shifts & trophic mismatches

Observations	Projections
AR5 WGII (Hoegh-Guldberg et al., 2014; Larsen et al., 2014)	Projections of phenological shifts and trophic mismatches were not assessed in this report.
Changes to sea temperature have altered the phenology, or timing of key life-history events such as plankton blooms, and migratory patterns and spawning in fish and invertebrates, over recent decades (*medium confidence*). There is *medium to high agreement* that these changes pose significant uncertainties and risks to fisheries, aquaculture, and other coastal activities. The highly productive high-latitude spring bloom systems in the northeastern Atlantic are responding to warming (*medium evidence, high agreement*), with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages, and the reorganisation of fish assemblages, with a range of consequences for fisheries (*high confidence*). Observed changes in the phenology of plankton groups in the North Sea over the past 50 years are driven by climate forcing, in particular regional warming (*high confidence*). On average, spring events in the ocean have advanced by 4.4 ± 0.7 days per decade (mean ± SE). Shifts in the timing and magnitude of seasonal biomass production could disrupt matched phenologies in the food webs, leading to decreased survival of dependent species (*medium confidence*). If the timing of primary and secondary production is no longer matched to the timing of spawning or egg release, survival could be impacted, with cascading implications to higher trophic levels. This impact would be exacerbated if shifts in timing occur rapidly (*medium confidence*). There is *medium to high confidence* that climate- induced disruptions in the synchrony between timing of spawning and hatching of some fish and shellfish and the seasonal increases in prey availability can result in increased larval or juvenile mortality or changes in the condition factor of fish and shellfish species in the Arctic marine ecosystems.	
SROCC (Bindoff et al., 2019)	
Phenology of marine ectotherms in the epipelagic systems are related to ocean warming (*high confidence*) and that	Projections of phenological shifts and trophic mismatches were not assessed in this report.

the timing of biological events has shifted earlier (*high confidence*). Timing of spring phenology of marine organisms is shifting to earlier in the year under warming, at an average rate of 4.4 ± 1.1 days per decade, although it is variable among taxonomic groups and among ocean regions.	
WGI AR6 Chapter 2 (Gulev et al., 2021)	
Phenological metrics for many species of marine organisms have changed in the last half-century (*high confidence*), though many regions and many species of marine organisms remain under-sampled or even unsampled. The changes vary with location and with species (*high confidence*). There is a strong dependence of survival in higher trophic-level organisms (fish, exploited invertebrates, birds) on the availability of food at various stages in their life cycle, which in turn depends on phenologies of both (*high confidence*). There is a gap in our understanding of how the varied responses of marine organisms to climate change, from a phenological perspective, might threaten the stability and integrity of entire ecosystems.	Projections of phenological shifts and trophic mismatches were not assessed in this report.

Since SROCC, field data have continued to show that the phenology of biological events in the ocean is *very likely* (*high* to *very high confidence*) advancing in response to climate change, with 71.9% of published observations consistent with these anticipated effects (Figure 3.16a,b; Table 3.19), although most reports (95.6%) were from the Northern Hemisphere (Figure 3.16a). Biological events that are shifting earlier in response to climate change include phytoplankton blooms (Scharfe and Wiltshire, 2019; Chivers et al., 2020) such as those of HAB species (Forsblom et al., 2019; Bucci et al., 2020); peaks in zooplankton abundance (Chevillot et al., 2017; Forsblom et al., 2019); the migration (Otero et al., 2014; Kovach et al., 2015; Chust et al., 2019) and spawning of commercial fish (McQueen and Marshall, 2017; Kanamori et al., 2019) including crabs and squid (Henderson et al., 2017); and breeding of marine reptiles (Mazaris et al., 2008; Cherkiss et al., 2020). Moreover, different trophic levels within epipelagic food webs are responding at different rates (*very high confidence*) (Table 3.19, Figure 3.16b,c), with greater and more consistent responses by lower trophic levels (phytoplankton, holozooplankton and meroplankton), but less consistent, weaker and more varied responses by higher trophic levels. There were too few independent time series to make robust estimates for benthic invertebrates, plants, marine reptiles and mammals. This differential response across trophic levels could lead to trophic mismatches (Neuheimer et al., 2018), where predators and their prey respond asynchronously to climate change (Edwards and Richardson, 2004; Rogers and Dougherty, 2019; Rubenstein et al., 2019; Émond et al., 2020), with potential population-level consequences, including declines in fish recruitment (Burthe et al., 2012; Chevillot et al., 2017; McQueen and Marshall, 2017; Asch et al., 2019; Durant et al., 2019; Régnier et al., 2019). Available evidence also suggests that feeding relationships could modulate species responses to climate change, as seen in breeding of surface-feeding and deeper-diving seabirds (Descamps et al., 2019). These differential responses could determine ‘winners’ and ‘losers’ under future climate change (Lindén, 2018).

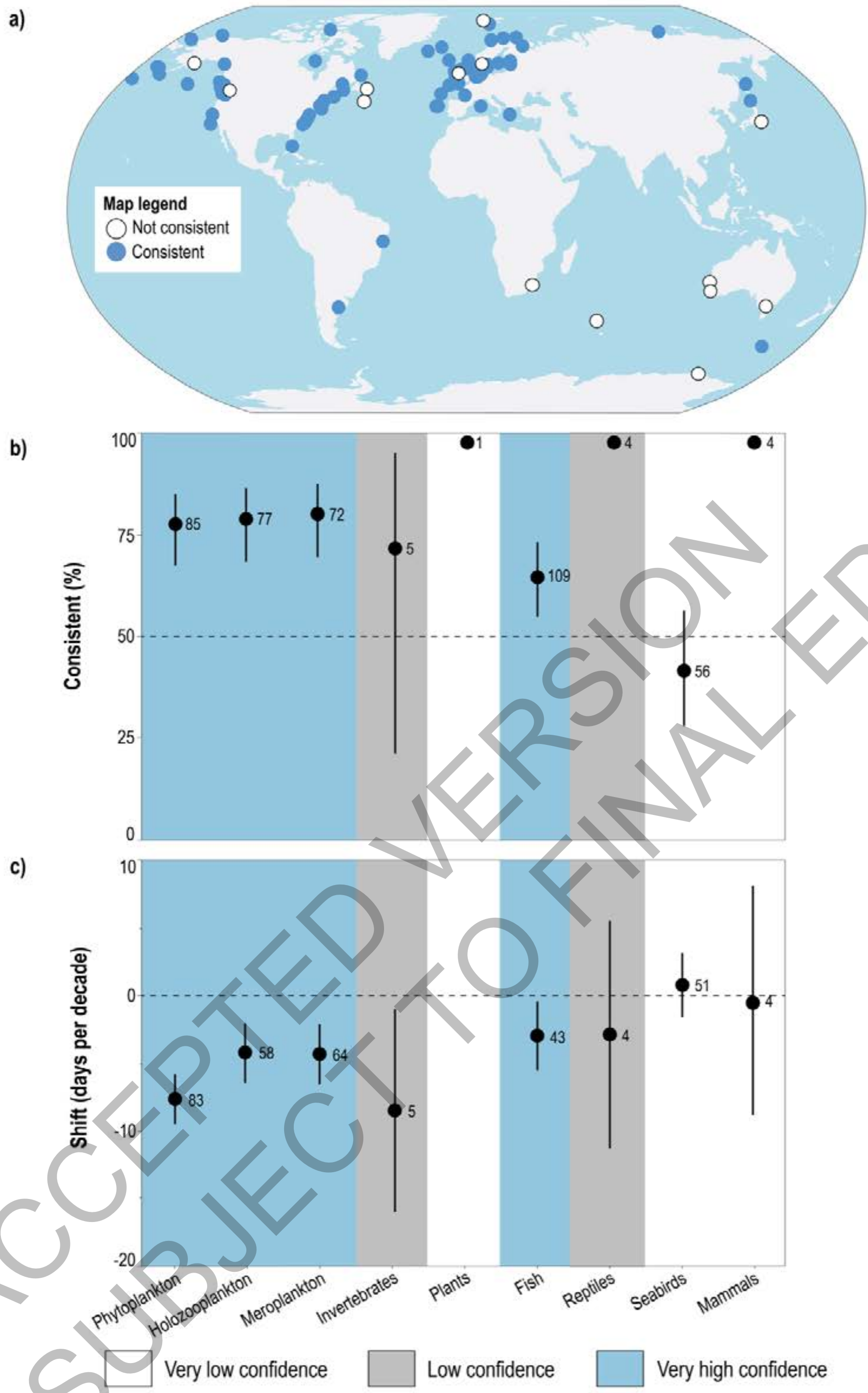


Figure 3.16: Observed responses to climate change based on a systematic Web of Science review of marine phenology studies exceeding 19 years in length to update the assessment in WGII AR5 Chapter 30 (Hoegh-Guldberg et al., 2014). Error bars indicate 95% confidence limits (i.e., the *extremely likely* range). (a) Global data showing changes in seasonal cycles of biota that are attributed (at least partly) to climate change (blue, n=297 observations), and changes that are inconsistent with climate change (white, n=116 observations). Each circle represents the centre of a study area. (b) The proportion of phenological observations (showing means and *extremely likely* ranges) that are attributed to climate change (i.e., generally showing earlier timing) by taxonomic group. (c) Observed shift in timing (days per decade, showing means and *extremely likely* ranges), by taxonomic group, that are attributed to climate change. Negative shifts are earlier, positive shifts are later. Details and additional plots are presented in SM3.3.3, Figure SM3.3 and Table SM3.1.

Table 3.19: Assessment of phenological shifts by taxon based on time series from field observations spanning at least 19 years published over the past 25 years.

Taxon	Rate of consistency of observations with climate change	Estimated mean rate of change in seasonal timing	Confidence	Notes
Phytoplankton	78.41% (n=85)	–7.5 days per decade (n=83)	*Very high confidence*	*Evidence most robust* for changes in timing of blooms in the North Atlantic (e.g., Chivers et al., 2020) and Baltic (e.g., Scharfe and Wiltshire, 2019; Wasmund et al., 2019), with *limited evidence* from the Southern Hemisphere.
Holozooplankton	79.74% (n=77)	–4.27 days per decade (n=58)	*Very high confidence*	*Evidence most robust* in the northeast Atlantic (e.g., Chevillot et al., 2017), but sparse elsewhere.
Meroplankton (taxa that are only temporarily in the plankton)	81.06% (n=72)	–4.34 days per decade (n=64)	*Very high confidence*	Includes earlier peak abundance of fish larvae in upwelling systems (e.g., Asch, 2015).
Benthic invertebrates	72.34% (n=5)	–8.5 days per decade (n=5)	*Low confidence* (*limited evidence, medium agreement*)	*Evidence is limited*, uncertainty levels are high. Rate of consistency of responses with climate change is not significantly different from random chance.
Plants	100% (n=1)	No estimate available	*Very low confidence*	Just a single study for seagrasses, and only for consistency (Diaz-Almela et al., 2007).
Fish	65.48% (n=109)	–3.02 days per decade (n=43)	*Very high confidence*	Includes earlier appearance of migratory fish in estuaries (e.g., Chevillot et al., 2017), earlier spawning migrations for anadromous fish such as salmon (e.g., Rubenstein et al., 2019), earlier migrations for sole (e.g., Fincham et al., 2013) and tuna (e.g., Dufour et al., 2010), and earlier spawning of key commercial demersal (bottom-dwelling) species such as cod (e.g., McQueen and Marshall, 2017).

Marine reptiles	100.0% (n=4)	–2.89 days per decade (n=4)	*Low confidence* (*limited evidence, low agreement*)	*Evidence is limited*, uncertainty levels are high. Mean phenological shift is not significantly different from zero.
Seabirds	42.36% (n=56)	+0.77 days per decade (n=51)	*Very low confidence* (*limited evidence, low agreement*)	Neither the rate of consistency with climate change nor the phenological shift differ significantly from null expectations (50% consistency and no shift). Many seabirds are breeding earlier (Byrd et al., 2008; Sydeman et al., 2009), while breeding among others in temperate and polar regions has been delayed, which has been linked to later sea-ice breakup or limited prey resources (Barbraud and Weimerskirch, 2006; Wanless et al., 2009; Chambers et al., 2014). Although the response of lifecycle events for many seabird species is variable in direction, there has usually been a more complex driver associated with climate that has been considered to be responsible (Sydeman et al., 2015). For many species, seasonal timing is moving earlier, especially in the Arctic (e.g., Byrd et al., 2008; Descamps et al., 2019), but for many species in the Southern Ocean, it is not (Barbraud and Weimerskirch, 2006; Chambers et al., 2014). This could be because of a much slower rate of warming in most of the Southern Ocean than in the Arctic.
Marine mammals	100.0% (n=4)	–0.34 days per decade (n=4)	*Very low confidence* (*limited evidence, low agreement*)	All studies of phenological changes for marine mammals have focused on whales (e.g., Ramp et al., 2015; Hauser et al.,

2017; Loseto et al., 2018) or polar bears (e.g., Cherry et al., 2013; Atwood et al., 2016; Escajeda et al., 2018) and have related timing to aspects of sea ice dynamics, highlighting the complexity of such processes. Mean phenological shift is not significantly different from zero at the global scale.

3.4.3.2.2 Projected changes

The CMIP6 ESM ensembles project that, by 2100, 18.8% ± 19.0% (mean ± *very likely* range) and 38.9% ± 9.4% of the ocean surface will *very likely* undergo a change of 20 days or more (advance or delay) in the start of the phytoplankton growth period under SSP1-2.6 and SSP5-8.5, respectively (Figure 3.17a,b) (*low confidence* due to the dependence with the projected changes in phytoplankton biomass which trends are reported with *low confidence*) (Section 3.4.3.4 and SROCC Section 5.2.3, Bindoff et al., 2019). Phytoplankton growth is projected to begin later in the Northern Hemisphere subtropics, and earlier at high latitudes in some regions around the Antarctic Peninsula, and over large areas in the Northern Hemisphere (*low to medium confidence* as there are improved constraints from historical variability in this region and consistency with CMIP5-based studies results) (Henson et al., 2018b; Asch et al., 2019). There is *high agreement* in model projections that the start of the phytoplankton growth period will *very likely* advance in the Arctic Ocean under a high-emission scenario for CMIP5 and CMIP6 (Figure 3.17b, Henson et al., 2018b; Asch et al., 2019; Tedesco et al., 2019; Lannuzel et al., 2020). The CMIP6 ensemble projections further show limited changes in phenology across most of the Southern Ocean, but large regional variations in the tropics (Figure 3.17). Overall, the regional patterns are qualitatively similar under SSP1-2.6 and SSP5-8.5, but with greater magnitude and larger areas under SSP5-8.5 (*low confidence*).

At latitudes >40ºN, temperature-linked phenology of fish reproduction with high geographic fidelity to spawning grounds (geographic spawners) is projected to change at double the rate of that for phytoplankton, which will *likely* cause phenological mismatches resulting in increased risk of starvation for fish larvae (*medium* to *high confidence*) (WGI AR6 Section 2.3.4.2.3, Asch et al., 2019; Durant et al., 2019; Régnier et al., 2019; Gulev et al., 2021; Laurel et al., 2021). Furthermore, under RCP8.5, trophic mismatch events exceeding ±30 days (Asch et al., 2019) leading to fish recruitment failure are expected to increase 10-fold for geographic spawners across much of the North Atlantic, North Pacific and Arctic Ocean basins (*low confidence*) (Neuheimer et al., 2018). In contrast, temporal mismatches between fish that relocate spawning grounds in response to environmental variations (environmental spawners) and phytoplankton blooms are projected to remain shorter and less varied, suggesting that across ocean basins, range shifts by environmental spawners may increase their resilience. Nevertheless, this compensation mechanism might fail at locations where phytoplankton bloom phenology is not controlled by temperature-driven water-column stratification, leading to a possible six-fold local increase in extreme mismatches under climate change (Asch et al., 2019).

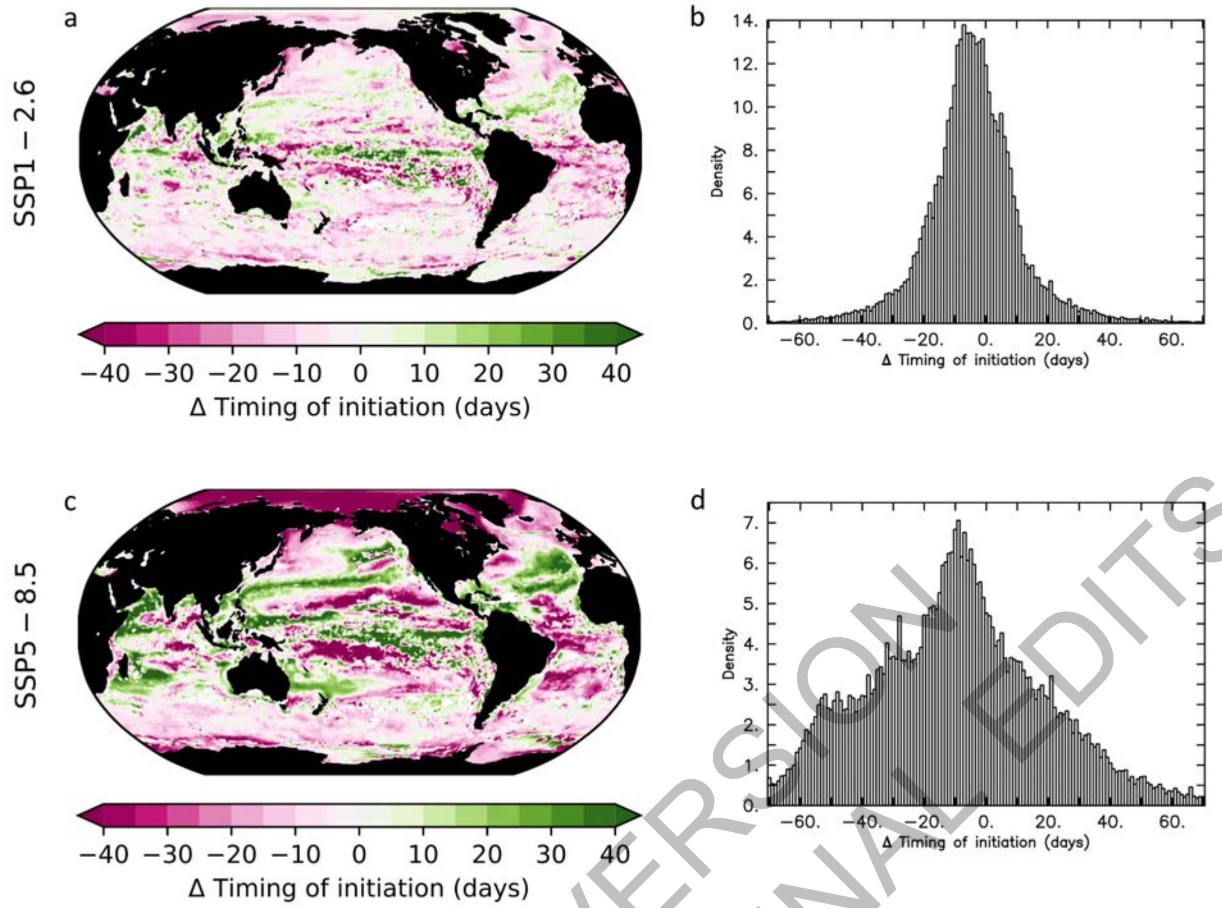


Figure 3.17: Projected phytoplankton phenology. (a,c) Spatial patterns and (b,d) density distributions of projected change in phytoplankton phenology by 2100 under Shared Socioeconomic Pathway (SSP)1-2.6 and SSP5-8.5, respectively. Difference in the start of the phytoplankton growth period is calculated as 2090–2099 minus 1996–2013. Negative (positive) values indicate earlier (later) start of the phytoplankton growth period by 2100. The ensemble projections of global changes in phytoplankton phenology include, under SSP1-2.6 and SSP5-8.5, respectively, a total of five Coupled Model Intercomparison Project 6 Earth System Models containing coupled ocean biogeochemical models that cover a wide range of complexity (Kwiatkowski et al., 2019). The phenology calculations are based on Racault et al. (2017) using updated data.

3.4.3.3 Changes in Community Composition and Biodiversity

3.4.3.3.1 Evidence of natural adaptive capacity based on species' responses to past climate variability

Responses to abrupt climate change in the geological past suggest that adaptive capacity is limited for marine animals (Cross-Chapter Box PALEO in Chapter 1). Temperatures during the last Interglacial (~125 ka), which were warmer than today, led to poleward range shifts of reef corals (*medium confidence*) (Kiessling et al., 2012; Jones et al., 2019a). Temperature has also driven marine range shifts over multi-million-year timescales (*medium confidence*) (Gibbs et al., 2016; Reddin et al., 2018). Warming climates, even with low ocean warming rates, inevitably decreased tropical marine biodiversity compared with mid-latitudes (*high confidence*) (Mannion et al., 2014; Crame, 2020; Yasuhara et al., 2020; Raja and Kiessling, 2021).

The paleo record confirms that marine biodiversity has been vulnerable to climate warming both globally and regionally (*very high confidence*) (Cross-Chapter Box PALEO in Chapter 1, Stanley, 2016). In extreme cases of warming (e.g., >5.2°C), marine mass extinctions occurred in the geological past, and there may be a relationship between warming magnitude and extinction toll (*medium confidence*) (Song et al., 2021b). A combination of warming and spreading anoxia caused marine extinctions in ancient episodes of rapid climate warming (*high confidence*) (Bond and Grasby, 2017; Benton, 2018; Penn et al., 2018; Them et al., 2018; Chen and Xu, 2019). The role of ocean acidification in ancient extinctions is yet to be resolved (*low confidence*) (Clapham and Payne, 2011; Clarkson et al., 2015; Jurikova et al., 2020; Müller et al., 2020).

3.4.3.3.2 Community Structure and Biodiversity

Observed contemporary changes

Ocean temperature is a major driver of species richness in the global ocean at evolutionary timescales (Tittensor et al., 2010; Chaudhary et al., 2021). This, together with temperature-driven range and phenology shifts evident across taxa and ocean ecosystems (Sections 3.4.3.1, 3.4.3.2), suggests that recent ocean warming (Section 3.2.2.1) should alter biodiversity at regional to global scales. Since previous assessments (Table 3.20), the most common evidence supporting these expected changes is replacement of cold-adapted species by warm-adapted species within an ecosystem as waters warm (Worm and Lotze, 2021). Known as tropicalisation (Section 3.4.2.3), this phenomenon has been attributed to ocean warming (*medium* to *high confidence*) in communities as diverse as kelp, invertebrates, plankton and fish (Burrows et al., 2019; Flanagan et al., 2019; Ajani et al., 2020; Villarino et al., 2020; Punzón et al., 2021; Smith et al., 2021).

Table 3.20: Summary of previous IPCC assessments of community composition and biodiversity.

Observations	Projections
AR5: (Hoegh-Guldberg et al., 2014; Pörtner et al., 2014)	
The paleoecological record shows that global climate changes comparable in magnitudes to those projected for the 21st century under all scenarios resulted in large-scale biome shifts and changes in community composition; and that for rates projected under RCP6 and 8.5 were associated with species extinctions in some groups (*high confidence*). Loss of corals due to bleaching has a potentially critical influence on the maintenance of marine biodiversity in the tropics (*high confidence*).	Spatial shifts of marine species due to projected warming will cause high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas (*medium confidence*). Species richness and fisheries catch potential are projected to increase, on average, at mid and high latitudes (*high confidence*) and decrease at tropical latitudes (*medium confidence*). Shifts in the geographical distributions of marine species cause changes in community composition and interactions. Thereby, climate change will reassemble communities and affect biodiversity, with differences over time and between biomes and latitudes (*high confidence*). Models are currently useful for developing scenarios of directional changes in net primary productivity, species distributions, community structure, and trophic dynamics of marine ecosystems, as well as their implications for ecosystem goods and services under climate change. However, specific quantitative projections by these models remain imprecise (*low confidence*).
SROCC (Bindoff et al., 2019)	
Ocean warming has contributed to observed changes in biogeography of organisms ranging from phytoplankton to marine mammals (*high confidence*), consequently changing community composition (*high confidence*), and in some cases, altering interactions between organisms and ecosystem function (*medium confidence*).	Poleward range shifts are projected to decrease species richness in tropical oceans, counterbalanced by increases in mid to high-latitude regions, leading to global-scale species turnover (*medium confidence* on trends, *low confidence* on magnitude because of model uncertainties and limited number of published model simulations). The projected intensity of species turnover is lower under low-emission scenarios (*high confidence*). Projections from multiple fish species distribution models show hotspots of decrease in species richness in the Indo-Pacific region, and semi-enclosed seas such as the Red Sea and Persian Gulf (*medium evidence, high agreement*). In addition, geographic barriers, such as land, bounding the poleward species range edge in semi-enclosed seas or low-oxygen water in deeper waters are projected to limit range shifts, resulting in larger relative decrease in species richness (*medium confidence*).

	The large variation in sensitivity of different zooplankton taxa to future conditions of warming and ocean acidification suggests elevated risk to community structure and inter-specific interactions of zooplankton in the 21st century (*medium confidence*).

At local to regional scales, tropicalisation often increases species richness where warm-water species extend their ranges to overlap with existing communities, and decreases species richness where warming waters extirpate species (*medium* to *high confidence*) (Friedland et al., 2020a; Chaudhary et al., 2021; Worm and Lotze, 2021). Latitudinal estimates from catalogued observations show declining species richness in equatorial waters over the past 50 years, with concomitant increases in species richness at mid-latitudes; the pattern is especially prominent in free-swimming pelagic species (Figure 3.18, Chaudhary et al., 2021). Similar patterns among marine animals have been described previously for historical warming events (Song et al., 2020b). Tropicalisation is associated with increased representation of herbivorous species (Vergés et al., 2016; Zarco-Perello et al., 2020; Smith et al., 2021), although observations and theory suggest that dietary generalism can also favour range-shifting species (Monaco et al., 2020; Wallingford et al., 2020).

Projected changes

At the community level, the magnitude and shape of biodiversity changes differ, depending on what groups are considered (*medium confidence*) (Chaudhary et al., 2021). Molecular-based richness measures indicate that the most dramatic increases in diversity relative to current conditions are expected for photosynthetic eukaryotes and copepods in the Arctic Ocean (Ibarbalz et al., 2019). However, component eukaryotic taxa, for example diatoms Busseni et al. (2020), are projected to lose diversity by 2100 under RCP8.5. Ecosystem models project a decline in nutrient supply that drives the disappearance of less-competitive and larger phytoplankton types, leading to extinction of up to 30% of diatom types, particularly in the northern hemisphere, by 2100 under RCP8.5 (Henson et al., 2021). Models further suggest that high latitudes are *likely* to encounter entirely novel phytoplankton communities by 2100 under RCP8.5 (100% change in community composition, Dutkiewicz et al., 2019; Reygondeau et al., 2020). At the polar edges, the increased richness is projected to coincide with high species turnover and increasing dominance of smaller phytoplankton types (Henson et al., 2021). These imply pronounced changes to both the oceans' ecological and biogeochemical function, as regions dominated by small phytoplankton typically support less-productive food webs (Section 3.4.3.4, Stock et al., 2017; Armengol et al., 2019) and sequester less particulate organic carbon in the deep ocean (Section 3.4.3.5, Mouw et al., 2016; Cram et al., 2018) than areas dominated by larger size classes (*high confidence*).

The profound climatic and environmental changes projected for the Arctic region by 2100 (Cross-Chapter Paper 6) are also anticipated to alter the composition of apex assemblages like marine mammals (Albouy et al., 2020, Box 3.2). Under both RCP2.6 and 8.5 scenarios the most vulnerable marine mammal species will be the North Pacific right whale (*Eubalaena japonica*, listed as an endangered species (IUCN, 2020)) and the gray whale (*Eschrichtius robustus*, which has critically endangered subpopulations (IUCN, 2020)). The extinction of the most-vulnerable species will disproportionately eliminate unique and important evolutionary lineages as well as functional diversity, with consequent impacts throughout the entire marine ecosystem (section 3.3.4). More generally, future warming and acidification simulated in mesocosm experiments support projections of a substantial increase in biomass and productivity of primary producers and secondary consumers, but a decrease by >40% of primary consumers (Nagelkerken et al., 2020). On longer time scales, alteration of energy flow through marine food webs may lead to ecological tipping points (Wernberg et al., 2016; Harley et al., 2017) after which the food web collapses into shorter, bottom-heavy trophic pyramids (*medium confidence*).

Global projections anticipate a *likely* future reorganisation of marine life of variable magnitude, contingent on emission scenario (Beaugrand et al., 2015; Jones and Cheung, 2015; Barton et al., 2016; García Molinos et al., 2016; Nagelkerken et al., 2020; Henson et al., 2021). Marine organism redistributions projected under RCP4.5 and RCP8.5 include extirpations and range contractions in the tropics, strongly decreasing tropical biodiversity, and range expansions at higher latitudes, associated with increased diversity and homogenisation of marine communities (Figure 3.18b). Under continuing climate change, the projected loss of biodiversity may ultimately threaten marine ecosystem stability (*medium confidence*) (Albouy et al., 2020;

Nagelkerken et al., 2020; Henson et al., 2021), altering both the functioning and structure of marine ecosystems and thus affecting service provisioning (*medium confidence*) (Section 3.5, Ibarbalz et al., 2019; Righetti et al., 2019).

However, biodiversity observations remain sparse, and statistical and modelling tools can provide conflicting diversity information (e.g., Righetti et al., 2019; Dutkiewicz et al., 2020) because correlative approaches assume that the modern-day relationship between marine species distribution and environmental conditions remains the same into the future, whereas mechanistic models permit marine species to respond dynamically to changing environmental forcing. Moreover, existing global projections of future biodiversity disproportionately focus on the effects sea surface temperature (Thomas et al., 2012), typically overlooking other factors such as ocean acidification, deoxygenation and nutrient availability (Section 3.2.3), and often failing to account for natural adaptation (e.g., Section 3.3.4, Box 3.1, Barton et al., 2016; Henson et al., 2021).

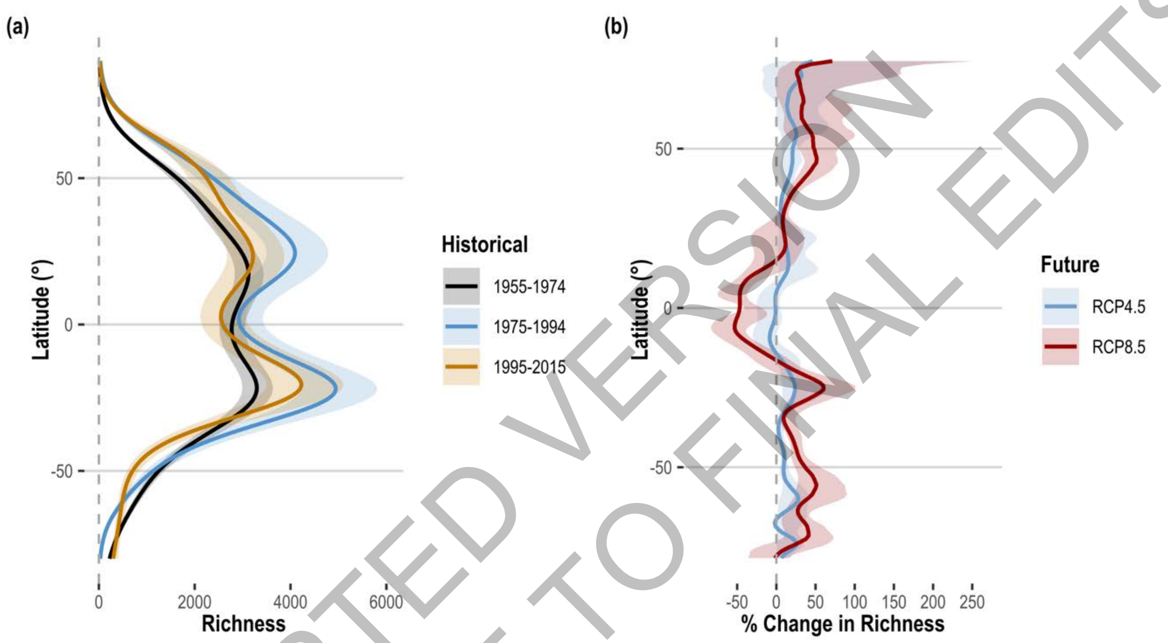


Figure 3.18: Changes in latitudinal marine species richness latitudinal distribution. (a) Observed species richness for three historical periods. The observed latitudinal patterns in species richness, are for a suite of taxonomic groups based on 48,661 marine species (Chaudhary et al., 2021). (b) Projected changes in species richness under RCP4.5 and RCP8.5 calculated as differences by grid cell by 2100 relative to 2006. Latitudinal global median (5° moving average) (based on Figure 1b,c in García Molinos et al., 2016). The projected latitudinal patterns in changes in species richness under climate change are based on a numerical model that includes species-specific information across a suite of taxonomic groups, based on 12,796 marine species (García Molinos et al., 2016).

[START BOX 3.2 HERE]

Box 3.2: Marine Birds and Mammals

Marine birds (seabirds and shorebirds) and mammals include charismatic species and species that are economically, culturally and ecologically important (Sydeman et al., 2015; Albouy et al., 2020; Pimiento et al., 2020). Their long generation times and slow population growth suggests limited evolutionary resilience to rapid climate change (Section 3.3.4, Sydeman et al., 2015; Miller et al., 2018). According to the Red List Species Assessments of the International Union for Conservation of Nature (IUCN, 2020), the greatest current hazards to these groups include human use of biological resources and areas, invasive species and pollution (Figure Box3.2.1, Dias et al., 2019; Lusseau et al., 2021). Impacts of climate change and severe weather are ranked among the five most-important hazards, influencing 131 and 45 bird and mammal species, respectively (see Figure Box 3.2.1 for selection of species), including 24 bird and seven mammal species that are currently listed as endangered, critically endangered or threatened. Furthermore, according to these IUCN assessments, climate change and severe weather are expected to impact an additional 122 and 18 marine bird and mammal species over the next 50–100 years, respectively (Figure Box 3.2.1 Dias et al., 2019).

Marine birds and mammals are vulnerable to climate-induced loss of breeding and foraging habitats such as sea ice (Section 3.4.2.12), sandy beaches (Section 3.4.2.6), salt marshes (Section 3.4.2.5) and seagrass beds (*high confidence*) (Section 3.4.2.5, Sydeman et al., 2015; Bindoff et al., 2019; Ropert-Coudert et al., 2019; Von Holle et al., 2019; Albouy et al., 2020; Amano et al., 2020; Bestley et al., 2020; Grose et al., 2020). With warming, shorebird population abundances decline in the tropics, *likely* due to heat stress and habitat loss, and increase at higher latitudes (Amano et al., 2020). Marine mammals dependent on sea-ice habitat are particularly vulnerable to warming (*medium confidence*) (Albouy et al., 2020; Bestley et al., 2020; Lefort et al., 2020), yet vulnerability can differ between populations. Ongoing sea-ice loss is decreasing some polar bear populations while others remain stable, *likely* related to past harvesting history, regional differences in sea-ice phenology and ecosystem productivity (Hamilton and Derocher, 2019; Molnár et al., 2020). Nevertheless, even under an intermediate emission scenario RCP4.5, increasing ice-free periods will *likely* reduce both recruitment and adult survival across most polar bear populations over the next four decades, threatening their existence (*medium confidence*) (Figure Box3.2.2, Molnár et al., 2020).

Climate change is affecting marine food-web dynamics (*high confidence*) (Sections 3.4.2, 3.4.3), and the vulnerability and adaptive capacity of marine birds and mammals to such changes is linked to the species' breeding and feeding ecology. Higher-vulnerability species include central-place foragers (confined to, for example, breeding colonies fixed in space), diet and habitat specialists, and species with restricted distributions such as marine mammal populations in SES (*medium confidence*) (McMahon et al., 2019; Ropert-Coudert et al., 2019; Albouy et al., 2020; Grose et al., 2020; Sydeman et al., 2021). Surface-feeding and piscivorous marine birds appear to be more vulnerable to food-web changes than diving seabirds and planktivorous seabirds (*medium confidence*) (Sydeman et al., 2021). During the 2014–2015 Pacific heatwave, around one million piscivorous common murres died along a 1500 km coastal stretch in the Pacific USA due to reduced prey availability (Jones et al., 2018b; Piatt et al., 2020). Marine birds are vulnerable to phenological shifts in food-web dynamics, as they have limited phenotypic plasticity of reproductive timing, with potentially little scope for evolutionary adaptation (*medium confidence*) (Keogan et al., 2018), although changes in reproduction timing are observed in several species (Section 3.4.4.1, Sydeman et al., 2015; Descamps et al., 2019; Sauve et al., 2019). There is *limited evidence* of marine mammals' capacity to adapt to shifting phenologies, but observed responses include changes in the onset of migrations, moulting and breeding (Section 3.4.4.1, Ramp et al., 2015; Hauser et al., 2017; Beltran et al., 2019; Bowen et al., 2020; Szesciorka et al., 2020).

Increased emergence of infectious disease in mammals and birds is expected with ocean warming, due to new transmission pathways from changing species distributions, higher species densities caused by habitat loss, and increased vulnerability due to environmental stress on individuals (*limited evidence*) (Sydeman et al., 2015; VanWormer et al., 2019; Sanderson and Alexander, 2020). Marine birds and mammals are *likely* to suffer from increased mortalities due to increasing frequencies of HABs, and of extreme weather, at sea, on sea ice, and in terrestrial breeding habitats (Broadwater et al., 2018; Gibble and Hoover, 2018; Ropert-Coudert et al., 2019; Grose et al., 2020). Also, climate-change driven distributional shifts have strengthened interactions with other anthropogenic impacts, through, for example, increasing risks of ship strikes and bycatch (*medium confidence*) (e.g., Hauser et al., 2018; Krüger et al., 2018; Record et al., 2019; Santora et al., 2020).

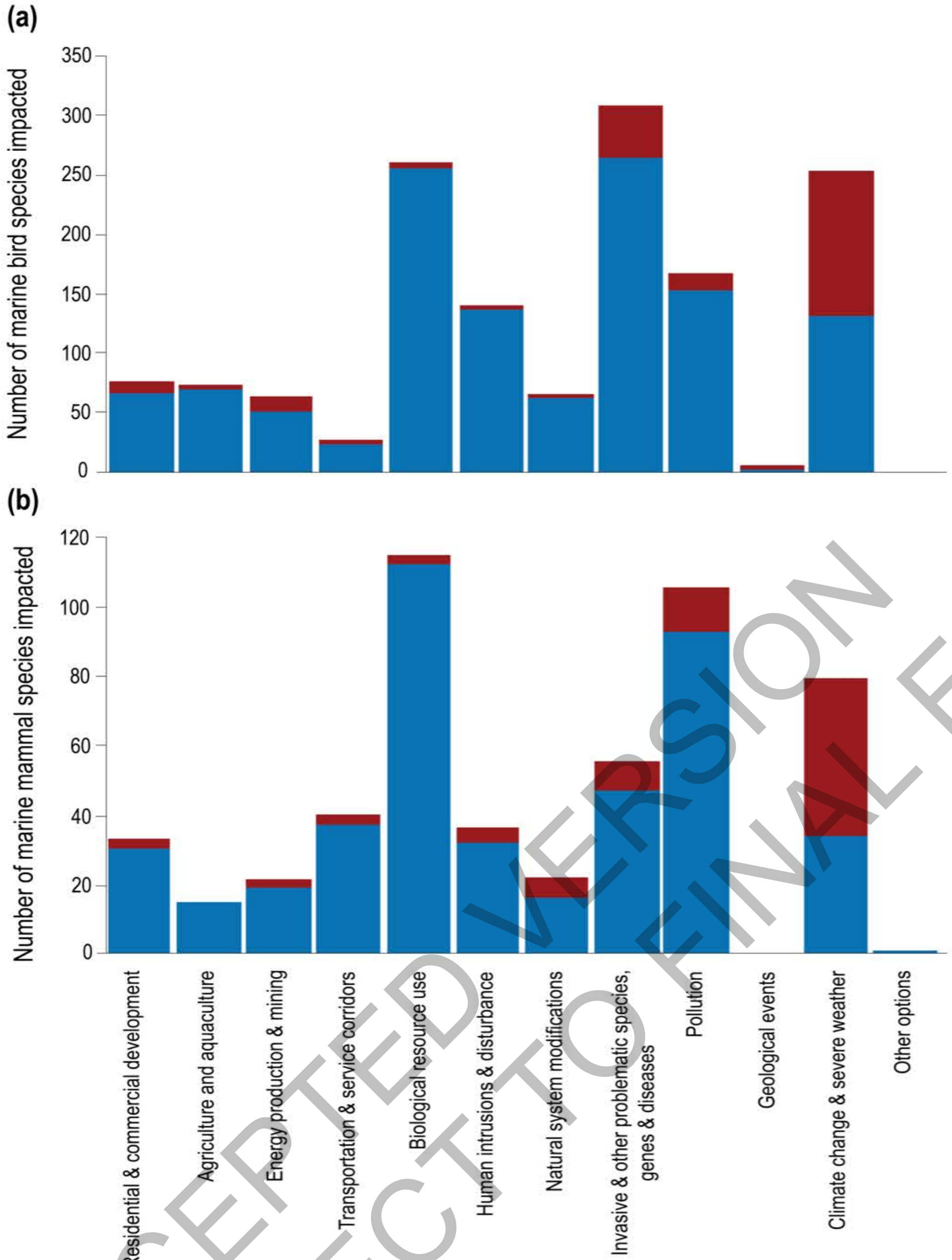


Figure Box 3.2.1: Hazard assessment for marine birds and mammals. Number of (a) marine birds and (b) mammals currently impacted by different hazards (blue), and numbers of additional species expected to be exposed to these threats over the next 50–100 years (red), as assessed in the International Union for Conservation of Nature Red List (IUCN, 2020). Seabird species include species in the key orders *Sphenisciformes*, *Pelecaniformes, Suliformes, Anseriformes, Procellariiformes* and *Charadriiformes* categorised as inhabitants of marine ecosystems (n = 483 species, assessed in the period 2016–2019). Marine mammal species include the species reviewed by Lusseau et al. (2021) (n = 136 species, assessed in the period 2008–2019).

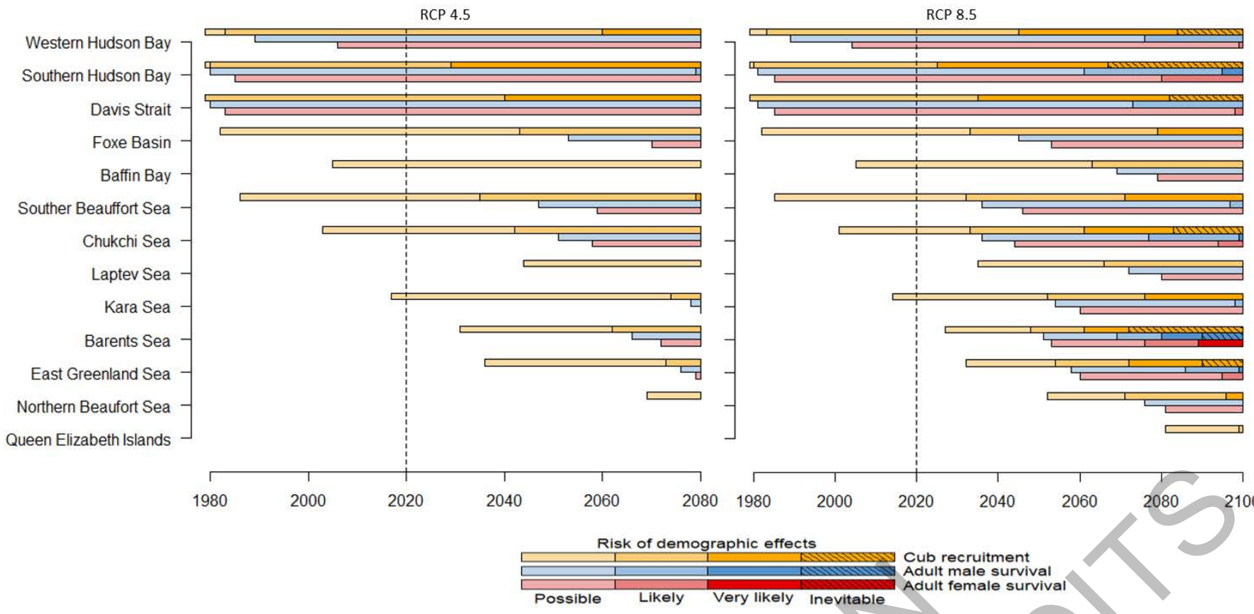


Figure Box 3.2.2: Modelled risk timelines for demographic impacts on circumpolar polar bear subpopulations, and associated confidence assessments, due to extended fasting periods with loss of sea ice. Years of first impact on cub recruitment (yellow), adult male survival (blue) and adult female survival (red) are shown for the (a) RCP4.5 and (b) RCP8.5. Data from Molnár et al. (2020).

[END BOX 3.2 HERE]

3.4.3.3.3 Abrupt ecosystem shifts and extreme events

Climate-change driven changes in ocean characteristics and the frequency and intensity of extreme events (Section 3.2) increase the risk of persistent, rapid and abrupt ecosystem change (*very high confidence*), often referred to as ecosystem collapses or regime shifts (AR6 WGI Chapter 9, Collins et al., 2019a; Canadell and Jackson, 2021; Ma et al., 2021). Such abrupt changes include altering ecosystem structure, function and biodiversity outside the range of natural fluctuations (Collins et al., 2019a; Canadell and Jackson, 2021). They can involve mass mortality events and 'tipping points' or 'critical transitions,' where strong positive feedbacks within an ecosystem lead to self-sustaining change (Figure 3.19a, Scheffer et al., 2012; Möllmann et al., 2015; Biggs et al., 2018). Abrupt ecosystem shifts have been observed in both large open-ocean ecosystems and coastal ecosystems (Section 3.4.2) with dramatic social consequences through significant loss of diverse ecosystem services (*high confidence*) (Section 3.5, Biggs et al., 2018; Pinsky et al., 2018; Beaugrand et al., 2019; Collins et al., 2019a; Filbee-Dexter et al., 2020b; Huntington et al., 2020; Trisos et al., 2020; Turner et al., 2020b; Canadell and Jackson, 2021; Ma et al., 2021; Ruthrof et al., 2021). A summary of previous assessments of abrupt ecosystem shifts and extreme events are provided in Table 3.21.

Table 3.21: Summary of previous IPCC assessments of observed and projected abrupt ecosystem shifts and extreme events.

Observations	Projections
AR5 (Wong et al., 2014)	
Observations of abrupt ecosystem shifts and extreme events were not assessed in this report.	Warming and acidification will lead to coral bleaching, mortality, and decreased constructional ability (*high confidence*), making coral reefs the most vulnerable marine ecosystem with little scope for adaptation. Temperate seagrass and kelp ecosystems will decline with the increased frequency of heatwaves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*).

SROCC (Collins et al., 2019a)	
Marine heatwaves (MHWs), periods of extremely high ocean temperatures, have negatively impacted marine organisms and ecosystems in all ocean basins over the last two decades, including critical foundation species such as corals, seagrasses and kelps (*very high confidence*)	Marine heatwaves are projected to further increase in frequency, duration, spatial extent and intensity (maximum temperature) (*very high confidence*). Climate models project increases in the frequency of marine heatwaves by 2081–2100, relative to 1850–1900, by approximately 50 times under RCP8.5 and 20 times under RCP2.6 (*medium confidence*). Extreme El Niño and La Niña events are projected to *likely* increase in frequency in the 21st century and to *likely* intensify existing hazards, with drier or wetter responses in several regions across the globe. Extreme El Niño events are projected to occur about as twice as often under both RCP2.6 and RCP8.5 in the 21st century when compared to the 20th century (*medium confidence*). Limiting global warming would reduce the risk of impacts of MHWs, but critical thresholds for some ecosystems (e.g., kelp forests, coral reefs) will be reached at relatively low levels of future global warming (*high confidence*)

Abrupt ecosystem shifts are associated with large-scale patterns of climate variability (Alheit et al., 2019; Beaugrand et al., 2019; Lehodey et al., 2020), some of which are projected to intensify with climate change (*medium confidence*) (WGI AR6 Chapter 1, Wang et al., 2017a; Collins et al., 2019a; Chen et al., 2021). Over the past 60 years, abrupt ecosystem shifts have generally followed El Niño/Southern Oscillation events of any strength, but some periods had geographically limited ecological shifts (~0.25% of the global ocean in 1984–1987) and others more extensive shifts (14% of the global ocean in 2012–2015) (*medium confidence*) (Figure 3.19b, Beaugrand et al., 2019). Typically, interacting drivers, such as eutrophication and overharvest, reduce ecosystem resilience to climate extremes (e.g., MHW, cyclones) or gradual warming, and hence promote ecosystem shifts (*high confidence*) (Figure 3.19a, Rocha et al., 2015; Biggs et al., 2018; Babcock et al., 2019; Turner et al., 2020b; Bergstrom et al., 2021; Canadell and Jackson, 2021; Tait et al., 2021). Also, shifts in different ecosystems may be connected through common drivers or through cascading effects (*medium confidence*) (Rocha et al., 2018a).

Recent MHWs (Section 3.2.2.1) have caused major ecosystem shifts and mass mortality in oceanic and coastal ecosystems, including corals, kelp forests and seagrass meadows (Sections 3.4.2.1, 3.4.2.3, 3.4.2.5, 3.4.2.6, 3.4.2.10, Cross-Chapter Box MOVING SPECIES in Chapter 5 and Cross-Chapter Box EXTREMES in Chapter 2), with dramatic declines in species foundational for habitat formation or trophic flow, biodiversity declines, and biogeographic shifts in fish stocks (*very high confidence*) (Table 3.15, Cross-Chapter Box MOVING SPECIES in Chapter 5, Canadell and Jackson, 2021). Three major bleaching episodes on Australia's Great Barrier Reef in 5 years corresponded with extreme temperatures in 2016, 2017 and 2020 (Pratchett et al., 2021). Between 1981 and 2017, marine heatwaves have increased more than 20-fold due to anthropogenic climate change (Section 3.2.2.1, WGI AR6 Chapter 9, Laufkötter et al., 2020; Fox-Kemper et al., 2021), increasing the risk of abrupt ecosystem shifts (*high confidence*) (Figure 3.19a, Cross-Chapter Box EXTREMES in Chapter 2, van der Bolt et al., 2018; Garrabou et al., 2021; Wernberg, 2021).

Ecosystems can recover from abrupt shifts (e.g., Babcock et al., 2019; Christie et al., 2019; Medrano et al., 2020). However, where climate change is a dominant driver, ecosystem collapses increasingly cause permanent transitions (*high confidence*), although the extents of such transitions depend on emission scenario (Trisos et al., 2020; Garrabou et al., 2021; Klein et al., 2021; Pratchett et al., 2021; Wernberg, 2021). Over the coming decades, MHW are projected to *very likely* become more frequent under all emission scenarios (Section 3.2, WGI AR6 Chapter 9, Fox-Kemper et al., 2021), with intensities and rates too high for recovery of degraded foundational species, habitats, or biodiversity (*medium confidence*) (Babcock et al., 2019; Garrabou et al., 2021; Klein et al., 2021; Serrano et al., 2021; Wernberg, 2021). Emission pathways that result in temperature overshoot above 1.5ºC will increase the risks of abrupt and irreversible shifts in coral reefs and other vulnerable ecosystems (Section 3.4.4).

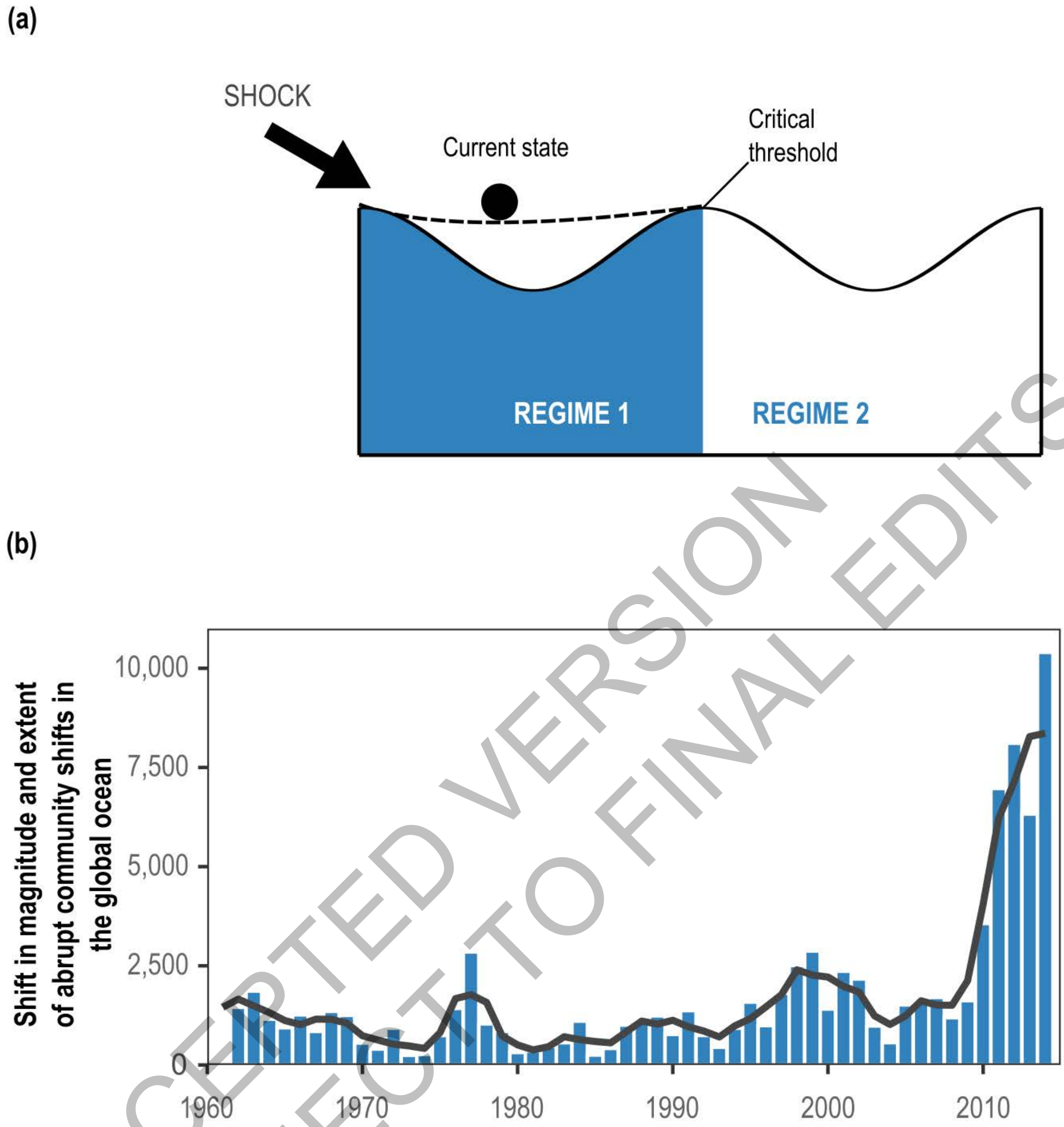


Figure 3.19: Observed ecological regime shifts and their drivers in the oceans. (a) A conceptual representation of ecosystem resilience and regime shifts. Shift from Regime 1 to Regime 2 can be triggered by either a large shock (i.e., an abrupt environmental transition) or gradual internal or external change that erodes the dominant balancing feedbacks, reducing ecosystem resilience (indicated by the shallower dotted line, relative to the deeper 'valley' reflecting higher resilience). Figure based on Biggs et al. (2018). (b) The sum of the magnitude and extent of the abrupt community shifts that has been estimated at each geographic cell in the global ocean during 1960–2014, calculated as the ratio of the amplitude of the change in a particular year to the average magnitude of the change over the entire time series (thus is dimensionless). Figure based on Beaugrand et al. (2019).

3.4.3.3.4 Time of emergence – species exposure to altered environments

Since SROCC, more studies have assessed the time of emergence for climate-impact drivers (Section 3.2.3), and the ecosystem attributes through which the impacts manifest. However, as in previous assessments (Table 3.22), the time of emergence for a given driver or ecosystem attribute depends on the reference period, the definition of the signal emergence threshold and the spatial and temporal scales considered (Box 5.1 in SROCC, Kirtman et al., 2013; Bindoff et al., 2019).

Table 3.22: Summary of previous IPCC assessments of projected time of emergence.

System	Projections
Coastal	Multiple climate-impact drivers will emerge in the 21st century under RCP8.5, while the time of emergence will be later and with few climatic hazards under RCP2.6. Non-climate impacts such as eutrophication add to, and in some cases, exacerbate these large-scale slow climate drivers beyond biological thresholds at local scale (e.g., deoxygenation).
Epipelagic	Observed range shifts in response to climate change in some regions such as the north Atlantic are strongly influenced by warming due to both multi-decadal climate change and variability, suggesting that there is a longer time-of-emergence of range shifts from natural variability and a need for longer biological time series for robust attribution.
Open Ocean	The timing for five primary drivers of marine ecosystem change (surface warming and acidification, oxygen loss, nitrate concentration and net primary production change) are all prior to 2100 for >60% of the ocean area under RCP8.5 and over 30% under RCP2.6 (*very likely*). Anthropogenic signals are expected to remain detectable over large parts of the ocean even under the RCP2.6 scenario for pH and SST but are *likely* to be less conspicuous for nutrients and NPP in the 21st century. For example, for the open ocean, the anthropogenic pH signal in Earth System Models (ESM) historical simulations is *very likely* to have emerged for three-quarters of the ocean prior to 1950 and it is *very likely* over 95% of the ocean has already been affected, with little discernible difference between scenarios. The climate signal of oxygen loss will *very likely* emerge by 2050 with a *very likely* range of 59–80% by 2031–2050 and increasing with a *very likely* range of 79–91% of the ocean area by 2081–2100 (RCP8.5 emissions scenario). The emergence of oxygen loss is smaller in area under RCP2.6 scenario in the 21st century and by 2090 the area where emergence is evident is declining. It has also been shown that signatures of altered oxygen solubility or utilisation may emerge earlier than for oxygen levels.
Deep sea	Emergence of risk is expected to occur later at around the mid-21st century under RCP8.5 for abyssal plain and chemosynthetic ecosystems (vents and seeps). All deep seafloor ecosystems are expected to be subject to at least moderate risk under RCP8.5 by the end of the 21st century, with cold water corals undergoing a transition from moderate to high risk below 3ºC.

Anthropogenically driven changes in chlorophyll-a concentrations across an ensemble of 30 ESMs are expected to exceed natural variability under RCP8.5 by 2100 in ~65–80% of the global oceans, when the natural variability is calculated using the ensemble's standard deviation (Schlunegger et al., 2020). However, if two standard deviations are used, then significant trends in chlorophyll-a concentration are expected under RCP8.5 across ~31% of the global oceans by 2100 (Dutkiewicz et al., 2019). In contrast, the anthropogenic signal in phytoplankton community structure, which has a lower natural variability, will emerge under RCP8.5 across 63% of the ocean by 2100 when two standard deviations are used (*limited evidence*) (Dutkiewicz et al., 2019).

The time of emergence of climate impacts on ecosystems will be modulated jointly by species-specific adaptation potential (Section 3.3.4, Jones and Cheung, 2018; Collins et al., 2020; Gamliel et al., 2020; Miller et al., 2020a), speed of range shifts and spatial reorganisation (*high confidence*) (Sections 3.3, 3.4.2,3.4.3). These ecosystem responses complicate projections of the time of emergence of environmental properties that impact biogeochemical cycling (Schlunegger et al., 2019; Schlunegger et al., 2020; Wrightson and Tagliabue, 2020), ecosystem structure and biodiversity (Figure 3.20a,c, Dutkiewicz et al., 2019; Trisos et al., 2020), and higher trophic levels, including fisheries targets (Cheung and Frölicher, 2020). Better accounting for multiple interacting factors in ESMs (Box 3.1), which will provide insight into how marine ecosystems will respond to future climate (*high confidence*).

The time of emergence of ecosystem responses supports planning for specific time-bound actions to reduce risks to ecosystems (Sections 3.6.3.2.1 Bruno et al., 2018; Trisos et al., 2020). Although under RCP 8.5, climate refugia from SST after 2050 are primarily in the Southern Ocean in tropical waters, these refugia are mainly from deoxygenation (Bruno et al., 2018). Marine assemblages in these places will be exposed to unprecedented temperatures after 2050, peaking in 2075 (Figure 3.20a,b, Trisos et al., 2020)(). In contrast, changes in phytoplankton community structure will emerge earlier, and primarily in the Pacific Ocean subtropics, and through much of the North Atlantic Ocean (Figure 3.20c,d, Dutkiewicz et al., 2019). Under RCP8.5, changes in phytoplankton community structure and, to a lesser extent, exposure of marine species to unprecedented temperatures, will emerge earlier in MPAs, covering ~7.7% of the global oceans, (Section 3.6.2.3.2.1, UNEP-WCMC and IUCN, 2020; UNEP-WCMC and IUCN, 2021) compared to non-MPAs (Figure 3.20b,d). Such assessment can support planning for future MPA placement and extent. Because MPAs can serve as refugia from non-climate drivers (Sections 3.6.2.3, 3.6.3.2.1), they facilitate opportunities for adaptation among marine species and communities in coastal oceans (Section 3.4.2).

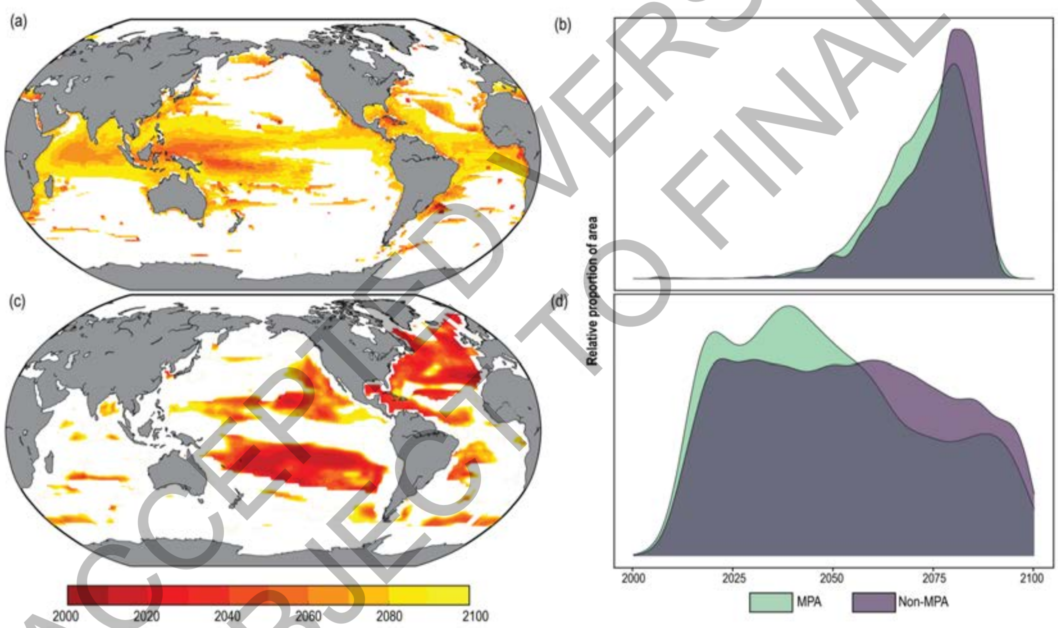


Figure 3.20: Time of exposure to altered environments. (a) Simulated spatial variation in the time of exposure of marine species to unprecedented temperatures under RCP8.5. Time of exposure is quantified as the median year after which local species are projected to encounter temperatures warmer than the historical maximum within their full geographic range for a period of at least five years. This estimate is based on 22 Coupled Model Intercomparison Project 5 (CMIP5) models, and is drawn from data presented by Trisos et al. (2020). Only regions that have times of emergence by 2100 are shown. (b) The distribution in the time of exposure to unprecedented temperatures within marine assemblages (Trisos et al., 2020) under RCP8.5 in marine protected areas (in turquoise) and in non-marine protected areas (in purple). Values were calculated after regridding to equal-area 0.5° hexagons. (c) Time of emergence for phytoplankton community structure changes (based on a proxy – ecosystem-model reflectance at 500 nm) under RCP8.5. Only regions with statistically significant ($p < 0.05$) trends, that are presently largely ice-free and that have times of emergence by 2100 are shown. Figure based on the results of one model numerical model from Dutkiewicz et al. (2019). (d) The distribution in the time of emergence for changes in phytoplankton community structure (same proxy as in Panel c) (Dutkiewicz et al., 2019) under RCP8.5 in marine protected areas (in turquoise) and in non-marine protected areas (in purple). Values were calculated after regridding to equal-area 0.5° hexagons.

3.4.3.4 Biomass

3.4.3.4.1 Observed changes

Observed changes in biomass in the global ocean, beyond those for phytoplankton (Table 3.23), have not routinely been attributed to climate-impact drivers, but rather to the compound effects of multiple drivers, especially fishing (Christensen et al., 2014; Palomares et al., 2020). We therefore do not assess observed changes in ocean biomass here.

3.4.3.4.2 Projected changes

Zooplankton biomass

Based on an ensemble of CMIP5 ESMs, SROCC projected declines in global zooplankton biomass by 2100 dependent on emission scenario (*low confidence*) (Table 3.23). The new CMIP6 ESM ensemble projects a decline in global zooplankton biomass by –3.9% ± 8.2%, (*very likely range*) and –9.0% ± 8.9% in the period 2081–2100 relative to 1995–2014 under SSP1-2.6 and SSP5-8.5, respectively (Figure 3.21d, Kwiatkowski et al., 2020), thus reinforcing the SROCC assessment albeit with greater inter-model uncertainties.

Table 3.23: Summary of previous IPCC assessments of changes in open ocean and deep sea biomass.

Measure	Observations	Projections
AR5 WGII: (Hoegh-Guldberg et al., 2014; Pörtner et al., 2014)		
Chlorophyll-*a*/phytoplankton biomass	Phytoplankton biomass: The approximately 15-year archived time series of satellite-chlorophyll (as a proxy of phytoplankton biomass) is too short to reveal trends over time and their causes (WGII AR5 Section 6.1.2, Pörtner et al., 2014). Chlorophyll concentrations measured by satellites have decreased in the subtropical gyres of the North Pacific, Indian, and North Atlantic Oceans by 9%, 12%, and 11%, respectively, over and above the inherent seasonal and interannual variability from 1998 to 2010 (*high confidence*; p-value ≤ 0.05). Significant warming over this period has resulted in increased water column stratification, reduced mixed layer depth, and possibly decreases in nutrient availability and ecosystem productivity (*limited evidence, medium agreement*). The short time frame of these studies against well-established patterns of long-term variability leads to the conclusion that these changes are about as *likely* as not due to climate change (WGII AR5 Chapter 30 Hoegh-Guldberg et al., 2014).	Owing to contradictory observations there is currently uncertainty about the future trends of major upwelling systems and how their drivers (enhanced productivity, acidification, and hypoxia) will shape ecosystem characteristics (*low confidence*) (WGII AR5 Chapter 6 Executive Summary, Pörtner et al., 2014).
Animal biomass	The climate-change-induced intensification of ocean upwelling in some eastern boundary systems, as observed in the last decades, may lead to regional cooling rather than warming of surface waters and cause enhanced productivity (*medium confidence*), but also enhanced hypoxia, acidification, and associated	

	biomass reduction in fish and invertebrate stocks.	
SROCC (Bindoff et al., 2019)		
Chlorophyll-*a*/phytoplankton biomass	Changes reported in overall open ocean chlorophyll levels (a proxy of phytoplankton biomass) of <±1% yr^{-1} for individual time periods. Regionally, trends of ±4% between 2002–2015 for different regions are found when different satellite products are merged, with increases at high latitudes and moderate decreases at low latitudes (SROCC Section 5.2.2.6, Bindoff et al., 2019).	
Animal biomass	Observed changes in open ocean and deep sea biomass were not assessed in this report.	There is *high agreement* in model projections that global zooplankton biomass will *very likely* reduce in the 21st century, with projected decline under RCP8.5 almost doubled that of RCP2.6 (*very likely*). However, the strong dependence of the projected declines on phytoplankton production (*low confidence*) and simplification in representation of the zooplankton communities and foodweb render their projections having *low confidence*. The global biomass of marine animals, including those that contribute to fisheries, is projected to decrease by 4.3 ± 2.0% (95% confidence intervals) and 15.0 ± 5.9% under RCP2.6 and RCP8.5, respectively, by 2080–2099 relative to 1986–2005, while the decrease is around 4.9% by 2031–2050 across all RCP2.6 and RCP8.5 (*very likely*). Regionally, total animal biomass decreases largely in tropical and mid-latitude oceans (*very likely*). Projected decrease in upper ocean export of organic carbon to the deep seafloor is expected to result in a loss of animal biomass on the deep seafloor by 5.2–17.6% by 2090–2100 compared to the present (2006–2015) under RCP8.5 with regional variations (*medium confidence*). Some increases are projected in the polar regions, due to enhanced stratification in the surface ocean, reduced primary production and shifts towards small phytoplankton (*medium confidence*). The projected impacts on biomass in the abyssal seafloor are larger under RCP8.5 than RCP4.5 (*very likely*).
WGI AR6 Chapter 2 (Gulev et al., 2021)		

Chlorophyll-*a*/phytoplankton biomass	The multi-sensor time series of chlorophyll-*a* concentration has been updated to cover two decades (1998–2018). Global trends in chlorophyll-*a* for the last two decades are insignificant over large areas of the global oceans, but some regions exhibit significant trends, with positive trends in parts of the Arctic and the Antarctic waters (>3% yr^{-1}), and both negative and positive trends (within ±3% yr^{-1}), in parts of the tropics, subtropics and temperate waters. In the last two decades, the concentration of phytoplankton at the base of the marine food web, as indexed by chlorophyll concentration, has shown weak and variable trends in low and mid-latitudes and an increase in high latitudes (*medium confidence*).	Projected changes in open ocean and deep sea biomass were not assessed in this report.

Marine animal biomass

Using an ensemble of global-scale marine ecosystem and fisheries models (Fish-MIP, Tittensor et al., 2018) with the CMIP5 ESM ensemble, SROCC concludes that projected ocean warming and decreased phytoplankton production and biomass will reduce global marine animal biomass during the 21st century (*medium confidence*). The simulated declines (with *very likely range*) are –3.5 ± 4.8% and –14.0 ± 14.6% under RCP2.6 and RCP8.5, respectively, by 2080–2099 relative to 1995–2014 (SROCC Section 5.2.3, Bindoff et al., 2019; Lotze et al., 2019)[1]. Updated Fish-MIP simulations with CMIP6 (Figure 3.21g,h,i) confirm the projected decline in total marine animal biomass in the 21st century (Tittensor et al., 2021). The simulated declines (with *very likely range*) are –5.7% ± 4.1% and –15.5% ± 8.5% under SSP1-2.6 and SSP5-8.5, respectively, by 2080–2099 relative to 1995–2014 (Figure 3.21g), showing greater declines and lower inter-model uncertainties (Tittensor et al., 2021). These declines result from combined warming and decreased primary production (with *low confidence* in future changes in primary production, Section 3.4.3.5) and are amplified at each trophic level within all ESM and marine ecosystem model projections across all scenarios (*medium confidence*) (Kwiatkowski et al., 2019; Lotze et al., 2019; Tittensor et al., 2021). However, there is *limited evidence* about how underlying food-web mechanisms amplify the climate signal from primary producers to higher trophic levels, and several putative mechanisms have been proposed (Section 3.4.4.2.2, Chust et al., 2014a; Stock et al., 2014; Kwiatkowski et al., 2019; Lotze et al., 2019; Heneghan et al., 2021). As assessed in SROCC, the biomass projections contain considerable regional variation, with declines in tropical to temperate regions and strong increases in total animal biomass are projected in polar regions under high-emission scenarios, with climate-change effects that are spatially similar but less pronounced under lower-emission scenarios (Figure 3.21b,c,e,f,h,i; Tai et al., 2019; Tittensor et al., 2021).

Benthic biomass

SROCC assessed that reduced food supply to the deep sea will drive a reduction in abyssal seafloor biota by 2100 for RCP8.5 (Table 3.23). Simulations from one size-resolved benthic biomass model coupled to an ocean-biogeochemistry model forced with the CMIP5 ESM HadGEM2-ES (Yool et al., 2017) project a decline in the globally integrated total seafloor biomass of –1.1% and –17.6% by 2100 under RCP2.6 and RCP8.5, respectively (*limited evidence, high agreement*). In waters shallower than 100 m, total benthic biomass is projected to increase by 3.2% on average by 2100 under RCP8.5, primarily driven warming-

[1] SROCC reported declines in total marine animal biomass have been recomputed using 1995–2014 as the baseline period and the *very likely* ranges (5–95%) are now computed from the model ensemble ranges assuming a normal distribution.

increased growth rates (Yool et al., 2013), while at depths >2000 m (representing 83% of the ocean seafloor), declines of –32% arise from climate-driven decreases in surface primary production and particulate organic carbon (POC) flux to the seafloor (Yool et al., 2013; Kelly-Gerreyn et al., 2014; Yool et al., 2015; Yool et al., 2017). These patterns are qualitatively similar under RCP2.6, except in the Pacific and Indian Ocean basins, where some increased total seafloor biomass is projected (Yool et al., 2013). Updated simulations with the same benthic biomass model (Kelly-Gerreyn et al., 2014) forced with the CMIP6 ESM UKESM-1 project declines in total seafloor biomass of –9.8% and –13.0% by 2081–2100 relative to 1995–2014 for SSP1-2.6 and SSP5-8.5, respectively (Figure 3.21j,k,l, updated from Yool et al., 2017). These projected changes in benthic biomass are based on *limited evidence*. Development of ensemble projections forced with a range of ESMs and a benthic model that considers the ecological roles of temperature (Hunt and Roy, 2006; Reuman et al., 2014), oxygen (Mosch et al., 2012) and ocean acidification (Andersson et al., 2011) will provide opportunities to better quantify uncertainty in projected declines in total seafloor biomass under climate change.

Conclusions

Overall, ocean warming and decreased phytoplankton production and biomass will drive a global decline in biomass for zooplankton (*low confidence*), marine animals (*medium confidence*) and seafloor benthos (*low confidence*), with regional differences in the direction and magnitude of changes (*high confidence*). There is increasing evidence that responses will amplify throughout the food web and at ocean depths, with relatively modest changes in surface primary producers translating into substantial changes at higher trophic levels and for deep-water benthic communities (*medium confidence*).

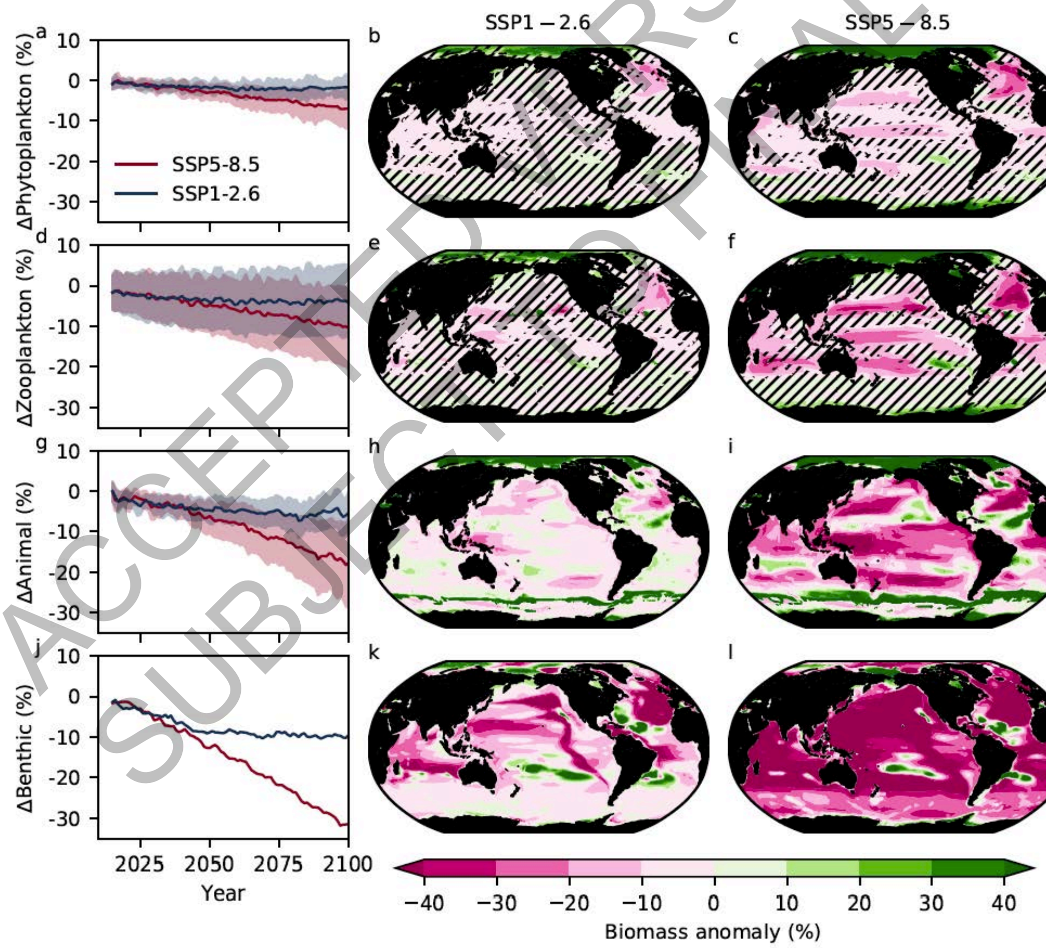


Figure 3.21: Projected change in marine biomass. Simulated global biomass changes of (a,b,c) surface phytoplankton, (d,e,f) zooplankton, (g,h,i) animals and (j,k,l) seafloor benthos. In (a,d,g,j), the multi-model mean (solid lines) and *very likely range* (envelope) over 2000–2100 relative to 1995–2014, for SSP1-2.6 and SSP5-8.5. Spatial patterns of simulated change by 2090–2099 are calculated relative to 1995–2014 for (b,e,h,k) SSP1-2.6 and (c,f,i,l) SSP5-8.5. Confidence intervals can be affected by the number of models available for the Coupled Model Intercomparison Project 6 (CMIP6) scenarios and for different variables. Only one model was available for panel (j), so no confidence interval is

calculated. For panels (a–f), the ensemble projections of global changes in phytoplankton and zooplankton biomasses updated based on Kwiatkowski et al. (2019) include, under SSP1-2.6 and SSP5-8.5, respectively, a total of nine and 10 CMIP6 Earth System Models (ESMs). For panels (g,h,i), the ensemble projections of global changes in total animal biomass updated based on Tittensor et al. (2021) include 6–9 published global fisheries and marine ecosystem models from the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP, Tittensor et al., 2018; Tittensor et al., 2021), forced with standardised outputs from two CMIP6 ESMs. For panels (j,k,l), globally integrated changes in total seafloor biomass have been updated based on Yool et al. (2017) with one benthic model (Kelly-Gerreyn et al., 2014) forced with the CMIP6 ESM HadGEM2-ES.

3.4.3.5 Changes in Primary Production and Biological Carbon Export Flux

3.4.3.5.1 Observed changes in primary production

Analyses of satellite-derived primary production over the past two decades (1998–2018) showed generally weak and negative trends (up to −3.0%) at low and mid latitudes (Kulk et al., 2020). In contrast, positive trends occurred in large areas of the South Atlantic and South Pacific Oceans, as well as in polar and coastal (upwelling) regions (up to +4.5%, Cross-Chapter Paper 6, Kulk et al., 2020). Data-assimilating ocean biogeochemical models estimate a global decline in primary production of 2.1% per decade in the period 1998–2015, driven by the shoaling mixed layer and decreasing nitrate concentrations (Gregg and Rousseaux, 2019). This is consistent with previous assessments that identified ocean warming and increased stratification as the main drivers (*high confidence*) affecting the regional variability in primary production Bindoff et al. (2019). However, as noted in SROCC and WGI AR6 Chapter 2 (Table 3.24, Gulev et al., 2021), observed inter-annual changes in primary production on global and regional scales are nonlinear and largely influenced by natural temporal variability, providing *low confidence* in the trends.

Table 3.24: Summary of previous IPCC assessments of ocean primary production and carbon export flux.

Process	Observed Impacts	Projected Impacts
SROCC (Bindoff et al., 2019)		
Open ocean primary production	Past open ocean productivity trends, including those determined by satellites, are appraised with *low confidence*, due to newly identified region-specific drivers of microbial growth and the lack of corroborating in situ time series datasets.	Net primary productivity is *very likely* to decline by 4–11% by 2081–2100, relative to 2006–2015, across CMIP5 models for RCP8.5, but there is *low confidence* for this estimate due to the *medium agreement* among models and the *limited evidence* from observations. The tropical ocean net primary productivity is *very likely* to decline by 7–16% for RCP8.5, with *medium confidence* as there are improved constraints from historical variability in this region.
Open ocean carbon export	Analyses of long-term trends in primary production and particle export production, as well as model simulations, reveal that increasing temperatures, leading to enhanced stratification and nutrient limitation, will have the greatest influence on decreasing the flux of particulate organic carbon (POC) to the deep ocean. However, different lines of evidence (including observation, modeling and experimental studies) provide *low confidence* on the mechanistic understanding of how climate-impact drivers affect different components of the biological pump in the epipelagic ocean, as well as	The projected changes in export production can be larger than global primary production because they are affected by both the net primary production changes, but also how shifts in food web structure modulates the 'transfer efficiency' of particulate organic material, which then affects the sinking speed and lability of exported particles through the ocean interior to the sea floor. As export production is a much better understood net integral of changing net nutrient supply and can be constrained by interior ocean nutrient and oxygen levels, there is *medium confidence* in

	changes in the efficiency and magnitude of carbon export in the deep ocean.	projections for global export production changes based on CMIP5 model runs.
WGI AR6 Chapters 2 and 5 (Canadell et al., 2021; Gulev et al., 2021)		
Open ocean primary production	Global ocean marine primary production is estimated to be 47 ± 7.8 PgC yr^{-1} with *low confidence* because of the small number of recent studies and the insufficient length of the time series analysed. A small decrease in productivity is evident globally for the period 1998–2015, but regional changes are larger and of opposing signs (*low confidence*) (WGI AR6 Section 2.3.4.2.2, Gulev et al., 2021).	In CMIP5 models run under RCP8.5, particulate organic carbon (POC) export flux is projected to decline by 1–12% by 2100 (Taucher and Oschlies, 2011; Laufkötter et al., 2015). Similar values are predicted in 18 CMIP6 models, with declines of 2.5–21.5% (median –14%) between 1900 and 2100 under the SSP5-8.5 scenario. The mechanisms driving these changes vary widely between models due to differences in parameterisation of particle formation, remineralisation and plankton community structure (WGI AR6 Section 5.4.4.2, Canadell et al., 2021).

3.4.3.5.2 Projected changes in primary production

Across 10 CMIP5 and 13 CMIP6 ESM ensembles, global mean net primary production is projected to decline by 2080–2099 relative to 2006–2015, under all RCPs and SSPs (Kwiatkowski et al., 2020). However, under comparable radiative forcing, the CMIP6 multi-model mean projections of primary production declines (mean ± SD: –0.56 ± 4.12% under SSP1-2.6, and –3.00 ± 9.10% under SSP5-8.5) are less than those of previous CMIP5 models (3.42 ± 2.47% under RCP2.6, and 8.54 ± 5.88% under RCP8.5) (WGI AR6 Section 5.4.4.2, Kwiatkowski et al., 2020; Canadell et al., 2021). The inter-model uncertainty associated with CMIP6 net primary production projections is larger than in CMIP5, and it is consistently larger than the scenario uncertainty. For each SSP across the CMIP6 ensemble, individual models project both increases and decreases in global primary production, reflecting a diverse suite of bottom-up and top-down ecological processes, which are variously parameterised across models (Laufkötter et al., 2015; Bindoff et al., 2019). Further, accurate simulation of many of the biogeochemical tracers upon which net primary production depends (e.g., the distribution of iron, Tagliabue et al., 2016; Bindoff et al., 2019) remains a significant and ongoing challenge to ESMs (*high confidence*) (Séférian et al., 2020).

Regionally, multi-model mean changes in primary production show generally similar patterns of large declines in the North Atlantic and the western equatorial Pacific, while in the high latitudes, primary production consistently increases in CMIP5 and CMIP6 by 2100 (Kwiatkowski et al., 2020, Cross-Chapter Paper 6). In the Indian Ocean and sub-tropical North Pacific, which were regions of consistent net primary production decline in CMIP5 projections (Bopp et al., 2013), the regional declines are reduced in magnitude, less spatially extensive, and are typically less robust in CMIP6. Further assessment of simultaneous changes in processes such as nutrient advection, nitrogen fixation, the microbial loop, and top-down grazing pressure (WGI AR6 Section 5.4.4.2, Laufkötter et al., 2015; Bindoff et al., 2019; Canadell et al., 2021) are required to fully understand the regional primary production response in CMIP6 (Kwiatkowski et al., 2020). Given the regional variations in the estimates of primary production changes and the uncertainty in the representation of the dominant drivers, there remains *low confidence* in the projected global decline in net primary production.

3.4.3.5.3 Observed processes driving changes in global export flux

The SROCC *medium confidence* assessment that warming, stratification, declines in productivity and changes in plankton community in the epipelagic zone result in reduced export of primary production to deeper layers (Table 3.24) is supported by subsequent literature (Bach et al., 2019; Leung et al., 2021). POC export efficiency is constrained by altered mixing and nutrient availability (Boyd et al., 2019; Lundgreen et al., 2019), particle fragmentation (Briggs et al., 2020), as well as viral, microbial, and planktonic community structure (Fu et al., 2016; Guidi et al., 2016; Flombaum et al., 2020; Kaneko et al., 2021) and metabolic rates

(Cavan et al., 2019). These processes are strongly interlinked and their net effect on primary production export from the upper ocean remain difficult to quantify observationally (Boyd et al., 2019). Since SROCC, there is increasing evidence that ocean deoxygenation can alter zooplankton community structure (Wishner et al., 2018), zooplankton respiration rates (Cass and Daly, 2014; Cavan et al., 2017) and patterns of diel vertical migration (Aumont et al., 2018), which may focus remineralisation of organic carbon at the upper margins of OMZs (Section 3.4.3.4 on depth shifts due to OMZ, Bianchi et al., 2013; Archibald et al., 2019).

Data on export flux from the upper ocean are limited either in coverage and consistency (ship-board sampling) or duration (sediment traps) and are subject to considerable spatial variability (as shown in satellite observations, Boyd et al., 2019). As a result, trends are weak, inconsistent and often not statistically significant (Lomas et al., 2010; Cael et al., 2017; Muller-Karger et al., 2019; Xie et al., 2019). Deep-ocean fluxes are similarly equivocal (Smith et al., 2018; Fischer et al., 2019; Fischer et al., 2020). In coming years, an increasing number of Argo floats equipped with bio-optical sensors should help improve estimates of particle flux spatial and temporal variability (e.g., Dall'Olmo et al., 2016).

Projected changes

SROCC and WGI AR6 reported global declines in POC export flux, between –8.9 to –15.8% by 2100 relative to 2000 under RCP8.5 in CMIP5 models, and –2.5 to –21.5% (median value –14%) between 1900 and 2100 under SSP5-8.5 in CMIP6 models (WGI AR6 5.4.4.2, Table 3.24, Bindoff et al., 2019; Canadell et al., 2021). In CMIP5 model runs, the decrease in the sinking flux of organic matter from the upper ocean into the ocean interior was strongly related to the changes in stratification that reduce net nutrient supply (Fu et al., 2016; Bindoff et al., 2019), especially in tropical regions, and the projections for global export production changes are reported with *medium confidence*. Increasing model complexity with more widespread representation of ocean biogeochemical processes between CMIP5 and CMIP6, and inclusion of more than one or two classes of phyto- and zooplankton will provide opportunities to improve assessments of how climate-impact drivers affect different components of biological carbon pump in the epipelagic ocean, as well as changes in the efficiency and magnitude of carbon export in the deep ocean (*high confidence*) (Box 3.3, Le Quéré et al., 2016; Séférian et al., 2020; Wright et al., 2021).

[START BOX 3.3 HERE]

Box 3.3: Deep Sea Ecosystems

Deep-sea ecosystems include all waters below the 200 m isobath as well as the underlying benthos, and they provide habitats for highly diversified and specialised biota, which play a key role in the cycling of carbon and other nutrients (Figure Box3.3.1, Thurber et al., 2014; Middelburg, 2018; Snelgrove et al., 2018). The deep sea covers >63% of Earth's surface (Costello and Cheung, 2010) and is exposed to climate-driven changes in abyssal, intermediate, and surface waters that influence sinking fluxes of particulate organic matter (*high confidence*) (Figure Box3.3.1, Sections 3.1, 3.2.1, 3.2.2, 3.4.3.4, WGII AR5 Section 30.5.7, SROCC Sections 5.2.3, 5.2.4, Hoegh-Guldberg et al., 2014; Bindoff et al., 2019). These ecosystems are also influenced by non-climate drivers, especially fisheries, oil and gas extraction (Thurber et al., 2014; Cordes et al., 2016; Zhang et al., 2019a); cable laying (United Nations, 2021); and mineral resource exploration (Hein et al., 2021); with proposed large-scale deep-sea mining a potential future source of impacts (Danovaro, 2018; Levin et al., 2020).

Ocean warming alters biological processes in deep-sea ecosystems in ways that affect deep-sea habitat, biodiversity, and material processing. Enhancement of microbial respiration by warming attenuates sinking POC, which has been associated with the globally projected declines in total seafloor biomass of –9.8% and –13.0% by 2081–2100 relative to 1995–2014 under SSP1-2.6 and SSP5-8.5, respectively (*limited evidence*) (Section 3.4.3.4). Additionally, climate-change-driven oxygen loss (Section 3.2.3.2, Luna et al., 2012; Belley et al., 2016), and geographic shifts in predator distributions (Section 3.4.3.1) are anticipated to affect deep-sea biodiversity (*limited evidence, high agreement*) (Smith et al., 2012; Morato et al., 2020). Complex responses of some bathyal crustacean assemblages to environmental change suggest an increase in phylogenetic diversity but limited decreases in abundances with temperature (Ashford et al., 2019). Acute mortality of some reef-forming cold-water corals to laboratory-simulated warming (Lunden et al., 2014) suggests that both long-term warming and the increase of MHWs in intermediate and deep waters (Elzahaby and Schaeffer, 2019) could pose significant risk to associated ecosystems (*high confidence*). Thermal tolerance thresholds (lethal and sub-lethal) of scleractinians in laboratory settings depend on their geographic position and capacity for thermal adaptation, as well as other factors including food, oxygen and pH (*medium to high confidence*) (Naumann et al., 2013; Hennige et al., 2014; Lunden et al., 2014; Naumann et al., 2014; Georgian et al., 2016; Gori et al., 2016; Maier et al., 2016; Büscher et al., 2017).

The extension and intensification of deep-water acidification (Section 3.2.3.1) has been identified as a further key risk to deep-water coral ecosystems (*medium confidence*) (Bindoff et al., 2019). Literature since SROCC supports this assessment (Morato et al., 2020; Puerta et al., 2020), although scleractinians and gorgonians are found in regions undersaturated with respect to aragonite (Thresher et al., 2011; Fillinger and Richter, 2013; Baco et al., 2017). Laboratory experiments on reef-forming scleractinians show variable results, with regional acclimation potential and population-genetic adaptations (Georgian et al., 2016; Kurman et al., 2017). *Desmophyllum pertusum*[6] and *M. oculata* maintain calcification in moderately low pH (7.75) and near-saturation of aragonite (Hennige et al., 2014; Maier et al., 2016; Büscher et al., 2017), but lower pH (7.6) and corrosive conditions lead to net dissolution of *D. pertusum* skeletons (*high confidence*) (Lunden et al., 2014; Kurman et al., 2017; Gómez et al., 2018). Experiments suggest that *D. dianthus* is more sensitive to warming than acidification and when both are high, as projected under climate change. Warming appears to compensate for declines in calcification, with fitness also sensitive to food availability (Bramanti et al., 2013; Movilla et al., 2014; Gori et al., 2016; Baussant et al., 2017; Büscher et al., 2017; Schönberg et al., 2017; Höfer et al., 2018; Maier et al., 2019).

In OMZ regions (Section 3.2.3.2), benthic species distributions (Sperling et al., 2016; Levin, 2018; Gallo et al., 2020), abundance and composition of demersal fishes in canyons (De Leo et al., 2012) and deep-pelagic zooplankton (Wishner et al., 2018) follow oxygen gradients, indicating that deep-sea biodiversity and ecosystem structure will be impacted by extension of hypoxic areas (*medium confidence*). Fossil records show benthic population collapse and turnover when oxygen ranged from oxic to mildly or severely hypoxic (Cross-Chapter Box PALEO in Chapter 1, Moffitt et al., 2015). Regional extirpations among cold-water corals in the paleorecord were associated with substantial declines in oxygen, coincident with abrupt warming and altered intermediate water masses properties (Wienberg et al., 2018; Hebbeln et al., 2019). Despite mortality and functional impacts from low oxygen concentrations observed in aquaria (Lunden et al., 2014), recent observations of the deep-water coral *D. pertusum* suggest adaptive capacity to hypoxia among specimens from OMZ regions that are highly productive (*low confidence*) (Hanz et al., 2019; Hebbeln et al., 2020).

Chemosynthetic ecosystems could be particularly prone to oxygen decline (*low to medium confidence*). Projected OMZ expansion in the vicinity of seep communities could favour sulphide-tolerant species, as suggested from fossil records (Moffitt et al., 2015), but this will exclude large symbiont-bearing foundation species of methane seep ecosystems (Fischer et al., 2012; Sweetman et al., 2017). Projected warming, or shifts in warm-current circulation along continental margins, could enhance dissociation of buried methane hydrates (Phrampus and Hornbach, 2012; Phrampus et al., 2014), either increasing anaerobic methane oxidation (Boetius and Wenzhöfer, 2013), which benefit seep communities, or increasing gas fluxes, which would decrease anaerobic methane oxidation rates and exclude chemosynthetic fauna.

Environmental niche models (FAO, 2019; Morato et al., 2020; Puerta et al., 2020) project that under RCP8.5, >50% of present-day scleractinian habitats in the North Atlantic Ocean, will become unsuitable by 2100, with greater impacts on *D. pertusum* than on *D. dianthus* or *Madrepora oculata*. For gorgonians, corresponding habitat loss is *likely* >80%. Much less is known about the environmental niches of deep-sea sponges, preventing a similar assessment (Kazanidis et al., 2019; Puerta et al., 2020).

Climate-driven impacts further limit the resilience of deep-sea ecosystems to impacts from human activities (*high confidence*) (Levin and Le Bris, 2015; Rogers, 2015; Sweetman et al., 2017). However, assessing cumulative climatic and non-climatic impacts is challenging for these data-poor environments (Ashford et al., 2018; Levin, 2018; Armstrong et al., 2019; Heffernan, 2019; Kazanidis et al., 2020; Orejas et al., 2020), where lack of knowledge increases the possibility of overlooking ecosystem vulnerabilities and risks (Levin, 2021). A paucity of information about the natural variability and historical trends of these habitats prevents

[6] Previously named *Lophelia pertusa*

robust assessment of adaptive capacities and potential vulnerabilities to extreme events (Aguzzi et al., 2019; Levin et al., 2019; Chapron et al., 2020; Danovaro et al., 2020; Le Bris and Levin, 2020; Levin, 2021). The spatial resolution of CMIP5 models is too coarse to robustly project changes in mesoscale circulation at the seafloor (Sulpis et al., 2019), on which deep-sea ecosystems depend for organic material supplies and dispersal of planktonic and planktotrophic larvae (*high confidence*) (Fox et al., 2016; Mitarai et al., 2016; Dunn et al., 2018). Higher-resolution modelling from CMIP6 (Orr et al., 2017), multiannual and high-frequency records of ocean bottom-water properties (Meinen et al., 2020), and better understanding and accounting of biogeochemical mechanisms of organic carbon transport to the ocean interior is expected to improve this capacity (Boyd et al., 2019; Séférian et al., 2020).

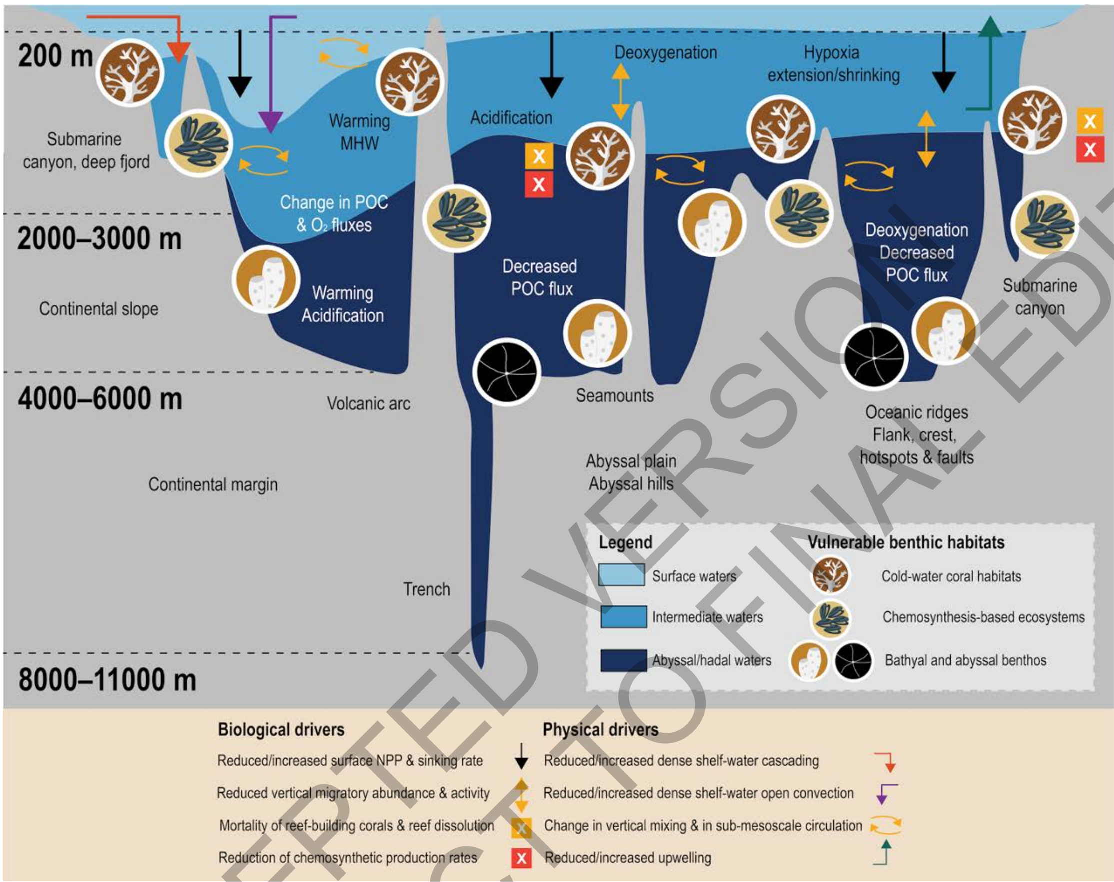


Figure Box3.3.1: Schematic of the combination of climate-impact drivers in different deep-ocean ecosystems. Key physical and biological drivers of change in the deep-sea and benthic habitats with specific vulnerabilities are discussed in Section 3.4.3.3.

[END BOX 3.3 HERE]

3.4.4 Reversibility and Impacts of Temporary Overshoot of 1.5°C or 2°C Warming

Scenarios limiting warming to the 1.5°C and 2°C limits in the Paris Agreement can involve temporarily exceeding those warming levels before declining again (WGI AR6 Section 4.6.2.1, Lee et al., 2021). The effect of such "overshoot" on marine and coastal ecosystems depends on the reversibility of both the response of climate-impact drivers, and the response of organisms and ecosystems to the climate-impact drivers, during the overshoot period. WGI AR6 assessed that temporary overshoot of a 2°C warming threshold has irreversible effects on global mean sea-level and also effects on ocean heat content that persist beyond 2100 (WGI AR6 Section 4.6.2.1, Lee et al., 2021). Model results indicate that sea surface temperatures (*high confidence*), Arctic sea ice (*high confidence*), surface ocean acidification (*very high confidence*) and surface ocean deoxygenation (*very high confidence*) are reversible within years to decades if net emissions reach zero or below (WGI AR6 Table 4.10, Lee et al., 2021). Although changes in these surface ocean variables are reversible, habitat-forming ecosystems including coral reefs and kelp forests may undergo irreversible phase shifts with >1.5°C warming (Section 3.4.2.1, 3.4.2.3), and are thus at high risk this century in 1.5°C or 2°C scenarios involving overshoot (Tachiiri et al., 2019). In an overshoot scenario in which CO_2 returns to 2040 levels by 2100 (SSP5-3.4-OS, O'Neill et al., 2016), SST and Arctic sea ice do not fully return by 2100 to levels prior to the CO_2 peak (*medium confidence*) (WGI AR6 Section 4.6.2.1, Lee et al., 2021), suggesting that reversal of marine ecological impacts from 21st century climate impacts would extend into the 22nd century or beyond (McManus et al., 2021). Models also indicate that global sea level rise, as well as warming, ocean acidification and deoxygenation at depth, are irreversible for centuries or longer (*very high confidence*) (WGI AR6 Section 4.6.2.1 and Table 4.10, Palter et al., 2018; Li et al., 2020c; Lee et al., 2021).

3.5 Vulnerability, Resilience and Adaptive Capacity in Marine Social-Ecological Systems, including Impacts to Ecosystem Services

3.5.1 Introduction

This Section assesses the impacts of climate change on ecosystem services (Table 3.25, Chapter 1) and the outcomes on social-ecological systems, building on previous assessments (Table 3.26). Section 3.5.2 assesses how changes in biodiversity influence ecosystem services. Then Sections 3.5.3 and 3.5.4 assess provisioning services (food and non-food), Section 3.5.5 assesses supporting and regulating services, and Section 3.5.6, cultural services. Where evidence exists, the section evaluates how the vulnerability and adaptive capacity of social-ecological systems govern the manifestation of impacts on each ecosystem service.

Table 3.25: Ocean and coastal ecosystem services. Adapted from IPBES (2017), with examples made specific to ocean and coastal ecosystems by Chapter 3 authors.

Ecosystem Service Category	Components	Ocean and Coastal Examples
Provisioning	Food and feed	Status of harvested marine fish, invertebrates, mammals, and plants.
	Medicinal, biochemical and genetic resources	Existence of and access to biological resources that could offer future prospects for development, including marine fish, invertebrates, mammals, plants, microbes, viruses.
	Materials and assistance	Existence of and access to minerals, shells, stones, coral branches, dyes used to create other goods; availability of marine organisms to exhibit in zoos, aquariums, and as pets.
	Energy	Existence of and access to sources of energy, including oil and gas reserves; solar, tidal, and thermal ocean energy; and biofuels from marine plants.
Supporting and Regulating	Habitat creation and maintenance	Status of nesting, feeding, nursery, and mating sites for birds, mammals, and other marine life, and of resting and overwintering places for migratory marine life or insects. Connectivity of ocean habitats.
	Dispersal and other propagules	Ability of marine life to spread gametes and larvae successfully by broadcast spawning reproduction, and ability of adults to disperse widely.
	Regulation of climate	Status of carbon storage and sequestration, methane cycling in

		wetlands, and dimethyl sulfide creation and destruction.
	Regulation of air quality	Status of aquatic processes that maintain and balance CO_2, oxygen, nitrogen oxides, sulfur oxides, volatile organic compounds, particulates, and aerosols.
	Regulation of ocean acidification (Section 3.2.3.1)	Status of chemical and biological aquatic processes that maintain and balance CO_2 and other acids/bases.
	Regulation of freshwater quantity, location and timing	Status of water storage by coastal systems, including groundwater flow; aquifer recharge; and flooding responses of wetlands, coastal water bodies, and developed spaces.
	Regulation of freshwater and coastal water quality	Status of chemical and biological aquatic processes that retain and filter coastal waters, capture pollutants and particles, and oxygenate water (e.g., natural filtration by sediments including adsorbent minerals and microbes).
	Regulation of organisms detrimental to humans and marine life	Status of grazing that controls harmful algal blooms and algal overgrowth of key ecosystems. Environmental conditions that suppress marine pathogens.
	Formation, protection and decontamination of soils and sediments	Status of chemical and biological aquatic processes that capture pollutants and particles (e.g., adsorption by minerals, microbial breakdown of pollutants).
	Regulation of hazards and extreme events	Ability of coastal environments to serve as wave energy dissipators, barriers, and wave breaks.
	Regulation of key elements	Status of aquatic processes that maintain and balance stocks of carbon, nitrogen, phosphorus, and other elements critical for life.
Cultural	Physical and psychological experiences	Existence of and access to recreational opportunities including visiting beaches and coastal environments; and aquatic activities such as fishing, boating, swimming, and diving.
	Supporting identities	Existence of and access to cultural, heritage, and religious activities, and opportunities for intergenerational knowledge transfer. Sense of place.
	Learning and inspiration	Existence of educational opportunities and characteristics to be emulated, as in biomimicry.
	Maintenance of options	Existence of opportunities to develop new medicines, materials, foods, and resources, or to adapt to a warmer climate and emergent diseases.

Table 3.26: Conclusions from previous IPCC assessments about observed and projected climate impacts to ocean and coastal biodiversity and ecosystem services.

Ecosystem service and chapter subsection	Observed Impacts	Projected Impacts
All (Section 3.5)	Climate change has affected marine "ecosystem services with regionally diverse outcomes, challenging their governance (*high confidence*). Both positive and negative impacts result for food security through fisheries (*medium confidence*), local cultures and livelihoods (*medium confidence*), and tourism and recreation (*medium confidence*). The impacts on ecosystem services have negative consequences for health and well-being (*medium confidence*), and for Indigenous Peoples and local communities dependent on fisheries (*high confidence*) (1.1, 1.5, 3.2.1, 5.4.1, 5.4.2, Figure SPM.2)" (SROCC SPM A.8, IPCC, 2019c).	"Long-term loss and degradation of marine ecosystems compromises the ocean's role in cultural, recreational, and intrinsic values important for human identity and well-being (*medium confidence*) (3.2.4, 3.4.3, 5.4.1, 5.4.2, 6.4)" (SROCC SPM B.8, IPCC, 2019c).
Biodiversity (Section 3.5.2)	"[Climate] Impacts are already observed on [coastal ecosystem] habitat area and biodiversity, as well as ecosystem functioning and services (*high confidence*) (4.3.2, 4.3.3, 5.3, 5.4.1, 6.4.2, Figure SPM.2)" (SROCC SPM A.6, IPCC, 2019c).	"Risks of severe impacts on biodiversity, structure and function of coastal ecosystems are projected to be higher for elevated temperatures under high compared to low emissions scenarios in the 21st century and beyond." (SROCC SPM B.6, IPCC, 2019c).
Food provision (Section 3.5.3)	"Warming-induced changes in the spatial distribution and abundance of some fish and shellfish stocks have had positive and negative impacts on catches, economic benefits, livelihoods, and local culture (*high confidence*). There are negative consequences for Indigenous Peoples and local communities that are dependent on fisheries (*high confidence*). Shifts in species distributions and abundance has challenged international and national ocean and fisheries governance, including in the Arctic, North Atlantic and Pacific, in terms of regulating fishing to secure ecosystem integrity and sharing of resources between fishing entities (*high confidence*) (3.2.4, 3.5.3, 5.4.2, 5.5.2, Figure SPM.2)". (SROCC SPM A.8.1 IPCC, 2019c).	"Future shifts in fish distribution and decreases in their abundance and fisheries catch potential due to climate change are projected to affect income, livelihoods, and food security of marine resource-dependent communities (*medium confidence*). Long-term loss and degradation of marine ecosystems compromises the ocean's role in cultural, recreational, and intrinsic values important for human identity and well-being (*medium confidence*) (3.2.4, 3.4.3, 5.4.1, 5.4.2, 6.4)" (SROCC SPM B.8,IPCC, 2019c).
Non-food consumable provisioning services (Section 3.5.4.1)	*Observed impacts on non-food provisioning services not previously assessed.*	"Reductions in marine biodiversity due to climate change and other anthropogenic stressors (Tittensor et al., 2010), such as ocean acidification (CBD, 2009) and pollution, might reduce the discovery of genetic resources from marine species useful in pharmaceutical, aquaculture, agriculture, and other industries (Arrieta et al., 2010), leading to a loss

		of option value from marine ecosystems.” (WGII AR5 Section 6.4.1.2, Pörtner et al., 2014)
Renewable energy (Section 3.5.4.2)	*Observed impacts on ocean renewable energy not previously assessed.*	“Ocean renewable energy can support climate change mitigation, and can comprise energy extraction from offshore winds, tides, waves, thermal and salinity gradient and algal biofuels. The emerging demand for alternative energy sources is expected to generate economic opportunities for the ocean renewable energy sector (*high confidence*), although their potential may also be affected by climate change (*low confidence*) (5.4.2, 5.5.1, Figure 5.23)”. (SROCC SPM C.2.5, IPCC, 2019c).
Habitat creation and maintenance (Section 3.5.5.1)	“[Climate] Impacts are already observed on [coastal ecosystem] habitat area and biodiversity, as well as ecosystem functioning and services (*high confidence*) (4.3.2, 4.3.3, 5.3, 5.4.1, 6.4.2, Figure SPM.2)” (SROCC SPM A.6, IPCC, 2019c). “In polar regions, ice associated marine mammals and seabirds have experienced habitat contraction linked to sea ice changes (*high confidence*).” (SROCC SPM A.5.2, IPCC, 2019c).	“In the Southern Ocean, the habitat of Antarctic krill, a key prey species for penguins, seals and whales, is projected to contract southwards under both RCP2.6 and RCP8.5 (*medium confidence*) (3.2.2, 3.2.3, 5.2.3)” (SROCC SPM B5.3, IPCC, 2019c). “Ocean warming, oxygen loss, acidification and a decrease in flux of organic carbon from the surface to the deep ocean are projected to harm habitat-forming cold-water corals, which support high biodiversity, partly through decreased calcification, increased dissolution of skeletons, and bioerosion (*medium confidence*).” (SROCC SPM B5.4, IPCC, 2019c).
Climate regulation and air quality (Section 3.5.5.2)	“Global ocean heat content continued to increase throughout [the 1951-present] period, indicating continuous warming of the entire climate system (*very high confidence*)” (WGI AR6 TS1.2.3, Arias et al., 2021).	“The increase in global ocean heat content (TS2.4) will *likely* continue until at least 2300 even for low-emission scenarios.” (WGI AR6 Box TS.9, Arias et al., 2021).
	“Land and ocean have taken up a near-constant proportion (globally about 56% year^{-1}) of CO_2 emissions from human activities over the past six decades, with regional differences (*high confidence*)” (WGI AR6 SPM A1.1, IPCC, 2021b).	“While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decrease with increasing cumulative CO_2 emissions. This is projected to result in a higher proportion of emitted CO_2 remaining in the atmosphere (*high confidence*)” (WGI AR6 SPM B4.1, IPCC, 2021b).
	Observed impacts on marine organisms’ contribution to climate regulation not previously assessed.	“The effect of climate change on marine biota will alter their contribution to climate regulation, that is, the maintenance of the chemical composition and physical processes in the atmosphere and oceans (*high confidence*) (Beaumont et al., 2007)”

		(WGII AR5 Section 6.4.1.3, Pörtner et al., 2014).
Provision of fresh water, maintenance of water quality, regulation of pathogens (Section 3.5.5.3)	*Observed climate impacts on salinisation of coastal soil and groundwater not previously assessed.*	"In the absence of more ambitious adaptation efforts compared to today, and under current trends of increasing exposure and vulnerability of coastal communities, risks, such as erosion and land loss, flooding, salinisation, and cascading impacts due to mean sea level rise and extreme events are projected to significantly increase throughout this century under all greenhouse gas emissions scenarios (*very high confidence*)." (SROCC SPM B9.1, IPCC, 2019c)
	"Global warming compromises seafood safety (*medium confidence*) through human exposure to elevated bioaccumulation of persistent organic pollutants and mercury in marine plants and animals (*medium confidence*), increasing prevalence of waterborne *Vibrio* sp. pathogens (*medium confidence*), and heightened likelihood of harmful algal blooms (*medium confidence*)." (SROCC SPM B.8.3, IPCC, 2019c).	"[Risks from marine-borne pollutants and pathogens] are projected to be particularly large for human communities with high consumption of seafood, including coastal Indigenous communities (*medium confidence*), and for economic sectors such as fisheries, aquaculture, and tourism (*high confidence*) (3.4.3, 5.4.2, Box 5.3)" (SROCC SPM B.8.3, IPCC, 2019c).
	"Since the early 1980s, the occurrence of harmful algal blooms (HABs) and pathogenic organisms (e.g., *Vibrio*) has increased in coastal areas in response to warming, deoxygenation and eutrophication, with negative impacts on food provisioning, tourism, the economy and human health (*high confidence*)." (SROCC Chapter 5 Executive Summary, Bindoff et al., 2019).	"Overall, the occurrence of HABs, their toxicity and risk on natural and human systems are projected to continue to increase with warming and rising CO_2 in the 21st century (Glibert et al., 2014; Martín-García et al., 2014; McCabe et al., 2016; Paerl et al., 2016; Gobler et al., 2017; McKibben et al., 2017; Rodríguez et al., 2017; Paerl et al., 2018; Riebesell et al., 2018) (*high confidence*)." (SROCC Box 5.4, Bindoff et al., 2019).
Regulation of physical hazards (Section 3.5.5.4)	"Coastal ecosystems are already impacted by the combination of sea level rise, other climate-related ocean changes, and adverse effects from human activities on ocean and land (*high confidence*)... Coastal and near-shore ecosystems including saltmarshes, mangroves, and vegetated dunes in sandy beaches, ... provide important services including coastal protection... (*high confidence*)" (SROCC Chapter 4 Executive Summary, Oppenheimer et al., 2019).	"The decline in warm water coral reefs is projected to greatly compromise the services they provide to society, such as...coastal protection (*high confidence*)..." (SROCC SPM B.8.2, IPCC, 2019c).
Ocean and coastal carbon storage (Section 3.5.5.5)	"Recent observations show that ocean carbon processes are starting to change in response to the growing ocean sink, and these changes are expected to contribute significantly to future weakening of the ocean sink under medium- to high-emission scenarios. However, the effects of these changes is not yet reflected in a weakening	"Emission scenarios SSP4-6.0 and SSP5-8.5 lead to warming of the surface ocean and large reductions of the buffering capacity, which will slow the growth of the ocean sink after 2050. Scenario SSP1-2.6 limits further reductions in buffering capacity and warming, and the ocean sink weakens in response to the declining rate of

	trend of the contemporary (1960–2019) ocean sink (*high confidence*)" (WGI AR6 Chapter 5 Executive Summary, Canadell et al., 2021).	increasing atmospheric CO_2. There is *low confidence* in how changes in the biological pump will influence the magnitude and direction of the ocean carbon feedback" (WGI AR6 Chapter 5 Executive Summary, Canadell et al., 2021).
	"Mangrove, seagrass, and salt marsh ecosystems offer important carbon storage and sequestration opportunities (*limited evidence, medium agreement*), in addition to ecosystem goods and services such as protection against coastal erosion and storm damage and maintenance of habitats for fisheries species." (WGII AR5 Technical Summary).	"…under high emission scenarios, sea level rise and warming are expected to reduce carbon sequestration by vegetated coastal ecosystems (*medium confidence*); however, under conditions of slow sea level rise, there may be net increase in carbon uptake by some coastal wetlands (*medium confidence*)" (SROCC Chapter 5, Bindoff et al., 2019).
Cultural Services (Section 3.5.6)	"Climate change impacts on marine ecosystems and their services put key cultural dimensions of lives and livelihoods at risk (*medium confidence*), including through shifts in the distribution or abundance of harvested species and diminished access to fishing or hunting areas. This includes potentially rapid and irreversible loss of culture and local knowledge and Indigenous knowledge, and negative impacts on traditional diets and food security, aesthetic aspects, and marine recreational activities (*medium confidence*)" (SROCC SPM B.8.4, IPCC, 2019c).	"Future shifts in fish distribution and decreases in their abundance and fisheries catch potential due to climate change are projected to affect income, livelihoods, and food security of marine resource-dependent communities (*medium confidence*). Long-term loss and degradation of marine ecosystems compromises the ocean's role in cultural, recreational, and intrinsic values important for human identity and well-being (*medium confidence*)" (SROCC SPM B.8, IPCC, 2019c).

3.5.2 Biodiversity

Climate change is a key agent of biodiversity change in numerous ocean and coastal ecosystems (*very high confidence*) (Table 3.26, Worm and Lotze, 2021), and climate change and biodiversity loss reinforce each other (Pörtner et al., 2021b). Biodiversity has changed in association with ocean warming and loss of sea ice (Sections 3.4.2.10, 3.4.3.3.3; Section CCP6 2.4.2), SLR (Section 3.4.2; Cross-Chapter Box SLR in Chapter 3), coral bleaching (Section 3.4.2.1), MHWs (Sections 3.4.2.1-3.4.2.5), and upwelling changes (*high confidence*) (Section 3.4.2.9). Overlapping non-climate drivers (Section 3.1) also decrease ocean and coastal ecosystem biodiversity (*very high confidence*) (O'Hara et al., 2021; Pörtner et al., 2021b). There is *medium confidence* that local and regional marine biodiversity losses from climate disrupt ecosystem services provided by specific ocean and coastal species or places (Sections 3.5.3–3.5.6, Figure 3.23, Table 3.26, Box 3.3, Dee et al., 2019a; Hossain, 2019; Smale et al., 2019; Teixeira et al., 2019; Martin et al., 2020; Pathak, 2020; Weiskopf et al., 2020; Zunino et al., 2020; Archer et al., 2021). However, adaptive capacity varies greatly among ecosystems, and ecological functions sometimes remain, despite changes in species assemblages, as in certain coral reef communities (Richardson et al., 2020). Projected changes in biodiversity due to climate change (Section 3.4.3.3.3) are expected to alter the flow and array of ocean and coastal ecosystem services (*high confidence*) (Smale et al., 2019; Cavanagh et al., 2021; Ruthrof et al., 2021; Worm and Lotze, 2021), but data gaps hinder developing projections of ecosystem service changes detailed enough to support decision making (Rosa et al., 2020).

Non-indigenous marine species are major agents of ocean and coastal biodiversity change, and climate and non-climate drivers interact to support their movement and success (*high confidence*) (Iacarella et al., 2020). At times, non-indigenous species act invasively and outcompete indigenous species, causing regional biodiversity shifts and altering ecosystem function, as seen in the Mediterranean region (*high confidence*) (e.g., Mannino et al., 2017; Bianchi et al., 2019; Hall-Spencer and Harvey, 2019; Verdura et al., 2019; García-Gómez et al., 2020; Dimitriadis et al., 2021). Warming-related range expansions of non-indigenous species have directly or indirectly decreased commercially important fishery species and nursery habitat (Booth et al., 2018). Non-indigenous species outperform indigenous species in coastal zones experiencing warming and freshening (McKnight et al., 2021). Non-climate drivers, especially marine shipping in newly ice-free locations (Chan et al., 2019), fishing pressure (Last et al., 2011), aquaculture of non-indigenous species (Mach et al., 2017; Ruby and Ahilan, 2018), and marine pollution and debris (Gall and Thompson, 2015; Carlton et al., 2018; Carlton and Fowler, 2018; Lasut et al., 2018; Miralles et al., 2018; Rech et al., 2018; Therriault et al., 2018), promote range shifts and movement of non-indigenous species (*high confidence*). Non-climate drivers can also intensify the ecological effects of non-indigenous species (Geraldi et al., 2020). Invasive marine species can alter species behaviour, reduce indigenous species abundance, reduce water clarity, bioaccumulate more heavy metals than indigenous species, and inhibit ecosystem resilience in the face of extreme events (*medium confidence*) (McDowell et al., 2017; Geburzi and McCarthy, 2018; Anton et al., 2019; Ruthrof et al., 2021). Risks from invasive species to the sources of other ecosystem services or aquatic goods, including valuable materials, mining activities, shipping, or ocean energy installations, have not been evaluated.

Reducing risk to ecosystem functions and services that depend on biodiversity requires an integrated approach that acknowledges the close linkages between the climate and biodiversity crises and common governance challenges (Pörtner et al., 2021b). Climate-focused solutions that employ nature-based solutions (NbS), technological interventions, and socio-institutional interventions (Section 3.6.2) can also safeguard biodiversity (Pörtner et al., 2021b), which in turn will help ocean and coastal ecosystems adapt to climate impacts as well as help sustain the services they provide to people (Sections 3.5.3–3.5.6).

3.5.3 Food Provision

Globally, about 17% of humans' average per capita intake of animal protein in 2017 came from marine and freshwater wild-caught and aquacultured aquatic animals (Costello et al., 2020; FAO, 2020a). Per capita intake of seafood is 50% or more in some Small Island Developing States (SIDS) (Vannuccini et al., 2018), and consumption per capita is 15 times higher in Indigenous Peoples than non-Indigenous Peoples (Cisneros-Montemayor et al., 2016). Fishery products also supply critical dietary micronutrients worldwide (Section 3.5.4.1, Hicks et al., 2019; Vianna et al., 2020). Marine and freshwater fisheries and aquaculture provide livelihoods for an estimated 10–12% of the world's population (Barange et al., 2018). Fishing and aquaculture provide women and their families with substantial amounts of food and income (Harper et al., 2020b), because at least 11% of small-scale fishers (Harper et al., 2020b) and up to half of all fishery and aquaculture workers (FAO, 2018) are women. This section assesses how climate-driven alterations of the abundance or nutritional quality of food from the sea could affect humans. Aquaculture, catch potential changes, and human adaptations to changes in wild and cultured harvests, are assessed in Section 5.9.

Ocean and coastal fauna are moving towards higher latitudes globally due to warming (*high confidence*) (Section 3.4.3.1, Table 3.26), challenging fishers and fisheries management (*high confidence*) as fishers also move poleward and diversify harvests (*medium evidence, high agreement*) (Table 3.26, Sections 3.4.3.3.3, 5.8.4, Leitão et al., 2018; Liang et al., 2018; Ottosen et al., 2018; Peck and Pinnegar, 2018; Pinsky et al., 2018; Erauskin-Extramiana et al., 2019; Free et al., 2019; Gianelli et al., 2019; Scott et al., 2019; Smith et al., 2019; Gervais et al., 2021). Model hindcasts have identified temperature-associated fisheries reductions worldwide (Free et al., 2019), and they have implicated overfishing as the primary non-climate driver increasing fishery vulnerability (Section 5.8.4, Peck and Pinnegar, 2018; Das et al., 2020). Catch composition is changing in many locations fished by smaller-scale, less mobile commercial, artisanal, and recreational fisheries (*high confidence*) (Booth et al., 2018; Townhill et al., 2019; Young et al., 2019b; Robinson et al., 2020; Champion et al., 2021). Limited exceptions have been noted, with wild harvests in some places remaining stable or increasing (e.g., Arreguín-Sánchez, 2019; Robinson et al., 2019b; Kainge et al., 2020). Where possible, fishers are maintaining harvests by broadening catch diversity, traveling poleward, and changing gear and strategies (*high confidence*) (Section 3.6.3.1.2, Barange et al., 2018; Dubik et al., 2019; Townhill et al., 2019). Fisheries and aquaculture adaptations, including management, are comprehensively assessed in Sections 3.6.3.1.2, 5.8.4, and 5.9.4.

Ocean acidification and deoxygenation caused by climate change are thought to influence fishing and aquaculture harvests, but *limited evidence* prevents assessing their present global impact on harvests. Substantial economic losses in the North American Pacific Coast shellfish aquaculture industry in the 2000s assessed in SROCC (Bindoff et al., 2019) and WGII AR5 (Pörtner et al., 2014) remain the clearest example of human harm from ocean acidification. Technology-based adaptations (Section 3.6.3) have minimised aquaculture losses from ocean acidification, including early warning systems to guide hatchery operations and culturing resilient shellfish strains (Section 5.9.4, Barton et al., 2015a). Laboratory studies show that ocean acidification decreases the fitness, growth, or survival of many economically and culturally important larval or juvenile shelled mollusks (*high confidence*) (Cao et al., 2018; Onitsuka et al., 2018; Stevens and Gobler, 2018; Griffith et al., 2019a; Mellado et al., 2019), and of several valuable wild-harvest crab species (Barton et al., 2015a; Punt et al., 2015; Miller et al., 2016; Swiney et al., 2017; Gravinese et al., 2018; Tomasetti et al., 2018; Long et al., 2019; Trigg et al., 2019). Ocean acidification alters larval settlement and metamorphosis of fish in laboratory studies (*high confidence*) (Cattano et al., 2018; Espinel-Velasco et al., 2018), suggesting possible changes in fish survival and thus fishery characteristics. Deoxygenation can decrease size and abundance of marine species and suppress trophic interactions (Levin, 2003), decrease the diversity within marine ecosystems (Sperling et al., 2016) while temporarily increasing catchability and increasing the risk of overfishing (Breitburg et al., 2018), and decrease the ecosystem services provided by specific fisheries (Orio et al., 2021). The chronic effects of deoxygenation on wild fisheries are complex and highly interactive with co-occurring drivers and overall ecosystem responses (*medium evidence, high agreement*) (Townhill et al., 2017; Rose et al., 2019). Detecting and attributing marine ecosystem responses to ocean acidification and deoxygenation outside of laboratory studies remains challenging because of the strong influence of co-occurring environmental changes on natural systems (Section 3.3.5, Rose et al., 2019; Doo et al., 2020).

Ocean and coastal organisms will continue moving poleward under RCP8.5 (*high confidence*) (Section 3.4.3.1.3, Figure 3.18), and this is expected to decrease fisheries harvests in low latitudes and alter species composition and abundance in higher latitudes (*high confidence*) (Table 3.26, Figure 3.23, Asch et al., 2018; Morley et al., 2018; Tai et al., 2019; Erauskin-Extramiana et al., 2020; Shelton et al., 2021). Species that succeed in new ranges or conditions may offer opportunities to diversify regional fisheries or aquaculture (Sections 3.6.3.1.2, 5.8.4, 5.9.4, Bindoff et al., 2019), or they may outcompete indigenous species and act as invasive species (Sections 3.4.2.10, 3.5.2).

Temperature will continue to be a major driver of fisheries changes globally, but other non-climate factors like organism physiology and ecosystem response (Section 3.3) and fishing pressure (Chapter 5), as well as other climate-impact drivers like acidification, deoxygenation, and sea-ice loss (Section 3.2), will play critical roles in future global and local fisheries changes (*high confidence*). Warming, acidification, and business-as-usual fishing policy under RCP8.5 are projected to place around 60% of global fisheries at very high risk (*medium confidence*) (Cheung et al., 2018). Model intercomparison showed that ocean acidification and protection affect ecosystems more than fishing pressure, and ecological adaptation greatly determines impacts on fishery biomass, catch and value until approximately 2050 (*medium confidence*) (Olsen et al., 2018). Ecosystem responses to warming water, fishing pressure, food-web changes, MHWs, and sea ice algal populations have been responsible for highly variable or collapsing populations of Northern Hemisphere high-latitude forage fish species including sand lances (*Ammodytes* spp.), Arctic cod (*Boreogadus saida*), capelin (*Mallotus catervarius*), and herring (*Clupea* spp.) (Lindegren et al., 2018; Steiner et al., 2019; Arimitsu et al., 2021; Suca et al., 2021). Declining stocks of forage fish are expected to have detrimental effects on seabirds, pelagic fish, and marine mammals (*medium confidence*) (Lindegren et al., 2018; Steiner et al., 2019), which may harm dependent human communities, including Arctic Indigenous Peoples (*low confidence*) (Arctic Monitoring and Assessment Programme, 2018; Steiner et al., 2019). Modelled fishery futures and revenue depend on environmental scenario, fishing fleet composition and management, and ocean acidification and temperature responses of harvested species (*high confidence*) (Punt et al., 2014; Punt et al., 2015; Seung et al., 2015; Fernandes et al., 2017; Rheuban et al., 2018; Tai et al., 2019; Punt et al., 2020). Detrimental effects of ocean acidification are projected to begin emerging in specific fisheries by 2030 (*limited evidence, high agreement*) [(southern Tanner crab (*Chionoecetes bairdi*) (Punt et al., 2015); sea scallop (*Placopecten magellanicus*) (Rheuban et al., 2018); Northeast Arctic cod (*Gadus morhua*) (Hänsel et al., 2020); Arctic fisheries (Lam et al., 2016)]. At the same time, projected hypoxic conditions of ~2 mg l^{-1} of oxygen will be consistently detrimental across taxonomic groups, developmental stages, and climate regions (*high confidence*) (Sampaio et al., 2021). Ecosystem-based management (Section 3.6.3.1.2) shows promise for decreasing risk from interacting climate and non-climate drivers to forage species and fished species.

3.5.4 Other Provisioning Services

3.5.4.1 Non-Food Consumable Products

The interaction of climate and non-climate drivers endangers the supply of non-food consumable products developed from marine organisms (*limited evidence, high agreement*). This broad class includes nutraceuticals (derived from fish, krill, shellfish, seaweeds, microbes), food preservatives or additives (derived from crustaceans, fish, microalgae and seaweeds, cyanobacteria), pharmaceuticals (derived from fish, shellfish, microbes, cyanobacteria, corals, sponges), or cosmetic products (derived from sponges, phytoplankton and seaweeds, fish, etc.) (Freitas et al., 2012; Dewapriya and Kim, 2014; Leal and Calado, 2015; Stengel and Connan, 2015; Greene et al., 2016; Ciavatta et al., 2017; Gutiérrez-Rodríguez et al., 2018). But biodiversity changes, warming, acidification, and non-climate drivers (especially fishing pressure) may decrease the availability of these organisms or the potency of the compounds they produce (Section 5.7.5.1, Table 3.26, Figure 3.23, Webster and Taylor, 2012; Mehbub et al., 2014; Kotta et al., 2018; Martins et al., 2018; Conrad et al., 2021). Observed and projected declines and movement of fish stocks due to fishing pressure and climate change impacts (IPCC, 2019b) have generated concerns that the supply and safety of fish and krill oil for human dietary supplements may decline (Section 5.7.5.1, Gribble et al., 2016; Lloret et al., 2016). This risk can be lowered by technological adaptations (Section 3.6.2.2) such as increasing the use of alternative sources, like marine phytoplankton, macroalgae, marine microbes (Dewapriya and Kim, 2014; Greene et al., 2016; Dave and Routray, 2018; Nguyen et al., 2020) and underutilised resources such as fish, seal, crab and shrimp byproducts (Dave and Routray, 2018), and by improving extraction and processing efficiency(Cashion et al., 2017). Climate effects on non-food consumable products could be widespread yet poorly detected, complicating assessment of impacts, risks, and vulnerability reduction.

There is *insufficient evidence* to develop global projections of future climate impacts on humans through changes in non-food consumable marine products, but specific local examples have been investigated, such as the Arctic ooligan (eulachon) (*Thaleichthys pacificus*), a small smelt fish. Ooligan grease has been used by Indigenous Peoples of the North Pacific coast (Phinney et al., 2009) for at least 5000 years to treat stomach aches, colds and skin conditions and as a traditional food source high in omega-3 fatty acids (Byram and Lewis, 2001; Cranmer, 2016; Patton et al., 2019). Analysis of remains have shown that ooligan could comprise up to 67% of traditional historical fisheries catches (Patton et al., 2019). Because ooligan spawning relies on the timing of the spring freshet, and because the species has declined in the last 25 years due to fishing pressure and predation, the species may be at risk from combined climate and non-climate drivers (*medium confidence*) (Talloni-Álvarez et al., 2019). Projections under RCP2.6 or RCP8.5 estimate reductions by 21% or 31% by 2050 in essential nutrients from traditional seafood for Indigenous Peoples in Canada, relative to 2000, with a modelled nutritional deficit that includes non-traditional dietary substitutions (Marushka et al., 2019).

3.5.4.2 Non-Consumable Goods

Limited evidence about climate impacts exists for valuable non-food aquatic materials. Ocean warming and acidification harm red coral (*Corallium rubrum*) (Bramanti et al., 2013) and communities hosting black coral (*Antipatharian* spp.), both used for jewellery (Ross et al., 2020). While no-take MPAs (Section 3.6.3.2) enhance red coral structural complexity, they only weakly compensate for warming effects (Cerrano et al., 2013; Montero-Serra et al., 2019). *Antipatharian* spp. are not well studied or monitored (Gress and Andradi-Brown, 2018). Acidification and warming negatively impact pearl oysters (Welladsen et al., 2010; Liu and He, 2012; Liu et al., 2012; Hoegh-Guldberg et al., 2014; Zhang et al., 2019b). Projected climate impacts for 2035 would decrease the average net present value of French Polynesia's pearl aquaculture industry by 29.1% compared to the present (Hilsenroth et al., 2021). Climate impacts on ornamental species sought by aquarists have not been well studied (Dee et al., 2019b).

Decreasing the vulnerability of renewable energy installations, particularly wind turbines, to climate risks (Table 3.26, Bindoff et al., 2019) could include technological adaptations (Section 3.6.2.2) such as storm "survival mode" settings (Penalba et al., 2018); preparation for hazards such as icing, SLR, drifting sea ice, and wave activity (Neill et al., 2018; Goodale and Milman, 2019; Solaun and Cerdá, 2019), and biofouling (*medium confidence*) (Want and Porter, 2018; Joyce et al., 2019; Vinagre et al., 2020), which is expected to increase in response to warming and acidification (*medium confidence*) (Dobretsov et al., 2019; Khosravi et al., 2019; Liu et al., 2020d; Lamim and Procópio, 2021). Macroalgae and fish processing byproducts are being tested for biofuel use (Greene et al., 2016; Alamsjah et al., 2017; Saifuddin and Boyce, 2017; Sakthivel et al., 2018; Sudhakar et al., 2019; Nguyen et al., 2020; Ramachandra and Hebbale, 2020; Tan et al., 2020), but weather variability could pose financial risk to this sector (Kleiman et al., 2021).

3.5.5 Supporting and Regulating Services

Ocean and coastal regulating services are detailed in Table 3.25. The economic value of all regulating ecosystem services in 2015 was estimated at 29.1 trillion USD, with water- and climate-regulating services contributing the most (Balasubramanian, 2019).

3.5.5.1 Habitat Creation and Maintenance and Larval Dispersal

Climate impacts have already altered ocean and coastal habitats (Section 3.4.2, Table 3.26, Gissi et al., 2021) in ways that have led to species range shifts, biodiversity changes, phenology changes, and regime shifts (Section 3.4.3) from the surface ocean to the seafloor (*very high confidence*) (Box 3.3, Figure 3.22). Continued ocean and coastal habitat impacts are projected, and their severities will depend on emissions scenario and co-occurring drivers (Section 3.4.3, Qiu et al., 2019) or extremes (e.g., Babcock et al., 2019). Warming and physical circulation are projected to change larval dispersal, a habitat-related service (Bashevkin et al., 2020), but identifying probable outcomes remains challenging owing to the high variability among species, locations, and recruitment (Schilling et al., 2020; King et al., 2021; Le Corre et al., 2021; Raventos et al., 2021). Climate risks to habitat can be decreased by reducing non-climate drivers, preserving ecosystems, or restoring habitat (Sections 3.6.2, 3.6.3.2). Risk to larval dispersal cannot be meaningfully addressed at scale by human-implemented adaptations; instead, declines in this service will pressure natural systems to adapt via physiological plasticity or evolution (Section 3.3, Bashevkin et al., 2020).

3.5.5.2 Climate Regulation and Air Quality

Climate regulation by the ocean depends on physical and biogeochemical processes (Sections 3.2–3.4) that create, move, and store heat, water vapor and other climate-active compounds including CO_2, methane, and dimethyl sulfide and methane (WGI AR6 Chapter 6, Naik et al., 2021). Over the 21st century, ocean heat and CO_2 uptake will continue (WGI AR6 SPMB4.1, B5.1, IPCC, 2021b) and sea ice loss from warming will allow some additional CO_2 uptake (Armstrong et al., 2019), but the ocean will take up a smaller fraction of CO_2 emissions as atmospheric CO_2 concentrations rise (*high confidence*) (Table 3.26, WGI AR6 SPM B4.1, IPCC, 2021b).

There is *very limited evidence* on climate-driven air-quality changes in the coastal zone. Increased humidity decreases the lifetime of ozone and increases particulate matter and indoor mold levels (USGCRP, 2016), potentially affecting near-shore air quality. However, coastal zone air pollution can enhance coastal climate impacts by increasing risk of acid rain, which worsens ocean acidification (nitrogen oxides, sulphur oxides, and mercury, Doney, 2010; Northcott et al., 2019).

3.5.5.3 Provision of Fresh Water, Maintenance of Water Quality, and Regulation of Pathogens

The salinities of many estuaries, deltas, coastal fresh water aquifers, and soils around the world are increasing, and this decrease in water quality is endangering human health and agricultural yields (*very high confidence*) (Table 3.26, Section 3.4.2.4, Bindoff et al., 2019; Bouderbala, 2019; Rahman et al., 2019; Naser et al., 2020; Rakib et al., 2020; Mastrocicco and Colombani, 2021). Coastal salinisation is attributed to regionally varying combinations of climate-impact drivers, like SLR and storm-related flooding by seawater, and non-climate drivers, like water withdrawal and land use changes (*very high confidence*) (Islam et al., 2019; Rahman et al., 2019; Paldor and Michael, 2021). Monitoring-related adaptations (Section 3.6.2.2.2) including advances in modeling and monitoring are providing decision-relevant, regional-scale information

(Colombani et al., 2016; Mukhopadhyay et al., 2019; Slama et al., 2020; Corwin, 2021). For example, new projections indicate which drinking water intake stations on China's Pearl River Estuary will be unable to meet demands by 2100 due to SLR and drought (Wang and Hong, 2021), while others show that SLR effects on seawater intrusion into the coastal aquifer in Kerala, India under both RCP4.5 and RCP8.5 scenarios are negligible (Sithara et al., 2020). Salinisation-associated changes may disproportionately burden women responsible for securing drinking water and fuel, such as in the Indian Sundarbans (Mukhopadhyay et al., 2019). Salinisation will continue to endanger coastal water and soil quality in the future (*high confidence*) (Islam et al., 2019; Paldor and Michael, 2021), but the evidence assessed above shows that subsequent impacts to human health and agriculture will depend heavily on regional variations in environment and human behaviour (*medium confidence*).

Together, climate and non-climate drivers can mobilise toxins and contaminants in ways that harm human and marine species health (*very high confidence*) (Box 3.2), and climate change is altering these relationships (*high confidence*) (Table 3.26, Bindoff et al., 2019). Under warming or ocean acidification, marine molluscs exposed to pharmaceuticals via wastewater experience more detrimental biological consequences or greater bioaccumulation (*limited evidence, high agreement*) (Costa et al., 2020a; Costa et al., 2020b; Dionísio et al., 2020; Freitas et al., 2020; Kibria et al., 2021). Physical circulation, temperature, and biogeochemical characteristics (Bowman et al., 2020; Liu et al., 2020a; Liu et al., 2020b; Sun et al., 2020; Zhang et al., 2020b) control the ubiquitous oceanic distribution of methylmercury, and ocean acidification- and warming-driven changes in planktonic speciation and interactions can promote additional food-web bioaccumulation of methylmercury (Tada and Marumoto, 2020; Wu et al., 2020b; Zhang et al., 2020b; Zhang et al., 2021a). Interactions among drivers also matter: temperature plus overfishing increased tissue methylmercury concentrations in Atlantic bluefin tuna from the 1970s to the 2000s more than the decreases in the late 1990s and 2000s from lower environmental mercury levels (Schartup et al., 2019). This appears true for persistent organic pollutants as well, but their bioaccumulation is related more to temperature effects on animal behaviour than on pollutant dynamics (Houde et al., 2019; Wagner et al., 2019; Kalia et al., 2021). By 2100 under RCP8.5, productivity changes and community structure shifts are expected to increase methylmercury concentrations in polar oceans and high-latitude phytoplankton and decrease it in low latitudes (Zhang et al., 2021a). The estimated average global cost of mercury-related health effects by 2050, mainly from seafood consumption during 2010–2050, will be 19 trillion USD (2020), assuming a 3% discount rate, if methylmercury emissions are not reduced (Zhang et al., 2021b).

Since previous assessments, evidence has increased that climate impacts such as warming, extreme weather, and SLR are increasing the geographic spread and risk of marine-borne human pathogen outbreaks, including *Vibrio* spp. (*very high confidence*) (Table 3.26, Bindoff et al., 2019; Logar-Henderson et al., 2019; Froelich and Daines, 2020; Montánchez and Kaberdin, 2020; Semenza, 2020; Ferchichi et al., 2021). Climate change affects at least 30 human pathogens with aquatic-system infection routes (e.g., ingestion of contaminated water or seafood, or contact with wounds, see Table SM3.2, Cross-Chapter Box ILLNESS in Chapter 2, Nichols et al., 2018). Conditions favourable for *Vibrio cholerae* are increasing globally, which raises risk to humans (Cross-Chapter Box ILLNESS in Chapter 2). Increased storm-related flooding and SLR further increase human encounters with *Vibrio* spp. (Froelich and Daines, 2020). Aquatic diseases, particularly *Vibrio* spp., have caused large economic losses in aquaculture by decreasing the quality or survival of cultured species (Lafferty et al., 2015; Novriadi, 2016). Temperature-based model projections show that all Canadian shellfish beds will experience conditions that promote high risk of *Vibrio* spp. growth by 2100 for both RCP4.5 and RCP8.5 scenarios (Ferchichi et al., 2021). Climate-impact drivers may increase *Vibrio* spp. loads in seafood species: laboratory-simulated heatwaves increase *Vibrio* spp. abundance in Pacific oyster (*Crassostrea gigas*) (Green et al., 2019) and simulated ocean acidification increases hard clam (*Mercenaria mercenaria*) susceptibility to *Vibrio* spp. infection (Schwaner et al., 2020). Projected increases in temperature, extreme and variable rainfall conditions, coastal flooding, and SLR (Section 3.2, Cross-Chapter Box SLR in Chapter 3) strongly increase the risk of frequent and severe aquatic human pathogen outbreaks in ocean and coastal areas that will continue to harm human health and cause economic losses (*high confidence*) (Cross-Chapter Box ILLNESS in Chapter 2, Froelich and Daines, 2020; Semenza, 2020; Ferchichi et al., 2021). Section 3.6.3.1.5 assesses human adaptations to increasing risk of marine-borne pathogens.

Climate-driven changes in temperature, salinity (from ice melt and precipitation changes), deoxygenation, and ocean acidification can alter dynamics of infectious diseases that target ocean and coastal species by increasing hosts' susceptibility or pathogens' abundance or virulence (*high confidence*) (Burge and Hershberger, 2020; Byers, 2021). Coral and urchin diseases have increased over time driven by warming-related declines in organism recovery and survival or immunity (*medium confidence*) (Cohen et al., 2018; Tracy et al., 2019). Seagrass and sea star wasting disease outbreaks have occurred under combinations of ocean warming or MHWs and non-climate drivers (e.g., eutrophication, bottom trawling), but attribution of these outbreaks to specific drivers is still not resolved (Harvell et al., 2019; Jakobsson-Thor et al., 2020; Krause-Jensen et al., 2021). Disease outbreaks threaten marine biodiversity, species that create habitat or dampen wave action, and keystone species (Harvell and Lamb, 2020). Attributing observed changes in marine disease patterns to climate remains extremely difficult owing to interacting climate and non-climate drivers (Burge and Hershberger, 2020) and lack of baseline data (Tracy et al., 2019). Projected increases in the frequency, duration, and intensity of warming events would reduce survival and recovery of some species from hot events, reduce immunity of other species to pathogens, extend poleward ranges of some pathogens, and increase infection risk when host species congregate in scarce habitat (Cohen et al., 2018). Pathogens that target ocean and coastal organisms may themselves be sensitive to future climate conditions or subsequent ecosystem changes, which challenges development of projections (Cohen et al., 2018; Burge and Hershberger, 2020).

Following the *high confidence* assessment of SROCC Table 3.26, Bindoff et al. (2019) that risks associated with HABs will continue to increase with warming and rising CO_2 in the 21st century, new examples have illustrated how toxic HABs interfere with regulating, provisioning (Section 3.5.3), and cultural ecosystem services (Section 3.5.6) in interconnected ways (*limited evidence, high agreement*). A massive toxic *Pseudo-nitzschia* spp. bloom in 2013–2016 along the United States (US) West Coast triggered Dungeness crab, rock crab, and razor clam fishery closures to protect human consumers (Sections 3.6.2, 3.6.3.1.5, McCabe et al., 2016), and this disproportionately harmed fishers, especially small-vessel owners, and fishing-support service industries, primarily through lost revenue (Ritzman et al., 2018; Moore et al., 2019; Trainer et al., 2019; Jardine et al., 2020; Moore et al., 2020a). Toxic *Alexandrium* spp. blooms promoted by climate-driven coastal extremes (e.g., MHWs, stratification, runoff) in Tasmania, Australia, in 2012 and Chile in 2016 caused fish kills, shellfish product recalls, substantial economic losses, and human sickness and death (Trainer et al., 2019). The Chile event caused an estimated loss of 800 million USD in the farmed salmon industry (Díaz et al., 2019) and resulted in a series of large, long-lasting regional protests calling for national aid (Delgado et al., 2019). New evidence, however, suggests that the perceived global increase in harmful algal blooms results from better monitoring and more detrimental bloom impacts rather than a climate-linked mechanism (Hallegraeff et al., 2021).

Natural and engineered systems have long been used effectively to manage precipitation and wastewater safely (Chapter 4, Box 4.5), and maintaining and enhancing them is a key nature-based adaptation strategy for coastal communities (Section 3.6.2.3, Cross-Chapter Paper 2). Estimated values of water purification and stormwater management provided by coastal ecosystems are in the hundreds to thousands of USD per hectare [e.g., 272 Euro per 0.01 $km^2\ yr^{-1}$ from the Mediterranean's sandy coastline (Hérivaux et al., 2018); 1100–2800 USD per 0.01 $km^2\ yr^{-1}$ from the state of Maryland, USA (Campbell et al., 2020b); 600 USD per 0.01 $km^2\ yr^{-1}$ in Zhuzhou City, China (Zhan et al., 2020)]. Both wild and cultured organisms also provide filtration services. Seagrasses' ability to purify water is well recognised by coastal residents and ocean resource users in tropical and temperate locations (Ambo-Rappe et al., 2019; Quevedo et al., 2020; Heckwolf et al., 2021; McKenzie et al., 2021a). Globally, aquacultured shellfish remove an estimated 49,000 tonnes of nitrogen and 6000 tonnes of phosphorus from coastal waters, worth a potential 1.20 billion USD, and they may help improve existing engineered wastewater treatment systems (van der Schatte Olivier et al., 2020). Climate change, especially episodic extreme rains and RSLR (Romero-Lankao et al., 2014), is challenging management and design of wastewater and stormwater systems (*high confidence*) (Flood and Cahoon, 2011; Trtanj et al., 2016; Hummel et al., 2018; Kirshen et al., 2018; Nazarnia et al., 2020; Reznik et al., 2020; McKenzie et al., 2021b) and integrity of coastal landfills (Beaven et al., 2020). Without substantial adaptation that addresses projected wastewater management challenges and community needs (Section 4.2.6.1, Kirshen et al., 2018; Kirchhoff and Watson, 2019; Kool et al., 2020; Nazarnia et al., 2020; Hughes et al., 2021), coastal water quality in many areas will decrease because of more frequent or severe releases of untreated wastes (*high confidence*) (Flood and Cahoon, 2011; Hummel et al., 2018; Hughes et al., 2021; McKenzie et al., 2021b), and this will have harmful consequences for human and coastal ecosystem health (*high confidence*) (Cross-Chapter Box ILLNESS in Chapter 2, Section 4.2.6.1, Bindoff et al., 2019).

3.5.5.4 Regulation of Physical Hazards

Coastal ecosystems physically protect people and property from storms and flooding, and climate change threatens this protection function (Table 3.26, Figure 3.22). Increasingly detailed models show how warm-water coral reefs (Reguero et al., 2019; Storlazzi et al., 2019; Reguero et al., 2021) mangroves (Blankespoor et al., 2017; Menéndez et al., 2020; Trégarot et al., 2021) and wetlands (Sun and Carson, 2020) prevent billions of USD of direct and indirect damage to private and public property and shield millions of people from flooding each year. Protection by mangroves provides more economic benefits in higher-income nations and shields more people in lower-income nations (Menéndez et al., 2020). Seagrasses (James et al., 2020; James et al., 2021), kelp (Morris et al., 2020b; Zhu, 2020), suspended shellfish aquaculture (Gentry et al., 2020; Zhu et al., 2020a), oyster reefs (Chowdhury et al., 2019) coastal wetlands (Möller, 2019; Keimer et al., 2021), and sandy coastlines (Section 3.4.2.6, Hérivaux et al., 2018) also measurably decrease wave energy. Non-climate drivers (e.g., invasive species (James et al., 2020), sediment supply changes (Ganju, 2019; Ladd et al., 2019; Ilia, 2020), erosion and storm damage (Mehvar et al., 2019; Bacopoulos and Clark, 2021)], acting together with climate-impact drivers and impacts (e.g., sea level rise (Cross-Chapter Box SLR in Chapter 3), changes in plant biodiversity (Section 3.5.2, Lee Smee, 2019; Silliman et al., 2019; Schoutens et al., 2020), MHWs (Section 3.4.3.7), and acidification (Section 3.4.2.1)) compromise physical protection by coastal ecosystems (*very high confidence*). See Cross-Chapter Box SLR in Chapter 3 and Sections 3.6.3.1 and 3.6.3.2.2 for assessment of adaptations that address this ecosystem service.

3.5.5.5 Regulation of Carbon Cycling in Ocean and Coastal Ecosystems

Current and future total carbon storage and cycling in the ocean are governed by past and future CO_2 emissions trajectories (Table 3.26), but regional ocean and coastal carbon stocks and cycling vary over time and space due to processes being altered by climate, including ocean circulation, sea-ice cover, coastal upwelling, and thermal stratification (Section 3.2.2.3); ocean primary production and export (Sections 3.2.3, 3.4.4); and marine ecosystem biodiversity (*high confidence*) (Figure 3.22, Section 3.5.2). Quantifying regional carbon fluxes and stocks is still challenging and relies on indirect measures (e.g., Fennel et al., 2019; Clay et al., 2020), especially in coastal ecosystems where drivers interact. Carbon cycling and storage co-occurs with other regulating services such as habitat provision, water quality maintenance, and coastal protection (Ouyang et al., 2018), particularly in vegetated coastal ecosystems (Box 3.4). Adaptations to support regional carbon cycling and storage generally focus on area-based management and conservation (Section 3.6.3.2), but interventions to enhance ocean carbon storage are being explored for mitigation (WGIII AR6 Chapter 7).

[START BOX 3.4 HERE]

Box 3.4: Blue Carbon Ecosystems

Climate change and other anthropogenic drivers, including eutrophication, land-use changes, and overexploitation, directly and indirectly threaten blue carbon ecosystems (Annex II: Glossary). Commonly considered blue carbon ecosystems include vegetated coastal ecosystems (Sections 3.4.2.3–3.4.2.5), whose mangroves, saltmarshes and seagrass beds host rooted, vascular plants known to store large amounts of carbon for long periods and to be amenable to management (Lovelock and Duarte, 2019). Other ocean and coastal taxa including rooted or floating macroalgae (e.g., non-vascular multicellular kelp or seaweed genera such as Macrocystis spp., Sargassum spp., or Laminaria spp., Filbee-Dexter and Wernberg, 2020), phytoplankton, and even pelagic fauna (e.g., finfish or whales, Chami et al., 2019) have also been proposed as blue carbon ecosystems. Terrestrial vascular-plant-derived material can also carry and store significant amounts of carbon in marine environments (Cragg et al., 2020). There is increasing evidence about the coverage and carbon content of macroalgal, planktonic, and faunal taxa, but *low agreement* about their long-term carbon storage potential and manageability (Alongi, 2018b; Wernberg and Filbee-Dexter, 2018; Lovelock and Duarte, 2019; Ortega et al., 2019; Pfister et al., 2019; Queirós et al., 2019; Filbee-Dexter et al., 2020a; Gallagher, 2020; Mariani et al., 2020; Thorhaug et al., 2020; van Son et al., 2020; Bach et al., 2021; Bayley et al., 2021; Cavanagh et al., 2021; Frontier et al., 2021; Martin et al., 2021; Pedersen et al., 2021; Weigel and Pfister, 2021). This section focuses on the array of ecosystem services and adaptation opportunities provided by vegetated coastal blue carbon ecosystems, where consensus and evidence are most abundant. Mitigation potential of blue carbon ecosystems is assessed with land-based mitigation options in WGIII AR6 Section 7.4.

Carbon storage and burial in mangroves, saltmarshes and seagrass meadows (Table Box3.4.1) help regulate ocean and coastal carbon cycling and may contribute to nature-based mitigation, although regional estimates vary widely based on climatic and edaphic conditions (WGIII AR6 Section 7.4). In addition, coastal vegetated ecosystems provide substantial and interdependent regulating, provisioning and cultural ecosystem services. These include disproportionately high biodiversity per unit area (Pörtner et al., 2021a); abundant habitat (Section 3.5.5.1) and nurseries for aquatic, terrestrial, aerial, and microbial species; natural filtration of waste and stormwater runoff into the coastal ocean (Sections 3.5.5.3, 4.2.7, Cross-Chapter Box ILLNESS in Chapter 2); coastal protection (Section 3.5.5.4, Ouyang et al., 2018; Quevedo et al., 2020); food and natural materials (Sections 3.5.3, 3.5.4); and support for tourism, livelihoods, and cultural activities (Section 3.5.6). Global estimates of services provided by coastal blue carbon ecosystems depend on the quality of available mapping, which is currently best developed for mangroves (Macreadie et al., 2019), and improving for saltmarshes and seagrasses (McOwen et al., 2017; McKenzie et al., 2020; Young et al., 2021).

Table Box3.4.1: Estimates of organic carbon storage and burial rates in mangroves, saltmarshes, and seagrass meadows. Estimates are the mean ± 95% confidence interval, where available (indicating the *extremely likely* range) and range. Carbon stocks for mangroves include above- and below-ground storage up to 3 m depth (sampling period 2007–2017). The estimates for saltmarsh and seagrass stocks are soil stocks up to 1 m depth (observations spanning 1983–2016 for saltmarshes and until 2016 for seagrass meadows). Date ranges for the burial rates are: 1989–2020, 1975–2020 and 1956–2016 for mangroves, saltmarshes and seagrass meadows, respectively.

	Mangroves	Saltmarshes	Seagrass meadows
Carbon stocks (MgC ha^{-1})	856 ± 64.2 (79–2208) (Kauffman et al., 2020)	317.2 ± 38.2 (27–1900) (Alongi, 2018c)	139.7 (9.1–628) (Fourqurean et al., 2012; Alongi, 2018d)
Carbon burial rate (g C m^{-2} yr^{-1})	194 ± 30 (6.2–1722) (Wang et al., 2020)	168 ± 14 (1.2–1167.5) (Wang et al., 2020)	220.7 ± 40.2 (-2094–2124) (Alongi, 2018d)
Global Carbon burial rate (TgC yr^{-1})	41 (Wang et al., 2020)	12.63 (Wang et al., 2020)	35.31 (Alongi, 2020)
Global areal coverage (Mha)	13.7 (Richards et al., 2020)	5.5 (McOwen et al., 2017)	16 (McKenzie et al., 2020)

Coastal vegetated ecosystems are vulnerable to harm from multiple climate and non-climate drivers, and together these have reduced wetland area globally (*high confidence*) (Section 3.4.2.5) and endangered the services provided by these ecosystems (*high confidence*). Loss of coastal vegetated ecosystems changes biodiversity (Sections 3.5.2, 3.4.2.3–3.4.2.5) (Numbere, 2019; Parreira et al., 2021), increases risk of damage and erosion from SLR and storms (Sections 3.4.2.3–3.4.2.5, Cross-Chapter Box SLR in Chapter 3, Galeano et al., 2017), and impacts provisioning (Sections 3.5.3–3.5.4, Li et al., 2018b; Maina et al., 2021). These changes also strongly determine the quantity and longevity of blue carbon storage (*high confidence*) (Macreadie et al., 2019; Lovelock and Reef, 2020). Specific site characteristics and ecosystem responses to climate change will determine future local blue carbon storage or loss (*high confidence*) (Table Box3.4.2). For instance, poleward migration of mangroves to areas dominated by salt marshes is expected to increase carbon storage (Kelleway et al., 2016); however, this change in the dominant vegetation and associated faunal changes can modify carbon stocks and sequestration, as well as other ecosystem services (Martinetto et al., 2016; Kelleway et al., 2017; Smee et al., 2017; Macreadie et al., 2019; Macy et al., 2019). Landward range expansion of mangroves, marshes, and seagrass in response to gradual RSLR can enhance carbon sequestration (Cross-Chapter Box SLR in Chapter 3, Section 3.4.2.5, Macreadie et al., 2019), but coastal squeeze can limit this (Phan et al., 2015; Schuerch et al., 2018) and RSLR can either submerge and bury or erode and release stored blue carbon (Section 3.4.2.5, Macreadie et al., 2019; Lovelock and Reef, 2020). Gains and losses of mangrove habitat area (and therefore carbon storage) projected for nations under RCP4.5 and RCP8.5 depend primarily on the combination of SLR rate, adaptation scenario (including coastal development), and island or continental status (Lovelock and Reef, 2020). The influence of warming, MHWs, and acidification on seagrass meadows (Kendrick et al., 2019; Strydom et al., 2020) and associated coralligenous reefs (Zunino et al., 2019) suggests that future warming and especially MHWs will cause more widespread loss of services from these ecosystems (Section 3.4.2.5). Loss of blue carbon ecosystems will not only halt carbon storage, but also release stored carbon: emissions after 2000 due to global mangrove deforestation have been estimated at 23.5–38.7 Tg Cyr^{-1} (Ouyang and Lee, 2020). Mitigation estimates for avoided conversion and restoration of coastal wetlands and the implications of the impacts of climate change are assessed in WGIII AR6 Section 7.4.

To date, initiatives aiming to restore coastal wetland ecosystems primarily address ecosystem characteristics other than carbon storage (Herr et al., 2017; de los Santos et al., 2019; Lovelock and Duarte, 2019; Friess et al., 2020a). But recovery of coastal vegetated ecosystems is expected to bring back the full suite of ecosystem services they provide, not just carbon storage (*medium confidence*) (Marbà et al., 2015a; Burden et al., 2019; Friess et al., 2020a), making coastal restoration a low-risk action that offers both adaptation and mitigation benefits (Steven et al., 2020; Gattuso et al., 2021). Successful restoration requires using appropriate plant species in suitable environmental settings (Wodehouse and Rayment, 2019; Friess et al., 2020a) with favourable geomorphology and biophysical conditions (Cameron et al., 2019; Ochoa-Gómez et al., 2019) and considering social, economic, policy, and operational constraints (Section 3.6.3.2.2, Cross-Chapter Box NATURAL in Chapter 2), now and in the future (*high confidence*) (Duarte et al., 2020; Lovelock and Reef, 2020). Nevertheless, restored spaces may not store carbon at rates equal to those of undisturbed spaces (Yang et al., 2020), and it may take decades to determine or achieve carbon storage outcomes of restoration (Sasmito et al., 2019; Duarte et al., 2020; Oreska et al., 2020). Integration improves efforts to restore or conserve coastal wetland ecosystems to accomplish both adaptation and mitigation outcomes (Steven et al., 2020). Government-led conservation of blue carbon ecosystems as part of national and subnational climate strategies (e.g., Friess et al., 2020a; Kelleway et al., 2020; Wedding et al., 2021) benefits from coordination with private activities, such as incentivising conservation with payments for ecosystem services (Muenzel and Martino, 2018; Friess et al., 2020a). Moreover, successful area-based protection measures consider both environmental and social issues (Section 3.6.3.2). Continued integration and alignment of policies at international to local levels (Section 3.6.5) will also support achieving the adaptation and mitigation benefit of blue carbon spaces (Friess et al., 2020a; Steven et al., 2020; Wu et al., 2020a).

Table Box 3.4.2: Examples of vegetated blue carbon ecosystem carbon storage gains and losses in response to climate-impact drivers, and key actions contributing to maintained or and increased carbon storage. "+C" indicates potential positive effects on blue carbon stocks, "–C" indicates negative effects, "0" indicates no effects, and "ΔC" indicates positive or negative effects. Effects on carbon stocks from 3.4.2.5, Macreadie et al. (2019); Lovelock and Reef (2020); Wang et al. (2020). Key actions to sustain blue carbon storage from Duarte et al. (2020); Wedding et al. (2021).

	Mangroves	Saltmarshes	Seagrasses
Sea-level rise			
Landward expansion by vegetation	+C	+C	+C
Coastal squeeze	–C	–C	–C
Loss of low-lying or submerged land or vegetation	–C	–C	–C
Human adaptation to increase accommodation space	+C	+C	
Extreme storms			
Erosion/ loss of area/ subsidence	–C	–C	0 to –C
Enhanced sedimentation	+C	+C	+C
Vegetation damage and mortality	–C to +C		–C
Warming			
Increased productivity	+C		+C
Vegetation mortality			–C
Increased decomposition of soil	–C	–C to +C	
Poleward expansion of mangroves	+C	–C	

Poleward expansion of seagrasses			+C
Poleward expansion of bioturbators	ΔC		
Change in dominant species	ΔC		
Rising concentrations of atmospheric CO_2			
Increased productivity of some species	ΔC	ΔC	+C
Biodiversity loss			–C
Altered precipitation			
Vegetation mortality	–C		
Reduced productivity	–C	–C	
Increased productivity	+C		+C
Increased remineralisation	–C	–C	
Low salinity events			0 to –C
Key actions to sustain blue carbon storage			
Protect ecosystems	X	X	X
Develop alternative livelihoods	X		
Provide space for landward migration	X	X	
Restore hydrological connections	X	X	
Maintain/restore sediment supply	X	X	
Restore ecosystems	X		X
Plant indigenous species		X	
Reduce nutrient inputs			X

[END BOX 3.4 HERE]

3.5.6 Cultural Services

Cultural services provided by ocean and coastal ecosystems help maintain psychological well-being, cultural development, human identities, educational opportunities, and reserves that could support development of future goods or activities (Table 3.25). Most recent studies of ocean and coastal cultural services simply detail local benefits using replicable methods (e.g., Drakou et al., 2018; Folkersen, 2018; Förster et al., 2019; Lau et al., 2019; Pouso et al., 2019; Weitzman, 2019; Yang et al., 2019), focusing on diverse ocean and coastal environments and ecosystems (Jobstvogt et al., 2014; Balzan et al., 2018; Drakou et al., 2018; Ingram et al., 2018; Pouso et al., 2018; Zapata et al., 2018; Ghermandi et al., 2019; Pouso et al., 2019; Tanner et al., 2019; Turner et al., 2019; Ortíz Liñán and Vázquez Solís, 2021). Cultural ecosystem services may directly benefit from marine development activities, such as marine aquaculture (e.g., Alleway et al., 2018), and indirectly benefit from marine activities that increase biodiversity (e.g., Causon and Gill, 2018). Cultural services are generally quantified using interviews and revealed-preference or stated-preference valuation (National Research Council, 2005; Sangha et al., 2019), but people often are especially reluctant to evaluate cultural ecosystem services in monetary terms, given the spiritual and community linkages to these services (Oleson et al., 2018).

Additional evidence since previous assessments (Table 3.26) confirms that climate-change impacts on ocean and coastal cultural ecosystem services have already disrupted people's place-based emotional attachments and cultural activities (*limited evidence, high agreement*) (Figure 3.22). Bleaching and mortality of corals in the Great Barrier Reef have induced measurable "reef grief," a type of solastalgia, among reef visitors and researchers (Conroy, 2019; Curnock et al., 2019; Marshall et al., 2019). The mental health of people in Tuvalu (Gibson et al., 2020), Alaska (Allen, 2020), and Honduras (Kent and Brondo, 2020) have suffered from both the experience of climate impacts on ocean and coastal ecosystems (e.g., SLR and changes in fisheries and wildlife), and the anticipation of more in the future. The climate-associated MHWs and harmful algal bloom events in 2014–2016 in the US Pacific Northwest (Moore et al., 2019) prevented seasonal razor clam harvests culturally important to Indigenous Peoples and the local community (Section 3.5.5.3, Crosman et al., 2019). SLR and storm-driven coastal erosion endanger coastal archaeological and heritage sites around the world (*very high confidence*) (Hoque and Hoque, 2008; Carmichael et al., 2018; Reimann et al., 2018; Elliott and Williams, 2019; Ravanelli et al., 2019; Anzidei et al., 2020; Chemeli et al., 2020; García Sánchez et al., 2020; Harkin et al., 2020; Hil, 2020; Rivera-Collazo, 2020).

Disruptions in ocean and coastal ecosystem services partly attributable to climate change have also caused economic losses (*limited evidence, high agreement*). Water quality deterioration over 24 years in a US temperate bay due to nutrient enrichment and warming caused 0.08–0.67 million USD per decade in lost recreational shellfish revenues (Luk et al., 2019). In southwestern Florida, USA, where nutrient enrichment, lake hydrology, and rainfall conditions control cyanobacterial HAB formation (Havens et al., 2019), toxic HAB events deterred visitors and recreation, leading to lodging and restaurant revenue losses (Bechard, 2020), decreased domestic and international arrivals and overall visitor spending (a 99 million USD loss from August to October 2018, Scanlon, 2019), and lost recreational spending from loss of boat-ramp access (a 3 million USD economic loss from June to September 2018, Alvarez et al., 2019). In Cornwall, England, HABs from 2009–2016 disrupted residents' sense of place, identity, and well-being by interrupting recreational and economic activities, and by creating feelings of uncertainty and unease around the safety or dependability of future ocean-related activities (Willis et al., 2018). Increasingly abundant *Sargassum* spp. floating macroalgae from the central Atlantic Ocean and Caribbean Sea, whose proliferation has been attributed to high sea surface temperatures and nutrient enrichment (Wang et al., 2019a), has substantially disrupted beach tourism in the Caribbean and Mexico and imposes millions of dollars of clean-up costs annually on affected beaches (Milledge and Harvey, 2016).

Observed disruption of ocean and coastal cultural services by climate impacts, plus increasingly severe and widespread projected climate change impacts on ocean and coastal ecosystems, imply that risk to cultural ecosystem services will remain constant or grow (*medium confidence*) (Figure 3.22, Table 3.26). Recent studies assert that cultural ecosystem services are at risk from climate change (*high confidence*) (Singh et al., 2019a; Koenigstein, 2020). However, *limited evidence* and complex social-ecological interactions (e.g., Ingram et al., 2018) challenge development of specific projections. For instance, the little auk (*Alle alle*) in the North Water Polynya is traditionally harvested by Indigenous Inughuit for food and community-wide celebrations and seasonal activities, but harvests are threatened to an undetermined degree as the seabird competes for food with recovering bowhead whale (*Balaena mysticetus*) populations and northward range shifts of capelin (*Mallotus villosus*) due to warming (Mosbech et al., 2018). Section 3.6 assesses the cultural implications of implemented human adaptations.

Figure 3.22: Observed global influence of climate-impact drivers on ecosystem services. (Coloured cells) The "observed impact" indicates the total effect of all climate-impact drivers on a specific ecosystem service, using expert judgement based on summary statements throughout Section 3.5. (Grey cells) Co-occurring non-climate drivers that affect the service. Cell colour shows whether the observed impact of the climate-impact driver on a group of ecosystem services is positive (beneficial), negative (detrimental) or mixed (usually resulting from location, the presence of interacting drivers, or changing effects over time). No assessment indicates that not enough evidence is available to assess the direction of impact.

3.6 Planned Adaptation and Governance to Achieve the Sustainable Development Goals (SDGs)

3.6.1 Point of Departure

Human adaptation comprises an array of measures (adaptation options, IPCC, 2014a) that modulate harm or exploit opportunities from climate change (Section 1.2.1.3). Adaptation options that respond to key ocean and coastal risks (Section 3.4) focus on individuals, livelihoods, and economic sectors that benefit from ocean and coastal ecosystem services (Section 3.5). AR5 concluded that local adaptation measures would not alone be enough to offset global effects of increased climate change on marine and coastal ecosystems, and that mitigation of emissions would also be necessary (*high confidence*) (Pörtner et al., 2014; Oppenheimer et al., 2019, Table 3.27). SROCC assessed that ecosystem-based adaptation, including MPAs (*high confidence*) (Bindoff et al., 2019) and adaptive management are effective to reduce climate change impacts (IPCC, 2018; IPCC, 2019b), but that existing marine governance is insufficient to provide an effective adaptation response in the marine ecosystem (*high confidence*) (IPCC, 2019c).

Table 3.27: Conclusions from previous IPCC assessments about implemented adaptation, enablers and limits and contribution to SDGs.

	AR5	SR15	SROCC
Degree of Implementation (Section 3.6.3.1)	The analysis and implementation of coastal adaptation toward climate-resilient and sustainable coasts has progressed more significantly in developed countries than in developing countries (*high confidence*) (Wong et al., 2014).	Adaptation (to SLR) is already happening (*high confidence*) and will remain important over multi-centennial time scales (Hoegh-Guldberg et al., 2018a).	A diversity of adaptation responses to coastal impacts and risks have been implemented around the world, but mostly as a reaction to current coastal risk or experienced disasters (*high confidence*) (Oppenheimer et al., 2019).
Conservation and Restoration (Section 3.6.3.2)	With continuing climate change, local adaptation measures (such as conservation) or a reduction in human activities (such as fishing) may not sufficiently offset global-scale effects on marine ecosystems (*high confidence*) (Pörtner et al., 2014).	Existing and restored natural coastal ecosystems may be effective in reducing the adverse impacts of rising sea levels and intensifying storms by protecting coastal and deltaic regions (*medium confidence*) (Hoegh-Guldberg et al., 2018a).	Ecosystem restoration may be able to locally reduce climate risks (*medium confidence*) but at relatively high cost and effectiveness limited to low emissions scenarios and to less sensitive ecosystems (*high confidence*) (Bindoff et al., 2019).
Enablers, Barriers and Limits of Adaptation (Section 3.6.3.3)	Adaptation strategies for ocean regions beyond coastal waters are generally poorly developed but will benefit from international legislation and expert networks, as well as marine spatial planning (*high agreement*) (Hoegh-Guldberg et al., 2014).	Lower rates of change [associated with a 1.5ºC temperature increase] enhance the ability of natural and human systems to adapt, with substantial benefits for a wide range of terrestrial, freshwater, wetland, coastal and ocean ecosystems (including coral reefs) (*high confidence*) (Hoegh-Guldberg et al., 2018a).	There are a broad range of identified barriers and limits for adaptation to climate change in ecosystems and human systems (*high confidence*). Limitations include […] availability of technology, knowledge and financial support and existing governance structures (*medium confidence*). (Bindoff et al., 2019). Existing ocean governance structures are already facing multi-dimensional, scale-related challenges because of climate change [...] (*high confidence*) (Bindoff et al., 2019).
SDGs and Other Policy Frameworks (Section 3.6.4)	Overall, there is a strong need to develop ecosystem-based monitoring and adaptation strategies to mitigate rapidly growing risks and uncertainties to the coastal and oceanic industries, communities, and nations (*high agreement*) (Hoegh-Guldberg et al., 2014).	Adaptation strategies can result in trade-offs with and among the SDGs (*medium evidence, high agreement*) (Roy et al., 2018).	Achieving [the SDGs] and charting Climate Resilient Development Pathways depends in part on ambitious and sustained mitigation efforts to contain SLR coupled with effective adaptation actions to reduce SLR impacts and risk (*medium evidence, high agreement*) (Oppenheimer et al., 2019).

This section builds on the SROCC assessment of the portfolio of available solutions, their applicability, and their effectiveness in reducing climate change-induced risks to ocean and coastal ecosystems. Section 3.6.2 assesses the set of planned adaptation measures. Section 3.6.3 assesses implementation of adaptation solutions and the enablers, barriers, and limitations that affect their feasibility. Section 3.6.4 evaluates the contribution of planned adaptation to the Sustainable Development Goals (SDGs) and other policy-relevant frameworks, and Section 3.6.5 synthesises emerging evidence about best practices.

3.6.2 Adaptation Solutions

Adaptation in ocean and coastal ecosystems continues to be informed primarily by theory, as there is still *limited evidence* about implemented solutions (*high agreement*) (Seddon et al., 2020) and their success across regions, especially in low-income nations (Chausson et al., 2020). Adapting to climate change depends on society's ability and willingness to anticipate the change, recognise its effects, plan to accommodate its consequences (Ling and Hobday, 2019; Wilson et al., 2020b), and implement a coordinated portfolio of informed solutions. Here, the complete portfolio of adaptation solutions is assessed using the taxonomy of Abram et al. (2019): (1) socio-institutional adaptation, (2) built infrastructure and technology, and (3) marine and coastal nature-based solutions (NbS) (Figure 3.23).

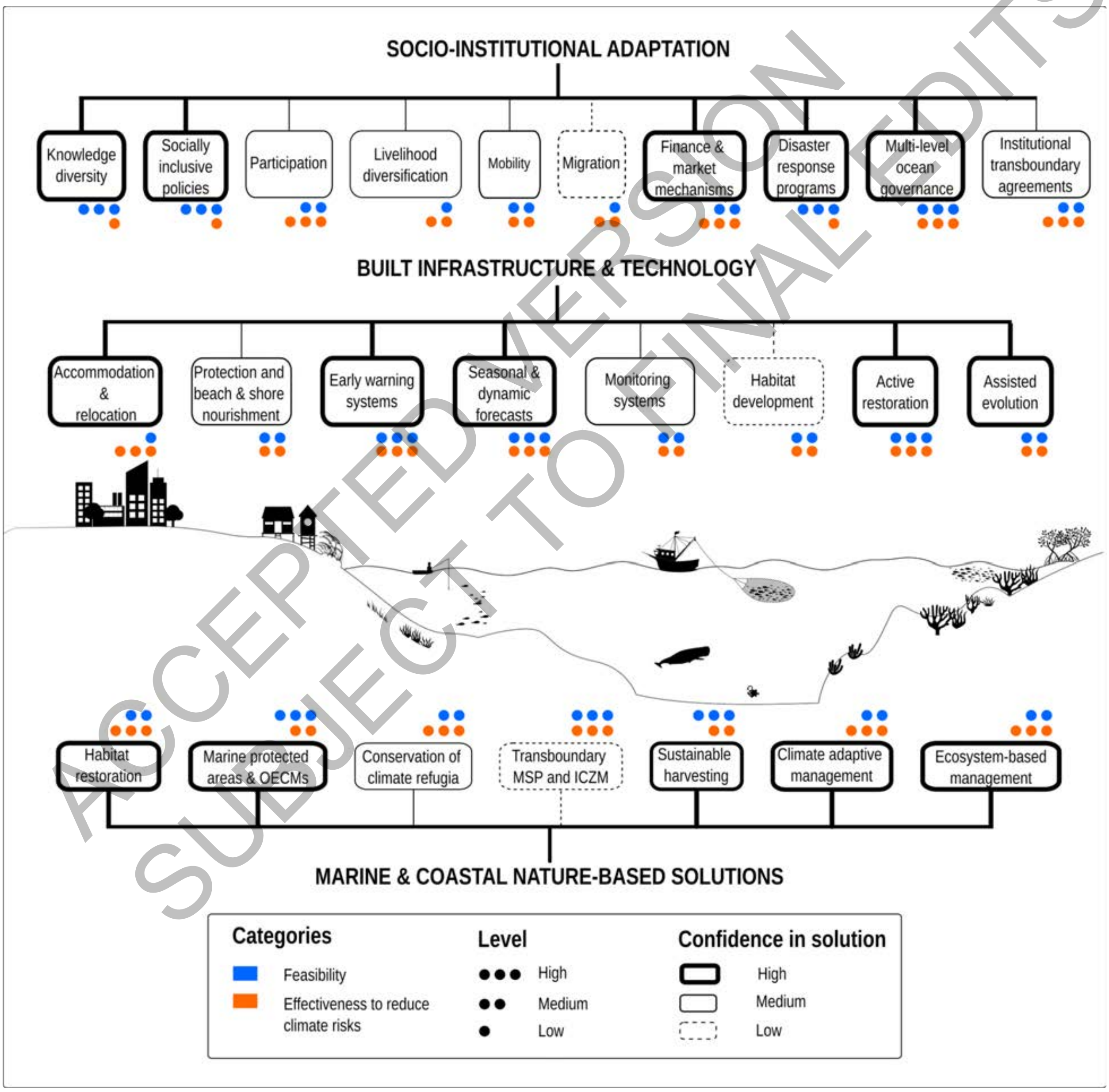


Figure 3.23: Adaptation solutions for ocean and coastal ecosystems that address climate-change risk in different ocean ecosystems, communities and economic sectors. Box-outline weights indicate confidence in the solution's potential to reduce mid-term risks (based on the amount of evidence and agreement supporting the solutions, see SM3.5.1 for full assessment). The feasibility and effectiveness of each solution (low, medium or high) indicates its ability to support ecosystems and societies as they adapt to climate change impacts, based on Table SM3.3.

3.6.2.1 Socio-Institutional Adaptation

Increasing evidence shows that an effective solution portfolio includes social and institutional adaptation (Figure 3.23, top; Table 3.28). Social adaptation to climate change is already occurring, as people use strategies ranging from accommodating change, to coping, adapting and transforming their livelihoods (Béné and Doyen, 2018; Fedele et al., 2019; Galappaththi et al., 2019; Barnes et al., 2020; Ojea et al., 2020; Green et al., 2021c). Although management and institutions have major roles in adaptation (Gaines et al., 2018; Barange, 2019), marine governance is impeded by increasing numbers of often-competing users and uses (Boyes and Elliott, 2014); sector-led, fragmented, efforts (Nunan et al., 2020); and a legal framework less clear than those on land (Crespo et al., 2019; Guggisberg, 2019). Future social responses depend on warming levels and on the institutional, socio-economic and cultural constructs that allow or limit livelihood changes (*medium confidence*) (Chapter 18, Galappaththi et al., 2019; Ford et al., 2020; Green et al., 2021c). Both social and institutional transformations are needed to change the structures of power, culture, politics and/or identity associated with marine ecosystems (Section 1.5.2, Wilson et al., 2020b). Ideally, institutional and social adaptation will work together to sustain knowledge systems and education, enhance participation and social inclusion, facilitate livelihood support and transformational change of dependent coastal communities, provide economic and financial instruments, and include polycentric and multi-level governance of transboundary management (Fedele et al., 2019; Fulton et al., 2019).

Table 3.28: Assessment of socio-institutional adaptation solutions to reduce mid-term climate impacts in oceans and coastal ecosystems. Confidence is assessed in SM3.5.1. Feasibility and effectiveness are assessed in Figure 3.24.

Solution	Confidence in solution *(mid-term potential)*	Contribution to adaptation	Selected references	Examples of implementation
Knowledge diversity	*High confidence*	Consideration of IK and LK systems is beneficial to communities, increases their resilience, and is relevant and transferable beyond the local scale.	(Norström et al., 2020; Petzold et al., 2020; Gianelli et al., 2021; Schlingmann et al., 2021)	Ecotourism (Section 3.6.3.1.3), conservation (Section 3.6.3.2.1)
Socially inclusive policies	*High confidence*	Policies that promote participation of a diversity of groups are able to address existing vulnerabilities in coastal communities, and promote adaptation and transformational change.	(Brodie Rudolph et al., 2020; Ford et al., 2020; Friedman et al., 2020)	Finance (Section 3.6.3.4.2)
Participation	*Medium confidence*	Participation in decision making and adaptation processes is recommended across a range of different hazards and contexts and has the potential to improve adaptation outcomes.	(Brodie Rudolph et al., 2020; Claudet et al., 2020a; Hügel and Davies, 2020; Sumaila et al., 2021)	Fisheries and mariculture (Section 3.6.3.1.2), Indigenous Peoples (Section 3.6.3.4.1).
Livelihood diversification	*Medium confidence*	Livelihood diversification in communities dependent on marine and coastal ecosystems reduces climate risks and confers flexibility	(Blanchard et al., 2017; Cinner and Barnes, 2019; Mohamed Shaffril et al., 2020; Owen, 2020; Pinsky, 2021; Taylor et al., 2021)	Fisheries and mariculture (Section 3.6.3.1.2), coastal communities (Cross-Chapter Box SLR in Chapter 3), tourism (Section 3.6.3.1.3)

		to individuals, which is key to adaptive capacity.		
Mobility	*Medium confidence*	When individuals are given the choice about mobility, they may elect to use this response to minimise climate risks and benefit their livelihoods.	(Barnett and McMichael, 2018)	Fisheries and mariculture (Section 3.6.3.1.2)
Migration	*Low confidence*	Migration often involves different spatio-temporal scales than mobility. Migration could be considered an adaptation solution for some coastal and island populations in the cases of extreme events, but also as a response to more gradual changes (e.g., coastal erosion from sea-level rise (SLR)).	(Maharjan et al., 2020; Biswas and Mallick, 2021; Zickgraf, 2021)	Coastal livelihoods (Section 3.6.3.1.1)
Finance and market mechanisms	*High confidence*	Financial mechanisms and credit provision for marine-dependent livelihoods are effective for overcoming impacts from SLR, extreme events and other climate-impact drivers.	(Shaffril et al., 2017; Dunstan et al., 2018; Hinkel et al., 2018; Moser et al., 2019; Sainz et al., 2019; Woodruff et al., 2020)	Economic dimensions (Section 3.6.3.4.2)
Disaster response programs	*High confidence*	Disaster response programs confer resilience to communities and contribute to adaptation, when designed to be inclusive, participatory and adaptive.	(Nurhidayah and McIlgorm, 2019)	Climate services (Section 3.6.3.4.3), tourism cruise ship sector (Section 3.6.3.1.3)
Multi-level ocean governance	*High confidence*	The multi-scale nature of ocean and coastal climate-change risk demands adaptation solutions at multiple levels of governance that consider the objectives and perceptions of all stakeholders to support local implementation of broad strategies.	(Miller et al., 2018; Gilfillan, 2019; Holsman et al., 2019; Obura et al., 2021).	Policy frameworks (Section 3.6.4.3)
Institutional transboundary agreements	*Medium confidence*	Institutional agreements for the management of transboundary marine resources are key for a	(Engler, 2020; Mason et al., 2020; Oremus et al., 2020; Melbourne-Thomas et al., 2021)	Fisheries (Section 3.6.3.1.2, Cross-Chapter Box MOVING SPECIES in Chapter 5)

		sustainable future given current impacts on marine species distribution due to climate change		

3.6.2.2 *Built Infrastructure and Technology*

Engineering and technology support marine and coastal adaptation (Table 3.29). Built infrastructure includes engineered solutions that protect, accommodate or relocate coastal assets using hard engineering, like seawalls, and soft engineering, such as beach and shore nourishment (Cross-Chapter Box SLR in Chapter 3). Technological tools include early-warning systems for extreme events (Bindoff et al., 2019; Collins et al., 2019a), improved forecast and hindcast models (Winter et al., 2020; Davidson et al., 2021; Spillman and Smith, 2021) and environmental monitoring (Claudet et al., 2020a; Wilson et al., 2020a; Melbourne-Thomas et al., 2021) that support informed decision making (Tommasi et al., 2017; Rilov et al., 2020; A. Maureaud et al., 2021). Emerging adaptation technologies, such as habitat development, active restoration and assisted evolution (Boström-Einarsson et al., 2020; Kleypas et al., 2021), intend to accelerate recovery of damaged ecosystems and promote ecological adaptation to climate change (Jones et al., 2018a; Boström-Einarsson et al., 2020; Kleypas et al., 2021).

Table 3.29: Assessment of built infrastructure and technology solutions to reduce mid-term climate impacts in oceans and coastal ecosystems. Confidence is assessed in SM3.5.1. Feasibility and effectiveness are assessed in Figure 3.24.

Solution	Confidence in solution *(mid-term potential)*	Contribution to adaptation	Selected references	Examples of implementation
Accommodation and relocation	*High confidence*	Asset modification and relocation of livelihoods to adapt to sea-level rise (SLR), extreme events and coastal erosion.	(Hanson and Nicholls, 2020; Monios and Wilmsmeier, 2020; Zickgraf, 2021)	Cross-Chapter Box SLR in Chapter 3, coastal development (Section 3.6.3.1.1).
Protection and beach and shore nourishment	*Medium confidence*	Protection of coastal ecosystems with interventions such as beach and shore nourishment is a common response to beach erosion around the world, and an alternative to hard protection structures such as seawalls.	(Pinto et al., 2020; de Schipper et al., 2021; Elko et al., 2021)	Cross-Chapter Box SLR in Chapter 3, coastal development (Section 3.6.3.1.1).
Early-warning systems	*High confidence*	Early-warning systems can support decision-making, limit economic losses from extreme events, and aid in the enterprise and development of adaptive management systems.	(Bindoff et al., 2019; Collins et al., 2019a; Winter et al., 2020; Neußner, 2021)	Coastal development (Section 3.6.3.1.1), human health (Section 3.6.3.1.5).
Seasonal and dynamic forecasts	*High confidence*	The proliferation of real-time and seasonal forecasts of temperature extremes, marine heatwaves (MHWs), storm surges, harmful algal blooms (HABs), and	(Payne et al., 2017; Hazen et al., 2018; Fernández-Montblanc et al., 2019; Holbrook et al., 2020; Winter et al., 2020; Bever et al., 2021; Davidson et al.,	Fisheries and mariculture (Section 3.6.3.1.2), MPAs (Section 3.6.3.2.1), climate services (Section 3.6.3.2.4).

		the distribution of living marine resources greatly contribute to adaptation through monitoring, early-warning systems, adaptive management and ecosystem-based management.	2021; Spillman and Smith, 2021)	
Monitoring systems	*Medium confidence*	Monitoring systems that address climate-impact drivers, ecosystem impacts and social vulnerabilities in marine social-ecological systems are key for adaptation.	(Nichols et al., 2019; Claudet et al., 2020a; Wilson et al., 2020a)	MPAs (Section 3.6.3.2.1), climate services (Section 3.6.3.2.4), fisheries (Section 3.6.3.1.2).
Habitat development	*Low confidence*	Accelerates the recovery of damaged ecosystems and promotes ecological or biological adaptation to future climate change.	(Jones et al., 2018a; Boström-Einarsson et al., 2020; Kleypas et al., 2021)	Restoration (Section 3.6.3.2.2).
Active restoration	*High confidence*	Reintroduces species or augments existing populations. For example, propagating and transplanting heat-tolerant coral species.	(Boström-Einarsson et al., 2020; Rinkevich, 2021)	Restoration (3.6.3.2.2).
Assisted evolution	*High confidence*	Manipulates species' genes to accelerate natural selection.	(Bulleri et al., 2018; National Academies of Sciences, 2019; Morris et al., 2020c)	Restoration (Section 3.6.3.2.2).

3.6.2.3 Marine and Coastal Nature-Based Solutions (NbS)

The ocean and coastal adaptation portfolio (Figure 3.23) also includes marine and coastal NbS (Table 3.30). NbS that contribute to climate adaptation, also known as ecosystem-based adaptations (EBA), are cross-cutting actions that harness ecosystem functions to restore, protect, and sustainably manage marine ecosystems facing climate change impacts, while also benefiting social systems and human security (Abelson et al., 2015; Barkdull and Harris, 2019) and supporting biodiversity (*high confidence*) (Annex II: Glossary, Cross-Chapter Box NATURAL in Chapter 2, Seddon et al., 2021). NbS are expected to contribute to global adaptation and mitigation goals (*high confidence*) (Beck et al., 2018; Cooley et al., 2019; Hoegh-Guldberg et al., 2019b; Menéndez et al., 2020; Morris et al., 2020a) by protecting coastal environments from SLR and storms (Cross-Chapter Box SLR, Reguero et al., 2018), and by storing substantial quantities of carbon (Sections 3.4.2.5, 3.6.3.1.5, WGIII AR6 Chapter 7, Howard et al., 2017; Chow, 2018; Smale et al., 2018; Singh et al., 2019b; Soper et al., 2019). Marine NbS are cost-effective, can generate social, economic and cultural co-benefits and can contribute to the conservation of biodiversity in the near- to mid-term (*high confidence*) (Secretariat of the Convention on Biological Diversity, 2009; Gattuso et al., 2018; Barkdull and Harris, 2019; McLeod et al., 2019).

Table 3.30: Assessment of marine and coastal nature-based solutions to reduce mid-term climate impacts in oceans and coastal ecosystems. Confidence is assessed in SM3.5.1. Feasibility and effectiveness are assessed in Figure 3.24.

Solution	Confidence in solution *(mid-term potential)*	Contribution to adaptation	Selected references	Examples of implementation

Habitat restoration	*High confidence*	Marine habitat restoration increases biodiversity and protects shorelines and coastal livelihoods from climate oceanic hazards.	(Colls et al., 2009; Arkema et al., 2017; Espeland and Kettenring, 2018; McLeod et al., 2019)	Restoration (Section 3.6.3.2.2)
Marine protected areas (MPAs) and other effective area-based conservation measures (OECMs)	*High confidence*	MPAs and MPA networks that are carefully designed to address climate change, strategically placed, and well enforced, hold great potential to deliver adaptation outcomes. OECMs can confer climate resilience to dependent communities outside of MPAs.	(Section 3.4.3.3.4, Queirós et al., 2016; Roberts et al., 2017; Maxwell et al., 2020a; Arafeh-Dalmau et al., 2021; Gurney et al., 2021; Sala et al., 2021)	Conservation (Section 3.6.3.2.1)
Conservation of climate refugia	*Medium confidence*	Protecting areas that retain climate and biodiversity conditions for longer durations under climate-change can increase the resilience of marine ecosystems to warming and marine heatwaves (MHWs) and facilitate marine species range shifts.	(Section 3.4.3.3.4, Cross-Chapter Box MOVING SPECIES in Chapter 5, Rilov et al., 2020; Wilson et al., 2020a; Arafeh-Dalmau et al., 2021)	Conservation (Section 3.6.3.2.1)
Transboundary marine spatial planning (MSP) and integrated coastal zone management (ICZM)	*Low confidence*	Transboundary MSP and ICZM that incorporate climate-change impacts and adaptation in their design can support climate adaptation and to foster international ocean cooperation.	(Rosendo et al., 2018; Tittensor et al., 2019; Frazão Santos et al., 2020; Rilov et al., 2020; Pinsky et al., 2021)	Tourism (Section 3.6.3.1.3), conservation, (Section 3.6.3.2.1.)
Sustainable harvesting	*High confidence*	Sustainable harvesting is a nature-based solution (NbS) that contributes to adaptation by safeguarding the provision of marine food and cultural services, while reducing the ecological vulnerability of marine ecosystems.	(Gattuso et al., 2018; Burden and Fujita, 2019; Duarte et al., 2020)	Fisheries and mariculture (Section 3.6.3.1.2)
Climate-adaptive management	*High confidence*	Incorporating climate-adaptive management allows climate knowledge and information available for the system to be iteratively updated in	(Cross-Chapter Box MOVING SPECIES in Chapter 5, Rilov et al., 2019; Free et al., 2020; Wilson et al., 2020a; Melbourne-Thomas et al., 2021)	Fisheries and mariculture (Section 3.6.3.1.2), conservation, (Section 3.6.3.2.1), restoration (Section 3.6.3.2.2)

		the management plan. It also facilitates consideration of species distribution shifts and other climate-change responses.		
Ecosystem-based management (EbM)	*High confidence*	EbM focuses on ecosystems. By incorporating many of the above tools, ecosystem-based adaptation (EbA) benefits adaptation of marine ecosystems and supports provision of ecosystem services to people.	(Fernandino et al., 2018; Lowerre-Barbieri et al., 2019)	Fisheries and mariculture (Section 3.6.3.1.2)

3.6.3 Implementation and Effectiveness of Adaptation and Mitigation Measures

This section assesses implemented adaptations introduced in Section 3.6.2 for selected marine sectors (Section 3.6.3.1) and ecosystems (Section 3.6.3.2), using case studies to emphasise characteristics that enable or inhibit adaptation (Section 3.6.3.3). The feasibility and effectiveness of these adaptations is assessed in Figure 3.24.

3.6.3.1 Degree of Implementation and Evidence of Effectiveness Across Sectors

3.6.3.1.1 Coastal community development and settlement

Coastal adaptation often addresses the risk of flooding and erosion from SLR, changes in storm activity and degradation of coastal ecosystems and their services (*high confidence*) (Sections 3.4.2, 3.5, Oppenheimer et al., 2019). Without coastal protection, people and property will be increasingly exposed to coastal flooding after 2050, especially under RCP8.5 (Cross-Chapter Box SLR in Chapter 3, Bevacqua et al., 2020; Kirezci et al., 2020). This section assesses adaptation responses for coastal ecosystems, addressing loss of natural coastal protection (Sections 3.4.2.1, 3.4.2.4–3.4.2.6), and the need for relocation (Section 3.6.2.1.2). Adaptation responses specific to SLR are assessed in detail in Cross-Chapter Box SLR in Chapter 3, while adaptation in coastal cities and settlements is assessed in Chapter 6.

Coastal conservation tends to involve cost-effective, low-impact actions that aim to support both adaptation and mitigation by conserving a wide array of ecosystem functions and services (Gattuso et al., 2018; Gattuso et al., 2021), and that are achievable by nations with extensive coastlines or low-income status (Herr et al., 2017; Taillardat et al., 2018). Where coastlines are undeveloped, the lowest-risk option is to avoid new development, but elsewhere, coastal conservation includes protection of key assets, accommodation of SLR, advancing defences seawards or upwards, or planned retreat from the coast (Cross-Chapter Box SLR in Chapter 3).

Hard engineered structures like seawalls are generally more costly than nature-based adaptations (*high confidence*) (Hérivaux et al., 2018; Haasnoot et al., 2019; Nicholls et al., 2019; Oppenheimer et al., 2019) and can lock communities into engineered responses in the future (Cross-Chapter Box SLR in Chapter 3), creating trade-offs with mitigation goals, which constitutes maladaptation (Nunn et al., 2021) that carries ecological and cultural costs (Sections 3.4.2.4, 3.4.2.6, 3.5.6). As a result there is *high agreement* on the importance of shifting from hard infrastructure to soft infrastructure for coastal defence (Toimil et al., 2020; Nunn et al., 2021). The common remedy for beach erosion is beach nourishment (Oppenheimer et al., 2019; Pinto et al., 2020; Elko et al., 2021), which provides rapid results but poorly quantified trade-offs between efficacy, long-term cost, utility to beach users and ecological damage (de Schipper et al., 2021).

Since SROCC, coastal adaptation using NbS, like restoration of coastal vegetation, has advanced substantially (Cohen-Shacham et al., 2019; Kuhl et al., 2020; Kumar et al., 2020; Morris et al., 2020a). Field and modelling studies confirm that wetland restoration and preservation are key actions to restore coastal protection and reduce community vulnerability to flooding (*very high confidenc*e) (see also Section 3.6, Chapter 15, Cross-Chapter Box SLR in Chapter 3, Jones et al., 2020; Menéndez et al., 2020; Van Coppenolle and Temmerman, 2020), while maintaining coastal ecosystem services (Section 3.5). Restoring coral reefs, oyster reefs and mangroves (Section 3.6.2.1), and protecting macrophyte meadows, dissipate wave energy (Section 3.4.2.1, Yates et al., 2017; Beck et al., 2018; Wiberg et al., 2019; Menéndez et al., 2020), accrete sediment, and elevate shorelines, which reduces exposure to waves and storm surges, and offsets erosional losses (*medium confidence*) (Kench and Mann, 2017; Pomeroy et al., 2018; Dasgupta et al., 2019; James et al., 2019; Morris et al., 2019; David and Schlurmann, 2020; Masselink et al., 2020). However, irreversible regime shifts in ocean ecosystems due to SLR and extreme events such as MHW can limit or compromise restoration in the long term (*high confidence*) (Section 3.4.3.3.3, Cross-Chapter Box SLR in Chapter 3, Marzloff et al., 2016; Johnson et al., 2017a). Under all warming scenarios, coastal wetlands will be impacted by warming and MHWs (Sections 3.2.2.1, 3.2.4.5, Cross-Chapter Box 9.1 in WGI Chapter 9, Fox-Kemper et al., 2021), while also being pressed inland by RSLR (Section 3.4.2.5, Cross-Chapter Box SLR in Chapter 3). Therefore, restoration and conservation are more successful when non-climate drivers are also minimised (*high confidence*) (Brodie et al., 2020; Duarte et al., 2020; Liu et al., 2021).

For highly exposed human settlements, migration is an adaptation option (e.g., for some island populations under extreme circumstances), but there are important uncertainties (Section 15.3.4.6), as international regimes develop around human rights, migration (Scobie, 2019a), displacement (George Puthucherril, 2012) and the implications for national sovereignty (Yamamoto and Esteban, 2014) of disappearing land spaces caused by climate change. Colonial power dynamics can influence climate change responses (Chapter 18), for example when external funders favour migration over local desires to adapt in place to preserve national identity and sovereignty (Bordner et al., 2020). Examples of relocation within livelihoods' customary land show some successes (Section 15.3.4.6).

Evidence since SROCC (Section, 5.5.2.3.3, Bindoff et al., 2019) continues to show that built infrastructure cannot address all of the adaptation challenges that coastal communities face. Coastal squeeze creates tensions between coastal development, armouring, and habitat management (Sections 3.4.2.4–3.4.2.6). Managed realignment is the best option to reduce risks from SLR (*high confidence*) (Cross-Chapter Box SLR in Chapter 3) but requires transformative changes in coastal development and settlement (Felipe Pérez and Tomaselli, 2021; Fitton et al., 2021; Mach and Siders, 2021; Siders et al., 2021). Implementation of protective measures varies among nations and lack of financial resources limits the options available (*very high confidence*) (Cross-Chapter Box SLR in Chapter 3, Hinkel et al., 2018; Klöck and Nunn, 2019).

[START CROSS-CHAPTER BOX SLR HERE]

Cross-Chapter Box SLR: Sea Level Rise

Authors: Gonéri Le Cozannet (France, Chapter 13, CCP4), Judy Lawrence (New Zealand, Chapter 11), David Schoeman (Australia, Chapter 3), Ibidun Adelekan (Nigeria, Chapter 9), Sarah Cooley (USA, Chapter 3), Bruce Glavovic (New Zealand/South Africa, Chapter 18, CCP2), Marjolijn Haasnoot (The Netherlands, Chapter 13, CCP2), Rebecca Harris (Australia, Chapter 2), Wolfgang Kiessling (Germany, Chapter 3), Robert E. Kopp (USA, WGI), Aditi Mukherji (Nepal, Chapter 4), Patrick Nunn (Australia, Chapter 15), Dieter Piepenburg (Germany, Chapter 13), Daniela Schmidt (UK/Germany, Chapter 13), Craig T. Simmons (Australia), Chandni Singh (India, Chapter 10, CCP2), Aimée Slangen (The Netherlands, WGI), Seree Supratid (Thailand, Chapter 4).

Sea-level rise (SLR) is already impacting ecosystems, human livelihoods, infrastructure, food security and climate mitigation at the coast and beyond. Ultimately, it threatens the existence of cities and settlements in low lying areas, and some island nations and their cultural heritage (Chapters 9– 15, Cross-Chapter Paper 2 and 4 Oppenheimer et al., 2019). The challenge can be addressed by mitigation of climate change and coastal adaptation.

Current impacts of sea level rise

The rate of global mean SLR was 1.35 mm yr^{-1} (0.78–1.92 mm yr^{-1}, *very likely* range) during 1901–1990, faster than during any century in at least 3000 years (*high confidence*) (WGI AR6 Chapter 9, Stanley and Warne, 1994; Woodroffe et al., 2016; Fox-Kemper et al., 2021). Global mean SLR has accelerated to 3.25 mm yr^{-1} (2.88–3.61 mm yr^{-1}, *very likely* range) during 1993–2018 (*high confidence*). Extreme sea levels have increased consistently across most regions (WGI AR6 Chapter 9, Fox-Kemper et al., 2021). The largest observed changes in coastal ecosystems are being caused by the concurrence of human activities, waves, current-induced sediment transport, and extreme storm events (*medium confidence*) (Chapters 3, 15 and 16, Takayabu et al., 2015; Mentaschi et al., 2018; Duvat, 2019; Murray et al., 2019; Oppenheimer et al., 2019). Early impacts of accelerating SLR detected at sheltered or subsiding coasts include chronic flooding at high tides, wetland salinisation and ecosystem transitions, increased erosion and coastal flood damage (Chapters 3, 11 and 13–16, WGI AR6 Chapter 9, Sweet and Park, 2014; Moftakhari et al., 2015; Nunn et al., 2017; Oppenheimer et al., 2019; Sharples et al., 2020; Fox-Kemper et al., 2021; Strauss et al., 2021). The exposure of many coastal populations and ecosystems to SLR is high: economic development is disproportionately concentrated in and around coastal cities and settlements (*virtually certain*) (Chapters 3 and 9–15, Cross-Chapter Papers 2 and 4).

Projected risks to coastal communities, infrastructure and ecosystems

Risks from SLR are *very likely* to increase by one order of magnitude well before 2100 without adaptation and mitigation action as agreed by parties to the Paris Agreement (*very high confidence*). Global mean SLR is *likely* to continue accelerating under SSP1-2.6 and more strongly forced scenarios (Figure SLR1, WGI AR6 Chapter 9, Oppenheimer et al., 2019; Fox-Kemper et al., 2021), increasing the risk of chronic coastal flooding at high-tide, extreme flooding during extreme events such as swells, storms and hurricanes, and erosion, and coastal ecosystem losses across many low-lying and erodible coasts (*very high confidence*) (Chapters 3 and 9–15, Cross-Chapter Paper 2, Hinkel et al., 2014; McLachlan and Defeo, 2018; Kulp and Strauss, 2019; Vousdoukas et al., 2020b). The compounding of rainfall, river flooding, rising water tables, coastal surges, and waves are projected to exacerbate SLR impacts on low-lying areas and rivers further inland (Chapters 4 and 11–15) (Bevacqua et al., 2020).

There is *high confidence* that coastal risks will increase by at least one order of magnitude over the 21st century due to committed SLR (Hinkel et al., 2013; Hinkel et al., 2014; IPCC, 2019b). Exposure of population and economic assets to coastal hazards is projected to increase over the next decades, particularly in coastal regions with fast-growing populations in Africa, Southeast Asia, and Small Islands (*medium evidence*) (Chapters 9–15, Cross-Chapter Papers 2 and 4, Neumann et al., 2015; Jones and O'Neill, 2016; Merkens et al., 2016; Merkens et al., 2018; Rasmussen et al., 2020). For RCP8.5, 2.5–9% of the global population and 12–20% of the global gross domestic product (GDP) is projected to be exposed to coastal flooding by 2100 (Kulp and Strauss, 2019; Kirezci et al., 2020; Rohmer et al., 2021). Above 3°C global warming levels (GWL) and with low adaptation, SLR may cause disruptions to ports and coastal infrastructure (Camus et al., 2019; Christodoulou et al., 2019; Verschuur et al., 2020; Yesudian and Dawson, 2021), which in turn may cascade and amplify across sectors and regions, generating impacts to financial systems (Chapters 11, 13, Mandel et al., 2021). Depending on the hydrogeological context, SLR causes salinisation of groundwater, estuaries, wetlands and soils, adding constraints to water management and livelihoods in agriculture sectors, for example, in deltas (Chapters 9, 15, Cross-Chapter Paper 4, Oppenheimer et al., 2019; Nicholls et al., 2020).

Coastal ecosystems can migrate landward or grow vertically in response to SLR, but their resilience and capacity to keep up with SLR will be compromised by ocean warming and other drivers, depending on regions and species, e.g., above 1.5°C for coral reefs (*high confidence*) (Chapter 3, 16, IPCC, 2018; Melbourne et al., 2018; Perry et al., 2018; IPCC, 2019b; Cornwall et al., 2021). Sediments and space for landward retreat are crucial for mangroves, saltmarshes and beach ecosystems (*high confidence*) (Chapter 3, Peteet et al., 2018; Schuerch et al., 2018; FitzGerald and Hughes, 2019; Friess et al., 2019; Leo et al., 2019; Schuerch et al., 2019). Loss of habitat is accompanied by loss of associated ecosystem services, including wave-energy attenuation, habitat provision for biodiversity, food production and carbon storage (Chapter 3, Cross-Chapter Box NATURAL in Chapter 2).

Under a high-emissions, low-likelihood/high-impact scenario, where *low confidence* ice-sheet mass loss occurs, global mean SLR could exceed the *likely* range by more than one additional metre in 2100 (Figure SLR1b, Cross-Chapter Box DEEP in Chapter 17, WGI AR6 Technical Summary and Chapter 9, Arias et al., 2021; Fox-Kemper et al., 2021). This is a reason for concern given that rapid SLR after the last glacial-interglacial transition caused a drowning of coral reefs (*high confidence*) (Camoin and Webster, 2015; Sanborn et al., 2017; Webster et al., 2018), extensive loss of coastal land and islands, habitats and associated biodiversity (*high confidence*) (AR6 WGI Chapter 9, Fruergaard et al., 2015; Fernández-Palacios et al., 2016; Hamilton et al., 2019; Helfensdorfer et al., 2019; Kane and Fletcher, 2020; Fox-Kemper et al., 2021) and triggered Neolithic migrations in Europe and Australia (*medium confidence*) (Cross-Chapter Box PALEO in Chapter 1, Turney and Brown, 2007; Brisset et al., 2018; Williams et al., 2018).

At centennial timescales, projected SLR represents an existential threat for island nations, low-lying coastal zones, and the communities, infrastructure, and cultural heritage therein (Chapters 9–15, Cross-Chapter Paper 4). Even if climate warming is stabilised at 2°C to 2.5°C GWL, coastlines will continue to reshape over millennia, affecting at least 25 megacities and drowning low-lying areas where 0.6–1.3 billion people lived in 2010 (*medium confidence*) (WGI AR6 Chapter 9 Marzeion and Levermann, 2014; Clark et al., 2016; Kulp and Strauss, 2019; Fox-Kemper et al., 2021; Strauss et al., 2021).

Solutions, opportunities and limits to adaptation

The ability to adapt to current coastal impacts, to cope with future coastal risks, and to prevent further acceleration of SLR beyond 2050 depends on immediate mitigation and adaptation actions (*very high confidence*). The most urgent adaptation challenge is chronic flooding at high tide (Chapters 10, 11, and 13–15). Reducing the acceleration of SLR beyond 2050 will only be achieved with fast and profound mitigation of climate change (Nicholls et al., 2018; Oppenheimer et al., 2019). Until 2050, adaptation planning and implementation needs are projected to increase significantly in most inhabited coastal regions (Figure SLR1, WGI AR6 Chapter 9, IPCC, 2019b; Fox-Kemper et al., 2021). For SSP1-2.6 and more strongly forced scenarios, SLR rates continue to increase (WGI AR6 Chapter 9, Fox-Kemper et al., 2021), and so do the scale and the frequency of adaptation interventions needed in coastal zones (Figure SLR1, Haasnoot et al., 2020).

Risks can be anticipated, planned, and decided upon, and adaptation interventions can be implemented over the coming decades, considering their often long lead- and life-times, irrespective of the large uncertainty about SLR beyond 2050 (*high confidence*) (Figure SLR1, Cross-Chapter Box DEEP in Chapter 17, Cross-Chapter Paper 2, Chapters 11, 13, Haasnoot et al., 2018; Stephens et al., 2018; Stammer et al., 2019). Adaptation capacity and governance to manage risks from projected SLR typically require decades to implement and institutionalise (*high confidence*) (Chapters 11,13, Haasnoot et al., 2021). Without considering both short- and long-term adaptation needs, including beyond 2100, communities are increasingly confronted with a shrinking solution space, and adverse consequences are disproportionately borne by exposed and socially vulnerable people (Chapters 1, 8). SLR is *likely* to compound social conflict in some settings (*high confidence*) (Oppenheimer et al., 2019).

Coastal impacts of SLR can be avoided by preventing new development in exposed coastal locations (Chapters 3, 9–15, Cross-Chapter Paper 2, Doberstein et al., 2019; Oppenheimer et al., 2019). For existing developments, a range of near-term adaptation options exists, including (1) engineered, sediment or ecosystem-based protection; (2) accommodation and land use planning, to reduce the vulnerability of people and infrastructure; (3) advance through, e.g., land reclamation; and (4) retreat through planned relocation or displacements and migrations due to SLR (Chapters 9–15, Cross-Chapter Paper 2, Oppenheimer et al., 2019). Only avoidance and relocation can remove coastal risks for the coming decades, while other measures only delay impacts for a time, have increasing residual risk or perpetuate risk and create ongoing legacy effects and *virtually certain* property and ecosystem losses (*high confidence*) (Cross-Chapter Paper 2, Siders et al., 2019). Large-scale relocation has immense cultural, political, social and economic costs, and equity implications, which can be reduced by fast implementation of climate mitigation and adaptation policies (Chapter 8, Cross-Chapter Paper 2, Gibbs, 2015; Haasnoot et al., 2021). While relocation may currently appear socially unacceptable, economically inefficient, or technically infeasible today (Lincke and Hinkel, 2021), it becomes the only feasible option as protection costs become unaffordable and the limits to accommodation become obvious (Chapters 11, 13, 15, Hino et al., 2017; Siders et al., 2019; Strauss et al., 2021). Effective responses to rising sea level involve locally applicable combinations of decision analysis, land use planning, public participation and conflict resolution approaches; together these can anticipate change and help to chart adaptation pathways, over time addressing the governance challenges due to rising sea level (*high confidence*) (Oppenheimer et al., 2019).

Ecosystem-based adaptation can reduce impacts on human settlements and bring substantial co-benefits such as ecosystem services restoration and carbon storage, but they require space for sediment and ecosystems and have site-specific physical limits, at least above 1.5°C GWL (*high confidence*) (Cross-Chapter Box NATURAL in Chapter 2, Chapters 3, 9, 11, 15, Herbert et al., 2015; Brown et al., 2019; Van Coppenolle and Temmerman, 2019; Watanabe et al., 2019; Neijnens et al., 2021). For example, planting and conserving vegetation helps sediment accumulation by dissipating wave energy and reducing impacts of storms, at least at present-day sea levels (*high confidence*) (Temmerman et al., 2013; Narayan et al., 2016; Romañach et al., 2018; Laengner et al., 2019; Leo et al., 2019). Coastal wetlands and ecosystems can be preserved by landward migration (Schuerch et al., 2018; Schuerch et al., 2019) or sediment supply (VanZomeren et al., 2018), but they can be seriously damaged by coastal defences designed to protect infrastructure (Chapters 3, 13, Cooper et al., 2020b). Sediment nourishment can prevent erosion, but it can also negatively impact beach amenities and ecosystems through ongoing dredging, pumping and deposition of sand and silts (VanZomeren et al., 2018; de Schipper et al., 2021; Harris et al., 2021).

There is increasing evidence that current governance and institutional arrangements are unable to address the escalating risks in low-lying coastal areas worldwide (*high confidence*). Barriers to adaptation such as decision-making driven by short-term thinking or vested interests, funding limitations, and inadequate financial policies and insurance can be addressed equitably and sustainably through implementation of suites of adaptation options and pathways, (Chapters 11, 13, 17–18, Cross-Chapter Paper 2). Improved coastal adaptation governance can be supported by approaches that consider changing risks over time, such as "dynamic adaptation pathways" planning (Chapters 11, 13, 18, Cross-Chapter Box DEEP in Chapter 17). Integrated Coastal Zone Management and land-use and infrastructure planning are starting to consider SLR by, for example, monitoring early signals (Haasnoot et al., 2018; Stephens et al., 2018; Kool et al., 2020), updating sea-level projections (Stephens et al., 2017; Hinkel et al., 2019; Kopp et al., 2019; Stammer et al., 2019), considering uncertainties of sea-level projections and coastal impacts (e.g., Stephens et al., 2017; Jevrejeva et al., 2019; Rohmer et al., 2019), as well as engaging with communities, practitioners and scientists, recognising the values of current and future generations (e.g., Nicholls et al., 2014; Buchanan et al., 2016b). While there is *high agreement* that the majority of adaptation needs are not met yet, there is *robust evidence* of sea level rise increasingly being considered in coastal adaptation decision making and being embedded in national and local guidance and regulations (Nicholls et al., 2014; Le Cozannet et al., 2017; Lawrence et al., 2018; Kopp et al., 2019; McEvoy et al., 2021).

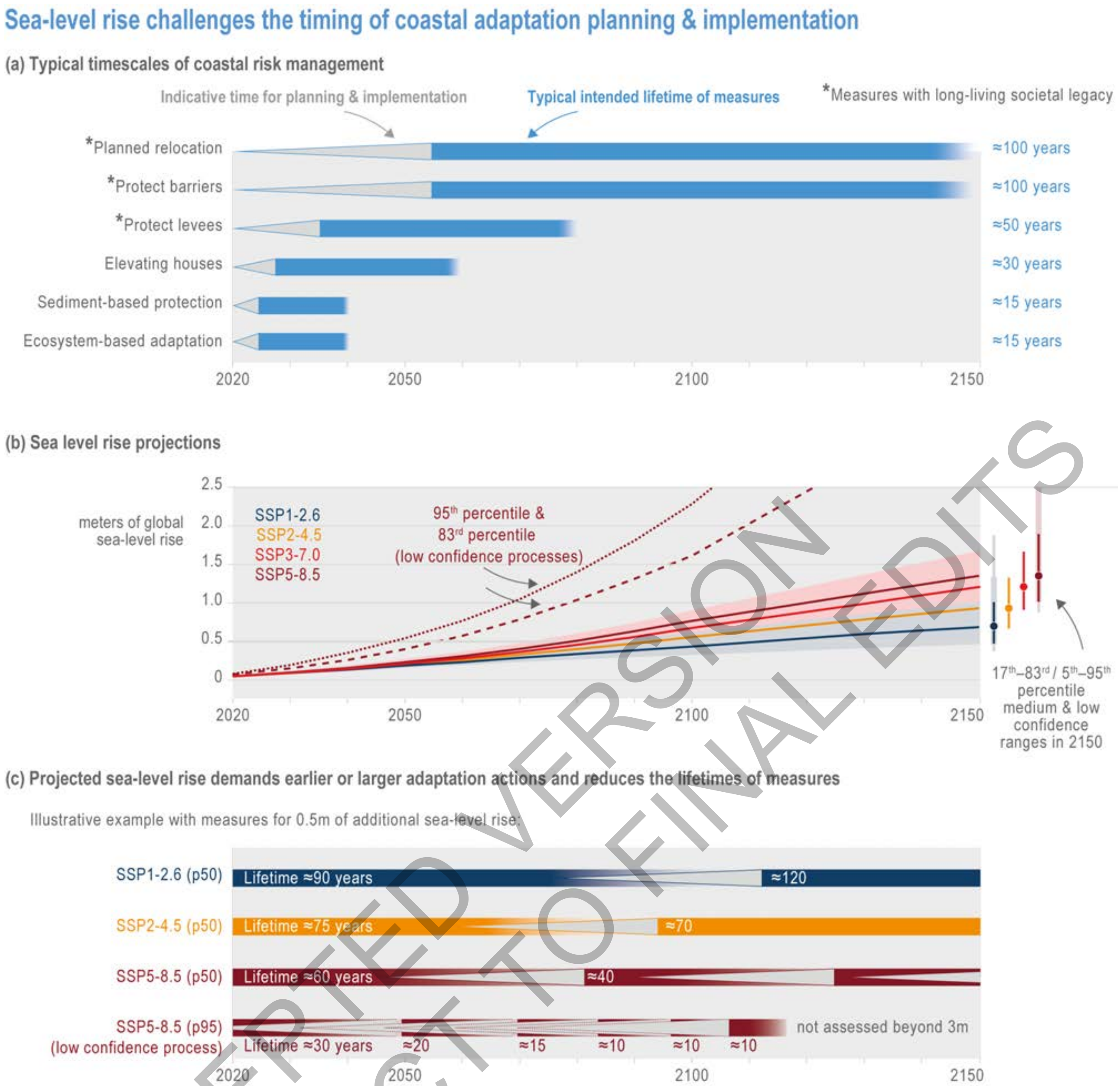


Figure Cross-Chapter Box SLR.1: The challenge of coastal adaptation in the era of sea-level rise (SLR): (a): typical timescales for the planning, implementation (grey triangles) and operational lifetime of current coastal risk-management measures (blue bars); (b): global sea-level projections, which are representative of relative SLR projected for 60 to 70% of global shorelines, within ±20% errors (WGI AR6 Chapter 9, Fox-Kemper et al., 2021); (c): Frequency of illustrative adaptation decisions to +0.5 m of SLR under different SSP-RCP scenarios. In response to accelerated SLR, adaptation either occurs earlier and faster, or accounts for higher amounts of SLR (e.g., to +1 m instead of to +0.5 m). Adaptation to +0.5 m from today's sea-levels have a lifetime of 90 years for SSP1-2.6, but lifetime is reduced to 60 years for SSP5-8.5 and 30 years for a high-end scenario involving *low confidence* processes. Adaptations to +0.5 m are comparable to e.g., the Thames Barrier in the United Kingdom, or the Delta Works in the Netherlands, which primarily had an intended lifetime of 100–200 years. Adaptation measures to +0.2 m may include nourishment or wetland or setback zones.

[END CROSS-CHAPTER BOX SLR HERE]

3.6.3.1.2 Fisheries and mariculture

SROCC (Bindoff et al., 2019) assessed adaptation in fisheries and mariculture (marine aquaculture), and socioeconomically focused updates are provided in Section 5.8.4 and Cross-Chapter Box MOVING SPECIES in Chapter 5. Here, we present a brief synthesis of how fisheries and mariculture adaptations interact with the natural environment, with further detail and supporting material in SM3.5.2.

Mobility allows fishing fleets and fishers to adapt to shifts in marine species distributions (*high agreement*) (Sections 3.4.3.1, 3.5.3, Peck and Pinnegar, 2018; Pinsky et al., 2018; Frazão Santos et al., 2020), but with limits and unintended consequences (Pinsky and Fogarty, 2012; Bell et al., 2021). Diversification of target species, harvest tactics and employment sectors, including transitions from fisheries to mariculture and ecotourism, allows some fishers to accommodate some impacts on their livelihoods (Miller et al., 2018; Robinson et al., 2020; Gonzalez-Mon et al., 2021). Technology and infrastructure adaptations can improve marine harvest efficiency, reduce risk, and support resource management goals (Friedman et al., 2020; Bell et al., 2021; Melbourne-Thomas et al., 2021), but their ability to overcome climate-change impacts remains uncertain (Bell et al., 2020). Improving capacity to predict anomalous conditions in coastal and marine ecosystems (Jacox et al., 2019; Holbrook et al., 2020; Jacox et al., 2020), storm-driven flooding in reef-lined coasts (Scott et al., 2020; Winter et al., 2020) and fisheries stocks (Payne et al., 2017; Tommasi et al., 2017; Muhling et al., 2018) can improve forecasts of coastal and marine resources. These can enhance sustainability of wild-capture fisheries under climate change (*high confidence*) (Blanchard et al., 2017; Tommasi et al., 2017; Pinsky et al., 2020a; Bell et al., 2021). Limiting overexploitation is the central goal of fishery management, and it *very likely* benefits fisheries adaptation to climate change (Burden and Fujita, 2019; Free et al., 2019; Sumaila and Tai, 2020). Conventional tools include catch and size limits, spatial management and adaptive management. Ecosystem-based fisheries management outperforms single-species management (Fulton et al., 2019), is widely legislated (Bryndum-Buchholz et al., 2021), and can reduce climate impacts in fisheries in the near-term, especially under low-emission scenarios (Karp et al., 2019; Holsman et al., 2020). Transboundary agreements on shifting fisheries will reduce the risk of overharvesting (*medium confidence*) (Gaines et al., 2018). Permits tradable across political boundaries could also address this challenge, but *limited evidence* is available regarding their efficacy (Cross-Chapter Box MOVING SPECIES in Chapter 5, Pinsky et al., 2018). Climate-smart conservation (Section 3.6.32.1) under the negotiations on areas beyond national jurisdiction (ABNJ) (Pinsky et al., 2018; Tittensor et al., 2019; Frazão Santos et al., 2020), and in the Convention on Biological Diversity (CBD) areas designed as other effective area-based conservation measures (OECMs, Tittensor et al., 2019) provide further benefits. Despite the potential for of adaptive management to achieve sustainable fisheries, outcomes will *very likely* be inequitable (Gaines et al., 2018; Lam et al., 2020) with lower-income countries suffering the greater biomass and economic losses, increasing inequalities especially under higher emission scenarios (*high confidence*) (Boyce et al., 2020). Flexible and polycentric governance approaches have facilitated some short-term successes in achieving equitable, sustainable fisheries practices, but these may be challenging to implement where other governance systems, especially hierarchical systems, are well-established (Cvitanovic et al., 2018; Bell et al., 2020).

3.6.3.1.3 Tourism

Coastal areas, coastal infrastructure and beaches, sustaining tourism that contributes significantly to local economies (James et al., 2019; Ruiz-Ramírez et al., 2019), are under threat from development, SLR and increased wave energy during storms and (*high confidence*) (Sections 3.4.2.6, 3.4.4–3.4.6, 3.5.6, Lithgow et al., 2019; Ruiz-Ramírez et al., 2019). Engineered solutions like seawalls and revetments have traditionally been used to address coastal erosion (Section 3.6.3.1.1), but soft infrastructure approaches, including beach nourishment, submerged breakwaters and groins, and NbS (Section 3.6.2.1), are becoming more common, partly due to demand from the tourism industry (*medium confidence*) (Pranzini, 2018; Pranzini et al., 2018).

Elsewhere, interactions between tourism and climate impacts worsen outcomes for coastal and ocean environments (Section 3.6.3.1.4). Climate change is opening up new cruise-ship routes in the Arctic (Sun et al., 2018), increasing number of visitors and associated stressors, such as litter, to previously undisturbed areas (Anfuso et al., 2020; Hovelsrud et al., 2020; Suaria et al., 2020). Risk reduction for cruise-ship tourism includes disaster response management, improved mapping, and passenger codes of conduct ensuring social, cultural and ecological sustainability (Stewart et al., 2015; Dawson et al., 2016).

Marine ecotourism, integrating conservation, education and provision of benefits to local communities (Donohoe and Needham, 2006), can provide significant economic benefits (Wabnitz, 2019), and is among the most common livelihood alternatives to support both marine conservation and climate change adaptation (Kutzner, 2019; Pham, 2020; Prasetyo et al., 2020). Ecotourism can enhance social and political will for marine conservation (Cisneros-Montemayor and Sumaila, 2014), and facilitates integration of local and Indigenous Peoples in employment, ownership, and industry governance. The community of Cabo Pulmo, Mexico, self-imposed an MPA and replaced fishing with ecotourism, which now generates millions of USD yr^{-1}, sustains locally owned and operated tour companies, and has increased some fish populations ten-fold (Knowlton, 2020). In Misool, Indonesia, local ecotourism incorporates IK by including local communities' preferences and sustainable resource use (Prasetyo et al., 2020).

Unintended consequences of ecotourism, such as detrimental ecological impacts on reefs (Giglio et al., 2020), sharks, marine birds (Monti et al., 2018), and whales (Higham et al., 2016; Barra et al., 2020; Hoarau et al., 2020), can be minimised by relying on evidence-based management of associated activities (Blumstein et al., 2017). Public perception of climate change connections to tourism can create obstacles (Meynecke et al., 2017; Atzori et al., 2018) such as deterring long-term investment in SIDS tourism initiatives (Santos-Lacueva et al., 2017), or benefits like inclining tourists to participate in conservation projects (Curnock et al., 2019; Miller et al., 2020b; Ziegler et al., 2021). Social and cultural networks may decrease climate vulnerability, as with Indigenous tourism operators in SIDS (Parsons et al., 2018). Tourism-based adaptation can also be improved by equitable access to resources, and recognition and inclusion of all stakeholders during policy planning and implementation. The principles of marine spatial planning (Papageorgiou, 2016) provide for effectively incorporating stakeholders and could inform development of activities to assess climate-associated risks (e.g., Tzoraki et al., 2018; Loehr, 2020). The recent decrease in global tourism due to the COVID-19 pandemic may offer opportunities to transform existing practices to more sustainable approaches (Cross-Chapter Box COVID in Chapter 7, Gössling et al., 2021).

3.6.3.1.4 Maritime transport

Increased maritime transport and cruise-ship tourism in the Arctic are already impacting local and Indigenous Peoples, revealing conflicts over the uses of the ocean and the governance needed to support local people and a sustainable blue economy (*high confidence*) (Debortoli et al., 2019; Palma et al., 2019; Berman et al., 2020; Dundas et al., 2020). While shipping and its associated environmental impacts are projected to grow (Palma et al., 2019; Dawson et al., 2020), adaptation efforts are only at the planning stage (Debortoli et al., 2019). Increased Arctic traffic due to ice loss can benefit trade, transportation and tourism (*medium confidence*), but will also affect Arctic marine ecosystems and livelihoods (*high confidence*) (Palma et al., 2019; Dawson et al., 2020). Increasing search-and-rescue activities (Ford and Clark, 2019) reveal capacity gaps to support future demands (Ford and Clark, 2019; Palma et al., 2019). The Low-Impact Shipping Corridors initiative has been developed as an adaptation strategy in the Arctic, although with limited inclusion of IK and LK (Dawson et al., 2020).

RSLR and the increased frequency and severity of storms are already affecting port activity, infrastructure, and supply chains, sometimes disrupting trade and transport (Monios and Wilmsmeier, 2020), but these hazards are not systematically incorporated into adaptation planning (*medium evidence*) (Monios and Wilmsmeier, 2020; O'Keeffe et al., 2020). Climate-change impacts that increase food insecurity, income loss, and poverty can exacerbate maritime criminal activity including illegal fishing, drug trafficking or piracy (*medium evidence*) (Germond and Mazaris, 2019). A transformational adaptation approach to address climate impacts on maritime activities and increase security (Germond and Mazaris, 2019) would relocate ports, change centers of demand, reduce shipping distances, or shorten supply chains (*medium agreement*) (Walsh et al., 2019; Monios and Wilmsmeier, 2020) as well as decrease marginalization of vulnerable groups, develop polycentric governance systems and eliminate maladaptive environmental policies and resource loss (Belhabib et al., 2020; O'Keeffe et al., 2020).

3.6.3.1.5 Human Health

Health-focused adaptations to climate-driven changes in ocean and coastal water quality (Section 3.5.5.3) mainly leverage technology and infrastructure (Section 3.6.2.2) to improve water-quality monitoring and forecasting to inform socio-institutional adaptation (Section 3.6.2.1) and NbS (Section 3.6.2.3). Seafood quality and safety are decreasing due to climate-driven increases in marine-borne diseases (Cross-Chapter Box ILLNESS in Chapter 2), toxic HABs, or toxin bioaccumulation (*high agreement*) (Karagas et al., 2012; Krabbenhoft and Sunderland, 2013; Rafaj et al., 2013; Curtis et al., 2019; Schartup et al., 2019; Thackray and Sunderland, 2019). Future exposure to seafood-borne contaminants also depends partly on consumers' seafood preferences (Elsayed et al., 2020) and seafood supply (Sunderland et al., 2018). Reducing this risk by decreasing seafood consumption increases risk of eating less nutritious foods, and loss of cultural practices (Chapter 5, Cross-Chapter Box MOVING SPECIES in Chapter 5, Donatuto et al., 2011; Bindoff et al., 2019). Models incorporating high-resolution satellite images, field survey data, meteorological observations and historical records can provide early-warning forecasts of HABs or conditions that favour microbial pathogen outbreaks (Cross-Chapter Box ILLNESS in Chapter 2, Semenza et al., 2017; Franks, 2018; Hattenrath-Lehmann et al., 2018; Borbor-Cordova et al., 2019; Davis et al., 2019; Campbell et al., 2020a; Davidson et al., 2021). Forecasts facilitate preventive public health measures (World Health Organisation and United Nations Children's Fund, 2017), or seafood harvest guidance (Maguire et al., 2016; Leadbetter et al., 2018; Anderson et al., 2019; Bolin et al., 2021), reducing risks of disease outbreaks, waste, and contaminated seafood entering the market (*medium confidence*) (Cross-Chapter Box ILLNESS in Chapter 2, Nichols et al., 2018). Monitoring of water quality and seafood safety (Cross-Chapter Box ILLNESS in Chapter 2), paired with effective public communication and education (Ekstrom et al., 2020) inform individual and local adaptations, including use of personal protective equipment, seafood selection and preparation (Elsayed et al., 2020; Froelich and Daines, 2020; Fielding et al., 2021), income diversification (Section 3.6.2.1, Moore et al., 2020b), public education (Borbor-Cordova et al., 2019), or community-level actions to decrease risk from coastal aquifer and soil salinisation (Slama et al., 2020; Mastrocicco and Colombani, 2021), HAB toxins (Ekstrom et al., 2020) and other contaminants (e.g., methylmercury, metals, persistent organic pollutants) in seafood (Chan et al., 2021). A full assessment of climate-change impacts on human health is found in Chapter 7 and Cross-Chapter Box ILLNESS in Chapter 2.

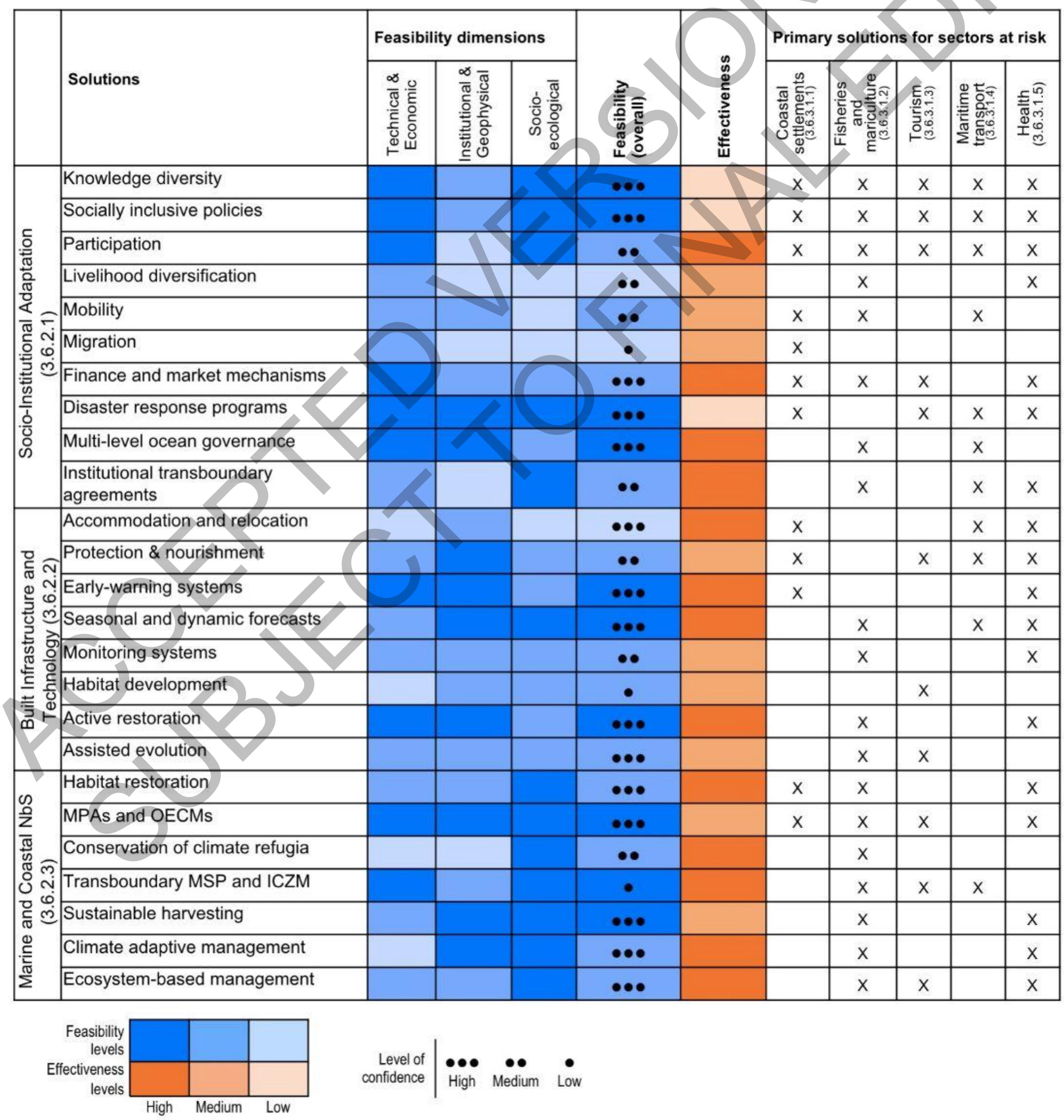


Figure 3.24: Assessment of feasibility and effectiveness of adaptation solutions for ocean and coastal ecosystems. Feasibility dimensions assessed include: technical and economic capacity to deliver and implement the solution, the

institutional and geophysical capacity to implement a solution; and associated social and ecological implications that make a solution more feasible. The general feasibility level is obtained from assessment of the three dimensions together. Note that feasibility is assessed for marine and coastal ecosystems as a whole and not by ecosystem type or region. Feasibility dimensions and assessment are updated and adapted from IPCC (2018) and Singh et al. (2020). Effectiveness: ability of the adaptation solution to reduce climate change mid-term risks. Main solutions are assessed per sector. Underlying data are available in Table SM3.3.

3.6.3.2 Cross-Cutting Solutions for Coastal and Ocean Ecosystems

SROCC concluded that protection, restoration and pollution reduction can support ocean and coastal ecosystems (*high confidence*), and that EbA lowers climate risks locally and provides multiple societal benefits (*high confidence*) (IPCC, 2019c). This section updates the assessment of the effectiveness of these strategies for addressing climate impacts.

3.6.3.2.1 Area-based protection: MPAs for adapting to climate change

Marine protected areas (MPAs) are the most widely implemented area-based management approach (Section 3.6.2.3.2), commonly intended to conserve, preserve, or restore biodiversity and habitats, protect species, or manage resources (especially fisheries) (National Research Council, 2001). By August 2021, 7.74% of the ocean was protected (in both MPAs and other effective conservation measures, OECMs) (UNEP-WCMC and IUCN, 2021), primarily within nations' Exclusive Economic Zones (EEZs). These MPAs support adaptation by sustaining nearshore ecosystems that provide natural erosion barriers (Sections 3.4.2.–3.4.2.5, Cross-Chapter Box SLR in Chapter 3), ecosystem function (Cheng et al., 2019), habitat, natural filtration, carbon storage, livelihoods, and cultural opportunities (Sections 3.5.5, 3.5.6, Erskine et al., 2021) and help ecosystems and livelihoods recover after extreme events (Roberts et al., 2017; Aalto et al., 2019; Wilson et al., 2020a). However, in 2021 only 2.7% of the ocean was in fully or highly protected MPAs (Marine Conservation Institute, 2021), the hard-to-achieve states that most effectively rebuild biomass and fish community structure (Sala and Giakoumi, 2017; Bergseth, 2018; Zupan et al., 2018; Ohayon et al., 2021). Only 1.18% of ABNJ is protected (UNEP-WCMC and IUCN, 2021), mostly due to governance limitations (O'Leary and Roberts, 2017; Vijayaraghavan, 2021), but calls to protect more ABNJ emphasise the need to protect habitat of long-range pelagic fish and marine mammals, maintain the ocean's regulating functions, and minimise impacts from uses such as maritime shipping or deep-sea mining (Table 3.30).

MPAs are theorised to facilitate ecological climate adaptation and contribute to SDG14 ("Life below water", Table 3.30, Figure 3.26, Bates et al., 2014; Lubchenco and Grorud-Colvert, 2015; Gattuso et al., 2018) because they alleviate non-climate drivers and promote biodiversity (i.e., "managed resilience hypothesis", Bruno et al., 2019; Maestro et al., 2019; Cinner et al., 2020). Current MPAs offer conservation benefits such as increases in biomass and diversity of habitats, populations, and communities (*high confidence*) (Pendleton et al., 2018; Bates et al., 2019; Stevenson et al., 2020; Lenihan et al., 2021; Ohayon et al., 2021), and these benefits may last after some (possibly climate-enhanced) disturbances (e.g., tropical cyclones, McClure et al., 2020). But current MPAs do not provide resilience against observed warming and heatwaves in tropical to temperate ecosystems (*medium confidence*) (Bates et al., 2019; Bruno et al., 2019; Freedman et al., 2020; Graham et al., 2020; Rilov et al., 2020). There is *robust evidence* that processes around MPA design and implementation strongly influence whether outcomes are beneficial or harmful for adjacent human communities (McNeill et al., 2018; Zupan et al., 2018; Ban et al., 2019).

Current placement and extent of MPAs will not provide substantial protections against projected climate change past 2050 (*high confidence*), as the placement of MPAs has been driven more often by political expediency (e.g., Leenhardt et al., 2013) than by managing key drivers of biodiversity loss (Cockerell et al., 2020; Stevenson et al., 2020) or climate-impact drivers (Bruno et al., 2018). Only 3.5% of the area currently protected will provide refuges from both SST and deoxygenation by 2050 under both RCP4.5 and RCP8.5 (Bruno et al., 2018) and MPAs are more exposed to climate change under RCP8.5 than non-MPAs (Section 3.4.3.3.4, Figure 3.20d). Community thermal tolerances will be exceeded by 2050 in the tropics and by 2150 for many higher-latitude MPAs (Bruno et al., 2018). Most MPA design has focused on the surface ocean, but MPAs are assumed to protect the entire water column and benthos. Climate-impact drivers (Section 3.2) throughout the water column and rapidly accelerating climate velocities at depths below 200 m (Johnson et al., 2018; Brito-Morales et al., 2020), are projected to affect virtually all North Atlantic deep-water and open ocean area-based management zones in the next 20–50 years (Johnson et al., 2018) and the conservation goals of benthic MPAs in the North Sea are not expected to be fulfilled (Weinert et al., 2021). Heightened risk of non-indigenous species immigration from vessel traffic plus climate change further endangers MPA success (Iacarella et al., 2020), a particular concern in the Mediterranean (D'Amen and Azzurro, 2020; Mannino and Balistreri, 2021), where the current MPA network is already highly vulnerable to climate change (Kyprioti et al., 2021). This new evidence supports SROCC's *high confidence* assessment that present governance arrangements including MPAs are too fragmented to provide integrated responses to the increasing and cascading risks from climate change in the ocean (SROCC SPMC1.2, IPCC, 2019c).

Strategic conservation planning can yield future MPA networks substantially more ready for climate change (e.g., Section 3.6.3.1.5, SROCC SPM C2.1, IPCC, 2019c; Frazão Santos et al., 2020; Rassweiler et al., 2020). Global protection is increasing (Worm, 2017; Claudet et al., 2020b) as nations pursue international targets (e.g., SDG14, "Life below water" aimed to conserve 10% of the ocean by 2020), and the UN CBD proposes to protect 30% by 2030 (Section 3.6.4, SM3.5.3, CBD, 2020). A growing body of evidence (Tittensor et al., 2019; Cabral et al., 2020; Zhao et al., 2020a; Pörtner et al., 2021b; Sala et al., 2021) underscores the urgent need to pursue biodiversity, ecosystem-service provision, and climate-adaptation goals simultaneously, while acknowledging inherent tradeoffs (Claudet et al., 2020a; Sala et al., 2021). Frameworks to create "climate-smart" MPAs (Tittensor et al., 2019) generally include: defining conservation goals that embrace resource vulnerabilities and co-occurring hazards; carefully selecting adaptation strategies that include LK and IK while respecting Indigenous rights and accommodating human behaviour (Kikiloi et al., 2017; Thomas, 2018; Yates et al., 2019; Failler et al., 2020; Wilson et al., 2020a; Croke, 2021; Reimer et al., 2021; Vijayaraghavan, 2021); developing protection that is appropriate for all ocean depths (Brito-Morales et al., 2018; Frazão Santos et al., 2020; Wilson et al., 2020a), especially considering climate velocity (Arafeh-Dalmau et al., 2021); using dynamic national and international management tools to accommodate extreme events or species distribution shifts (Gaines et al., 2018; Pinsky et al., 2018; Bindoff et al., 2019; Scheffers and Pecl, 2019; Tittensor et al., 2019; Cashion et al., 2020; Crespo et al., 2020; Frazão Santos et al., 2020; Maxwell et al., 2020b), which could build on dynamic regulations already in place for fishing or ship strikes (Maxwell et al., 2020b); and seeking to increase connectivity (Wilson et al., 2020a), using genomic or multispecies model insights (Xuereb et al., 2020; Friesen et al., 2021; Lima et al., 2021).

There is growing international support for a 30% conservation target for 2030 (Gurney et al., 2021), that will need efforts beyond protected areas. For example, Other Effective area-based Conservation Measures (OECMs) recognise management interventions that sustain biodiversity, irrespective of their main objective (Maxwell et al., 2020b; Gurney et al., 2021). There is *high agreement* on the potential of OECMs to contribute to conservation and equity, for example by recognising Indigenous territories as OECMs (Maxwell et al., 2020b; Gurney et al., 2021). However, the capacity of these conservation tools to provide adaptation outcomes remains unexplored.

In summary, MPAs and other marine spatial planning tools have great potential to address climate change mitigation and adaptation in ocean and coastal ecosystems, if they are designed and implemented in a coordinated way that takes into account ecosystem vulnerability and responses to projected climate conditions, considers existing and future ecosystem uses and non-climate drivers, and supports effective governance (*high confidence*).

3.6.3.2.2 Ecological restoration, interventions and their limitations

Restoration of degraded ecosystems is a common NbS increasingly deployed at local scales in response to climate change (Cross-Chapter Box NATURAL in Chapter 2, Duarte et al., 2020; Bertolini and da Mosto, 2021; Braun de Torrez et al., 2021). Despite covering limited areas and having uncertain efficacy under future climate change (Gordon et al., 2020), these actions have successfully restored marine populations and ecosystems at regional to global scales (Duarte et al., 2020), and enhanced livelihoods and wellbeing of coastal peoples as well as biodiversity and resilience of ecological communities (Silver et al., 2019; Gordon et al., 2020; Braun de Torrez et al., 2021). Technology-based approaches like active restoration, assisted evolution, and ecological forecasting can aid in moving beyond restoring ecosystems (Section 3.6.2.3) towards enhancing resilience, reviving biodiversity and guarding against loss of foundational, ornamental or iconic species (Bulleri et al., 2018; Collins et al., 2019a; da Silva et al., 2019; National Academies of Sciences, 2019; Boström-Einarsson et al., 2020; Fredriksen et al., 2020; Morris et al., 2020c; Kleypas et al., 2021).

Local restoration projects often target vegetated ecosystems like mangroves, seagrasses and saltmarshes that are valued and used by coastal communities (Veettil et al., 2019; Duarte et al., 2020; Wu et al., 2020a; Bertolini and da Mosto, 2021) Detail on mangroves and corals as EbA and protection/restoration hotspots is provided in SuppMat 3.8. Common and effective actions (Sasmito et al., 2019; Duarte et al., 2020; Oreska et al., 2020) include securing accommodation space (Sections 3.4.2.4–3.4.2.5), restoring hydrological (Kroeger et al., 2017; Al-Haj and Fulweiler, 2020) and sediment dynamics; managing harvesting (particularly in mangroves); reducing pollution (especially in seagrasses, de los Santos et al., 2019); and replanting appropriate species in suitable environmental settings (Wodehouse and Rayment, 2019; Friess et al., 2020a). Although efficacy is context dependent (Zeng et al., 2020; Krause-Jensen et al., 2021), and implementation is most often local (Alongi, 2018a), such projects allow tangible community engagement in climate action. Moreover, because these ecosystems sequester disproportionate amounts of carbon (blue carbon, Annex II: Glossary, Box 3.4), restoration supports climate-change mitigation (Lovelock and Reef, 2020; Gattuso et al., 2021). Yet, constraints remain. For instance, Southeast Asia has 1.21 million km^2 of terrestrial, freshwater and mangrove area biophysically suitable for reforestation, which could mitigate 3.43 ± 1.29 Pg CO_2e yr^{-1} through 2030; however, reforestation is only feasible in a small fraction of this area (0.3–18%) given financial, land-use and operational constraints (Zeng et al., 2020). Nevertheless, the multiple benefits offered by ecosystem restoration will *likely* outweigh competing costs, and increase its relevance as part of adaptation strategy portfolios (Silver et al., 2019; Wedding et al., 2021), national carbon-accounting systems, and NDCs (Friess et al., 2020a; Wu et al., 2020a).

Restoration efficacy of coral reefs, kelp forests and other habitat-forming coastal ecosystems (Section 3.4.2.2–3.4.2.6) are jeopardised by the near-term nature of climate-driven risks (McLeod et al., 2019; National Academies of Sciences, 2019; Coleman et al., 2020b). Modelling studies indicate that available practices will not prevent degradation of coral reefs from >1.5°C of global average surface warming (Figure 3.25, National Academies of Sciences Engineering and Medicine, 2019; Condie et al., 2021; Hafezi et al., 2021). Proposed interventions, not yet implemented, include assisted migration (Boström-Einarsson et al., 2020; Fredriksen et al., 2020; Morris et al., 2020c), assisted evolution (Bay et al., 2019; National Academies of Sciences, 2019) and other engineering solutions like artificial shading and enhanced upwelling (Condie et al., 2021; Kleypas et al., 2021).

Transplanting heat-tolerant coral colonies can increase reef resistance to bleaching (Morikawa and Palumbi, 2019; Howells et al., 2021), but potentially lowering species diversity and altering ecosystem function (Section 3.4.2.1). Genetic manipulation or assisted evolution that propagates genes from heat-tolerant populations could enhance restoration of corals (Anthony et al., 2017; Epstein et al., 2019) and kelp (*medium agreement, limited evidence*) (Coleman and Goold, 2019; Coleman et al., 2020b; Fredriksen et al., 2020; Wade et al., 2020). Managed breeding of corals has also had limited success in the laboratory and at small local scales (National Academies of Sciences, 2019). There is also *limited evidence* that physiological interventions like algal-symbiont or microbiome manipulation could increase coral thermal tolerance in the field (National Academies of Sciences, 2019). Employing the natural adaptive capacity of species or individuals in active restoration for corals and kelps with current technology involves fewer risks than assisted evolution or long-distance relocation (*high confidence*) (Filbee-Dexter and Smajdor, 2019; National Academies of Sciences, 2019). More ambitious engineered interventions like reef shading remain theoretical and not scalable to the reef level (Condie et al., 2021). Debate continues on how to apply planned adaptation in cost-effective ways that will accomplish the intended goals (National Academies of Sciences, 2019; Duarte et al., 2020; Kleypas et al., 2021).

Models show that a combination of available management approaches (restoration, reducing non-climate drivers) and speculative interventions (enhanced corals, reef shading) can contribute to sustaining some coral reefs beyond 1.5°C of global warming with declining effectiveness beyond 2°C of global warming (*medium confidence*) (Figure 3.25, WGII Chapter 17). These proposed interventions are also currently theoretical and impractical over large scales; for example, engineered solutions like reef shading are untested and not scalable at the reef level (Condie et al., 2021). Existing projects suggest that restoration and ecological interventions to habitat-forming ecosystems have additional benefits of raising local awareness, promoting tourism, and creating jobs and economic benefits (Fadli et al., 2012; Boström-Einarsson et al., 2020; Hafezi et al., 2021), provided communities are involved in planning, operation and monitoring (Boström-Einarsson et al., 2020).

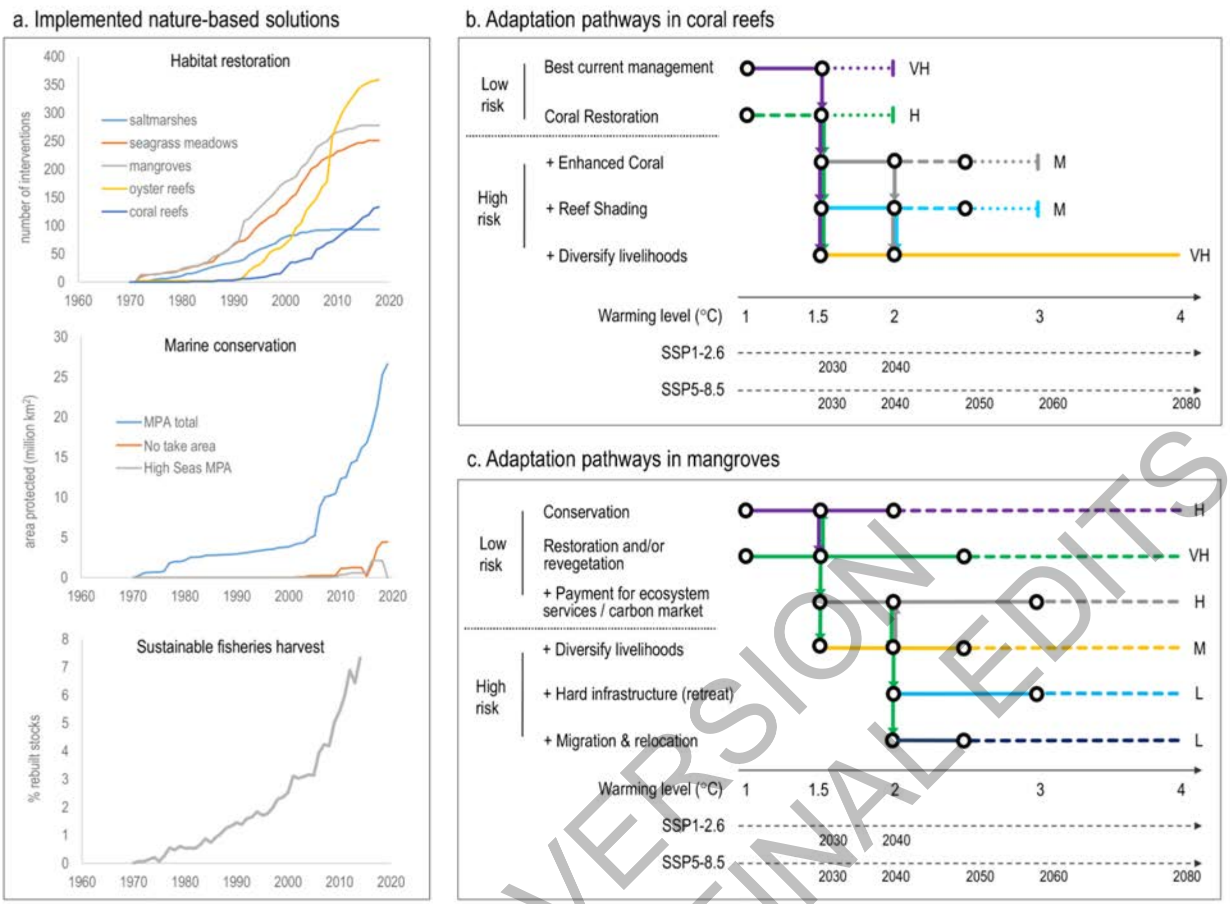


Figure 3.25: Implemented and potential future adaptations in ocean and coastal ecosystems. (a) Global implementation since 1970 of (top) cumulative habitat-restoration projects (Duarte et al., 2020), (middle) cumulative area-based conservation protected area (MPA total, Boonzaier and Pauly, 2016), no-take areas (UN Environment World Conservation Monitoring Centre et al., 2018; UNEP-WCMC, 2019), and (bottom) percentage of total fish stocks rebuilt (Kleisner et al., 2013). (b) Adaptation pathways for coral reefs to maintain healthy cover (line weight: solid lines, *likely* effectiveness; dashed lines, *more likely* than not to *likely;* dotted lines = *unlikely to more likely than not*), with confidence noted for each intervention (VH = *Very High*, H = *High*, M = *Medium*) (Section 3.4.2.1, 3.6.3.2, Anthony et al., 2019; National Academies of Sciences Engineering and Medicine, 2019). Circles denote when other measures must also be implemented. (c) As in (b), but for mangrove ecosystems. Underlying data are available in Tables SM3.4–3.6.

3.6.3.3 Enablers, Barriers and Limitations of Adaptation and Mitigation

Not only is mitigation necessary to support ocean and coastal adaptation (Pörtner et al., 2014; Oppenheimer et al., 2019), but the global emission pathways also impose limits to ocean and coastal adaptation, with lower warming levels enabling greater effectiveness of adaptations (*high confidence*) (Figure 3.25). Chapter 17 broadly assesses the limits to adaptation, while this section focuses on barriers and limits to adaptation imposed by cultural (Section 3.6.3.3.1), economic (Section 3.6.3.3.2) and governance (Section 3.6.3.3.3) dimensions (Hinkel et al., 2018). Globally, these factors more strongly influence ocean development than does local natural resource availability (Cisneros-Montemayor et al., 2021), and are key to avoiding maladaptation. This section also assesses enablers and limits to mitigation (Section 3.6.3.3.4).

3.6.3.3.1 Sociocultural dimensions (culture, ethics, identity, behaviour)

Every coastal community values marine ecosystems for more than the material and intangible resources they deliver, or the physical protection they offer (Díaz et al., 2018). Cultural services that provide identity, spiritual and cultural continuity, religious meaning, or options for the future (e.g., genetic or mineral resources, Bindoff et al., 2019), are not substitutable. Furthermore, interactions between climate impacts and existing inequalities can threaten the human rights of already-marginalised peoples by disrupting livelihoods and food security, which further erodes people's social, economic, and cultural rights (Finkbeiner et al., 2018). For instance, European colonisation and ongoing development blocked the Cucapá Indigenous People's access and rights to resources in the Colorado River Delta, USA, over the 20th century. Recent reallocation of water rights and fishing access is allowing the Cucapá people to reconstruct their cultural identity (Sangha et al., 2019), but future climate change impacts could reverse the community's recovery of their cultural heritage. Adaptations that consider local needs may help sustain cultural services (Ortíz Liñán and Vázquez Solís, 2021).

Interactions with oceans are fundamental to the identities of many coastal Indigenous Peoples (Norman, 2017) and this influences Indigenous responses to climate hazards and adaptation. Around 30 million Indigenous Peoples live along coasts (Cisneros-Montemayor et al., 2016). Seafood consumption among Indigenous Peoples is much higher than for non-Indigenous populations, and marine species support many cultural, medicinal and traditional activities contributing to public health (Section 3.5.3.1, Kenny et al., 2018). Perpetuation of Indigenous cultures depends on protecting marine ecosystems and on adapting to changes in self-led ways (see Section 3.5.6, Sangha et al., 2019) that promote self-determination (von der Porten et al., 2019). Indigenous resurgence, or reinvigorating Indigenous ways of life and traditional management, can include marine resource protection and ocean-sector development founded on culturally appropriate strategies and partnerships, that are consistent with traditional norms and beneficial to local communities (von der Porten et al., 2019). Successful adaptation would simultaneously improve ecosystem health and address current and historical inequities (Bennett, 2018). Examples include practicing traditional resource management, protecting traditional territories, engaging with monitoring, collaborations with non-Indigenous partners, and reinvesting benefits into capacity-building within communities (von der Porten et al., 2019; Equator Initiative, 2020). The legitimacy of different adaptation strategies depends on local and Indigenous Peoples' acceptance, which is based on cultural values (Adger et al., 2017); financial gain cannot compensate for loss of IK or LK (Wilson et al., 2020b). Palau's recent goal of shifting seafood consumption away from reef fishes (Remengesau Jr., 2019) and limiting and closely monitoring the expansion of ecotourism was prompted by the cultural importance of protecting these reefs and associated traditional fisheries for local consumption, a recognition of the importance of tourism, and the hazard of climate change (Wabnitz et al., 2018a).

Adaptations implemented at the local level that consider IK and LK systems are beneficial (*high confidence*) (Nalau et al., 2018; Sultana et al., 2019). Studies in SIDS and the Arctic have shown how IK and LK facilitate the success of EbA (Nalau et al., 2018; Peñaherrera-Palma et al., 2018; Raymond-Yakoubian and Daniel, 2018), reinforce and improve institutional approaches and enhance the provision of ecosystem services (Ross et al., 2019; Terra Stori et al., 2019). Perspectives on adaptation also vary among groups of age, race, (dis)ability, class, caste, and gender (Wilson et al., 2020b), so engaging different groups results in more robust and equitable adaptation to climate change (Cross-Chapter Box GENDER in Chapter 18, McLeod et al., 2018). Some coastal communities have developed substantial social capital and dense local networks based on trust and reciprocity (Petzold and Ratter, 2015), with individual and community flexibility to learn, adapt, and organise themselves to help local adaptation governance (Silva et al., 2020). Recent evidence suggests that policies supporting local institutions can improve adaptation outcomes (*medium confidence*) (Berman et al., 2020). Coastal communities can be engaged using novel approaches to co-generate adaptation solutions (van der Voorn et al., 2017; Flood et al., 2018) that benefit education (Koenigstein et al., 2020) and engagement in adaptation processes (Rumore et al., 2016). Successful adaptation implementation in line with climate-resilient development pathways (WGII Chapter 18) depends on bottom-up, participatory and inclusive processes (Section 3.6.1.2.1) that engage diverse stakeholders (Basel et al., 2020; McNamara et al., 2020; Ogier et al., 2020; Williams et al., 2020), and that protect Indigenous customary rights (Farbotko and McMichael, 2019; Ford et al., 2020), empower women, and give rights to climate refugees (McLeod et al., 2018).

3.6.3.3.2 Economic dimensions (planning, finance, costs)

Finance is a key barrier globally for ocean health, governance and adaptation to climate change (*high agreement*) (Annex II: Glossary, Cross-Chapter Box FINANCE in Chapter 17, Hinkel et al., 2018; Miller et al., 2018; Wabnitz and Blasiak, 2019; Woodruff et al., 2020; Sumaila et al., 2021). Global adaptation finance was estimated to total 30 billion USD yr^{-1} in 2017–2018, or 5% of all climate finance (CPI, 2019), with no tracking specifically for coastal or marine adaptation in low- to middle-income countries. Marine-focused adaptation finance is difficult to trace and label due to the cross-sectoral nature of many projects (Blasiak and Wabnitz, 2018) and the lack of clear definitions about what qualifies as adaptation or as new and additional finance (Donner et al., 2016; Weikmans and Roberts, 2019). Finance for marine conservation from Overseas Development Assistance doubled between 2003 and 2016, reaching 634 million USD in 2016, similar to the level provided by philanthropic foundations (Berger et al., 2019). Yet coastal adaptation to SLR alone is projected to cost hundreds of billions of USD yr^{-1}, depending on the model and emission scenario (e.g., Wong et al., 2014; Nicholls et al., 2019). Economic and financing barriers to marine adaptation are often higher in low- to middle-income countries, where resources influence governance and constrain options for implementation and maintenance (*high confidence*) (Hinkel et al., 2018; Klöck and Nunn, 2019; Tompkins et al., 2020) and impacts on their coastal and marine ecosystems could total several percentage points of their gross domestic product (Wong et al., 2014). Current financial flows are insufficient to meet the costs of coastal and marine impacts of climate change (*very high confidence*) and ocean-focused finance is unevenly distributed, with higher flows within and to developed countries (*very high confidence*).

Development assistance can help resolve resource constraints, but additional governance and coordination challenges can arise from short-term, project-based funding, shifting priorities of donor institutions, and pressures placed on human resources in the receiving nation (Parsons and Nalau, 2019; Nunn et al., 2020). Innovative policy instruments like concessional loans, tax-policy reforms, climate bonds and public-debt forgiveness can supplement traditional financial instruments (Bisaro and Hinkel, 2018; McGowan et al., 2020). Mechanisms for solving the persistent problem of securing upfront investments for coastal protection and other adaptation measures (Bisaro and Hinkel, 2018; Moser et al., 2019; Kok et al., 2021) include integrating adaptation investments into insurance schemes (Reguero et al., 2020) and using debt financing to bridge the time until benefits are realised (Ware and Banhalmi-Zakar, 2020). Insurance mechanisms that link payments to losses from a trigger event (e.g., MHW) can confer resilience to marine-dependent communities (Sumaila et al., 2021). All innovative financial instruments are most effective when they are inclusive and reach vulnerable groups and marginalised communities (*low evidence, high agreement*) (Claudet et al., 2020a; Sumaila et al., 2021).

Countries with large ocean areas within their EEZs have opportunities to develop “blue-green economies” to reduce emissions and finance adaptation pathways (Chen et al., 2018a; Lee et al., 2020). Shifting from grants to results-based financing can help attract more private capital to ocean adaptation (Lubchenco et al., 2016; Claudet et al., 2020a). Public-private partnerships can also increase ocean adaptation finance (Goldstein et al., 2019; Sumaila et al., 2021). For example, the financial benefits that biodiversity conservation confers to seafood harvest resilience could be used to leverage industry participation in adaptation and conservation finance (Barbier et al., 2018). Connecting restoration of blue carbon ecosystems with offset markets (e.g., Vanderklift et al., 2019) shows potential, but uncertainties remain about the international emissions trading under the UN Framework Convention on Climate Change and climate impacts on blue-carbon ecosystems (Section 3.6.3.1.6, Lovelock et al., 2017a; Macreadie et al., 2019).

Transparency, coherence between different actors and initiatives, and project monitoring and evaluation enhance success in adapting and achieving SDG14 (Life below water) (Blasiak et al., 2019). Maladaptation (WGII Chapter 16, Magnan et al., 2016), is a common risk of current project-based funding due to the pressure to produce concrete results (*medium confidence*) (Parsons and Nalau, 2019; Nunn et al., 2020; Nunn et al., 2021). Maladaptation can be avoided through a focus on building adaptive capacity, community-based management, drivers of vulnerability and site-specific measures (*low confidence*) (Magnan and Duvat, 2018; Piggott-McKellar et al., 2020; Schipper, 2020). More research is needed to identify ways that governance and financing agreements can help overcome financial barriers and socio-cultural constraints to avoid maladaptation in coastal ecosystems (*high confidence*) (Hinkel et al., 2018; Miller et al., 2018; Piggott-McKellar et al., 2020; Schipper, 2020).

3.6.3.3.3 Governance dimension (institutional settings, decision making)

Ocean governance has become increasingly complex as new initiatives, new international agreements, institutions, and scientific evidence arise at global, national, and sub-national scales (*high agreement*) (Bindoff et al., 2019; Scobie, 2019b), limiting the present effectiveness of adaptation (IPCC, 2019c). Marine climate governance is within the normatively contested marine governance space (Frazão Santos et al., 2020), which is influenced by geopolitics (Gray et al., 2020) and profit maximisation (Flannery et al., 2016; Haas et al., 2021) in ways that can entrench exclusionary processes in decision making, science management and funding (Levin et al., 2018). This limits just and inclusive ocean governance (Bennett, 2018), perpetuates historical and cultural extractive practices and climate inaction, and leaves little space for Indigenous-led adaptation frameworks and approaches (Nursey-Bray et al., 2019). At the national level, ocean governance for climate-change adaptation is often transversal, requiring consideration of biophysical and environmental conditions (Furlan et al., 2020), while fitting into existing economic (Kim, 2020) and political processes. Adaptation governance that couples existing top-down structures with decentralised and participatory approaches generates shared goals and unlocks required resources and monitoring (Gupta et al., 2016; Haas et al., 2021).

Communities and governments at all levels increasingly use decision-making frameworks (e.g., structured decision making) or decision-analysis tools to evaluate trade-offs between different responses, rather than applying generic best practices to different physical, technical or cultural contexts (*high confidence*) (Watkiss et al., 2015; Haasnoot et al., 2019; Palutikof et al., 2019). Increased effort has also been devoted to developing climate services (actionable information and data products) that bridge the gap between climate prediction and decision-making (Hewitt et al., 2020). Climate services have the potential to inform decision making related to disaster-risk reduction, adaptation responses, marine environmental management (e.g., fisheries management and MPA management) and ocean-based climate mitigation (e.g., renewable energy installations, Le Cozannet et al., 2017; Gattuso et al., 2019; Gattuso et al., 2021). Although improving observational and modelling capacity is important to developing ocean-focused services, particularly in high-risk regions like SIDS where regional climate projections are scarce (WGI AR6 Chapter 9, Morim et al., 2019; Fox-Kemper et al., 2021), data is not the only limiting factor in decision-making (Weichselgartner and Arheimer, 2019). Focusing on user engagement, relationship-building and the decision-making context ensures that climate services are useful to and used by different stakeholders (*high confidence*) (Soares et al., 2018; Mackenzie et al., 2019; Weichselgartner and Arheimer, 2019; Findlater et al., 2021; West et al., 2021).

3.6.3.3.4 Mitigation

Ocean and coastal NbS can contribute to global mitigation efforts, especially with ocean renewable energy and restoration and preservation of carbon ecosystems (Box 3.4, Section 3.6.2.3). Technological, economic and financing barriers presently hamper development of renewable ocean energy (AR6 WGIII Chapter 6). Such development could help small nations reliant on imported fuel meet their climate-mitigation goals and decrease risk from global fuel supply dynamics (Millar et al., 2017; Chen et al., 2018a), but progress is limited by lack of investment (Millar et al., 2017; Lee et al., 2020) or equipment (Aderinto and Li, 2018; Rusu and Onea, 2018). Wave-energy installations, possibly co-located with wind turbines(Perez-Collazo et al., 2018), are promising for both low- to middle-income nations and areas with significant island or remote coastal geographies (Lavidas and Venugopal, 2016; Bergillos et al., 2018; Jakimavičius et al., 2018; Kompor et al., 2018; Penalba et al., 2018; Saprykina and Kuznetsov, 2018; Lavidas, 2019). Wave-energy capture may also diminish storm-induced coastal erosion (Abanades et al., 2018; Bergillos et al., 2018). Tidal energy is a relatively new technology (Haslett et al., 2018; Liu et al., 2018; Neill et al., 2018) with limiting siting requirements (Mofor et al., 2013). Ocean renewable energy expansion faces other technological obstacles including lack of implementable or scalable energy-capture devices, access to offshore sites, competing coastal uses, potential environmental impacts, and lack of power-grid infrastructure at the coast (Aderinto and Li, 2018; Neill et al., 2018).

3.6.4 Contribution to the Sustainable Development Goals and Other Relevant Policy Frameworks

The impacts of climate change on ocean and coastal ecosystems and their services threaten achievement of the UN SDGs by 2030 (*high confidence*), particularly ocean targets (Table 3.31, Nilsson et al., 2016; Pecl et al., 2017; IPCC, 2018; Singh et al., 2019a; Claudet et al., 2020a). Nevertheless, local to international decision-making bodies have assigned the lowest priority to SDG14, Life Below Water (Nash et al., 2020).

Table 3.31: Sustainable Development Goals, grouped into broader categories as discussed in this section (http://sdgs.un.org/goals).

Category	Goal
Society	SDG1: No Poverty
	SDG2: Zero Hunger
	SDG3: Good Health & Well-Being
	SDG4: Quality Education
	SDG5: Gender Equality

Economy	SDG6: Clean Water & Sanitation SDG7: Affordable & Clean Energy SDG8: Decent Work & Economic Growth SDG9: Industry, Innovation & Infrastructure SDG10: Reduced Inequality
Environment	SDG11: Sustainable Cities & Communities SDG12: Responsible Consumption & Production SDG13: Climate Action SDG14: Life Below Water SDG15: Life on Land
Governance	SDG16: Peace and Justice Strong Institutions SDG17: Partnerships to achieve the Goals

3.6.4.1 Climate Mitigation Effects on Ocean-Related SDGs

SROCC underscored the need for ambitious mitigation to control climate hazards in the ocean to achieve SDGs (*medium evidence, high agreement*) (Bindoff et al., 2019; Oppenheimer et al., 2019). Delays in achieving ocean-dependent SDGs observed in SROCC and SR15 can be addressed with ambitious planned adaptation and mitigation action (*high agreement*) (Hoegh-Guldberg et al., 2019b). Since the ocean can contribute substantially to the attainment of mitigation targets aiming to limit warming to 1.5ºC above pre-industrial (Hoegh-Guldberg et al., 2019b), and to adaptation solutions facilitating attainment of social and economic SDGs, climate policy is treating the ocean less as a victim of climate change and more as a central participant in solving the global climate challenge (Cooley et al., 2019; Hoegh-Guldberg et al., 2019a; Dundas et al., 2020).

Relationships between Climate Action (SDG13) targets and SDG14 targets are mostly synergistic (Figure 3.26, Fuso Nerini et al., 2019). Responding to climate-change impacts requires transformative governance (*high confidence*) (Chapters 1 and 18, Collins et al., 2019a; Brodie Rudolph et al., 2020; Claudet et al., 2020a), especially for extreme events and higher-impact scenarios (e.g., higher emissions) (Fedele et al., 2019), and for achieving SDGs through one of the global ecosystems transitions (Chapter 18, Sachs et al., 2019; Brodie Rudolph et al., 2020). Opportunities to transform ocean governance exist in developing new international and local agreements, regulations and policies that reduce the risks of relocating ocean and coastal activities (Section 3.6.3.1.1) or in reinventing established practices (Section 3.6.3.3.3). Policy transformations improving ocean sustainability under SDG14 also help address SDG13 (Brodie Rudolph et al., 2020; Dundas et al., 2020; Claudet, 2021; Sumaila et al., 2021). Emergent situations such as the COVID-19 pandemic may provide opportunities to implement transformative "green recovery plans" that support achievement of the SDGs and NDCs (Cross-Chapter Box COVID in Chapter 7).

3.6.4.2 Contribution of Ocean Adaptation to SDGs

Marine-focused adaptations show promise in helping achieve social SDGs, especially when they are designed to achieve multiple benefits (*medium confidence*) (Figure 3.26, Ntona and Morgera, 2018; Claudet et al., 2020a). Technology- and infrastructure-focused adaptations (Section 3.6.2.2) can help relieve coastal communities from risks associated with poverty (SDG1), hunger (SDG2), health and water sanitation (SDG3 and SDG6), and inequality (SDG10) by supporting aquaculture (Sections 3.5.3, 3.6.3.1), alerting the public about poor water quality (Sections 3.5.5.3, 3.6.3.1), and empowering marginalised groups, such as women and Indigenous Peoples, with decision-relevant information (*medium evidence, high agreement*) (Sections 3.5.5.3, 3.6.3.1). Effectively implemented and managed marine NbS (Section 3.6.2.3) contribute to attainment of social SDGs by preserving biodiversity (Carlton and Fowler, 2018; Warner, 2018; Scheffers and Pecl, 2019), which benefits most ocean and coastal ecosystem services (Section 3.5.3, Figure 3.22), by increasing marine fishery and aquaculture sustainability (Section 3.6.3), by including vulnerable people and communities in management (Section 3.6.3.2.1), by lowering risk of flooding from storms and SLR (Cross-Chapter Box SLR in Chapter 3, Sections 3.6.3.1.1), and by implementing spatial management tools that make room for new uses like renewable energy development (Section 3.6.3.3.4). NbS can therefore help support achievement of No Poverty (SDG1) (Ntona and Morgera, 2018), Zero Hunger (SDG2), Good Health and Well-Being (SDG3) (Duarte et al., 2020), Affordable and Clean Energy (SDG7) (Fuso Nerini et al., 2019; Levin et al., 2020), and Reduced Inequality (SDG10). Socio-institutional marine adaptations (Section

3.6.2.2) that support current livelihoods and help develop alternatives can contribute to attainment of social SDGs by enhancing social equity and supporting societal transformation (*medium confidence*) (Cisneros-Montemayor et al., 2019; Pelling and Garschagen, 2019; Nash et al., 2021). Even societal changes that are not directly marine-related can decrease human vulnerability to ocean and coastal climate risks by improving overall human adaptive capacity (Section 1.2).

Marine adaptation also shows promise for helping support achievement of economic SDGs (*medium confidence*) (Figure 3.26). Marine NbS could help blue economy frameworks achieve Decent Work and Economic Growth (SDG8) (Lee et al., 2020), by sustainably and equitably incorporating ecosystem-based fisheries management, restoration or conservation (Sections 3.6.3.1.2, 3.6.3.2.1 and 3.6.3.2.2) (Voyer et al., 2018; Cisneros-Montemayor et al., 2019; Cohen et al., 2019; Okafor-Yarwood et al., 2020). NbS that involve active restoration or accommodation can contribute to Sustainable Cities and Communities (SDG11) and Infrastructure (SDG9) (Section 3.6.3.1.1). Newly developed marine industries and livelihoods associated with NbS might support attainment of Sustainable Communities (SDG11) (Cisneros-Montemayor et al., 2019). Finance and market mechanisms to support disaster relief or ocean ecosystem services, such as blue carbon or food provisioning, and innovations (SDG9) including new technologies like vessel-monitoring systems (Kroodsma et al., 2018), can contribute to Responsible Consumption and Production (SDG12) (Sumaila and Tai, 2020). Blue economy growth that includes sustainable shipping, tourism, renewable ocean energy, and transboundary fisheries management (Pinsky et al., 2018) have the potential to contribute to Economic Development (SDG8), affordable and clean energy (SDG7) (as well as global mitigation efforts, SDG13, (Hoegh-Guldberg et al., 2019b; Duarte et al., 2020)). Participatory approaches and co-management systems (Section 3.6.2.1) in many maritime sectors can contribute to SDG11 and SDG12 while helping align the blue economy and the SDGs (*high agreement*) (Lee et al., 2020; Okafor-Yarwood et al., 2020).

Developing marine adaptation pathways that offer multiple benefits requires transformational adaptation (*high confidence*) (Claudet et al., 2020a; Friedman et al., 2020; Wilson et al., 2020b; Nash et al., 2021) that avoids risky and maladaptive actions (Magnan and Duvat, 2018; Ojea et al., 2020). Ocean and coastal extreme events and other hazards disproportionately harm the most vulnerable communities in SIDS, tropical and Arctic regions, and Indigenous Peoples (Chapter 8.2.1.2). Presently implemented adaptation activity, at the aggregate level, adversely affects multiple gender targets under SDG5 (*high confidence*) (Cross-Chapter Box GENDER in Chapter 18). Although women make up over half of the global seafood production workforce (fishing and processing sectors), provide more than half the artisanal landings in Pacific region (Harper et al., 2013), dominate some seafood sectors such as seaweed (Howard and Pecl, 2019) and shellfish harvesting (Turner et al., 2020a), and account for 11% of global artisanal fisheries participants (Harper et al., 2020b), they are often not specifically counted in datasets and excluded from decision-making and support programs (Cross-Chapter Box GENDER in Chapter 18, Harper et al., 2020b; Michalena et al., 2020). Targeted efforts to incorporate knowledge diversity, and include artisanal fishers, women and Indigenous Peoples within international, regional, and local policy planning promote marine adaptation that supports achievement of gender equality (SDG5) and reduces inequalities (SDG10) (*limited evidence, high agreement*) (FAO, 2015). Integrated planning, financing, and implementation can help overcome these limitations (Section 3.6.3.3.2, Cross-Chapter Box FINANCE in Chapter 17), ensuring that marine adaptations do not compromise overall human equity or specific SDGs (Österblom et al., 2020; Nash et al., 2021), but are in fact fully synergistic with these goals (Bennett et al., 2021).

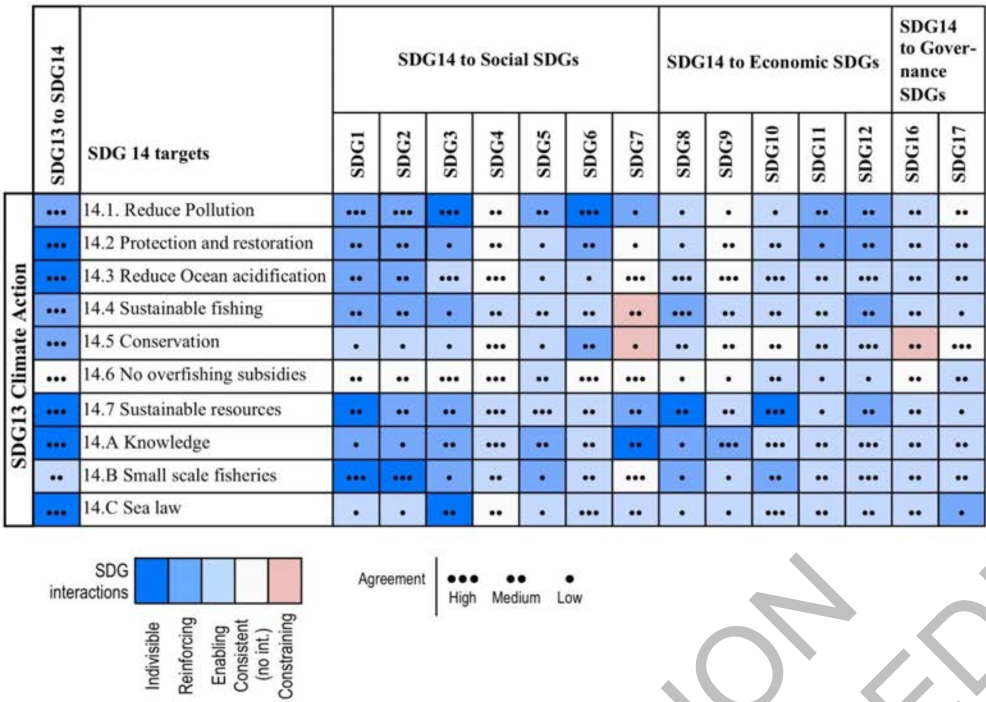


Figure 3.26: Synergies and trade-offs between SDG13 Climate Action, SDG14 Life Below Water and social, economic and governance SDGs. Achieving SDG13 provides positive outcomes and supports the achievement of all SDG14 targets. In turn, meeting SDG14 drives mostly positive interactions with social, economic and governance SDGs. The interaction types, 'Indivisible' (inextricably linked to the achievement of another goal), 'Reinforcing' (aids the achievement of another goal), 'Enabling' (creates conditions that further another goal), 'Consistent' (no significant positive or negative interactions), 'Constraining' (limits options on another goal), follows Nilsson et al. (2016)'s scoring system based on authors' assessment, and agreement denotes consistency across author ratings. Full data available in Table SM3.7.

3.6.4.3 Relevant Policy Frameworks for Ocean Adaptation

The intricacy, scope, timescales, and uncertainties associated with climate change challenge ocean governance, which already is extremely complex because it encompasses a variety of overlapping spatial scales, concerns, and governance structures (Figure CB3.1 in SROCC Chapter 1, Prakash et al., 2019). Assessment of how established global agreements and regional, sectoral, or scientific bodies address climate adaptation and resilience, and how current practices can be improved, is found in SM3.5.3.

There is growing momentum to include the ocean in international climate policy (*robust evidence*), paving the way for a more integrated approach to both mitigation and adaptation. Following adoption of the Paris Agreement in 2015, the UN SDGs (Table 3.31) came into force in 2016, including SDG14 specifically dedicated to life below water (Table 3.31). In 2017, the first UN Ocean Conference was held (United Nations, 2017), the UNFCCC adopted the Ocean Pathway to increase ocean-targeted multilateral climate action (COP23, 2017), and the UN Assembly declared 2021–2030 the Decade for Ocean Science for Sustainable Development (Visbeck, 2018; Lee et al., 2020). Next, 14 world leaders formed the High-Level Panel for a Sustainable Ocean Economy to produce the New Ocean Action Agenda, founded on 100% sustainable management of national ocean spaces by 2025 (Ocean Panel, 2020). All of these initiatives position oceans centrally within the climate-policy and biodiversity-conservation landscapes and seek to develop a coherent effort and common frameworks to achieve marine sustainability (Visbeck, 2018; Lee et al., 2020), new economic opportunities (Konar and Ding, 2020; Lee et al., 2020), more equitable outcomes (Österblom et al., 2020), and decisive climate mitigation and adaptation (Hoegh-Guldberg et al., 2019a), to achieve truly transformative change (Claudet et al., 2020a).

There is *high confidence* in the literature that multilateral environmental agreements need better alignment and integration to support achievement of ambitious international development, climate mitigation, and adaptation goals (Swilling et al., 202; Duarte et al., 2020; Friedman et al., 2020; Conservation International and IUCN, 2021; Pörtner et al., 2021b; Sumaila et al., 2021). The ocean targets of the CBD (e.g., the Post-2020 Global Biodiversity Framework), the SDGs (Agenda 2030) and the Paris Agreement are already inclusive and synergistic (Duarte et al., 2020). However, specific policy instruments and sectors within them could be additionally integrated, especially to address such cross-cutting impacts as ocean acidification and deoxygenation (Gallo et al., 2017; Bindoff et al., 2019), increasing plastic pollution (Ostle et al., 2019; Duarte et al., 2020), high-seas governance (Johnson et al., 2019; Leary, 2019), or deep sea uses (Wright et al., 2019; Levin et al., 2020; Orejas et al., 2020). National adaptation plans present opportunities to synergistically build on mitigation to support equitable development (Morioka et al., 2020), economic planning (Dundas et al., 2020; Lee et al., 2020), and ocean stewardship (von Schuckmann et al., 2020). Alignment of multilateral agreements is expected to increase mitigation impact as well as increase adaptation options (Section 3.6.3, Figure 3.25, Roberts et al., 2020). Opportunities to improve multilateral environmental agreements and policies beyond UNFCCC and CBD processes are discussed in SM3.5.3, and an assessment of commercial species management initiatives and needs is in Chapter 5.

3.6.5 Emerging Best Practices for Ocean and Coastal Climate Adaptation

There is *robust evidence* that a combination of global and local solutions offers the greatest benefit in reducing climate risk (Gattuso et al., 2018; Hoegh-Guldberg et al., 2019a; Hoegh-Guldberg et al., 2019b). Ambitious and swift global mitigation offers more adaptation options and pathways to sustain ecosystems and their services (Figure 3.25). Some solutions target both mitigation and adaptation (e.g., blue carbon conservation, Cross-Chapter Box NATURAL in Chapter 2, Box 3.4), and cross-cutting solutions simultaneously support several ocean-related sectors (e.g., area-based measures support fishing, tourism; Section 3.6.3.2.1) or ecosystem functions (e.g., NbS support coastal protection, biodiversity, habitat, etc., Section 3.6.3.2.2, Sala et al., 2021). Combined solutions also leverage a variety of existing policies and governance systems (Section 3.6.4.3, Duarte et al., 2020) to advance climate mitigation and adaptation. Even communities that face the limits of adaptation, like those who must relocate to cope with rising seas (McMichael et al., 2019; Bronen et al., 2020), urgently require solutions that combine scientific projections, IK and LK, cultural and community values, and ways to preserve cultural identity to support planning and implementation of relocation (McMichael and Katonivualiku, 2020).

NbS are showing promising results in achieving adaptation and mitigation outcomes across marine and coastal ecosystems (Sections 3.6.3.2.1–3.6.3.2.2), but NbS have different degrees of readiness in marine ecosystems (Duarte et al., 2020). Habitat restoration and recovery are highly effective in specific settings and conditions (McLeod et al., 2019). Restoring and conserving vegetated coastal habitats (Sections 3.4.2.4–3.4.2.5) represent robust NbS, especially in the tropics, and particularly when paired with restoration and conservation of terrestrial ecosystems (*robust evidence*) (e.g., peatlands and forests, WGIII AR6 Chapter 7, Hoegh-Guldberg et al., 2019b; Duarte et al., 2020; Griscom et al., 2020). Although most of the focus on NbS efficacy has been on coastal and shelf ecosystems (Section 3.6.3.2), recent advances point to an emerging role of NbS beyond coastal waters in the form of area-based management tools in marine areas beyond national jurisdiction (Section 3.6.2.3, Gaines et al., 2018; Pinsky et al., 2018; Crespo et al., 2020; O'Leary et al., 2020; Visalli et al., 2020; Wagner et al., 2020), because sustainable fisheries and aquaculture and climate-responsive MPAs have high potential to adapt (Tittensor et al., 2019).

Adaptation efforts (Sections 3.6.3.1–3.6.3.2) have three common characteristics that facilitate implementation and success and contribute to climate-resilient development pathways (Chapter 18). First, availability of multiple types of information (e.g., monitoring, models, climate services, Section 3.6.3.3) exposes the magnitude and nature of the adaptation challenge. Well-developed observation and modelling capabilities (Reusch et al., 2018) offer insights on climate-associated risks at different timescales (Cvitanovic et al., 2018; Hobday et al., 2018), and this facilitates adaptation within multiple areas (e.g., industries over shorter timescales, societies over longer scales) (Hobday et al., 2018). Environmental data has supported building societal and political (socio-institutional) will to adopt national and subnational adaptive management principles (Hobday et al., 2016b; Champion et al., 2018; McDonald et al., 2019). However, incorporating IK and LK at the same time provides more diverse social-environmental insight (Section 3.6.3.4.1, Goeldner-Gianella et al., 2019; Petzold and Magnan, 2019; Wilson et al., 2020b). This can help align adaptation solutions with cultural values and increase their legitimacy with Indigenous and local communities (Chapter 1.3.2.3), achieving climate resilient development pathways (Chapter 18, Adger et al., 2017; Nalau et al., 2018; Peñaherrera-Palma et al., 2018; Raymond-Yakoubian and Daniel, 2018; Wamsler and Brink, 2018). Second, implementation of multiple low-risk options (Hoegh-Guldberg et al., 2019a; Gattuso et al., 2021) such as economic diversification (Section 3.6.2.1) can provide culturally acceptable livelihood alternatives and food supplies (e.g., fishing to ecotourism and mariculture, (Froehlich et al., 2019) while also providing environmental benefits (e.g., seaweed mariculture's potential carbon storage co-benefits (WGIII AR6 Chapter 7, Hoegh-Guldberg et al., 2019a; Gattuso et al., 2021). Third, inclusive governance that is well-aligned to the systems at risk from climate change is fundamental for effective adaptation (Barange et al., 2018). Solutions implemented within polycentric governance systems (Section 3.6.3, Bellanger et al., 2020) benefit from synergies between knowledge, action and socio-ecological contexts and stimulate governance responses at appropriate spatial and temporal scales (Cvitanovic and Hobday, 2018). Governance aligned with Indigenous structures and local structures supports successful outcomes that prioritise the concerns and rights of involved communities (Section 3.6.3, Mawyer and Jacka, 2018) and better leverages existing social organisation (i.e., network structures), learning processes and power dynamics (Barnes et al., 2020).

There is an opportunity to improve current practices when developing new ocean and coastal adaptation efforts so that they routinely contain these successful characteristics and resolve technical, economic, institutional, geophysical, ecological and social constraints (Figure 3.25, Section 3.6.3.3, IPCC, 2018; Singh et al., 2020). Enhancements are needed in human, technical and financial resources; regulatory frameworks (Ojwang et al., 2017); political support (Rosendo et al., 2018); institutional conditions and resources for fair governance (Gupta et al., 2016; Scobie, 2018); political leadership; stakeholder engagement; multidisciplinary data availability (Gopalakrishnan et al., 2018); funding and public support for adaptation (Cross-Chapter Box FINANCE in Chapter 17, Ford and King, 2015); and incorporating IK and LK in decision making (Nalau et al., 2018; Jabali et al., 2020; Petzold et al., 2020). As climate change continues to challenge ocean and coastal regions, there is *high confidence* associated with the benefits of developing robust, equitable adaptation strategies that incorporate scientific projections, employ portfolios of low-risk options, internalise IK and LK, and address social aspects of governance from international to local scales (Finkbeiner et al., 2018; Gattuso et al., 2018; Miller et al., 2018; Raymond-Yakoubian and Daniel, 2018; Cheung et al., 2019; Gattuso et al., 2021).

[START FAQ3.2 HERE]

FAQ3.2: Are we approaching so-called tipping points in the ocean and what can we do about it?

A tipping point is a threshold beyond which an abrupt or rapid change in a system occurs. Tipping points that have already been reached in ocean systems include the melting of sea ice in the Arctic, thermal bleaching of tropical coral reefs and the loss of kelp forests. Human-induced climate change will continue to force ecosystems into abrupt and often irreversible change, absent strong mitigation and adaptation action.

A gradual change in water temperature or oxygen concentration can lead to a fundamental shift in the structure and/or composition of an ecosystem when a tipping point is exceeded. For example, all species have upper temperature limits below which they can thrive. In the tropics, prolonged warm temperatures can cause fatal 'bleaching' of tropical corals, leading reef ecosystems to degrade and become dominated by algae. In temperate regions, marine heatwaves can kill or reduce the growth of kelp, threatening the other species that depend on the tall canopy-forming marine plants for habitat. In the Arctic, rising temperatures are melting sea ice, and reducing the available habitat for communities of ice-dependent species.

Once a tipping point is passed, the effects can be long-lasting and/or irreversible over timescales of decades or longer. An ecosystem or a population can remain in the new state, even if the driver of the change returns to previous levels. For example, once a coral reef has been affected by bleaching, it can take decades for corals to grow back, even if temperatures remain below the bleaching threshold. Crossing a tipping point can cause entire populations to collapse, causing local extinctions.

Tipping points are widespread across oceanic provinces and their ecosystems for climate variables like water temperature, oxygen concentration and acidification. Evidence suggests that ocean tipping points are being surpassed more frequently as the climate changes; scientists have estimated that abrupt shifts in communities of marine species occurred over 14% of the ocean in 2015, up from 0.25% of the ocean in the 1980s. Other human stresses to the ocean, including habitat destruction, overfishing, pollution and the spread of diseases, combine with climate change to push marine systems beyond tipping points. As an example, nutrient pollution from land together with climate change can lead to low-oxygen coastal areas referred to as "dead zones".

Human communities can also experience tipping points that alter people's relationships with marine ecosystem services. Indigenous Peoples and local communities may be forced to move from a particular location due to sea-level rise, erosion, or loss of marine resources. Current activities that help sustain Indigenous Peoples and their cultures may no longer be possible in the coming decades, and traditional diets or territories may have to be abandoned. These tipping points have implications for physical and mental health of marine-dependent human communities.

Adaptation solutions to the effects of ecological tipping points are rarely able to reverse their environmental impacts, and instead often require human communities to transform their livelihoods in different ways. Examples include diversifying income by shifting from fishing to tourism and relocating communities threatened by flooding to other areas to continue their livelihoods. Tipping points are being passed already in coral reefs and polar systems, and more will probably be reached in the near future, given climate-change projections. Nevertheless, the chances of moving beyond additional tipping points in the future will be minimised if we reduce greenhouse gas emissions, and we also act to limit other human impacts on the ocean, such as overfishing and nutrient pollution.

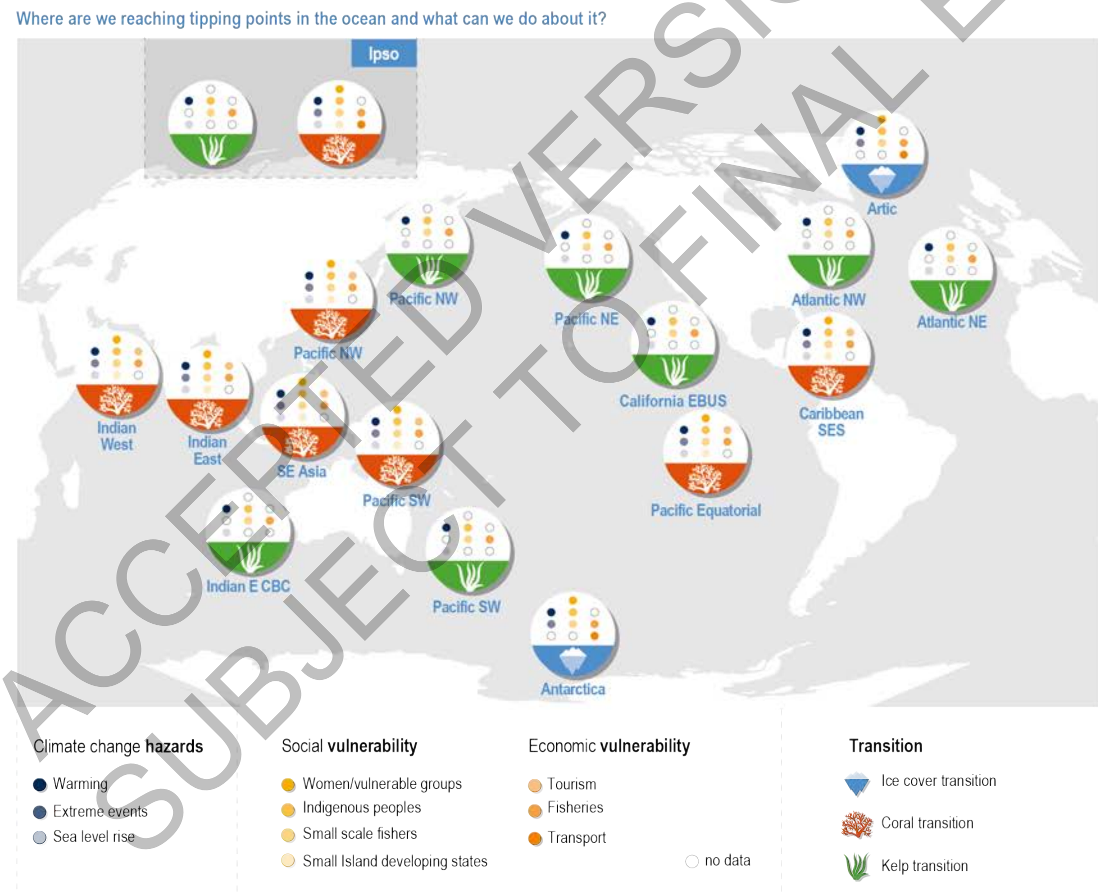


Figure FAQ3.2: Global map with examples of tipping points that have been passed in ocean systems around the world. Tipping points in ecological systems are linked to increasing impacts and vulnerability of dependent human communities. SES: semi-enclosed sea, EBUS: eastern boundary upwelling system, CBC; coastal boundary current.

[END FAQ3.2 HERE]

[START FAQ3.3 HERE]

FAQ3.3: How are marine heatwaves affecting marine life and human communities?

Heatwaves happen in the ocean as well as in the atmosphere. Marine heatwaves (MHWs) are extended periods of unusually warm ocean temperatures, relative to the typical temperatures for that location and time of year. Due to climate change, the number of days with MHWs have increased by 54% over the past century. MHWs cause mortalities in a wide variety of marine species, from corals to kelp to seagrasses to fish to seabirds, and have consequent effects on ecosystems and industries like aquaculture and fisheries.

Extreme events in the ocean can have damaging effects on marine ecosystems and the human communities that depend on them. The most common form of ocean extremes are marine heatwaves (MHWs), extended periods of unusually warm ocean temperatures, which are becoming more frequent and intense due to global warming. Because seawater absorbs and releases heat more slowly than air, temperature extremes in the ocean are not as pronounced as over land, but they can persist for much longer, often for weeks to months over areas covering hundreds of thousands of square kilometres. These MHWs can be more detrimental for marine species, in comparison to land species, because marine species are usually adapted to relatively stable temperatures.

A commonly used definition of MHWs is a period of at least five days whose temperatures are warmer than 90% of the historical records for that location and time of year. MHWs are described by their abruptness, magnitude, duration, intensity, and other metrics. In addition, targeted methods are used to characterize MHWs that threaten particular ecosystems; for example, the accumulated heat stress above typical summer temperatures, described by “degree heating weeks”, is used to estimate the likelihood of coral bleaching.

Over the past century, MHWs have doubled in frequency, become more intense, lasted for longer and extended over larger areas. MHWs have occurred in every ocean region over the past few decades, most markedly in association with regional climate phenomena such as the El Niño/Southern Oscillation. During the 2015–2016 El Niño event, 70% of the world’s ocean surface encountered MHWs.

MHWs cause mortality of a wide variety of marine species, from corals to kelp to seagrasses to fish to seabirds, and they have consequent effects on ecosystems and industries such as mariculture and fisheries. Warm-water coral reefs, estuarine seagrass meadows and cold-temperate kelp forests are among the ecosystems most threatened by MHWs since they are attached to the seafloor (FAQ 3.2). Unusually warm temperatures cause bleaching and associated death of warm-water corals, which can lead to shifts to low-diversity or algae-dominated reefs, changes in fish communities, and deterioration of the physical reef structure, which causes habitat loss and increases the vulnerability of nearby shorelines to large-wave events and sea-level rise. Since the early 1980s, the frequency and severity of mass coral bleaching events have increased sharply worldwide. For example, from 2016 through 2020, the Great Barrier Reef experienced mass coral bleaching three times in five years.

Mass loss of kelp from MHWs effects on the canopy-forming species has occurred across ocean basins, including the coasts of Japan, Canada, Mexico, Australia and New Zealand. In southern Norway and the northeast U.S., mortality from MHWs contributed to the decline of sugar kelp over the last two decades, and to the spread of turf algal ecosystems that prevent recolonisation by the original canopy-forming species.

One of the largest and longest-duration MHWs, nicknamed the 'Blob,' occurred in the Northeast Pacific Ocean, extending from California north towards the Bering Sea, from 2013 through 2015. Warming from the MHW persisted into 2016 off the U.S. West Coast and into 2018 in the deeper waters of a Canadian fjord. The consequent effects of this expansive MHW included widespread shifts in abundance, distribution and nutritional value of invertebrates and fish, a bloom of toxic algae off the US west coast that impacted fisheries, the decline of California kelp forests that contributed to the collapse of the abalone fishery, and mass mortality of seabirds.

The projected increase in the frequency, severity, duration, and areal extent of MHWs threaten many marine species and ecosystems. MHWs may exceed the thermal limits of species, and they may occur too frequently for the species to acclimate or for populations to recover. The majority of the world’s coral reefs are projected to decline and begin eroding due to more frequent bleaching-level MHWs if the world warms by more than 1.5°C. Recent research suggests possible shifts to more heat-tolerant coral communities, but at the expense of species and habitat diversity. Other systems, including kelp forests, are most threatened near the edges of their ranges, although more research is needed into the effect of re-occurring MHWs on kelp forests and other vulnerable systems.

The projected ecological impacts of MHWs threaten local communities' and Indigenous Peoples' cultures, incomes, fisheries, tourism, and, in the case of coral reefs, shoreline protection from waves. High-resolution forecasts and early-warning systems, currently most advanced for coral reefs, can help people and industries prepare for MHWs and also collect data on their effects. Identifying and protecting locations and habitats with reduced exposure to MHWs is a key scientific endeavour. For example, corals may be protected from MHWs in tidally-stirred waters or in reefs where cooler water upwells from subsurface. Marine protected areas and no-take zones, in addition to terrestrial protection surrounding vulnerable coastal ecosystems, cannot prevent MHWs from occurring. But, depending on the location and adherence by people to restrictions on certain activities, the cumulative effect of other stressors on vulnerable ecosystems can be reduced, potentially helping to enhance the rate of recovery of marine life.

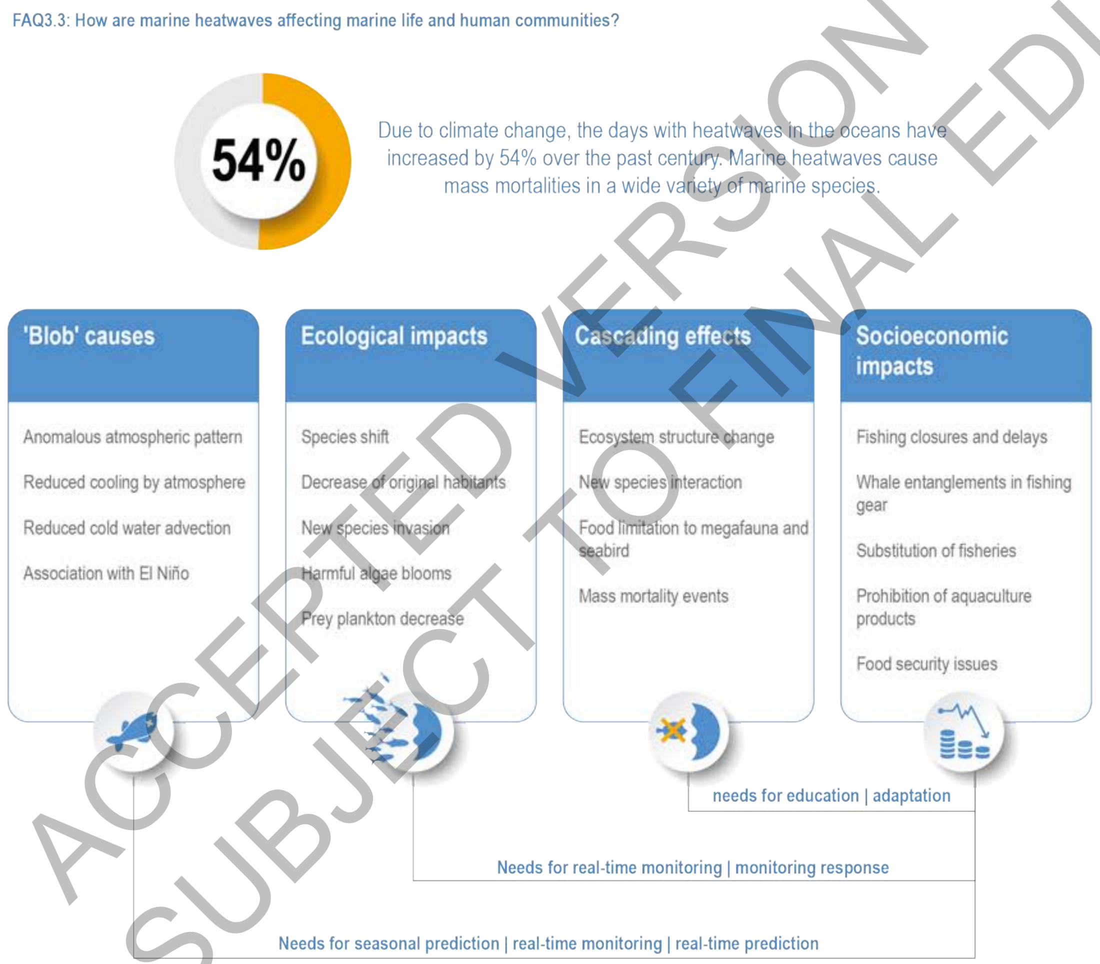


Figure FAQ 3.3: Impact pathway of a massive extreme marine heatwave, the NW Pacific "Blob," from causal mechanisms, to initial effects, resulting non-linear effects, and the consequent impacts for humans. Lessons learnt from the "Blob" include the need to advance seasonal forecasts, real-time predictions, monitoring responses, education, possible fisheries impacts and adaptation.

[END FAQ3.3 HERE]

[START FAQ3.4 HERE]

FAQ3.4: Which industries and jobs are most vulnerable to the impacts of climate change in the oceans?

The global ocean underpins human well-being through the provision of resources that directly and indirectly feed and employ many millions of people. In many regions, climate change is degrading ocean health and altering stocks of marine resources. Together with over-harvesting, climate change is threatening the future of the sustenance provided to Indigenous Peoples, the livelihoods of artisanal fisheries, and marine-based industries including tourism, shipping and transportation.

The ocean is the lifeblood of the planet. In addition to regulating planetary cycles of carbon, water and heat, the ocean and its vast resources support human livelihoods, cultural practices, jobs and industries. The impacts of climate change on the ocean can influence human activities and employment by altering resource availability, spreading pathogens, flooding shorelines and degrading ocean ecosystems. Fishing and mariculture are highly exposed to change. The global ocean and inland waters together provide more than 3.3 billion people at least 20% of the protein they eat and provide livelihoods for 60 million people. Changes in the nutritional quality or abundance of food from the oceans could influence billions of people.

Substantial economic losses for fisheries resulting from recent climate-driven harmful algal blooms and marine pathogen outbreaks have been recorded in Asia, North America and South America. A 2016 event in Chile caused an estimated loss of 800 million USD in the farmed salmon industry and led to regional government protests. The recent closure of the U.S. Dungeness crab and razor clam fishery due to a climate-driven algal bloom harmed 84% of surveyed residents from 16 California coastal communities. Fishers and service industries that support commercial and recreational fishing experienced the most substantial economic losses, and fishers were the least able to recover their losses. This same event also disrupted subsistence and recreational fishing for razor clams, important activities for Indigenous Peoples and local communities in the Pacific Northwest of the U.S.A.

Other goods from the ocean, including non-food products like dietary supplements, food preservatives, pharmaceuticals, biofuels, sponges and cosmetic products, as well as luxury products like jewellery coral, cultured pearls, and aquarium species, will change in abundance or quality due to climate change. For instance, ocean warming is endangering the "candlefish" ooligan (*Thaleichthys pacificus*), whose oil is a traditional food source and medicine of Indigenous Peoples of the Pacific Northwest of North America. Declines in tourism and real estate values have also been recorded in the United States, France, and England associated with climate-driven harmful algal blooms.

Small-scale fisheries livelihoods and jobs are the most vulnerable to climate-driven changes in marine resources and ecosystem services. The abundance and composition of their harvest depend on suitable environmental conditions and on Indigenous knowledge and local knowledge developed over generations. Large-scale fisheries, though still vulnerable, are more able to adapt to climate change due to greater mobility and greater resources for changing technologies. These fisheries are already adapting by broadening catch diversity, increasing their mobility to follow shifting species, and changing gear, technology and strategies. Adaptation in large-scale fisheries, however, is at times constrained by regulations and governance challenges.

Jobs, industries and livelihoods which depend on particular species or are tied to the coast can also be at risk to climate change. Species-dependent livelihoods (e.g., a lobster fishery or oyster farm) are vulnerable due to a lack of substitutes if the fished species are declining, biodiversity is reduced, or mariculture is threatened by climate change or ocean acidification. Coastal activities and industries ranging from fishing (e.g., gleaning on a tidal flat) to tourism to shipping and transportation are also vulnerable to sea-level rise and other climate-change impacts on the coastal environment. The ability of coastal systems to protect the shoreline will decline due to sea-level rise and simultaneous degradation of nearshore systems including coral reefs, kelp forests and coastal wetlands.

The vulnerability of communities to losses in marine ecosystem services varies within and among communities. Tourists seeking to replace lost cultural services can adapt by engaging in the activity elsewhere. But communities who depend on tourism for income or who have strong cultural identity linked to the ocean have a more difficult time. Furthermore, climate-change impacts exacerbate existing inequalities already experienced by some communities, including Indigenous Peoples, Pacific Island countries and territories, and marginalized peoples, like migrants and women in fisheries and mariculture. These inequities increase the risk to their fundamental human rights by disrupting livelihoods and food security, while leading to loss of social, economic, and cultural rights. These maladaptive outcomes can be avoided by securing tenure and access rights to resources and territories for all people depending on the ocean, and by supporting decision-making processes that are just, participatory and equitable.

A key adaptation solution is improving access to credit and insurance in order to buffer against variability in resource access and abundance. Further actions that decrease social and institutional vulnerability are also important, such as inclusive decision-making processes, access to resources and land to Indigenous Peoples, and participatory approaches in management. For the fishing industry, international fisheries agreements and investing in sustainable mariculture and fisheries reforms is often recommended. Immediate adaptations to other challenges, such as harmful algal blooms, frequently include fishing-area closures. These can be informed by early-warning forecasts, public communications, and education. These types of adaptations are more effective when built on trusted relationships and effective coordination among involved parties, and are inclusive of the diversity of actors in a coastal community.

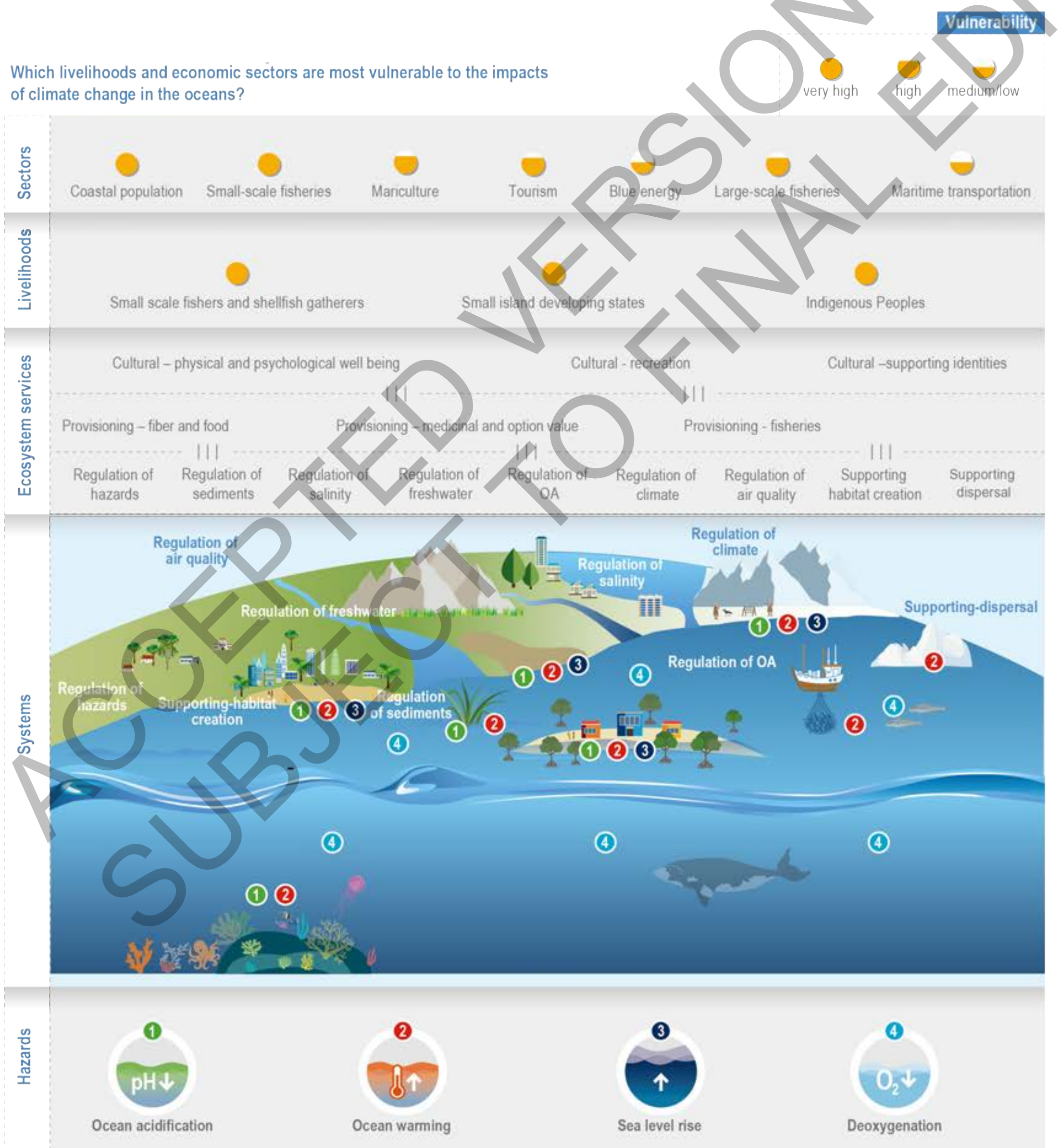


Figure FAQ3.4: Illustration that identifies vulnerable groups and stresses the hazards or impacts over coastal and ocean systems.

[END FAQ3.4 HERE]

[START FAQ3.5 HERE]

FAQ3.5: How can nature-based solutions, including marine protected areas, help us to adapt to climate driven changes in the oceans?

Coastal habitats like mangroves or vegetated dunes protect coastal communities from sea-level rise and storm surges, while supporting fisheries, sequestering carbon and providing other ecosystem services as well. Efforts to restore, conserve and/or recover these natural habitats help people confront the impacts of climate change. These marine nature-based solutions like marine protected areas, habitat restoration and sustainable fisheries are cost-effective and provide myriad benefits to society.

In the oceans, nature-based solutions comprise attempts to recover, restore or conserve coastal and marine habitats to reduce the impacts of climate change on nature and society. Marine habitats such as seagrasses and coral reefs provide services like food and flood regulation, in the same way as forests do so on land. Coastal habitats like mangroves or vegetated dunes protect coastal communities from sea-level rise and storm surges, while supporting fisheries, recreational and aesthetic services as well. Seagrasses, coral reefs and kelp forests also provide important benefits that help humans adapt to climate change, including sustainable fishing, recreation and shoreline protection services. By recognizing these services and benefits of the ocean, nature-based solutions can improve the quality and integrity of the marine ecosystems.

Nature-based solutions offer a wide range of potential benefits, including protecting ecosystem services, supporting biodiversity and mitigating climate change. Coastal and marine examples include marine protected areas, habitat restoration, habitat development and maintaining sustainable fisheries. While local communities with limited resources might find nature-based solutions challenging to implement, they are generally “no-regret” options, which bring societal and ecological benefits regardless of the level of climate change.

Carefully designed and placed marine protected areas, especially when they exclude fishing, can increase resilience to climate change by removing additional stressors on ecosystems. While marine protected areas do not prevent extreme events like marine heatwaves (FAQ3.3), they can provide marine plants and animals with a better chance to adapt to a changing climate. Current marine protected areas, however, are often too small, too poorly connected and too static to account for climate-induced shifts in the range of marine species. Marine protected area networks that are large, are connected, have adaptable boundaries, and are designed following systematic analysis of future climate projections can better support climate resilience.

Habitat restoration and development in coastal systems can support biodiversity, protect communities from flooding and erosion, support the local economy, and enhance the livelihoods and wellbeing of coastal peoples. Restoration of mangroves, saltmarshes and seagrass meadows provide effective ways to remove carbon dioxide from the atmosphere and at the same time to protect coasts from the impacts of storms and sea-level rise. Active restoration techniques that target heat-resistant individuals or species are increasingly recommended for coral reefs and kelp forests, which are highly vulnerable to marine heatwaves and climate change.

Sustainable fishing is also seen as a nature-based solution because managing marine commercial species within sustainable limits maximizes the catch and food production, thus contributing to the UN’s Sustainable Development Goal 2 – Zero Hunger. Currently, the oceans provide 17% of the animal protein eaten by the global population, but the contribution could be larger if fisheries were managed sustainably. Aquaculture, such as oyster farming, can be efficient and sustainable means of food production and also provide additional benefits like shoreline protection. Through nature-based solutions that conserve and restore marine habitats and species, we can sustain marine biodiversity, respond to climate change, and provide benefits to society.

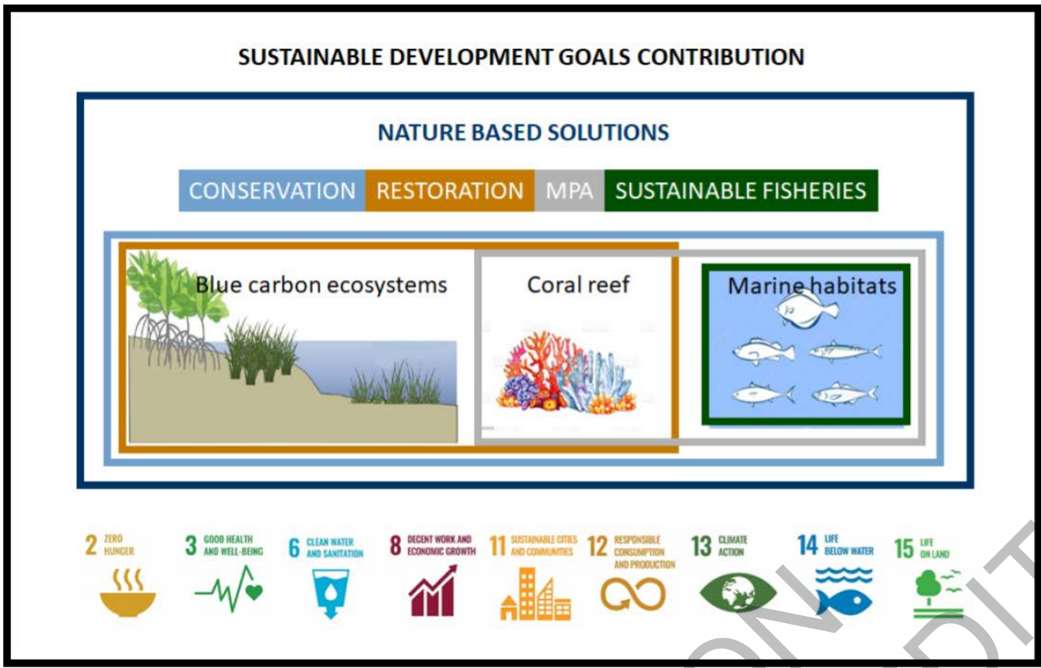


Figure FAQ3.5: Contributions of nature-based solutions in the oceans to the Sustainable Development Goals. The icons in the bottom show the Sustainable Development Goals to which nature-based solutions in the ocean possibly contribute. [Placeholder figure -- authoritative version on FMS]

[END FAQ3.5 HERE]

Acknowledgements

We acknowledge the kind contributions of Rita Erven (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany), Miriam Seifert (Alfred Wegener Institute for Polar and Marine Research, Germany), Sebastian Rokitta (Alfred Wegener Institute for Polar and Marine Research, Germany), Amy Marie Campbell (National Oceanography Centre, Southampton/Centre for Environment, Fisheries and Aquaculture Science, United Kingdom), Mariana Castaneda-Guzman (Virginia Polytechnic Institute and State University, USA), Stephen Goult (Plymouth Marine Laboratory/National Centre for Earth Observation, United Kingdom), Josh Douglas (Plymouth Marine Laboratory, United Kingdom), Carl Reddin (Museum für Naturkunde, Berlin, Germany) and the PML Communications and Graphics Team (Plymouth Marine Laboratory, United Kingdom) who assisted in drafting figures and tables.

References

A. Maureaud, A. et al., 2021: Are we ready to track climate-driven shifts in marine species across international boundaries? - A global survey of scientific bottom trawl data. *Global Change Biology*, **27**(2), 220-236, doi:10.1111/gcb.15404.

Aalto, E. A. et al., 2019: Catastrophic Mortality, Allee Effects, and Marine Protected Areas. *The American naturalist*, **193**(3), 391-408, doi:10.1086/701781.

Aarflot, J. M., H. R. Skjoldal, P. Dalpadado and M. Skern-Mauritzen, 2018: Contribution of *Calanus* species to the mesozooplankton biomass in the Barents Sea. *ICES Journal of Marine Science*, **75**(7), 2342-2354, doi:10.1093/icesjms/fsx221.

Abanades, J., G. Flor-Blanco, G. Flor and G. Iglesias, 2018: Dual wave farms for energy production and coastal protection. *Ocean & Coastal Management*, **160**, 18-29, doi:10.1016/j.ocecoaman.2018.03.038.

Abella Perez, E., A. Marco, S. Martins and L. A. Hawkes, 2016: Is this what a climate change-resilient population of marine turtles looks like? *Biological Conservation*, **193**, 124-132, doi:10.1016/j.biocon.2015.11.023.

Abelson, A. et al., 2015: Upgrading marine ecosystem restoration using ecological-social concepts. *BioScience*, **66**(2), 156-163, doi:10.1093/biosci/biv171.

Ablain, M. et al., 2019: Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration. *Earth System Science Data*, **11**(3), 1189-1202, doi:10.5194/essd-11-1189-2019.

Abrahams, A., R. W. Schlegel and A. J. Smit, 2021: Variation and Change of Upwelling Dynamics Detected in the World's Eastern Boundary Upwelling Systems. *Frontiers in Marine Science*, **8**(29), doi:10.3389/fmars.2021.626411.

Abram, N. J. et al., 2019: Framing and Context of the Report. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. In press.

Aderinto, T. and H. Li, 2018: Ocean wave energy converters: status and challenges. *Energies*, **11**(5), 1250, doi:10.3390/en11051250.

Adger, W. N., C. Butler and K. Walker-Springett, 2017: Moral reasoning in adaptation to climate change. *Environmental Politics*, **26**(3), 371-390, doi:10.1080/09644016.2017.1287624.

Agostini, S. et al., 2018: Ocean acidification drives community shifts towards simplified non-calcified habitats in a subtropical−temperate transition zone. *Scientific Reports*, **8**(1), 11354, doi:10.1038/s41598-018-29251-7.

Aguirre, C., M. Rojas, R. D. Garreaud and D. A. Rahn, 2019: Role of synoptic activity on projected changes in upwelling-favourable winds at the ocean's eastern boundaries. *npj Climate and Atmospheric Science*, **2**(1), 44, doi:10.1038/s41612-019-0101-9.

Aguzzi, J. et al., 2019: New High-Tech Flexible Networks for the Monitoring of Deep-Sea Ecosystems. *Environmental Science & Technology*, **53**(12), 6616-6631, doi:10.1021/acs.est.9b00409.

Ajani, P. A., C. H. Davies, R. S. Eriksen and A. J. Richardson, 2020: Global Warming Impacts Micro-Phytoplankton at a Long-Term Pacific Ocean Coastal Station. *Frontiers in Marine Science*, **7**(878), doi:10.3389/fmars.2020.576011.

Al-Haj, A. N. and R. W. Fulweiler, 2020: A synthesis of methane emissions from shallow vegetated coastal ecosystems. *Global Change Biology*, **26**(5), 2988-3005, doi:10.1111/gcb.15046.

Al-Said, T. et al., 2018: High total organic carbon in surface waters of the northern Arabian Gulf: implications for the oxygen minimum zone of the Arabian Sea. *Marine Pollution Bulletin*, **129**(1), 35-42, doi:10.1016/j.marpolbul.2018.02.013.

Alabia, I. D. et al., 2021: Marine biodiversity refugia in a climate-sensitive subarctic shelf. *Global Change Biology*, **27**(14), 3299-3311, doi:10.1111/gcb.15632.

Alabia, I. D. et al., 2020: Multiple facets of marine biodiversity in the Pacific Arctic under future climate. *Science of The Total Environment*, **744**, 140913, doi:10.1016/j.scitotenv.2020.140913.

Alamsjah, M. A., A. A. Abdillah, H. Mustikawati and S. D. P. Atari (eds.), Screening of biodiesel production from waste tuna oil (Thunnus sp.), seaweed Kappaphycus alvarezii and Gracilaria sp. AIP Conference Proceedings, 2017.

Albano, P. G. et al., 2021: Native biodiversity collapse in the eastern Mediterranean. *Proceedings of the Royal Society B: Biological Sciences*, **288**(1942), 20202469, doi:10.1098/rspb.2020.2469.

Albouy, C. et al., 2020: Global vulnerability of marine mammals to global warming. *Scientific Reports*, **10**(1), 548, doi:10.1038/s41598-019-57280-3.

Albouy, C. et al., 2013: Projected climate change and the changing biogeography of coastal Mediterranean fishes. *Journal of Biogeography*, **40**(3), 534-547, doi:10.1111/jbi.12013.

Alheit, J. et al., 2019: What happened in the mid-1990s? The coupled ocean-atmosphere processes behind climate-induced ecosystem changes in the Northeast Atlantic and the Mediterranean. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **159**, 130-142, doi:10.1016/j.dsr2.2018.11.011.

Allen, M. D., 2020: Climate change in Alaska: Social workers' attitudes, beliefs, and experiences. *International Journal of Social Welfare*, **29**(4), 310-320, doi:10.1111/ijsw.12443.

Alleway, H. K. et al., 2018: The ecosystem services of marine aquaculture: valuing benefits to people and nature. *BioScience*, **69**(1), 59-68, doi:10.1093/biosci/biy137.

Allyn, A. J. et al., 2020: Comparing and synthesizing quantitative distribution models and qualitative vulnerability assessments to project marine species distributions under climate change. *PLOS ONE*, **15**(4), e0231595, doi:10.1371/journal.pone.0231595.
Almpanidou, V., E. Katragkou and A. D. Mazaris, 2018: The efficiency of phenological shifts as an adaptive response against climate change: a case study of loggerhead sea turtles (*Caretta caretta*) in the Mediterranean. *Mitigation and Adaptation Strategies for Global Change*, **23**(7), 1143-1158, doi:10.1007/s11027-017-9777-5.
Almpanidou, V., V. Markantonatou and A. D. Mazaris, 2019: Thermal heterogeneity along the migration corridors of sea turtles: Implications for climate change ecology. *Journal of Experimental Marine Biology and Ecology*, **520**, 151223, doi:10.1016/j.jembe.2019.151223.
Alongi, D. M., 2018a: The Blue Economy: Mitigation and Adaptation. In: *Blue Carbon: Coastal Sequestration for Climate Change Mitigation* [Alongi, D. M. (ed.)]. Springer International Publishing, Cham, pp. 59-84. ISBN 978-3-319-91698-9.
Alongi, D. M., 2018b: Kelp Forests. In: *Blue Carbon: Coastal Sequestration for Climate Change Mitigation* [Alongi, D. M. (ed.)]. Springer International Publishing, Cham, pp. 53-57. ISBN 978-3-319-91698-9.
Alongi, D. M., 2018c: Salt Marshes. In: *Blue Carbon: Coastal Sequestration for Climate Change Mitigation* [Alongi, D. M. (ed.)]. Springer International Publishing, Cham, pp. 9-22. ISBN 978-3-319-91698-9.
Alongi, D. M., 2018d: Seagrass Meadows. In: *Blue Carbon: Coastal Sequestration for Climate Change Mitigation* [Alongi, D. M. (ed.)]. Springer International Publishing, Cham, pp. 37-51. ISBN 978-3-319-91698-9.
Alongi, D. M., 2020: Global Significance of Mangrove Blue Carbon in Climate Change Mitigation. *Sci*, **2**(3), doi:10.3390/sci2030067.
Alsuwaiyan, N. A. et al., 2021: Genotypic variation in response to extreme events may facilitate kelp adaptation under future climates. *Marine Ecology Progress Series*, **672**, 111-121.
Altieri, A. H. and K. B. Gedan, 2015: Climate change and dead zones. *Global Change Biology*, **21**(4), 1395-1406, doi:10.1111/gcb.12754.
Alvarez, S., F. Lupi, D. Solís and M. Thomas, 2019: Valuing provision scenarios of coastal ecosystem services: the case of boat ramp closures due to harmful algae blooms in Florida. *Water*, **11**(6), 1250, doi:10.3390/w11061250.
Amano, T. et al., 2020: Responses of global waterbird populations to climate change vary with latitude. *Nature Climate Change*, **10**, 959-964, doi:10.1038/s41558-020-0872-3.
Ambo-Rappe, R. et al., 2019: Perspectives on seagrass ecosystem services from a coastal community. *IOP Conference Series: Earth and Environmental Science*, **370**, 012022, doi:10.1088/1755-1315/370/1/012022.
Amélineau, F. et al., 2019: Arctic climate change and pollution impact little auk foraging and fitness across a decade. *Scientific Reports*, **9**(1), 1014, doi:10.1038/s41598-018-38042-z.
Andersen, J. H. et al., 2020: Relative impacts of multiple human stressors in estuaries and coastal waters in the North Sea–Baltic Sea transition zone. *Science of The Total Environment*, **704**, 135316, doi:10.1016/j.scitotenv.2019.135316.
Anderson, C. R. et al., 2019: Scaling up from regional case studies to a global harmful algal bloom observing system. *Frontiers in Marine Science*, **6**, 250, doi:10.3389/fmars.2019.00250.
Andersson, A. J. and F. T. Mackenzie, 2004: Shallow-water oceans: a source or sink of atmospheric CO_2? *Frontiers in Ecology and the Environment*, **2**(7), 348-353, doi:10.1890/1540-9295(2004)002[0348:SOASOS]2.0.CO;2.
Andersson, A. J., F. T. Mackenzie and J.-P. Gattuso, 2011: Effects of ocean acidification on benthic processes, organisms, and ecosystems. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, United Kingdom, pp. 122-153. ISBN 9780199591084.
Andres, K., M. Savarese, B. Bovard and M. Parsons, 2019: Coastal Wetland Geomorphic and Vegetative Change: Effects of Sea-Level Rise and Water Management on Brackish Marshes. *Estuaries and Coasts*, **42**(5), 1308-1327, doi:10.1007/s12237-019-00538-w.
Andrews, A. J. et al., 2019: Boreal marine fauna from the Barents Sea disperse to Arctic Northeast Greenland. *Scientific Reports*, **9**(1), 5799, doi:10.1038/s41598-019-42097-x.
Anfuso, G. et al., 2020: Beach litter distribution in Admiralty Bay, King George Island, Antarctica. *Marine Pollution Bulletin*, **160**, 111657, doi:10.1016/j.marpolbul.2020.111657.
Anthony, K. et al., 2017: New interventions are needed to save coral reefs. *Nature Ecology & Evolution*, **1**(10), 1420-1422, doi:10.1038/s41559-017-0313-5.
Anthony, K., J. Bowen, D. Mead and P. Hardisty, 2019: *Reef Restoration and Adaptation Program: Intervention Analysis and Recommendations*. A report provided to the Australian Government by the Reef Restoration and Adaptation Program, 64 pp.
Anton, A. et al., 2019: Global ecological impacts of marine exotic species. *Nature Ecology & Evolution*, **3**(5), 787-800, doi:10.1038/s41559-019-0851-0.
Anton, A. et al., 2020: Differential thermal tolerance between algae and corals may trigger the proliferation of algae in coral reefs. *Global Change Biology*, **26**(8), 4316-4327, doi:10.1111/gcb.15141.
Anzidei, M. et al., 2020: Sea Level Rise Scenario for 2100 A.D. in the Heritage Site of Pyrgi (Santa Severa, Italy). *Journal of Marine Science and Engineering*, **8**(2), doi:10.3390/jmse8020064.
Aoki, L. R., K. J. McGlathery, P. L. Wiberg and A. Al-Haj, 2020: Depth Affects Seagrass Restoration Success and Resilience to Marine Heat Wave Disturbance. *Estuaries and Coasts*, **43**(2), 316-328, doi:10.1007/s12237-019-00685-0.

Appeaning Addo, K., E. K. Brempong and P. N. Jayson-Quashigah, 2020: Assessment of the dynamics of the Volta river estuary shorelines in Ghana. *Geoenvironmental Disasters*, **7**(1), 19, doi:10.1186/s40677-020-00151-1.

Appeltans, W. et al., 2012: The magnitude of global marine species diversity. *Current Biology*, **22**(23), 2189-2202, doi:10.1016/j.cub.2012.09.036.

Arafeh-Dalmau, N. et al., 2021: Incorporating climate velocity into the design of climate-smart networks of marine protected areas. *Methods in Ecology and Evolution*, **00**, 1-15, doi:10.1111/2041-210X.13675.

Arafeh-Dalmau, N. et al., 2019: Extreme marine heatwaves alter kelp forest community near its equatorward distribution limit. *Frontiers in Marine Science*, **6**, 499, doi:10.3389/fmars.2019.00499.

Arafeh-Dalmau, N. et al., 2020: Marine heat waves threaten kelp forests. *Science*, **367**(6478), 635, doi:10.1126/science.aba5244.

Aranguren-Gassis, M., C. T. Kremer, C. A. Klausmeier and E. Litchman, 2019: Nitrogen limitation inhibits marine diatom adaptation to high temperatures. *Ecology Letters*, **22**(11), 1860-1869, doi:10.1111/ele.13378.

Archer, E. et al., 2021: Biodiversity and ecosystem services on the African continent – What is changing, and what are our options? *Environmental Development*, **37**, 100558, doi:10.1016/j.envdev.2020.100558.

Archibald, K. M., D. A. Siegel and S. C. Doney, 2019: Modeling the Impact of Zooplankton Diel Vertical Migration on the Carbon Export Flux of the Biological Pump. *Global Biogeochemical Cycles*, **33**(2), 181-199, doi:10.1029/2018GB005983.

Arctic Monitoring and Assessment Programme, 2018: *AMAP assessment 2018: Arctic Ocean acidification*. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, 187 pp pp.

Ardyna, M. and K. R. Arrigo, 2020: Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change*, **10**(10), 892-903, doi:10.1038/s41558-020-0905-y.

Arias, P. A. et al., 2021: Technical Summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Arias-Ortiz, A. et al., 2018: A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. *Nature Climate Change*, **8**(4), 338-344, doi:10.1038/s41558-018-0096-y.

Arimitsu, M. L. et al., 2021: Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. *Global Change Biology*, **27**(9), 1859-1878, doi:10.1111/gcb.15556.

Arkema, K. K. et al., 2017: Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Annals of the New York Academy of Sciences*, **1399**(1), 5-26, doi:10.1111/nyas.13322.

Armengol, L. et al., 2019: Planktonic food web structure and trophic transfer efficiency along a productivity gradient in the tropical and subtropical Atlantic Ocean. *Scientific Reports*, **9**(1), 2044, doi:10.1038/s41598-019-38507-9.

Armstrong, C. W. et al., 2019: Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic. *Frontiers in Marine Science*, **6**, 158, doi:10.3389/fmars.2019.00158.

Arreguín-Sánchez, F., 2019: Climate change and the rise of the octopus fishery in the Campeche Bank, México. *Regional Studies in Marine Science*, **32**, 100852, doi:10.1016/j.rsma.2019.100852.

Arrieta, J. M., S. Arnaud-Haond and C. M. Duarte, 2010: What lies underneath: Conserving the oceans' genetic resources. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(43), 18318, doi:10.1073/pnas.0911897107.

Arrigo, K. R., 2014: Sea Ice Ecosystems. *Annual Review of Marine Science*, **6**(1), 439-467, doi:10.1146/annurev-marine-010213-135103.

Asch, R. G., 2015: Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(30), E4065-E4074, doi:10.1073/pnas.1421946112.

Asch, R. G., W. W. L. Cheung and G. Reygondeau, 2018: Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. *Marine Policy*, **88**, 285-294, doi:10.1016/j.marpol.2017.08.015.

Asch, R. G., C. A. Stock and J. L. Sarmiento, 2019: Climate change impacts on mismatches between phytoplankton blooms and fish spawning phenology. *Global Change Biology*, **25**(8), 2544-2559, doi:10.1111/gcb.14650.

Ashford, O. S. et al., 2018: Phylogenetic and functional evidence suggests that deep-ocean ecosystems are highly sensitive to environmental change and direct human disturbance. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1884), 20180923, doi:10.1098/rspb.2018.0923.

Ashford, O. S. et al., 2019: Investigating the environmental drivers of deep-seafloor biodiversity: A case study of peracarid crustacean assemblages in the Northwest Atlantic Ocean. *Ecology and Evolution*, **9**(24), 14167-14204, doi:10.1002/ece3.5852.

Assis, J., M. B. Araújo and E. A. Serrão, 2018: Projected climate changes threaten ancient refugia of kelp forests in the North Atlantic. *Global Change Biology*, **24**(1), e55-e66, doi:10.1111/gcb.13818.

Assis, J. et al., 2016: Deep reefs are climatic refugia for genetic diversity of marine forests. *Journal of Biogeography*, **43**(4), 833-844, doi:10.1111/jbi.12677.

Assis, J. et al., 2020: A fine-tuned global distribution dataset of marine forests. *Scientific Data*, **7**(1), 119, doi:10.1038/s41597-020-0459-x.
Atwood, T. C. et al., 2016: Rapid Environmental Change Drives Increased Land Use by an Arctic Marine Predator. *PLOS ONE*, **11**(6), e0155932, doi:10.1371/journal.pone.0155932.
Atzori, R., A. Fyall and G. Miller, 2018: Tourist responses to climate change: potential impacts and adaptation in Florida's coastal destinations. *Tourism Management*, **69**, 12-22, doi:10.1016/j.tourman.2018.05.005.
Aumont, O., O. Maury, S. Lefort and L. Bopp, 2018: Evaluating the Potential Impacts of the Diurnal Vertical Migration by Marine Organisms on Marine Biogeochemistry. *Global Biogeochemical Cycles*, **32**(11), 1622-1643, doi:10.1029/2018GB005886.
Babcock, R. C. et al., 2019: Severe continental-scale impacts of climate change are happening now: extreme climate events impact marine habitat forming communities along 45% of Australia's coast. *Frontiers in Marine Science*, **6**, 411, doi:10.3389/fmars.2019.00411.
Bach, L. T. et al., 2019: Effects of elevated CO_2 on a natural diatom community in the subtropical NE Atlantic. *Frontiers in Marine Science*, **6**(MAR), 1--16, doi:10.3389/fmars.2019.00075.
Bach, L. T., K. T. Lohbeck, T. B. H. Reusch and U. Riebesell, 2018: Rapid evolution of highly variable competitive abilities in a key phytoplankton species. *Nature Ecology & Evolution*, **2**(4), 611-613, doi:10.1038/s41559-018-0474-x.
Bach, L. T. et al., 2015: A unifying concept of coccolithophore sensitivity to changing carbonate chemistry embedded in an ecological framework. *Progress in Oceanography*, **135**, 125-138, doi:10.1016/j.pocean.2015.04.012.
Bach, L. T. et al., 2021: Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. *Nature Communications*, **12**(1), 2556, doi:10.1038/s41467-021-22837-2.
Baco, A. R. et al., 2017: Defying Dissolution: Discovery of Deep-Sea Scleractinian Coral Reefs in the North Pacific. *Scientific Reports*, **7**(1), 5436, doi:10.1038/s41598-017-05492-w.
Bacopoulos, P. and R. R. Clark, 2021: Coastal erosion and structural damage due to four consecutive-year major hurricanes: Beach projects afford resilience and coastal protection. *Ocean & Coastal Management*, **209**, 105643, doi:10.1016/j.ocecoaman.2021.105643.
Bagheri-Gavkosh, M. et al., 2021: Land subsidence: A global challenge. *Science of The Total Environment*, **778**, 146193, doi:10.1016/j.scitotenv.2021.146193.
Bakun, A. et al., 2015: Anticipated effects of climate change on coastal upwelling ecosystems. *Current Climate Change Reports*, **1**(2), 85-93, doi:10.1007/s40641-015-0008-4.
Balasubramanian, M., 2019: Economic value of regulating ecosystem services: a comprehensive at the global level review. *Environmental Monitoring and Assessment*, **191**(10), 616, doi:10.1007/s10661-019-7758-8.
Balch, W. M., D. T. Drapeau, B. C. Bowler and T. G. Huntington, 2012: Step-changes in the physical, chemical and biological characteristics of the Gulf of Maine, as documented by the GNATS time series. *Marine Ecology Progress Series*, **450**, 11-35.
Balogh, R. and M. Byrne, 2020: Developing in a warming intertidal, negative carry over effects of heatwave conditions in development to the pentameral starfish in *Parvulastra exigua*. *Marine Environmental Research*, **162**, 105083, doi:10.1016/j.marenvres.2020.105083.
Balzan, M. V., M. Potschin-Young and R. Haines-Young, 2018: Island ecosystem services: insights from a literature review on case-study island ecosystem services and future prospects. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **14**(1), 71-90, doi:10.1080/21513732.2018.1439103.
Ban, N. C. et al., 2019: Well-being outcomes of marine protected areas. *Nature Sustainability*, **2**(6), 524-532, doi:10.1038/s41893-019-0306-2.
Bar-On, Y. M., R. Phillips and R. Milo, 2018: The biomass distribution on Earth. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(25), 6506, doi:10.1073/pnas.1711842115.
Barange, M., 2019: Avoiding misinterpretation of climate change projections of fish catches. *ICES Journal of Marine Science*, fsz061, doi:10.1093/icesjms/fsz061.
Barange, M. et al., 2018: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options*. FAO Technical Report No. 627, Food and Agriculture Organisation of the United Nations, Rome, Italy, 628 pp.
Barbier, E. B., J. C. Burgess and T. J. Dean, 2018: How to pay for saving biodiversity. *Science*, **360**(6388), 486, doi:10.1126/science.aar3454.
Barbier, E. B. et al., 2011: The value of estuarine and coastal ecosystem services. *Ecological Monographs*, **81**(2), 169-193, doi:10.1890/10-1510.1.
Barbraud, C. and H. Weimerskirch, 2006: Antarctic birds breed later in response to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **103**(16), 6248, doi:10.1073/pnas.0510397103.
Bargahi, H. R., M. R. Shokri, F. Kaymaram and M. R. Fatemi, 2020: Changes in reef fish assemblages following multiple bleaching events in the world's warmest sea (Kish Island, the Persian Gulf). *Coral Reefs*, **39**(3), 603-624, doi:10.1007/s00338-020-01945-3.
Barkdull, J. and P. G. Harris, 2019: Emerging responses to global climate change: ecosystem-based adaptation. *Global Change, Peace & Security*, **31**(1), 19-37, doi:10.1080/14781158.2018.1475349.
Barkley, H. C. et al., 2018: Repeat bleaching of a central Pacific coral reef over the past six decades (1960–2016). *Communications Biology*, **1**(1), 177, doi:10.1038/s42003-018-0183-7.

Barnes, M. L. et al., 2020: Social determinants of adaptive and transformative responses to climate change. *Nature Climate Change*, **10**(9), 823-828, doi:10.1038/s41558-020-0871-4.
Barnett, J. and C. McMichael, 2018: The effects of climate change on the geography and timing of human mobility. *Population and Environment*, **39**(4), 339-356, doi:10.1007/s11111-018-0295-5.
Barra, T. et al., 2020: Social Media Reveal High Rates of Agonistic Behaviors of Humpback Whales in Response to Swim-with Activities Off Reunion Island. *Tourism in Marine Environments*, **15**(3-4), 191-209, doi:10.3727/154427320X15960647825531.
Barton, A. et al., 2015a: Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography*, **28**(2), 146-159, doi:10.5670/oceanog.2015.38.
Barton, A. D., A. J. Irwin, Z. V. Finkel and C. A. Stock, 2016: Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(11), 2964, doi:10.1073/pnas.1519080113.
Barton, A. D., M. S. Lozier and R. G. Williams, 2015b: Physical controls of variability in North Atlantic phytoplankton communities. *Limnology and Oceanography*, **60**(1), 181-197, doi:10.1002/lno.10011.
Basel, B., G. Goby and J. Johnson, 2020: Community-based adaptation to climate change in villages of Western Province, Solomon Islands. *Marine Pollution Bulletin*, **156**, 111266, doi:10.1016/j.marpolbul.2020.111266.
Bashevkin, S. M. et al., 2020: Larval dispersal in a changing ocean with an emphasis on upwelling regions. *Ecosphere*, **11**(1), e03015, doi:10.1002/ecs2.3015.
Bates, A. E. et al., 2019: Climate resilience in marine protected areas and the 'protection paradox'. *Biological Conservation*, **236**, 305-314, doi:10.1016/j.biocon.2019.05.005.
Bates, A. E. et al., 2014: Defining and observing stages of climate-mediated range shifts in marine systems. *Global Environmental Change*, **26**, 27-38, doi:10.1016/j.gloenvcha.2014.03.009.
Baudron, A. R. et al., 2020: Changing fish distributions challenge the effective management of European fisheries. *Ecography*, **43**(4), 494-505, doi:10.1111/ecog.04864.
Baumann, H. and E. M. Smith, 2018: Quantifying Metabolically Driven pH and Oxygen Fluctuations in US Nearshore Habitats at Diel to Interannual Time Scales. *Estuaries and Coasts*, **41**(4), 1102-1117, doi:10.1007/s12237-017-0321-3.
Baums, I. B. et al., 2019: Considerations for maximizing the adaptive potential of restored coral populations in the western Atlantic. *Ecological Applications*, **29**(8), e01978, doi:10.1002/eap.1978.
Baussant, T. et al., 2017: Physiological responses and lipid storage of the coral *Lophelia pertusa* at varying food density. *Journal of Toxicology and Environmental Health, Part A*, **80**(5), 266-284, doi:10.1080/15287394.2017.1297274.
Bay, L. K. et al., 2019: *Reef Restoration and Adaptation Program: Intervention Technical Summary*. A report provided to the Australian Government by the Reef Restoration and Adaptation Program, 89 pp pp.
Bay, R. A., N. H. Rose, C. A. Logan and S. R. Palumbi, 2017: Genomic models predict successful coral adaptation if future ocean warming rates are reduced. *Science Advances*, **3**(11), e1701413, doi:10.1126/sciadv.1701413.
Bayley, D. T. I. et al., 2021: Valuation of kelp forest ecosystem services in the Falkland Islands: A case study integrating blue carbon sequestration potential. *One Ecosystem*, **6**, e62811, doi:10.3897/oneeco.6.e62811.
Beas-Luna, R. et al., 2020: Geographic variation in responses of kelp forest communities of the California Current to recent climatic changes. *Global Change Biology*, **26**(11), 6457-6473, doi:10.1111/gcb.15273.
Beaugrand, G. et al., 2019: Prediction of unprecedented biological shifts in the global ocean. *Nature Climate Change*, **9**(3), 237-243, doi:10.1038/s41558-019-0420-1.
Beaugrand, G. et al., 2015: Future vulnerability of marine biodiversity compared with contemporary and past changes. *Nature Climate Change*, **5**(7), 695-701, doi:10.1038/nclimate2650.
Beaulieu, C. et al., 2013: Factors challenging our ability to detect long-term trends in ocean chlorophyll. *Biogeosciences*, **10**(4), 2711-2724, doi:10.5194/bg-10-2711-2013.
Beaumont, N. J. et al., 2007: Identification, definition and quantification of goods and services provided by marine biodiversity: Implications for the ecosystem approach. *Marine Pollution Bulletin*, **54**(3), 253-265, doi:10.1016/j.marpolbul.2006.12.003.
Beaven, R. P. et al., 2020: Future challenges of coastal landfills exacerbated by sea level rise. *Waste Management*, **105**, 92-101, doi:10.1016/j.wasman.2020.01.027.
Bechard, A., 2020: The economic impacts of harmful algal blooms on tourism: an examination of Southwest Florida using a spline regression approach. *Natural Hazards*, doi:10.1007/s11069-020-04182-7.
Beck, M. W. et al., 2018: The global flood protection savings provided by coral reefs. *Nature Communications*, **9**(1), 2186, doi:10.1038/s41467-018-04568-z.
Bedford, J. et al., 2020: Lifeform indicators reveal large-scale shifts in plankton across the North-West European shelf. *Global Change Biology*, **26**(6), 3482-3497, doi:10.1111/gcb.15066.
Bednaršek, N. et al., 2019: Systematic review and meta-analysis toward synthesis of thresholds of ocean acidification impacts on calcifying pteropods and interactions with warming. *Frontiers in Marine Science*, **6**, 227, doi:10.3389/fmars.2019.00227.
Belhabib, D., P. Le Billon and D. J. Wrathall, 2020: Narco-Fish: Global fisheries and drug trafficking. *Fish and Fisheries*, **21**(5), 992-1007, doi:10.1111/faf.12483.

Bell, J. D. et al., 2021: Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, doi:10.1038/s41893-021-00745-z.
Bell, R. J., J. Odell, G. Kirchner and S. Lomonico, 2020: Actions to Promote and Achieve Climate-Ready Fisheries: Summary of Current Practice. *Marine and Coastal Fisheries*, **12**(3), 166-190, doi:10.1002/mcf2.10112.
Bellanger, M. et al., 2020: Addressing Marine and Coastal Governance Conflicts at the Interface of Multiple Sectors and Jurisdictions. *Frontiers in Marine Science*, **7**(743), doi:10.3389/fmars.2020.544440.
Belley, R., P. V. R. Snelgrove, P. Archambault and S. K. Juniper, 2016: Environmental drivers of benthic flux variation and ecosystem functioning in Salish Sea and Northeast Pacific sediments. *PLOS ONE*, **11**(3), e0151110, doi:10.1371/journal.pone.0151110.
Beltran, R. S. et al., 2019: Reproductive success delays moult phenology in a polar mammal. *Scientific Reports*, **9**(1), 5221, doi:10.1038/s41598-019-41635-x.
Ben-Hasan, A. and V. Christensen, 2019: Vulnerability of the marine ecosystem to climate change impacts in the Arabian Gulf—an urgent need for more research. *Global Ecology and Conservation*, **17**, e00556, doi:10.1016/j.gecco.2019.e00556.
Béné, C. and L. Doyen, 2018: From Resistance to Transformation: A Generic Metric of Resilience Through Viability. *Earth's Future*, **6**(7), 979-996, doi:10.1002/2017EF000660.
Bennett, H. M. et al., 2017: Interactive effects of temperature and pCO_2 on sponges: from the cradle to the grave. *Global Change Biology*, **23**(5), 2031-2046, doi:10.1111/gcb.13474.
Bennett, N. J., 2018: Navigating a just and inclusive path towards sustainable oceans. *Marine Policy*, **97**, 139-146, doi:10.1016/j.marpol.2018.06.001.
Bennett, N. J. et al., 2021: Advancing Social Equity in and Through Marine Conservation. *Frontiers in Marine Science*, **8**(994), doi:10.3389/fmars.2021.711538.
Bentley, B. P., M. R. Kearney, S. D. Whiting and N. J. Mitchell, 2020a: Microclimate modelling of beach sand temperatures reveals high spatial and temporal variation at sea turtle rookeries. *Journal of Thermal Biology*, **88**, 102522, doi:10.1016/j.jtherbio.2020.102522.
Bentley, J. W. et al., 2020b: Retrospective analysis of the influence of environmental drivers on commercial stocks and fishing opportunities in the Irish Sea. *Fisheries Oceanography*, **29**(5), 415-435, doi:10.1111/fog.12486.
Benton, M. J., 2018: Hyperthermal-driven mass extinctions: killing models during the Permian–Triassic mass extinction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2130), 20170076, doi:10.1098/rsta.2017.0076.
Benway, H. M. et al., 2019: Ocean Time Series Observations of Changing Marine Ecosystems: An Era of Integration, Synthesis, and Societal Applications. *Frontiers in Marine Science*, **6**(393), doi:10.3389/fmars.2019.00393.
Berger, M. F., V. Caruso and E. Peterson, 2019: An updated orientation to marine conservation funding flows. *Marine Policy*, **107**, 103497, doi:10.1016/j.marpol.2019.04.001.
Bergillos, R. J. et al., 2018: The role of wave energy converter farms on coastal protection in eroding deltas, Guadalfeo, southern Spain. *Journal of Cleaner Production*, **171**, 356-367, doi:10.1016/j.jclepro.2017.10.018.
Bergseth, B. J., 2018: Effective marine protected areas require a sea change in compliance management. *ICES Journal of Marine Science*, **75**(3), 1178-1180, doi:10.1093/icesjms/fsx105.
Bergstrom, D. M. et al., 2021: Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology*, **27**(9), 1692-1703, doi:10.1111/gcb.15539.
Berman, M. et al., 2020: Adaptation to climate change in coastal communities: findings from seven sites on four continents. *Climatic Change*, **159**(1), 1-16, doi:10.1007/s10584-019-02571-x.
Bertolini, C. and J. da Mosto, 2021: Restoring for the climate: a review of coastal wetland restoration research in the last 30 years. *Restoration Ecology*, **n/a**(n/a), e13438, doi:10.1111/rec.13438.
Bertrand, A., R. Vögler and O. Defeo, 2018: Chapter 15: Climate change impacts, vulnerabilities and adaptations: Southwest Atlantic and Southeast Pacific marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 325-346. ISBN 9789251306079.
Bestion, E., C. E. Schaum and G. Yvon-Durocher, 2018: Nutrient limitation constrains thermal tolerance in freshwater phytoplankton. *Limnology and Oceanography Letters*, **3**(6), 436-443, doi:10.1002/lol2.10096.
Bestley, S. et al., 2020: Marine Ecosystem Assessment for the Southern Ocean: Birds and Marine Mammals in a Changing Climate. *Front. ecol. evol.*, **8**(338), doi:10.3389/fevo.2020.566936.
Bevacqua, E. et al., 2020: More meteorological events that drive compound coastal flooding are projected under climate change. *Communications Earth & Environment*, **1**(1), 47, doi:10.1038/s43247-020-00044-z.
Bever, A. J., M. A. M. Friedrichs and P. St-Laurent, 2021: Real-time environmental forecasts of the Chesapeake Bay: Model setup, improvements, and online visualization. *Environmental Modelling & Software*, **140**, 105036, doi:10.1016/j.envsoft.2021.105036.
Bianchi, C. N. et al., 2019: Consequences of the marine climate and ecosystem shift of the 1980-90s on the Ligurian Sea biodiversity (NW Mediterranean). *The European Zoological Journal*, **86**(1), 458-487, doi:10.1080/24750263.2019.1687765.

Bianchi, D., C. Stock, E. D. Galbraith and J. L. Sarmiento, 2013: Diel vertical migration: Ecological controls and impacts on the biological pump in a one-dimensional ocean model. *Global Biogeochemical Cycles*, **27**(2), 478-491, doi:10.1002/gbc.20031.
Biggs, R., G. D. Peterson and J. C. Rocha, 2018: The Regime Shifts Database: a framework for analyzing regime shifts in social-ecological systems. *Ecology and Society*, **23**(3), 9, doi:10.5751/ES-10264-230309.
Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. In press.
Bisaro, A. and J. Hinkel, 2018: Mobilizing private finance for coastal adaptation: A literature review. *WIREs Climate Change*, **9**(3), e514, doi:10.1002/wcc.514.
Biswas, B. and B. Mallick, 2021: Livelihood diversification as key to long-term non-migration: evidence from coastal Bangladesh. *Environment, Development and Sustainability*, **23**(6), 8924-8948, doi:10.1007/s10668-020-01005-4.
Bitter, M. C., L. Kapsenberg, J. P. Gattuso and C. A. Pfister, 2019: Standing genetic variation fuels rapid adaptation to ocean acidification. *Nature Communications*, **10**(1), 5821, doi:10.1038/s41467-019-13767-1.
Bladow, R. A. and S. L. Milton, 2019: Embryonic mortality in green *(Chelonia mydas)* and loggerhead *(Caretta caretta)* sea turtle nests increases with cumulative exposure to elevated temperatures. *Journal of Experimental Marine Biology and Ecology*, **518**, 151180, doi:10.1016/j.jembe.2019.151180.
Blanchard, J. L. et al., 2017: Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nature Ecology & Evolution*, **1**(9), 1240-1249, doi:10.1038/s41559-017-0258-8.
Blankespoor, B., S. Dasgupta and G.-M. Lange, 2017: Mangroves as a protection from storm surges in a changing climate. *Ambio*, **46**(4), 478-491, doi:10.1007/s13280-016-0838-x.
Blasiak, R. and C. C. C. Wabnitz, 2018: Aligning fisheries aid with international development targets and goals. *Marine Policy*, **88**, 86-92, doi:10.1016/j.marpol.2017.11.018.
Blasiak, R. et al., 2019: Towards greater transparency and coherence in funding for sustainable marine fisheries and healthy oceans. *Marine Policy*, **107**, 103508, doi:10.1016/j.marpol.2019.04.012.
Blumstein, D. T., B. Geffroy, D. S. M. Samia and E. Bessa, 2017: Creating a research-based agenda to reduce ecotourism impacts on wildlife. In: *Ecotourism's Promise and Peril: A Biological Evaluation* [Blumstein, D. T., B. Geffroy, D. S. M. Samia and E. Bessa (eds.)]. Springer, Cham, Switzerland, pp. 179-185. ISBN 9783319583310.
Boetius, A. and F. Wenzhöfer, 2013: Seafloor oxygen consumption fuelled by methane from cold seeps. *Nature Geoscience*, **6**(9), 725-734, doi:10.1038/ngeo1926.
Boissin, E. et al., 2019: Evolutionary history of green turtle populations, *Chelonia mydas*, from French Polynesia highlights the putative existence of a glacial refugium. *Marine Biodiversity*, **49**(6), 2725-2733, doi:10.1007/s12526-019-01001-6.
Bolin, J. A. et al., 2021: Achieving sustainable and climate-resilient fisheries requires marine ecosystem forecasts to include fish condition. *Fish and Fisheries*, **22**(5), 1067-1084, doi:10.1111/faf.12569.
Boltachev, A. R. and E. P. Karpova, 2014: Faunistic revision of alien fish species in the Black Sea. *Russian Journal of Biological Invasions*, **5**(4), 225-241, doi:10.1134/S2075111714040018.
Bond, D. P. G. and S. E. Grasby, 2017: On the causes of mass extinctions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **478**, 3-29, doi:10.1016/j.palaeo.2016.11.005.
Bongaerts, P., T. Ridgway, E. M. Sampayo and O. Hoegh-Guldberg, 2010: Assessing the 'deep reef refugia' hypothesis: focus on Caribbean reefs. *Coral Reefs*, **29**(2), 309-327, doi:10.1007/s00338-009-0581-x.
Boonzaier, L. and D. Pauly, 2016: Marine protection targets: an updated assessment of global progress. *Oryx*, **50**(1), 27-35, doi:10.1017/S0030605315000848.
Booth, D. J. et al., 2018: Tropical Marine Fishes and Fisheries and Climate Change. In: *Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis, I* [Phillips, B. F. and M. Pérez-Ramírez (eds.)]. Wiley Blackwell, pp. 875-896. ISBN 9781119154044.
Bopp, L. et al., 2013: Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences*, **10**(10), 6225-6245, doi:10.5194/bg-10-6225-2013.
Bopp, L. et al., 2017: Ocean (de)oxygenation from the last glacial maximum to the twenty-first century: insights from Earth system models. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **375**(2102), 20160323, doi:10.1098/rsta.2016.0323.
Borbor-Cordova, M. J. et al., 2019: Oceanography of Harmful Algal Blooms on the Ecuadorian Coast (1997–2017): Integrating Remote Sensing and Biological Data. *Frontiers in Marine Science*, **6**(13), doi:10.3389/fmars.2019.00013.
Bordner, A. S., C. E. Ferguson and L. Ortolano, 2020: Colonial dynamics limit climate adaptation in Oceania: Perspectives from the Marshall Islands. *Global environmental change*, **v. 61**, 2020 v.2061, doi:10.1016/j.gloenvcha.2020.102054.
Boström-Einarsson, L. et al., 2020: Coral restoration – A systematic review of current methods, successes, failures and future directions. *PLOS ONE*, **15**(1), e0226631, doi:10.1371/journal.pone.0226631.
Bouderbala, A., 2019: The impact of climate change on groundwater resources in coastal aquifers: case of the alluvial aquifer of Mitidja in Algeria. *Environmental Earth Sciences*, **78**(24), 698, doi:10.1007/s12665-019-8702-5.

Bourque, J. et al., 2020: Climate-associated drivers of plasma cytokines and contaminant concentrations in Beaufort Sea polar bears (*Ursus maritimus*). *Science of The Total Environment*, **745**, 140978, doi:10.1016/j.scitotenv.2020.140978.
Bouyoucos, I. A. et al., 2020: Thermal tolerance and hypoxia tolerance are associated in blacktip reef shark (*Carcharhinus melanopterus*) neonates. *The Journal of Experimental Biology*, **223**(14), jeb221937, doi:10.1242/jeb.221937.
Bowen, W. D. et al., 2020: Exploring causal components of plasticity in grey seal birthdates: Effects of intrinsic traits, demography, and climate. *Ecology and Evolution*, **10**(20), 11507-11522, doi:10.1002/ece3.6787.
Bowler, D. E. et al., 2020: Mapping human pressures on biodiversity across the planet uncovers anthropogenic threat complexes. *People and Nature*, **2**(2), 380-394, doi:10.1002/pan3.10071.
Bowman, K. L., C. H. Lamborg and A. M. Agather, 2020: A global perspective on mercury cycling in the ocean. *Science of The Total Environment*, **710**, 136166, doi:10.1016/j.scitotenv.2019.136166.
Boyce, D. G. et al., 2020: Future ocean biomass losses may widen socioeconomic equity gaps. *Nature Communications*, **11**(1), 2235, doi:10.1038/s41467-020-15708-9.
Boyd, P. W., 2019: Physiology and iron modulate diverse responses of diatoms to a warming Southern Ocean. *Nature Climate Change*, **9**(2), 148-152, doi:10.1038/s41558-018-0389-1.
Boyd, P. W. et al., 2019: Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature*, **568**(7752), 327-335, doi:10.1038/s41586-019-1098-2.
Boyd, P. W. et al., 2018: Experimental strategies to assess the biological ramifications of multiple drivers of global ocean change—a review. *Global Change Biology*, **24**(6), 2239-2261, doi:10.1111/gcb.14102.
Boyd, P. W. et al., 2016: Biological responses to environmental heterogeneity under future ocean conditions. *Global Change Biology*, **22**(8), 2633-2650, doi:10.1111/gcb.13287.
Boyd, P. W. et al., 2015a: Physiological responses of a Southern Ocean diatom to complex future ocean conditions. *Nature Climate Change*, **6**, 207-213, doi:10.1038/nclimate2811.
Boyd, P. W., S. T. Lennartz, D. M. Glover and S. C. Doney, 2015b: Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nature Climate Change*, **5**(1), 71-79, doi:10.1038/nclimate2441.
Boyes, S. J. and M. Elliott, 2014: Marine legislation – The ultimate 'horrendogram': International law, European directives & national implementation. *Marine Pollution Bulletin*, **86**(1), 39-47, doi:10.1016/j.marpolbul.2014.06.055.
Bramanti, L. et al., 2013: Detrimental effects of ocean acidification on the economically important Mediterranean red coral (*Corallium rubrum*). *Global Change Biology*, **19**(6), 1897-1908, doi:10.1111/gcb.12171.
Brandenburg, K. M., M. Velthuis and D. B. Van de Waal, 2019: Meta-analysis reveals enhanced growth of marine harmful algae from temperate regions with warming and elevated CO_2 levels. *Global Change Biology*, **25**(8), 2607-2618, doi:10.1111/gcb.14678.
Brauko, K. M. et al., 2020: Marine Heatwaves, Sewage and Eutrophication Combine to Trigger Deoxygenation and Biodiversity Loss: A SW Atlantic Case Study. *Frontiers in Marine Science*, **7**(1038), doi:10.3389/fmars.2020.590258.
Braun de Torrez, E. C. et al., 2021: Seasick: Why Value Ecosystems Severely Threatened by Sea-Level Rise? *Estuaries and Coasts*, **44**(4), 899-910, doi:10.1007/s12237-020-00850-w.
Breitburg, D. et al., 2018: Declining oxygen in the global ocean and coastal waters. *Science*, **359**(6371), eaam7240, doi:10.1126/science.aam7240.
Brennan, G. and S. Collins, 2015: Growth responses of a green alga to multiple environmental drivers. *Nature Climate Change*, **5**(9), 892-897, doi:10.1038/nclimate2682.
Brennan, G. L., N. Colegrave and S. Collins, 2017: Evolutionary consequences of multidriver environmental change in an aquatic primary producer. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(37), 9930-9935, doi:10.1073/pnas.1703375114.
Briggs, N., G. Dall'Olmo and H. Claustre, 2020: Major role of particle fragmentation in regulating biological sequestration of CO2 by the oceans. *Science*, **367**(6479), 791, doi:10.1126/science.aay1790.
Brisset, E., F. Burjachs, B. J. Ballesteros Navarro and J. Fernández-López de Pablo, 2018: Socio-ecological adaptation to Early-Holocene sea-level rise in the western Mediterranean. *Global and Planetary Change*, **169**, 156-167, doi:10.1016/j.gloplacha.2018.07.016.
Brito-Morales, I. et al., 2018: Climate velocity can inform conservation in a warming world. *Trends in Ecology & Evolution*, **33**(6), 441-457, doi:10.1016/j.tree.2018.03.009.
Brito-Morales, I. et al., 2020: Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. *Nature Climate Change*, **10**, 576-581, doi:10.1038/s41558-020-0773-5.
Broadwater, M. H., F. M. Van Dolah and S. E. Fire, 2018: Vulnerabilities of Marine Mammals to Harmful Algal Blooms. In: *Harmful Algal Blooms*, pp. 191-222.
Brodeur, R. D., M. E. Hunsicker, A. Hann and T. W. Miller, 2019: Effects of warming ocean conditions on feeding ecology of small pelagic fishes in a coastal upwelling ecosystem: a shift to gelatinous food sources. *Marine Ecology Progress Series*, **617–618**, 149-163, doi:10.3354/meps12497.
Brodie, G. et al., 2020: Seagrasses and seagrass habitats in Pacific small island developing states: Potential loss of benefits via human disturbance and climate change. *Marine Pollution Bulletin*, **160**, 111573, doi:10.1016/j.marpolbul.2020.111573.

Brodie Rudolph, T. et al., 2020: A transition to sustainable ocean governance. *Nature Communications*, **11**(1), 3600, doi:10.1038/s41467-020-17410-2.

Brodnicke, O. B. et al., 2019: Unravelling the links between heat stress, bleaching and disease: fate of tabular corals following a combined disease and bleaching event. *Coral Reefs*, **38**(4), 591-603, doi:10.1007/s00338-019-01813-9.

Bronen, R. et al., 2020: Usteq: integrating indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation. *Polar Geography*, **43**(2-3), 188-205, doi:10.1080/1088937X.2019.1679271.

Bronselaer, B. et al., 2020: Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean. *Nature Geoscience*, **13**(1), 35-42, doi:10.1038/s41561-019-0502-8.

Brooker, B. and U. M. Scharler, 2020: The importance of climatic variability and human influence in driving aspects of temporarily open-closed estuaries. *Ecohydrology*, **13**(4), e2205, doi:10.1002/eco.2205.

Brown, A. and S. Thatje, 2015: The effects of changing climate on faunal depth distributions determine winners and losers. *Global Change Biology*, **21**(1), 173-180, doi:10.1111/gcb.12680.

Brown, J. et al., 2020: Contrasting responses to salinity and future ocean acidification in arctic populations of the amphipod Gammarus setosus. *Marine Environmental Research*, **162**, 105176, doi:10.1016/j.marenvres.2020.105176.

Brown, N. E., T. W. Therriault and C. D. Harley, 2016: Field-based experimental acidification alters fouling community structure and reduces diversity. *Journal of Animal Ecology*, **85**(5), 1328-1339, doi:10.1111/1365-2656.12557.

Brown, N. E. M., J. R. Bernhardt, K. M. Anderson and C. D. G. Harley, 2018a: Increased food supply mitigates ocean acidification effects on calcification but exacerbates effects on growth. *Scientific Reports*, **8**(1), 9800, doi:10.1038/s41598-018-28012-w.

Brown, S. et al., 2018b: What are the implications of sea-level rise for a 1.5, 2 and 3 °C rise in global mean temperatures in the Ganges-Brahmaputra-Meghna and other vulnerable deltas? *Regional Environmental Change*, **18**(6), 1829-1842, doi:10.1007/s10113-018-1311-0.

Brown, S. et al., 2019: Land raising as a solution to sea-level rise: an analysis of coastal flooding on an artificial island in the Maldives. *Journal of Flood Risk Management*, e12567, doi:10.1111/jfr3.12567.

Brun, P. et al., 2019: Climate change has altered zooplankton-fuelled carbon export in the North Atlantic. *Nature Ecology & Evolution*, **3**(3), 416-423, doi:10.1038/s41559-018-0780-3.

Bruno, J. F. et al., 2018: Climate change threatens the world's marine protected areas. *Nature Climate Change*, **8**(6), 499-503, doi:10.1038/s41558-018-0149-2.

Bruno, J. F., I. M. Côté and L. T. Toth, 2019: Climate change, coral loss, and the curious case of the parrotfish paradigm: why don't marine protected areas improve reef resilience? *Annual Review of Marine Science*, **11**(1), 307-334, doi:10.1146/annurev-marine-010318-095300.

Bryan-Brown, D. N. et al., 2020: Global trends in mangrove forest fragmentation. *Scientific Reports*, **10**(1), 7117, doi:10.1038/s41598-020-63880-1.

Bryndum-Buchholz, A. et al., 2019: Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. *Global Change Biology*, **25**(2), 459-472, doi:10.1111/gcb.14512.

Bryndum-Buchholz, A., D. P. Tittensor and H. K. Lotze, 2021: The status of climate change adaptation in fisheries management: Policy, legislation and implementation. *Fish and Fisheries*, **n/a**(n/a), doi:10.1111/faf.12586.

Bucci, A. F., A. C. Thomas and I. Cetinić, 2020: Interannual Variability in the Thermal Habitat of Alexandrium catenella in the Bay of Fundy and the Implications of Climate Change. *Frontiers in Marine Science*, **7**(1060), doi:10.3389/fmars.2020.587990.

Buchanan, J. R. et al., 2016a: Living on the edge: vulnerability of coral-dependent fishes in the Gulf. *Marine Pollution Bulletin*, **105**(2), 480–488, doi:10.1016/j.marpolbul.2015.11.033.

Buchanan, M. K., R. E. Kopp, M. Oppenheimer and C. Tebaldi, 2016b: Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Climatic Change*, **137**(3), 347-362, doi:10.1007/s10584-016-1664-7.

Buckley, L. B. and R. B. Huey, 2016: How Extreme Temperatures Impact Organisms and the Evolution of their Thermal Tolerance. *Integrative and Comparative Biology*, **56**(1), 98-109, doi:10.1093/icb/icw004.

Buerger, P. et al., 2020: Heat-evolved microalgal symbionts increase coral bleaching tolerance. *Science Advances*, **6**(20), eaba2498, doi:10.1126/sciadv.aba2498.

Buffington, K. J., A. C. Goodman, C. M. Freeman and K. M. Thorne, 2020: Testing the interactive effects of flooding and salinity on tidal marsh plant productivity. *Aquatic Botany*, **164**, 103231, doi:10.1016/j.aquabot.2020.103231.

Bulleri, F. et al., 2018: Harnessing positive species interactions as a tool against climate-driven loss of coastal biodiversity. *PLOS Biology*, **16**(9), e2006852, doi:10.1371/journal.pbio.2006852.

Burden, A., A. Garbutt and C. D. Evans, 2019: Effect of restoration on saltmarsh carbon accumulation in Eastern England. *Biology Letters*, **15**(1), 20180773, doi:10.1098/rsbl.2018.0773.

Burden, M. and R. Fujita, 2019: Better fisheries management can help reduce conflict, improve food security, and increase economic productivity in the face of climate change. *Marine Policy*, **108**, 103610, doi:10.1016/j.marpol.2019.103610.

Burge, C. A. and P. Hershberger, 2020: Climate change can drive marine diseases. In: *Marine Disease Ecology*. Oxford University Press, pp. 83-94.

Burger, F. A., J. G. John and T. L. Frölicher, 2020: Increase in ocean acidity variability and extremes under increasing atmospheric CO_2. *Biogeosciences*, **17**(18), 4633-4662, doi:10.5194/bg-17-4633-2020.
Burrows, M. T. et al., 2019: Ocean community warming responses explained by thermal affinities and temperature gradients. *Nature Climate Change*, **9**(12), 959-963, doi:10.1038/s41558-019-0631-5.
Burrows, M. T. et al., 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334**(6056), 652-655, doi:10.1126/science.1210288.
Burt, J. A. et al., 2019: Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. *Coral Reefs*, **38**(4), 567-589, doi:10.1007/s00338-019-01767-y.
Burthe, S. et al., 2012: Phenological trends and trophic mismatch across multiple levels of a North Sea pelagic food web. *Marine Ecology Progress Series*, **454**, 119-134.
Burvingt, O. et al., 2018: Climate forcing of regionally-coherent extreme storm impact and recovery on embayed beaches. *Marine Geology*, **401**, 112-128, doi:10.1016/j.margeo.2018.04.004.
Büscher, J. V., A. U. Form and U. Riebesell, 2017: Interactive effects of ocean acidification and warming on growth, fitness and survival of the cold-water coral *lophelia pertusa* under different food availabilities. *Frontiers in Marine Science*, **4**, 101, doi:10.3389/fmars.2017.00101.
Busseni, G. et al., 2020: Large scale patterns of marine diatom richness: Drivers and trends in a changing ocean. *Global Ecology and Biogeography*, **n/a**(n/a), doi:10.1111/geb.13161.
Butler, C. L., V. L. Lucieer, S. J. Wotherspoon and C. R. Johnson, 2020: Multi-decadal decline in cover of giant kelp Macrocystis pyrifera at the southern limit of its Australian range. *Marine Ecology Progress Series*, **653**, 1-18, doi:10.3354/meps13510.
Byers, J. E., 2021: Marine Parasites and Disease in the Era of Global Climate Change. *Annual Review of Marine Science*, **13**(1), 397-420, doi:10.1146/annurev-marine-031920-100429.
Byram, S. and D. G. Lewis, 2001: Ourigan: Wealth of the Northwest Coast. *Oregon Historical Quarterly* **102**(2), 127-157.
Byrd, G. V., W. J. Sydeman, H. M. Renner and S. Minobe, 2008: Responses of piscivorous seabirds at the Pribilof Islands to ocean climate. *Deep Sea Research Part II: Topical Studies in Oceanography*, **55**(16), 1856-1867, doi:10.1016/j.dsr2.2008.04.015.
Byrne, M., S. A. Foo, P. M. Ross and H. M. Putnam, 2020: Limitations of cross- and multigenerational plasticity for marine invertebrates faced with global climate change. *Global Change Biology*, **26**(1), 80-102, doi:10.1111/gcb.14882.
Byrne, M. et al., 2013: Vulnerability of the calcifying larval stage of the Antarctic sea urchin *Sterechinus neumayeri* to near-future ocean acidification and warming. *Global Change Biology*, **19**(7), 2264-2275, doi:10.1111/gcb.12190.
Cabral, H., V. Fonseca, T. Sousa and M. Costa Leal, 2019: Synergistic Effects of Climate Change and Marine Pollution: An Overlooked Interaction in Coastal and Estuarine Areas. *International Journal of Environmental Research and Public Health*, **16**(15), doi:10.3390/ijerph16152737.
Cabral, R. B. et al., 2020: A global network of marine protected areas for food. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(45), 28134, doi:10.1073/pnas.2000174117.
Cabré, A., I. Marinov, R. Bernardello and D. Bianchi, 2015: Oxygen minimum zones in the tropical Pacific across CMIP5 models: mean state differences and climate change trends. *Biogeosciences*, **12**(18), 5429-5454, doi:10.5194/bg-12-5429-2015.
Cabrerizo, M. J. et al., 2021: Temperature Fluctuation Attenuates the Effects of Warming in Estuarine Microbial Plankton Communities. *Frontiers in Marine Science*, **8**(351), doi:10.3389/fmars.2021.656282.
Cael, B. B., K. Bisson and M. J. Follows, 2017: How have recent temperature changes affected the efficiency of ocean biological carbon export? *Limnology and Oceanography Letters*, **2**(4), 113-118, doi:10.1002/lol2.10042.
Cahoon, D. R., K. L. McKee and M. James, 2021: How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Estuaries and Coasts*, **44**, 883-898, doi:10.1007/s12237-020-00834-w.
Cai, W.-J. et al., 2021: Natural and Anthropogenic Drivers of Acidification in Large Estuaries. *Annual Review of Marine Science*, **13**(1), 23-55, doi:10.1146/annurev-marine-010419-011004.
Cai, W.-J. et al., 2011: Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience*, **4**(11), 766-770, doi:10.1038/ngeo1297.
Cai, W.-J. et al., 2020: Controls on surface water carbonate chemistry along North American ocean margins. *Nature Communications*, **11**(1), 2691, doi:10.1038/s41467-020-16530-z.
Calderón-Liévanos, S. et al., 2019: Survival and respiration of green abalone (*Haliotis fulgens*) facing very short-term marine environmental extremes. *Marine and Freshwater Behaviour and Physiology*, **52**(1), 1-15, doi:10.1080/10236244.2019.1607734.
Calosi, P. et al., 2017: Regional adaptation defines sensitivity to future ocean acidification. *Nature Communications*, **8**(1), 13994, doi:10.1038/ncomms13994.
Cambers, G. and S. P. Wynne, 2019: Beach changes and associated ecosystem services in Anguilla, West Indies, 1992–2014. *Aquatic Ecosystem Health & Management*, **22**(2), 193-204, doi:10.1080/14634988.2019.1628585.
Cameron, C., L. B. Hutley, D. A. Friess and B. Brown, 2019: Community structure dynamics and carbon stock change of rehabilitated mangrove forests in Sulawesi, Indonesia. *Ecological Applications*, **29**(1), e01810, doi:10.1002/eap.1810.

Camoin, G. F. and J. M. Webster, 2015: Coral reef response to Quaternary sea-level and environmental changes: State of the science. *Sedimentology*, **62**(2), 401-428, doi:10.1111/sed.12184.
Campana, S. E., R. B. Stefánsdóttir, K. Jakobsdóttir and J. Sólmundsson, 2020: Shifting fish distributions in warming sub-Arctic oceans. *Scientific Reports*, **10**(1), 16448, doi:10.1038/s41598-020-73444-y.
Campbell, A. M., M.-F. Racault, S. Goult and A. Laurenson, 2020a: Cholera Risk: A Machine Learning Approach Applied to Essential Climate Variables. *International Journal of Environmental Research and Public Health*, **17**(24), doi:10.3390/ijerph17249378.
Campbell, E., R. Marks and C. Conn, 2020b: Spatial modeling of the biophysical and economic values of ecosystem services in Maryland, USA. *Ecosystem Services*, **43**, 101093, doi:10.1016/j.ecoser.2020.101093.
Camus, P. et al., 2019: Probabilistic assessment of port operation downtimes under climate change. *Coastal Engineering*, **147**, 12-24, doi:10.1016/j.coastaleng.2019.01.007.
Canadell, J. G. and R. B. Jackson, 2021: *Ecosystem Collapse and Climate Change*. Ecological Studies, Springer, Cham, 366 pp. ISBN 978-3-030-71329-4.
Canadell, J. G. et al., 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Cao, R. et al., 2018: CO_2-induced ocean acidification impairs the immune function of the Pacific oyster against *Vibrio splendidus* challenge: an integrated study from a cellular and proteomic perspective. *Science of The Total Environment*, **625**, 1574-1583, doi:10.1016/j.scitotenv.2018.01.056.
Capotondi, A. et al., 2012: Enhanced upper ocean stratification with climate change in the CMIP3 models. *Journal of Geophysical Research: Oceans*, **117**(C4), doi:10.1029/2011jc007409.
Carlton, J. T. et al., 2018: Ecological and biological studies of ocean rafting: Japanese tsunami marine debris in North America and the Hawaiian Islands. *Aquatic Invasions*, **13**(1), 1-9, doi:10.3391/ai.2018.13.1.01.
Carlton, J. T. and A. E. Fowler, 2018: Ocean rafting and marine debris: a broader vector menu requires a greater appetite for invasion biology research support. *Aquatic Invasions*, **13**(1), 11-15, doi:10.3391/ai.2018.13.1.02.
Carmichael, B. et al., 2018: Local and Indigenous management of climate change risks to archaeological sites. *Mitigation and Adaptation Strategies for Global Change*, **23**(2), 231-255, doi:10.1007/s11027-016-9734-8.
Carozza, D. A., D. Bianchi and E. D. Galbraith, 2019: Metabolic impacts of climate change on marine ecosystems: implications for fish communities and fisheries. *Global Ecology and Biogeography*, **28**(2), 158-169, doi:10.1111/geb.12832.
Carr, M. H. and D. C. Reed, 2015: Shallow rocky reefs and kelp forests. In: *Ecosystems of California* [Mooney, H. A. and E. Zavaleta (eds.)]. University of California Press, Berkeley, California, pp. 311-336.
Carstensen, J., J. H. Andersen, B. G. Gustafsson and D. J. Conley, 2014: Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(15), 5628, doi:10.1073/pnas.1323156111.
Cashion, T. et al., 2020: Shifting seas, shifting boundaries: Dynamic marine protected area designs for a changing climate. *PLOS ONE*, **15**(11), e0241771, doi:10.1371/journal.pone.0241771.
Cashion, T., P. Tyedmers and R. W. R. Parker, 2017: Global reduction fisheries and their products in the context of sustainable limits. *Fish and Fisheries*, **18**(6), 1026-1037, doi:10.1111/faf.12222.
Cass, C. J. and K. L. Daly, 2014: Eucalanoid copepod metabolic rates in the oxygen minimum zone of the eastern tropical north Pacific: Effects of oxygen and temperature. *Deep-Sea Research Part I: Oceanographic Research Papers*, **94**, 137-149, doi:10.1016/j.dsr.2014.09.003.
Castro, L. C. et al., 2020: Combined mechanistic modelling predicts changes in species distribution and increased co-occurrence of a tropical urchin herbivore and a habitat-forming temperate kelp. *Diversity and Distributions*, **26**(9), 1211-1226, doi:10.1111/ddi.13073.
Cattano, C., J. Claudet, P. Domenici and M. Milazzo, 2018: Living in a high CO_2 world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. *Ecological Monographs*, **88**(3), 320-335, doi:10.1002/ecm.1297.
Causon, P. D. and A. B. Gill, 2018: Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms. *Environmental Science & Policy*, **89**, 340-347, doi:10.1016/j.envsci.2018.08.013.
Cavan, E. L., S. A. Henson, A. Belcher and R. Sanders, 2017: Role of zooplankton in determining the efficiency of the biological carbon pump. *Biogeosciences*, **14**(1), 177-186, doi:10.5194/bg-14-177-2017.
Cavan, E. L., S. A. Henson and P. W. Boyd, 2019: The sensitivity of subsurface microbes to ocean warming accentuates future declines in particulate carbon export. *Front. ecol. evol.*, **6**, 230, doi:10.3389/fevo.2018.00230.
Cavanagh, R. D. et al., 2021: Future Risk for Southern Ocean Ecosystem Services Under Climate Change. *Frontiers in Marine Science*, **7**(1224), doi:10.3389/fmars.2020.615214.
Caves, E. M. and S. Johnsen, 2021: The sensory impacts of climate change: bathymetric shifts and visually mediated interactions in aquatic species. *Proceedings of the Royal Society B: Biological Sciences*, **288**(1949), 20210396, doi:10.1098/rspb.2021.0396.

Cavicchioli, R. et al., 2019: Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, **17**(9), 569-586, doi:10.1038/s41579-019-0222-5.
Cazenave, A. et al., 2018: Global sea-level budget 1993-present. *Earth System Science Data*, **10**(3), 1551-1590, doi:10.5194/essd-10-1551-2018.
CBD, 2009: *Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity*. Secretariat of the Convention on Biological Diversity (CBD) Technical Series No. 46, CBD, Montreal, Canada, 61 pp.
CBD, 2020: Zero Draft of the Post-2020 Global Biodiversity Framework, Kunming, China. Available at: https://www.cbd.int/article/2020-01-10-19-02-38 (accessed 27/10/2020).
Cerrano, C. et al., 2013: Red coral extinction risk enhanced by ocean acidification. *Scientific Reports*, **3**, 1457, doi:10.1038/srep01457.
Chambault, P. et al., 2020: The impact of rising sea temperatures on an Arctic top predator, the narwhal. *Scientific Reports*, **10**(1), 18678, doi:10.1038/s41598-020-75658-6.
Chambers, L. E., P. Dann, B. Cannell and E. J. Woehler, 2014: Climate as a driver of phenological change in southern seabirds. *International Journal of Biometeorology*, **58**(4), 603-612, doi:10.1007/s00484-013-0711-6.
Chami, R., T. Cosimano, C. Fullenkamp and S. Oztosun, 2019: Nature's solution to climate change. International Monetary Fund, Washington, D.C., 34-38 pp.
Champion, C., S. Brodie and M. A. Coleman, 2021: Climate-Driven Range Shifts Are Rapid Yet Variable Among Recreationally Important Coastal-Pelagic Fishes. *Frontiers in Marine Science*, **8**(156), doi:10.3389/fmars.2021.622299.
Champion, C., A. J. Hobday, S. R. Tracey and G. T. Pecl, 2018: Rapid shifts in distribution and high-latitude persistence of oceanographic habitat revealed using citizen science data from a climate change hotspot. *Global Change Biology*, **24**(11), 5440-5453, doi:10.1111/gcb.14398.
Chan, F. T. et al., 2019: Climate change opens new frontiers for marine species in the Arctic: current trends and future invasion risks. *Global Change Biology*, **25**(1), 25-38, doi:10.1111/gcb.14469.
Chan, H. M. et al., 2021: Levels of metals and persistent organic pollutants in traditional foods consumed by First Nations living on-reserve in Canada. *Canadian Journal of Public Health*, **112**(1), 81-96, doi:10.17269/s41997-021-00495-7.
Chan, K. Y. K., D. Grünbaum, M. Arnberg and S. Dupont, 2016: Impacts of ocean acidification on survival, growth, and swimming behaviours differ between larval urchins and brittlestars. *ICES Journal of Marine Science*, **73**(3), 951-961, doi:10.1093/icesjms/fsv073.
Chapman, C. C. et al., 2020: Defining Southern Ocean fronts and their influence on biological and physical processes in a changing climate. *Nature Climate Change*, **10**(3), 209-219, doi:10.1038/s41558-020-0705-4.
Chapron, L. et al., 2020: Long term monitoring of cold-water coral growth shows response to episodic meteorological events in the NW Mediterranean. *Deep Sea Research Part I: Oceanographic Research Papers*, **160**, 103255, doi:10.1016/j.dsr.2020.103255.
Charles, S. P. et al., 2019: Experimental Saltwater Intrusion Drives Rapid Soil Elevation and Carbon Loss in Freshwater and Brackish Everglades Marshes. *Estuaries and Coasts*, **42**(7), 1868-1881, doi:10.1007/s12237-019-00620-3.
Chaudhary, C., A. J. Richardson, D. S. Schoeman and M. J. Costello, 2021: Global warming is causing a more pronounced dip in marine species richness around the equator. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(15), e2015094118, doi:10.1073/pnas.2015094118.
Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, **n/a**(n/a), doi:10.1111/gcb.15310.
Chefaoui, R. M., C. M. Duarte and E. A. Serrão, 2018: Dramatic loss of seagrass habitat under projected climate change in the Mediterranean Sea. *Global Change Biology*, **24**(10), 4919-4928, doi:10.1111/gcb.14401.
Chemeli, A., J. M. Njoroge and P. B. Agufana, 2020: Climate Change and Immovable Cultural Heritage in Kenya: Impact and Response Strategies. In: *Handbook of Climate Change Management: Research, Leadership, Transformation* [Leal Filho, W., J. Luetz and D. Ayal (eds.)]. Springer International Publishing, Cham, pp. 1-22. ISBN 978-3-030-22759-3.
Chen, C. T. A. et al., 2017: Deep oceans may acidify faster than anticipated due to global warming. *Nature Climate Change*, **7**(12), 890-894, doi:10.1038/s41558-017-0003-y.
Chen, D. et al., 2021: Framing, Context, and Methods In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Chen, I.-C. et al., 2011: Rapid range shifts of species associated with high levels of climate warming. *Science*, **333**(6045), 1024-1026, doi:10.1126/science.1206432.
Chen, J. and Y.-g. Xu, 2019: Establishing the link between Permian volcanism and biodiversity changes: Insights from geochemical proxies. *Gondwana Research*, **75**, 68-96, doi:10.1016/j.gr.2019.04.008.
Chen, S., C. De Bruyne and M. Bollempalli, 2018a: *Blue Economy: Community Solutions* [Dickson, C. (ed.)]. UNDP, New York. Available at: https://www.thegef.org/sites/default/files/publications/SGP-Blue%20Economy%20Community%20Solutions-Publication-Digital%20%281%29_0.pdf.

Chen, Y. et al., 2018b: Differential sediment trapping abilities of mangrove and saltmarsh vegetation in a subtropical estuary. *Geomorphology*, **318**, 270-282, doi:10.1016/j.geomorph.2018.06.018.
Cheng, B. S., A. H. Altieri, M. E. Torchin and G. M. Ruiz, 2019: Can marine reserves restore lost ecosystem functioning? A global synthesis. *Ecology*, **100**(4), e02617, doi:10.1002/ecy.2617.
Cherkiss, M. et al., 2020: Shifts in hatching date of American crocodile (Crocodylus acutus) in southern Florida. *Journal of Thermal Biology*, **88**, doi:10.1016/j.jtherbio.2020.102521.
Cherry, S. G., A. E. Derocher, G. W. Thiemann and N. J. Lunn, 2013: Migration phenology and seasonal fidelity of an Arctic marine predator in relation to sea ice dynamics. *Journal of Animal Ecology*, **82**(4), 912-921, doi:10.1111/1365-2656.12050.
Cheung, W., Y. Ota and A. Cisneros-Montemayor (eds.), 2019: *Predicting future oceans: sustainability of ocean and human systems amidst global environmental change*, 1st ed., Elsevier, 582 pp. ISBN 978012817946-8.
Cheung, W. W. L., R. D. Brodeur, T. A. Okey and D. Pauly, 2015: Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progress in Oceanography*, **130**, 19-31, doi:10.1016/j.pocean.2014.09.003.
Cheung, W. W. L. and T. L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, **10**(1), 6678, doi:10.1038/s41598-020-63650-z.
Cheung, W. W. L., M. C. Jones, G. Reygondeau and T. L. Frölicher, 2018: Opportunities for climate-risk reduction through effective fisheries management. *Global Change Biology*, **24**(11), 5149-5163, doi:10.1111/gcb.14390.
Cheung, W. W. L., R. Watson and D. Pauly, 2013: Signature of ocean warming in global fisheries catch. *Nature*, **497**, 365-368, doi:10.1038/nature12156.
Chevillot, X. et al., 2017: Toward a phenological mismatch in estuarine pelagic food web? *PLOS ONE*, **12**(3), e0173752, doi:10.1371/journal.pone.0173752.
Chivers, D. P. et al., 2014: Impaired learning of predators and lower prey survival under elevated CO_2 : a consequence of neurotransmitter interference. *Global Change Biology*, **20**(2), 515-522, doi:10.1111/gcb.12291.
Chivers, W. J., M. Edwards and G. C. Hays, 2020: Phenological shuffling of major marine phytoplankton groups over the last six decades. *Diversity and Distributions*, **26**(5), 536-548, doi:10.1111/ddi.13028.
Choo, L. Q., T. M. P. Bal, E. Goetze and K. T. C. A. Peijnenburg, 2021: Oceanic dispersal barriers in a holoplanktonic gastropod. *Journal of Evolutionary Biology*, **34**(1), 224-240, doi:10.1111/jeb.13735.
Chow, J., 2018: Mangrove management for climate change adaptation and sustainable development in coastal zones. *Journal of Sustainable Forestry*, **37**(2), 139-156, doi:10.1080/10549811.2017.1339615.
Chowdhury, M. S. N. et al., 2019: Oyster breakwater reefs promote adjacent mudflat stability and salt marsh growth in a monsoon dominated subtropical coast. *Scientific Reports*, **9**(1), 8549, doi:10.1038/s41598-019-44925-6.
Christensen, J. et al., 2007: Regional climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 847-940. ISBN 9780521880091.
Christensen, V. et al., 2014: A century of fish biomass decline in the ocean. *Marine Ecology Progress Series*, **512**, 155-166.
Christian, J. R., 2014: Timing of the Departure of Ocean Biogeochemical Cycles from the Preindustrial State. *PLOS ONE*, **9**(11), e109820, doi:10.1371/journal.pone.0109820.
Christie, H. et al., 2019: Shifts Between Sugar Kelp and Turf Algae in Norway: Regime Shifts or Fluctuations Between Different Opportunistic Seaweed Species? *Frontiers in Marine Science*, **6**(72), doi:10.3389/fmars.2019.00072.
Christodoulou, A., P. Christidis and H. Demirel, 2019: Sea-level rise in ports: a wider focus on impacts. *Maritime Economics & Logistics*, **21**(4), 482-496, doi:10.1057/s41278-018-0114-z.
Chu, J. W. F. and V. Tunnicliffe, 2015: Oxygen limitations on marine animal distributions and the collapse of epibenthic community structure during shoaling hypoxia. *Global Change Biology*, **21**(8), 2989-3004, doi:10.1111/gcb.12898.
Chung, W.-S. et al., 2014: Ocean acidification slows retinal function in a damselfish through interference with $GABA_A$; receptors. *The Journal of Experimental Biology*, **217**(3), 323, doi:10.1242/jeb.092478.
Church, J. A. and N. J. White, 2011: Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, **32**(4-5), 585-602, doi:10.1007/s10712-011-9119-1.
Chust, G. et al., 2014a: Biomass changes and trophic amplification of plankton in a warmer ocean. *Global Change Biology*, **20**(7), 2124-2139, doi:10.1111/gcb.12562.
Chust, G. et al., 2014b: Are *Calanus* spp. shifting poleward in the North Atlantic? A habitat modelling approach. *ICES Journal of Marine Science*, **71**(2), 241-253, doi:10.1093/icesjms/fst147.
Chust, G. et al., 2019: Earlier migration and distribution changes of albacore in the Northeast Atlantic. *Fisheries Oceanography*, **28**(5), 505-516, doi:10.1111/fog.12427.
Ciavatta, M. L. et al., 2017: Marine mollusk-derived agents with antiproliferative activity as promising anticancer agents to overcome chemotherapy resistance. *Medicinal Research Reviews*, **37**(4), 702-801, doi:10.1002/med.21423.
Cinner, J. E. and M. L. Barnes, 2019: Social Dimensions of Resilience in Social-Ecological Systems. *One Earth*, **1**(1), 51-56, doi:10.1016/j.oneear.2019.08.003.

Cinner, J. E. et al., 2020: Meeting fisheries, ecosystem function, and biodiversity goals in a human-dominated world. *Science*, **368**(6488), 307, doi:10.1126/science.aax9412.
Cisneros-Montemayor, A. M. et al., 2021: Enabling conditions for an equitable and sustainable blue economy. *Nature*, **591**(7850), 396-401, doi:10.1038/s41586-021-03327-3.
Cisneros-Montemayor, A. M. et al., 2019: Social equity and benefits as the nexus of a transformative blue economy: a sectoral review of implications. *Marine Policy*, **109**, 103702, doi:10.1016/j.marpol.2019.103702.
Cisneros-Montemayor, A. M., D. Pauly, L. V. Weatherdon and Y. Ota, 2016: A global estimate of seafood consumption by coastal Indigenous peoples. *PLOS ONE*, **11**(12), e0166681, doi:10.1371/journal.pone.0166681.
Cisneros-Montemayor, A. M. and U. R. Sumaila, 2014: Economic rationale for shark conservation. In: *Sharks: Conservation, Governance and Management*, 1 ed. Routledge, pp. 197-212. ISBN 978-0415844765.
Clapham, M. E., 2019: Conservation evidence from climate-related stressors in the deep-time marine fossil record. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **374**(1788), 20190223, doi:10.1098/rstb.2019.0223.
Clapham, M. E. and J. L. Payne, 2011: Acidification, anoxia, and extinction: A multiple logistic regression analysis of extinction selectivity during the Middle and Late Permian. *Geology*, **39**(11), 1059-1062, doi:10.1130/G32230.1.
Clark, P. U. et al., 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, **6**(4), 360-369, doi:10.1038/nclimate2923.
Clark, T. D. et al., 2020: Ocean acidification does not impair the behaviour of coral reef fishes. *Nature*, **577**(7790), 370-375, doi:10.1038/s41586-019-1903-y.
Clarkson, M. O. et al., 2015: Ocean acidification and the Permo-Triassic mass extinction. *Science*, **348**(6231), 229-232, doi:10.1126/science.aaa0193.
Claudet, J., 2021: The seven domains of action for a sustainable ocean. *Cell*, **184**(6), 1426-1429, doi:10.1016/j.cell.2021.01.055.
Claudet, J. et al., 2020a: A Roadmap for Using the UN Decade of Ocean Science for Sustainable Development in Support of Science, Policy, and Action. *One Earth*, **2**(1), 34-42, doi:10.1016/j.oneear.2019.10.012.
Claudet, J., C. Loiseau, M. Sostres and M. Zupan, 2020b: Underprotected Marine Protected Areas in a Global Biodiversity Hotspot. *One Earth*, **2**(4), 380-384, doi:10.1016/j.oneear.2020.03.008.
Clay, P. M. et al., 2020: Ocean and coastal indicators: understanding and coping with climate change at the land-sea interface. *Climatic Change*, **163**(4), 1773-1793, doi:10.1007/s10584-020-02940-x.
Clements, J. C. and H. L. Hunt, 2015: Marine animal behaviour in a high CO_2 ocean. *Marine Ecology Progress Series*, **536**, 259-279, doi:10.3354/meps11426.
Cockerell, B. et al., 2020: Representation does not necessarily reduce threats to biodiversity: Australia's Commonwealth marine protected area system, 2012–2018. *Biological Conservation*, **252**, 108813, doi:10.1016/j.biocon.2020.108813.
Cohen, M. C. L. et al., 2020: Impacts of Holocene and modern sea-level changes on estuarine mangroves from northeastern Brazil. *Earth Surface Processes and Landforms*, **45**(2), 375-392, doi:10.1002/esp.4737.
Cohen, P. J. et al., 2019: Securing a Just Space for Small-Scale Fisheries in the Blue Economy. *Frontiers in Marine Science*, **6**(171), doi:10.3389/fmars.2019.00171.
Cohen, R. E. et al., 2018: Marine host-pathogen dynamics: influences of global climate change. *Oceanography*, **31**(2), 182-193, doi:10.5670/oceanog.2018.201.
Cohen-Shacham, E. et al., 2019: Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science & Policy*, **98**, 20-29, doi:10.1016/j.envsci.2019.04.014.
Coldren, G. A., J. A. Langley, I. C. Feller and S. K. Chapman, 2019: Warming accelerates mangrove expansion and surface elevation gain in a subtropical wetland. *Journal of Ecology*, **107**(1), 79-90, doi:10.1111/1365-2745.13049.
Cole, V. J. et al., 2016: Effects of multiple climate change stressors: ocean acidification interacts with warming, hyposalinity, and low food supply on the larvae of the brooding flat oyster Ostrea angasi. *Marine Biology*, **163**(5), 125, doi:10.1007/s00227-016-2880-4.
Coleman, M. A. and H. D. Goold, 2019: Harnessing synthetic biology for kelp forest conservation. *Journal of Phycology*, **55**(4), 745-751, doi:10.1111/jpy.12888.
Coleman, M. A., A. J. P. Minne, S. Vranken and T. Wernberg, 2020a: Genetic tropicalisation following a marine heatwave. *Scientific Reports*, **10**(1), 12726, doi:10.1038/s41598-020-69665-w.
Coleman, M. A. et al., 2020b: Restore or redefine: future trajectories for restoration. *Frontiers in Marine Science*, **7**(237), doi:10.3389/fmars.2020.00237.
Collins, M. et al., 2019a: Extremes, Abrupt Changes and Managing Risks. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. In press.
Collins, M. et al., 2019b: Moderate reductions in dissolved oxygen may compromise performance in an ecologically-important estuarine invertebrate. *Science of The Total Environment*, **693**, 133444, doi:10.1016/j.scitotenv.2019.07.250.
Collins, S., P. W. Boyd and M. A. Doblin, 2020: Evolution, microbes, and changing ocean conditions. *Annual Review of Marine Science*, **12**(1), doi:10.1146/annurev-marine-010318-095311.
Colls, A., N. Ash and N. Ikkala, 2009: *Ecosystem-based adaptation: a natural response to climate change*. IUCN, Gland, Switzerland, 16 pp pp. Available at: https://cmsdata.iucn.org/downloads/iucn_eba_brochure.pdf.

Colman, L. P. et al., 2019: Thirty years of leatherback turtle *Dermochelys coriacea* nesting in Espírito Santo, Brazil, 1988-2017: reproductive biology and conservation. *Endangered Species Research*, **39**, 147-158, doi:10.3354/esr00961.
Colombani, N., A. Osti, G. Volta and M. Mastrocicco, 2016: Impact of Climate Change on Salinization of Coastal Water Resources. *Water Resources Management*, **30**(7), 2483-2496, doi:10.1007/s11269-016-1292-z.
Comeau, S. et al., 2019: Resistance to ocean acidification in coral reef taxa is not gained by acclimatization. *Nature Climate Change*, **9**(6), 477-483, doi:10.1038/s41558-019-0486-9.
Comeau, S., P. J. Edmunds, N. B. Spindel and R. C. Carpenter, 2014: Diel pCO_2 oscillations modulate the response of the coral *Acropora hyacinthus* to ocean acidification. *Marine Ecology Progress Series*, **501**, 99-111, doi:10.3354/meps10690.
Cominassi, L. et al., 2019: Combined effects of ocean acidification and temperature on larval and juvenile growth, development and swimming performance of European sea bass (*Dicentrarchus labrax*). *PLOS ONE*, **14**(9), e0221283, doi:10.1371/journal.pone.0221283.
Cominassi, L. et al., 2020: Food availability modulates the combined effects of ocean acidification and warming on fish growth. *Scientific Reports*, **10**(1), 2338, doi:10.1038/s41598-020-58846-2.
Condie, S. A. et al., 2021: Large-scale interventions may delay decline of the Great Barrier Reef. *Royal Society Open Science*, **8**(4), 201296, doi:10.1098/rsos.201296.
Coni, E. O. C. et al., 2021: Ocean acidification may slow the pace of tropicalization of temperate fish communities. *Nature Climate Change*, **11**(3), 249-256, doi:10.1038/s41558-020-00980-w.
Conrad, K., R. Cleland and N. Reyes, 2021: Evolving Marine Health Threats to Humans. In: *From Hurricanes to Epidemics: The Ocean's Evolving Impact on Human Health - Perspectives from the U.S.* [Conrad, K. (ed.)]. Springer International Publishing, Cham, pp. 81-94. ISBN 978-3-030-55012-7.
Conroy, G., 2019: 'Ecological grief' grips scientists witnessing Great Barrier Reef's decline. *Nature*, **573**, 318-319, doi:10.1038/d41586-019-02656-8.
Conservation International and IUCN, 2021: *Addressing Ocean and Climate Issues Across Relevant Multilateral Environmental Agreements*. Addressing Ocean and Climate Issues, Conservation International and IUCN, 1-8 pp. Available at: https://www.iucn.org/sites/dev/files/content/documents/policybrief_climatechangeandmultilateralagreements.pdf.
Cooley, S. R. et al., 2019: Overlooked ocean strategies to address climate change. *Global Environmental Change*, **59**, 101968, doi:10.1016/j.gloenvcha.2019.101968.
Cooper, J. A. G. et al., 2020a: Sandy beaches can survive sea-level rise. *Nature Climate Change*, **10**(11), 993-995, doi:10.1038/s41558-020-00934-2.
Cooper, J. A. G., M. C. O'Connor and S. McIvor, 2020b: Coastal defences versus coastal ecosystems: A regional appraisal. *Marine Policy*, **111**, 102332, doi:10.1016/j.marpol.2016.02.021.
COP23, 2017: *The Ocean Pathway: Towards an Ocean Inclusive UNFCCC Process* [COP23 Fiji: UN Climate Change Conference (ed.)]. Available at: https://cop23.com.fj/the-ocean-pathway/.
Cordes, E. E. et al., 2016: Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies. *Frontiers in Environmental Science*, **4**(58), doi:10.3389/fenvs.2016.00058.
Cornwall, C. E. et al., 2020: A coralline alga gains tolerance to ocean acidification over multiple generations of exposure. *Nature Climate Change*, **10**(2), 143-146, doi:10.1038/s41558-019-0681-8.
Cornwall, C. E. et al., 2018: Resistance of corals and coralline algae to ocean acidification: physiological control of calcification under natural pH variability. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1884), 20181168, doi:10.1098/rspb.2018.1168.
Cornwall, C. E. et al., 2021: Global declines in coral reef calcium carbonate production under ocean acidification and warming. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(21), e2015265118, doi:10.1073/pnas.2015265118.
Cornwall, C. E., S. Comeau and M. T. McCulloch, 2017a: Coralline algae elevate pH at the site of calcification under ocean acidification. *Global Change Biology*, **23**(10), 4245-4256, doi:10.1111/gcb.13673.
Cornwall, C. E., G. Diaz-Pulido and S. Comeau, 2019: Impacts of ocean warming on coralline algal calcification: meta-analysis, knowledge gaps, and key recommendations for future research. *Frontiers in Marine Science*, **6**, 186, doi:10.3389/fmars.2019.00186.
Cornwall, C. E. et al., 2017b: Inorganic carbon physiology underpins macroalgal responses to elevated CO_2. *Scientific Reports*, **7**(1), 46297, doi:10.1038/srep46297.
Corwin, D. L., 2021: Climate change impacts on soil salinity in agricultural areas. *European Journal of Soil Science*, **72**(2), 842-862, doi:10.1111/ejss.13010.
Costa, M. D. P. et al., 2021: Potential future climate-induced shifts in marine fish larvae and harvested fish communities in the subtropical southwestern Atlantic Ocean. *Climatic Change*, **165**(3), 66, doi:10.1007/s10584-021-03097-x.
Costa, S. et al., 2020a: The influence of climate change related factors on the response of two clam species to diclofenac. *Ecotoxicology and Environmental Safety*, **189**, 109899, doi:10.1016/j.ecoenv.2019.109899.
Costa, S. et al., 2020b: Biochemical and physiological responses of two clam species to Triclosan combined with climate change scenario. *Science of The Total Environment*, **724**, 138143, doi:10.1016/j.scitotenv.2020.138143.
Costello, C. et al., 2020: The future of food from the sea. *Nature*, doi:10.1038/s41586-020-2616-y.

Costello, M. J. and A. a. Cheung, 2010: Surface area and the seabed area, volume, depth, slope and topographic variation for the world's seas, oceans and countries. *Environmental Science & Technology*, 8821–8828, doi:10.1021/es1012752.
Couch, C. S. et al., 2017: Mass coral bleaching due to unprecedented marine heatwave in Papahānaumokuākea Marine National Monument (Northwestern Hawaiian Islands). *PLOS ONE*, **12**(9), e0185121, doi:10.1371/journal.pone.0185121.
Courtney, T. A. et al., 2020: Disturbances drive changes in coral community assemblages and coral calcification capacity. *Ecosphere*, **11**(4), e03066, doi:10.1002/ecs2.3066.
CPI, 2019: *Global Landscape of Climate Finance 2019* [Bucher, B., A. Clark, A. Falconer, R. Macquarie, C. Meattle, R. Tolentino and C. Wetherbee (eds.)]. Climate Policy Initiative, London. Available at: https://climatepolicyinitiative.org/publication/global-climate-finance-2019/.
Cragg, S. M. et al., 2020: Vascular Plants Are Globally Significant Contributors to Marine Carbon Fluxes and Sinks. *Annual Review of Marine Science*, **12**(1), 469-497, doi:10.1146/annurev-marine-010318-095333.
Crain, C. M., K. Kroeker and B. S. Halpern, 2008: Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters*, **11**(12), 1304-1315, doi:10.1111/j.1461-0248.2008.01253.x.
Cram, J. A. et al., 2018: The Role of Particle Size, Ballast, Temperature, and Oxygen in the Sinking Flux to the Deep Sea. *Global Biogeochemical Cycles*, **32**(5), 858-876, doi:10.1029/2017GB005710.
Crame, J. A., 2020: Early Cenozoic evolution of the latitudinal diversity gradient. *Earth-Science Reviews*, **202**, 103090, doi:10.1016/j.earscirev.2020.103090.
Cramer, W. et al., 2018: Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, **8**(11), 972-980, doi:10.1038/s41558-018-0299-2.
Cranmer, N. D., 2016: Chapter 12 – Dzaxwan (Oolichan Fish): Stories my Elders Told Me. In: *Knowing Home: Braiding Indigenous Science with Western Science, Book 1* [Snively, G. and W. L. Williams (eds.)]. University of Victoria, Victoria, BC, Canada, pp. 165-176.
Crespo, G. O. et al., 2019: High-seas fish biodiversity is slipping through the governance net. *Nature Ecology & Evolution*, **3**(9), 1273-1276, doi:10.1038/s41559-019-0981-4.
Crespo, G. O. et al., 2020: Beyond static spatial management: Scientific and legal considerations for dynamic management in the high seas. *Marine Policy*, 104102, doi:10.1016/j.marpol.2020.104102.
Croke, R., 2021: Incorporating climate change adaptation into large marine protected areas: the case of Ascension Island MPA. Dalhousie University, Halifax, Nova Scotia.
Crosman, K. M., E. L. Petrou, M. B. Rudd and M. D. Tillotson, 2019: Clam hunger and the changing ocean: characterizing social and ecological risks to the Quinault razor clam fishery using participatory modeling. *Ecology and Society*, **24**(2), doi:10.5751/ES-10928-240216.
Cummins, P. F. and T. Ross, 2020: Secular trends in water properties at Station P in the northeast Pacific: An updated analysis. *Progress in Oceanography*, **186**, 102329, doi:10.1016/j.pocean.2020.102329.
Curnock, M. I. et al., 2019: Shifts in tourists' sentiments and climate risk perceptions following mass coral bleaching of the Great Barrier Reef. *Nature Climate Change*, **9**(7), 535-541, doi:10.1038/s41558-019-0504-y.
Curtis, A. N. et al., 2019: Effects of temperature, salinity, and sediment organic carbon on methylmercury bioaccumulation in an estuarine amphipod. *Science of The Total Environment*, **687**, 907-916, doi:10.1016/j.scitotenv.2019.06.094.
Cusset, F. et al., 2019: Arctic seabirds and shrinking sea ice: egg analyses reveal the importance of ice-derived resources. *Scientific Reports*, **9**(1), 15405, doi:10.1038/s41598-019-51788-4.
Cvitanovic, C. and A. J. Hobday, 2018: Building optimism at the environmental science-policy-practice interface through the study of bright spots. *Nature Communications*, **9**(1), 3466, doi:10.1038/s41467-018-05977-w.
Cvitanovic, C. et al., 2018: Governing fisheries through the critical decade: the role and utility of polycentric systems. *Reviews in Fish Biology and Fisheries*, **28**(1), 1-18, doi:10.1007/s11160-017-9495-9.
Cziesielski, M. J., S. Schmidt-Roach and M. Aranda, 2019: The past, present, and future of coral heat stress studies. *Ecology and Evolution*, **9**(17), 10055-10066, doi:10.1002/ece3.5576.
D'Alelio, D., L. Russo, B. Hay Mele and F. Pomati, 2021: Intersecting Ecosystem Services Across the Aquatic Continuum: From Global Change Impacts to Local, and Biologically Driven, Synergies and Trade-Offs. *Front. ecol. evol.*, **9**(199), doi:10.3389/fevo.2021.628658.
D'Amario, B. et al., 2020: Coccolithophore community response to ocean acidification and warming in the Eastern Mediterranean Sea: results from a mesocosm experiment. *Scientific Reports*, **10**(1), 12637, doi:10.1038/s41598-020-69519-5.
D'Amen, M. and E. Azzurro, 2020: Lessepsian fish invasion in Mediterranean marine protected areas: a risk assessment under climate change scenarios. *ICES Journal of Marine Science*, **77**(1), 388-397, doi:10.1093/icesjms/fsz207.
da Silva, R. et al., 2019: Assessing the conservation potential of fish and corals in aquariums globally. *Journal for Nature Conservation*, **48**, 1-11, doi:10.1016/j.jnc.2018.12.001.
Dahlke, F. et al., 2020a: Fish embryo vulnerability to combined acidification and warming coincides with a low capacity for homeostatic regulation. *The Journal of Experimental Biology*, **223**(11), jeb212589, doi:10.1242/jeb.212589.
Dahlke, F. T. et al., 2018: Northern cod species face spawning habitat losses if global warming exceeds 1.5°C. *Science Advances*, **4**(11), eaas8821, doi:10.1126/sciadv.aas8821.

Dahlke, F. T. et al., 2017: Effects of ocean acidification increase embryonic sensitivity to thermal extremes in Atlantic cod, *Gadus morhua*. *Global Change Biology*, **23**(4), 1499-1510, doi:10.1111/gcb.13527.
Dahlke, F. T., S. Wohlrab, M. Butzin and H.-O. Pörtner, 2020b: Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, **369**(6499), 65-70, doi:10.1126/science.aaz3658.
Dall'Olmo, G. et al., 2016: Substantial energy input to the mesopelagic ecosystem from the seasonal mixed-layer pump. *Nature Geoscience*, **9**(11), 820-823, doi:10.1038/ngeo2818.
Dam, H. G., 2013: Evolutionary Adaptation of Marine Zooplankton to Global Change. *Annual Review of Marine Science*, **5**(1), 349-370, doi:10.1146/annurev-marine-121211-172229.
Dangendorf, S. et al., 2017: Reassessment of 20th century global mean sea level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(23), 5946-5951, doi:10.1073/pnas.1616007114.
Danovaro, R., 2018: Climate change impacts on the biota and on vulnerable habitats of the deep Mediterranean Sea. *Rendiconti Lincei. Scienze Fisiche e Naturali*, **29**(3), 525-541, doi:10.1007/s12210-018-0725-4.
Danovaro, R. et al., 2020: Ecological variables for developing a global deep-ocean monitoring and conservation strategy. *Nature Ecology & Evolution*, **4**(2), 181-192, doi:10.1038/s41559-019-1091-z.
Darling, E. S. and I. M. Côté, 2018: Seeking resilience in marine ecosystems. *Science*, **359**(6379), 986, doi:10.1126/science.aas9852.
Darling, E. S. et al., 2019: Social–environmental drivers inform strategic management of coral reefs in the Anthropocene. *Nature Ecology & Evolution*, **3**(9), 1341-1350, doi:10.1038/s41559-019-0953-8.
Darmaraki, S., S. Somot, F. Sevault and P. Nabat, 2019: Past variability of Mediterranean Sea marine heatwaves. *Geophysical Research Letters*, **46**(16), 9813-9823, doi:10.1029/2019GL082933.
Das, I. et al., 2020: Effects of climate change and management policies on marine fisheries productivity in the north-east coast of India. *Science of The Total Environment*, **724**, 138082, doi:10.1016/j.scitotenv.2020.138082.
Dasgupta, S. et al., 2019: Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. *PLOS ONE*, **14**(3), e0214079, doi:10.1371/journal.pone.0214079.
Dave, D. and W. Routray, 2018: Current scenario of Canadian fishery and corresponding underutilized species and fishery byproducts: a potential source of omega-3 fatty acids. *Journal of Cleaner Production*, **180**, 617-641, doi:10.1016/j.jclepro.2018.01.091.
David, C. G. and T. Schlurmann, 2020: Hydrodynamic Drivers and Morphological Responses on Small Coral Islands—The Thoondu Spit on Fuvahmulah, the Maldives. *Frontiers in Marine Science*, **7**(885), doi:10.3389/fmars.2020.538675.
Davidson, K. et al., 2021: HABreports: Online Early Warning of Harmful Algal and Biotoxin Risk for the Scottish Shellfish and Finfish Aquaculture Industries. *Frontiers in Marine Science*, **8**, 350.
Davies, T. W., J. P. Duffy, J. Bennie and K. J. Gaston, 2014: The nature, extent, and ecological implications of marine light pollution. *Frontiers in Ecology and the Environment*, **12**(6), 347-355, doi:10.1890/130281.
Davis, B., J. K. et al., 2019: Vibrio parahaemolyticus in the Chesapeake Bay: Operational In Situ Prediction and Forecast Models Can Benefit from Inclusion of Lagged Water Quality Measurements. *Applied and Environmental Microbiology*, **85**(17), e01007-01019, doi:10.1128/AEM.01007-19.
Davis, G. E. et al., 2020: Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. *Global Change Biology*, **26**(9), 4812-4840, doi:10.1111/gcb.15191.
Dawson, J. et al., 2020: Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. *Environmental Science & Policy*, **105**, 19-36, doi:10.1016/j.envsci.2019.11.013.
Dawson, J., E. J. Stewart, M. E. Johnston and C. J. Lemieux, 2016: Identifying and evaluating adaptation strategies for cruise tourism in Arctic Canada. *Journal of Sustainable Tourism*, **24**(10), 1425-1441, doi:10.1080/09669582.2015.1125358.
Day, J. W. and J. M. Rybczyk, 2019: Chapter 36 - Global Change Impacts on the Future of Coastal Systems: Perverse Interactions Among Climate Change, Ecosystem Degradation, Energy Scarcity, and Population. In: *Coasts and Estuaries* [Wolanski, E., J. W. Day, M. Elliott and R. Ramachandran (eds.)]. Elsevier, pp. 621-639. ISBN 978-0-12-814003-1.
de la Hoz, C. F., E. Ramos, A. Puente and J. A. Juanes, 2019: Climate change induced range shifts in seaweeds distributions in Europe. *Marine Environmental Research*, **148**, 1-11, doi:10.1016/j.marenvres.2019.04.012.
De Leo, F. C. et al., 2012: The effects of submarine canyons and the oxygen minimum zone on deep-sea fish assemblages off Hawai'i. *Deep Sea Research Part I: Oceanographic Research Papers*, **64**, 54-70, doi:10.1016/j.dsr.2012.01.014.
de los Santos, C. B. et al., 2019: Recent trend reversal for declining European seagrass meadows. *Nature Communications*, **10**(1), 3356, doi:10.1038/s41467-019-11340-4.
de Schipper, M. A. et al., 2021: Beach nourishment has complex implications for the future of sandy shores. *Nature Reviews Earth & Environment*, **2**(1), 70-84, doi:10.1038/s43017-020-00109-9.
Debortoli, N. S. et al., 2019: An integrative climate change vulnerability index for Arctic aviation and marine transportation. *Nature Communications*, **10**(1), 2596, doi:10.1038/s41467-019-10347-1.

DeCarlo, T. M., S. Comeau, C. E. Cornwall and M. T. McCulloch, 2018: Coral resistance to ocean acidification linked to increased calcium at the site of calcification. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1878), 20180564, doi:10.1098/rspb.2018.0564.
DeCarlo, T. M. et al., 2020: Nutrient-supplying ocean currents modulate coral bleaching susceptibility. *Science Advances*, **6**(34), eabc5493, doi:10.1126/sciadv.abc5493.
DeCarlo, T. M. et al., 2019: Acclimatization of massive reef-building corals to consecutive heatwaves. *Proceedings of the Royal Society B: Biological Sciences*, **286**(1898), 20190235, doi:10.1098/rspb.2019.0235.
Dee, L. E. et al., 2019a: When do ecosystem services depend on rare species? *Trends in Ecology & Evolution*, **34**(8), 746-758, doi:10.1016/j.tree.2019.03.010.
Dee, L. E., K. A. Karr, C. J. Landesberg and D. J. Thornhill, 2019b: Assessing vulnerability of fish in the U.S. marine aquarium trade. *Frontiers in Marine Science*, **5**, 527, doi:10.3389/fmars.2018.00527.
Del Castillo, C. E., S. R. Signorini, E. M. Karaköylü and S. Rivero-Calle, 2019: Is the Southern Ocean Getting Greener? *Geophysical Research Letters*, **46**(11), 6034-6040, doi:10.1029/2019GL083163.
Del Giudice, D., V. R. R. Matli and D. R. Obenour, 2020: Bayesian mechanistic modeling characterizes Gulf of Mexico hypoxia: 1968–2016 and future scenarios. *Ecological Applications*, **30**(2), e02032, doi:10.1002/eap.2032.
Delgado, L. E. et al., 2019: Environmental Governance for the Coastal Marine Ecosystem Services of Chiloé Island (Southern Chile). In: *Social-ecological Systems of Latin America: Complexities and Challenges* [Delgado, L. E. and V. H. Marín (eds.)]. Springer International Publishing, Cham, pp. 389-405. ISBN 978-3-030-28452-7.
Denechaud, C. et al., 2020: A century of fish growth in relation to climate change, population dynamics and exploitation. *Global Change Biology*, doi:10.1111/gcb.15298.
Deppeler, S. L. and A. T. Davidson, 2017: Southern Ocean phytoplankton in a changing climate. *Frontiers in Marine Science*, **4**, 40, doi:10.3389/fmars.2017.00040.
Derolez, V. et al., 2020: Fifty years of ecological changes: Regime shifts and drivers in a coastal Mediterranean lagoon during oligotrophication. *Science of The Total Environment*, **732**, 139292, doi:10.1016/j.scitotenv.2020.139292.
Descamps, S. et al., 2019: Diverging phenological responses of Arctic seabirds to an earlier spring. *Global Change Biology*, **25**(12), 4081-4091, doi:10.1111/gcb.14780.
Deutsch, C. et al., 2015: Climate change tightens a metabolic constraint on marine habitats. *Science*, **348**(6239), 1132-1135, doi:10.1126/science.aaa1605.
Deutsch, C., J. L. Penn and B. Seibel, 2020: Metabolic trait diversity shapes marine biogeography. *Nature*, **585**(7826), 557-562, doi:10.1038/s41586-020-2721-y.
Devol, A. H., 2015: Denitrification, anammox, and N_2 production in marine sediments. *Annual Review of Marine Science*, **7**(1), 403-423, doi:10.1146/annurev-marine-010213-135040.
Dewapriya, P. and S.-k. Kim, 2014: Marine microorganisms: an emerging avenue in modern nutraceuticals and functional foods. *Food Research International*, **56**, 115-125, doi:10.1016/j.foodres.2013.12.022.
DeWitt, T. J., A. Sih and D. S. Wilson, 1998: Costs and limits of phenotypic plasticity. *Trends in Ecology & Evolution*, **13**(2), 77-81, doi:10.1016/S0169-5347(97)01274-3.
Dezutter, T. et al., 2019: Mismatch between microalgae and herbivorous copepods due to the record sea ice minimum extent of 2012 and the late sea ice break-up of 2013 in the Beaufort Sea. *Progress in Oceanography*, **173**, 66-77, doi:10.1016/j.pocean.2019.02.008.
Di Lorenzo, E. et al., 2009: Nutrient and salinity decadal variations in the central and eastern North Pacific. *Geophysical Research Letters*, **36**(14), doi:10.1029/2009GL038261.
Dias, M. P. et al., 2019: Threats to seabirds: a global assessment. *Biological Conservation*, **237**, 525-537, doi:10.1016/j.biocon.2019.06.033.
Díaz, P. A. et al., 2019: Impacts of harmful algal blooms on the aquaculture industry: Chile as a case study. *Perspectives in Phycology*, **6**(1-2), 39-50, doi:10.1127/pip/2019/0081.
Diaz, R. J. and R. Rosenberg, 2008: Spreading dead zones and consequences for marine ecosystems. *Science*, **321**(5891), 926-929, doi:10.1126/science.1156401.
Díaz, S. et al., 2018: Assessing nature's contributions to people. *Science*, **359**(6373), 270-272, doi:10.1126/science.aap8826.
Diaz-Almela, E., N. MarbÀ and C. M. Duarte, 2007: Consequences of Mediterranean warming events in seagrass (Posidonia oceanica) flowering records. *Global Change Biology*, **13**(1), 224-235, doi:10.1111/j.1365-2486.2006.01260.x.
Dickinson, G. H. et al., 2012: Interactive effects of salinity and elevated CO_2 levels on juvenile eastern oysters, *Crassostrea virginica*. *The Journal of Experimental Biology*, **215**(1), 29-43, doi:10.1242/jeb.061481.
Dieterich, C., M. Gröger, L. Arneborg and H. C. Andersson, 2019: Extreme sea levels in the Baltic Sea under climate change scenarios – Part 1: model validation and sensitivity. *Ocean Science*, **15**(6), 1399-1418, doi:10.5194/os-15-1399-2019.
Dimitriadis, C. et al., 2021: Long Term Interactions of Native and Invasive Species in a Marine Protected Area Suggest Complex Cascading Effects Challenging Conservation Outcomes. *Diversity*, **13**(2), doi:10.3390/d13020071.
Dionísio, R. et al., 2020: Effects of pH on salicylic acid toxicity in terms of biomarkers determined in the marine gastropod Gibbula umbilicalis. *Marine Environmental Research*, **158**, 104995, doi:10.1016/j.marenvres.2020.104995.

Doberstein, B., J. Fitzgibbons and C. Mitchell, 2019: Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience. *Natural Hazards*, **98**(1), 31-50, doi:10.1007/s11069-018-3529-z.
Dobretsov, S. et al., 2019: The oceans are changing: impact of ocean warming and acidification on biofouling communities. *Biofouling*, **35**(5), 585-595, doi:10.1080/08927014.2019.1624727.
Donahue, K., C. Klaas, P. W. Dillingham and L. J. Hoffmann, 2019: Combined effects of ocean acidification and increased light intensity on natural phytoplankton communities from two Southern Ocean water masses. *Journal of Plankton Research*, **41**(1), 30-45, doi:10.1093/plankt/fby048.
Donatuto, J. L., T. A. Satterfield and R. Gregory, 2011: Poisoning the body to nourish the soul: prioritising health risks and impacts in a Native American community. *Health, Risk & Society*, **13**(2), 103-127, doi:10.1080/13698575.2011.556186.
Doney, S. C., 2010: The growing human footprint on coastal and open-ocean biogeochemistry. *Science*, **328**(5985), 1512-1516, doi:10.1126/science.1185198.
Doney, S. C., D. S. Busch, S. R. Cooley and K. J. Kroeker, 2020: The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. *Annual Review of Environment and Resources*, doi:10.1146/annurev-environ-012320-083019.
Doney, S. C., V. J. Fabry, R. A. Feely and J. A. Kleypas, 2009: Ocean Acidification: The Other CO2 Problem. *Annual Review of Marine Science*, **1**(1), 169-192, doi:10.1146/annurev.marine.010908.163834.
Doney, S. C. et al., 2007: Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(37), 14580-14585, doi:10.1073/pnas.0702218104.
Dong, K., K. Kvile, N. C. Stenseth and L. C. Stige, 2021: Associations between timing and magnitude of spring blooms and zooplankton dynamics in the southwestern Barents Sea. *Marine Ecology Progress Series*, **668**, 57-72.
Donner, S. D., 2009: Coping with commitment: projected thermal stress on coral reefs under different future scenarios. *PLOS ONE*, **4**(6), e5712, doi:10.1371/journal.pone.0005712.
Donner, S. D. and J. Carilli, 2019: Resilience of Central Pacific reefs subject to frequent heat stress and human disturbance. *Scientific Reports*, **9**(1), 3484, doi:10.1038/s41598-019-40150-3.
Donner, S. D., M. Kandlikar and S. Webber, 2016: Measuring and tracking the flow of climate change adaptation aid to the developing world. *Environ.Res.Lett.*, **11**(5), 054006, doi:10.1088/1748-9326/11/5/054006.
Donner, S. D., G. J. Rickbeil and S. F. Heron, 2017: A new, high-resolution global mass coral bleaching database. *PLOS ONE*, **12**(4), e0175490, doi:10.1371/journal.pone.0175490.
Donohoe, H. M. and R. D. Needham, 2006: Ecotourism: the evolving contemporary definition. *Journal of Ecotourism*, **5**(3), 192-210, doi:10.2167/joe152.0.
Doo, S. S. et al., 2020: The challenges of detecting and attributing ocean acidification impacts on marine ecosystems. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsaa094.
Doughty, C. L., K. C. Cavanaugh, R. F. Ambrose and E. D. Stein, 2019: Evaluating regional resiliency of coastal wetlands to sea level rise through hypsometry-based modeling. *Global Change Biology*, **25**(1), 78-92, doi:10.1111/gcb.14429.
Douglass, J. G., R. H. Chamberlain, Y. Wan and P. H. Doering, 2020: Submerged Vegetation Responses to Climate Variation and Altered Hydrology in a Subtropical Estuary: Interpreting 33 Years of Change. *Estuaries and Coasts*, **43**(6), 1406-1424, doi:10.1007/s12237-020-00721-4.
Dowd, W. W., F. A. King and M. W. Denny, 2015: Thermal variation, thermal extremes and the physiological performance of individuals. *The Journal of Experimental Biology*, **218**(12), 1956, doi:10.1242/jeb.114926.
Drakou, E. G., J. Virdin and L. Pendleton, 2018: Mapping the global distribution of locally-generated marine ecosystem services: the case of the West and Central Pacific Ocean tuna fisheries. *Ecosystem Services*, **31**, 278-288, doi:10.1016/j.ecoser.2018.05.008.
du Pontavice, H. et al., 2020: Climate change undermines the global functioning of marine food webs. *Global Change Biology*, **26**(3), 1306-1318, doi:10.1111/gcb.14944.
Duarte, B. et al., 2018: Climate change impacts on seagrass meadows and macroalgal forests: an integrative perspective on acclimation and adaptation potential. *Frontiers in Marine Science*, **5**, 190, doi:10.3389/fmars.2018.00190.
Duarte, C. M. et al., 2020: Rebuilding marine life. *Nature*, **580**(7801), 39-51, doi:10.1038/s41586-020-2146-7.
Duarte, C. M. et al., 2021: The soundscape of the Anthropocene ocean. *Science*, **371**(6529), aba4658, doi:10.1126/science.aba4658.
Duarte, C. M. et al., 2013: Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuaries and Coasts*, **36**(2), 221-236, doi:10.1007/s12237-013-9594-3.
Dubik, B. A. et al., 2019: Governing fisheries in the face of change: Social responses to long-term geographic shifts in a U.S. fishery. *Marine Policy*, **99**, 243-251, doi:10.1016/j.marpol.2018.10.032.
Ducrotoy, J. P. et al., 2019: Chapter 33 - Temperate estuaries: their ecology under future environmental changes. In: *Coasts and Estuaries* [Wolanski, E., J. W. Day, M. Elliott and R. Ramachandran (eds.)]. Elsevier, pp. 577-594. ISBN 978-0-12-814003-1.
Dueri, S., L. Bopp and O. Maury, 2014: Projecting the impacts of climate change on skipjack tuna abundance and spatial distribution. *Global Change Biology*, **20**(3), 742-753, doi:10.1111/gcb.12460.

Duffy-Anderson, J. T. et al., 2019: Responses of the Northern Bering Sea and Southeastern Bering Sea Pelagic Ecosystems Following Record-Breaking Low Winter Sea Ice. *Geophysical Research Letters*, **46**(16), 9833-9842, doi:10.1029/2019GL083396.

Dufour, F., H. Arrizabalaga, X. Irigoien and J. Santiago, 2010: Climate impacts on albacore and bluefin tunas migrations phenology and spatial distribution. *Progress in Oceanography*, **86**(1), 283-290, doi:10.1016/j.pocean.2010.04.007.

Duke, N. C., L. B. Hutley, J. R. Mackenzie and D. Burrows, 2021: Processes and Factors Driving Change in Mangrove Forests: An Evaluation Based on the Mass Dieback Event in Australia's Gulf of Carpentaria. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 221-264. ISBN 978-3-030-71330-0.

Dulvy, N. K. et al., 2008: Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, **45**(4), 1029-1039, doi:10.1111/j.1365-2664.2008.01488.x.

Dundas, S. J. et al., 2020: Integrating oceans into climate policy: Any green new deal needs a splash of blue. *Conservation Letters*, **n/a**(n/a), e12716, doi:10.1111/conl.12716.

Dunn, D. C. et al., 2018: A strategy for the conservation of biodiversity on mid-ocean ridges from deep-sea mining. *Science Advances*, **4**(7), eaar4313, doi:10.1126/sciadv.aar4313.

Dunstan, P. K. et al., 2018: How can climate predictions improve sustainability of coastal fisheries in Pacific small-island developing states? *Marine Policy*, **88**, 295-302, doi:10.1016/j.marpol.2017.09.033.

Dupont, N. and D. L. Aksnes, 2013: Centennial changes in water clarity of the Baltic Sea and the North Sea. *Estuarine, Coastal and Shelf Science*, **131**, 282-289, doi:10.1016/j.ecss.2013.08.010.

Durant, J. M. et al., 2019: Contrasting effects of rising temperatures on trophic interactions in marine ecosystems. *Scientific Reports*, **9**(1), 15213, doi:10.1038/s41598-019-51607-w.

Durant, J. M., K. Ono, N. C. Stenseth and Ø. Langangen, 2020: Nonlinearity in interspecific interactions in response to climate change: Cod and haddock as an example. *Global Change Biology*, **26**(10), 5554-5563, doi:10.1111/gcb.15264.

Dutkiewicz, S. et al., 2020: Dimensions of marine phytoplankton diversity. *Biogeosciences*, **17**(3), 609-634, doi:10.5194/bg-17-609-2020.

Dutkiewicz, S. et al., 2019: Ocean colour signature of climate change. *Nature Communications*, **10**(1), 578, doi:10.1038/s41467-019-08457-x.

Duvat, V. et al., 2019: High human influence on beach response to tropical cyclones in small islands: Saint-Martin Island, Lesser Antilles. *Geomorphology*, **325**, 70-91, doi:10.1016/j.geomorph.2018.09.029.

Duvat, V. K. E., 2019: A global assessment of atoll island planform changes over the past decades. *WIREs Climate Change*, **10**(1), e557, doi:10.1002/wcc.557.

Eakin, C. M., H. P. A. Sweatman and R. E. Brainard, 2019: The 2014–2017 global-scale coral bleaching event: insights and impacts. *Coral Reefs*, **38**(4), 539-545, doi:10.1007/s00338-019-01844-2.

Eberlein, T. et al., 2016: Interactive effects of ocean acidification and nitrogen limitation on two bloom-forming dinoflagellate species. *Marine Ecology Progress Series*, **543**, 127-140, doi:10.3354/meps11568.

Edwards, M. et al., 2021: North Atlantic warming over six decades drives decreases in krill abundance with no associated range shift. *Communications Biology*, **4**(1), 644, doi:10.1038/s42003-021-02159-1.

Edwards, M. and A. J. Richardson, 2004: Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430**(7002), 881-884, doi:10.1038/nature02808.

Egea, L. G. et al., 2018: Interactive effect of temperature, acidification and ammonium enrichment on the seagrass Cymodocea nodosa. *Marine Pollution Bulletin*, **134**, 14-26, doi:10.1016/j.marpolbul.2018.02.029.

Eger, A. M., E. Marzinelli, P. Steinberg and A. Verges, 2020: Worldwide Synthesis of Kelp Forest Reforestation, 1 [OSF (ed.)]. Available at: https://osf.io/5bgtw/ (accessed 29/10/2020).

Ekstrom, J. A., S. K. Moore and T. Klinger, 2020: Examining harmful algal blooms through a disaster risk management lens: A case study of the 2015 U.S. West Coast domoic acid event. *Harmful Algae*, **94**, 101740, doi:10.1016/j.hal.2020.101740.

Elko, N. et al., 2021: A century of U.S. beach nourishment. *Ocean & Coastal Management*, **199**, 105406, doi:10.1016/j.ocecoaman.2020.105406.

Elliott, M., J. W. Day, R. Ramachandran and E. Wolanski, 2019: Chapter 1 - A synthesis: what is the future for coasts, estuaries, deltas and other transitional habitats in 2050 and beyond? In: *Coasts and Estuaries* [Wolanski, E., J. W. Day, M. Elliott and R. Ramachandran (eds.)]. Elsevier, pp. 1-28. ISBN 978-0-12-814003-1.

Elliott, P. and H. Williams, 2019: Evaluating sea-level rise hazards on coastal archaeological sites, Trinity Bay, Texas. *The Journal of Island and Coastal Archaeology*, 1-19, doi:10.1080/15564894.2019.1701149.

Elsayed, H. et al., 2020: Methylmercury bioaccumulation among different food chain levels in the EEZ of Qatar (Arabian Gulf). *Regional Studies in Marine Science*, **37**, 101334, doi:10.1016/j.rsma.2020.101334.

Elzahaby, Y. and A. Schaeffer, 2019: Observational Insight Into the Subsurface Anomalies of Marine Heatwaves. *Frontiers in Marine Science*, **6**, 745, doi:10.3389/fmars.2019.00745.

Émond, K., B. Sainte-Marie and J. Bêty, 2020: Long-term trends and drivers of larval phenology and abundance of dominant brachyuran crabs in the Gulf of St. Lawrence (Canada). *Fisheries Oceanography*, **29**(2), 185-200, doi:10.1111/fog.12463.

Enbody, E. D. et al., 2021: Ecological adaptation in European eels is based on phenotypic plasticity. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(4), e2022620118, doi:10.1073/pnas.2022620118.
Engler, C., 2020: Transboundary fisheries, climate change, and the ecosystem approach: taking stock of the international law and policy seascape. *Ecology and Society*, **25**(4), doi:10.5751/ES-11988-250443.
Enríquez-de-Salamanca, Á., 2020: Evolution of coastal erosion in Palmarin (Senegal). *Journal of Coastal Conservation*, **24**(2), 25, doi:10.1007/s11852-020-00742-y.
Epstein, H. E., H. A. Smith, G. Torda and M. J. H. van Oppen, 2019: Microbiome engineering: enhancing climate resilience in corals. *Frontiers in Ecology and the Environment*, **17**(2), 100-108, doi:10.1002/fee.2001.
Equator Initiative, 2020: What's the Equator Prize?, Equator Initiative. Available at: https://www.equatorinitiative.org/equator-prize/.
Erauskin-Extramiana, M. et al., 2020: Are shifts in species distribution triggered by climate change? A swordfish case study. *Deep Sea Research Part II: Topical Studies in Oceanography*, **175**, 104666, doi:10.1016/j.dsr2.2019.104666.
Erauskin-Extramiana, M. et al., 2019: Large-scale distribution of tuna species in a warming ocean. *Global Change Biology*, **25**(6), 1-8, doi:10.1111/gcb.14630.
Eriander, L., A. L. Wrange and J. N. Havenhand, 2015: Simulated diurnal pH fluctuations radically increase variance in—but not the mean of—growth in the barnacle *Balanus improvisus*. *ICES Journal of Marine Science*, **73**(3), 596-603, doi:10.1093/icesjms/fsv214.
Erickson, K. A. et al., 2021: Changing climate associated with the range-wide decline of an estuarine finfish. *Global Change Biology*, **27**(11), 2520-2536, doi:10.1111/gcb.15568.
Ericson, J. A. et al., 2019: Near-future ocean acidification does not alter the lipid content and fatty acid composition of adult Antarctic krill. *Scientific Reports*, **9**(1), 12375, doi:10.1038/s41598-019-48665-5.
Ern, R., J. L. Johansen, J. L. Rummer and A. J. Esbaugh, 2017: Effects of hypoxia and ocean acidification on the upper thermal niche boundaries of coral reef fishes. *Biology Letters*, **13**(7), 20170135, doi:10.1098/rsbl.2017.0135.
Erskine, E., R. Baillie and D. Lusseau, 2021: Marine Protected Areas provide more cultural ecosystem services than other adjacent coastal areas. *One Earth*, **4**(8), 1175-1185, doi:10.1016/j.oneear.2021.07.014.
Esbaugh, A. J., 2018: Physiological implications of ocean acidification for marine fish: emerging patterns and new insights. *Journal of Comparative Physiology B*, **188**(1), 1-13, doi:10.1007/s00360-017-1105-6.
Escajeda, E. et al., 2018: Identifying shifts in maternity den phenology and habitat characteristics of polar bears (*Ursus maritimus*) in Baffin Bay and Kane Basin. *Polar Biology*, **41**(1), 87-100, doi:10.1007/s00300-017-2172-6.
Espeland, E. K. and K. M. Kettenring, 2018: Strategic plant choices can alleviate climate change impacts: a review. *Journal of Environmental Management*, **222**, 316-324, doi:10.1016/j.jenvman.2018.05.042.
Espinel-Velasco, N. et al., 2018: Effects of ocean acidification on the settlement and metamorphosis of marine invertebrate and fish larvae: a review. *Marine Ecology Progress Series*, **606**, 237-257, doi:10.3354/meps12754.
Eswar, D., R. Karuppusamy and S. Chellamuthu, 2021: Drivers of soil salinity and their correlation with climate change. *Current Opinion in Environmental Sustainability*, doi:10.1016/j.cosust.2020.10.015.
Evans, R., M. A. Lea, M. A. Hindell and K. M. Swadling, 2020: Significant shifts in coastal zooplankton populations through the 2015/16 Tasman Sea marine heatwave. *Estuarine, Coastal and Shelf Science*, **235**, 106538, doi:10.1016/j.ecss.2019.106538.
Fabricius, K. E., G. De'ath, S. Noonan and S. Uthicke, 2014: Ecological effects of ocean acidification and habitat complexity on reef-associated macroinvertebrate communities. *Proceedings of the Royal Society B: Biological Sciences*, **281**(1775), 20132479, doi:10.1098/rspb.2013.2479.
Fabricius, K. E. et al., 2015: In situ changes of tropical crustose coralline algae along carbon dioxide gradients. *Scientific Reports*, **5**(1), 9537, doi:10.1038/srep09537.
Fabricius, K. E. et al., 2011: Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change*, **1**(3), 165-169, doi:10.1038/nclimate1122.
Fadli, N. et al., 2012: The role of habitat creation in coral reef conservation: a case study from Aceh, Indonesia. *Oryx*, **46**(4), 501-507, doi:10.1017/S0030605312000142.
Fagherazzi, S. et al., 2020: Salt Marsh Dynamics in a Period of Accelerated Sea Level Rise. *Journal of Geophysical Research: Earth Surface*, **125**(8), e2019JF005200, doi:10.1029/2019JF005200.
Failler, P. et al., 2020: Perception of threats and related management measures: The case of 32 marine protected areas in West Africa. *Marine Policy*, **117**, 103936, doi:10.1016/j.marpol.2020.103936.
Faleiro, F. et al., 2015: Seahorses under a changing ocean: the impact of warming and acidification on the behaviour and physiology of a poor-swimming bony-armoured fish. *Conservation Physiology*, **3**(1), doi:10.1093/conphys/cov009.
Falkenberg, L. J. et al., 2015: Species interactions can maintain resistance of subtidal algal habitats to an increasingly modified world. *Global Ecology and Conservation*, **4**, 549-558, doi:10.1016/j.gecco.2015.10.003.
Falkenberg, L. J., S. Dupont and R. G. J. Bellerby, 2018: Approaches to reconsider literature on physiological effects of environmental change: examples from ocean acidification research. *Frontiers in Marine Science*, **5**, 453, doi:10.3389/fmars.2018.00453.

FAO, 2015: *Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication*. Nations, F. a. A. O. o. t. U., Rome, Italy, 19 pp pp. Available at: http://www.fao.org/3/a-i4356en.pdf.
FAO, 2018: *The state of world fisheries and aquaculture 2018 - meeting the sustainable development goals*. Food and Agriculture Organisation of the United Nations, Rome, 211 pp pp.
FAO, 2019: *Deep-ocean climate change impacts on habitat, fish and fisheries* [Levin, L., M. Baker and A. Thompson (eds.)]. FAO Fisheries and Aquaculture Technical Paper No. 638, FAO, Rome, Italy, 186 pp. Available at: http://www.fao.org/3/ca2528en/ca2528en.pdf.
FAO, 2020a: *Fishery and Aquaculture Statistics 2018/FAO annuaire. Statistiques des pêches et de l'aquaculture 2018/ FAO anuario. Estadísticas de pesca y acuicultura 2018*. FAO Yearbook of Fishery and Aquaculture Statistics, FAO, Rome, Italy, 110 pp.
FAO, 2020b: *The State of World Fisheries and Aquaculture 2020. Sustainability in Action*. FAO, Rome, Italy, 244 pp.
Farbotko, C. and C. McMichael, 2019: Voluntary immobility and existential security in a changing climate in the Pacific. *Asia Pacific Viewpoint*, **60**(2), 148-162, doi:10.1111/apv.12231.
Fauchald, P. et al., 2021: Poleward shifts in marine fisheries under Arctic warming. *Environ.Res.Lett.*, **16**(7), 074057, doi:10.1088/1748-9326/ac1010.
Fedele, G. et al., 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116-125, doi:10.1016/j.envsci.2019.07.001.
Feely, R. A. et al., 2018: The combined effects of acidification and hypoxia on pH and aragonite saturation in the coastal waters of the California current ecosystem and the northern Gulf of Mexico. *Continental Shelf Research*, **152**, 50-60, doi:10.1016/j.csr.2017.11.002.
Feely, R. A. et al., 2012: Decadal changes in the aragonite and calcite saturation state of the Pacific Ocean. *Global Biogeochemical Cycles*, **26**(3), doi:10.1029/2011GB004157.
Felipe Pérez, B. and A. Tomaselli, 2021: Indigenous Peoples and climate-induced relocation in Latin America and the Caribbean: managed retreat as a tool or a threat? *Journal of Environmental Studies and Sciences*, doi:10.1007/s13412-021-00693-2.
Fennel, K. et al., 2019: Carbon cycling in the North American coastal ocean: a synthesis. *Biogeosciences*, **16**(6), 1281-1304, doi:10.5194/bg-16-1281-2019.
Ferchichi, H., A. St-Hilaire, T. B. M. J. Ouarda and B. Lévesque, 2021: Impact of the future coastal water temperature scenarios on the risk of potential growth of pathogenic Vibrio marine bacteria. *Estuarine, Coastal and Shelf Science*, **250**, 107094, doi:10.1016/j.ecss.2020.107094.
Fernandes, J. A. et al., 2017: Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. *Fish and Fisheries*, **18**(3), 389-411, doi:10.1111/faf.12183.
Fernández, P. A. et al., 2020: Nitrogen sufficiency enhances thermal tolerance in habitat-forming kelp: implications for acclimation under thermal stress. *Scientific Reports*, **10**(1), 3186, doi:10.1038/s41598-020-60104-4.
Fernández-Montblanc, T. et al., 2019: Towards robust pan-European storm surge forecasting. *Ocean Modelling*, **133**, 129-144, doi:10.1016/j.ocemod.2018.12.001.
Fernández-Palacios, J. M. et al., 2016: Towards a glacial-sensitive model of island biogeography. *Global Ecology and Biogeography*, **25**(7), 817-830, doi:10.1111/geb.12320.
Fernandino, G., C. I. Elliff and I. R. Silva, 2018: Ecosystem-based management of coastal zones in face of climate change impacts: challenges and inequalities. *Journal of Environmental Management*, **215**, 32-39, doi:10.1016/j.jenvman.2018.03.034.
Ferrari, M. C. O. et al., 2015: Interactive effects of ocean acidification and rising sea temperatures alter predation rate and predator selectivity in reef fish communities. *Global Change Biology*, **21**(5), 1848-1855, doi:10.1111/gcb.12818.
Fiechter, J. et al., 2021: Projected shifts in 21st century sardine distribution and catch in the California Current. *Frontiers in Marine Science*, **8**, 685241, doi:10.3389/fmars.2021.685241.
Field, C. B., M. J. Behrenfeld, J. T. Randerson and P. Falkowski, 1998: Primary production of the biosphere: integrating terrestrial and oceanic components. *Science*, **281**(5374), 237-240, doi:10.1126/science.281.5374.237.
Fielding, R. et al., 2021: Demographic and geographic patterns of cetacean-based food product consumption and potential mercury exposure within a Caribbean whaling community. *Human and Ecological Risk Assessment: An International Journal*, **27**(6), 1671-1695, doi:10.1080/10807039.2020.1870865.
Figueira, W. F., B. Curley and D. J. Booth, 2019: Can temperature-dependent predation rates regulate range expansion potential of tropical vagrant fishes? *Marine Biology*, **166**(6), 73, doi:10.1007/s00227-019-3521-5.
Filbee-Dexter, K., C. J. Feehan and R. E. Scheibling, 2016: Large-scale degradation of a kelp ecosystem in an ocean warming hotspot. *Marine Ecology Progress Series*, **543**, 141-152, doi:10.3354/meps11554.
Filbee-Dexter, K. et al., 2020a: Carbon export is facilitated by sea urchins transforming kelp detritus. *Oecologia*, **192**(1), 213-225, doi:10.1007/s00442-019-04571-1.
Filbee-Dexter, K. and R. E. Scheibling, 2014: Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. *Marine Ecology Progress Series*, **495**, 1-25, doi:10.3354/meps10573.
Filbee-Dexter, K. and A. Smajdor, 2019: Ethics of assisted evolution in marine conservation. *Frontiers in Marine Science*, **6**, 20, doi:10.3389/fmars.2019.00020.

Filbee-Dexter, K. and T. Wernberg, 2018: Rise of turfs: a new battlefront for globally declining kelp forests. *BioScience*, **68**(2), 64-76, doi:10.1093/biosci/bix147.
Filbee-Dexter, K. and T. Wernberg, 2020: Substantial blue carbon in overlooked Australian kelp forests. *Scientific Reports*, **10**(1), 12341, doi:10.1038/s41598-020-69258-7.
Filbee-Dexter, K. et al., 2020b: Marine heatwaves and the collapse of marginal North Atlantic kelp forests. *Scientific Reports*, **10**(1), 13388, doi:10.1038/s41598-020-70273-x.
Fillinger, L. and C. Richter, 2013: Vertical and horizontal distribution of *Desmophyllum dianthus* in Comau Fjord, Chile: a cold-water coral thriving at low pH. *PeerJ*, **1**, e194, doi:10.7717/peerj.194.
Fincham, J. I., A. D. Rijnsdorp and G. H. Engelhard, 2013: Shifts in the timing of spawning in sole linked to warming sea temperatures. *Journal of Sea Research*, **75**, 69-76, doi:10.1016/j.seares.2012.07.004.
Findlater, K., S. Webber, M. Kandlikar and S. Donner, 2021: Climate services promise better decisions but mainly focus on better data. *Nature Climate Change*, **11**(9), 731-737, doi:10.1038/s41558-021-01125-3.
Finkbeiner, E. M. et al., 2018: Exploring trade-offs in climate change response in the context of Pacific Island fisheries. *Marine Policy*, **88**, 359-364, doi:10.1016/j.marpol.2017.09.032.
Fischer, D. et al., 2012: Interaction between hydrocarbon seepage, chemosynthetic communities, and bottom water redox at cold seeps of the Makran accretionary prism: insights from habitat-specific pore water sampling and modeling. *Biogeosciences*, **9**(6), 2013-2031, doi:10.5194/bg-9-2013-2012.
Fischer, G. et al., 2020: Long-Term Changes of Particle Flux in the Canary Basin Between 1991 and 2009 and Comparison to Sediment Trap Records Off Mauritania. *Frontiers in Earth Science*, **8**(280), doi:10.3389/feart.2020.00280.
Fischer, G. et al., 2019: Changes in the Dust-Influenced Biological Carbon Pump in the Canary Current System: Implications From a Coastal and an Offshore Sediment Trap Record Off Cape Blanc, Mauritania. *Global Biogeochemical Cycles*, **33**(8), 1100-1128, doi:10.1029/2019GB006194.
Fitton, J. M. et al., 2021: Challenges to climate change adaptation in coastal small towns: Examples from Ghana, Uruguay, Finland, Denmark, and Alaska. *Ocean & Coastal Management*, **212**, 105787, doi:10.1016/j.ocecoaman.2021.105787.
Fitzer, S. C., V. R. Phoenix, M. Cusack and N. A. Kamenos, 2014: Ocean acidification impacts mussel control on biomineralisation. *Scientific Reports*, **4**, 6218, doi:10.1038/srep06218.
FitzGerald, D. M. and Z. Hughes, 2019: Marsh processes and their response to climate change and sea-level rise. *Annual Review of Earth and Planetary Sciences*, **47**(1), 481-517, doi:10.1146/annurev-earth-082517-010255.
Flanagan, P. H., O. P. Jensen, J. W. Morley and M. L. Pinsky, 2019: Response of marine communities to local temperature changes. *Ecography*, **42**(1), 214-224, doi:10.1111/ecog.03961.
Flannery, W. et al., 2016: Exploring the winners and losers of marine environmental governance/Marine spatial planning: Cui bono?/“More than fishy business”: epistemology, integration and conflict in marine spatial planning/Marine spatial planning: power and scaping/Surely not all planning is evil?/Marine spatial planning: a Canadian perspective/Maritime spatial planning – “ad utilitatem omnium”/Marine spatial planning: “it is better to be on the train than being hit by it”/Reflections from the perspective of recreational anglers and boats for hire/Maritime spatial planning and marine renewable energy. *Planning Theory & Practice*, **17**(1), 121-151, doi:10.1080/14649357.2015.1131482.
Flombaum, P., W.-L. Wang, F. W. Primeau and A. C. Martiny, 2020: Global picophytoplankton niche partitioning predicts overall positive response to ocean warming. *Nature Geoscience*, **13**(2), 116-120, doi:10.1038/s41561-019-0524-2.
Flood, J. F. and L. B. Cahoon, 2011: Risks to Coastal Wastewater Collection Systems from Sea-Level Rise and Climate Change. *Journal of Coastal Research*, **27**(4), 652-660, 659.
Flood, S., N. A. Cradock-Henry, P. Blackett and P. Edwards, 2018: Adaptive and interactive climate futures: systematic review of 'serious games' for engagement and decision-making. *Environ.Res.Lett.*, **13**(6), 063005, doi:10.1088/1748-9326/aac1c6.
Flynn, E. E., B. E. Bjelde, N. A. Miller and A. E. Todgham, 2015: Ocean acidification exerts negative effects during warming conditions in a developing Antarctic fish. *Conservation Physiology*, **3**(1), doi:10.1093/conphys/cov033.
Folkersen, M. V., 2018: Ecosystem valuation: changing discourse in a time of climate change. *Ecosystem Services*, **29**, 1-12, doi:10.1016/j.ecoser.2017.11.008.
Foo, S. A. and M. Byrne, 2017: Marine gametes in a changing ocean: impacts of climate change stressors on fecundity and the egg. *Marine Environmental Research*, **128**, 12-24, doi:10.1016/j.marenvres.2017.02.004.
Ford, J. and D. Clark, 2019: Preparing for the impacts of climate change along Canada's Arctic coast: The importance of search and rescue. *Marine Policy*, **108**, 103662, doi:10.1016/j.marpol.2019.103662.
Ford, J. D. and D. King, 2015: A framework for examining adaptation readiness. *Mitigation and Adaptation Strategies for Global Change*, **20**(4), 505-526, doi:10.1007/s11027-013-9505-8.
Ford, J. D. et al., 2020: The Resilience of Indigenous Peoples to Environmental Change. *One Earth*, **2**(6), 532-543, doi:10.1016/j.oneear.2020.05.014.
Fordyce, A. J., T. D. Ainsworth, S. F. Heron and W. Leggat, 2019: Marine heatwave hotspots in coral reef environments: physical drivers, ecophysiological outcomes, and impact upon structural complexity. *Frontiers in Marine Science*, **6**(498), doi:10.3389/fmars.2019.00498.

Forsblom, L. et al., 2019: Environmental variables driving species and genus level changes in annual plankton biomass. *Journal of Plankton Research*, **41**(6), 925-938, doi:10.1093/plankt/fbz063.
Förster, J., E. McLeod, M. M. Bruton-Adams and H. Wittmer, 2019: Climate change impacts on small island states: ecosystem services risks and opportunities. In: *Atlas of Ecosystem Services: Drivers, Risks, and Societal Responses* [Schröter, M., A. Bonn, S. Klotz, R. Seppelt and C. Baessler (eds.)]. Springer International Publishing, Cham, pp. 353-359. ISBN 978-3-319-96229-0.
Forster, P. M., A. C. Maycock, C. M. McKenna and C. J. Smith, 2020: Latest climate models confirm need for urgent mitigation. *Nature Climate Change*, **10**(1), 7-10, doi:10.1038/s41558-019-0660-0.
Fossheim, M. et al., 2015: Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change*, **5**(7), 673-677, doi:10.1038/nclimate2647.
Foster, G. L., P. Hull, D. J. Lunt and J. C. Zachos, 2018: Placing our current 'hyperthermal' in the context of rapid climate change in our geological past. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2130), 20170086, doi:10.1098/rsta.2017.0086.
Foster, K. L., B. M. Braune, A. J. Gaston and M. L. Mallory, 2019: Climate Influence on Legacy Organochlorine Pollutants in Arctic Seabirds. *Environmental Science & Technology*, **53**(5), 2518-2528, doi:10.1021/acs.est.8b07106.
Fourqurean, J. W. et al., 2012: Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, **5**(7), 505-509, doi:10.1038/ngeo1477.
Fox, A. D., L. A. Henry, D. W. Corne and J. M. Roberts, 2016: Sensitivity of marine protected area network connectivity to atmospheric variability. *Royal Society Open Science*, **3**(11), 160494, doi:10.1098/rsos.160494.
Fox, L., S. Stukins, T. Hill and C. G. Miller, 2020: Quantifying the Effect of Anthropogenic Climate Change on Calcifying Plankton. *Scientific Reports*, **10**(1), 1620, doi:10.1038/s41598-020-58501-w.
Fox, R. J. et al., 2019: Beyond buying time: the role of plasticity in phenotypic adaptation to rapid environmental change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **374**(1768), 20180174, doi:10.1098/rstb.2018.0174.
Fox-Kemper, B. et al., 2021: Ocean, Cryosphere and Sea Level Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Frade, P. R. et al., 2018: Deep reefs of the Great Barrier Reef offer limited thermal refuge during mass coral bleaching. *Nature Communications*, **9**(1), 3447, doi:10.1038/s41467-018-05741-0.
Frainer, A. et al., 2021: Increased functional diversity warns of ecological transition in the Arctic. *Proceedings of the Royal Society B: Biological Sciences*, **288**(1948), 20210054, doi:10.1098/rspb.2021.0054.
Frajka-Williams, E. et al., 2019: Atlantic meridional overturning circulation: observed transport and variability. *Frontiers in Marine Science*, **6**, doi:10.3389/fmars.2019.00260.
Franco, B. C. et al., 2020: Climate change impacts on the atmospheric circulation, ocean, and fisheries in the southwest South Atlantic Ocean: a review. *Climatic Change*, **162**(4), 2359-2377, doi:10.1007/s10584-020-02783-6.
Frank, K. T., B. Petrie, W. C. Leggett and D. G. Boyce, 2018: Exploitation drives an ontogenetic-like deepening in marine fish. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(25), 6422, doi:10.1073/pnas.1802096115.
Franks, P. J. S., 2018: Recent Advances in Modelling of Harmful Algal Blooms. In: *Global Ecology and Oceanography of Harmful Algal Blooms* [Glibert, P. M., E. Berdalet, M. A. Burford, G. C. Pitcher and M. Zhou (eds.)]. Springer International Publishing, Cham, pp. 359-377. ISBN 978-3-319-70069-4.
Frazão Santos, C. et al., 2020: Integrating climate change in ocean planning. *Nature Sustainability*, **3**(7), 505-516, doi:10.1038/s41893-020-0513-x.
Fredriksen, S. et al., 2020: Green gravel: a novel restoration tool to combat kelp forest decline. *Scientific Reports*, **10**(1), 3983, doi:10.1038/s41598-020-60553-x.
Fredston, A. et al., 2021: Range edges of North American marine species are tracking temperature over decades. *Global Change Biology*, **27**(13), 3145-3156, doi:10.1111/gcb.15614.
Fredston-Hermann, A. et al., 2020: Cold range edges of marine fishes track climate change better than warm edges. *Global Change Biology*, **26**(5), 2908-2922, doi:10.1111/gcb.15035.
Free, C. M. et al., 2020: Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLOS ONE*, **15**(3), e0224347, doi:10.1371/journal.pone.0224347.
Free, C. M. et al., 2019: Impacts of historical warming on marine fisheries production. *Science*, **363**(6430), 979-983, doi:10.1126/science.aau1758.
Freedman, R. M., J. A. Brown, C. Caldow and J. E. Caselle, 2020: Marine protected areas do not prevent marine heatwave-induced fish community structure changes in a temperate transition zone. *Scientific Reports*, **10**(1), 21081, doi:10.1038/s41598-020-77885-3.
Freitas, A. C. et al., 2012: Marine biotechnology advances towards applications in new functional foods. *Biotechnology Advances*, **30**(6), 1506-1515, doi:10.1016/j.biotechadv.2012.03.006.
Freitas, R. et al., 2020: Impacts of salicylic acid in Mytilus galloprovincialis exposed to warming conditions. *Environmental Toxicology and Pharmacology*, **80**, 103448, doi:10.1016/j.etap.2020.103448.

Friedland, K. D. et al., 2020a: Changes in higher trophic level productivity, diversity and niche space in a rapidly warming continental shelf ecosystem. *Science of The Total Environment*, **704**, 135270, doi:10.1016/j.scitotenv.2019.135270.
Friedland, K. D. et al., 2020b: Trends and change points in surface and bottom thermal environments of the US Northeast Continental Shelf Ecosystem. *Fisheries Oceanography*, **29**(5), 396-414, doi:10.1111/fog.12485.
Friedlander, A. M. et al., 2020: Kelp forests at the end of the earth: 45 years later. *PLOS ONE*, **15**(3), e0229259, doi:10.1371/journal.pone.0229259.
Friedman, W. R. et al., 2020: Research Priorities for Achieving Healthy Marine Ecosystems and Human Communities in a Changing Climate. *Frontiers in Marine Science*, **7**, 5, doi:10.3389/fmars.2020.00005.
Friesen, S. K. et al., 2021: Effects of changing ocean temperatures on ecological connectivity among marine protected areas in northern British Columbia. *Ocean & Coastal Management*, **211**, 105776, doi:10.1016/j.ocecoaman.2021.105776.
Friess, D. A. et al., 2020a: Mangrove Blue Carbon in the Face of Deforestation, Climate Change, and Restoration. *Annual Plant Reviews online*, 427-456, doi:10.1002/9781119312994.apr0752.
Friess, D. A. et al., 2019: The state of the world's mangrove forests: past, present, and future. *Annual Review of Environment and Resources*, **44**, doi:10.1146/annurev-environ-101718-033302.
Friess, D. A. et al., 2020b: Mangroves give cause for conservation optimism, for now. *Current Biology*, **30**(4), R153-R154, doi:10.1016/j.cub.2019.12.054.
Froehlich, H. E., J. C. Afflerbach, M. Frazier and B. S. Halpern, 2019: Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. *Current Biology*, **29**(18), 3087-3093.e3083, doi:10.1016/j.cub.2019.07.041.
Froelich, B. A. and D. A. Daines, 2020: In hot water: effects of climate change on Vibrio–human interactions. *Environmental Microbiology*, **22**(10), 4101-4111, doi:10.1111/1462-2920.14967.
Frölicher, T. L., E. M. Fischer and N. Gruber, 2018: Marine heatwaves under global warming. *Nature*, **560**(7718), 360-364, doi:10.1038/s41586-018-0383-9.
Frontier, N., F. de Bettignies, A. Foggo and D. Davoult, 2021: Sustained productivity and respiration of degrading kelp detritus in the shallow benthos: Detached or broken, but not dead. *Marine Environmental Research*, **166**, 105277, doi:10.1016/j.marenvres.2021.105277.
Fruergaard, M. et al., 2015: Stratigraphy, evolution, and controls of a holocene transgressive–regressive barrier island under changing sea level: Danish North Sea Coast. *Journal of Sedimentary Research*, **85**(7), 820-844, doi:10.2110/jsr.2015.53.
Fu, F.-X. et al., 2007: Effects of increased temperature and CO_2 on photosynthesis, growth, and elemental ratios in marine *Synechococcus* and *Prochlorococcus* (cyanobacteria). *Journal of Phycology*, **43**(3), 485-496, doi:10.1111/j.1529-8817.2007.00355.x.
Fu, W. W., J. T. Randerson and J. K. Moore, 2016: Climate change impacts on net primary production (NPP) and export production (EP) regulated by increasing stratification and phytoplankton community structure in the CMIP5 models. *Biogeosciences*, **13**(18), 5151-5170, doi:10.5194/bg-13-5151-2016.
Fuchs, H. L. et al., 2020: Wrong-way migrations driven by ocean warming andlarval transport. *Nature Climate Change*, 1-20, doi:10.1038/s41558-020-0894-x.
Fuentes, M. M. P. B. et al., 2019: Exposure of marine turtle nesting grounds to named storms along the continental USA. *Remote Sensing*, **11**(24), 2996, doi:10.3390/rs11242996.
Fujiwara, A. et al., 2016: Influence of timing of sea ice retreat on phytoplankton size during marginal ice zone bloom period on the Chukchi and Bering shelves. *Biogeosciences*, **13**(1), 115-131, doi:10.5194/bg-13-115-2016.
Fulton, E. A., C. M. Bulman, H. Pethybridge and S. D. Goldsworthy, 2018: Modelling the Great Australian Bight Ecosystem. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **157-158**, 211-235, doi:10.1016/j.dsr2.2018.11.002.
Fulton, E. A. et al., 2019: Ecosystems say good management pays off. *Fish and Fisheries*, **20**(1), 66-96, doi:10.1111/faf.12324.
Furlan, E. et al., 2020: Multi-scenario analysis in the Adriatic Sea: A GIS-based Bayesian network to support maritime spatial planning. *Science of The Total Environment*, **703**, 134972, doi:10.1016/j.scitotenv.2019.134972.
Fuso Nerini, F. et al., 2019: Connecting climate action with other Sustainable Development Goals. *Nature Sustainability*, **2**(8), 674-680, doi:10.1038/s41893-019-0334-y.
Gafar, N. A., B. D. Eyre and K. G. Schulz, 2019: A comparison of species specific sensitivities to changing light and carbonate chemistry in calcifying marine phytoplankton. *Scientific Reports*, **9**(1), 2486, doi:10.1038/s41598-019-38661-0.
Gaines, S. D. et al., 2018: Improved fisheries management could offset many negative effects of climate change. *Science Advances*, **4**(8), eaao1378, doi:10.1126/sciadv.aao1378.
Gaitán-Espitia, J. D. and A. J. Hobday, 2021: Evolutionary principles and genetic considerations for guiding conservation interventions under climate change. *Global Change Biology*, **27**(3), 475-488, doi:10.1111/gcb.15359.
Gaitán-Espitia, J. D. et al., 2017a: Geographical gradients in selection can reveal genetic constraints for evolutionary responses to ocean acidification. *Biology Letters*, **13**(2), 20160784, doi:10.1098/rsbl.2016.0784.
Gaitán-Espitia, J. D. et al., 2017b: Spatio-temporal environmental variation mediates geographical differences in phenotypic responses to ocean acidification. *Biology Letters*, **13**(2), 20160865, doi:10.1098/rsbl.2016.0865.

Galappaththi, E. K., J. D. Ford and E. M. Bennett, 2019: A framework for assessing community adaptation to climate change in a fisheries context. *Environmental Science & Policy*, **92**, 17-26, doi:10.1016/j.envsci.2018.11.005.
Galeano, A., L. E. Urrego, V. Botero and G. Bernal, 2017: Mangrove resilience to climate extreme events in a Colombian Caribbean Island. *Wetlands Ecology and Management*, **25**(6), 743-760, doi:10.1007/s11273-017-9548-9.
Galic, N., T. Hawkins and V. E. Forbes, 2019: Adverse impacts of hypoxia on aquatic invertebrates: a meta-analysis. *Science of The Total Environment*, **652**, 736-743, doi:10.1016/j.scitotenv.2018.10.225.
Gall, S. C. and R. C. Thompson, 2015: The impact of debris on marine life. *Marine Pollution Bulletin*, **92**(1), 170-179, doi:10.1016/j.marpolbul.2014.12.041.
Gallagher, J. B., 2020: Comment: blue carbon is not substantial in Australian kelp forests. *OSF Preprints*, doi:10.31219/osf.io/et2n3.
Gallego, D. et al., 2021: A Shift in the Wind Regime of the Southern End of the Canary Upwelling System at the Turn of the 20th Century. *Journal of Geophysical Research: Oceans*, **126**(5), e2020JC017093, doi:10.1029/2020JC017093.
Gallego-Tévar, B. et al., 2020: Interactive effects of salinity and inundation on native *Spartina foliosa*, invasive *S. densiflora* and their hybrid from San Francisco Estuary, California. *Annals of Botany*, **125**(2), 377-389, doi:10.1093/aob/mcz170.
Gallo, N. D. et al., 2020: Dissolved oxygen and temperature best predict deep-sea fish community structure in the Gulf of California with climate change implications. *Marine Ecology Progress Series*, **637**, 159-180, doi:10.3354/meps13240.
Gallo, N. D., D. G. Victor and L. A. Levin, 2017: Ocean commitments under the Paris Agreement. *Nature Climate Change*, **7**(11), 833-838, doi:10.1038/nclimate3422.
Gamliel, I. et al., 2020: Incorporating physiology into species distribution models moderates the projected impact of warming on selected Mediterranean marine species. *Ecography*, **43**(7), 1090-1106, doi:10.1111/ecog.04423.
Ganju, N. K., 2019: Marshes Are the New Beaches: Integrating Sediment Transport into Restoration Planning. *Estuaries and Coasts*, **42**(4), 917-926, doi:10.1007/s12237-019-00531-3.
Gao, K. et al., 2019: Effects of ocean acidification on marine photosynthetic organisms under the concurrent influences of warming, UV radiation, and deoxygenation. *Frontiers in Marine Science*, **6**, 322, doi:10.3389/fmars.2019.00322.
Gao, K., G. Gao, Y. Wang and S. Dupont, 2020: Impacts of ocean acidification under multiple stressors on typical organisms and ecological processes. *Marine Life Science & Technology*, **2**(3), 279-291, doi:10.1007/s42995-020-00048-w.
Gao, K. et al., 2012: Rising CO_2 and increased light exposure synergistically reduce marine primary productivity. *Nature Climate Change*, **2**(7), 519-523, doi:10.1038/nclimate1507.
García Molinos, J., M. T. Burrows and E. S. Poloczanska, 2017: Ocean currents modify the coupling between climate change and biogeographical shifts. *Scientific Reports*, **7**(1), 1332, doi:10.1038/s41598-017-01309-y.
García Molinos, J. et al., 2016: Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, **6**(1), 83-88, doi:10.1038/nclimate2769.
Garcia, N. S. et al., 2011: Interactive effects of irradiance and CO_2 on CO_2 fixation and N_2 fixation in the diazotroph *Trichodesmium erythraeum* (cyanobacteria). *Journal of Phycology*, **47**(6), 1292-1303, doi:10.1111/j.1529-8817.2011.01078.x.
García Sánchez, F., H. García Sánchez and C. Ribalaygua, 2020: Cultural heritage and sea level rise threat: risk assessment of coastal fortifications in the Canary Islands. *Journal of Cultural Heritage*, **44**, 211-217, doi:10.1016/j.culher.2020.02.005.
García-Aguilar, M. C. et al., 2018: Climate change and the northern elephant seal (*Mirounga angustirostris*) population in Baja California, Mexico. *PLOS ONE*, **13**(2), e0193211, doi:10.1371/journal.pone.0193211.
García-Gómez, J. C. et al., 2020: From exotic to invasive in record time: The extreme impact of Rugulopteryx okamurae (Dictyotales, Ochrophyta) in the strait of Gibraltar. *Science of The Total Environment*, **704**, 135408, doi:10.1016/j.scitotenv.2019.135408.
García-Reyes, M. and J. Largier, 2010: Observations of increased wind-driven coastal upwelling off central California. *Journal of Geophysical Research: Oceans*, **115**(C4), doi:10.1029/2009JC005576.
García-Reyes, M. et al., 2015: Under pressure: climate change, upwelling, and eastern boundary upwelling ecosystems. *Frontiers in Marine Science*, **2**, 109, doi:10.3389/fmars.2015.00109.
Garrabou, J. et al., 2019: Collaborative database to track mass mortality events in the Mediterranean Sea. *Frontiers in Marine Science*, **6**, 707, doi:10.3389/fmars.2019.00707.
Garrabou, J. et al., 2021: Sliding Toward the Collapse of Mediterranean Coastal Marine Rocky Ecosystems. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 291-324. ISBN 978-3-030-71330-0.
Garrote, J., A. Díaz-Álvarez, V. H. Nganhane and G. Garzón Heydt, 2018: The severe 2013–14 winter storms in the historical evolution of Cantabrian (Northern Spain) beach-dune systems. *Geosciences*, **8**(12), 459, doi:10.3390/geosciences8120459.

Garzke, J., U. Sommer and S. M. H. Ismar-Rebitz, 2020: Zooplankton growth and survival differentially respond to interactive warming and acidification effects. *Journal of Plankton Research*, **42**(2), 189-202, doi:10.1093/plankt/fbaa005.
Gattuso, J.-P. et al., 2015: Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science*, **349**(6243), aac4722, doi:10.1126/science.aac4722.
Gattuso, J.-P. et al., 2018: Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, **5**, 337, doi:10.3389/fmars.2018.00337.
Gattuso, J.-P., P. Williamson, C. M. Duarte and A. K. Magnan, 2021: The Potential for Ocean-Based Climate Action: Negative Emissions Technologies and Beyond. *Frontiers in Climate*, **2**, 37, doi:10.3389/fclim.2020.575716.
Gattuso, J. P. et al., 2019: *Opportunities for increasing ocean action in climate strategies*. Policy Brief, IDDRI. Available at: https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Propositions/201911-PB0219-ocean%20NDCs_0.pdf.
Gazeau, F. et al., 2010: Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*. *Biogeosciences*, **7**(7), 2051-2060, doi:10.5194/bg-7-2051-2010.
Geburzi, J. C. and M. L. McCarthy (eds.), How do they do it? – understanding the success of marine invasive species. YOUMARES 8 – Oceans Across Boundaries: Learning from each other, Cham, Springer International Publishing, 109-124 pp. ISBN 978-3-319-93284-2.
Gehlen, M. et al., 2014: Projected pH reductions by 2100 might put deep North Atlantic biodiversity at risk. *Biogeosciences*, **11**(23), 6955-6967, doi:10.5194/bg-11-6955-2014.
Genevier, L. G. C. et al., 2019: Marine heatwaves reveal coral reef zones susceptible to bleaching in the Red Sea. *Global Change Biology*, **25**(7), 2338-2351, doi:10.1111/gcb.14652.
Gentry, R. R. et al., 2020: Exploring the potential for marine aquaculture to contribute to ecosystem services. *Reviews in Aquaculture*, **12**(2), 499-512, doi:10.1111/raq.12328.
George Puthucherril, T., 2012: Climate Change, Sea Level Rise and Protecting Displaced Coastal Communities: Possible Solutions. *Global Journal of Comparative Law*, **1**(2), 225, doi:10.1163/2211906X-00102004.
Georgian, S. E. et al., 2016: Biogeographic variability in the physiological response of the cold-water coral *Lophelia pertusa* to ocean acidification. *Marine Ecology*, **37**(6), 1345-1359, doi:10.1111/maec.12373.
Geraldi, N. R. et al., 2020: Ecological effects of non-native species in marine ecosystems relate to co-occurring anthropogenic pressures. *Global Change Biology*, **26**(3), 1248-1258, doi:10.1111/gcb.14930.
Germond, B. and A. D. Mazaris, 2019: Climate change and maritime security. *Marine Policy*, **99**, 262-266, doi:10.1016/j.marpol.2018.10.010.
Gervais, C. R., C. Champion and G. T. Pecl, 2021: Species on the move around the Australian coastline: A continental-scale review of climate-driven species redistribution in marine systems. *Global Change Biology*, **27**(14), 3200-3217, doi:10.1111/gcb.15634.
Ghermandi, A., D. Obura, C. Knudsen and P. A. L. D. Nunes, 2019: Marine ecosystem services in the Northern Mozambique Channel: a geospatial and socio-economic analysis for policy support. *Ecosystem Services*, **35**, 1-12, doi:10.1016/j.ecoser.2018.10.009.
Gianelli, I. et al., 2019: Evidence of ocean warming in Uruguay''s fisheries landings: the mean temperature of the catch approach. *Marine Ecology Progress Series*, **625**, 115-125, doi:10.3354/meps13035.
Gianelli, I. et al., 2021: Harnessing scientific and local knowledge to face climate change in small-scale fisheries. *Global Environmental Change*, **68**, 102253, doi:10.1016/j.gloenvcha.2021.102253.
Gibble, C. M. and B. A. Hoover, 2018: Interactions between Seabirds and Harmful Algal Blooms. In: *Harmful Algal Blooms*, pp. 223-242.
Gibbs, M. T., 2015: Pitfalls in developing coastal climate adaptation responses. *Climate Risk Management*, **8**, 1-8, doi:10.1016/j.crm.2015.05.001.
Gibbs, S. J. et al., 2016: Ocean warming, not acidification, controlled coccolithophore response during past greenhouse climate change. *Geology*, **44**(1), 59-62, doi:10.1130/G37273.1.
Gibson, K. E., J. Barnett, N. Haslam and I. Kaplan, 2020: The mental health impacts of climate change: Findings from a Pacific Island atoll nation. *Journal of Anxiety Disorders*, **73**, 102237, doi:10.1016/j.janxdis.2020.102237.
Giglio, V. J., O. J. Luiz and C. E. L. Ferreira, 2020: Ecological impacts and management strategies for recreational diving: A review. *Journal of Environmental Management*, **256**, 109949, doi:10.1016/j.jenvman.2019.109949.
Gilfillan, D., 2019: The health sector's role in governance of climate change adaptation in Myanmar. *Climate and Development*, **11**(7), 574-584, doi:10.1080/17565529.2018.1510364.
Gintert, B. E. et al., 2018: Marked annual coral bleaching resilience of an inshore patch reef in the Florida Keys: A nugget of hope, aberrance, or last man standing? *Coral Reefs*, **37**(2), 533-547, doi:10.1007/s00338-018-1678-x.
Giomi, F. et al., 2019: Oxygen supersaturation protects coastal marine fauna from ocean warming. *Science Advances*, **5**(9), eaax1814, doi:10.1126/sciadv.aax1814.
Gissi, E. et al., 2021: A review of the combined effects of climate change and other local human stressors on the marine environment. *Science of The Total Environment*, **755**, 142564, doi:10.1016/j.scitotenv.2020.142564.
Glibert, P. M. et al., 2014: Vulnerability of coastal ecosystems to changes in harmful algal bloom distribution in response to climate change: projections based on model analysis. *Global Change Biology*, **20**(12), 3845-3858, doi:10.1111/gcb.12662.

Global Ocean Oxygen Network, 2018: *The ocean is losing its breath: declining oxygen in the world's ocean and coastal waters* [Breitburg, D., M. Gregoire and K. Isensee (eds.)]. IOC Technical Series, IOC-UNESCO, Paris, 40 pp. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000265196.
Gobler, C. J. and H. Baumann, 2016: Hypoxia and acidification in ocean ecosystems: coupled dynamics and effects on marine life. *Biology Letters*, **12**(5), 20150976, doi:10.1098/rsbl.2015.0976.
Gobler, C. J. et al., 2017: Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(19), 4975, doi:10.1073/pnas.1619575114.
Goeldner-Gianella, L. et al., 2019: The perception of climate-related coastal risks and environmental changes on the Rangiroa and Tikehau atolls, French Polynesia: The role of sensitive and intellectual drivers. *Ocean & Coastal Management*, **172**, 14-29, doi:10.1016/j.ocecoaman.2019.01.018.
Goldberg, L., D. Lagomasino, N. Thomas and T. Fatoyinbo, 2020: Global declines in human-driven mangrove loss. *Global Change Biology*, **26**(10), 5844-5855, doi:10.1111/gcb.15275.
Goldsmit, J. et al., 2020: What and where? Predicting invasion hotspots in the Arctic marine realm. *Global Change Biology*, **26**(9), 4752-4771, doi:10.1111/gcb.15159.
Goldstein, A., W. R. Turner, J. Gladstone and D. G. Hole, 2019: The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, **9**(1), 18-25, doi:10.1038/s41558-018-0340-5.
Gómez, C. E. et al., 2018: Growth and feeding of deep-sea coral *Lophelia pertusa* from the California margin under simulated ocean acidification conditions. *PeerJ*, **6**, e5671, doi:10.7717/peerj.5671.
Gómez-Gras, D. et al., 2021: Climate change transforms the functional identity of Mediterranean coralligenous assemblages. *Ecology Letters*, **24**(5), 1038-1051, doi:10.1111/ele.13718.
Gonneea, M. et al., 2019: Salt marsh ecosystem restructuring enhances elevation resilience and carbon storage during accelerating relative sea-level rise. *Estuarine, Coastal and Shelf Science*, **217**, 56-68, doi:10.1016/j.ecss.2018.11.003.
González-Alemán, J. J. et al., 2019: Potential increase in hazard from Mediterranean hurricane activity with global warming. *Geophysical Research Letters*, **46**(3), 1754-1764, doi:10.1029/2018GL081253.
Gonzalez-Espinosa, P. C. and S. D. Donner, 2021: Cloudiness reduces the bleaching response of coral reefs exposed to heat stress. *Global Change Biology*, **n/a**(n/a), doi:10.1111/gcb.15676.
Gonzalez-Mon, B. et al., 2021: Spatial diversification as a mechanism to adapt to environmental changes in small-scale fisheries. *Environmental Science & Policy*, **116**, 246-257, doi:10.1016/j.envsci.2020.11.006.
Goodale, M. W. and A. Milman, 2019: Assessing the cumulative exposure of wildlife to offshore wind energy development. *Journal of Environmental Management*, **235**, 77-83, doi:10.1016/j.jenvman.2019.01.022.
Gopalakrishnan, S., C. E. Landry and M. D. Smith, 2018: Climate Change Adaptation in Coastal Environments: Modeling Challenges for Resource and Environmental Economists. *Review of Environmental Economics and Policy*, **12**(1), 48-68, doi:10.1093/reep/rex020.
Gordon, T. A. C., A. N. Radford, S. D. Simpson and M. G. Meekan, 2020: Marine restoration projects are undervalued. *Science*, **367**(6478), 635, doi:10.1126/science.aba9141.
Gori, A. et al., 2016: Physiological response of the cold-water coral *Desmophyllum dianthus* to thermal stress and ocean acidification. *PeerJ*, **4**, e1606, doi:10.7717/peerj.1606.
Gössling, S., D. Scott and C. M. Hall, 2021: Pandemics, tourism and global change: a rapid assessment of COVID-19. *Journal of Sustainable Tourism*, **29**(1), 1-20, doi:10.1080/09669582.2020.1758708.
Götze, S. et al., 2020: Single and combined effects of the "Deadly trio" hypoxia, hypercapnia and warming on the cellular metabolism of the great scallop Pecten maximus. *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology*, **243-244**, 110438, doi:10.1016/j.cbpb.2020.110438.
Graham, N. A. J., J. E. Cinner, A. V. Norström and M. Nyström, 2014: Coral reefs as novel ecosystems: embracing new futures. *Current Opinion in Environmental Sustainability*, **7**, 9-14, doi:10.1016/j.cosust.2013.11.023.
Graham, N. A. J. et al., 2015: Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature*, **518**(7537), 94-97, doi:10.1038/nature14140.
Graham, N. A. J. et al., 2020: Changing role of coral reef marine reserves in a warming climate. *Nature Communications*, **11**(1), 2000, doi:10.1038/s41467-020-15863-z.
Gravem, S. A. and S. G. Morgan, 2017: Shifts in intertidal zonation and refuge use by prey after mass mortalities of two predators. *Ecology*, **98**(4), 1006-1015, doi:10.1002/ecy.1672.
Gravinese, P. M., I. C. Enochs, D. P. Manzello and R. van Woesik, 2018: Warming and pCO_2 effects on Florida stone crab larvae. *Estuarine, Coastal and Shelf Science*, **204**, 193-201, doi:10.1016/j.ecss.2018.02.021.
Gray, N. J., L. Acton and L. M. Campbell, 2020: A Research Agenda for Environmental Geopolitics. In: *Science, territory, and the geopolitics of high seas conservation*. Edward Elgar Publishing, UK, USA, pp. 30-43. ISBN 9781788971232.
Grebmeier, J. M., K. E. Frey, L. W. Cooper and M. Kędra, 2018: Trends in Benthic Macrofaunal Populations, Seasonal Sea Ice Persistence, and Bottom Water Temperatures in the Bering Strait Region. *Oceanography*, **31**(2), 136-151, doi:10.5670/oceanog.2018.224.
Green, A. E., R. K. F. Unsworth, M. A. Chadwick and P. J. S. Jones, 2021a: Historical Analysis Exposes Catastrophic Seagrass Loss for the United Kingdom. *Frontiers in Plant Science*, **12**(261), doi:10.3389/fpls.2021.629962.

Green, H. L. et al., 2021b: Satellite Observations Are Needed to Understand Ocean Acidification and Multi-Stressor Impacts on Fish Stocks in a Changing Arctic Ocean. *Frontiers in Marine Science*, **8**(692), doi:10.3389/fmars.2021.635797.
Green, K. M. et al., 2021c: How adaptive capacity shapes the Adapt, React, Cope response to climate impacts: insights from small-scale fisheries. *Climatic Change*, **164**(1), 15, doi:10.1007/s10584-021-02965-w.
Green, T. J. et al., 2019: Simulated Marine Heat Wave Alters Abundance and Structure of Vibrio Populations Associated with the Pacific Oyster Resulting in a Mass Mortality Event. *Microbial Ecology*, **77**(3), 736-747, doi:10.1007/s00248-018-1242-9.
Greenan, B. J. W. et al., 2019: Climate Change Vulnerability of American Lobster Fishing Communities in Atlantic Canada. *Frontiers in Marine Science*, **6**, 579, doi:10.3389/fmars.2019.00579.
Greene, C. H. et al., 2016: Marine Microalgae: Climate, Energy, and Food Security from the Sea. *Oceanography*, **29**(4), 10-15, doi:10.5670/oceanog.2016.91.
Gregg, W. W. and C. S. Rousseaux, 2019: Global ocean primary production trends in the modern ocean color satellite record (1998–2015). *Environ.Res.Lett.*, **14**, 124011, doi:10.1088/1748-9326/ab4667.
Gress, E. and D. A. Andradi-Brown, 2018: Assessing population changes of historically overexploited black corals (Order: Antipatharia) in Cozumel, Mexico. *PeerJ*, **6**, e5129, doi:10.7717/peerj.5129.
Gribble, M. O. et al., 2016: Mercury, selenium and fish oils in marine food webs and implications for human health. *Journal of the Marine Biological Association of the United Kingdom*, **96**(1), 43-59, doi:10.1017/S0025315415001356.
Grieger, R., S. J. Capon, W. L. Hadwen and B. Mackey, 2020: Between a bog and a hard place: a global review of climate change effects on coastal freshwater wetlands. *Climatic Change*, **163**(1), 161-179, doi:10.1007/s10584-020-02815-1.
Grieve, B. D., J. A. Hare and V. S. Saba, 2017: Projecting the effects of climate change on *Calanus finmarchicus* distribution within the U.S. Northeast Continental Shelf. *Scientific Reports*, **7**(1), 6264, doi:10.1038/s41598-017-06524-1.
Griffith, A. W. and C. J. Gobler, 2017: Transgenerational exposure of North Atlantic bivalves to ocean acidification renders offspring more vulnerable to low pH and additional stressors. *Scientific Reports*, **7**(1), 11394, doi:10.1038/s41598-017-11442-3.
Griffith, A. W., S. E. Shumway and C. J. Gobler, 2019a: Differential mortality of North Atlantic bivalve molluscs during harmful algal blooms caused by the dinoflagellate, *Cochlodinium* (*a.k.a. Margalefidinium*) *polykrikoides*. *Estuaries and Coasts*, **42**(1), 190-203, doi:10.1007/s12237-018-0445-0.
Griffith, G. P. et al., 2019b: Ecological resilience of Arctic marine food webs to climate change. *Nature Climate Change*, **9**(11), 868-872, doi:10.1038/s41558-019-0601-y.
Griffiths, H. J., A. J. S. Meijers and T. J. Bracegirdle, 2017: More losers than winners in a century of future Southern Ocean seafloor warming. *Nature Climate Change*, **7**(10), 749-754, doi:10.1038/nclimate3377.
Griscom, B. W. et al., 2020: National mitigation potential from natural climate solutions in the tropics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190126, doi:10.1098/rstb.2019.0126.
Grose, S. O. et al., 2020: Climate Change Will Re-draw the Map for Marine Megafauna and the People Who Depend on Them. *Frontiers in Marine Science*, **7**(547), doi:10.3389/fmars.2020.00547.
Große, F., K. Fennel, H. Zhang and A. Laurent, 2020: Quantifying the contributions of riverine vs. oceanic nitrogen to hypoxia in the East China Sea. *Biogeosciences*, **17**(10), 2701-2714, doi:10.5194/bg-17-2701-2020.
Gruber, N., 2011: Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369**(1943), 1980-1996, doi:10.1098/rsta.2011.0003.
Gruber, N., P. W. Boyd, T. L. Frölicher and M. Vogt, 2021: Ocean biogeochemical extremes and compound events. *Nature*, Accepted.
Gu, H. et al., 2019: Hypoxia aggravates the effects of ocean acidification on the physiological energetics of the blue mussel *Mytilus edulis*. *Marine Pollution Bulletin*, **149**, 110538, doi:10.1016/j.marpolbul.2019.110538.
Gu, J. et al., 2018: Losses of salt marsh in China: Trends, threats and management. *Estuarine, Coastal and Shelf Science*, **214**, 98-109, doi:10.1016/j.ecss.2018.09.015.
Guggisberg, S., 2019: The roles of nongovernmental actors in improving compliance with fisheries regulations. *Review of European, Comparative & International Environmental Law*, 1-14, doi:10.1111/reel.12304.
Guidi, L. et al., 2016: Plankton networks driving carbon export in the oligotrophic ocean. *Nature*, **532**(7600), 465-470, doi:10.1038/nature16942.
Gulev, S. K. et al., 2021: Changing State of the Climate System. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Guo, H. et al., 2017: Coastal regime shifts: rapid responses of coastal wetlands to changes in mangrove cover. *Ecology*, **98**(3), 762-772, doi:10.1002/ecy.1698.
Guo, W. et al., 2020: Ocean Acidification Has Impacted Coral Growth on the Great Barrier Reef. *Geophysical Research Letters*, **47**(19), e2019GL086761, doi:10.1029/2019GL086761.

Gupta, J. et al., 2016: The adaptive capacity of institutions in the spatial planning, water, agriculture and nature sectors in the Netherlands. *Mitigation and Adaptation Strategies for Global Change*, **21**(6), 883-903, doi:10.1007/s11027-014-9630-z.

Güraslan, C., B. A. Fach and T. Oguz, 2017: Understanding the impact of environmental variability on anchovy overwintering migration in the Black Sea and its implications for the fishing industry. *Frontiers in Marine Science*, **4**, 275, doi:10.3389/fmars.2017.00275.

Gurgel, C. F. D. et al., 2020: Marine Heatwave Drives Cryptic Loss of Genetic Diversity in Underwater Forests. *Current Biology*, **30**(7), 1199-1206.e1192, doi:10.1016/j.cub.2020.01.051.

Gurney, G. G. et al., 2021: Biodiversity needs every tool in the box: use OECMs. *Nature*, **595**, 646-649, doi:10.1038/d41586-021-02041-4.

Gutiérrez, J. M. et al., 2021: Atlas. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Gutiérrez-Rodríguez, A. G., C. Juárez-Portilla, T. Olivares-Bañuelos and R. C. Zepeda, 2018: Anticancer activity of seaweeds. *Drug Discovery Today*, **23**(2), 434-447, doi:10.1016/j.drudis.2017.10.019.

Haas, B. et al., 2021: The future of ocean governance. *Reviews in Fish Biology and Fisheries*, doi:10.1007/s11160-020-09631-x.

Haasnoot, M. et al., 2019: Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. *Environmental Research Communications*, **1**(7), 071006, doi:10.1088/2515-7620/ab1871.

Haasnoot, M. et al., 2020: Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environ.Res.Lett.*, **15**(3), 034007, doi:10.1088/1748-9326/ab666c.

Haasnoot, M., J. Lawrence and A. K. Magnan, 2021: Pathways to coastal retreat. *Science*, **372**(6548), 1287, doi:10.1126/science.abi6594.

Haasnoot, M., S. van 't Klooster and J. van Alphen, 2018: Designing a monitoring system to detect signals to adapt to uncertain climate change. *Global Environmental Change*, **52**, 273-285, doi:10.1016/j.gloenvcha.2018.08.003.

Hadaidi, G. et al., 2018: Ecological and molecular characterization of a coral black band disease outbreak in the Red Sea during a bleaching event. *PeerJ*, **6**, e5169, doi:10.7717/peerj.5169.

Hafezi, M. et al., 2021: Evaluating coral reef ecosystem services outcomes from climate change adaptation strategies using integrative system dynamics. *Journal of Environmental Management*, **285**, 112082, doi:10.1016/j.jenvman.2021.112082.

Hagens, M., K. A. Hunter, P. S. Liss and J. J. Middelburg, 2014: Biogeochemical context impacts seawater pH changes resulting from atmospheric sulfur and nitrogen deposition. *Geophysical Research Letters*, **41**(3), 935-941, doi:10.1002/2013GL058796.

Hall, S. J., 2002: The continental shelf benthic ecosystem: current status, agents for change and future prospects. *Environmental Conservation*, **29**(3), 350-374, doi:10.1017/S0376892902000243.

Hall-Spencer, J. M. and B. P. Harvey, 2019: Ocean acidification impacts on coastal ecosystem services due to habitat degradation. *Emerging Topics in Life Sciences*, **3**(2), 197-206, doi:10.1042/ETLS20180117.

Hallegraeff, G. M. et al., 2021: Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. *Communications Earth & Environment*, **2**(1), 117, doi:10.1038/s43247-021-00178-8.

Hallett, C. S. et al., 2018: Observed and predicted impacts of climate change on the estuaries of south-western Australia, a Mediterranean climate region. *Regional Environmental Change*, **18**(5), 1357-1373, doi:10.1007/s10113-017-1264-8.

Hallin, C., M. Larson and H. Hanson, 2019: Simulating beach and dune evolution at decadal to centennial scale under rising sea levels. *PLOS ONE*, **14**(4), e0215651, doi:10.1371/journal.pone.0215651.

Halpern, B. S. et al., 2019: Recent pace of change in human impact on the world's ocean. *Scientific Reports*, **9**(1), 11609, doi:10.1038/s41598-019-47201-9.

Hameau, A., J. Mignot and F. Joos, 2019: Assessment of time of emergence of anthropogenic deoxygenation and warming: insights from a CESM simulation from 850 to 2100 CE. *Biogeosciences*, **16**(8), 1755-1780, doi:10.5194/bg-16-1755-2019.

Hamilton, C. A. et al., 2019: Sediment supply and barrier dynamics as driving mechanisms of Holocene coastal change for the southern North Sea basin. *Quaternary International*, **500**, 147-158, doi:10.1016/j.quaint.2019.02.028.

Hamilton, S. E. and D. Casey, 2016: Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). *Global Ecology and Biogeography*, **25**(6), 729-738, doi:10.1111/geb.12449.

Hamilton, S. G. and A. E. Derocher, 2019: Assessment of global polar bear abundance and vulnerability. *Animal Conservation*, **22**(1), 83-95, doi:10.1111/acv.12439.

Hancock, A. M. et al., 2020: Effects of ocean acidification on Antarctic marine organisms: A meta-analysis. *Ecology and Evolution*, **10**(10), 4495-4514, doi:10.1002/ece3.6205.

Hänsel, M. C. et al., 2020: Ocean warming and acidification may drag down the commercial Arctic cod fishery by 2100. *PLOS ONE*, **15**(4), e0231589, doi:10.1371/journal.pone.0231589.

Hansen, C., R. D. M. Nash, K. F. Drinkwater and S. S. Hjøllo, 2019: Management Scenarios Under Climate Change – A Study of the Nordic and Barents Seas. *Frontiers in Marine Science*, **6**, 668, doi:10.3389/fmars.2019.00668.

Hanson, S. E. and R. J. Nicholls, 2020: Demand for Ports to 2050: Climate Policy, Growing Trade and the Impacts of Sea-Level Rise. *Earth's Future*, **8**(8), e2020EF001543, doi:10.1029/2020EF001543.

Hanz, U. et al., 2019: Environmental factors influencing benthic communities in the oxygen minimum zones on the Angolan and Namibian margins. *Biogeosciences*, **16**(22), 4337-4356, doi:10.5194/bg-16-4337-2019.

Hapsari, K. A. et al., 2020: Intertwined effects of climate and land use change on environmental dynamics and carbon accumulation in a mangrove-fringed coastal lagoon in Java, Indonesia. *Global Change Biology*, **26**(3), 1414-1431, doi:10.1111/gcb.14926.

Hare, J. A. et al., 2016: A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf. *PLOS ONE*, **11**(2), e0146756, doi:10.1371/journal.pone.0146756.

Harkin, D. et al., 2020: Impacts of climate change on cultural heritage. *MCCIP Science Review 2020*, 616-641, doi:10.14465/2020.arc26.che.

Harley, C. D., 2011: Climate change, keystone predation, and biodiversity loss. *Science*, **334**(6059), 1124-1127, doi:10.1126/science.1210199.

Harley, C. D. G. et al., 2017: Conceptualizing ecosystem tipping points within a physiological framework. *Ecology and Evolution*, **7**(15), 6035-6045, doi:10.1002/ece3.3164.

Harper, D. T. et al., 2020a: The Magnitude of Surface Ocean Acidification and Carbon Release During Eocene Thermal Maximum 2 (ETM-2) and the Paleocene-Eocene Thermal Maximum (PETM). *Paleoceanography and Paleoclimatology*, **35**(2), e2019PA003699, doi:10.1029/2019PA003699.

Harper, S. et al., 2020b: Valuing invisible catches: estimating the global contribution by women to small-scale marine capture fisheries production. *PLOS ONE*, **15**(3), e0228912, doi:10.1371/journal.pone.0228912.

Harper, S. et al., 2013: Women and fisheries: contribution to food security and local economies. *Marine Policy*, **39**, 56-63, doi:10.1016/j.marpol.2012.10.018.

Harris, B. D. et al., 2021: Establishment of soil strength in a nourished wetland using thin layer placement of dredged sediment. *PLOS ONE*, **16**(5), e0251420, doi:10.1371/journal.pone.0251420.

Harris, D. L. et al., 2018: Coral reef structural complexity provides important coastal protection from waves under rising sea levels. *Science Advances*, **4**(2), eaao4350, doi:10.1126/sciadv.aao4350.

Harvell, C. D. and J. B. Lamb, 2020: Disease outbreaks can threaten marine biodiversity. In: *Marine Disease Ecology*. Oxford University Press, Oxford. ISBN 9780198821632.

Harvell, C. D. et al., 2019: Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (*Pycnopodia helianthoides*). *Science Advances*, **5**(1), eaau7042, doi:10.1126/sciadv.aau7042.

Harvey, M. E. et al., 2020: Effects of Elevated Sea Levels and Waves on Southern California Estuaries During the 2015–2016 El Niño. *Estuaries and Coasts*, **43**(2), 256-271, doi:10.1007/s12237-019-00676-1.

Haslett, J. R. et al., 2018: Offshore renewable energy and nature conservation: the case of marine tidal turbines in Northern Ireland. *Biodiversity and Conservation*, **27**(7), 1619-1638, doi:10.1007/s10531-016-1268-6.

Hassoun, A. E. R. et al., 2015: Acidification of the Mediterranean Sea from anthropogenic carbon penetration. *Deep-Sea Research Part I: Oceanographic Research Papers*, **102**, 1-15, doi:10.1016/j.dsr.2015.04.005.

Hattenrath-Lehmann, T. K. et al., 2018: Evaluation of rapid, early warning approaches to track shellfish toxins associated with *Dinophysis* and *Alexandrium* Blooms. *Marine Drugs*, **16**(1), 28, doi:10.3390/md16010028.

Hátún, H. et al., 2016: An inflated subpolar gyre blows life toward the northeastern Atlantic. *Progress in Oceanography*, **147**, 49-66, doi:10.1016/j.pocean.2016.07.009.

Hauck, J. et al., 2015: On the Southern Ocean CO_2 uptake and the role of the biological carbon pump in the 21st century. *Global Biogeochemical Cycles*, **29**(9), 1451-1470, doi:10.1002/2015GB005140.

Hauser, D. D. W. et al., 2017: Decadal shifts in autumn migration timing by Pacific Arctic beluga whales are related to delayed annual sea ice formation. *Global Change Biology*, **23**(6), 2206-2217, doi:10.1111/gcb.13564.

Hauser, D. D. W., K. L. Laidre and H. L. Stern, 2018: Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(29), 7617, doi:10.1073/pnas.1803543115.

Havens, K. E. et al., 2019: Dynamics of cyanobacteria blooms are linked to the hydrology of shallow Florida lakes and provide insight into possible impacts of climate change. *Hydrobiologia*, **829**(1), 43-59, doi:10.1007/s10750-017-3425-7.

Hawkins, E. and R. Sutton, 2012: Time of emergence of climate signals. *Geophysical Research Letters*, **39**(1), L01702, doi:10.1029/2011GL050087.

Hay, C. C., E. Morrow, R. E. Kopp and J. X. Mitrovica, 2015: Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, **517**(7535), 481-484, doi:10.1038/nature14093.

Hayashida, H., R. J. Matear and P. G. Strutton, 2020: Background nutrient concentration determines phytoplankton bloom response to marine heatwaves. *Global Change Biology*, **26**(9), 4800-4811, doi:10.1111/gcb.15255.

Hazen, E. L. et al., 2018: A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, **4**(5), eaar3001, doi:10.1126/sciadv.aar3001.

He, Q. and B. R. Silliman, 2019: Climate Change, Human Impacts, and Coastal Ecosystems in the Anthropocene. *Current Biology*, **29**(19), R1021-R1035, doi:10.1016/j.cub.2019.08.042.

Hebbeln, D., R. d. C. Portilho-Ramos, C. Wienberg and J. Titschack, 2019: The Fate of Cold-Water Corals in a Changing World: A Geological Perspective. *Frontiers in Marine Science*, **6**, 119, doi:10.3389/fmars.2019.00119.
Hebbeln, D. et al., 2020: Cold-water coral reefs thriving under hypoxia. *Coral Reefs*, **39**(4), 853-859, doi:10.1007/s00338-020-01934-6.
Heckwolf, M. J. et al., 2021: From ecosystems to socio-economic benefits: A systematic review of coastal ecosystem services in the Baltic Sea. *Science of The Total Environment*, **755**, 142565, doi:10.1016/j.scitotenv.2020.142565.
Heffernan, O., 2019: Seabed mining is coming - bringing mineral riches and fears of epic extinctions. *Nature*, **571**(7766), 465-468, doi:10.1038/d41586-019-02242-y.
Heiden, J. P., K. Bischof and S. Trimborn, 2016: Light intensity modulates the response of two Antarctic diatom species to ocean acidification. *Frontiers in Marine Science*, **3**, 260, doi:10.3389/fmars.2016.00260.
Hein, J. R. et al., 2021: Chapter 18: Changes in seabed mining. In: *The Second World Ocean Assessment*. United Nations, New York, pp. 257-280. ISBN 978-92-1-1-130422-0.
Heinze, C. et al., 2021: The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(9), e2008478118, doi:10.1073/pnas.2008478118.
Helfensdorfer, A. M., H. E. Power and T. C. T. Hubble, 2019: Modelling Holocene analogues of coastal plain estuaries reveals the magnitude of sea-level threat. *Scientific Reports*, **9**(1), 2667, doi:10.1038/s41598-019-39516-4.
Helle, I. et al., 2020: Impacts of Oil Spills on Arctic Marine Ecosystems: A Quantitative and Probabilistic Risk Assessment Perspective. *Environmental Science & Technology*, **54**(4), 2112-2121, doi:10.1021/acs.est.9b07086.
Helm, K. P., N. L. Bindoff and J. A. Church, 2011: Observed decreases in oxygen content of the global ocean. *Geophysical Research Letters*, **38**(23), L23602, doi:10.1029/2011gl049513.
Henderson, M. E. et al., 2017: Effects of spring onset and summer duration on fish species distribution and biomass along the Northeast United States continental shelf. *Reviews in Fish Biology and Fisheries*, **27**(2), 411-424, doi:10.1007/s11160-017-9487-9.
Heneghan, R. F. et al., 2021: Disentangling diverse responses to climate change among global marine ecosystem models. *Progress in Oceanography*, 102659, doi:10.1016/j.pocean.2021.102659.
Henley, S. F. et al., 2020: Changing Biogeochemistry of the Southern Ocean and Its Ecosystem Implications. *Frontiers in Marine Science*, **7**(581), doi:10.3389/fmars.2020.00581.
Hennige, S. J. et al., 2014: Short-term metabolic and growth responses of the cold-water coral Lophelia pertusa to ocean acidification. *Deep Sea Research Part II: Topical Studies in Oceanography*, **99**, 27-35, doi:10.1016/j.dsr2.2013.07.005.
Henson, S. A., S. R. Allen, B. B. Cael and S. Dutkiewicz, 2021: Future phytoplankton diversity in a changing climate. *Nature Communications*, Accepted, doi:10.1038/s41467-021-25699-w.
Henson, S. A. et al., 2018a: Detection of climate change-driven trends in phytoplankton phenology. *Global Change Biology*, **24**(1), e101-e111, doi:10.1111/gcb.13886.
Henson, S. A. et al., 2018b: Controls on open-ocean North Atlantic pCO_2 at seasonal and interannual time scales are different. *Geophysical Research Letters*, **45**, doi:10.1029/2018GL078797.
Herbert, E. R. et al., 2015: A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. *Ecosphere*, **6**(10), art206, doi:10.1890/ES14-00534.1.
Hérivaux, C. et al., 2018: Benefits of adapting to sea level rise: the importance of ecosystem services in the French Mediterranean sandy coastline. *Regional Environmental Change*, **18**(6), 1815-1828, doi:10.1007/s10113-018-1313-y.
Hernvann, P.-Y. and D. Gascuel, 2020: Exploring the impacts of fishing and environment on the Celtic Sea ecosystem since 1950. *Fisheries Research*, **225**, 105472, doi:10.1016/j.fishres.2019.105472.
Herr, D., M. von Unger, D. Laffoley and A. McGivern, 2017: Pathways for implementation of blue carbon initiatives. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **27**(S1), 116-129, doi:10.1002/aqc.2793.
Hewitt, C. D. et al., 2020: Making society climate resilient: international progress under the global framework for climate services. *Bulletin of the American Meteorological Society*, **101**(2), E237-E252, doi:10.1175/BAMS-D-18-0211.1.
Hewson, I. et al., 2014: Densovirus associated with sea-star wasting disease and mass mortality. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(48), 17278-17283, doi:10.1073/pnas.1416625111.
Hicks, C. C. et al., 2019: Harnessing global fisheries to tackle micronutrient deficiencies. *Nature*, **574**(7776), 95-98, doi:10.1038/s41586-019-1592-6.
Hidalgo, M., V. Mihneva, M. Vasconcellos and M. Bernal, 2018: Chapter 7: Climate change impacts, vulnerabilities and adaptations: Mediterranean Sea and the Black Sea marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 139-158. ISBN 9789251306079.
Higham, J. E. S. et al., 2016: Managing whale-watching as a non-lethal consumptive activity. *Journal of Sustainable Tourism*, **24**(1), 73-90, doi:10.1080/09669582.2015.1062020.
Hil, G., 2020: Better Management Through Measurement: Integrating Archaeological Site Features into a GIS-Based Erosion and Sea Level Rise Impact Assessment—Blueskin Bay, New Zealand. *The Journal of Island and Coastal Archaeology*, **15**(1), 104-126, doi:10.1080/15564894.2018.1531331.

Hildebrandt, N. et al., 2016: Ocean acidification does not alter grazing in the calanoid copepods *Calanus finmarchicus* and *Calanus glacialis*. *ICES Journal of Marine Science*, **73**(3), 927-936, doi:10.1093/icesjms/fsv226.

Hilsenroth, J., K. A. Grogan and T. K. Frazer, 2021: Assessing the effects of increasing surface seawater temperature on black pearl production in French Polynesia: A bioeconomic simulation. *Ecological Economics*, **181**, 106914, doi:10.1016/j.ecolecon.2020.106914.

Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8**(7), 570-578, doi:10.1038/s41558-018-0176-z.

Hinkel, J. et al., 2019: Meeting user needs for sea level rise information: a decision analysis perspective. *Earth's Future*, **7**(3), 320-337, doi:10.1029/2018EF001071.

Hinkel, J. et al., 2014: Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(9), 3292, doi:10.1073/pnas.1222469111.

Hinkel, J. et al., 2013: A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. *Global and Planetary Change*, **111**, 150-158, doi:10.1016/j.gloplacha.2013.09.002.

Hino, M., C. B. Field and K. J. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, **7**, 364-370, doi:10.1038/nclimate3252.

Hinrichsen, H. H. et al., 2016: Oxygen depletion in coastal seas and the effective spawning stock biomass of an exploited fish species. *Royal Society Open Science*, **3**(1), 150338, doi:10.1098/rsos.150338.

Hoarau, L. et al., 2020: Assessing and Mitigating Humpback Whale (Megaptera Novaeangliae) Disturbance of Whale-watching Activities in Reunion Island. *Tourism in Marine Environments*, **15**(3-4), 173-189, doi:10.3727/154427320X15943326793398.

Hobbs, L. et al., 2021: A marine zooplankton community vertically structured by light across diel to interannual timescales. *Biology Letters*, **17**(2), 20200810, doi:10.1098/rsbl.2020.0810.

Hobday, A. J. et al., 2016a: A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, **141**, 227-238, doi:10.1016/j.pocean.2015.12.014.

Hobday, A. J. et al., 2016b: Planning adaptation to climate change in fast-warming marine regions with seafood-dependent coastal communities. *Reviews in Fish Biology and Fisheries*, **26**(2), 249-264, doi:10.1007/s11160-016-9419-0.

Hobday, A. J. et al., 2018: A framework for combining seasonal forecasts and climate projections to aid risk management for fisheries and aquaculture. *Frontiers in Marine Science*, **5**, 137, doi:10.3389/fmars.2018.00137.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, **50**(8), 839-866, doi:10.1071/MF99078.

Hoegh-Guldberg, O. et al., 2014: The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731. ISBN 9781107058163.

Hoegh-Guldberg, O. et al., 2019a: *The Ocean as a Solution to Climate Change: Five Opportunities for Action* [Institute, W. R. (ed.)]. Washington, D.C. Available at: https://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf.

Hoegh-Guldberg, O. et al., 2018a: Impacts of 1.5ºC global warming on natural and human systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.

Hoegh-Guldberg, O. et al., 2018b: Securing a long-term future for coral reefs. *Trends in Ecology & Evolution*, **33**(12), 936-944, doi:10.1016/j.tree.2018.09.006.

Hoegh-Guldberg, O., E. Northrop and J. Lubchenco, 2019b: The ocean is key to achieving climate and societal goals. *Science*, **365**(6460), 1372, doi:10.1126/science.aaz4390.

Höfer, J. et al., 2018: All you can eat: the functional response of the cold-water coral *Desmophyllum dianthus* feeding on krill and copepods. *PeerJ*, **6**, e5872, doi:10.7717/peerj.5872.

Hoffmann, A. A. and C. M. Sgrò, 2011: Climate change and evolutionary adaptation. *Nature*, **470**(7335), 479-485, doi:10.1038/nature09670.

Holbrook, N. J. et al., 2019: A global assessment of marine heatwaves and their drivers. *Nature Communications*, **10**(1), 2624, doi:10.1038/s41467-019-10206-z.

Holbrook, N. J. et al., 2020: Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment*, **1**(9), 482-493, doi:10.1038/s43017-020-0068-4.

Holland, O., J. Shaw, J. S. Stark and K. A. Wilson, 2021: Hull fouling marine invasive species pose a very low, but plausible, risk of introduction to East Antarctica in climate change scenarios. *Diversity and Distributions*, **27**(6), 973-988, doi:10.1111/ddi.13246.

Holsman, K. et al., 2018: Chapter 6: Climate change impacts, vulnerabilities and adaptations: North Pacific and Pacific Arctic marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane and S. Funge-Smith (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 113-138. ISBN 9789251306079.
Holsman, K. K. et al., 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11**(1), 4579, doi:10.1038/s41467-020-18300-3.
Holsman, K. K. et al., 2019: Towards climate resiliency in fisheries management. *ICES Journal of Marine Science*, **76**(5), 1368-1378, doi:10.1093/icesjms/fsz031.
Hong, B. et al., 2020: Potential physical impacts of sea-level rise on the Pearl River Estuary, China. *Journal of Marine Systems*, **201**, 103245, doi:10.1016/j.jmarsys.2019.103245.
Hong, B. C. and J. B. Shurin, 2015: Latitudinal variation in the response of tidepool copepods to mean and daily range in temperature. *Ecology*, **96**(9), 2348-2359, doi:10.1890/14-1695.1.
Hönisch, B. et al., 2012: The Geological Record of Ocean Acidification. *Science*, **335**(6072), 1058-1063, doi:10.1126/science.1208277.
Hop, H. et al., 2019: Pelagic Ecosystem Characteristics Across the Atlantic Water Boundary Current From Rijpfjorden, Svalbard, to the Arctic Ocean During Summer (2010–2014). *Frontiers in Marine Science*, **6**(181), doi:10.3389/fmars.2019.00181.
Hoppe, C. J. M., C. M. Flintrop and B. Rost, 2018a: The Arctic picoeukaryote Micromonas pusilla benefits synergistically from warming and ocean acidification. *Biogeosciences*, **15**(14), 4353-4365, doi:10.5194/bg-15-4353-2018.
Hoppe, C. J. M. et al., 2013: Iron limitation modulates ocean acidification effects on Southern Ocean phytoplankton communities. *PLOS ONE*, **8**(11), e79890, doi:10.1371/journal.pone.0079890.
Hoppe, C. J. M., L.-M. Holtz, S. Trimborn and B. Rost, 2015: Ocean acidification decreases the light-use efficiency in an Antarctic diatom under dynamic but not constant light. *New Phytologist*, **207**(1), 159-171, doi:10.1111/nph.13334.
Hoppe, C. J. M. et al., 2018b: Compensation of ocean acidification effects in Arctic phytoplankton assemblages. *Nature Climate Change*, **8**(6), 529-533, doi:10.1038/s41558-018-0142-9.
Hoque, S. and M. M. Hoque (eds.), Sea Level Rise and Its Impact on Archaeological Sites in South Bangladesh: A Preliminary Study. Man and Water: Seminar on Archaeology, Supply and Sanitation in Bangladesh and Beyond, Goeth-Institute Dhaka, Bangladesh, Goeth-Institute Bangladesh, 13-22 pp. ISBN 978-3-00-030065-3.
Horton, B. P. et al., 2018: Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data. *Nature Communications*, **9**(1), 2687, doi:10.1038/s41467-018-05080-0.
Horwitz, R. et al., 2020: Near-future ocean warming and acidification alter foraging behaviour, locomotion, and metabolic rate in a keystone marine mollusc. *Scientific Reports*, **10**(1), 5461, doi:10.1038/s41598-020-62304-4.
Hossain, M. M., 2019: Future importance of healthy oceans: ecosystem functions and biodiversity, marine pollution, carbon sequestration, ecosystem goods and servcies. *Journal of Ocean and Coastal Economics*, **6**(2), 4, doi:10.15351/2373-8456.1103.
Houde, M. et al., 2019: Trends of persistent organic pollutants in ringed seals (Phoca hispida) from the Canadian Arctic. *Science of The Total Environment*, **665**, 1135-1146, doi:10.1016/j.scitotenv.2019.02.138.
Hovelsrud, G. K., B. P. Kaltenborn and J. Olsen, 2020: Svalbard in transition: adaptation to cross-scale changes in Longyearbyen. *The Polar Journal*, 1-23, doi:10.1080/2154896X.2020.1819016.
Howard, E. M. et al., 2020a: Attributing Causes of Future Climate Change in the California Current System With Multimodel Downscaling. *Global Biogeochemical Cycles*, **34**(11), e2020GB006646, doi:10.1029/2020GB006646.
Howard, E. M. et al., 2020b: Climate-driven aerobic habitat loss in the California Current System. *Science Advances*, **6**(20), eaay3188, doi:10.1126/sciadv.aay3188.
Howard, J. et al., 2017: Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, **15**(1), 42-50, doi:10.1002/fee.1451.
Howard, P. L. and G. T. Pecl, 2019: Introduction: Autochthonous human adaptation to biodiversity change in the Anthropocene. *Ambio*, **48**(12), 1389-1400, doi:10.1007/s13280-019-01283-x.
Howells, E. J. et al., 2021: Enhancing the heat tolerance of reef-building corals to future warming. *Science Advances*, **7**(34), eabg6070, doi:10.1126/sciadv.abg6070.
Howells, E. J. et al., 2020: Annual outbreaks of coral disease coincide with extreme seasonal warming. *Coral Reefs*, **39**(3), 771-781, doi:10.1007/s00338-020-01946-2.
Hügel, S. and A. R. Davies, 2020: Public participation, engagement, and climate change adaptation: A review of the research literature. *WIREs Climate Change*, **11**(4), e645, doi:10.1002/wcc.645.
Huggel, C., I. Wallimann-Helmer, D. Stone and W. Cramer, 2016: Reconciling justice and attribution research to advance climate policy. *Nature Climate Change*, **6**(10), 901-908, doi:10.1038/nclimate3104.
Hughes, D. J. et al., 2020: Coral reef survival under accelerating ocean deoxygenation. *Nature Climate Change*, **10**(4), 296-307, doi:10.1038/s41558-020-0737-9.
Hughes, J. et al., 2021: Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Climate Risk Management*, **31**, 100262, doi:10.1016/j.crm.2020.100262.

Hughes, T. P. et al., 2018a: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, **359**(6371), 80-83, doi:10.1126/science.aan8048.
Hughes, T. P. et al., 2019: Global warming impairs stock–recruitment dynamics of corals. *Nature*, **568**(7752), 387-390, doi:10.1038/s41586-019-1081-y.
Hughes, T. P. et al., 2018b: Global warming transforms coral reef assemblages. *Nature*, **556**(7702), 492-496, doi:10.1038/s41586-018-0041-2.
Hummel, M. A., M. S. Berry and M. T. Stacey, 2018: Sea Level Rise Impacts on Wastewater Treatment Systems Along the U.S. Coasts. *Earth's Future*, **6**(4), 622-633, doi:10.1002/2017EF000805.
Hunt, G. and K. Roy, 2006: Climate change, body size evolution, and Cope's rule in deep-sea ostracodes. *Proceedings of the National Academy of Sciences of the United States of America*, **103**(5), 1347-1352, doi:10.1073/pnas.0510550103.
Hunt, G. L. et al., 2016: Advection in polar and sub-polar environments: Impacts on high latitude marine ecosystems. *Progress in Oceanography*, **149**, 40-81, doi:10.1016/j.pocean.2016.10.004.
Huntington, H. P. et al., 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10**(4), 342-348, doi:10.1038/s41558-020-0695-2.
Huserbråten, M. B. O., E. Eriksen, H. Gjøsæter and F. Vikebø, 2019: Polar cod in jeopardy under the retreating Arctic sea ice. *Communications Biology*, **2**(1), 407, doi:10.1038/s42003-019-0649-2.
Hutchins, D. A. et al., 2013: Taxon-specific response of marine nitrogen fixers to elevated carbon dioxide concentrations. *Nature Geoscience*, **6**(9), 790-795, doi:10.1038/ngeo1858.
Hyndes, G. A. et al., 2016: Accelerating tropicalization and the transformation of temperate seagrass meadows. *BioScience*, **66**(11), 938-945, doi:10.1093/biosci/biw111.
Iacarella, J. C. et al., 2020: Climate change and vessel traffic create networks of invasion in marine protected areas. *Journal of Applied Ecology*, **57**(9), 1793-1805, doi:10.1111/1365-2664.13652.
Ibarbalz, F. M. et al., 2019: Global trends in marine plankton diversity across kingdoms of life. *Cell*, **179**(5), 1084-1097.e1021, doi:10.1016/j.cell.2019.10.008.
Idier, D., X. Bertin, P. Thompson and M. D. Pickering, 2019: Interactions Between Mean Sea Level, Tide, Surge, Waves and Flooding: Mechanisms and Contributions to Sea Level Variations at the Coast. *Surveys in Geophysics*, **40**(6), 1603-1630, doi:10.1007/s10712-019-09549-5.
Ilia, A., 2020: The potential role of artificial marsh on coastal protection in Long Island Sound. *Preprints*, 2020120694 doi:10.20944/preprints202012.0694.v1.
Ingram, R. J., K. L. L. Oleson and J. M. Gove, 2018: Revealing complex social-ecological interactions through participatory modeling to support ecosystem-based management in Hawai'i. *Marine Policy*, **94**, 180-188, doi:10.1016/j.marpol.2018.05.002.
IPBES, 2017: *Update on the classification of nature's contributions to people by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Report of the Executive Secretary on the implementation of the work programme for the period 2014–2018, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 1-8 pp. Available at: https://ipbes.net/sites/default/files/downloads/pdf/ipbes-5-inf-24.pdf.
IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. ISBN 9781107057991.
IPCC, 2014a: Annex II: Glossary [Agard, J., E.L.F. Schipper, J. Birkmann, M. Campos, C. Dubeux, Y. Nojiri, L. Olsson, B. Osman-Elasha, M. Pelling, M.J. Prather, M.G. Rivera-Ferre, O.C. Ruppel, A. Sallenger, K.R. Smith, A.L. St Clair, K.J. Mach, M.D. Mastrandrea, and T.E. Bilir (eds.)]. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1757-1776.
IPCC, 2014b: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp. ISBN 9781107058071.
IPCC, 2014c: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp. ISBN 9781107058163.

IPCC, 2014d: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1435 pp. ISBN 9781107058217.

IPCC, 2018: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In press pp. ISBN 9789291691517.

IPCC, 2019a: Annex 1: Glossary [Weyer, N. M. (ed.)]. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. In press.

IPCC, 2019b: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. In press.

IPCC, 2019c: Summary for Policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. In press.

IPCC, 2019d: Technical Summary. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.

IPCC, 2021a: Annex VII: Glossary [Matthews, J. B. R., J. S. Fuglestvedt, V. Masson-Delmotte, V. Möller, C. Méndez, R. van Diemen, A. Reisinger, S. Semenov (ed.)]. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

IPCC, 2021b: *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Islam, M. A., M. A. Hoque, K. M. Ahmed and A. P. Butler, 2019: Impact of Climate Change and Land Use on Groundwater Salinization in Southern Bangladesh—Implications for Other Asian Deltas. *Environmental Management*, **64**(5), 640-649, doi:10.1007/s00267-019-01220-4.

Ito, T., S. Minobe, M. C. Long and C. Deutsch, 2017: Upper ocean O_2 trends: 1958–2015. *Geophysical Research Letters*, **44**(9), 4214-4223, doi:10.1002/2017GL073613.

Ito, T. et al., 2016: Acceleration of oxygen decline in the tropical Pacific over the past decades by aerosol pollutants. *Nature Geoscience*, **9**(6), 443-447, doi:10.1038/ngeo2717.

IUCN, 2020: The IUCN Red List of Threatened Species, International Union for Conservation of Nature. Available at: https://www.iucnredlist.org.

Jabali, W., A. Wamukota and B. Fulanda, 2020: The role of indigenous knowledge in the management of marine resources: a case study of Kuruwitu and Mkunguni fishing areas in Kenya. *Western Indian Ocean Journal of Marine Science*, **19**(1), 19-31, doi:10.4314/wiojms.v19i1.2.

Jaccard, S. L. and E. D. Galbraith, 2012: Large climate-driven changes of oceanic oxygen concentrations during the last deglaciation. *Nature Geoscience*, **5**, 151-156, doi:10.1038/ngeo1352.

Jackson, R. C., A. J. Dugmore and F. Riede, 2018: Rediscovering lessons of adaptation from the past. *Global Environmental Change*, **52**, 58-65, doi:10.1016/j.gloenvcha.2018.05.006.

Jacox, M. G. et al., 2020: Seasonal-to-interannual prediction of North American coastal marine ecosystems: Forecast methods, mechanisms of predictability, and priority developments. *Progress in Oceanography*, **183**, 102307, doi:10.1016/j.pocean.2020.102307.

Jacox, M. G. et al., 2019: Predicting the evolution of the 2014–2016 California Current system marine heatwave from an ensemble of coupled global climate forecasts. *Frontiers in Marine Science*, **6**, 497, doi:10.3389/fmars.2019.00497.

Jakimavičius, D., J. Kriaučiūnienė and D. Šarauskienė, 2018: Assessment of wave climate and energy resources in the Baltic Sea nearshore (Lithuanian territorial water). *Oceanologia*, **60**(2), 207-218, doi:10.1016/j.oceano.2017.10.004.

Jakobsson-Thor, S., J. Brakel, G. B. Toth and H. Pavia, 2020: Complex Interactions of Temperature, Light and Tissue Damage on Seagrass Wasting Disease in Zostera marina. *Frontiers in Marine Science*, **7**(865), doi:10.3389/fmars.2020.575183.
Jambeck, J. R. et al., 2015: Plastic waste inputs from land into the ocean. *Science*, **347**(6223), 768-771, doi:10.1126/science.1260352.
James, R. K. et al., 2020: Seagrass coastal protection services reduced by invasive species expansion and megaherbivore grazing. *Journal of Ecology*, **108**(5), 2025-2037, doi:10.1111/1365-2745.13411.
James, R. K. et al., 2021: Tropical Biogeomorphic Seagrass Landscapes for Coastal Protection: Persistence and Wave Attenuation During Major Storms Events. *Ecosystems*, **24**(2), 301-318, doi:10.1007/s10021-020-00519-2.
James, R. K. et al., 2019: Maintaining tropical beaches with seagrass and algae: a promising alternative to engineering solutions. *BioScience*, **69**(2), 136-142, doi:10.1093/biosci/biy154.
Jardine, S. L., M. C. Fisher, S. K. Moore and J. F. Samhouri, 2020: Inequality in the economic impacts from climate shocks in fisheries: the case of harmful algal blooms. *Ecological Economics*, **176**, 106691, doi:10.1016/j.ecolecon.2020.106691.
Jarrold, M. D. et al., 2020: Elevated CO_2 affects anxiety but not a range of other behaviours in juvenile yellowtail kingfish. *Marine Environmental Research*, **157**(104863), doi:10.1016/j.marenvres.2019.104863.
Jarvis, B. M. et al., 2020: Modeling Spatiotemporal Patterns of Ecosystem Metabolism and Organic Carbon Dynamics Affecting Hypoxia on the Louisiana Continental Shelf. *Journal of Geophysical Research: Oceans*, **125**(4), e2019JC015630, doi:10.1029/2019JC015630.
Jayathilake, D. R. M. and M. J. Costello, 2018: A modelled global distribution of the seagrass biome. *Biological Conservation*, **226**, 120-126, doi:10.1016/j.biocon.2018.07.009.
Jayathilake, D. R. M. and M. J. Costello, 2020: A modelled global distribution of the kelp biome. *Biological Conservation*, **252**, 108815, doi:10.1016/j.biocon.2020.108815.
Jensen, M. P. et al., 2018: Environmental warming and feminization of one of the largest sea turtle populations in the world. *Current Biology*, **28**(1), 154-159.e154, doi:10.1016/j.cub.2017.11.057.
Jensen, M. P. et al., 2019: The evolutionary history and global phylogeography of the green turtle (*Chelonia mydas*). *Journal of Biogeography*, **46**(5), 860-870, doi:10.1111/jbi.13483.
Jevrejeva, S. et al., 2019: Probabilistic sea level projections at the coast by 2100. *Surveys in Geophysics*, 1-24, doi:10.1007/s10712-019-09550-y.
Jevrejeva, S. et al., 2014: Trends and acceleration in global and regional sea levels since 1807. *Global and Planetary Change*, **113**, 11-22, doi:10.1016/j.gloplacha.2013.12.004.
Jiang, L. et al., 2020: Effects of sea-level rise on tides and sediment dynamics in a Dutch tidal bay. *Ocean Science*, **16**(2), 307-321, doi:10.5194/os-16-307-2020.
Jiang, L.-Q. et al., 2019: Surface ocean pH and buffer capacity: past, present and future. *Scientific Reports*, **9**(1), 18624, doi:10.1038/s41598-019-55039-4.
Jin, P. et al., 2013: Ocean acidification alters the photosynthetic responses of a coccolithophorid to fluctuating ultraviolet and visible radiation. *Plant Physiology*, **162**(4), 2084-2094, doi:10.1104/pp.113.219543.
Jobstvogt, N. et al., 2014: Twenty thousand sterling under the sea: Estimating the value of protecting deep-sea biodiversity. *Ecological Economics*, **97**, 10-19, doi:10.1016/j.ecolecon.2013.10.019.
Johnson, C., M. Inall, S. Gary and S. Cunningham, 2020: Significance of Climate Indices to Benthic Conditions Across the Northern North Atlantic and Adjacent Shelf Seas. *Frontiers in Marine Science*, **7**, 2, doi:10.3389/fmars.2020.00002.
Johnson, C. R., R. H. Chabot, M. P. Marzloff and S. Wotherspoon, 2017a: Knowing when (not) to attempt ecological restoration. *Restoration Ecology*, **25**(1), 140-147, doi:10.1111/rec.12413.
Johnson, D., M. Adelaide Ferreira and E. Kenchington, 2018: Climate change is likely to severely limit the effectiveness of deep-sea ABMTs in the North Atlantic. *Marine Policy*, **87**, 111-122, doi:10.1016/j.marpol.2017.09.034.
Johnson, D. et al., 2019: The Global Ocean Biodiversity Initiative: Promoting scientific support for global ocean governance. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **29**(S2), 162-169, doi:10.1002/aqc.3024.
Johnson, K. M. and G. E. Hofmann, 2020: Combined stress of ocean acidification and warming influence survival and drives differential gene expression patterns in the Antarctic pteropod, *Limacina helicina antarctica*. *Conservation Physiology*, **8**(1), doi:10.1093/conphys/coaa013.
Johnson, K. S., F. P. Chavez and G. E. Friederich, 1999: Continental-shelf sediment as a primary source of iron for coastal phytoplankton. *Nature*, **398**(6729), 697-700, doi:10.1038/19511.
Johnson, M. D., S. Comeau, C. A. Lantz and J. E. Smith, 2017b: Complex and interactive effects of ocean acidification and temperature on epilithic and endolithic coral-reef turf algal assemblages. *Coral Reefs*, **36**(4), 1059-1070, doi:10.1007/s00338-017-1597-2.
Jones, B. and B. C. O'Neill, 2016: Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environ.Res.Lett.*, **11**(8), 084003, doi:10.1088/1748-9326/11/8/084003.
Jones, H. P. et al., 2018a: Restoration and repair of Earth's damaged ecosystems. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1873), 20172577, doi:10.1098/rspb.2017.2577.
Jones, H. P. et al., 2020: Global hotspots for coastal ecosystem-based adaptation. *PLOS ONE*, **15**(5), e0233005, doi:10.1371/journal.pone.0233005.

Jones, L. A. et al., 2019a: Coupling of palaeontological and neontological reef coral data improves forecasts of biodiversity responses under global climatic change. *Royal Society Open Science*, **6**(4), 182111, doi:10.1098/rsos.182111.
Jones, M. C. and W. W. L. Cheung, 2015: Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES Journal of Marine Science*, **72**(3), 741-752, doi:10.1093/icesjms/fsu172.
Jones, M. C. and W. W. L. Cheung, 2018: Using fuzzy logic to determine the vulnerability of marine species to climate change. *Global Change Biology*, **24**(2), e719-e731, doi:10.1111/gcb.13869.
Jones, M. C. et al., 2019b: Rapid inundation of southern Florida coastline despite low relative sea-level rise rates during the late-Holocene. *Nature Communications*, **10**(1), 3231, doi:10.1038/s41467-019-11138-4.
Jones, T. et al., 2018b: Massive mortality of a planktivorous seabird in response to a marine heatwave. *Geophysical Research Letters*, **45**(7), 3193-3202, doi:10.1002/2017GL076164.
Jorda, G. et al., 2020: Ocean warming compresses the three-dimensional habitat of marine life. *Nature Ecology & Evolution*, **4**(1), 109-114, doi:10.1038/s41559-019-1058-0.
Joyce, P. W. S. et al., 2019: Stay clean: direct steam exposure to manage biofouling risks. *Marine Pollution Bulletin*, **142**, 465-469, doi:10.1016/j.marpolbul.2019.04.011.
Jurikova, H. et al., 2020: Permian–Triassic mass extinction pulses driven by major marine carbon cycle perturbations. *Nature Geoscience*, **13**(11), 745-750, doi:10.1038/s41561-020-00646-4.
Kaartvedt, S. and J. Titelman, 2018: Planktivorous fish in a future Arctic Ocean of changing ice and unchanged photoperiod. *ICES Journal of Marine Science*, **75**(7), 2312-2318, doi:10.1093/icesjms/fsx248.
Kaiho, K., M. Katabuchi, M. Oba and M. Lamolda, 2014: Repeated anoxia–extinction episodes progressing from slope to shelf during the latest Cenomanian. *Gondwana Research*, **25**(4), 1357-1368, doi:10.1016/j.gr.2012.12.008.
Kainge, P. et al., 2020: Fisheries yields, climate change, and ecosystem-based management of the Benguela Current Large Marine Ecosystem. *Environmental Development*, **36**, 100567, doi:10.1016/j.envdev.2020.100567.
Kakehi, S. et al., 2021: Bottom temperature warming and its impact on demersal fish off the Pacific coast of northeastern Japan. *Marine Ecology Progress Series*, Accepted, doi:10.3354/meps13852.
Kalia, V. et al., 2021: Relationship between the Pacific Decadal Oscillation (PDO) and persistent organic pollutants in sympatric Alaskan seabird (Uria aalge and U. lomvia) eggs between 1999 and 2010. *Chemosphere*, **262**, 127520, doi:10.1016/j.chemosphere.2020.127520.
Kanamori, Y., A. Takasuka, S. Nishijima and H. Okamura, 2019: Climate change shifts the spawning ground northward and extends the spawning period of chub mackerel in the western North Pacific. *Marine Ecology Progress Series*, **624**, 155-166.
Kane, H. H. and C. H. Fletcher, 2020: Rethinking Reef Island Stability in Relation to Anthropogenic Sea Level Rise. *Earth's Future*, **8**(10), e2020EF001525, doi:10.1029/2020EF001525.
Kaneko, H. et al., 2021: Eukaryotic virus composition can predict the efficiency of carbon export in the global ocean. *iScience*, **24**(1), doi:10.1016/j.isci.2020.102002.
Kaplan, I. C. and K. N. Marshall, 2016: A guinea pig's tale: learning to review end-to-end marine ecosystem models for management applications. *ICES Journal of Marine Science*, **73**(7), 1715-1724, doi:10.1093/icesjms/fsw047.
Karagas, M. R. et al., 2012: Evidence on the human health effects of low-level methylmercury exposure. *Environmental Health Perspectives*, **120**(6), 799-806, doi:10.1289/ehp.1104494.
Karp, M. A. et al., 2019: Accounting for shifting distributions and changing productivity in the development of scientific advice for fishery management. *ICES Journal of Marine Science*, **76**(5), 1305-1315, doi:10.1093/icesjms/fsz048.
Kasmi, S. et al., 2020: Increasing pressures, eroding beaches and climate change in Morocco. *Journal of African Earth Sciences*, **164**, 103796, doi:10.1016/j.jafrearsci.2020.103796.
Kauffman, J. B. et al., 2020: Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. *Ecological Monographs*, **90**(2), e01405, doi:10.1002/ecm.1405.
Kazanidis, G. et al., 2020: Assessing the environmental status of selected North Atlantic deep-sea ecosystems. *Ecological Indicators*, **119**, 106624, doi:10.1016/j.ecolind.2020.106624.
Kazanidis, G. et al., 2019: Distribution of Deep-Sea Sponge Aggregations in an Area of Multisectoral Activities and Changing Oceanic Conditions. *Frontiers in Marine Science*, **6**, 163, doi:10.3389/fmars.2019.00163.
Keeling, R. F., A. Körtzinger and N. Gruber, 2010: Ocean deoxygenation in a warming world. *Annual Review of Marine Science*, **2**(1), 199-229, doi:10.1146/annurev.marine.010908.163855.
Keimer, K. et al., 2021: Ecosystem services in coastal wetlands: Investigating bio- and hydro-mechanical traits of salt marsh vegetation. In: *EGU General Assembly 2021*, 19-30 April 2021, Online, doi:10.5194/egusphere-egu21-8626.
Kelleway, J. J. et al., 2017: Review of the ecosystem service implications of mangrove encroachment into salt marshes. *Global Change Biology*, **23**(10), 3967-3983, doi:10.1111/gcb.13727.
Kelleway, J. J. et al., 2016: Seventy years of continuous encroachment substantially increases 'blue carbon' capacity as mangroves replace intertidal salt marshes. *Global Change Biology*, **22**(3), 1097-1109, doi:10.1111/gcb.13158.
Kelleway, J. J. et al., 2020: A national approach to greenhouse gas abatement through blue carbon management. *Global Environmental Change*, **63**, 102083, doi:10.1016/j.gloenvcha.2020.102083.

Kelly, M. W., J. L. Padilla-Gamiño and G. E. Hofmann, 2013: Natural variation and the capacity to adapt to ocean acidification in the keystone sea urchin *Strongylocentrotus purpuratus*. *Global Change Biology*, **19**(8), 2536-2546, doi:10.1111/gcb.12251.
Kelly-Gerreyn, B. A. et al., 2014: Benthic biomass size spectra in shelf and deep-sea sediments. *Biogeosciences*, **11**(22), 6401-6416, doi:10.5194/bg-11-6401-2014.
Kemp, A. C. et al., 2018: Relative sea-level change in Newfoundland, Canada during the past ~3000 years. *Quat. Sci. Rev.*, **201**, 89-110, doi:10.1016/j.quascirev.2018.10.012.
Kench, P. S. and T. Mann, 2017: Reef Island Evolution and Dynamics: Insights from the Indian and Pacific Oceans and Perspectives for the Spermonde Archipelago. *Frontiers in Marine Science*, **4**, 145.
Kendrick, G. A. et al., 2019: A Systematic Review of How Multiple Stressors From an Extreme Event Drove Ecosystem-Wide Loss of Resilience in an Iconic Seagrass Community. *Frontiers in Marine Science*, **6**(455), doi:10.3389/fmars.2019.00455.
Kenny, T.-A. et al., 2018: Calories are cheap, nutrients are expensive – the challenge of healthy living in Arctic communities. *Food Policy*, **80**, 39-54, doi:10.1016/j.foodpol.2018.08.006.
Kent, S. and K. V. Brondo, 2020: "Years Ago the Crabs Was so Plenty": Anthropology's Role in Ecological Grieving and Conservation Work. *Culture, Agriculture, Food and Environment*, **42**(1), 16-24, doi:10.1111/cuag.12235.
Keogan, K. et al., 2018: Global phenological insensitivity to shifting ocean temperatures among seabirds. *Nature Climate Change*, **8**(4), 313-317, doi:10.1038/s41558-018-0115-z.
Kessouri, F. et al., 2021: Coastal eutrophication drives acidification, oxygen loss, and ecosystem change in a major oceanic upwelling system. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(21), e2018856118, doi:10.1073/pnas.2018856118.
Keyes, A. A., J. P. McLaughlin, A. K. Barner and L. E. Dee, 2021: An ecological network approach to predict ecosystem service vulnerability to species losses. *Nature Communications*, **12**(1), 1586, doi:10.1038/s41467-021-21824-x.
Khojasteh, D., W. Glamore, V. Heimhuber and S. Felder, 2021: Sea level rise impacts on estuarine dynamics: A review. *Science of The Total Environment*, **780**, 146470, doi:10.1016/j.scitotenv.2021.146470.
Khosravi, M. et al., 2019: Impact of warming on biofouling communities in the northern Persian Gulf. *Journal of Thermal Biology*, **85**, 102403, doi:10.1016/j.jtherbio.2019.102403.
Kibria, G., D. Nugegoda, G. Rose and A. K. Y. Haroon, 2021: Climate change impacts on pollutants mobilization and interactive effects of climate change and pollutants on toxicity and bioaccumulation of pollutants in estuarine and marine biota and linkage to seafood security. *Marine Pollution Bulletin*, **167**, 112364, doi:10.1016/j.marpolbul.2021.112364.
Kiessling, W. and A. T. Kocsis, 2015: Biodiversity dynamics and environmental occupancy of fossil azooxanthellate and zooxanthellate scleractinian corals. *Paleobiology*, **41**(3), 402-414, doi:10.1017/pab.2015.6.
Kiessling, W. and C. Simpson, 2011: On the potential for ocean acidification to be a general cause of ancient reef crises. *Global Change Biology*, **17**(1), 56-67, doi:10.1111/j.1365-2486.2010.02204.x.
Kiessling, W. et al., 2012: Equatorial decline of reef corals during the last Pleistocene interglacial. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(52), 21378-21383, doi:10.1073/pnas.1214037110.
Kifani, S. et al., 2018: Chapter 8: Climate change impacts, vulnerabilities and adaptations: Eastern Central Atlantic marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 159-183. ISBN 9789251306079.
Kikiloi, K. et al., 2017: Papahānaumokuākea: Integrating Culture in the Design and Management of one of the World's Largest Marine Protected Areas. *Coast. Manage.*, **45**(6), 436-451, doi:10.1080/08920753.2017.1373450.
Kim, J.-H. et al., 2020: Global warming offsets the ecophysiological stress of ocean acidification on temperate crustose coralline algae. *Marine Pollution Bulletin*, **157**, 111324, doi:10.1016/j.marpolbul.2020.111324.
Kim, S. K., 2020: The Economic Effects of Climate Change Adaptation Measures: Evidence from Miami-Dade County and New York City. *Sustainability*, **12**(3), doi:10.3390/su12031097.
Kimball, M. E., D. M. Allen, P. D. Kenny and V. Ogburn-Matthews, 2020: Decadal-Scale Changes in Subtidal Nekton Assemblages in a Warm-Temperate Estuary. *Estuaries and Coasts*, **43**(4), 927-939, doi:10.1007/s12237-019-00692-1.
Kimmel, D. G., L. B. Eisner, M. T. Wilson and J. T. Duffy-Anderson, 2018: Copepod dynamics across warm and cold periods in the eastern Bering Sea: implications for walleye pollock (*Gadus chalcogrammus*) and the oscillating control hypothesis. *Fisheries Oceanography*, **27**(2), 143-158, doi:10.1111/fog.12241.
King, N. G. et al., 2019: Evidence for different thermal ecotypes in range centre and trailing edge kelp populations. *Journal of Experimental Marine Biology and Ecology*, **514–515**, 10-17, doi:10.1016/j.jembe.2019.03.004.
King, N. G. et al., 2021: Climate change accelerates range expansion of the invasive non-native species, the Pacific oyster, Crassostrea gigas. *ICES Journal of Marine Science*, **78**(1), 70-81, doi:10.1093/icesjms/fsaa189.
Kirchhoff, C. J. and P. L. Watson, 2019: Are Wastewater Systems Adapting to Climate Change? *JAWRA Journal of the American Water Resources Association*, **55**(4), 869-880, doi:10.1111/1752-1688.12748.

Kirezci, E. et al., 2020: Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific Reports*, **10**(1), 11629, doi:10.1038/s41598-020-67736-6.
Kirshen, P. et al., 2018: Integrated urban water management applied to adaptation to climate change. *Urban Climate*, **24**, 247-263, doi:10.1016/j.uclim.2018.03.005.
Kirtman, B. et al., 2013: Near-term Climate Change: Projections and Predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 953-1028.
Kirwan, M. L. and K. B. Gedan, 2019: Sea-level driven land conversion and the formation of ghost forests. *Nature Climate Change*, **9**(6), 450-457, doi:10.1038/s41558-019-0488-7.
Kjesbu, O. S. et al., 2014: Synergies between climate and management for Atlantic cod fisheries at high latitudes. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(9), 3478-3483, doi:10.1073/pnas.1316342111.
Kleiman, R. M., G. W. Characklis, J. D. Kern and R. Gerlach, 2021: Characterizing weather-related biophysical and financial risks in algal biofuel production. *Applied Energy*, **294**, 116960, doi:10.1016/j.apenergy.2021.116960.
Klein, E. S. et al., 2018: Impacts of rising sea temperature on krill increase risks for predators in the Scotia Sea. *PLOS ONE*, **13**(1), e0191011, doi:10.1371/journal.pone.0191011.
Klein, S. G. et al., 2021: Projecting coral responses to intensifying marine heatwaves under ocean acidification. *Global Change Biology*, **n/a**(n/a), doi:10.1111/gcb.15818.
Kleinhaus, K. et al., 2020: Science, diplomacy, and the Red Sea's unique coral reef: it's time for action. *Frontiers in Marine Science*, **7**, 90, doi:10.3389/fmars.2020.00090.
Kleisner, K., D. Zeller, R. Froese and D. Pauly, 2013: Using global catch data for inferences on the world's marine fisheries. *Fish and Fisheries*, **14**(3), 293-311, doi:10.1111/j.1467-2979.2012.00469.x.
Kleypas, J. et al., 2021: Designing a blueprint for coral reef survival. *Biological Conservation*, **257**, 109107, doi:10.1016/j.biocon.2021.109107.
Kline, D. I. et al., 2019: Living coral tissue slows skeletal dissolution related to ocean acidification. *Nature Ecology & Evolution*, **3**(10), 1438-1444, doi:10.1038/s41559-019-0988-x.
Klöck, C. and P. D. Nunn, 2019: Adaptation to climate change in small island developing states: a systematic literature review of academic research. *The Journal of Environment & Development*, 1-23, doi:10.1177/1070496519835895.
Knowlton, N., 2020: Ocean Optimism: Moving Beyond the Obituaries in Marine Conservation. *Annual Review of Marine Science*, **13**, 479-499, doi:10.1146/annurev-marine-040220-101608.
Kobusińska, M. E. et al., 2020: Precursors of polychlorinated dibenzo-p-dioxins and dibenzofurans in Arctic and Antarctic marine sediments: Environmental concern in the face of climate change. *Chemosphere*, **260**, 127605, doi:10.1016/j.chemosphere.2020.127605.
Koenigstein, S., 2020: Arctic Marine Ecosystems, Climate Change Impacts, and Governance Responses: An Integrated Perspective from the Barents Sea. In: *Arctic Marine Sustainability: Arctic Maritime Businesses and the Resilience of the Marine Environment* [Pongrácz, E., V. Pavlov and N. Hänninen (eds.)]. Springer International Publishing, Cham, pp. 45-71. ISBN 978-3-030-28404-6.
Koenigstein, S., L.-H. Hentschel, L. C. Heel and C. Drinkorn, 2020: A game-based education approach for sustainable ocean development. *ICES Journal of Marine Science*, **77**(5), 1629-1638, doi:10.1093/icesjms/fsaa035.
Koenigstein, S. et al., 2016: Modelling climate change impacts on marine fish populations: process-based integration of ocean warming, acidification and other environmental drivers. *Fish and Fisheries*, **17**(4), 972-1004, doi:10.1111/faf.12155.
Kok, S. et al., 2021: The potential of nature-based flood defences to leverage public investment in coastal adaptation: Cases from the Netherlands, Indonesia and Georgia. *Ecological Economics*, **179**, 106828, doi:10.1016/j.ecolecon.2020.106828.
Kompor, W., C. Ekkawatpanit and D. Kositgittiwong, 2018: Assessment of ocean wave energy resource potential in Thailand. *Ocean & Coastal Management*, **160**, 64-74, doi:10.1016/j.ocecoaman.2018.04.003.
Konar, M. and H. Ding, 2020: *A Sustainable Ocean Economy for 2050: Approximating Its Benefits and Costs*. High Level Panel for a Sustainable Ocean Economy, Washington, D.C., USA. Available at: https://oceanpanel.org/sites/default/files/2020-07/Ocean%20Panel_Economic%20Analysis_FINAL.pdf.
Kondrik, D., D. Pozdnyakov and L. Pettersson, 2017: Particulate inorganic carbon production within *E. huxley*i blooms in subpolar and polar seas: a satellite time series study (1998–2013). *International Journal of Remote Sensing*, **38**(22), 6179-6205, doi:10.1080/01431161.2017.1350304.
Kong, C. E., S. Yoo and C. J. Jang, 2019: East China Sea ecosystem under multiple stressors: Heterogeneous responses in the sea surface chlorophyll-a. *Deep-Sea Research Part I: Oceanographic Research Papers*, **151**, 103078, doi:10.1016/j.dsr.2019.103078.
Kool, R., J. Lawrence, M. Drews and R. Bell, 2020: Preparing for Sea-Level Rise through Adaptive Managed Retreat of a New Zealand Stormwater and Wastewater Network. *Infrastructures*, **5**(11), doi:10.3390/infrastructures5110092.
Kopp, R. E. et al., 2019: Usable Science for Managing the Risks of Sea-Level Rise. *Earth's Future*, **7**(12), 1235-1269, doi:10.1029/2018EF001145.

Kopp, R. E. et al., 2016: Temperature-driven global sea-level variability in the common era. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(11), E1434-E1441, doi:10.1073/pnas.1517056113.
Kornder, N. A., B. M. Riegl and J. Figueiredo, 2018: Thresholds and drivers of coral calcification responses to climate change. *Global Change Biology*, **24**(11), 5084-5095, doi:10.1111/gcb.14431.
Koslow, J. A., P. Davison and E. a. Ferrer, 2019: The evolving response of mesopelagic fishes to declining midwater oxygen concentrations in the southern and central California Current. *ICES Journal of Marine Science*, **76**(3), 626-638, doi:10.1093/icesjms/fsy154.
Kotta, J. et al., 2018: Predicting the cover and richness of intertidal macroalgae in remote areas: a case study in the Antarctic Peninsula. *Ecology and Evolution*, **8**(17), 9086-9094, doi:10.1002/ece3.4463.
Kottmeier, D. M., S. D. Rokitta and B. Rost, 2016: Acidification, not carbonation, is the major regulator of carbon fluxes in the coccolithophore Emiliania huxleyi. *New Phytologist*, **211**(1), 126-137, doi:10.1111/nph.13885.
Kovach, R. P., S. C. Ellison, S. Pyare and D. A. Tallmon, 2015: Temporal patterns in adult salmon migration timing across southeast Alaska. *Global Change Biology*, **21**(5), 1821-1833, doi:10.1111/gcb.12829.
Krabbenhoft, D. P. and E. M. Sunderland, 2013: Global change and mercury. *Science*, **341**(6153), 1457-1458, doi:10.1126/science.1242838.
Kram, S. L. et al., 2016: Variable responses of temperate calcified and fleshy macroalgae to elevated pCO_2 and warming. *ICES Journal of Marine Science*, **73**(3), 693-703, doi:10.1093/icesjms/fsv168.
Kranz, S. A. et al., 2010: Combined effects of CO_2 and light on the N_2-fixing cyanobacterium *Trichodesmium* IMS101: physiological responses. *Plant Physiology*, **154**(1), 334-345, doi:10.1104/pp.110.159145.
Krause-Jensen, D., C. M. Duarte, K. Sand-Jensen and J. Carstensen, 2021: Century-long records reveal shifting challenges to seagrass recovery. *Global Change Biology*, **27**(3), 563-575, doi:10.1111/gcb.15440.
Krause-Jensen, D. et al., 2019: Deep Penetration of Kelps Offshore Along the West Coast of Greenland. *Frontiers in Marine Science*, **6**(375), doi:10.3389/fmars.2019.00375.
Krauss, K. W., 2021: Use of 'accommodation space' in tidal wetlands. A commentary on Kerrylee Rogers' 'Accommodation space as a framework for assessing the response of mangroves to relative sea-level rise'. *Singapore Journal of Tropical Geography*, **42**(2), 184-189, doi:10.1111/sjtg.12360.
Kroeger, K. D., S. Crooks, S. Moseman-Valtierra and J. Tang, 2017: Restoring tides to reduce methane emissions in impounded wetlands: A new and potent Blue Carbon climate change intervention. *Scientific Reports*, **7**(1), 11914, doi:10.1038/s41598-017-12138-4.
Kroeker, K. J. et al., 2013a: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology*, **19**(6), 1884-1896, doi:10.1111/gcb.12179.
Kroeker, K. J., R. L. Kordas and C. D. G. Harley, 2017: Embracing interactions in ocean acidification research: confronting multiple stressor scenarios and context dependence. *Biology Letters*, **13**(3), 20160802, doi:10.1098/rsbl.2016.0802.
Kroeker, K. J., F. Micheli and M. C. Gambi, 2013b: Ocean acidification causes ecosystem shifts via altered competitive interactions. *Nature Climate Change*, **3**(2), 156-159, doi:10.1038/nclimate1680.
Kroeker, K. J. et al., 2016: Interacting environmental mosaics drive geographic variation in mussel performance and predation vulnerability. *Ecology Letters*, **19**(7), 771-779, doi:10.1111/ele.12613.
Kroodsma, D. A. et al., 2018: Tracking the global footprint of fisheries. *Science*, **359**(6378), 904, doi:10.1126/science.aao5646.
Krüger, L. et al., 2018: Projected distributions of Southern Ocean albatrosses, petrels and fisheries as a consequence of climatic change. *Ecography*, **41**(1), 195-208, doi:10.1111/ecog.02590.
Krumhansl, K. A. et al., 2016: Global patterns of kelp forest change over the past half-century. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(48), 13785-13790, doi:10.1073/pnas.1606102113.
Krvavica, N. and I. Ružić, 2020: Assessment of sea-level rise impacts on salt-wedge intrusion in idealized and Neretva River Estuary. *Estuarine, Coastal and Shelf Science*, **234**, 106638, doi:10.1016/j.ecss.2020.106638.
Kubicek, A., B. Breckling, O. Hoegh-Guldberg and H. Reuter, 2019: Climate change drives trait-shifts in coral reef communities. *Scientific Reports*, **9**(1), 3721, doi:10.1038/s41598-019-38962-4.
Kuffner, I. B. et al., 2008: Decreased abundance of crustose coralline algae due to ocean acidification. *Nature Geoscience*, **1**(2), 114-117, doi:10.1038/ngeo100.
Kuhl, L., K. Van Maanen and S. Scyphers, 2020: An analysis of UNFCCC-financed coastal adaptation projects: Assessing patterns of project design and contributions to adaptive capacity. *World Development*, **127**, 104748, doi:10.1016/j.worlddev.2019.104748.
Kulk, G. et al., 2020: Primary Production, an Index of Climate Change in the Ocean: Satellite-Based Estimates over Two Decades. *Remote Sensing*, **12**(5), doi:10.3390/rs12050826.
Kulp, S. A. and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, **10**(1), 4844, doi:10.1038/s41467-019-12808-z.
Kumagai, N. H. et al., 2018: Ocean currents and herbivory drive macroalgae-to-coral community shift under climate warming. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(36), 8990, doi:10.1073/pnas.1716826115.

Kumar, P. et al., 2020: Towards an operationalisation of nature-based solutions for natural hazards. *Science of The Total Environment*, **731**, 138855, doi:10.1016/j.scitotenv.2020.138855.
Kunz, K. L. et al., 2018: Aerobic capacities and swimming performance of polar cod (*Boreogadus saida*) under ocean acidification and warming conditions. *The Journal of Experimental Biology*, **221**(21), jeb184473, doi:10.1242/jeb.184473.
Kunz, K. L. et al., 2016: New encounters in Arctic waters: a comparison of metabolism and performance of polar cod (*Boreogadus saida*) and Atlantic cod (*Gadus morhua*) under ocean acidification and warming. *Polar Biology*, **39**(6), 1137-1153, doi:10.1007/s00300-016-1932-z.
Kurman, M. D. et al., 2017: Intra-specific variation reveals potential for adaptation to ocean acidification in a cold-water coral from the Gulf of Mexico. *Frontiers in Marine Science*, **4**, 111, doi:10.3389/fmars.2017.00111.
Kutzner, D., 2019: Environmental change, resilience, and adaptation in nature-based tourism: conceptualizing the social-ecological resilience of birdwatching tour operations. *Journal of Sustainable Tourism*, **27**(8), 1142-1166, doi:10.1080/09669582.2019.1601730.
Kvernvik, A. C. et al., 2020: Higher sensitivity towards light stress and ocean acidification in an Arctic sea-ice-associated diatom compared to a pelagic diatom. *New Phytologist*, **226**(6), 1708-1724, doi:10.1111/nph.16501.
Kwiatkowski, L., O. Aumont and L. Bopp, 2019: Consistent trophic amplification of marine biomass declines under climate change. *Global Change Biology*, **25**(1), 218-229, doi:10.1111/gcb.14468.
Kwiatkowski, L. et al., 2016: Nighttime dissolution in a temperate coastal ocean ecosystem increases under acidification. *Scientific Reports*, **6**, 22984, doi:10.1038/srep22984.
Kwiatkowski, L. and J. C. Orr, 2018: Diverging seasonal extremes for ocean acidification during the twenty-first century. *Nature Climate Change*, **8**(2), 141-145, doi:10.1038/s41558-017-0054-0.
Kwiatkowski, L. et al., 2020: Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences*, **17**(13), 3439-3470, doi:10.5194/bg-17-3439-2020.
Kyprioti, A. et al., 2021: Is the current Mediterranean network of marine protected areas resilient to climate change? *Science of The Total Environment*, **792**, 148397, doi:10.1016/j.scitotenv.2021.148397.
Lachkar, Z., M. Lévy and K. S. Smith, 2019: Strong intensification of the Arabian Sea oxygen minimum zone in response to Arabian Gulf warming. *Geophysical Research Letters*, **46**(10), 5420-5429, doi:10.1029/2018GL081631.
Lacoue-Labarthe, T. et al., 2016: Impacts of ocean acidification in a warming Mediterranean Sea: an overview. *Regional Studies in Marine Science*, **5**, 1-11, doi:10.1016/j.rsma.2015.12.005.
Ladd, C. J. T. et al., 2019: Sediment Supply Explains Long-Term and Large-Scale Patterns in Salt Marsh Lateral Expansion and Erosion. *Geophysical Research Letters*, **46**(20), 11178-11187, doi:10.1029/2019GL083315.
Laengner, L. M., K. Siteur and D. van der Wal, 2019: Trends in the seaward extent of saltmarshes across europe from long-term satellite data. *Remote Sensing*, **11**(14), 1653, doi:10.3390/rs11141653.
Lafferty, K. D. et al., 2015: Infectious Diseases Affect Marine Fisheries and Aquaculture Economics. *Annual Review of Marine Science*, **7**(1), 471-496, doi:10.1146/annurev-marine-010814-015646.
Laloë, J.-O. et al., 2017: Climate change and temperature-linked hatchling mortality at a globally important sea turtle nesting site. *Global Change Biology*, **23**(11), 4922-4931, doi:10.1111/gcb.13765.
Laloë, J.-O. et al., 2020: Production of male hatchlings at a remote South Pacific green sea turtle rookery: conservation implications in a female-dominated world. *Marine Biology*, **167**(5), 70, doi:10.1007/s00227-020-03686-x.
Lam, V. W. Y. et al., 2020: Climate change, tropical fisheries and prospects for sustainable development. *Nature Reviews Earth & Environment*, **1**(9), 440-454, doi:10.1038/s43017-020-0071-9.
Lam, V. W. Y., W. W. L. Cheung and U. R. Sumaila, 2016: Marine capture fisheries in the Arctic: winners or losers under climate change and ocean acidification? *Fish and Fisheries*, **17**(2), 335-357, doi:10.1111/faf.12106.
Lamborg, C. H. et al., 2014: A global ocean inventory of anthropogenic mercury based on water column measurements. *Nature*, **512**(7512), 65-68, doi:10.1038/nature13563.
Lamim, V. B. and L. Procópio, 2021: Influence of Acidification and Warming of Seawater on Biofouling by Bacteria Grown over API 5L Steel. *Indian Journal of Microbiology*, **61**(2), 151-159, doi:10.1007/s12088-021-00925-7.
Lamont, M. M., D. Johnson and R. R. Carthy, 2020: The incubation environment of nests deposited by a genetically distinct group of loggerhead sea turtles in Northwest Florida. *Global Ecology and Conservation*, **23**, e01070, doi:10.1016/j.gecco.2020.e01070.
Landrum, L. and M. M. Holland, 2020: Extremes become routine in an emerging new Arctic. *Nature Climate Change*, doi:10.1038/s41558-020-0892-z.
Langbehn, T. J. and Ø. Varpe, 2017: Sea-ice loss boosts visual search: fish foraging and changing pelagic interactions in polar oceans. *Global Change Biology*, **23**(12), 5318-5330, doi:10.1111/gcb.13797.
Lange, I. D. and C. T. Perry, 2019: Bleaching impacts on carbonate production in the Chagos Archipelago: influence of functional coral groups on carbonate budget trajectories. *Coral Reefs*, **38**(4), 619-624, doi:10.1007/s00338-019-01784-x.
Langston, A. K., O. Durán Vinent, E. R. Herbert and M. L. Kirwan, 2020: Modeling long-term salt marsh response to sea level rise in the sediment-deficient Plum Island Estuary, MA. *Limnology and Oceanography*, doi:10.1002/lno.11444.

Lannuzel, D. et al., 2020: The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems. *Nature Climate Change*, **10**(11), 983-992, doi:10.1038/s41558-020-00940-4.
Larsen, J. N. et al., 2014: Polar regions. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1567-1612.
Laruelle, G. G. et al., 2017: Global high-resolution monthly pCO2 climatology for the coastal ocean derived from neural network interpolation. *Biogeosciences*, **14**(19), 4545-4561, doi:10.5194/bg-14-4545-2017.
Last, P. R. et al., 2011: Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global Ecology and Biogeography*, **20**(1), 58-72, doi:10.1111/j.1466-8238.2010.00575.x.
Lasut, M. T. et al. (eds.), From Coral Triangle to Trash Triangle—How the Hot spot of Global Marine Biodiversity Is Threatened by Plastic Waste. Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea, 2018//, Cham, Springer International Publishing, 107-113 pp. ISBN 978-3-319-71279-6.
Lau, J. D., C. C. Hicks, G. G. Gurney and J. E. Cinner, 2019: What matters to whom and why? Understanding the importance of coastal ecosystem services in developing coastal communities. *Ecosystem Services*, **35**, 219-230, doi:10.1016/j.ecoser.2018.12.012.
Laubenstein, T. D., M. D. Jarrold, J. L. Rummer and P. L. Munday, 2020: Beneficial effects of diel CO_2 cycles on reef fish metabolic performance are diminished under elevated temperature. *Science of The Total Environment*, **735**, 139084, doi:10.1016/j.scitotenv.2020.139084.
Laubenstein, T. D., J. L. Rummer, M. I. McCormick and P. L. Munday, 2019: A negative correlation between behavioural and physiological performance under ocean acidification and warming. *Scientific Reports*, **9**(1), 4265, doi:10.1038/s41598-018-36747-9.
Laubenstein, T. D. et al., 2018: Correlated effects of ocean acidification and warming on behavioral and metabolic traits of a large pelagic fish. *Diversity*, doi:10.3390/D10020035.
Lauchlan, S. S. and I. Nagelkerken, 2020: Species range shifts along multistressor mosaics in estuarine environments under future climate. *Fish and Fisheries*, **21**(1), 32-46, doi:10.1111/faf.12412.
Laufkötter, C. et al., 2015: Drivers and uncertainties of future global marine primary production in marine ecosystem models. *Biogeosciences*, **12**(23), 6955-6984, doi:10.5194/bg-12-6955-2015.
Laufkötter, C., J. Zscheischler and T. L. Frölicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science*, **369**(6511), 1621-1625, doi:10.1126/science.aba0690.
Laurel, B. J. et al., 2021: Regional warming exacerbates match/mismatch vulnerability for cod larvae in Alaska. *Progress in Oceanography*, **193**, 102555, doi:10.1016/j.pocean.2021.102555.
Laurent, A. et al., 2017: Eutrophication-induced acidification of coastal waters in the northern Gulf of Mexico: Insights into origin and processes from a coupled physical-biogeochemical model. *Geophysical Research Letters*, **44**(2), 946-956, doi:10.1002/2016GL071881.
Lavidas, G., 2019: Energy and socio-economic benefits from the development of wave energy in Greece. *Renewable Energy*, **132**, 1290-1300, doi:10.1016/j.renene.2018.09.007.
Lavidas, G. and V. Venugopal, 2016: Prospects and applicability of wave energy for South Africa. *International Journal of Sustainable Energy*, **37**(3), 230-248, doi:10.1080/14786451.2016.1254216.
Lawrence, J. et al., 2018: National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. *Environmental Science & Policy*, **82**, 100-107, doi:10.1016/j.envsci.2018.01.012.
Layton, C. et al., 2020: Kelp Forest Restoration in Australia. *Frontiers in Marine Science*, **7**(74), doi:10.3389/fmars.2020.00074.
Le Bris, A. et al., 2018: Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(8), 1831, doi:10.1073/pnas.1711122115.
Le Bris, N. and L. A. Levin, 2020: Climate change cumulative impacts on deep-sea ecosystems. In: *Natural Capital and Exploitation of the Deep Ocean*. Oxford University Press, Oxford. ISBN 9780198841654.
Le Corre, N., P. Pepin, G. Han and Z. Ma, 2021: Potential impact of climate change on northern shrimp habitats and connectivity on the Newfoundland and Labrador continental shelves. *Fisheries Oceanography*, **30**(3), 331-347, doi:10.1111/fog.12524.
Le Cozannet, G. et al., 2019: Quantifying uncertainties of sandy shoreline change projections as sea level rises. *Scientific Reports*, **9**, 42, doi:10.1038/s41598-018-37017-4.
Le Cozannet, G. et al., 2017: Sea level change and coastal climate services: the way forward. *Journal of Marine Science and Engineering*, **5**(4), 49, doi:10.3390/jmse5040049.
Le Nohaïc, M. et al., 2017: Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia. *Scientific Reports*, **7**(1), 14999, doi:10.1038/s41598-017-14794-y.
Le Quéré, C. et al., 2016: Role of zooplankton dynamics for Southern Ocean phytoplankton biomass and global biogeochemical cycles. *Biogeosciences*, **13**(14), 4111-4133, doi:10.5194/bg-13-4111-2016.

Leadbetter, A., J. Silke and C. Cusack, 2018: *Creating a weekly harmful algal bloom bulletin*. Best Practice Description Document, Institute, M., Galway, Ireland, 59 pp pp. Available at: http://hdl.handle.net/10793/1344 (accessed 2018-04-10t13:54:37z).
Leal, M. C. and R. Calado, 2015: Marine natural products: biodiscovery, biodiversity, and bioproduction. In: *Bioactive Natural Products: Chemistry and Biology* [Brahmachari, G. (ed.)]. Wiley Blackwell, pp. 473-490. ISBN 9783527684403.
Leary, D., 2019: Agreeing to disagree on what we have or have not agreed on: The current state of play of the BBNJ negotiations on the status of marine genetic resources in areas beyond national jurisdiction. *Marine Policy*, **99**, 21-29, doi:10.1016/j.marpol.2018.10.031.
Lee, J. Y. et al., 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Lee, K.-H., J. Noh and J. S. Khim, 2020: The Blue Economy and the United Nations' sustainable development goals: Challenges and opportunities. *Environment International*, **137**, 105528, doi:10.1016/j.envint.2020.105528.
Lee Smee, D., 2019: Coastal Ecology: Living Shorelines Reduce Coastal Erosion. *Current Biology*, **29**(11), R411-R413, doi:10.1016/j.cub.2019.04.044.
Leenhardt, P. et al., 2013: The rise of large-scale marine protected areas: Conservation or geopolitics? *Ocean & Coastal Management*, **85**, 112-118, doi:10.1016/j.ocecoaman.2013.08.013.
Lefevre, S., 2016: Are global warming and ocean acidification conspiring against marine ectotherms? A meta-analysis of the respiratory effects of elevated temperature, high CO_2 and their interaction. *Conservation Physiology*, **4**(1), cow009, doi:10.1093/conphys/cow009.
Lefort, K. J., C. J. Garroway and S. H. Ferguson, 2020: Killer whale abundance and predicted narwhal consumption in the Canadian Arctic. *Global Change Biology*, **26**(8), 4276-4283, doi:10.1111/gcb.15152.
Lefort, S. et al., 2015: Spatial and body-size dependent response of marine pelagic communities to projected global climate change. *Global Change Biology*, **21**(1), 154-164, doi:10.1111/gcb.12679.
Leggat, W. P. et al., 2019: Rapid coral decay is associated with marine heatwave mortality events on reefs. *Current Biology*, **29**(16), 2723-2730.e2724, doi:10.1016/j.cub.2019.06.077.
Lehman, P. W., T. Kurobe and S. J. Teh, 2020: Impact of extreme wet and dry years on the persistence of *Microcystis* harmful algal blooms in San Francisco Estuary. *Quaternary International*, doi:10.1016/j.quaint.2019.12.003.
Lehodey, P. et al., 2020: ENSO Impact on Marine Fisheries and Ecosystems. In: *El Niño Southern Oscillation in a Changing Climate* [McPhaden, M. J., A. Santoso and W. Cai (eds.)], pp. 429-451.
Leitão, F. et al., 2018: The effect of regional sea surface temperature rise on fisheries along the Portuguese Iberian Atlantic coast. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **28**(6), 1351-1359, doi:10.1002/aqc.2947.
Lembke-Jene, L. et al., 2018: Rapid shift and millennial-scale variations in Holocene North Pacific intermediate water ventilation. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(21), 5365-5370, doi:10.1073/pnas.1714754115.
Lenihan, H. S. et al., 2021: Evidence that spillover from Marine Protected Areas benefits the spiny lobster (Panulirus interruptus) fishery in southern California. *Scientific Reports*, **11**(1), 2663, doi:10.1038/s41598-021-82371-5.
Lenoir, J. et al., 2020: Species better track the shifting isotherms in the oceans than on lands. *Nature Ecology & Evolution*, **4**(8), 1044-1059, doi:10.1038/s41559-020-1198-2.
Leo, K. L. et al., 2019: Coastal habitat squeeze: a review of adaptation solutions for saltmarsh, mangrove and beach habitats. *Ocean & Coastal Management*, **175**, 180-190, doi:10.1016/j.ocecoaman.2019.03.019.
Leriorato, J. C. and Y. Nakamura, 2019: Unpredictable extreme cold events: a threat to range-shifting tropical reef fishes in temperate waters. *Marine Biology*, **166**(8), 110, doi:10.1007/s00227-019-3557-6.
Leung, S., A. Cabré and I. Marinov, 2015: A latitudinally banded phytoplankton response to 21st century climate change in the Southern Ocean across the CMIP5 model suite. *Biogeosciences*, **12**(19), 5715-5734, doi:10.5194/bg-12-5715-2015.
Leung, S. W., T. Weber, J. A. Cram and C. Deutsch, 2021: Variable particle size distributions reduce the sensitivity of global export flux to climate change. *Biogeosciences* **18**, 229-250, doi:10.5194/bg-18-229-2021.
Leuven, J. R. F. W. et al., 2019: Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. *Nature Climate Change*, **9**(12), 986-992, doi:10.1038/s41558-019-0608-4.
Levin, L. A., 2003: Oxygen minimum zone benthos: adaptation and community response to hypoxia. *Oceanography and Marine Biology*, **41**, 1-45.
Levin, L. A., 2018: Manifestation, drivers, and emergence of open ocean deoxygenation. *Annual Review of Marine Science*, **10**(1), 229-260, doi:10.1146/annurev-marine-121916-063359.
Levin, L. A., 2021: IPCC and the Deep Sea: A Case for Deeper Knowledge. *Frontiers in Climate*, **3**(92), doi:10.3389/fclim.2021.720755.
Levin, L. A. et al., 2019: Global Observing Needs in the Deep Ocean. *Frontiers in Marine Science*, **6**(241), doi:10.3389/fmars.2019.00241.

Levin, L. A. et al., 2009: Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences*, **6**(10), 2063-2098, doi:10.5194/bg-6-2063-2009.
Levin, L. A. and N. Le Bris, 2015: The deep ocean under climate change. *Science*, **350**(6262), 766-768, doi:10.1126/science.aad0126.
Levin, L. A. et al., 2020: Climate change considerations are fundamental to management of deep-sea resource extraction. *Global Change Biology*, **26**(9), 4664-4678, doi:10.1111/gcb.15223.
Levin, N. et al., 2018: Evaluating the potential for transboundary management of marine biodiversity in the Western Indian Ocean. *Australasian Journal of Environmental Management*, **25**(1), 62-85, doi:10.1080/14486563.2017.1417167.
Lewis, K. M., G. L. van Dijken and K. R. Arrigo, 2020: Changes in phytoplankton concentration now drive increased Arctic Ocean primary production. *Science*, **369**(6500), 198, doi:10.1126/science.aay8380.
Li, F. et al., 2016: Physiological responses of coastal and oceanic diatoms to diurnal fluctuations in seawater carbonate chemistry under two CO_2 concentrations. *Biogeosciences*, **13**(22), 6247-6259, doi:10.5194/bg-13-6247-2016.
Li, G. and D. A. Campbell, 2013: Rising CO_2 interacts with growth light and growth rate to alter photosystem II photoinactivation of the coastal diatom *Thalassiosira pseudonana*. *PLOS ONE*, **8**(1), e55562, doi:10.1371/journal.pone.0055562.
Li, G. et al., 2020a: Increasing ocean stratification over the past half-century. *Nature Climate Change*, doi:10.1038/s41558-020-00918-2.
Li, L. et al., 2018a: Divergence and plasticity shape adaptive potential of the Pacific oyster. *Nature Ecology & Evolution*, **2**(11), 1751-1760, doi:10.1038/s41559-018-0668-2.
Li, X., R. Bellerby, C. Craft and S. E. Widney, 2018b: Coastal wetland loss, consequences, and challenges for restoration. *Anthropocene Coasts*, **1**(1), 1-15, doi:10.1139/anc-2017-0001.
Li, X. et al., 2020b: Rapid Loss of Tidal Flats in the Yangtze River Delta since 1974. *International Journal of Environmental Research and Public Health*, **17**(5), doi:10.3390/ijerph17051636.
Li, X. et al., 2020c: Irreversibility of Marine Climate Change Impacts Under Carbon Dioxide Removal. *Geophysical Research Letters*, **47**(17), e2020GL088507, doi:10.1029/2020GL088507.
Li, Y. et al., 2019: Distribution, seasonality, and fluxes of dissolved organic matter in the Pearl River (Zhujiang) estuary, China. *Biogeosciences*, **16**(13), 2751-2770, doi:10.5194/bg-16-2751-2019.
Liang, C., W. Xian and D. Pauly, 2018: Impacts of ocean warming on china's fisheries catches: an application of “mean temperature of the catch” concept. *Frontiers in Marine Science*, **5**, 26, doi:10.3389/fmars.2018.00026.
Lima, L. S. et al., 2021: Potential changes in the connectivity of marine protected areas driven by extreme ocean warming. *Scientific Reports*, **11**(1), 10339, doi:10.1038/s41598-021-89192-6.
Limburg, K. E., D. Breitburg, D. P. Swaney and G. Jacinto, 2020: Ocean Deoxygenation: A Primer. *One Earth*, **2**(1), 24-29, doi:10.1016/j.oneear.2020.01.001.
Linares, C. et al., 2015: Persistent natural acidification drives major distribution shifts in marine benthic ecosystems. *Proceedings of the Royal Society B: Biological Sciences*, **282**(1818), 20150587, doi:10.1098/rspb.2015.0587.
Lincke, D. and J. Hinkel, 2021: Coastal Migration due to 21st Century Sea-Level Rise. *Earth's Future*, **9**(5), e2020EF001965, doi:10.1029/2020EF001965.
Lindberg, R. T. and S. Collins, 2020: Quality–quantity trade-offs drive functional trait evolution in a model microalgal ‘climate change winner’. *Ecology Letters*, **23**(5), 780-790, doi:10.1111/ele.13478.
Lindegren, M. et al., 2018: Productivity and recovery of forage fish under climate change and fishing: North Sea sandeel as a case study. *Fisheries Oceanography*, **27**(3), 212-221, doi:10.1111/fog.12246.
Lindén, A., 2018: Adaptive and nonadaptive changes in phenological synchrony. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(20), 5057, doi:10.1073/pnas.1805698115.
Ling, S. D., 2008: Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: a new and impoverished reef state. *Oecologia*, **156**(4), 883-894, doi:10.1007/s00442-008-1043-9.
Ling, S. D. and A. J. Hobday, 2019: National research planning accelerates relevance and immediacy of climate-adaptation science. *Marine and Freshwater Research*, **70**(1), 62-70, doi:10.1071/MF17330.
Listmann, L. et al., 2016: Swift thermal reaction norm evolution in a key marine phytoplankton species. *Evolutionary Applications*, **9**(9), 1156-1164, doi:10.1111/eva.12362.
Lithgow, D. et al., 2019: Exploring the co-occurrence between coastal squeeze and coastal tourism in a changing climate and its consequences. *Tourism Management*, **74**, 43-54, doi:10.1016/j.tourman.2019.02.005.
Liu, C., L. Chen, S. Liang and Y. Li, 2020a: Distribution of total mercury and methylmercury and their controlling factors in the East China Sea. *Environmental Pollution*, **258**, 113667, doi:10.1016/j.envpol.2019.113667.
Liu, M. et al., 2020b: Methylmercury Bioaccumulation in Deepest Ocean Fauna: Implications for Ocean Mercury Biotransport through Food Webs. *Environmental Science & Technology Letters*, **7**(7), 469-476, doi:10.1021/acs.estlett.0c00299.
Liu, S. et al., 2020c: Impact of Climate Change on Wintering Ground of Japanese Anchovy (*Engraulis japonicus*) Using Marine Geospatial Statistics. *Frontiers in Marine Science*, **7**(604), doi:10.3389/fmars.2020.00604.
Liu, T.-X., S. Kinn-Gurzo and K. Y. K. Chan, 2020d: Resilience of invasive tubeworm (Hydroides dirampha) to warming and salinity stress and its implications for biofouling community dynamics. *Marine Biology*, **167**(10), 145, doi:10.1007/s00227-020-03758-y.

Liu, W. and M. He, 2012: Effects of ocean acidification on the metabolic rates of three species of bivalve from southern coast of China. *Chinese Journal of Oceanology and Limnology*, **30**(2), 206-211, doi:10.1007/s00343-012-1067-1.
Liu, W., X. Huang, J. Lin and M. He, 2012: Seawater acidification and elevated temperature affect gene expression patterns of the pearl oyster *Pinctada fucata*. *PLOS ONE*, **7**(3), e33679, doi:10.1371/journal.pone.0033679.
Liu, Y., C. Ma and B. Jiang, 2018: Development and the environmental impact analysis of tidal current energy turbines in China. *IOP Conference Series Earth and Environmental Science*, **121**(4), 042003, doi:10.1088/1755-1315/121/4/042003.
Liu, Z., S. Fagherazzi and B. Cui, 2021: Success of coastal wetlands restoration is driven by sediment availability. *Communications Earth & Environment*, **2**(1), 44, doi:10.1038/s43247-021-00117-7.
Liu, Z. C., W. P. de Lange and K. R. Bryan, 2020e: Estuary rejuvenation in response to sea level rise: an example from Tairua Estuary, New Zealand. *Geo-Marine Letters*, **40**(2), 269-280, doi:10.1007/s00367-019-00603-0.
Ljungström, G., T. J. Langbehn and C. Jørgensen, 2021: Light and energetics at seasonal extremes limit poleward range shifts. *Nature Climate Change*, **11**(6), 530-536, doi:10.1038/s41558-021-01045-2.
Lloret, J., H. J. Rätz, J. Lleonart and M. Demestre, 2016: Challenging the links between seafood and human health in the context of global change. *Journal of the Marine Biological Association of the United Kingdom*, **96**(1), 29-42, doi:10.1017/S0025315415001988.
Lluch-Cota, S. E., F. Arreguín-Sánchez, C. J. Salvadeo and P. Del Monte Luna, 2018: Chapter 10: Climate change impacts, vulnerabilities and adaptations: Northeast Tropical Pacific marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 207-218. ISBN 9789251306079.
Lluch-Cota, S. E. et al., 2014: Cross-Chapter Box on Uncertain Trends in Major Upwelling Ecosystems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 149-151. ISBN 9781107058071.
Loehr, J., 2020: The Vanuatu Tourism Adaptation System: a holistic approach to reducing climate risk. *Journal of Sustainable Tourism*, **28**(4), 515-534, doi:10.1080/09669582.2019.1683185.
Logan, C. A. et al., 2021: Quantifying global potential for coral evolutionary response to climate change. *Nature Climate Change*, **11**, 537-542, doi:10.1038/s41558-021-01037-2.
Logar-Henderson, C., R. Ling, A. R. Tuite and D. N. Fisman, 2019: Effects of large-scale oceanic phenomena on non-cholera vibriosis incidence in the United States: implications for climate change. *Epidemiology & Infection*, **147**, e243, doi:10.1017/S0950268819001316.
Lohbeck, K. T., U. Riebesell and T. B. H. Reusch, 2012: Adaptive evolution of a key phytoplankton species to ocean acidification. *Nature Geoscience*, **5**(5), 346-351, doi:10.1038/ngeo1441.
Lomas, M. W. et al., 2010: Increased ocean carbon export in the Sargasso Sea linked to climate variability is countered by its enhanced mesopelagic attenuation. *Biogeosciences*, **7**(1), 57-70, doi:10.5194/bg-7-57-2010.
Long, W. C., P. Pruisner, K. M. Swiney and R. J. Foy, 2019: Effects of ocean acidification on the respiration and feeding of juvenile red and blue king crabs (*Paralithodes camtschaticus* and *P. platypus*). *ICES Journal of Marine Science*, fsz090, doi:10.1093/icesjms/fsz090.
Lonhart, S. I. et al., 2019: Shifts in the distribution and abundance of coastal marine species along the eastern Pacific Ocean during marine heatwaves from 2013 to 2018. *Marine Biodiversity Records*, **12**(1), 13, doi:10.1186/s41200-019-0171-8.
Lopes, J. F., C. L. Lopes and J. M. Dias, 2019: Climate Change Impact in the Ria de Aveiro Lagoon Ecosystem: A Case Study. *Journal of Marine Science and Engineering*, **7**(10), doi:10.3390/jmse7100352.
Loseto, L. L. et al., 2018: Beluga whales (Delphinapterus leucas), environmental change and marine protected areas in the Western Canadian Arctic. *Estuarine, Coastal and Shelf Science*, **212**, 128-137, doi:10.1016/j.ecss.2018.05.026.
Lotze, H. K. et al., 2019: Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(26), 12907-12912, doi:10.1073/pnas.1900194116.
Lourenço, C. R. et al., 2016: Upwelling areas as climate change refugia for the distribution and genetic diversity of a marine macroalga. *Journal of Biogeography*, **43**(8), 1595-1607, doi:10.1111/jbi.12744.
Lovelock, C. E. et al., 2017a: Assessing the risk of carbon dioxide emissions from blue carbon ecosystems. *Frontiers in Ecology and the Environment*, **15**(5), 257-265, doi:10.1002/fee.1491.
Lovelock, C. E. and C. M. Duarte, 2019: Dimensions of Blue Carbon and emerging perspectives. *Biology Letters*, **15**(3), 20180781, doi:10.1098/rsbl.2018.0781.
Lovelock, C. E. et al., 2017b: Mangrove dieback during fluctuating sea levels. *Scientific Reports*, **7**(1), 1680, doi:10.1038/s41598-017-01927-6.
Lovelock, C. E. and R. Reef, 2020: Variable Impacts of Climate Change on Blue Carbon. *One Earth*, **3**(2), 195-211, doi:10.1016/j.oneear.2020.07.010.

Lowerre-Barbieri, S. K., I. A. Catalán, A. Frugård Opdal and C. Jørgensen, 2019: Preparing for the future: integrating spatial ecology into ecosystem-based management. *ICES Journal of Marine Science*, **76**(2), 467-476, doi:10.1093/icesjms/fsy209.
Lubchenco, J., E. B. Cerny-Chipman, J. N. Reimer and S. A. Levin, 2016: The right incentives enable ocean sustainability successes and provide hope for the future. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(51), 14507, doi:10.1073/pnas.1604982113.
Lubchenco, J. and K. Grorud-Colvert, 2015: Making waves: the science and politics of ocean protection. *Science*, **350**(6259), 382-383, doi:10.1126/science.aad5443.
Luek, J. L. et al., 2017: Persistent organic pollutants in the Atlantic and southern oceans and oceanic atmosphere. *Science of The Total Environment*, **583**, 64-71, doi:10.1016/j.scitotenv.2016.12.189.
Luijendijk, A. et al., 2018: The state of the world's beaches. *Scientific Reports*, **8**, 6641, doi:10.1038/s41598-018-28915-8.
Luk, S. Y. et al., 2019: Modeling the effect of water quality on the recreational shellfishing cultural ecosystem service of Buzzards Bay, Massachusetts. *Marine Pollution Bulletin*, **140**, 364-373, doi:10.1016/j.marpolbul.2018.12.047.
Luna, G. M. et al., 2012: The dark portion of the Mediterranean Sea is a bioreactor of organic matter cycling. *Global Biogeochemical Cycles*, **26**(2), doi:10.1029/2011GB004168.
Lunden, J. J. et al., 2014: Acute survivorship of the deep-sea coral *Lophelia pertusa* from the Gulf of Mexico under acidification, warming, and deoxygenation. *Frontiers in Marine Science*, **1**(78), doi:10.3389/fmars.2014.00078.
Lundgreen, R. B. C. et al., 2019: Eukaryotic and cyanobacterial communities associated with marine snow particles in the oligotrophic Sargasso Sea. *Scientific Reports*, **9**(1), 8891, doi:10.1038/s41598-019-45146-7.
Lusseau, D. et al., 2021: Chapter 6D. Marine Mammals. In: *The Second World Ocean Assessment*. United Nations, New York, N.Y., pp. 15. ISBN 97892111304220.
Ma, J., H. Hung and R. W. Macdonald, 2016: The influence of global climate change on the environmental fate of persistent organic pollutants: a review with emphasis on the Northern Hemisphere and the Arctic as a receptor. *Global and Planetary Change*, **146**, 89-108, doi:10.1016/j.gloplacha.2016.09.011.
Ma, S. et al., 2021: Critical transitions and ecological resilience of large marine ecosystems in the Northwestern Pacific in response to global warming. *Global Change Biology*, **n/a**(n/a), doi:10.1111/gcb.15815.
Ma, S. et al., 2019: Climate-induced long-term variations in ecosystem structure and atmosphere-ocean-ecosystem processes in the Yellow Sea and East China Sea. *Progress in Oceanography*, **175**, 183-197, doi:10.1016/j.pocean.2019.04.008.
Mach, K. J. and A. R. Siders, 2021: Reframing strategic, managed retreat for transformative climate adaptation. *Science*, **372**(6548), 1294, doi:10.1126/science.abh1894.
Mach, M. E., C. D. Levings and K. M. A. Chan, 2017: Nonnative species in British Columbia eelgrass beds spread via shellfish aquaculture and stay for the mild climate. *Estuaries and Coasts*, **40**(1), 187-199, doi:10.1007/s12237-016-0124-y.
Machado Monteiro, C. M. et al., 2019: Is geographical variation driving the transcriptomic responses to multiple stressors in the kelp *Saccharina latissima*? *BMC Plant Biology*, **19**(1), 513, doi:10.1186/s12870-019-2124-0.
Macias, D. M., E. Garcia-Gorriz and A. Stips, 2015: Productivity changes in the Mediterranean Sea for the twenty-first century in response to changes in the regional atmospheric forcing. *Frontiers in Marine Science*, **2**, 79, doi:10.3389/fmars.2015.00079.
Mackenzie, B. et al., 2019: The role of stakeholders in creating societal value from coastal and ocean observations. *Frontiers in Marine Science*, **6**, 137, doi:10.3389/fmars.2019.00137.
Mackenzie, F. T., L. M. Ver and A. Lerman, 2000: Coastal-zone biogeochemical dynamics under global warming. *International Geology Review*, **42**(3), 193-206, doi:10.1080/00206810009465077.
Macreadie, P. I. et al., 2019: The future of blue carbon science. *Nature Communications*, **10**(1), 3998, doi:10.1038/s41467-019-11693-w.
Macy, A. et al., 2019: Tropicalization of the barrier islands of the northern Gulf of Mexico: A comparison of herbivory and decomposition rates between smooth cordgrass (*Spartina alterniflora*) and black mangrove (*Avicennia germinans*). *PLOS ONE*, **14**(1), e0210144, doi:10.1371/journal.pone.0210144.
Maestro, M., M. L. Pérez-Cayeiro, J. A. Chica-Ruiz and H. Reyes, 2019: Marine protected areas in the 21st century: Current situation and trends. *Ocean & Coastal Management*, **171**, 28-36, doi:10.1016/j.ocecoaman.2019.01.008.
Mafi-Gholami, D., E. K. Zenner, A. Jaafari and D. T. Bui, 2020: Spatially explicit predictions of changes in the extent of mangroves of Iran at the end of the 21st century. *Estuarine, Coastal and Shelf Science*, **237**, 106644, doi:10.1016/j.ecss.2020.106644.
Magel, J. M. T., J. H. R. Burns, R. D. Gates and J. K. Baum, 2019: Effects of bleaching-associated mass coral mortality on reef structural complexity across a gradient of local disturbance. *Scientific Reports*, **9**(1), 2512, doi:10.1038/s41598-018-37713-1.
Magnan, A. K. and V. K. E. Duvat, 2018: Unavoidable solutions for coastal adaptation in Reunion Island (Indian Ocean). *Environmental Science & Policy*, **89**, 393-400, doi:10.1016/j.envsci.2018.09.002.
Magnan, A. K. et al., 2016: Addressing the risk of maladaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **7**(5), 646-665, doi:10.1002/wcc.409.
Magolan, J. L. and J. N. Halls, 2020: A Multi-Decadal Investigation of Tidal Creek Wetland Changes, Water Level Rise, and Ghost Forests. *Remote Sensing*, **12**(7), doi:10.3390/rs12071141.

Maguire, J. et al., 2016: Applied simulations and integrated modelling for the understanding of toxic and harmful algal blooms (ASIMUTH): Integrated HAB forecast systems for Europe's Atlantic Arc. *Harmful Algae*, **53**, 160-166, doi:10.1016/j.hal.2015.11.006.
Maharaj, R. R., V. W. Y. Lam, D. Pauly and W. W. L. Cheung, 2018: Regional variability in the sensitivity of Caribbean reef fish assemblages to ocean warming. *Marine Ecology Progress Series*, **590**, 201-209, doi:10.3354/meps12462.
Maharjan, A. et al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, **6**(1), 1-16, doi:10.1007/s40641-020-00153-z.
Maier, C. et al., 2016: Effects of elevated CO_2 and feeding on net calcification and energy budget of the Mediterranean cold-water coral *Madrepora oculata*. *The Journal of Experimental Biology*, **219**(20), 3208, doi:10.1242/jeb.127159.
Maier, C., M. G. Weinbauer and J.-P. Gattuso, 2019: Fate of Mediterranean Scleractinian Cold-Water Corals as a Result of Global Climate Change. A Synthesis. In: *Mediterranean Cold-Water Corals: Past, Present and Future: Understanding the Deep-Sea Realms of Coral* [Orejas, C. and C. Jiménez (eds.)]. Springer International Publishing, Cham, pp. 517-529. ISBN 978-3-319-91608-8.
Maina, J. M. et al., 2021: Identifying global and local drivers of change in mangrove cover and the implications for management. *Global Ecology and Biogeography*, **n/a**(n/a), doi:10.1111/geb.13368.
Maksym, T., 2019: Arctic and Antarctic Sea Ice Change: Contrasts, Commonalities, and Causes. *Annual Review of Marine Science*, **11**(1), 187-213, doi:10.1146/annurev-marine-010816-060610.
Maltby, K. M. et al., 2020: Projected impacts of warming seas on commercially fished species at a biogeographic boundary of the European continental shelf. *Journal of Applied Ecology*, **00**, 1-2, doi:10.1111/1365-2664.13724.
Mandel, A. et al., 2021: Risks on global financial stability induced by climate change: the case of flood risks. *Climatic Change*, **166**(1), 4, doi:10.1007/s10584-021-03092-2.
Mangan, S. et al., 2017: Fluctuating seawater pH/pCO_2 regimes are more energetically expensive than static pH/pCO_2 levels in the mussel *Mytilus edulis*. *Proceedings of the Royal Society B: Biological Sciences*, **284**(1865), 20171642, doi:10.1098/rspb.2017.1642.
Mannino, A. M. and P. Balistreri, 2021: Invasive alien species in Mediterranean Marine Protected Areas: the Egadi Islands (Italy) case study. *Biodiversity*, 1-11, doi:10.1080/14888386.2021.1875263.
Mannino, A. M., P. Balistreri and A. Deidun, 2017: The Marine Biodiversity of the Mediterranean Sea in a Changing Climate: The Impact of Biological Invasions. In: *Mediterranean Identities: Environment, Society, Culture* [Spanò, N. and E. De Domenico (eds.)]. IntechOpen.
Mannion, P. D., P. Upchurch, R. B. J. Benson and A. Goswami, 2014: The latitudinal biodiversity gradient through deep time. *Trends in Ecology & Evolution*, **29**(1), 42-50, doi:10.1016/j.tree.2013.09.012.
Marangon, E., S. U. Goldenberg and I. Nagelkerken, 2020: Ocean warming increases availability of crustacean prey via riskier behavior. *Behavioral Ecology*, **31**(2), 287-291, doi:10.1093/beheco/arz196.
Marañón, E., M. P. Lorenzo, P. Cermeño and B. Mouriño-Carballido, 2018: Nutrient limitation suppresses the temperature dependence of phytoplankton metabolic rates. *The ISME Journal*, **12**(7), 1836-1845, doi:10.1038/s41396-018-0105-1.
Marbà, N. et al., 2015a: Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks. *Journal of Ecology*, **103**(2), 296-302, doi:10.1111/1365-2745.12370.
Marbà, N. et al., 2015b: Footprints of climate change on Mediterranean Sea biota. *Frontiers in Marine Science*, **2**, 56, doi:10.3389/fmars.2015.00056.
Marchini, A. et al., 2019: Intertidal Mediterranean Coralline Algae Habitat Is Expecting a Shift Toward a Reduced Growth and a Simplified Associated Fauna Under Climate Change. *Frontiers in Marine Science*, **6**(106), doi:10.3389/fmars.2019.00106.
Mardones, M. L., P. B. Fenberg, S. Thatje and C. Hauton, 2021: Variation in thermal tolerance response associated with geographic location during early development of the neogastropod Ocenebra erinaceus (Linnaeus, 1758). *Journal of Experimental Marine Biology and Ecology*, **542-543**, 151590, doi:10.1016/j.jembe.2021.151590.
Mariani, G. et al., 2020: Let more big fish sink: Fisheries prevent blue carbon sequestration—half in unprofitable areas. *Science Advances*, **6**(44), eabb4848, doi:10.1126/sciadv.abb4848.
Marine Conservation Institute, The Marine Protection Atlas, Marine Conservation Institute. Available at: https://mpatlas.org.
Marshall, K. N. et al., 2017: Risks of ocean acidification in the California Current food web and fisheries: ecosystem model projections. *Global Change Biology*, **23**(4), 1525-1539, doi:10.1111/gcb.13594.
Marshall, N. et al., 2019: Reef grief: investigating the relationship between place meanings and place change on the Great Barrier Reef, Australia. *Sustainability Science*, **14**(3), 579-587, doi:10.1007/s11625-019-00666-z.
Martin, A. H., H. C. Pearson, G. K. Saba and E. M. Olsen, 2021: Integral functions of marine vertebrates in the ocean carbon cycle and climate change mitigation. *One Earth*, **4**(5), 680-693, doi:10.1016/j.oneear.2021.04.019.
Martin, C. L., S. Momtaz, T. Gaston and N. A. Moltschaniwskyj, 2020: Estuarine cultural ecosystem services valued by local people in New South Wales, Australia, and attributes important for continued supply. *Ocean & Coastal Management*, **190**, 105160, doi:10.1016/j.ocecoaman.2020.105160.

Martin, K. L. M., E. A. Pierce, V. V. Quach and M. Studer, 2019: Population trends of beach-spawning California grunion *Leuresthes tenuis* monitored by citizen scientists. *ICES Journal of Marine Science*, fsz086, doi:10.1093/icesjms/fsz086.
Martín-García, L. et al., 2014: Predicting the potential habitat of the harmful cyanobacteria Lyngbya majuscula in the Canary Islands (Spain). *Harmful Algae*, **34**, 76-86, doi:10.1016/j.hal.2014.02.008.
Martinetto, P. et al., 2016: Crab bioturbation and herbivory may account for variability in carbon sequestration and stocks in South West Atlantic salt marshes. *Frontiers in Marine Science*, **3**(122), doi:10.3389/fmars.2016.00122.
Martínez, B. et al., 2018: Distribution models predict large contractions of habitat-forming seaweeds in response to ocean warming. *Diversity and Distributions*, **24**(10), 1350-1366, doi:10.1111/ddi.12767.
Martins, R. M. et al., 2018: Macroalgae extracts from Antarctica have antimicrobial and anticancer potential. *Frontiers in Microbiology*, **9**, 412, doi:10.3389/fmicb.2018.00412.
Marushka, L. et al., 2019: Potential impacts of climate-related decline of seafood harvest on nutritional status of coastal First Nations in British Columbia, Canada. *PLOS ONE*, **14**(2), e0211473, doi:10.1371/journal.pone.0211473.
Marx, S. K. et al., 2020: Examining the response of an eastern Australian mangrove forest to changes in hydro-period over the last century. *Estuarine, Coastal and Shelf Science*, **241**, 106813, doi:10.1016/j.ecss.2020.106813.
Marzeion, B. and A. Levermann, 2014: Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environ.Res.Lett.*, **9**(3), 034001, doi:10.1088/1748-9326/9/3/034001.
Marzloff, M. P., L. R. Little and C. R. Johnson, 2016: Building Resilience Against Climate-Driven Shifts in a Temperate Reef System: Staying Away from Context-Dependent Ecological Thresholds. *Ecosystems*, **19**(1), 1-15, doi:10.1007/s10021-015-9913-6.
Mason, N. et al., 2020: Global opportunities and challenges for transboundary conservation. *Nature Ecology & Evolution*, **4**(5), 694-701, doi:10.1038/s41559-020-1160-3.
Masselink, G., E. Beetham and P. Kench, 2020: Coral reef islands can accrete vertically in response to sea level rise. *Science Advances*, **6**(24), eaay3656, doi:10.1126/sciadv.aay3656.
Mastrocicco, M. and N. Colombani, 2021: The issue of groundwater salinization in coastal areas of the Mediterranean region: A review. *Water*, **13**(1), 90, doi:10.3390/w13010090.
Mathis, J. T., J. N. Cross, W. Evans and S. C. Doney, 2015: Ocean Acidification in the Surface Waters of the Pacific-Arctic Boundary Regions. *Oceanography*, **28**(2), 122-135, doi:10.5670/oceanog.2015.36.
Matsumoto, K. et al., 2014: Seasonal variability of primary production and phytoplankton biomass in the western Pacific subarctic gyre: control by light availability within the mixed layer. *Journal of Geophysical Research: Oceans*, **119**(9), 6523-6534, doi:10.1002/2014JC009982.
Matz, M. V., E. A. Treml and B. C. Haller, 2020: Estimating the potential for coral adaptation to global warming across the Indo-West Pacific. *Global Change Biology*, **26**(6), 3473-3481, doi:10.1111/gcb.15060.
Mawyer, A. and J. K. Jacka, 2018: Sovereignty, conservation and island ecological futures. *Environmental Conservation*, **45**(3), 238-251, doi:10.1017/S037689291800019X.
Maximino, C. and T. M. a. de Brito, 2010: Measuring anxiety in zebrafish: A critical review. *Behavioural Brain Research*, **214**(2), 157-171, doi:10.1016/j.bbr.2010.05.031.
Maxwell, S. L. et al., 2020a: Area-based conservation in the twenty-first century. *Nature*, **586**(7828), 217-227, doi:10.1038/s41586-020-2773-z.
Maxwell, S. M., K. M. Gjerde, M. G. Conners and L. B. Crowder, 2020b: Mobile protected areas for biodiversity on the high seas. *Science*, **367**(6475), 252-254, doi:10.1126/science.aaz9327.
Mazaris, A. D., A. S. Kallimanis, S. P. Sgardelis and J. D. Pantis, 2008: Do long-term changes in sea surface temperature at the breeding areas affect the breeding dates and reproduction performance of Mediterranean loggerhead turtles? Implications for climate change. *Journal of Experimental Marine Biology and Ecology*, **367**(2), 219-226, doi:10.1016/j.jembe.2008.09.025.
Mazurais, D. et al., 2020: Long-term exposure to near-future ocean acidification does not affect the expression of neurogenesis- and synaptic transmission-related genes in the olfactory bulb of European sea bass (D*icentrarchus labrax)*. *Journal of Comparative Physiology B*, **190**(2), 161-167, doi:10.1007/s00360-019-01256-2.
McArley, T. J., A. J. R. Hickey and N. A. Herbert, 2020: Acute high temperature exposure impairs hypoxia tolerance in an intertidal fish. *PLOS ONE*, **15**(4), e0231091, doi:10.1371/journal.pone.0231091.
McCabe, R. M. et al., 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43**(19), 10,366-310,376, doi:10.1002/2016GL070023.
McCarthy, A. H., L. S. Peck, K. A. Hughes and D. C. Aldridge, 2019: Antarctica: The final frontier for marine biological invasions. *Global Change Biology*, **25**(7), 2221-2241, doi:10.1111/gcb.14600.
McClure, E. C. et al., 2020: Higher fish biomass inside than outside marine protected areas despite typhoon impacts in a complex reefscape. *Biological Conservation*, **241**, 108354, doi:10.1016/j.biocon.2019.108354.
McCormick, L. R. and L. A. Levin, 2017: Physiological and ecological implications of ocean deoxygenation for vision in marine organisms. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **375**(2102), 20160322, doi:10.1098/rsta.2016.0322.
McCoy, S. J. et al., 2018: A mineralogical record of ocean change: decadal and centennial patterns in the California mussel. *Global Change Biology*, **24**(6), 2554-2562, doi:10.1111/gcb.14013.
McDonald, J. et al., 2019: Adaptation pathways for conservation law and policy. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(1), e555, doi:10.1002/wcc.555.

McDowell, W. G., W. H. McDowell and J. E. Byers, 2017: Mass mortality of a dominant invasive species in response to an extreme climate event: Implications for ecosystem function. *Limnology and Oceanography*, **62**(1), 177-188, doi:10.1002/lno.10384.
McEvoy, S., M. Haasnoot and R. Biesbroek, 2021: How are European countries planning for sea level rise? *Ocean & Coastal Management*, **203**, 105512, doi:10.1016/j.ocecoaman.2020.105512.
McGovern, M. et al., 2019: Implications of Coastal Darkening for Contaminant Transport, Bioavailability, and Trophic Transfer in Northern Coastal Waters. *Environmental Science & Technology*, **53**(13), 7180-7182, doi:10.1021/acs.est.9b03093.
McGowan, J. et al., 2020: Prioritizing debt conversion opportunities for marine conservation. *Conservation Biology*, **n/a**(n/a), doi:10.1111/cobi.13540.
McKenzie, L. J. et al., 2020: The global distribution of seagrass meadows. *Environ.Res.Lett.*, **15**(7), 074041, doi:10.1088/1748-9326/ab7d06.
McKenzie, L. J. and R. L. Yoshida, 2020: Over a decade monitoring Fiji's seagrass condition demonstrates resilience to anthropogenic pressures and extreme climate events. *Marine Pollution Bulletin*, **160**, 111636, doi:10.1016/j.marpolbul.2020.111636.
McKenzie, L. J. et al., 2021a: Seagrass ecosystem contributions to people's quality of life in the Pacific Island Countries and Territories. *Marine Pollution Bulletin*, **167**, 112307, doi:10.1016/j.marpolbul.2021.112307.
McKenzie, T., S. Habel and H. Dulai, 2021b: Sea-level rise drives wastewater leakage to coastal waters and storm drains. *Limnology and Oceanography Letters*, **6**(3), 154-163, doi:10.1002/lol2.10186.
McKibben, S. M. et al., 2017: Climatic regulation of the neurotoxin domoic acid. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(2), 239, doi:10.1073/pnas.1606798114.
McKnight, E. et al., 2021: Non-native species outperform natives in coastal marine ecosystems subjected to warming and freshening events. *Global Ecology and Biogeography*, **30**(8), 1698-1712, doi:10.1111/geb.13318.
McLachlan, A. and O. Defeo, 2018: *The Ecology of Sandy Shores*, 3rd ed., Academic Press, 572 pp. ISBN 9780128094679.
McLaskey, A. K. et al., 2019: Early life stages of *Calanus pacificus* are neither exposed nor sensitive to low pH waters. *Journal of Plankton Research*, **41**(6), 893-896, doi:10.1093/plankt/fbz059.
McLean, M. et al., 2019: Fish communities diverge in species but converge in traits over three decades of warming. *Global Change Biology*, doi:10.1111/gcb.14785.
McLeod, E. et al., 2019: The future of resilience-based management in coral reef ecosystems. *Journal of Environmental Management*, **233**, 291-301, doi:10.1016/j.jenvman.2018.11.034.
McLeod, E. et al., 2018: Raising the voices of Pacific Island women to inform climate adaptation policies. *Marine Policy*, **93**, 178-185, doi:10.1016/j.marpol.2018.03.011.
McMahon, K. W. et al., 2019: Divergent trophic responses of sympatric penguin species to historic anthropogenic exploitation and recent climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(51), 25721, doi:10.1073/pnas.1913093116.
McMahon, S. J. et al., 2020: Elevated temperature and CO_2 have positive effects on the growth and survival of larval Australasian snapper. *Marine Environmental Research*, **161**, 105054, doi:10.1016/j.marenvres.2020.105054.
McManus, L. C. et al., 2021: Evolution and connectivity influence the persistence and recovery of coral reefs under climate change in the Caribbean, Southwest Pacific, and Coral Triangle. *Global Change Biology*, **27**(18), 4307-4321, doi:10.1111/gcb.15725.
McManus, L. C. et al., 2020: Extreme temperature events will drive coral decline in the Coral Triangle. *Global Change Biology*, **26**(4), 2120-2133, doi:10.1111/gcb.14972.
McMichael, C. and M. Katonivualiku, 2020: Thick temporalities of planned relocation in Fiji. *Geoforum*, **108**, 286-294, doi:10.1016/j.geoforum.2019.06.012.
McMichael, C., M. Katonivualiku and T. Powell, 2019: Planned relocation and everyday agency in low-lying coastal villages in Fiji. *The Geographical Journal*, **185**(3), 325-337, doi:10.1111/geoj.12312.
McNamara, K. E. et al., 2020: An assessment of community-based adaptation initiatives in the Pacific Islands. *Nature Climate Change*, **10**(7), 628-639, doi:10.1038/s41558-020-0813-1.
McNeil, B. I. and T. P. Sasse, 2016: Future ocean hypercapnia driven by anthropogenic amplification of the natural CO_2 cycle. *Nature*, **529**(7586), 383-386, doi:10.1038/nature16156.
McNeill, A., J. Clifton and E. S. Harvey, 2018: Attitudes to a marine protected area are associated with perceived social impacts. *Marine Policy*, **94**, 106-118, doi:10.1016/j.marpol.2018.04.020.
McOwen, C. J. et al., 2017: A global map of saltmarshes. *Biodiversity data journal*, **5**, e11764, doi:10.3897/BDJ.5.e11764.
McPherson, M. L. et al., 2021: Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave. *Communications Biology*, **4**(1), 298, doi:10.1038/s42003-021-01827-6.
McQueen, K. and C. T. Marshall, 2017: Shifts in spawning phenology of cod linked to rising sea temperatures. *ICES Journal of Marine Science*, **74**(6), 1561-1573, doi:10.1093/icesjms/fsx025.
Medrano, A. et al., 2020: From marine deserts to algal beds: Treptacantha elegans revegetation to reverse stable degraded ecosystems inside and outside a No-Take marine reserve. *Restoration Ecology*, **28**(3), 632-644, doi:10.1111/rec.13123.

Mehbub, M. F., J. Lei, C. Franco and W. Zhang, 2014: Marine sponge derived natural products between 2001 and 2010: trends and opportunities for discovery of bioactives. *Marine Drugs*, **12**(8), 4539-4577, doi:10.3390/md12084539.
Mehvar, S. et al., 2019: Climate change-driven losses in ecosystem services of coastal wetlands: A case study in the west coast of Bangladesh. *Ocean & Coastal Management*, **169**, 273-283, doi:10.1016/j.ocecoaman.2018.12.009.
Meinen, C. S. et al., 2020: Observed Ocean Bottom Temperature Variability at Four Sites in the Northwestern Argentine Basin: Evidence of Decadal Deep/Abyssal Warming Amidst Hourly to Interannual Variability During 2009–2019. *Geophysical Research Letters*, **47**(18), e2020GL089093, doi:10.1029/2020GL089093.
Melbourne, L. A. et al., 2018: The importance of wave exposure on the structural integrity of rhodoliths. *Journal of Experimental Marine Biology and Ecology*, **503**, 109-119, doi:10.1016/j.jembe.2017.11.007.
Melbourne-Thomas, J. et al., 2021: Poleward bound: adapting to climate-driven species redistribution. *Reviews in Fish Biology and Fisheries*, doi:10.1007/s11160-021-09641-3.
Mellado, C. et al., 2019: Ocean acidification exacerbates the effects of paralytic shellfish toxins on the fitness of the edible mussel *Mytilus chilensis*. *Science of The Total Environment*, **653**, 455-464, doi:10.1016/j.scitotenv.2018.10.399.
Melzner, F., F. C. Mark, B. A. Seibel and L. Tomanek, 2020: Ocean acidification and coastal marine invertebrates: tracking CO_2 effects from seawater to the cell. *Annual Review of Marine Science*, **12**, doi:10.1146/annurev-marine-010419-010658.
Menéndez, P. et al., 2020: The Global Flood Protection Benefits of Mangroves. *Scientific Reports*, **10**(1), 4404, doi:10.1038/s41598-020-61136-6.
Meng, Y. et al., 2018: Ocean acidification reduces hardness and stiffness of the Portuguese oyster shell with impaired microstructure: a hierarchical analysis. *Biogeosciences*, **15**(22), 6833-6846, doi:10.5194/bg-15-6833-2018.
Menge, B. A. et al., 2016: Sea star wasting disease in the keystone predator *Pisaster ochraceus* in Oregon: insights into differential population impacts, recovery, predation rate, and temperature effects from long-term research. *PLOS ONE*, **11**(5), e0153994, doi:10.1371/journal.pone.0153994.
Mentaschi, L. et al., 2018: Global long-term observations of coastal erosion and accretion. *Scientific Reports*, **8**(1), 12876, doi:10.1038/s41598-018-30904-w.
Meredith, M. P. et al., 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. In press.
Merilä, J. and A. P. Hendry, 2014: Climate change, adaptation, and phenotypic plasticity: the problem and the evidence. *Evolutionary Applications*, **7**(1), 1-14, doi:10.1111/eva.12137.
Mérillet, L. et al., 2020: Environment outweighs the effects of fishing in regulating demersal community structure in an exploited marine ecosystem. *Global Change Biology*, **26**(4), 2106-2119, doi:10.1111/gcb.14969.
Merkens, J.-L. et al., 2018: Regionalisation of population growth projections in coastal exposure analysis. *Climatic Change*, **151**(3), 413-426, doi:10.1007/s10584-018-2334-8.
Merkens, J.-L., L. Reimann, J. Hinkel and A. T. Vafeidis, 2016: Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, **145**, 57-66, doi:10.1016/j.gloplacha.2016.08.009.
Messmer, V. et al., 2017: Global warming may disproportionately affect larger adults in a predatory coral reef fish. *Global Change Biology*, **23**(6), 2230-2240, doi:10.1111/gcb.13552.
Meyer, J. and I. Kröncke, 2019: Shifts in trait-based and taxonomic macrofauna community structure along a 27-year time-series in the south-eastern North Sea. *PLOS ONE*, **14**(12), e0226410, doi:10.1371/journal.pone.0226410.
Meynecke, J.-O., R. Richards and O. Sahin, 2017: Whale watch or no watch: the Australian whale watching tourism industry and climate change. *Regional Environmental Change*, **17**(2), 477-488, doi:10.1007/s10113-016-1034-z.
Michael, H. A., V. E. A. Post, A. M. Wilson and A. D. Werner, 2017: Science, society, and the coastal groundwater squeeze. *Water Resources Research*, **53**(4), 2610-2617, doi:10.1002/2017WR020851.
Michalena, E. et al., 2020: Promoting sustainable and inclusive oceans management in Pacific islands through women and science. *Marine Pollution Bulletin*, **150**, 110711, doi:10.1016/j.marpolbul.2019.110711.
Middelburg, J. J., 2018: Reviews and syntheses: to the bottom of carbon processing at the seafloor. *Biogeosciences*, **15**(2), 413-427, doi:10.5194/bg-15-413-2018.
Miladinova, S., A. Stips, E. Garcia-Gorriz and D. Macias Moy, 2017: Black Sea thermohaline properties: long-term trends and variations. *Journal of Geophysical Research: Oceans*, **122**(7), 5624-5644, doi:10.1002/2016JC012644.
Millar, R. J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience*, **10**(10), 741-747, doi:10.1038/ngeo3031.
Milledge, J. J. and P. J. Harvey, 2016: Golden Tides: Problem or Golden Opportunity? The Valorisation of Sargassum from Beach Inundations. *Journal of Marine Science and Engineering*, **4**(3), doi:10.3390/jmse4030060.
Miller, A. D. et al., 2020a: Local thermal adaptation and limited gene flow constrain future climate responses of a marine ecosystem engineer. *Evolutionary Applications*, **13**(5), 918-934, doi:10.1111/eva.12909.
Miller, D. D. et al., 2018: Adaptation strategies to climate change in marine systems. *Global Change Biology*, **24**(1), e1-e14, doi:10.1111/gcb.13829.
Miller, J. J. et al., 2016: Exposure to low pH reduces survival and delays development in early life stages of Dungeness crab (Cancer magister). *Marine Biology*, **163**(5), 118, doi:10.1007/s00227-016-2883-1.

Miller, L. B. et al., 2020b: On the edge of the world: examining pro-environmental outcomes of last chance tourism in Kaktovik, Alaska. *Journal of Sustainable Tourism*, **28**(11), 1703-1722, doi:10.1080/09669582.2020.1720696.
Miner, C. M. et al., 2018: Large-scale impacts of sea star wasting disease (SSWD) on intertidal sea stars and implications for recovery. *PLOS ONE*, **13**(3), e0192870, doi:10.1371/journal.pone.0192870.
Miralles, L. et al., 2018: Alert calling in port areas: Marine litter as possible secondary dispersal vector for hitchhiking invasive species. *Journal for Nature Conservation*, **42**, 12-18, doi:10.1016/j.jnc.2018.01.005.
Mitarai, S. et al., 2016: Quantifying dispersal from hydrothermal vent fields in the western Pacific Ocean. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(11), 2976, doi:10.1073/pnas.1518395113.
Mitchell-Olds, T., J. H. Willis and D. B. Goldstein, 2007: Which evolutionary processes influence natural genetic variation for phenotypic traits? *Nature Reviews Genetics*, **8**(11), 845-856, doi:10.1038/nrg2207.
Moffitt, S. E., T. M. Hill, P. D. Roopnarine and J. P. Kennett, 2015: Response of seafloor ecosystems to abrupt global climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(15), 4684-4689, doi:10.1073/pnas.1417130112.
Mofor, L., M. Isaka, H. Wade and A. Soakai, 2013: *Pacific lighthouses – renewable energy roadmapping for islands*. IRENA, Abu Dhabi, United Arab Emirates, 47 pp pp. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/Pacific-Lighthouse-Roadmapping.pdf.
Moftakhari, H. R. et al., 2015: Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future. *Geophysical Research Letters*, **42**(22), 9846-9852, doi:10.1002/2015GL066072.
Mohamed Shaffril, H. A. et al., 2020: Systematic literature review on adaptation towards climate change impacts among indigenous people in the Asia Pacific regions. *Journal of Cleaner Production*, **258**, 120595, doi:10.1016/j.jclepro.2020.120595.
Møller, E. F. and T. G. Nielsen, 2020: Borealization of Arctic zooplankton—smaller and less fat zooplankton species in Disko Bay, Western Greenland. *Limnology and Oceanography*, **65**(6), 1175-1188, doi:10.1002/lno.11380.
Möller, I., 2019: Applying Uncertain Science to Nature-Based Coastal Protection: Lessons From Shallow Wetland-Dominated Shores. *Frontiers in Environmental Science*, **7**, 49, doi:10.3389/fenvs.2019.00049.
Möllmann, C., C. Folke, M. Edwards and A. Conversi, 2015: Marine regime shifts around the globe: theory, drivers and impacts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**(1659), 20130260, doi:10.1098/rstb.2013.0260.
Molnár, P. K. et al., 2020: Fasting season length sets temporal limits for global polar bear persistence. *Nature Climate Change*, **10**(8), 732-738, doi:10.1038/s41558-020-0818-9.
Monaco, C. J. et al., 2021: Natural and anthropogenic climate variability shape assemblages of range-extending coral-reef fishes. *Journal of Biogeography*, **48**(5), 1063-1075, doi:10.1111/jbi.14058.
Monaco, C. J. et al., 2020: Dietary generalism accelerates arrival and persistence of coral-reef fishes in their novel ranges under climate change. *Global Change Biology*, **26**(10), 5564-5573, doi:10.1111/gcb.15221.
Monios, J. and G. Wilmsmeier, 2020: Deep adaptation to climate change in the maritime transport sector – a new paradigm for maritime economics? *Maritime Policy & Management*, 1-20, doi:10.1080/03088839.2020.1752947.
Monnereau, I. et al., 2017: The impact of methodological choices on the outcome of national-level climate change vulnerability assessments: an example from the global fisheries sector. *Fish and Fisheries*, **18**(4), 717-731, doi:10.1111/faf.12199.
Monsinjon, J. et al., 2019: Effects of temperature and demography on the phenology of loggerhead sea turtles in Brazil. *Marine Ecology Progress Series*, **623**, 209-219, doi:10.3354/meps12988.
Montánchez, I. and V. R. Kaberdin, 2020: *Vibrio harveyi*: A brief survey of general characteristics and recent epidemiological traits associated with climate change. *Marine Environmental Research*, **154**, 104850, doi:10.1016/j.marenvres.2019.104850.
Montero-Serra, I., M. Edwards and M. J. Genner, 2015: Warming shelf seas drive the subtropicalization of European pelagic fish communities. *Global Change Biology*, **21**(1), 144-153, doi:10.1111/gcb.12747.
Montero-Serra, I. et al., 2019: Marine protected areas enhance structural complexity but do not buffer the consequences of ocean warming for an overexploited precious coral. *Journal of Applied Ecology*, **56**(5), 1063-1074, doi:10.1111/1365-2664.13321.
Montgomery, D. W. et al., 2019: Rising CO_2 enhances hypoxia tolerance in a marine fish. *Scientific Reports*, **9**(1), 15152, doi:10.1038/s41598-019-51572-4.
Monti, F. et al., 2018: The price of success: integrative long-term study reveals ecotourism impacts on a flagship species at a UNESCO site. *Animal Conservation*, **21**(6), 448-458, doi:10.1111/acv.12407.
Moore, C. M. et al., 2013: Processes and patterns of oceanic nutrient limitation. *Nature Geoscience*, **6**(9), 701-710, doi:10.1038/ngeo1765.
Moore, J. K. et al., 2018a: Sustained climate warming drives declining marine biological productivity. *Science*, **359**(6380), 1139-1143, doi:10.1126/science.aao6379.
Moore, K. M. et al., 2020a: Harmful algal blooms: identifying effective adaptive actions used in fishery-dependent communities in response to a protracted event. *Frontiers in Marine Science*, **6**(803), doi:10.3389/fmars.2019.00803.

Moore, S. E., P. J. Stabeno, J. M. Grebmeier and S. R. Okkonen, 2018b: The Arctic Marine Pulses Model: linking annual oceanographic processes to contiguous ecological domains in the Pacific Arctic. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **152**, 8-21, doi:10.1016/j.dsr2.2016.10.011.
Moore, S. K. et al., 2019: An index of fisheries closures due to harmful algal blooms and a framework for identifying vulnerable fishing communities on the U.S. West Coast. *Marine Policy*, 103543, doi:10.1016/j.marpol.2019.103543.
Moore, S. K. et al., 2020b: Harmful algal blooms and coastal communities: Socioeconomic impacts and actions taken to cope with the 2015 U.S. West Coast domoic acid event. *Harmful Algae*, **96**, 101799, doi:10.1016/j.hal.2020.101799.
Mora, C. et al., 2013: Biotic and Human Vulnerability to Projected Changes in Ocean Biogeochemistry over the 21st Century. *PLOS Biology*, **11**(10), e1001682, doi:10.1371/journal.pbio.1001682.
Morato, T. et al., 2020: Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. *Global Change Biology*, **26**(4), 2181-2202, doi:10.1111/gcb.14996.
Moreno-Marín, F., F. G. Brun and M. F. Pedersen, 2018: Additive response to multiple environmental stressors in the seagrass Zostera marina L. *Limnology and Oceanography*, **63**(4), 1528-1544, doi:10.1002/lno.10789.
Morgan, R. et al., 2020: Low potential for evolutionary rescue from climate change in a tropical fish. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(52), 33365, doi:10.1073/pnas.2011419117.
Mori, N., S. Nakajo, S. Iwamura and Y. Shibutani, 2018: Projection of decrease in Japanese beaches due to climate change using a geographic database. *Coastal Engineering Journal*, **60**(2), 239-246, doi:10.1080/21664250.2018.1488513.
Morikawa, M. K. and S. R. Palumbi, 2019: Using naturally occurring climate resilient corals to construct bleaching-resistant nurseries. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(21), 10586-10591, doi:10.1073/pnas.1721415116.
Morim, J. et al., 2019: Robustness and uncertainties in global multivariate wind-wave climate projections. *Nature Climate Change*, **9**(9), 711-718, doi:10.1038/s41558-019-0542-5.
Morioka, K., M. McGann, S. Mackay and B. Mackey, 2020: Applying information for national adaptation planning and decision making: present and future practice in the Pacific Islands. *Regional Environmental Change*, **20**(4), 135, doi:10.1007/s10113-020-01715-5.
Morley, J. W. et al., 2018: Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLOS ONE*, **13**(5), e0196127, doi:10.1371/journal.pone.0196127.
Morrell, B. K. and C. J. Gobler, 2020: Negative Effects of Diurnal Changes in Acidification and Hypoxia on Early-Life Stage Estuarine Fishes. *Diversity*, **12**(1), doi:10.3390/d12010025.
Morris, R. et al., 2019: Developing a nature-based coastal defence strategy for Australia. *Australian Journal of Civil Engineering*, **17**(2), 167-176, doi:10.1080/14488353.2019.1661062.
Morris, R. L., A. Boxshall and S. E. Swearer, 2020a: Climate-resilient coasts require diverse defence solutions. *Nature Climate Change*, **10**(6), 485-487, doi:10.1038/s41558-020-0798-9.
Morris, R. L. et al., 2020b: Kelp beds as coastal protection: wave attenuation of *Ecklonia radiata* in a shallow coastal bay. *Annals of Botany*, **125**(2), 235-246, doi:10.1093/aob/mcz127.
Morris, R. L. et al., 2020c: Key Principles for Managing Recovery of Kelp Forests through Restoration. *BioScience*, **70**(8), 688-698, doi:10.1093/biosci/biaa058.
Mosbech, A. et al., 2018: On the crucial importance of a small bird: The ecosystem services of the little auk (Alle alle) population in Northwest Greenland in a long-term perspective. *Ambio*, **47**(2), 226-243, doi:10.1007/s13280-018-1035-x.
Mosch, T. et al., 2012: Factors influencing the distribution of epibenthic megafauna across the Peruvian oxygen minimum zone. *Deep-Sea Research Part I: Oceanographic Research Papers*, **68**, 123-135, doi:10.1016/j.dsr.2012.04.014.
Moser, S. C., J. A. Ekstrom, J. Kim and S. Heitsch, 2019: Adaptation finance archetypes: local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecology and Society*, **24**(2), 28, doi:10.5751/ES-10980-240228.
Moustaka-Gouni, M. et al., 2016: Warming and Acidification Effects on Planktonic Heterotrophic Pico- and Nanoflagellates in a Mesocosm Experiment. *Protist*, **167**(4), 389-410, doi:10.1016/j.protis.2016.06.004.
Mouw, C. B. et al., 2016: Phytoplankton size impact on export flux in the global ocean. *Global Biogeochemical Cycles*, **30**(10), 1542-1562, doi:10.1002/2015GB005355.
Movilla, J. et al., 2014: Differential response of two Mediterranean cold-water coral species to ocean acidification. *Coral Reefs*, **33**(3), 675-686, doi:10.1007/s00338-014-1159-9.
Muenzel, D. and S. Martino, 2018: Assessing the feasibility of carbon payments and Payments for Ecosystem Services to reduce livestock grazing pressure on saltmarshes. *Journal of Environmental Management*, **225**, 46-61, doi:10.1016/j.jenvman.2018.07.060.
Muhling, B. A. et al., 2018: Regional-scale surface temperature variability allows prediction of Pacific bluefin tuna recruitment. *ICES Journal of Marine Science*, **75**(4), 1341-1352, doi:10.1093/icesjms/fsy017.
Mukhopadhyay, A. et al., 2019: Mangrove spatial distribution in the Indian Sundarbans: Predicting salinity-induced migration in a changing climate. *Journal of Management and Sustainability*, **9**(1), 1-13, doi:10.5539/jms.v9n1p1.

Mulders, Y. R. and T. Wernberg, 2020: Fifteen years in a global warming hotspot: changes in subtidal mobile invertebrate communities. *Marine Ecology Progress Series*, **656**, 227-238, doi:10.3354/meps13567.
Müller, T. et al., 2020: Ocean acidification during the early Toarcian extinction event: Evidence from boron isotopes in brachiopods. *Geology*, doi:10.1130/G47781.1.
Müller, T. et al., 2017: New multiproxy record of the Jenkyns event (also known as the Toarcian oceanic anoxic event) from the Mecsek Mountains (Hungary): differences, duration and drivers. *Sedimentology*, **64**(1), 66-86, doi:10.1111/sed.12332.
Muller-Karger, F. E. et al., 2019: The Scientific Legacy of the CARIACO Ocean Time-Series Program. *Annual Review of Marine Science*, **11**(1), 413-437, doi:10.1146/annurev-marine-010318-095150.
Munday, P. L. et al., 2020: Methods matter in repeating ocean acidification studies. *Nature*, **586**(7830), E20-E24, doi:10.1038/s41586-020-2803-x.
Munday, P. L., M. D. Jarrold and I. Nagelkerken, 2019: 9 - Ecological effects of elevated CO_2 on marine and freshwater fishes: From individual to community effects. In: *Fish Physiology* [Grosell, M., P. L. Munday, A. P. Farrell and C. J. Brauner (eds.)]. Academic Press, pp. 323-368. ISBN 1546-5098.
Munday, P. L. et al., 2013: Predicting evolutionary responses to climate change in the sea. *Ecology Letters*, **16**(12), 1488-1500, doi:10.1111/ele.12185.
Munday, P. L. et al., 2016: Effects of elevated CO_2 on early life history development of the yellowtail kingfish, *Seriola lalandi*, a large pelagic fish. *ICES Journal of Marine Science*, **73**, 641--649, doi:10.1093/icesjms/fsv210.
Murray, C. S., A. Malvezzi, C. J. Gobler and H. Baumann, 2014: Offspring sensitivity to ocean acidification changes seasonally in a coastal marine fish. *Marine Ecology Progress Series*, **504**, 1-11, doi:10.3354/meps10791.
Murray, N. J. et al., 2019: The global distribution and trajectory of tidal flats. *Nature*, **565**(7738), 222-225, doi:10.1038/s41586-018-0805-8.
Nagelkerken, I., C. Doney Scott and L. Munday Philip, 2019: Consequences of Anthropogenic Changes in the Sensory Landscape of Marine Animals. In: *Oceanography and Marine Biology* [Hawkins, S. J., A. L. Allcock, A. E. Bates, L. B. Firth, I. P. Smith, S. E. Swearer and P. A. Todd (eds.)]. CRC Press, Leiden, The Netherlands, pp. 229-263. ISBN 9780429026379.
Nagelkerken, I. et al., 2020: Trophic pyramids reorganize when food web architecture fails to adjust to ocean change. *Science*, **369**(6505), 829-832, doi:10.1126/science.aax0621.
Nagelkerken, I. and P. L. Munday, 2016: Animal behaviour shapes the ecological effects of ocean acidification and warming: moving from individual to community-level responses. *Global Change Biology*, **22**(3), 974-989, doi:10.1111/gcb.13167.
Naik, V. et al., 2021: Short-Lived Climate Forcers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Nakamura, Y. and A. Oka, 2019: CMIP5 model analysis of future changes in ocean net primary production focusing on differences among individual oceans and models. *Journal of Oceanography*, **75**(5), 441-462, doi:10.1007/s10872-019-00513-w.
Nalau, J. et al., 2018: The role of Indigenous and traditional knowledge in ecosystem-based adaptation: a review of the literature and case studies from the Pacific Islands. *Weather, Climate, and Society*, **10**(4), 851-865, doi:10.1175/WCAS-D-18-0032.1.
Narayan, S. et al., 2016: The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLOS ONE*, **11**(5), e0154735, doi:10.1371/journal.pone.0154735.
Naser, A. M. et al., 2020: Consequences of access to water from managed aquifer recharge systems for blood pressure and proteinuria in south-west coastal Bangladesh: a stepped-wedge cluster-randomized trial. *International Journal of Epidemiology*, doi:10.1093/ije/dyaa098.
Nash, K. L. et al., 2021: Developing achievable alternate futures for key challenges during the UN Decade of Ocean Science for Sustainable Development. *Reviews in Fish Biology and Fisheries*, doi:10.1007/s11160-020-09629-5.
Nash, K. L. et al., 2020: To Achieve a Sustainable Blue Future, Progress Assessments Must Include Interdependencies between the Sustainable Development Goals. *One Earth*, **2**(2), 161-173, doi:10.1016/j.oneear.2020.01.008.
National Academies of Sciences, 2019: *A research review of interventions to increase the persistence and resilience of coral reefs*. The National Academies Press, Washington, D.C., 258 pp pp.
National Academies of Sciences Engineering and Medicine, 2019: *A Decision Framework for Interventions to Increase the Persistence and Resilience of Coral Reefs*. The National Academies Press, Washington, D.C.
National Research Council, 2001: *Marine Protected Areas: Tools for Sustaining Ocean Ecosystems*. The National Academies Press, Washington, DC, 288 pp. Available at: https://www.nap.edu/catalog/9994/marine-protected-areas-tools-for-sustaining-ocean-ecosystems.
National Research Council, 2005: Ecosystem Valuation: Synthesis and Future Directions. In: *Valuing Ecosystem Services: Toward Better Environmental Decision-Making* The National Academies Press, Washington, D.C.
Naumann, M. S., C. Orejas and C. Ferrier-Pagès, 2013: High thermal tolerance of two Mediterranean cold-water coral species maintained in aquaria. *Coral Reefs*, **32**(3), 749-754, doi:10.1007/s00338-013-1011-7.

Naumann, M. S., C. Orejas and C. Ferrier-Pagès, 2014: Species-specific physiological response by the cold-water corals Lophelia pertusa and Madrepora oculata to variations within their natural temperature range. *Deep Sea Research Part II: Topical Studies in Oceanography*, **99**, 36-41, doi:10.1016/j.dsr2.2013.05.025.
Nazarnia, H., M. Nazarnia, H. Sarmasti and W. O. Wills, 2020: A Systematic Review of Civil and Environmental Infrastructures for Coastal Adaptation to Sea Level Rise. *Civil Engineering Journal*, **6**(7), 1375-1399, doi:10.28991/cej-2020-03091555.
Neijnens, F. K., K. Siteur, J. van de Koppel and M. Rietkerk, 2021: Early Warning Signals for Rate-induced Critical Transitions in Salt Marsh Ecosystems. *Ecosystems*, doi:10.1007/s10021-021-00610-2.
Neill, S. P. et al., 2018: Tidal range energy resource and optimization – past perspectives and future challenges. *Renewable Energy*, **127**, 763-778, doi:10.1016/j.renene.2018.05.007.
Nepper-Davidsen, J., D. T. Andersen and M. F. Pedersen, 2019: Exposure to simulated heatwave scenarios causes long-term reductions in performance in *Saccharina latissima*. *Marine Ecology Progress Series*, **630**, 25-39, doi:10.3354/meps13133.
Neuheimer, A. B., B. R. MacKenzie and M. R. Payne, 2018: Temperature-dependent adaptation allows fish to meet their food across their species' range. *Science Advances*, **4**(7), eaar4349, doi:10.1126/sciadv.aar4349.
Neukermans, G., L. Oziel and M. Babin, 2018: Increased intrusion of warming Atlantic water leads to rapid expansion of temperate phytoplankton in the Arctic. *Global Change Biology*, **24**(6), 2545-2553, doi:10.1111/gcb.14075.
Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. *PLOS ONE*, **10**(3), e0118571, doi:10.1371/journal.pone.0118571.
Neußner, O., 2021: Early warning alerts for extreme natural hazard events: A review of worldwide practices. *International Journal of Disaster Risk Reduction*, **60**, 102295, doi:10.1016/j.ijdrr.2021.102295.
Newcomb, L. A., M. N. George, M. J. O'Donnell and E. Carrington, 2020: Only as strong as the weakest link: structural analysis of the combined effects of elevated temperature and pCO2 on mussel attachment. *Conservation Physiology*, **7**(1), doi:10.1093/conphys/coz068.
Newton, A. et al., 2020: Anthropogenic, Direct Pressures on Coastal Wetlands. *Front. ecol. evol.*, **8**(144), doi:10.3389/fevo.2020.00144.
Nguyen, T., M. Pham and T. L. Anh, 2020: Spray, combustion, performance and emission characteristics of a common rail diesel engine fueled by fish-oil biodiesel blends. *Fuel*, **269**, doi:10.1016/j.fuel.2020.117108.
Ni, W., M. Li and J. M. Testa, 2020: Discerning effects of warming, sea level rise and nutrient management on long-term hypoxia trends in Chesapeake Bay. *Science of The Total Environment*, **737**, 139717, doi:10.1016/j.scitotenv.2020.139717.
Nicholls, R. J., W. N. Adger, C. W. Hutton and S. E. Hanson, 2020: *Deltas in the Anthropocene*. Palgrave Macmillan, Cham, 282 pp. ISBN 978-3-030-23517-8.
Nicholls, R. J. et al., 2018: Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160448, doi:10.1098/rsta.2016.0448.
Nicholls, R. J. et al., 2014: Sea-level scenarios for evaluating coastal impacts. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(1), 129-150, doi:10.1002/wcc.253.
Nicholls, R. J., J. Hinkel, D. Lincke and T. van der Pol, 2019: *Global Investment Costs for Coastal Defense through the 21st Century (English)*. Policy Research Working Paper, no. WPS 8745, World Bank Group, Washington, D.C., 64 pp pp.
Nichols, C. R. et al., 2019: Collaborative Science to Enhance Coastal Resilience and Adaptation. *Frontiers in Marine Science*, **6**(404), doi:10.3389/fmars.2019.00404.
Nichols, G., I. Lake and C. Heaviside, 2018: Climate change and water-related infectious diseases. *Atmosphere*, **9**(10), 385, doi:10.3390/atmos9100385.
Niemi, A. et al., 2021: Biological Impact of Ocean Acidification in the Canadian Arctic: Widespread Severe Pteropod Shell Dissolution in Amundsen Gulf. *Frontiers in Marine Science*, **8**(222), doi:10.3389/fmars.2021.600184.
Nilsson, G. E. et al., 2012: Near-future carbon dioxide levels alter fish behaviour by interfering with neurotransmitter function. *Nature Climate Change*, **2**(3), 201-204, doi:10.1038/nclimate1352.
Nilsson, M., D. Griggs and M. Visbeck, 2016: Policy: map the interactions between sustainable development goals. *Nature*, **534**(7607), 320-322, doi:10.1038/534320a.
Nishioka, J. et al., 2011: Oceanic iron supply mechanisms which support the spring diatom bloom in the Oyashio region, western subarctic Pacific. *Journal of Geophysical Research: Oceans*, **116**(C2), C02021, doi:10.1029/2010JC006321.
Nohe, A. et al., 2020: Marked changes in diatom and dinoflagellate biomass, composition and seasonality in the Belgian Part of the North Sea between the 1970s and 2000s. *Science of The Total Environment*, **716**, 136316, doi:10.1016/j.scitotenv.2019.136316.
Noisette, F., H. Egilsdottir, D. Davoult and S. Martin, 2013: Physiological responses of three temperate coralline algae from contrasting habitats to near-future ocean acidification. *Journal of Experimental Marine Biology and Ecology*, **448**, 179-187, doi:10.1016/j.jembe.2013.07.006.
Norman, E. S., 2017: Standing up for inherent rights: the role of Indigenous-led activism in protecting sacred waters and ways of life. *Society & Natural Resources*, **30**(4), 537-553, doi:10.1080/08941920.2016.1274459.

Norström, A. V. et al., 2020: Principles for knowledge co-production in sustainability research. *Nature Sustainability*, **3**(3), 182-190, doi:10.1038/s41893-019-0448-2.
Northcott, D. et al., 2019: Impacts of urban carbon dioxide emissions on sea-air flux and ocean acidification in nearshore waters. *PLOS ONE*, **14**(3), e0214403, doi:10.1371/journal.pone.0214403.
Novriadi, R., 2016: Vibriosis in aquaculture. *Omni-Akuatika*, **12**(1), 1-12, doi:10.20884/1.oa.2016.12.1.24.
Nowicki, J. P., G. M. Miller and P. L. Munday, 2012: Interactive effects of elevated temperature and CO_2 on foraging behavior of juvenile coral reef fish. *Journal of Experimental Marine Biology and Ecology*, **412**, 46-51, doi:10.1016/j.jembe.2011.10.020.
Nowicki, R. J. et al., 2017: Predicting seagrass recovery times and their implications following an extreme climate event. *Marine Ecology Progress Series*, **567**, 79-93, doi:10.3354/meps12029.
Ntona, M. and E. Morgera, 2018: Connecting SDG 14 with the other Sustainable Development Goals through marine spatial planning. *Marine Policy*, **93**, 214-222, doi:10.1016/j.marpol.2017.06.020.
Numbere, A. O., 2019: Impact of Invasive Nypa Palm (Nypa Fruticans) on Mangroves in Coastal Areas of the Niger Delta Region, Nigeria. In: *Impacts of Invasive Species on Coastal Environments: Coasts in Crisis* [Makowski, C. and C. W. Finkl (eds.)]. Springer International Publishing, Cham, pp. 425-454. ISBN 978-3-319-91382-7.
Nunan, F. et al., 2020: The silos of natural resource governance
implications of sector-led coastal management at the village level in Kenya and Zanzibar-Tanzania. *Conservation & Society*, **18**(2), 148-160.
Nunn, P. D., C. Klöck and V. Duvat, 2021: Seawalls as maladaptations along island coasts. *Ocean & Coastal Management*, **205**, 105554, doi:10.1016/j.ocecoaman.2021.105554.
Nunn, P. D., A. Kohler and R. Kumar, 2017: Identifying and assessing evidence for recent shoreline change attributable to uncommonly rapid sea-level rise in Pohnpei, Federated States of Micronesia, northwest Pacific Ocean. *Journal of Coastal Conservation*, **21**(6), 719-730, doi:10.1007/s11852-017-0531-7.
Nunn, P. D. et al., 2020: Adaptation to climate change: contemporary challenges and perspectives. In: *Climate Change and Impacts in the Pacific* [Kumar, L. (ed.)]. Springer International Publishing, Cham, pp. 499-524. ISBN 978-3-030-32878-8.
Nurhidayah, L. and A. McIlgorm, 2019: Coastal adaptation laws and the social justice of policies to address sea level rise: An Indonesian insight. *Ocean & Coastal Management*, **171**, 11-18, doi:10.1016/j.ocecoaman.2019.01.011.
Nursey-Bray, M., R. Palmer, T. F. Smith and P. Rist, 2019: Old ways for new days: Australian Indigenous peoples and climate change. *Local Environment*, **24**(5), 473-486, doi:10.1080/13549839.2019.1590325.
Nye, J. A., J. S. Link, J. A. Hare and W. J. Overholtz, 2009: Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series*, **393**, 111-129, doi:10.3354/meps08220.
O'Leary, B. C. et al., 2020: Options for managing human threats to high seas biodiversity. *Ocean & Coastal Management*, **187**, 105110, doi:10.1016/j.ocecoaman.2020.105110.
O'Leary, B. C. and C. M. Roberts, 2017: The Structuring Role of Marine Life in Open Ocean Habitat: Importance to International Policy. *Frontiers in Marine Science*, **4**(268), doi:10.3389/fmars.2017.00268.
O'Neill, B. C. et al., 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, **9**(9), 3461-3482, doi:10.5194/gmd-9-3461-2016.
O'Hara, C. C., M. Frazier and B. S. Halpern, 2021: At-risk marine biodiversity faces extensive, expanding, and intensifying human impacts. *Science*, **372**(6537), 84, doi:10.1126/science.abe6731.
O'Keeffe, J. M. et al., 2020: Stakeholder awareness of climate adaptation in the commercial seaport sector: A case study from Ireland. *Marine Policy*, **111**, 102404, doi:10.1016/j.marpol.2016.04.044.
OBIS, 2020: Ocean Biodiversity Information System, Intergovernmental Oceanographic Commission of UNESCO. Available at: https://obis.org/?query=kelp.
Obura, D. O. et al., 2021: Integrate biodiversity targets from local to global levels. *Science*, **373**(6556), 746, doi:10.1126/science.abh2234.
Ocaña, F. A., D. Pech, N. Simões and I. Hernández-Ávila, 2019: Spatial assessment of the vulnerability of benthic communities to multiple stressors in the Yucatan Continental Shelf, Gulf of Mexico. *Ocean & Coastal Management*, **181**, 104900, doi:10.1016/j.ocecoaman.2019.104900.
Ocean Panel, 2020: *Transformations for a Sustainable Ocean Economy: A Vision for Protection, Production and Prosperity*. The High Level Panel for a Sustainable Ocean Economy, 1-19 pp. Available at: https://www.oceanpanel.org/ocean-action/files/transformations-sustainable-ocean-economy-eng.pdf.
Ochoa-Gómez, J. G. et al., 2019: Mangrove wetland productivity and carbon stocks in an arid zone of the Gulf of California (La Paz Bay, Mexico). *Forest Ecology and Management*, **442**, 135-147, doi:10.1016/j.foreco.2019.03.059.
Ogier, E. et al., 2020: Responding to Climate Change: Participatory Evaluation of Adaptation Options for Key Marine Fisheries in Australia's South East. *Frontiers in Marine Science*, **7**, 97, doi:10.3389/fmars.2020.00097.
Ohayon, S., I. Granot and J. Belmaker, 2021: A meta-analysis reveals edge effects within marine protected areas. *Nature Ecology & Evolution*, doi:10.1038/s41559-021-01502-3.
Ojea, E., S. E. Lester and D. Salgueiro-Otero, 2020: Adaptation of Fishing Communities to Climate-Driven Shifts in Target Species. *One Earth*, **2**(6), 544-556, doi:10.1016/j.oneear.2020.05.012.

Ojwang, L. et al., 2017: Assessment of Coastal Governance for Climate Change Adaptation in Kenya. *Earth's Future*, **5**(11), 1119-1132, doi:10.1002/2017EF000595.
Okafor-Yarwood, I. et al., 2020: The Blue Economy–Cultural Livelihood–Ecosystem Conservation Triangle: The African Experience. *Frontiers in Marine Science*, **7**(586), doi:10.3389/fmars.2020.00586.
Oleson, K. L. L. et al., 2018: Charting progress towards system-scale ecosystem service valuation in islands. *Environmental Conservation*, **45**(3), 212-226, doi:10.1017/S0376892918000140.
Oliver, E. C. J. et al., 2019: Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Frontiers in Marine Science*, **6**, 734, doi:10.3389/fmars.2019.00734.
Oliver, E. C. J. et al., 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9**(1), 1324, doi:10.1038/s41467-018-03732-9.
Olsen, E. et al., 2018: Ocean futures under ocean acidification, marine protection, and changing fishing pressures explored using a worldwide suite of ecosystem models. *Frontiers in Marine Science*, **5**, 64, doi:10.3389/fmars.2018.00064.
Onda, D. F. L. et al., 2017: Seasonal and interannual changes in ciliate and dinoflagellate species assemblages in the Arctic Ocean (Amundsen Gulf, Beaufort Sea, Canada). *Frontiers in Marine Science*, **4**, 16, doi:10.3389/fmars.2017.00016.
Ondiviela, B. et al., 2020: Vulnerability of *Zostera noltei* to Sea Level Rise: the Use of Clustering Techniques in Climate Change Studies. *Estuaries and Coasts*, doi:10.1007/s12237-020-00742-z.
Onitsuka, T. et al., 2018: Effects of ocean acidification with pCO2 diurnal fluctuations on survival and larval shell formation of Ezo abalone, Haliotis discus hannai. *Marine Environmental Research*, **134**, 28-36, doi:10.1016/j.marenvres.2017.12.015.
Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. In press.
Orejas, C. et al., 2020: Towards a common approach to the assessment of the environmental status of deep-sea ecosystems in areas beyond national jurisdiction. *Marine Policy*, **121**, 104182, doi:10.1016/j.marpol.2020.104182.
Oremus, K. L. et al., 2020: Governance challenges for tropical nations losing fish species due to climate change. *Nature Sustainability*, **3**(4), 277-280, doi:10.1038/s41893-020-0476-y.
Oreska, M. P. J. et al., 2020: The greenhouse gas offset potential from seagrass restoration. *Scientific Reports*, **10**(1), 7325, doi:10.1038/s41598-020-64094-1.
Orio, A., Y. Heimbrand and K. Limburg, 2021: Deoxygenation impacts on Baltic Sea cod: Dramatic declines in ecosystem services of an iconic keystone predator. *Ambio*, doi:10.1007/s13280-021-01572-4.
Orr, J. C. et al., 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**(7059), 681-686, doi:10.1038/nature04095.
Orr, J. C. et al., 2017: Biogeochemical protocols and diagnostics for the CMIP6 Ocean Model Intercomparison Project (OMIP). *Geoscientific Model Development*, **10**(6), 2169-2199, doi:10.5194/gmd-10-2169-2017.
Ortega, A. et al., 2019: Important contribution of macroalgae to oceanic carbon sequestration. *Nature Geoscience*, **12**(9), 748-754, doi:10.1038/s41561-019-0421-8.
Ortiz, J.-C. et al., 2018: Impaired recovery of the Great Barrier Reef under cumulative stress. *Science Advances*, **4**(7), eaar6127, doi:10.1126/sciadv.aar6127.
Ortíz Liñán, M. E. and V. Vázquez Solís, 2021: The tourism inventory: a tool for territorial management of tourism in natural attractions in the state of San Luis Potosi, Mexico. *Investigaciones Turísticas*, **21**, 305-327, doi:10.14198/INTURI2021.21.14.
Oschlies, A., P. Brandt, L. Stramma and S. Schmidtko, 2018: Drivers and mechanisms of ocean deoxygenation. *Nature Geoscience*, **11**(7), 467-473, doi:10.1038/s41561-018-0152-2.
Osman, E. O. et al., 2018: Thermal refugia against coral bleaching throughout the northern Red Sea. *Global Change Biology*, **24**(2), e474-e484, doi:10.1111/gcb.13895.
Österblom, H., C. C. C. Wabnitz and D. Tladi, 2020: *Towards Ocean Equity*. World Resources Institute, Washington, DC. Available at: www.oceanpanel.org/how-distribute-benefits-ocean-equitably.
Ostle, C. et al., 2019: The rise in ocean plastics evidenced from a 60-year time series. *Nature Communications*, **10**(1), 1622, doi:10.1038/s41467-019-09506-1.
Ostrowski, A., R. M. Connolly and M. Sievers, 2021: Evaluating multiple stressor research in coastal wetlands: A systematic review. *Marine Environmental Research*, **164**, 105239, doi:10.1016/j.marenvres.2020.105239.
Otero, J. et al., 2014: Basin-scale phenology and effects of climate variability on global timing of initial seaward migration of Atlantic salmon (Salmo salar). *Global Change Biology*, **20**(1), 61-75, doi:10.1111/gcb.12363.
Ottosen, K. M., P. Steingrund, E. Magnussen and M. R. Payne, 2018: Distribution and timing of spawning Faroe Plateau cod in relation to warming spring temperatures. *Fisheries Research*, **198**, 14-23, doi:10.1016/j.fishres.2017.10.022.
Ouyang, X. and S. Y. Lee, 2020: Improved estimates on global carbon stock and carbon pools in tidal wetlands. *Nature Communications*, **11**(1), 317, doi:10.1038/s41467-019-14120-2.
Ouyang, X., S. Y. Lee, R. M. Connolly and M. J. Kainz, 2018: Spatially-explicit valuation of coastal wetlands for cyclone mitigation in Australia and China. *Scientific Reports*, **8**(1), 3035, doi:10.1038/s41598-018-21217-z.

Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071, doi:10.1016/j.gloenvcha.2020.102071.
Padilla-Gamiño, J. L., J. D. Gaitán-Espitia, M. W. Kelly and G. E. Hofmann, 2016: Physiological plasticity and local adaptation to elevated pCO_2 in calcareous algae: an ontogenetic and geographic approach. *Evolutionary Applications*, **9**(9), 1043-1053, doi:10.1111/eva.12411.
Paerl, H. W. et al., 2016: Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. *Harmful Algae*, **54**, 213-222, doi:10.1016/j.hal.2015.09.009.
Paerl, H. W., T. G. Otten and R. Kudela, 2018: Mitigating the Expansion of Harmful Algal Blooms Across the Freshwater-to-Marine Continuum. *Environmental Science & Technology*, **52**(10), 5519-5529, doi:10.1021/acs.est.7b05950.
Pal, J. S. and E. A. B. Eltahir, 2016: Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change*, **6**(2), 197-200, doi:10.1038/nclimate2833.
Paldor, A. and H. A. Michael, 2021: Storm Surges Cause Simultaneous Salinization and Freshening of Coastal Aquifers, Exacerbated by Climate Change. *Water Resources Research*, **57**(5), e2020WR029213, doi:10.1029/2020WR029213.
Palma, D. et al., 2019: Cruising the marginal ice zone: climate change and Arctic tourism. *Polar Geography*, **42**(4), 215-235, doi:10.1080/1088937X.2019.1648585.
Palomares, M. L. D. et al., 2020: Fishery biomass trends of exploited fish populations in marine ecoregions, climatic zones and ocean basins. *Estuarine, Coastal and Shelf Science*, **243**, 106896, doi:10.1016/j.ecss.2020.106896.
Palter, J. B., T. L. Frölicher, D. Paynter and J. G. John, 2018: Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5 K warming. *Earth Syst. Dynam.*, **9**(2), 817-828, doi:10.5194/esd-9-817-2018.
Palumbi, S. R., D. J. Barshis, N. Traylor-Knowles and R. A. Bay, 2014: Mechanisms of reef coral resistance to future climate change. *Science*, **344**(6186), 895-898, doi:10.1126/science.1251336.
Palutikof, J. P., R. B. Street and E. P. Gardiner, 2019: Decision support platforms for climate change adaptation: an overview and introduction. *Climatic Change*, **153**(4), 459-476, doi:10.1007/s10584-019-02445-2.
Panassa, E., C. Völker, D. Wolf-Gladrow and J. Hauck, 2018: Drivers of Interannual Variability of Summer Mixed Layer Depth in the Southern Ocean Between 2002 and 2011. *Journal of Geophysical Research: Oceans*, **123**(8), 5077-5090, doi:10.1029/2018JC013901.
Pandolfi, J. M., S. R. Connolly, D. J. Marshall and A. L. Cohen, 2011: Projecting coral reef futures under global warming and ocean acidification. *Science*, **333**(6041), 418-422, doi:10.1126/science.1204794.
Pandolfi, J. M. and W. Kiessling, 2014: Gaining insights from past reefs to inform understanding of coral reef response to global climate change. *Current Opinion in Environmental Sustainability*, **7**, 52-58, doi:10.1016/j.cosust.2013.11.020.
Papageorgiou, M., 2016: Coastal and marine tourism: a challenging factor in marine spatial planning. *Ocean & Coastal Management*, **129**, 44-48, doi:10.1016/j.ocecoaman.2016.05.006.
Pardo, J. C. F. and T. M. Costa, 2021: Multiple-stressor effects of warming and acidification on the embryonic development of an estuarine fiddler crab. *Estuarine, Coastal and Shelf Science*, **254**, 107296, doi:10.1016/j.ecss.2021.107296.
Parker, L. M. et al., 2017: Adult exposure to ocean acidification is maladaptive for larvae of the Sydney rock oyster *Saccostrea glomerata* in the presence of multiple stressors. *Biology Letters*, **13**(2), 20160798, doi:10.1098/rsbl.2016.0798.
Parker, L. M. et al., 2012: Adult exposure influences offspring response to ocean acidification in oysters. *Global Change Biology*, **18**(1), 82-92, doi:10.1111/j.1365-2486.2011.02520.x.
Parker, V. T. and K. E. Boyer, 2019: Sea-Level Rise and Climate Change Impacts on an Urbanized Pacific Coast Estuary. *Wetlands*, **39**(6), 1219-1232, doi:10.1007/s13157-017-0980-7.
Parmesan, C. et al., 2013: Beyond climate change attribution in conservation and ecological research. *Ecology Letters*, **16**(s1), 58-71, doi:10.1111/ele.12098.
Parreira, F. et al., 2021: Biodiversity consequences of Caulerpa prolifera takeover of a coastal lagoon. *Estuarine, Coastal and Shelf Science*, **255**, 107344, doi:10.1016/j.ecss.2021.107344.
Parsons, D. M. et al., 2020: An uncertain future: Effects of ocean acidification and elevated temperature on a New Zealand snapper (*Chrysophrys auratus*) population. *Marine Environmental Research*, **161**, 105089, doi:10.1016/j.marenvres.2020.105089.
Parsons, M., C. Brown, J. Nalau and K. Fisher, 2018: Assessing adaptive capacity and adaptation: insights from Samoan tourism operators. *Climate and Development*, **10**(7), 644-663, doi:10.1080/17565529.2017.1410082.
Parsons, M. and J. Nalau, 2019: Adaptation policy and planning in Pacific small island developing states. In: *Research Handbook on Climate Change Adaptation Policy*. Edward Elgar Publishing, Cheltenham, UK. ISBN 9781786432513.
Pathak, S., 2020: Marine bioprospecting: bioactive compounds from Cnidarians and Molluscs – a review. In: *Proceedings of the National Conference on Innovations in Biological Sciences (NCIBS)*, Saurashtra University, Gujarat, India, doi:10.2139/ssrn.3567752.
Patrício, A. R. et al., 2019: Climate change resilience of a globally important sea turtle nesting population. *Global Change Biology*, **25**(2), 522-535, doi:10.1111/gcb.14520.

Patton, A. K. et al., 2019: Finding eulachon: The use and cultural importance of *Thaleichthys pacificus* on the northern Northwest Coast of North America. *Journal of Archaeological Science: Reports*, **23**, 687-699, doi:10.1016/j.jasrep.2018.11.033.
Paula, J. R. et al., 2019: Neurobiological and behavioural responses of cleaning mutualisms to ocean warming and acidification. *Scientific Reports*, **9**(1), 12728, doi:10.1038/s41598-019-49086-0.
Pauls, S. U., C. Nowak, M. Bálint and M. Pfenninger, 2013: The impact of global climate change on genetic diversity within populations and species. *Molecular Ecology*, **22**(4), 925-946, doi:10.1111/mec.12152.
Pauly, D. and D. Zeller, 2016: Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature Communications*, **7**, 10244, doi:10.1038/ncomms10244.
Payne, M. R. et al., 2016: Uncertainties in projecting climate-change impacts in marine ecosystems. *ICES Journal of Marine Science*, **73**(5), 1272-1282, doi:10.1093/icesjms/fsv231.
Payne, M. R. et al., 2017: Lessons from the first generation of marine ecological forecast products. *Frontiers in Marine Science*, **4**, 289, doi:10.3389/fmars.2017.00289.
Peck, M. A. et al., 2018: Projecting changes in the distribution and productivity of living marine resources: A critical review of the suite of modelling approaches used in the large European project VECTORS. *Estuarine, Coastal and Shelf Science*, **201**, 40-55, doi:10.1016/j.ecss.2016.05.019.
Peck, M. A. and J. K. Pinnegar, 2018: Chapter 5: Climate change impacts, vulnerabilities and adaptations: North Atlantic and Atlantic Arctic marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 87-112. ISBN 9789251306079.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science*, **355**(6332), eaai9214, doi:10.1126/science.aai9214.
Pecuchet, L. et al., 2020a: Novel feeding interactions amplify the impact of species redistribution on an Arctic food web. *Global Change Biology*, **26**(9), 4894-4906, doi:10.1111/gcb.15196.
Pecuchet, L. et al., 2020b: Spatio-temporal dynamics of multi-trophic communities reveal ecosystem-wide functional reorganization. *Ecography*, **43**(2), 197-208, doi:10.1111/ecog.04643.
Pedersen, M. F. et al., 2021: Carbon sequestration potential increased by incomplete anaerobic decomposition of kelp detritus. *Marine Ecology Progress Series*, **660**, 53-67.
Peleg, O. et al., 2020: Tropicalization may invert trophic state and carbon budget of shallow temperate rocky reefs. *Journal of Ecology*, **108**(3), 844-854, doi:10.1111/1365-2745.13329.
Pelling, M. and M. Garschagen, 2019: Put equity first in climate adaptation. *Nature*, **569**, 327-329, doi:10.1038/d41586-019-01497-9.
Peñaherrera-Palma, C. et al., 2018: Evaluating abundance trends of iconic species using local ecological knowledge. *Biological Conservation*, **225**, 197-207, doi:10.1016/j.biocon.2018.07.004.
Penalba, M. et al., 2018: Wave energy resource variation off the west coast of Ireland and its impact on realistic wave energy converters' power absorption. *Applied Energy*, **224**, 205-219, doi:10.1016/j.apenergy.2018.04.121.
Pendleton, L. H. et al., 2018: Debating the effectiveness of marine protected areas. *ICES Journal of Marine Science*, **75**(3), 1156-1159, doi:10.1093/icesjms/fsx154.
Penman, D. E. et al., 2014: Rapid and sustained surface ocean acidification during the Paleocene-Eocene thermal maximum. *Paleoceanography and Paleoclimatology*, **29**(5), 357-369, doi:10.1002/2014pa002621.
Penn, J. L., C. Deutsch, J. L. Payne and E. A. Sperling, 2018: Temperature-dependent hypoxia explains biogeography and severity of end-Permian marine mass extinction. *Science*, **362**(6419), eaat1327, doi:10.1126/science.aat1327.
Perez, F. F. et al., 2018: Meridional overturning circulation conveys fast acidification to the deep Atlantic Ocean. *Nature*, **554**(7693), 515-518, doi:10.1038/nature25493.
Perez-Collazo, C., D. Greaves and G. Iglesias, 2018: A novel hybrid wind-wave energy converter for jacket-frame substructures. *Energies*, **11**(3), 637, doi:10.3390/en11030637.
Peristeraki, P. et al., 2019: Investigation of spatiotemporal patterns in mean temperature and mean trophic level of MEDITS survey catches in the Mediterranean Sea. *Scientia Marina*, **83**, 165-174, doi:10.3989/scimar.04835.12A.
Perry, C. T. and L. Alvarez-Filip, 2019: Changing geo-ecological functions of coral reefs in the Anthropocene. *Functional Ecology*, **33**(6), 976-988, doi:10.1111/1365-2435.13247.
Perry, C. T. et al., 2018: Loss of coral reef growth capacity to track future increases in sea level. *Nature*, **558**(7710), 396-400, doi:10.1038/s41586-018-0194-z.
Perry, C. T. and K. M. Morgan, 2017: Bleaching drives collapse in reef carbonate budgets and reef growth potential on southern Maldives reefs. *Scientific Reports*, **7**, 40581, doi:10.1038/srep40581.
Pespeni, M. H., F. Chan, B. A. Menge and S. R. Palumbi, 2013: Signs of Adaptation to Local pH Conditions across an Environmental Mosaic in the California Current Ecosystem. *Integrative and Comparative Biology*, **53**(5), 857-870, doi:10.1093/icb/ict094.
Peteet, D. M. et al., 2018: Sediment starvation destroys New York City marshes' resistance to sea level rise. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(41), 10281-10286, doi:10.1073/pnas.1715392115.
Pethybridge, H. R. et al., 2020: Contrasting Futures for Australia's Fisheries Stocks Under IPCC RCP8.5 Emissions – A Multi-Ecosystem Model Approach. *Frontiers in Marine Science*, **7**(846), doi:10.3389/fmars.2020.577964.

Petraitis, P. S. and S. R. Dudgeon, 2020: Declines over the last two decades of five intertidal invertebrate species in the western North Atlantic. *Communications Biology*, **3**(1), 591, doi:10.1038/s42003-020-01326-0.
Petrou, K. et al., 2019: Acidification diminishes diatom silica production in the Southern Ocean. *Nature Climate Change*, **9**(10), 781-786, doi:10.1038/s41558-019-0557-y.
Petzold, J. et al., 2020: Indigenous knowledge on climate change adaptation: a global evidence map of academic literature. *Environ.Res.Lett.*, **15**, 113007, doi:10.1088/1748-9326/abb330.
Petzold, J. and A. K. Magnan, 2019: Climate change: thinking small islands beyond Small Island Developing States (SIDS). *Climatic Change*, **152**(1), 145-165, doi:10.1007/s10584-018-2363-3.
Petzold, J. and B. M. W. Ratter, 2015: Climate change adaptation under a social capital approach – An analytical framework for small islands. *Ocean & Coastal Management*, **112**, 36-43, doi:10.1016/j.ocecoaman.2015.05.003.
Pfister, C. A., M. A. Altabet and B. L. Weigel, 2019: Kelp beds and their local effects on seawater chemistry, productivity, and microbial communities. *Ecology*, **100**(10), e02798, doi:10.1002/ecy.2798.
Pfister, C. A. et al., 2016: Historical baselines and the future of shell calcification for a foundation species in a changing ocean. *Proceedings of the Royal Society B: Biological Sciences*, **283**(1832), 20160392, doi:10.1098/rspb.2016.0392.
Pham, T. T. T., 2020: Tourism in marine protected areas: Can it be considered as an alternative livelihood for local communities? *Marine Policy*, **115**, 103891, doi:10.1016/j.marpol.2020.103891.
Phan, L., K. , J. van Thiel de Vries, S. M. and M. Stive, J. F. , 2015: Coastal mangrove squeeze in the Mekong Delta. *Journal of Coastal Research*, **31**(2), 233-243, doi:10.2112/JCOASTRES-D-14-00049.1.
Phinney, S. D., J. A. Wortman and D. Bibus, 2009: Oolichan grease: a unique marine lipid and dietary staple of the North Pacific coast. *Lipids*, **44**(1), 47-51, doi:10.1007/s11745-008-3243-9.
Phlips, E. J., S. Badylak, N. G. Nelson and K. E. Havens, 2020: Hurricanes, El Niño and harmful algal blooms in two sub-tropical Florida estuaries: Direct and indirect impacts. *Scientific Reports*, **10**(1), 1910, doi:10.1038/s41598-020-58771-4.
Phrampus, B. J. and M. J. Hornbach, 2012: Recent changes to the Gulf Stream causing widespread gas hydrate destabilization. *Nature*, **490**(7421), 527-530, doi:10.1038/nature11528.
Phrampus, B. J., M. J. Hornbach, C. D. Ruppel and P. E. Hart, 2014: Widespread gas hydrate instability on the upper U.S. Beaufort margin. *Journal of Geophysical Research: Solid Earth*, **119**(12), 8594-8609, doi:10.1002/2014JB011290.
Piatt, J. F. et al., 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. *PLOS ONE*, **15**(1), e0226087, doi:10.1371/journal.pone.0226087.
Picado, A. et al., 2014: Assessment of chlorophyll variability along the northwestern coast of Iberian Peninsula. *Journal of Sea Research*, **93**, 2-11, doi:10.1016/j.seares.2014.01.008.
Piggott, J. J., C. R. Townsend and C. D. Matthaei, 2015: Reconceptualizing synergism and antagonism among multiple stressors. *Ecology and Evolution*, **5**(7), 1538-1547, doi:10.1002/ece3.1465.
Piggott-McKellar, A. E., P. D. Nunn, K. E. McNamara and S. T. Sekinini, 2020: Dam(n) Seawalls: A Case of Climate Change Maladaptation in Fiji. In: *Managing Climate Change Adaptation in the Pacific Region* [Leal Filho, W. (ed.)]. Springer International Publishing, Cham, pp. 69-84. ISBN 978-3-030-40552-6.
Pike, D. A., 2013: Forecasting range expansion into ecological traps: climate-mediated shifts in sea turtle nesting beaches and human development. *Global Change Biology*, **19**(10), 3082-3092, doi:10.1111/gcb.12282.
Pimentel, M. S. et al., 2016: Foraging behaviour, swimming performance and malformations of early stages of commercially important fishes under ocean acidification and warming. *Climatic Change*, **137**(3), 495-509, doi:10.1007/s10584-016-1682-5.
Pimiento, C. et al., 2020: Functional diversity of marine megafauna in the Anthropocene. *Science Advances*, **6**(16), eaay7650, doi:10.1126/sciadv.aay7650.
Pinkerton, M. H. et al., 2021: Evidence for the Impact of Climate Change on Primary Producers in the Southern Ocean. *Front. ecol. evol.*, **9**(134), doi:10.3389/fevo.2021.592027.
Piñones, A. and A. V. Fedorov, 2016: Projected changes of Antarctic krill habitat by the end of the 21st century. *Geophysical Research Letters*, **43**(16), 8580-8589, doi:10.1002/2016GL069656.
Pinsky, M. L., 2021: Diversification spins a heatwave safety net for fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(3), e2024412118, doi:10.1073/pnas.2024412118.
Pinsky, M. L. et al., 2019: Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, **569**(7754), 108-111, doi:10.1038/s41586-019-1132-4.
Pinsky, M. L. et al., 2021: Fish and fisheries in hot water: What is happening and how do we adapt? *Population Ecology*, **63**(1), 17-26, doi:10.1002/1438-390X.12050.
Pinsky, M. L. and M. Fogarty, 2012: Lagged social-ecological responses to climate and range shifts in fisheries. *Climatic Change*, **115**(3), 883-891, doi:10.1007/s10584-012-0599-x.
Pinsky, M. L. et al., 2018: Preparing ocean governance for species on the move. *Science*, **360**(6394), 1189-1191, doi:10.1126/science.aat2360.
Pinsky, M. L., L. A. Rogers, J. W. Morley and T. L. Frölicher, 2020a: Ocean planning for species on the move provides substantial benefits and requires few trade-offs. *Science Advances*, **6**(50), eabb8428, doi:10.1126/sciadv.abb8428.

Pinsky, M. L., R. L. Selden and Z. J. Kitchel, 2020b: Climate-Driven Shifts in Marine Species Ranges: Scaling from Organisms to Communities. *Annual Review of Marine Science*, **12**(1), 153-179, doi:10.1146/annurev-marine-010419-010916.
Pinsky, M. L. et al., 2013: Marine taxa track local climate velocities. *Science*, **341**(6151), 1239-1242, doi:10.1126/science.1239352.
Pinto, C. A., T. M. Silveira and S. B. Teixeira, 2020: Beach nourishment practice in mainland Portugal (1950–2017): Overview and retrospective. *Ocean & Coastal Management*, **192**, 105211, doi:10.1016/j.ocecoaman.2020.105211.
Piroddi, C. et al., 2017: Historical changes of the Mediterranean Sea ecosystem: modelling the role and impact of primary productivity and fisheries changes over time. *Scientific Reports*, **7**, 44491, doi:10.1038/srep44491.
Pistevos, J. C. A., I. Nagelkerken, T. Rossi and S. D. Connell, 2017: Antagonistic effects of ocean acidification and warming on hunting sharks. *Oikos*, **126**(2), doi:10.1111/oik.03182.
Pistevos, J. C. A. et al., 2015: Ocean acidification and global warming impair shark hunting behaviour and growth. *Scientific Reports*, **5**(1), 16293, doi:10.1038/srep16293.
Pitois, S. G. and C. J. Fox, 2006: Long-term changes in zooplankton biomass concentration and mean size over the Northwest European shelf inferred from Continuous Plankton Recorder data. *ICES Journal of Marine Science*, **63**(5), 785-798, doi:10.1016/j.icesjms.2006.03.009.
Pitts, K. A., J. E. Campbell, J. Figueiredo and N. D. Fogarty, 2020: Ocean acidification partially mitigates the negative effects of warming on the recruitment of the coral, Orbicella faveolata. *Coral Reefs*, **39**(2), 281-292, doi:10.1007/s00338-019-01888-4.
Poloczanska, E. S., C. J. Limpus and G. C. Hays, 2009: Vulnerability of marine turtles to climate change. In: *Advances in Marine Biology* [Sims, D. W. (ed.)]. Academic Press, pp. 151-211. ISBN 9780080959672.
Pomeroy, A. W. M. et al., 2018: Spatial Variability of Sediment Transport Processes Over Intratidal and Subtidal Timescales Within a Fringing Coral Reef System. *Journal of Geophysical Research: Earth Surface*, **123**(5), 1013-1034, doi:10.1002/2017JF004468.
Porteus, C. S. et al., 2018: Near-future CO_2 levels impair the olfactory system of a marine fish. *Nature Climate Change*, **8**(8), 737-743, doi:10.1038/s41558-018-0224-8.
Pörtner, H.-O., C. Bock and F. C. Mark, 2017: Oxygen- and capacity-limited thermal tolerance: bridging ecology and physiology. *The Journal of Experimental Biology*, **220**(15), 2685-2696, doi:10.1242/jeb.134585.
Pörtner, H.-O. and J. Gutt, 2016: Impacts of climate variability and change on (marine) animals: physiological underpinnings and evolutionary consequences. *Integrative and Comparative Biology*, **56**(1), 31-44, doi:10.1093/icb/icw019.
Pörtner, H.-O. et al., 2014: Ocean systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484. ISBN 9781107058071.
Pörtner, H.-O., L. S. Peck and G. N. Somero, 2012: Mechanisms Defining Thermal Limits and Adaptation in Marine Ectotherms: An Integrative View. *Antarctic Ecosystems*, 379-416, doi:10.1002/9781444347241.ch13.
Pörtner, H.-O. et al., 2021a: *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change* [IPBES and IPCC (ed.)]. Available at: https://doi.org/10.5281/zenodo.4659159.
Pörtner, H. O. et al., 2021b: *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change* [IPBES and IPCC (ed.)]. Available at: https://zenodo.org/record/5101133#.YStZ_i1L1TY.
Pouso, S., Á. Borja, J. Martín and M. C. Uyarra, 2019: The capacity of estuary restoration to enhance ecosystem services: system dynamics modelling to simulate recreational fishing benefits. *Estuarine, Coastal and Shelf Science*, **217**, 226-236, doi:10.1016/j.ecss.2018.11.026.
Pouso, S., M. C. Uyarra and Á. Borja, 2018: The recovery of estuarine quality and the perceived increase of cultural ecosystem services by beach users: a case study from northern Spain. *Journal of Environmental Management*, **212**, 450-461, doi:10.1016/j.jenvman.2018.02.033.
Pozo Buil, M. et al., 2021: A Dynamically Downscaled Ensemble of Future Projections for the California Current System. *Frontiers in Marine Science*, **8**(324), doi:10.3389/fmars.2021.612874.
Prakash, A. et al., 2019: Cross-Chapter Box 3: Governance of the Ocean, Coasts and the Cryosphere under Climate Change. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Pranzini, E., 2018: Coastal erosion and shore protection: a brief historical analysis. *Journal of Coastal Conservation*, **22**(5), 827-830, doi:10.1007/s11852-017-0521-9.
Pranzini, E. et al., 2018: Shore protection structures increase and evolution on the northern Tuscany coast (Italy): influence of tourism industry. *Water*, **10**(11), 1647, doi:10.3390/w10111647.
Prasetyo, N., A. Carr and S. Filep, 2020: Indigenous Knowledge in Marine Ecotourism Development: The Case of Sasi Laut, Misool, Indonesia. *Tourism Planning & Development*, **17**(1), 46-61, doi:10.1080/21568316.2019.1604424.

Pratchett, M. S., S. F. Heron, C. Mellin and G. S. Cumming, 2021: Recurrent Mass-Bleaching and the Potential for Ecosystem Collapse on Australia's Great Barrier Reef. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 265-289. ISBN 978-3-030-71330-0.
Price, N. N. et al., 2019: Global biogeography of coral recruitment: tropical decline and subtropical increase. *Marine Ecology Progress Series*, **621**, 1-17, doi:10.3354/meps12980.
Przeslawski, R., M. Byrne and C. Mellin, 2015: A review and meta-analysis of the effects of multiple abiotic stressors on marine embryos and larvae. *Global Change Biology*, **21**(6), 2122-2140, doi:10.1111/gcb.12833.
Puerta, P. et al., 2020: Influence of Water Masses on the Biodiversity and Biogeography of Deep-Sea Benthic Ecosystems in the North Atlantic. *Frontiers in Marine Science*, **7**(239), doi:10.3389/fmars.2020.00239.
Punt, A. E., M. G. Dalton and R. J. Foy, 2020: Multispecies yield and profit when exploitation rates vary spatially including the impact on mortality of ocean acidification on North Pacific crab stocks. *Fisheries Research*, **225**, 105481, doi:10.1016/j.fishres.2019.105481.
Punt, A. E., D. Poljak, M. G. Dalton and R. J. Foy, 2014: Evaluating the impact of ocean acidification on fishery yields and profits: The example of red king crab in Bristol Bay. *Ecological Modelling*, **285**, 39-53, doi:10.1016/j.ecolmodel.2014.04.017.
Punt, A. E. et al., 2015: Effects of long-term exposure to ocean acidification conditions on future southern Tanner crab (*Chionoecetes bairdi*) fisheries management. *ICES Journal of Marine Science*, **73**(3), 849-864, doi:10.1093/icesjms/fsv205.
Punzón, A. et al., 2021: Tracking the effect of temperature in marine demersal fish communities. *Ecological Indicators*, **121**, 107142, doi:10.1016/j.ecolind.2020.107142.
Putnam, H. M. et al., 2020: Environmentally-induced parental or developmental conditioning influences coral offspring ecological performance. *Scientific Reports*, **10**(1), 13664, doi:10.1038/s41598-020-70605-x.
Qiu, Z. et al., 2019: Future climate change is predicted to affect the microbiome and condition of habitat-forming kelp. *Proceedings of the Royal Society B: Biological Sciences*, **286**(1896), 20181887, doi:10.1098/rspb.2018.1887.
Queirós, A. M. et al., 2016: Solutions for ecosystem-level protection of ocean systems under climate change. *Global Change Biology*, **22**(12), 3927-3936, doi:10.1111/gcb.13423.
Queirós, A. M. et al., 2019: Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. *Ecological Monographs*, **89**(3), e01366, doi:10.1002/ecm.1366.
Queste, B. Y., C. Vic, K. J. Heywood and S. A. Piontkovski, 2018: Physical Controls on Oxygen Distribution and Denitrification Potential in the North West Arabian Sea. *Geophysical Research Letters*, **45**(9), 4143-4152, doi:10.1029/2017GL076666.
Quevedo, J. M. D., Y. Uchiyama and R. Kohsaka, 2020: Perceptions of the seagrass ecosystems for the local communities of Eastern Samar, Philippines: Preliminary results and prospects of blue carbon services. *Ocean & Coastal Management*, **191**, 105181, doi:10.1016/j.ocecoaman.2020.105181.
Rabalais, N. N. and M. M. Baustian, 2020: Historical Shifts in Benthic Infaunal Diversity in the Northern Gulf of Mexico since the Appearance of Seasonally Severe Hypoxia. *Diversity*, **12**(2), doi:10.3390/d12020049.
Rabalais, N. N. et al., 2010: Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences*, **7**(2), 585-619, doi:10.5194/bg-7-585-2010.
Racault, M.-F., S. Sathyendranath, N. Menon and T. Platt, 2017: Phenological responses to ENSO in the global oceans. *Surveys in Geophysics*, **38**(1), 277-293, doi:10.1007/s10712-016-9391-1.
Rafaj, P., I. Bertok, J. Cofala and W. Schöpp, 2013: Scenarios of global mercury emissions from anthropogenic sources. *Atmospheric Environment*, **79**, 472-479, doi:10.1016/j.atmosenv.2013.06.042.
Rahman, M. M. et al., 2019: Salinization in large river deltas: Drivers, impacts and socio-hydrological feedbacks. *Water Security*, **6**, 100024, doi:10.1016/j.wasec.2019.100024.
Raja, N. B. and W. Kiessling, 2021: Out of the extratropics: the evolution of the latitudinal diversity gradient of Cenozoic marine plankton. *Proceedings of the Royal Society B: Biological Sciences*, **288**(1950), 20210545, doi:10.1098/rspb.2021.0545.
Rakib, M. A. et al., 2020: Groundwater salinization and associated co-contamination risk increase severe drinking water vulnerabilities in the southwestern coast of Bangladesh. *Chemosphere*, **246**, 125646, doi:10.1016/j.chemosphere.2019.125646.
Ramachandra, T. V. and D. Hebbale, 2020: Bioethanol from macroalgae: Prospects and challenges. *Renewable and Sustainable Energy Reviews*, **117**, 109479, doi:10.1016/j.rser.2019.109479.
Ramajo, L. et al., 2016: Food supply confers calcifiers resistance to ocean acidification. *Scientific Reports*, **6**(1), 19374, doi:10.1038/srep19374.
Ramajo, L. et al., 2020: Upwelling intensity modulates the fitness and physiological performance of coastal species: Implications for the aquaculture of the scallop Argopecten purpuratus in the Humboldt Current System. *Science of The Total Environment*, **745**, 140949, doi:10.1016/j.scitotenv.2020.140949.
Ramírez-Flandes, S., B. González and O. Ulloa, 2019: Redox traits characterize the organization of global microbial communities. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(9), 3630-3635, doi:10.1073/pnas.1817554116.
Ramp, C. et al., 2015: Adapting to a Warmer Ocean—Seasonal Shift of Baleen Whale Movements over Three Decades. *PLOS ONE*, **10**(3), e0121374, doi:10.1371/journal.pone.0121374.

Rasmussen, D. J. et al., 2020: Climate scientists may misrepresent future flood risks using popular extreme sea level metrics. *Earth and Space Science Open Archive*, Preprint, doi:10.1002/essoar.10503428.2.
Rassweiler, A., E. Ojea and C. Costello, 2020: Strategically designed marine reserve networks are robust to climate change driven shifts in population connectivity. *Environ.Res.Lett.*, **15**(3), 034030, doi:10.1088/1748-9326/ab6a25.
Ravanelli, R. et al., 2019: Sea level rise scenario for 2100 A.D. for the archaeological site of Motya. *Rendiconti Lincei. Scienze Fisiche e Naturali*, **30**(4), 747-757, doi:10.1007/s12210-019-00835-3.
Raventos, N. et al., 2021: Temperature reduces fish dispersal as larvae grow faster to their settlement size. *Journal of Animal Ecology*, **90**(6), 1419-1432, doi:10.1111/1365-2656.13435.
Raw, J. L., C. L. Julie and J. B. Adams, 2019: A comparison of soil carbon pools across a mangrove-salt marsh ecotone at the southern African warm-temperate range limit. *South African Journal of Botany*, **127**, 301-307, doi:10.1016/j.sajb.2019.11.005.
Raw, J. L. et al., 2020: Salt marsh elevation and responses to future sea-level rise in the Knysna Estuary, South Africa. *African Journal of Aquatic Science*, **45**(1-2), 49-64, doi:10.2989/16085914.2019.1662763.
Raymond-Yakoubian, J. and R. Daniel, 2018: An Indigenous approach to ocean planning and policy in the Bering Strait region of Alaska. *Marine Policy*, **97**, 101-108, doi:10.1016/j.marpol.2018.08.028.
Rech, S., S. Salmina, Y. J. Borrell Pichs and E. García-Vazquez, 2018: Dispersal of alien invasive species on anthropogenic litter from European mariculture areas. *Marine Pollution Bulletin*, **131**, 10-16, doi:10.1016/j.marpolbul.2018.03.038.
Record, N. R. et al., 2019: Rapid climate-driven circulation changes threaten conservation of endangered North Atlantic right whales. *Oceanography*, **32**(2), 162-169, doi:10.5670/oceanog.2019.201.
Reddin, C. J., Á. T. Kocsis and W. Kiessling, 2018: Marine invertebrate migrations trace climate change over 450 million years. *Global Ecology and Biogeography*, **27**(6), 704-713, doi:10.1111/geb.12732.
Reddin, C. J. et al., 2020: Marine clade sensitivities to climate change conform across timescales. *Nature Climate Change*, **10**(3), 249-253, doi:10.1038/s41558-020-0690-7.
Régnier, T., F. M. Gibb and P. J. Wright, 2019: Understanding temperature effects on recruitment in the context of trophic mismatch. *Scientific Reports*, **9**(1), 15179, doi:10.1038/s41598-019-51296-5.
Reguero, B. G. et al., 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLOS ONE*, **13**(4), e0192132, doi:10.1371/journal.pone.0192132.
Reguero, B. G. et al., 2020: Financing coastal resilience by combining nature-based risk reduction with insurance. *Ecological Economics*, **169**, 106487, doi:10.1016/j.ecolecon.2019.106487.
Reguero, B. G. et al., 2019: The Risk Reduction Benefits of the Mesoamerican Reef in Mexico. *Frontiers in Earth Science*, **7**(125), doi:10.3389/feart.2019.00125.
Reguero, B. G. et al., 2021: The value of US coral reefs for flood risk reduction. *Nature Sustainability*, doi:10.1038/s41893-021-00706-6.
Reimann, L. et al., 2018: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications*, **9**(1), 4161, doi:10.1038/s41467-018-06645-9.
Reimer, J. M., R. Devillers and J. Claudet, 2021: Benefits and gaps in area-based management tools for the ocean Sustainable Development Goal. *Nature Sustainability*, **4**(4), 349-357, doi:10.1038/s41893-020-00659-2.
Remengesau Jr., T. E., 2019: Presidential Directive No. 19-36: Choose Pelagics (passed 1 May 2019), Office of the President, Republic of Palau, Palau. Available at: https://www.palaugov.pw/wp-content/uploads/2019/05/Presidential-Directive-No.-19-36-re.-Choose-Pelagics.pdf (accessed 31/10/2020).
Renaud, P. E. et al., 2018: Pelagic food-webs in a changing Arctic: a trait-based perspective suggests a mode of resilience. *ICES Journal of Marine Science*, **75**(6), 1871-1881, doi:10.1093/icesjms/fsy063.
Renaud, P. E. et al., 2019: Arctic Sensitivity? Suitable Habitat for Benthic Taxa Is Surprisingly Robust to Climate Change. *Frontiers in Marine Science*, **6**(538), doi:10.3389/fmars.2019.00538.
Repolho, T. et al., 2017: Seagrass ecophysiological performance under ocean warming and acidification. *Scientific Reports*, **7**(1), 41443, doi:10.1038/srep41443.
Resplandy, L., L. Bopp, J. C. Orr and J. P. Dunne, 2013: Role of mode and intermediate waters in future ocean acidification: analysis of CMIP5 models. *Geophysical Research Letters*, **40**(12), 3091-3095, doi:10.1002/grl.50414.
Reum, J. C. P. et al., 2020: Ensemble Projections of Future Climate Change Impacts on the Eastern Bering Sea Food Web Using a Multispecies Size Spectrum Model. *Frontiers in Marine Science*, **7**(124), doi:10.3389/fmars.2020.00124.
Reuman, D. C., R. D. Holt and G. Yvon-Durocher, 2014: A metabolic perspective on competition and body size reductions with warming. *Journal of Animal Ecology*, **83**(1), 59-69, doi:10.1111/1365-2656.12064.
Reusch, T. B. H. et al., 2018: The Baltic Sea as a time machine for the future coastal ocean. *Science Advances*, **4**(5), eaar8195, doi:10.1126/sciadv.aar8195.
Reygondeau, G. et al., 2020: Climate Change-Induced Emergence of Novel Biogeochemical Provinces. *Frontiers in Marine Science*, **7**(657), doi:10.3389/fmars.2020.00657.
Reznik, A., Y. Jiang and A. Dinar, 2020: The Impacts of Climate Change on Wastewater Treatment Costs: Evidence from the Wastewater Sector in China. *Water*, **12**(11), doi:10.3390/w12113272.

Rheuban, J. E., S. C. Doney, S. R. Cooley and D. R. Hart, 2018: Projected impacts of future climate change, ocean acidification, and management on the US Atlantic sea scallop (Placopecten magellanicus) fishery. *PLOS ONE*, **13**(9), e0203536, doi:10.1371/journal.pone.0203536.
Rheuban, J. E., S. C. Doney, D. C. McCorkle and R. W. Jakuba, 2019: Quantifying the Effects of Nutrient Enrichment and Freshwater Mixing on Coastal Ocean Acidification. *Journal of Geophysical Research: Oceans*, **124**(12), 9085-9100, doi:10.1029/2019JC015556.
Richards, D. R., B. S. Thompson and L. Wijedasa, 2020: Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change. *Nature Communications*, **11**(1), 4260, doi:10.1038/s41467-020-18118-z.
Richardson, L. E., N. A. J. Graham and A. S. Hoey, 2020: Coral species composition drives key ecosystem function on coral reefs. *Proceedings of the Royal Society B: Biological Sciences*, **287**(1921), 20192214, doi:10.1098/rspb.2019.2214.
Richardson, L. E. et al., 2018: Mass coral bleaching causes biotic homogenization of reef fish assemblages. *Global Change Biology*, **24**(7), 3117-3129, doi:10.1111/gcb.14119.
Riebesell, U. et al., 2018: Toxic algal bloom induced by ocean acidification disrupts the pelagic food web. *Nature Climate Change*, **8**(12), 1082-1086, doi:10.1038/s41558-018-0344-1.
Riebesell, U. and J.-P. Gattuso, 2014: Lessons learned from ocean acidification research. *Nature Climate Change*, **5**, 12-14, doi:10.1038/nclimate2456.
Riebesell, U. et al., 2000: Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature*, **407**(6802), 364-367, doi:10.1038/35030078.
Righetti, D. et al., 2019: Global pattern of phytoplankton diversity driven by temperature and environmental variability. *Science Advances*, **5**(5), eaau6253, doi:10.1126/sciadv.aau6253.
Rilov, G. et al., 2020: A fast-moving target: achieving marine conservation goals under shifting climate and policies. *Ecological Applications*, **30**(1), e02009, doi:10.1002/eap.2009.
Rilov, G. et al., 2019: Adaptive marine conservation planning in the face of climate change: What can we learn from physiological, ecological and genetic studies? *Global Ecology and Conservation*, **17**, e00566, doi:10.1016/j.gecco.2019.e00566.
Rinkevich, B., 2021: Augmenting coral adaptation to climate change via coral gardening (the nursery phase). *Journal of Environmental Management*, **291**, 112727, doi:10.1016/j.jenvman.2021.112727.
Ritphring, S., C. Somphong, K. Udo and S. Kazama, 2018: Projections of future beach loss due to sea level rise for sandy beaches along Thailand's coastlines. *Journal of Coastal Research*, **85**(SI), 541-545, doi:10.2112/SI85-109.1.
Ritzman, J. et al., 2018: Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae*, **80**, 35-45, doi:10.1016/j.hal.2018.09.002.
Rivas, M. L., N. Esteban and A. Marco, 2019: Potential male leatherback hatchlings exhibit higher fitness which might balance sea turtle sex ratios in the face of climate change. *Climatic Change*, **156**(1), 1-14, doi:10.1007/s10584-019-02462-1.
Rivera-Collazo, I. C., 2020: Severe Weather and the Reliability of Desk-Based Vulnerability Assessments: The Impact of Hurricane Maria to Puerto Rico's Coastal Archaeology. *The Journal of Island and Coastal Archaeology*, **15**(2), 244-263, doi:10.1080/15564894.2019.1570987.
Rivest, E. B., S. Comeau and C. E. Cornwall, 2017: The role of natural variability in shaping the response of coral reef organisms to climate change. *Current Climate Change Reports*, **3**(4), 271-281, doi:10.1007/s40641-017-0082-x.
Roach, L. A. et al., 2020: Antarctic Sea Ice Area in CMIP6. *Geophysical Research Letters*, **47**(9), e2019GL086729, doi:10.1029/2019GL086729.
Roberts, C. M., B. C. O'Leary and J. P. Hawkins, 2020: Climate change mitigation and nature conservation both require higher protected area targets. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190121, doi:10.1098/rstb.2019.0121.
Roberts, C. M. et al., 2017: Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(24), 6167-6175, doi:10.1073/pnas.1701262114.
Roberts, S. D. et al., 2019: Marine Heatwave, Harmful Algae Blooms and an Extensive Fish Kill Event During 2013 in South Australia. *Frontiers in Marine Science*, **6**, 610, doi:10.3389/fmars.2019.00610.
Robinson, J. P. W. et al., 2020: Diversification insulates fisher catch and revenue in heavily exploited tropical fisheries. *Science Advances*, **6**(8), eaaz0587, doi:10.1126/sciadv.aaz0587.
Robinson, J. P. W., S. K. Wilson, S. Jennings and N. A. J. Graham, 2019a: Thermal stress induces persistently altered coral reef fish assemblages. *Global Change Biology*, **25**(8), 2739-2750, doi:10.1111/gcb.14704.
Robinson, J. P. W. et al., 2019b: Productive instability of coral reef fisheries after climate-driven regime shifts. *Nature Ecology & Evolution*, **3**(2), 183-190, doi:10.1038/s41559-018-0715-z.
Rocha, J. et al., 2015: Marine regime shifts: drivers and impacts on ecosystems services. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**(1659), 20130273, doi:10.1098/rstb.2013.0273.
Rocha, J. C., G. Peterson, Ö. Bodin and S. Levin, 2018a: Cascading regime shifts within and across scales. *Science*, **362**(6421), 1379-1383, doi:10.1126/science.aat7850.

Rocha, L. A. et al., 2018b: Mesophotic coral ecosystems are threatened and ecologically distinct from shallow water reefs. *Science*, **361**(6399), 281-284, doi:10.1126/science.aaq1614.
Rodrigues, M., A. B. Fortunato and P. Freire, 2019: Saltwater Intrusion in the Upper Tagus Estuary during Droughts. *Geosciences*, **9**(9), doi:10.3390/geosciences9090400.
Rodríguez, F. et al., 2017: "Canary Islands (NE Atlantic) as a biodiversity 'hotspot' of Gambierdiscus: Implications for future trends of ciguatera in the area". *Harmful Algae*, **67**, 131-143, doi:10.1016/j.hal.2017.06.009.
Rodríguez-Romero, A. et al., 2016: Multi-generational responses of a marine polychaete to a rapid change in seawater *p*CO_2. *Evolutionary Applications*, **9**(9), 1082-1095, doi:10.1111/eva.12344.
Rogers, A. D., 2015: Environmental change in the deep ocean. *Annual Review of Environment and Resources*, **40**(1), 1-38, doi:10.1146/annurev-environ-102014-021415.
Rogers, A. D. et al., 2020: Antarctic Futures: An Assessment of Climate-Driven Changes in Ecosystem Structure, Function, and Service Provisioning in the Southern Ocean. *Annual Review of Marine Science*, **12**(1), 87-120, doi:10.1146/annurev-marine-010419-011028.
Rogers, K., 2021: Accommodation space as a framework for assessing the response of mangroves to relative sea-level rise. *Singapore Journal of Tropical Geography*, **42**(2), 163-183, doi:10.1111/sjtg.12357.
Rogers, K. et al., 2019: Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. *Nature*, **567**(7746), 91-95, doi:10.1038/s41586-019-0951-7.
Rogers, K. and K. W. Krauss, 2018: Moving from generalisations to specificity about mangrove –saltmarsh dynamics. *Wetlands*, 1-24, doi:10.1007/s13157-018-1067-9.
Rogers, L. A. and A. B. Dougherty, 2019: Effects of climate and demography on reproductive phenology of a harvested marine fish population. *Global Change Biology*, **25**(2), 708-720, doi:10.1111/gcb.14483.
Rogers-Bennett, L. and C. A. Catton, 2019: Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, **9**(1), 15050, doi:10.1038/s41598-019-51114-y.
Roggatz, C. C., M. Lorch, J. D. Hardege and D. M. Benoit, 2016: Ocean acidification affects marine chemical communication by changing structure and function of peptide signalling molecules. *Global Change Biology*, **22**(12), 3914-3926, doi:10.1111/gcb.13354.
Rohmer, J., G. Le Cozannet and J.-C. Manceau, 2019: Addressing ambiguity in probabilistic assessments of future coastal flooding using possibility distributions. *Climatic Change*, **155**(1), 95-109, doi:10.1007/s10584-019-02443-4.
Rohmer, J. et al., 2021: Unravelling the Importance of Uncertainties in Global-Scale Coastal Flood Risk Assessments under Sea Level Rise. *Water*, **13**(6), doi:10.3390/w13060774.
Rokitta, S. D. and B. Rost, 2012: Effects of CO_2 and their modulation by light in the life-cycle stages of the coccolithophore *Emiliania huxleyi*. *Limnology and Oceanography*, **57**(2), 607-618, doi:10.4319/lo.2012.57.2.0607.
Roman, M. R., S. B. Brandt, E. D. Houde and J. J. Pierson, 2019: Interactive Effects of Hypoxia and Temperature on Coastal Pelagic Zooplankton and Fish. *Frontiers in Marine Science*, **6**, 139, doi:10.3389/fmars.2019.00139.
Romañach, S. S. et al., 2018: Conservation and restoration of mangroves: global status, perspectives, and prognosis. *Ocean & Coastal Management*, **154**, 72-82, doi:10.1016/j.ocecoaman.2018.01.009.
Romero-Lankao, P. et al., 2014: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439-1498.
Ropert-Coudert, Y. et al., 2019: Happy feet in a hostile world? The future of penguins depends on proactive management of current and expected threats. *Frontiers in Marine Science*, **6**, 248, doi:10.3389/fmars.2019.00248.
Rosa, I. M. D. et al., 2020: Challenges in producing policy-relevant global scenarios of biodiversity and ecosystem services. *Global Ecology and Conservation*, **22**, e00886, doi:10.1016/j.gecco.2019.e00886.
Rosa, R. et al., 2013: Lower hypoxia thresholds of cuttlefish early life stages living in a warm acidified ocean. *Proceedings of the Royal Society B: Biological Sciences*, **280**(1768), 20131695, doi:10.1098/rspb.2013.1695.
Rose, K. A. et al., 2019: Impacts of ocean deoxygenation on fisheries. In: *Ocean deoxygenation: Everyone's problem. Causes, impacts, consequences and solutions*. International Union for Conservation of Nature and Natural Resources, Gland, Switzerland, pp. 519-544. ISBN 978-2-8317-2013-5.
Rosencranz, J. A. et al., 2018: Sea-level rise, habitat loss, and potential extirpation of a salt marsh specialist bird in urbanized landscapes. *Ecology and Evolution*, **8**(16), 8115-8125, doi:10.1002/ece3.4196.
Rosendo, S., L. Celliers and M. Mechisso, 2018: Doing more with the same: A reality-check on the ability of local government to implement Integrated Coastal Management for climate change adaptation. *Marine Policy*, **87**, 29-39, doi:10.1016/j.marpol.2017.10.001.
Ross, H., D. S. Adhuri, A. Y. Abdurrahim and A. Phelan, 2019: Opportunities in community-government cooperation to maintain marine ecosystem services in the Asia-Pacific and Oceania. *Ecosystem Services*, **38**, 100969, doi:10.1016/j.ecoser.2019.100969.
Ross, T., C. Du Preez and D. Ianson, 2020: Rapid deep ocean deoxygenation and acidification threaten life on Northeast Pacific seamounts. *Global Change Biology*, **26**(11), 6424-6444, doi:10.1111/gcb.15307.

Rossi, T., J. C. A. Pistevos, S. D. Connell and I. Nagelkerken, 2018: On the wrong track: ocean acidification attracts larval fish to irrelevant environmental cues. *Scientific Reports*, **8**(1), 5840, doi:10.1038/s41598-018-24026-6.
Roy, J. et al., 2018: Sustainable development, poverty eradication and reducing inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.
Rubenstein, M. A., R. Christophersen and J. I. Ransom, 2019: Trophic implications of a phenological paradigm shift: bald eagles and salmon in a changing climate. *Journal of Applied Ecology*, **56**(3), 769-778, doi:10.1111/1365-2664.13286.
Ruby, P. and B. Ahilan, 2018: An overview of climate change impact in fisheries and aquaculture. *Climate Change*, **4**(13), 87-94.
Ruiz-Ramírez, J. D., J. I. Euán-Ávila and V. H. Rivera-Monroy, 2019: Vulnerability of coastal resort cities to mean sea level rise in the Mexican Caribbean. *Coast. Manage.*, **47**(1), 23-43, doi:10.1080/08920753.2019.1525260.
Rumore, D., T. Schenk and L. Susskind, 2016: Role-play simulations for climate change adaptation education and engagement. *Nature Climate Change*, **6**(8), 745-750, doi:10.1038/nclimate3084.
Rusu, E. and F. Onea, 2018: A review of the technologies for wave energy extraction. *Clean Energy*, **2**(1), 10-19, doi:10.1093/ce/zky003.
Ruthrof, K. X. et al., 2021: Extreme Events Trigger Terrestrial and Marine Ecosystem Collapses in the Southwestern USA and Southwestern Australia. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 187-217. ISBN 978-3-030-71330-0.
Rykaczewski, R. R. et al., 2015: Poleward displacement of coastal upwelling-favorable winds through the 21st century. *Geophysical Research Letters*, **42**, 6424-6431, doi:10.1002/2015GL064694.
Saba, V. S. et al., 2012: Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, **2**(11), 814-820, doi:10.1038/nclimate1582.
Sachs, J. D. et al., 2019: Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability*, **2**(9), 805-814, doi:10.1038/s41893-019-0352-9.
Sadykova, D. et al., 2020: Ecological costs of climate change on marine predator–prey population distributions by 2050. *Ecology and Evolution*, **10**(2), 1069-1086, doi:10.1002/ece3.5973.
Saifuddin, M. and A. N. Boyce, 2017: Biodiesel production from fish (Cyprinus carpio) waste and evaluation of engine performance. *Sains Malaysiana*, **46**(10), 1771-1778, doi:10.17576/jsm-2017-4610-14.
Saintilan, N. et al., 2020: Thresholds of mangrove survival under rapid sea level rise. *Science*, **368**(6495), 1118, doi:10.1126/science.aba2656.
Saintilan, N. et al., 2018: Climate change impacts on the coastal wetlands of Australia. *Wetlands*, 1-10, doi:10.1007/s13157-018-1016-7.
Sainz, J. F. et al., 2019: Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in Southern California. *Frontiers in Marine Science*, **6**(253), doi:10.3389/fmars.2019.00253.
Sakthivel, R., K. Ramesh, R. Purnachandran and P. Mohamed Shameer, 2018: A review on the properties, performance and emission aspects of the third generation biodiesels. *Renewable and Sustainable Energy Reviews*, **82**, 2970-2992, doi:10.1016/j.rser.2017.10.037.
Sala, E. and S. Giakoumi, 2017: No-take marine reserves are the most effective protected areas in the ocean. *ICES Journal of Marine Science*, **75**(3), 1166-1168, doi:10.1093/icesjms/fsx059.
Sala, E. et al., 2021: Protecting the global ocean for biodiversity, food and climate. *Nature*, **592**(7854), 397-402, doi:10.1038/s41586-021-03371-z.
Salgado-Hernanz, P. M., M.-F. Racault, J. S. Font-Muñoz and G. Basterretxea, 2019: Trends in phytoplankton phenology in the Mediterranean Sea based on ocean-colour remote sensing. *Remote Sensing of Environment*, **221**, 50-64, doi:10.1016/j.rse.2018.10.036.
Sallée, J.-B. et al., 2021: Summertime increases in upper-ocean stratification and mixed-layer depth. *Nature*, **591**(7851), 592-598, doi:10.1038/s41586-021-03303-x.
Salvadeo, C. J. et al., 2010: Climate change and a poleward shift in the distribution of the Pacific white-sided dolphin in the northeastern Pacific. *Endangered Species Research*, **11**(1), 13-19.
Sampaio, E. et al., 2021: Impacts of hypoxic events surpass those of future ocean warming and acidification. *Nature Ecology & Evolution*, **5**(3), 311-321, doi:10.1038/s41559-020-01370-3.
Sanborn, K. L. et al., 2017: New evidence of Hawaiian coral reef drowning in response to meltwater pulse-1A. *Quat. Sci. Rev.*, **175**, 60-72, doi:10.1016/j.quascirev.2017.08.022.
Sanderson, C. E. and K. A. Alexander, 2020: Unchartered waters: Climate change likely to intensify infectious disease outbreaks causing mass mortality events in marine mammals. *Global Change Biology*, **26**(8), 4284-4301, doi:10.1111/gcb.15163.
Sandø, A. B. et al., 2021: Barents Sea plankton production and controlling factors in a fluctuating climate. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsab067.

Sandoval-Castillo, J. et al., 2020: Adaptation of plasticity to projected maximum temperatures and across climatically defined bioregions. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(29), 17112, doi:10.1073/pnas.1921124117.
Sanford, E. et al., 2019: Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. *Scientific Reports*, **9**(1), 4216, doi:10.1038/s41598-019-40784-3.
Sangha, K. K., N. Stoeckl, N. Crossman and R. Costanza, 2019: A state-wide economic assessment of coastal and marine ecosystem services to inform sustainable development policies in the Northern Territory, Australia. *Marine Policy*, **107**, 103595, doi:10.1016/j.marpol.2019.103595.
Santa Cruz, F., B. Ernst, J. A. Arata and C. Parada, 2018: Spatial and temporal dynamics of the Antarctic krill fishery in fishing hotspots in the Bransfield Strait and South Shetland Islands. *Fisheries Research*, **208**, 157-166, doi:10.1016/j.fishres.2018.07.020.
Santidrián Tomillo, P. et al., 2020: The impacts of extreme El Niño events on sea turtle nesting populations. *Climatic Change*, **159**(2), 163-176, doi:10.1007/s10584-020-02658-w.
Santora, J. A. et al., 2020: Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications*, **11**(1), 536, doi:10.1038/s41467-019-14215-w.
Santos, K. C., M. Livesey, M. Fish and A. C. Lorences, 2017: Climate change implications for the nest site selection process and subsequent hatching success of a green turtle population. *Mitigation and Adaptation Strategies for Global Change*, **22**(1), 121-135, doi:10.1007/s11027-015-9668-6.
Santos-Lacueva, R., S. Anton Clavé and Ò. Saladié, 2017: The vulnerability of coastal tourism destinations to climate change: the usefulness of policy analysis. *Sustainability*, **9**(11), 2062, doi:10.3390/su9112062.
Saprykina, Y. and S. Kuznetsov, 2018: Analysis of the variability of wave energy due to climate changes on the example of the Black Sea. *Energies*, **11**(8), 2020, doi:10.3390/en11082020.
Saraiva, S. et al., 2019: Baltic Sea ecosystem response to various nutrient load scenarios in present and future climates. *Climate Dynamics*, **52**(5), 3369-3387, doi:10.1007/s00382-018-4330-0.
Sasmito, S. D. et al., 2019: Effect of land-use and land-cover change on mangrove blue carbon: A systematic review. *Global Change Biology*, **25**(12), 4291-4302, doi:10.1111/gcb.14774.
Sauve, D., G. Divoky and V. L. Friesen, 2019: Phenotypic plasticity or evolutionary change? An examination of the phenological response of an arctic seabird to climate change. *Functional Ecology*, **33**(11), 2180-2190, doi:10.1111/1365-2435.13406.
Savva, I. et al., 2018: Thermal tolerance of Mediterranean marine macrophytes: vulnerability to global warming. *Ecology and Evolution*, **8**(23), 12032-12043, doi:10.1002/ece3.4663.
Scalpone, C. R. et al., 2020: Simulated Estuary-Wide Response of Seagrass (Zostera marina) to Future Scenarios of Temperature and Sea Level. *Frontiers in Marine Science*, **7**(873), doi:10.3389/fmars.2020.539946.
Scanes, E., P. R. Scanes and P. M. Ross, 2020a: Climate change rapidly warms and acidifies Australian estuaries. *Nature Communications*, **11**(1), 1803, doi:10.1038/s41467-020-15550-z.
Scanes, P. R., A. Ferguson and J. Potts, 2020b: Catastrophic events and estuarine connectivity influence presence of aquatic macrophytes and trophic status of intermittently-open coastal lagoons in eastern Australia. *Estuarine, Coastal and Shelf Science*, **238**, 106732, doi:10.1016/j.ecss.2020.106732.
Scanlon, N. L., 2019: Miami, Florida: a destination study of climate change impacts on tourism. In: *9th Advances in Hospitality and Tourism Marketing and Management Conference*, Portsmouth, United Kingdom, [Ekinci, Y., L. Sharples, G. Viglia and D. Gursoy (eds.)], pp. 160-170.
Scharfe, M. and K. H. Wiltshire, 2019: Modeling of intra-annual abundance distributions: Constancy and variation in the phenology of marine phytoplankton species over five decades at Helgoland Roads (North Sea). *Ecological Modelling*, **404**, 46-60, doi:10.1016/j.ecolmodel.2019.01.001.
Schartup, A. T. et al., 2019: Climate change and overfishing increase neurotoxicant in marine predators. *Nature*, **572**(7771), 648-650, doi:10.1038/s41586-019-1468-9.
Schaum, C. E., B. Rost and S. Collins, 2016: Environmental stability affects phenotypic evolution in a globally distributed marine picoplankton. *The ISME Journal*, **10**(1), 75-84, doi:10.1038/ismej.2015.102.
Scheffer, M. et al., 2012: Anticipating critical transitions. *Science*, **338**(6105), 344-348, doi:10.1126/science.1225244.
Scheffers, B. R. and G. Pecl, 2019: Persecuting, protecting or ignoring biodiversity under climate change. *Nature Climate Change*, **9**(8), 581-586, doi:10.1038/s41558-019-0526-5.
Schepers, L., M. Kirwan, G. Guntenspergen and S. Temmerman, 2017: Spatio-temporal development of vegetation die-off in a submerging coastal marsh. *Limnology and Oceanography*, **62**(1), 137-150, doi:10.1002/lno.10381.
Schiebelhut, L. M., J. B. Puritz and M. N. Dawson, 2018: Decimation by sea star wasting disease and rapid genetic change in a keystone species, Pisaster ochraceus. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(27), 7069-7074, doi:10.1073/pnas.1800285115.
Schiel, D. R. and M. S. Foster, 2015: *The Biology and Ecology of Giant Kelp Forests*, 1st ed., University of California Press, Berkeley, CA, USA, 416 pp. ISBN 9780520278868.
Schiffer, M. et al., 2014: Temperature tolerance of different larval stages of the spider crab *Hyas araneus* exposed to elevated seawater pCO_2. *Frontiers in Zoology*, **11**(1), 87, doi:10.1186/s12983-014-0087-4.
Schilling, H. T. et al., 2020: Multiple spawning events promote increased larval dispersal of a predatory fish in a western boundary current. *Fisheries Oceanography*, **29**(4), 309-323, doi:10.1111/fog.12473.

Schipper, E. L. F., 2020: Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, **3**(4), 409-414, doi:10.1016/j.oneear.2020.09.014.
Schlingmann, A. et al., 2021: Global patterns of adaptation to climate change by Indigenous Peoples and local communities. A systematic review. *Current Opinion in Environmental Sustainability*, **51**, 55-64, doi:10.1016/j.cosust.2021.03.002.
Schlunegger, S. et al., 2019: Emergence of anthropogenic signals in the ocean carbon cycle. *Nature Climate Change*, **9**(9), 719-725, doi:10.1038/s41558-019-0553-2.
Schlunegger, S. et al., 2020: Time of Emergence and Large Ensemble Intercomparison for Ocean Biogeochemical Trends. *Global Biogeochemical Cycles*, **34**(8), e2019GB006453, doi:10.1029/2019GB006453.
Schmidt, K. et al., 2020: Increasing picocyanobacteria success in shelf waters contributes to long-term food web degradation. *Global Change Biology*, **26**(10), 5574-5587, doi:10.1111/gcb.15161.
Schmidt, M. et al., 2017: Impact of ocean warming and acidification on the behaviour of two co-occurring gadid species, *Boreogadus saida* and *Gadus morhua*, from Svalbard. *Marine Ecology Progress Series*, **571**, 183-191, doi:10.3354/meps12130.
Schmidtko, S., L. Stramma and M. Visbeck, 2017: Decline in global oceanic oxygen content during the past five decades. *Nature*, **542**(7641), 335-339, doi:10.1038/nature21399.
Schoepf, V. et al., 2020: Thermally variable, macrotidal reef habitats promote rapid recovery from mass coral bleaching. *Frontiers in Marine Science*, **7**(245), doi:10.3389/fmars.2020.00245.
Schönberg, C. H. L. et al., 2017: Bioerosion: the other ocean acidification problem. *ICES Journal of Marine Science*, **74**(4), 895-925, doi:10.1093/icesjms/fsw254.
Schoutens, K. et al., 2020: Nature-based shoreline protection by tidal marsh plants depends on trade-offs between avoidance and attenuation of hydrodynamic forces. *Estuarine, Coastal and Shelf Science*, **236**, 106645, doi:10.1016/j.ecss.2020.106645.
Schuerch, M., T. Spencer and B. Evans, 2019: Coupling between tidal mudflats and salt marshes affects marsh morphology. *Marine Geology*, **412**, 95-106, doi:10.1016/j.margeo.2019.03.008.
Schuerch, M. et al., 2018: Future response of global coastal wetlands to sea-level rise. *Nature*, **561**(7722), 231-234, doi:10.1038/s41586-018-0476-5.
Schultz, J. A., R. N. Cloutier and I. M. Côté, 2016: Evidence for a trophic cascade on rocky reefs following sea star mass mortality in British Columbia. *PeerJ*, **4**, e1980, doi:10.7717/peerj.1980.
Schwaner, C. et al., 2020: Experimental acidification increases susceptibility of Mercenaria mercenaria to infection by Vibrio species. *Marine Environmental Research*, **154**, 104872, doi:10.1016/j.marenvres.2019.104872.
Schwieterman, D. G. et al., 2019: Combined effects of acute temperature change and elevated pCO_2 on the metabolic rates and hypoxia tolerances of clearnose skate (*Rostaraja eglanteria*), summer flounder (*Paralichthys dentatus*), and thorny skate (*Amblyraja radiata*). *Biology*, **8**(3), 56, doi:10.3390/biology8030056.
Sciandra, A. et al., 2003: Response of coccolithophorid *Emiliania huxleyi* to elevated partial pressure of CO_2 under nitrogen limitation. *Marine Ecology Progress Series*, **261**, 111-122, doi:10.3354/meps261111.
Scobie, M., 2018: Accountability in climate change governance and Caribbean SIDS. *Environment, Development and Sustainability*, **20**(2), 769-787, doi:10.1007/s10668-017-9909-9.
Scobie, M., 2019a: Climate change, human rights, and migration. In: *Emerging threats to human rights: resources, violence, and deprivation of citizenship* [Smith-Cannoy, H. (ed.)]. Temple University Press, USA.
Scobie, M., 2019b: Global marine and ocean governance, and Caribbean SIDS. In: *Global Environmental Governance and Small States: Architectures and Agency in the Caribbean*. Edward Elgar Publishing, Cheltenham, UK, pp. 90-117. ISBN 9781786437266.
Scott, F. et al., 2020: Hydro-morphological characterization of coral reefs for wave runup prediction. *Frontiers in Marine Science*, **7**(361), doi:10.3389/fmars.2020.00361.
Scott, M. E. et al., 2019: Latitudinal and seasonal variation in space use by a large, predatory reef fish, *Plectropomus leopardus*. *Functional Ecology*, **33**(4), 670-680, doi:10.1111/1365-2435.13271.
Seabra, R. et al., 2019: Reduced nearshore warming associated with eastern boundary upwelling systems. *Frontiers in Marine Science*, **6**, 104, doi:10.3389/fmars.2019.00104.
Secretariat of the Convention on Biological Diversity, 2009: *Connecting biodiversity and climate change mitigation and adaptation: report of the second ad hoc technical expert group on biodiversity and climate change*. Technical Series No. 41, Secretariat of the Convention on Biological Diversity, 126 pp pp. Available at: https://www.cbd.int/doc/publications/cbd-ts-41-en.pdf.
Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190120, doi:10.1098/rstb.2019.0120.
Seddon, N. et al., 2021: Getting the message right on nature-based solutions to climate change. *Global Change Biology*, **27**(8), 1518-1546, doi:10.1111/gcb.15513.
Séférian, R. et al., 2020: Tracking Improvement in Simulated Marine Biogeochemistry Between CMIP5 and CMIP6. *Current Climate Change Reports*, **6**(3), 95-119, doi:10.1007/s40641-020-00160-0.
Seifert, M., B. Rost, S. Trimborn and J. Hauck, 2020: Meta-analysis of multiple driver effects on marine phytoplankton highlights modulating role of pCO_2. *Global Change Biology*, doi:10.1111/gcb.15341.

Selden, R. L., R. D. Batt, V. S. Saba and M. L. Pinsky, 2018: Diversity in thermal affinity among key piscivores buffers impacts of ocean warming on predator–prey interactions. *Global Change Biology*, **24**(1), 117-131, doi:10.1111/gcb.13838.

Selig, E. R. et al., 2019: Mapping global human dependence on marine ecosystems. *Conservation Letters*, **12**(2), e12617, doi:10.1111/conl.12617.

Semenza, J. C., 2020: Cascading risks of waterborne diseases from climate change. *Nature Immunology*, **21**(5), 484-487, doi:10.1038/s41590-020-0631-7.

Semenza, J. C. et al., 2017: Environmental suitability of *Vibrio* infections in a warming climate: an early warning system. *Environmental Health Perspectives*, **125**(10), 107004, doi:10.1289/EHP2198.

Semiletov, I. et al., 2016: Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon. *Nature Geoscience*, **9**(5), 361-365, doi:10.1038/ngeo2695.

Sen Gupta, A. et al., 2020: Drivers and impacts of the most extreme marine heatwave events. *Scientific Reports*, **10**(1), 19359, doi:10.1038/s41598-020-75445-3.

Seo, H. et al., 2012: What determines the spatial pattern in summer upwelling trends on the U.S. West Coast? *Journal of Geophysical Research: Oceans*, **117**(C8), doi:10.1029/2012JC008016.

Serrano, O. et al., 2021: Impact of Marine Heatwaves on Seagrass Ecosystems. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 345-364. ISBN 978-3-030-71330-0.

Sett, S. et al., 2014: Temperature modulates coccolithophorid sensitivity of growth, photosynthesis and calcification to Increasing seawater pCO$_2$. *PLOS ONE*, **9**(2), e88308, doi:10.1371/journal.pone.0088308.

Seung, C. K. et al., 2015: Economic Impacts Of Changes In An Alaska Crab Fishery From Ocean Acidification. *Climate Change Economics*, **6**(4), 1550017, doi:10.1142/s2010007815500177.

Seuront, L., K. R. Nicastro, G. I. Zardi and E. Goberville, 2019: Decreased thermal tolerance under recurrent heat stress conditions explains summer mass mortality of the blue mussel *Mytilus edulis*. *Scientific Reports*, **9**(1), 17498, doi:10.1038/s41598-019-53580-w.

Shackell, N. L., D. Ricard and C. Stortini, 2014: Thermal Habitat Index of Many Northwest Atlantic Temperate Species Stays Neutral under Warming Projected for 2030 but Changes Radically by 2060. *PLOS ONE*, **9**(3), e90662, doi:10.1371/journal.pone.0090662.

Shaffril, H. A. M., A. Abu Samah and J. L. D'Silva, 2017: Adapting towards climate change impacts: strategies for small-scale fishermen in Malaysia. *Marine Policy*, **81**, 196-201, doi:10.1016/j.marpol.2017.03.032.

Shalby, A., M. Elshemy and B. A. Zeidan, 2020: Modeling of climate change impacts on Lake Burullus, coastal lagoon (Egypt). *International Journal of Sediment Research*, doi:10.1016/j.ijsrc.2019.12.006.

Shanks, A. L. et al., 2020: Marine heat waves, climate change, and failed spawning by coastal invertebrates. *Limnology and Oceanography*, **65**(3), 627-636, doi:10.1002/lno.11331.

Sharples, C. et al., 2020: Ocean Beach, Tasmania: A swell-dominated shoreline reaches climate-induced recessional tipping point? *Marine Geology*, **419**, 106081, doi:10.1016/j.margeo.2019.106081.

Shelton, A. O. et al., 2021: Redistribution of salmon populations in the northeast Pacific ocean in response to climate. *Fish and Fisheries*, **22**(3), 503-517, doi:10.1111/faf.12530.

Shi, Y. et al., 2020: Inter-annual and seasonal variations in zooplankton community structure in the Yellow Sea with possible influence of climatic variability. *Progress in Oceanography*, **185**, 102349, doi:10.1016/j.pocean.2020.102349.

Shields, E. C., D. Parrish and K. Moore, 2019: Short-Term Temperature Stress Results in Seagrass Community Shift in a Temperate Estuary. *Estuaries and Coasts*, **42**(3), 755-764, doi:10.1007/s12237-019-00517-1.

Shih, S.-S., 2020: Spatial Habitat Suitability Models of Mangroves with *Kandelia obovata*. *Forests*, **11**(4), doi:10.3390/f11040477.

Shlesinger, T. et al., 2018: Can mesophotic reefs replenish shallow reefs? Reduced coral reproductive performance casts a doubt. *Ecology*, **99**(2), 421–437, doi:10.1002/ecy.2098.

Shlesinger, T. and Y. Loya, 2019: Breakdown in spawning synchrony: a silent threat to coral persistence. *Science*, **365**(6457), 1002-1007, doi:10.1126/science.aax0110.

Shrivastava, J., M. Ndugwa, W. Caneos and G. De Boeck, 2019: Physiological trade-offs, acid-base balance and ion-osmoregulatory plasticity in European sea bass (Dicentrarchus labrax) juveniles under complex scenarios of salinity variation, ocean acidification and high ammonia challenge. *Aquatic Toxicology*, **212**, 54-69, doi:10.1016/j.aquatox.2019.04.024.

Siders, A. R., I. Ajibade and D. Casagrande, 2021: Transformative potential of managed retreat as climate adaptation. *Current Opinion in Environmental Sustainability*, **50**, 272-280, doi:10.1016/j.cosust.2021.06.007.

Siders, A. R., M. Hino and K. J. Mach, 2019: The case for strategic and managed climate retreat. *Science*, **365**(6455), 761-763, doi:10.1126/science.aax8346.

Siedlecki, S. A. et al., 2021: Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences*, **18**(9), 2871-2890, doi:10.5194/bg-18-2871-2021.

Silliman, B. R. et al., 2019: Field Experiments and Meta-analysis Reveal Wetland Vegetation as a Crucial Element in the Coastal Protection Paradigm. *Current Biology*, **29**(11), 1800-1806.e1803, doi:10.1016/j.cub.2019.05.017.

Silva, M. R. O., M. G. Pennino and P. F. M. Lopes, 2020: A social-ecological approach to estimate fisher resilience: a case study from Brazil. *Ecology and Society*, **25**(1), doi:10.5751/ES-11361-250123.

Silver, J. M. et al., 2019: Advancing Coastal Risk Reduction Science and Implementation by Accounting for Climate, Ecosystems, and People. *Frontiers in Marine Science*, **6**(556), doi:10.3389/fmars.2019.00556.
SIMIP Community, 2020: Arctic Sea Ice in CMIP6. *Geophysical Research Letters*, **47**(10), e2019GL086749, doi:10.1029/2019GL086749.
Simpson, J. H. and J. Sharples, 2012: *Introduction to the Physical and Biological Oceanography of Shelf Seas*. Cambridge University Press, Cambridge, United Kingdom, 466 pp. ISBN 9780521877626.
Singh, C. et al., 2020: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Climatic Change*, **162**(2), 255-277, doi:10.1007/s10584-020-02762-x.
Singh, G. G. et al., 2019a: Climate impacts on the ocean are making the Sustainable Development Goals a moving target travelling away from us. *People and Nature*, **1**(3), 317-330, doi:10.1002/pan3.26.
Singh, P. K., K. Papageorgiou, H. Chudasama and E. I. Papageorgiou, 2019b: Evaluating the Effectiveness of Climate Change Adaptations in the World's Largest Mangrove Ecosystem. *Sustainability*, **11**(23), doi:10.3390/su11236655.
Sithara, S., S. K. Pramada and S. G. Thampi, 2020: Impact of projected climate change on seawater intrusion on a regional coastal aquifer. *Journal of Earth System Science*, **129**(1), 218, doi:10.1007/s12040-020-01485-y.
Sklar, F. H., C. Carlson, C. Coronado-Molina and A. C. Maran, 2021: Coastal Ecosystem Vulnerability and Sea Level Rise (SLR) in South Florida: A Mangrove Transition Projection. *Front. ecol. evol.*, **9**(278), doi:10.3389/fevo.2021.646083.
Skogen, M. D., S. S. Hjøllo, A. B. Sandø and J. Tjiputra, 2018: Future ecosystem changes in the Northeast Atlantic: a comparison between a global and a regional model system. *ICES Journal of Marine Science*, **75**(7), 2355-2369, doi:10.1093/icesjms/fsy088.
Slama, F., E. Gargouri-Ellouze and R. Bouhlila, 2020: Impact of rainfall structure and climate change on soil and groundwater salinization. *Climatic Change*, **163**(1), 395-413, doi:10.1007/s10584-020-02789-0.
Smale, D. A., 2019: Impacts of ocean warming on kelp forest ecosystems. *New Phytologist*, doi:10.1111/nph.16107.
Smale, D. A. et al., 2018: Appreciating interconnectivity between habitats is key to blue carbon management. *Frontiers in Ecology and the Environment*, **16**(2), 71-73, doi:10.1002/fee.1765.
Smale, D. A. and T. Wernberg, 2013: Extreme climatic event drives range contraction of a habitat-forming species. *Proceedings of the Royal Society B: Biological Sciences*, **280**(1754), 20122829, doi:10.1098/rspb.2012.2829.
Smale, D. A. et al., 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9**(4), 306-312, doi:10.1038/s41558-019-0412-1.
Smee, D. L., J. A. Sanchez, M. Diskin and C. Trettin, 2017: Mangrove expansion into salt marshes alters associated faunal communities. *Estuarine, Coastal and Shelf Science*, **187**, 306-313, doi:10.1016/j.ecss.2017.02.005.
Smith, C. R. et al., 2012: A large population of king crabs in Palmer Deep on the west Antarctic Peninsula shelf and potential invasive impacts. *Proceedings of the Royal Society B: Biological Sciences*, **279**(1730), 1017-1026, doi:10.1098/rspb.2011.1496.
Smith, J. N. et al., 2020: Shifts in coralline algae, macroalgae, and coral juveniles in the Great Barrier Reef associated with present-day ocean acidification. *Global Change Biology*, **26**(4), 2149-2160, doi:10.1111/gcb.14985.
Smith, K. A., C. E. Dowling and J. Brown, 2019: Simmered then boiled: multi-decadal poleward shift in distribution by a temperate fish accelerates during marine heatwave. *Frontiers in Marine Science*, **6**, 407, doi:10.3389/fmars.2019.00407.
Smith, K. L. et al., 2018: Episodic organic carbon fluxes from surface ocean to abyssal depths during long-term monitoring in NE Pacific. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(48), 12235, doi:10.1073/pnas.1814559115.
Smith, S. M. et al., 2021: Tropicalization and kelp loss shift trophic composition and lead to more winners than losers in fish communities. *Global Change Biology*, **27**(11), 2537-2548, doi:10.1111/gcb.15592.
Smith, T. B. et al., 2014: A depth refugium from catastrophic coral bleaching prevents regional extinction. *Ecology*, **95**(6), 1663-1673, doi:10.1890/13-0468.1.
Snelgrove, P. V. R. et al., 2018: Global Carbon Cycling on a Heterogeneous Seafloor. *Trends in Ecology & Evolution*, **33**(2), 96-105, doi:10.1016/j.tree.2017.11.004.
Soares, M. B., M. Daly and S. Dessai, 2018: Assessing the value of seasonal climate forecasts for decision-making. *Wiley Interdisciplinary Reviews: Climate Change*, **9**(4), e523, doi:10.1002/wcc.523.
Solaun, K. and E. Cerdá, 2019: Climate change impacts on renewable energy generation. A review of quantitative projections. *Renewable and Sustainable Energy Reviews*, **116**, 109415, doi:10.1016/j.rser.2019.109415.
Song, G. et al., 2020a: Summertime Oxygen Depletion and Acidification in Bohai Sea, China. *Frontiers in Marine Science*, **7**(252), doi:10.3389/fmars.2020.00252.
Song, H. et al., 2020b: Flat latitudinal diversity gradient caused by the Permian–Triassic mass extinction. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(30), 17578, doi:10.1073/pnas.1918953117.
Song, H. et al., 2021a: Strong and regionally distinct links between ice-retreat timing and phytoplankton production in the Arctic Ocean. *Limnology and Oceanography*, **66**(6), 2498-2508, doi:10.1002/lno.11768.
Song, H. et al., 2021b: Thresholds of temperature change for mass extinctions. *Nature Communications*, **12**(1), 4694, doi:10.1038/s41467-021-25019-2.

Soper, F. M. et al., 2019: Non-native mangroves support carbon storage, sediment carbon burial, and accretion of coastal ecosystems. *Global Change Biology*, **25**(12), 4315-4326, doi:10.1111/gcb.14813.
Søreide, J. E. et al., 2010: Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic. *Global Change Biology*, **16**(11), 3154-3163, doi:10.1111/j.1365-2486.2010.02175.x.
Sorte, C. J. B. et al., 2019: Thermal tolerance limits as indicators of current and future intertidal zonation patterns in a diverse mussel guild. *Marine Biology*, **166**, 6, doi:10.1007/s00227-018-3452-6.
Sorte, C. J. B. et al., 2017: Long-term declines in an intertidal foundation species parallel shifts in community composition. *Global Change Biology*, **23**(1), 341-352, doi:10.1111/gcb.13425.
Sousa, A. I., J. F. da Silva, A. Azevedo and A. I. Lillebø, 2019: Blue Carbon stock in *Zostera noltei* meadows at Ria de Aveiro coastal lagoon (Portugal) over a decade. *Scientific Reports*, **9**(1), 14387, doi:10.1038/s41598-019-50425-4.
Spear, A., J. Napp, N. Ferm and D. Kimmel, 2020: Advection and in situ processes as drivers of change for the abundance of large zooplankton taxa in the Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, **177**, 104814, doi:10.1016/j.dsr2.2020.104814.
Spencer, T. et al., 2016: Global coastal wetland change under sea-level rise and related stresses: The DIVA wetland change model. *Global and Planetary Change*, **139**, 15-30, doi:10.1016/j.gloplacha.2015.12.018.
Sperling, E. A., C. A. Frieder and L. A. Levin, 2016: Biodiversity response to natural gradients of multiple stressors on continental margins. *Proceedings of the Royal Society B: Biological Sciences*, **283**(1829), 20160637, doi:10.1098/rspb.2016.0637.
Spillman, C. M. and G. A. Smith, 2021: A New Operational Seasonal Thermal Stress Prediction Tool for Coral Reefs Around Australia. *Frontiers in Marine Science*, **8**(808), doi:10.3389/fmars.2021.687833.
Sswat, M. et al., 2018: Food web changes under ocean acidification promote herring larvae survival. *Nature Ecology & Evolution*, **2**(5), 836-840, doi:10.1038/s41559-018-0514-6.
Stammer, D. et al., 2019: Framework for high-end estimates of sea level rise for stakeholder applications. *Earth's Future*, **7**(8), 923-938, doi:10.1029/2019EF001163.
Stanley, D. J. and A. G. Warne, 1994: Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. *Science*, **265**(5169), 228-231, doi:10.1126/science.265.5169.228.
Stanley, S. M., 2016: Estimates of the magnitudes of major marine mass extinctions in earth history. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(42), E6325-E6334, doi:10.1073/pnas.1613094113.
Stein, E. D. et al., 2020: Establishing Targets for Regional Coastal Wetland Restoration Planning Using Historical Ecology and Future Scenario Analysis: The Past, Present, Future Approach. *Estuaries and Coasts*, **43**(2), 207-222, doi:10.1007/s12237-019-00681-4.
Steinberg, D. K. and M. R. Landry, 2017: Zooplankton and the ocean carbon cycle. *Annual Review of Marine Science*, **9**(1), 413-444, doi:10.1146/annurev-marine-010814-015924.
Steiner, N. S. et al., 2019: Impacts of the Changing Ocean-Sea Ice System on the Key Forage Fish Arctic Cod (Boreogadus Saida) and Subsistence Fisheries in the Western Canadian Arctic—Evaluating Linked Climate, Ecosystem and Economic (CEE) Models. *Frontiers in Marine Science*, **6**(179), doi:10.3389/fmars.2019.00179.
Steiner, Z., A. V. Turchyn, E. Harpaz and J. Silverman, 2018: Water chemistry reveals a significant decline in coral calcification rates in the southern Red Sea. *Nature Communications*, **9**(1), 3615, doi:10.1038/s41467-018-06030-6.
Steneck, R. S. and D. Pauly, 2019: Fishing through the Anthropocene. *Current Biology*, **29**(19), R987-R992, doi:10.1016/j.cub.2019.07.081.
Stengel, D. B. and S. Connan, 2015: Marine algae: a source of biomass for biotechnological applications. In: *Natural Products From Marine Algae: Methods and Protocols* [Stengel, D. B. and S. Connan (eds.)]. Springer New York, New York, N.Y., pp. 1-37. ISBN 978-1-4939-2684-8.
Stenson, G. B., T. Haug and M. O. Hammill, 2020: Harp Seals: Monitors of Change in Differing Ecosystems. *Frontiers in Marine Science*, **7**(738), doi:10.3389/fmars.2020.569258.
Stephens, A. S., G. R. Bell and J. Lawrence, 2017: Applying principles of uncertainty within coastal hazard assessments to better support coastal adaptation. *Journal of Marine Science and Engineering*, **5**(3), 40, doi:10.3390/jmse5030040.
Stephens, G., R. Bell and J. Lawrence, 2018: Developing signals to trigger adaptation to sea-level rise. *Environ.Res.Lett.*, **13**(10), 104004, doi:10.1088/1748-9326/aadf96.
Steven, A. et al., 2020: *Coastal Development: Resilience, Restoration and Infrastructure Requirements*. World Resources Institute, Washington, D.C. Available at: www.oceanpanel.org/blue-papers/coastal-development-resilience-restoration-and-infrastructure-requirements.
Stevens, A. M. and C. J. Gobler, 2018: Interactive effects of acidification, hypoxia, and thermal stress on growth, respiration, and survival of four North Atlantic bivalves. *Marine Ecology Progress Series*, **604**, 143-161, doi:10.3354/meps12725.
Stevenson, S. L., S. N. C. Woolley, J. Barnett and P. Dunstan, 2020: Testing the presence of marine protected areas against their ability to reduce pressures on biodiversity. *Conservation Biology*, **34**(3), 622-631, doi:10.1111/cobi.13429.

Stewart, E., J. Dawson and M. Johnston, 2015: Risks and opportunities associated with change in the cruise tourism sector: community perspectives from Arctic Canada. *The Polar Journal*, **5**(2), 403-427, doi:10.1080/2154896X.2015.1082283.
Stewart, H. A. and A. J. Jamieson, 2019: The five deeps: The location and depth of the deepest place in each of the world's oceans. *Earth-Science Reviews*, **197**, 102896, doi:10.1016/j.earscirev.2019.102896.
Stiasny, M. H. et al., 2019: Divergent responses of Atlantic cod to ocean acidification and food limitation. *Global Change Biology*, **25**(3), 839-849, doi:10.1111/gcb.14554.
Stock, C. A., J. P. Dunne and J. G. John, 2014: Drivers of trophic amplification of ocean productivity trends in a changing climate. *Biogeosciences*, **11**(24), 7125-7135, doi:10.5194/bg-11-7125-2014.
Stock, C. A. et al., 2017: Reconciling fisheries catch and ocean productivity. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(8), E1441, doi:10.1073/pnas.1610238114.
Storch, D., L. Menzel, S. Frickenhaus and H.-O. Pörtner, 2014: Climate sensitivity across marine domains of life: limits to evolutionary adaptation shape species interactions. *Global Change Biology*, **20**(10), 3059-3067, doi:10.1111/gcb.12645.
Storlazzi, C. D. et al., 2020: Internal tides can provide thermal refugia that will buffer some coral reefs from future global warming. *Scientific Reports*, **10**(1), 13435, doi:10.1038/s41598-020-70372-9.
Storlazzi, C. D. et al., 2019: *Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction*. Open-File Report, Survey, U. S. G., Reston, VA, 52 pp. Available at: http://pubs.er.usgs.gov/publication/ofr20191027.
Stortini, C. H., D. Chabot and N. L. Shackell, 2017: Marine species in ambient low-oxygen regions subject to double jeopardy impacts of climate change. *Global Change Biology*, **23**(6), 2284-2296, doi:10.1111/gcb.13534.
Stortini, C. H., N. L. Shackell, P. Tyedmers and K. Beazley, 2015: Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada. *ICES Journal of Marine Science*, **72**(6), 1731-1743, doi:10.1093/icesjms/fsv022.
Stramma, L. et al., 2012: Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, **2**(1), 33-37, doi:10.1038/nclimate1304.
Stramma, L. and S. Schmidtko, 2021: Tropical deoxygenation sites revisited to investigate oxygen and nutrient trends. *Ocean Sci.*, **17**(3), 833-847, doi:10.5194/os-17-833-2021.
Stramma, L. et al., 2020: Trends and decadal oscillations of oxygen and nutrients at 50 to 300 m depth in the equatorial and North Pacific. *Biogeosciences*, **17**(3), 813-831, doi:10.5194/bg-17-813-2020.
Straub, S. C. et al., 2019: Resistance, Extinction, and Everything in Between – The Diverse Responses of Seaweeds to Marine Heatwaves. *Frontiers in Marine Science*, **6**, 763, doi:10.3389/fmars.2019.00763.
Strauss, B. H. et al., 2021: Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. *Nature Communications*, **12**(1), 2720, doi:10.1038/s41467-021-22838-1.
Strona, G. et al., 2021: Global tropical reef fish richness could decline by around half if corals are lost. *Proceedings of the Royal Society B: Biological Sciences*, **288**(1953), 20210274, doi:10.1098/rspb.2021.0274.
Strydom, S. et al., 2020: Too hot to handle: Unprecedented seagrass death driven by marine heatwave in a World Heritage Area. *Global Change Biology*, **26**(6), 3525-3538, doi:10.1111/gcb.15065.
Stuart-Smith, R. D., C. J. Brown, D. M. Ceccarelli and G. J. Edgar, 2018: Ecosystem restructuring along the Great Barrier Reef following mass coral bleaching. *Nature*, **560**(7716), 92-96, doi:10.1038/s41586-018-0359-9.
Stuart-Smith, R. D., C. Mellin, A. E. Bates and G. J. Edgar, 2021: Habitat loss and range shifts contribute to ecological generalization among reef fishes. *Nature Ecology & Evolution*, **5**(5), 656-662, doi:10.1038/s41559-020-01342-7.
Suaria, G. et al., 2020: Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition. *Environment International*, **136**, 105494, doi:10.1016/j.envint.2020.105494.
Suca, J. J. et al., 2021: Sensitivity of sand lance to shifting prey and hydrography indicates forthcoming change to the northeast US shelf forage fish complex. *ICES Journal of Marine Science*, **78**(3), 1023-1037, doi:10.1093/icesjms/fsaa251.
Suchley, A. and L. Alvarez-Filip, 2018: Local human activities limit marine protection efficacy on Caribbean coral reefs. *Conservation Letters*, **11**(5), e12571, doi:10.1111/conl.12571.
Sudhakar, M. P., B. R. Kumar, T. Mathimani and K. Arunkumar, 2019: A review on bioenergy and bioactive compounds from microalgae and macroalgae-sustainable energy perspective. *Journal of Cleaner Production*, **228**, 1320-1333, doi:10.1016/j.jclepro.2019.04.287.
Sudo, K., K. Watanabe, N. Yotsukura and M. Nakaoka, 2020: Predictions of kelp distribution shifts along the northern coast of Japan. *Ecological Research*, **35**(1), 47-60, doi:10.1111/1440-1703.12053.
Sully, S. et al., 2019: A global analysis of coral bleaching over the past two decades. *Nature Communications*, **10**(1), 1264, doi:10.1038/s41467-019-09238-2.
Sully, S. and R. van Woesik, 2020: Turbid reefs moderate coral bleaching under climate-related temperature stress. *Global Change Biology*, **26**(3), 1367-1373, doi:10.1111/gcb.14948.
Sulpis, O. et al., 2018: Current $CaCO_3$ dissolution at the seafloor caused by anthropogenic CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(46), 11700-11705, doi:10.1073/pnas.1804250115.
Sulpis, O. et al., 2019: Reduced CaCO3 Flux to the Seafloor and Weaker Bottom Current Speeds Curtail Benthic CaCO3 Dissolution Over the 21st Century. *Global Biogeochemical Cycles*, **33**(12), 1654-1673, doi:10.1029/2019GB006230.

Sultana, P. et al., 2019: Transforming local natural resource conflicts to cooperation in a changing climate: Bangladesh and Nepal lessons. *Climate Policy*, **19**(sup1), S94-S106, doi:10.1080/14693062.2018.1527678.
Sumaila, U. R. and T. C. Tai, 2020: End Overfishing and Increase the Resilience of the Ocean to Climate Change. *Frontiers in Marine Science*, **7**, 523, doi:10.3389/fmars.2020.00523.
Sumaila, U. R. et al., 2021: Financing a sustainable ocean economy. *Nature Communications*, **12**(1), 3259, doi:10.1038/s41467-021-23168-y.
Sun, F. and R. T. Carson, 2020: Coastal wetlands reduce property damage during tropical cyclones. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(11), 5719-5725, doi:10.1073/pnas.1915169117.
Sun, L. et al., 2018: Cruise route simulation designs for South Asia. *Journal of Coastal Research*, **82**, 254-262, doi:10.2112/SI82-037.1.
Sun, R. et al., 2020: Methylmercury produced in upper oceans accumulates in deep Mariana Trench fauna. *Nature Communications*, **11**(1), 3389, doi:10.1038/s41467-020-17045-3.
Sunday, J. et al., 2019: Thermal tolerance patterns across latitude and elevation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **374**(1778), 20190036, doi:10.1098/rstb.2019.0036.
Sunday, J. M. et al., 2016: Ocean acidification can mediate biodiversity shifts by changing biogenic habitat. *Nature Climate Change*, **7**, 81-85, doi:10.1038/nclimate3161.
Sunday, J. M. et al., 2015: Species traits and climate velocity explain geographic range shifts in an ocean-warming hotspot. *Ecology Letters*, **18**(9), 944-953, doi:10.1111/ele.12474.
Sunderland, E. M., M. Li and K. Bullard, 2018: Decadal changes in the edible supply of seafood and methylmercury exposure in the United States. *Environmental Health Perspectives*, **126**(1), 017006, doi:10.1289/EHP2644.
Sundin, J. et al., 2019: Long-term acclimation to near-future ocean acidification has negligible effects on energetic attributes in a juvenile coral reef fish. *Oecologia*, **190**(3), 689-702, doi:10.1007/s00442-019-04430-z.
Sutton, A. J. et al., 2019: Autonomous seawater pCO_2 and pH time series from 40 surface buoys and the emergence of anthropogenic trends. *Earth System Science Data*, **11**(1), 421-439, doi:10.5194/essd-11-421-2019.
Sutton, A. J. et al., 2016: Using present-day observations to detect when anthropogenic change forces surface ocean carbonate chemistry outside preindustrial bounds. *Biogeosciences*, **13**(17), 5065-5083, doi:10.5194/bg-13-5065-2016.
Suyadi, J. Gao, C. J. Lundquist and L. Schwendenmann, 2019: Land-based and climatic stressors of mangrove cover change in the Auckland Region, New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **29**(9), 1466-1483, doi:10.1002/aqc.3146.
Sweet, W. V. and J. Park, 2014: From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future*, **2**(12), 579-600, doi:10.1002/2014EF000272.
Sweetman, A. K. et al., 2017: Major impacts of climate change on deep-sea benthic ecosystems. *Elementa: Science of the Anthropocene*, **5**, 1-23, doi:10.1525/elementa.203.
Swilling, M. et al., 202: *The Ocean Transition: What to Learn from System Transitions*. World Resources Institute, Washington, DC. Available at: https://oceanpanel.org/sites/default/files/2020-09/The%20Ocean%20Transition%20What%20to%20Learn%20from%20System%20Transitions.pdf.
Swiney, K. M., W. C. Long and R. J. Foy, 2017: Decreased pH and increased temperatures affect young-of-the-year red king crab (*Paralithodes camtschaticus*). *ICES Journal of Marine Science*, **74**(4), 1191-1200, doi:10.1093/icesjms/fsw251.
Sydeman, W. J. et al., 2014: Climate change and wind intensification in coastal upwelling ecosystems. *Science*, **345**(6192), 77-80, doi:10.1126/science.1251635.
Sydeman, W. J. et al., 2009: *Seabirds and climate in the California Current–A synthesis of change*. CalCOFI Report, **50**, 82-104 pp. Available at: http://calcofi.org/publications/calcofireports/v50/82-104_Sydeman.pdf.
Sydeman, W. J., E. Poloczanska, T. E. Reed and S. A. Thompson, 2015: Climate change and marine vertebrates. *Science*, **350**(6262), 772-777, doi:10.1126/science.aac9874.
Sydeman, W. J. et al., 2021: Hemispheric asymmetry in ocean change and the productivity of ecosystem sentinels. *Science*, **372**(6545), 980, doi:10.1126/science.abf1772.
Szesciorka, A. R. et al., 2020: Timing is everything: Drivers of interannual variability in blue whale migration. *Scientific Reports*, **10**(1), 7710, doi:10.1038/s41598-020-64855-y.
Tachiiri, K., D. Silva Herran, X. Su and M. Kawamiya, 2019: Effect on the Earth system of realizing a 1.5 °C warming climate target after overshooting to the 2 °C level. *Environ.Res.Lett.*, **14**(12), 124063, doi:10.1088/1748-9326/ab5199.
Tada, Y. and K. Marumoto, 2020: Uptake of methylmercury by marine microalgae and its bioaccumulation in them. *Journal of Oceanography*, **76**(1), 63-70, doi:10.1007/s10872-019-00525-6.
Tagliabue, A. et al., 2016: How well do global ocean biogeochemistry models simulate dissolved iron distributions? *Global Biogeochemical Cycles*, **30**(2), 149-174, doi:10.1002/2015GB005289.
Tagliabue, A. et al., 2017: The integral role of iron in ocean biogeochemistry. *Nature*, **543**(7643), 51-59, doi:10.1038/nature21058.
Tai, T. C. et al., 2019: Evaluating present and future potential of arctic fisheries in Canada. *Marine Policy*, **108**, 103637, doi:10.1016/j.marpol.2019.103637.

Taillardat, P., D. A. Friess and M. Lupascu, 2018: Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. *Biology Letters*, **14**(10), 20180251, doi:10.1098/rsbl.2018.0251.
Tait, L. W. et al., 2021: Loss of Giant Kelp, Macrocystis pyrifera, Driven by Marine Heatwaves and Exacerbated by Poor Water Clarity in New Zealand. *Frontiers in Marine Science*, **8**(1168), doi:10.3389/fmars.2021.721087.
Takahashi, T. et al., 2014: Climatological distributions of pH, pCO$_2$, total CO$_2$, alkalinity, and CaCO$_3$ saturation in the global surface ocean, and temporal changes at selected locations. *Mar. Chem.*, **164**, 95-125, doi:10.1016/j.marchem.2014.06.004.
Takao, S. et al., 2015: Projecting the impacts of rising seawater temperatures on the distribution of seaweeds around Japan under multiple climate change scenarios. *Ecology and Evolution*, **5**(1), 213-223, doi:10.1002/ece3.1358.
Takayabu, I. et al., 2015: Climate change effects on the worst-case storm surge: a case study of Typhoon Haiyan. *Environ.Res.Lett.*, **10**(6), 064011, doi:10.1088/1748-9326/10/6/064011.
Talke, S. A. et al., 2020: Sea Level, Tidal, and River Flow Trends in the Lower Columbia River Estuary, 1853–present. *Journal of Geophysical Research: Oceans*, **125**(3), e2019JC015656, doi:10.1029/2019JC015656.
Talloni-Álvarez, N. E., U. R. Sumaila, P. Le Billon and W. W. L. Cheung, 2019: Climate change impact on Canada's Pacific marine ecosystem: The current state of knowledge. *Marine Policy*, **104**, 163-176, doi:10.1016/j.marpol.2019.02.035.
Tamir, R. et al., 2019: Light environment drives the shallow-to-mesophotic coral community transition. *Ecosphere*, **10**(9), e02839, doi:10.1002/ecs2.2839.
Tan, I. S. et al., 2020: Advances of macroalgae biomass for the third generation of bioethanol production. *Chinese Journal of Chemical Engineering*, **28**(2), 502-517, doi:10.1016/j.cjche.2019.05.012.
Tanaka, K. R. et al., 2021: North Pacific warming shifts the juvenile range of a marine apex predator. *Scientific Reports*, **11**(1), 3373, doi:10.1038/s41598-021-82424-9.
Tanner, M. K. et al., 2019: Mangroves in the Galapagos: ecosystem services and their valuation. *Ecological Economics*, **160**, 12-24, doi:10.1016/j.ecolecon.2019.01.024.
Taucher, J. and A. Oschlies, 2011: Can we predict the direction of marine primary production change under global warming? *Geophysical Research Letters*, **38**(2), doi:10.1029/2010GL045934.
Taylor, B. et al., 2020: The need for ecocentrism in biodiversity conservation. *Conservation Biology*, **34**(5), 1089-1096, doi:10.1111/cobi.13541.
Taylor, S. F. W. et al., 2021: The complex relationship between asset wealth, adaptation, and diversification in tropical fisheries. *Ocean & Coastal Management*, **212**, 105808, doi:10.1016/j.ocecoaman.2021.105808.
Tedesco, L., M. Vichi and E. Scoccimarro, 2019: Sea-ice algal phenology in a warmer Arctic. *Science Advances*, **5**(5), eaav4830, doi:10.1126/sciadv.aav4830.
Teixeira, H. et al., 2019: Linking biodiversity to ecosystem services supply: patterns across aquatic ecosystems. *Science of The Total Environment*, **657**, 517-534, doi:10.1016/j.scitotenv.2018.11.440.
Teixidó, N. et al., 2018: Functional biodiversity loss along natural CO$_2$ gradients. *Nature Communications*, **9**, 5149, doi:10.1038/s41467-018-07592-1.
Temmerman, S. et al., 2013: Ecosystem-based coastal defence in the face of global change. *Nature*, **504**(7478), 79-83, doi:10.1038/nature12859.
Terhaar, J. et al., 2020: Evaluation of Data-Based Estimates of Anthropogenic Carbon in the Arctic Ocean. *Journal of Geophysical Research: Oceans*, **125**(6), e2020JC016124, doi:10.1029/2020JC016124.
Terra Stori, F., C. M. Peres, A. Turra and R. L. Pressey, 2019: Traditional Ecological Knowledge Supports Ecosystem-Based Management in Disturbed Coastal Marine Social-Ecological Systems. *Frontiers in Marine Science*, **6**, 571, doi:10.3389/fmars.2019.00571.
Tessler, Z. D., C. J. Vörösmarty, I. Overeem and J. P. M. Syvitski, 2018: A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. *Geomorphology*, **305**, 209-220, doi:10.1016/j.geomorph.2017.09.040.
Thackray, C. P. and E. M. Sunderland, 2019: Chapter 6 - Seafood methylmercury in a changing ocean. In: *Predicting Future Oceans* [Cisneros-Montemayor, A. M., W. W. L. Cheung and Y. Ota (eds.)]. Elsevier, pp. 61-68. ISBN 978-0-12-817945-1.
Them, T. R. et al., 2018: Thallium isotopes reveal protracted anoxia during the Toarcian (early Jurassic) associated with volcanism, carbon burial, and mass extinction. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(26), 6596-6601, doi:10.1073/pnas.1803478115.
Therriault, T. W. et al., 2018: The invasion risk of species associated with Japanese Tsunami Marine Debris in Pacific North America and Hawaii. *Marine Pollution Bulletin*, **132**, 82-89, doi:10.1016/j.marpolbul.2017.12.063.
Thibault, C. et al., 2020: Within- and trans-generational responses to combined global changes are highly divergent in two congeneric species of marine annelids. *Marine Biology*, **167**(4), 41, doi:10.1007/s00227-019-3644-8.
Thiéblemont, R. et al., 2019: Likely and high-end impacts of regional sea-level rise on the shoreline change of European sandy coasts under a high greenhouse gas emissions scenario. *Water*, **11**(12), 2607, doi:10.3390/w11122607.
Thom, B. et al., 2020: The role of coastal processes in the management of the mouth of the River Murray, Australia: Present and future challenges. *River Research and Applications*, **36**(4), 656-667, doi:10.1002/rra.3551.
Thomas, E., 2018: Protecting Cultural Rights in the South Pacific Islands: Using UNESCO and Marine Protected Areas to Plan for Climate Change. *Fordham Environmental Law Review*, **29**(3), 413-483.

Thomas, J. T., P. L. Munday and S.-A. Watson, 2020: Toward a Mechanistic Understanding of Marine Invertebrate Behavior at Elevated CO_2. *Frontiers in Marine Science*, **7**, 345, doi:10.3389/fmars.2020.00345.
Thomas, M. K. et al., 2017: Temperature–nutrient interactions exacerbate sensitivity to warming in phytoplankton. *Global Change Biology*, **23**(8), 3269-3280, doi:10.1111/gcb.13641.
Thomas, M. K., C. T. Kremer, C. A. Klausmeier and E. Litchman, 2012: A Global Pattern of Thermal Adaptation in Marine Phytoplankton. *Science*, **338**(6110), 1085, doi:10.1126/science.1224836.
Thomas, Y. et al., 2019: Effects of hypoxia on metabolic functions in marine organisms: observed patterns and modelling assumptions within the context of dynamic energy budget (DEB) theory. *Journal of Sea Research*, **143**, 231-242, doi:10.1016/j.seares.2018.05.001.
Thomsen, J. et al., 2013: Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. *Global Change Biology*, **19**(4), 1017-1027, doi:10.1111/gcb.12109.
Thomsen, J. et al., 2017: Naturally acidified habitat selects for ocean acidification–tolerant mussels. *Science Advances*, **3**(4), e1602411, doi:10.1126/sciadv.1602411.
Thomsen, M. S. et al., 2019: Local extinction of bull kelp (*Durvillaea* spp.) due to a marine heatwave. *Frontiers in Marine Science*, **6**, 84, doi:10.3389/fmars.2019.00084.
Thor, P. et al., 2018: No maternal or direct effects of ocean acidification on egg hatching in the Arctic copepod *Calanus glacialis*. *PLOS ONE*, **13**(2), e0192496, doi:10.1371/journal.pone.0192496.
Thorhaug, A. et al., 2020: Coastal and estuarine blue carbon stocks in the greater Southeast Asia region: Seagrasses and mangroves per nation and sum of total. *Marine Pollution Bulletin*, **160**, 111168, doi:10.1016/j.marpolbul.2020.111168.
Thresher, R. E. et al., 2011: Effects of chronic low carbonate saturation levels on the distribution, growth and skeletal chemistry of deep-sea corals and other seamount megabenthos. *Marine Ecology Progress Series*, **442**, 87-99, doi:10.3354/meps09400.
Thurber, A. R. et al., 2014: Ecosystem function and services provided by the deep sea. *Biogeosciences*, **11**(14), 3941-3963, doi:10.5194/bg-11-3941-2014.
Tilley, D. et al., 2019: No evidence of fine scale thermal adaptation in green turtles. *Journal of Experimental Marine Biology and Ecology*, **514-515**, 110-117, doi:10.1016/j.jembe.2019.04.001.
Tills, O. et al., 2016: Reduced pH affects pulsing behaviour and body size in ephyrae of the moon jellyfish, *Aurelia aurita*. *Journal of Experimental Marine Biology and Ecology*, **480**, 54-61, doi:10.1016/j.jembe.2016.03.014.
Tittensor, D. P. et al., 2019: Integrating climate adaptation and biodiversity conservation in the global ocean. *Science Advances*, **5**(11), eaay9969, doi:10.1126/sciadv.aay9969.
Tittensor, D. P. et al., 2018: A protocol for the intercomparison of marine fishery and ecosystem models: Fish-MIP v1.0. *Geoscientific Model Development*, **11**(4), 1421-1442, doi:10.5194/gmd-11-1421-2018.
Tittensor, D. P. et al., 2010: Global patterns and predictors of marine biodiversity across taxa. *Nature*, **466**(7310), 1098-1101, doi:10.1038/nature09329.
Tittensor, D. P. et al., 2021: Next-generation ensemble projections reveal higher climate risks for marine ecosystems. *Nature Climate Change*, Accepted.
Todd, P. A. et al., 2019: Towards an urban marine ecology: characterizing the drivers, patterns and processes of marine ecosystems in coastal cities. *Oikos*, **128**(9), 1215-1242, doi:10.1111/oik.05946.
Toimil, A. et al., 2020: Addressing the challenges of climate change risks and adaptation in coastal areas: A review. *Coastal Engineering*, **156**, 103611, doi:10.1016/j.coastaleng.2019.103611.
Tomasetti, S. J., B. K. Morrell, L. R. Merlo and C. J. Gobler, 2018: Individual and combined effects of low dissolved oxygen and low pH on survival of early stage larval blue crabs, *Callinectes sapidus*. *PLOS ONE*, **13**(12), e0208629, doi:10.1371/journal.pone.0208629.
Tommasi, D. et al., 2017: Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. *Progress in Oceanography*, **152**, 15-49, doi:10.1016/j.pocean.2016.12.011.
Tompkins, E. L. et al., 2020: Adapting to Change: People and Policies. In: *Deltas in the Anthropocene* [Nicholls, R. J., W. N. Adger, C. W. Hutton and S. E. Hanson (eds.)]. Springer International Publishing, Cham, pp. 201-222. ISBN 978-3-030-23517-8.
Törnqvist, T. E., D. R. Cahoon, J. T. Morris and J. W. Day, 2021: Coastal Wetland Resilience, Accelerated Sea-Level Rise, and the Importance of Timescale. *AGU Advances*, **2**(1), e2020AV000334, doi:10.1029/2020AV000334.
Törnqvist, T. E., K. L. Jankowski, Y.-X. Li and J. L. González, 2020: Tipping points of Mississippi Delta marshes due to accelerated sea-level rise. *Science Advances*, **6**(21), eaaz5512, doi:10.1126/sciadv.aaz5512.
Torres, O. et al., 2021: Characterizing Mean and Extreme Diurnal Variability of Ocean CO2 System Variables Across Marine Environments. *Geophysical Research Letters*, **48**(5), e2020GL090228, doi:10.1029/2020GL090228.
Torstensson, A. et al., 2021: Sea-ice microbial communities in the Central Arctic Ocean: Limited responses to short-term pCO2 perturbations. *Limnology and Oceanography*, **66**(S1), S383-S400, doi:10.1002/lno.11690.
Toth, L. T. et al., 2019: The unprecedented loss of Florida's reef-building corals and the emergence of a novel coral-reef assemblage. *Ecology*, **100**(9), e02781, doi:10.1002/ecy.2781.
Towle, E. K., I. C. Enochs and C. Langdon, 2015: Threatened Caribbean Coral Is Able to Mitigate the Adverse Effects of Ocean Acidification on Calcification by Increasing Feeding Rate. *PLOS ONE*, **10**(4), e0123394, doi:10.1371/journal.pone.0123394.

Townhill, B. L. et al., 2019: Marine recreational fishing and the implications of climate change. *Fish and Fisheries*, **20**(5), 977-992, doi:10.1111/faf.12392.
Townhill, B. L. et al., 2017: Consequences of climate-induced low oxygen conditions for commercially important fish. *Marine Ecology Progress Series*, **580**, 191-204, doi:10.3354/meps12291.
Tracy, A. M. et al., 2019: Increases and decreases in marine disease reports in an era of global change. *Proceedings of the Royal Society B: Biological Sciences*, **286**(1912), 20191718, doi:10.1098/rspb.2019.1718.
Trainer, V. L. et al., 2019: Pelagic harmful algal blooms and climate change: lessons from nature's experiments with extremes. *Harmful Algae*, **91**, 101591, doi:10.1016/j.hal.2019.03.009.
Trathan, P. N. et al., 2015: Pollution, habitat loss, fishing, and climate change as critical threats to penguins. *Conservation Biology*, **29**(1), 31-41, doi:10.1111/cobi.12349.
Trégarot, E. et al., 2021: Mangrove ecological services at the forefront of coastal change in the French overseas territories. *Science of The Total Environment*, **763**, 143004, doi:10.1016/j.scitotenv.2020.143004.
Trigg, S. A. et al., 2019: Uncovering mechanisms of global ocean change effects on the Dungeness crab (*Cancer magister*) through metabolomics analysis. *Scientific Reports*, **9**, 10717, doi:10.1038/s41598-019-46947-6.
Tripp-Valdez, M. A. et al., 2017: Metabolic response and thermal tolerance of green abalone juveniles (*Haliotis fulgens*: Gastropoda) under acute hypoxia and hypercapnia. *Journal of Experimental Marine Biology and Ecology*, **497**, 11-18, doi:10.1016/j.jembe.2017.09.002.
Trisos, C. H., C. Merow and A. L. Pigot, 2020: The projected timing of abrupt ecological disruption from climate change. *Nature*, **580**(7804), 496-501, doi:10.1038/s41586-020-2189-9.
Troast, B., R. Paperno and G. S. Cook, 2020: Multidecadal shifts in fish community diversity across a dynamic biogeographic transition zone. *Diversity and Distributions*, **26**(1), 93-107, doi:10.1111/ddi.13000.
Trolle, D. et al., 2019: Effects of changes in land use and climate on aquatic ecosystems: Coupling of models and decomposition of uncertainties. *Science of The Total Environment*, **657**, 627-633, doi:10.1016/j.scitotenv.2018.12.055.
Trtanj, J. et al., 2016: *Climate Impacts on Water-Related Illness*. The Impacts of Climate Change on Human Health in the United States: A Scientific Asssessment, U.S. Global Change Research Program, Washington, D.C., 157-188 pp.
Turk, D. et al., 2019: Time of Emergence of Surface Ocean Carbon Dioxide Trends in the North American Coastal Margins in Support of Ocean Acidification Observing System Design. *Frontiers in Marine Science*, **6**(91), doi:10.3389/fmars.2019.00091.
Turner, K. L., C. J. Idrobo, A. A. Desmarais and A. M. Peredo, 2020a: Food sovereignty, gender and everyday practice: the role of Afro-Colombian women in sustaining localised food systems. *The Journal of Peasant Studies*, 1-27, doi:10.1080/03066150.2020.1786812.
Turner, M. G. et al., 2020b: Climate change, ecosystems and abrupt change: science priorities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190105, doi:10.1098/rstb.2019.0105.
Turner, P. J., A. D. Thaler, A. Freitag and P. Colman Collins, 2019: Deep-sea hydrothermal vent ecosystem principles: identification of ecosystem processes, services and communication of value. *Marine Policy*, **101**, 118-124, doi:10.1016/j.marpol.2019.01.003.
Turney, C. S. M. and H. Brown, 2007: Catastrophic early Holocene sea level rise, human migration and the Neolithic transition in Europe. *Quat. Sci. Rev.*, **26**(17), 2036-2041, doi:10.1016/j.quascirev.2007.07.003.
Tzoraki, O. et al., 2018: Resilience of touristic island beaches under sea level rise: a methodological framework. *Coast. Manage.*, **46**(2), 78-102, doi:10.1080/08920753.2018.1426376.
UN Environment World Conservation Monitoring Centre, International Union for Conservation of Nature and National Geographic Society, 2018: *Protected planet report 2018* [Belle, E., N. Kingston, N. Burgess, T. Sandwith, N. Ali and K. MacKinnon (eds.)]. UNEP-WCMC, IUCN and NGS, Cambridge, U.K., Gland, Switzerland., Washington, D.C., 57 pp pp.
UNEP-WCMC, 2019: *User manual for the World Database on Protected Areas and world database on other effective area-based conservation measures: 1.6*. UNEP-WCMC, Cambridge, United Kingdom. Available at: http://wcmc.io/WDPA_Manual.
UNEP-WCMC and IUCN, 2020: Protected Planet: The World Database on Protected Areas (WDPA), Cambridge, United Kingdom. Available at: https://www.protectedplanet.net (accessed 2/11/2020).
UNEP-WCMC and IUCN, 2021: *Protected Planet Report 2020*. UNEP-WCMC and IUCN, Cambridge, UK; Gland, Switzerland. Available at: https://livereport.protectedplanet.net.
UNEP-WCMC, WorldFish Centre, WRI and TNC, 2018: Global distribution of warm-water coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project, 4.0 [UN Environment World Conservation Monitoring Centre (ed.)], Cambridge, United Kingdom. Available at: http://data.unep-wcmc.org/datasets/1 (accessed 27/10/2020).
United Nations (ed.), Resolution adopted by the General Assembly on 6 July 2017: 71/312. Our ocean, our future: call for action. Seventy-first session, United Nations.
United Nations, 2021: *The Second World Ocean Assessment*. United Nations, New York, 500 pp. ISBN 978-92-1-1-130422-0.
Urrego, L. E., M. A. Prado, G. Bernal and A. Galeano, 2019: Mangrove responses to droughts since the little ice age in the Colombian Caribbean. *Estuarine, Coastal and Shelf Science*, **230**, 106432, doi:10.1016/j.ecss.2019.106432.

USGCRP, 2016: Air Quality Impacts. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* [Crimmins, A., J. Balbus, J. L. Gamble, C. B. Beard, J. E. Bell, D. Dodgen, R. J. Eisen, N. Fann, M. D. Hawkins, S. C. Herring, L. Jantarasami, D. M. Mills, S. Saha, M. C. Sarofim, J. Trtanj and L. Ziska (eds.)]. Global Change Research Program, Washington, DC, pp. 312.
Valladares, F., E. Gianoli and J. M. Gómez, 2007: Ecological limits to plant phenotypic plasticity. *New Phytologist*, **176**(4), 749-763, doi:10.1111/j.1469-8137.2007.02275.x.
Valverde-Cantillo, V., N. J. Robinson and P. Santidrián Tomillo, 2019: Influence of oceanographic conditions on nesting abundance, phenology and internesting periods of east Pacific green turtles. *Marine Biology*, **166**(7), 93, doi:10.1007/s00227-019-3541-1.
Van Coppenolle, R. and S. Temmerman, 2019: A global exploration of tidal wetland creation for nature-based flood risk mitigation in coastal cities. *Estuarine, Coastal and Shelf Science*, **226**, 106262, doi:10.1016/j.ecss.2019.106262.
Van Coppenolle, R. and S. Temmerman, 2020: Identifying global hotspots where coastal wetland conservation can contribute to nature-based mitigation of coastal flood risks. *Global and Planetary Change*, **187**, 103125, doi:10.1016/j.gloplacha.2020.103125.
Van de Waal, D. B. et al., 2013: Ocean acidification reduces growth and calcification in a marine dinoflagellate. *PLOS ONE*, **8**(6), e65987, doi:10.1371/journal.pone.0065987.
van der Bolt, B. et al., 2018: Climate reddening increases the chance of critical transitions. *Nature Climate Change*, **8**(6), 478-484, doi:10.1038/s41558-018-0160-7.
van der Lingen, C. D. and I. Hampton, 2018: Chapter 11: Climate change impacts, vulnerabilities and adaptations: Southeast Atlantic and Southeast Indian Ocean marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 219-250. ISBN 9789251306079.
van der Schatte Olivier, A. et al., 2020: A global review of the ecosystem services provided by bivalve aquaculture. *Reviews in Aquaculture*, **12**(1), 3-25, doi:10.1111/raq.12301.
van der Sleen, P. et al., 2018: Non-stationary responses in anchovy (*Engraulis encrasicolus*) recruitment to coastal upwelling in the Southern Benguela. *Marine Ecology Progress Series*, **596**, 155-164, doi:10.3354/meps12567.
van der Voorn, T., J. Quist, C. Pahl-Wostl and M. Haasnoot, 2017: Envisioning robust climate change adaptation futures for coastal regions: a comparative evaluation of cases in three continents. *Mitigation and Adaptation Strategies for Global Change*, **22**(3), 519-546, doi:10.1007/s11027-015-9686-4.
van Son, T. C. et al., 2020: Achieving Reliable Estimates of the Spatial Distribution of Kelp Biomass. *Frontiers in Marine Science*, **7**(107), doi:10.3389/fmars.2020.00107.
van Woesik, R. and C. W. Cacciapaglia, 2021: Thermal stress jeopardizes carbonate production of coral reefs across the western and central Pacific Ocean. *PLOS ONE*, **16**(4), e0249008, doi:10.1371/journal.pone.0249008.
van Woesik, R. and C. J. Randall, 2017: Coral disease hotspots in the Caribbean. *Ecosphere*, **8**(5), e01814, doi:10.1002/ecs2.1814.
Vancoppenolle, M. et al., 2013: Future Arctic Ocean primary productivity from CMIP5 simulations: uncertain outcome, but consistent mechanisms. *Global Biogeochemical Cycles*, **27**(3), 605-619, doi:10.1002/gbc.20055.
Vanderklift, M. A. et al., 2019: Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. *Marine Policy*, **107**, 103429, doi:10.1016/j.marpol.2019.02.001.
Vannuccini, S. et al., 2018: Chapter 3: Understanding the impacts of climate change for fisheries and aquaculture: global and regional supply and demand trends and prospects. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organisation of the United Nations, Rome, Italy, pp. 41-62. ISBN 9789251306079.
VanWormer, E. et al., 2019: Viral emergence in marine mammals in the North Pacific may be linked to Arctic sea ice reduction. *Scientific Reports*, **9**(1), 15569, doi:10.1038/s41598-019-51699-4.
VanZomeren, C. M., J. F. Berkowitz, C. D. Piercy and J. R. White, 2018: Restoring a degraded marsh using thin layer sediment placement: Short term effects on soil physical and biogeochemical properties. *Ecological Engineering*, **120**, 61-67, doi:10.1016/j.ecoleng.2018.05.012.
Vaqué, D. et al., 2019: Warming and CO_2 enhance Arctic heterotrophic microbial activity. *Frontiers in Microbiology*, **10**, 494, doi:10.3389/fmicb.2019.00494.
Vaquer-Sunyer, R. and C. M. Duarte, 2008: Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(40), 15452, doi:10.1073/pnas.0803833105.
Varela, M. R. et al., 2019: Assessing climate change associated sea-level rise impacts on sea turtle nesting beaches using drones, photogrammetry and a novel GPS system. *Global Change Biology*, **25**(2), 753-762, doi:10.1111/gcb.14526.
Varela, R. et al., 2015: Has upwelling strengthened along worldwide coasts over 1982-2010? *Scientific Reports*, **5**(1), 10016, doi:10.1038/srep10016.
Varela, R., L. Rodríguez-Díaz, M. de Castro and M. Gómez-Gesteira, 2021: Influence of Eastern Upwelling systems on marine heatwaves occurrence. *Global and Planetary Change*, **196**, 103379, doi:10.1016/j.gloplacha.2020.103379.

Vargas, C. A. et al., 2017: Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. *Nature Ecology & Evolution*, **1**(4), 0084, doi:10.1038/s41559-017-0084.
Veettil, B. K. et al., 2019: Mangroves of Vietnam: Historical development, current state of research and future threats. *Estuarine, Coastal and Shelf Science*, **218**, 212-236, doi:10.1016/j.ecss.2018.12.021.
Veldkornet, D. A. and A. Rajkaran, 2019: Predicting Shifts in the Geographical Distribution of Two Estuarine Plant Species from the Subtropical and Temperate Regions of South Africa. *Wetlands*, **39**(6), 1179-1188, doi:10.1007/s13157-019-01218-y.
Velez, C., E. Figueira, A. M. V. M. Soares and R. Freitas, 2016: Combined effects of seawater acidification and salinity changes in *Ruditapes philippinarum*. *Aquatic Toxicology*, **176**, 141-150, doi:10.1016/j.aquatox.2016.04.016.
Velez, Z. et al., 2019: Short- and medium-term exposure to ocean acidification reduces olfactory sensitivity in gilthead seabream. *Frontiers in Physiology*, **10**, 731, doi:10.3389/fphys.2019.00731.
Venegas, R. M. et al., 2019: The rarity of depth refugia from coral bleaching heat stress in the Western and Central Pacific Islands. *Scientific Reports*, **9**(1), 19710, doi:10.1038/s41598-019-56232-1.
Verdura, J. et al., 2019: Biodiversity loss in a Mediterranean ecosystem due to an extreme warming event unveils the role of an engineering gorgonian species. *Scientific Reports*, **9**(1), 5911, doi:10.1038/s41598-019-41929-0.
Vergés, A. et al., 2016: Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(48), 13791-13796, doi:10.1073/pnas.1610725113.
Vergés, A. et al., 2019: Tropicalisation of temperate reefs: Implications for ecosystem functions and management actions. *Functional Ecology*, **33**(6), 1000-1013, doi:10.1111/1365-2435.13310.
Vernet, M. et al., 2017: Models of plankton community changes during a warm water anomaly in Arctic waters show altered trophic pathways with minimal changes in carbon export. *Frontiers in Marine Science*, **4**, 160, doi:10.3389/fmars.2017.00160.
Verschuur, J., E. E. Koks and J. W. Hall, 2020: Port disruptions due to natural disasters: Insights into port and logistics resilience. *Transportation Research Part D: Transport and Environment*, **85**, 102393, doi:10.1016/j.trd.2020.102393.
Veytia, D. et al., 2020: Circumpolar projections of Antarctic krill growth potential. *Nature Climate Change*, **10**(6), 568-575, doi:10.1038/s41558-020-0758-4.
Vianna, G. M. S., D. Zeller and D. Pauly, 2020: Fisheries and Policy Implications for Human Nutrition. *Current Environmental Health Reports*, **7**(3), 161-169, doi:10.1007/s40572-020-00286-1.
Viitasalo, M. et al., 2015: Environmental Impacts—Marine Ecosystems. In: *Second Assessment of Climate Change for the Baltic Sea Basin* [Team, T. B. I. A. (ed.)]. Springer International Publishing, Cham, Germany, pp. 363-380. ISBN 978-3-319-16006-1.
Vijayaraghavan, V., 2021: Marine Protected Areas on the Uncertain Frontiers of Climate Change. *The Environmental Law Reporter*, **51**(2).
Villarino, E. et al., 2020: Response of copepod communities to ocean warming in three time-series across the North Atlantic and Mediterranean Sea. *Marine Ecology Progress Series*, **636**, 47-61.
Vinagre, P. A. et al., 2020: Marine Biofouling: A European Database for the Marine Renewable Energy Sector. *Journal of Marine Science and Engineering*, **8**(7), doi:10.3390/jmse8070495.
Visalli, M. E. et al., 2020: Data-driven approach for highlighting priority areas for protection in marine areas beyond national jurisdiction. *Marine Policy*, 103927, doi:10.1016/j.marpol.2020.103927.
Visbeck, M., 2018: Ocean science research is key for a sustainable future. *Nature Communications*, **9**(1), 690, doi:10.1038/s41467-018-03158-3.
Vitousek, S., P. L. Barnard and P. Limber, 2017a: Can beaches survive climate change? *Journal of Geophysical Research: Earth Surface*, **122**(4), 1060-1067, doi:10.1002/2017JF004308.
Vitousek, S. et al., 2017b: A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *Journal of Geophysical Research: Earth Surface*, **122**(4), 782-806, doi:10.1002/2016JF004065.
von der Porten, S., Y. Ota, A. Cisneros-Montemayor and S. Pictou, 2019: The Role of Indigenous Resurgence in Marine Conservation. *Coast. Manage.*, **47**(6), 527-547, doi:10.1080/08920753.2019.1669099.
Von Holle, B. et al., 2019: Effects of future sea level rise on coastal habitat. *The Journal of Wildlife Management*, **83**(3), 694-704, doi:10.1002/jwmg.21633.
von Schuckmann, K., E. Holland, P. Haugan and P. Thomson, 2020: Ocean science, data, and services for the UN 2030 Sustainable Development Goals. *Marine Policy*, **121**, 104154, doi:10.1016/j.marpol.2020.104154.
Vousdoukas, M. I. et al., 2020a: Reply to: Sandy beaches can survive sea-level rise. *Nature Climate Change*, **10**(11), 996-997, doi:10.1038/s41558-020-00935-1.
Vousdoukas, M. I. et al., 2020b: Sandy coastlines under threat of erosion. *Nature Climate Change*, **10**(3), 260-263, doi:10.1038/s41558-020-0697-0.
Voyer, M., G. Quirk, A. McIlgorm and K. Azmi, 2018: Shades of blue: what do competing interpretations of the blue economy mean for oceans governance? *Journal of Environmental Policy & Planning*, **20**(5), 595-616, doi:10.1080/1523908X.2018.1473153.

Wabnitz, C. C. C., 2019: Chapter 21 - Adapting tourist seafood consumption practices in Pacific Islands to climate change. In: *Predicting Future Oceans* [Cisneros-Montemayor, A. M., W. W. L. Cheung and Y. Ota (eds.)]. Elsevier, pp. 215-225. ISBN 978-0-12-817945-1.
Wabnitz, C. C. C. and R. Blasiak, 2019: The rapidly changing world of ocean finance. *Marine Policy*, **107**, 103526, doi:10.1016/j.marpol.2019.103526.
Wabnitz, C. C. C., A. M. Cisneros-Montemayor, Q. Hanich and Y. Ota, 2018a: Ecotourism, climate change and reef fish consumption in Palau: benefits, trade-offs and adaptation strategies. *Marine Policy*, **88**, 323-332, doi:10.1016/j.marpol.2017.07.022.
Wabnitz, C. C. C. et al., 2018b: Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. *PLOS ONE*, **13**(5), e0194537, doi:10.1371/journal.pone.0194537.
Wade, R. et al., 2020: Macroalgal germplasm banking for conservation, food security, and industry. *PLOS Biology*, **18**(2), e3000641, doi:10.1371/journal.pbio.3000641.
Wagner, C. C. et al., 2019: A Global 3-D Ocean Model for PCBs: Benchmark Compounds for Understanding the Impacts of Global Change on Neutral Persistent Organic Pollutants. *Global Biogeochemical Cycles*, **33**(3), 469-481, doi:10.1029/2018GB006018.
Wagner, D. et al., 2020: Coral Reefs of the High Seas: Hidden Biodiversity Hotspots in Need of Protection. *Frontiers in Marine Science*, **7**(776), doi:10.3389/fmars.2020.567428.
Wallingford, P. D. et al., 2020: Adjusting the lens of invasion biology to focus on the impacts of climate-driven range shifts. *Nature Climate Change*, **10**(5), 398-405, doi:10.1038/s41558-020-0768-2.
Wallingford, P. D. and C. J. B. Sorte, 2019: Community regulation models as a framework for direct and indirect effects of climate change on species distributions. *Ecosphere*, **10**(7), e02790, doi:10.1002/ecs2.2790.
Walsh, C. et al., 2019: Trade and trade-offs: Shipping in changing climates. *Marine Policy*, **106**, 103537, doi:10.1016/j.marpol.2019.103537.
Walworth, N. G. et al., 2020: Microbial evolutionary strategies in a dynamic ocean. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(11), 5943, doi:10.1073/pnas.1919332117.
Wamsler, C. and E. Brink, 2018: Mindsets for Sustainability: Exploring the Link Between Mindfulness and Sustainable Climate Adaptation. *Ecological Economics*, **151**, 55-61, doi:10.1016/j.ecolecon.2018.04.029.
Wang, D. W., T. C. Gouhier, B. A. Menge and A. R. Ganguly, 2015: Intensification and spatial homogenization of coastal upwelling under climate change. *Nature*, **518**(7539), 390-394, doi:10.1038/nature14235.
Wang, F. et al., 2020: Global blue carbon accumulation in tidal wetlands increases with climate change. *National Science Review*, doi:10.1093/nsr/nwaa296.
Wang, G. et al., 2017a: Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nature Climate Change*, **7**(8), 568-572, doi:10.1038/nclimate3351.
Wang, J. and B. Hong, 2021: Threat posed by future sea-level rise to freshwater resources in the upper Pearl River estuary. *Journal of Marine Science and Engineering*, **9**(3), 291, doi:10.3390/jmse9030291.
Wang, M. et al., 2019a: The great Atlantic *Sargassum* belt. *Science*, **365**(6448), 83, doi:10.1126/science.aaw7912.
Wang, W. et al., 2018a: Zooplankton community structure, abundance and biovolume in Jiaozhou Bay and the adjacent coastal Yellow Sea during summers of 2005–2012: relationships with increasing water temperature. *Journal of Oceanology and Limnology*, **36**(5), 1655-1670, doi:10.1007/s00343-018-7099-4.
Wang, X. et al., 2019b: How will the key marine calcifier *Emiliania huxleyi* respond to a warmer and more thermally variable ocean? *Biogeosciences*, **16**(22), 4393-4409, doi:10.5194/bg-16-4393-2019.
Wang, X. et al., 2019c: Roles of fishing and climate change in long-term fish species succession and population dynamics in the outer Beibu Gulf, South China Sea. *Acta Oceanologica Sinica*, **38**(10), 1-8, doi:10.1007/s13131-019-1484-5.
Wang, X. et al., 2017b: Impact of ocean acidification on the early development and escape behavior of marine medaka (*Oryzias melastigma*). *Marine Environmental Research*, **131**, 10-18, doi:10.1016/j.marenvres.2017.09.001.
Wang, Y. et al., 2018b: Elevated pCO_2 Affects Feeding Behavior and Acute Physiological Response of the Brown Crab *Cancer pagurus*. *Frontiers in Physiology*, **9**, 1164, doi:10.3389/fphys.2018.01164.
Wang, Z. et al., 2018c: Middle Holocene marine flooding and human response in the south Yangtze coastal plain, East China. *Quat. Sci. Rev.*, **187**, 80-93, doi:10.1016/j.quascirev.2018.03.001.
Wanless, S., M. Frederiksen, J. Walton and M. P. Harris, 2009: Long-term changes in breeding phenology at two seabird colonies in the western North Sea. *Ibis*, **151**(2), 274-285, doi:10.1111/j.1474-919X.2008.00906.x.
Want, A. and J. Porter (eds.), BioFREE: An International Study of Biofouling Impacts on the Marine Renewable Energy Industry. 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO), 28–31 May 2018, Kobe, Japan, IEEE, 1-7 pp.
Ware, D. and Z. Banhalmi-Zakar, 2020: Strategies for governments to help close the coastal adaptation funding gap. *Ocean & Coastal Management*, **198**, 105223, doi:10.1016/j.ocecoaman.2020.105223.
Warner, R., 2018: Oceans in transition: incorporating climate-change impacts into environmental impact assessment for marine areas beyond national jurisdiction. *Ecology Law Quarterly*, **45**(1), 31-53, doi:10.15779/Z38M61BQ0J.
Wasmund, N. et al., 2019: Extension of the growing season of phytoplankton in the western Baltic Sea in response to climate change. *Marine Ecology Progress Series*, **622**, 1-16, doi:10.3354/meps12994.
Watanabe, K. et al., 2019: Relative sea-level change regulates organic carbon accumulation in coastal habitats. *Global Change Biology*, **25**(3), 1063-1077, doi:10.1111/gcb.14558.

Watkiss, P., A. Hunt, W. Blyth and J. Dyszynski, 2015: The use of new economic decision support tools for adaptation assessment: a review of methods and applications, towards guidance on applicability. *Climatic Change*, **132**(3), 401-416, doi:10.1007/s10584-014-1250-9.
Watson, S.-A. et al., 2018: Ocean warming has a greater effect than acidification on the early life history development and swimming performance of a large circumglobal pelagic fish. *Global Change Biology*, **24**(9), 4368-4385, doi:10.1111/gcb.14290.
Watson, S.-A. et al., 2014: Marine mollusc predator-escape behaviour altered by near-future carbon dioxide levels. *Proceedings of the Royal Society B: Biological Sciences*, **281**(1774), 20132377, doi:10.1098/rspb.2013.2377.
Waycott, M. et al., 2009: Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(30), 12377-12381, doi:10.1073/pnas.0905620106.
Webster, J. M. et al., 2018: Response of the Great Barrier Reef to sea-level and environmental changes over the past 30,000 years. *Nature Geoscience*, **11**(6), 426-432, doi:10.1038/s41561-018-0127-3.
Webster, N. S. and M. W. Taylor, 2012: Marine sponges and their microbial symbionts: love and other relationships. *Environmental Microbiology*, **14**(2), 335-346, doi:10.1111/j.1462-2920.2011.02460.x.
Wedding, L. M. et al., 2021: Incorporating blue carbon sequestration benefits into sub-national climate policies. *Global Environmental Change*, **69**, 102206, doi:10.1016/j.gloenvcha.2020.102206.
Wei, Q. et al., 2019: Deoxygenation and Its Controls in a Semienclosed Shelf Ecosystem, Northern Yellow Sea. *Journal of Geophysical Research: Oceans*, **124**(12), 9004-9019, doi:10.1029/2019JC015399.
Weichselgartner, J. and B. Arheimer, 2019: Evolving climate services into knowledge–action systems. *Weather, Climate, and Society*, **11**(2), 385-399, doi:10.1175/WCAS-D-18-0087.1.
Weigel, B. L. and C. A. Pfister, 2021: The dynamics and stoichiometry of dissolved organic carbon release by kelp. *Ecology*, **102**(2), e03221, doi:10.1002/ecy.3221.
Weijerman, M. et al., 2015: An integrated coral reef ecosystem model to support resource management under a changing climate. *PLOS ONE*, **10**(12), e0144165, doi:10.1371/journal.pone.0144165.
Weikmans, R. and J. T. Roberts, 2019: The international climate finance accounting muddle: is there hope on the horizon? *Climate and Development*, **11**(2), 97-111, doi:10.1080/17565529.2017.1410087.
Weinert, M. et al., 2021: Climate change effects on marine protected areas: Projected decline of benthic species in the North Sea. *Marine Environmental Research*, **163**, 105230, doi:10.1016/j.marenvres.2020.105230.
Weiskopf, S. R. et al., 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782, doi:10.1016/j.scitotenv.2020.137782.
Weissert, H., 2019: Mesozoic C-cycle perturbations and climate: evidence for increased resilience of the Cretaceous biosphere to greenhouse pulses. *Canadian Journal of Earth Sciences*, doi:10.1139/cjes-2018-0227.
Weitzman, B. et al., 2021: Changes in Rocky Intertidal Community Structure During a Marine Heatwave in the Northern Gulf of Alaska. *Frontiers in Marine Science*, **8**(115), doi:10.3389/fmars.2021.556820.
Weitzman, J., 2019: Applying the ecosystem services concept to aquaculture: a review of approaches, definitions, and uses. *Ecosystem Services*, **35**, 194-206, doi:10.1016/j.ecoser.2018.12.009.
Welladsen, H. M., P. C. Southgate and K. Heimann, 2010: The effects of exposure to near-future levels of ocean acidification on shell characteristics of *Pinctada fucata* (Bivalvia: Pteriidae). *Molluscan Research*, **30**(3), 125-130.
Wells, M. L. et al., 2020: Future HAB science: Directions and challenges in a changing climate. *Harmful Algae*, **91**, 101632, doi:10.1016/j.hal.2019.101632.
Wernberg, T., 2021: Marine Heatwave Drives Collapse of Kelp Forests in Western Australia. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 325-343. ISBN 978-3-030-71330-0.
Wernberg, T. et al., 2016: Climate-driven regime shift of a temperate marine ecosystem. *Science*, **353**(6295), 169, doi:10.1126/science.aad8745.
Wernberg, T. and K. Filbee-Dexter, 2018: Grazers extend blue carbon transfer by slowing sinking speeds of kelp detritus. *Scientific Reports*, **8**(1), 17180, doi:10.1038/s41598-018-34721-z.
Wernberg, T., K. Krumhansl, K. Filbee-Dexter and M. F. Pedersen, 2019: Status and trends for the world's kelp forests. In: *World Seas: An Environmental Evaluation (Second Edition), Volume III: Ecological Issues and Environmental Impacts*, 2nd edition ed. [Sheppard, C. (ed.)]. Academic Press, pp. 57-78. ISBN 978-0-12-805052-1.
West, J. J., L. Järnberg, E. Berdalet and C. Cusack, 2021: Understanding and Managing Harmful Algal Bloom Risks in a Changing Climate: Lessons From the European CoCliME Project. *Frontiers in Climate*, **3**, 39.
Westerbom, M., A. Lappalainen, O. Mustonen and A. Norkko, 2018: Trophic overlap between expanding and contracting fish predators in a range margin undergoing change. *Scientific Reports*, **8**(1), 7895, doi:10.1038/s41598-018-25745-6.
Westerhold, T. et al., 2020: An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science*, **369**(6509), 1383-1387, doi:10.1126/science.aba6853.
Weydmann, A., W. Walczowski, J. Carstensen and S. Kwaśniewski, 2018: Warming of Subarctic waters accelerates development of a key marine zooplankton *Calanus finmarchicus*. *Global Change Biology*, **24**(1), 172-183, doi:10.1111/gcb.13864.

White, E. D. et al., 2019: Mitigating the effects of sea-level rise on estuaries of the Mississippi Delta Plain using river diversions. *Water*, **11**(10), 2028, doi:10.3390/w11102028.
Whiteley, N. M. et al., 2018: Sensitivity to near-future CO2 conditions in marine crabs depends on their compensatory capacities for salinity change. *Scientific Reports*, **8**(1), 15639, doi:10.1038/s41598-018-34089-0.
Whitt, A. A. et al., 2020: March of the mangroves: Drivers of encroachment into southern temperate saltmarsh. *Estuarine, Coastal and Shelf Science*, **240**, 106776, doi:10.1016/j.ecss.2020.106776.
Wiberg, P. L. et al., 2019: Wave Attenuation by Oyster Reefs in Shallow Coastal Bays. *Estuaries and Coasts*, **42**(2), 331-347, doi:10.1007/s12237-018-0463-y.
Wienberg, C. et al., 2018: The giant Mauritanian cold-water coral mound province: Oxygen control on coral mound formation. *Quat. Sci. Rev.*, **185**, 135-152, doi:10.1016/j.quascirev.2018.02.012.
Williams, A. N. et al., 2018: Sea-level change and demography during the last glacial termination and early Holocene across the Australian continent. *Quat. Sci. Rev.*, **182**, 144-154, doi:10.1016/j.quascirev.2017.11.030.
Williams, B. et al., 2021: Ocean Acidification Reduces Skeletal Density of Hardground-Forming High-Latitude Crustose Coralline Algae. *Geophysical Research Letters*, **48**(5), e2020GL091499, doi:10.1029/2020GL091499.
Williams, D. S. et al., 2020: A Method for Enhancing Capacity of Local Governance for Climate Change Adaptation. *Earth's Future*, **8**(7), e2020EF001506, doi:10.1029/2020EF001506.
Williamson, P. and V. A. Guinder, 2021: Chapter 5 - Effect of climate change on marine ecosystems. In: *The Impacts of Climate Change* [Letcher, T. M. (ed.)]. Elsevier, pp. 115-176. ISBN 978-0-12-822373-4.
Williamson, P., H. O. Pörtner, S. Widdicombe and J. P. Gattuso, 2021: Ideas and perspectives: When ocean acidification experiments are not the same, repeatability is not tested. *Biogeosciences*, **18**(5), 1787-1792, doi:10.5194/bg-18-1787-2021.
Willis, C., E. Papathanasopoulou, D. Russel and Y. Artioli, 2018: Harmful algal blooms: the impacts on cultural ecosystem services and human well-being in a case study setting, Cornwall, UK. *Marine Policy*, **97**, 232-238, doi:10.1016/j.marpol.2018.06.002.
Wilson, K. L. and H. K. Lotze, 2019: Climate change projections reveal range shifts of eelgrass Zostera marina in the Northwest Atlantic. *Marine Ecology Progress Series*, **620**, 47-62.
Wilson, K. L., M. A. Skinner and H. K. Lotze, 2019: Projected 21st-century distribution of canopy-forming seaweeds in the northwest Atlantic with climate change. *Diversity and Distributions*, **25**(4), 582-602, doi:10.1111/ddi.12897.
Wilson, K. L., D. P. Tittensor, B. Worm and H. K. Lotze, 2020a: Incorporating climate change adaptation into marine protected area planning. *Global Change Biology*, **26**(6), 3251-3267, doi:10.1111/gcb.15094.
Wilson, R. S., A. Herziger, M. Hamilton and J. S. Brooks, 2020b: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, **10**(3), 200-208, doi:10.1038/s41558-020-0691-6.
Winter, A. et al., 2013: Poleward expansion of the coccolithophore *Emiliania huxleyi*. *Journal of Plankton Research*, **36**(2), 316-325, doi:10.1093/plankt/fbt110.
Winter, G. et al., 2020: Steps to develop early warning systems and future scenarios of storm wave-driven flooding along coral reef-lined coasts. *Frontiers in Marine Science*, **7**, 199, doi:10.3389/fmars.2020.00199.
Wishner, K. F. et al., 2018: Ocean deoxygenation and zooplankton: very small oxygen differences matter. *Science Advances*, **4**(12), eaau5180, doi:10.1126/sciadv.aau5180.
Wittmann, A. C. and H.-O. Pörtner, 2013: Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change*, **3**(11), 995-1001, doi:10.1038/nclimate1982.
Wodehouse, D. C. J. and M. B. Rayment, 2019: Mangrove area and propagule number planting targets produce sub-optimal rehabilitation and afforestation outcomes. *Estuarine, Coastal and Shelf Science*, **222**, 91-102, doi:10.1016/j.ecss.2019.04.003.
Wolf, K. K. E., C. J. M. Hoppe and B. Rost, 2018: Resilience by diversity: large intraspecific differences in climate change responses of an Arctic diatom. *Limnology and Oceanography*, **63**(1), 397-411, doi:10.1002/lno.10639.
Wolf, K. K. E. et al., 2019: Company matters: the presence of other genotypes alters traits and intraspecific selection in an Arctic diatom under climate change. *Global Change Biology*, **25**(9), 2869-2884, doi:10.1111/gcb.14675.
Wolff, N. H., P. J. Mumby, M. Devlin and K. R. N. Anthony, 2018: Vulnerability of the Great Barrier Reef to climate change and local pressures. *Global Change Biology*, **24**(5), 1978-1991, doi:10.1111/gcb.14043.
Wollschläger, J. et al., 2021: Editorial: Climate Change and Light in Aquatic Ecosystems: Variability & Ecological Consequences. *Frontiers in Marine Science*, **8**(506), doi:10.3389/fmars.2021.688712.
Wong, P. P. et al., 2014: Coastal systems and low-lying areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.
Wood, G. et al., 2021: Genomic vulnerability of a dominant seaweed points to future-proofing pathways for Australia's underwater forests. *Global Change Biology*, **27**(10), 2200-2212, doi:10.1111/gcb.15534.
Woodland, R. J. et al., 2021: Environmental Drivers of Forage Fishes and Benthic Invertebrates at Multiple Spatial Scales in a Large Temperate Estuary. *Estuaries and Coasts*, **44**(4), 921-938, doi:10.1007/s12237-020-00835-9.

Woodroffe, C. D. et al., 2016: Mangrove sedimentation and response to relative sea-level rise. *Annual Review of Marine Science*, **8**(1), 243-266, doi:10.1146/annurev-marine-122414-034025.
Woodruff, S. C., M. Mullin and M. Roy, 2020: Is coastal adaptation a public good? The financing implications of good characteristics in coastal adaptation. *Journal of Environmental Planning and Management*, **63**(12), 2082-2101, doi:10.1080/09640568.2019.1703656.
Wooldridge, S. A., 2020: Excess seawater nutrients, enlarged algal symbiont densities and bleaching sensitive reef locations: 1. Identifying thresholds of concern for the Great Barrier Reef, Australia. *Marine Pollution Bulletin*, **152**, 107667, doi:10.1016/j.marpolbul.2016.04.054.
World Health Organisation and United Nations Children's Fund, 2017: *Wash in the 2030 agenda: new global indicators for drinking water, sanitation and hygeine*. World Health Organisation, 8 pp pp. Available at: https://www.who.int/water_sanitation_health/monitoring/coverage/jmp-2017-wash-in-the-2030-agenda.pdf?ua=1 (accessed 22nd April 2019).
Worm, B., 2017: How to heal an ocean. *Nature*, **543**(7647), 630-631, doi:10.1038/nature21895.
Worm, B. and H. K. Lotze, 2021: Chapter 21 - Marine biodiversity and climate change. In: *Climate Change (Third Edition)* [Letcher, T. M. (ed.)]. Elsevier, pp. 445-464. ISBN 978-0-12-821575-3.
Wright, G. et al., 2019: Marine spatial planning in areas beyond national jurisdiction. *Marine Policy*, 103384, doi:10.1016/j.marpol.2018.12.003.
Wright, R. M. et al., 2021: Role of jellyfish in the plankton ecosystem revealed using a global ocean biogeochemical model. *Biogeosciences*, **18**(4), 1291-1320, doi:10.5194/bg-18-1291-2021.
Wrightson, L. and A. Tagliabue, 2020: Quantifying the Impact of Climate Change on Marine Diazotrophy: Insights From Earth System Models. *Frontiers in Marine Science*, **7**(635), doi:10.3389/fmars.2020.00635.
Wu, J. et al., 2020a: Opportunities for blue carbon strategies in China. *Ocean & Coastal Management*, **194**, 105241, doi:10.1016/j.ocecoaman.2020.105241.
Wu, P., E. J. Zakem, S. Dutkiewicz and Y. Zhang, 2020b: Biomagnification of Methylmercury in a Marine Plankton Ecosystem. *Environmental Science & Technology*, **54**(9), 5446-5455, doi:10.1021/acs.est.9b06075.
Wyatt, A. S. J. et al., 2020: Heat accumulation on coral reefs mitigated by internal waves. *Nature Geoscience*, **13**(1), 28-34, doi:10.1038/s41561-019-0486-4.
Xiao, X. et al., 2021: Seaweed farms provide refugia from ocean acidification. *Science of The Total Environment*, **776**, 145192, doi:10.1016/j.scitotenv.2021.145192.
Xie, F. et al., 2019: Spatial and Temporal Variations of Particulate Organic Carbon Sinking Flux in Global Ocean from 2003 to 2018. *Remote Sensing*, **11**(24), doi:10.3390/rs11242941.
Xiong, T.-q. et al., 2020: Comparing Subsurface Seasonal Deoxygenation and Acidification in the Yellow Sea and Northern East China Sea Along the North-to-South Latitude Gradient. *Frontiers in Marine Science*, **7**(686), doi:10.3389/fmars.2020.00686.
Xu, K., F.-X. Fu and D. A. Hutchins, 2014: Comparative responses of two dominant Antarctic phytoplankton taxa to interactions between ocean acidification, warming, irradiance, and iron availability. *Limnology and Oceanography*, **59**(6), 1919-1931, doi:10.4319/lo.2014.59.6.1919.
Xue, L. et al., 2018: Native and non-native halophytes resiliency against sea-level rise and saltwater intrusion. *Hydrobiologia*, **806**(1), 47-65, doi:10.1007/s10750-017-3333-x.
Xuereb, A. et al., 2020: Marine Conservation and Marine Protected Areas. In: *Population Genomics: Marine Organisms* [Oleksiak, M. F. and O. P. Rajora (eds.)]. Springer International Publishing, Cham, pp. 423-446. ISBN 978-3-030-37936-0.
Yamaguchi, R. and T. Suga, 2019: Trend and Variability in Global Upper-Ocean Stratification Since the 1960s. *Journal of Geophysical Research: Oceans*, **124**(12), 8933-8948, doi:10.1029/2019JC015439.
Yamamoto, L. and M. Esteban, 2014: *Atoll Island States and International Law: Climate Change Displacement and Sovereignty*. Climate Change Displacement and Sovereignty, Springer, Berlin, Heidelberg, 307 pp. ISBN 9783642381850.
Yan, H. et al., 2019: Regional coral growth responses to seawater warming in the South China Sea. *Science of The Total Environment*, **670**, 595-605, doi:10.1016/j.scitotenv.2019.03.135.
Yang, H. et al., 2020: Enhanced Carbon Uptake and Reduced Methane Emissions in a Newly Restored Wetland. *Journal of Geophysical Research: Biogeosciences*, **125**(1), e2019JG005222, doi:10.1029/2019JG005222.
Yang, Q. et al., 2019: Donor-side evaluation of coastal and marine ecosystem services. *Water Research*, **166**, 115028, doi:10.1016/j.watres.2019.115028.
Yasuhara, M. et al., 2020: Past and future decline of tropical pelagic biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, 201916923, doi:10.1073/pnas.1916923117.
Yasunaka, S. et al., 2014: Mapping of sea surface nutrients in the North Pacific: Basin-wide distribution and seasonal to interannual variability. *Journal of Geophysical Research: Oceans*, **119**(11), 7756-7771, doi:10.1002/2014JC010318.
Yasunaka, S. et al., 2016: Long-term variability of surface nutrient concentrations in the North Pacific. *Geophysical Research Letters*, **43**(7), 3389-3397, doi:10.1002/2016GL068097.
Yates, K. K., D. G. Zawada, N. A. Smiley and G. Tiling-Range, 2017: Divergence of seafloor elevation and sea level rise in coral reef ecosystems. *Biogeosciences*, **14**(6), 1739-1772, doi:10.5194/bg-14-1739-2017.

Yates, K. L., B. Clarke and R. H. Thurstan, 2019: Purpose vs performance: What does marine protected area success look like? *Environmental Science & Policy*, **92**, 76-86, doi:10.1016/j.envsci.2018.11.012.
Yati, E. et al., 2020: Marine Ecosystem Variations Over the North Pacific and Their Linkage to Large-Scale Climate Variability and Change. *Frontiers in Marine Science*, **7**(925), doi:10.3389/fmars.2020.578165.
Yemane, D. et al., 2014: Assessing changes in the distribution and range size of demersal fish populations in the Benguela Current Large Marine Ecosystem. *Reviews in Fish Biology and Fisheries*, **24**(2), 463-483, doi:10.1007/s11160-014-9357-7.
Yeruham, E., G. Rilov, M. Shpigel and A. Abelson, 2015: Collapse of the echinoid *Paracentrotus lividus* populations in the Eastern Mediterranean—result of climate change? *Scientific Reports*, **5**, 13479, doi:10.1038/srep13479.
Yesudian, A. N. and R. J. Dawson, 2021: Global analysis of sea level rise risk to airports. *Climate Risk Management*, **31**, 100266, doi:10.1016/j.crm.2020.100266.
Yool, A. et al., 2017: Big in the benthos: future change of seafloor community biomass in a global, body size-resolved model. *Global Change Biology*, **23**(9), 3554-3566, doi:10.1111/gcb.13680.
Yool, A., E. E. Popova and A. C. Coward, 2015: Future change in ocean productivity: is the Arctic the new Atlantic? *Journal of Geophysical Research: Oceans*, **120**(12), 7771-7790, doi:10.1002/2015JC011167.
Yool, A. et al., 2013: Climate change and ocean acidification impacts on lower trophic levels and the export of organic carbon to the deep ocean. *Biogeosciences*, **10**(9), 5831-5854, doi:10.5194/bg-10-5831-2013.
Young, C. S., A. Lowell, B. Peterson and C. J. Gobler, 2019a: Ocean acidification and food limitation combine to suppress herbivory by the gastropod *Lacuna vincta*. *Marine Ecology Progress Series*, **627**, 83-94, doi:10.3354/meps13087.
Young, M. A. et al., 2021: National scale predictions of contemporary and future blue carbon storage. *Science of The Total Environment*, **800**, 149573, doi:10.1016/j.scitotenv.2021.149573.
Young, T. et al., 2019b: Adaptation strategies of coastal fishing communities as species shift poleward. *ICES Journal of Marine Science*, **76**(1), 93-103, doi:10.1093/icesjms/fsy140.
Yu, M. et al., 2019: Landscape-Level Consequences of Rising Sea-Level on Coastal Wetlands: Saltwater Intrusion Drives Displacement and Mortality in the Twenty-First Century. *Wetlands*, **39**(6), 1343-1355, doi:10.1007/s13157-019-01138-x.
Yurkowski, D. J., T. A. Brown, P. J. Blanchfield and S. H. Ferguson, 2020: Atlantic walrus signal latitudinal differences in the long-term decline of sea ice-derived carbon to benthic fauna in the Canadian Arctic. *Proceedings of the Royal Society B: Biological Sciences*, **287**(1940), 20202126, doi:10.1098/rspb.2020.2126.
Zapata, C. et al., 2018: Assessment of ecosystem services of an urbanized tropical estuary with a focus on habitats and scenarios. *PLOS ONE*, **13**(10), e0203927, doi:10.1371/journal.pone.0203927.
Zarco-Perello, S. et al., 2020: Range-extending tropical herbivores increase diversity, intensity and extent of herbivory functions in temperate marine ecosystems. *Functional Ecology*, **34**(11), 2411-2421, doi:10.1111/1365-2435.13662.
Zarco-Perello, S., T. Wernberg, T. J. Langlois and M. A. Vanderklift, 2017: Tropicalization strengthens consumer pressure on habitat-forming seaweeds. *Scientific Reports*, **7**(1), 820, doi:10.1038/s41598-017-00991-2.
Zeng, Y. et al., 2020: Economic and social constraints on reforestation for climate mitigation in Southeast Asia. *Nature Climate Change*, **10**(9), 842-844, doi:10.1038/s41558-020-0856-3.
Zeng, Z. et al., 2019: Effects of climate change and fishing on the Pearl River Estuary ecosystem and fisheries. *Reviews in Fish Biology and Fisheries*, **29**(4), 861-875, doi:10.1007/s11160-019-09574-y.
Zhan, W., H. Cheng and S. Shen, 2020: Evaluation of urban wetland ecosystem service value in Zhuzhou City. *Nature Environment and Pollution Technology*, **10**(2), 453-467, doi:10.46488/NEPT.2020.v19i02.003.
Zhang, F. and M. Li, 2019: Impacts of Ocean Warming, Sea Level Rise, and Coastline Management on Storm Surge in a Semienclosed Bay. *Journal of Geophysical Research: Oceans*, **124**(9), 6498-6514, doi:10.1029/2019JC015445.
Zhang, G. et al., 2019a: Giant discoveries of oil and gas fields in global deepwaters in the past 40 years and the prospect of exploration. *Journal of Natural Gas Geoscience*, **4**(1), 1-28, doi:10.1016/j.jnggs.2019.03.002.
Zhang, H. and K. Wang, 2019: Simulated CO_2-induced ocean acidification for ocean in the East China: historical conditions since preindustrial time and future scenarios. *Scientific Reports*, **9**(1), 18559, doi:10.1038/s41598-019-54861-0.
Zhang, R., L. Xie and Z. Yan, 2019b: Ecological study on biomineralization in *Pinctada fucata*. In: *Biomineralization Mechanism of the Pearl Oyster, Pinctada fucata* [Zhang, R., L. Xie and Z. Yan (eds.)]. Springer Singapore, Singapore, pp. 661-694. ISBN 978-981-13-1459-9.
Zhang, W. et al., 2020a: Stratification duration and the formation of bottom hypoxia over the Texas-Louisiana shelf. *Estuarine, Coastal and Shelf Science*, **238**, 106711, doi:10.1016/j.ecss.2020.106711.
Zhang, Y., L. T. Bach, K. G. Schulz and U. Riebesell, 2015: The modulating effect of light intensity on the response of the coccolithophore *Gephyrocapsa oceanica* to ocean acidification. *Limnology and Oceanography*, **60**(6), 2145-2157, doi:10.1002/lno.10161.
Zhang, Y., S. Dutkiewicz and E. M. Sunderland, 2021a: Impacts of climate change on methylmercury formation and bioaccumulation in the 21st century ocean. *One Earth*, **4**(2), 279-288, doi:10.1016/j.oneear.2021.01.005.
Zhang, Y., A. L. Soerensen, A. T. Schartup and E. M. Sunderland, 2020b: A Global Model for Methylmercury Formation and Uptake at the Base of Marine Food Webs. *Global Biogeochemical Cycles*, **34**(2), e2019GB006348, doi:10.1029/2019GB006348.

Zhang, Y. et al., 2021b: Global health effects of future atmospheric mercury emissions. *Nature Communications*, **12**, 3035, doi:10.1038/s41467-021-23391-7.
Zhang, Z., S. Mammola, W. Xian and H. Zhang, 2020c: Modelling the potential impacts of climate change on the distribution of ichthyoplankton in the Yangtze Estuary, China. *Diversity and Distributions*, **26**(1), 126-137, doi:10.1111/ddi.13002.
Zhao, H.-D. et al., 2017: Effects of stratification, organic matter remineralization and bathymetry on summertime oxygen distribution in the Bohai Sea, China. *Continental Shelf Research*, **134**, 15-25, doi:10.1016/j.csr.2016.12.004.
Zhao, Q. et al., 2020a: Where Marine Protected Areas would best represent 30% of ocean biodiversity. *Biological Conservation*, **244**, 108536, doi:10.1016/j.biocon.2020.108536.
Zhao, X. et al., 2020b: Holocene climate change and its influence on early agriculture in the Nile Delta, Egypt. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **547**, 109702, doi:10.1016/j.palaeo.2020.109702.
Zhu, L., 2020: Wave attenuation capacity of suspended aquaculture structures with sugar kelp and mussels. University of Maine, Maine.
Zhu, L. et al., 2020a: Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies. *Coastal Engineering*, **160**, 103737, doi:10.1016/j.coastaleng.2020.103737.
Zhu, Z., Z. Yang and T. J. Bouma, 2020b: Biomechanical properties of marsh vegetation in space and time: effects of salinity, inundation and seasonality. *Annals of Botany*, **125**(2), 277-290, doi:10.1093/aob/mcz063.
Zickgraf, C., 2021: Climate change, slow onset events and human mobility: reviewing the evidence. *Current Opinion in Environmental Sustainability*, **50**, 21-30, doi:10.1016/j.cosust.2020.11.007.
Ziegler, J. et al., 2021: Can ecotourism change community attitudes towards conservation? *Oryx*, **55**(4), 546-555, doi:10.1017/S0030605319000607.
Zimmerman, R. C., 2021: Scaling up: Predicting the Impacts of Climate Change on Seagrass Ecosystems. *Estuaries and Coasts*, **44**(2), 558-576, doi:10.1007/s12237-020-00837-7.
Zunino, S., D. M. Canu, V. Zupo and C. Solidoro, 2019: Direct and indirect impacts of marine acidification on the ecosystem services provided by coralligenous reefs and seagrass systems. *Global Ecology and Conservation*, **18**, e00625, doi:10.1016/j.gecco.2019.e00625.
Zunino, S., D. Melaku Canu, F. Marangon and S. Troiano, 2020: Cultural ecosystem services provided by coralligenous assemblages and *Posidonia Oceanica* in the Italian seas. *Frontiers in Marine Science*, **6**, 823, doi:10.3389/fmars.2019.00823.
Zupan, M. et al., 2018: How good is your marine protected area at curbing threats? *Biological Conservation*, **221**, 237-245, doi:10.1016/j.biocon.2018.03.013.

Chapter 4: Water

Coordinating Lead Authors: Martina Angela Caretta (Sweden), Aditi Mukherji (India)

Lead Authors: Md Arfanuzzaman (Bangladesh), Richard A. Betts (United Kingdom), Alexander Gelfan (Russian Federation), Yukiko Hirabayashi (Japan), Tabea Katharina Lissner (Germany), Elena Lopez Gunn (Spain), Junguo Liu (China), Ruth Morgan (Australia), Sixbert Mwanga (Tanzania), Seree Supratid (Thailand)

Contributing Authors: Malcolm Araos (Canada/USA), Soumya Balasubramanya (Sri Lanka/India), Angelica Katharina Casparina Brackel (The Netherlands), John Caesar (United Kingdom), Holly B. Caggiano (USA), Benjamin Cook (USA), Constantino Dockendorff (Germany/Chile), Calynn Dowler (USA), Robert Dunn (UK/Germany), Lina Elisabeth Erika Eklund (Sweden), Zhang Fan (China), Valeria Fanghella (Italy), Colin M. Finlayson (Australia), Sabine Fuss (Germany), Animesh Kumar Gain (Italy/Bangladesh), Freya Garry (United Kingdom), Laila Gohar (United Kingdom), Valentin Golosov (Russian Federation), Sharlene Liane Gomes (The Netherlands/Canada), Benjamin Jerome Gray (USA), Lukas Gudmundsson (Switzerland/Germany/Iceland), Tania Guillen Bolaneos (Germany/Nicaragua), Kate Halladay (United Kingdom), Ed Hawkins (United Kingdom), Greeshma Hegde (India), Masoud Irannezhad (China/Iran), Bjørn Kløve (Finland/Norway), Aristeidis G. Koutroulis (Greece), Manish Kumar (India), Jonathan Lautze (South Africa/USA), Deborah Ley (Mexico/Guatemala), Ashwina Mahanti (India), Ganquan Mao (China), Deborah McGregor (Canada), Mamta Mehar (India), Megan Mills-Novoa (USA), Tessa Möller (Germany/Luxemburg), Sanchari Mukhopadhyay (India), Tero Mustonen (Finland), Lakshmikantha N R (India), Gustavo Naumann (Italy/Argentina/Germany), Prajjwal Kumar Panday (USA/Nepal), Vishnu Prasad Pandey (Nepal), Jagadish Parajuli (USA/Nepal), Assela Pathirana (Netherlands/Sri Lanka), Ritu Priya (India), B. Uday Bhaskar Reddy (India), Ekaterina Rets (Russian Federation), Rodrigo Fernandez Reynosa (USA/Guatemala), Pamela Rittelmeyer (USA), Conrado M. Rudorff (Brazil), Orie Sasaki (Japan), Corinne Schuster Wallace (Canada/Wales), Christopher A. Scott (USA), Cydney Kate Seigerman (USA), Sonali Senaratna Sellamuttu (Myanmar/Sri Lanka), Rinan Shah (India), Mohammad Shamsudduha (United Kingdom/Bangladesh), Gitta Shrestha (Nepal), Afreen Siddiqui (USA/Pakistan), Balsher Singh Sidhu (Canada/India), Aprajita Singh (USA/India), Anna Sinisalo (Norway/Finland), Francesca Spagnuolo (Italy), Jaishri Srinivasan (USA/India), Makere Stewart-Harawira (Canada/New Zealand), Debra Tan (Hong Kong, Special Administrative Region, China/Malaysia), Masahiro Tanoue (Japan), Brock Ternes (USA), William Rigoberto Delgado Thompson (USA/United Kingdom/Mexico), Peter Uhe (United Kingdom/Australia), Astrid Ulloa (Colombia), Nicole van Maanen (Germany/The Netherlands), Shuchi Vora (India), Yashoda Yashoda (India)

Review Editors: Blanca Elena Jimenez Cisneros (France/Mexico), Zbigniew Kundzewicz (Poland)

Chapter Scientists: Vishnu Prasad Pandey (Nepal), Rodrigo Fernandez Reynosa (USA/Guatemala)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

This chapter assesses observed and projected climate-induced changes in the water cycle, their current impacts and future risks on human and natural systems and the benefits and effectiveness of water-related adaptation efforts now and in the future.

Currently, ~4 billion out of 7.8 billion people are estimated to experience severe water scarcity for at least one month per year due to climatic and non-climatic factors *(medium confidence*[1]*)*. Since the 1970s, 44% of all disaster events have been flood-related. Not surprisingly, a large share of adaptation interventions (~60%) is forged in response to water-related hazards *(high confidence).* {4.1, Box 4.1, 4.2.1.1, 4.2.1.2, 4.2.2, 4.2.4, 4.2.5, 4.2.6, 4.3.8, 4.6, 4.7}

Intensification of the hydrological cycle due to human-induced climate change is affecting physical aspects of water security *(high confidence),* thereby exacerbating existing water-related vulnerabilities caused by other socioeconomic factors. {4.2, 4.2.1.1, 4.2.1.2, 4.2.1.3, 4.2.2, 4.2.4, 4.2.5, 4.2.6, 4.3}

Nearly half a billion people live in unfamiliarly wet areas, where the long-term average precipitation is as high as previously seen in only about one in six years *(medium confidence)*. Approximately 163 million people live in unfamiliarly dry areas now *(medium confidence).* {4.2.1.1}

The intensity of heavy precipitation has increased in many regions since the 1950s *(high confidence).* Substantially more people (~709 million) live in regions where annual maximum one-day precipitation has increased than regions where it has decreased (~86 million) *(medium confidence)*. At the same time, more people (~700 million) are also experiencing longer dry spells than shorter dry spells since the 1950s *(medium confidence).* {4.2.1.1}

During the last two decades, the global glacier mass loss rate exceeded 0.5 meters water equivalent year^{-1} (*high confidence*), impacting humans and ecosystems, including cultural uses of water among vulnerable high mountain and polar communities *(high confidence).* {4.2.2, 4.3.8}

There is a clear trend of increases in streamflow in the northern higher latitudes *(high confidence),* with climatic factors being more important than direct human influence in a larger share of major global basins *(medium confidence)*. At the same time, groundwater in aquifers across the tropics has experienced enhanced episodic recharge from intense precipitation and flooding events *(medium confidence)*, with implications for sectoral water use. {4.2.3, 4.2.6, 4.3.1, 4.3.4}

Extreme weather events causing highly impactful floods and droughts have become more likely and (or) more severe due to anthropogenic climate change *(high confidence).* {4.2.4, 4.2.5, Cross-Chapter Box DISASTER in Chapter 4}

Anthropogenic climate change has contributed to the increased likelihood and severity of the impact of droughts (especially agricultural and hydrological droughts) in many regions *(high confidence).* Between 1970 to 2019, 7% of all disaster events worldwide were drought-related. Yet, they contributed to 34% of disaster-related deaths, mostly in Africa. {4.2.5, 4.3.1, 4.3.2, Cross-Chapter Box DISASTER in Chapter 4}

Several recent heavy rainfall events, such as in western Europe, China, Japan, the United States, Peru, Brazil and Australia that led to substantial flooding, were made more likely by anthropogenic climate change *(high confidence)*. There is *high confidence* that the warming in the last 40-60 years has led to ~10 days earlier spring floods per decade. Between 1970 to 2019, 31% of all economic losses were flood-related. {4.2.4, Cross-Chapter Box DISASTER in Chapter 4}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

There is increasing evidence of observed changes in hydrological cycle on people and ecosystems. A significant share of those impacts is negative and felt disproportionately by already vulnerable communities *(high confidence).* {4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5,4.3.6, 4.3.8}

Agriculture and energy production have been impacted by changes in the hydrological cycle *(high confidence)*. Between 1983 and 2009, approximately three-quarters of the global harvested areas (~454 million hectares) experienced yield losses induced by meteorological drought, with the cumulative production losses corresponding to the US $166 billion. There is *medium confidence* that current global thermoelectric and hydropower production has been negatively affected due to droughts with ~4 to 5% reduction in plant utilization rates during drought years compared to long-term average values since the 1980s. {4.3.1, 4.3.2}

Climate change and changes in land use and water pollution are key drivers of loss and degradation of freshwater ecosystems *(high confidence),* with impacts observed on culturally significant terrestrial and freshwater species and ecosystems in the Arctic, high mountain areas *(high confidence)*. In addition, precipitation and extreme weather events are linked to increased incidence and outbreaks of water-related diseases *(high confidence).* {4.3.3, 4.3.4, 4.3.5, 4.3.8}

Changes in water-related hazards disproportionately impact vulnerable populations such as the poor, women, children, Indigenous Peoples, and the elderly in all locations, especially in the Global South, due to systemic inequities stemming from historical, socioeconomic and political marginalization *(medium confidence).* {4.3.1, 4.3.3, 4.3.4, 4.3.8}

Water-related risks are projected to increase with every degree of global warming *(high confidence)*, and more vulnerable and exposed regions and peoples are projected to face greater risks *(medium confidence).* {Box 4.1, 4.4.1, 4.4.1.1, 4.4.4, 4.5.4, 4.5.5, 4.5.6, Box 4.2}

Climate change impacts via water availability changes are projected to increase with every degree of global warming *(high confidence)*, but there are high regional uncertainties. Between 3 to 4 billion people are projected to be exposed to physical water scarcity at 2°C and 4°C global warming levels (GWL), respectively *(medium confidence).* {Box.4.1; 4.4.1, 4.4.3, 4.4.5, 4.6.1}

By 2100, 1/3rd of the 56 large-scale glacierized catchments are projected to experience a mean annual run-off decline by over 10%, with the most significant reductions in Central Asia and Andes (*medium confidence)*. Expected impacts may be felt by roughly 1.5 billion people who are projected to critically depend on run-off from the mountains by the mid-21st century (RCP6.0 scenario). {4.4.2, 4.4.3, 4.5.8}

By 2050, environmentally critical streamflow is projected to be affected in 42% to 79% of the world's watersheds, causing negative impacts on freshwater ecosystems *(medium confidence)*. Modified streamflow is also projected to affect inflows to urban storage reservoirs and increase the vulnerability of urban water services to hydro-meteorological extremes, particularly in less developed countries *(high confidence)*. {4.4.6, 4.5.4, 4.4.5}

Future water-related impacts of climate change on various sectors of the economy are projected to lower global Gross Domestic Product (GDP) (ranging from 0.49% of GDP by mid-century (SSP3) to less than 0.1% (RCP8.5, SSP5), with higher projected losses expected in low-and middle-income countries *(medium confidence).* {4.7.5}

Drought and flood risks and societal damages are projected to increase with every degree of global warming *(medium confidence).* {4.4.4, 4.4.5, 4.4.7, 4.5.1, 4.5.2}

Drought risks are projected to increase over the 21st century in many regions *(very high confidence)*, increasing economy-wide risks *(high confidence)*. With RCP6.0 and SSP2, the global population exposed to extreme-to-exceptional total water storage drought is projected to increase from 3% to 8% over the 21st century *(medium confidence).* {4.4.5}

The projected increase in precipitation intensity *(high confidence)* will increase rain-generated local flooding *(medium confidence)*. Direct flood damages are projected to increase by 4 to 5 times at 4°C compared to 1.5°C *(medium confidence).* {Box 4.1, 4.4.1, 4.4.1.1, 4.4.4, 4.5.4, 4.5.5}

At 4°C global warming by the end of the century, approximately 10 % of the global land area is projected to face simultaneously increasing high extreme streamflow and decreasing low extreme streamflow, affecting roughly over 2.1 billion people *(medium confidence). {4.4.3}.* The increase in extreme events is projected to compromise the efficacy of WaSH services and slow progress towards reductions in WaSH-related disease burdens *(medium confidence).* {4.5.3}

Limiting global warming to 1.5°C would reduce water-related risks across regions and sectors *(high confidence). {*4.4.2, 4.4.5, 4.5.2, 4.5.3, 4.5.4, 4.5.6, 4.5.7, 4.6.1, 4.7.2}

Projected increases in hydrological extremes pose increasing risks, with a potential doubling of flood risk between 1.5°C and 3°C of warming and an estimated 120% to 400% increase in population at risk of river flooding at 2°C and 4°C, respectively. Projected losses include a 1.2 to 1.8-fold increase in GDP loss due to flooding between 1.5°C and 2°C warming *(medium confidence).* {4.4.3, 4.4.4, 4.4.5, 4.5.6, 4.6.1, 4.7.2}

Over large areas of northern South America, the Mediterranean, western China and high latitudes in North America and Eurasia, extreme agricultural drought are projected to be at least twice as likely at 1.5°C global warming, 150 to 200% more likely at 2°C warming, and over 200% at 4°C *(medium confidence)*. Due to the combined effects of water and temperature changes, risks to agricultural yields could be three times higher at 3°C compared to 2°C *(medium confidence).* {4.5.1, 4.6.1}

In Mediterranean parts of Europe, hydropower potential reductions of up to 40% are projected under 3°C warming, while declines below 10% and 5% are projected under 2°C and 1.5°C warming levels, respectively.

Climate-induced hydrological changes are projected to increase migration in the last half of the century, with an almost 7-fold increase in asylum seekers to the EU for RP4.5 compared to RCP2.6. The number of internally displaced people in Sub-Saharan Africa, South Asia and Latin America increased almost 5 times for RCP 8.5 compared to RCP2.6 (*low confidence).* {4.5.7}

Observed water adaptation responses have multiple benefits *(high confidence)*, yet evidence of effectiveness of adaptation in reducing climate risks is not clear due to methodological challenges *(medium confidence)*. {4.6, 4.7.1, 4.7.3}

A large share of adaptation interventions (~60%) are shaped in response to water-related hazards *(high confidence)* and involve water interventions (irrigation, rainwater harvesting, soil moisture conservation). Adaptation responses in developing countries tend to be autonomous, incremental and focused on managing water-related risks in agriculture. In contrast, responses are more policy-oriented and urban-focused in developed countries *(high confidence).* {4.6.2, box 4.3, 4.6.5, 4.7.1, 4.7.2}

Irrigation helps stabilise and increase crop yields and is often a preferred strategy for farmers and policymakers for risk reduction, but irrigation is also associated with a range of adverse outcomes, including groundwater over-extraction (*medium confidence*). In addition, large-scale irrigation also affects local to regional climates, both in terms of temperature and precipitation change (*high confidence*) {4.2.6, 4.6.2, Box. 4.2}.

Water adaptation measures tend to have positive economic and environmental outcomes in developing and developed countries, respectively *(high confidence).* Roughly 1/3rd and 1/4th of case studies on water adaptation also documents maladaptation and co-benefits, respectively *(high confidence).* A significant knowledge gap remains in knowing if observed adaptation benefits also translate to climate risk reduction, if so, by how much and under what conditions *(medium confidence).* {4.7.1, 4.7.2, 4.7.4}

Future projected adaptations are effective in reducing risks to a varying extent *(medium confidence)*, but effectiveness falls sharply beyond 2°C, underscoring the need for limiting warming to 1.5°C *(high confidence).* {4.6, 4.7.2, 4.7.3}

Adaptations that are beneficial now (e.g., crop and water-related ones) are also projected to effectively reduce specific future risks to a moderate to a large extent *(medium confidence)*. However, residual impacts remain for some options and regions at all levels of warming, and the overall effectiveness decreases at higher warming levels *(high confidence)*, further underscoring the need for limiting warming to 1.5°C. {Box 4.2, 4.7.1, 4.7.2, 4.7.3, 4.7.4}

At warming levels beyond 1.5°C, the potential to reach biophysical limits to adaptation due to limited water resources are reported for Small Islands (*medium confidence*) and regions dependent on glaciers and snowmelt (*medium confidence*). {4.7.4}

Water security is critical for meeting Sustainable Development Goals (SDGs) and systems transitions needed for climate-resilient development, yet many mitigation measures have high water footprint which can compromise SDGs and adaptation outcomes *(high confidence)*. {4.1, Box 4.4, 4.6, 4.6.2, 4.6.3, 4.7, 4.7.1, 4.7.4, 4.7.5.7}

Water features prominently in Nationally Determined Contributions (NDCs) and National Adaptation Plans of most countries. SDGs cannot be met without adequate and safe water *(high confidence),* and water is fundamental to all systems transition *(high confidence)*. {4.1, 4.7, 4.7.1, 4.8, 4.8.7}

Water garners a significant share of public and private adaptation funds *(high confidence)*. However, barriers remain for low-income countries to access funds *(medium confidence)*, and there is insufficient evidence on benefits for marginalized groups *(medium confidence). {4.8.2}*

Many mitigation measures, such as carbon capture and storage, bio-energy, and afforestation and reforestation, can have a high-water footprint (*high confidence*). The water intensity of mitigation must be managed in socially and politically acceptable ways to increase synergies with SDGs, improve water security, and reduce trade-offs with adaptation *(medium confidence)*. {4.7.6}

A common set of enabling principles underpinned by strong political support can help meet the triple goals of water security, sustainable and climate-resilient development *(high confidence*) *{4.8, 4.8.3, 4.8.4. 4.8.5, 4.8.6, 4.8.7*

Many countries and social groups most threatened by climate change have contributed the least to the problem and do not have the adequate resources to adapt *(high confidence)*. Water adaptation policies enabled through ethical co-production between holders of Indigenous Knowledge, local knowledge and technical knowledge *(medium confidence)*; through cooperation and coordinated actions among multiple actors, including women and all marginalized groups, at various levels of governance *(medium confidence)* is needed for effective transitions towards Climate Resilient Development. {4.8, 4.8.3,4.8.4, 4.8.5, 4.8.6}

4.1 Centrality of Water Security in Climate Change and Climate Resilient Development

Water security is defined as "*the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*" (Grey and Sadoff (2007)). Risks emanating from various aspects of water insecurity have emerged as a significant global challenge. The Global Risks Report by the World Economic Forum lists water crisis as one of the top five risks in all its reports since 2015 (WEF, 2015; WEF, 2016; WEF, 2017; WEF, 2018; WEF, 2019; WEF, 2020). Water also features prominently in the Sustainable Development Goals (SDGs) (4.8) and plays a central role in various systems transitions needed for climate-resilient development. Most SDGs cannot be met without access to adequate and safe water (Ait-Kadi, 2016; Mugagga, 2016}. In addition, without adequate adaptation, future water-related impacts of climate change on various sectors of the economy are projected to lower global gross domestic product (GDP) by mid-century, with higher projected losses expected in low-and middle-income countries (World Bank, 2017; GCA, 2019).

There are at least four reasons for the centrality of water security in adapting to, and mitigating climate change.

First, approximately half the world's population (~4 billion out of 7.8 billion people) are assessed as being currently subject to severe water scarcity for at least one month per year (*medium confidence*) due to climatic and non-climate factors (Box 4.1). Water insecurity arises from many factors, both environmental and societal. Environmental factors include too little freshwater due to drought or pollution, and too much water, due to extreme precipitation and flooding, and are being affected by climate change. Societal factors include economic and governance-related barriers to water access or protection from water-related damages. Currently, many people are experiencing climate change on a day to day basis through water-related impacts such as the increased frequency and intensity of heavy precipitation (*high confidence*) (4.2.1.1, WGI 11.4.2); accelerated melting of glaciers (*high confidence*) (4.2.2, WGI 8.3.1); changes in frequency, magnitude and timing of floods (*high confidence*) (4.2.4, WGI 11.5.2); more frequent and severe droughts in some places (*high confidence*) (4.2.5, WGI 11.6.2); decline in groundwater storage and reduction in recharge (*medium confidence*) (4.2.6, WGI 8.3.1) and water quality deterioration due to extreme events (*medium confidence*) (4.2.7). For example, since the 1970s, 44% of all disaster events have been flood-related (WMO, 2020). With the added stressor of climate change, globally, a larger fraction of land and population are projected to face increased water scarcity due to climate change. For example, at approximately 2°C global warming level (GWL), between 0.9 and 3.9 billion people are projected to be at increased exposure to water stress, depending on regional patterns of climate change and the socio-economic scenarios considered (Koutroulis et al., 2019).

Second, while climate change directly affects freshwater availability across space and time, it also affects water requirements for different uses, such as irrigation, potentially adding to existing societal challenges (Bijl et al., 2018). Vulnerability to water-related impacts of climate change and extreme weather are already felt in all major sectors and are projected to intensify in the future, e.g., in agriculture (*high confidence*) (4.3.1, 4.5.1); energy and industry (*high confidence* for observed drought impacts and projected impacts) (4.3.2, 4.5.2); water for health and sanitation (*high confidence* about links to precipitation extremes and disease outbreaks) (4.3.3, 4.5.3); water for urban, peri-urban and municipal sectors (*medium confidence*) (4.3.4, 4.5.4) and freshwater ecosystems (*high confidence* in climate change as a driver in degradation of freshwater ecosystems) (4.3.5, 4.5.5). Agriculture and irrigation account for the most significant proportion of consumptive water use and accounts for 60-70% of total water withdrawals (Hanasaki et al., 2018; Burke et al., 2020; Müller Schmied et al., 2021). Globally, 10% of the most water-stressed basins account for 35% of global irrigated calorie production (Qin et al., 2019), and food production is at risk in those basins, and worldwide due to changes in hydrological components of climate change. Lack of access to clean water and sanitation has been one of the leading causes of water-borne diseases. In 2017, approximately 2.2 billion people lacked access to safe drinking water, and roughly 4.2 billion people could not access safe sanitation (WHO and UNICEF, 2019). Inequities in access to safe water are being amplified during the current COVID-19 pandemic (Box 4. 5 and Cross-Chapter Box COVID in Chapter 7). The same 10% of most water-stressed basins also account for 19% of global thermal electricity generation (Qin et al., 2019), and globally, both production of hydropower and thermal power has been negatively affected by droughts and other extreme events. Globally, between 16% and 39% of cities experienced surface-water deficits between 1971-2000. If environmental flow requirements (EFRs) are accounted for, these numbers increase to 36% and 63%, respectively. Even under a scenario where urban water gets the highest priority, more than 440.5 million people in cities globally are projected to face a water deficit by 2050 (Flörke et al., 2018). The situation is particularly precarious in the Global South, where most of the population lacks access to piped water (WRI, 2019).

Third, a large majority (~60%) of all adaptation responses documented since 2014 are about adapting to water-related hazards like droughts, floods and rainfall variability (Berrang-Ford et al., 2021b) (*high confidence*). Water-related adaptation action features prominently in nationally determined contributions (NDC) pledges by a large majority of countries in both Global North and Global South (GWP, 2018). These adaptation responses and their current benefits and effectiveness in reducing water-related risks in the future are systematically assessed in this chapter (4.6, 4.7.1, 4.7.2 and 4.7.3). These adaptation measures aim to reduce impacts of water-related hazards through responses such as irrigation, water and soil moisture conservation, rainwater harvesting, changes in crops and cultivars, improved agronomic practices, among others (4.6.2; 4.7.1). Only ~20% of all documented case studies on observed water-related adaptations measure outcomes (positive or negative), but the link between positive outcomes and climate risk reduction is unclear and remains challenging to assess (4.7.1) (*medium confidence*). On the other hand, most of the future projected water-related adaptations are effective at lower global warming levels (GWLs) (1.5°C) than at higher GWLs showing the importance of mitigation for future adaptations to remain effective (*high confidence*).

Finally, while limiting global warming to 1.5°C would minimize the increase in risks in the various water use sectors and keep adaptation effective, many mitigation measures can potentially impact future water security. For example, bioenergy with carbon capture and storage (BECCS) and afforestation and reforestation can have a considerable water footprint if done at inappropriate locations (4.7.6, see also Canadell et al. (2021)). Therefore, minimizing the risks to water security from climate change will require a full-systems view that considers the direct impacts of mitigation measures on water resources and their indirect effect via limiting climate change (*high confidence*).

This chapter draws on previous IPCC reports and new methodologies (4.1.1 and SM4.1, SM4.2) and assesses the impacts of climate change on natural and human dimensions of the water cycle with a particular focus on water-related vulnerabilities and adaptation responses (Figure 4.1). Section 4.2 assesses observed changes in the hydrological cycle, and Section 4.3 focuses on their societal impacts and detects which parts of these changes are directly attributable to climate change. Section 4.4 assesses projected risks of changes in the hydrological cycle on various components of the hydrological cycle, and Section 4.5 assesses the same for sectoral risks. Projections and risks assessments for future impacts are framed in terms of GWLs and time horizons, as these are useful for informing mitigation policy under the Paris Agreement and informing adaptation planning. Sections 4.6 and 4.7 assesses current and future water-related adaptation responses in reducing climate and associated impacts and risks and looks at limits to adaptations, especially in a future warmer world. Finally, Section 4.8 outlines the enabling principles for meeting water security, sustainable development goals and climate-resilient development.

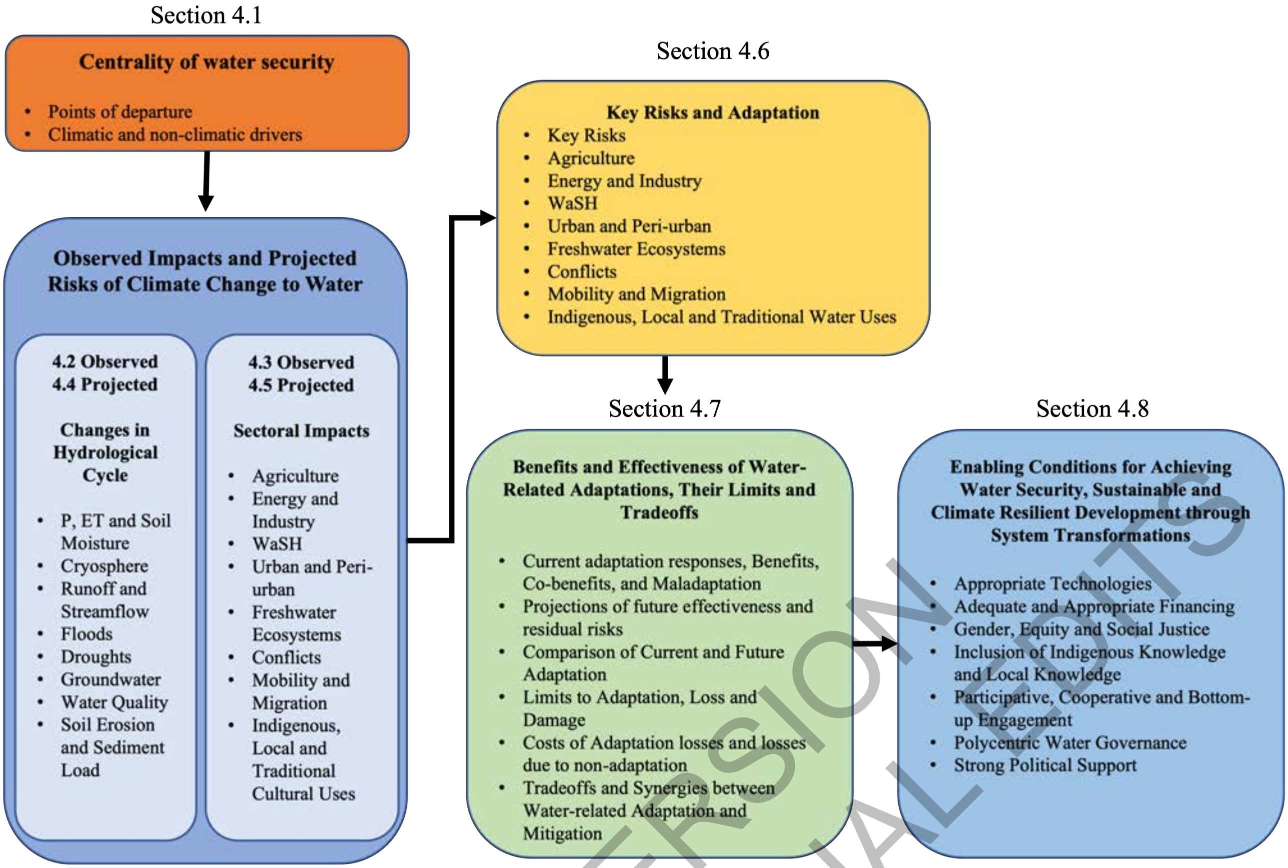


Figure 4.1: Chapter structure.

[START BOX 4.1 HERE]

Box 4.1: Implications of Climate Change for Water Scarcity and Water Insecurity

Water scarcity and water insecurity are related concepts but not identical, and each has a range of interpretations leading to some overlap. Water scarcity can be broadly described as a mismatch between the demand for fresh water and its availability, quantified in physical terms. Water security/insecurity is a broader concept with definitions beyond physical water scarcity, encompassing access to water services, safety from poor water quality and flooding, and appropriate water governance that ensures access to safe water (Sadoff et al., 2020). Metrics of water security include both physical and socio-economic components and are a tool for comparison between different locations and countries regarding relative levels of water security in the context of water-related risks. Some definitions of water scarcity also incorporate these broader issues. For example, 'economic water scarcity' has been defined as a situation where "human, institutional, and financial capital limit access to water, even though water in nature is available locally to meet human demands" (Comprehensive Assessment of Water Management in Agriculture, 2007). Economic water scarcity can also occur where infrastructure exists, but water distribution is inequitable (Jaeger et al., 2017). Much of the literature exploring the impacts of climate change on water security, however, focuses on quantifying physical water scarcity. Discussions in this box consider physical water scarcity as a quantifiable measure of water availability compared to its demand and consider the societal elements of economic water scarcity to be part of the more comprehensive concept of water insecurity.

Physical water scarcity

Definitions of water scarcity have evolved to take account of a broader set of factors. For example, physical water scarcity indicates that an insufficient quantity of water is available to meet requirements. A commonly-used measure of physical water scarcity is the Falkenmark index which measures the amount of renewable freshwater available per capita (Falkenmark et al., 1989; White et al., 2014). However, the Falkenmark index is now regarded as an incomplete measure, as it does not account for water needed for non-human needs (as quantified with Environmental Flow Requirements, EFRs). Therefore, EFRs have begun to be incorporated in recent water scarcity assessments (Liu et al., 2016; Liu et al., 2017b). Quality-induced water scarcity is an additional factor beginning to be considered (Liu J. and D., 2020).

Using a Water Scarcity Index (WSI) defined as the ratio of demand and availability, accounting for EFRs, it is estimated that 4 billion people live under conditions of severe water scarcity for at least one month per year (Figure Box 4.1.1(a): (Mekonnen and Hoekstra, 2016)). Nearly half of these people live in India and China. Although regions with high water scarcity are already naturally dry (*virtually certain*[2]), human influence on climate is leading to reduced water availability in many regions. It is *very likely* that global patterns of soil moisture change are being driven by human influence on climate, and an overall global decline in soil moisture is attributable to greenhouse forcing [4.2.1.3]. Climate-change patterns of streamflow change include declines in western North America, north-east South America, the Mediterranean and South Asia (*medium confidence*) [4.2.3]. However, quantification of the contribution of anthropogenic climate change to current levels of water scarcity is not yet available.

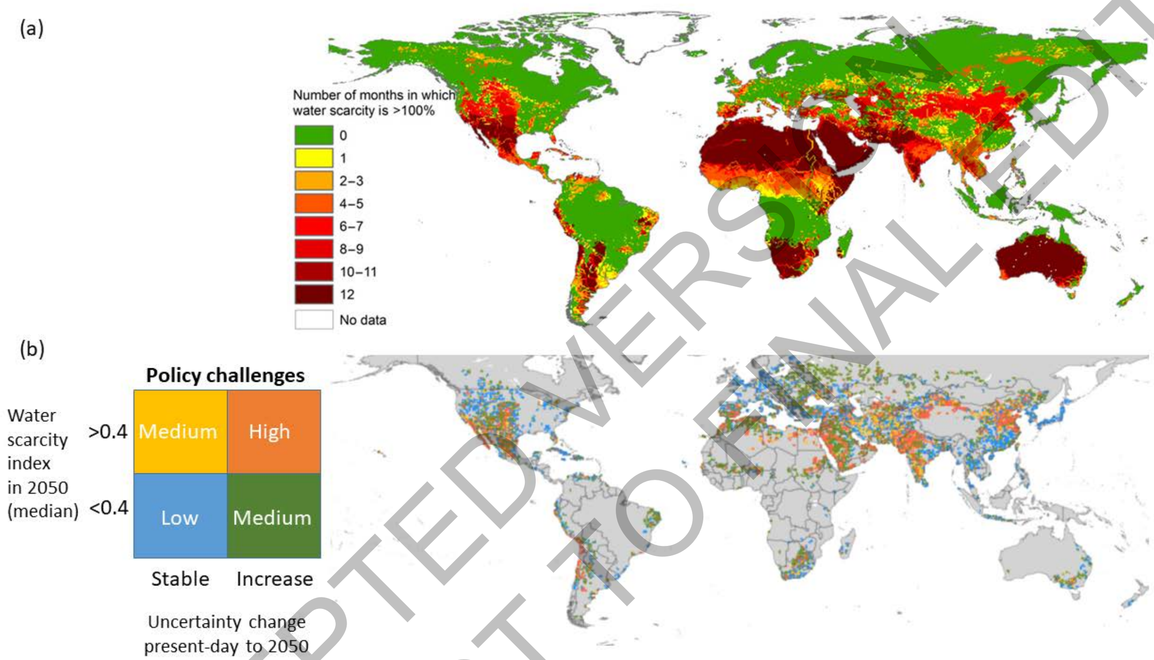


Figure Box 4.1.1: Geographical distributions of current water scarcity and levels of challenge for policies addressing future change. (a) The number of months per year with severe water scarcity (ratio of water demand to availability > 1.0). Reproduced from (Mekonnen and Hoekstra, 2016). (b) Local levels of policy challenges for addressing water scarcity by 2050, considering both the central estimate (median) and the change uncertainty in projections of a Water Scarcity Index (WSI) from the present day to 2050 (Greve et al., 2018). Projections used five CMIP5 climate models, three global hydrological models from ISIMIP, and three Shared Socioeconomic Pathways (SSPs). Levels of policy challenges refer to the scale and nature of policies to address water scarcity and range from monitoring and reviewing risks ('low') through transitional changes in water systems ('medium') to transformational changes ('high'). Low policy challenges arise when the projected water scarcity in 2050 is lower (< 0.4), and the level of uncertainty remains relatively stable in future projections. Medium policy challenge arises when either the central estimate of water scarcity remains low, but uncertainty increases or the uncertainty is stable, but the central estimate of water scarcity for 2050 is higher (>0.4). High policy challenges arise when the central estimate of water scarcity is higher and the uncertainty increases. Grey areas show gridpoints defined as non-water scarce (75th quantile of the WSI < 0.1 at all times) or very low average water demand. Hatched areas show countries with no data for at least one component. Reproduced from (Greve et al., 2018).

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

Water demand is projected to change as a direct result of socio-economic changes. For example, the global water demand for domestic, industrial and agricultural uses, presently about 4,600 km³ per year, is projected to increase by 20% to 30% by 2050 (Greve et al., 2018), depending on the socio-economic scenario. Changes in water availability and demand have been projected in several studies using climate models and socio-economic scenarios (e.g., (Arnell and Lloyd-Hughes, 2014; Gosling and Arnell, 2016; Greve et al., 2018; Koutroulis et al., 2019)). In such studies, the projected changes in water availability arise from differences in precipitation (P) and evapotranspiration (ET). However, both P and ET are also subject to very high uncertainty in key processes such as regional climate change patterns (Uhe et al., 2021) and the influence of vegetation responses to elevated CO_2 on transpiration (Betts et al., 2015).

Human factors are projected to be the dominant driver of future water scarcity on a global scale (Graham et al., 2020a). However, at regional scales, high uncertainty in climate changes means that reduced water availability is *more likely than not* in many major river basins and remains a risk in most basins even where the central estimate is for increased water availability due to climate change (Figure 4.12). Such substantial uncertainties in projected water scarcity are crucial factors causing water management policies and planning challenges in the future. Therefore, locations projected to see significant increases in water scarcity with large uncertainty can be considered to be subject to the highest challenges for water management policy (Figure Box 4.1.1(b): (Greve et al., 2018)).

Water security and insecurity

Unlike physical water scarcity, water security or insecurity cannot be quantified in absolute terms. However, relative levels of water security in different places can be compared using metrics representing critical aspects of security (Gain et al., 2016; Young et al., 2019), ideally with thresholds for secure/insecure compared with local experience to assess validity (Young et al., 2019).

(Gain et al., 2016) define a Global Water Security Index (GWSI) metric on a scale of 0 to 1 combining indicators of relative levels of availability of freshwater, accessibility to water services, water management, and water quality and safety (including flood risk, which can affect water quality as well as being a direct physical hazard). Global application of this index indicates large worldwide differences in water security arising from different combinations of reasons (Figure Box 4.1.2(a)). In North Africa, the Middle East, large parts of the Indian Subcontinent and north China, low water security arises predominantly from low water availability. However, many areas with relatively high-water availability have relatively low levels of water security due to other factors. In 2015, 29% of the world's population did not have access to safe drinking water (Ritchie and Roser, 2019). In large parts of South and South-East Asia, significant contributions to water insecurity came from increased flood risk and deteriorated water quality (Burgess et al., 2010; Ward et al., 2017; Farinosi et al., 2018). Water availability is relatively high across most of Africa, but water security is relatively low due to low accessibility, management, and safety/quality standards. Most people in Africa do not have access to safe drinking water and improved sanitation (Marson and Savin, 2015; Naik, 2017; Armah et al., 2018).

In contrast, some high physical water scarcity areas, such as some parts of the USA, Australia, and Southern Europe, show relatively high-water security levels due to good governance, safety and quality, and accessibility. Nevertheless, marginalized groups such as Indigenous Peoples experience reduced access to water even within regions in the Global North. For example, in both Canada and the US, many Indigenous Peoples living on reserves lack access to piped water (Collins et al., 2017; Hanrahan, 2017; Marshall et al., 2018) and (or) are on boil water advisories (Patrick et al., 2019). In Australia, 25-40% of Aboriginal people live in remote rural areas with poor access to clean water (Bowles, 2015; NCCARF, 2018).

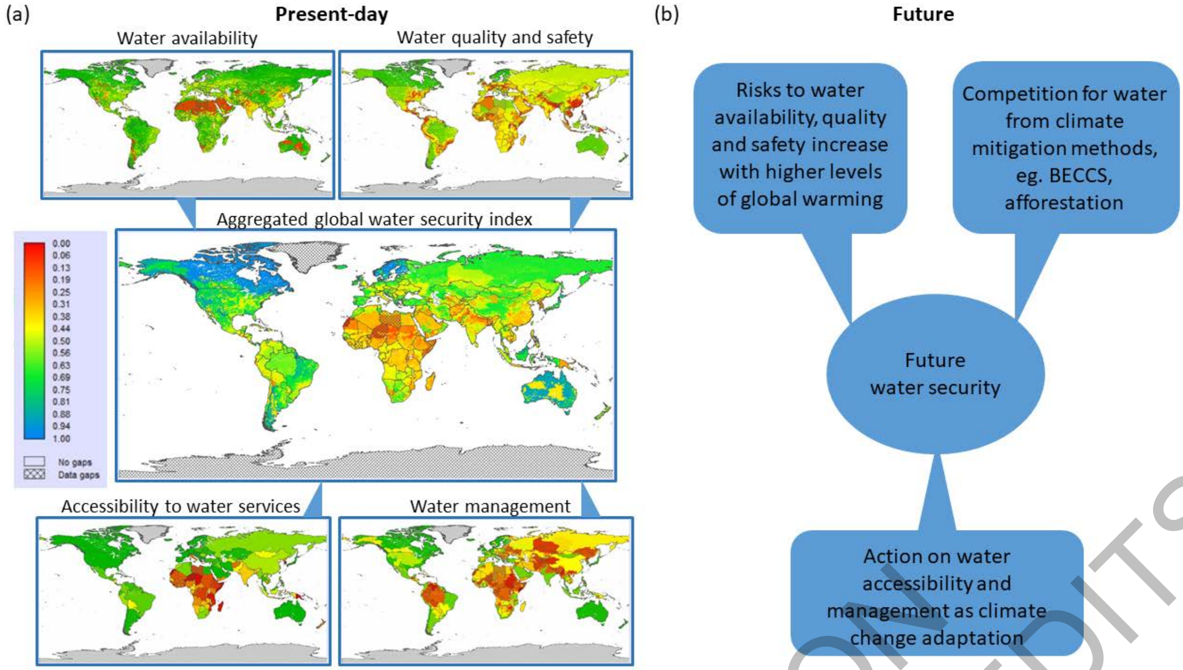


Figure Box 4.1.2: Global Water Security Index (GWSI) and its components for the present day, and factors affecting future change in water security. Low values (red) indicate the lowest levels of water security (a) Centre: a global map of local values of GWSI, constructed from the following components with their subjectively-weighted contribution to the combined metric indicated in brackets. Top left: relative availability of fresh water (45%), comprising a Water Scarcity Index, Drought Index and the groundwater depletion rate. Top right: relative accessibility to water services (20%), including drinking water and sanitation. Bottom left: relative water quality and safety (20%), including a water quality index and flood frequency index. Bottom right: relative effectiveness of water management (15%), comprising a World Governance index at country scale (itself representing six components: Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption) and indicators of transboundary legal frameworks and political tensions at a river basin scale. Data for the components do not apply to the same set of dates but are generally applicable to recent decades up to 2010. For further details, see (Gain et al., 2016). (b) Factors through which climate change or action on mitigation or adaptation could influence water security.

The discrepancy between physical water scarcity and overall water insecurity is a function of socio-economic vulnerabilities and governance gaps. Therefore, improving societal aspects of water management will be key in adapting to climate change-driven increases in water scarcity in the future (*high confidence*).

Future water security will depend on the magnitude, rate and regional details of future climate change and non-climatic factors, including agricultural practices, water demand, governance. In many cases, climate change may not be the dominant factor affecting water security. Nevertheless, climate change poses clear risks to water security in many regions through potential impacts on water availability, quality, and flooding. The range of possible outcomes is extremely large, and assessing the likelihood of particular outcomes depends on consideration of uncertain regional climate changes and uncertain socio-economic futures. Uncertainty in future water scarcity projections makes climate change risks to water security and planning for adaptation challenging. Limiting climate change to lower levels of global warming would reduce the risks to water security arising from climate change, partly because uncertainties in regional climate change is smaller at lower levels of warming.

In summary, approximately 4 billion people are assessed as currently subject to severe water scarcity for at least one month per year due to climatic and non-climatic factors, and this is projected to exacerbate at higher levels of warming (*medium confidence*). General water insecurity issues are seen worldwide, particularly in South Asia, North China, Africa and the Middle East, due to high population densities often coupled with low water availability, accessibility, quality, and governance (*high confidence*). Areas with high water availability can also be water-insecure due to increased flood risk, deteriorated water quality, and poor governance (*high confidence*). Future water security will depend on the evolution of all these socio-economic and governance factors and future regional climate change (*high confidence*). The main climate change contribution to water insecurity is the potential for reduced water availability, with a secondary contribution from increased flooding risk (*medium confidence*). Future socio-economic conditions are a crucial driver of water insecurity, implying the need for further adaptation to some level of future climate change (*medium confidence*). However, policy challenges are high in many regions, with uncertainty in the regional climate outcomes being a key factor (*high confidence*).

[END BOX 4.1 HERE]

4.1.1 Points of Departure and Advancements since AR5

The Fifth Assessment Report (AR5) concluded that for each degree of global warming, approximately 7% of the global population, under a scenario of moderate population growth, was projected to be exposed to a decrease of renewable water resources of at least 20%. In addition, AR5 reported negative impacts on streamflow volumes, its seasonality (specifically in cryospheric zones), a decline in raw water quality *(medium evidence, high agreement)*, and projected reduction in renewable surface water and groundwater in most dry tropical regions. AR5 projected an increase in meteorological, agricultural and hydrological droughts in dry regions *(medium confidence)* (Jiménez Cisneros et al., 2014).

The Special Report on Global Warming of 1.5°C (SR1.5) assessed that limiting global warming to 1.5°C is expected to substantially reduce the probability of extreme droughts, precipitation deficits and risks associated with water availability in some regions *(medium confidence)*. On the other hand, higher risks to natural and human systems in a 2.0°C world would mean increased vulnerability for the poor, showing that socio-economic drivers are expected to have a more significant influence on water-related risks and vulnerabilities than changes in climate alone *(medium confidence)* (Hoegh-Guldberg et al., 2018).

The Special Report on Oceans and Cryosphere in a Changing Climate (SROCC) confirmed findings from AR5, with *robust evidence* of declines in snow cover and negative mass balance in most glaciers globally. Glacier melting seriously threatens water supply to mountain communities and millions living downstream through water shortages, jeopardizing hydropower generation, irrigation, and urban water uses (Hock et al., 2019b). Additionally, Arctic hydrology and vegetation will be affected by permafrost changes, negatively impacting Arctic communities' health and cultural identity (Meredith et al., 2019).

The Special Report on Climate Change and Land (SRCCL) stated that groundwater over-extraction for irrigation is causing depletion of groundwater storage (*high confidence*). The report also noted that precipitation changes, coupled with human drivers, will have a role in causing desertification, and water-driven soil erosion is projected to increase due to climate change (*medium confidence*). The population vulnerable to impacts related to water is projected to increase progressively at 1.5°C, 2°C and 3°C of global warming, with half of those impacted residing in South Asia, followed by Central Asia, West Africa and East Asia. SRCCL stated that improved irrigation techniques (e.g., drip irrigation) and moisture conservation (e.g., rainwater harvesting using Indigenous and local practices) could increase farmers' adaptive capacity *(high confidence)* (Mirzabaev et al., 2019).

The Sixth Assessment Report (AR6) Working Group I (WGI) (Douville et al., 2021) concluded that anthropogenic climate change has increased atmospheric moisture and precipitation intensity (*very likely* by 2-3% per 1°C) (*high confidence*), increased terrestrial ET (*medium confidence*) and contributed to drying in dry summer climates including in the Mediterranean, southwestern Australia, southwestern South America, South Africa and western North America (*medium to high confidence*), and has caused earlier onset of snowmelt and increased melting of glaciers (*high confidence*) since the mid-20th century. The report also stated with *high confidence* that the water cycle variability and extremes are projected to intensify, regardless of the mitigation policy. The share of the global population affected by water-related hazards and water availability issues is projected to increase with the intensification of water cycle variability and extremes. They concluded with *high confidence* that strong and rapid mitigation initiatives are needed to avert the manifestation of climate change in all components of the global water cycle.

Building on these previous reports, this chapter advances understanding climate change-induced hydrological changes and their societal impacts and risk in several key ways.

First, since AR5, the methodology of climate change impact studies has advanced and these methodological advances are described in SM4.1. AR6 uses new projections (CMIP6) based on the SSPs and other scenarios and we assess those results in this chapter alongside those using other projections and scenarios.

Second, this chapter follows the developments set in motion by SR 1.5, SRCCL and SROCC to incorporate Indigenous Knowledge (IK), traditional knowledge (TK) and local knowledge (LK). SR 1.5 stated that disadvantaged and vulnerable populations, including Indigenous Peoples and certain local communities, are at disproportionately higher risk of suffering adverse consequences due to global warming of 1.5°C or more (Roy et al., 2018). SRCCL highlighted the enhanced efficacy of decision-making and governance with the involvement of local stakeholders, particularly those most vulnerable to climate change, such as Indigenous Peoples (Arneth et al., 2019). SROCC found adaptation efforts have benefited from the inclusion of IK and LK (Abram et al., 2019). In this chapter, we engage directly with Indigenous contributing authors and use multiple evidence-based approaches, as undertaken by the IPBES (Tengö et al., 2014; Tengö et al., 2017). This approach is guided by the understanding that the co-production of knowledge (between scholars and local communities) about water and climate change vulnerability, impacts and adaptation has the potential to lead to new water knowledge and context-specific governance strategies (Arsenault et al., 2019; Chakraborty and Sherpa, 2021). Additionally, shifting beyond the exclusive use of technical knowledge and Western viewpoints redresses the shortcomings of resource- and security-oriented understandings to water and acknowledges the more holistic and relational approaches common to IK and LK (4.8.4) (Stefanelli et al., 2017; Wilson, 2019; Chakraborty and Sherpa, 2021).

Finally, grounded in the AR6 goal to expand the solution space, this chapter advances the understanding of adaptation in the water sector since AR5 by deploying a meta-analysis of adaptation measures. The meta-analysis focuses on both current adaptation responses (4.7.1) and future projected adaptation responses, which have been modelled (4.7.2). The meta-review assesses the outcomes of current adaptation responses and effectiveness of future projected adaptations in reducing climate and associated risks. Studies derived from Global Adaptation Mapping Initiative (GAMI) database (Berrang-Ford et al., 2021a) (see Chapter 16), were coded systematically following a meta-review protocol developed specifically for this assessment ((Mukherji et al., 2021), SM4.2). A similar meta-review protocol was also developed to assess effectiveness of adaptations to reduce projected climate risks (4.7.2; SM4.2).

4.1.2 Climatic and Non-Climatic Drivers of Changes in the Water Cycle

The water cycle is affected by both climatic and non-climatic factors (Douville et al., 2021). Radiative forcing by changes in greenhouse gas (GHG) concentrations, aerosols, and surface albedo drives global and regional changes in evaporation and precipitation (Douville et al., 2021). A warmer atmosphere holds more moisture, increasing global and regional mean precipitation; and more extreme precipitation (Allan et al., 2014; Giorgi et al., 2019; Allan et al., 2020). Regional precipitation responses vary according to changes in atmospheric circulation. Geographical variation in aerosols drives changes in atmospheric circulation, affecting precipitation patterns such as the Asian monsoon (Ganguly et al., 2012; Singh et al., 2019). (Section 4.2.1)

Warming increases glacier melt and is expected to decrease snowfall globally and lead to shorter snow seasons with earlier but less rapid snowmelt. It can also lead to local increases in snowfall intensity (Allan et al., 2020). These changes affect the seasonality of river flows in glacier-fed or snow-dominated basins. (4.2.2)

Rising atmospheric CO_2 generally decreases plant transpiration, affecting soil moisture, runoff, stream flows, the return of moisture to the atmosphere and surface temperature (Skinner et al., 2017). However, in some regions, these can be offset by increased leaf area ("global greening") driven by elevated CO_2, land-use change, nitrogen deposition and effects of climate change itself (Zhu Z et al., 2016; Zeng Z et al., 2018). Increased ozone can impact plant functioning, reducing transpiration (Arnold et al., 2018). (4.2.1)

Direct human interventions include abstraction of surface water and groundwater for drinking, irrigation, and other freshwater uses, as well as streamflow impoundment behind dams and large-scale inter-basin transfers (Zhao et al., 2015; Donchyts et al., 2016; McMillan et al., 2016; Shumilova et al., 2018). The consequences of these interventions are substantial and are discussed below briefly. In addition, these direct human interventions can change due to various societal and economic factors, including changes in land use and urbanization (4.3 and 4.5).

Irrigation can reduce river flows and groundwater levels via abstraction and increase local precipitation (Alter et al., 2015; Cook et al., 2015), alter precipitation remotely through moisture advection (de Vrese et al., 2016), and change the timing of monsoons through land-sea temperature contrasts (Guimberteau et al., 2012). The land cover change affects ET and precipitation (Li et al., 2015; Douville et al., 2021), interception of precipitation by vegetation canopies (de Jong and Jetten, 2007), infiltration (Sun et al., 2018a), and runoff (Bosmans et al., 2017) (4.5.1, 4.6.2, Box 4.3). Land cover impacts on the hydrological cycle are of similar magnitude as human water use (Bosmans et al., 2017).

Urbanization decreases land surface permeability (Choi et al., 2016), which can increase fast runoff and flooding risks and reduce local rainfall by decreasing moisture return to the atmosphere (Wang et al., 2018). But urbanization can also increase the sensible heat flux driving greater or more extreme precipitation (Kusaka et al., 2014; Niyogi et al., 2017). (4.3.4, 4.5.4)

In summary, radiative forcing by GHG and aerosols drives changes in evapotranspiration and precipitation at global and regional scales, and the associated warming shifts the balance between frozen and liquid water (*high confidence*). Rising CO_2 concentrations also affect the water cycle via plant physiological responses affecting transpiration, including via reduced stomatal opening and increased leaf area (*high confidence* regarding the individual processes; *medium confidence* regarding their net impact). Land cover changes and urbanization affect both the climate and land hydrology by altering the exchanges of energy and moisture between the atmosphere and surface (*high confidence*) and changing the permeability of the land surface. Direct human interventions in river systems and groundwater systems are non-climatic drivers with substantial impacts on the water cycle (*high confidence*) and have the potential to change as part of societal responses to climate change (Figure 4.2).

Figure 4.2: The water cycle, including direct human interventions. Water fluxes on land precipitation, land evaporation, river discharge, groundwater recharge, and groundwater discharge to the ocean from (Douville et al., 2021). Human water withdrawals for various sectors are shown from (Hanasaki et al., 2018; Sutanudjaja et al., 2018; Burek et al., 2020; Droppers et al., 2020; Müller Schmied et al., 2021). Green water use (Abbott et al., 2019) refers to the use of soil moisture for agriculture and forestry. Irrigation water use (called blue water) is not included in green water use).

4.2 Observed Changes in Hydrological Cycle due to Climate Change

All components of the global water cycle have been modified due to climate change in recent decades (*high confidence*) (Douville et al., 2021), with hundreds of millions of people now regularly experiencing hydrological conditions that were previously unfamiliar (4.2.1.1, 4.2.4, 4.2.5). Extensive records from weather stations, satellites and radar clearly show that precipitation patterns have shifted worldwide. Three major shifts documented are (a) some regions receiving more annual or seasonal precipitation and others less, (b) many regions have seen increased heavy precipitation, and many have seen either increases or decreases in dry spells, (c) some regions have seen shifts towards heavier precipitation events separated by more prolonged dry spells (4.2.1.1). Observationally-based calculations suggest that evapotranspiration (ET) has changed in response to changes in precipitation and increasing temperatures, resulting in changing patterns of soil moisture worldwide which are now detectable by satellite remote sensing (4.2.1.2, 4.2.1.3). Rising temperatures have caused profound and extensive changes in the global cryosphere, with mountain glaciers, land ice and snow cover shrinking, causing substantial, permanent impacts on the ways of life of people in these regions, particularly Indigenous Peoples with strong cultural links to long-term or seasonally-frozen environments (4.2.2, 4.3.8). Groundwater recharge in spring may have been reduced due to shorter snowmelt seasons, although the dominant impact on groundwater has been non-climatic and through intensification of irrigation (4.2.6). The global-scale pattern of streamflow changes is now attributable to observed historical climate change, with human land and water use insufficient by themselves to explain the observed streamflow changes at global scales (4.2.3). Numerous examples of extreme hydrometeorological events, including heavy precipitation, flooding, drought and wildfire events causing deaths, high levels of economic damage and extensive ecological impacts, have been shown to have been made more *likely* by human influence on climate through increased GHG concentrations in the atmosphere (4.2.1.1, 4.2.4, 4.2.5). Overall, there is a clear picture of human alteration of the global water cycle, which is now affecting societies and ecosystems across the world. This section describes changes in the hydrological cycle through a lens of societal impacts.

4.2.1 Observed Changes in Precipitation, Evapotranspiration and Soil Moisture

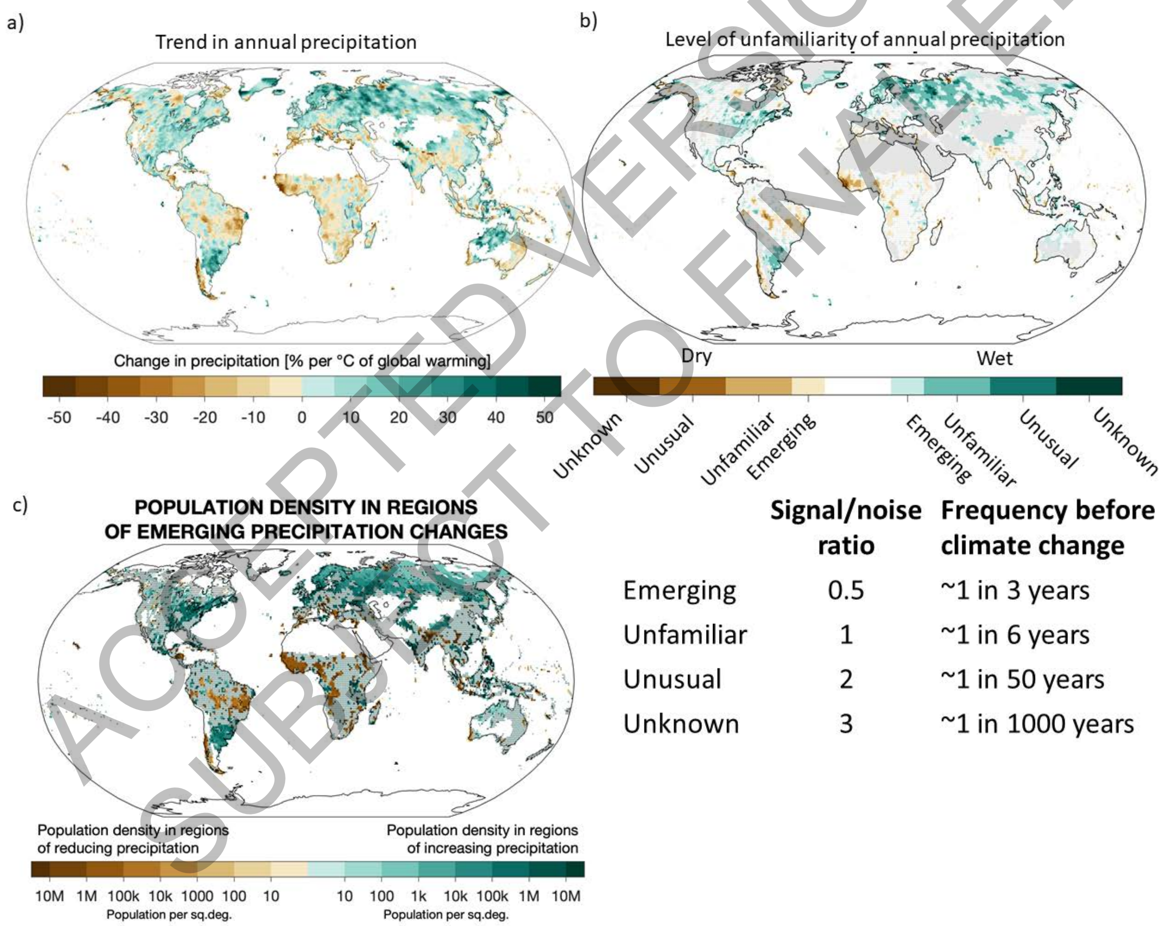
4.2.1.1 Observed Changes in Precipitation and Heavy Precipitation

AR6 WG1 (Douville et al., 2021) concluded that GHG forcing has driven increased contrasts in precipitation amounts between wet and dry seasons and weather regimes over tropical land areas (*medium confidence*), with a detectable precipitation increase in the northern high latitudes (*high confidence*). GHG forcing has also contributed to drying in dry summer climates, including the Mediterranean, south-western Australia, south-western South America, South Africa, and western North America (*medium to high confidence*) (Figure 4.3). AR6 WG1 (Seneviratne et al., 2021) also concluded that the frequency and intensity of heavy precipitation events have *likely* increased at the global scale over most land regions with good observational coverage. Heavy precipitation has *likely* increased on the continental scale over North America, Europe, and Asia. Regional increases in heavy precipitation frequency and (or) intensity have been observed with at least *medium confidence* for nearly half of the AR6 WG1 climatic regions (Figure 4.3). Human influence, in particular GHG emissions, is *likely* the main driver of the observed global-scale intensification of heavy precipitation in land regions

Large numbers of people live in regions where the annual mean precipitation is now “unfamiliar” compared to the mean and variability between 1891 and 2016 (Figure 4.3, g). “Unfamiliar” is defined as the long-term change being greater than one standard deviation in the annual data (Figure 4.3 (b)). In 2020, approximately 498 million people lived in unfamiliarly wet areas, where the long-term average precipitation is as high as previously seen in only about one in six years (*medium confidence*) (Figure 4.3, c). These areas are primarily in mid and high latitudes (Hawkins et al., 2020). On the other hand, approximately 163 million people lived in unfamiliarly dry areas, mostly in low latitudes (*medium confidence*). Due to high variability over time, the signal of long-term change in annual mean precipitation is not distinguishable from the noise of variability in many areas (Hawkins et al., 2020), implying that the local annual precipitation cannot yet be defined “unfamiliar” by the above definition.

Notably, many regions have seen increased precipitation for part of the year and decreased precipitation at other times (*high confidence*) (Figure 4.3, d, e), leading to small changes in the annual mean precipitation. Therefore, the numbers of people seeing unfamiliar seasonal precipitation levels are expected to be higher than those quoted above for unfamiliar annual precipitation changes (*medium confidence*). Still, quantified analysis of this is not yet available.

The intensity of heavy precipitation has increased in many regions (*high confidence*), including much of North America, most of Europe, most of the Indian sub-continent, parts of northern and south-eastern Asia, much of southern South America, parts of southern Africa and parts of central, northern and western Australia (Figure 4.3, f) (Dunn et al., 2020; Sun et al., 2020). Conversely, heavy precipitation has decreased in some regions, including eastern Australia, north-eastern South America and western Africa. The length of dry spells has also changed, with increases in annual mean consecutive dry days (CDD) in large areas of western, eastern and southern Africa, eastern and south-western South America, and South-East Asia and decreases across much of North America. Precipitation extremes have changed in some places where annual precipitation shows no trend. Some regions such as southern Africa and parts of southern South America are seeing increased heavy precipitation and longer dry spells. Many regions with changing extremes are highly populated, such as the Indian sub-continent, South-East Asia, Europe, and parts of North America, South America and Southern Africa (Figure 4.3, h). Substantially more people (~709 million) live in regions where annual maximum one-day precipitation has increased than regions where it has decreased (~86 million) (*medium confidence*). However, more people are experiencing longer dry spells than shorter dry spells: approximately 701 million people live in places where annual mean CDD is longer than in the 1950s, and ~404 million in places with shorter CDD (*medium confidence*) (Figure 4.3)).



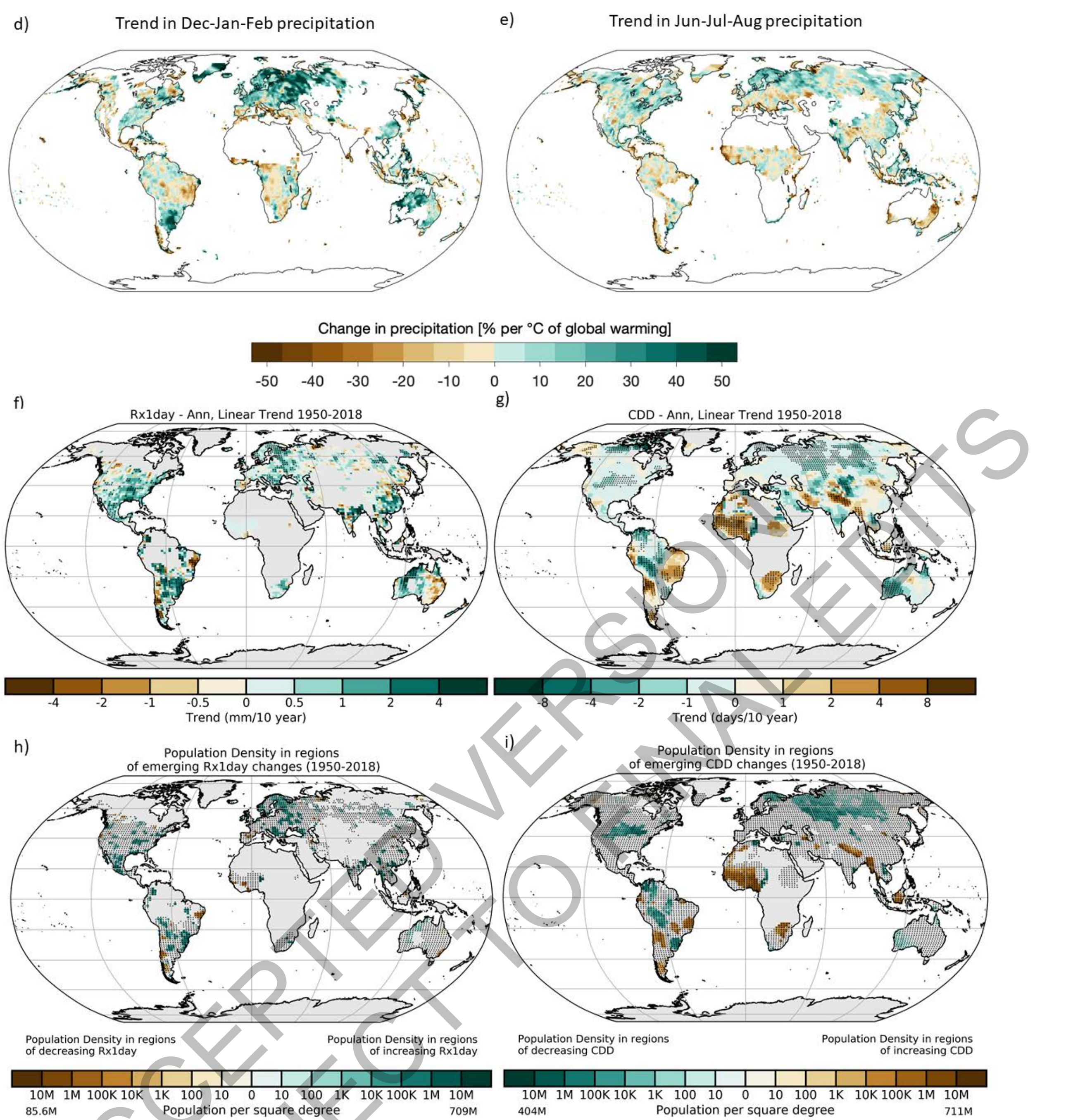


Figure 4.3: Observed mean and extreme precipitation changes, and people experiencing the emergence of historically unfamiliar precipitation and changes in extreme precipitation. (a) Changes in annual mean precipitation over land (1891–2019) in the Global Precipitation Climatology (GPCC) v2020 dataset (Schneider et al., 2017; Schneider et al., 2020). Green shows increasing precipitation, orange/red show decreases. (b) Emergence of wetter and drier climates, defined as the ratio of the signal S of change to the noise N of variability, where the latter is defined as one standard deviation in annual data with the trend removed, i.e., occurs approximately one in six years: "unfamiliar": S/N>1.0; "unusual": S/N>2.0; "unknown": S/N>3.0. Grey regions are either unobserved (oceans) or deserts (<250 mm/year). Stippling indicates where the signal of change is not significant. See (Hawkins et al., 2020) for further details. (c) Precipitation trends from the CRU dataset in December, January, and February (mm day^{-1} decade^{-1}). [to be replaced with GPCC for consistency with panel; (b) (d) As (c) for June-July-August. (e) Changes in annual mean maximum 1-day precipitation (Rx1day) in the HadEX3 dataset (Dunn et al., 2020). (f) Trend in annual mean consecutive dry days (CDD), 1950 – 2018, in HadEX3. (g) Population densities in grid boxes with emerging precipitation changes, at 1° resolutions. (h) Population densities per grid box where the trend in Rx1day is significantly different from zero. (i) Population densities per grid box where the trend in CDD is significantly different from zero. Stipples in (h) and (i) show where HadEX3 data is available. Population data in (g), (h) and (i) are for 2020 from (CIESIN, 2018a; CIESIN, 2018b).

In summary, annual mean precipitation is increasing in many regions worldwide and decreasing over a smaller area, particularly in the tropics. Nearly half a billion people live in areas with historically unfamiliar wet conditions, and over 160 million in areas with historically unfamiliar dry conditions (*medium confidence*). Over 600 million people experience heavy precipitation significantly more intense than in the 1950s, but less than 80 million experience decreased heavy precipitation. Compared to the 1950s, 601 million people now experience longer dry spells and 364 million experience shorter dry spells.

4.2.1.2 Observed and Reconstructed Changes in Evapotranspiration

WG1 (Douville et al., 2021) conclude with *high confidence* that global terrestrial annual ET has increased since the early 1980s, driven by both increasing atmospheric water demand and vegetation greening (*medium confidence*), and can be partly attributed to anthropogenic forcing (*high confidence)*.

Regional changes in ET depend on changes in both the climate and the properties of the land surface and ecosystems. The latter also responds to changes in climate and atmospheric composition. For example, a warming climate increases evaporative demand (Huang M et al., 2015; Berg et al., 2016), although seasonal rainfall totals (Hovenden et al., 2014) affect the amount of soil moisture available for evaporation. Since transpiration accounts for much of the land-atmosphere water flux (Good et al., 2015), vegetation changes also play a significant role in overall changes in ET.

With higher CO_2, the increase in evaporative demand can, to some extent, be counteracted by reduced stomatal conductance ('physiological effect'), which reduces transpiration and increases leaf-level water use efficiency (WUE), but is highly species-specific. There is evidence for recent increases in leaf-scale WUE from tree rings (14 ±10 %, broadleaf to 22 ±6 %, evergreen over the 20th century: (Frank et al., 2015)), carbon isotopes (30 to 35 % increase in 150 years: (van der Sleen et al., 2014)), and satellite-based measurements (1982–2008) combined with data-driven models (Huang M et al., 2015). WUE is also affected by aerodynamic conductance (Knauer et al., 2017), nutrient limitation (Medlyn et al., 2015; Donohue et al., 2017), soil moisture availability (Bernacchi and VanLoocke, 2015; Medlyn et al., 2015), and ozone pollution (King et al., 2013; Frank et al., 2015).

Higher CO_2 also increases photosynthesis rates, though this may not be maintained in the longer term (Warren et al., 2015; Adams et al., 2020), particularly where temperatures exceed the thermal maxima for photosynthesis (Duffy Katharyn et al., 2021). Higher photosynthesis increases leaf area index (LAI) ('structural effect') and therefore transpiration; 55±25% of observed increases in ET (1980–2011) have been attributed to LAI change (Zeng Z et al., 2018). Increases in ET driven by increased LAI (from satellite observations 1982–2012) are estimated at 0.32 ± 0.07 mm month^{-1} per decade, generating a climate forcing of -0.31 Wm^{-2} per decade (Zeng et al., 2017).

Overall regional transpiration change depends on the balance between the physiological and structural effects (e.g. (Tor-ngern et al., 2015; Ukkola et al., 2015)). In dry regions, ET may increase due to increasing LAI (Huang M et al., 2015), but in some densely vegetated regions, the stomatal effect dominates (Mao et al., 2015). Reductions in transpiration due to rising CO_2 concentrations may also be offset by a longer growing season (Frank et al., 2015; Mankin et al., 2019). Other factors modulate the transpiration effect both temporally and spatially, for example, additional vegetation structural changes (Kim et al., 2015; Domec et al., 2017), vegetation disturbance and age (Donohue et al., 2017) and species (Bernacchi and VanLoocke, 2015).

Recent studies report global ET increases from the early 1980s to 2009 and 2013 (Table 4.1). Calculations informed by observations suggest that ET has increased in most regions, with statistically significant ($p<0.05$) trends of up to 10mm yr^{-2} observed in large parts of North America and northern Eurasia. Larger increases in ET are also observed in several regions, including northeast Brazil, western central Africa, southern Africa, southern India, southern China, and northern Australia. Decreases of around 10mm yr^{-2} are reported for western Amazonia and central Africa (Miralles et al., 2014), although not across all datasets (Zeng et al., 2018). In estimates of past changes in long-term drying or wetting of the land surface driven by climate, uncertainties in ET observations or reconstructions make a more substantial contribution to the overall uncertainty than observed changes in precipitation (Greve et al., 2014). Other changes in ET are also driven strongly by land cover changes and irrigation (Bosmans et al., 2017).

Table 4.1: Trends in global evapotranspiration for different periods between 1981-1982 and 2009-2013.

Trend (mm yr^{-2})	Period	Data source	Author(s)
+0.54	1981 to 2012	Observations	(Zhang Y et al., 2016)
+1.18	1982 to 2010	Observations	(Mao et al., 2015)
+0.93±0.31	1982 to 2010	LSMs	(Mao et al., 2015)
+0.88	1982 to 2013	Remote-sensing data	(Zhang K et al., 2015)
+1.5	1982 to 2009	Remote-sensing and surface observations	(Zeng et al., 2014)

The contribution of changes in WUE to observed changes in ET is a key knowledge gap. WG1 assigned *low confidence* to this contribution. Estimating large-scale transpiration response to increased CO_2 based on leaf-level responses of WUE is not straightforward (Bernacchi and VanLoocke, 2015; Medlyn et al., 2015; Tor-ngern et al., 2015; Walker et al., 2015; Kala et al., 2016) and new methodological approaches are needed.

In summary, there is *high confidence* that ET increased by between approximately 0.5 and 1.5mm yr^{-2} between the 1980s and early 2010s due to warming-induced increased atmospheric demand worldwide and greening of vegetation in many regions. Increases in many areas are 10mm yr^{-2} or more, but in some tropical land areas, ET has decreased by 10mm yr^{-2}. Plant stomatal responses to rising CO_2 concentrations may play a role, but there is *low confidence* in quantifying this. Changes in land cover and irrigation have also changed regional ET (*medium confidence*).

4.2.1.3 Observed and Estimated Past Changes in Soil Moisture and Aridity

AR6 WG1 (Douville et al., 2021) find that a global trend in soil moisture is detectable in a reanalysis and is attributable to GHG forcing, and conclude that it is *very likely* that anthropogenic climate change affected global patterns of soil moisture over the 20th century.

Changes in soil moisture and land surface aridity are due to changes in the relative balance of precipitation and ET. Regional trends derived from satellite remote sensing products show increases and decreases in annual surface soil moisture of up to 20% or more between the late 1970s and mid-2010s (Figure 4.4). For example, using the ESA CCI SM v03.2 COMBINED products (van der Schalie et al., 2021), approximately 0.9 billion people live in regions with decreasing surface soil moisture, and 2.1 billion people live in regions with increasing surface soil moisture (Figure 4.4, b). However, there are disagreements between datasets on the direction of change in some regions (Seneviratne et al., 2010; Feng and Zhang, 2015; Feng, 2016), so quantification is subject to *low confidence*.

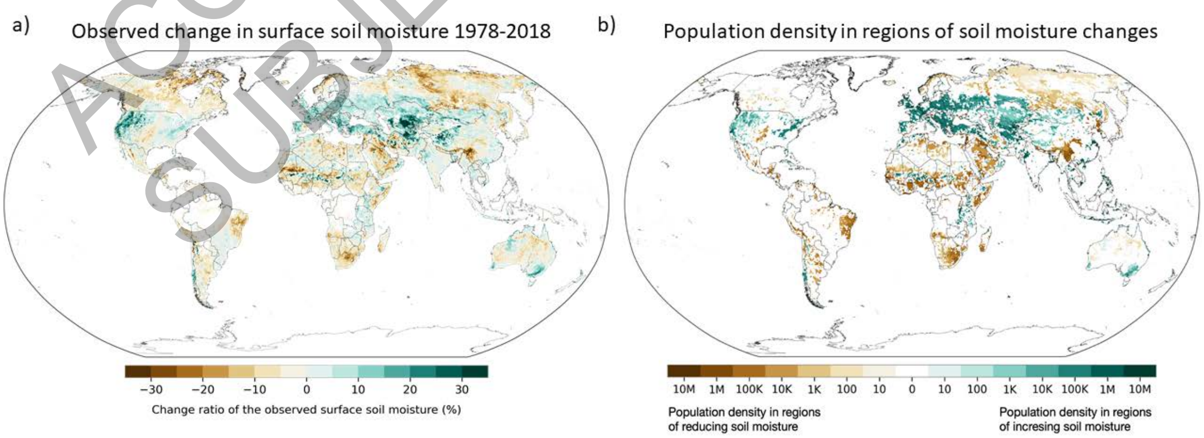


Figure 4.4: Global patterns of changes in soil moisture and people in regions with significant changes. (a) Percentage changes in surface soil moisture (0–5cm) for 1978–2015 from satellite remote sensing: the "COMBINED" product of European Space Agency Climate Change Initiative Soil Moisture (ESA CCI SM v03.2), which blends data products from two microwave instruments, a scatterometer measuring radar backscattering and a radiometer measuring

brightness temperature (van der Schalie et al., 2021). (b) The population density in 0.25°grid boxes with trends of significantly increasing and decreasing soil moisture from (a).

Analysis of changes in precipitation-evapotranspiration estimates for 1948-2005 (Greve et al., 2014) suggests that geographical variations in soil moisture trends are more complex than the "wet get wetter, dry get drier" (WGWDGD) paradigm. This is also supported by remote sensing data, with ESA CCI data for 1979-2013 showing only 15% of land following the WGWDGD paradigm for soil moisture (Feng and Zhang, 2015). Defining arid, humid and transitional areas according to precipitation and temperature regimes, all three classes of regions see more widespread trends of declining soil moisture than increasing soil moisture (Feng and Zhang, 2015). In the ESA CCI product, increasing soil moisture trends are mainly seen in humid or transitional areas and are rare in arid regions (Table 4.2)

Table 4.2: Proportions of arid, transitional and humid areas with drying and wetting trends in surface soil moisture from remote sensing, 1979-2013 (Feng and Zhang, 2015).

Areas	% of the area with a drying trend	% of the area with a wetting trend
Arid	38.4	2.9
Transitional	13.0	10.5
Humid	16.3	8.1

Reconstructions of historical soil moisture trends with data-driven models and process-based land surface models indicate drier dry seasons predominantly in extratropical latitudes, including Europe, western North America, northern Asia, southern South America, Australia and eastern Africa, consistent with climate model simulations of changes due to human-induced climate change (Padrón et al., 2020). Furthermore, reduced water availability in the dry season is generally a consequence of increasing ET rather than decreasing precipitation (Padrón et al., 2020).

While observationally-based data for soil moisture are now more widely available, regional trends remain uncertain due to disagreements between datasets, so confident assessments of soil moisture changes remain a knowledge gap.

In summary, global mean soil moisture has slightly decreased, but regional changes vary, with both increases and decreases of 20% or more in some regions (*medium confidence*). Drying soil moisture trends are more widespread than wetting trends, not only in arid areas but also in humid and transitional areas (*medium confidence*). Reduced dry-season water availability is driven mainly by increasing transpiration (*medium confidence*)

4.2.2 Observed Changes in Cryosphere (Snow, Glaciers, and Permafrost)

AR5 reported a decrease in snow cover over most of the Northern Hemisphere, decreases in the extent of permafrost and increases in its average temperature, and glacier mass loss in most parts of the world (Jiménez Cisneros et al., 2014). SROCC (IPCC, 2019c) stated with *very high* or *high confidence* (a) reduction in seasonal snow cover (snow cover extent decreased by 13.4% per decade for 1967-2018); (b) glacier mass budget of all mountain regions (excluding the Canadian and Russian Arctic, Svalbard, Antarctica, Greenland) was 490±100 kg m^{-2} yr^{-1} in 2006-2015; (c) warming of permafrost (e.g. permafrost temperatures increased by 0.39°C in the Arctic for 2007-2017). Tourism and recreation activities have been negatively impacted by declining snow cover, glaciers and permafrost in high mountains (*medium confidence*).

Recent studies confirmed with *high confidence* that snow cover extent continues to decrease across the northern hemisphere in all months of the year (see (Douville et al., 2021; Eyring et al., 2021; Fox-Kemper et al., 2021) for more details). From 1922 to 2018, snow cover extent in the northern hemisphere peaked in the 1950s-1970s (Mudryk et al., 2020) and consistently reduced since the end of the 20th century (Hernández-Henríquez et al., 2015; Thackeray et al., 2016; Mudryk et al., 2017; Beniston et al., 2018; Hammond et al., 2018; Thackeray et al., 2019; Mudryk et al., 2020). The consistently negative snow-mass trend of approximately 5 Gt yr^{-1} in 1981-2018 for all winter-spring months (Mudryk et al., 2020), including 4.6 Gt yr^{-1} decrease of snow mass across North America and a negligible trend across Eurasia, has been observed (Pulliainen et al., 2020). Negative trends in snow-dominated period duration of 2.0 to 6.5 weeks decade-1 was detected from surface and satellite observations during 1971–2014 (Allchin and Déry, 2017), mainly owing to earlier seasonal snowmelt (Fox-Kemper et al., 2021). The observed decrease of snow cover metrics (extent, mass, duration) led to changes in runoff seasonality and has impacted water supply infrastructure (Blöschl et al., 2017; Huss et al., 2017), particularly in south-western Russia, western US and Central Asia. In these regions, snowmelt runoff accounts for more than 30% of irrigated water supplies (Qin et al., 2020). Negative impacts on hydropower production due to changes in the seasonality of snowmelt have also been documented (Kopytkovskiy et al., 2015).

During the last two decades, the global glacier mass loss rate exceeded 0.5-meter water equivalent (m w.e.) year^{-1} compared to an average of 0.33 m w.e. y^{-1} in 1950–2000. This volume of mass loss is the highest since the start of the entire observation period (*very high confidence*) (Zemp et al., 2015; Zemp et al., 2019; Hugonnet et al., 2021) (also see (Douville et al., 2021; Fox-Kemper et al., 2021; Gulev et al., 2021) for more details). Regional estimates of glacier mass balance are also mostly negative (Dussaillant et al., 2019; Menounos et al., 2019; Zemp et al., 2019; Douville et al., 2021; Fox-Kemper et al., 2021; Hugonnet et al., 2021), except for West Kunlun, Eastern Pamir and the northern Karakoram (Brun et al., 2017; Lin et al., 2017; Berthier and Brun, 2019). Changes in glacier metrics estimated in post-SROCC publications are summarized in Figure 4.5.

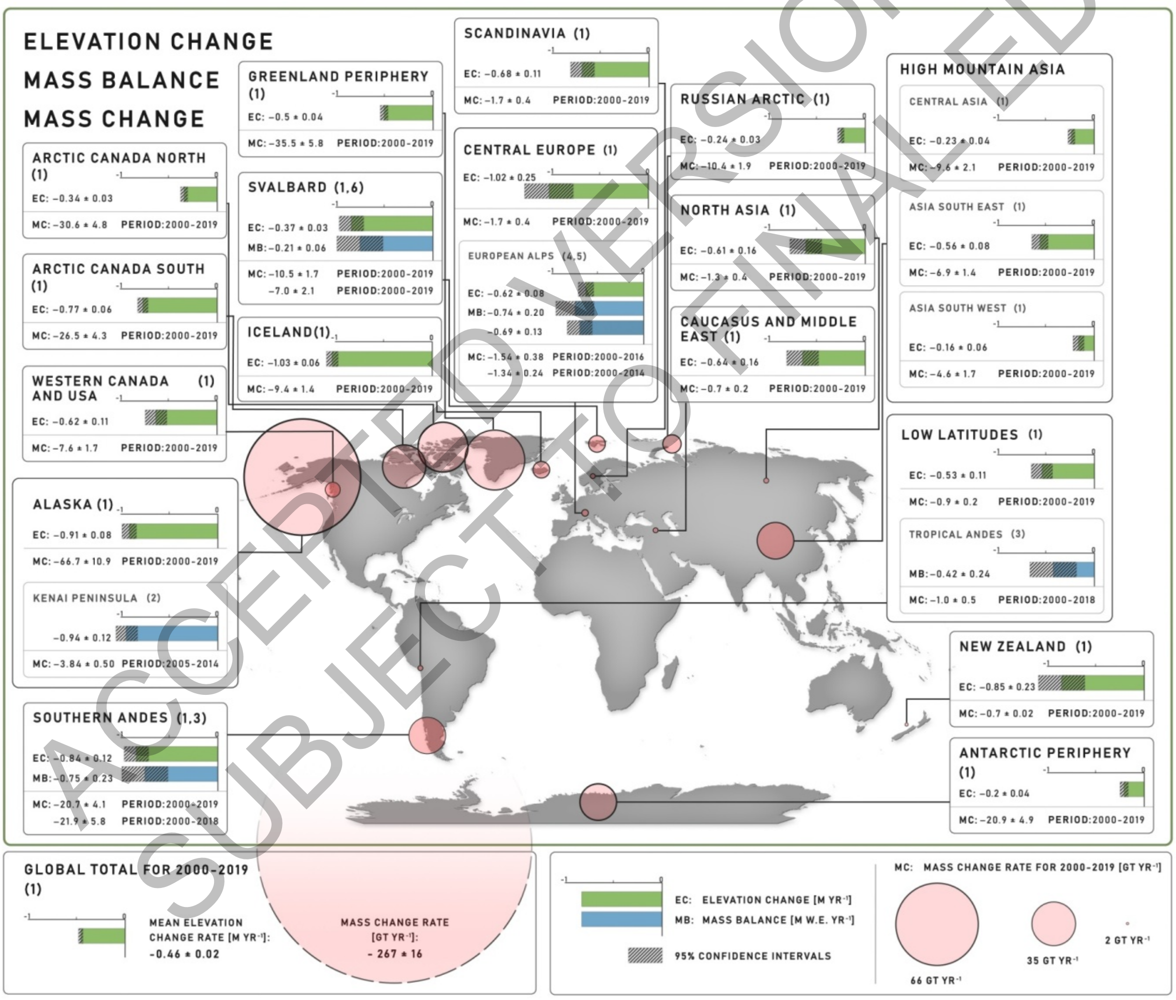


Figure 4.5: Global and regional estimates of changes in glacier characteristics (elevation, m yr^{-1}; mass Gt yr^{-1}, mass balance, m.w.e. yr^{-1}) and 95% confidence intervals of the estimates. Results are taken from the post-SROCC publications, which are labelled in the chart titles as 1 - (Hugonnet et al., 2021); 2 - (Yang et al., 2020); 3 - (Dussaillant et al., 2019); 4 - (Davaze et al., 2020); 5 - (Sommer et al., 2020); 6 - (Schuler et al., 2020).

Regional and global decreasing trends in glacier mass loss are about linear until 1990, after which they accelerated, especially in Western Canada, the USA, and Southern Andes (WGMS, 2017). There is a worldwide growth in the number, total area and total volume of glacial lakes by around 50% between 1990 to 2018 due to the global increase in glacier melt rate (Shugar et al., 2020). An increase in area, number and volume of glacial lakes can potentially increase risks of GLOFs with significant negative societal impacts (Ikeda et al., 2016). A drop in glacier runoff has happened in the regions where the glaciers have already passed their peak water stage, example, as in Canadian Rocky Mountains, European Alps, tropical Andes, North Caucasus (Bard et al., 2015; Hock et al., 2019b; Rets et al., 2020). There is *medium confidence* that the accelerated melting of glaciers has negatively impacted glacier-supported irrigation systems worldwide (Buytaert et al., 2017; Nüsser and Schmidt, 2017; Xenarios et al., 2019). Varying impacts on hydropower production (Schaefli et al., 2019) and tourism industry in some places due to cryosphere changes have also been documented (Hoy et al., 2016; Steiger et al., 2019).

Permafrost changes mainly refer to changes in temperature and active layer thickness (ALT) (Hock et al., 2019b; Fox-Kemper et al., 2021; Gulev et al., 2021). Permafrost temperature near the depth of zero annual temperature amplitude increased globally by 0.29 ± 0.12 °C during 2007–2016: by 0.39 ± 0.15 °C in the continuous permafrost and by 0.20 ± 0.10° in the discontinuous permafrost (Biskaborn et al., 2019). Thus, permafrost is warming during the last 3-4 decades (Romanovsky et al., 2017) with a rate of 0.4−1.4 °C decade^{-1} throughout the Russian Arctic, 0.1−0.8 °C decade^{-1} in Alaska and Arctic Canada during 2007−2016 (Biskaborn et al., 2019) and 0.1-0.24 °C decade^{-1} in Tibetan plateau (Wu et al., 2015). The ALT is also increasing in the European and Russian Arctic and high mountain areas of Eurasia since the mid-1990s (Hock et al., 2019b; Fox-Kemper et al., 2021; Gulev et al., 2021). Unfortunately, unlike glaciers and snow, the lack of in-situ observations on permafrost still cannot be compensated by remote sensing. Still, some methodological progress on this front has been happening recently (Nitze et al., 2018).

There is *high confidence* that degradation of the cryosphere components is negatively affecting terrestrial ecosystems, infrastructure and settlements in the high-latitude and high-altitude areas (Fritz et al., 2017; Oliva and Fritz, 2018; Streletskiy et al., 2019). Similarly, communities in the North polar regions and the ecosystems on which they depend for their livelihoods are at risk (Mustonen, 2015; Pecl et al., 2017; Mustonen and Lehtinen, 2020) (Figure 4.6).

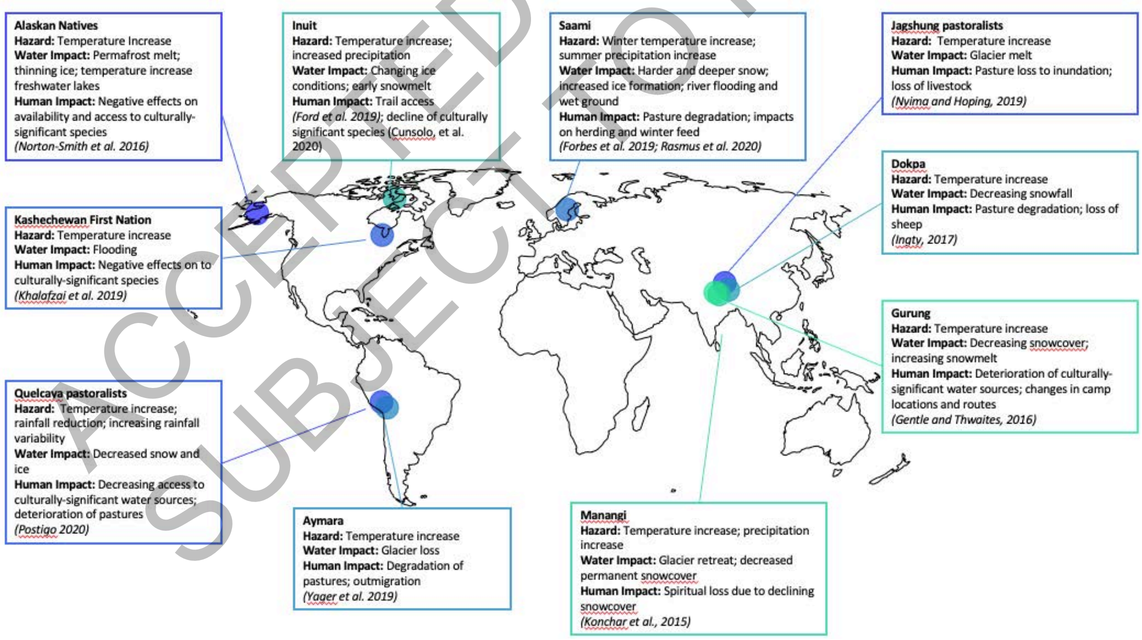


Figure 4.6: Map of selected observed impacts on cultural water uses of Indigenous Peoples of the cryosphere. Map location is approximate; text boxes provide names of the Indigenous Peoples whose cultural water uses have been impacted by climate change; changed climate variable; impact on water; and specific climate impact on cultural water use (4.3.7).

In summary, the cryosphere is one of the most sensitive indicators of climate change. There is *high confidence* that cryosphere components (glaciers, snow, permafrost) are melting or thawing since the end of the 20th and beginning of the 21st century. Widespread cryosphere changes are affecting humans and ecosystems in mid-to-high latitudes and the high mountains regions (*high confidence*). These changes are already impacting irrigation, hydropower, water supply, cultural and other services provided by the cryosphere, and populations depending on ice, snow and permafrost.

4.2.3 Observed Changes in Streamflow

AR5 (Jiménez Cisneros et al., 2014) concluded with *medium evidence* and *high agreement* that trends in annual streamflow have generally followed observed changes in regional precipitation and temperature since the 1950s. AR6 WGI (Eyring et al., 2021; Gulev et al., 2021) (12.4.5) conclude with *medium confidence* that anthropogenic climate change has altered local and regional streamflow in various parts of the world, but with no clear signal in the global mean.

Between the 1950s and 2010s, stream flows showed decreasing trends in parts of western and central Africa, eastern Asia, southern Europe, western North America and eastern Australia, and increasing trends in northern Asia, northern Europe, and northern and eastern North America (Dai, 2016; Gudmundsson et al., 2017; Gudmundsson et al., 2019; Li et al., 2020b; Masseroni et al., 2020). Significant spatial heterogeneity is also found in streamflow changes at the regional scale. For instance, in Canada, annual streamflow trends were mixed. Significant declines occurred at 11% of stations and significant increases at 4% of stations, with most decreases occurring in southern Canada (Bonsal et al., 2019). An increasing trend (1950-2010) is found in the northern region, mainly due to climate warming. Mixed trends are found in other regions.

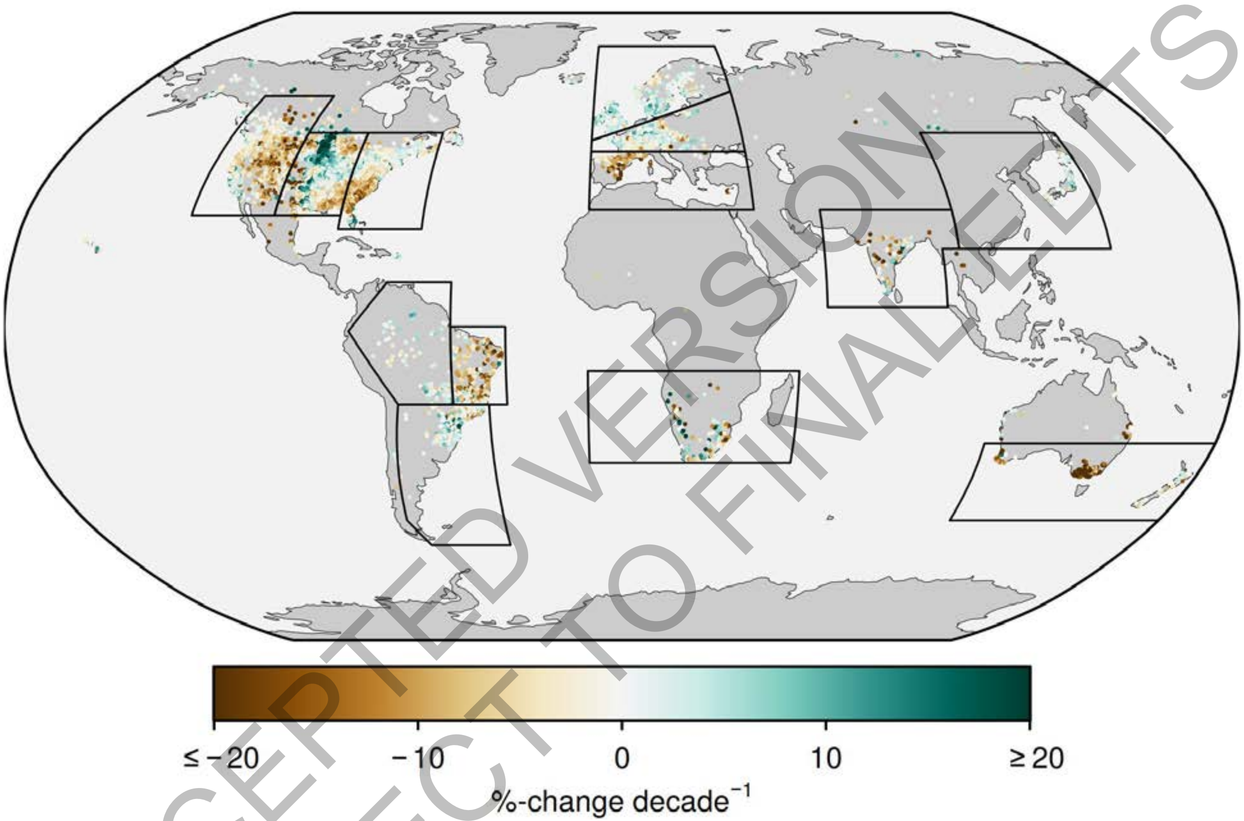
The spatial differences in annual mean streamflow trends around the world are influenced by climatic factors, particularly changes in precipitation and evaporation (Zang and Liu, 2013; Greve et al., 2014; Hannaford, 2015; Ficklin et al., 2018), as well as by anthropogenic forcing (Gudmundsson et al., 2016; Gudmundsson et al., 2017; Gudmundsson et al., 2021). Other factors (e.g. land-use change and CO_2 effects on vegetation) dominate in some areas, especially dryland regions (Berghuijs et al., 2017b). Human activities can reduce run-off through water withdrawal and land-use changes (Zaherpour et al., 2018; Sun et al., 2019a; Vicente-Serrano et al., 2019), and human regulation of streamflows via impounding reservoirs can also play a major role (Hodgkins et al., 2019).

Streamflow trends are attributed to varying combinations of climate change and direct human influence through water and land use in different basins worldwide, with conclusions on the relative contribution of climatic and anthropogenic factors sometimes depending on the methodology (Dey and Mishra, 2017). Precipitation explains over 80% of the changes in discharge of large rivers from 1950 to 2010 in northern Asia and northern Europe, where the impact of human activities is relatively limited (Li et al., 2020b). In northwest Europe, precipitation and evaporation changes explain many observed trends in streamflow (Vicente-Serrano et al., 2019). In several polar areas in Northern Europe (e.g. Finland), North America (e.g. British Columbia in Canada), and Siberia, many studies reported increased wintertime streamflow primarily due to climate warming, for instance, more rainfall instead of snowfall and more glacier run-off in the winter period (e.g. (Bonsal et al., 2020)) (4.2.2). A similar phenomenon of the earlier snowmelt run-off is also found in North America during 1960-2014 (Dudley et al., 2017). Thus, climate drivers largely explain changes in the average and maximum run-off of predominantly snow-fed rivers (Yang et al., 2015a; Bring et al., 2016; Tananaev et al., 2016; Frolova et al., 2017b; Ficklin et al., 2018; Magritsky et al., 2018; Rets et al., 2018).

In contrast, in southwestern Europe, land cover changes and increased water demands by irrigation are the main drivers of streamflow reduction (Vicente-Serrano et al., 2019) (4.3.1). In addition, the human intervention also contributed to the increase of the wintertime streamflow due to the release of water in the winter season for hydropower generation in large rivers in the northern regions (Rawlins et al., 2021). In some regions, the impact of human activities on run-off and streamflow outplays the climate factors, e.g. in typical basins in China after 2000 (Zhai and Tao, 2017).

(Shi et al., 2019) find that in 40 major basins worldwide, both climatic and direct human impact contribute to observed flow changes to varying degrees. Climate change or variability is the main contributor to changes in basin-scale trends for 75% of rivers, while direct human effects on streamflow dominate for 25%. However, this does not consider attribution of the climate drivers to anthropogenic forcing. Using time series of low, mean, and high river flows from 7250 observatories around the world (1971 to 2010) and global hydrological models (GHMs) driven by Earth System Model simulations with and without anthropogenic forcing of climate change, (Gudmundsson et al., 2021) also found direct human influence to have a relatively small impact on global patterns of streamflow trends. (Gudmundsson et al., 2021) further identified anthropogenic climate change as a causal driver of the global pattern of recent trends in mean and extreme river flow (Figure 4.7). Overall, the sign of observed trends and simulations accounting for human influence on the climate system was found to be consistent for decreased mean flows in western and eastern North America, southern Europe, north-east South America and the Indian subcontinent, and increased flows in northern Europe. Similar conclusions were drawn for low and high flows, except for the Indian subcontinent. However, in some regions, the observed trend was opposite to that simulated with anthropogenic climate forcing. Thus, human water and land use alone did not explain the observed pattern of trends.

a)



b)

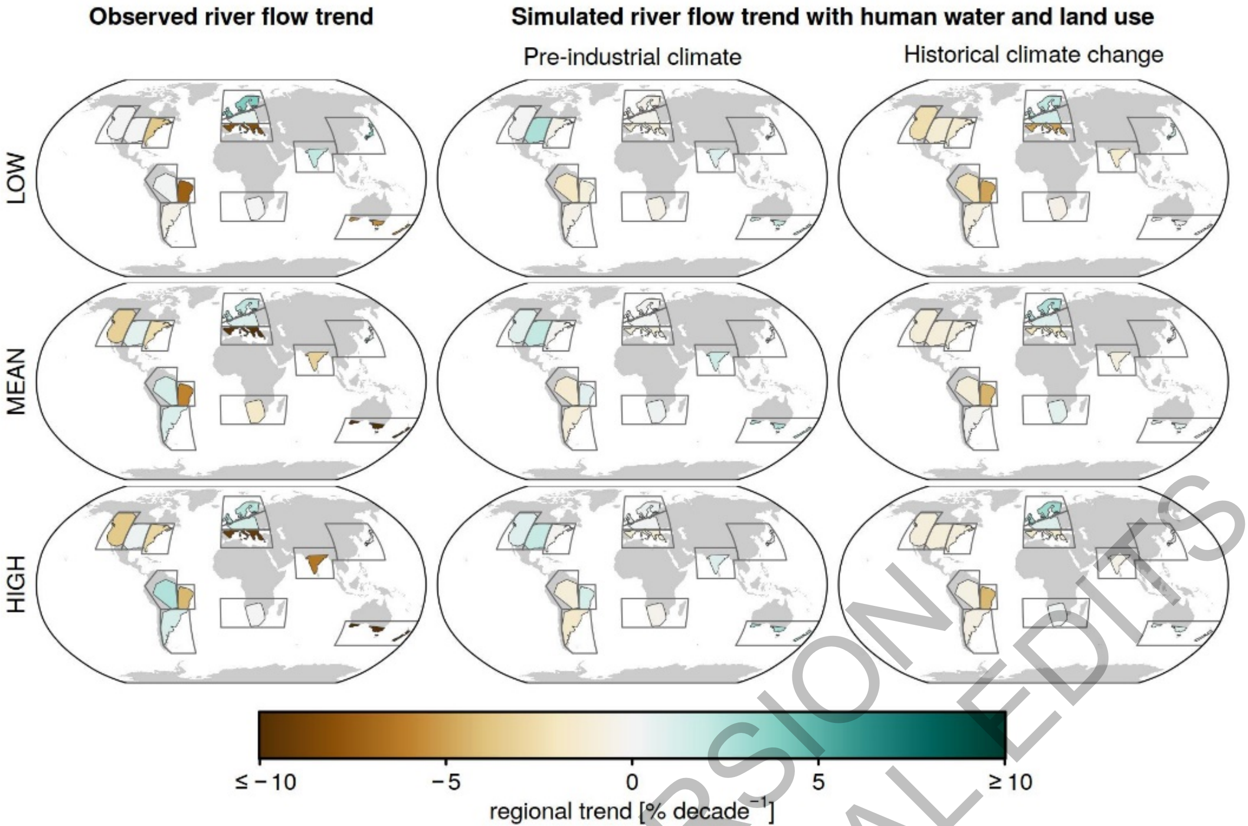


Figure 4.7: Observed changes in river flows and attribution to externally forced climate change. (a) Percentage changes in flow in individual rivers 1971 to 2010. Black box outlines show climatic regions with at least 80 gauging stations with almost complete daily observations over 1971-2010, using the SREX (Seneviratne et al., 2012) regions. (b) Left column: observed regional median trends from 1971 to 2010 in SREX regions with at least 80 gauging stations with almost complete daily observations over that period. Middle column: trends simulated by eight Global Hydrological Models driven by four CMIP5 Earth System Models, with human water and land use from 1971 to 2020 and the pre-industrial control climate state. Right column: same as the middle column but with ESM-simulated climates from 1971 to 2010 with both anthropogenic forcings (greenhouse gases, aerosols and land use) and natural external forcings (solar variability and volcanic eruptions). Top row: low flows (annual 10th percentile); Middle row: mean flows; Bottom row: high flows (annual 90th percentile). Reproduced from (Gudmundsson et al., 2021).

Although there are different observational and simulated run-off and streamflow datasets (e.g., Global Runoff Data Center, GRDC), it is still challenging to obtain and update long-term river discharge records in several regions, particularly Africa, South and East Asia (Dai, 2016). When observed data are scarce, hydrological models are used to detect trends in run-off and streamflow. However, simulations of streamflow can differ between models depending on their structures and parameterizations, contributing to uncertainties for trend detection, especially when considering human intervention (e.g. (Caillouet et al., 2017; Hattermann et al., 2017; Smith et al., 2019b; Telteu et al., 2021)).

In summary, both climate change and human activities influence the magnitude and direction of change in run-off and streamflow. There are no clear trends of changing streamflow on the global level. However, trends emerge on a regional level (a general increasing trend in the northern higher latitude region and mixed trend in the rest of the word) (*high confidence*). Climatic factors contribute to these trends in most basins (*high confidence*). They are more important than direct human influence in a larger share of major global basins (*medium confidence*), although direct human influence dominates in some (*medium confidence*). Overall anthropogenic climate change is attributed as a driver to the global pattern of change in streamflow (*medium confidence*).

4.2.4 Observed Changes in Floods

AR6 WGI Chapter 11 (Seneviratne et al., 2021) assessed with *high confidence* the increase in the extreme precipitation and associated increase in the frequency and magnitude of river floods. However, there is *low* *confidence* in changes in the river flooding regionally, which is strongly dependent upon complex catchment characteristics and land use patterns. SROCC (Hock et al., 2019b) summarized with *high confidence* that changes in the cryosphere have led to changes in frequency, magnitude and location of rain-on-snow floods, snowmelt floods and glacier-related floods.

There is *high confidence* that the frequency and magnitude of river floods have changed in the past several decades in some regions mentioned below (and in WGI 11.5.2; SM4.1) with impacts across human and natural systems (4.3). A global flood database based on *in situ* measurement and satellite remote-sensing during 1985–2015 show that floods have increased 4-fold and 2.5–fold in the tropics and northern mid-latitudes, respectively (Najibi and Devineni, 2018). Estimates of flood exposure using satellite-derived inundation area and high-resolution population data showed a 20-24% increase during 2000–2018 (Tellman et al., 2021). Analyses of in situ streamflow measurement showed both increases and decreases in the frequency of river floods for 1960–2010 in Europe (Berghuijs et al., 2017a; Blöschl et al., 2019a) and the United States (Berghuijs et al., 2017a), an overall increase in China, Brazil and Australia (Berghuijs et al., 2017a) but decrease in some areas in the Mediterranean (Tramblay et al., 2019) and southern Australia (Ishak et al., 2013; Do et al., 2017). Warming in the last 40-60 years has led to 1 to10 day earlier per decade spring flood occurrence depending on the location (the most frequent being 2 to 4 days/decade) (*high confidence*) (Yang L. et al., 2015; Blöschl et al., 2017; Dudley et al., 2017; Solander et al., 2017; Rokaya et al., 2018; Kireeva et al., 2020).

Between 1970 to 2019, 44% of all disasters, and 31% of all economic losses were flood related (WMO, 2021). Observed flood risks changes in recent decades are often caused by human factors such as increased urbanization and population growth rather than climate change alone (Tramblay et al., 2019). There is *medium confidence* that flood vulnerability varies among various regions and countries (Jongman et al., 2012; Scussolini et al., 2016; Tanoue et al., 2016) (Figure 4.8), reflecting differences in GDP, severity and characteristics of hazard and political and social conditions (Rufat et al., 2015). Flood vulnerability has decreased with economic development in many regions, while increased exposure has elevated risk in some places (Mechler, 2016; Tanoue et al., 2016). Global annual mean exposed population considering the current flood protection standard is estimated to be US$ 54 million under the climate of 1976-2005 and unevenly distributed (Alfieri et al., 2017). Similar estimation using different models shows an increase of flood exposure in the past (US$31 million for 1971-1990 and US$ 45 million for 1991-2010 without population change as fixed in 2010) (Tanoue et al., 2016) (4.7.5).

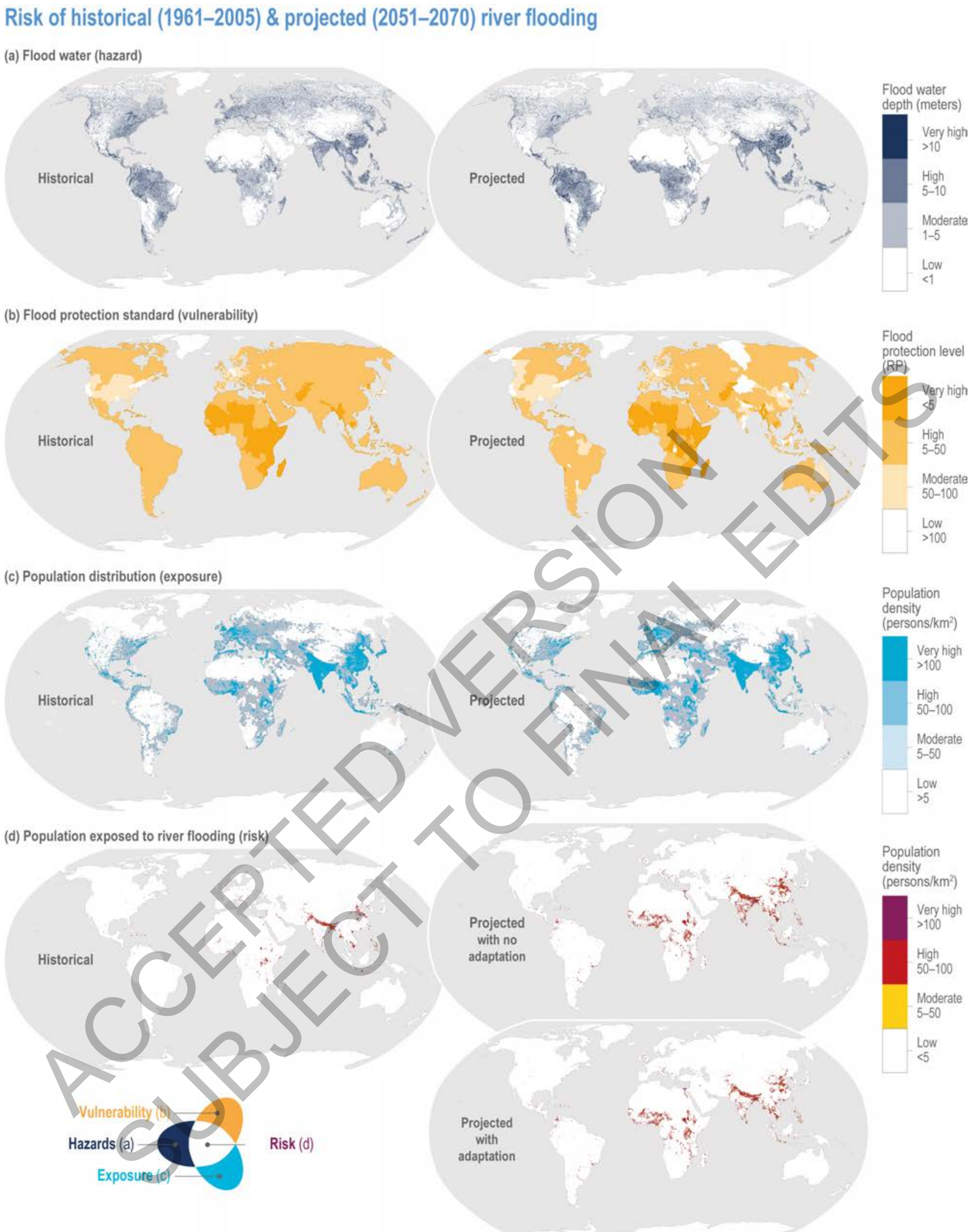


Figure 4.8: (a) Local flood protection standard (return period) at sub-country scale (Scussolini et al., 2016) based on published reports and documents, websites and personal communications with experts. Note that the vulnerability of this map reflects local flood protection such as complex infrastructure and does not fully reflect the other source of vulnerabilities, including exposure. (b) Modelled mean global fluvial flood water depth (Tanoue et al., 2016; Tanoue et al., 2021) based on a land surface model and a river and inundation model driven by reanalysis climate forcing of 5 CMIP5 GCMs (metres). The annual maximum daily river water was allocated along elevations, and inundation depth was calculated for each year and averaged for the target period. (c) Population distribution per 30 arc second grid cell (Klein Goldewijk et al., 2010; Klein Goldewijk et al., 2011). (d) Population exposed to flood (number of people where inundation occurs) per 30 arc-second grid cell. Population under inundation depth > 0 m (a) was counted when the

return period of annual maximum daily river water exceeds the flood protection standard (c) calculated by the authors. All values are averages for the period 1958-2010 for the past and 2050-2070 for the future.

The link between rainfall and flooding is complex. While observed increases in extreme precipitation have increased the frequency and magnitude of pluvial floods and river floods in some regions, floods could decrease in some regions due to other factors. These factors could include soil wetness condition, cryosphere change, land cover change and river system management, adaptation measures or water usage within the river basin (WGI FAQ8.2). For example, in the USA and Europe, a study indicated that major (e.g., 25–100-year return period) floods did not show significant long-term trends (Hodgkins et al., 2019). Nevertheless, anthropogenic climate change increased the likelihood of a number of major heavy precipitation events and floods that resulted in disastrous impacts in southern and eastern Asia, Europe, North America and South America (Table 4.3) (*high confidence*). (Davenport et al., 2021) demonstrated that anthropogenic changes in precipitation extremes had contributed one-third of the cost of flood damages (from1988 to 2017) in the USA. Anthropogenic climate change has altered 64% (8 out of 22 events increased, 8 decreased) of floods events with significant loss and damage during 2010-2013 (Hirabayashi et al., 2021a). (Gudmundsson et al., 2021) attributed observed change in extreme river flow trends to anthropogenic climate change (4.2.3). Although there is growing evidence on the effects of anthropogenic climate change on each event, given the relatively poor regional coverage and high model uncertainty, there is *low confidence* in the attribution of human-induced climate change to flood change on the global scale.

Table 4.3: Selected major heavy precipitation events from 2014-2021 that led to flooding and their impacts. Studies were selected for presentation based on the availability of impacts information. This is not a systematic assessment of event attributions studies and their physical science conclusions. "Sign of influence" indicates whether anthropogenic climate change was found to have made the event *more or less likely*, and "mechanism/magnitude of influence" quantifies the change in likelihood and the processes or quantities involved.

Year	Country / Region	Impact	Anthropogenic climate change influence the likelihood of an event		Reference
			Sign of influence	Mechanism / magnitude of influence	
2021	Germany, Belgium, Luxembourg and neighbouring countries	At least 222 fatalities, substantial damage to infrastructure, economic costs of €4.5 to €5.5 billion in Germany and over €0.35 billion in Belgium.	Increase	1-day rainfall intensity increased by 3 - 19%, the likelihood of event increased by a factor between 1.2 and 9	(Kreienkamp et al., 2021)
2019	Canada (Ottawa)	Thousands of people evacuated, extended states of emergency, and about $200 million in insured losses	Increase	Spring maximum 30-day rainfall accumulation in 2019 was 3 times as likely with anthropogenic forcing	(Kirchmeier-Young et al., 2021)
	Southern China	Over 6 million people across several southern China provinces were affected by heavy rains, floods, and landslides. These extremes caused at least 91 deaths, collapsed over 19,000 houses, damaged around 83,000 houses, and affected 419,400 ha of crops (China Ministry of Emergency Management 2020). The direct economic loss was estimated to be more than 20 billion	Decrease	Anthropogenic forcings have reduced the likelihood of heavy precipitation in southern China like the 2019 March–July event by about 60%	(Li et al., 2021b)

		RMB (equivalent to 3 billion USD)			
2018	USA (Mid-Atlantic)	1 fatality, $12 million damages	Increase	1.1 to 2.3 times more likely	(Winter et al., 2020)
	Central Western China	Persistent heavy rain led to floods, landslides and house collapse affecting 2.9 million people. The direct economic loss of over US$ 1.3 billion	Decrease	~47% reduction in the probability	(Zhang et al., 2020b)
	North-western China	Extreme flooding in the Upper Yellow River basin affected about 1.4 million people and led to 30 deaths and disappearances.	Decrease	34% reduction in the probability	(Ji et al., 2020)
	Japan	237 fatalities, more than 6,000 buildings destroyed by floods and landslides	Increase	7% increase in total precipitation	(Kawase et al., 2020)
	Australia (Tasmania)	$100 million in insurance claims	Unknown	Unknown	(Tozer et al., 2020)
2017	Peru	Widespread flooding and landslides affected 1.7 million people, 177 fatalities, estimated total damage of $3.1 billion	Increase	At least 1.5 times more likely	(Christidis et al., 2019)
	Uruguay and Brazil	Direct economic loss in Brazil of US$102 million, displacement of more than 3,500 people in Uruguay	Increase	At least double, with a most likely increase of about fivefold	(de Abreu et al., 2019)
	North-East Bangladesh	Flash flood-affected ~850,000 households, ~220,000 ha of nearly harvestable Boro rice damaged. Crop failure contributed to a record 30% rice price hike compared to the previous year	Increase	Doubled the likelihood of the 2017 pre-monsoon extreme 6-day rainfall event	(Rimi et al., 2019)
	China	7.8 million people affected 34 fatalities, about 0.8 million people displaced, 605,000 hectares of crops affected, 116,000 hectares without harvest. 32,000 houses collapsed, 41,000 were severely damaged. Direct economic loss 24.12 billion Chinese Yuan (~ US$3.6 billion)	Increase	Doubled the probability from 0.6% to 1.2%	(Sun et al., 2019b)
2016	South China	Widespread severe flooding, waterlogging, and landslides in the Yangtze–Huai region.	Increase	1.5-fold (0.6 to 4.7) increase in the probability	(Sun and Miao, 2018)
	China (Wuhan)	237 fatalities, 93 people missing, at least US$22 billion in damage	Increase	Approximately 60% of the risk	(Zhou et al., 2018a)

	China (Yangtze River)	The direct economic loss of about US$10 billion	Increase	Increased probability by 38% (± 21%)	(Yuan et al., 2018)
	Australia	Flooding and wild weather impacted some agriculture and power generation.	None	Minimal	(Hope et al., 2018)
2015	India (Chennai)	City declared a disaster area. Damages estimated as $3 billion	None	None	(van Oldenborgh et al., 2017a)
2014	Indonesia (Jakarta)	26 reported deaths Thousands of buildings flooded, much infrastructure damaged. Losses up to US $384 million	Unclear	2-day rain event approximately 2.4 times more likely compared to 1900, but cause not established	(Siswanto et al., 2015)

In snow-dominated regions, 1~10 days earlier spring floods per decades due to warmer temperature are reported for the last decades (*high confidence*), such as in Europe (Morán-Tejeda et al., 2014; Kormann et al., 2015; Matti et al., 2016; Vormoor et al., 2016; Blöschl et al., 2017), the European part of Russia (Frolova et al., 2017a; Frolova et al., 2017b; Kireeva et al., 2020), Canada (Yang L. et al., 2015; Burn et al., 2016; Rokaya et al., 2018), and the United States (Mallakpour and Villarini, 2015; Solander et al., 2017).

There is a knowledge gap in how ice-related floods, including glacier-related and ice-jam floods, respond to ongoing climate change. Despite the increase in the number of glacial lake studies (Wang and Zhou, 2017; Harrison et al., 2018; Begam and Sen, 2019; Bolch et al., 2019), changes in the frequency of occurrence of glacier-related floods associated with climate change remain unclear (*medium confidence*). Studies show that the compound occurrence of high surges and high river discharge has increased in some regions (WGI Chapter 11), but few studies quantify changes and impacts. Increases in precipitation from tropical cyclones (WGI Chapter 11) and associated high tide are expected to exacerbate coastal flooding. However, more studies are required to quantify their impacts. In addition, limitations in the duration of data hinder the assessment of trends in low-likelihood high-impact flooding (WGI BOX 11.2).

In summary, the frequency and magnitude of river floods have changed in the past several decades with high regional variations (*high confidence*). Anthropogenic climate change has increased the likelihood of extreme precipitation events and the associated increase in the frequency and magnitude of river floods (*high confidence*). There is *high confidence* that the warming in the last 40-60 years has led to ~10 days earlier spring floods per decade, shifts in timing and magnitude of ice-jam floods and changes in frequency and magnitude of snowmelt floods.

4.2.5 Observed Changes in Droughts

There are different types of droughts, and they are interconnected in terms of processes (Douville et al., 2021). *Meteorological droughts* (periods of persistent low precipitation) propagate over time into deficits in soil moisture, streamflow, and water storage, leading to a reduction in water supply (*hydrological drought*). Increased atmospheric evaporative demand increases plant water stress, leading to *agricultural and ecological drought*.

Hydrological drought can result in shortages of drinking water and cause substantial economic damages. Agricultural drought threatens food production through crop damage and yield decreases (e.g. (Tigkas et al., 2019), 4.3.1) (*high confidence*) and consequent economic impacts (Table 4.4). For example, drought in India in 2014 was reported to have led to an estimated US $30 billion in losses (Ward and Makhija, 2018). Ecological drought increases the risks of wildfire (Table 4.4). Cascading effects of droughts can include health issues triggered by a lack of sanitation (4.3.3); can cause human displacements, loss of social ties, sense of place and cultural identity; and migration to unsafe settlements (*medium confidence*) (Serdeczny et al., 2017) (4.3.7). Between 1970 and 2019, only 7% of all disaster events were drought-related, yet they contributed disproportionately to 34% of disaster-related death, mostly in Africa (WMO, 2021). Nevertheless, Indigenous knowledge, traditional knowledge and local knowledge have increased drought resilience among crop and livestock farmers, for example, in South Africa (Muyambo et al., 2017), Uganda (Barasa et al., 2020) and India (Patel et al., 2020) (4.8.4).

When hazard, vulnerability, and exposure are considered together, drought risk is lower for sparsely populated regions, such as tundra and tropical forests, and higher for populated areas and intensive crop and livestock farming regions, such as South and Central Asia, the Southeast of South America, Central Europe, and the Southeast of the USA (Figure 4.9). Dynamics in exposure and vulnerability are rarely addressed (Jurgilevich et al., 2017; Hagenlocher et al., 2019). Quantifying economic vulnerability to drought in terms of damages as a percentage of exposed Gross Domestic Product, (Formetta and Feyen, 2019) show a disproportionate burden of drought impact on low-income countries, but with a clear decrease in global economic drought vulnerability between 1980–1989 and 2007–2016 including a convergence between lower-income and higher-income countries due to stronger vulnerability reduction in less-developed countries. Nevertheless, in 2007-2016 economic vulnerability to drought was twice as high in lower income countries compared to higher-income countries (Formetta and Feyen, 2019).

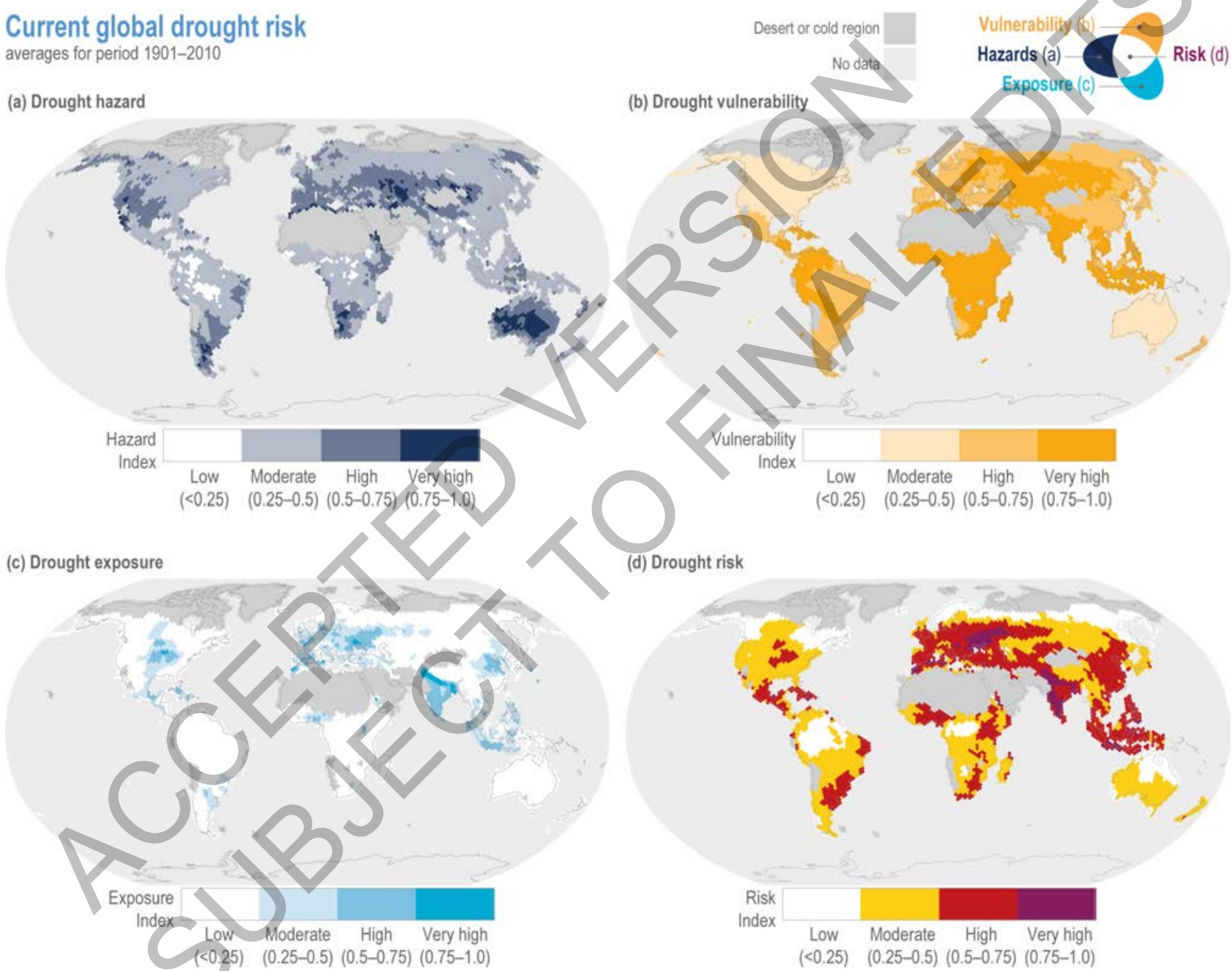


Figure 4.9: Current global drought risk and its components. (a) Drought hazard computed for the events between 1901–2010 by the probability of exceedance the median of global severe precipitation deficits, using precipitation data from the Global Precipitation Climatology Center (GPCC) for 1901–2010. (b) Drought vulnerability is derived from an arithmetic composite model combining social, economic, and infrastructural factors proposed by (UNISDR, 2004). (c) Drought exposure computed at the sub-national level with the non-compensatory DEA (Data Envelopment Analysis) model (Cook et al., 2014). (d) Drought risk based on the above components of hazard, vulnerability and exposure, scored on a scale of 0 (lowest risk) to 1(highest risk) with the lowest and highest hazard, exposure, and vulnerability (Carrão et al., 2016).

AR6 WG1 (Douville et al., 2021; Seneviratne et al., 2021) found that increasing agricultural and ecological droughts trends are more evident than increasing trends in meteorological drought in several regions due to increased evaporative demand. Therefore, WG1 concluded with *high confidence* that the increased frequency and the severity of agricultural/ecological droughts over the last decades in the Mediterranean and western North America can be attributed to anthropogenic warming.

In addition, there is *high confidence* in anthropogenic influence on increased meteorological drought in south-western Australia and *medium confidence* that recent drying and severe droughts in southern Africa and south-western South America can be attributed to human influence. Increased agricultural/ecological and (or) meteorological and (or) hydrological drought is also seen with either *medium confidence* or *high confidence* in the trend but with *low confidence* on attribution to anthropogenic climate change in western, north-eastern and central Africa; central, eastern and southern Asia; eastern Australia; southern and north-eastern South America and the South American monsoon region; and western and central Europe. Finally, decreased drought in one or more categories is seen with *medium confidence* in western and eastern Siberia; northern and central Australia; south-eastern South America; central North America and northern Europe, but with *low confidence* in attribution to anthropogenic influence except in northern Europe where anthropogenic influence on decreased meteorological drought is assessed with *medium confidence*.

Major drought events worldwide have had substantial societal and ecological impacts, including reduced crop yields, shortages of drinking water, wildfires causing deaths of people, very large numbers of animals and impacting the habitats of threatened species, and widespread economic losses (Table 4.4, Cross-Chapter Box DISASTER in Chapter 4). In addition, anthropogenic climate change was found to have increased the likelihood or severity of most such events examined in event attribution studies.

Table 4.4: Selected major drought events from 2013-2020 and their societal impact. Studies were selected for presentation based on the availability of impacts information, including an example of events which was not found to have a component attributable to climate change. This is not a systematic assessment of event attributions studies and their physical science conclusions. "Sign of influence" indicates whether anthropogenic climate change was found to have made the event more or less likely, and "mechanism/magnitude of influence" quantifies the change in likelihood and the processes or quantities involved.

Year	Country / region	Impact	Influence of anthropogenic climate on the likelihood of an event		Reference
			Sign of influence	*Mechanism/magnitude of influence*	
2019 / 2020	Australia	Wildfires burning ~97,000 km^2 across southern and eastern Australia. 34 human fatalities; 5900 buildings destroyed; millions of people affected by hazardous air quality; between 0.5 and 1.5 billion wild animals and tens of thousands of livestock killed; at least 30% of habitat affected for seventy taxa, including 21 already listed as threatened with extinction, over US$110 billion financial loss.	Increase	Extreme high temperatures causing drying of fuel. The likelihood of extreme heat at least doubled due to the long-term warming trend, and the likelihood of Fire Weather Index as severe or worse as observed in 2019/20 by at least 30 %, despite no attributable increase in meteorological (precipitation) drought.	(van Oldenborgh et al., 2020; Ward et al., 2020; Haque et al., 2021)
2019	Western Cape, South Africa	Water supply was reduced to 20% of capacity in January 2018. Agricultural yields in 2019 declined by 25%	Increase	Anthropogenic greenhouse forcing at least doubled the likelihood of drought levels seen in 2015-2019, offsetting anthropogenic aerosol forcing.	(Kam et al., 2021)
	Yunnan, south-western China	Water scarcity affected nearly 7 million residents and resulted in crop failure over at least 1.35 × 104 km2 cropland (Fig. 1).	Increase	Anthropogenic influence increased the risk of 2019 March–June hot and dry extremes over Yunnan province in south-western	(Wang et al., 2021b)

		More than 94% of the total area in the province was drought-stricken, and around 2 million people faced drinking water shortages, with a direct economic loss of about 6.56 billion RMB		China by 123%–157% and 13%–23%, respectively.	
	Southwestern China	Over 640,100 hectares of crops with rice, corn, and potatoes were extensively damaged. Over 100 rivers and 180 reservoirs dried out. Over 824,000 people and 566,000 head of livestock having a severe lack of drinking water, with a direct economic loss of 2.81 billion Chinese Yuan ($400 million)	Increase	Anthropogenic forcing has likely increased the like-lihood of the May–June 2019 severe low precipita-tion event in south-western China by approximately 1.4 to 6 times.	(Lu et al., 2021)
	South China	A lightning-caused forest fire in Muli County killed 31 firefighters and burned about 30 ha of forest	Increase	Anthropogenic global warming increased the weather-related risk of extreme wildfire by 7.2 times. In addition, the El Niño event increased risk by 3.6 times.	Du et al. (2021)
	Middle and lower reaches of the Yangtze River, China	Reduced agriculture productivity and increased load on power system supplies and transportations, and on human health.	Decrease	Anthropogenic forcing reduced the probability of rainfall amount in the extended rainy winter of 2018/19 by ~19% but exerted no influence on the excessive rainy days	Hu et al. (2021)
2018	South China	Shrinking reservoirs, water shortages. Area and yield for early rice reduced by 350 thousand hectares and 1.28 million tons relative to 2017	Increase	Likelihood increased by 17 times in the HadGEM3-A model. However, the event did not occur without human influence in the CAM5 model.	Zhang et al. (2020)
	China (Beijing)	A record 145 Consecutive Dry Days (|CDD), severe drought, increased risk of wildfires.	Increase	The likelihood of the record 145 CDD was increased by between 1.29 and 2.09 times by anthropogenic climate change and between 1.43 and 4.59 times by combining the La Niña event and weak Arctic polar vortex.	(Du et al., 2021)
2017	USA (Northern Great Plains)	"billion-dollar disaster"; widespread wildfires (one of Montana's worst wildfire seasons on record) compromised water resources, destruction of property, livestock sell-offs, reduced agricultural production, agricultural losses of $2.5 billion	Increase	1.5 times more likely due to increased evapotranspiration (minimal anthropogenic impact on precipitation)	(Hoell et al., 2019)
	East Africa	Extensive drought across Tanzania, Ethiopia, Kenya, and Somalia contributed to extreme food insecurity	Increase	Likelihood doubled	(Funk et al., 2019)

		approaching near-famine conditions			
2016	Southern Africa	Millions of people were affected by famine, disease, and water shortages. In addition, a 9-million ton cereal deficit resulted in 26 million people in need of humanitarian assistance.	Increase	Anthropogenic climate change *likely* increased the intensity of the 2015/16 El Niño, and a drought of this severity would have been very unlikely (probability ~9%) in the pre-industrial climate.	(Funk et al., 2018)
2016	Brazil	Três Marias, Sobradinho, and Itaparica reservoirs reached 5% of volume capacity. (Ceará), registered 39 (of 153) reservoirs empty in Ceará. Another 42 reached inactive volume. 96 (of 184) Ceará municipalities experienced water supply interruption.	Not found	Not found	(Martins et al., 2018)
2016	Thailand	Severe drought affected 41 Thai provinces, had devastating effects on major crops, such as rice and sugar cane, and incurred a total loss in the agricultural production of about half a billion US dollars	Increase	The record temperature of April 2016 in Thailand would not have occurred without the influence of both anthropogenic forcings and El Niño. Anthropogenic forcing has contributed to drier Aprils, but El Niño was the dominant cause of low rainfall.	(Christidis et al., 2018)
2015	Washington state, USA	The US $335 million loss for the agricultural industry	Increase	Snowpack drought resulted from exceedingly high temperatures despite normal precipitation	(Fosu et al., 2016)
2014	São Paulo, Brazil	In January 2015, the largest water supply system used for Sao Paulo, Cantareira, sank to a water volume of just 5% of capacity, and the number of people supplied fell from 8.8 million people to 5.3 million people, with other systems taking over supplies for the remainder.	No impact	Anthropogenic climate change is not found to be a major influence on the hazard, whereas increasing population and water consumption increased vulnerability.	(Otto et al., 2015)
2014	Southern Levant, Syria	While the extent to which the 2007/08 drought in the Levant region destabilized the Syrian government was not clear, "there is no questioning the enormous toll this extreme event took on the region's population. The movement of refugees from both the drought and war-affected regions into Jordan and Lebanon ensured that the anomalously low precipitation in the winter of 2013/14 amplified	Increase	The persistent drought in the 2014 rainy season was unprecedented for the critical January–February period in the observational record, and was made ~45% more likely by anthropogenic climate change.	(Bergaoui et al., 2015)

		impacts on already complex water and food provisions."			
2013-2014	Mediterranean coastal Middle East, northward through Turkey and eastward through Kazakhstan, Uzbekistan and Kyrgyzstan	The Eastern (main) basin of the Aral Sea dried up for the first time in modern history	Unclear	High western Pacific sea surface temperatures (SSTs) linked to drought in the Middle East and central-southwest Asia, and the SSTs in that region showed a strong warming trend.	(Barlow and Hoell, 2015)
2014	East Africa	Some isolated food security crises	Increase	Anthropogenic warming contributed to the 2014 East African drought by increasing East African and west Pacific temperatures, and increasing the gradient between standardized western and central Pacific SST causing reduced rainfall, evapotranspiration, and soil moisture.	(Funk et al., 2018)

Although long-term drought trends are clearer for agricultural or ecological drought compared to meteorological droughts (Douville et al., 2021; Seneviratne et al., 2021), most attribution studies for individual extreme events focus on meteorological (precipitation) drought and sometimes also considers temperature anomalies. A complete examination of drought relevant to societal impacts often requires consideration of hydrological and agricultural drought, so extreme event attribution conclusions relating to precipitation alone may not fully capture the processes leading to societal effects. There is, therefore, a critical knowledge gap in the attribution of changes in drought indicators more closely related to societal impacts such as soil moisture and the availability of fresh water supplies.

In summary, droughts can have substantial societal impacts (*virtually certain*), and agricultural and ecological drought conditions in particular have become more frequent and severe in many parts of the world but less frequent and severe in some others (*high confidence*). Drought-induced economic losses relative to GDP are approximately twice as high in lower-income countries compared to higher-income countries, although the gap has narrowed since the 1980s and at the global scale there is a decreasing trend of economic vulnerability to drought (*medium confidence*). Nevertheless, anthropogenic climate change has contributed to the increased likelihood or severity of drought events in many parts of the world, causing reduced agricultural yields, drinking water shortages for millions of people, increased wildfire risk, loss of lives of humans and other species and loss of billions of dollars of economic damages (*medium confidence*).

4.2.6 Observed Changes in Groundwater

AR5 concluded that the extent to which groundwater abstractions are affected by climate change is not well known due to the lack of long-term observational data (Jiménez Cisneros et al., 2014). AR 6 (Douville et al., 2021) confirmed that, despite considerable progress since AR5, limitations in the spatio-temporal coverage of groundwater monitoring networks, abstraction data, and numerical representations of groundwater recharge processes continue to constrain understanding of climate change impacts on groundwater.

Globally groundwater use has societal and economic benefits providing a critical buffer against precipitation variability. Groundwater irrigation has ensured food security, livelihood support, and poverty alleviation, for example, in India (Sekhri, 2014), Bangladesh (Salem et al., 2018), and sub-Saharan Africa (Taylor et al., 2013a; Cuthbert et al., 2019b). Groundwater is a safe drinking water source during natural hazard-induced disasters (Richts and Vrba, 2016). However, groundwater over-exploitation leads to the attenuation of societal benefits, including reduced agricultural production (Asoka and Mishra, 2020; Jain et al., 2021), decrease in adaptive capacity of communities (Blakeslee et al., 2020), and water quality deterioration (Mas-Pla and Menció, 2019). Loss of traditional water systems based on groundwater, such as *foggara* in Tunisia (Mokadem et al., 2018), *qanat* in Pakistan (Mustafa and Usman Qazi, 2008), *aflaj* in Oman (Remmington, 2018), and spring boxes in the Himalayas (Kumar and Sen, 2018) also leads to loss of cultural values for local communities.

Even though global groundwater abstraction (789 ± 30 km3 yr−1) is just about 6 percent of the annual recharge (~13,466 km^3) (Hanasaki et al., 2018), few hotspots of groundwater depletion have emerged at local to regional scales since the end of 20th century to beginning of 21st century due to intensive groundwater use for irrigation. The variability in groundwater storage is a function of human abstraction and natural recharge, which is in turn controlled by local geology (Green, 2016). In humid regions, precipitation influences recharge, and linear associations between precipitation and recharge are often observed (Kotchoni et al., 2019); for example, over humid locations in sub-Saharan Africa (Cuthbert et al., 2019b).

A global review (Bierkens and Wada, 2019) of groundwater storage changes highlight that estimates of depletion rates at the global scale are variable. These estimates range from approximately 113 to 510 km^3 $year^{-1}$ and variation in estimates is due to methods and spatio-temporal scales considered (*high confidence*). Global hydrological models (Herbert and Döll, 2019) show that human-induced groundwater depletion at rates exceeding 20 mm $year^{-1}$ (2001–2010) is occurring in the major aquifers systems such as the High Plains and California Central Valley aquifers (USA), Arabian aquifer (Middle East), North-Western Sahara aquifer (North Africa), Indo-Gangetic Basin (India) and North China Plain (China) (*high confidence*). Groundwater depletion at lower rates (<10 mm $year^{-1}$) is taking place in the Amazon Basin (Brazil) and Mekong River Basin (South East Asia), primarily due to climate variability and change (*high confidence*). A global-scale analysis (Shamsudduha and Taylor, 2020) of GRACE satellite measurements (2002–2016) for the 37 world's large aquifer systems reveals that trends in groundwater storage are mostly nonlinear and declines are not secular (*high confidence*). There are strong statistical associations between changes in groundwater storage and extreme annual precipitation from 1901 to 2016 in the Great Artesian Basin (Australia) and the California Central Valley aquifer (USA). Groundwater recharge of high magnitudes can be generated from intensive precipitation events. On the other hand, recharge can become more episodic, mostly in arid to semi-arid locations (*robust evidence, medium agreement*). For example, in central Tanzania, seven rainfall events between 1955 and 2010 generated 60% of total recharge (Taylor et al., 2013b). Similarly, in southern India (Asoka et al., 2018) and southwestern USA (Thomas et al., 2016), focused recharge via losses from ephemeral river channels, overland flows, and floodwaters is documented (Cuthbert et al., 2019b).

In cold regions, where snowmelt dominates the local hydrological processes (Irannezhad et al., 2016) and (Vincent et al., 2019) show high recharge to aquifers from glacial meltwater; while (Nygren et al., 2020) report a decrease in groundwater recharge due to a shift in main recharge period from spring (snowmelt) to winter (rainfall). In Finland, a sustained reduction (almost 100 mm in 100 years) of long-term snow accumulation combined with early snowmelt has reduced spring-time recharge (Irannezhad et al., 2016) (*medium confidence*).

Data from ground-based long-term records in the Indo-Gangetic Basin reveals that sustainable groundwater supplies are constrained more by extensive contamination (e.g., arsenic, salinity) than depletion (MacDonald et al., 2016). Many low-lying coastal aquifers are contaminated with increased salinity due to land-use change, rising sea levels, reduced stream flows, and increased storm surge inundation (Lall et al., 2020). Nearly 26 million people are currently exposed to very high (>1500 $\mu S\ cm^{-1}$) salinity in shallow groundwater in coastal Bangladesh (Shamsudduha and Taylor, 2020).

Groundwater Dependent Ecosystems (GDEs), such as terrestrial wetlands, stream ecosystems, estuarine and marine ecosystems (Kløve et al., 2014), support wetlands, biodiversity, provide water supply, baseflows to rivers, offers recreational services, and help control floods (Rohde et al., 2017). Globally, 10% to 23% of the watersheds have reached the environmental flow limits due to groundwater pumping (de Graaf et al., 2019). A recent study of 4.2 million wells across the USA shows that induced groundwater recharge in nearly two-thirds of these wells could reduce stream discharges, thereby threatening GDEs (Jasechko et al., 2021). (Work, 2020) found reduced spring flow due to increased groundwater abstraction in 26 out of 56 springs studied in Florida (USA). GDEs in semi-arid and arid regions tend to have much longer groundwater response times and may be more resilient to climate change than those in humid areas where groundwater occurrence is mostly at shallow levels (Cuthbert et al., 2019a; Opie et al., 2020). However, groundwater depletion impacts on the full range of ecosystem services remain understudied (Bierkens and Wada, 2019).

A better understanding of and incorporating subsurface storage dynamics into earth system models will improve climate-groundwater interactions under global warming (Condon et al., 2020). Long-term groundwater-level monitoring data are of critical importance (Famiglietti, 2014) for understanding the sensitivity of recharge processes to climate variability and, more critically, calibration and validation of hydrological models (Goderniaux et al., 2015). GRACE satellite-derived groundwater storage estimates provide important insights at a regional scale (Rodell et al., 2018) but overlook more localized depletion or short-term storage gains. Low and middle-income countries, e.g., in Central Asia and Sub-Saharan Africa, lack such monitoring networks, which is a significant knowledge gap.

In summary, groundwater storage has declined in many parts of the world, most notably since the beginning of the 21st century, due to the intensification of groundwater-fed irrigation (*high confidence*). Groundwater in aquifers across the tropics appears to be more resilient to climate change as enhanced recharge is observed to occur mostly episodically from intense precipitation and flooding events (*robust evidence, medium agreement*). In higher altitudes, warmer climates have altered groundwater regimes and may have led to reduced spring-time recharge due to reduced duration and snowmelt discharges (*medium confidence*).

4.2.7 Observed Changes in Water Quality

AR5 (Jiménez Cisneros et al., 2014) concluded with *medium evidence* and *high agreement* that climate change affected water quality, posing additional risks to drinking water quality and human health (Field et al., 2014b), particularly due to increased eutrophication at higher temperatures or release of contaminants due to extreme floods (Jiménez Cisneros et al., 2014). In addition, SROCC (Hock et al., 2019b; Meredith et al., 2019) assessed that glacier decline and permafrost degradation impacts water quality through increases in legacy contaminants *(medium evidence, high agreement)*.

Warming temperatures and extreme weather events are can potentially impact water quality (Khan et al., 2015). Water quality can be compromised through algal blooms that affect the taste and odour of recreational and drinking water and can harbour toxins and pathogens (Khan et al., 2015). Warming directly affects thermal water regimes, promoting harmful algal blooms (Li et al., 2018; Noori et al., 2018) (4.3.5). Additionally, permafrost degradation leads to an increased flux of contaminants (MacMillan et al., 2015; Roberts et al., 2017; Mu et al., 2019). The increased meltwater from glaciers (Zhang et al., 2019) releases deposited contaminants and reduces water quality downstream (Zhang et al., 2017; Hock et al., 2019b).

Floods intensify the mixing of floodwater with wastewater and the redistribution of pollutants (Andrade et al., 2018). In addition, contaminated floodwaters pose an immediate health risk through waterborne diseases (Huang et al., 2016b; Paterson et al., 2018; Setty et al., 2018). Wildfires, along with heavy rainfalls and floods, can also affect turbidity, which increases drinking water treatment challenges and has been linked to increases in gastrointestinal illness (de Roos et al., 2017. Droughts reduce river dilution capacities and groundwater levels {Wen, 2017 #2093), increasing the risk of groundwater contamination (Kløve et al., 2014). More generally, contaminated water diminishes its aesthetic value, compromising recreational activities, reducing tourism and property values, and creating challenges for management and drinking water treatment (Eves and Wilkinson, 2014; Khan et al., 2015; Walters et al., 2015).

Between 2000−2010, ~10% of the global population faced adverse water quality issues (van Vliet et al., 2021). Adverse drinking water quality has been associated with extreme weather events in countries located in Asia, Africa, and South and North America (Jagai et al., 2015; Levy et al., 2016; Huynh and Stringer, 2018; Leal Filho et al., 2018; Abedin et al., 2019) (*medium evidence, high agreement*). Dilution factors in 635 of 1049 US streams fell extremely low during drought conditions. Additionally, the safety threshold for endocrine-disrupting compound concentration exceeded in roughly a third of streams studied (Rice and Westerhoff, 2017). Natural acid rock drainage, which can potentially release toxic substances, has experienced an intensification in an alpine catchment of Central Pyrenees due to climate change and severe droughts in the last decade. River length affected by natural acid drainage increased from 5 km in 1945 to 35 km in 2018 (Zarroca et al., 2021). Three-fold increases in contaminants and five-fold increases in nutrients have been observed in water sources after wildfires (Khan et al., 2015). Due to permafrost thawing, the concentration of major ions, especially SO_4^{2-} in two high Arctic lakes, has rapidly increased up to 500% and 340% during 2006–2016 and 2008–2016, respectively (Roberts et al., 2017). The exports of Dissolved Organic Carbon, Particulate Organic Carbon and Mercury in six Arctic rivers were reported to increase with significant deepening active layers caused by climate warming during 1999−2015 (Mu et al., 2019). Sustained warming in Lake Tanganyika in Zambia during the last ∼150 years reduced lake mixing, which has depressed algal production, shrunk the oxygenated benthic habitat by 38%, and further reduced fish yield and mollusc (Cohen et al., 2016). From 1994 to 2010, coastal benthos at King George Island in Antarctica has observed a remarkable shift primarily linked to ongoing climate warming and the increased sediment runoff triggered by glacier retreats (Sahade et al., 2015). The recovery time of macroinvertebrates from floods was found longer in cases of pre-existing pollution problems (Smith et al., 2019a).

In summary, although climate-induced water quality degradation due to increases in water and surface temperatures or melting of the cryosphere has been observed (*medium confidence*), evidence of global-scale changes in water quality is *limited* because many studies are isolated and have limited regional coverage.

4.2.8 Observed Changes in Soil Erosion and Sediment Load

AR5 established potential impacts of climate change on soil erosion and sediment loads in mountain regions with glacier melt (*low to medium evidence*) (Jiménez Cisneros et al., 2014). SRCCL (Olsson et al., 2020) reported with *high confidence* that rainfall changes attributed to human-induced climate change have already intensified drivers of land degradation. Nonetheless, attributing land degradation to climate change alone is challenging because of the role of land management practices (*medium evidence, high agreement*).

Climate change impacts soil erosion and sedimentation rates both directly from increasing rainfall or snowmelt intensity (Vanmaercke et al., 2014; Polyakov et al., 2017; Diodato et al., 2018; Golosov et al., 2018; Li et al., 2020a; Li et al., 2020b) and indirectly from increasing wildfires (Gould et al., 2016; Langhans et al., 2016; DeLong et al., 2018), permafrost thawing (Schiefer et al., 2018; Lafrenière and Lamoureux, 2019; Ward Jones et al., 2019), vegetation cover changes (Micheletti et al., 2015; Potemkina and Potemkin, 2015; Carrivick and Heckmann, 2017; Beel et al., 2018). In addition, accelerated soil erosion and sedimentation have severe societal impacts through land degradation, reduced soil productivity and water quality (4.2.7), increased eutrophication and disturbance to aquatic ecosystems (4.3.5), sedimentation of waterways and damage to infrastructure (Graves et al., 2015; Issaka and Ashraf, 2017; Schellenberg et al., 2017; Hewett et al., 2018; Panagos et al., 2018; Sartori et al., 2019) (*medium confidence*).

In the largest river basin of the Colombian Andes, regional climate change and land use activities (ploughing, grazing, deforestation) caused a 34% erosion rate increase over 10 years, with the anthropogenic soil erosion rate exceeding the climate-driven erosion rate (Restrepo and Escobar, 2018). Sedimentation increases due to soil erosion in mountainous regions burned by wildfires, as a result of warming and altered precipitation, is documented with *high confidence* in the USA (Gould et al., 2016; DeLong et al., 2018), Australia (Nyman et al., 2015; Langhans et al., 2016), China (Cui et al., 2014), Greece (Karamesouti et al., 2016), and can potentially damage downstream aquatic ecosystems (4.3.5) and water quality (4.2.7) (Cui et al., 2014; Murphy et al., 2015; Langhans et al., 2016) (*medium confidence*). In Australia, for instance, sediment yields from post-fire debris flows (113–294 t ha^{-1}) are 2–3 orders of magnitude higher than annual background erosion rates from undisturbed forests (Nyman et al., 2015). The positive trend in sediment yield in small ponds in the semi-arid southwestern USA over the last 90 years was not entirely related to the rainfall or runoff trends, but was a result of complex interaction between long-term changes in vegetation, soil, and channel networks (Polyakov et al., 2017).

Regional climate changes (precipitation decrease) and human activities (landscape engineering, terracing, large-scale vegetation restoration, soil conservation) over the Loess Plateau (China) caused a distinct stepwise reduction in sediment loads from the upper-middle reach of the Yellow River, with 30% of the change related to climate change (Tian et al., 2019). Substantial increases in sediment flux were identified on the Tibetan Plateau (Li et al., 2020a; Li et al., 2021a), e.g. the sediment load from the Tuotuohe headwater increased by 135% from 1985-1997 to 1998-2016, mainly due to climate change (Li et al., 2020a). In 1986-2015, the sedimentation rate in dry valley bottoms of the Southern Russian Plain was 2 to 5 times lower than in 1963–1986 due to the warming-induced surface runoff reduction during spring snowmelt (Golosov et al., 2018). Declining erosion trends are primarily associated with soil conservation management in northern Germany (Steinhoff-Knopp and Burkhard, 2018) and reforestation in southwestern China (Zhou et al., 2020).

The climate change impact on erosion and sediment load varies significantly over the world (Li et al., 2020b) (*high confidence*). There was a statistically significant correlation between sediment yield and air temperature for the non-Mediterranean region of Western and Central Europe (Vanmaercke et al., 2014) and Northern Africa (Achite and Ouillon, 2016). Still, such correlation is yet to be found for the other European rivers (Vanmaercke et al., 2015). Increased sediment and particulate organic carbon fluxes in the Arctic regions are caused by permafrost warming (Schiefer et al., 2018; Lafrenière and Lamoureux, 2019; Ward Jones et al., 2019). (Potemkina and Potemkin, 2015) demonstrate that regional warming and permafrost degradation have contributed to an increased forested area over the last 40–70 years, reducing soil erosion in Eastern Siberia. The sediment dynamics of small rivers in the eastern Italian Alps, depending on extreme floods, is sensitive to climate change (Rainato et al., 2017). In the north-eastern Italian Alps, precipitation change in 1986-2010 affected soil wetness conditions, influencing sediment load (Diodato et al., 2018). Regional warming in northern Africa (Algeria) dramatically changed river streamflow and increased sediment load over 4 decades (84% more every decade compared to the previous) (Achite and Ouillon, 2016).

A long-term global soil erosion monitoring network based on the unified methodological approach is needed to correctly evaluate erosion rate, detect its changes and attribute them to climate or other drivers.

In summary, in the areas with high human activity, the latter impact soil erosion and sediment flux more significantly than the climatic factors (*high confidence*). On the other hand, in natural conditions, e.g. in high latitudes and high mountains, the influence of climate change on the acceleration of the erosion rate is observed (*limited evidence, medium agreement*).

4.3 Observed Sectoral Impacts of Current Hydrological Changes

The intensification of the hydrological cycle due to anthropogenic climate change has multifaceted and severe impacts for cultural, economic, social and political pathways. In this section, we assess burgeoning evidence since AR5 which shows that environmental quality, economic development, and social well-being have been affected by climate induced hydrological changes since many aspects of the economy, environment, and society are dependent upon water resources. We advance previous IPCC reports by assessing evidence on the impacts of climate change-induced water insecurity for energy production (4.3.2), urbanization (4.3.4), conflicts (4.3.6), human mobility (4.3.7) and cultural usage of water (4.3.8).

Integrating qualitative and quantitative data, we show that it is evident that societies heightened exposure to water-induced disasters – as floods and droughts – and other hydrological changes have increased vulnerability across most sectors and regions, with few exceptions. Through the assessment of literature relying on Indigenous knowledge, we are also able to present evidence on how observed changes impact particularly Indigenous Peoples, local communities, and marginalized groups, as women, people without social protections and minorities.

Importantly, we note, that climate change induced hydrological changes are, for most sectors, one of the several factors, often coupled with urbanization, population growth and heightened economic disparities, that have increased societal vulnerability and required communities across the globe to alter their productive and cultural practices.

4.3.1 Observed Impacts on Agriculture

AR5 concluded with *high confidence* that agricultural production was negatively affected by climate change, with droughts singled out as a major driver of food insecurity. In contrast, evidence of floods on food production was *limited* (Porter et al., 2014).

Globally 23% of croplands are irrigated, providing 34% of global calories production. Of these lands, 68% experience blue water scarcity at the least one month-yr and 37% up to 5 months-yr. Such agricultural water scarcity is experienced in mostly drought-prone areas in low-income countries (Rosa et al., 2020a). Approximately three-quarters of the global harvested areas (~454 million hectares) experienced drought-induced yield losses between 1983 and 2009, and the cumulative production losses corresponded to US$166 billion (Kim et al., 2019). Globally, droughts affected both harvested areas and yields, with a reported cereal production loss of 9-10% due to weather extremes between 1964 and 2007. Yield losses were greater by about 7% during recent droughts (1985-2007) due to greater damage – reducing harvested area - compared to losses from earlier droughts (1964-1984), with 8-11% greater losses in high-income countries than in low-income ones (Lesk et al., 2016). Globally, between 1961 and 2006, it has been estimated that 25% yield loss occurred, with yield loss probability increasing by 22% for maize, 9% for rice, and 22% for soybean under drought conditions (Leng and Hall, 2019). Mean climate, and climate extremes are responsible for 20-49% of yield anomalies variance, with 18-45% of this variance attributable to droughts and heatwaves (Vogel et al., 2019). Drought has been singled out as a major driver of yield reductions globally (*high confidence*) (Lesk et al., 2016; Meng et al., 2016; Zipper et al., 2016; Anderson et al., 2019; Leng and Hall, 2019).

Yields of major crops in semi-arid regions, including the Mediterranean, sub-Saharan Africa, South Asia and Australia, are negatively affected by precipitation declines in the absence of irrigation (Iizumi et al., 2018; Ray et al., 2019), but this trend is less evident in wetter regions (Iizumi et al., 2018). Precipitation and temperature changes reduced global mean yields of maize, wheat and soybeans by 4.1%, 1.8% and 4.5%, respectively (Iizumi et al., 2018). Of the global rice yield variability of ~32%, precipitation variability accounted for a larger share in drier South Asia than in wetter East and Southeast Asia (Ray et al., 2015). Between 1910-2014 agro-climatic conditions became more conducive to maize and soybean yield growth in the American Midwest due to increases in summer precipitation and cooling due to irrigation (Iizumi and Ramankutty, 2016; Mueller et al., 2016) (Box 4.3). In Australia, between 1990 and 2015, the negative effects of reduced precipitation and rising temperature led to yield losses, but yield losses were partly avoided because of elevated CO_2 atmospheric concentration and technological advancements (Hochman et al., 2017a). Overall, temperature-only effects are stronger in wetter regions like Europe and East and Southeast Asia, and precipitation-only effects are stronger in drier regions (Iizumi et al., 2018; Ray et al., 2019) *(medium evidence, high agreement)*. In Asia, the gap between rainfed and irrigated maize yield widened from 5% in the 1980s to 10% in the 2000s (Meng et al., 2016). In North America, yields of maize and soybeans have increased (1958-2007), yet meteorological drought has been associated with 13% of overall yield variability. However, yield variability was not a concern where irrigation is prevalent (Zipper et al., 2016). However, when water scarcity has reduced irrigation, yields have been negatively impacted (Elias et al., 2016). In Europe, yields have been affected negatively by droughts (Beillouin et al., 2020), with losses tripling between 1964 and 2015 (Brás et al., 2021). In West Africa between 2000 and 2009, drought, among other altered climate conditions, led to millet and sorghum yield reductions between 10-20% and 5-15%, respectively (Sultan et al., 2019). Between 2006 to 2016, droughts contributed to food insecurity and malnutrition in northern, eastern, and southern Africa, Asia and the Pacific. In 36% of these nations – mainly in Africa – where severe droughts occurred, undernourishment rose (Phalkey et al., 2015; Cooper et al., 2019). An attribution study showed that anthropogenic emissions increased the chances of October-December droughts over the region by 1.4 to 4.3 times and resulted in below-average harvests in Zambia and South Africa (Nangombe et al., 2020). Root crops, a staple in many tropics and sub-tropical countries, and vegetables are particularly prone to drought, leading to smaller fruits or crop failure (Daryanto et al., 2017; Bisbis et al., 2018). Livestock production has also been affected by changing seasonality, increasing frequency of drought, rising temperatures and vector-borne diseases and parasites through changes in the overall availability, as well as reduced nutritional value, of forage and feed crops (Varadan and Kumar, 2014; Naqvi et al., 2015; Zougmoré et al., 2016; Henry et al., 2018; Godde et al., 2019) *(medium confidence)*.

Floods have led to harvest failure, crop and fungal contamination (Liu et al., 2013; Uyttendaele et al., 2015). Globally, between 1980 and 2018, excess soil moisture has reduced rice, maize, soybean and wheat yields between 7 and 12% (Borgomeo et al., 2020). Changes in groundwater storage and availability, which are affected by the intensity of irrigated agriculture, also negatively impacted crop yields and cropping patterns (4.2.6, Box 4.3, 4.7.2). Moreover, extreme precipitation can lead to increased surface flooding, waterlogging, soil erosion and susceptibility to salinization (*high confidence*). For example, in Bangladesh, in March and April 2017, floods affected 220,000 ha of nearly ready to be harvested summer paddy crop and resulted in almost a 30% year on year increase in paddy prices. An attribution study of those pre-monsoon extreme rainfall events in Bangladesh concluded that anthropogenic climate change doubled the likelihood of the extreme rainfall event (Rimi et al., 2019). Moreover, floods, extreme weather events and cyclones have led to animal escapes and infrastructure damage in aquaculture (Beveridge et al., 2018; Islam and Hoq, 2018; Naskar et al., 2018; Lebel et al., 2020) (see 5.9.1).

Worldwide, the magnitudes of climate-induced water-related hazards and their impact on agriculture are differentiated across populations and genders (4.3.6; 4.8.3). Evidence shows that hydroclimatic factors pose high food insecurity risks to subsistence farmers, whose first and only source of livelihood is agriculture, and who are situated at low latitudes where the climate is hotter and drier (Shrestha and Nepal, 2016; Sujakhu et al., 2016). Historically, they have been the most vulnerable to observed climate-induced hydrological changes (Savo et al., 2016). Indigenous and local communities, often heavily reliant on agriculture, have a wealth of knowledge about observed changes. These are important because they shape farmers' perceptions, which in turn shape the adaptation measures farmers will undertake (Caretta and Börjeson, 2015; Savo et al., 2016; Sujakhu et al., 2016; Su et al., 2017) (4.8.4) (*high confidence)*.

In summary, ongoing climate change in temperate climates has some positive impacts on agricultural production. In subtropical/tropical climates, climate-induced hazards such as floods and droughts negatively impact agricultural production (*high confidence*). People living in deprivation and Indigenous people have been disproportionally affected. They often rely on rain-fed agriculture in marginal areas with high exposure and high vulnerability to water-related stress and low adaptive capacity (*high confidence)*.

4.3.2 Observed Impacts on Energy and Industrial Water Use

AR5 (Jiménez Cisneros et al., 2014) concluded with *medium evidence* and *high agreement* that hydropower negatively impacts freshwater ecosystems. SROCC (IPCC, 2019a) concluded with *medium confidence* that climate change has led to both increases and decreases in annual/seasonal water inputs to hydropower plants.

Water is a crucial input for hydroelectric and thermoelectric energy production, which together account for 94.7% of the world's current electricity generation (Petroleum, 2020). Climate change impacts hydropower production through changes in precipitation, evaporation, volume, and timing of run-off; and impacts cooling of thermoelectric power plants through reduced streamflow and increased water temperatures (Yalew et al., 2020). In addition, extreme weather events, like tropical cyclones, landslides, and floods, damage energy infrastructure (MCTI, 2020; Yalew et al., 2020), while high temperature and humidity increase the energy requirement for cooling (Maia-Silva et al., 2020).

With 1,308 GW installed capacity in 2019, hydropower became the world's largest single source of renewable energy (IHA, 2020) (also see Figure 6.12, WGIII). While hydropower reduces emissions relative to fossil fuel-based energy production, hydropower reservoirs are being increasingly associated with GHG emissions caused by submergence and later re-emergence of vegetation under reservoirs due to water level fluctuations (Räsänen et al., 2018; Song et al., 2018; Maavara et al., 2020). A recent global study concluded that reservoirs might emit more carbon than they bury, especially in the tropics (Keller et al., 2021) (*medium confidence*).

In Ghana, between 1970 and 1990, rainfall variability accounted for 21% of inter-annual variations in hydropower generation (Boadi and Owusu, 2019). In Brazil's São Francisco River, following drought events in 2016 and 2017, hydropower plants operated with an average capacity factor of only 23% and 17%, respectively (de Jong et al., 2018). In Switzerland, increased glacier melt contributed to 3% to 4% of hydropower production since 1980 (Schaefli et al., 2019) (4.2.2). In the USA, hydropower generation dropped by nearly 27% for every standard deviation increase in water scarcity. Equivalent social costs of loss in hydropower generation between 2001-2012 were approximately US$330,000 (at 2015 value) per month for every power plant that experienced water scarcity (Eyer and Wichman, 2018). Globally, for the period 1981-2010, the utilization rate of hydropower was reduced by 5.2% during drought years compared to long-term average values (van Vliet et al., 2016a). Thus, there is a growing body of evidence of negative impacts of extreme events on hydropower production (*high confidence*).

Impacts of water scarcity on thermoelectric plants are more unequivocal than hydropower plants. For example, a simulation study showed that 32% of the world's coal-fired power plants are currently experiencing water scarcity for at least five months or more in a year. The majority of these plants are in China (52%), followed by India (15%) and the USA (11%) (Rosa et al., 2020c). In the United Kingdom, almost 50% of freshwater thermal capacity is lost on extreme high-temperature days, causing losses in the range of average GBP 29-66 million/year. In the case of ~20% of particularly vulnerable power plants, these losses could increase to GBP 66-95 million/year annualized over 30 years (Byers et al., 2020). Globally, for the period 1981-2010, the utilization rate of thermoelectric power was reduced by 3.8% during drought years compared to long-term average values (van Vliet et al., 2016a); and none of the studies reported increases in thermoelectric power production as a consequence of climate change (*high confidence*).

In energy sector, a large number of studies document the impact of extreme climate events (e.g., droughts, or extreme temperature days) on production of hydropower and thermo-electric power, yet, there are limited studies that measure trends in energy production due to long term climate change. This remains a knowledge gap.

Mining in regions already vulnerable to climate change-induced water scarcity is under threat, leading some countries like El Salvador to ban metal mining completely (Odell et al., 2018). Likewise, food and agro-processing companies are aware of water-related threats to their operations, with 77% of 35 publicly traded companies evaluated in 2019 explicitly citing water as a risk factor in their annual reports, up from 59% in 2017 (CDP, 2018; CERES, 2019). Changes in water availability affect the mining, electrical, metal, and agro-processing sector (UNIDO, 2017; Odell et al., 2018; Frost and Hua, 2019), but these impacts are less understood due to the lack of studies.

In summary, there is *high confidence* that climate change has had negative impacts on hydro and thermal power production globally due to droughts, changes in the seasonality of river flows, and increasing ambient water temperatures.

4.3.3 Observed Impacts on Water, Sanitation and Hygiene (WaSH)

AR5 showed that local changes in temperature and rainfall had altered the distribution of some water-related diseases (*medium confidence*), and extreme weather events disrupt water supplies, impacting morbidity, mortality, and mental health (*very high confidence*) (Field et al., 2014b). In addition, melting and thawing of snow, ice, and permafrost (4.2.2) have also adversely impacted water quality, security, and health (*high confidence*) (IPCC, 2019a) (4.2.7).

Literature since AR5 confirms that temperature, precipitation, and extreme weather events are linked to increased incidence and outbreaks of water-related and neglected tropical diseases (Colón-González et al., 2016; Levy et al., 2016; Azage et al., 2017; Harp et al., 2021) (*high confidence*). For example, the rainy season in Senegal has been associated with an 84% increase in relative risk of childhood diarrhoea, and an additional wet day per week was associated with up to 2% increases in diarrheal disease in Mozambique (Thiam et al., 2017; Horn et al., 2018). In Ecuador, increases of 1.5 cases of diarrhoea per 1000 were associated with heavy rainfall after dry periods, while a decrease of 1 case per 1000 was associated with heavy rain after wet periods (Carlton et al., 2014). Floods have been associated with 22% increases in relative risk of diarrhoea in China (Liu et al., 2018c). In addition, higher levels of faecal contamination of drinking water and hands (i.e., lack of WaSH) has been statistically significantly associated with increased child diarrhoea (Goddard et al., 2020).

In 2020, 2 billion people lacked access to uncontaminated water, while 771 million lacked basic sanitation services, primarily in sub-Saharan Africa and rural areas (WHO and UNICEF, 2021). Even in high-income countries, poor quality drinking water can be a health issue (Murphy et al., 2014). For example, in a sampled population in Canada, reported exposure to exposure routes for waterborne illness included 7% from private wells and 71.8% from municipal water (David et al., 2014). Drinking water treatment can be compromised by degraded source water quality and extreme weather events, including droughts, storms, ice storms and wildfires that overwhelm or cause infrastructure damage (Sherpa et al., 2014; Khan et al., 2015; Howard et al., 2016; White et al., 2017) (*high confidence*). Adverse health effects are exacerbated due to the absence of adequate WaSH, particularly in poorer households (Khan et al., 2015; Kostyla et al., 2015; Cissé et al., 2016), WaSH infrastructure failure (Khan et al., 2015; Wanda et al., 2017), or inadequate WaSH facilities in emergency shelters (Alam and Rahman, 2014). For example, WaSH coverage decreased from 65% to 51% due to damage from floods and earthquakes in Malawi (Wanda et al., 2017). Loss of electricity also impacts WaSH service delivery (Cashman, 2014), and infrastructure damage caused by climate hazards may reverse progress on universal access to WaSH (Kohlitz et al., 2017) (*limited evidence, high agreement*). In addition, wastewater outflows have been associated with a 13% increased relative risk of gastrointestinal illness through contaminated drinking water sources (Jagai et al., 2015) (*limited evidence, high agreement*). Harmful algal blooms represent an emerging health risk, but lack of monitoring and reporting prevent risk exposure assessments (Carmichael and Boyer, 2016; Nichols et al., 2018) (*limited evidence, high agreement*). Chemical contaminants (e.g., nitrates, arsenic) have been linked to non-communicable diseases, including neurological disorders, liver and kidney damage, and cancers (Jones Rena et al., 2016), and to some water-related diseases (e.g., schistosomiasis) (*low evidence, medium agreement*).

Water insecurity and inadequate WaSH have been associated with increased disease risk (*high confidence*), stress and adverse mental health (*limited evidence, medium agreement*), food insecurity and adverse nutritional outcomes, and poor cognitive and birth outcomes (*limited evidence, medium agreement*) (Workman and Ureksoy, 2017; Sclar et al., 2018; Boateng et al., 2020; Rosinger and Young, 2020; Wutich et al., 2020). Climate-induced water scarcity and supply disruptions disproportionately impact women and girls. The necessity of water collection takes away time from income-generating activities, child care, and education (Yadav and Lal, 2018; Schuster et al., 2020) (*medium evidence, medium agreement*). Consumption of larger volumes of water is essential for healthy women during pregnancy, lactation, and caregiving, which increases the amount of water that has to be fetched. Fetching of water is associated with increased risk of sexual abuse, demand for sexual favours at controlled water collection points, physical injuries (e.g., musculoskeletal or from animal attacks), domestic violence for not completing daily water-related domestic tasks (*limited evidence, high agreement*), and poorer maternal and child health (Mercer and Hanrahan, 2017; Pommells et al., 2018; Anwar et al., 2019; Collins et al., 2019a; Geere and Hunter, 2020; Venkataramanan et al., 2020) (*medium evidence, high agreement*). Menstrual hygiene management is a public health issue but poorly linked to climate change, despite relationships between lack of adequate WaSH, poor menstrual hygiene, and urinary tract infections (Ellis et al., 2016; Pouramin et al., 2020). Water insecurity also affects emotional, spiritual, and cultural relationships that are often critical to Indigenous health (Wilson et al., 2019) (*limited evidence, high agreement*).

There are gaps in data on climate-driven water-related disease burden for both infectious and non-communicable diseases. Increased demands for water and WaSH services for infectious diseases, such as HIV/AIDs and COVID-19 (Box4.4) exacerbate existing vulnerabilities and inequities (Stanley et al., 2017; Armitage and Nellums, 2020a; Rodriguez-Lonebear et al., 2020). Additionally, limited research has been undertaken to quantify the effects of climate-compromised WaSH on health and wellbeing.

In summary, WaSH-related household water insecurity and disease incidence are products of geography, politics, social and environmental determinants, vulnerability, and climate change (Bardosh et al., 2017; Stoler et al., 2021).

4.3.4 Observed Impacts on Urban and Peri-Urban Sectors

All previous IPCC reports have focused on future water-related risks to urban areas due to climate change rather than documented observed impacts.

Climate extremes have profound implications for urban and peri-urban water management, particularly in an increasingly urbanized world (*high confidence*). Over half (54%) of the global population currently lives in cities (WWAP, 2019), and global urbanization rates continue to increase across all SSPs (Jiang and O'Neill, 2017). Using observed station data for 217 urban areas worldwide, (Mishra et al., 2015) noted that 17% of cities experienced statistically significant increases (p-value <0.05) in the frequency of daily precipitation extremes from 1973 to 2012. (Mishra et al., 2015) hypothesized that such observed climate changes in urban areas were largely due to large scale changes rather than local land cover changes.

Since AR5, factors such as rapid population growth, urbanization, ageing infrastructure, and changes in water use have also magnified climate risks, such as drought and flooding, and contributed to urban and peri-urban water insecurity (*medium agreement, medium evidence*) (4.1.2). For example, despite an increase in flooding events from 1.1 flood events per year (1986-2005) to 5 flood events per year (2006-2016) in Ouagadougou (Burkina Faso), analyses of rainfall indices showed few have significant trends at 5% level over the period 1961-2015 and that the generalized extreme value distribution fit the time-series of annual maximum daily rainfall (Tazen et al., 2019). On the other hand, long-term annual variations of maximum hourly precipitation in Shanghai (China) increased significantly during 1916-2014, especially from 1981.

Advances in the attribution of extreme weather events have made it possible to determine the causal relationship between droughts, floods, and climate change for some cities, particularly those with long hydro-meteorological records (Bader et al., 2018; Otto et al., 2020). Attribution analysis shows that urbanization contributed to the increase in both frequencies of local and abrupt heavy rainfall events in the city, at a rate of 1.5 and 1.8 (10yr)-1, respectively (Liang and Ding, 2017). A multi-method attribution showed that the likelihood of prolonged rainfall deficit in Cape Town (South Africa) during 2015-17 was made more likely by a factor of 3.3 (1.4-6.4) due to anthropogenic climate change (Otto et al., 2018). These results show that climate change has impacted the return time of extreme droughts in the Western Cape, exceeding the capacity of the existing water supply system to cope (Otto et al., 2018) (Box 9.4; 9.8.2). In Baton Rouge (USA), a rapid attribution study showed that the probability of an event such as the intense precipitation and flash flooding of August 2016 has increased by at least a factor of 1.4 due to radiative forcing (USA) (van der Wiel et al., 2017). In Houston (USA), a study found that the combination of urbanization and climate change nearly doubled peak discharge (84%) during Hurricane Harvey (August 2017), suggesting that land-use change magnified the effects of climate change on catchment response to extreme precipitation events (Sebastian et al., 2019) (14.4.3.1; Box 14.5 The Economic Consequences of Climate Change in North America, Cross-Chapter Box DISASTER in Chapter 4). According to a multi-method approach, the 2014/15 drought event in Sao Paulo (Brazil) was more likely to have been driven by water use changes and population growth than climate change (Otto et al., 2015) (Cross-Chapter Box DISASTER in Chapter 4).

The science of weather event attribution requires high-quality observational data and climate models that are currently available only in highly developed countries (Otto et al., 2020). In addition, further research is necessary to determine the impacts of climate change on water-related extremes in the urban areas of developing countries (Bai et al., 2018). For example, a combination of observational analysis and global coupled climate models showed that the 2015 flooding event in Chennai (India) could not be attributed to anthropogenic climate change, with the effects of that being relatively small in the region due to the impact of greenhouse gas increases being largely counteracted by those of aerosols (van Oldenborgh et al., 2017a) (4.2.5). Further research is also required to determine the impacts of climate change on water-related extremes in informal settlements where vulnerability to water insecurity is high due to poverty, overcrowding, poor-quality housing, and lack of basic infrastructure (Scovronick et al., 2015; Grasham et al., 2019; Williams et al., 2019; Satterthwaite et al., 2020).

In summary, water-related hazards such as drought and flooding have been exacerbated by climate change in some cities (*high confidence*). Further research is necessary to determine the extent and nature of water-related climate change impacts in the urban areas of developing countries (*high confidence*).

[START CROSS-CHAPTER BOX DISASTER HERE]

Cross-Chapter Box DISASTER: Disasters as the Public Face of Climate Change

Authors: Aditi Mukherji (India, Chapter 4), Guéladio Cissé (Mauritania/Switzerland/France, Chapter 7), Caroline Zickgraf (Contributing Author), Paulina Aldunce (Chile, Chapter 7), Liliana Raquel Miranda Sara (Peru, Chapter 12), William Solecki, (USA, Chapter 17), Friederike Otto (United Kingdom, WGI), François Gemenne (France, WGI), Martina Angela Caretta (Sweden, Chapter 4);, Richard Jones (United Kingdom, WGI); Richard Betts (United Kingdom, Chapter 4), Maarten van Aalst (Netherlands, Chapter 16), Jakob Zscheischler (Switzerland), Kris Murray (UK), Mauro E. González (Chile).

Introduction

Some extreme weather events are increasing in frequency and (or) severity as a result of climate change (Seneviratne et al., 2021) (*high confidence*). These include extreme rainfall events (Roxy et al., 2017; Myhre et al., 2019; Tabari, 2020); extreme and prolonged heat leading to catastrophic fires (Bowman et al., 2017; Krikken et al., 2019; van Oldenborgh et al., 2020); and more frequent and stronger cyclones/hurricanes and resulting extreme rainfall (Griego et al., 2020). These extreme events, coupled with high vulnerability and exposure in many parts of the world, turn into disasters and affect millions of people every year. New advances enable the detection and attribution of these extreme events to climate change (Otto et al., 2016; Seneviratne et al., 2021), with the most recent study saying that heavy rains leading to devasting floods in the Western Europe that captured the world's attention in July 2021 was made more likely due to climate change (Kreienkamp et al., 2021). Most WGII chapters (this volume) report various extreme event-induced disasters and their societal impacts. This cross-chapter box brings together authors from WGI and WGII to underscore that disasters following extreme events have become the most visible and public face of climate change (Solecki and Rosenzweig, 2014). These disasters reflect immediate societal and political implications of rising risks (*high confidence*) but also provide windows of opportunity to raise awareness about climate change and to implement disaster reduction policies and strategies (*high confidence*) (Albright, 2020; Boudet et al., 2020).

Here, we document eight catastrophic climate-related disasters that took place between 2017-2021. These disasters resulted in the loss of lives, livelihoods, had adverse impacts on biodiversity, health, infrastructure, and the economy. It provided important rallying points for discussions around climate change, equity, and vulnerability in some cases. These disasters also offer valuable lessons about the role of effective climate change adaptation in managing disaster risks and the importance of loss and damage mechanisms in global negotiation processes (Jongman et al., 2014; Mechler et al., 2014; Cutter and Gall, 2015).

Case 1. Compounded Events and Impacts on Human Systems: Cyclones Idai and Kenneth in Mozambique in 2019

While individual events alone can lead to major disasters, when several events occur in close spatial and temporal proximity, impacts get compounded with catastrophic results (Zscheischler et al., 2018; Zscheischler et al., 2020). In March 2019, Cyclone Idai (Category 2) was the deadliest storm on record to strike the African continent, with the coastal city of Beira in Mozambique being particularly hard hit with at least 602 deaths (CRED, 2019; Zehra et al., 2019; Phiri et al., 2020). Nationally, Idai caused massive housing, water supply, drainage and sanitation destruction, but its impact extended to South Africa through disruption of the regional electricity grid (Yalew et al., 2020). In April 2019, amidst heightened vulnerabilities in the aftermath of cyclone Idai, cyclone Kenneth (Category 4) hit the country, affecting 254,750 people and destroying more than 45,000 homes (Kahn et al., 2019). These circumstances caused the rapid spread of cholera, which triggered a massive vaccination program to control the epidemic (Kahn et al., 2019; Lequechane et al., 2020). While there were no specific detection and attribution studies for Idai and Kenneth, overall, there is *high confidence* that the rainfall associated with tropical cyclones is more intense because of global warming. However, there remain significant uncertainties about the impact of climate change on the numbers and strength of tropical cyclones *per se* (Walsh et al., 2019; Zhang G. et al., 2020).

Case 2. COVID-19 as the compounding risk factor: Cyclone Amphan in India and Bangladesh, 2020

Cyclone Amphan hit coastal West Bengal and Bangladesh on 20th May 2020. It was the first super cyclone to form in the Bay of Bengal since 1999 and one of the fiercest to hit West Bengal, India, in the last 100 years. The cyclone intensified from a cyclonic storm (Category 1) to a super cyclone (Category 5) in less than 36 hours (Balasubramanian and Chalamalla, 2020). Several hours before and on 20th May, extreme rain events resulted in heavy cumulative rainfall, flash flooding, and landslides in several adjoining districts (Mishra and Vanganuru, 2020). As per the initial estimates, about 1,600 km^2 area in the mangrove forests of *Sundarbans* were damaged, and over 100 lives were lost. Earlier cyclones in the region have shown that impacts of these events are gendered (Roy, 2019). The cyclone damage was somewhat lessened due to the delta's mangroves (Sen, 2020). The estimated damage was US$13.5 billion. Cyclone Amphan was the largest source of displacement in 2020, with 2.4 million displacements in India alone, of which 800,000 were pre-emptive evacuations by authorities (IDMC., 2020). Because it happened amidst the COVID19 crisis, evacuation plans were constrained due to social distancing norms (Baidya et al., 2020). Social media played an important role in disseminating pre-cyclone warnings, and information on post-cyclone relief work (Crayton et al., 2020; Poddar et al., 2020).

Case 3. Further exacerbating inequities in Human Systems: Hurricane Harvey, US, 2017

Hurricane Harvey, a Category 4 hurricane, made landfall on Texas and Louisiana in August 2017, causing catastrophic flooding and 80 deaths and inflicting $125 billion (2017 USD) in damage, of which $67 billion (2017 USD) was attributable to climate change (Frame et al., 2020). Several studies estimated the return period of the rainfall associated with this event and assessed that human-induced climate change increased the likelihood by a factor of approximately 3 using a combination of observations and climate models (Risser and Wehner, 2017; van Oldenborgh et al., 2017b). The impacts of Hurricane Harvey were exacerbated by extensive residential development in flood-prone locations. A study showed that urbanization increased the probability of such extreme flood events several folds (Zhang W. et al., 2018) through the alteration of ground cover and disruption and redirection of water flow. Water quality in cities also deteriorated (Horney et al., 2018; Landsman et al., 2019) and 85% of flooded land subsided at a rate of 5mm/yr following the event (Miller and Shirzaei, 2019). Notably, the impacts of Harvey were unequally distributed along racial and social categories in the greater Houston area. Neighbourhoods with larger Black, Hispanic and disabled populations were the worst affected by the flooding following the storm and rainfall (Chakraborty et al., 2018; Chakraborty et al., 2019; Collins et al., 2019b). In addition, racial and ethnic disparities were shown to impact post-disaster needs, ranging from household damage to mental health and recovery (Collins et al., 2019b; Flores et al., 2020; Griego et al., 2020).

Case 4. Impacts worsened due to socio-cultural and political conditions: The "Coastal Niño" in Peru, 2017

The Coastal Niño event of 2017 led to extreme rainfall in Peru, which was made more likely by at least 1.5 times as compared to pre-industrial times due to anthropogenic climate change and Coastal Niño (Christidis et al., 2019) and comparable to the El Niño events of 1982–83 and 1997–98 (Poveda et al., 2020). This event showed evidence of larger anomalies in flood exposure (Muis et al., 2018; Christidis et al., 2019; Rodríguez-Morata et al., 2019) and sediment transport (Morera et al., 2017). In Peru, this Niño event led to 6 to 9 billion US dollars of monetary losses, more than a million inhabitants were affected, 6,614 km of roads were damaged, 326 bridges were destroyed, 41,632 homes were damaged or became uninhabitable, and 2,150 schools and 726 health posts were damaged (French and Mechler, 2017; French et al., 2020), leaving half of the country in a state of emergency (Christidis et al., 2019). Furthermore, institutional and systemic socio-cultural and political conditions at multiple levels significantly worsened disaster risk management which hampered response and recovery (French et al., 2020). Citizens and zero-orders responders proved to be more effective and quicker than national disaster risk management response (Briones et al., 2019).

Case 5. Triggering institutional response for future preparedness: Mega Fires of Chile, 2017

The megafire that occurred in Chile in January 2017 had the highest severity recorded on the planet (CONAF, 2017), burning in three weeks an area close to 350,000 hectares in south-central Chile. These events have been associated with the prolonged ongoing drought that has persisted for more than one decade and with the increase in heat waves (González et al., 2018; Miranda et al., 2020). This extreme drought and the total burned area of the last decades have been attributed to anthropogenic climate change in at least 25% and 20% of their severity, respectively (Boisier et al., 2016). The megafire of summer 2017 resulted in 11 deaths, more than 1,500 houses burned and the destruction of the small town of Santa Olga. The smoke from these fires exposed 9.5 million people to air pollution, causing an estimated 76 premature deaths (Bowman et al., 2017; González et al., 2020). The direct costs incurred by the State exceeded USD 360 million (González et al., 2020). The 2017 megafires led to a series of institutional responses such as management plans that include preventive forestry techniques, regulatory plans containing rural-urban interface areas, an emergency forest fire plan, and promotion of native species (González et al., 2020).

Case 6. Loss of human lives and biodiversity: Bushfires in Australia, 2019/20

In the summer of 2019/20, bushfires in Australia killed 417 people due to smoke, between 0.5 and 1.5 billion wild animals and tens of thousands of livestock (van Oldenborgh et al., 2020). These fires also destroyed approximately 5,900 buildings and burnt 97,000 km^2 of vegetation, which provided habitat for 832 species of native vertebrate fauna. Seventy taxa had more than 30% of their habitat impacted, including 21 already identified as threatened with extinction (Ward et al., 2020). In addition, millions of people experienced levels of smoke 20 times higher than the government-identified safe level. The year 2019 had been Australia's warmest and driest year on record. In 2019/20 summer, the seasonal mean and mean maximum temperatures were the hottest by almost 1°C above the previous record. Eight of the ten hottest days on record for national mean temperatures occurred in December 2019. While the prevailing weather conditions were strongly influenced by the Indian Ocean Dipole pressure pattern, with a contribution from weakly positive ENSO conditions in the Pacific, the fact that Australia is approximately 1°C warmer than the early 20th century demonstrates links to anthropogenic climate change. Eight climate models using event attribution methodologies (comparison of simulations with present-day and pre-industrial forcings) indicates that anthropogenic climate change made the heat conditions of December 2019 more than twice as likely (van Oldenborgh et al., 2020).

Case 7. Improved preparedness reduced mortality: Heatwave in Europe, 2019

In 2019, Europe experienced several record-breaking heatwaves. In June, the first one featured record heat for that time in early summer, with temperatures of 6-10°C above normal over most of France and Germany, northern Spain, northern Italy, Switzerland, Austria, and the Czech Republic (Climate., 2019). The second heatwave also resulted in all-time records for Belgium, Germany, Luxembourg, the Netherlands, and the United Kingdom in July. Attribution studies (Vautard et al., 2020) demonstrated that these would have had extremely small odds in the absence of human-induced climate change or would have been 1.5-3°C colder without human-induced climate change. This study concluded that state-of-the-art climate models underestimate the trends in local heat extremes compared to the observed trend. Since the 2003 heatwave, which resulted in tens of thousands of deaths across Europe, many European countries have adopted heatwave plans, including early warning systems. Therefore, mortality in 2019 was substantially lower than it might have been. Unfortunately, mortality is not registered systematically across Europe, and therefore comprehensive analyses are missing. But even based on the countries that provide the numbers, more specifically France, Belgium and the Netherlands, the European heatwave of 2019 resulted in over 2500 deaths (CRED, 2019). Despite their deadliness and the fact that climate change increases the frequency, intensity and duration of heatwaves globally (Perkins-Kirkpatrick and Lewis, 2020) , heatwaves are not consistently reported in many countries (Harrington and Otto, 2020), rendering it currently impossible to estimate climate change impacts on lives and livelihoods comprehensively.

Case 8. Loss of human lives and property: Floods in Europe in 2021

From 12th to 15th July 2021, extreme rainfall in Germany, Belgium, Luxembourg and neighbouring countries led to severe flooding. The severe flooding was caused by very heavy rainfall over a period of 1-2 days, wet conditions prior to the event and local hydrological factors. The observed rainfall amounts in the Ahr/Erft region and the Belgian part of the Meuse catchment substantially exceeded previous records for observed rainfall. An attribution study (Kreienkamp et al., 2021) focused on the heavy rainfall rather than river discharge and water levels, because sufficient hydrological data was not available, partly because hydrological monitoring systems were destroyed by the event. Considering a larger region of Western Europe between the northern side of the Alps and the Netherlands, in any given location one such event can be expected every 400 years on average in the current climate. The floods resulted in least 222 fatalities and substantial damage to houses, roads, communication infrastructure, motorways, railway lines and bridges.

Table Cross-Chapter Box DISASTER.1: Summarizing impacts, loss and damage, displacement, and climate change detection and attribution of these seven disasters case studies

Name of the disaster event	Impacts, loss and damage; and displacement	Climate change detection and attribution

Cyclones Idai and Kenneth, March and April 2019, Mozambique, Africa	254,750 affected people, and more than 45,000 houses were destroyed. Sparked cholera outbreaks that resulted in 6,600 cases and over 200 deaths. More than 500,000 people were displaced in 2019. As of 31st December 2019, more than 132,000 people were internally displaced in Mozambique (IDMC., 2020).	There are no D&A studies on Idai and Kenneth, but it is known that rainfall associated with tropical cyclones are now more intense because of global warming, but there remain significant uncertainties concerning changes in the number and strength of the cyclones themselves (Walsh et al., 2019; Zhang G. et al., 2020).
Cyclone Amphan, May 2020, West Bengal, India and Bangladesh	About 1,600 km^2 area in the mangrove forests of Sundarbans was damaged. The city of Kolkata lost a substantial portion of its green cover due to Amphan. The estimated damage was US$13.5 billion. Cyclone Amphan was the largest source of displacement in 2020, with 2.4 million displacements in India and a similar number in Bangladesh. Out of these 2.4 million, roughly 800,000 were pre-emptive evacuations or organized by the authorities (IDMC., 2020).	The combined decline of both aerosols (due to COVID-19 related lockdowns) and clouds may have contributed to the increased sea surface temperature, further compounding the climate change-related warming of the oceans (Vinoj and Swain, 2020). However, there are no attribution studies on tropical cyclones in the Indian Ocean.
Hurricane Harvey, 2017, USA	Catastrophic flooding and many deaths inflicted $125 billion (2017 USD). In addition, economic costs due to the rainfall are estimated at $90 billion, of which $67bn are attributed to climate change (Frame et al., 2020).	Several attribution studies found that the rainfall associated with Harvey has increased by a factor of 3, while intensity in rainfall and wind speed also increased due to human-induced climate change (Emanuel, 2017; Risser and Wehner, 2017; Patricola and Wehner, 2018; van Oldenborgh et al., 2020)
Coastal Niño 2017, Peru	US$ 6 to 9 billion monetary losses with 114 deaths, 414 injuries and 1.08 million inhabitants affected. In addition, 6,614 km of improved roads were damaged, 326 bridges destroyed, 41,632 homes destroyed or uninhabitable, and 242,433 homes, 2,150 schools and 726 health centres damaged.	Clear anthropogenic climate change fingerprint detected. For example, while the anomalously warm ocean favoured extreme rainfall of March 2017 in Peru, the human influence was estimated to make such events at least 1.5 times more likely (Christidis et al., 2019).
Mega fires in Chile, January 2017	The megafire that occurred in Chile in January 2017 burned in three weeks an area close to 3500 km^2 in south-central Chile. As a result, thousands of people were displaced.	There is no attribution study on the fires in Chile (yet). Still, there is an increasing number of attribution studies on wildfires worldwide, finding that because climate change has increased the likelihood of extreme heat, which is part of the fire weather, the likelihood of wildfire weather conditions has increased too (Krikken et al., 2019; van Oldenborgh et al., 2020).
Australian bushfires of 2019/2020	Killed 417 people due to smoke, between 0.5 and 1.5 billion wild animals and tens of thousands of livestock. Destroyed ~ 5,900 buildings and burnt 97,000 km^2 of vegetation that provided habitat for 832 species of native vertebrate fauna.	Anthropogenic climate change made the extreme heat condition of December 2019 more than twice as likely (van Oldenborgh et al., 2020).
Heatwaves of Europe, 2019	Record heat in several European countries, and deadliest global disaster of 2019, with over 2500 deaths (CRED, 2019).	There have been many attribution studies on heatwaves in Europe, finding that human-induced climate change is increasing the frequency and intensity of

		heatwaves. In the case of 2019, the observed heat would have been extremely unlikely without climate change. The studies also find that climate models underestimate the increase in heat waves in Europe compared to observed trends (Vautard et al., 2020).
Floods in Western Europe (Germany, Belgium), July 2021	Severe flooding resulting in at least 222 fatalities and substantial damage to houses, roads, communication infrastructure, motorways, railway lines and bridges. Some communities were cut off for days due to road closures, inhibiting emergency responses including evacuation. The cost of the event was estimated at €4.5 to €5.5 billion in Germany and over €0.35 billion in Belgium.	Climate change was found to have increased the intensity of the maximum 1-day rainfall event in the summer season in this large region by about 3 - 19% compared to a global climate 1.2 °C cooler than at the present day. The increase was similar for the 2-day event. The likelihood of such an event today was found to have increased by a factor between 1.2 and 9 for both the 1-day and 2-day events in the large region (Kreienkamp et al., 2021).

Disaster risk reduction needs to be a central component of adaptation and mitigation for meeting SDGs and for climate-resilient future

Disasters resulting from extreme events are increasingly experienced by a large section of human population (Hoegh-Guldberg et al., 2018). Disasters expose inequalities in natural and managed systems and human systems as they disproportionately affect poor and marginalized communities like ethnic minorities, people of colour, Indigenous Peoples, women and children. Therefore, disaster risk reduction is fundamental for climate justice and climate-resilient development (UNISDR., 2015). Far from being disconnected policy objectives, disaster risk reduction and climate change mitigation/adaptation are two sides of the same coin as recognized explicitly by the Paris Agreement and Sendai Framework of 2015. There can be no sustainable development without disaster risk reduction, as explicitly recognized by the Sustainable Development Goals of 2015. Furthermore, disaster events can increase awareness among citizens and provide a platform for all important stakeholders, including climate activists, to come together, and give a clarion call for the urgency of climate action.

In summary, disasters are a stark illustration of the potential for extreme weather events to impact people and other species. With the frequency, severity and (or) likelihood of several types of extreme weather increasing, disasters can increasingly be regarded as “the public face of climate change” (*high confidence*). Detection and attribution studies make the climate change fingerprint of several types of disasters increasingly clear (*high confidence*). Moreover, existing vulnerabilities and exposures play an important role in turning extreme events into disasters, further exacerbating existing racial, gender and social inequalities (*high confidence*). Therefore, disaster risk reduction needs to be central to adaptation and mitigation efforts to meet the Sustainable Development Goals (SDGs) and the Paris Agreement for a climate-resilient future.

[END CROSS-CHAPTER BOX DISASTER HERE]

4.3.5 Observed Impacts on Freshwater Ecosystems

The loss and degradation of freshwater ecosystems have been widely documented, and SRCCL assessed with *medium confidence* the loss of wetlands since the 1970s (Olsson et al., 2020).

The links between air and water temperatures and ecological processes in freshwater ecosystems are well recognized. Increasing temperatures affect wetlands by influencing biophysical processes, affecting feeding and breeding habits and species' distribution ranges, including their ability to compete with others. Increased temperatures can also cause deoxygenation in the lower depths of the water columns and throughout the entire water column if heating destabilizes the water column. Under extreme heat, often associated with minimal rainfall or water flows, the drying of shallower areas and the migration or death of individual organisms can occur (Dell et al., 2014; Miller et al., 2014; Scheffers et al., 2016; Szekeres et al., 2016; Myers et al., 2017; FAO, 2018a) (*high confidence*). A global systematic review of studies since 2005 shows that climate change is a critical direct driver of freshwater ecosystems impacts through increasing temperatures or declining rainfall, for example, by causing physiological stress or death (thermal stress, dehydration or desiccation), limiting food supplies, or resulting in migration of animals to other feeding or breeding areas, and possibly increased competition with animals already present in those migrating locations (Bustamante et al., 2018; Diaz et al., 2019). Other drivers include land-use changes, water pollution, extraction of water, drainage and conversion, and invasive species, which to varying extents interact synergistically with climate change or are exacerbated due to climate change (Finlayson et al., 2017; Ramsar Convention, 2018).

The Global Wetland Outlook (Ramsar Convention, 2018) reported that between 1970 and 2015, the area of freshwater wetlands declined by approximately 35% (Davidson and Finlayson, 2018), with high levels of the overall percentage of threatened species recorded in Madagascar and Indian Ocean Islands (43%); in Europe (36%); in the tropical Andes (35%); and New Zealand (41%) (Ramsar Convention, 2018). Where long term data are available, only 13% of the wetlands recorded in and around the year 1700 remained by 2000. However, these data may overestimate the rate of loss (Davidson, 2014) (*limited evidence, medium agreement*). Many wetland-dependent species have seen a long-term decline, with the Living Planet Index showing that 81% of populations of freshwater species are in decline and others being threatened by extinction (Davidson and Finlayson, 2018; Darrah et al., 2019; Diaz et al., 2019) (*high confidence*).

Temperature changes lead to changes in the distribution patterns of freshwater species. Poleward and up-elevation range shifts due to warming temperatures tend to ultimately lead to reduced range sizes. Freshwater species in the tropics are particularly vulnerable (Jezkova and Wiens, 2016; Sheldon, 2019). Systematic shifts towards higher elevation and upstream were found for 32 stream fish species in France (Comte and Grenouillet, 2013). In North America, for the bull trout (*Salvelinus confluentus*) a reduction in the number of occupied sites was documented in a watershed in Montana (Eby et al., 2014). Other impacts include disruption of seasonal movements of migratory waterbirds that regularly visit freshwater ecosystems, with adverse impacts on their feeding and breeding (Finlayson et al., 2006; Bussière et al., 2015). Keystone species, such as the beaver (*Caster Canadensis*) in North America, have been moving into new areas as the vegetation structure has changed in response to higher temperatures enabling shrubs to establish in the Arctic and alpine tundra ecosystems (Jung et al., 2016). Increased occurrence and intensity of algal blooms have occurred due to the interactive effects of thermal extremes and low dissolved oxygen concentrations in water (Griffith and Gobler, 2020) (4.2.7). A global review found that almost 90% of all studies reviewed documented a decline in salmonid populations in North Amercia and Europe, and identified knowledge gaps elsewhere (Myers et al., 2017). Another review (Pecl et al., 2017) found declines in Atlantic salmon in Finland, and poleward shift in coastal fish species, while another review (Scheffers et al., 2016) noted hybridization between freshwater species like invasive rainbow trout (*Oncorhynchus mykiss*) and native cutthroat trout (*O. clarkia*).

Lakes have been warming, as shown by an increasing trend of summer surface water temperatures between 1985 and 2009 of 0.34°C per decade (O'Reilly et al., 2015). However, responses of individual lakes to warming were very dependent on local characteristics (O'Reilly et al., 2015), with warming enhancing the impacts of eutrophication in some instances (Sepulveda-Jauregui et al., 2018). For example, temperature increases led to lower oxygen concentrations in eutrophied coastal wetlands due to phytoplankton and microbial respiration (Jenny et al., 2016) and stimulated algal blooms (Michalak, 2016) and affected the community structure of fish and other biotas (Mantyka-Pringle et al., 2014; Poesch et al., 2016).

Rising temperatures have a strong impact in the arctic zone, where the southern limit of permafrost is moving north and leading to changes in the landscape (Arp et al., 2016; Minayeva et al., 2018). Thawing of the permafrost leads to increased erosion and runoff and changes in the geomorphology and vegetation of arctic peatlands (Nilsson et al., 2015; Sun et al., 2018b). Permafrost thawing has led to the expansion of lakes in the Tibetan Plateau (Li et al., 2014). As northern high latitude peatlands store a large amount of carbon, permafrost thawing can increase methane and carbon dioxide emissions (Schuur et al., 2015;

Moomaw et al., 2018). This represents a major gap in our understanding of the rates of change and their consequences for freshwater ecosystems.

The extent of past degradation due to multiple drivers is important as climate change is expected to interact synergistically and cumulatively with these (Finlayson et al., 2006), exacerbate existing problems for wetland managers, and potentially increase emissions from carbon-rich wetland soils (Finlayson et al., 2017; Moomaw et al., 2018). Freshwater ecosystems are also under extreme pressure from changes in land use and water pollution, with climate change exacerbating these, such as the further decline of snow cover (DeBeer et al., 2016) and increased consumptive use of fresh water, and leading to the decline, and possibly extinction, of many freshwater-dependent populations (*high confidence*). Thus, differentiating between the impacts of multiple drivers is needed, especially given the synergistic and cumulative nature of such impacts, which remains a knowledge gap.

In summary, climate change is one of the key drivers of the loss and degradation of freshwater ecosystems and the unprecedented decline and extinction of many freshwater dependent populations. The predominant key drivers are changes in land use and water pollution (*high confidence*).

4.3.6 Observed Impacts on Water-related Conflicts

According to AR5, violent conflict increases vulnerability to climate change (Field et al., 2014a) (*medium evidence, high agreement*). Furthermore, the IPCC SRCCL (Hurlbert et al., 2019) concluded with *medium confidence* that climatic stressors can exacerbate the negative impacts of conflict.

Since AR5, only a few studies focused specifically on the association between observed changes in the hydrological cycle linked to climate change and conflicts (Zografos et al., 2014; Dinar et al., 2015). Some studies associate conflicts with local abundance of water (Salehyan and Hendrix, 2014; Selby and Hoffmann, 2014; de Juan, 2015), mainly because of political mobilization around abundant waters and the need for developing new rules of allocation among competing users. Others provide evidence that the increase in water availability in some areas versus a decrease in other surrounding areas can affect the risk of a conflict in a region (de Juan, 2015) *(low to medium confidence).* However, the large majority acknowledges reduction of water availability due to climate change as having the potential to exacerbate tensions (de Stefano et al., 2017; Waha et al., 2017), especially in regions and within groups dependent on agriculture for food production (von Uexkull et al., 2016; Koubi, 2019) (*high confidence*). Particularly representative is the case of Syria, where drought aggravated existing water and agricultural insecurity (Kelley et al., 2015). However, whether drought caused civil unrest in Syria remains highly debated (Gleick, 2014; Kelley et al., 2017; Selby et al., 2017; Ash and Obradovich, 2019). Additionally, there is no consensus on the causal association between observed climate changes and conflict (Hsiang Solomon et al., 2013; Burke et al., 2015; Selby, 2019). However, evidence suggests that changes in rainfall patterns amplify existing tensions (Abel et al., 2019); examples include Syria, Iraq (Abbas et al., 2016; von Lossow, 2016) and Yemen (Mohamed et al., 2017) (*medium confidence*). There is also *medium evidence* that in some regions of Africa (e.g., Kenya, Democratic Republic of Congo), there are links between observed water stress and individual attitude for participating in violence, particularly for the least resilient individuals (von Uexkull et al., 2020) (*medium confidence*). A reverse association from conflict to climate impacts has also been observed (Buhaug, 2016). For example, conflict-affected societies cannot address climate-change impacts due to other associated vulnerabilities such as poverty, food insecurity, and political instability.

For transboundary waters, the probability of inter-state conflict can both increase and decrease (Dinar et al., 2019) depending on climatic variables (e.g. less precipitation) and other socio-economic and political factors, such as low levels of economic development and political marginalization (Koubi, 2019). Climate change concerns also play a role in stimulating cooperative efforts, as in the case of the Ganges-Brahmaputra-Meghna River Basin (Mirumachi, 2015; Link et al., 2016) (*medium confidence*). More generally, there is some evidence that when hydrological conditions change in transboundary river basins, formal agreements (e.g., water treaties or river basin organizations) can enhance cooperation (de Stefano et al., 2017; Dinar et al., 2019) (*medium evidence, high agreement*). Still, more cooperation does not necessarily reduce the risk of conflict, especially when water variability increases beyond a certain threshold (*low evidence, medium agreement*) (Dinar et al., 2015; Dinar et al., 2019).

In summary, there is no consensus on the causal association between observed climate change and conflicts. Still, evidence exists that those tensions can be amplified depending on climatic variables and other concomitant socio-economic and political factors.

4.3.7 Observed Impacts on Human Mobility and Migration

AR5 (Adger and Pulhin, 2014), found links between climate change and migration in general (*medium evidence, high agreement*), but provided no assessment of climate-induced hydrological changes and migration specifically. Likewise, SRCCL (Mirzabaev et al., 2019; Olsson et al., 2020) and SROCC (Hock et al., 2019b) noted that migration is complex and that migration decisions and outcomes are influenced by a combination of social, demographic, economic, environmental and political factors and contexts (see Cross-Chapter Box MIGRATE in Chapter 7). This chapter confirms this evidence, focusing on climate-induced hydrological changes.

Climate-induced hydrological changes can, through slow-onset (e.g. drought) or rapid onset (e.g., flood) events, influence human mobility and migration through effects on the economy and livelihoods (Adger et al., 2018). There is *medium confidence* that climate-induced hydrological changes have affected bilateral migration (Backhaus et al., 2015; Cattaneo and Peri, 2016; Falco et al., 2019). However, there is *medium evidence* and *low agreement* on the effects on the movements of refugees globally (Missirian and Schlenker, 2017; Owain and Maslin, 2018; Abel et al., 2019; Schutte et al., 2021).

There is *robust evidence* that floods and droughts have, mainly through adverse impacts on agriculture (Mastrorillo et al., 2016; Nawrotzki and Bakhtsiyarava, 2017; Bergmann et al., 2021; Zouabi, 2021) (4.6.2), both increased and decreased the risk of temporary or permanent migration (Obokata et al., 2014; Afifi et al., 2016; Thiede et al., 2016; Murray-Tortarolo and Salgado, 2021; Wesselbaum, 2021). However, migration effects depend on the nature of the hydrological change, for example, whether it is a slow-onset or rapid onset event (Kaczan and Orgill-Meyer, 2020), the perception of change (Koubi et al., 2016; de Longueville et al., 2020), as well as the socio-economic situation of the affected communities (Ocello et al., 2015; Afifi et al., 2016; Thiede et al., 2016) *(robust evidence; medium agreement)*.

The Internal Displacement Monitoring Centre (IDMC) estimates that an average of 12 million new displacements happen each year due to droughts and floods alone. By the end of 2020, there were 7 million people displaced due to natural disasters, including drought and floods (IDMC., 2020). Furthermore, household water insecurity has also been singled out as a driver of migration, given its physical and mental health and socio-economic effects (Stoler et al., 2021) *(medium confidence)*.

More research is needed to understand better the contexts in which climate-induced hydrological changes affect the likelihood of migration or alters existing patterns (Obokata et al., 2014; Gray and Wise, 2016; Cattaneo et al., 2019).

In summary, climate-induced hydrological changes can increase and decrease the likelihood of migration *(robust evidence, medium agreement).* The outcome is determined mainly by the socio-economic, political, and environmental context *(medium confidence)*.

4.3.8 Observed Impacts on the Cultural Water Uses of Indigenous Peoples, Local Communities and Traditional Peoples

AR5 concluded with *high confidence* that the livelihoods and cultural practices of the diverse Indigenous Peoples of the Arctic have been impacted by climate change (Larsen et al., 2014). SROCC found with *high confidence* that cryospheric and associated hydrological changes have affected culturally significant terrestrial and freshwater species and ecosystems in high mountain and polar regions, thus impacting residents' livelihoods and cultural identity, including Indigenous Peoples (Hock et al., 2019b; IPCC, 2019a; Meredith et al., 2019). SROCC also concluded that Indigenous Knowledge (IK) and Local Knowledge (LK) are vital in determining community responses to environmental risk. The report further noted that IK and LK helps increase adaptive capacity and reduces long-term vulnerability, but did not assess climate-related impacts on cultural water uses on low-lying islands (Oppenheimer et al., 2019).

Freshwater (including ice and snow) has diverse meanings and symbolic representations, as well as associated practices, management and reciprocal responsibilities for many Indigenous Peoples, local communities and traditional peoples (Cave and McKay, 2016; Craft, 2018; Hansen and Antsanen, 2018; Ngata, 2018; Chiblow 2019; Wilson et al., 2019; Moggridge and Thompson, 2021). Climate-driven hydrological changes are affecting culturally significant terrestrial and freshwater species and ecosystems, particularly for Indigenous Peoples, local communities and traditional peoples in the Arctic, high-mountain areas, and small islands (*high confidence*). These climate impacts on cultural water uses are influencing travel, hunting, herding, fishing, and gathering practices, which have negative implications for livelihoods, cultural traditions, economies, and self-determination (Table 4.5).

Some of these losses may be classified as non-economic loss and damage, such as loss of culture and traditions (Thomas and Benjamin, 2018b; McNamara et al., 2021). The vulnerability of these cultural uses to climate change is exacerbated by historical and ongoing processes of colonialism and capitalism, which dispossessed Indigenous Peoples and disrupted culturally significant multi-species relationships (Whyte, 2017; Whyte, 2018; Wilson et al., 2019; Whyte, 2020; Rice et al., 2021) (14.4.7.3; 9.13.2.4). Despite these significant structural barriers, there is *medium confidence* that some Indigenous Peoples, local communities and traditional peoples are adapting to the risks of climate-driven hydrological changes to cultural water uses and practices (4.6.9).

There is *high confidence* that the prospect of loss (anticipatory grief) due to climate-related hydrological change, such as inundation, or relocation, affects Indigenous Peoples, local communities and traditional peoples. These communities are especially susceptible to detrimental mental health impacts because of the implications of climate change for their cultural, land-based practices (du Bray et al., 2017). For example, fears of cultural loss in Tuvalu (Gibson et al., 2019) are resulting in worry, anxiety and sadness among local people, with similar responses reported in Fiji and other Pacific islands (du Bray et al., 2017; Yates et al., 2021) (Box 15.1).

There is *high confidence* that glacier retreat and increasing glacier runoff variability are negatively affecting cultural beliefs and practices in high mountain areas. For example, the loss of glaciers threatens the ethnic identity of the Indigenous Manangi community of the Annapurna Conservation Area of Nepal (Konchar et al., 2015; Mukherji et al., 2019). Likewise, ice loss in the Cordillera Blanca in the Peruvian Andes has challenged traditional approaches of interacting with the glaciers (Motschmann et al., 2020) (4.2.2). There is *high confidence* that cryosphere changes in high mountain areas also impact traditional pastoral practices by altering seasonal conditions, pasture quality, and water availability. For example, pasture quality in India (Ingty, 2017), Tibet Autonomous Region (Nyima and Hopping, 2019), and Bolivia (Yager et al., 2019) has been negatively impacted by climate-related hydrological changes, leading some Indigenous herders to diversify livestock, while herders in Nepal (Popular and Rik, 2016) and Peru (Postigo, 2020) have altered their routes in response to local water scarcity. Local communities in high mountain areas understand these hydrological changes through cultural and spiritual frameworks (*medium evidence, high agreement*). For instance, in the Peruvian Andes and the Hindu Kush Himalaya, changing ice is attributed to a lack of spiritual devotion (Drenkhan et al., 2015; Konchar et al., 2015; Scoville-Simonds, 2018). Communities in the Peruvian Andes also interpret climate impacts in the broader context of socio-economic and political injustice and inequality (Drenkhan et al., 2015; Paerregaard, 2018).

In polar areas, there is *high confidence* that the appearance of land previously covered by ice, changes in snow cover, and thawing permafrost are contributing to changing seasonal activities. These include changes in accessibility, abundance and distribution of culturally important plant and animal species. These changes are harming the livelihoods and cultural identity of Indigenous Peoples, local communities and traditional peoples. In northern Fennoscandia, for example, reindeer herders reported experiences of deteriorated foraging conditions due to changes in the winter climate (Forbes et al., 2019; Rasmus et al., 2020). In addition, Inuit and First Nations communities in Canada (Ford et al., 2019; Khalafzai et al., 2019) and Alaskan Natives and Native American communities in the United States (Norton-Smith et al., 2016) identified disruption to access routes to traditional hunting grounds and climate-related stresses to culturally-important species.

Further research is needed to provide culturally informed integrated assessments of climate change impacts on Indigenous Peoples', local communities' and traditional uses of water in the context of multiple stresses, disparities, and inequities (Yates et al., 2021). In the Arctic, for example, increased rates of development and resource extraction, including hydropower dams, mining, fisheries, and sport hunting, all threaten water quality, habitat condition, and the ecosystem services provided by Arctic freshwaters (Mustonen and Mustonen, 2016; Knopp et al., 2020).

In summary, the cultural water uses of Indigenous Peoples, local communities and traditional peoples are being impacted by climate change (*high confidence*), with implications for cultural practices and food and income security, particularly in the Arctic, high mountain areas, and small low-lying islands.

Table 4.5: Selected Observed Impacts on Cultural Water Uses of Indigenous Peoples (also see Figure 4.6).

Region	Indigenous Peoples	Climate hazard	Water-related impact	Situated knowledge	Reference
Asia	Manangi	Increased temperatures; increased precipitation	Glacier retreat; decreased permanent snow cover	Manangi villagers reported a deep sense of spiritual loss associated with the decline of mountain snows and the receding glacier, which some attributed to a lack of spiritual devotion.	(Konchar et al., 2015);(Mukherji et al., 2019)
Asia	Gurung	Increased temperatures	Decreasing snow; increased snowmelt	Indigenous Gurung herders reported water scarcity in traditional water sources such as streams and wells along traditional livestock migration routes. As a result of these changes, they have altered their routes and camp locations.	(Popular and Rik, 2016)
Asia	Dokpa	Increased temperatures	Decreasing snowfall	Dokpa herders reported that pasture conditions have deteriorated due to shallower snowpack, shorter winters and erratic rainfall, which has impacted sheep populations. As a result of these changes, Dokpa herders are replacing traditionally important sheep with yaks, which are more tolerant to poor-quality pasturage.	(Ingty, 2017)
Asia	Jagshung pastoralists	Increased temperatures	Glacier melt	Due to the expansion of the majority of large lakes on the Tibetan Plateau, herders in Jagshung Village have lost large areas of pastures to inundation. As a result, the quality of nearby feed has also deteriorated, which has led to reduced livestock populations and productivity.	(Nyima and Hopping, 2019)
Central and South America	Aymara	Increased temperatures	Glacier loss	Decreasing rain and snow have led to degraded and dry peatland pastures (*bofedales*). This reduction of pasture contributes to out-migration, over-grazing, and the loss of ancestral practices and community commitment to pasture management (Table 12.5).	(Yager et al., 2019)
Central and South America	Quelcaya pastoralists	Increased temperatures; reduced rainfall; increasing precipitation variability	Decreased snow and ice	Pastoralists reported water scarcity in traditional water sources along migration routes. As a result, women pastoralists had to herd livestock farther to find water. Pastoralists also reported the deterioration of pasture due to decreasing water availability Table 12.5).	Postigo, 2020 #4261}
Europe	Saami	Increased Winter temperature;	Harder and deeper snow	Changes in the quality of winter pastures (especially decreased access to forage and the amount of forage)	(Forbes et al., 2019); (Rasmus et al., 2020)

		Increased Summer precipitation	cover; increased ice formation; flooding rivers and wet ground	have increased the number of working hours and altered reindeer herding practices. Rainy summers increase the difficulty of gathering and moving reindeer to round-up sites and limit hay production for supplementary winter feed (13.8.1.2).	
North America	Kashechewan First Nation	Increased temperatures	Flooding	The timing and extent of spring flooding have changed, which, combined with inadequate infrastructure, have increased the frequency and risk of flooding for the Kashechewan community. Earlier snowmelt has also affected the migration patterns of migratory birds and reduced the duration of traditional hunting and harvesting camps for culturally important species 14.4.6.7, 14.4.7.1.	(Khalafzai et al., 2019)
North America	Inuit	Increased temperatures (an average of 2.18°C from 1985 to 2016)	Changing ice conditions	Trail access models showed that overall land and water trail access in the Inuit Nunangat had been minimally affected by temperature increase between 1985 to 2016. However, these findings illustrate that although Inuit are developing new trails and alternative forms of transport, these changes could negatively impact cultural identity and well-being 14.4.6.7, 14.4.7.1.	(Ford et al., 2019)
North America	Inuit	Increased temperatures; increased precipitation	Early snowmelt	Inuit in Labrador, Canada, are grieving the rapid decline of culturally significant caribou, which is partly due to rising temperatures in the circumpolar north and the associated changes to caribou habitat and migration. In addition, the decline of this species is negatively affecting their sense of cultural identity because of the importance of hunting and cultural continuity 14.4.6.7, 14.4.7.1..	(Cunsolo et al., 2020)
North America	Alaskan Natives	Increasing temperatures	Increasing temperature of freshwater lakes; permafrost melt; thinning ice	In Alaska, permafrost melting and the shorter ice season make it more difficult for hunters to access traditional hunting grounds. Increased temperatures are changing the habitats and migration patterns of culturally important freshwater species. Declining fish health and populations threaten requirements of treaty rights and tribal shares of harvestable fish populations 14.4.6.7, 14.4.7.1.	(Albert et al., 2018); (Norton-Smith et al., 2016)
Small Islands	iTaukei	Sea level rise	Flooding, inundation and salt-water intrusion	The village of Vunidogola was relocated in response to inundation, storm surges and flooding, which villagers found emotionally and spiritually distressing. Although the village was relocated as a single unit and on customary lands, the shift away from the coast has impacted spiritual relationships, as the ocean is an integral part of village culture (15.6.5).	(Charan et al., 2017); (Piggott-McKellar et al., 2019a)

Small Islands	iTaukei	Sea level rise	Coastal erosion; inundation	Villagers of Viti Levu reported their grief at the potential loss of their traditions and livelihoods. In addition, they are concerned as to how climate change is affecting their cosmology and cultural traditions and understand possible relocation as another source of cultural loss (15.6.5).	(du Bray et al., 2017); (McNamara et al., 2021)
Small Islands	Funafuti	Sea level rise	Coastal erosion; inundation	In addition to climate impacts and stresses affecting Tuvalu, the potential for further environmental hardships in the future exacerbated worry and distress for local people, who are anxious about future cultural loss arising from sea level rise (15.6.5)..	(Gibson et al., 2019); (Yates et al., 2021); (McNamara et al., 2021)

4.4 Projected Changes in Hydrological Cycle due to Climate Change

The terrestrial hydrological cycle is projected to intensify through a higher exchange of water between the land surface and the atmosphere. A rise of near-surface atmospheric water capacity is projected because of greater warming leading to changes in the atmospheric circulation patterns, the intensification of the convection processes, and the increased temperature of the underlying surface. Continuation of projected warming and other physical mechanisms will further accelerate the melting of the snow cover, glaciers and permafrost *(high confidence).*

Methodologically, the projected changes in the hydrological cycle due to climate change are assessed directly from climate models or hydrological system models driven by the climate models' projections (SM4.1). The latter is simulated by the CMIP-based multi-model experiments carried out under the scenarios of future climate forcing and socio-economic changes (e.g., RCPs, SSPs scenarios) or the pre-assigned global warming levels over the 21st century. Since AR5, there has been an improvement of the physical basis of the climate change impact projections owing to the advances in modelling clouds, precipitation, surface fluxes, vegetation, snow, floodplains, groundwater and other processes relevant to the water cycle (Douville et al., 2021), SM4.1).

The sub-sections highlight the projected responses of these hydrological systems/processes to multiple drivers, high variability and the uncertainty of the projections, depending on regions, seasons, temporal and spatial scales, the influence of the non-climatic factors.

4.4.1 Projected Changes in Precipitation, Evapotranspiration, and Soil Moisture

4.4.1.1 Projected Changes in Precipitation and Heavy Precipitation

WG1 (Douville et al., 2021) conclude with *high confidence* that without large-scale reduction in GHG emissions, global warming is projected to cause substantial changes in the water cycle at both global and regional scales. However, WG1 also note large uncertainties in many aspects of regional water cycle projections by climate models. Water cycle variability and extremes are projected to increase faster than average changes in most regions of the world and under all emission scenarios (*high confidence*). The concept of "wetter-regions-get-wetter, drier-regions-get-drier" from AR5 (Collins et al., 2013) is assessed by AR6 WG1 (Douville et al., 2021) as too simplistic. WG1 (Seneviratne et al., 2021) further conclude that heavy precipitation will generally become more frequent and more intense with additional global warming.

In the CMIP6 multi-model ensemble, as in previous generations of ensembles, the projected changes in annual mean precipitation vary substantially across the world. Importantly, in most land regions the future changes are subject to high uncertainty even in the sign of the projected change (*high confidence*). Figure 4.10 illustrates this using the 5th, 50th and 95th percentile changes across the ensemble at individual grid points. For any given location, the range of projected changes generally increases with global warming (*high confidence*).

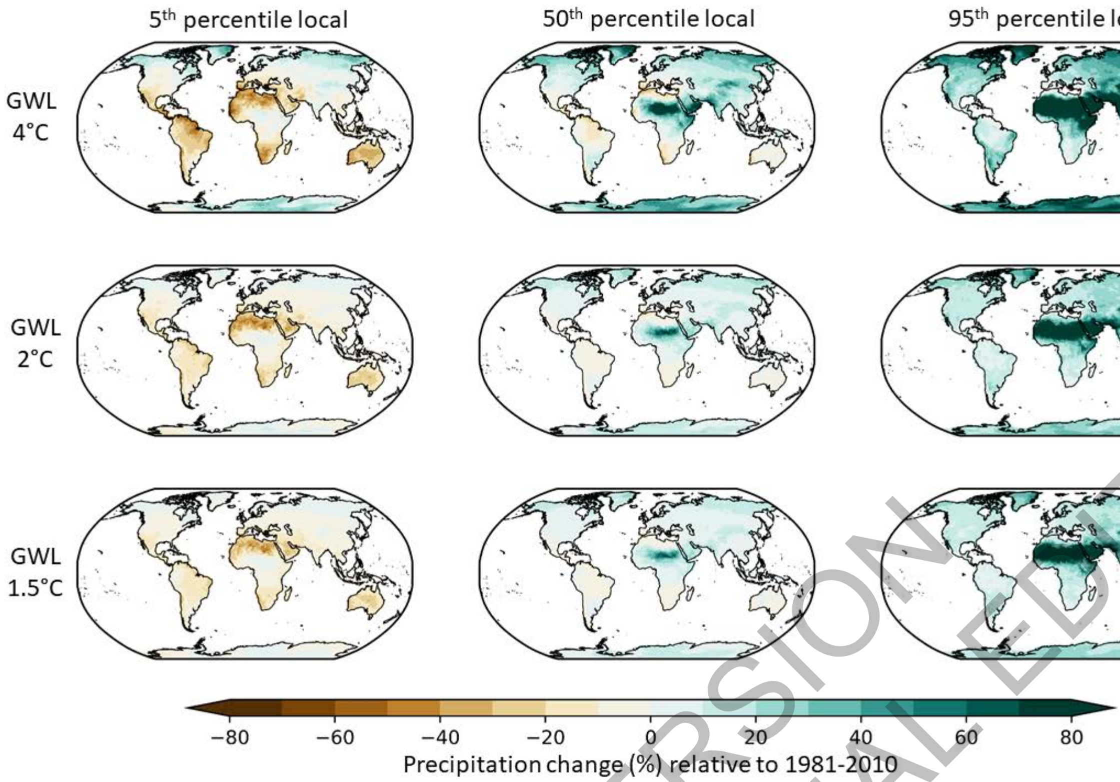


Figure 4.10: Projected percentage changes in annual mean precipitation at global warming levels (GWLs) of 4°C (top), 2°C (middle) and 1.5°C (bottom) for the CMIP6 multi-model ensemble of GCMs driven by the SSP5-85 scenario. For any given GWL, similar ranges of changes are seen with other scenarios that reach that GWL, and the difference between scenarios is smaller than the ensemble uncertainty (Seneviratne et al., 2021). The distribution of outcomes is shown at local scales with the 5th, 50th and 95th percentile precipitation changes in individual grid boxes. Note that these are uncertainties at the individual point and are not spatially coherent, i.e., they do not represent plausible global patterns of change. Results for 1.5°C, 2°C and 4°C global warming are defined as 20-year means relative to 1850-1900 and use 40, 40 and 31 ensemble members respectively, due to some members not reaching 4°C global warming.

For example, in parts of the Indian subcontinent, the projected changes in mean precipitation at 1.5°C global warming range from a 10-20% decrease to a 40-50% increase. The multi-model median change is close to zero. Most other regions show a smaller range of changes (except for very dry regions where a small absolute change in precipitation appears as a larger percentage change). Nevertheless, across most global land regions, both increases and decreases in precipitation are projected across the ensemble. At 1.5°C global warming, a complete consensus on increased precipitation is seen only in the central and eastern Sahel, south-central Asia, parts of Greenland and Antarctica, and the far northern regions of North America and Asia, with projected increases in the latter ranging up to 20-30%. No land regions see a complete consensus on decreased precipitation, but South America, southern Africa and the Mediterranean region show a stronger consensus towards reduced precipitation.

The geographical patterns of local agreement/disagreement in projected precipitation change remain broadly similar with increased global warming, but the range of uncertainty generally increases (*high confidence*). For example, in the north-eastern Amazonia, the driest projections increase from a 10% decrease at 1.5°C global warming to a 40% decrease at 4°C global warming. In comparison, the wettest projections remain at up to a 10% increase. In the far north of North America and Asia, the higher end of projected increases in precipitation extends to approximately 40-60%. A few regions are projected to see a shift in the consensus on the sign of the change. These include parts of the Indian subcontinent where at 4°C global warming, the projected changes shift to a consensus on increased precipitation ranging between a few per cent to over 70%.

Notably, the multi-model median change in precipitation is relatively small in many regions – less than 10% over most of the global land surface at 1.5°C global warming. In contrast, in many locations, the 5^{th} to 95^{th} percentile range can include changes that are much larger changes than the median and also changes that are relatively large but opposite in sign. At 4°C global warming, the median projected changes are larger, ranging from a 20% decrease to a 40% increase (excluding very dry areas, where percentage changes can be much larger due to very small baseline values), but nevertheless often remain a poor indicator of the range of changes across the ensemble. Therefore, use of the median or mean projected changes for future adaptation decisions could substantially underestimate the risk of large changes in precipitation. It could mean that the risk of the opposite sign of changes are not accounted for. Indeed, for mean precipitation, different multi-model ensembles can show different levels of significance of the central estimate of change ((Uhe et al., 2021): Figure 4.11.a). Consequently, information on the range of possible outcomes can be valued by users for effectively informing risk assessments (Lowe et al., 2018).

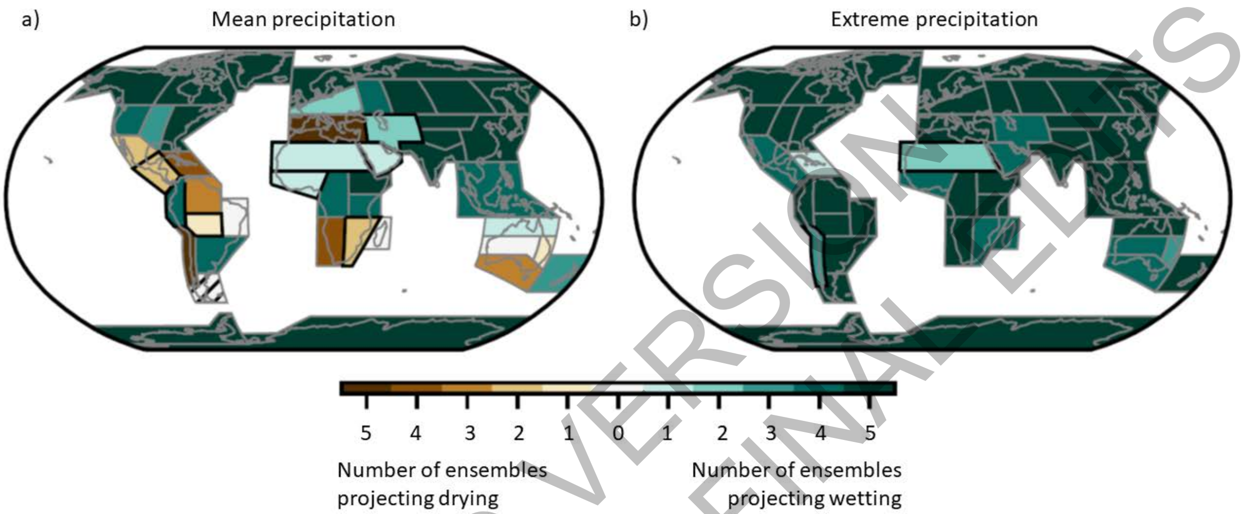


Figure 4.11: Agreement between different multi-model ensembles on significant changes in (a) annual mean precipitation and (b) annual maximum 1-day precipitation (Rx1day), at 2°C global warming (Uhe et al., 2021). Using central estimates from 5 ensembles of climate models (CMIP5, CMIP6, HAPPI, HELIX and UKCP18) using different models and different experimental designs for the ensembles, the maps show the number of ensembles for which the central estimate shows a significant drying or wetting change at 2°C global warming relative to pre-industrial. The different ensembles reach 2°C global warming at different times. The projected changes are aggregated over the new climatic regions defined for IPCC AR6 (Iturbide et al., 2020). Hatched regions show where different ensembles project significant changes in opposite directions, i.e., there is no agreement on either drying or wetting. Regions with thick outlines are where CMIP6 disagrees with 3 of the other 4 ensembles on the significance of the change, highlighting where over-relying on CMIP6 alone may not fully represent the level of confidence in the projections.

There is a stronger consensus on changes in heavy precipitation than mean precipitation within individual ensembles such as CMIP6 (Figure 4.12, a,b,c) and especially between the means of the different ensembles (Figure 4.11, b). At 4°C global warming, the 50^{th} percentile projection is for increased annual maximum 1-day precipitation over virtually all global land, with the median increase being over 20% for a majority of the land. The 95^{th} percentile increase is 20-40% over most mid-latitude areas and at least 40-70% over the tropics and sub-tropics, exceeding 80% over western Amazonia, central Africa, and most Indian subcontinent. The 5^{th} percentile also shows an increase over most global land, i. e: decreased heavy precipitation has less than a 5% probability in these regions (Figure 4.12, a), although decreases remain possible but of low probability in some regions particularly northern South America and northern and western Africa. At the 50^{th} and 95th percentiles, similar global patterns of change are projected at 2°C and 1.5°C global warming, with smaller local magnitudes (Figure 4.12, e,f,h,i). At the 5^{th} percentile, decreased Rx1day is seen over much larger land areas Figure 4.12, d,g), which may be a result of internal climate variability being relatively larger than the long-term trend at lower GWLs In CMIP5, precipitation extremes are projected to be *more likely* to increase than to decrease on average over both the humid and arid regions of the world, but with larger uncertainty in arid areas (Donat et al., 2019).

Annual maximum daily precipitation (Rx1day)

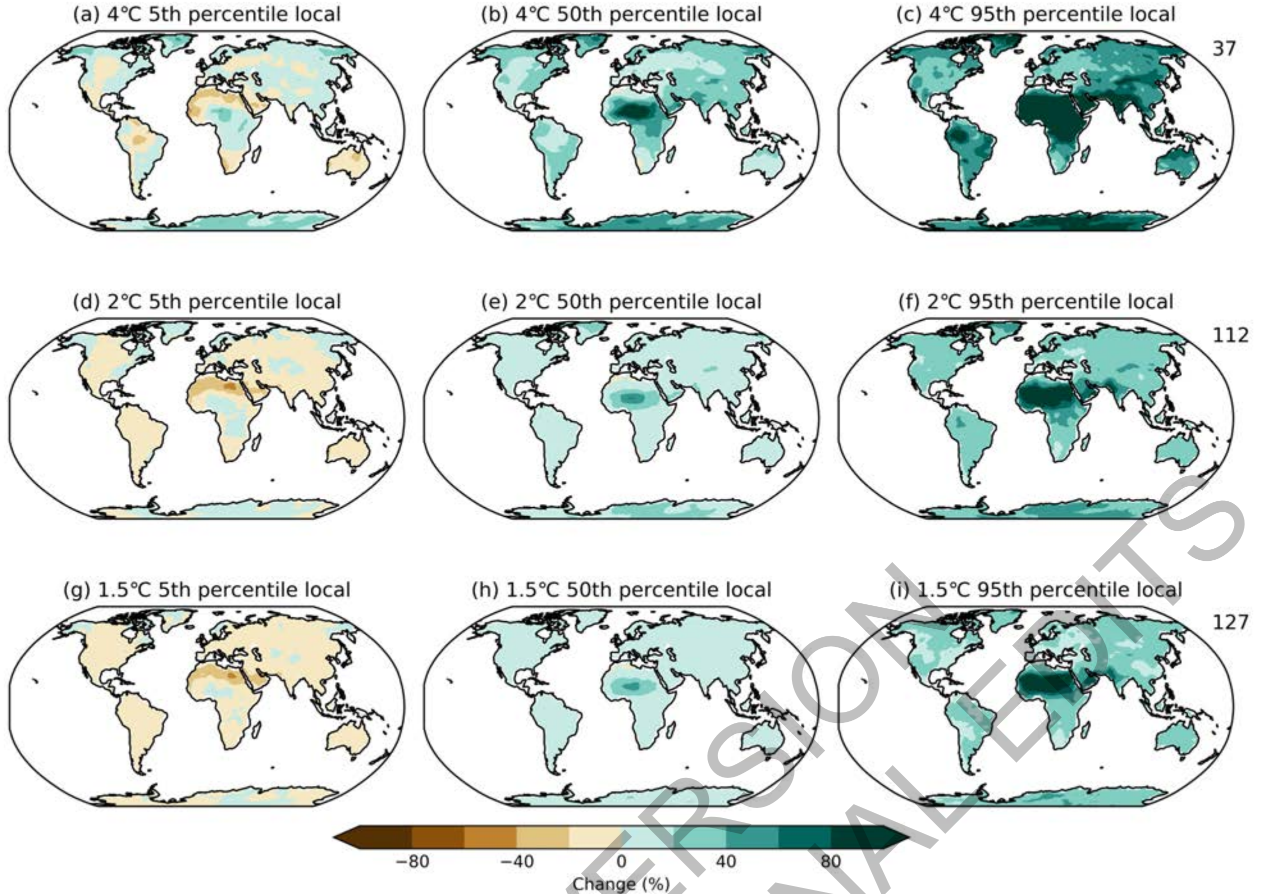


Figure 4.12: Projected percentage changes in annual maximum daily precipitation (RX1day) averaged over 20-years centred at the time of first passing (a-c) 4°C, (d-f) 2°C and (g-i) 1.5°C global warming levels (GWLs) relative to 1851-1900. Results are based on simulations from the CMIP6 multi-model ensemble under the SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. Uncertainties in the projections are quantified with the (a,d,g) 5th, (b,e,h) 50th and (c,f,i) 95th percentile local values from the ensemble at each GWL. Note that these are uncertainties at the individual point and are not spatially coherent, i.e., they do not represent plausible global patterns of change. The 50th percentile maps (b, e h,) present the same data over land as Figure 11.16 of (Seneviratne et al., 2021). The numbers on the right indicate the number of simulations included at each warming level, including multiple realisations from some models with varying initial conditions, depending on data availability. Results for the 1.5°C GWL include 37 unique models. Fewer models and realisations are available for the 2°C and 4°C GWLs as fewer scenarios and/or models reach those warming levels. For individual models, the global patterns of changes are very similar across scenarios and any differences between scenarios are smaller than the ensemble uncertainty for an individual scenario. The CMIP6 projections of changes in mean and extreme precipitation are discussed in more detail by WG1 (Doblas-Reyes et al., 2021; Seneviratne et al., 2021).

In the 50th percentile projections at 4°C global warming, dry spells are projected to become up to 40 days longer in South America and southern Africa and up to 20 days shorter in large parts of Asia (Figure 4.13, a,b,c). In most regions, the projected changes in dry spell lengths are highly uncertain. In southern Africa, the increase in dry spell length ranges from 10 days to over 40 days. In northeast Asia, dry spells are projected to become shorter by up to 20-30 days. In much of South America, dry spells could increase by over 40 days or decrease by over 10 days. Similar global patterns with smaller magnitudes of change are projected for 2°C and 1.5°C global warming in all three percentiles (Figure 4.13, d,e,f,g,h,i).

Consecutive dry days

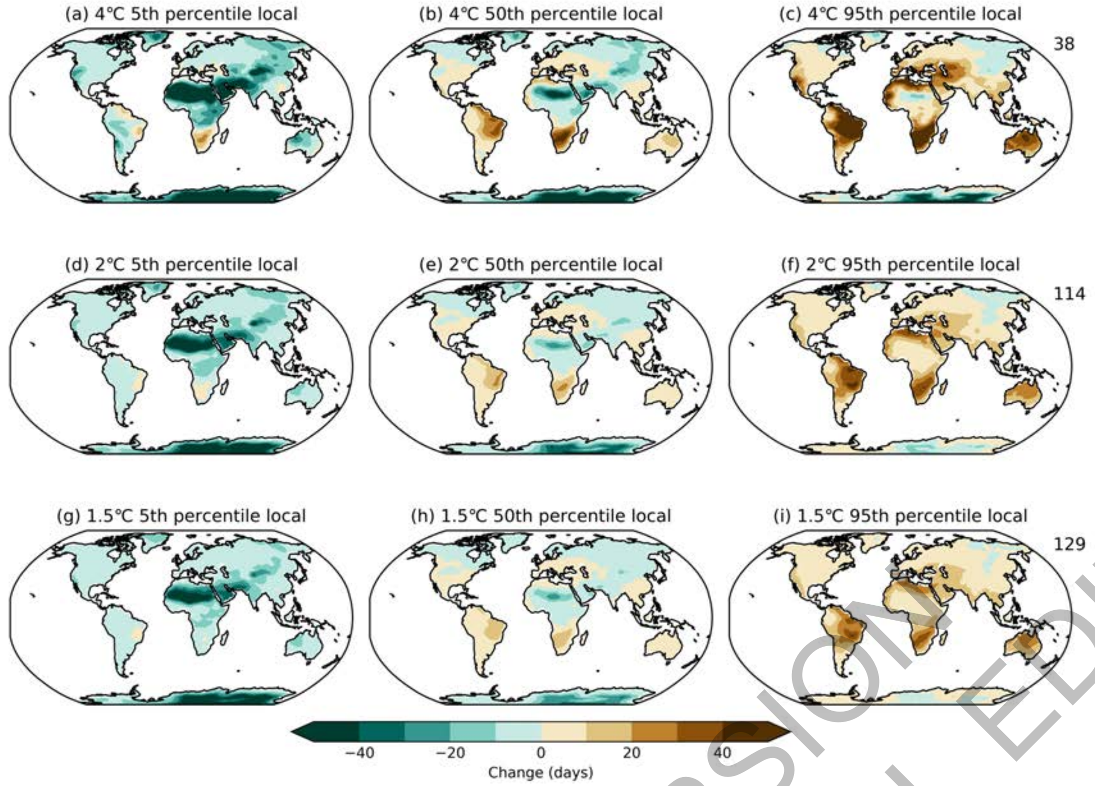


Figure 4.13: As Figure 4.12 for projected changes in annual consecutive dry days (CDD), the highest number of days per year with precipitation < 1mm. The 50th percentile maps (b, e h,) present the same data as Figure 11.19 (a,b,c) of (Seneviratne et al., 2021).

Taken together, these projections of more intense precipitation and changes in the length of dry spells give a clear picture of increasingly volatile precipitation regimes, with many regions seeing both longer dry spells and heavier events when precipitation does occur (*high confidence*).

The critical knowledge gap for precipitation projections is the ability to make precise projections. With such large uncertainties in many regions, climate model projections can inform risk assessments but cannot provide confident predictions of specific outcomes.

In summary, the annual mean precipitation range is projected to increase or decrease by up to 40% or more at 4°C global over many land areas. The ranges of projected precipitation changes are smaller at lower levels of global warming (*high confidence*). Either an increase or decrease is possible in most regions, but there is an agreement among models on the increase in the far north (*high confidence*). There is a stronger model consensus on heavy precipitation increasing with global warming over most land areas (*high confidence*). There are widely varying projections of change in dry spell length (*high confidence*), but in regions with increasing projected dry spells, the potential increase is larger at higher levels of global warming (*high confidence*).

4.4.1.2 Projected Changes in Evapotranspiration

AR5 (Collins et al., 2013) found that the CMIP5 model projections of ET increases or decreases followed the same pattern over land as precipitation projections, with additional impacts of reduced transpiration due to plant stomatal closure in response to rising CO_2 concentrations. AR6 WG1 (Douville et al., 2021) assessed that it is *very likely* that evapotranspiration will increase over land, with regional exceptions in drying areas.

In most CMIP5 and CMIP6 models, projected ET changes are driven not just by meteorological conditions and soil moisture but also by plant physiological responses to elevated CO_2, which themselves influence meteorology and soil moisture through surface fluxes (Halladay and Good, 2017; Lemordant and Gentine, 2019). Elevated CO_2 causes stomatal closure which decreases ET, but also increases leaf area index (LAI) which in turn increases ET, but these do not necessarily compensate (Skinner et al., 2017). Higher LAI increases transpiration, depleting soil moisture but increasing shading, thus reducing soil evaporation (Skinner et al., 2017), but LAI may not increase in areas where it is already high (Lemordant et al., 2018). Projected ET decreases from physiological effects alone are widespread but greatest in tropical forests (Swann et al., 2016; Kooperman et al., 2018).

Future changes in regional evapotranspiration (ET) are therefore highly uncertain. The CMIP6 multi-model ensemble projects changes in ET varying both in magnitude and sign across the ensemble members (Figure 4.14). At 4°C global warming, the ensemble median projection shows increased ET of approximately 25% in mid/high latitudes but decreases of up to 10% across most of tropical South America, southern Africa, and Australia. These CMIP6 ensemble projections resemble ET changes projected by the CMIP5 ensemble, except over central Africa and Southeast Asia (Berg and Sheffield, 2019). However, the ensemble ranges are wide and include both increases and decreases in projected ET in many locations, with mid-latitude ET increases being up to approximately 50% and ET decreases in southern Africa being up to approximately 30%. Projected changes are proportionally smaller at lower levels of global warming, while patterns of change remain similar.

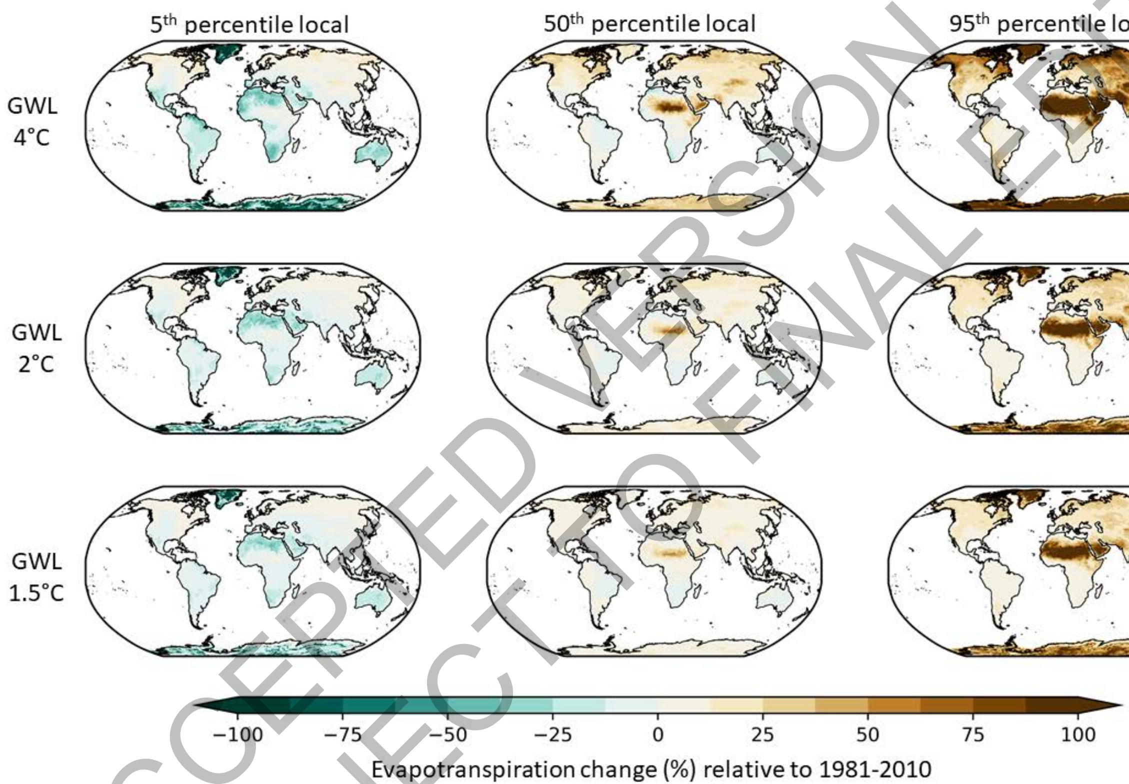


Figure 4.14: Projected percentage changes in annual mean ET at global warming levels (GWLs) of 4°C (top), 2°C (middle) and 1.5°C (bottom) for the CMIP6 multi-model ensemble of GCMs driven by SSP5-85 concentrations. The distribution of outcomes is shown at local scales with the 5th, 50th and 95th percentile ET changes in individual grid boxes. Note that these are uncertainties at the individual point and are not spatially coherent, i.e., they do not represent plausible global patterns of change. Results for 1.5°C, 2°C and 4°C global warming are defined as 20-year means relative to 1850-1900 and use 40, 40 and 31 ensemble members respectively, due to some members not reaching 4°C global warming.

The relative importance of the physiological and radiative effects of CO_2 on future ET is a crucial knowledge gap, partly because many Earth System Model land surface schemes still use representations of this process based on older experimental studies. Furthermore, large-scale experimental studies using Free-Air CO_2 Enrichment (FACE) techniques to constrain the models have not yet been performed in certain critical ecosystems, such as tropical forests. Finally, uncertainties in Equilibrium Climate Sensitivity (ECS) imply uncertainties in the CO_2 concentration accompanying any given level of warming (Betts et al., 2018).

In summary, the sign of projected ET change depends on region, but there is *medium confidence* that ET will increase in the global mean and mid/high latitudes and decrease in northern South America and southern

Africa. In addition, the impacts of rising CO_2 concentrations on plant stomata and leaf area play a role in model projections of evapotranspiration change (*high confidence*), but there is *low confidence* in their overall contribution to global ET change.

4.4.1.3 Projected Changes in Soil Moisture

AR5 (Collins et al., 2013) mainly focused on surface (upper 10cm) soil moisture, summarizing multi-model projections of 21st-century annual mean soil moisture changes as broadly decreasing in the subtropics and Mediterranean region and increasing in east Africa and central Asia across the RCPs, with the changes tending to become stronger as global warming increases. AR6 WG1 (Douville et al., 2021) draw broadly similar conclusions based on new Earth System Models, noting that compared to CMIP5, the CMIP6 models project more consistent drying in the Amazon basin, Siberia, westernmost North Africa and southwestern Australia. WG1 (Douville et al., 2021) also note that soil moisture in the upper 10cm shows more widespread drying than in the total soil column.

The CMIP6 multi-model ensemble of Earth System Models (ESMs) shows varying levels of consensus on projected changes in surface soil moisture with global warming (Figure 4.15). As in CMIP5 (Cheng et al., 2017), uncertainties are substantial, often associated with uncertainties in projected regional precipitation changes (4.4.1.1), and in most regions, both increases and decreases are projected across the ensemble. In the far north of North America and Asia, projected changes in soil moisture at 4°C global warming range from a 20–30% decrease to an increase of 30-40%. In northern mid-latitudes, projection range from a 10-20% decrease to an increase of 20-30%, except for eastern North America where the projected changes (both increases and decreases) are less than 10%, and western Europe and the Mediterranean where there is a stronger consensus towards decreased soil moisture of up to 25%. South America and southern Africa, and Asia also show a stronger consensus towards decreased soil moisture of up to 40% or more in some regions.

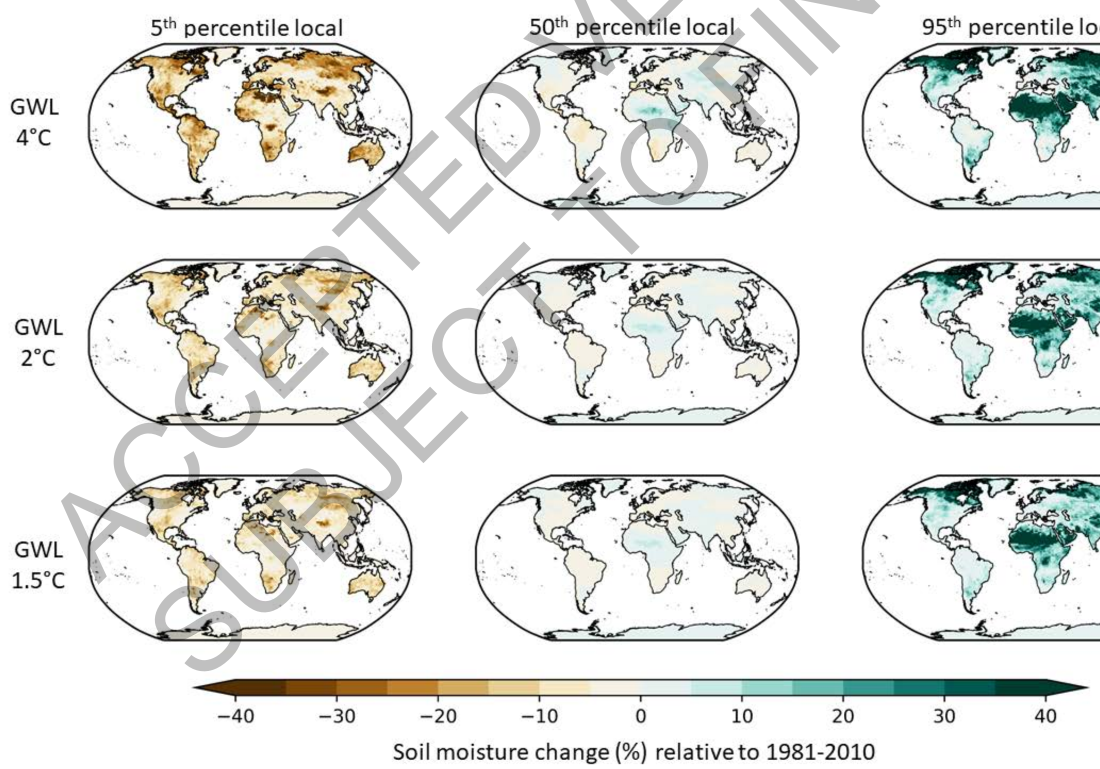


Figure 4.15: Projected percentage changes in annual mean total column soil moisture relative to 1981-2010 at global warming levels (GWLs) of 4°C (top), 2°C (middle) and 1.5°C (bottom) for the CMIP6 multi-model ensemble of GCMs driven by SSP5-85 concentrations. The distribution of outcomes is shown at local scales with the 5th, 50th and 95th percentile soil moisture changes in individual grid boxes. Note that these are uncertainties at individual points and are not spatially coherent, i.e., they do not represent plausible global patterns of change. Results for 1.5°C, 2°C and 4°C global warming are defined as 20-year means relative to 1850-1900 and use 34, 34 and 26 ensemble members respectively, due to some members not reaching 4°C global warming. Fewer models are shown here than in Figure 4.10 on precipitation and Figure 4.14 on ET because some do not provide soil moisture output.

Most CMIP6 models simulate direct CO_2 effects on plant transpiration, which has been shown to be a strong influence on projected future changes in soil moisture (Milly and Dunne, 2016). Approaches that neglect this process project greater decreases in soil moisture availability than the climate models (Roderick et al., 2015; Swann et al., 2016). Therefore, although several studies project increased global aridity and dryland expansion (Feng and Fu, 2013; Sherwood and Fu, 2014; Huang et al., 2016a), these may overestimate future drying (Berg et al, 2017). Nevertheless, land surface models, including vegetation responses to $CO_{2,}$ still project reduced soil moisture in many regions (Grillakis, 2019).

A critical knowledge gap concerns the relative importance of climate and CO_2 physiological effects on soil moisture, in relation to uncertainties in climate sensitivity. For a given level of global warming, the relative importance of climate effects and the direct effects of CO_2 on transpiration depend on the CO_2 concentration accompanying that level of warming (Betts et al., 2018). Some CMIP6 models have very high climate sensitivities (Meehl et al., 2020), which are assessed as being of low probability on the basis of other lines of evidence (Sherwood et al., 2020). This means that the CO_2 concentration accompanying specific global warming levels may be too low and lead to overly-large projections of soil moisture decrease in those models.

In summary, projected soil moisture changes increase with levels of global warming (*high confidence*), although there remains substantial disagreement on specific regional changes. In the CMIP6 multi-model ensemble at 4°C global warming, decreased soil moisture of up to 40% is projected in Amazonia, southern Africa and western Europe in all models (*high confidence*). In all other regions, there is no consensus on the sign of projected soil moisture changes, and projected changes at 4°C global warming include decreases of up to 30% and increases of up to 40%. Projected changes are smaller at lower levels of global warming, with similar geographical patterns of change.

4.4.2 Projected Changes in Cryosphere (Snow, Glaciers, and Permafrost)

The AR5 noted that global glacier mass loss is *very likely* to increase further during the 21^{st} century (Jiménez Cisneros et al., 2014). According to the SROCC (Hock et al., 2019b), it is *very likely* that glaciers will continue to lose mass throughout the 21st century: from 18% (by 2100, relative to 2015) for RCP2.6 to 36% for RCP8.5. The AR5 (Collins et al., 2013) and the SROCC (Meredith et al., 2019) reported with *high confidence* that permafrost would continue to thaw in the 21st century, but the projections are uncertain. Constraining warming to 1.5°C would prevent the thawing of a permafrost area of 1.5 to 2.5 million km^2 compared to thawing under 2°C (*medium confidence*) (IPCC, 2018b). The AR5 (Collins et al., 2013) and the SROCC (Meredith et al., 2019) concluded that Northern hemisphere snow extent and mass would likely reduce by the end of the 21^{st} century, both in plain and mountain regions. AR6 assessed with *medium confidence* that under RCP 2.6 and RCP 8.5 from 2015 to 2100, glaciers are expected to lose 18% and 36% of their early 21st-century mass, respectively (AR6 WGI, (Fox-Kemper et al., 2021)).

Global glacier mass loss between 2015 and 2100 was estimated at the level 18 ± 13% under the RCP2.6 scenario and 36 ± 20% under the RCP8.5 scenario (Marzeion et al., 2020), which corresponds with previous findings (Radić et al., 2014; Hock et al., 2019a; Shannon et al., 2019). The regional glacier loss rates projections are unevenly distributed worldwide and considerably vary between scenarios (Huss and Hock, 2018; Hock et al., 2019a). In most regions 'peak water' has already been reached, or is expected to be reached, before mid-century (with an earlier 'peak water' for RCP2.6 scenario compared with RCP8.5) (Huss and Hock, 2018; Pritchard, 2019; Marzeion et al., 2020; Rounce et al., 2020). The influence of the expected subsequent decrease in glacier run-off by the end of the 21^{st} century will be more pronounced during droughts and dry seasons (Farinotti et al., 2016; Huss and Fischer, 2016; Hanzer et al., 2018; Brunner et al., 2019).

Such changes in run-off could potentially lead to water shortages for over 200 million people in the High Mountains of Asia (Pritchard, 2019; Shahgedanova et al., 2020). There is *medium confidence* that under a 4ºC warming scenario, 40% of current irrigated demand in sub-basins relying primarily on snow-melt run-off would need to be supplemented from other water sources (Qin et al., 2020). Basins, where such alternate sources are not available, will face agricultural water scarcity (4.5.1). Globally, 1.5 billion people are projected to critically depend on run-off from the mountains by the mid-21st century under a 'middle of the road' (RCP6.0) scenario (Viviroli et al., 2020). Furthermore, there is *medium confidence* that projected changes in snow and glacier melt run-off will affect water inputs to hydropower, leading to a decline in hydroelectricity production in mountain basins, e.g., in India (Ali et al., 2018), Switzerland (Schaefli et al., 2019), USA (Lee et al., 2016) (4.5.2), IPCC AR6 WGI, 2021 (Sections 9.5.1.3 and 8.4.1.7.1).

Projections of snow cover metrics (IPCC AR6 WGI, 2021 (Section 9.5.3.3)) suggest a further decrease in snow water equivalent (SWE) and snow cover extent (SCE), though the inter-model spread is considerable (Lute et al., 2015; Thackeray et al., 2016; Kong and Wang, 2017; Henderson et al., 2018) (*high confidence*). The projected CMIP6 SCE and SWE changes share the broad features of the CMIP5 projections: SCE is expected to decrease in the northern hemisphere by approximately 20%, relative to the 1995–2014 mean value, around 2060 and stabilize afterwards under the RCP2.6 scenario, while RCP8.5 scenario leads to snow cover losses up to 60% by 2100 (Mudryk et al., 2020). Regionally, the SWE loss will probably lead to more frequent snow droughts, e.g., the frequency of consecutive snow droughts is projected to increase to 80-100% of years at 4˚C warming in western Canada (Shrestha et al., 2021) and 42% of years under the RCP8.5 scenario in the western US (Marshall et al., 2019) by 2100. Thus, by the mid-to-late-21st century, for more than 2/3 of snow-dominated areas in the western US, the ability to predict seasonal droughts and prepare robust water management plans will decline (Livneh and Badger, 2020)(4.4.5).

There is a *high agreement* between the CMIP6 projections and the previous findings that permafrost will undergo increasing thaw and degradation during the 21st century worldwide (IPCC AR6 WG1, 2021 (Sections 9.5.2.3)). The CMIP6 models project that the annual mean frozen volume in the top 2 m of the soil could decrease by 10 %–40 % for every degree increase of global temperature (Burke et al., 2020; Yokohata et al., 2020b). The CMIP5-based equilibrium sensitivity of permafrost extent to stabilized global mean warming is established to be about 4.0×10^6 km^2 $°C^{-1}$ (Chadburn et al., 2017). The southern boundary of the permafrost is projected the move to the North: 1–3.5° northward (relative to 1986–2005), at the level of 1.5 °C temperature rise (Kong and Wang, 2017).

The observational knowledge gaps (4.2.2) impede efforts to calibrate and evaluate models that simulate the past and future evolution of the cryosphere and its social impacts.

In summary, in most basins fed by glaciers, runoff is projected to increase initially in the 21st century and then decline (*medium confidence*). Projections suggest a further decrease in seasonal snow cover extent and mass in mid-to-high latitudes and high mountains (*high confidence*) though the projection spread is considerable. Permafrost will continue to thaw throughout the 21st century (*high confidence*). There is *medium confidence* that future changes in cryospheric components will negatively affect irrigated agriculture and hydropower production in regions dependent on snow-melt run-off.

4.4.3 Projected Changes in Streamflow

AR5 (Jiménez Cisneros et al., 2014) concluded that increases in the mean annual run-off are projected in high latitudes and the wet tropics and decreases in dry tropical regions, but with very considerable uncertainty. Both the patterns of change and uncertainties were found to be primarily driven by projected changes in precipitation. SR1.5 (Hoegh-Guldberg et al., 2018) concluded with *medium confidence* that areas with either positive or negative changes in mean annual run-off/streamflow are projected to be smaller for 1.5°C than for 2°C of global warming. AR6 WG1 (Douville et al., 2021) conclude with *medium confidence* that global run-off will increase with global warming but with significant regional and seasonal variations. WG1 further concluded with *high confidence* that run-off will increase in the high northern latitudes and decrease in the Mediterranean and southern Africa. However, there was *medium confidence* that run-off will increase in central and eastern African regions and decrease in Central America and parts of southern South America. The magnitude of the change is projected to increase with emissions. There is *medium confidence* that the seasonality of run-off and streamflow will increase with global warming in the subtropics. In snow-dominated regions, there is *high confidence* that peak flows associated with spring snowmelt will occur earlier in the year and *medium confidence* that snowmelt-induced run-off will decrease with reduced snow, except in glacier-fed basins where run-off may increase in the near term.

Changes in run-off and streamflow are projected over most of the ice-free land surface with all recent climate and hydrological model ensembles (Figure 4.16). Changes in streamflow could increase the number of people facing water scarcity or insecurity (*high confidence*) (Schewe et al., 2014; Gosling and Arnell, 2016; McMillan et al., 2016). Projections of future run-off at basin scales show considerable uncertainty in many regions, including differences in signs in many regions (Figure 4.16). This uncertainty is driven by uncertainties in regional precipitation patterns and hydrological models (Koirala et al., 2014; Asadieh et al., 2016), including vegetation responses to CO_2 and its effects on ET (Betts et al., 2015). This uncertainty in future water availability contributes to the policy challenges for adaptation, for example, for managing risks of water scarcity ((Greve et al., 2018); Box 4.1). In many regions, some models project large changes in run-off/streamflow but with low consistency between models on the sign of the change (Figure 4.16). In streamflow projections driven by 11 CMIP5 models with the RCP8.5 scenario, strong model consistency (agreement by at least ten models) is only seen over 21% of global land (Koirala et al., 2014). Consensus on the sign of projected change is smaller with the RCP4.5 scenario.

Considering a wider set of projections, the consensus on increased flows becomes stronger at higher GWLs in (for example) the Yukon, Mackenzie, Kemijoki, Amur, Hwang Ho, Yangtze, Mekong, Ganges-Brahmaputra, Nile, Zaire and Parana basins (Figure 4.16). The consensus on decreased flows becomes stronger for higher GWLs in (for example) the Colorado, Tagus, Helmand, Tigris-Euphrates and Amazon. However, in both cases, some models have projected changes of the opposite sign to the consensus. Moreover, the distribution of projected outcomes becomes notably broader at higher GWLs in (for example) the Mississippi, Yangtze and Amazon. Therefore, even with a strong global climate change signal, uncertainties in changes in mean run-off/streamflow can remain large or even increase. Nevertheless, since projected changes typically increase with global warming, limiting warming to 1.5°C or 2°C substantially reduces the potential for either large increases or decreases in mean streamflow compared to 3°C or 4°C ((Warszawski et al., 2014; Falkner, 2016; Gosling et al., 2017); Figure 4.16) (*high confidence*).

In CMIP5, strong model consistency on changes in high and low streamflows is seen with similar global patterns to the mean flows, but over smaller areas (Koirala et al., 2014) (Koirala et al., 2014). By the end of the 21st century with RCP8.5, increases in mean, high and low flows are projected for the Lena; mean and low flows for the MacKenzie (Gelfan et al., 2017; Pechlivanidis et al., 2017; Döll et al., 2018). Increased mean and high flows are projected in the Ganges, high flow in the Rhine and Mississippi while decreasing mean and low flows in the Rhine (Krysanova et al., 2017; Pechlivanidis et al., 2017; Vetter et al., 2017). Decreases in mean, high and low flows are projected for the Tagus Krysanova, 2017 #1394; Vetter, 2017 #697}. Low flows are projected to decrease in the Mediterranean region and increase in the Alps and Northern Europe (Marx et al., 2018). A general shift in the run-off distribution towards more extreme low run-off in Mexico, western United States, Western Europe, southeastern China, West Siberian Plain and more extreme high run-off in Alaska, northern Canada, and large parts of Asia are projected (Zhai et al., 2020).

While projected changes in high and low flows are similar to those in mean flows in many regions, this is not the case everywhere. When a single hydrological model and a sample of climate models are selected to explore uncertainties systematically, approximately 56% of the global population is projected to be affected by increased extreme high flows at 1.5°C warming, rising to 61% at 2°C warming (Zhai et al., 2020). Those affected by extreme low flows decrease is projected to remain close to 45% at both 1.5°C and 2°C warming. However, these results are based on the median of the ensemble projections, so they are subject to high uncertainty. At 1.5°C global warming, 15% of the population is projected to be affected concurrently by decreased extreme low flows and increased extreme high flows, increasing to 20% at 2°C warming. In 25 combinations of five CMIP5 climate models and five global hydrological models under the RCP8.5 scenario reaching approximately 4°C GWL at the end of the century, 10 % of the global land area is projected to face simultaneously increasing high extreme streamflow and decreasing low extreme streamflow. These regions include the British Isles and the shores of the North Sea, large parts of the Tibetan Plateau, South Asia, and western Oceania, and smaller regions of Africa and North and South America, affecting over 2.1 billion people with 2015 population distributions (Asadieh and Krakauer, 2017). With 11 CMIP5 models driving a single hydrological model, simultaneous increases in high flows and decreases in low flows are projected over 7% of global land (Koirala et al., 2014).

By the end of the 21st century, global changes in streamflow extremes are projected to be approximately twice as large with RCP8.5 (over 4°C GWL) than with RCP2.6 (approximately 2°C GWL) (Asadieh and Krakauer, 2017).

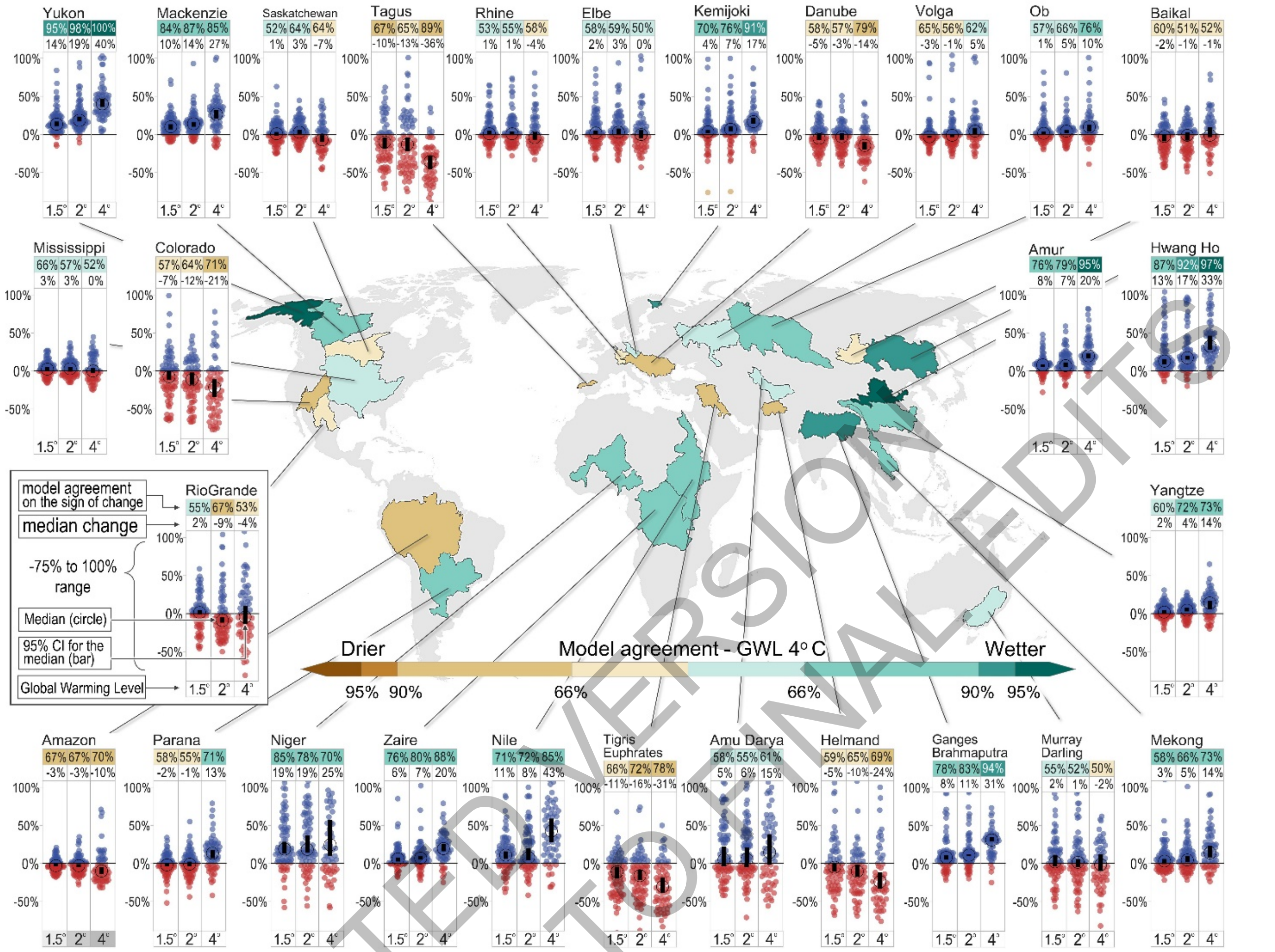


Figure 4.16: Projected changes in the annual mean run-off in selected river basins at Global Warming Levels (GWLs) of 1.5°C, 2°C and 4°C in a combined ensemble. For each named basin, the sinaplot dots show individual model outcomes for percentage increased flows (blue) and decreased flows (red) at each GWL. Black circles show the ensemble median, and black bars show the 95% confidence range in the median. See inset with the Rio Grande sinaplot for additional guidance on interpretation. In the map, the colours in the basins show the percentage model agreement on the sign of the projected change in streamflow at the 4°C GWL. The combined ensemble is comprised of 4 multi-model ensembles: the CMIP5 multi-model ensemble of GCMs driven with RCP8.5; the CMIP6 multi-model ensemble of GCMs driven with SSP5-85; varying combinations of hydrological models with 5 GCMs in the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP), and; the JULES land ecosystems and hydrology model driven by GCMs from the HELIX study (Betts et al., 2018; Koutroulis et al., 2019). In CMIP5 and CMIP6, the projected run-off changes are directly from the GCM land surface schemes without bias correction. In ISIMIP and HELIX, bias-corrected climate model outputs were used to drive the hydrology models. A comparison of the projected changes at the 4°C GWL for the four individual ensembles is shown in Figure Cross-Chapter Box CLIMATE.1 in Chapter 1.

Glacier retreat and associated run-off changes represent a major global sustainability concern (4.4.2). By 2100, using an ensemble of 14 CMIP5 climate models driven by the RCP4.5 scenario, 1/3rd of the 56 large-scale glacierized catchments are projected to experience a mean annual run-off decline by over 10%, with the most significant reductions in central Asia and the Andes (Huss and Hock, 2018). Thus, communities dependent on glacier run-off are particularly vulnerable (Jiménez Cisneros et al., 2014).

Societal impacts of change in run-off spread throughout several socio-economic sectors, such as agriculture, health, energy production, affecting overall water security (Wang et al., 2021a). Decreases in run-off may lead to water scarcity and result in increased multisectoral effects in Sub-Saharan Africa (Serdeczny et al., 2017), Western Africa, Middle East, Mexico, North Eastern Brazil, Central Argentina, Mediterranean Africa and Europe (Gosling and Arnell, 2016; Greve et al., 2018), and South-Eastern Australia (Barnett et al., 2015).

In summary, mean and extreme streamflow changes are projected over most of the ice-free land surface (*high confidence*). The magnitude of streamflow change is projected to increase with global warming in most regions (*high confidence*), but there is often high uncertainty on the sign of change. There is *high confidence* that mean streamflows will increase in the northern high latitudes and decrease in the Mediterranean and southern Africa. Annual mean run-off in one-third of glacierized catchments is projected to decline by at least 10% by 2100, with the most significant reductions in central Asia and the Andes (*medium confidence*). Elsewhere, projections include both increased and decreased flows. Substantial fractions of ensemble projections disagree with the multi-model mean (*high confidence*), with implications for long-term planning for water management. With 1.5°C and 2°C global warming, approximately 15% and 20% of the current global population would experience both an increase in high streamflows and a decrease in low streamflows (*medium confidence*). At 4°C global at the end of the century, 10 % of the global land area is projected to simultaneously experience an increase in high extreme streamflow and decrease in low extreme streamflow.

4.4.4 Projected Changes in Floods

SR1.5 (Hoegh-Guldberg et al., 2018) concluded with *medium confidence* that global warming of 2°C would lead to an expansion of the area affected by flood hazards, compared to conditions at 1.5°C global warming. Both AR5 (Jiménez Cisneros et al., 2014) and SROCC (Hock et al., 2019b) concluded that spring snowmelt floods would be earlier (*high confidence*), and hazards from floods involving meltwater will gradually diminish, particularly at low elevation (*medium confidence*). SROCC (Hock et al., 2019b) and AR6 WGI Chapter 9 stated that given *limited evidence* and the complexity of the process, the changes of glacier-related floods under climate change are not clear. AR6 WGI Chapters 8 and 11 summarized that there is *medium confidence* for a general increase in flooding due to warming, but there are significant regional and seasonal variations.

There is *high confidence* that the frequency and magnitude of river floods are projected to change at a global scale. For example, the frequency of river floods is projected to increase in many regions, including Asia, central Africa, western Europe, Central and South America and eastern North America, and decrease in northern North America, southern South America, Mediterranean, eastern Europe in 2050 and beyond (Koirala et al., 2014; Arnell et al., 2016) (Figure 4.17). There is *low agreement* in projections in changes to snowmelt flood magnitude. A negative trend in snowmelt flood magnitude, together with an increase in rain-fed winter floods, is projected with *medium confidence*, for example, in mid-latitudes and low-altitude basins of Scandinavia (Arheimer and Lindström, 2015; Vormoor et al., 2016) and throughout Europe as a whole (Kundzewicz et al., 2017), and northeastern North America (Arnell and Lloyd-Hughes, 2014). With *medium confidence*, a positive trend is projected in high-latitude basins, e.g., for large Arctic Rivers, such as Lena and Mackenzie (Eisner et al., 2017; Gelfan et al., 2017; Pechlivanidis et al., 2017) and high-altitude upstreams, such as Ganges, Brahmaputra, Salween, Mekong and the upper Indus Basin (Lutz et al., 2014) and Alpine catchments (Hall et al., 2014). Moderate decreasing trends or insignificant changes are projected for snowmelt floods in the Fraser River Basin of British Columbia (Shrestha et al., 2017).

There is *high confidence* that climate change and projected socio-economic development would increase exposure in inundation areas (Figure 4.17), resulting in a large increase in direct flood damages as several times more in all warming levels (Table 4.6). (Alfieri et al., 2017) estimated a 120% and 400% increase in population affected by river flooding for 2°C and 4 °C warming, respectively, and a 170% increase in damage for 2°C warming without socio-economic impact development (4.7.5). (Dottori et al., 2018) estimated the same but with a 134% increase in fatalities with population increase under the SSP3 scenario. The highest numbers of people affected by river flooding are projected for countries in southern, eastern and south-eastern Asia, with tens of millions of people per year per country projected to be affected (Figure 4.17; (Alfieri et al., 2017; Hirabayashi et al., 2021b). (Kinoshita et al., 2018) showed that climate change contributes a 2.8 to 28.8% increase in global fatality for the period 2071-2100, compared to 1991-2005, but socio-economic change (~131.3% increase) and associated vulnerability change (~72.1% reduction) have a greater impact of the projected flood-related fatality rate than climate change alone. (Winsemius et al., 2016) discussed that projected flood damage could be reduced to 1/20th in absolute value with adequate adaptation strategies. Direct flood damages are projected to increase by 4-5 times at 4°C compared to 1.5°C, highly depending on scenarios and assumptions (Table 4.6; Box 4.7).

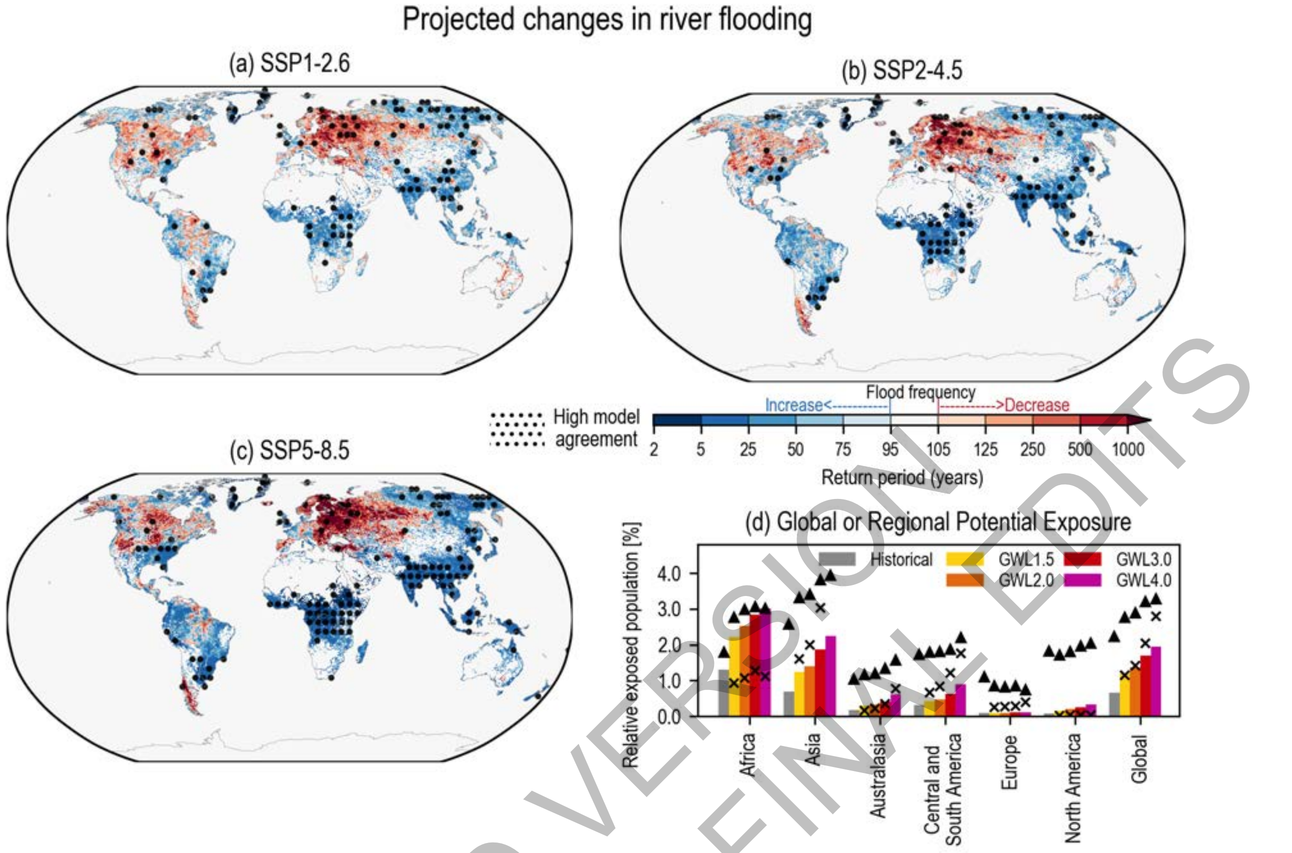


Figure 4.17: Multi-model median return period (years) in the 2080s for the 20th-century 100-year river flood, based on a global river and inundation model, CaMa-Flood, driven by runoff output of 9 CMIP6 Models in the SSP1-2.6 (a), SSP2-4.5 (b) and SSP5-8.5 (c) scenario respectively. All changes are estimated in 2071-2100 relative to 1970-2000. A dot indicates regions with high model consistency (more than 7 models out of 9 show the same direction of change). (d) Global or regional potential exposure (% to the total population affected by flooding) under different warming levels with constant population scenario of CMIP5 (Alfieri et al., 2017) and with population scenario of SSP5 of CMIP6 (bar chart, (Hirabayashi et al., 2021b)). Inundation is calculated when the magnitude of flood exceeds current flood protection (Scussolini et al., 2016). Note that number of GCMs used to calculate Global Warming Level (GWL) 4.0 is less than that for other SWLs, as the global mean temperature of some GCMs did not exceed 4°C.

Table 4.6: Projected economic impact by river flooding in billion US$ in different emission scenarios or for different global warming levels (GWL). The percentage of the total GDP of the region is given in brackets.

Description	The economic impact in billion US$ (% of GDP)	Reference
No adaptation with current flood protection, no economic development (fixed at the level of 2010), US$ at 2010 PPP, mean of 7 GCMs with RCP8.5 scenario	• Current (1976-2005): 75 (0.11 %) • GWL 1.5°C: 145 (0.22 %) (Asia 92, Australasia 8, Europe 29, Africa 7, North America 3, Central and South America 5) • GWL 2°C: 172 (0.26 %) (Asia 114, Australasia 7, Europe 32, Africa 9, North America 4, Central and South America 7) • GWL 3°C: 249 (0.37 %) (Asia 176, Australasia 9, Europe 38, Africa 11, North America 4, Central and South America 11) • GWL 4°C: 343 (0.51 %) (Asia 241, Australasia 19, Europe 55, Africa 9, North America 6, Central and South America 14)	(Alfieri et al., 2017), with regional aggregation and currency conversion
No adaptation with current flood protection, US$ at 2010 PPP,	• Current (1976-2005): 142 (0.21 %) • GWL 1.5°C, SSP3: 370 (0.55 %), SSP5: 485 (0.72%)	(Dottori et al., 2018) with

mean of 5 CMIP5 GCMs and 10 hydrological models	• GWL 2°C, SSP3: 597 (0.89 %), SSP5: 888 (1.32%) • GWL 3°C, SSP3: 1,024 (1.52 %), SSP5: 1,616 (2.40%)	currency conversion
No adaptation and no flood protection, mean value in 2030 (2010-2030) and 2080 (2010-2080), US$ at 2010 PPP, mean of 5 CMIP5 GCMs	• Current (1960-1999): 1,032 (1.6 %) • RCP2.6, SSP1: 2030: 2,366 (1.44%), 2080: 7,429 (1.43%) • RCP6.0, SSP3: 2030: 1,987 (1.44%), 2080: 3,353(1.14%) • RCP8.5, SSP5: 2030: 2,304 (1.37%), 2080: 3,684(1.77%)	(Winsemius et al., 2016)
Partial adaptation (protected against 100-year floods in high-income countries, against 5-year floods for all others), mean value in 2030 (2010-2030) and 2080 (2010-2080), US$ at 2010 PPP, mean of 5 CMIP5 GCMs	• Current (1960-1999): 163 (0.25 %) • RCP2.6, SSP1: 2030: 558 (0.34%), 2080: 851 (0.48%) • RCP6.0, SSP3: 2030: 418 (0.29%), 2080: 413(0.32%) • RCP8.5, SSP5: 2030: 418 (0.33%), 2080: 441 (0.57%)	(Winsemius et al., 2016)
A model calibrated to fit reported damages, future vulnerability scenarios considering autonomous adaptation, US$ at 2005 PPP, mean of 11 CMIP5 GCMs,	• Current (1991-2005): 14 (0.044 %) • RCP2.6, SSP1: 2081-2100, 121 (0.037 %) • RCP6.0, SSP2: 2081-2100, 133 (0.042 %) • RCP8.5, SSP3: 2081-2100, 130 (0.063 %)	(Kinoshita et al., 2018)
No adaptation and current flood protection, US$ at 2005 PPP, mean of 5 CMIP5 GCMs	• Current (1961-2005): 102 (0.39 %) • RCP2.6, SSP1: 2020-2100, 2333 (0.99 %) • RCP4.5, SSP2: 2020-2100, 2221 (0.99 %) • RCP6.0, SSP3: 2020-2100, 1328 (0.80%) • RCP8.5, SSP5: 2020-2100, 4007 (1.21 %)	(Tanoue et al., 2021)
Optimized adaptation, US$ at 2005 PPP, mean of 5 CMIP5 GCMs	• Current (1961-2005): 102 (0.39 %) • RCP2.6, SSP1: 2020-2100, 1621 (0.69 %) • RCP4.5, SSP2: 2020-2100, 1567 (0.70 %) • RCP6.0, SSP3: 2020-2100, 872 (0.52 %) • RCP8.5, SSP5: 2020-2100, 2558 (0.77 %)	(Tanoue et al., 2021)

In all climate scenarios projected, earlier snowmelt leads to earlier spring floods (*high confidence*), for example, in northern and eastern Europe (Gobiet et al., 2014; Hall et al., 2014; Etter et al., 2017; Lobanova et al., 2018), northern North America (Vano et al., 2015; Musselman et al., 2018; Islam et al., 2019b), large Arctic rivers (Gelfan et al., 2017; Pechlivanidis et al., 2017), and high-altitude Asian basins (Lutz et al., 2014; Winsemius et al., 2016). There is *high confidence* that snowmelt floods will occur 25-30 days earlier in the year by the end of the 21st century with RCP8.5, but there is only *low agreement* in the projected magnitude of snowmelt flood (Arheimer and Lindström, 2015; Vormoor et al., 2016; Islam et al., 2019b).

Challenges to projecting flood risk are large because of the complexity of the projecting snowmelt, high-intensity rainfall and soil wetness in large river basins. Even though increases in the number and area of glacier lakes may cause increases in glacier-related floods (4.2.2), knowledge of the frequency or magnitude of glacier-related projected floods is limited. Some local studies indicate that the severity of ice-jam flooding is projected to decrease (Rokaya et al., 2019; Das et al., 2020), but a model study in Canada projected increases in damage of ice-jam floods (Turcotte et al., 2020). While most flood risk projections do not consider the impact of urban expansion, (Güneralp et al., 2015) estimate that urban areas exposed to flooding will increase by a factor of 2.7 due to urban growth by 2030 (4.5.4). Given the significant differences in assumption in flood protection, exposure or vulnerability scenario among studies, uncertainties in the global estimation of flood loss and damages are large (Table 4.6, 4.7.5).

Floods and their societal impacts, especially the enhancement of hazards and increase in vulnerability, depend on complex political, economic, and cultural processes (Carey et al., 2017; Caretta et al., 2021). Thus, assessments that analyze long term flood impacts need to account for the interplay of water and society relations. Unfortunately, such studies remain scarce (Pande and Sivapalan, 2017; Ferdous et al., 2018; Caretta et al., 2021). In particular, projected socio-economic, cultural and political impacts on the vulnerable group are understudied, as is their resourcefulness through local knowledge, adaptive capacity and community-led adaptation (4.6.9; 4.8.4; Cross-Chapter Box INDIG in Chapter 18).

In summary, there is *high confidence* that the magnitude, frequency and seasonality of flood are projected to increase in many regions, including Asia, central Africa, western Europe, Central and South America and eastern North America, and decrease in northern North America, southern South America, Mediterranean and Eastern Europe. Projected increases in flooding pose increasing risks, with a 1.2 to 1.8 and 4 to 5 times increase in global GDP loss at 2°C and 4°C compared to 1.5°C warming, respectively (*medium confidence*). However, regional differences in risks are large because of the strong influence of socio-economic conditions and significant uncertainty in flood hazard projection. In small river basins and urban areas, there is *medium confidence* that projected increases in heavy rainfall would contribute to increases in rain-generated local flooding. However, the snowmelt floods are projected to decrease (*medium confidence*) and occur 25-30 days earlier in the year by the end of the 21st century with RCP8.5 (*high confidence*).

4.4.5 Projected Changes in Droughts

AR6 WG1 (Douville et al., 2021) concluded that the total land area subject to increasing drought frequency and severity would expand (*high confidence*), and in the Mediterranean, south-western South America, and western North America, future aridification will far exceed the magnitude of change seen in the last millennium (*high confidence*). WG1 (Seneviratne et al., 2021) also find many consistencies among projections of climate change effects on different forms of drought (meteorological, agricultural/ecological and hydrological and drought, 4.2.5), but also significant differences in some regions, particularly in the levels of confidence in projected changes.

Many studies focus on precipitation-based drought indices (Carrão et al., 2018), but higher evaporative demands and changes in snow cover are additional drivers of hydrological, agricultural and ecological drought (*medium confidence*) in many regions of the world (Koirala et al., 2014; Prudhomme et al., 2014; Touma et al., 2015; Wanders et al., 2015; Zhao and Dai, 2015; Naumann et al., 2018; Cook et al., 2020a). Furthermore, these droughts (hydrological, agricultural and ecological) are often modulated by prevailing soil and hydro-morphological characteristics. Therefore, the choice of drought definition can affect the magnitude and even the sign of the projected drought change.

In a study with multiple climate models, global water models and scenarios, the choice of drought definition was the dominant source of uncertainty in the sign of projected change in drought frequency in over 17% of global land by 2070-2099, including several major wheat and maize-growing areas where agricultural (soil moisture) drought is of high importance (Satoh et al., 2021). (Cook et al., 2020a) noted that in the CMIP6 projections, soil moisture and runoff drying is more robust, spatially extensive, and severe than precipitation, resulting in the frequency of agricultural drought increasing over wider areas than for meteorological drought. At 1.5°C global warming, the likelihood of extreme agricultural (soil moisture) drought is projected to at least double (100% increase) over large areas of northern South America, the Mediterranean, western China and high latitudes in North America and Eurasia (Figure 4.18, left column). The likelihood is projected to increase by 150% to 200% in these regions at 2°C global warming, with an expansion of the affected areas, and increase by over 200% at 4°C global warming. Agricultural drought likelihood also increases by 100% to 250% at 4°C global warming in south-western North America, south-west Africa, southern Asia and Australia. The likelihood of extreme drought is projected to decrease in central North America, the Sahel, the horn of Africa, the eastern Indian sub-continent, and parts of western and eastern Asia. Using eight global hydrological models driven by a subset of four of the CMIP5 climate models, (Lange et al., 2020) projected a 370% (30–790%) increase of the global population annually exposed to agricultural (soil moisture) droughts in response to 2°C global warming. Therefore, it is essential to consider the drought type when applying drought projections to impact and risk in decision-making, especially for informing adaptation. For example, if responses are explicitly tailored to agricultural (soil moisture) drought changes, projected changes in a meteorological (precipitation) drought metric may not provide accurate information.

Compared to CMIP5, the CMIP6 ensemble projects more consistent drying in the Amazon basin (Parsons, 2020), more extensive declines in total soil moisture in Siberia (Cook et al., 2020a), and stronger declines in westernmost North Africa and south-western Australia. Projected declines in soil moisture in these geographies would cause a significant risk of agricultural drought. Also, importantly, projected changes in drought in many regions depend on the season and may not be evident in annual mean changes. For example, in north-western Asia, hydrological (runoff) drought frequency is projected to decrease by 50-100% in autumn and winter but increase by up to 250% in spring and summer (Cook et al., 2020a). In contrast, meteorological (precipitation) drought frequency is projected to increase by up to 350% throughout the year.

Drought projections are subject to uncertainties due to limits of predictability and understanding of the relevant biophysical processes. Uncertainties in regional climate changes are significant in many regions (see Figure 4.10, Figure 4.13, Figure 4.15), and in climate model ensembles, the range of regional outcomes generally increases with global warming. This widening of the range of outcomes can contribute to the increased likelihood of extreme droughts across the ensemble as a whole (Figure 4.18, right column). The response of transpiration to elevated CO_2 is also a significant uncertainty. The inclusion of CO_2 physiological effects leads to smaller projected increases in agricultural, ecological or hydrological drought (Milly and Dunne, 2016; Yang et al., 2020). However, the level of uncertainties in representing the effects of CO_2 is still very high, precluding conclusive results in a global analysis (de Kauwe et al., 2013; Prudhomme et al., 2014; Yang et al., 2016). Most CMIP6 climate models include CO_2 physiological effects, but many hydrological models used for impacts studies do not.

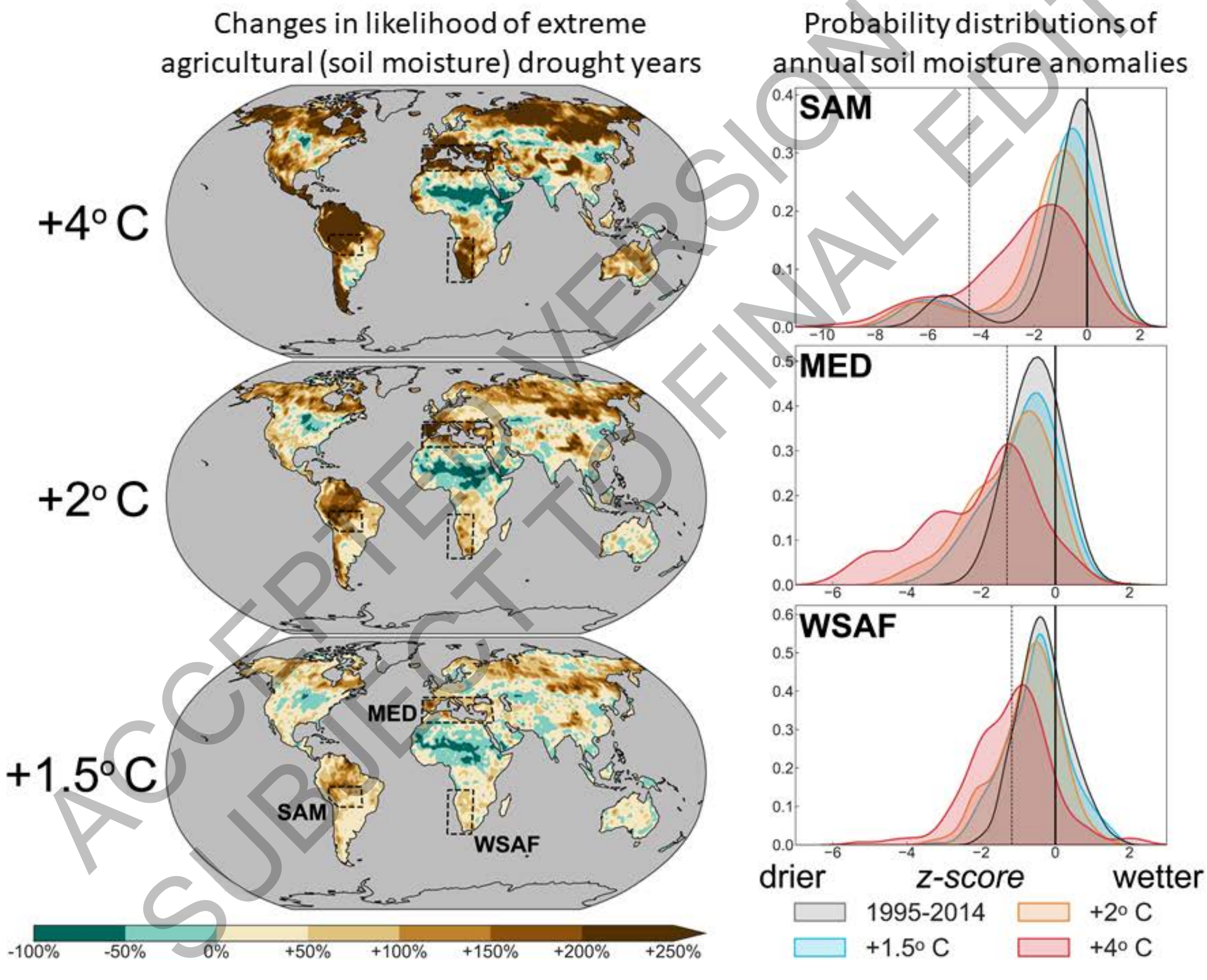


Figure 4.18: Projected changes in the likelihood of an extreme single-year agricultural (soil moisture) drought event, with extreme drought defined as the driest 10% of years from 1995-2014, using total soil moisture projections pooled from the CMIP6 ensemble following (Cook et al., 2020a). All ensemble members are treated as equally likely potential outcomes, and likelihoods are calculated using the whole ensemble, left: Percentage change in the likelihood of extreme drought at GWLs of 4°C (top), 2°C (middle) and 1.5°C (bottom), with "extreme drought" defined locally as the 10th percentile in individual grid boxes. Right: probability distribution functions of regional mean soil moisture anomalies for the climatic regions Mediterranean (MED), South American Monsoon (SAM) and West Southern Africa (WSAF) (Iturbide et al., 2020), at 1.5°C, 2°C and 4°C GWLs. The solid vertical line shows the baseline, i.e., 50th percentile in 1995-2014. The dashed vertical line shows the 10th percentile for 1995-2014, defining "extreme drought" at the regional scale. Projections used the SSP5-8.5 scenario to maximize the number of ensemble members at higher GWLs, but

global patterns of change are very similar for all scenarios (Cook et al., 2020a) and for any given GWL, similar results can be expected with other scenarios (Seneviratne et al., 2021).

Terrestrial water storage (TWS) is the sum of continental water stored in canopies, snow and ice, rivers, lakes and reservoirs, wetlands, soil and groundwater (Pokhrel et al., 2021). TWS drought can therefore be considered to be a combination of agricultural, ecological and hydrological drought. The proportion of the global population exposed to TWS drought is projected to increase with ongoing climate change (Figure 4.19). By the late 21st century, under RCP6.0, the global land area in extreme-to-exceptional TWS drought is projected to increase from 3% to 7% (Pokhrel et al., 2021), with increasing uncertainty over time. Combined with a medium population growth scenario (SSP2), this leads to the global population in this level of drought increasing from 3% to 8%, again with increasing uncertainty over time. Hydrological droughts can also be driven by direct human impact via water abstraction (Javadinejad et al., 2019).

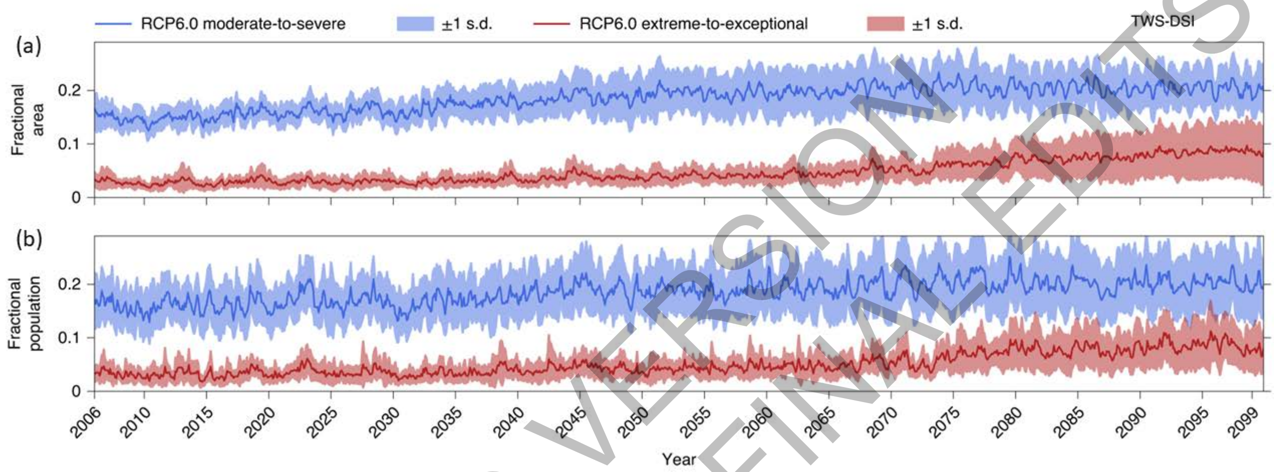


Figure 4.19: Projected changes in the area under drought and population affected, defined with changes in Terrestrial Water Storage – Drought Severity Index (TWS-DSI) projected with 7 terrestrial hydrology models driven by 4 CMIP5 climate models using the RCP6.0 concentration pathway. (a) Fractional global land area under moderate-to-severe drought (blue), defined as −0.8 ≤ TWS-DSI < −1.6, and extreme-to-exceptional drought (red), defined as TWS-DSI < −1.6. (b) Fraction of global population exposed to moderate-to-severe (blue) and extreme-to-exceptional (red) drought, using the SSP2 population projection. Dark lines show the ensemble means; shaded areas indicate uncertainty as ±1 standard deviation. Reproduced from (Pokhrel et al., 2021).

Critical knowledge gaps include uncertainties in regional drought due to regional climate change uncertainties, challenges in constraining plant physiological responses to atmospheric CO_2, and the uncertainties in modelling the role of different population projections in projecting regional drought risk.

In summary, the likelihood of drought is projected to increase in many regions over the 21st century (*high confidence*) even with strong climate change mitigation, more severely in the absence of this. Different forms of drought broadly show similar patterns of projected change in many regions (*high confidence*), but the frequency of agricultural drought is projected to increase over wider areas than for meteorological drought (*medium confidence*). Clarity on the definition of drought is therefore important for informing decision-making. With the RCP6.0 and SSP2 scenarios, the global population exposed to extreme-to-exceptional terrestrial water storage drought is projected to increase from 3% to 8% over the 21st century.

4.4.6 Projected Changes in Groundwater

AR5 concluded that the range of projected future changes in groundwater storage was large, from statistically significant declines to increases due to several uncertainties in existing models (Jiménez Cisneros et al., 2014). AR6 (Douville et al., 2021) concluded with *high confidence* that projected increases in precipitation alone cannot ensure an increase in groundwater storage under a warming climate unless unsustainable trends in groundwater extraction are also reversed.

Projected impacts of climate change on groundwater systems are commonly simulated using models at local to global scales (Bierkens and Wada, 2019). The relations between climate change and groundwater are more complex than those embedded in current numerical models (Cuthbert et al., 2019b). For instance, groundwater systems register effects of drought with several years of lag effect, and aquifer response times to changes in hydraulic forcing also vary across aquifers (Cuthbert et al., 2019a). For instance, long groundwater response times can buffer drought impacts and lengthen recovery times to sustained drought events (Van Lanen et al., 2013; Opie et al., 2020).

Global total and non-renewable groundwater withdrawals are projected to increase from 952 km^3 $year^{-1}$ (2010) to 1,621 km^3 $year^{-1}$ (2099) and from 304 km^3 $year^{-1}$ (2010) to 597 km^3 $year^{-1}$ (2099), respectively (Bierkens and Wada, 2019). At the same time, groundwater depletion is projected to increase from approximately 204 (±30) km^3 $year^{-1}$ in 2000 to 427 (±56) km^3 $year^{-1}$ by 2099 (Wada, 2016). Much of the projected depletion is a function of increased future abstraction of groundwater for irrigation and increased evapotranspiration (Condon et al., 2020) in a warmer climate. For example, the projected doubling of average water use by 2050 in Tunisia is attributed partly (3.8% to 16.4%) to climate change and mainly to socioeconomic policies (Guermazi et al., 2019). Similarly, groundwater depletion in the Bengal Basin and North China Plain is more due to irrigation development than climate change per se (Leng et al., 2015; Kirby et al., 2016).

A recent synthesis of modelling studies conducted in various climates showed that out of 33 studies, 21 reported a decrease in the projected groundwater recharge or storage, eight reported an increase, and the rest showed no substantial change (Amanambu et al., 2020). A global-scale multi-model ensemble study projected decreasing recharge in southern Chile, Brazil, central continental USA, the Mediterranean, and East China, but consistent and increasing recharge for northern Europe and East Africa (Reinecke et al., 2021). In continental Spain, a modelling study (Pulido-Velazquez et al., 2018) projected significant reductions in groundwater recharge in the central and southeast region but a small and localized increase in east and north-eastern areas. In subarctic Alaska, increased contribution of glacier melts to streamflow and aquifer recharge under a warming climate is projected (Liljedahl et al., 2017). In contrast, over the Iranian and Anatolia Plateaus, groundwater recharge is projected to reduce by ~77% in the spring season (March-May) due to a decrease in snowfall (Wu et al., 2020). Overall, several recent studies of climate change impacts on groundwater in different parts of the world have concluded that projected groundwater recharge could either increase or decrease, and results are often uncertain (*high confidence*) (Meixner et al., 2016; Zaveri et al., 2016; Hartmann et al., 2017; Mehran et al., 2017; Tillman et al., 2017; Kahsay et al., 2018; Herbert and Döll, 2019).

(Wu et al., 2020) report a projected increase in future groundwater storage in the semi-arid regions of northwest India, North China Plain, Guarani Aquifer in South America, and Canning Basin in Australia due to significant increases in projected precipitation. However, the projected irrigation expansion could negate this positive gain in groundwater storage (Sishodia et al., 2018; Wu et al., 2020). In drylands (e.g., playas in Southwestern USA), where focused groundwater recharge processes dominate, greater recharge is projected to occur from the increased number of significant runoff-generating extreme precipitation events in the future (McKenna and Sala, 2018). Overall, an emerging body of studies have projected amplification of episodic recharge in the tropics and semi-arid regions due to extreme precipitation under global warming (*medium confidence*).

Climate change is also projected to impact groundwater dependent ecosystems and groundwater quality negatively (*medium confidence*). Projected increase in precipitation intensity and storms can contaminate groundwater by mobilizing contaminants such as chemical fertilizers, pesticides, antibiotics, and leaching of human waste from pit latrines into groundwater (Amanambu et al., 2020; Lall et al., 2020). By 2050, environmentally critical streamflow is projected to be affected in 42% to 79% of the world's watersheds. The majority of these watersheds currently experience intensive groundwater use, and changes in critical streamflow are projected to negatively impact aquatic ecosystems (de Graaf et al., 2019). Using a global synthesis of 9,404 data points from 32 countries across six continents, (McDonough et al., 2020) report increases in dissolved organic carbon (DOC) concentrations in groundwater following projected changes in precipitation and temperature. For example, hotspots of high DOC concentration (increases of up to 45%)

are associated mainly with increased temperatures in the wettest quarter of the year in the south-eastern USA under RCP8.5 scenarios.

The projected rise in sea levels can lead to saline intrusion into aquifers in low-lying areas and small islands and threaten coastal ecosystems and livelihoods resilience, for example, in already vulnerable countries like Bangladesh and vulnerable ecosystems like the Mangrove Forest of *Sundarbans* (Befus et al., 2020; Dasgupta et al., 2020; Shamsudduha et al., 2020). However, hydrogeologic properties, aquifer settings, and impacts of over-abstraction are more important determinants of salinization of coastal aquifers than slowly rising sea levels (Michael et al., 2013; Taylor et al., 2013a). The projected contribution of global groundwater depletion to sea-level rise is expected to increase from 0.57 (±0.09) mm year^{-1} in 2000 to 0.82 (±0.13) mm year^{-1} by 2050, driven by a growing trend in groundwater extraction (Wada, 2016). However, several uncertainties around model parameterization remain (Wada et al., 2017).

There are several knowledge gaps in our understanding of the global-scale sensitivity of groundwater systems to climate change and resulting feedbacks (Maxwell and Condon, 2016; Cuthbert et al., 2019a). There are process uncertainties in groundwater recharge simulation due to the potential impact of atmospheric CO_2 on vegetation and resulting changes in evapotranspiration (Reinecke et al., 2021). There are uncertainties in impact models due to poor representation of recharge pathways (diffuse vs. focused) and inability to adequately capture feedbacks among climate, land use, and groundwater systems (Meixner et al., 2016). Finally, there are gaps in long-term observational data, especially in less-developed countries (Amanambu et al., 2020), making it challenging to evaluate the of performance of impact models (Gleeson et al., 2020).

In summary, groundwater abstraction is projected to deplete the long-term, non-renewable storage as withdrawals are projected to increase significantly in all major aquifers worldwide (*medium evidence, high agreement*). In the tropics and semi-arid regions, growing precipitation intensification under global warming may enhance the resilience of groundwater through increased episodic recharge (*medium confidence*). However, in the semi-arid areas, over-abstraction continues to be a threat to groundwater storage and can nullify the benefits of increased future recharge.

4.4.7 Projected Changes in Water Quality

AR5 concluded that climate change was projected to reduce water quality (Jiménez Cisneros et al., 2014). SR 1.5 assessed with *low confidence* differences in projected impacts under 1.5°C versus 2°C of warming (Hoegh-Guldberg et al., 2018). In addition, SROCC reported the water quality degradation due to the release of legacy contaminants in glaciers and permafrost (*medium confidence*) (Hock et al., 2019b). AR6 WGI Report does not explicitly mention water quality issues.

Water insecurity due to water quality degradation is projected to increase under climate change due to warming, enhanced floods and sea-level rise (Arnell and Lloyd-Hughes, 2014; Dyer et al., 2014; Whitehead et al., 2015) (*medium confidence*). Drought-driven diminishing river and lake levels (Jeppesen et al., 2015) and continued water abstraction for irrigation (Aragüés et al., 2015) may contribute to the salinization of soil and water. In addition, warming is projected to disrupt the historical sequestration of contaminants in permafrost in the Arctic and mountain regions (Bond and Carr, 2018).

Quantitative projections on climate-induced water quality degradation are sparse. Aminomethylphosphonic acid and glyphosate are projected to exceed drinking water quality standards in dry years in a high emissions scenario in the Meuse River in Europe by 2050 (Sjerps et al., 2017). From 2020 to 2050, based on scenarios RCP2.6, RCP4.5, and RCP8.5, the incidences of total nitrogen pollution are projected as 97.3%, 97.1% and 94.6% in drought–flood abrupt alternation months comparing to 69.3%, 69.7% and 67.5% in normal months in the Luanhe river basin in China (Bi et al., 2019). From 2012 to 2050, freshwater river area is expected to decrease from 40.8% to 17.1%-19.7% under different sea-level rise scenarios in the southwest coastal zone of Bangladesh (Dasgupta et al., 2013). Under the warming scenario +4.8°C increase by the end of the century, the average nutrient abundance are projected to triple in a shallow lake in the Northwest of England (Richardson et al., 2019).

While there is some understanding of the potential effect of glacier and permafrost degradation on water quality, projections are lacking. Research is limited mainly in Europe and North America, and quantifying the future water quality changes is still incipient.

In summary, climate change is projected to increase water pollution incidences, salinization, and eutrophication due to increasing drought and flood events, sea level rise, and water temperature rise, respectively in some local rivers and lakes, but there is dearth of exact quantification at a global scale (*medium confidence*).

4.4.8 Projected Changes in Soil Erosion and Sediment Load

AR5 stated that soil erosion and sediment load are projected to change (*low confidence*) due to warming and increased rainfall intensity (Jiménez Cisneros et al., 2014). SRCCL concluded that future climate change will increase, with *medium confidence*, the potential for water-driven soil erosion in many dryland areas, causing soil organic carbon decline (Mirzabaev et al., 2019). SR1.5 (Hoegh-Guldberg et al., 2018) concluded that, because of the complex interactions among climate change, land cover, soil management, etc., the differences between mean annual sediment load under 1.5°C and 2°C of warming are unclear.

Globally, climate change is estimated to be responsible for 30-66% increase of soil erosion by 2070, while socioeconomic developments impacting land use may lead to ±10% change of soil erosion (Borrelli et al., 2020). At a regional scale, different effects of the climate change impact on soil losses are found owing to the ensemble experiments with climate models coupled with regional/local models of soil erosion and sediment yield. In the 21st century, the soil erosion rates are projected to increase for the European countries (Czech Republic (Svoboda et al., 2016), Belgium (Mullan et al., 2019), Spain (Eekhout et al., 2018; Eekhout and de Vente, 2019a; Eekhout and De Vente, 2019b), Germany (Gericke et al., 2019) by 10-80% depending on the emission scenario and time period of the projection, as well as for the USA (Garbrecht and Zhang, 2015) and Australia (Yang et al., 2015b; Zhu et al., 2020). Only a few studies demonstrated decreasing trend in soil erosion, e.g. up to 9% with RCP8.5 scenario in Greece (Vantas et al., 2020). Sediment yield is projected to both increase (5-16% with the SRES A1, B1, B2 scenarios in Vietnam and Laos (Giang et al., 2017), 11% with the RCP8.5 scenario and 8% with the SRES A2 scenario in the U.S. (Yasarer et al., 2017) and (Wagena et al., 2018), respectively), 19-37% with the RCP4.5, RCP8.5 scenarios in Burkina Faso (Op de Hipt et al., 2018)) and decrease (30% with the SRES A1B scenario in the southwest U.S. ((Francipane et al., 2015), 8-11% with the SRES A1B scenario in Spain (Rodríguez-Blanco et al., 2016), 11-52% with the RCP4.5, RCP8.5 scenarios in Ethiopia (Gadissa et al., 2018), 13-62% with the RCP2.6, RCP8.5 scenarios in Canada (Loiselle et al., 2020)) over the different regions of the world in the 21st century.

Post-fire sedimentation is projected to increase for nearly nine tenths of watersheds by >10% and for more than one third of watersheds by >100% by the 2041 to 2050 decade in the western USA with SRES A1B scenario (Sankey et al., 2017).

In summary, soil losses mainly depend on the combined effects of climate and land use changes. Herewith, recent studies demonstrate increasing impact of the projected climate change (increase of precipitation, thawing permafrost) on soil erosion (*medium confidence*).

4.5 Projected Sectoral Water-related Risks

Observed sectoral water-related impacts have been documented across world regions. Climate change is projected to further exacerbate many of these risks, especially at warming levels above 1.5°C (Figure 4.20). For some sectors and regions, climate change may also hold the potential for beneficial outcomes, though feedback and cascading effects as well as risks of climate extremes are not always well understood and often underestimated in impact projections. Risks manifest as a consequence of the interplay of human and natural vulnerability, sector-specific exposure as well as the climate hazard as a driver of climate change. Challenges to water security are driven by factors across these components of risk, where climate change is but one facet of driving water insecurity in the face of global change. While the focus of this chapter is on climate change and its effects on water security, for many sectors and regions the dynamics of socio-economic conditions is a core driver. They play an essential role in understanding and alleviating water security risks. The following sections outline sectoral risks for both, risks driven by water-related impacts, such as drought, flood or changes in water availability, as well as risks with effects on water uses, mainly focusing on changing water demand as a consequence of climate change. It therefore does not cover all climate change driven risks to the respective sectors, but is limited to those that stand in relation to water. The focus within this chapter is on global to regional processes (additional regional to local information in Table SM4.4; Figure 4.20 as well as across regional chapters of this report).

4.5.1 Projected Risks to Agriculture

AR5 concluded that overall irrigation water demand would increase by 2080, while the vulnerability of rainfed agriculture will further increase (Jiménez Cisneros et al., 2014). SR1.5 concluded that both the food and the water sectors would be negatively impacted by global warming with higher risks at 2°C than at 1.5°C, and these risks could coincide spatially and temporally, thus increasing hazards, exposures and vulnerabilities across populations and regions *(medium confidence)*. SR1.5 further reinforced AR5 conclusions in terms of projected crop yield reductions, especially for wheat and rice (*high confidence*), loss of livestock, and increased risks for small-scale fisheries and aquaculture *(medium confidence)* (Hoegh-Guldberg et al., 2018), conclusions which are further corroborated by SRCCL (Mbow et al., 2019).

Climate change impacts agriculture through various pathways (5.4 – crop-based systems), with projected yield losses of up to 32% by 2100 (RCP8.5) due to the combined effects of temperature and precipitation. Limiting warming could significantly reduce potential impacts (up 12% yield reduction by 2100 under RCP4.5) (Ren et al., 2018a). Though overall changes differ across models, regions and seasons, differences in impacts between 1.5°C and 2°C can also be identified (Ren et al., 2018a; Ruane et al., 2018; Schleussner et al., 2018). Globally, 11% (±5%) of croplands are estimated to be vulnerable to projected climate-driven water scarcity by 2050 (Fitton et al., 2019).

Overall drought-driven yield loss is estimated to increase by 9% to 12% (wheat), 5.6% to 6.3% (maize), 18.1% to19.4% (rice) and 15.1% to16.1%(soybean) by 2071-2100, relative to 1961-2016 (RCP8.5) (Leng and Hall, 2019). In addition, temperature-driven increases in water vapour deficit could have additional negative effects, further exacerbating drought-induced plant mortality and thus impacting yields (Grossiord et al., 2020) (see also Cross-Chapter Box 1 in Chapter 5 of WGI report). Currently, global agricultural models do not fully differentiate crop responses to elevated CO_2 under temperature and hydrological extremes (Deryng et al., 2016) and largely underestimate the effects of climate extremes (Schewe et al., 2019).

Flood-related risks to agricultural production are projected to increase over Europe, with a mean increase of expected annual output losses of approximately € 11million (at 1.5°C GWL); €12m (at 2°C GWL) and €15 million (at 3°C GWL) relative to the 2010 baseline (Koks et al., 2019). In parts of Asia, where flooding impacts on agriculture are already significant, projections indicate an increase in damage to area under paddy by up to 50% in Nepal; 16% in the Philippines; 55% in Indonesia; 23% in Cambodia and Vietnam and 13% in Thailand (2075-2099 vs 1979-2003; RCP8.5) (Shrestha et al., 2019a).

Global crop water consumption of green water resources (soil moisture) is projected to increase by about 8.5% by 2099 relative to 1971-2000 as a result of climate drivers (RCP6.0), with additional smaller contributions by land-use change (Huang et al., 2019) (4.4.1.3, 4.4.8). In India, a substantial increase in green and blue water consumption is projected for wheat and maize, with a slight reduction of blue water consumption for paddy (Mali et al., 2021). Temperate drylands, especially higher latitude regions, may become more suitable for rain-fed agriculture (Bradford et al., 2017). Locally and regionally, however, some of those areas with currently larger areas under rain-fed production, for example, in Europe, may become less suitable for rain-fed agriculture (Table 1 to 4.5.1) (Bradford et al., 2017; Shahsavari et al., 2019).

While global crop models and estimates of yield impacts often focus on major staple crops relevant for global food security, crops of high economic value are projected to become increasingly water dependent. For example, climate-driven yield increases for tea are projected for various tea-producing regions if no water limitations and full irrigation is assumed but decreases in yields are projected under continued present-day irrigation assumptions (Beringer et al., 2020). Water-related impacts on global cotton production are highly dependent on the CO_2-fertilisation effect, with increases projected for higher CO_2 concentration if no water limitations are implemented. However, substantial decreases in cotton production are projected if lower or no fertilization effects are accounted for due to increasing water limitations (Jans et al., 2018). Reductions in economically valuable crops will probably increase the vulnerability of population groups, especially small-holder farmers with limited response options (Morel et al., 2019).

To stabilize yields against variations in moisture availability, irrigation is the often the most common adaptation response (4.6.2, Box 4.3). Projections indicate a potentially substantial increase in irrigation water requirements (Boretti and Rosa, 2019). Increasing agricultural water demand is driven by various factors, including population growth, increased irrigated agriculture, cropland expansion and higher demand for bio-energy crops for mitigation ((Chaturvedi et al., 2015; Grafton et al., 2015; Turner et al., 2019), 4.7.6). Depending on underlying assumptions and the constraints on water resources implemented in the global agricultural models, irrigation water requirements are projected to increase two to three-fold by the end of the century (Hejazi et al., 2014; Bonsch et al., 2015; Chaturvedi et al., 2015; Huang et al., 2019). While the combined effects of population and land-use change as well as irrigation expansion account for the significant part of the projected increases in irrigation water demand by the end of the century, around 14% of the increase are directly attributed to climate change (RCP6.0) (Huang et al., 2019).

With various degrees of water stress being experienced under current conditions and further changes in regional water availability projected, as well as continuing groundwater depletion as a consequence of over-abstraction for irrigation purposes (4.2.6 and 4.4.6), limitations to major irrigation expansion will occur in some regions, including South and Central Asia, the Middle East, parts of North and Central America (Grafton et al., 2015; Turner et al., 2019). Constraining projections of available irrigation water through consideration of environmental flow requirements further reduces the potential for irrigation capacity and expansion (Bonsch et al., 2015). Changes in land use and production patterns, e.g. expansion of rain-fed production and increasing inter-regional trade, would be required to meet growing food demand while preserving environmental flow requirements, though this may increase local food security-related vulnerabilities (Cross-Chapter Box INTERREG in Chapter 16) (Pastor et al., 2014). Where climate impacts on yields are not a consequence of water limitations (mainly for C4 crops), irrigation cannot offset negative yield impacts (Levis et al., 2018).

Over 50% of the global lowlands equipped for irrigation will depend heavily on run-off contributions from the mountain cryosphere by 2041–2050 (SSP2–RCP6.0) and are projected to make unsustainable use of blue water resources (Viviroli et al., 2020). Projected changes in snowmelt patterns indicate that for all regions dependent on snowmelt for irrigation during warm seasons, alternative water sources will have to be found for up to 20% (at 2°C GWL) and up to 40% (at 4°C GWL) of seasonal irrigation water use, relative to current water use patterns (1986-2015) (Qin et al., 2020). Regional studies further corroborate these global findings (Biemans et al., 2019; Malek et al., 2020). Basins, where such alternate sources are not available, will face agricultural water scarcity.

Elevated CO_2 concentrations play an important role in determining future yields in general and have the potential to beneficially affect plant water use efficiency (Deryng et al., 2016; Ren et al., 2018a; Nechifor and Winning, 2019). The elevated CO_2 effects are projected to be most prominent for rain-fed C3 crops (Levis et al., 2018). Combined results from field experiments and global crop models show that CO_2 fertilization could reduce consumptive water use by 4-17% (Deryng et al., 2016). To account for uncertainties, global agricultural models provide output with and without account for CO_2 fertilization effects, though recent progress on reducing model uncertainty indicates that non-CO_2 model runs may no longer be needed for adequate projections of yield impacts (Toreti et al., 2019).

Due to the complex interactions among determinants for livestock production, the future signal of water-related risks to this sector is unclear. Globally, 10% (±5%) of pasture areas are projected to be vulnerable to climate-induced water scarcity by 2050 (Fitton et al., 2019). Water use efficiency gains through elevated CO_2 concentrations have the potential to increase forage quantities, though effects of nutritional values are ambiguous (Augustine et al., 2018; Derner et al., 2018; Rolla et al., 2019). In addition, spatial shifts in temperature-humidity regimes may shift suitable regions for livestock production, opening up new suitable areas for some regions or encouraging shifts in specific breeds better adapted to future climatic regimes (Rolla et al., 2019) (5.5 – Livestock Systems and 5.10. Mixed Systems).

Projections of climate impacts on freshwater aquaculture are limited (5.9.3.1 – Projected Impacts; Inland freshwater and brackish aquaculture). In particular, in tropical regions, reductions in water availability, deteriorating water quality, and increasing water temperatures pose risks to terrestrial aquaculture, including temperature-related diseases and endocrine disruption ((Kibria et al., 2017), Section 4.4.7). On the other hand, freshwater aquaculture in temperate and arctic polar regions may benefit from temperature increases with an extension of the fish growing season (Kibria et al., 2017).

Global crop models, which provide the basis for most projections of agricultural risk, continue to have limitations in resolving water availability. As a result, they do not fully resolve the effects of elevated CO_2 for changing water use efficiency, for example (Durand et al., 2018), potentially overestimating drought impacts on maize yield (Fodor et al., 2017) and may underestimate limitations to further expansion of irrigation (Elliott et al., 2014; Frieler et al., 2017b; Winter et al., 2017; Jägermeyr and Frieler, 2018; Kimball et al., 2019; Yokohata et al., 2020a).

In summary, agricultural water use is projected to increase globally due to cropland expansion and intensification and climate change-induced changes in water requirements (*high confidence*). Parts of temperate drylands may experience increases in suitability for rain-fed production based on mean climate conditions; however, risks to rain-fed agriculture increase globally because of increasing variability in precipitation regimes and changes in water availability (*high confidence*). Water-related impacts on economically valuable crops will increase regional economic risks (*medium evidence, high agreement*). Regions reliant on snowmelt for irrigation purposes will be affected by substantial reductions in water availability (*high confidence*).

4.5.2 Projected Risks to Energy and Industrial Water Use

AR5 concluded with *high confidence* that climate induced changes, including changes in water flows, will affect energy production, and the actual impact will depend on the technological processes, and location of energy production facilities (Arent et al., 2014). SR1.5 concluded with *high confidence* that climate change is projected to affect the hydropower production of Northern European countries positively. However, Mediterranean countries like Greece, Spain, and Portugal are projected to experience approximately a 10% reduction in hydropower potential under 2°C warming level, which could be reduced by half if global warming could be limited to 1.5°C (Hoegh-Guldberg et al., 2018). In addition, SROCC concluded with *high confidence* that an altered amount and seasonality of water supply from snow and glacier melt is projected to affect hydropower production negatively (IPCC, 2019a).

Since AR5, a large number of studies have modeled future changes in hydropower production due to climate-induced changes in volume and seasonality of streamflow and changes in sediment load due to accelerated melting of cryosphere at both global (van Vliet et al., 2016b; Turner et al., 2017) and regional scales (Tarroja et al., 2016; Ali et al., 2018; de Jong et al., 2018; Tobin et al., 2018; Arango-Aramburo et al., 2019; Carvajal et al., 2019; Arias et al., 2020; Meng et al., 2021).

For hydropower production at a global scale, (Turner et al., 2017), projected an uncertainty in the direction of change in global hydropower production to the tune of +5% to -5% by 2080s, under a high emissions scenario. On the other hand, (van Vliet et al., 2016b), projected an increase in global hydropower production between +2.4% to +6.3% under RCP 4.5 and RCP 8.5 respectively by 2080s, as compared to a baseline period of 1971-2000, but with significant regional variations (*high confidence*). For example, regions like Central Africa, India, Central Asia, and northern high-latitude areas are projected to see more than 20% increases in gross hydropower potential (*high confidence*). On the other hand, Southern Europe, Northern Africa, southern United States, and parts of South America, southern Africa, and southern Australia are projected to experience more than 20% decreases in gross hydropower potential. The Mediterranean region is projected to see almost a 40% reduction in hydropower production (*high confidence*) (Turner et al., 2017). On the other hand, northern Europe and India are projected to add to their hydropower production capacity due to climate change by mid-century (*high confidence*) (van Vliet et al., 2016b; Turner et al., 2017; Emodi et al., 2019).

In hydropower plants located in the Zambezi basin, electricity output is projected to decline by 10-20% by 2070 compared to baseline (1948-2008) under a drying climate; only marginal increases are projected under a wetting climate (Spalding-Fecher et al., 2017). In the Mekong basin, the total hydropower generation is projected to decline by 3.0% and 29.3% under 1.5°C and 2°C (Meng et al., 2021). In this context, 1.5°C will come up in 2036 under RCP2.6 and in 2033 under RCP6.0; and 2°C will come up in 2056 under RCP6.0 (Frieler et al., 2017a). In India, hydropower production is projected to increase by up to 25% by the end of the 21st century due to increased temperature and precipitation under the RCP8.5 scenario. However, hydropower production is projected to decline in plants located in snow-dominated rivers due to earlier snowmelt (Ali et al., 2018). In Colombia, hydropower production is projected to decrease by ~10% under the RCP4.5 dry scenario by 2050 (Arango-Aramburo et al., 2019). In a sub-basin of the Amazon River (one of the hydropower hotspots in Brazil), dry season hydropower potential is projected to decline by -7.4 to -5.4% from historical baseline conditions under RCP4.5 (Arias et al., 2020). In the São Francisco basin of Brazil, hydropower production is projected to reduce by -15% to -20% by 2100 under the IPCC A1B scenario (de Jong et al., 2018), which will affect the Brazilian energy mix in the future. In Ecuador, under various policy pathways and dry and wet scenarios under RCP4.5, hydropower production is projected to increase by +7% to +21% or decline by -25% to -44% by 2050 (Carvajal et al., 2019). In Europe, different impacts are projected across different sub-regions (WGII, Chapter 13, Table 13.7- Projected climate change risks for energy supply in Europe by 2100). In Northern Europe, up to 20% of hydropower potential increases are projected under 3°C warming; increases of up to 15% and 10% are projected under 2°C and 1.5°C warming levels. In Mediterranean parts of Europe, hydropower potential reductions of up to -40% are projected under 3°C warming; while reductions below -10% and -5% are projected under 2°C and 1.5°C warming levels, respectively (van Vliet et al., 2016b; Tobin et al., 2018). Hydropower plants in Switzerland are projected to lose ~ 1.0 TWh of hydroelectricity production per year by 2070-90 due to net glacier mass loss in the earlier part of the century (Schaefli et al., 2019). In the Italian Alps, under the warmest scenario of RCP8.4, up to 4% decreases in hydropower production are projected (Bombelli et al., 2019). The magnitude of change differs significantly among models. In California, USA, the average annual hydropower generation is expected to decline by 3.1% under RCP4.5 by 2040-2050, compared to the baseline 2000-2010 (Tarroja et al., 2016). In the Skagit river basin in the US, hydropower generation is projected to increase by 19% in the winter/spring, and a decline by 29% in summer by the 2080s (Lee et al., 2016).

Apart from climate impacts on hydropower production, climate-induced flood loads and reservoir water level change may lead to dam failure under RCP2.6 and RCP4.5 scenarios (Fluixá-Sanmartín et al., 2018; Fluixá-Sanmartín et al., 2019) (*medium confidence*). For example, the incidence of 100-year floods in the Skagit river basin in the US and peak winter sediments are projected to increase by 49% and 335%, respectively, by 2080, necessitating fundamental changes in hydropower plant operation. Nevertheless, some risks, such as floods, will remain unmitigated even with changes in hydropower operation rules (Lee et al., 2016). Overall, impacts of future extreme events on energy infrastructure have been less studied than impacts of gradual changes (Cronin et al., 2018). Furthermore, future hydropower development may also impact areas of high freshwater megafauna in South America, South and East Asia, and in the Balkan region, and sub-catchments with a high share of threatened freshwater species are particularly vulnerable (Zarfl et al., 2019). Therefore, future hydropower dams will need to be sited carefully (Dorber et al., 2020).

There is *high confidence* that changes in future cooling water availability are projected to affect thermoelectric production capacity negatively at global (van Vliet et al., 2016b; Zhou et al., 2018b) and regional scales (Bartos and Chester, 2015; Behrens et al., 2017; Ganguli et al., 2017; Zhou et al., 2018b; Emodi et al., 2019). Global mean water temperature is projected to increase by +1°C for RCP2.6 and +2.7°C for RCP8.5 (van Vliet et al., 2016b). Correspondingly, global cooling water sufficiency is projected to decline by -7.9% to -11.4% by 2040-2069 and -11.3% to -18.6% by 2070-90 (Zhou et al., 2018b), thereby impacting thermoelectric power production.

In Asia, under a 2°C global warming scenario, coal power plants annual usable capacity factor in Mongolia, Southeast Asia, and parts of China and India are projected to decrease due to water constraints (Wang et al., 2019b). In the European Union, an assessment of 1326 thermal electric plants in 818 basins projected that the number of basins with water stress would increase from 47 in 2014 to 54 in 2030 (Behrens et al., 2017) with consequent impacts on cooling water supplies. In the Western USA, by 2050, vulnerable power plants are projected to lose 1.1% to 3.0% of average summertime generation capacity, which could rise to 7.2 to 8.8% loss under a ten-year drought condition (Bartos and Chester, 2015). Further, 27% of thermoelectric production in the USA may be at severe risk of low-capacity utilization due to water stress by 2030 (Ganguli et al., 2017). Thermoelectric plant capacity on the hottest summer day in the USA and EU are projected to fall by 2% under a 2°C global warming and by 3.1% under a 4°C global warming requiring overbuilding of electricity infrastructure by 1% to 7% given the current energy mix portfolio (Coffel and Mankin, 2020). A systematic review showed consistent decreases in mid to end of the century in thermal power production capacity due to insufficiency of cooling water in Southern, Western and Eastern Europe (*high confidence*); North America and Oceania (*high confidence*), Central, Southern, and Western Asia (*high confidence*) and Western and Southern Africa (*medium confidence*) (Emodi et al., 2019). Overall, apart from emissions benefits, moving away from thermal power generation to other renewable energy will also lower the chances of climate induced curtailment of energy production (*high confidence*).

Global freshwater demand for the energy sector is projected to increase under all 2°C scenarios due to the rapid increase in electricity demand in developing countries (Fricko et al., 2016). Despite the water shortage and climate change impacts, industry and energy sectors' share in global water demand has been projected to rise to 24% by 2050 (UN Water, 2020), which will increase the competition among various water-use sectors (Boretti and Rosa, 2019). Furthermore, mining activities, which are highly dependent on sufficient water availability, are also at risk due to climate change (Aleke and Nhamo, 2016). Given that some of the intensely mined regions, such as the Atacama Desert in Chile, are already water-scarce, even small changes in rainfall could destabilize water-intensive mining operations and affect the production and processing activities at mines (Odell et al., 2018). Overall, there is a lack of literature on the impact of climate change on future mining activities and other water-intensive industries.

In summary, globally, hydropower and thermoelectric power capacities are projected to increase and decrease, respectively, due to changes in river run-off and increases in ambient water temperatures (*high confidence*). In the future, freshwater demand for energy and industrial sectors is projected to rise significantly at the global level, triggering competition for water across sectors. Although climate change also poses risks to mining and other water-intensive industries, quantifying these risks is difficult due to limited studies.

4.5.3 Projected Risks to Water, Sanitation and Hygiene (WaSH)

Climate-related extreme events impact WaSH services and local water security. While not WaSH-specific, AR5 showed that more people would experience water scarcity and floods (*high confidence*) and identified WaSH failure due to climate change as an emergent risk (*medium confidence*) leading to higher diarrhoea risk (Field et al., 2014b). In addition, both SR 1.5 (IPCC, 2018a) and SRCCL (IPCC, 2019b) projected the risk from droughts, heavy precipitation, water scarcity, wildfire damage, and permafrost degradation to be higher at 2°C warming than 1.5°C (*medium confidence*) and all these could potentially impact water quality and WaSH services.

Waterborne diseases result from complex causal relationships between climate, environmental, and socio-economic factors that are not fully understood or modelled (Boholm and Prutzer, 2017) (*high confidence*). WaSH-related health risks are related to extreme events, harmful algal blooms and WaSH practices (Chapter 7 WGII 7.3.2). In addition, changes in thermotolerance and chlorine resistance of certain viruses have been observed in laboratory experiments simulating different temperatures and sunlight conditions (Carratalà et al., 2020), increasing potential health risks even where traditional water treatment exists (Jiménez Cisneros et al., 2014) (*low confidence*). Studies show that degraded water quality increases the willingness to pay for clean water regardless of national economic status. However, payment for clean, potable water, particularly in low- and middle-income countries, can represent a significant percentage of people's income, limiting economic wellbeing and the possibility for re-investment in other livelihoods or activities (Constantine et al., 2017; van Houtven et al., 2017; Price et al., 2019).

Collectively, drinking water treatment, sanitation, and hygiene interrupt disease transmission pathways, particularly for water-related diseases. However, WaSH systems themselves are vulnerable to extreme events (4.3.3). For example, sewage overflows resulting from heavy rainfall events are expected to increase waterborne disease outbreaks (Khan et al., 2015). High diarrhoeal disease burdens mean that small changes in climate-associated risk are projected to have significant impacts on disease burdens (Levy et al., 2018). For example, up to 2.2 million more cases of *E. coli* by 2100 in Bangladesh under a 2.1°C GWL is projected (Philipsborn et al., 2016), while up to an 11-fold and 25-fold increase by 2050 and 2080, respectively under 2 to 4ºC GWL, in disability-adjusted life years associated with cryptosporidiosis and giardiasis in Canada is projected (Smith et al., 2015). In addition, and an additional 48,000 deaths in children under 15 years of age globally from diarrhoea by 2030 is also projected (WHO, 2014). Notably, high levels of treatment compliance and boiling water before consumption offset the projected impact of climate change on giardiasis in Canada in the 2050 scenario but could not wholly offset the projected impact in 2080 (Smith et al., 2015). Climate change impacts on WaSH-attributable disease burden are also projected to delay China's progress towards disease reduction by almost 9% under RCP 8.5 (Hodges et al., 2014). Disruptions in the drinking water supply can lead to increased household water storage, potentially increasing vector larvae breeding habitats (see Section 3.6.3). In combination with the projected expansion of vector ranges given climate change (Liu-Helmersson et al., 2019), there is the potential for increased risk of vector-borne disease during periods of water shortage or natural disasters (4.3.3). Moreover, energy requirements for water and wastewater treatment are indirectly responsible for greenhouse gas emissions, while the breakdown of excreta contributes directly to emissions (Box 4.5, Section 4.7.6). These contributions need to be better articulated and accounted for as part of the WaSH and climate change dialogue (Dickin et al., 2020).

In summary, climate change is expected to compromise WaSH services, compounding existing vulnerabilities and increasing water-related health risks (*medium evidence, high agreement*). Therefore, additional research is required on disease-, country-, and population-specific risks due to future climate change impacts (Baylis, 2017; Bhandari et al., 2020; Harper et al., 2020).

4.5.4 Projected Risks to Urban and Peri-Urban Sectors

AR5 reported with *medium confidence* that climate change would impact residential water demand, supply and management (Revi et al., 2014). According to AR5, water utilities are also confronted by changes to the availability of supplies; water quality; and saltwater intrusion into aquifers in coastal areas due to higher ambient and water temperatures (*medium evidence, high agreement*), altered streamflow patterns, drier conditions, increased storm runoff, sea-level rise, and more frequent forest wildfires in catchments (Jiménez Cisneros et al., 2014). SR1.5 found with *medium confidence* that constraining warming to 1.5°C instead of 2°C might mitigate risks for water availability, but socioeconomic drivers could affect water availability more than variations in warming levels, while the risks differ across regions (Hoegh-Guldberg et al., 2018).

In nearly a third of the world's largest cities, water demand may exceed surface water availability by 2050, based on RCP6.0 projections and the WaterGAP3 modelling framework (Flörke et al., 2018). Under all SSPs, the global volume of domestic water withdrawal is projected to reach 700-1500 km^3yr^{-1} by 2050, indicating an increase of 50 to 250%, compared to the 2010 water use intensity (400-450 km^3yr^{-1}) (Wada et al., 2016). Increasing water demand by cities is already spurring competition between cities and agricultural users for water, which is expected to continue (Garrick et al., 2019) (4.5.1). By 2030, South and Southeast Asia are expected to have almost three-quarters of the urban land under high-frequency flood risk (10.4.6). South Asia, South America and Mid-Latitudinal Africa are projected have the largest urban extents exposed to floods and droughts (Güneralp et al., 2015). An analysis of 571 European cities from the Urban Audit database (using RCP8.5 projections without assessing urban heat island effects) found drought conditions are expected to intensify (compared to the historical period 1951-2000) in southern European cities, particularly in Portugal and Spain ((Guerreiro et al., 2018); CCP4.3.3). Changes in river flooding are projected to affect cities in north-western European cities and the United Kingdom between 2051-2100 (Guerreiro et al., 2018) (6.2.3.2, CCP2.2.1, CCP2.2.3).

Globally, climate change is projected to exacerbate existing challenges for urban water services. These challenges include population growth, the rapid pace of urbanisation and inadequate investment, particularly in less developed economies with limited governance capacity (*high confidence*) (Ceola et al., 2016; van Leeuwen et al., 2016; Reckien et al., 2017; Tapia et al., 2017; Veldkamp et al., 2017). More specifically, in Arusha (Tanzania), a combination of urban growth modelling, satellite imagery, and groundwater modelling projected that rapid urbanisation would reduce groundwater recharge by 23% to 44% of 2015 levels by 2050 (under business as usual and RCP8.5 scenario), causing groundwater levels to drop up to 75m (Olarinoye et al., 2020). Flood risk modelling showed a median increase in flood risk of 183% in 2030 based on baseline conditions in Jakarta (Indonesia) with flood risks increasing by up to 45% due to land-use changes alone (Budiyono et al., 2016). A probabilistic analysis of surface water flood risk in London (UK) using the UKCP09 Weather Generator (with 10th and 90th percentile uncertainty bounds) found that the annual damage is expected to increase from the baseline by 101% and 128% under 2030 and 2050 high emission scenarios, respectively (Jenkins et al., 2018).

Modified streamflow is projected to affect the amount and variability of inflow to urban storage reservoirs (*high confidence*), which may exacerbate existing challenges to urban reservoir capacity, such as sedimentation and poor water quality (Goharian et al., 2016; Howard et al., 2016; Yasarer and Sturm, 2016). For example, in Melbourne (Australia), a combination of stochastic hydro-climatological modelling, rainfall-runoff modelling and climate model data projects a mean precipitation shift over catchments by -2% at 1.5ºC and -3.3% at 2ºC, relative to 1961-1990. Considering an annual water demand of 0.75 of the mean yearly inflow, the median water supply shortage risk was calculated to be 0.6% and 2.9% at 1.5ºC and 2ºC warming levels, respectively. At the higher demand level of 0.85 of the mean annual inflow, the median water shortage risk is higher, between 9.6% to 20.4% at 1.5ºC, and at 2ºC warming, respectively, without supply augmentation desalination (Henley et al., 2019).

As climate change poses a substantial challenge to urban water management, further refinement of urban climate models, downscaling and correction methods (e.g. (Gooré Bi et al., 2017; Jaramillo and Nazemi, 2018) is needed. Additionally, given that 90% of urban growth will occur in less developed regions, where urbanisation is largely unplanned (UN-Habitat, 2019), further research is needed to quantify the water-related risks of climate change and urbanisation on informal settlements ((Grasham et al., 2019; Satterthwaite et al., 2020), 4.5.3).

In summary, rapid population growth, urbanisation, ageing infrastructure, and changes in water use are responsible for increasing the vulnerability of urban and peri-urban areas to extreme rainfall and drought, particularly in less developed economies with limited governance capacity (*high confidence*). In addition, modified stream flows due to climate change (4.4.3) is projected to affect the amount and variability of inflows to storage reservoirs that serve urban areas and may exacerbate challenges to reservoir capacity, such as sedimentation and poor water quality (*high confidence*).

4.5.5 Projected Risks to Freshwater Ecosystems

AR5 concluded that climate change is projected to be an important stressor on freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios of RCP6.0 and RCP8.5 (*high confidence*), even though direct human impacts will continue to be the dominant threat (Settele et al., 2014). Rising water temperatures are also projected to cause shifts in freshwater species distribution and worsen water quality problems (*high confidence*), especially in those systems that already experience high anthropogenic loading of nutrients (Settele et al., 2014).

Changes in precipitation and temperatures are projected to affect freshwater ecosystems and their species through, for example, direct physiological responses from higher temperatures or drier conditions or a loss of habitat for feeding or breeding (Settele et al., 2014; Knouft and Ficklin, 2017; Blöschl et al., 2019b). In addition, increased water temperatures could lead to shifts in the structure and composition of species assemblages following changes in metabolic rates, body size, timing of migration, recruitment, range size and destabilization of food webs. A review of the impact of climate change on biodiversity and functioning of freshwater ecosystems found that under all scenarios, except the one with the lowest GHG emission scenario, freshwater biodiversity is expected to decrease proportionally to the degree of warming and precipitation alteration (Settele et al., 2014) **(***medium evidence, high agreement***)**.

These are several examples of such projected changes. Due to higher water temperatures, changes in macroinvertebrates and fish are projected under all future warming scenarios (Mantyka-Pringle et al., 2014). Decreased abundance of many fish species, such as salmonids, under higher temperatures, are also projected, although the effects between species are variable (Myers et al., 2017). Poleward and shifts of freshwater species are projected as they try to stay within preferred cooler environmental conditions (Pecl et al., 2017). Other anticipated changes include physiological adjustments with impacts on morphology with some species shrinking in body size because large surface-to-volume ratios are generally favoured under warmer conditions (Scheffers et al., 2016) and changes in species communities and food webs as a consequence of increases in metabolic rates in response to increased temperatures with the flow-on effects for many ecosystem processes (Woodward et al., 2010). Changes in the seasonality of flow regimes and variability

(Blöschl et al., 2019b) and more intermittent flows (Pyne and Poff, 2017) are also projected and could result in decreased food chain lengths through the loss of large-bodied top predators (Sabo et al., 2010) and changes in nutrient loadings and water quality (Woodward et al., 2010). The impacts on freshwater systems in drylands are projected to be more severe (Jaeger et al., 2014; Gudmundsson et al., 2016). Changes to snow and glacier melting, including the complete melting of some glaciers (Leadley et al., 2014; Kraaijenbrink et al., 2017), are projected to reduce water availability and cause declines in biodiversity in high altitudes through local extirpations and species extinctions in regions of high endemism. Lake nutrient dynamics are expected to change, for example, at 2 °C warming, net increase in CH_4 emissions by 101% to 183% in hypereutrophic lakes and 47 –56% in oligotrophic lakes in Europe are projected (Sepulveda-Jauregui et al., 2018). Similarly, under the high GHG emission scenario, lake stratification is projected to begin 22.0 ± 7.0 days earlier and end 11.3 ± 4.7 days later by the end of this century (Woolway et al., 2021). While overall future trends on climate change on freshwater species and habitats are largely negative, evidence indicates that different species are projected to respond at different rates, with interactions between species expected to be disrupted and which may result in novel biological communities and rapid change in ecological processes and functions (Pecl et al., 2017).

These impacts are expected to be most noticeable where significant air temperature increases are projected, leading to local or regional population extinctions for cold-water species because of range shrinking, especially under the RCP 4.5, 6.0 and 8.5 scenarios (Comte and Olden, 2017). The consequences for freshwater species are projected to be severe with local extinctions as the freshwater ecosystems dry. In the Americas, under all scenarios that have been examined, the risk of extinction of freshwater species is projected to increase above that already occurring levels due to biodiversity loss caused by pollution, habitat modification, over-exploitation, and invasive species (IPBES, 2019). Freshwater ecosystems are also at risk of abrupt and irreversible change, especially those in the higher latitudes and altitudes with significant changes in species distributions, including those induced by melting permafrost systems (Moomaw et al., 2018; IPBES, 2019).

While changes in the species distribution across freshwater ecosystems are projected, the extent of change and the ability of individual species or populations to adapt is not widely known. Species that cannot move to more amenable habitats may become extinct, whereas those who migrate may relocate. An unknown outcome could be establishing novel ecosystems with new assemblages of species, including invasive alien species, in response to changes in the environment with the prospect of irreversible changes in freshwater ecosystems (Moomaw et al., 2018).

In summary, changes in precipitation and temperatures are projected to affect all types of freshwater ecosystems and their species. Under all scenarios, except the one with the lowest GHG emission scenario, freshwater biodiversity is expected to decrease proportionally to the degree of warming and precipitation change (*medium evidence, high agreement*).

4.5.6 Projected Risks to Water-related Conflicts

AR5 concluded with *medium confidence* climate change can indirectly increase the risks of violent conflicts, though the link to hydrological changes were not spelled out (Jiménez Cisneros et al., 2014). Furthermore, according to IPCC SR1.5 (Hoegh-Guldberg et al., 2018), if the world warms by 2ºC- 4ºC by 2050, rates of human conflict could increase, but again, role of hydrological change in this was not explicit (*medium confidence*).

The impact of climate change on shared water resources might increase tensions among states, particularly in the absence of strong institutional capacity (Petersen-Perlman et al., 2017; Dinar et al., 2019). On the other hand, although the mere existence of formal agreements does not necessarily reduce the risks of conflicts, robust treaties and institutions can promote cooperative events, even under hydrological stress (Link et al., 2016). Yet, since both conflictive and cooperative events are possible under conditions of climatic variability, whether conflict arises or increases depends on several contextual socio-economic and political factors, including the adaptive capacity of the riparian states (Koubi, 2019), the existence of power asymmetries (Dinar et al., 2019) and pre-existing social tensions (*medium confidence*).

At the intra-state level, analysis suggests that additional climate change will increase the probability of conflict risks, with 13% increase probability at 2˚C GWL and 26% probability at 4˚C GWL scenario (Mach et al., 2019). However, to date, other factors are considered more influential drivers of conflict, including lack of natural resource use regulations (Linke et al., 2018b), societal exclusion (von Uexkull et al., 2016; van Weezel, 2019), poor infrastructures and a history of violent conflict (Detges, 2016) (*high confidence*). In addition, *medium-high evidence* exists that climate change imposes additional pressures on regions that are already fragile and conflict-prone (Matthew, 2014; Earle et al., 2015) (*medium agreement*).

Recent research indicates that climatic change can multiply tensions in regions dependent on agriculture when coupled with other socio-economic and political factors (Koubi, 2019), including a low level of human development (Ide et al., 2020) and deterioration of individual living conditions (Vestby, 2019). On the other side, intergroup cohesion (De Juan and Hänze, 2020) and policies that improve societal development and good governance reduce the risk of conflict associated with the challenges to adaptation to climate change (Hegre et al., 2016; Witmer et al., 2017) (*medium confidence*) at both the intra-state and inter-state level.

Increased risk of conflict between different sectors (agriculture, industry, domestic) and needs (urban, rural) is projected to arise in several river basins due to climate change and socio-economic developments, including urbanization (Flörke et al., 2018). Future climatic conditions and population growth are expected to exert additional pressures on managing already stressed basins such as the Nile, the Indus, Colorado, the Feni, the Irrawaddy, the Orange and the Okavango (Farinosi et al., 2018). In addition, recent scenario analysis in global transboundary basins supports the finding that there is more potential for conflict in areas already under water stress, such as Central Asia and the northern parts of Africa (Munia et al., 2020) (*medium confidence*).

In summary, the impact of climate change on water resources might increase tensions, particularly in the absence of strong institutional capacity. However, whether conflict arises or increases depends on several contextual socio-economic and political factors. Evidence exists that climate change imposes additional pressures on regions already under water stress or fragile and conflict-prone *(medium confidence).*

4.5.7 Projected Risks to Human Mobility and Migration

SR1.5 found with *medium confidence* that migration is expected to increase with further warming but that there are major knowledge gaps preventing more detailed assessments (Hoegh-Guldberg et al., 2018). However, as in AR5, there was no specific focus on hydrological changes induced migration.

In general, the projected population growth in at-risk areas, especially in low-income countries, is expected to increase future migration and displacement (McLeman et al., 2016; Rigaud et al., 2018). For example, a study looking at potential flood exposure found that low-income countries, particularly in Africa, are at higher risk for flood-induced displacement (Kakinuma et al., 2020). One model, focusing on slow-onset climate impacts as water stress, crop failure, sea-level rise projected between 31 to 72 million people (RCP2.6, SSP4) and 90 to 143 million people (RCP8.5, SSP4) internally displaced by 2050 in Sub-Saharan Africa, South Asia and Latin America (Rigaud et al., 2018). Another estimate, incorporating temperature increase and precipitation, projects that asylum applications to the EU could increase by between 0.098 million (RCP4.5) and 0.66 million (RCP8.5) per year, as a consequence of temperature increases in agricultural areas of low-income countries (Missirian and Schlenker, 2017) (*limited evidence; medium agreement*).

More detailed local and regional models are needed, incorporating migrant destinations (Abel et al., 2019) and immobility (Zickgraf, 2018).

In summary, research that projects future migration changes due to climate-induced hydrological changes is *limited* and shows significant uncertainties about the number of migrants and their destinations *(limited evidence; medium agreement)*.

4.5.8 Projected Risks to the Cultural Water Uses of Indigenous Peoples, Local Communities and Traditional Peoples

AR5 found that climate change will threaten cultural practices and values, although the risks vary across societies and over time (*medium evidence, high agreement*). Furthermore, AR5 concluded that significant changes in the natural resource base on which many cultures depend would directly affect the cultural core, worldviews, cosmologies and symbols of Indigenous cultures (Adger and Pulhin, 2014). SR1.5 concluded with *high confidence* that limiting global warming to 1.5°C, rather than 2°C, will strongly benefit terrestrial and wetland ecosystems and their services, including the cultural services provided by these ecosystems (Hoegh-Guldberg et al., 2018). SROCC found with *high confidence* that cultural assets are projected to be negatively affected by future cryospheric and associated hydrological changes (Hock et al., 2019b).

There is *high confidence* that the cultural water uses of Indigenous Peoples, local communities, and traditional peoples are at risk of climate change-related hydrological change (Table 4.7). Climate-driven variations in streamflow, saltwater intrusion, and projected increases in water temperature will exacerbate declines of culturally important species and lead to variations or depletion of culturally important places and subsistence practices. For example, in New Zealand, the increasing risk of flood events may impact culturally important fish species for Māori (Carter, 2019), while habitat changes may shift the distribution of culturally significant plants (Bond et al., 2019). In Australia, Yuibera and Koinmerburra Traditional Owners fear the saltwater inundation of culturally significant sites and waterholes (Lyons et al., 2019), while the flooding of culturally significant wetlands will negatively affect the Lumbee Tribe (USA) (Emanuel, 2018). Moreover, changes in the carrying capacity of ice, snow quality and formation will probably increase the physical risks to Saami practising reindeer herding (Jaakkola et al., 2018).

Further research is necessary to assess the extent and nature of climate-driven risks to cultural water uses in the context of broader socio-economic, cultural and political challenges facing diverse Indigenous Peoples, local and traditional communities. In addition, given the significance of Indigenous Knowledge and local knowledge to adaptive capacity and community-led adaptation, the potential risks of climate-related hydrological changes to diverse cultural water uses warrant closer study (4.6.9, 4.8.4, Cross-Chapter Box INDIG in Chapter 18).

In sum, there is *high confidence* that climate-driven hydrological changes to cultural water uses and culturally significant ecosystems and species are projected to pose risks to the physical wellbeing of Indigenous Peoples, local communities and traditional peoples.

Table 4.7: Selected Projected Risks to Indigenous Peoples' Uses of Water.

Region	Indigenous People	Climate hazard	Water-related Risk	Situated knowledge	Reference
Asia	Ifugao	Increased temperatures; increasing rainfall (wet season); decreasing rainfall (dry season)	Flooding (Wet season); Water deficit (dry season)	Increases in future wet season rainfall pose increase risks of excess surface water runoff and potential for soil erosion, which may cause the collapse of Ifugao rice terraces. Reductions in future dry season rainfall and warmer temperatures indicate significant water deficits during the growing season of local *tinawon* rice.	(Soriano and Herath, 2020)
Australasia	Yuibera and Koinmerburra Traditional Owner groups	Sea level rise	Flooding	Culturally important coastal waterholes, wetlands and sites are at risk of saltwater inundation due to rising sea levels. If inundated, traditional owners may not be able to maintain cultural connections to these important sites (11.4.1).	Lyons, 2019 #2810}
Australasia	Māori	Increased precipitation	Flooding	Increasing flood events may negatively impact spawning and fishing sites of the culturally important īnaka (whitebait; *Galaxias maculates*) in the Waikōuaiti River (11.4.2).	(Carter, 2019)
Australasia	Māori	Increased temperature;	Ecosystem change	Changes in temperature and precipitation are projected to shift the range of wetland	(Bond et al., 2019)

		precipitation variability		plants (Kūmarahou and Kuta) in New Zealand, which may decrease access to these culturally significant species, which are used for medicinal and weaving purposes. The changing distribution of these plants may lead to a loss of Indigenous Knowledge and affect inter-tribal reciprocity and gifting practices (11.4.2).	
Central and South America	Warao	Sea level rise	Flooding	The partial or total inundation of the Orinoco Delta will result in the loss of freshwater wetlands and species, which will produce rapid shifts in the culturally significant lands and resources of the Warao. Among the affected species is the *Mauritia* palm, on which Warao culture and livelihoods are based.	(Vegas-Vilarrúbia et al., 2015)
Europe	Saami	Increased temperatures; changes in precipitation	Winter thaw	Reindeer herding is culturally important for Saami and provides a means to maintain traditions, language and cultural identity, thus constituting an essential part of Saami physical and mental wellbeing. More frequent ice formation on soil and snow, which will reduce the availability and quality of winter forage for reindeer, will negatively impact reindeer herding and thus Saami identity and wellbeing (13.8.1.2).	(Jaakkola et al., 2018); (Markkula et al., 2019)
North America	Lumbee Tribe	Increased temperatures; increased rainfall variability	Flooding	Climate-related degradation and flooding of wetlands and streams in the Lumbee River watershed will negatively affect cultural practices of fishing and harvesting that rely on access to and resources obtained from the area.	(Emanuel, 2018)

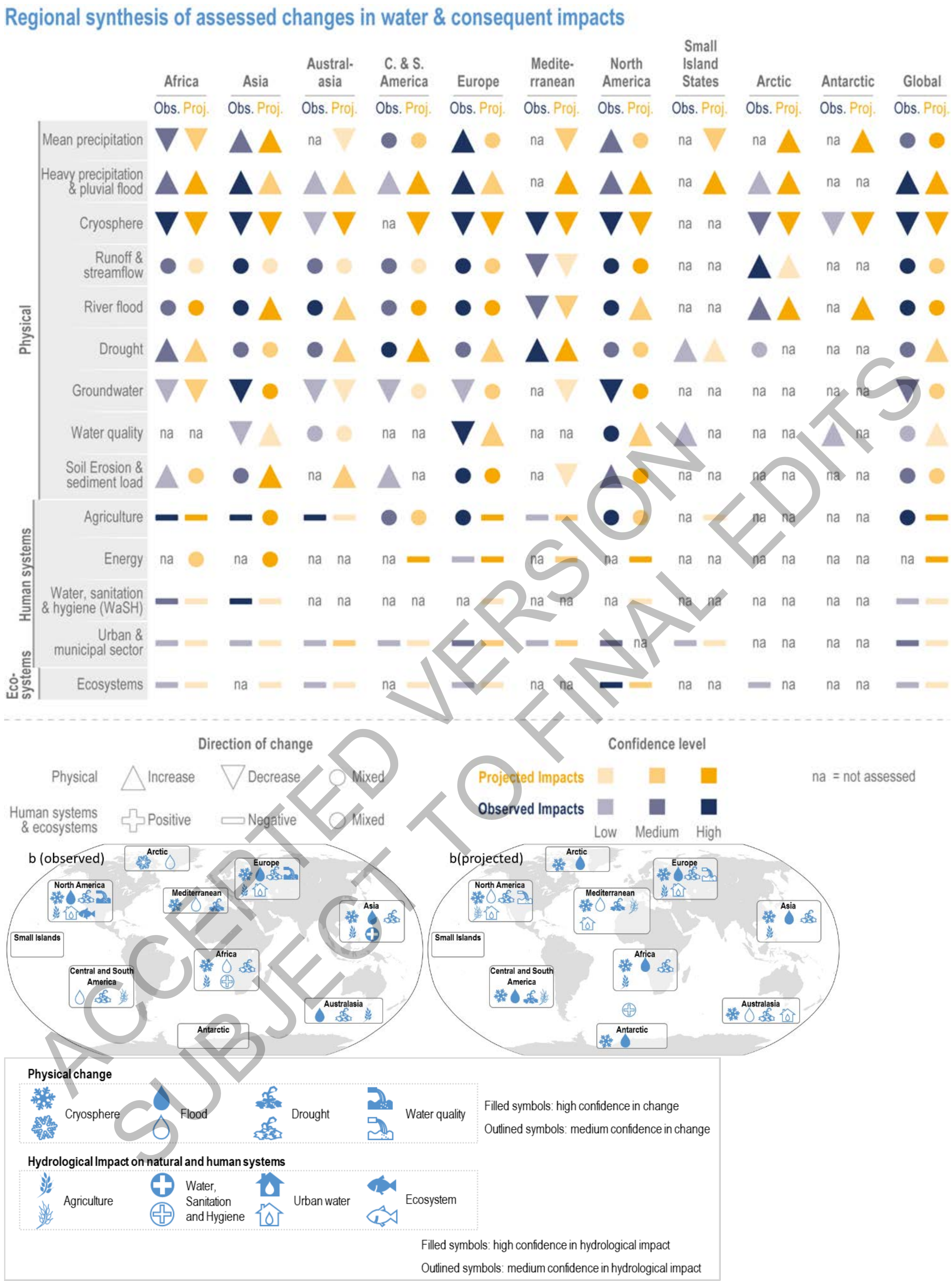


Figure 4.20: Regional synthesis of changes in water and consequent impacts assessed in this chapter. (a) Regional changes and impacts of selected variables. Confidence levels higher than medium are shown. (b) Assessment result of all variables. For each region, physical changes, impacts on ecosystems, and impacts on human systems are shown. For physical changes, upward/downward triangles refer to an increase/decrease, respectively, in the amount or frequency of

the measured variable, and the level of confidence refers to confidence that the change has occurred. For impacts on ecosystems and human systems, plus or minus marks depicts whether an observed impact of hydrological change is positive (beneficial) or negative (adverse), respectively, to the given system, and the level of confidence refers to confidence in attributing an impact on that system to a climate-induced hydrological change. The hydrological impact may be different to the overall change in the system; for example, over much of the world, crop yields have increased overall, largely for non-climatic reasons, but in some areas hydrological impacts of climate change are countering this. Circles indicate that within that region, both increase and decrease of physical changes are found, but are not necessarily equal; the same holds for cells showing 'both' assessed impacts. Cells assigned 'na' indicates variables not assessed due to limited evidences. Decrease (increase) in water quality refers to adverse (positive) change in quality. Agriculture refers to impacts on crop production. Note - Energy refers to impacts on hydro and thermoelectric power generation. Ecosystems refers to impacts on freshwater ecosystem.

4.6 Key Risks and Adaptation Responses in Various Water Use Sectors

Anthropogenic climate change has impacted every aspect of the water cycle (4.2), and risks are projected to intensify with every degree of global warming (4.4), with impacts already visible in all sectors of the economy and ecosystems (4.3) and projected to intensify further (4.5). In response to climate and non-climate induced water insecurity, people and governments worldwide are undertaking various adaptation responses across all sectors. In addition, there are several projected studies for future adaptation responses. We draw upon a list of 359 case studies of observed adaptation and 45 articles on projected future adaptation. Further information on selection and inclusion criteria is available in SM4.2. In this section, we document those adaptation responses (current and future) in different water-use sectors. In the next section (4.7.1, 4.7.2, 4.7.3) benefits of current adaptation, and effectiveness of future adaptation are discussed.

4.6.1 Key Risks Related to Water

The preceding sections have outlined the various pathways along which climate affects water resources and water-using sectors. In synthesis, fundamental changes in observed climate are already visible in water-related outcomes (*high confidence*), including ~500 million people experiencing historically unfamiliar precipitation regimes (4.2.1.1); cryosphere changes impacting various societal and ecosystem components (4.2.2); increasing vulnerability to flood impacts, driven both by climate as well as socio-economic factors (4.2.4); as well as climate change-driven increases in drought impacts (4.2.5).

Further increases in risks are projected to manifest at different levels of warming. Climate change is impacting all components of the hydrological cycle, but the water use sectors are also facing the consequences of climate change, given the central role of water for all aspects of human and environmental systems (4.1, Box 4.1). Therefore, risks to water security are also identified as a Representative Key Risk (RKR) (WGII, Chapter 16, Section 16.5.2.3.7).

Approximately, 4 billion people globally face physical water scarcity for at least one month per year which is driven by climatic as well as non-climatic factors (Mekonnen and Hoekstra, 2016). Increases in physical water scarcity are projected, with estimates between 800 million and 3 billion for 2°C global warming and up to approximately 4 billion for 4°C global warming (Gosling and Arnell, 2016). Projected increases in hydrological extremes pose increasing risks to societal systems globally (*high confidence*), with a potential doubling of flood risk between 1.5°C and 3°C of warming (Dottori et al., 2018) and an estimated 120% to 400% increase in population at risk of river flooding at 2°C and 4°C, respectively (Alfieri et al., 2017). Also projected are increasing risks of fatalities and socio-economic impacts (4.4.4). Similarly, a near-doubling of drought duration (Naumann et al., 2018) and an increasing share of the population affected by various types, durations and severity levels of drought are projected (*high confidence*) (4.4.5). Increasing return periods of high-end hydrological extremes pose significant challenges to adaptation, requiring integrated approaches to risk management, which take into account the various economic and non-economic, as well as direct and indirect losses and damages into account (Jongman, 2018).

Increasing sectoral risks are reported across regions and sectors with rising temperatures and associated hydrometeorological changes (Cross-Chapter Box INTEREG in Chapter 16). Risks to agricultural yields due to combined effects of water and temperature changes, for example, could be three times higher at 3°C compared to 2°C (Ren et al., 2018b), with additional risks as a consequence of increasing climate extremes

(Leng and Hall, 2019). In addition, climate-driven water scarcity and increasing crop water demands, including for irrigation, pose additional challenges for agricultural production in many regions (*high confidence*). Regional water-related risks to agricultural production are diverse and vary strongly across regions and crops (4.5.1). As there are limitations to how well global agricultural models can represent available water resources (Elliott et al., 2014; Jägermeyr et al., 2017), water limitations to agricultural production may well be underestimated. For example, the potential for irrigation, commonly assumed to play an important role in ensuring food security, could be more limited than models assume (Box 4.3).

With higher levels of warming, risks to water-dependent energy production increase substantially across regions (van Vliet et al., 2017). While there are increasing potentials of ~2% to 6% for hydropower production by 2080 (*medium confidence*), risks to thermoelectric power production increase for most regions (*high confidence*), for example, with potentially near doubling risks to European electricity production from 1.5°C to 3°C (Tobin et al., 2018). Shifting to a higher share of renewable sources less dependent on water resources for energy production could substantially reduce the vulnerability of this sector (4.5.2).

Increasing hydrological extremes also have consequences for the maintenance and further improvement of the provision of Water, Sanitation and Hygiene (WaSH) services (*medium confidence*). Risks related to the lack or failure of WaSH services under climate change include increased incidence and outbreaks of water-related diseases, physical injuries, stress, exacerbation of the underlying disease, and risk of violence, which is often gendered (4.5.3). Although globally, the regional potential infestation areas for disease-carrying vectors could be five times higher at 4°C than at 2°C (Liu-Helmersson et al., 2019), climate projections suggest up to 2.2 million more cases of *E. coli* by 2100 (2.1ºC increase) in Bangladesh (Philipsborn et al., 2016), up to an 11-fold and 25-fold increase by 2050 and 2080, respectively (2-4ºC increase), in disability-adjusted life years associated with cryptosporidiosis and giardiasis in Canada (Smith et al., 2015), and an additional 48,000 deaths in children under 15 years of age globally from diarrhoea by 2030 (WHO, 2014).

Increasing water demand in conjunctions with changing precipitation patterns will pose risks to urban water security by mid-century, with water demand in nearly a third of the world's largest cities potentially exceeding surface water availability by 2050 (RCP6.0) (Flörke et al., 2018) and the global volume of domestic water withdrawal projected to increase by 50 to 250% (Wada et al., 2016) (4.5.4). Globally, climate change will exacerbate existing challenges for urban water services, driven by further population growth, the rapid pace of urbanization and inadequate investment, particularly in less developed economies with limited governance capacity (*high confidence*).

Risks to freshwater ecosystems increase with progressing climate change, with freshwater biodiversity decreasing proportionally with increasing warming if 1.5°C is exceeded (*medium evidence, high agreement*). Risks include range shift, a decline in species population, extirpation as well as extinction (4.5.5).

The potential for climate change to influence conflict is highly contextual and depends on various socio-economic and political factors. However, water-specific conflicts between sectors and users may be exacerbated for some regions of the world (*high confidence*) (4.5.7).

Human migration takes many forms and can be considered a consequence and impact of climate change and an adaptation response (4.5.8). Projections indicate a potentially substantial increase in internal and international displacement due to water-related climate risks (Missirian and Schlenker, 2017; Rigaud et al., 2018). In the context of water-related adaptation, short-term migration as an income diversification approach is commonly documented. However, permanent relocation and fundamental changes to livelihoods are more transformational and yet can be associated with tangible and intangible losses (Mechler et al., 2019). In the context of climate-induced hydrological change, increased vulnerability among migrants and the risk of trapped populations poses significant additional risks. However, quantifications that disentangle different climate drivers and show specific risks emanating from hydrological change are unavailable (Rigaud et al., 2018).

Hydrological change, especially increasing extreme events, pose risks to the cultural uses of water of Indigenous Peoples, local communities and traditional peoples (*high confidence*), with implications for the physical of these groups (*high confidence*). Increasing risks are documented across groups and regions, however, partly due to the unquantifiable nature of these risks, the lack of research funding for the social dimensions of climate change, particularly in the Global South, and the systemic underrepresentation of marginalized groups in scientific research, quantitative projections are limited (4.5.8).

Adaptation is already playing an integral part in reducing climate impacts and prepare for increasing climate risk, and it will grow in importance evermore with increasing risks at higher levels of warming. Remaining sub-sections describe these adaptation responses.

[START BOX 4.2 HERE]

Box 4.2: Observed Risks, Projected Impacts and Adaptation Responses to Water Security in Small Island States

AR5 and SR1.5 recognized the exceptional vulnerability of islands, especially concerning water security and potential limits to adaptation that may be reached due to freshwater resources (Klein et al., 2014; Hoegh-Guldberg et al., 2018; Roy et al., 2018).

Small islands are already regularly experiencing droughts and freshwater shortages (*high confidence*) (Holding et al., 2016; Pearce et al., 2018; Gheuens et al., 2019; MacDonald et al., 2020). Freshwater supply systems vary from household or small community systems such as rainwater harvesting systems and private wells to large public water supply systems using surface, groundwater and, in some cases, desalinated water (Alsumaiei and Bailey, 2018b; Falkland and White, 2020). In many cases, communities rely on more than one water source, including a strong reliance on rainwater and groundwater (Elliott et al., 2017; MacDonald et al., 2020). Groundwater resources in freshwater lenses (FWLs) are essential in providing access to freshwater resources, especially during droughts when the collected rainwater is insufficient (Barkey and Bailey, 2017; Bailey et al., 2018). lead to greater risks of water-borne diseases, with significant effects on nutrition (Elliott et al., 2017; Savage et al., 2020), and improper sanitation poses additional risks to the limited groundwater resources (MacDonald et al., 2017). Drought events have also severely affected freshwater lenses (FWL) recharge (Barkey and Bailey, 2017), with extraction rates further threatening available groundwater volumes (Post et al., 2018). In conjunction with sea-level rise, this poses serious risks to groundwater salinization (Alsumaiei and Bailey, 2018b; Storlazzi et al., 2018; Deng and Bailey, 2019). In addition, FWLs are threatened by climate change due to changes in rainfall patterns, extended droughts and wash over events caused by storm surges and SLR (*high confidence*) (see Chapter 15) (Chui and Terry, 2015; Alsumaiei and Bailey, 2018a; Alsumaiei and Bailey, 2018b; Post et al., 2018; Storlazzi et al., 2018; Deng and Bailey, 2019). After small-scale wash over events, the FWLs have been shown to recover to pre-wash over salinity levels within a month (Oberle et al., 2017).

Due to wash over events exacerbated by sea-level rise (SLR) and lens thinning due to pumping, recovery time for FWLs is projected to take substantially longer (Oberle et al., 2017; Alsumaiei and Bailey, 2018a; Storlazzi et al., 2018). Projections indicate that atolls may be unable to provide domestic freshwater resources due to the lack of potable groundwater by 2030 (RCP8.5+ice- sheet collapse), 2040 (RCP8.5), or 2060s (RCP4.5) (Storlazzi et al., 2018). Projections of future freshwater availability in Small Islands further underline these substantial risks to island water security (Karnauskas et al., 2016; Karnauskas et al., 2018). Population growth, changes in rainfall patterns and agricultural demand are projected to increase water stress in Small Islands (Gohar et al., 2019; Townsend et al., 2020). While some islands are projected to experience an increase in rainfall patterns, this may refer to shorter intense rainfall events, thereby increasing the risk of flooding during the wet season, while not decreasing their risk of droughts during dry periods (Aladenola et al., 2016; Gheuens et al., 2019). In addition, projected shifts in the timing of the rainfall season might pose an additional risk for water supply systems (Townsend et al., 2020).

Observed adaptation during drought events includes community water-sharing (Bailey et al., 2018; Pearce et al., 2018) as well as using alternative water resources such as water purchased from private companies (Aladenola et al., 2016), desalination units (Cashman and Yawson, 2019; MacDonald et al., 2020) or accessing deeper or new groundwater resources (Pearce et al., 2018). Rainwater harvesting to adapt the water supply system in the Kingston Basin in Jamaica was able significantly alleviate water stress, for example. Still, it would not fill the total supply gap caused by climate change (Townsend et al., 2020). Likewise, groundwater sustainability with increasing climate change in Barbados cannot be ensured without aquifer protection, leading to higher optimized food prices if no additional adaptation measures are implemented (Gohar et al., 2019). The potential of using multiple water sources is rarely assessed in future water supply projections in Small Islands (Elliott et al., 2017). In the Republic of Marshall Islands, more than half of all interviewed households have already had to migrate once due to a water shortage (MacDonald et al., 2020). In Cariacou, Grenada, increases in migration rates have been observed following drought events (Cashman and Yawson, 2019). with long-term cross border and internal migration shown to be having significant impacts on well-being, community-cohesion, livelihoods and people-land relationships (Yates et al., 2021).

In sum, small islands are already regularly experiencing droughts and freshwater shortages (*high confidence*). For atoll islands, freshwater availability may be severely limited as early as 2030 (*low confidence*). The effects of temperature increase, changing rainfall patterns, sea level rise and population pressure, combined with limited options available for water-related adaptation leave small islands partially water insecure currently, with increasing risks in the near-term and at warming above 1.5°C (*high confidence*).

[END BOX 4.2 HERE]

4.6.2 Adaptation in the Agricultural Sector

AR5 reported a range of available hard and soft adaptation options for water-related adaptation in the agricultural sector. However, the evidence on the effectiveness of these adaptation responses, now and in the future, was not assessed (Noble et al., 2014; Porter et al., 2014). Assessing the feasibility of different irrigation measures as adaptation, SR1.5 (de Coninck et al., 2018) found mixed evidence, depending on the applied methodology.

There is *high confidence* that water-related adaptation is occurring in the agricultural sector (Acevedo et al., 2020; Ricciardi et al., 2020), and water-related adaptation in the agricultural sector makes up the majority of documented local, regional and global evidence of implemented adaptation (*high confidence*) (4.7.1, Figure 4.23 and Figure 4.24, Table 4.8). However, while there is increasing evidence of adaptation and its benefits across multiple dimensions, the link between adaptation benefits and climate risk reduction is unclear due to methodological challenges (*medium confidence*) (4.7.1). On the other hand, while it is methodologically possible to measure the effectiveness of future adaptation in reducing climate risks, here the main limitation is that not all possible range of future adaptations can be modelled given the limitations of climate and impact models (*high confidence*) (4.7.2). Furthermore, findings on current adaptation are constrained by what is documented in peer-reviewed articles. At the same time, there may be a range of options implemented on the ground by local governments or as a part of corporate social responsibility that is not published in peer-reviewed publications.

Water and soil conservation measures (e.g. reduced tillage, contour ridges, or mulching) are frequently documented as adaptation responses to reduce water-related climate impacts (Kimaro et al., 2016; Traore et al., 2017). This measure features in all continents' top four adaptation responses except Australasia (Figure 4.27). Especially for rain-fed farming, which currently is the norm in most of Africa, large parts of Central and South America and Europe, water and soil conservation measures and various components of conservation agriculture are some of the most frequently used adaptation responses (Jat et al., 2019). This measure is deemed to have economic benefits and benefits for vulnerable communities who adopt this measure (*high confidence*) and benefits in terms of water-saving and positive ecological and socio-cultural benefits (*medium confidence*). However, this measure can be sometimes maladaptive (*low evidence, medium agreement*) and can have mitigation co-benefits (*low evidence, high agreement*) (Figure 4.29). Furthermore, water and soil management related measures show high potential efficacy in reducing impacts in a 1.5°C world, with declining effectiveness at higher levels of warming (Figure 4.28 and Figure 4.29)

Changes in cropping patterns, the timing of sowing and harvesting, crop diversification towards cash crops, and the adoption of improved crop cultivars that can better withstand hazards like floods and drought are among the most used adaptation responses by farmers. This is among the top two measures in Asia and Africa (Figure 4.27). Extra income allows households to re-invest in improved agricultural techniques and improved cultivars (Taboada et al., 2017; Khanal et al., 2018b). Beneficial outcomes are documented in terms of increases in incomes and yields and water-related outcomes (*medium confidence*, from *robust evidence, but medium agreement*), but benefits to vulnerable communities are not always apparent on the whole (Figure FAQ4.4.1). Changes in cropping patterns and systems are also among those adaptation options assessed for their potential to reduce future climate impacts, though effectiveness is shown to be limited (Brouziyne et al., 2018; Paymard et al., 2018). Assessments of the future effectiveness of crop rotation systems for adaptation show a continued reduction in required irrigation water use, though studies of effectiveness beyond 2°C global mean temperature increase are not available (Kothari et al., 2019; Yang et al., 2019b) (Figure 4.28 and Figure 4.29).

Conservation agriculture and climate-smart agriculture (includes improved cultivars and agronomic practices) have proven to increase soil carbon, yields and technical efficiency (Penot et al., 2018; Salat and Swallow, 2018; Ho and Shimada, 2019; Makate and Makate, 2019; Okunlola et al., 2019). Some water-related measures in conservation agriculture include allowing for shading and soil moisture retention, with the co-benefit of reducing pest attacks (Thierfelder et al., 2015; Raghavendra and Suresh, 2018; Islam et al., 2019a). Especially for traditional food grains in smallholder agriculture, improved practices such as modern varieties or integrated nutrient management can play an important role in making production more resilient to climate stress (Handschuch and Wollni, 2016). This measure is also among the top four most frequent adaptation measures in all continents except Australia and North America (Figure 4.27). In addition, this measure is shown to have positive economic benefits (*high confidence*) and also benefits on other parameters (*medium confidence*) (Figure FAQ4.4.1). Such approaches are also among those most frequently assessed for their effectiveness in addressing future climate change but show limited effectiveness across warming levels (Figure 4.28 and Figure 4.29).

The use of non-conventional water sources, i.e. desalinated and treated waste-water, is emerging as an important component of increasing water availability for agriculture (DeNicola et al., 2015; Martínez-Alvarez et al., 2018b; Morote et al., 2019). While desalination has a high potential in alleviating agricultural water stress in arid coastal regions, proper management and water quality standards for desalinated irrigation water are essential to ensure continued or increased crop productivity. In addition to the energy intensity (4.7.6), risks of desalinated water include lower mineral content, higher salinity, crop toxicity, and soil sodicity (Martínez-Alvarez et al., 2018b). Similarly, waste-water reuse can be an important contribution to buffer against the increasing variability of water resources. However, waste-water guidelines that ensure the adequate treatment to reduce adverse health and environmental outcomes due to pathogens or other chemical and organic contaminants will be essential (Angelakis and Snyder, 2015; Dickin et al., 2016) (Box 4.5; 4.6.4).

Indigenous Knowledge and local knowledge are crucial determinants of adaptation in agriculture for many communities globally. Indigenous Peoples have intimate knowledge about their surrounding environment and are attentive observers of climate changes. As a result, they are often best placed to enact successful adaptation measures, including shifting to different crops, changing cropping times or returning to traditional varieties (Mugambiwa, 2018; Kamara et al., 2019; Nelson et al., 2019) (4.8.4).

Migration and livelihood diversification is often an adaptation response to water-related hazards and involves securing income sources away from agriculture, including off-farm employment, temporary or permanent migration, and these are particularly important in Asia and Africa (Figure 4.27). Income and remittances are sometimes re-invested, for instance, for crop diversification (Rodriguez-Solorzano, 2014; Musah-Surugu et al., 2018; Mashizha, 2019). While there is extensive documentation on the benefits of migration, the quality of studies is such that links between migration and subsequent benefits are not clear, making our conclusion of benefits from this measure as having *medium confidence*. On the other hand, there is more rigorous evidence on the maladaptive nature of migration as an adaptation measure (Figure FAQ4.4.1). However, adverse climatic conditions, especially droughts, have been found to reduce international migration, as resources are unavailable to consider this option (Nawrotzki and Bakhtsiyarava, 2017), resulting in limits to adaptation (Ayeb-Karlsson et al., 2016; Brottem and Brooks, 2018; Ferdous et al., 2019). In addition, it is difficult to model this option in future climate adaptation models.

Policies, institutions, capacity building, are important adaptation measures in agriculture and often have beneficial outcomes, with quality of studies precludes a high degree of certainty about those impacts (Figure FAQ4.4.1). Access to credits, subsidies or insurance builds an important portfolio of reducing reliance on agricultural income alone (Rahut and Ali, 2017; Wossen et al., 2018). Training and capacity building are essential tools to ensure effective adaptation in agriculture, increasing food security (Chesterman et al., 2019; Makate and Makate, 2019), through better understanding the implementation of available responses reduce exposure to climate impacts. In addition, public regulations, including water policies and allocations and incentive instruments, availability of appropriate finance play an essential role in shaping and enabling (4.8.5, 4.8.6, 4.8.7), but also limiting (4.8.2), water-related adaptation for agriculture (see also Chapter 17).

Water stressed regions already rely on importing agricultural resources, thus importing water embedded in these commodities (D'Odorico et al., 2014). Virtual water trade will continue to play a role in reducing water-related food insecurity (Cross-Chapter Box INTERREG in Chapter 16) (Pastor et al., 2014; Graham et al., 2020b).

While an increasing body of literature documents water-related adaptation in the agricultural sector, both in reducing current climate impacts and addressing future climate risk, knowledge gaps remain about assessing the effectiveness of such measures to reduce impacts and risks. Additional considerations on co-benefits of trade-offs for overall sustainable development are not always sufficiently considered in the available literature.

In sum, water-related adaptation in the agricultural sector is widely documented, with irrigation, agricultural water management, crop diversification and improved agronomic practices among the most common adaptation measures adopted (*high confidence*). However, the projected future effectiveness of available water-related adaptation for agriculture decreases with increasing warming (*medium evidence, high agreement*).

[START BOX 4.3 HERE]

Box 4.3: Irrigation as an Adaptation Response

Irrigation has consistently been used as a crop protection and yield enhancement strategy and has become even more critical in a warming world (Siebert et al., 2014). Approximately 40% of global yields come from irrigated agriculture, with a doubling of irrigated areas over the last 50 years and now constituting around 20% of the total harvested area (FAO, 2018b; Meier et al., 2018; Rosa et al., 2020b). Thus, irrigation is one of the most frequently applied adaptation responses in agriculture and features centrally in projections of adaptation at all scales. Expansions of irrigated areas over the coming century are projected, leading to shifts from rain-fed to irrigated agriculture in response to climate change (Malek and Verburg, 2018; Huang et al., 2019; Nechifor and Winning, 2019). However, there are regional limitations to this expansion due to renewable water resource limitations, including water quality issues (Zaveri et al., 2016; Turner et al., 2019). Depending on the specific spatial, temporal and technological characteristics of irrigation expansion, up 35% of current rain-fed production could sustainably shift to irrigation with limited negative environmental effects (Rosa et al., 2020b).

Irrigation increases resilience and productivity relative to rain-fed production by reducing drought and heat stress on crop yields and by lowering ET demand by cooling canopy temperatures (Siebert et al., 2014; Tack et al., 2017; Li and Troy, 2018; Zaveri and B. Lobell, 2019; Agnolucci et al., 2020; Rosa et al., 2020b). Large-scale irrigation also affects local and regional climates (Cook et al., 2020b). While cooling effects, including reduction of the extreme heat due to irrigation, have been observed (Qian et al., 2020; Thiery et al., 2020), increases in humid heat extremes because of irrigation with potentially detrimental health outcomes have also been reported (Krakauer et al., 2020; Mishra et al., 2020). For the heavily irrigated North China Plain, a night-time temperature increase overcompensated daytime cooling effects, leading to an overall warming effect (Chen and Jeong, 2018). In addition, modification of rainfall patterns has been linked to irrigation (Alter et al., 2015; Kang and Eltahir, 2019; Mathur and AchutaRao, 2020). For example, increases in extreme rainfall in Central India in recent decades has been linked to the intensification of irrigated paddy cultivation in northwest India (Devanand et al., 2019).

Different irrigation techniques are associated with significant differences in irrigation water productivity (Deligios et al., 2019) and replacing inefficient systems can reduce average non-beneficial water consumption by up to 76% while maintaining stable crop yields (Jägermeyr et al., 2015). Several adjustments can improve water use efficiency, including extending irrigation intervals, shortening the time of watering crops or reducing the size of the plot being irrigated (Caretta and Börjeson, 2015; da Cunha et al., 2015; Dumenu and Obeng, 2016). Deficit irrigation is an important mechanism for improving water productivity (Zheng et al., 2018) and increasing regional crop production under drying conditions (Malek and Verburg, 2018). Access to irrigation can also play a role in alleviating poverty, contributing to reducing vulnerability and risks (Balasubramanya and Stifel, 2020). However, the diversity of irrigation related techniques and the consequent differences in effect and water-use intensity is often underreported (Vanschoenwinkel and Van Passel, 2018).

The use of water-saving technologies like laser levelling, micro-irrigation, efficient pumps and water distribution systems (Kumar et al., 2016); increasing irrigation efficiency (Wang et al., 2019a) through improved agronomic practices (Kakumanu et al., 2018) and economic instruments like water trading in developed countries like Australia (Kirby et al., 2014) are known to reduce water application rates and increase yields, and "save" water at the plot level, but may exacerbate basin-scale water scarcity (van der Kooij et al., 2013; Zhou et al., 2021).

Asia accounts for 69-73% of the world's irrigated area. However, irrigation currently plays a relatively minor role in most Africa, except in the contiguous irrigated area along the Nile basin and North Africa and South Africa (Meier et al., 2018). In India, long-term data (1956-1999) on the irrigated area shows that farmers adjust their irrigation investments and crop choices in response to medium-run rainfall variability (Taraz, 2017). (da Cunha et al., 2015) report that farmers' income tends to be higher on irrigated lands in Brazil. In Bangladesh, farmers invest a part of their increased incomes in improving irrigation access (Delaporte and Maurel, 2018). The severity of drought increases the likelihood of farmers adopting supplementary irrigation in Bangladesh (Alauddin and Sarker, 2014). In Vietnam, irrigation improvement had the highest positive impact on crop yield among all farm-level adaptive practices (Ho and Shimada, 2019). In South Africa, access to irrigation was one of the most important predictors of whether or not farmers would adopt a whole suite of other adaptation responses (Samuel and Sylvia, 2019).

Irrigation is also associated with adverse environmental and socio-economic outcomes, including groundwater over-abstraction, aquifer salinization (Foster et al., 2018; Pulido-Bosch et al., 2018; Quan et al., 2019; Blakeslee et al., 2020); land degradation (Singh et al., 2018). Further, while irrigation expansion is one of the most commonly proposed adaptation responses, there are limitations to further increases in water use, as many regions are already facing water limitations under current climatic conditions (Rockström et al., 2014; Steffen et al., 2015; Kummu et al., 2016).

Projections of the future effectiveness of irrigation indicate a varying degree of effectiveness depending on the region and specific type and combination of approaches used. At the same time, overall residual impacts increase at higher levels of warming (4.7.1.2). Uncertainties in regional climate projections and limitations in the ability of agricultural models to fully represent water resources are important limitations in our understanding of the potential of further irrigation expansion (4.5.1) (Greve et al., 2018).

In light of the volume of irrigated agriculture globally, and the projected increase in water requirements for food production, increasing water productivity and thus improving the ratio of water used per unit of agricultural output, is necessary globally to meet agricultural water demand (4.5.1) (Jägermeyr et al., 2015; Jägermeyr et al., 2017). For example, assuming a doubling of global maize production by 2050 increased water productivity could reduce total water consumption compared to the baseline productivity by 20 to 60% (Zheng et al., 2018). Under economic optimization assumptions, shifts towards less water-intensive and less climate-sensitive crops would be optimal in terms of water use efficiency and absolute yield increases; however, this could pose risks to food security as production shifts away from main staple crops (Nechifor and Winning, 2019). Shifting currently rain-fed production areas to irrigation will be an important element in ensuring food security with increasing temperatures, though investment in storage capacities to buffer seasonal water shortage will be essential to ensure negative environmental impacts are minimised (Rosa et al., 2020b).

[END BOX 4.3 HERE]

4.6.3 Adaptation in Energy and Industrial Sectors

While AR5 (Arent et al., 2014) had looked at demand and supply changes in the energy sector due to climate change, none of the AR5 chapters had assessed adaptations in the energy sector *per se*. A modeling study by (van Vliet et al., 2016b) demonstrated that increasing the efficiency of hydropower plants by up to 10% could offset the impacts of decreased water availability in most regions by mid-century, under both RCP2.6 and RCP8.5 scenarios (*medium confidence*). Changing hydropower operation protocol and plant design can be effective adaptation measures, yet may be insufficient to mitigate all future risks related to increased floods and sediment loads (Lee et al., 2016).

(van Vliet et al., 2016b) projected that even a 20% increase in efficiency of thermoelectric power plants might not be enough to offset the risks of water stress by mid-century (*medium confidence*). Therefore, thermoelectric power plants will need additional adaptation measures such as changes in cooling water sources and alternative cooling technologies (van Vliet et al., 2016c). In China, many coal-fired power plants in water-scarce North China have adopted air cooling technologies (Zhang et al., 2016a). In Europe, wet/dry cooling towers (Byers et al., 2016) and seawater cooling (Behrens et al., 2017) have been the preferred options. Overall, freshwater withdrawals for adapted cooling systems under all scenarios are projected to decline by -3% to -63% by 2100 compared to the base year of 2000 (Fricko et al., 2016) (*medium confidence*).

Diversifying energy portfolios to reduce water-related impacts on the energy sector is another effective adaptation strategy with high mitigation co-benefits. A modelling study from Europe shows that for a 3°C scenario, an energy mix with an 80% share of renewable energy can potentially reduce the overall negative impacts on the energy sector by a factor of 1.5 times or more (Tobin et al., 2018). In addition, hydropower can also play a role in compensating for the intermittency of other renewable energies (François et al., 2014). For example, integrating hydro, solar, and wind power in energy generation strategies in Grand Ethiopian Renaissance Dam can potentially deliver multiple benefits, including decarbonization, compliance with environmental flow norms, and reduce potential conflicts among Nile riparian countries (Sterl et al., 2021). Furthermore, reducing the share of thermoelectric power with solar and wind energy (Tobin et al., 2018; Arango-Aramburo et al., 2019; Emodi et al., 2019) can be synergistic from both climate and water perspectives, as solar and wind energy has lower water footprints (*high confidence*).

Indigenous Peoples, mountain communities, and marginalized minorities often bear the brunt of environmental and social disruptions due to hydropower. As a consequence, hydropower operators face resistance prior to and during construction. Benefit sharing mechanisms help redistribute some of the gains from hydropower generation to the communities in the immediate vicinity of the project. For instance, sharing of hydropower revenues and profits to fund local infrastructure and pay dividends to local people has been practiced in Nepal and in some countries of the Mekong basin to enhance the social acceptability of hydropower projects (Balasubramanya et al., 2014; Shrestha et al., 2016) (*low confidence*).

Most water-intensive industries are increasingly facing water stress, making the reuse of water an attractive adaptation strategy (see Box 4.5). For example, Singapore, where the share of industrial water use is projected to grow from 55% in 2016 to 70% in 2060, is increasing its NEWater (highly treated wastewater) supply share from 30% to 55% to meet the growing demand of industrial and cooling activities (PUB, 2016). In addition, the mining industry has also adopted water adaptations measures, such as water recycling and reuse; using brackish or saline sources; and working with regional water utilities to reduce water extraction and improve water use efficiency (Northey et al., 2017; Odell et al., 2018).

In summary, energy and industrial sector companies have undertaken several adaptation measures to reduce water stress, with varying effectiveness levels. However, residual risks will remain, especially at higher levels of warming (*medium confidence*).

4.6.4 Adaptation in Water, Sanitation and Hygiene (WaSH) Sector

AR5 pointed to adaptive water management techniques (*limited evidence, high agreement*) (Field et al., 2014b), while SR1.5 documented the need for reducing vulnerabilities and promoting sustainable development and disaster risk reduction synergies (*high confidence*) (IPCC, 2018a). WaSH has also been identified as a low regrets adaptation measure (Cutter et al., 2012).

Access to appropriate, reliable WaSH protects against water-related diseases, particularly after climate hazards such as heavy rainfalls and floods (Carlton et al., 2014; Jones et al., 2020). WaSH interventions have been demonstrated to reduce diarrhoea risk by 25-75% depending on the specific intervention (Wolf et al., 2018) (*high confidence*). Conversely, inadequate WaSH is associated with an estimated annual loss of 50 million Daily Adjusted Life Years (Prüss-Ustün et al., 2019), of which 89% of deaths are due to diarrhoea, and 8% of deaths from acute respiratory infections (Chapter 7 WGII 7.3.2), making universal access to WaSH (i.e., achievement of SDG 6.1, 6.2), a critical adaptation strategy (*high confidence*). However, not all WaSH solutions are suited to all climate conditions (Sherpa et al., 2014; Howard et al., 2016) so health outcome improvements are not always sustained under changing climate impacts (Dey et al., 2019) (*medium evidence, high agreement*). As such, WaSH infrastructure also needs to be climate-resilient (Smith et al., 2015; Shah et al., 2020). In addition to new WaSH infrastructure design and implementation, expansion and replacement of existing infrastructure offer opportunities to implement climate-resilient designs and reduce greenhouse emissions (Boholm and Prutzer, 2017; Dickin et al., 2020) (*medium evidence; high agreement*).

Effective adaptation strategies include protecting source water and managing both water supply and demand. Source water protection (Shaffril et al., 2020) has proven effective in reducing contamination. Improved integrated (urban) water resources management (Kirshen et al., 2018; Tosun and Leopold, 2019), governance (Chu, 2017; Miller et al., 2020), and enhanced ecosystem management (Adhikari et al., 2018b) lead to policies and regulations that reduce water insecurity and, when developed appropriately, reduce inequities (*medium confidence*). Supply (source) augmentation, including dams, storage, and rainwater/fog harvesting, can increase the supply or reliability of water for drinking, sanitation, and hygiene (DeNicola et al., 2015; Pearson et al., 2015; Majuru et al., 2016; Poudel and Duex, 2017; Lucier and Qadir, 2018; Goodrich et al., 2019) (*high confidence*). For example, rainwater harvesting in an Inuit community increased water for hygiene by 17%, reduced water retrieval efforts by 40%, and improved psychological and financial health (Mercer and Hanrahan, 2017). However, climate change impacts will affect amounts of rainwater available. A recent study concluded that domestic water demand met through rainwater harvesting generally improves under climate change scenarios for select communities in Canada and Uganda, with the exception of drier summers in some areas of Canada (Schuster-Wallace et al., 2021). Further, it is important to recognize that many of these interventions require financial investments that make them inaccessible to the poorest (Eakin et al., 2016). Demand for water can be decreased through reductions in water loss from the system (e.g., pipe leakage) (Orlove et al., 2019) and water conservation measures (Duran-Encalada et al., 2017) (*medium confidence*).

During periods of water insecurity, people often implement maladaptive strategies (Magnan et al., 2016), i.e., strategies that can increase the risk of adverse health impacts, increase exposure to violence, or cause malnutrition (Kher et al., 2015; Pommells et al., 2018; Collins et al., 2019a; Schuster et al., 2020) (*medium evidence, high agreement*). Examples include walking further, using less safe water sources, prioritizing drinking and cooking over personal/household hygiene, or reducing food/water intake. Conversely, some rebalancing of gender roles can occur when women and girls cannot source sufficient water, with men building additional water supply or storage infrastructure or fetching water (Singh and Singh, 2015; Magesa and Pauline, 2016; Shrestha et al., 2019b). Some adaptation strategies create unintended health threats such as increased odds (1.55) of mosquito larvae in water storage pots (Ferdousi et al., 2015), which could have even more significant impacts in the future given projected range expansion for vectors as a result of climate change (Liu-Helmersson et al., 2019). Other unintended consequences include pathogen contamination (Gwenzi et al., 2015) and time or financial tradeoffs (Schuster et al., 2020) (*medium evidence, high agreement*). Wastewater reuse for irrigation may have adverse health impacts if wastewater is not treated (Dickin et al., 2016). Conversely, especially where women are responsible for domestic and productive water management, adaptive agricultural water strategies, such as water-efficient irrigation or low-water crops, mean that less water from finite water supplies are used for agriculture, leaving more water locally available for domestic purposes (see section 4.6.2). These co-benefits across sectors become important community water stress adaptations (Chinwendu et al., 2017), with water savings from one use leading to more water available for other uses. This can reduce domestic water burdens and, therefore, gender inequities (4.8.3) (*limited evidence, high agreement*). Further analyses of co-benefits, particularly employing a gender lens, are required to improve adaptation strategies (McIver et al., 2016).

In summary, ensuring access to climate-resilient WaSH infrastructure and practices represents a key adaptation strategy that can protect beneficiaries against water-related diseases induced by climate change (*high confidence*). Better management of water resources, supply augmentation, and demand management are important adaptation strategies (*high confidence*). Reliable, safe drinking water reduces adverse physical and psychological impacts of climate-related water stress and extreme events (*robust evidence, medium agreement*). WaSH infrastructure expansion and replacement provide opportunities to redesign and increase resilience in rural and urban contexts (*limited evidence, high agreement*).

[START BOX 4.4 HERE]

Box 4.4: COVID-19 Amplifies Challenges for WaSH Adaptation

While COVID-19 is an airborne disease (see Cross-Chapter Box COVID in Chapter 7), public health responses to the COVID-19 pandemic and the associated socio-economic and environmental impacts of these measures intersect with WaSH (Armitage and Nellums, 2020a). Notably, COVID-19 and climate change act as compound risks in the context of water-induced disasters, exacerbating existing threats to sustainable development (Neal, 2020).

The principal WaSH response to COVID-19 relates to hand hygiene, an infection control intervention that requires access to sufficient, clean and affordable water beyond cooking, hydration, and general sanitation needs, as outlined in SDG6 (Armitage and Nellums, 2020a). However, despite significant progress, more than 800 million people in Central and Southern Asia, and 760 million in sub-Saharan Africa, lack basic hand-washing facilities in the home (UNICEF, 2020). Notably, one in four healthcare facilities in select low- and middle-income countries lack basic water access, and one in six lack hand-washing facilities (WHO, 2019) (4.3.3). Moreover, household water insecurity also impacts marginalised and minority groups in the Global North (Deitz and Meehan, 2019; Rodriguez-Lonebear et al., 2020; Stoler et al., 2021).

Compound disasters have arisen due to either the co-occurrence of drought, storms or floods and COVID-19. COVID-19 acts as a stress multiplier for women and girls in charge of water collection and minorities and disabled people who are not engaged in water management (Phillips et al., 2020; Rodriguez-Lonebear et al., 2020). Across the world, existing inequalities deepened due to lockdowns, which further limited access to clean water and education for women and girls, and reinstated gendered responsibilities of child, elderly and sick care, which had been previously externalised (Cousins, 2020; Neal, 2020; Zavaleta-Cortijo et al., 2020). Accordingly, COVID-19 has further steepened the path to reach SDGs 2, 3, 4, 5, and 11 (Lambert et al., 2020; Mukherjee et al., 2020; Neal, 2020; Pramanik et al., 2021). In addition, the pandemic exacerbated food insecurity in drought-affected eastern and southern Africa (Phillips et al., 2020; Mishra et al., 2021). As the twin risk of COVID-19 and hurricanes on the US Gulf Coast (Pei et al., 2020; Shultz et al., 2020) and cyclone Amphan in Bangladesh (Pramanik et al., 2021) showed, increased hand-washing, additional WaSH and evacuation and shelter infrastructures proved essential for preventing further spread of COVID-19 (Baidya et al., 2020; Ebrahim et al., 2020; Guo et al., 2020; Mukherjee et al., 2020; Pei et al., 2020; Shultz et al., 2020; Pramanik et al., 2021). Moreover, while immediate steps can be taken during disaster response to minimise climate-attributable loss of life, climate adaptation requires long-term strategies that intersect with pandemic preparedness (Phillips et al., 2020).

Public health responses to COVID-19 geared towards infection control and caring for the sick can trigger increased water demand where population numbers and density are high (Mukherjee et al., 2020; Sivakumar, 2021). As COVID-19 has highlighted the importance of WaSH (4.3.3), this pandemic could also result in long-term positive outcomes in community resilience, improved infection control, and health protection while addressing longer-term environmental challenges of climate change (Phillips et al., 2020).

[END BOX 4.4 HERE]

4.6.5 Adaptation in Urban and Peri-Urban Sectors

AR5 reported that although case studies of the potential effectiveness of adaptation measures in cities are growing, not all considered how adaptation would be implemented in practice (Jiménez Cisneros et al., 2014). Furthermore, AR5 concluded that more attention had been given to adaptations that help ensure sufficient water supplies than to increasing the capacity of sewage and drainage systems to adapt to heavier rainfall or sea-level rise (Revi et al., 2014).

Since AR5 knowledge on urban adaptation has advanced, even though there is still a limited documentation of urban of water adaptation in urban context as compared to other adaptation responses (Figure 4.23.) Majority of the case studies on urban documentation are also from developed countries, with case studies on adaptation in the urban sector being most common in Europe and Australasia (Figure 4.24). Water-related urban and peri-urban climate change adaptation can involve 'hard'-engineering structures (grey), managed or restored biophysical systems (green and blue), or hybrid approaches that combine these strategies (Ngoran and Xue, 2015; Palmer et al., 2015) (Figure 4.21, also see Figure 4.22 for types of urban adaptation options).

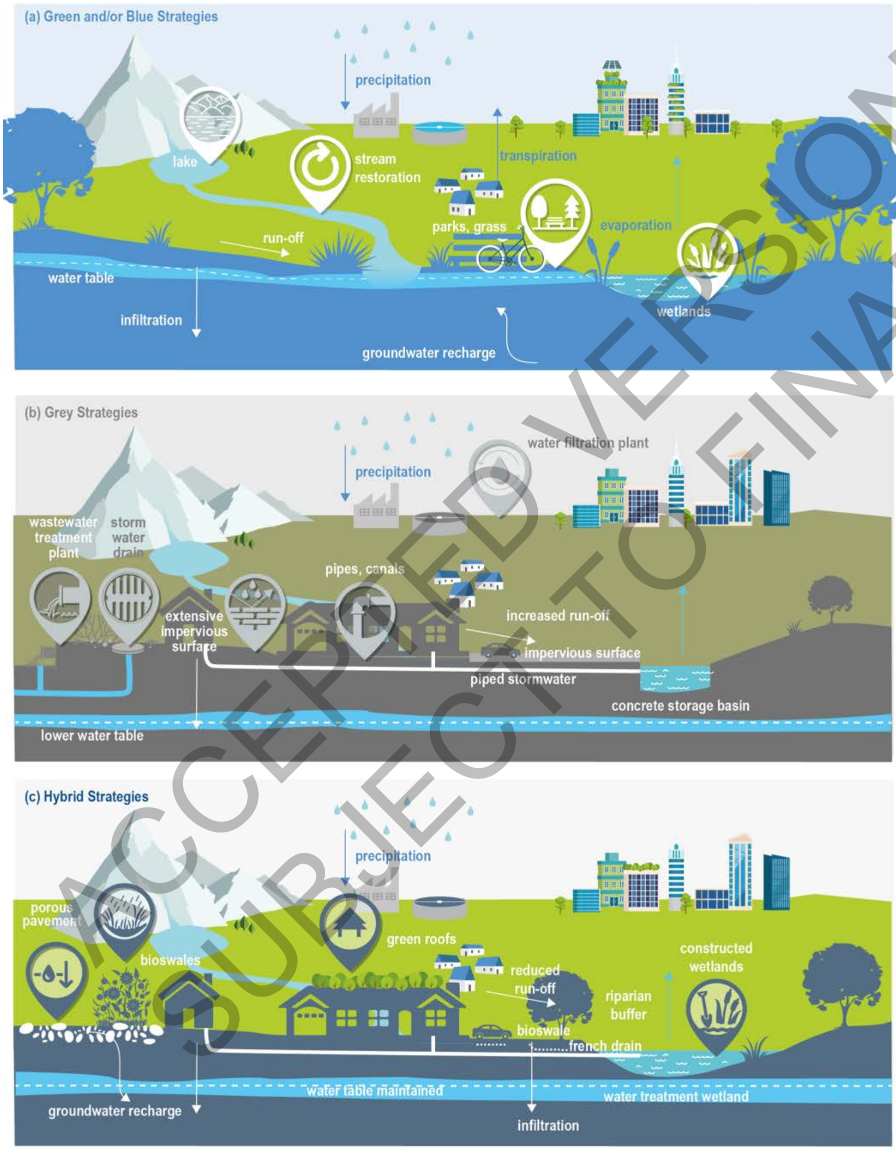


Figure 4.21: Strategies for Urban Water Adaptation a) Green and blue strategies of urban water adaptation prioritise ecosystem restoration, such as wetlands restoration. b) Grey water strategies are hard engineering approaches to urban water adaptation, including infrastructure such as pipes and canals, with extensive areas of impervious surfaces. c) Hybrid approaches combine green, blue, and grey adaptation strategies, such that ecosystem functions are complemented by engineered infrastructure, such as constructed wetlands, green roofs, and riparian buffers. Green and blue, and hybrid approaches are variously classified in terms of circular economy, water sensitive urban design, nature-based solutions (NBS), integrated urban water management, and ecological infrastructure. Adapted from (Depietri and McPhearson, 2017).

In most regions, hybrid adaptation approaches are underway. For example, sustainable urban drainage systems (SUDS) are a common adaptation measure that can reduce flooding and improve stormwater quality while reducing the urban heat island effect (e.g. (Chan et al., 2019; Loiola et al., 2019; Song et al., 2019; Huang et al., 2020; Lin et al., 2020)) (Box 4.6; 12.5.5.3.2; 12.7.1). Municipal, catchment and local community plans to minimise water-related climate risks are another form of adaptation (Stults and Larsen, 2018). Plans involve supply augmentation (Chu, 2017; Bekele et al., 2018), as well as floodplain management, land-use planning, stakeholder coordination, and water demand management (Andrew and Sauquet, 2017; Flyen et al., 2018; Robb et al., 2019; Tosun and Leopold, 2019), with some US cities including strategies to address social inequalities that climate change may exacerbate (Chu and Cannon, 2021).

Such adaptation measures are concentrated in more developed countries (Olazabal et al., 2019). For example, about 80% of European cities with more than 500,000 inhabitants have either mitigation and/or adaptation plans (Reckien et al., 2018). In contrast, a survey of cities with more than one million inhabitants found 92% of Asian cities, 89% African cities, and 87% of Latin American cities did not report adaptation initiatives (Araos et al., 2016) (12.5.8.1). Autonomous adaptation measures (e.g., elevating housing and drainage maintenance) are pursued to reduce flood risk in urban Senegal (Schaer, 2015), Kenya (Thorn et al., 2015), Brazil (Mansur et al., 2018), and Guyana (Mycoo, 2014) (Box 4.7; 9.8.5.1; 12.5.5.3; FAQ 12.2).

Further studies are required to ascertain the effectiveness of adaptation measures implemented since AR5, particularly for the growing populations of informal and peri-urban settlements. For example, in urban Africa, such informal settlements are sites of political contestation as residents resist municipal relocation strategies for flood alleviation (Douglas, 2018). In addition, the growing complexity of challenges facing urban water management, such as climate change, urbanisation and environmental degradation, warrants a transformative shift away from prevailing siloed approaches of water supply, sanitation and drainage to more integrated systems that enhance adaptive capacity (Ma et al., 2015; Franco-Torres et al., 2020).

In summary, although water-related adaptation is underway in the urban, peri-urban and municipal sectors of some nations, governance, technical, and economic barriers remain in implementing locally-informed strategies, particularly in developing countries (*high confidence*).

[START BOX 4.5 HERE]

Box 4.5: Reduce, Remove, Re-use and Recycle (4Rs): Wastewater Re-use and Desalination as an Adaptation Response

Circular economies can increase the available sustainable adaptation space by moving away from a linear mode of production of "extract-produce-use-discard" to a '4Rs' closed loop to reduce pollution at the source, remove contaminants from wastewater, re-use treated wastewater, and recover valuable by-products ((UN Water, 2017)}, see WGIII 11.3.3).

It is estimated that 380 billion m^3 of wastewater is produced annually worldwide, which equals about 15% of agricultural water withdrawals. The recovery of nitrogen, phosphorus and potassium from wastewater can offset 13.4% of the global agriculture demand for these nutrients (Jiménez and Asano, 2008; Fernández-Arévalo et al., 2017). Recycling human waste worldwide could satisfy an estimated 22% of the global demand for phosphorus (UN Water, 2017). It has been estimated that some 36 million ha worldwide (some 12% of all irrigated land) re-use urban wastewater, mainly for irrigation. However, only around 15% is adequately treated (Thebo et al., 2017), thus the need to invest in sustainable, low-cost wastewater treatment to protect public health. The irrigation potential of this volume of wastewater stands at 42 million ha. Wastewater production is expected to increase globally to 574 billion m^3 by 2050, a 51% increase compared to 2015, mainly due to a growing urban population (Qadir et al., 2020). Water re-use with treated wastewater for potable and nonpotable purposes can be practised in a manner that is protective of public health and the environment (WHO, 2006; WHO, 2017). For example, when implemented with sufficient treatment standards, the use of recycled water for the irrigation of crops is protective of public health (Blaine et al., 2013; Paltiel et al., 2016), as was determined by an appointed panel of experts in the state of California (Cooper et al., 2012). However, there are several barriers to the adoption of wastewater re-use, these include technical barriers and public health aspects related to microbiological and pharmaceuticals risks (Jiménez and Asano, 2008; Jaramillo and Restrepo, 2017; Saurí and Arahuetes, 2019). These are currently being addressed by strengthening regulatory standards, with, e.g., 11 out of 22 Arab States adopting legislation permitting the use of treated wastewater (WHO, 2006; US EPA, 2017; WHO, 2017; EC, 2020). Benefits of wastewater re-use usually outweigh the costs (Stacklin, 2012; Hernández-Sancho et al., 2015; UN Water, 2017).

Desalination is particularly important in arid and semi-arid climates, coastal cities, and small island states (Box 4.2). There are 16,000 operational desalination plants globally, with a daily desalinated water production of 95 million m^3 per day in 2017 (IDA, 2020). In 2012 desalinated water was equivalent to 0.6% of the global water supply and 75.2 TWh of energy per year was used to generate desalinated water i.e. about 0.4% of the worldwide electricity consumption (IRENA, 2012). Unfortunately, only 1% of total desalinated water uses renewable sources (IRENA, 2012; Amy et al., 2017; Balaban, 2017; Martínez-Alvarez et al., 2018a; Jones et al., 2019) (4.7.6). Desalination has already helped to meet urban and peri-urban water supply, particularly during annual or seasonal drought events, with half of the world's desalination capacity in the Arab region (UN Environment, 2019; UN Water, 2021). In addition, seawater desalination could help address water scarcity in 146 (50%) large cities (including 12 (63.2%) megacities) (He et al., 2021). Desalination is also being adopted for irrigation. For example, in the island of Gran Canary (Spain), 30% of the agricultural surface area is irrigated with desalinated water to irrigate high-value crops (Burn et al., 2015; Martínez-Alvarez et al., 2018a; Monterrey-Viña et al., 2020). The expected growth of desalination, if not coupled with renewable energy (RE), causes a projected 180% increase in carbon emissions by 2040 (GCWDA, 2015; Pistocchi et al., 2020). There have been advances in large scale and on-farm renewable desalination (Abdelkareem et al., 2018). Using renewable energy to decarbonize desalination has meant that the projected global average levelised cost of water has decreased from 2.4 €/m^3 (2015) to approximately 1.05€/m^3 by 2050, considering unsubsidized fossil fuel costs (Caldera and Breyer, 2020). Desalination will be maladaptive if fossil fuel is used (Tubi and Williams, 2021).

In summary, a resilient circular economy is central to deliver access to water, sanitation, wastewater treatment, desalination, and water re-use as viable adaptation options compatible with the Paris agreement, while safeguarding ecological flows according to the SDG6 targets for climate-resilient development *(medium evidence, high agreement).*

[END BOX 4.5 HERE]

4.6.6 Adaptation for Communities Dependant on Freshwater Ecosystems

AR5 concluded that some adaptation responses in the urban and agricultural sectors could negatively impact freshwater ecosystems (*medium confidence*) (Settele et al., 2014).

Adaptation measures to cope with changes in ecosystems, including freshwater ecosystems, include Ecosystem-based Adaptation (EbA) interventions and gained wide recognition at the global policy level (Reid, 2016; Barkdull and Harris, 2019; Piggott-McKellar et al., 2019b).These have been implemented in many locations around the world, yet, challenges remain, including improving the evidence base of their effectiveness, scaling up of these interventions, mainstreaming across sectors and receiving more adaptation finance (*medium confidence*).

A systematic review of 132 academic papers and 32 articles from non-peer-reviewed literature (Doswald et al., 2014) provided a comprehensive global overview of EbA, which showed that EbA interventions were used in various ecosystems, including inland wetlands (linked to 30 publications). An investigation of EbA effectiveness by (Reid et al., 2019), where nine case studies covering South Asia, Africa and South America were associated with freshwater systems, concluded that EbA enabled the enhancement of the adaptive capacity or resilience to climate change, particularly for the more vulnerable groups in the community. An assessment of the potential for EbA in three sub-basins of the Murray-Darling Basin, Australia, concluded that EbA can augment catchment management practices but that there were also institutional challenges

(Lukasiewicz et al., 2016). In urban settings, EbA has been associated with ecological structures for reducing risks, including the use of urban wetlands (Barkdull and Harris, 2019). EbA is a subset of Nature based Solutions (NbS) that is rooted in climate change adaptation and covers both mitigation (Pauleit et al., 2017) (4.6.5, Box 4.6). Although adaptation measures for freshwater ecosystems have been implemented in many places (Shaw et al., 2014; Lukasiewicz et al., 2016; Karim and Thiel, 2017; Milman and Jagannathan, 2017; FAO, 2018a; Piggott-McKellar et al., 2019b), the evidence base for the effectiveness of these measures to cope with changes in freshwater ecosystems needs improvement. These measures also require further financial support, mainstreaming across sectors, and the scaling up of individual measures (*medium confidence*).

In summary, adaptation measures to cope with changes in freshwater ecosystems have been implemented in many locations around the world. However, challenges remain, including improving the evidence base of their effectiveness, scaling up these interventions, mainstreaming across sectors and receiving more adaptation finance (*medium confidence*).

[START BOX 4.6 HERE]

Box 4.6: Nature Based Solutions for Water-related Adaptation

In the context of climate change-induced water insecurity, NbS are an adaptation response that relies on natural processes to enhance water availability, water quality and mitigates risks associated with water-related disasters (IUCN, 2020).

Until recently, NbS has been considered mainly for mitigation (Kapos et al., 2020; Seddon et al., 2020). Yet, NbS increases the low-cost adaptation options that expand the adaptation space due to its multiple co-benefits (Cross-Chapter Box NATURAL in Chapter 2). Furthermore, a meta-review of 928 NbS measures globally shows that NbS largely addresses water-related hazards like heavy precipitation (37%) and drought (28%) }(Kapos et al., 2020).

Natural infrastructure (green and blue) uses natural or semi-natural systems, e.g., wetlands, healthy freshwater ecosystems, etc., to supply clean water, regulate flooding, enhance water quality, and control erosion (6.3.3.1 to 6.3.3.6.). Grey infrastructure can damage biophysical and hydrological processes, seal soils, and bury streams. Compared with grey physical infrastructure, natural infrastructure is often more flexible, cost-effective, and can provide multiple societal and environmental benefits simultaneously (McVittie et al., 2018; UN Water, 2018; IPBES, 2019). There is increasing evidence and assessment methods on the role of NbS for climate change adaptation and disaster risk reduction at different scales (Chausson et al., 2020; Seddon et al., 2020; Cassin and Matthews, 2021) (4.6.5).

At the landscape scale, there is evidence that impacts from fluvial and coastal floods can be mitigated through water-based NBS like detention /retention basins, river restoration, and wetlands (Thorslund et al., 2017; Debele et al., 2019; Huang et al., 2020). Several examples show the effectiveness of floodplain restoration, natural flood management and making room for the river measures (see FAQ 2.5, (Hartmann et al., 2019; Mansourian et al., 2019; Wilkinson et al., 2019)) (*medium evidence, high agreement*). Likewise, the use of managed aquifer recharge (MAR) in both urban and rural settings will be crucial for groundwater-related adaptation (Zhang et al., 2020a).

At the urban and peri-urban scale, the use and effectiveness of NbS is a crucial feature to build resilience in cities for urban stormwater management and heat mitigation (Depietri and McPhearson, 2017; Carter et al., 2018; Huang et al., 2020; Babí Almenar et al., 2021) (*high confidence*). NbS have been used for stormwater management by combining water purification and retention functions (Prudencio and Null, 2018; Oral et al., 2020). NbS have also been used to mitigate impacts from high impact extreme precipitation events by integrating large scale NBS investment plans into urban planning in cities like New York and Copenhagen, highlighting the importance of blended finance and investment (including insurance) to mainstream NbS investments (Liu and Jensen, 2017; Rosenzweig et al., 2019; Lopez-Gunn et al., 2021). According to the

CDP database, one in three cities use NBS to address climate hazards, and this trend is growing (Kapos et al., 2020).

NbS are cost-effective and can complement or replace grey solutions (Cross-Chapter Box FEASIB in Chapter 18, 3.2.3), (Chausson et al., 2020)). Moreover, estimates of NbS are increasingly based on integrated economic valuations that incorporate co-design with stakeholders to incorporate local knowledge (Pagano et al., 2019; Giordano et al., 2020; Hérivaux and Le Coent, 2021; Palomo et al., 2021) (*medium evidence, high agreement*). Yet, the performance of NbS themselves may be limited at higher GWLs (Calliari et al., 2019; Morecroft et al., 2019).

More knowledge is needed on the long term benefits of NbS, particularly to hydro-meteorological hazards (Debele et al., 2019). There is still *low evidence* for slow onset events, including the applicability of NbS to manage highly vulnerable ecosystems and in agriculture (Sonneveld, 2018),

In summary, there is growing evidence on NBS effectiveness as an adaptation measure and critical role for transformative adaptation to address climate change water-related hazards and water security (*medium evidence, high agreement*). Moreover, several NBS– as, e.g. natural (blue and green) and grey infrastructure can help address water-related hazards, e.g., coastal hazards, heavy precipitation, drought, erosion and low water quality (*high confidence*).

[END BOX 4.6 HERE]

4.6.7 Adaptation Responses for Water-related Conflicts

AR5 concluded with *high confidence* that challenges for adaptation actions (though not water) are particularly high in regions affected by conflicts (Field et al., 2014a). Although climate-conflict linkages are disputed (4.3.6), the potential for synergies between conflict risk reduction and adaptation to climate change exists (Mach et al., 2019). For example, discourses around climate-conflict inter-linkages can present opportunities for peace-building and cooperation (Matthew, 2014; Abrahams, 2020). Indeed, adaptation efforts are needed in the context of conflict, where the pre-existing vulnerability undermines the capacity to manage climatic stresses. In addition, adaptive capacity depends on contextual factors such as power relations and historical, ethnic tensions (Petersen-Perlman et al., 2017; Eriksen et al., 2021), which need to be adequately considered in the design of adaptation strategies.

Some adaptation options, such as water conservation, storage and infrastructure, voluntary migration, planned relocation due to flood risk/sea-level rise, and international water treaties, can reduce vulnerability to climate change and conflicts. However, on the other hand, these adaptation options sometimes may have unintended consequences by increasing existing tensions (Milman and Arsano, 2014); displacing climate hazards to more vulnerable and marginalized groups (Milman and Arsano, 2014; Mach et al., 2019), e.g. pastoralists (Zografos et al., 2014); favouring some over others, e.g. industry over agriculture (Iglesias and Garrote, 2015), upstream countries over downstream countries (Veldkamp et al., 2017), men over women (Chandra et al., 2017). Such unintended consequences may happen when adaptation measures intended to reduce vulnerability produce maladaptive outcomes by rebounding or shifting vulnerability to other actors (Juhola et al., 2016). For example, in the Mekong River basin, the construction of dams and water reservoirs contributes to the adaptation efforts of the upstream southeast Asia countries while increasing current/future vulnerability to floods and droughts in downstream countries and can emerge as a cause of conflict (Earle et al., 2015; Ngô et al., 2016).

Furthermore, adaptation in the context of water-related conflicts is also constrained by economic, institutional, political, competing for development (Anguelovski et al., 2014) and gender considerations (Sultana, 2014; Chandra et al., 2017), which need to be taken into account when designing adaptation plans/measures.

4.6.8 Adaptations Through Human Mobility and Migration

AR5 noted that whether migration is adaptive or maladaptive depends on the context and the individuals involved, however it did not focus specifically on hydrological changes-induced migration (Noble et al., 2014). Migration is often regarded as a transformational adaptation strategy in response to climate-induced hydrological changes (Gemenne and Blocher, 2017) but rarely as the primary or only adaptation measure ((Wiederkehr et al., 2018; de Longueville et al., 2020), Cross-Chapter Box MIGRATE in Chapter 7). Migration is among one of the top five adaptation responses documented in Asia and Africa (Figure 4.27) and confers several benefits to migrants yet maladaptations are also documented (Figure 4.29). This strategy is not available to everyone. Vulnerable populations exposed to hydrological changes may become trapped due to a lack of economic and social capital required for migration (Adams, 2016; Zickgraf, 2018) *(medium confidence)*.

Spontaneous migration, undertaken without outside assistance, has shown the potential to improve the resilience of migrants and communities (Call et al., 2017; Jha et al., 2018a) but may also lead to increased vulnerability and insecurity in some instances (Adger et al., 2018; Linke et al., 2018a; Singh and Basu, 2020). Migration is not a viable strategy for everyone, but age, gender and socio-economic status play a significant role in encouraging or inhibiting the chances of successful migration (Maharjan et al., 2020; Bergmann et al., 2021; Erwin et al., 2021). Migration has increased vulnerability among women and female-headed households (Patel and Giri, 2019) but has also triggered gender positive processes, e.g., increased female school enrolment (Gioli et al., 2014) *(medium confidence)*. Remittances, i.e., transfers of money from migrants to beneficiaries in sending areas, may reduce vulnerability and increase adaptive capacity to climate-induced hydrological changes (Ng'ang'a et al., 2016; Jha et al., 2018b) *(medium confidence)*. Managed retreat refers to the planned and assisted moving of people and assets away from risk areas, such as government- or community-led resettlement (Hino et al., 2017; Maldonado and Peterson, 2018; Tadgell et al., 2018; Arnall, 2019). Such initiatives may reduce exposure to risk (Lei et al., 2017). However, they often fail to include affected populations in the process and may lead to greater impoverishment and increased vulnerability (Wilmsen and Webber, 2015) *(medium confidence)*.

More research on how to ensure migration becomes a successful adaptation strategy is needed (McLeman et al., 2016). In addition, impacts on women, youth and marginalized groups (McLeman et al., 2016; Miletto, 2017) and immobility issues need more attention (Zickgraf, 2018).

In summary, measures that facilitate successful migration and inclusive resettlement may facilitate adaptation to climate-induced hydrological changes *(medium confidence)*.

4.6.9 Adaptation of the Cultural Water Uses of Indigenous Peoples, Local Communities and Traditional Peoples

AR5 reported that religious and sacred values inform actions taken to adapt to climate change (Noble et al., 2014). Neither AR5 nor SR1.5 reviewed adaptation of Indigenous, local and traditional uses of water. SROCC highlighted the context-specific adaptation strategies of vulnerable communities in coastal, polar and high mountain areas, reporting that adaptive capacity and adaptation limits are not only physical, technical, institutional and financial, but also culturally-informed (Hock et al., 2019b; Meredith et al., 2019; Oppenheimer et al., 2019).

There is *high confidence* that some Indigenous Peoples, local communities, and traditional peoples could and are adapting to climate-driven hydrological changes and their impacts on culturally-significant sites, species, ecosystems, and practices in polar, high mountain and coastal areas, where sufficient funding, decision-making power and resourcing exist (e.g., (Golden et al., 2015; Bunce et al., 2016; Anderson et al., 2018). However, there is also *high confidence* that there are significant structural barriers and limits to their adaptation, and that the outcomes of some adaptation strategies can be uneven and maladaptive (*medium evidence, high agreement*) (4.7.4; 4.8.3). These barriers include the lack of recognition of Indigenous sovereignty and exclusion of Indigenous Peoples from decision-making institutions (Ford et al., 2017; Labbé et al., 2017; Eira et al., 2018; McLeod et al., 2018; MacDonald and Birchall, 2020) (14.4.4.2.2; 13.8.1.2). At the same time, the rate and scale of climate change can impede the ability of vulnerable communities to turn their adaptive capacity into effective adaptation responses (Ford et al., 2015; Herman-Mercer et al., 2019).

There is *high confidence* that local people are adapting to the cultural impacts of climate-driven glacier retreat and decline in snow cover and ice in polar and high mountain areas. However, there is also *high confidence* that such adaptation can be detrimental and disrupt local cultures. For example, in the Peruvian Andes, concerns about water availability for ritual purposes has led to restrictions on pilgrims' removal of ice and limiting the size of ritual candles to preserve the glacier (Paerregaard, 2013; Allison, 2015). Relatedly, some local people have questioned the cosmological order, and re-oriented their spiritual relationships accordingly (Paerregaard, 2013; Carey et al., 2017). In Siberia (Mustonen, 2015) and northern Finland (Turunen et al., 2016), community-led decisions among herders favour alternative routing, pasture areas, and shifts in nomadic cycles in response to changing flood events and permafrost conditions (Box 13.2). However, loss of grazing land and pasture fragmentation pose adaptation limits, and some strategies such as supplementary feeding and new technologies may further affect cultural traditions of herding communities (Risvoll and Hovelsrud, 2016; Jaakkola et al., 2018).

There is *high confidence* that relocation (managed retreat) is an adaptation response for communities in areas impacted by, or at risk of, inundation and other hydrological changes (15.3.4.7; 15.5.3). However, relocation can be culturally, socially, financially, politically and geographically constrained due to the importance of cultural relationships with traditional, customary or ancestral lands (*high confidence*) (Albert et al., 2018; Narayan et al., 2020; Yates et al., 2021). Among Pacific islands, for example, the prospect of migration raises concerns about the loss of cultural identity and Indigenous Knowledge (IK) and practices, which can impact emotional well-being (Yates et al., 2021).

As cultural beliefs influence risk perception, there is *medium confidence* that some cultural understandings can foster a false sense of security among Indigenous Peoples, local communities and traditional peoples regarding climate-driven hydrological changes. For example, some members of the Rolwaling Sherpa community in Nepal believe that mountain deities protect them from glacial lake outburst floods (GLOFs) (Sherry and Curtis, 2017)(4.2.2). Elsewhere, such as in the islands of Fiji and St. Vincent, cultural beliefs can diminish human agency because change is viewed as inevitable and beyond human intervention (Smith and Rhiney, 2016; Currenti et al., 2019). Yet such cultural beliefs are not necessarily maladaptive, as they potentially support other resilience factors, such as IK and local knowledge (4.8.5; (Ford et al., 2020)), as well as cultural connections and social ties (Yates et al., 2021).

In sum, although some Indigenous Peoples, local communities and traditional peoples can and are adapting to climate-driven hydrological changes, and their impacts on and risks to culturally significant practices and beliefs (*medium confidence*), these strategies are constrained by structural barriers and adaptation limits (*high confidence*).

[START BOX 4.7 HERE]

Box 4.7: Flood-related Adaptation Responses

Floods, due to their rapid onset and destructive force, require specific adaptation measures. Historically, to address flood damages and risk protection, retreat and accommodation were most common, emphasizing protecting and retreating (Wong et al., 2014; Bott and Braun, 2019). Figure 4.22 identifies five major adaptation strategies from a meta-review of water-related adaptation responses that helps in protecting, retreating and accommodating (4.7.1).

Globally, structural measures for flood protection through hard infrastructure are the most common measures as they directly manage flood hazards by controlling flow through streams and prevent water overflow (Andrew and Sauquet, 2017; Duží et al., 2017). These measures include dikes, flood control gates, weirs, dams, storage and proper waste management (Barua et al., 2017; Egbinola et al., 2017). Infrastructure measures require high maintenance, such as dredging clearing channels and overpasses (Egbinola et al., 2017). A negative aspect of protective infrastructural measures is that, while they eliminate the hazard up to a certain magnitude (Di Baldassarre et al., 2013), they also generate an illusion of no risk by diminishing frequent floods (Duží et al., 2017; Logan et al., 2018). In addition, specific engineering solutions that might be introduced from other localities without proper contextual adjustments may lead to maladaptation (Mycoo, 2014; Pritchard and Thielemans, 2014). Nature-Based Solutions (NbS, Box 4.6) have shifted infrastructure measures from purely grey onto mixed engineering and environmental measures. Examples include Sustainable Urban Drainage Systems (SUDS), which aid in decreasing flow peaks and are affordable, aesthetically pleasing and socially acceptable while also reducing heat and hence the production of storms (Chan et al., 2019) (4.6.5).

Non-structural or soft measures for flood adaptation include human actions that generate capacities, information and, therefore, awareness of floods (Du et al., 2020). Soft measures aim to integrate flood resilience within city management and planning (Wijaya, 2015; Andrew and Sauquet, 2017; Abbas et al., 2018). Social support between members of a community and economic mechanisms such as loans or remittances are soft measures that promote recovery or resilience to floods (Barua et al., 2017; Musah-Surugu et al., 2018; Bott and Braun, 2019). Communities with heightened awareness and knowledge of floods are probably going to elect political leaders that will affect flood protection and policies that include adaptation (Abbas et al., 2018). Soft measures can be an anchoring factor for policies that promote early warning systems, infrastructure, flood resilient housing and environmental restoration (Andrew and Sauquet, 2017; Abbas et al., 2018). However, soft measures, especially at large scale, may also lead to maladaptation as lack of synchronization between international, national and local levels (Hedelin, 2016; Lu, 2016; Jamero et al., 2017), and can further be hampered by bureaucracy (Pinto et al., 2018).

Early warning systems (EWS) are defined as integrated systems of hazard monitoring, forecasting and prediction, disaster risk assessment, communication, and preparedness activities systems to enable individuals, communities, governments, businesses to take timely action to reduce disaster risks in advance of hazardous events (UNISDR, 2021). By this definition, EWS are directly dependent on soft and hard infrastructure measures that increase capacity and reduce hazard (Abbas et al., 2018). Aside from the capacity dependent on soft measures and the monitoring infrastructure, communication at all scales, from national weather services to local leaders, needs to be effective for prompt action (Devkota et al., 2014). In many cases, early warning systems might be the only option to reduce flood casualties (Kontar et al., 2015).

Accommodating floods has gained popularity as the effects of climate change become more apparent, and notable hydroclimatic events exceed the limitations of protective measures (Pritchard and Thielemans, 2014). NbS measures like wetland restoration can act as modern infrastructure protection with clear mitigation co-benefit and provides opportunities for accommodating floods. For example, initiatives such as Room for the River consider flood safety combined with other values such as landscape, environment and cultural values (Zevenbergen et al., 2015). A popular ecosystem-based adaptation measure has been wetland restoration, which can control flood peaks, serve as storage ponds in addition to restoring the environment (Pinto et al., 2018; Saroar, 2018). However, its effectiveness under different conditions is yet to be assessed (Wamsler et al., 2016). Flood resilient housing is another form of accommodating and living with floods. These comprise mostly of elevated homes or different flood protection measures considering vegetation around the house to make those flood resilient (Ling et al., 2015; Abbas et al., 2018; Ferdous et al., 2019).

Despite different degrees of effectiveness, no flood adaptation measure is uniquely effective to eliminate flood risk. Adaptation to floods needs to be considered at a local level, considering the types of floods, community's capacities and available livelihoods (Fenton et al., 2017a). Ideally, flood adaptation strategies need to include short term actions linked to long term goals, be flexible, consider multiple strategies and interlink investment agendas of stakeholders (Zevenbergen et al., 2015). Most importantly, flood adaptation and management options have been proven effective to reduce loss of human lives, but not entirely at sustaining livelihoods and reducing infrastructure damages (Rahman and Alam, 2016; Bower et al., 2019; Ferdous et al., 2019).

[END BOX 4.7 HERE]

4.7 Benefits and Effectiveness of Water-Related Adaptations, Their Limits and Trade-offs

The previous section documented adaptation responses in water use sectors we assess in this chapter (4.6), and noted that in many instances, effectiveness of those responses is not clear. While, there are thousands of case studies of implemented adaptation responses (observed adaptation) to water insecurity, there is a lack of synthesized understanding about the effectiveness and benefits of adaptation (Berrang-Ford et al., 2021a) and whether or not those benefits also translate into climate risk reduction (Singh et al., 2021). In contrast, literature on the effectiveness of future projected adaptation in reducing climate risks is limited in number. Yet, even then, the findings are not synthesized across various options to make an overall assessment of the effectiveness of future projected adaptation. In this section, we draw on two meta-review protocols (see SM4.2 for a description of each protocol) and assess the benefits of current adaptation and effectiveness of future projected adaptation in reducing climate risks. We also assess limits to adaptation and trade-offs and synergies between adaptation and mitigation.

4.7.1 Current Water-related Adaptation Responses, Benefits, Co-benefits and Maladaptation

AR5 (Jiménez Cisneros et al., 2014) concluded that developing countries needed a larger share of adaptation investments for anticipatory adaptation in the water sector (*medium evidence, high agreement*) and that adaptive water management measures were critical in addressing climate-related uncertainty. (Noble et al., 2014) listed various examples of adaptation options, and water-related adaptation featured prominently in almost all categories. They also discussed the challenges of developing metrics for measuring adaptation outcomes; and stressed the importance of transformational adaptation instead of incremental adaptation. Finally, SR 1.5 (de Coninck et al., 2018) made one of the first attempts to systematically assess the feasibility of adaptation options (Singh and Basu, 2020).

4.7.1.1 Current Water-related Adaptation Responses

We define an adaptation response as a water-related adaptation if the hazard is water-related (e.g., floods, droughts, extreme rainfall events, groundwater depletion, melting and thawing of cryosphere (Figure 4.25); or the adaptation intervention is water-related (e.g., irrigation, rainwater harvesting, soil moisture conservation etc.). Adaptation responses were implemented across all water use sub-sectors assessed in this chapter (4.6, Figure 4.23). Given the overall interest in assessing adaptations that documents outcomes, we limited our analysis to a set of 359 unique articles that measures outcomes of adaptation across pre-defined outcome categories (SM4.2, Table SM4.5, (Berrang-Ford et al., 2021a; Mukherji et al., 2021). A total of 1054 adaptation responses were documented in the 359 case studies; these were categorized into 16 categories (Figure 4.22). These adaptation responses are not always specific to long term climate change impacts (that is, changes in annual mean fluxes) but rather respond to changes in variability in the water cycle and specific water hazards. Adaptation to internal variability is needed to increase the resilience to projected water cycle changes because water cycle changes primarily manifest as changes in variability (Douville et al., 2021).

There is *high confidence* that a significant share of water-related adaptations is occurring in the agriculture sector. Agriculture accounts 60-70% of total water withdrawals (Hanasaki et al., 2018; Burek et al., 2020; Müller Schmied et al., 2021) and supports the livelihoods of a large majority of people in the developing countries. Within the agriculture sector, there is *high confidence* in the quality and quantity of evidence of adaptation responses such as improved cultivars and agronomic practices, on-farm irrigation and water management and water and soil moisture conservation, and *medium confidence*, derived from *robust evidence*, and *medium agreement* for other most other adaptation responses (Figure 4.23 and Figure 4.24). Most of these adaptation case studies are from Asia and Africa, and agriculture is the pre-dominant sector where most of these adaptation responses are being implemented (*high confidence*) (4.6.2). However, the sectoral nature of adaptation responses varies across continents. Agriculture is the most important sector in all continents, except Europe and Australasia, where the most adaptation occurs in the urban sector (*high confidence*) (Figure 4.24).

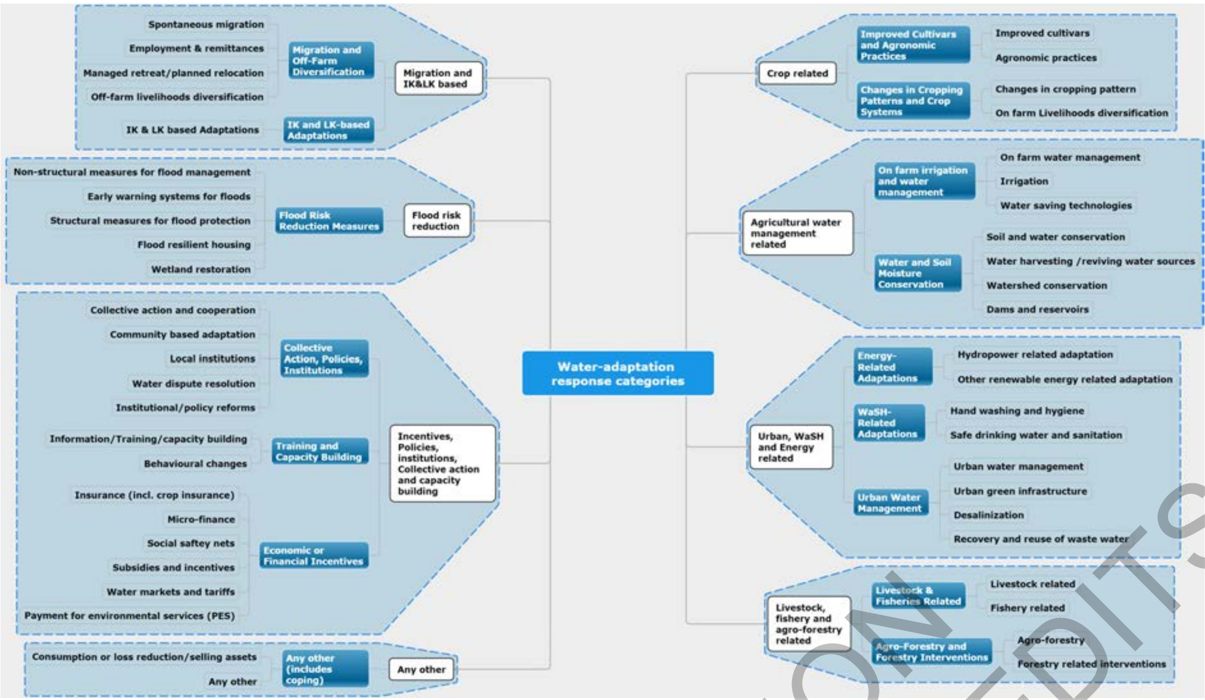


Figure 4.22: Decision tree, documenting the classification of water-related adaptation responses across 48 subcategories, into16 intermediate and 8 larger categories. We use the 16 intermediate categories of adaptation responses for further analysis in this section.

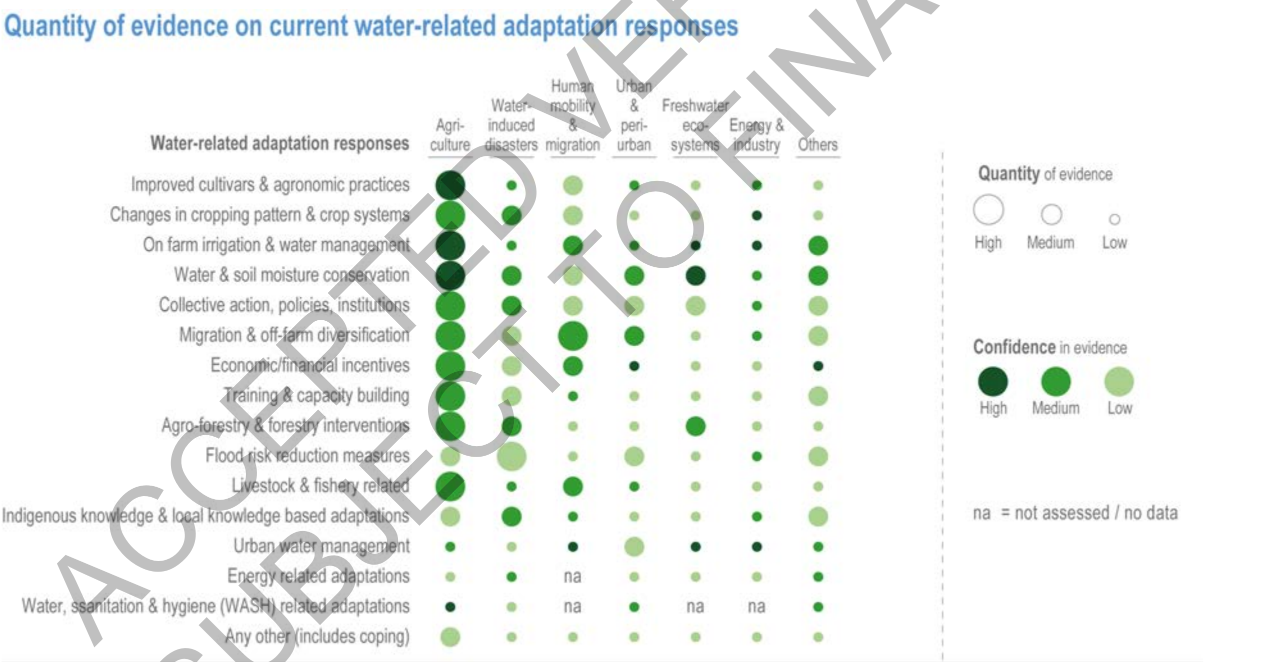


Figure 4.23: Sectoral distribution of documented water-related adaptation responses (observed adaptation) across the 16 categories derived from Figure 4.22. The quantity of evidence is derived from the number of papers in a particular adaptation response category where High >40 papers, Medium: 10-40 papers; Low <10 papers. Confidence in evidence relates to the way the article links outcomes of adaptation with the adaptation response. Category 1: studies causally link adaptation outcomes to the adaptation response by constructing credible counterfactuals; Category 2: studies correlate responses and outcomes without causal attribution; Category 3: studies describe adaptation outcomes without making any causal or correlation claims between adaptation outcomes and adaptation responses. *High confidence*: more than 67% of the studies fall in categories 1 and 2; *medium confidence*: 50-67% of the studies are in categories 1 and 2, and *low confidence* is less than 50% of studies are in categories 1 and 2.

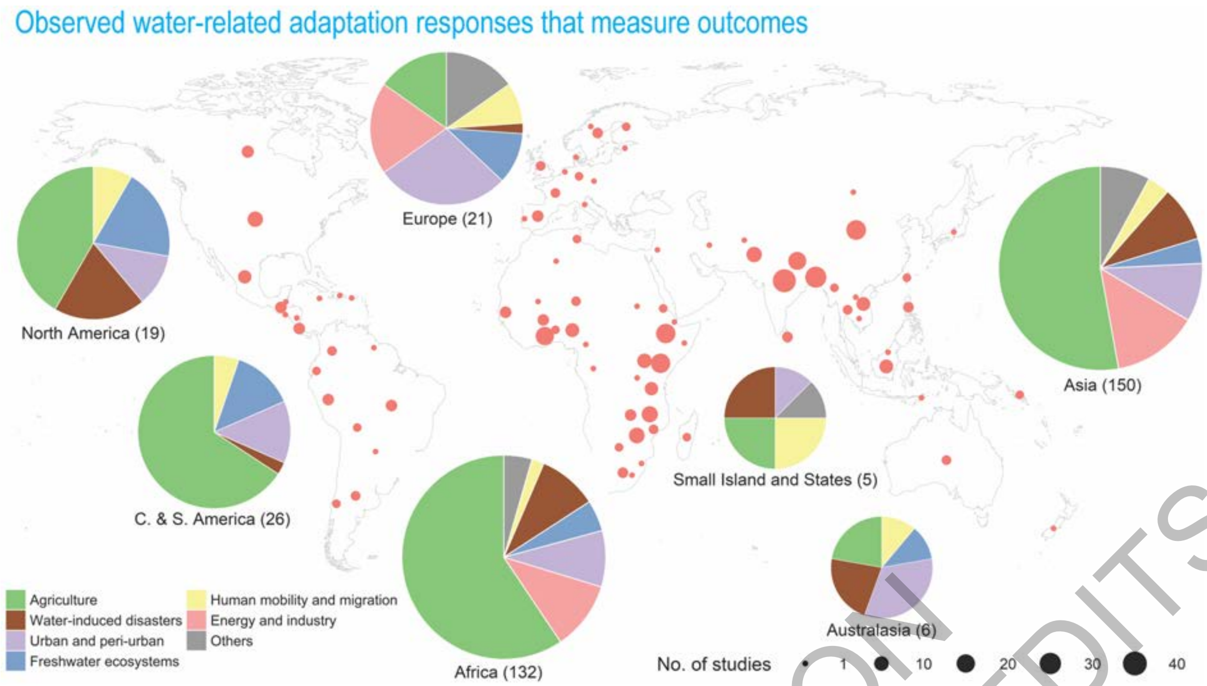


Figure 4.24: Location of case studies on water-related adaptation which measure adaptation outcomes (n=359) and their sectoral distribution across all regions. Circles denote the number of case studies in a particular location in the continent. The pie chart shows the sectors in which adaptation is taking place. The sectors correspond to water use sectors described in sections 4.3, 4.5 and 4.6 of this chapter.

The top four adaptation responses in terms of frequency of documentation are changes in the cropping pattern and crop systems (145 responses), improved crop cultivars and agronomic practices (139 responses), irrigation and water management practices (115 responses) and water and soil conservation measures (102 responses). These top four responses provide several benefits such as higher incomes and yields, better water use efficiencies and related outcomes (*high confidence*) (Table 4.9 and Figure 4.27). However, those benefits are incremental, that is, it helps improve crop production and incomes, at least in the short run, but may not automatically lead to transformative outcomes and climate risk reductions (Pelling et al., 2015; Fedele et al., 2019). One way to move from incremental to transformative adaptation could be to invest gains from incremental adaptation in education and capacity building to improve overall adaptive capacity (Vermeulen et al., 2018). Responses such as migration, including spontaneous and planned relocation, are also relatively well documented (*medium confidence*), as are responses such as collective action, training and capacity building and economic and financial measures for increasing adaptive capacities (*medium confidence*). These categories of adaptation can potentially lead to transformative outcomes, such as a shift to livelihoods that are less exposed to climate hazards. However, transformative pathways are not always straightforward (Pahl-Wostl et al., 2020) (Table 4.8).

Table 4.8: Illustrative examples of case studies of water-related adaptation responses where outcomes were measured (n=359). These cases include instances where adaptation benefits were positive, negative, or neutral. Examples also include studies with or without causal and correlation links between adaptation response and outcomes (categories 1, 2 and 3 studies as described in caption of Figure 4.23. The purpose of the table is to provide a list of illustrative examples to showcase the wide range of adaptation responses that are being implemented. Table 4.9 zooms into examples where adaptation had positive benefits on any of the selected parameters described in 4.7.1.2.

Name of the adaptation response (number of documented responses that category)	Description of adaptation response	Sources
Changes in the cropping pattern and crop systems (145 responses)	Changes in cropping pattern; e.g., the introduction of sugarcane and rice in Costa Rica; crop diversification in Ethiopia and Zimbabwe; crop diversification in Tanzania.	(Singh et al., 2014; Warner et al., 2015; Asmare et al., 2019; Lalou et al., 2019; Makate et al., 2019)
	Changes in the timing of sowing and harvesting, e.g., in China; India and Pakistan	(Yu et al., 2014; Macchi et al., 2015)
	On-farm diversification, e.g., an integrated crop-livestock system in France	(Havet et al., 2014)
Improved crop cultivars and agronomic practices (139 responses)	Improved crop cultivars, e.g., short-duration paddy varieties in Nepal; saline tolerate rice cultivar in Bangladesh; drought-tolerant maize varieties in Malawi, Nigeria, Zimbabwe, Uganda	(Kabir et al., 2016; Wossen et al., 2017; Khanal et al., 2018a; Makate et al., 2019)
	Improved agronomic practices, e.g., conservation agriculture to conserve soil moisture in Malawi, Tanzania; climate-smart agricultural practices in Zambia; alternate wetting and drying and direct seeding of rice in India.	(Thierfelder et al., 2015; Kimaro et al., 2016; Traore et al., 2017; Kakumanu et al., 2019)
Irrigation and water management practices (115 responses)	Irrigation, e.g., construction of local irrigation infrastructure in Chile; funding of community wells in Canada; drilling of borewells in Thailand; irrigation in Ethiopia; spate irrigation in Sudan; night-time irrigation scheduling to reduce evaporative demand in the UK	(Hurlbert and Pittman, 2014; Ferchichi et al., 2017; Rey et al., 2017; Pak-Uthai and Faysse, 2018; Fadul et al., 2019; Lemessa et al., 2019; Lillo-Ortega et al., 2019; Torres-Slimming et al., 2020)
	On-farm water management and water-saving technologies, e.g., use of surface pipes for irrigation water conveyance in China; drip irrigation in China; and use of water-saving measures in India	(Hong and Yabe, 2017; Tan and Liu, 2017; Deligios et al., 2019; Rouabhi et al., 2019)
Water and soil conservation (102 responses)	On-farm water and soil conservation measures, e.g., in Burkina Faso; terraces and contour bunds in Ethiopia.	(West Colin et al., 2016; Kosmowski, 2018)
	Water harvesting through on sand dams in Kenya; in-situ and ex-situ water harvesting in Uganda and India	(Ngigi et al., 2018; Sullivan-Wiley and Short Gianotti, 2018; Kalungu et al., 2021)
	Watershed conservation programs, e.g., in Ethiopia.	(Siraw et al., 2018)
	Revival of water bodies; e.g., creation of artificial lakes in Portugal.	(Santos et al., 2018)
Collective action, policies and institutions (95 responses)	Collective action and cooperation; e.g., grassroots-level collective action for conflict resolution in Guatemala; collective decision to reduce water withdrawals during drought in Japan.	(Hellin et al., 2018; Tembata and Takeuchi, 2018)
	Community-based adaptation in Bangladesh, community-based management of rangelands in Mongolia.	(Fernández-Giménez et al., 2015; Roy, 2018)
	Local institutions, e.g., multi-stakeholder platforms for disaster risk reduction and agriculture in Peru; and several African countries; Adaptation Learning Program.	(Mapfumo et al., 2017; Lindsay, 2018)
	Water dispute resolution; e.g., water conflict mitigation in Costa Rica.	(Kuzdas et al., 2016)

	Institutional and policy reforms; e.g., local water and land use planning instruments in Australia; the Dutch Delta Program in the Netherlands; implementation of EU Flood Directives in Sweden.	(Fallon and Sullivan, 2014; Zevenbergen et al., 2015; Hedelin, 2016)
Migration and off-farm diversification (92 responses)	Spontaneous migration, e.g., voluntary relocation in the Solomon Islands and rural to urban migration in Ethiopia and Pakistan.	(Birk and Rasmussen, 2014; Iqbal et al., 2018)
	Employment and remittances, e.g., in Senegal.	(Romankiewicz et al., 2016)
	Planned relocation; e.g., the Massive Southern Shaanxi Migration Program in China; resettlement of flood-prone communities in Bangladesh.	(Islam et al., 2014; Lei et al., 2017)
	Off-farm diversification; e.g., migration to towns and engaging in off-farm labour wage-earning in Niger, Ghana Bangladesh; shifting to non-pastoral livelihoods in Ethiopia.	(Mussetta et al., 2016; Basupi et al., 2019)
Livestock and fishery-related (63 responses)	Livestock related, e.g., livestock species diversification in Ethiopia and Kenya; insuring livestock in Pakistan; changes in range management practices in the USA	(Opiyo et al., 2015; Yung et al., 2015; Wako et al., 2017; Rahut and Ali, 2018)
	Fishery related, e.g., non-destructive fishery gears and techniques in Ghana and Tanzania	(Yang et al., 2019a)
Training and capacity building (57 responses)	Information, training and capacity building; e.g., climate information services in Kenya and Senegal; Training contributed new learning about digging canals to avoid prolonged water logging in the Philippines; soil conservation training program in Ethiopia.	(Bacud, 2018; McKune et al., 2018; Chesterman et al., 2019)
Agro-forestry and forestry-related responses (56 responses)	Agro-forestry related measures in India, Kenya, Nigeria, Farmer-Managed Natural Regeneration FMNR in Ghana	(Weston et al., 2015; Pandey et al., 2017; Fuchs et al., 2019; Okunlola et al., 2019)
	Forestry related; e.g., Coastal afforestation by planting salinity-resistant trees in Bangladesh, in Colombia.	(Pandey et al., 2016; Barrucand et al., 2017; Barua et al., 2017)
Economic and financial incentives (54 responses)	Insurance; rice crop insurance program in Indonesia; agricultural insurance program in South Africa.	(Dewi et al., 2018; Elum et al., 2018)
	Micro-finance and credit programs, e.g., in Bangladesh.	(Fenton et al., 2017b)
	Social safety nets; e.g., food-based safety net programs in Brazil, food for work programs in Ethiopia.	(Mesquita and Bursztyn, 2017; Sain et al., 2017; Tesfamariam and Hurlbert, 2017; Gao and Mills, 2018)
	Subsidies and incentives, e.g., farm input subsidy program in Malawi; financing programs in Canada to help producers with resources to improve/maintain the quality of soil, water, biodiversity for drought mitigation.	(Hurlbert, 2014; Kawaye and Hutchinson, 2018)
	Water markets and tariffs; e.g., urban water tariffs in Zaragoza, Spain; informal groundwater markets in China.	(Kayaga and Smout, 2014; Zhang et al., 2016b)
	Payment for ecosystems services, e.g., in Mexico.	(Newsham et al., 2018)
IK and LK based adaptations (41 responses)	Use of traditional knowledge of Konda Reddy's in India to shift agro-forestry practices; and among *Khasia* and Tripura communities in Bangladesh; use of local ecological knowledge is by small-scale fisher-farmers in the Amazon floodplains, Brazil; traditional water sharing system "*bethma*" in Sri Lanka; Indigenous methods of water harvesting in India	(Sarkar et al., 2015; Burchfield and Gilligan, 2016; Kodirekkala, 2018; Ahmed and Atiqul Haq, 2019)
	Non-structural measures for flood management; e.g., changes in day-to-day practices in Indonesia; place-specific social structures in the UK.	(Petzold, 2018; Bott and Braun, 2019)

Flood risk reduction measures include (40 responses)	Structural measures for flood management; improvement of the drainage system in Indonesia; flood walls in Beira, Mozambique; dredging and construction of culverts in Nigeria.	(Bahinipati and Patnaik, 2015; Wijaya, 2015; Egbinola et al., 2017; Spekker and Heskamp, 2017)
	Early warning systems; e.g., flood forecasting in Nepal, Indonesia, Nigeria.	(Ajibade and McBean, 2014; Devkota et al., 2014; Sari and Prayoga, 2018)
	Flood resilient housing; e.g., houses on stilts in Guyana, in Pakistan, Vietnam, Philippines.	(Mycoo, 2014; Ling et al., 2015; Abbas et al., 2018)
	Wetland restoration; e.g., in USA and Netherlands.	(Zevenbergen et al., 2015; Pinto et al., 2018)
Urban water management (22 responses)	Urban water management, e.g., incorporating low impact development and urban design features for sustainable urban drainage systems in Spain and Malaysia; demand management and tariff reforms in several European countries.	(Flyen et al., 2018; Rodríguez-Sinobas et al., 2018; Stavenhagen et al., 2018; Chan et al., 2019)
	Green infrastructure; e.g., ecological stormwater management and re-naturalization processes in Sweden; pavement watering in France, Ghana, India, Kenya, Bangladesh	(Hendel and Royon, 2015; Wamsler et al., 2016; Tauhid and Zawani, 2018; Birtchnell et al., 2019)
	Desalinization for water supplies in Spain	(Martínez-Alvarez et al., 2016; Morote et al., 2019)
Energy related adaptations (8 responses)	Hydropower related; e.g., hydropower benefit sharing in the Mekong basin and Nepal	(Balasubramanya et al., 2014; Suhardiman et al., 2014; Shrestha et al., 2015)
	Other renewable energy-related, e.g., "Raising Water and Planting Electricity project" in Taiwan	(Lin and Chen, 2016)
WaSH related adaptations (5 responses)	Hand washing and hygiene, e.g., provision of latrines and washing hands with soap in Bangladesh	(Dey et al., 2019)
	Safe drinking water and sanitation; e.g., piped water supply, China	(Su et al., 2017)
Any other including coping strategies (20 responses)	Reduction in consumption, selling off assets etc.; e.g., selling of household property and livestock in Nigeria; consumption smoothing in Ghana; reducing consumption in Nepal	(Musah-Surugu et al., 2018; Rai et al., 2019)

Droughts, followed by precipitation variability and extreme precipitation, are the two most common hazards against which adaptation responses are forged. The other three top hazards are general climate impacts, heat-related hazards and inland and riverine flooding (Figure 4.25). The majority of the adaptation responses across all categories were introduced by individuals and households, followed by the civil society, and hence autonomous (Figure 4.26). The private sector (defined as profit-making companies and distinct from individual farmers and households) has played a relatively minor role in initiating adaptation responses. However, the low participation of the private sector in initiating adaptation responses could be partly an artefact of the nature of documentation.

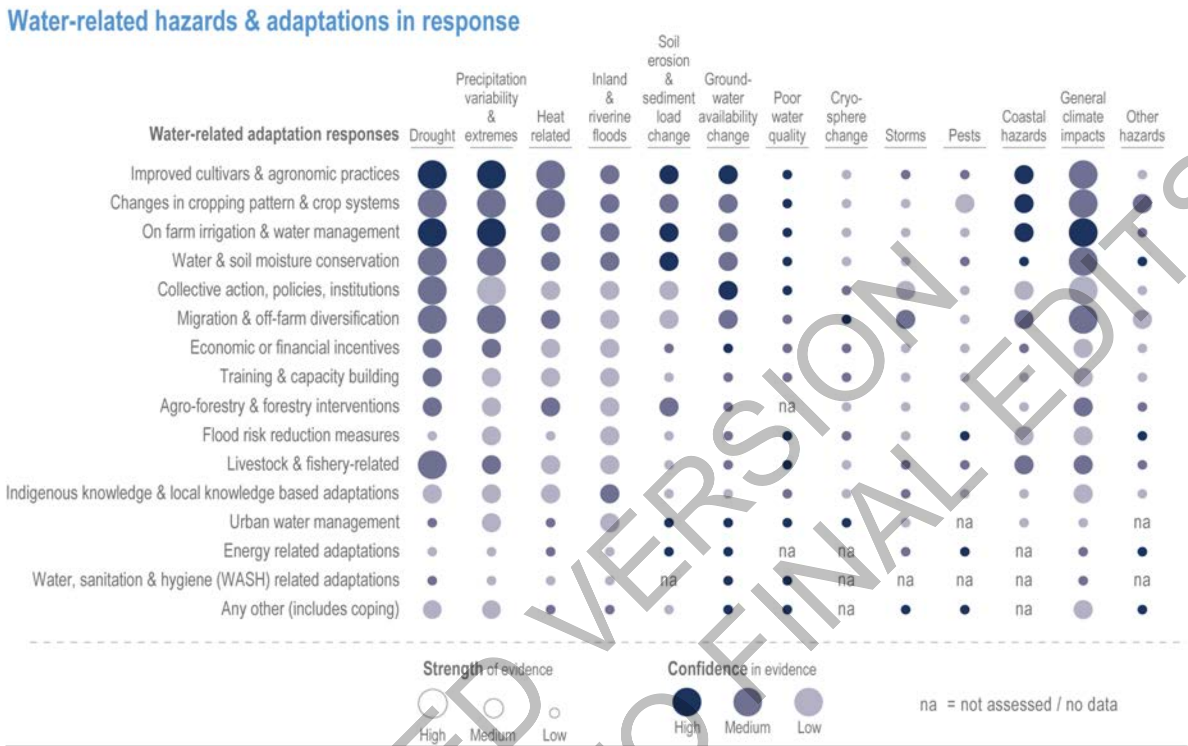


Figure 4.25: Water-related adaptations and climate hazards against which adaptation responses are forged. Evidence and confidence are derived in the same way as in Figure 4.23.

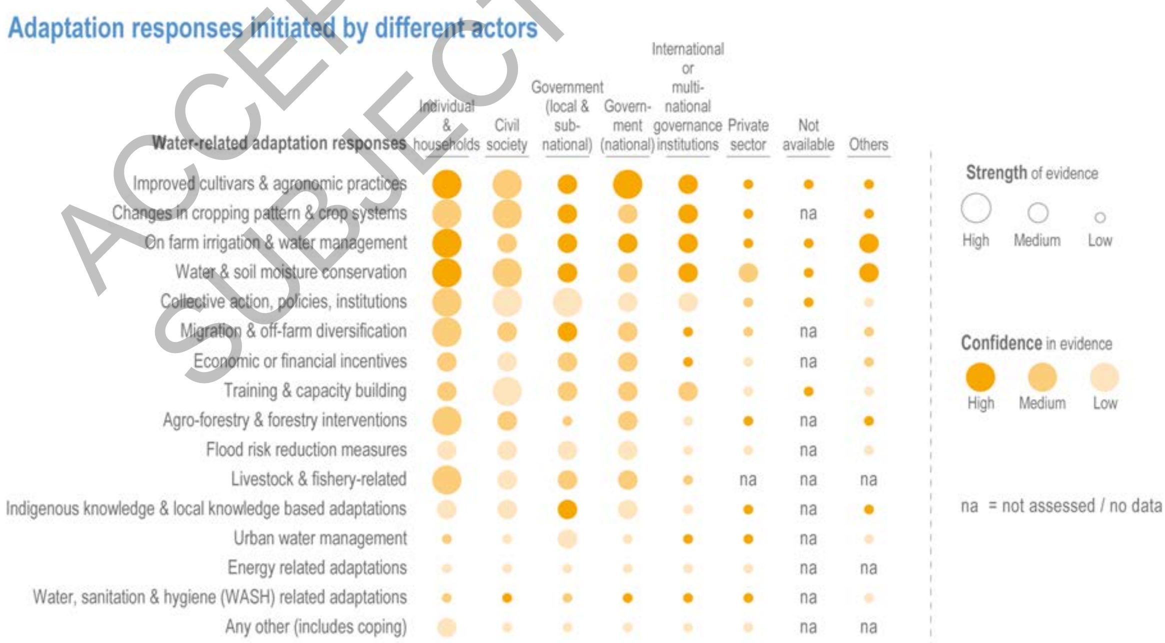


Figure 4.26: Water-related adaptations and their initiators. Initiator of adaptation is defined broadly, and includes the entities who initiates a response, implements that response, or engages in that response in any way, including leading, financing or enabling. Evidence and confidence are derived in the same way as in Figure 4.23.

4.7.1.2 Benefits, Including Co-benefits of Water-related Adaptation Responses and Resulting Maladaptation

There is no consensus in the literature about ways of measuring the effectiveness of current adaptation responses in reducing climate-related impacts (Singh et al., 2021). However, various methodologies, including feasibility assessment, has been deployed (Williams et al., 2021). Given the methodological challenges in defining and measuring the effectiveness of adaptation in reducing climate risks, in this section, we focus on outcomes of water-related adaptation across several dimensions. A total of 359 studies were identified to contain sufficiently *robust evidence* of documented adaptation outcomes to form the basis of this assessment (SM4.2, Table SM4.5, (Berrang-Ford et al., 2021a; Mukherji et al., 2021)). Positive outcomes denote benefits of adaptation, while negative outcomes may mean that adaptation wasn't effective in bringing any benefits or that it was maladaptive (Schipper, 2020).

We assess outcomes across five indicators: a) economic and financial indicators, such as improvements in crop yields and resulting incomes; increase in profits, higher savings, or lesser losses from hazards; b) impacts on vulnerable people, e.g. on women, children; Indigenous Peoples; c) water-related impacts, e.g. improved water use efficiency, water saving, reduction in water withdrawals and application; d) ecological and environmental impacts such as lesser energy use, better soil structures, and better thermal comfort.; e) institutional and socio-cultural impacts such as improved social capital and stronger communities of practice, equity; and strengthening of local institutions or national policies. Of these 359 studies, 319 documented beneficial outcomes across one or more indicators, while the remaining 40 presented no beneficial outcomes. Illustrative examples are shown in Table 4.9, while the distribution of these responses with positive outcomes are shown in Figure 4.27, and indicates that economic benefits of adaptation are more common in developing countries, while benefits along ecological dimensions are more common in the developed countries,

Table 4.9: Illustrative examples of adaptation responses and their benefits across different outcome indicators. All these studies are either category 1 or category 2 studies in that the link between adaptation response and the outcome is either causal or correlated with one another. These benefits notwithstanding, links of adaptation benefits to climate and associated risk reduction are not always clear. Some of these adaptation responses can have beneficial outcomes in one of the five parameters but can have maladaptive outcomes in others.

Hazard	Adaptation responses	Outcome category	Adaptation outcome	Reference
Droughts, floods, and general climate impacts in Nepal	Improved crop cultivars, agronomic practices, irrigation, soil water conservation measures	Economic and financial outcomes	Farming households that adapted produced about 33% more rice than households that did not adapt after controlling for all heterogeneity.	(Khanal et al., 2018a)
Increased rainfall variability in India	Farmer's training on agronomic measures, e.g., alternate drying and wetting AWD, modified system of rice intensification MSRI and direct-seeded rice DSR		The capacity building and water-saving increased crop yields by 960kg/ha, 930 kg/ha and 770 kg/kg through the adoption of AWD, MSRI and DSR, respectively. The three practices have increased farmers' income and decreased the cost of cultivation by up to US$169/ha.	(Kakumanu et al., 2019)
Droughts and changes in the seasonality of rainfall in Pakistan	Adjusting sowing time of wheat		Household income and wheat yields were higher for households who adjusted the sowing time to cope with climate risks than those who did not, after controlling for other factors.	(Rahut and Ali, 2017)

Droughts in North China Plains	Irrigation		Adding one extra irrigation could increase wheat yield by up to 12.8% in a severe drought year.	(Wang et al., 2019a)
Soil degradation; extreme rainfall events high run-off causing erosion in Mali	Soil and water conservation using contour ridges and improved millet and sorghum cultivars		Millet grain yield in 2012-14 was statistically higher in contour ridge terrace plots than the control, with yield differences ranging from 301kg/ha in 2012 to 622 kg/ha in 2013. Improved varieties produced on average 55% more yield than the local ones.	(Traore et al., 2017)
Drought, floods, hailstorm and erratic rainfall, Ethiopia	On-farm agricultural water management		The net revenue from adopting a combination of agricultural water management and modern seeds or inorganic fertilizer is significantly higher by 7600 and 1500 Birr/ha respectively than adopting modern seeds or inorganic fertilizer alone. Birr is the Ethiopian currency.	(Teklewold et al., 2017)
Droughts and general climate impacts, South Africa	Crop insurance and irrigation		Farmers who insured their farm business, and had access to irrigation, had relatively higher net revenue than those who did not, but this link is not causal. Instead, it shows causality could go either way, including those farmers who were better off getting their business insured.	(Elum et al., 2018)
Droughts and floods in Kenya	Migration		Remittance income enables uptake of costlier adaptation measures such as a change in livestock species, which also have higher returns for households. Therefore, the study was not causal in its inference.	(Ng'ang'a et al., 2016)
Droughts in Nigeria	Drought-tolerant varieties		Per capita, food expenditure of those who adopted drought-tolerant maize was significantly lower than those who did not after controlling for everything else and causal inference.	(Wossen et al., 2017)
General climate impacts, including rainfall variability in Brazil	Agro-forestry systems as land use in rural municipalities		The land value in the municipalities with agro-forestry was higher than that of the municipalities where the agro-forestry scheme was not implemented.	(Schembergue et al., 2017)
Water quality deterioration due to floods in Bangladesh	Water, sanitation and health WaSH program	Outcomes for vulnerable people	Children: Prevalence of childhood diarrhoea reduced by 35% in midline prevalence 8.9% and by 73% in end line prevalence 3.6% compared to baseline prevalence 13.7%. Inferences are causal.	(Dey et al., 2019)
Droughts in Zimbabwe	Adoption of drought-tolerant maize varieties by smallholder farmers		Smallholder farmers: Smallholder farmers practising conservation agriculture CA were as likely to adopt drought-tolerant maize varieties as other farmers and thus benefit from increased yields and incomes.	(Makate et al., 2019)
General climate impacts, including	Crop diversification		Poor households: Crop diversification mainly benefits the most vulnerable households; the impact on the poorest group ranges from double to triple the impact on the wealthiest group.	(Asfaw et al., 2018)

droughts in Niger				
Droughts and general climate impacts in Malawi and Zimbabwe	Conservation agriculture; drought-tolerant maize and improved legume varieties		Female farmers: Yield and income effects on the adoption of conservation agriculture and improved varieties of maize and legumes were both positive for men and women	(Makate et al., 2019)
Historically widespread and severe droughts in Ethiopia in 1999, 2002, 2003, 2005 and 2008.	Government safety net program called Productive Safety Net Program PSNP		Poor households: PSNP transfers reduce chronic poverty level from 15.7% to 10.6% and increase the never poor share from 11.5% to 15.8%.	(Gao and Mills, 2018)
Droughts in Kenya	Water harvesting structures, e.g., sand dams	Water-related outcomes	Sand dams increase groundwater storage in riverbanks by up to 40%, which is maintained throughout the year	(Ryan and Elsner, 2016)
Millennium drought in Australia	Water trading		Irrigation application rates fell in the dairy industry from 4.2 million litres/ha in 2000–2001 to 3.5 million litres/ha in 2005–2006	(Kirby et al., 2014)
Droughts, floods, and soil erosion and sediment load in a river basin in France	Agreement signed between water and electricity utilities and farmers		Agreement between water and electricity utilities to compensate farmers for reducing water use resulted in a decrease in water demand from 310 Mm^3 in 1997 to 220 Mm^3 in 2012 in the Durance Valley irrigation system in France	(Andrew and Sauquet, 2017)
Drought in India	The reducing area under irrigated rice crop		Reduced rice irrigation resulted in over 60 mm/ha of water savings compared to irrigated rice crops on that land.	(Hochman et al., 2017b)
Floods due to cyclonic storms and tidal inundation in Bangladesh	Planting of vetiver grass for stabilizing coastal embankments	Ecological and environmental outcomes	Households who planted vetiver grass around their homestead and nearby road managed to save their houses and assets from the recent cyclonic storm and tidal inundation	(Barua et al., 2017)
General climate impacts, including rainfall variability in Brazil	Agro-forestry systems as land use in rural municipalities		Trees planted as a part of the agro-forestry program provide thermal comfort to both animals and humans	(Schembergue et al., 2017)
Drought in 2015 in Ethiopia	Contour ridge terraces as soil water conservation measure		Contour ridge terraces primarily controlled water run-off and soil erosion and acted as a buffer during the 2015 Ethiopian drought	(Kosmowski, 2018)
Drought and rainfall variability in Pakistan	Climate-smart agricultural practices	Institutional and socio-cultural outcomes	Farmers who adopted climate-smart practices also tended to form a better relationship with local extension agents and reached out to them more frequently. Again, however, causality might as well lie the other way round.	(Imran et al., 2019)
Droughts, Mexico	Strengthening of local water users' associations through external assistance programs		Local water user's associations were able to reduce water abstractions during years of severe droughts.	(Villamayor-Tomas and García-López, 2017)

Rainfall variability in Niger	Community-based adaptation and through adaptation learning programs	More robust social networks where women were able to take important decisions.	(Vardakoulias and Nicholles, 2015)

Figure 4.27: Top panel: location of case studies of water-related adaptation responses (996 data points from 319 studies). In these 996 data points, at least one positive outcome was recorded in one of the five outcome indicators. These outcome indicators are economic/financial, outcomes for vulnerable people, ecological/environmental, water-related, and socio-cultural and institutional. Middle panel: the top six documented adaptation options per region as a fraction of the total of reported studies, with grey bars containing the share of all other adaptation responses. In most instances, the top six adaptation categories include nearly 3/4th of the studies. Bottom panel: The spider diagrams show

the number of studies reporting beneficial outcomes for one or more dimensions for the top six adaptation options identified in each region. Due to a small number of studies in small island states, a spider diagram was not generated for the Small Island States.

Co-benefits are defined as mitigation benefits resulting from an adaptation response (Deng et al., 2017). Around a quarter of papers that documented positive adaptation outcomes also reported mitigation co-benefits. Agro-forestry, community forests and forest-based adaptations are the most oft-cited examples of mitigation co-benefits ((Bhatta et al., 2015; Etongo et al., 2015; Weston et al., 2015; Pandey et al., 2017; Sain et al., 2017; Sánchez and Izzo, 2017; Wood et al., 2017; Adhikari et al., 2018a; Hellin et al., 2018; Aniah et al., 2019; Quandt et al., 2019), also see Box 5.11). Other examples include mitigation benefits of climate-smart agricultural practices that reduce input intensity and helps in carbon sequestration (Arslan et al., 2015; Somanje et al., 2017); retrofitting buildings in urban areas with energy-efficient devices for lowering electricity bills and emissions (Fitzgerald and Lenhart, 2016) and re-use of treated wastewater for irrigation and urban uses (Morote et al., 2019) (Box 4.5, 4.7.6,).

Not all adaptation responses reduce risks, and some may have long term maladaptive outcomes, even if they are beneficial in the short term. Maladaptation often stems from poor planning and implementation of adaptation responses and because of not addressing the root causes of vulnerability (Schipper, 2020; Eriksen et al., 2021). Of the 319 case studies where adaptation response was found to have some beneficial outcomes, around 1/3rd of them also mentioned the possibility of maladaptation. Migration can often have maladaptive outcomes because migration can exacerbate the inherent vulnerabilities of migrants (4.6.8). For example, slum dwellers in cities may earn higher incomes, but their quality of life worsens (Ayeb-Karlsson et al., 2016). In some instances, even wage rates in migration hotspots can remain low due to the high volume of the migrant population (Fenton et al., 2017b); as such, it does not help buffer consumption against rainfall shocks (Gao and Mills, 2018). Migration also has gendered impacts, with girls from migrating families being taken out of school (Gioli et al., 2014) or interrupting children's education overall (Warner and Afifi, 2014). In planned relocation from vulnerable urban slums, relocation sites can be far from job sites and increase social conflicts (Tauhid and Zawani, 2018).

Adaptation responses that focus on improving incomes through production intensification can have maladaptive outcomes. An oft-cited example of this is groundwater over-use as a result of irrigation intensification. There is widespread evidence of groundwater over-use in many countries in Africa (Mapfumo et al., 2017) and in the Middle East and North Africa (Petit et al., 2017; Daly-Hassen et al., 2019); in Asia (Burchfield and Gilligan, 2016; Zhang et al., 2016b; Kattumuri et al., 2017), in Spain (Petit et al., 2017) and Australia (Kirby et al., 2014) (4.2.6, 4.6.2, Box 4.3). Intensification based approaches also increase costs of cultivation (Mussetta et al., 2016; Wang and Chen, 2018; Quan et al., 2019), can lead to more use of fertilizers and herbicides (Thierfelder et al., 2015; Sujakhu et al., 2016; Khanal et al., 2018a; Yamba et al., 2019). Diversification away from food crops can also compromise domestic food security (Kloos and Renaud, 2014; Brüssow et al., 2017).

Even interventions that have positive carbon co-benefits like forestry and agro-forestry can have maladaptive consequences on land and water resources, especially if inappropriate species (Etongo et al., 2015) with higher water demands are grown (Krishnamurthy et al., 2019) (4.7.6).

In summary, current adaptation responses have benefits across several dimensions. In developing countries, most adaptation measures improve economic outcomes (*high confidence*). Adaptation responses also have benefits in terms of water outcomes and environmental and ecological parameters, and these benefits are more commonly manifested in developed countries (*high confidence*). Of the papers assessed for water-related adaptation, roughly 1/4th reported adaptation co-benefits (*high confidence*). In contrast, 1/3rd of studies reported maladaptive outcomes, now or in the future (*high confidence*), underscoring the importance of looking at synergies and trade-offs. Despite many adaptation case studies, there is a knowledge gap in understanding if the benefits of adaptation also translate into a reduction of climate impacts, and if so, to what extent, and under conditions (*high confidence*). In view of this critical knowledge gap, our assessment is limited to benefits of current adaptation responses.

4.7.2 Projections of Future Effectiveness of Adaptation Responses

Several adaptation options have been shown to have beneficial effects on societally relevant outcomes under current climate conditions (4.7.1.2) and will remain critical to adapt to future climate change. However, there is limited quantitative information on the future viability of available responses to reduce projected climate impacts effectively. However, the context-specific nature of adaptation on the ground and the uncertainties associated with future climate outcomes, both in terms of policy decisions around mitigation and model-inherent uncertainties, make long-term projections of adaptation effectiveness of limited use for decision-making on the ground. However, such projections are still needed to understand the efficacy of current technical and managerial solutions to reduce climate risk. Consequently, an increasing body of literature focuses on the effectiveness of specific interventions to reduce projected climate risks in a local to regional setting.

This section provides a quantitative aggregate assessment of effectiveness of projected water-related climate adaptations at different levels of GWLs (SM4.2). Effectiveness is defined as the potential of a given adaptation measure to address projected changes in climate and return the system under analysis to baseline conditions. If the measure cannot fully compensate for the projected climate risk, residual risks remain, defined as the fraction of risk remaining after adaptation. For example, in many regions, projected temperature-driven yield loss can be reduced by shifting to or increasing irrigation. However, yields often do not always fully return to baseline conditions without climate change, leaving residual risk after adaptation. Assessed option are limited to technical solutions, which have quantitative entry-points to global climate impact models.

Most adaptation projections focus on water-related interventions in the agricultural sector, including irrigation-related responses, shifting planting dates, changing crops and cultivars, and water and soil conservation. Sectoral projections of adaptation effectiveness are limited in forestry and agro-forestry related responses, flood protection measures (excluding here options that are solely related to effects of sea-level rise), urban water-related adaptation as well as energy-related responses. The majority of assessed studies focus on comparing different variations of one or several response options in terms of timing or duration, for example, a shift in planting dates of 10 days and 20 days, relative to present-day practice and provide results for a range of scenarios and (or) timeframes.

A total of 45 studies were identified for this assessment, based on their quantitative assessment of the effects of adaptation on projected impacts (SM4.2 for the method of future projected effectiveness assessment). From each study, the distinct combinations of specific variations of adaptations, scenarios and timeframes assessed were considered as individual data points, providing a total of 450 unique data points for the assessment (Table SM4.6). The study-specific temperature increase was classified relative to the 1850-1900 baseline for each data point, based on the model and scenario specifications provided and grouped into outcomes at 1.5°C, 2°C, 3°C and 4°C. The effectiveness is assessed based on the fraction of risk that an option can reduce. Co-benefits are defined as a situation where outcomes improve relative to baseline conditions, whereas maladaptive outcomes describe a situation where risks increase after adaptation has been implemented.

Several studies assess the future effectiveness of improved cultivars and agronomic practices, such as changing fertilizer application or switching to drought-resistant crops (5 studies; 85 data points). Results show a range of effectiveness levels across regions and warming levels and vary depending on the tested response options (Qin et al., 2018) (Figure 4.29), with moderate to small effectiveness, large residual impacts or potential maladaptive outcomes as well as decreasing effectiveness with increasing warming (Figure 4.28) (*high confidence*). For studies testing results across a range of scenarios, approaches show increasingly mixed (Qin et al., 2018) and limited effects (Amouzou et al., 2019) with higher warming, with overall reductions across warming levels for most tested responses (Qin et al., 2018).

Changes in cropping patterns and crop systems (Figure 4.28) (5 studies; 31 data points) indicate limited potential to reduce projected climate risks, with the majority of studies providing results of up to 1.5°C of warming and limited evidence for higher warming levels. At 1.5°C, effectiveness in Africa is mostly insufficient, with substantial maladaptive potential (Brouziyne et al., 2018). Over Asia, effectiveness is mostly small at 1.5°C with substantial residual impacts, further reducing to insufficient effectiveness at large residual risks at 4°C (Figure 4.28 Projected effectiveness) (*robust evidence; medium agreement*) (Boonwichai et al., 2019; Dai et al., 2020; Mehrazar et al., 2020). Amongst the options related to changes in cropping patterns and crop systems, shifting planting dates is projected to retain moderate to high residual risks under some specifications in Iran (Paymard et al., 2018) and Morocco (Brouziyne et al., 2018), while high effectiveness is reported for similar specifications in Thailand (Boonwichai et al., 2019), Australia (Luo et al., 2016), Morocco ((Brouziyne et al., 2018) and Iran (Mehrazar et al., 2020). Of the assessed adaptation options, changes in cropping patterns and cropping systems appear least effective in reducing climate risk, with decreasing effectiveness at higher levels of warming.

Studies assessing the future effectiveness of irrigation related responses (Figure 4.28) focus on a range of specific approaches, including increasing irrigation efficiency, deficit irrigation, irrigated area expansion or shifting from rain-fed to irrigated agriculture, as well as specific types of irrigation (21 studies; 103 data points). As a frequently implemented option with direct entry points to agricultural models, this option provides the most robust set of data points across regions and warming levels. For all regions, a reduction in effectiveness is apparent from 1.5°C to higher levels of warming, leading to increased residual risk with increasing warming (*high confidence*). Irrigation can increase yield relative to present-day, showing co-benefits for some regions, though the share of co-benefits decreases with higher warming (*high confidence*) (Figure 4.28). However, since many of these studies rely on global agricultural models and these do not fully represent the actual availability of water, further expansion of irrigation at the scale assumed in those studies may not be realistic (4.3.1.2. 4.3.1.3) (Elliott et al., 2014).

A wide range of water and soil management-related options (Figure 4.28), including mulching, no tilling, or contour farming, has been assessed for future effectiveness (8 studies; 49 data points). Results underline the context-specific nature and need to carefully adjust the specific options to a regional setting, with variations of options leading to effective outcomes or residual impacts within individual studies (Qiu et al., 2019) and across regions and warming levels.

Similar to observed adaptation, studies assessing combinations of the agricultural adaptation options outlined above (11 studies; 36 data points) show the highest effectiveness across agricultural adaptation outcomes and generally project moderate to high effectiveness with the potential for co-benefits (Figure 4.28). Though maladaptive outcomes are also documented, residual risks are limited, also at higher levels of warming. Therefore, developing integrated plans of synergistic options linked to adequate monitoring and evaluation approaches and designed to adjust to changing conditions continuously is desirable to minimize climate risk and ensure food security (Babaeian et al., 2021).

Globally, agro-forestry related adaptation (4 studies; 18 data points) is moderate to highly effective, with the potential for substantial co-benefits at 1.5° and 2°C of warming, with a sharp decline in effectiveness at 3°C and 4°C and a substantial increase in residual risk and maladaptive outcomes (Figure 4.28).

Flood risk related adaptation (4 studies; 47 data points) is associated with the potential for substantial co-benefits relative to present-day flood risk, indicating a current adaptation gap larger than for other impact areas. These co-benefits decline with increasing warming. Limits to the tested options become increasingly apparent at 3°C and 4°C of warming, where residual risks increase for most assessed cases (Figure 4.28).

Adaptation projections for urban water risks as well as the energy sector are limited to one study each, with one data point for urban adaptation (Rosenberger et al., 2021) and 80 data points for different variations of adaptation outcomes across regions and scenarios for the energy sector (van Vliet et al., 2016c). Sustainable stormwater management, focusing on a combination of nature-based solutions, is shown to be highly effective and yields co-benefits at 3°C. However, these results were gained in a specific case study setting in a European city with limited generalizability (Figure 4.28).

The assessment of adaptation in the hydropower and thermo-electric power-generation sector indicates high effectiveness and co-benefits across all regions for 1.5°C, with decreasing effectiveness and increasing residual risks for 2°C and 3°C of warming and highest reductions in effectiveness for Central and South America (Figure 4.28).

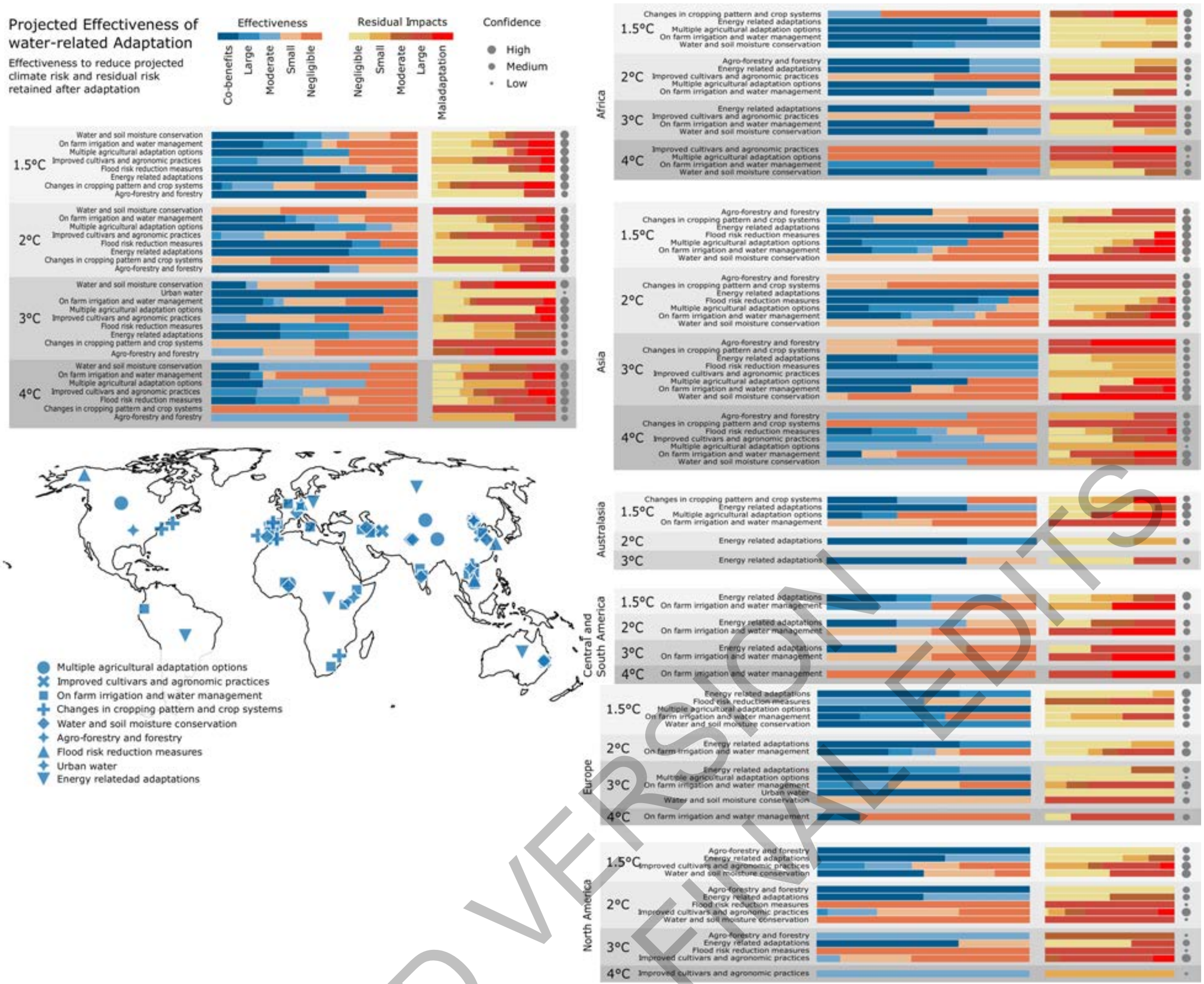


Figure 4.28: Projected effectiveness of adaptation options in returning the system to a study-specific baseline state relative to the projected climate impact; and level of residual risk retained after adaptation, relative to baseline conditions. Regional summaries are based on IPCC regions. Warming levels refer to the global mean temperature (GMT) increase relative to a 1850-1900 baseline. For each data point, the study-specific GMT increase was calculated to show effectiveness at 1.5°C, 2°C, 3°C and 4°C. Based on the ability of an implemented option to return the system to its baseline state, the effectiveness is classified based on the share of risk the option can reduce: Large (>80%); Moderate (80-50%); Small (<50-30%); Insufficient (<30%). Where the system state is improved relative to baseline, Co-benefits are identified. Residual impacts show the share of remaining impacts after adaptation has been implemented: Negligible (<5%); Small (5 to <20%); Moderate (20 to <50); Large (50% and more). Where risks increase after adaptation, data points are shown as maladaptation. All underlying data is provided in Table SM4.6.

Quantitative projections of future adaptation depend on available impact models to analyze the effect of specific adaptation interventions. However, since not all possible future adaptation responses can be incorporated in climate impact models, this is a major limitation to assessing the full scope of options available in the future. For example, many frequently implemented measures showing effective outcomes, such as behavioral and capacity building focused responses or migration and off-farm diversification (4.7.1.2), are not incorporated in quantitative water-related climate impact projection models. In addition, projections of future adaptation depend on currently available technologies or approaches, but new methods and technologies will probably emerge. Thus, improving the representation of adaptation in future projections is a significant knowledge gap that remains to be addressed.

Whether specific adaptation responses are shown to be effective and even lead to co-benefits or are associated with residual impacts is highly contextual, location and crop-specific. In addition, the specific climate-impact-scenario combinations play an important role in determining assessed outcomes.

In practice, responding to increasing climate risk will need to be context-specific and sufficiently agile to respond to ever-changing realities on the ground. The adaptive pathways approach underline that a sequence of different options responding to climate change over time may be most effective (Babaeian et al., 2021). In addition, impact models generally underestimate or underrepresent climate extremes (Schewe et al., 2019), limiting the ability of the present analysis to reflect adaptation requirements to extremes, which are likely to push systems to their limits (4.7.4). While currently known structural adaptation responses can reduce some of the projected risks across sectors and regions, residual impacts remain at all levels of warming, and effectiveness decreases at higher levels of warming. Adaptation generally performs more effectively at 1.5°C, though residual damages are projected at this warming level across sectors and regions (*high confidence*). A range of options also shows the potential for further increasing negative effects (maladaptation) across sectors, regions, and warming levels, further underlining the need for contextualized approaches.

4.7.3 Comparing Current and Future Water-related Adaptation Responses

Water-related adaptation is being observed across sectors and regions (4.6), and beneficial outcomes are documented across different dimensions (4.7.1). A limited set of frequently documented adaptation responses is also represented in quantitative projections of adaptation effectiveness (4.7.2, Figure 4.29). However, due to the largely different assessment methodologies for measuring beneficial outcomes for current adaptations and effectiveness to reduce impacts for future adaptations, comparing current and future adaptation outcomes is not straightforward. For current adaptation responses, beneficial outcomes may or may not translate to climate risk reduction, making risk reduction potential of observed adaptation a significant gap in our current understanding. The large diversity of outcomes across regions and assessed options becomes apparent for future adaptation options, with the group of 'inconclusive' outcomes indicating a large spread of results across regions. This underlines the contextual nature of adaptation and boundary conditions for implementation that can determine the success of adaptation outcomes, now or in the future.

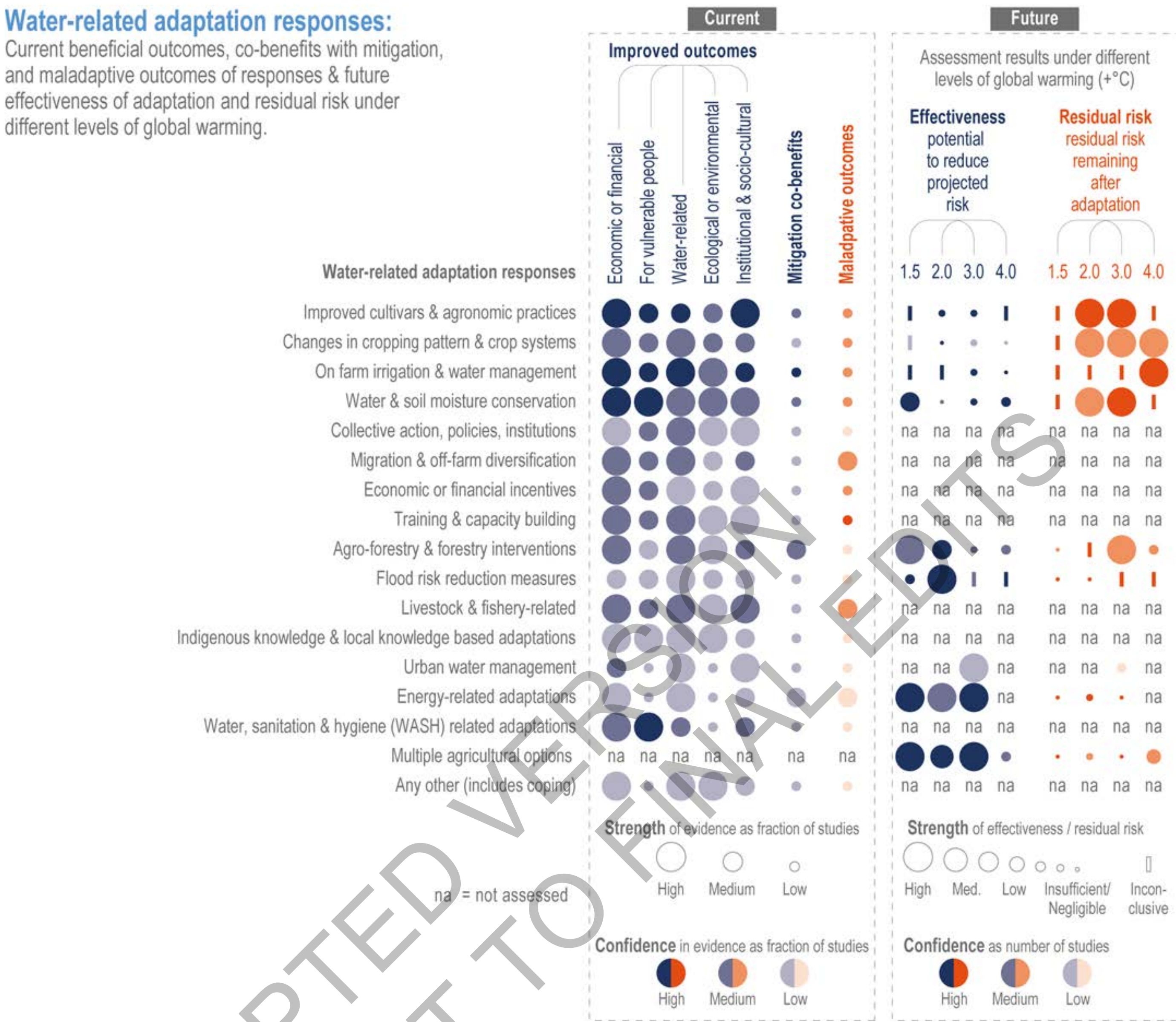


Figure 4.29: Panel on the left side shows observed benefits of adaptation. Observed outcomes are reported across five dimensions of benefits, co-benefits as well as maladaptation outcomes. Benefits are measured across five dimensions. Strength of evidence is high if >80% of adaptation responses in that category has at least one beneficial outcome; medium if between 50-80% of adaptation responses in that category has at least one beneficial outcome, and low if <50% of adaptation responses have at least one beneficial outcome. Confidence in evidence relates to the way the article links outcomes of adaptation with the adaptation response. Category 1: studies causally link adaptation outcomes to the adaptation response by constructing credible counterfactuals; Category 2: studies correlate responses and outcomes without causal attribution; Category 3: studies describe adaptation outcomes without making any causal or correlation claims between adaptation outcomes and adaptation responses. *High confidence*: more than 67% of the studies fall in categories 1 and 2; *medium confidence*: 50-67% of the studies are in categories 1 and 2, and *low confidence* is less than 50% of studies are in categories 1 and 2. The panel on the right-hand side shows the effectiveness of future adaptations. Future outcomes are assessed in terms of their effectiveness to reduce climate impacts at 1.5°C, 2°C, 3°C and 4°C of global temperature increase relative to 1850-1900. Effectiveness is defined as the fraction of adaptation that the option is able to reduce; residual risks is the fraction of risk remaining after adaptation. If>66% of assessed data points agree on the effectiveness class, a response-temperature combination is shown as belonging to that class. Where results diverge, the result is inconclusive, with studies showing high and low effectiveness across regions and studies. Confidence is based on the number of data points available for each response-temperature combination with *high confidence*: 5 or more data points; *medium confidence*: 2-4 datapoints; *low confidence*: 1 datapoint. Also, see Figure 4.28 for further explanations and Tables SM4.5 and SM4.6 provide underlying data.

Documented implemented adaptations show several beneficial outcomes, with most studies (319 of 356) documenting positive rather than negative outcomes. However, there may be a positive reporting bias in the literature, as positive outcomes are more likely to be reported than negative ones. Also, positive outcome in one parameter does not preclude negative outcomes in others, so maladaptation is still possible even when an adaption has some positive benefits (4.7.1.2). In addition, much of the adaptation happening on the ground may not be published in peer-reviewed publications and, therefore, not covered by the literature assessed in this report. Further, there is limited knowledge about the effectiveness of current adaptation in reducing climate-related risks due to documentation and methodological challenges elaborated in 4.7.1.2 (SM4.2).

In contrast, evaluating the effectiveness for future projected adaptations is methodologically possible (4.7.2, and SM4.2), but every adaptation that is happening now cannot be modelled for the future. Therefore, projections of future adaptation effectiveness are limited to those options that can be incorporated into (global) quantitative climate impact models. Unfortunately, an extensive range of options, such as capacity building or training, migration and employment, which are essential building blocks in the portfolio of available (water-related) adaptation options, are currently not quantitatively represented in adaptation projections. In addition, the future will probably bring further development in technical solutions, which are currently also not modelled. While implementing the modelled technical options may be feasible in general, several barriers and constraints (4.7.4) and enabling conditions, which influence adaptation action in practice, are not included in current modelling studies. Therefore, the modelling studies may present optimistic assessments of adaptation effectiveness for the future.

Adaptations that are beneficial now (e.g., crop and water-related ones) are also projected to be effective to varying extents in reducing future risks, with the degree of effectiveness strongly depending on future GWLs. For example, beyond a certain level of warming (2°C and upwards), the effectiveness of most options is projected to reduce, and residual impacts are projected to increase. Reduction in the effectiveness of future adaptation at higher global warming levels underscores the need for limiting warming to 1.5°C, as space for adaptation solution starts to shrink beyond that for most options for which future projections exists (*high confidence*).

To sum up, there are two significant knowledge gaps in our understanding of water-related adaptations. First, the nature of literature on current adaptation makes it challenging to infer their effectiveness in reducing climate risks, even though the benefits of adaptation are clear (*high confidence*). Second, not all adaptation responses that are possible in the future can be modelled because of inherent limitations to what can be modelled. Thus, advancement in tools and metrics for measuring the effectiveness of current adaptation in reducing climate risks and suitable downscaled climate and impact models that incorporate economic, social, cultural and management aspects for an extensive range of future adaptation options is needed.

4.7.4 Limits to Adaptation and Loss and Damage

The core constraints identified in AR5 (Klein et al., 2014) for freshwater-related adaptation were lack of governance, financial resources and information, while water availability was singled out as a core constraint to diversifying options for water-dependent sectors. SR1.5 showed that increasing aridity and decreased freshwater availability, including limited groundwater supply in fossil aquifers in conjunction with rising sea levels may pose hard limits to adaptation for Small Islands (Roy et al., 2018). SR1.5 also shows that water-related risks can be reduced substantially by limiting warming to 1.5°C (*high confidence*) (Hoegh-Guldberg et al., 2018), thereby also reducing the potential to reach hard limits to adaptation. SROCC highlighted that several barriers and limits to adapt to reduced water availability in mountain areas, such as lack of finance and technical knowledge (Hock et al., 2019b). The SRCCL further highlighted the critical importance of water-related climate change adaptation, and potential limits to adaptation in the land sector, when extreme forms of desertification lead to a complete loss of land productivity *(high confidence)* (Mirzabaev et al., 2019).

Institutional constraints, including path-dependency and lengthy decision-making processes, remain major limitations to successful adaptation globally *(high confidence)* (Barnett et al., 2015; Oberlack, 2017), as well as for the water sector (Kingsborough et al., 2016; Oberlack, 2017; Azhoni and Goyal, 2018). For example, a lack of institutional support has limited the ability of farmers to implement adaptation, even if information about the benefits is acknowledged (Nambi et al., 2015). A lack of inter-sectoral coordination and communication within institutions and conflicting interests between water sectors limit the potential for integrated policies. For all water related adaptation options, which have shown to be effective in one or more dimensions (4.7.1.2), governance and institutional constraints were identified to be the most commonly encountered to a moderate or significant extent (Figure 4.30). Water-energy-food-nexus approaches can help overcome these inter-sectoral barriers (Box 4.8) (Rasul and Sharma, 2016; Ernst and Preston, 2017). In addition, trade-offs between different policy goals must be considered to ensure the broader significance of the implemented adaptation strategies, such as water quality implication of adaptation efforts in the agricultural or energy sectors (4.7.6) (Fezzi et al., 2015).

The lack of financial and technological resources constrains adaptation implementation (Castells-Quintana et al., 2018; Iglesias et al., 2018) and were identified as significant or moderate across all water-related adaptation responses, with significant constraints especially present in options related to the agricultural sector (Figure 4.30). For example, financial resources were significant constraints to implementing Climate Smart Agriculture in Guatemala, a relevant adaptation strategy to improve food security, resilience, and low emission development (Sain et al., 2017).

While financial barriers played an important role in adopting new technologies at the farm level in Spain, acceptance, common understanding and awareness were amongst the most frequently identified barriers across different adaptation options (Esteve et al., 2018). Limitations in knowledge and understanding of complex processes, feedback effects and interconnections in the water sector pose challenges to effective adaptation and adaptation decision-making (Kundzewicz et al., 2018). Such constraints are identified as moderate across the range of options assessed in this chapter (Figure 4.30). For tropical and mountainous regions and the African continent, in particular, significant uncertainties in available data and a lack of reliable climate projections remain one of the biggest obstacles in long-term adaptation planning (Antwi-Agyei et al., 2015), especially in the water sector (Watson et al., 2017; Azhoni and Goyal, 2018; Hirpa et al., 2018; González-Zeas et al., 2019). There is also often a discrepancy between the level of awareness among different stakeholders, for example, between affected farmers whose agency is limited by the lack of knowledge by local authorities (Chu, 2017).

For some regions of the world, such as Small Islands (Karnauskas et al., 2016; Karnauskas et al., 2018) (Box 4.2) and the Mediterranean (Cross-Chapter Paper 4) (Schleussner et al., 2016), aridity increases have the potential to pose hard adaptation limits. In mountain and polar regions, changes in the cryosphere (4.2.2, 4.4.2) may limit water availability for irrigation systems that depend on melt-water (4.5.1) (Qin et al., 2020). Biophysical limits may also be reached through impacts of hydrological extremes, such as crop loss as a consequence of extreme precipitation events (Huggel et al., 2019; van der Geest et al., 2019). Such limits are reported to a limited to moderate extent across all adaptation options assessed (Figure 4.30). However, knowledge gaps remain about physical and biological constraints to adaptation in the water sector. Climate impacts, such as droughts in East Africa or glacier melt in the cryosphere, indicate that biophysical limits to adaptation may exist, even under current climate conditions (Figure 4.31) (Warner and van der Geest, 2013; Huggel et al., 2019; van der Geest et al., 2019). A lack of investment in relevant infrastructure, such as dikes for example, as well as maladaptive effects of certain measures could increase existing risks and exacerbate impacts (van der Geest et al., 2019).

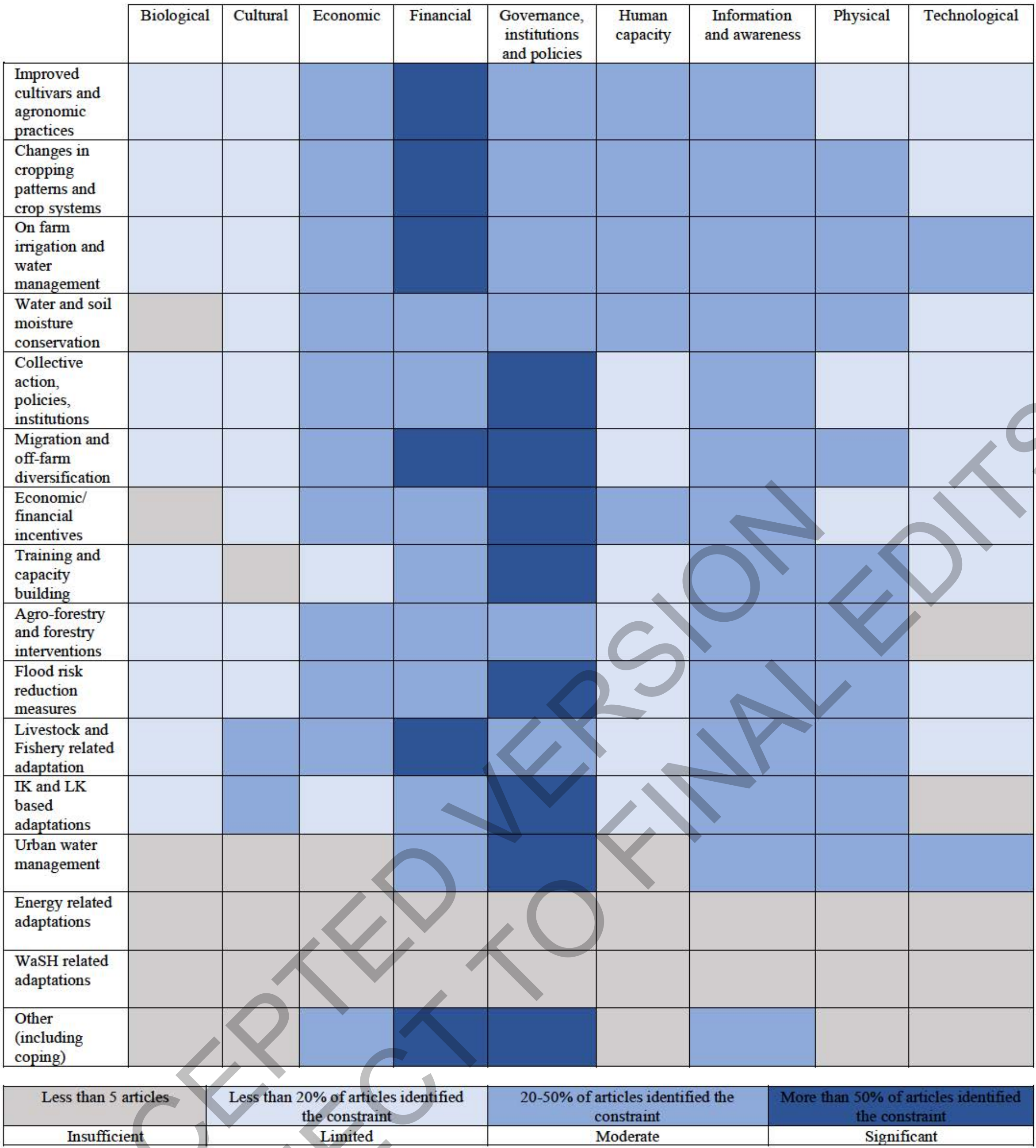


Figure 4.30: Adaptation constraints manifest across a range of dimensions and here are assessed based on a meta-review of water-related adaptation (4.7.1, SM4.2, and Table SM4.5). Where less than five articles are available for assessment, data is insufficient to assess the extent to which a constraint is present. Where less than 20% of the articles reporting on the respective adaptation option identify the presence of a constraint, it is classified as 'limited', where 20 to 50% report on a specific constraint it is considered as 'moderate'. Where more than 50% of articles report on the presence, the constraint is considered 'significant'. This assessment is based on the available peer-reviewed literature assessing adaptation benefits in the water sector - in practice, these or other constraints may still be significant, but have not have been identified in peer-review sources.

Integrated approaches, such as linking land-use and water policies (Mehdi et al., 2015), inter-institutional networks (Azhoni et al., 2017), nexus approaches (Box 4.8) (Conway et al., 2015) as well as consideration of linkages to the SDGs (4.8) (Gunathilaka et al., 2018) are crucial to overcoming constraints in water adaptation. In addition, monitoring and evaluating the effectiveness of adaptation measures, policies and actions can contribute to knowledge, awareness and data to support adaptation implementation in the future (4.7.1; 4.8) (Klostermann et al., 2018). Although the information on climate change adaptation that has beneficial impacts, including enabling conditions and success factors specific to the water sector, is emerging, significant knowledge gaps remain (4.7.1.2) (Gotgelf et al., 2020). Further understanding the constraints and limits that exist with regard to adaptation in the water sector is becoming urgent in light of increasing slow (e.g., droughts) and rapid (e.g., floods) onset impacts associated with climate change.

Taking action towards adaptation critically determines the outcomes and impacts of climate change processes across space and time. Where efforts to reduce risk do not effectively occur, losses and damages occur as a consequence of climate change, some of which can have irreversible and existential effects (van der Geest and Warner, 2015; Page and Heyward, 2016; Thomas and Benjamin, 2018a; Mechler et al., 2019). Water-related impacts that occurred despite implemented adaptation have been documented across all world regions (*high confidence*) (Figure 4.31).

	Hazard	Adaptation	Loss and Damage
A	Temperature increase, permafrost thawing	Outmigration	**Loss of livelihoods, ecosystems and infrastructure**
B	Drought	Crop-livestock integration, soil fertility management, crop variety, migration	**Loss of food security**
	Drought, climate variability	Pastoralism (moving cattle to regions with abundant pasture)	**Loss of food security**
C	Hurricanes, storms, droughts	Using savings, borrowing, government assistance	**Loss of income sources, loss of access to finance, depletion of assets, health problems, damage to housing and agriculture**
D	Landslides	Diversify livelihoods, physical barriers, house adjustments, migration	**Loss of life, loss of property and infrastructure**
	Changing monsoon patterns	Irrigation channels, water sharing mechanisms, crop diversification	**Loss of access to water and loss of crops**
	Floods, cyclones, surges, coastal flooding	Physical protection, creating buffers, build safety nets	**Loss of livelihoods, harvest failure and damage to infrastructure**
E	Floods, storms and drought	irrigation, diversification of crops, regeneration of degraded forests, animal husbandry	**Loss of food security, crops, income, livelihoods and land**
	Floods, landslides, typhoons	Food relief, temporary shelter and loaning money	**Loss of livelihoods, infrastructure and ecosystems**
F	Freshwater scarcity, aridity, cyclones, El Nino, flooding	Seasonal work and outmigration, early warning systems	**Loss of life, livelihoods, homes, crops, contamination of drinking water, displacement**
G	Changes in glacier runoff, permafrost thawing, GLOFs	Outmigration, new livelihoods (e.g. tourism)	**Loss of cultural heritage, loss of income, loss of lives**

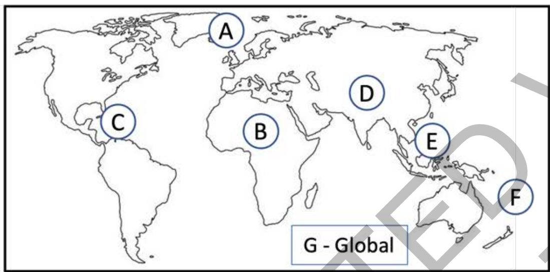


Figure 4.31: Examples of regional studies where experienced negative impacts despite or beyond implemented adaptation have been documented. Panels indicate the climate hazard that leads to the need for adaptation, the adaptation option implemented and the recorded impacts per region (A – Arctic (Landauer and Juhola, 2019), B – Africa (van der Geest et al., 2019), C – Caribbean (Lashley and Warner, 2015), D – South Asia (Kusters and Wangdi, 2013; van der Geest and Schindler, 2016; Bhowmik et al., 2021), E – Southeast Asia (Acosta et al., 2016; Beckman and Nguyen, 2016), F - Pacific the Small Island States (Gawith et al., 2016; Handmer and Nalau, 2019), G – Global effect: Mountain Cryosphere (Huggel et al., 2019)). Presented examples are limited to the available peer-reviewed literature that focuses explicitly on impacts that have been documented despite documented evidence that adaptation in relation to water hazards had previously been implemented. Section 4.3 provides a full assessment of observed impacts across sectors and regions.

Advances in climate change attribution (4.2; SM4.3; Figure 4.20) show the direct effects of anthropogenic climate change, also with regard to climate extremes. These advances also provide the basis for climate litigation (Marjanac and Patton, 2018) to hold countries/companies accountable for climate change impacts, for example, concerning risks of glacial lake outburst in Peru (Frank et al., 2019).

A further increase in the frequency and/or intensity of water-related extremes (4.4) will also increase consequent risks and associated losses and damages (4.5), primarily for exposed and vulnerable communities globally (Bouwer, 2019). After assessing the future potential of currently available technologies to reduce projected water-related climate impacts, there is evidence that residual impacts will remain after adaptation for most adaptation options and levels of warming, with increasing residual risks at higher warming levels (4.7.2). Financial, technical and legal support will be needed when hard limits are transgressed and loss and damage occurs (Mechler et al., 2020). Knowledge gaps remain regarding quantified information on limits and constraints to adaptation in the water sector.

In summary, institutional constraints (governance, institutions, policy), including path dependency and financial and information constraints, are the main challenge to adaptation implementation in the water sector (*high confidence*). Water-related losses and damages that manifest despite or beyond implemented adaptation have been observed across world regions, primarily for exposed and vulnerable communities (*high confidence*). Hard limits to adaptation due to limited water resources will emerge for Small Islands (*medium evidence, high agreement*) and regions dependent on glacier- and snowmelt (*medium evidence, high agreement*).

4.7.5 Costs of Adaptation and Losses due to Non-Adaptation

Estimating adaptation costs for climate change impacts on the various water use sectors is vital for decision-making, budgeting, and resource allocation (Chambwera et al., 2014). However, in AR5, studies on adaptation costs for water were deemed to have 'limited coverage' and mainly focused on 'isolated case studies'; costs in agriculture were 'extremely limited' (Chambwera et al., 2014).

One estimate on observed losses due to climate change from the United Kingdom notes that almost 50% of freshwater thermal capacity is lost on extreme high-temperature days, causing losses in the range of average GBP 29-66 million/year (Byers et al., 2020). However, global estimates of current losses because of climate change impacts on water resources remain few. Most of the evidence is focused on projected damages rather than actual ones (World Bank, 2016; Rozenberg and Fay, 2019).

Without adaptation, water-related impacts of climate change are projected to reduce global GDP by 0.49% in 2050 under SSP3, with significant regional variations for the Middle East (14%); Sahel (11.7%); Central Asia (10.7%), and East Asia (7%) (World Bank, 2016). In Asia, water-related impacts of climate change on all sectors of the economy are projected to reduce GDP by 0.9% (in high-income Asia) to 2.7% (in low-income Asia) by 2050 without adaptation or mitigation. Under the A1B scenario, real GDP is projected to fall by 0.78% by 2030 in South Asia (Ahmed and Suphachalasai, 2014). In Sub-Saharan Africa, damages from floods in 2100 are projected at 0.5% of GDP under a 2ºC temperature rise without adaptation; and will be non-uniformly spread across countries (Markandya, 2017; Dottori et al., 2018). In Europe, annual damages due to coastal flooding are projected at €93 billion by 2100 under RCP 8.5-SSP3 (Ciscar et al., 2018). Global direct damages from fluvial floods are projected to rise to €1250 billion per year under a 3ºC global warming level and SSP5 socio-economic scenario (Dottori et al., 2018). A model-based study of selected water-related sectors like fluvial and coastal flooding, agricultural productivity of major crops, hydroelectric power generation, and thermal power generation provides much conservative estimates of GDP loss (Takakura et al., 2019). The study shows that without adaptation, loss of global GDP could be 0.094% under RCP8.5 and SSP5 and 0.013% under RCP2.6 and SSP1 scenarios in 2090 (2080-2099), with regional values for Africa (0.017 to 0.286%), Asia (0.015 to 0.104%), Australasia (-0.012 to 0.003%), North America (-0.002 to 0.005%) and South and Central America (0.011 to 0.055%) (Takakura et al., 2019). So, while there is general agreement about negative impacts on GDP due to water-related risks in the future, the magnitude of GDP loss estimates varies substantially and depends on various model assumptions (*high confidence*). Updating costs while improving the modelling of uncertainties is essential for evidence-based decision-making (Ginbo et al., 2020).

Costs of water-related infrastructure in adaptation have received attention at the global and regional level to bridge the 'adaptation gap' (Hallegatte et al., 2018; UNEP, 2018; Dellink et al., 2019; GCA, 2019). For example, (Rozenberg and Fay, 2019) estimated that subsidizing capital costs to extend irrigation to its full potential would cost 0.13% of the GDP per year of low-and middle-income countries between 2015 and 2030. The coastal and riverine protection cost was between 0.06% to 1% of these countries' GDP per year over the same period. Projected economic damage due to coastal inundation was US$ 169–482 billion in 2100 under RCP8.5-SSP3 without adaptation, but US$ 43-203 billion cost to raise dike height will reduce 40% of the total damage (Tamura et al., 2019). Hard infrastructure for river floods, costing $4-9 billion per year, can reduce damage by US $22-74 billion per year (Tanoue et al., 2021). Damages are estimated to be up to six-time larger than the cost of implementing efficient adaptation measures (H2020., 2014). (GCA, 2019) reported that investing US$1.8 trillion globally, e.g., in early warning systems, climate-resilient infrastructure; dryland crop production; mangrove protection; and improving the resilience of water resources between 2020 and 2030 could generate US$ 7.1 trillion in benefits.

Comparatively, less attention has been paid to low-regret options, especially at the national and local levels. Conservation agriculture and integrated production systems, early-warning systems, restoration of wetlands, and zoning are postulated to have lower investment and lock-in costs than engineering-based options (Mechler, 2016; Cronin et al., 2018; Johnson et al., 2020). However, they require regular maintenance and high technical and human capacity, which are likely to vary by scale, location, and context (Chandra et al., 2018; Khanal et al., 2019; Mutenje et al., 2019; Rahman and Hickey, 2019). Global studies suggest improvements in returns on adaptation investments by delivering better services and reducing water wastage through appropriate water pricing and regulations (Damania et al., 2017; Bhave et al., 2018). For example, under scenarios SSP1 and SSP3, water pricing and regulation are projected to reverse losses in expected 2050 global GDP of 0.49% to gains of 0.09%. GDP losses are projected to drastically reduce in the Middle East, eliminated in the Sahel and Central Africa, and reversed into gains in Central Asia and East Africa, with benefits concentrated in worst-affected regions (World Bank, 2016). More local and national studies are needed to identify low regret options and their benefits and actual costs (Blackburn and Pelling, 2018; Abedin et al., 2019; Brown et al., 2019; Momblanch et al., 2019; Page and Dilling, 2020) (*limited evidence, high agreement*).

In summary, climate change impacts on water resources are projected to lower GDP in many low-and middle-income countries without adequate adaptation measures (*high confidence*). However, estimating the exact quantum of future GDP loss due to water-related impacts of climate change is fraught with several methodological challenges. Adaptation measures that focus on reducing water-related impacts of climate change will help stem losses further. Still, more work needs to be done on actual benefits and costs of adaptation strategies and residual impacts and risks of delaying adaptation action (*medium confidence*). In addition, better evidence on the costs and benefits of low-regret solutions, such as water pricing, increasing water use efficiency through technology and service improvements, and enhanced support for autonomous adaptation, is also needed for informed decision-making (*high confidence*).

4.7.6 Trade-offs and Synergies between Water-related Adaptation and Mitigation

In AR5, there was *medium evidence* and *high agreement* that some adaptation and mitigation measures can lead to maladaptive outcomes, such as a rise in GHG emissions, while further exacerbating water scarcity leading to increased vulnerability to climate change, now or in the future (Noble et al., 2014). In addition, SR1.5 (Hoegh-Guldberg et al., 2018; IPCC, 2018a) and SRCCL (IPCC, 2019b) reiterated the challenge of trade-offs that may undermine sustainable development. Conversely, adaptation, when framed and implemented appropriately, can synergistically reduce emissions and enhance sustainable development.

Different mitigation pathways can either increase or decrease water withdrawals or water consumption (or both, or either) depending on the specific combination of mitigation technologies deployed (*high confidence*) (Fricko et al., 2016; Jakob and Steckel, 2016; Mouratiadou et al., 2016; Fujimori et al., 2017; Parkinson et al., 2019). For example, the impacts of climate change mitigation on future global water demand depend largely on assumptions regarding socioeconomic and water policy conditions and range from reduction of 15,000 km^3 to an increase of more than 160,000 km^3 by the end of century (Mouratiadou et al., 2016). This section assesses some of the mitigation and adaptation measures from a water trade-off and synergy lens.

Solar pumps for irrigation are increasingly introduced where conventional energy is not available (Senthil Kumar et al., 2020) or supply is intermittent or expensive (Shah et al., 2018), e.g., in Africa (Schmitter et al., 2018), Europe (Rubio-Aliaga et al., 2016) and South Asia (Sarkar and Ghosh, 2017). Solar pumps can replace diesel and electric pumps (Rajan et al., 2020), potentially reduce 8-11% of India's carbon emissions (~45.3–62.3 MMT of CO_2) attributable to groundwater pumping while also boosting agricultural productivity (Gupta, 2019). However, in the absence of incentives to deter groundwater over-exploitation (Shah et al., 2018), solar pumps may exacerbate groundwater depletion (Closas and Rap, 2017; Gupta, 2019) (*low evidence, medium agreement*).

In many places, treatment and reuse of wastewater from urban residential and industrial sources may be the principal supply option under acute water scarcity (US EPA, 2017) and help reduce other freshwater withdrawals (Tram Vo et al., 2014; Diaz-Elsayed et al., 2019). While reuse may recover valuable nutrients, capture energy as methane, and save water, effluent containing heavy metals may degrade land and surface and groundwater quality and pose a salinization risk in semi-arid regions (*medium evidence, high agreement*). Agricultural reuse of poor-quality wastewater will become increasingly necessary, but treatment is energy-intensive and may contribute to further GHG emissions (Qadir et al., 2014; Salgot and Folch, 2018) (Box 4.5).

Desalination of seawater or brackish water is an adaptation measure in many coastal water-scarce regions (Hanasaki et al., 2016; Jones et al., 2019). Solar desalination is developing rapidly, and it lessens the carbon footprint of conventional, fossil-fuel-powered desalinization plants (Pouyfaucon and García-Rodríguez, 2018) (also see Box 4.5). However, the desalinization process is energy-intensive (Caldera et al., 2018); it ejects brine that is difficult to manage inland, has high salinity and other contaminants (Wilder et al., 2016) (*medium evidence, high agreement*) (Box 4.5).

Negative-emission technologies, such as direct air capture (DAC) of CO_2, could reduce emissions up to 3GtCO_2/year by 2035, equivalent to 7% of 2019 global emissions. However, they can increase net water consumption by 35 km^3/year in 2050 (Fuhrman et al., 2020) under the low-overshoot emissions scenario. According to other estimates, capturing 10Gt of CO_2 could translate to water losses between 10-100 km^3, depending on the technology deployed and climatic conditions (temperate vs. tropical) (Chapter 12, WGIII). Some DAC technologies that include solid sorbents also produce water as a by-product, but not in quantities that can offset total water losses (Beuttler et al., 2019; Fasihi et al., 2019)(*medium confidence*).

Developing countries are projected to witness the highest increase in future energy demand under 2°C global warming leading to significant increases in water use for energy production (Fricko et al., 2016) (4.5.2). Results from a simulation study on retrofitting coal-fired power plants built after 2000 with carbon capture and storage (CCS) technologies show an increase in global water consumption, currently at 9.66 km^3/year, by 31% to 50% (to 12.66 km^3/year and 14.47 km^3/year, respectively) depending on the cooling and CCS technology deployed, and hence are best deployed in locations which are not water scarce (Rosa et al., 2020c) (*medium confidence*). In Asia, the near-term mitigation scenario with high CCS deployment increases the average regional water withdrawal intensity of coal generation by 50-80% compared to current withdrawals (Wang et al., 2019b). Carbon can be 'scrubbed' from thermo-electric power-plant emissions and injected for storage in deep geological strata (Turner et al., 2018), but this can lead to pollution of deep aquifers (Chen et al., 2021) and have health consequences (*low confidence*).

Bio-energy crop with carbon capture and storage (BECCS) involves CO_2 sequestration as biofuel or forest bioenergy (Creutzig et al., 2015). BECCS has profound implications for water resources (Ai et al., 2020), depending on factors including the scale of deployment, land use, and other local conditions. Evaporative losses from biomass irrigation and thermal bioelectricity generation are projected to peak at 183 km^3/year in 2050 under a low overshoot scenario (Fuhrman et al., 2020). (Senthil Kumar et al., 2020) projected that while BECCS strategies like irrigating biomass plantations can limit global warming by the end of the 21st century to 1.5°C, this will double the global area and population living under severe water stress compared to the current baseline. Both BECCS (Muratori et al., 2016) and DAC can significantly impact food prices via demand for land and water (Fuhrman et al., 2020). The direction and magnitude of price movement will depend on future carbon prices, while vulnerable people in the Global South will be most severely affected (*medium evidence, high agreement*).

Afforestation and reforestation are considered one of the most cost-effective ways of storing carbon. An additional 0.9 billion ha of canopy cover in suitable locations could store 205 Gt of carbon (Bastin et al., 2019), but this estimate is deemed unrealistic. Aggressive afforestation and reforestation efforts can result in trade-offs between biodiversity, carbon sequestration, and water use (Smith et al., 2008). In northern China, ecological restoration by regreening drylands resulted in several environmental and social benefits (Mirzabaev et al., 2019) but also led to increased freshwater use in some pockets (Zhao et al., 2020). Afforestation and reforestation with appropriate broad-leaf species in temperate Europe (Schwaab et al., 2020) can offer water quality and quantity-related benefits, mitigate extreme heat, and buffer against drought (Staal et al., 2018). A global assessment on forest and water showed that forests influence the overall water cycle, including downstream water availability via rainfall-runoff dynamics and downwind water availability via recycled rainfall effects (Creed and van Noordwijk, 2018). The study concluded that afforestation and reforestation should be concentrated (Ellison et al., 2017) in water-abundant locations (to offset downstream impacts) and where transpiration can potentially be captured downwind as precipitation (Creed et al., 2019) (Cross-Chapter Box NATURAL in Chapter 2). Overall, extensive BECCS and afforestation/reforestation deployment can alter the water cycle at regional scales (*high confidence*) (Cross-Chapter Box 5.1 in Chapter 5, WGI, (Canadell et al., 2021)).

On the other hand, demand-side mitigation options, such as dietary changes to more plant-based diets, reduced food waste (Aleksandrowicz et al., 2016; Springmann et al., 2018; Kim et al., 2020), can reduce water use (*medium evidence, high agreement*).

In summary, many adaptation and mitigation measures have synergistic or maladaptive consequences for water use, depending on associated incentives, policies, and governance that guide their deployment. Many mitigation measures have a considerable water footprint (*high confidence*), which must be managed in socially and politically acceptable ways to reduce the water intensity of mitigation while increasing synergies with sustainable development (*medium evidence, high agreement*).

[START BOX 4.8 HERE]

Box 4.8: Water-Energy-Food (WEF) Nexus Approaches for Managing Synergies and Trade-offs

WEF nexus is an approach that recognizes that water, energy, and food are linked in a complex web of relationships in the hydrological, biological, social, and technological realms (D'Odorico et al., 2018; Liu et al., 2018b; Märker et al., 2018). For instance, agricultural production requires significant energy inputs due to intensive groundwater pumping (Siddiqi and Wescoat, 2013; Gurdak, 2018; Putra et al., 2020). Similarly, hydropower production often has trade-offs with irrigation, affecting food production, carbon emission, and forest protection (Meng et al., 2020). New technologies, such as desalination plants for urban water supply against future climate change and drought, are also very energy-intensive (Caldera et al., 2018) (Box 4.5). Quantifying the complex interdependencies among food, energy, and water is critical to achieving the SDGs; and reducing trade-offs (Liu et al., 2018a; Liu et al., 2018b; UN, 2019). A key benefit of the nexus approach is to leverage the interconnection of WEF and achieve the most efficiency in the overall systems. Hence, this approach allows for widening the set of salient stakeholders and, therefore solution possibilities, that may otherwise not be possible in single domain efforts and helps connect these stakeholders to achieve synergistic goals (Ernst and Preston, 2017; Mercure et al., 2019).

The WEF nexus approach thus opens up possibilities for strategic interventions across sectors through a better understanding of trade-offs (Albrecht et al., 2018). Policies and strategies aiming to cope with climate change may amplify rather than reduce negative externalities and trade-offs within the nexus: low carbon transition, the shift to non-conventional water resources, and agricultural intensification, all implemented to mitigate and adapt to climate change, are not always nexus-smart. Hence, a nexus approach that integrates management and governance across these three sectors can enhance WEF security by minimizing trade-offs and maximizing synergies between sectors. At the same time, renewable energy offers the opportunity to decouple water and food production from fossil fuel supply, leading to several advantages from both a socio-economic and environmental point of view (Cipollina et al., 2015; Pistocchi et al., 2020). WEF nexus approaches can achieve overall system efficiency when maximizing the use and recovery of water, energy, nutrients, and materials (Pistocchi et al., 2020; Tian et al., 2021). These types of holistic system thinking of WEF show promising strategies to catalyze transformative changes. Suppose the specific types and extent of WEF linkages in a region are well understood. In that case, it becomes possible to intervene through one element to cause an effect on another connected component that may have proven difficult for direct intervention (Mukherji, 2020).

Several challenges remain for sound operationalization of the nexus, notably insufficient data, information, and knowledge in understanding the WEF inter-linkages and lack of systematic tools to address trade-offs involved in the nexus and to generate future projections (Liu et al., 2017a; Liu et al., 2018b). There are recent signs of progress in developing models and tools for addressing the nexus trade-offs, e.g., the bioenergy–water nexus (Ai et al., 2020). There is a need to move beyond viewing the WEF nexus as a way of problem identification to seek integrated solutions to interconnected problems.

[END BOX 4.8 HERE]

4.8 Enabling Principles for Achieving Water Security, Sustainable and Climate Resilient Development Through Systems Transformations

Sustainable development is a global policy priority and commitment, as is keeping temperatures well below 2°C as per the Paris Agreement. Water is central to almost all SDGs (Box 4.1). Water is explicitly referred to in SDG6 (clean water and sanitation) and SDG11 (sustainable communities and cities) (UN, 2015) (4.1). SDG1 (no poverty) is statistically linked to SDG6 (clean water and sanitation) (Pradhan, 2019), since reducing poverty can help increase adaptive capacity in line with the Paris Agreement adaptation goals (see Chapter 1 and Chapter 18). SDG2 (zero hunger) cannot be achieved without access to adequate water for agriculture. Meeting SDG 3 (health and wellbeing) will rely on access to basic infrastructure like water and sanitation ((Delany-Crowe et al., 2019), see Cross-Chapter Box HEALTH in Chapter 7, 4.3.3, 4.3.5), while SDG 7 (affordable and clean energy), will need water for hydropower production under changing climate (Berga, 2016; Byers et al., 2016) (4.5.2). Meeting SDG11 (sustainable cities and communities) will require reducing the impacts from water related disasters.

Water is also fundamental to all systems transitions, namely, transitions in energy, industrial, land and ecosystem and urban systems. Within energy and industrial system transitions, water stress for electricity generation has already caused impacts (4.3.2). Therefore, water efficiency measures are increasingly applied in both energy and industrial systems with benefits for mitigation and adaptation (4.6.3). Water is inextricably entwined with land and ecosystems transitions, with forested areas and ecosystems being integral components of the water cycle, regulating streamflow, fostering groundwater recharge and contributing to atmospheric water recycling (Takata and Hanasaki, 2020) (4.2). However, mitigation action of large afforestation, can have negative water impacts (Cross-Chapter Box 1 in Chapter 5 of WGI repor, 4.7.6), making it imperative to consider water footprint of land and forest-based mitigation (Muricho et al., 2019; Seddon et al., 2020) (4.7.6). Sustainable forest management and nature-based solutions (NbS) are promising alternatives for good water management (Muricho et al., 2019; Seddon et al., 2020). Water will also play a crucial role in sustainable urban transitions. Cities are already facing water related impacts (4.3.4), which are projected to intensify with every degree of global warming (Flörke et al., 2018; Nazemi and Madani, 2018) (4.5.4). Mitigation and adaptation measures in urban spaces, such as green infrastructure (Liu and Jensen, 2018), sustainable water supply management through recycling of wastewater and storm water runoff (Box 4.5), and NbS like sponge cities are fundamentally about water (Box 4.6).

Thus, water remains central to achieving SDGs, and will play a fundamental role in systems transitions needed for climate resilient development. We outline a set of seven enabling principles that are needed to achieving water security, and will also help in achieving SDGs and facilitate systems transitions.

4.8.1 Appropriate Technologies

AR5 concluded that successful adaptation across all sectors depends on access to technology, and technology transfer can play an essential role in building up adaptive capacity (Noble et al., 2014). SR1.5 discussed the role of efficient irrigation technologies in adaptation (de Coninck et al., 2018).

Technologies that reduce carbon emissions by promoting the efficient use of water can support successful adaptation (Biagini et al., 2014), provided they do not have adverse distributional outcomes (*medium evidence, high agreement*). Water management in agriculture has long seen the use of technology. For example, the use of technology to improve access to water, e.g., through the diffusion of groundwater pumps in the 1970s in South Asia, had several livelihood benefits but made agriculture more carbon-intensive (Zaveri et al., 2016). More recently, technology has been used to improve water use efficiency in agriculture through the adoption of drip and sprinkler irrigation (Zhuo and Hoekstra, 2017; Grafton et al., 2018); and the use of the Internet of Things (IoT) (Keswani et al., 2019). In addition, innovations to re-use water through various wastewater recovery technologies (Diaz-Elsayed et al., 2019; Capodaglio, 2020); and to create potable water through desalinization (Caldera et al., 2018); and re-use of wastewater in agriculture (Salgot and Folch, 2018) are also on the rise (Box 4.5). Solar technologies are increasingly used for irrigation, wastewater recovery, desalinization, and water harvesting (Algarni et al., 2018; Pouyfaucon and García-Rodríguez, 2018; Tu et al., 2018; Zhao F. et al., 2020). Machine learning and artificial intelligence technologies (Doorn, 2021) have started being used in many water-use sectors, such as urban (Nie et al., 2020); wastewater management (Abdallah et al., 2020; Ben Ammar et al., 2020), and agricultural water management, but mostly in high-income countries mostly on an experimental basis (Tsang and Jim, 2016; González Perea et al., 2018). Technology is being increasingly used in hydrological sciences for measurements and monitoring (SM4.1), as well as for creating comprehensive hydrometeorological warning systems (Funk et al., 2015). Lack of technology and knowledge transfer, especially related to remote sensing, is an adaptation barrier in states with less resources (Funk et al., 2015).

Adoption of technologies depends on the availability of finance (4.8.2). The effectiveness of technology in reducing climate-related risks depends on its appropriateness to the local context (Biagini et al., 2014; Mfitumukiza et al., 2020) and other factors, including institutional and governance frameworks (*high confidence*). Water technologies can also have unintended outcomes leading to maladaptation in some cases. For example, efficient irrigation technologies like drip and sprinkler irrigation, while reducing water application rates per unit of land, can increase overall water extraction by increasing total land under irrigation (van der Kooij et al., 2013; Grafton et al., 2018; Mpanga and Idowu, 2021). Water-related technologies can also have adverse distributional outcomes when gains from technology adoption accrue disproportionately to a small section of the population; for example, only rich and male farmers can adopt high-cost technologies like solar irrigation pumps (Gupta, 2019) (*medium confidence*).

In summary, technology is an important part of water adaptation response, and outcomes of technology adoption are mediated through other societal factors, including institutions, governance frameworks, and equity and justice issues (*medium evidence, high agreement*).

4.8.2 Adequate and Appropriate Financing

Although AR5 did not explicitly mention finance for water-related adaptation actions, it considered urban adaptation (Revi et al., 2014) and risk financing (Arent et al., 2014). SR1.5 (de Coninck et al., 2018) discussed governance and finance limitations, while SRCCL discussed finance in adapting to floods and droughts (Hurlbert et al., 2019).

Mitigation garners the significant share of committed climate finance. For example, of the total US$ 15.4 billion climate finance commitments through Green Bonds, 79% accrued to mitigation and the rest to adaptation (World Bank, 2017). However, within adaptation finance, water garners a significant share of adaptation funds, with 13% of the Adaptation Fund's investments were for water management, 12% for coastal management, and 10% for disaster risk reduction (Adaptation Fund, 2018). Similarly, within the urban adaptation landscape, which got ~3% to 5% of total adaptation finance flows of US$ 30.8 billion tracked in 2017-18 (Richmond et al., 2021), water and wastewater management projects received the largest share of urban adaptation finance (US$ 761 million annually) followed by disaster risk management (US$ 323 million) (Richmond et al., 2021). However, more frequent tracking of public financing is required, with a greater focus on transparency and accountability (Ciplet et al., 2018; Khan et al., 2020) and justice and social equity (Emrich et al., 2020) (also see Cross-Chapter Box FINANCE in Chapter 17).

Private financing remains a minor source of adaptation financing (World Bank, 2019). Around 39% of green bonds issued in 2017 were for water, wastewater, and solid waste management (World Bank, 2017). In 2018, US$100.5 billion of water-themed bonds were issued, mainly in Europe (63%), the Asia Pacific (19.6%), and North America (14.9%) (Filkova et al., 2018; World Bank, 2019). Such financing focuses on returns and scale (Cholibois, 2020), and as such, local needs, especially those of the poor, may not be adequately represented (Manuamorn et al., 2020; Williams, 2020) (*medium confidence).*

COVID-19 will probably affect adaptation financing in water. Countries will be fiscally stretched to finance public investments domestically and through international development aid (Barbier and Burgess, 2020). However, investments in flood and drought management (Phillips et al., 2020) and water and sanitation (Armitage and Nellums, 2020b; Bhowmick et al., 2020) are critical for building resilience against pandemics, are also crucial elements of adaptation in water. Therefore, integrated approaches that achieve both goals need to be deployed (Barbier and Burgess, 2020; Newell and Dale, 2020) (Box 4.4., Cross-Chapter Box COVID in Chapter 7).

In summary, water garners a significant share of public and private adaptation funds (*high confidence*). However, current COVID-related cuts in adaptation financing may further impede developing countries' ability to invest in adequate water adaptation.

4.8.3 Gender, Equity and Social Justice

SR 1.5 acknowledged that the adaptative capacity of a population was going to reduce with each degree of warming and that vulnerability to climate change was due to gender, race and level of education, which can compound existing and future vulnerabilities (IPCC, 2018a).

Gender, class, race, age, physical ability and educational level determine access to water, financial and societal resources, potentially adverting climate-induced water hazards, reducing vulnerability and facilitating adaptation. However, insufficient attention has been given to the role of improving equity in access to water (Abedin et al., 2019; Eakin et al., 2020). Not all water adaptation strategies are accessible to the poorest, who may turn to maladaptive strategies if their access to water is negatively affected (Eakin et al., 2016). Consequently, there have been calls for mainstreaming equity considerations into adaptation (Blackburn and Pelling, 2018) *(medium evidence, high agreement)*. It has been shown that people living in poverty, racial minorities and those ageing are more vulnerable to climate-induced water hazards and that their adaptive capacity is limited (Szewrański et al., 2018; Winsemius et al., 2018; Nyantakyi-Frimpong, 2020; Erwin et al., 2021). Among these categories, gender is the one that has been most analyzed in the context of water and climate change.

Women’s water rights are hampered by societal patriarchal norms that prevent women from accessing water and participating in water management. Gender power relations effectively limit women’s decision-making power, mobility and access to resources, including water, which makes them more vulnerable to climate-related hazards (Caretta and Börjeson, 2015; Djoudi et al., 2016; Sultana, 2018; Yadav and Lal, 2018). In most societies in developing countries, women and girls are in charge of fetching water. The necessity of water collection takes away time from income-generating activities and education (*high confidence*) (Fontana and Elson, 2014; Kookana et al., 2016; Yadav and Lal, 2018). In addition, the distances women and girls would have to walk as a result of growing water scarcity due to climate change may increase (*limited evidence, high confidence*) (Becerra et al., 2016) (4.3.3, 4.5.3). Numerous studies substantiate a male bias in information access, employment opportunities, resource availability, and decision-making in water-related adaptation measures (Huynh and Resurreccion, 2014; Sinharoy and Caruso, 2019).

Although women are often depicted as victims of climate change-induced water scarcity (Huynh and Resurreccion, 2014; Djoudi et al., 2016; Gonda, 2016; Yadav and Lal, 2018), they are also proactive adaptation actors (Singh and Singh, 2015) (Cross-Chapter Box GENDER in Chapter 18). Notably, women are not a homogenous group, and local gender roles are not immutable or generalizable (Carr and Thompson, 2014; Djoudi et al., 2016; Gonda, 2016; Sultana, 2018). Coping responses and adaptation mechanisms to climate change are profoundly gendered. Women and men approach the diversification of agricultural and pastoral livelihoods differently in response to climate change (Caretta and Börjeson, 2015; Kankwamba et al., 2018; Singh et al., 2018; Basupi et al., 2019). For example, reliance on women’s self-help groups and associations has proven successful in ensuring women’s participation in decision-making in adaptation interventions as a response to climate change-induced shifting precipitation patterns and increasing droughts (Chu, 2017; Mersha and van Laerhoven, 2018; Phuong et al., 2018; Walch, 2019). Studies feature water harvesting, crop diversification, cash transfer programs, and food subsidies as adaptation measures that enhance gender equality. Adaptation to climate change in these instances promoted gender equality because it allowed women to reap the benefits of these new measures in terms of economic and health wellbeing (Tesfamariam and Hurlbert, 2017; Lindoso et al., 2018; Walch, 2019).

Meanwhile, adaptation interventions such as drip irrigation, the adoption of more labor-intensive crops, and livelihood diversification through male out-migration have proven to increase women’s burden (Caretta and Börjeson, 2015; Kattumuri et al., 2017). Hence, a lack of gender-sensitive analysis before implementing water management projects can lead to maladaptation and increase gender vulnerability (Phan et al., 2019; Eriksen et al., 2021) (*high confidence)*.

Acknowledging and understanding the implications of climate-related water adaptation policies in terms of equity and justice is a prerequisite for ensuring their legitimacy and inclusiveness and promotes social justice (Carr and Thompson, 2014; Djoudi et al., 2016; Jost et al., 2016; Sultana, 2018). Furthermore, integrating the principle of gender inclusivity in adaptation is morally and ethically appropriate and effective because women hold much of the local and traditional knowledge in many agricultural communities and can fruitfully provide insights on how to design and implement adaptation responses (Fauconnier et al., 2018; James, 2019).

In summary, there is *high confidence* that the effects of climate change-induced water insecurity are not evenly felt across populations. Particularly vulnerable groups are women, children, disabled and Indigenous Peoples, whose ability to access adequate water is limited and varies across race, ethnicity and caste. Equity and justice are central to climate change adaptation and sustainable development, as the world's poorest people and countries feel the adverse impacts of a changing climate most acutely. These groups can become even more vulnerable due to adaptation actions that are not equitable.

4.8.4 Inclusion of Indigenous Knowledge and Local Knowledge

AR5 concluded that there is *robust evidence* that mutual integration and co-production of local and traditional and scientific knowledge increase adaptive capacity and reduce vulnerability (Adger and Pulhin, 2014). SROCC stated with *medium confidence* that Indigenous Knowledge (IK) and local knowledge (LK) provide context-specific and socio-culturally relevant understandings for effective climate change responses and policies (Abram et al., 2019). SRCCL found that IK and LK contribute to enhancing resilience against climate change and combating desertification (*medium confidence*). The combination of IK and LK with new sustainable land management techniques, SRCCL stated with *high confidence*, can contribute to raising resilience to the challenges of climate change and desertification (Mirzabaev et al., 2019).

There is *high confidence* that adaptation efforts benefit from the inclusion of IK and LK (Mustonen et al., 2021). IK and LK can inform how climate change impacts and risks are understood and experienced. Holders of IK and LK can also help to develop place-based and culturally appropriate adaptation strategies that meet their expectations (Comberti et al., 2019; Martinez Moscoso, 2019) (Cross-Chapter Box INDIG in Chapter 18).

There is *high confidence* that genuine partnerships with Indigenous Peoples and local communities can assist in decolonising approaches to freshwater management (Arsenault et al., 2019; Wilson et al., 2019), which recognise the importance of knowledge that is not grounded on the technocratic division between nature and society (Goldman et al., 2018). There is also *high confidence* that Indigenous-led freshwater management can facilitate culturally inclusive decision-making and collaborative planning processes at the local and national levels (Somerville, 2014; Harmsworth et al., 2016; Parsons et al., 2017). However, market-based models of water rights regimes can impede the ability of Indigenous Peoples to exercise their rights and deploy traditional ecological knowledge regarding freshwater protection (Nursey-Bray and Palmer, 2018) (*medium evidence, high agreement*).

Community-led actions and restoration measures are helping to ameliorate climate impacts and provide "safe havens" to affected freshwater species (*high confidence*). For example, the Skolt Sámi of Finland have introduced adaptation measures to aid survival of culturally-significant Atlantic salmon stocks in the Näätämö watershed. Atlantic salmon had declined as northern pike, which preys on juvenile salmon, expanded its range in response to warmer water temperatures. Indigenous co-management measures included increasing the catch of pike and documenting important sites (such as lost spawning beds) to ensure ecological restoration encourages further habitat and increased salmon reproduction (Pecl et al., 2017; Mustonen and Feodoroff, 2018).

Community-led applications of IK and LK in conjunction with external knowledge and funding can improve water security (*high confidence*). For example, Borana pastoralists in Ethiopia (Iticha and Husen, 2019) and Ati and Suludnon people (Philippines) (Nelson et al., 2019) utilise both IK and technical information for weather forecasting, while Calanguya people (Philippines) collaborated with local government and NGOs to diversify crops and protect the watershed (Gabriel and Mangahas, 2017). With assistance from municipalities, Indigenous Peoples are rehabilitating springs and traditional water wells in Bangladesh hill tracts (Sultana et al., 2019) and Micronesia (McLeod et al., 2019). In response to changing cryosphere conditions in the Peruvian Andes, Indigenous Quechua farmers use IK and technical information in community-led research to preserve biocultural knowledge and emblematic crops (Sayre et al., 2017). In Galena, Alaska (USA), a flood-preparedness and response program have benefitted from the long-term cooperation between emergency management and tribal officials (Kontar et al., 2015) (12.5.3.2 Main concepts and approaches). IK and LK can enhance the visibility of Indigenous Peoples and local communities that are excluded from official decision-making processes. In southwest Burkina Faso, for example, Indigenous Peoples are using IK and LK to balance (and sometimes resist) official technical estimates of water availability, which enhances their political visibility and enables them to address water scarcity (Roncoli et al., 2019).

There are structural and institutional challenges in knowledge co-production between holders of IK and LK and "technical" knowledge. These challenges include issues of water rights, language, and extractive research practices (Ford et al., 2016; Simms et al., 2016; Stefanelli et al., 2017; Arsenault et al., 2019), and colonial uses of IK and LK (Castleden et al., 2017), which can produce distrust among holders of IK and LK (David-Chavez and Gavin, 2018). In addition, some IK is sacred and cannot be shared with outsiders (Sanderson et al., 2015).

In summary, IK and LK are dynamic and have developed over time to adapt to climate and environmental change in culturally specific and place-based ways (*high confidence*). Ethical co-production between holders of IK and LK and technical knowledge is a key enabling condition for successful adaptation measures and strategies pertaining to water security, as well as other areas (*medium evidence, high agreement*). Knowledge co-production is a vital and developing approach to the water-related impacts of climate change that recognises the culture, agency and concerns of Indigenous Peoples and local communities. It is critical to developing effective, equitable and meaningful strategies for addressing the water-related impacts of global warming (Cross-Chapter Box INDIG in Chapter 18).

4.8.5 Participative, Cooperative and Bottom-up Engagement

Participation, cooperation and bottom-up engagement are critical to optimal adaptation *(medium evidence-high agreement).* There is *high confidence* that many of the countries and social groups most threatened by climate change have contributed the least to global emissions and do not have not the resources to adapt. Effective participation of these actors in climate change adaptation planning in the water sector can contribute to more just adaptation actions *(high confidence).*

There is *medium evidence*, *high agreement* that optimal adaptation depends critically on inter-state cooperation (Banda, 2018), which in turn requires trust and norms of reciprocity among all those involved (Ostrom, 2014). Reciprocity is central to international cooperation on climate change, where actors are more inclined to cooperate when they perceive that the expected outcome will be fair in terms of costs and benefits of implementation (Keohane and Oppenheimer, 2016). Indeed, cooperation at the international level is less probable to occur if participants do not trust each other's (Hamilton and Lubell, 2018). In climate-related water adaptation, transboundary cooperation is essential, as 60% of global freshwater resources contained in 276 river and lake basins are shared between countries (Timmerman et al., 2017). Yet, more than 50% of the world 310 international river basins lack any type of cooperative framework (McCracken and Meyer, 2018).

SDG 6 on water and sanitation includes a specific indicator (6.5.2) to assess cooperation over transboundary waters. While the methodology for measuring this indicator is debated, it is clear that its composition will influence international and national water policy and law (McCracken and Meyer, 2018) and possibly help build an environment of trust among riparian states. Moreover, although the 2030 Agenda for Sustainable Development (A/RES/70/1) makes it clear that without the participation of local communities (e.g., SDG 6, target 6. B) and women (e.g., SDG5, target 5.5.), the SDGs will not be met, the involvement of these actors in formal water governance processes and water management is still limited (Fauconnier et al., 2018). This is due partly to the absence, in many regions of the world, of adequate legal, regulatory and institutional frameworks for effective stakeholder's participation, partly to the influence of local social and cultural contexts, which can discourage inclusive water governance (Andajani-Sutjahjo et al., 2015; Dang, 2017). Yet, inclusion and effective participation in bottom-up decision-making processes of those disproportionately affected by climate change – including women and Indigenous Peoples - is particularly important to ensure the legitimacy and inclusiveness of the decision-making process and the design of socially just adaptation actions (Shi et al., 2016). Moreover, incentives for bottom-up and participative decision-making in the water sector can facilitate effective stakeholder engagement (OECD, 2015), which helps build public confidence and trust in water governance.

4.8.6 Polycentric Water Governance

SR1.5 concluded with *high confidence* that cooperation and coordinated actions at various governance levels are vital to ensuring participation, transparency, capacity-building and learning among different actors (IPCC, 2018a). According to SRCCL, adaptive governance builds on multi-level and polycentric governance (Hurlbert et al., 2019), where efforts taken by multiple actors across different scales provide learning opportunities for all (Hurlbert, 2018).

Polycentrism is characterized by the absence of a unique centre of authority. Therefore, the legitimacy of the decisions taken by multiple decision-makers at different levels of water governance derives from the perceived fairness of the decision-making process (Baldwin et al., 2018) and the inclusion of women, Indigenous Peoples and young people (Iza, 2019) (*medium confidence*). Evidence-based approaches can also enhance the legitimacy of polycentric governance (Boelens et al., 2015; Arriagada et al., 2018) by generating knowledge to support localized and multileveled decision-making, as in the case of water user communities in Peru (Buytaert et al., 2014; Buytaert et al., 2016).

The advantages of polycentric approaches to climate governance include improved communication, inclusiveness, consensus and better outcomes (Ostrom, 2014; Cole, 2015; Keohane and Victor, 2016; Morrison et al., 2017; Tormos-Aponte and García-López, 2018) (*high agreement*). However, polycentric governance systems require cross-scale information sharing, coordination and democratic participation to work appropriately (Pahl-Wostl and Knieper, 2014; Carlisle and Gruby, 2017; Morrison et al., 2017; Biesbroek and Lesnikowski, 2018; Frey et al., 2021) (*high confidence*). For example, efficient information sharing has been necessary to implement groundwater governance in transboundary contexts (Albrecht et al., 2017).

Empirical studies that examined the potential of polycentric governance to address water challenges in the face of climate change showed that polycentrism could encourage and support participatory, decentralized and deliberative adaptation. These, in turn, can produce better environmental outcomes and improve water governance outcomes (*high confidence*). Polycentric water governance can be an effective enabler for adaptation when it ensures interconnectedness with multiple public and private actors across the different sectors (e.g. irrigation users, domestic users, industrial users, watershed institutions, etc.) and across different levels (e.g. local, regional and national governments) to help come up with well-coordinated water adaptation responses (*high confidence*) (Pahl-Wostl and Knieper, 2014; McCord et al., 2017; Baldwin et al., 2018; Hamilton and Lubell, 2018; Kellner et al., 2019).

Questions remain about the extent to which polycentrism can result in either greater climate justice or exacerbate existing inequalities due, for example, to existing power inequalities which may affect the performance and effectiveness of a polycentric system (Pahl-Wostl and Knieper, 2014; Morrison et al., 2017; Hamilton and Lubell, 2018; Okereke, 2018). For instance, historical inequities and injustices due to settler colonialism and top-down water policies, governance and laws (Collins et al., 2017; Arsenault et al., 2018; Johnson et al., 2018; Robison et al., 2018) have resulted in long-term water insecurity in many Indigenous communities in North America (Simms et al., 2016; Medeiros et al., 2017; Conroy-Ben and Richard, 2018; Diver, 2018; Emanuel, 2018) (*high confidence*) (4.6.9). Additionally, studies highlight that power dynamics can undermine the success of those initiatives. For example, in the Sao Paulo water crisis, polycentric governance did not fully realize its potential when it was guided by authoritarian governance favouring political interests over social, territorial and environmental justice (Frey et al., 2021). Likewise, in the Thau basin (France), the most important and influential actors shaped policy measures in response to climate change, thus limiting the potential for radical changes in water use (Aubin et al., 2019).

In summary, polycentric governance can enable improved water governance and effective climate change adaptation (*medium confidence*). However, it can also exacerbate existing inequalities as long as less powerful actors, such as women, Indigenous Peoples and young people, are not adequately involved in the decision-making process *(high confidence).*

4.8.7 Strong Political Support

According to AR5 (Jiménez Cisneros et al., 2014), barriers to adaptation in the water sector include lack of institutional capacity, which, together with political support, constitutes one of the feasibility dimensions towards limiting global warming to 1.5°C (de Coninck et al., 2018). As the IPCC SROCC (IPCC, 2019a) and SRCCL (Shukla et al., 2019) suggest, limited institutional support can challenge adaptation efforts in water management.

Climate adaptation planning approaches can be constrained by several economic, institutional, developmental and political barriers (Anguelovski et al., 2014; Eisenack et al., 2014), including strong political support, that is, the lack of collective willingness to take action. Despite the ongoing accumulation of scientific evidence as to the seriousness of the impact of climate change on water resources, state action has not always been effective. There are now a rising number of case laws addressing the state's failure to implement adaptation policies and resultant climate change litigation (Setzer and Vanhala, 2019; Peel and Osofsky, 2020), including in the water sector, as in the leading case Leghari v Federation of Pakistan (2015 WP. No. 25501/201), in which a farmer sued the national government for failure to carry out national climate change policies impacting on the constitutional right to life (Preston, 2016).

The 2015 Paris Agreement made a significant impact on the status quo, with almost all the countries agreeing to limit global warming to 2°C or less. The preparation of NDCs under the Paris Agreement contributed positively to national climate policies and helped focus on the centrality of water in adaptation planning (Röser et al., 2020). 92% of countries that mention adaptation in NDCs also include water (GWP, 2018). Low-income countries make specific reference to rainfed or irrigated agriculture and livestock. In contrast, middle and high-income countries include developing management, governance mechanisms and increased disaster risk reduction in their NDC pledges (GWP, 2018). Floods were the critical climate hazards identified in the adaptation components of NDCs, followed by droughts (85 out of countries for floods and 80 out of 137 for drought). Also, the water sector was identified as the top priority sector for adaptation actions in the NDCs for 118 out of 137 countries, followed closely by the agricultural sector with 100 out 137 (GWP, 2018) based on data from (UNFCCC, 2017). Many developing countries have included quantitative targets for adaptation in the water sector (Pauw et al., 2018). Similarly, water-related impacts and adaptation often feature prominently in NAPs (DEFRA, 2018).

Evidence suggests that adaptation failure in the water sector is due to policy and regulatory failures (Keohane and Victor, 2016; Oberlack and Eisenack, 2018; Javeline et al., 2019) reflecting political myopia (Muller, 2018; Empinotti et al., 2019; Pralle, 2019) (*high confidence*).

International donors and supranational/transnational legislation (e.g. EU law) can support the capacity of national and sub-national governments to act and remove possible barriers to the effective implementation of climate change adaptation policies in the water sector, including obstacles posed due to lack of financial support for the developing countries (Massey et al., 2014; Tilleard and Ford, 2016; Biesbroek et al., 2018; Rahman and Tosun, 2018) (*medium confidence*).

[START FAQ4.1 HERE]

FAQ4.1: What is water security, and how will climate change affect it?

Water is essential for all societal and ecosystems needs. Water security is multi-dimensional and not just about water availability. Water needs to be available in sufficient quantity and quality and needs to be accessible in an acceptable form. Accordingly, a situation of water security indicates the availability and accessibility of sufficient clean water to allow a population to sustainably ensure its livelihoods, health, and socio-economic development and political stability. Many socio-economic factors, such as population *growth and food consumption patterns, play an important role in determining water security. Still, climate change is increasingly shown to be an important contributor to water insecurity worldwide, with some regions more at risk than others.*

Climate change can affect these different dimensions of water security in different ways. Most directly, climate change is affecting the overall availability of water across regions and during important seasons. More extended periods of dry spells and droughts are already affecting water availability, especially in the arid areas of India, China, the USA and Africa. Other extremes, such as heavy precipitation and flooding, can affect water quality, making water unsafe for drinking, for example. In coastal regions and small islands, the combined effects of higher sea levels and more intense storms affect water security by increasing the salinization of groundwater resources. Indirect effects of climate change on water security include impacts on infrastructure for the provision and recovery of water resources, which can affect the safe access to adequate water resources, both in terms of quality and quantity.

In terms of assessing the extent of water scarcity, studies estimate that currently, between 1.5 and 2.5 billion people live within areas exposed to water scarcity globally. These numbers are projected to increase continuously, with estimates of up to 3 billion at 2°C and up to 4 billion at 4°C by 2050. Many socio-economic factors, such as population growth and food consumption patterns, determine water scarcity. Still, climate is increasingly shown to be an important component that drives scarcity across the world. Water scarcity is often a seasonal occurrence, and climate change is projected to increase seasonal extremes. Often consecutive years with drier conditions lead to a long-term decrease in groundwater tables, affecting water availability directly and soil moisture in the longer term.

As an essential component of water security, climate change will affect water quality in different ways. Drier conditions lead to a reduction in water availability, causing a potential increase in the concentration of contaminants. Increasing runoff and floods can wash pollutants into water bodies. With climate change projected to increase the variability of rain over space and time, such impacts on water quality are becoming increasingly likely. Higher temperatures add to deteriorating water quality by reducing oxygen levels.

Another critical component to ensure secure access to water resources is adequate water infrastructure for access, disposal and sanitation. Unfortunately, increasing extremes due to climate change, especially floods and increasing storm activity, have great potential to damage such infrastructure, especially in developing world regions, where infrastructure is much more susceptible to damage and pollution.

There are substantial differences in the distribution of risks across regions, with some areas facing a much higher risk burden than others. Also, projections of the potential impacts of climate change on water security vary across regions. However, patterns of projected water-related extremes are emerging more clearly globally with increasing confidence.

[END FAQ4.1 HERE]

[START FAQ4.2 HERE]

FAQ4.2: Which places are becoming wetter and which are becoming drier, and what risks do these bring to people?

Due to climate change, substantial numbers of people are now living in climates with average precipitation levels significantly different to the average over the 20th century. Nearly half a billion people are living in unfamiliar wet conditions, mostly in mid- and high-latitudes, and over 160 million people are living in unfamiliar dry conditions, mostly in the tropics and sub-tropics. In addition to changes in average precipitation, precipitation patterns over time are also changing, as well as river flows. Societal impacts and increased risks from both wetter and drier conditions are starting to emerge.

Some parts of the world are becoming wetter and some are becoming drier, in terms of either changes in precipitation and/or the water available in the soil, in rivers, or underground. Soil moisture, river water and groundwater are affected by changes in precipitation and also by changes in evaporation, which is affected by temperature and by uptake by vegetation.

All these factors are affected by climate change. Rising temperatures drive higher evaporation, which dries the landscape, although this can be offset in some areas by reduced uptake of water from the soil by plants in response to rising CO_2 concentrations. A warming climate brings more precipitation overall, although changes in global wind patterns mean that some areas are seeing less precipitation.

As a result, substantial numbers of people are now living in climates with average precipitation levels significantly different to the average over the 20th century. Nearly half a billion people are living in unfamiliar wet conditions, mostly in mid- and high-latitudes, and over 160 million in unfamiliar dry conditions, mostly in the tropics and sub-tropics (Figure FAQ4.2.1).

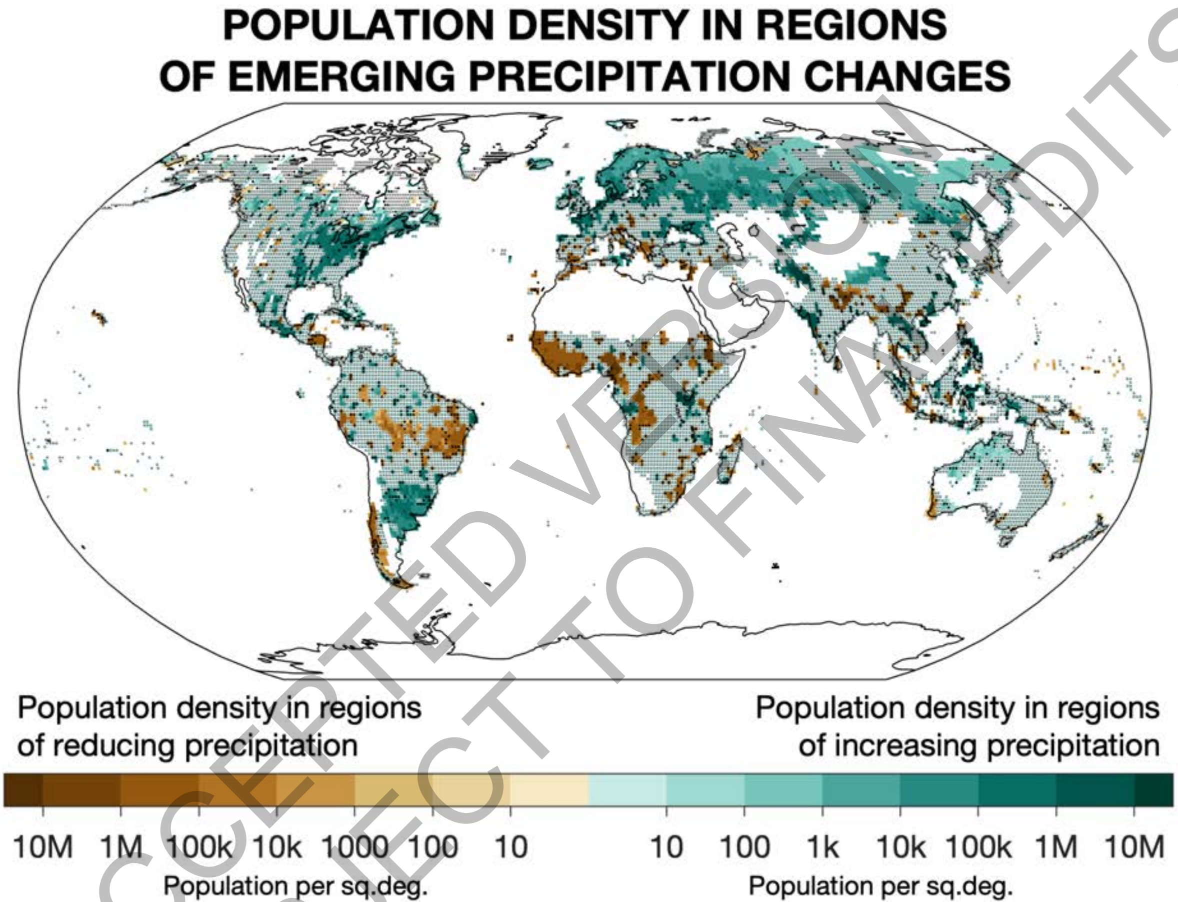


Figure FAQ4.2.1: Numbers of people seeing increases and decreases in precipitation.

In addition to changes in average precipitation, the patterns over time are also changing, such as the length of dry spells and the amount of precipitation falling in heavy events. Again, these changes vary across the world due to shifting wind patterns. Approximately 600 million people live in places with longer dry spells than in the 1950s, mostly in West Africa, south Asia and parts of South America. Approximately 360 million people experience shorter dry spells, in North America, northern Asia and other parts of South America.

In contrast, far more people (about 600 million people) are seeing heavier precipitation than less heavy precipitation (80 million). A more widespread increase in heavy precipitation is expected in a warming world, where the warmer atmosphere takes up more moisture and hotter ground drives more intense storms.

River flows are also changing in many parts of the world, often due to changes in precipitation, although direct human impacts are also important. Generally, the most widespread increased river flows are seen high latitudes, while decreasing flows are seen in mid- and low- latitudes, although there are major exceptions to these trends and data is sparse in many regions (Figure FAQ4.2.2).

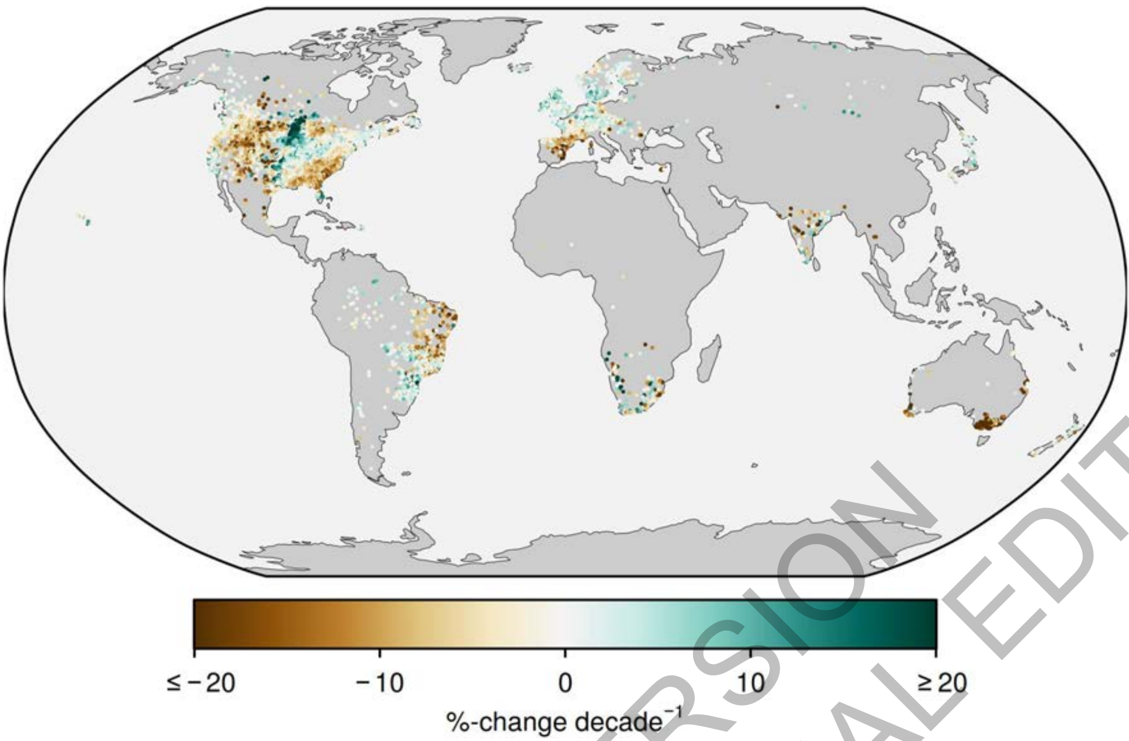


Figure FAQ4.2.2: Observed changes in mean river flows from 1971-2010

Some of these changes are starting to have impacts on society. For example, increasing rainfall in the USA has led to increased crop yields. Heavy rainfall and long periods of rainfall lead to flooding, causing deaths, injuries, infrastructural damage, spread of disease, disruptions to employment and education, psychological trauma, and territorial displacement. The weather conditions associated with many recent major flooding events were made *more likely* by climate change, although non-climatic factors remain the dominant driver of increased flooding.

Drier soils have made heatwaves more severe. A drying of the landscape has increased the length of the fire season across much of the world, contributing to unprecedented severity of wildfires in recent years. In recent years, several major drought events with impacts on agriculture were made *more likely* by climate change.

Overall, the general picture is of increased average precipitation and/or longer periods of precipitation in the mid and high latitudes, but decreased precipitation and/or longer times between precipitation across much of the tropics and sub-tropics. Where heavy precipitation is changing, this is mostly towards increasing intensity. Societal impacts and increased risks from both wetter and drier conditions are starting to emerge.

[END FAQ4.2 HERE]

[START FAQ4.3 HERE]

FAQ4.3: How will climate change impact the severity of water-related disasters, such as droughts and floods?

Climate change will lead to populations becoming more vulnerable to floods and droughts due to an increase in the frequency, magnitude, and total area affected by water-related disasters. Floods and droughts will also affect more people in the course of this century as a result of population growth and increased urbanization, especially if warming cannot be limited to 1.5°C. The impact of floods and droughts *are expected to increase across all economic sectors, resulting in negative outcomes for the global production of goods and services, industry output, employment, trade, and household consumption. Floods will pose additional risks to people's lives and health through inundation, facilitating the further spread of waterborne diseases. At the same time, droughts can have adverse health impacts due to the limited availability of food and water for drinking and hygienic purposes. All losses, both in terms of lives and in economic terms, will be more limited in a 1.5°C than in a 3°C warmer world.*

Anthropogenic land-use changes and climate change will exacerbate the intensity, frequency and spatial extent of floods and droughts, leading to populations becoming more vulnerable. According to projections, these increases in extreme events will be more significant with higher levels of global warming. However, the location and severity of floods and droughts are context-dependent and complex phenomena.

The processes that lead to droughts include lack of or less frequent precipitation, increased evapotranspiration, and decreased soil moisture, snow cover, runoff, and streamflow. For example, warming temperatures may result in higher evapotranspiration, in turn leading to drier soils. In addition, reduced soil moisture diminishes the amount of water filtering into rivers in both the short and long term while also increasing the aridity that can foster the conditions for fire. Moreover, decreased snow cover represents less runoff supply to downstream areas during warmer seasons. Depending on this process and the propagation of a meteorological drought onto further systems, a drought can be defined as hydrological, agricultural or ecological. Agricultural drought threatens food production through crop damage and yield decreases, and consequent economic impacts and, therefore, can be the most impactful to humans. Geographically the likelihood of agricultural drought is projected to increase across most of southern Africa, Australia, the majority of Europe, the southern and western United States, Central America and the Caribbean, north-west China, parts of South America, and the Russian Federation; but due to increased precipitation, it is projected to decline in, Southeastern South America, Central Africa, central Canada, western India and the south of the Arabian Peninsula.

Flood hazard natural processes usually result from increases in heavy precipitation events, but they can also be caused by saturated soils, increased runoff and land-use changes. A warming climate usually causes greater energy for the intense upward motion for storm formation and increases evapotranspiration, which leads to heavier precipitation. Many places around the world will experience more than average rainfall, which may increase soil moisture. Wetter soils saturate faster during precipitation events, resulting in increased runoff that can muddy the waters and lead to floods. Anthropogenic land-use changes, such as urbanization, deforestation, grasslands, and agricultural extension, can also reduce the amount of water infiltrating the soil and leading to frequent flooding. Floods are expected to increase in Asia, the U.S., and Europe, particularly in areas dependent on glaciers' water where melting will lead to earlier spring floods. Additionally, fluvial floods are projected to be more frequent in some regions in central Africa and northern high latitudes and less frequent in the southern areas of North America, southern South America, the Mediterranean, parts of Australia and southern parts of Europe.

Globally, socioeconomic development will lead to heightened societal hazards. Due to population growth and increased urbanization, floods and droughts will affect more people in the course of this century, especially if warming cannot be limited to 1.5°C. All losses, both in lives and in economic terms, will be more limited in a 1.5°C than in a 3°C warmer world. The impacts of floods and droughts are expected to increase across all economic sectors, from agriculture to energy production, resulting in negative outcomes for our global production of goods and services, industry output, employment, trade and household consumption. Landslides, sinkholes and avalanches arising from heavy rainfall events will increasingly threaten infrastructure and agricultural production. In cities, increased flood frequency could disrupt waste management systems, resulting in the clogging of waterways. In addition, unprecedented flood magnitudes could overwhelm hydraulic infrastructure, affecting the energy, industry, and transportation sectors. An expansion in inundation area, coupled with urban sprawl, would increase flood damage. Floods will pose additional risks to people's lives and health through inundation, facilitating the spread of waterborne diseases. At the same time, drought can have adverse health impacts due to the limited availability of food and water for drinking and hygienic purposes. Although there are no agreed-upon projections for migration and displacement due to water-related disasters, it is known that drought and desertification cause harvest failures, which may lead subsistence farmers to relocate to urban areas. Whether temporary or permanent, displacement is often mired with diminished safety, loss of social ties, and a weakened sense of place and cultural identity.

Finally, vulnerable groups such as people living in poverty, women, children, Indigenous Peoples, uninsured workers, and the elderly will be the most affected by water-related disasters.

[END FAQ4.3 HERE]

[START FAQ4.4 HERE]

FAQ4.4: Globally, agriculture is the largest user of water. How will climate change impact this sector, and how can farmers adapt to these changes?

Climate-induced changes in the global hydrological cycle are already impacting agriculture through floods, droughts and increased rainfall variability, which have affected yields of major crops such as maize, soybeans, rice and wheat. These changes are projected to continue in a warmer world, which will cause yields of rain-fed crops to decline and reduce the amount of water available for irrigation in water-stressed regions. Farmers already use adaptation and coping strategies to manage agricultural water use. Some of the most important adaptation responses are the application of irrigation, on-farm water and soil conservation; changing cropping patterns; adopting improved cultivars, and improved agronomic practices. In many parts of the world, farmers increasingly use Indigenous Knowledge and local knowledge to inform their decisions of what to grow, when to grow, and how much to irrigate. To offset the risks of market-related volatility coupled with climate change, farmers also adopt economic and financial instruments such as index-based crop insurance. Training and capacity building programs and social safety nets are other forms of adaptation that farmers are using to respond to these changes.

Worldwide, and especially in developing countries, agriculture (including crop cultivation and livestock and fisheries) is the largest water user, accounting for 50% to 90% of all water use. Moreover, a substantial part of the water used in agriculture is "consumptive" use, which means that the water is "consumed" for crop growth and is not immediately available for other uses. This is different from other sectors, such as energy production, where only a fraction of the water is "consumed", and other downstream users can re-use the rest. Agriculture also accounts for a large share of employment in developing countries, with 60 to 80% of the rural population dependent on agriculture for their livelihoods. Agriculture provides food security for all. This makes farmers and agriculture particularly vulnerable to climate change.

Climate-induced changes in the global hydrological cycle are already impacting agriculture through floods, droughts and increased rainfall variability. For example, loss in yields has been reported for major crops such as maize (by 4.1%), soybeans (by 4.5%), rice (by 1.8%) and wheat (by 1.8%) due to changes in precipitation between 1981 to 2010. In addition, drought has affected both the area under cultivation and the yields of major crops. According to one estimate, globally, there has been a loss of 9 to 10% of total cereal production due to droughts and other weather extremes. Similarly, floods are one of the significant reasons for crop losses worldwide. Climate change-induced losses in livestock and fisheries have also been documented. In some parts of the world, especially in cold temperate zones, agro-climatic zones have become more conducive to yield growth in crops like maize and soybean due to increases in summer precipitation. Yet, negative impacts far outweigh positive impacts.

Projected impacts on agriculture due to changes in water availability are also severe. For example, yields of rain-fed crops such as maize are projected to decline by 1/5th to 1/3rd by the end of the century. In contrast, many areas which currently support multiple crops may become unsuitable for rain-fed farming or support only one crop in a year. Irrigation, which is often one of the most effective adaptive strategies against water-induced stress, is also projected to be affected by a reduction of the amount of water available for irrigation in some parts of the world that are already water-stressed or as a result of groundwater depletion in places such as India, North China, and the north-western United States. Overall, future droughts and floods will pose a major risk to food security, and agriculture and impacts will be more severe on countries and communities that are already food insecure.

Given that farmers are already dealing with variability in the amount and timing of rainfall. In many places, demand for agricultural water is greater than supply, and farmers are using many adaptations and coping strategies to meet water demands for their crops, fish and livestock. Some of the most popular adaptation responses around crops and water include:

- changing cropping patterns to less water-intensive crops, and changes in the timing of sowing and harvesting to respond to unfamiliar trends in the onset of rains;
- adoption of improved cultivars, such as drought and flood-resistant seed varieties;
- improved agronomic practices, including conservation agriculture that helps reduce water application rates;
- irrigation and water-saving technologies such as efficient irrigation and on-farm water management techniques;
- on-farm water and soil moisture conservation.

Most of these measures are beneficial across multiple indicators (water saving, increased incomes etc.), however, whether they also reduce climate related risks is not well understood and remains a knowledge gap. Irrigation and changes in crop choices and cultivars are also shown to be effective for future adaptation, especially at 1.5°C global warming levels, but much less effective at 2°C and 3°C when these responses will not mitigate a large part of the climate risk. Most of these adaptation measures mentioned above are autonomous. However, some, such as improved seeds and cultivars, are supported by national agricultural research agencies, international research coalitions such as the CGIAR, and private seed companies. In many parts of the world, farmers are also increasingly using Indigenous Knowledge and local knowledge to inform these decisions of what to grow, when to grow, and how much to irrigate.

Given the predominance of market economies worldwide, most farmers also depend on the market to sell their produce, and market fluctuations affect their incomes. In addition, market-related volatility coupled with climate change is a source of increased risk for farmers. Several economic and financial instruments are being used with varying levels of success to offset some of these interlinked impacts. Index-based crop insurance is one such instrument that compensates farmers for losing crops due to hazards such as floods and droughts. However, several limitations in their implementation remain.

In cases of severe droughts and floods, which have debilitating impacts on already poor and vulnerable populations, national governments provide social safety programs, such as food or cash-for-work programs, which are shown to be successful in reducing risks for the most vulnerable people, even though there are often concerns with targeting efficiency. Providing training and capacity building of farmers to adopt new farming practices and technologies to manage risk better are also known to be effective when the training is conceptualized, targeted and implemented in consultation with farmers. Planned adaptation practices include managing weather and market risks through insurance products, social safety nets for vulnerable populations, and providing the right mix of training and capacity building. These adaptation practices are generally implemented by civil society, governments and the private sector.

Figure FAQ4.4.1: Water-related adaptation responses in agriculture sector: benefits, co-benefits with mitigation, and possible maladaptation

[END FAQ4.4 HERE]

[START FAQ4.5 HERE]

FAQ4.5: Which principles can communities implement to sustainably adapt to the ways that climate change is impacting their water security?

For communities to sustainably adapt to climate impacts on water security, their participation, cooperation, and bottom-up engagement are critical in all stages of decision-making processes. In addition to enhancing the legitimacy of the decision-making process, the community's involvement can increase the equitability *and effectiveness of the adaptation approach. As water insecurity disproportionately affects marginalised social groups, their participation in water governance and implementation can help improve their water security. Combining and integrating local, Indigenous and traditional ecological knowledge with Western understandings of climate change can enhance the effectiveness of adaptation measures and strategies while ensuring that the adaptation is equitable and just. Improving water security is fundamental to achieving many of the 17 Sustainable Development Goals (SDGs).*

For decades, communities worldwide have already been adapting to climate change-induced hydrological changes to maintain their livelihood and safety. Adaptation is a multi-faceted process that is implemented differently depending on the sector affected by changes in the hydrological cycle and the region where these changes happen. For instance, farmers in the semi-arid areas might adapt to changing rain patterns through irrigation (see also FAQ4.4). At the same time, urban dwellers can adopt measures such as rainwater harvesting and other nature-based solutions. Several principles have been documented as crucial for achieving sustainable adaptation as they support communities in becoming more resilient to climate change. However, these principles can be implemented singularly or in tandem, and it is essential to acknowledge that long-term adaptation success is context-specific. Therefore, it is critical to involve local communities in co-designing effective adaptation responses.

For communities to sustainably adapt to climate impacts on water security, participation, cooperation, and bottom-up engagement are critical in all stages of the decision-making processes, from planning to full implementation. Many of the countries and social groups most threatened by climate change have contributed least to global warming and do not have access to adequate resources to adapt. Effective participation of these actors in water-related climate change adaptation planning can contribute to more equitable adaptation actions. The involvement of the most vulnerable in the design of adaptation responses makes it more probable that these solutions will suit their needs and have therefore a higher change of being effective to be effective. Accessible, inclusive and well-coordinated efforts to enhance water security will improve the legitimacy of water governance and work synergistically with reducing inequalities (UN Sustainable Development Goal, SDG 10) and encouraging more sustainable communities (SDG 11). Communities can also be involved in sector-specific adaptation responses. These are often water-related and help ensure that climate action (SDG13) is well aligned with clean water and sanitation (SGD6).

The participation of traditionally excluded groups such as women and marginalised communities and Indigenous people and ethnic minorities contributes to more equitable and socially just adaptation actions. Water insecurity disproportionately affects these marginalised groups, and their participation in water governance and implementation can help alleviate this burden.

Recognising the importance of Indigenous Knowledge and Local Knowledge in improving water security is vital to ensuring that decisions and solutions align with the interests of Indigenous and local peoples and benefit their communities culturally and economically. Furthermore, the effectiveness of adaptation measures and strategies improves when local, Indigenous Knowledge and traditional ecological knowledge is combined and integrated with technical understandings of climate change.

The climate adaptation plans led by national governments and local authorities will only be accepted and adequately implemented when supported by the community. Therefore, strong political and societal support is necessary to ensure effective policy changes, whether local or national. Significantly, access to financial assistance from private and public sources expands the range of strategies that communities can consider for enhancing their water security.

These principles are also conducive to the achievement of the United Nations Sustainable Development Goals. Actions that reduce climate risk and enhance water security can positively interact with sustainable development objectives (synergies). Therefore, improving water security is fundamental to achieving many of the 17 Sustainable Development Goals (SDGs).

References

Abbas, A. et al., 2018: Sustainable survival under climatic extremes: linking flood risk mitigation and coping with flood damages in rural Pakistan. *Environmental Science and Pollution Research*, **25** (32), 32491-32505, doi:10.1007/s11356-018-3203-8.

Abbas, N., S. A. Wasimi and N. Al-Ansari, 2016: Impacts of Climate Change on Water Resources on Diyala River Bssin, Iraq. *Journal of Civil Engineering and Architecture*, **10**, 1059-1074, doi:10.17265/1934-7359/2016.09.009.

Abbott, B. W. et al., 2019: Human domination of the global water cycle absent from depictions and perceptions. *Nature Geoscience*, **12** (7), 533-540, doi:10.1038/s41561-019-0374-y.

Abdallah, M. et al., 2020: Artificial intelligence applications in solid waste management: A systematic research review. *Waste Management*, **109**, 231-246, doi:https://doi.org/10.1016/j.wasman.2020.04.057.

Abdelkareem, M. A., M. El Haj Assad, E. T. Sayed and B. Soudan, 2018: Recent progress in the use of renewable energy sources to power water desalination plants. *Desalination*, **435**, 97-113, doi:https://doi.org/10.1016/j.desal.2017.11.018.

Abedin, M. A., A. E. Collins, U. Habiba and R. Shaw, 2019: Climate change, water scarcity, and health adaptation in southwestern coastal Bangladesh. *International Journal of Disaster Risk Science*, **10** (1), 28-42.

Abel, G. J., M. Brottrager, J. Crespo Cuaresma and R. Muttarak, 2019: Climate, conflict and forced migration. *Global Environmental Change*, **54**, 239-249, doi:https://doi.org/10.1016/j.gloenvcha.2018.12.003.

Abrahams, D., 2020: Conflict in abundance and peacebuilding in scarcity: Challenges and opportunities in addressing climate change and conflict. *World Development*, **132**, 104998, doi:https://doi.org/10.1016/j.worlddev.2020.104998.

Abram, N. et al., 2019: Framing and context of the report. *IPCC special report on the ocean and cryosphere in a changing climate*.

Acevedo, M. et al., 2020: A scoping review of adoption of climate-resilient crops by small-scale producers in low-and middle-income countries. *Nature plants*, **6** (10), 1231-1241.

Achite, M. and S. Ouillon, 2016: Recent changes in climate, hydrology and sediment load in the Wadi Abd, Algeria (1970–2010). *Hydrology and Earth System Sciences*, **20** (4), 1355-1372, doi:10.5194/hess-20-1355-2016.

Acosta, L. A. et al., 2016: Loss and damage from typhoon-induced floods and landslides in the Philippines: community perceptions on climate impacts and adaptation options. *International Journal of Global Warming*, **9** (1), 33-65, doi:10.1504/ijgw.2016.074307.

Adams, H., 2016: Why populations persist: mobility, place attachment and climate change. *Population and Environment*, **37** (4), 429-448.

Adams, M. A., T. N. Buckley and T. L. Turnbull, 2020: Diminishing CO2-driven gains in water-use efficiency of global forests. *Nature Climate Change*, **10** (5), 466-471, doi:10.1038/s41558-020-0747-7.

Adaptation Fund, 2018: Briefing Note.

Adger, W. N. et al., 2018: Mobility, displacement and migration, and their interactions with vulnerability and adaptation to environmental risks. In: Routledge handbook of environmental displacement and migration, 29-41.

Adger, W. N. and J. M. e. a. Pulhin, 2014: Human Security. In: limate Change 2014: Impacts, adaptation and vulnerability. Part A: Global and Sectoral Aspects: Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [al, F. C. B. e. (ed.)]. Cambridge University Press, Cambridge, 755-791.

Adhikari, S., H. Baral and C. Nitschke, 2018a: Adaptation to climate change in Panchase Mountain ecological regions of Nepal. *Environments*, **5** (3), 42.

Adhikari, S. P., K. P. Timsina and J. Lamichhane, 2018b: Adoption and impact of rain water harvesting technology on rural livelihoods: The case of Makwanpur district, Nepal. *Rural Extension and Innovation Systems Journal*, **14** (1), 34-40.

Afifi, T. et al., 2016: Human mobility in response to rainfall variability: opportunities for migration as a successful adaptation strategy in eight case studies. *Migration and Development*, **5** (2), 254-274, doi:10.1080/21632324.2015.1022974.

Agnolucci, P. et al., 2020: Impacts of rising temperatures and farm management practices on global yields of 18 crops. *Nature Food*, **1** (9), 562-571.

Ahmed, M. and S. Suphachalasai, 2014: *Assessing the costs of climate change and adaptation in South Asia*. Asian Development Bank.

Ahmed, M. N. Q. and S. M. Atiqul Haq, 2019: Indigenous people's perceptions about climate change, forest resource management, and coping strategies: a comparative study in Bangladesh. *Environment, Development and Sustainability*, **21** (2), 679-708, doi:10.1007/s10668-017-0055-1.

Ai, Z. et al., 2020: Simulating second-generation herbaceous bioenergy crop yield using the global hydrological model H08 (v.bio1). *Geosci. Model Dev.*, **13** (12), 6077-6092, doi:10.5194/gmd-13-6077-2020.

Ait-Kadi, M., 2016: Water for Development and Development for Water: Realizing the Sustainable Development Goals (SDGs) Vision. *Aquatic Procedia*, **6**, 106-110, doi:10.1016/j.aqpro.2016.06.013.

Ajibade, I. and G. McBean, 2014: Climate extremes and housing rights: A political ecology of impacts, early warning and adaptation constraints in Lagos slum communities. *Geoforum*, **55**, 76-86, doi:https://doi.org/10.1016/j.geoforum.2014.05.005.
Aladenola, O., A. Cashman and D. Brown, 2016: Impact of El Niño and Climate Change on Rainwater Harvesting in a Caribbean State. *Water Resources Management*, **30** (10), 3459-3473, doi:10.1007/s11269-016-1362-2.
Alam, K. and M. H. Rahman, 2014: Women in natural disasters: A case study from southern coastal region of Bangladesh. *International Journal of Disaster Risk Reduction*, **8**, 68-82, doi:https://doi.org/10.1016/j.ijdrr.2014.01.003.
Alauddin, M. and M. A. R. Sarker, 2014: Climate change and farm-level adaptation decisions and strategies in drought-prone and groundwater-depleted areas of Bangladesh: an empirical investigation. *Ecological Economics*, **106**, 204-213.
Albert, S. et al., 2018: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, **18** (8), 2261-2272, doi:10.1007/s10113-017-1256-8.
Albrecht, T. R., A. Crootof and C. A. Scott, 2018: The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, **13** (4), 043002, doi:10.1088/1748-9326/aaa9c6.
Albrecht, T. R. et al., 2017: Governing a shared hidden resource: A review of governance mechanisms for transboundary groundwater security. *Water Security*, **2**, 43-56, doi:https://doi.org/10.1016/j.wasec.2017.11.002.
Albright, E. A., 2020: Disaster-driven discussion. *Nature Climate Change*, **10** (1), 12-13, doi:10.1038/s41558-019-0664-9.
Aleke, B. I. and G. Nhamo, 2016: Information and communication technology and climate change adaptation: Evidence from selected mining companies in South Africa. *Jàmbá: Journal of Disaster Risk Studies; Vol 8, No 3 (2016)DO - 10.4102/jamba.v8i3.250*.
Aleksandrowicz, L. et al., 2016: The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PLOS ONE*, **11** (11), e0165797, doi:10.1371/journal. pone.0165797.
Alfieri, L. et al., 2017: Global projections of river flood risk in a warmer world. *Earth's Future*, **5** (2), 171-182, doi:10.1002/2016ef000485.
Algarni, S., C. A. Saleel and M. A. Mujeebu, 2018: Air-conditioning condensate recovery and applications—Current developments and challenges ahead. *Sustainable Cities and Society*, **37**, 263-274, doi:https://doi.org/10.1016/j.scs.2017.11.032.
Ali, S. A., S. Aadhar, H. L. Shah and V. Mishra, 2018: Projected increase in hydropower production in India under climate change. *Scientific Reports*, **8** (1), 1-12.
Allan, R. P. et al., 2020: Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, **1472** (1), 49-75, doi:https://doi.org/10.1111/nyas.14337.
Allan, R. P. et al., 2014: Physically Consistent Responses of the Global Atmospheric Hydrological Cycle in Models and Observations. *Surveys in Geophysics*, **35** (3), 533-552, doi:10.1007/s10712-012-9213-z.
Allchin, M. I. and S. J. Déry, 2017: A spatio-temporal analysis of trends in Northern Hemisphere snow-dominated area and duration, 1971–2014. *Annals of Glaciology*, **58** (75pt1), 21-35, doi:10.1017/aog.2017.47.
Allison, E. A., 2015: The spiritual significance of glaciers in an age of climate change. *WIREs Climate Change*, **6** (5), 493-508, doi:10.1002/wcc.354.
Alsumaiei, A. A. and R. T. Bailey, 2018a: Quantifying threats to groundwater resources in the Republic of Maldives Part I: Future rainfall patterns and sea-level rise. *Hydrological Processes*, **32** (9), 1137-1153, doi:https://doi.org/10.1002/hyp.11480.
Alsumaiei, A. A. and R. T. Bailey, 2018b: Quantifying threats to groundwater resources in the Republic of Maldives Part II: Recovery from tsunami marine overwash events. *Hydrological Processes*, **32** (9), 1154-1165, doi:https://doi.org/10.1002/hyp.11473.
Alter, R. E., E.-S. Im and E. A. B. Eltahir, 2015: Rainfall consistently enhanced around the Gezira Scheme in East Africa due to irrigation. *Nature Geoscience*, **8**, 763, doi:10.1038/ngeo2514
https://www.nature.com/articles/ngeo2514#supplementary-information.
Amanambu, A. C. et al., 2020: Groundwater system and climate change: Present status and future considerations. *Journal of Hydrology*, **589**, 125163, doi:https://doi.org/10.1016/j.jhydrol.2020.125163.
Amouzou, K. A. et al., 2019: Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. *Field Crops Research*, **235**, 104-117, doi:https://doi.org/10.1016/j.fcr.2019.02.021.
Amy, G. et al., 2017: Membrane-based seawater desalination: Present and future prospects. *Desalination*, **401**, 16-21, doi:https://doi.org/10.1016/j.desal.2016.10.002.
Andajani-Sutjahjo, S., S. Chirawatkul and E. Saito, 2015: Gender and water in northeast Thailand: Inequalities and women's realities. *Journal of International Women's Studies*, **16**, 200-212.
Anderson, D., J. D. Ford and R. G. Way, 2018: The Impacts of Climate and Social Changes on Cloudberry (Bakeapple) Picking: a Case Study from Southeastern Labrador. *Human Ecology*, **46** (6), 849-863, doi:10.1007/s10745-018-0038-3.
Anderson, W. et al., 2019: Synchronous crop failures and climate-forced production variability. *Science Advances*, **5** (7), eaaw1976.

Andrade, L., J. O'Dwyer, E. O'Neill and P. Hynds, 2018: Surface water flooding, groundwater contamination, and enteric disease in developed countries: A scoping review of connections and consequences. *Environmental Pollution*, **236**, 540-549, doi:https://doi.org/10.1016/j.envpol.2018.01.104.
Andrew, J. T. and E. Sauquet, 2017: Climate Change Impacts and Water Management Adaptation in Two Mediterranean-Climate Watersheds: Learning from the Durance and Sacramento Rivers. *Water*, **9** (2), doi:10.3390/w9020126.
Angelakis, A. N. and S. A. Snyder, 2015: Wastewater Treatment and Reuse: Past, Present, and Future. *Water*, **7** (9), doi:10.3390/w7094887.
Anguelovski, I., E. Chu and J. Carmin, 2014: Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South. *Global Environmental Change*, **27**, 156-167, doi:https://doi.org/10.1016/j.gloenvcha.2014.05.010.
Aniah, P., M. K. Kaunza-Nu-Dem and J. A. Ayembilla, 2019: Smallholder farmers' livelihood adaptation to climate variability and ecological changes in the savanna agro ecological zone of Ghana. *Heliyon*, **5** (4), e01492-e01492, doi:10.1016/j.heliyon.2019.e01492.
Antwi-Agyei, P., A. J. Dougill and L. C. Stringer, 2015: Barriers to climate change adaptation: evidence from northeast Ghana in the context of a systematic literature review. *Climate and Development*, **7** (4), 297-309, doi:10.1080/17565529.2014.951013.
Anwar, N. H., A. Sawas and D. Mustafa, 2019: 'Without water, there is no life': Negotiating everyday risks and gendered insecurities in Karachi's informal settlements. *Urban Studies*, **57** (6), 1320-1337, doi:10.1177/0042098019834160.
Aragüés, R. et al., 2015: Soil salinization as a threat to the sustainability of deficit irrigation under present and expected climate change scenarios. *Irrigation Science*, **33** (1), 67-79, doi:10.1007/s00271-014-0449-x.
Arango-Aramburo, S. et al., 2019: Climate impacts on hydropower in Colombia: A multi-model assessment of power sector adaptation pathways. *Energy Policy*, **128**, 179-188, doi:https://doi.org/10.1016/j.enpol.2018.12.057.
Araos, M. et al., 2016: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science & Policy*, **66**, 375-382, doi:https://doi.org/10.1016/j.envsci.2016.06.009.
Arent, D. J. et al., 2014: Key economic sectors and services. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659-708.
Arheimer, B. and G. Lindström, 2015: Climate impact on floods: changes in high flows in Sweden in the past and the future (1911–2100). *Hydrol. Earth Syst. Sci.*, **19** (2), 771-784, doi:10.5194/hess-19-771-2015.
Arias, M. E. et al., 2020: Impacts of climate change and deforestation on hydropower planning in the Brazilian Amazon. *Nature Sustainability*, **3** (6), 430-436, doi:10.1038/s41893-020-0492-y.
Armah, F. A. et al., 2018: Access to improved water and sanitation in sub-Saharan Africa in a quarter century. *Heliyon*, **4** (11), e00931, doi:https://doi.org/10.1016/j.heliyon.2018.e00931.
Armitage, R. and L. B. Nellums, 2020a: COVID-19 and the Gypsy, Roma and Traveller population. *Public health*, **185**, 48-48, doi:10.1016/j.puhe.2020.06.003.
Armitage, R. and L. B. Nellums, 2020b: Water, climate change, and COVID-19: prioritising those in water-stressed settings. *The Lancet Planetary Health*, **4** (5), e175, doi:10.1016/S2542-5196(20)30084-X.
Arnall, A., 2019: Resettlement as climate change adaptation: what can be learned from state-led relocation in rural Africa and Asia? *Climate and Development*, **11** (3), 253-263, doi:10.1080/17565529.2018.1442799.
Arnell, N. W. et al., 2016: The impacts of climate change across the globe: A multi-sectoral assessment. *Climatic Change*, **134** (3), 457-474, doi:10.1007/s10584-014-1281-2.
Arnell, N. W. and B. Lloyd-Hughes, 2014: The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Climatic Change*, **122** (1), 127-140, doi:10.1007/s10584-013-0948-4.
Arneth, A., e. al. and e. al., 2019: Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems.
Arnold, S. R. et al., 2018: Simulated Global Climate Response to Tropospheric Ozone-Induced Changes in Plant Transpiration. *Geophysical Research Letters*, **45** (23), 13070-13079, doi:https://doi.org/10.1029/2018GL079938.
Arp, C. D. et al., 2016: Threshold sensitivity of shallow Arctic lakes and sublake permafrost to changing winter climate. *Geophysical Research Letters*, **43** (12), 6358-6365, doi:https://doi.org/10.1002/2016GL068506.
Arriagada, R. et al., 2018: Climate change governance in the Anthropocene: Emergence of Polycentrism in Chile. *Elem Sci Anth*, **6**, 68, doi:10.1525/elementa.329.
Arsenault, R. et al., 2019: Including Indigenous Knowledge Systems in Environmental Assessments: Restructuring the Process. *Global Environmental Politics*, **19** (3), 120-132, doi:10.1162/glep_a_00519.
Arsenault, R. et al., 2018: Shifting the Framework of Canadian Water Governance through Indigenous Research Methods: Acknowledging the Past with an Eye on the Future. *Water*, **10** (1), doi:10.3390/w10010049.
Arslan, A. et al., 2015: Climate Smart Agriculture? Assessing the Adaptation Implications in Zambia. *Journal of Agricultural Economics*, **66** (3), 753-780, doi:10.1111/1477-9552.12107.

Asadieh, B., N. Krakauer and B. Fekete, 2016: Historical Trends in Mean and Extreme Runoff and Streamflow Based on Observations and Climate Models. *Water*, **8**, 189, doi:10.3390/w8050189.
Asadieh, B. and N. Y. Krakauer, 2017: Global change in streamflow extremes under climate change over the 21st century. *Hydrol. Earth Syst. Sci.*, **21** (11), 5863-5874, doi:10.5194/hess-21-5863-2017.
Asfaw, S., G. Pallante and A. Palma, 2018: Diversification Strategies and Adaptation Deficit: Evidence from Rural Communities in Niger. *World Development*, **101**, 219-234, doi:https://doi.org/10.1016/j.worlddev.2017.09.004.
Ash, K. and N. Obradovich, 2019: Climatic Stress, Internal Migration, and Syrian Civil War Onset. *Journal of Conflict Resolution*, **64** (1), 3-31, doi:10.1177/0022002719864140.
Asmare, F., H. Teklewold and A. Mekonnen, 2019: The effect of climate change adaptation strategy on farm households welfare in the Nile basin of Ethiopia: Is there synergy or trade-offs? *International Journal of Climate Change Strategies and Management*, **11** (4), 518-535, doi:10.1108/IJCCSM-10-2017-0192.
Asoka, A. and V. Mishra, 2020: A strong linkage between seasonal crop growth and groundwater storage variability in India. *Journal of Hydrometeorology*, 1-39, doi:10.1175/JHM-D-20-0085.1.
Asoka, A., Y. Wada, R. Fishman and V. Mishra, 2018: Strong Linkage Between Precipitation Intensity and Monsoon Season Groundwater Recharge in India. *Geophysical Research Letters*, **45** (11), 5536-5544, doi:10.1029/2018gl078466.
Aubin, D., C. Riche, V. Vande Water and I. La Jeunesse, 2019: The adaptive capacity of local water basin authorities to climate change: The Thau lagoon basin in France. *Science of The Total Environment*, **651**, 2013-2023, doi:https://doi.org/10.1016/j.scitotenv.2018.10.078.
Augustine, D. J. et al., 2018: Elevated CO2 induces substantial and persistent declines in forage quality irrespective of warming in mixedgrass prairie. *Ecological Applications*, **28** (3), 721-735, doi:https://doi.org/10.1002/eap.1680.
Ayeb-Karlsson, S. et al., 2016: A people-centred perspective on climate change, environmental stress, and livelihood resilience in Bangladesh. *Sustainability Science*, **11** (4), 679-694.
Azage, M. et al., 2017: Effect of climatic variability on childhood diarrhea and its high risk periods in northwestern parts of Ethiopia. *PLOS ONE*, **12** (10), e0186933, doi:10.1371/journal.pone.0186933.
Azhoni, A. and M. K. Goyal, 2018: Diagnosing climate change impacts and identifying adaptation strategies by involving key stakeholder organisations and farmers in Sikkim, India: Challenges and opportunities. *Science of The Total Environment*, **626**, 468-477, doi:https://doi.org/10.1016/j.scitotenv.2018.01.112.
Azhoni, A., I. Holman and S. Jude, 2017: Contextual and interdependent causes of climate change adaptation barriers: Insights from water management institutions in Himachal Pradesh, India. *Science of The Total Environment*, **576**, 817-828, doi:https://doi.org/10.1016/j.scitotenv.2016.10.151.
Babaeian, F., M. Delavar, S. Morid and R. Srinivasan, 2021: Robust climate change adaptation pathways in agricultural water management. *Agricultural Water Management*, **252**, 106904, doi:https://doi.org/10.1016/j.agwat.2021.106904.
Babí Almenar, J. et al., 2021: Nexus between nature-based solutions, ecosystem services and urban challenges. *Land Use Policy*, **100**, 104898, doi:https://doi.org/10.1016/j.landusepol.2020.104898.
Backhaus, A., I. Martinez-Zarzoso and C. Muris, 2015: Do climate variations explain bilateral migration? A gravity model analysis. *IZA Journal of Migration*, **4** (1), 3, doi:10.1186/s40176-014-0026-3.
Bacud, S. T., 2018: Integration of Indigenous and Scientific Knowledge in Disaster Risk Reduction: Resilience Building of a Marginalized Sampaguita Growing Community in the Philippines. *Procedia Engineering*, **212**, 511-518.
Bader, D. A. et al., 2018: Urban climate science (Chapter 2). In: Climate Change and Cities: Second Assessment Report [Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim (ed.)]. Urban Climate Change Research Network, Cambridge University Press. New York, 27-60.
Bahinipati, C. S. and U. Patnaik, 2015: The damages from climatic extremes in India: do disaster-specific and generic adaptation measures matter? *Environmental Economics and Policy Studies*, **17** (1), 157-177, doi:10.1007/s10018-014-0094-x.
Bai, X. et al., 2018: Six Research Priorities for Cities and Climate Change. *Nature*, **555**, doi:10.1038/d41586-018-02409-z.
Baidya, D. K., S. Maitra and S. Bhattacharjee, 2020: Facing Post-Cyclone Disaster in Times of COVID-19 Pandemic in India: Possible Testing Strategy to Reduce Further Spread of Disease. *Asia Pacific Journal of Public Health*, **32** (6-7), 376-376, doi:10.1177/1010539520944717.
Bailey, R. T. et al., 2018: Sustainability of rainwater catchment systems for small island communities. *Journal of Hydrology*, **557**, 137-146, doi:https://doi.org/10.1016/j.jhydrol.2017.12.016.
Balaban, M., 2017: Desalination 1966-2016, The origins, evolution and role of the Desalination Journal. *Desalination*, **401**, xvi-xx, doi:https://doi.org/10.1016/S0011-9164(16)31652-6.
Balasubramanian, S. and V. K. Chalamalla, 2020: *Super Cyclone Amphan: A Dynamical Case Study*. 1–10 [Available at: http://arxiv.org/abs/2007.02982].
Balasubramanya, S., M. Giordano, D. Wichelns and T. Sherpa, 2014: Sharing hydropower revenues in Nepal, over time and across districts and regions. *Water Resources and Rural Development*, **4**, 104-111, doi:https://doi.org/10.1016/j.wrr.2014.10.007.
Balasubramanya, S. and D. Stifel, 2020: Viewpoint: Water, agriculture & poverty in an era of climate change: Why do we know so little? *Food Policy*, **93**, 101905, doi:https://doi.org/10.1016/j.foodpol.2020.101905.

Baldwin, E., P. McCord, J. Dell'Angelo and T. Evans, 2018: Collective action in a polycentric water governance system. *Environmental Policy and Governance*, **28** (4), 212-222, doi:10.1002/eet.1810.
Banda, M. L., 2018: Climate Adaptation Law: Governing Multi-Level Public Goods across Borders. *Journal of Transnational Law*, **51** (4), 1027-1074.
Barasa, B. et al., 2020: The role of indigenous knowledge (IK) in adaptation to drought by agropastoral smallholder farmers in Uganda.
Barbier, E. B. and J. C. Burgess, 2020: Sustainability and development after COVID-19. *World Development*, **135**, 105082, doi:https://doi.org/10.1016/j.worlddev.2020.105082.
Bard, A. et al., 2015: Trends in the hydrologic regime of Alpine rivers. *Journal of Hydrology*, **529**, 1823-1837, doi:https://doi.org/10.1016/j.jhydrol.2015.07.052.
Bardosh, K. L. et al., 2017: Addressing vulnerability, building resilience: community-based adaptation to vector-borne diseases in the context of global change. *Infectious Diseases of Poverty*, **6** (1), 166, doi:10.1186/s40249-017-0375-2.
Barkdull, J. and P. G. Harris, 2019: Emerging responses to global climate change: Ecosystembased adaptation. Taylor & Francis, **31**, 19-37, doi:10.1080/14781158.2018.1475349.
Barkey, B. L. and R. T. Bailey, 2017: Estimating the Impact of Drought on Groundwater Resources of the Marshall Islands. *Water*, **9** (1), doi:10.3390/w9010041.
Barlow, M. and A. Hoell, 2015: Drought in the Middle East and Central–Southwest Asia During Winter 2013/14. *Bulletin of the American Meteorological Society*, **96** (12), S71-S76, doi:10.1175/BAMS-D-15-00127.1.
Barnett, J. et al., 2015: From barriers to limits to climate change adaptation: path dependency and the speed of change. *Ecology and Society*, **20** (3), doi:10.5751/ES-07698-200305.
Barrucand, M. G., C. Giraldo Vieira and P. O. Canziani, 2017: Climate change and its impacts: perception and adaptation in rural areas of Manizales, Colombia. *Climate and Development*, **9** (5), 415-427, doi:10.1080/17565529.2016.1167661.
Bartos, M. D. and M. V. Chester, 2015: Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change*, **5**, 748, doi:10.1038/nclimate2648
https://www.nature.com/articles/nclimate2648#supplementary-information.
Barua, P., H. Rahman Syed and H. Molla Morshed, 2017: Sustainable adaptation for resolving climate displacement issues of south eastern islands in Bangladesh. *International Journal of Climate Change Strategies and Management*, **9** (6), 790-810, doi:10.1108/IJCCSM-02-2017-0026.
Bastin, J.-F. et al., 2019: The global tree restoration potential. *Science*, **365** (6448), 76-79, doi:10.1126/science.aax0848.
Basupi, L. V., C. H. Quinn and A. J. Dougill, 2019: Adaptation strategies to environmental and policy change in semi-arid pastoral landscapes: Evidence from Ngamiland, Botswana. *Journal of Arid Environments*, **166**, 17-27, doi:https://doi.org/10.1016/j.jaridenv.2019.01.011.
Baylis, M., 2017: Potential impact of climate change on emerging vector-borne and other infections in the UK. *Environmental Health*, **16** (1), 112.
Becerra, S., M. Saqalli, F. Gangneron and A. H. Dia, 2016: Everyday vulnerabilities and "social dispositions" in the Malian Sahel, an indication for evaluating future adaptability to water crises? *Regional Environmental Change*, **16** (5), 1253-1265, doi:10.1007/s10113-015-0845-7.
Beckman, M. and M. V. T. Nguyen, 2016: Upland development, climate-related risk and institutional conditions for adaptation in Vietnam. *Climate and Development*, **8** (5), 413-422, doi:10.1080/17565529.2015.1067178.
Beel, C. R., S. F. Lamoureux and J. F. Orwin, 2018: Fluvial Response to a Period of Hydrometeorological Change and Landscape Disturbance in the Canadian High Arctic. *Geophysical Research Letters*, **45** (19), 10,446-10,455, doi:10.1029/2018gl079660.
Befus, K. M. et al., 2020: Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nature Climate Change*, **10** (10), 946-952, doi:10.1038/s41558-020-0874-1.
Begam, S. and D. Sen, 2019: Mapping of moraine dammed glacial lakes and assessment of their areal changes in the central and eastern Himalayas using satellite data. *Journal of Mountain Science*, **16** (1), 77-94.
Behrens, P. et al., 2017: Climate change and the vulnerability of electricity generation to water stress in the European Union. *Nature Energy*, **2**, nenergy2017114, doi:10.1038/nenergy.2017.114.
Beillouin, D. et al., 2020: Impact of extreme weather conditions on European crop production in 2018. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1810), 20190510, doi:10.1098/rstb.2019.0510.
Bekele, E. et al., 2018: Water Recycling via Aquifers for Sustainable Urban Water Quality Management: Current Status, Challenges and Opportunities. *Water*, **10**, 457, doi:10.3390/w10040457.
Ben Ammar, R., M. Ben Ammar and A. Oualha, 2020: Photovoltaic power forecast using empirical models and artificial intelligence approaches for water pumping systems. *Renewable Energy*, **153**, 1016-1028, doi:https://doi.org/10.1016/j.renene.2020.02.065.
Beniston, M. et al., 2018: The European mountain cryosphere: a review of its current state, trends, and future challenges. *The Cryosphere*, **12** (2), 759-794, doi:10.5194/tc-12-759-2018.
Berg, A. et al., 2016: Land–atmosphere feedbacks amplify aridity increase over land under global warming. *Nature Climate Change*, **6**, 869, doi:10.1038/nclimate3029
https://www.nature.com/articles/nclimate3029#supplementary-information.

Berg, A. and J. Sheffield, 2019: Evapotranspiration Partitioning in CMIP5 Models: Uncertainties and Future Projections. *Journal of Climate*, **32** (10), 2653-2671, doi:10.1175/jcli-d-18-0583.1.
Berga, L., 2016: The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. *Engineering*, **2** (3), 313-318, doi:https://doi.org/10.1016/J.ENG.2016.03.004.
Bergaoui, K. et al., 2015: The Contribution of Human-Induced Climate Change to the Drought of 2014 in the Southern Levant Region. *Bulletin of the American Meteorological Society*, **96** (12), S66-S70, doi:10.1175/BAMS-D-15-00129.1.
Berghuijs, W. R. et al., 2017a: Recent changes in extreme floods across multiple continents. *Environmental Research Letters*, **12** (11), 114035, doi:10.1088/1748-9326/aa8847.
Berghuijs, W. R., J. R. Larsen, T. H. M. van Emmerik and R. A. Woods, 2017b: A Global Assessment of Runoff Sensitivity to Changes in Precipitation, Potential Evaporation, and Other Factors. *Water Resources Research*, **53** (10), 8475-8486, doi:10.1002/2017wr021593.
Bergmann, J. et al., 2021: Too much, too little water: Addressing climate risks, no-analog threats and migration in Peru. *Migration, Environment and Climate Change: Policy Brief Series*, **1** (6), 1-16.
Beringer, T. et al., 2020: First process-based simulations of climate change impacts on global tea production indicate large effects in the World's major producer countries. *Environmental Research Letters*, **15** (3), 034023, doi:10.1088/1748-9326/ab649b.
Bernacchi, C. J. and A. VanLoocke, 2015: Terrestrial Ecosystems in a Changing Environment: A Dominant Role for Water. *Annual Review of Plant Biology*, **66** (1), 599-622, doi:10.1146/annurev-arplant-043014-114834.
Berrang-Ford, L. et al., 2021a: The Global Adaptation Mapping Initiative (GAMI): Part 1 – Introduction and overview of methods. *Protocol Exchange*, doi:10.21203/rs.3.pex-1240/v1.
Berrang-Ford, L. et al., 2021b: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, **In Press**.
Berthier, É. and F. Brun, 2019: Karakoram geodetic glacier mass balances between 2008 and 2016: persistence of the anomaly and influence of a large rock avalanche on Siachen Glacier. *Journal of Glaciology*, **65** (251), 494-507.
Betts, R. A. et al., 2018: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376** (2119), 20160452, doi:doi:10.1098/rsta.2016.0452.
Betts, R. A. et al., 2015: Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences*, **12** (5), 1317-1338, doi:10.5194/bg-12-1317-2015.
Beuttler, C., L. Charles and J. Wurzbacher, 2019: The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. *Frontiers in Climate*, **1**, 10.
Beveridge, M. et al., 2018: Climate change and aquaculture: interactions with fisheries and agriculture.
Bhandari, D. et al., 2020: Climate change and infectious disease research in Nepal: Are the available prerequisites supportive enough to researchers? *Acta tropica*, **204**, 105337, doi:https://doi.org/10.1016/j.actatropica.2020.105337.
Bhatta, L. D., B. E. H. Van Oort, N. E. Stork and H. Baral, 2015: Ecosystem services and livelihoods in a changing climate: Understanding local adaptations in the Upper Koshi, Nepal. *International Journal of Biodiversity Science, Ecosystem Services and Management*, **11** (2), 145-155, doi:10.1080/21513732.2015.1027793.
Bhave, A. G., D. Conway, S. Dessai and D. A. Stainforth, 2018: Water Resource Planning Under Future Climate and Socioeconomic Uncertainty in the Cauvery River Basin in Karnataka, India. *Water Resources Research*, **54** (2), 708-728, doi:10.1002/2017wr020970.
Bhowmick, G. D. et al., 2020: Coronavirus disease 2019 (COVID-19) outbreak: some serious consequences with urban and rural water cycle. *npj Clean Water*, **3** (1), 32, doi:10.1038/s41545-020-0079-1.
Bhowmik, J., H. M. Irfanullah and S. A. Selim, 2021: Empirical evidence from Bangladesh of assessing climate hazard-related loss and damage and state of adaptive capacity to address them. *Climate Risk Management*, **31**, 100273, doi:https://doi.org/10.1016/j.crm.2021.100273.
Bi, W. et al., 2019: Evolution of Drought⁻Flood Abrupt Alternation and Its Impacts on Surface Water Quality from 2020 to 2050 in the Luanhe River Basin. *International Journal of Environmental Research and Public Health*, **16** (5), 691, doi:10.3390/ijerph16050691.
Biagini, B., L. Kuhl, K. S. Gallagher and C. Ortiz, 2014: Technology transfer for adaptation. *Nature Climate Change*, **4** (9), 828-834, doi:10.1038/nclimate2305.
Biemans, H. et al., 2019: Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, **2** (7), 594-601, doi:10.1038/s41893-019-0305-3.
Bierkens, M. F. P. and Y. Wada, 2019: Non-renewable groundwater use and groundwater depletion: a review. *Environmental Research Letters*, **14** (6), 063002, doi:10.1088/1748-9326/ab1a5f.
Biesbroek, G. R. and A. Lesnikowski, 2018: Adaptation: The Neglected Dimension of Polycentric Climate Governance. In: Governing Climate Change: Polycentricity in Action? [Jordan, A., D. Huitema, H. Van Asselt and J. Forster (eds.)]. Cambridge University Press, 303-319.
Biesbroek, R. et al., 2018: Do Administrative Traditions Matter for Climate Change Adaptation Policy? A Comparative Analysis of 32 High-Income Countries. *Review of Policy Research*, **35** (6), 881-906, doi:10.1111/ropr.12309.

Bijl, D. L. et al., 2018: A Global Analysis of Future Water Deficit Based On Different Allocation Mechanisms. *Water Resources Research*, **54** (8), 5803-5824, doi:10.1029/2017wr021688.
Birk, T. and K. Rasmussen, 2014: Migration from atolls as climate change adaptation: Current practices, barriers and options in Solomon Islands. *Natural Resources Forum*, **38** (1), 1-13, doi:10.1111/1477-8947.12038.
Birtchnell, T., N. Gill and R. Sultana, 2019: Sleeper cells for urban green infrastructure: Harnessing latent competence in greening Dhaka's slums. *Urban Forestry & Urban Greening*, **40**, 93-104, doi:https://doi.org/10.1016/j.ufug.2018.05.014.
Bisbis, M. B., N. Gruda and M. Blanke, 2018: Potential impacts of climate change on vegetable production and product quality–A review. *Journal of Cleaner Production*, **170**, 1602-1620.
Biskaborn, B. K. et al., 2019: Permafrost is warming at a global scale. *Nature Communications*, **10** (1), 264, doi:10.1038/s41467-018-08240-4.
Blackburn, S. and M. Pelling, 2018: The political impacts of adaptation actions: Social contracts, a research agenda. *WIREs Climate Change*, **9** (6), e549, doi:10.1002/wcc.549.
Blaine, A. C. et al., 2013: Uptake of Perfluoroalkyl Acids into Edible Crops via Land Applied Biosolids: Field and Greenhouse Studies. *Environmental Science & Technology*, **47** (24), 14062-14069, doi:10.1021/es403094q.
Blakeslee, D., R. Fishman and V. Srinivasan, 2020: Way Down in the Hole: Adaptation to Long-Term Water Loss in Rural India. *American Economic Review*, **110** (1), 200-224, doi:10.1257/aer.20180976.
Blöschl, G. et al., 2019a: Twenty-three unsolved problems in hydrology (UPH) – a community perspective. *Hydrological Sciences Journal*, **64** (10), 1141-1158, doi:10.1080/02626667.2019.1620507.
Blöschl, G. et al., 2017: Changing climate shifts timing of European floods. *Science*, **357** (6351), 588-590, doi:10.1126/science.aan2506.
Blöschl, G. et al., 2019b: Changing climate both increases and decreases European river floods. *Nature*, **573** (7772), 108-111, doi:10.1038/s41586-019-1495-6.
Boadi, S. A. and K. Owusu, 2019: Impact of climate change and variability on hydropower in Ghana. *African Geographical Review*, **38** (1), 19-31, doi:10.1080/19376812.2017.1284598.
Boateng, G. O. et al., 2020: The syndemic effects of food insecurity, water insecurity, and HIV on depressive symptomatology among Kenyan women. *Social Science & Medicine*, 113043, doi:https://doi.org/10.1016/j.socscimed.2020.113043.
Boelens, R., J. Hoogesteger and M. Baud, 2015: Water reform governmentality in Ecuador: Neoliberalism, centralization, and the restraining of polycentric authority and community rule-making. *Geoforum*, **64**, 281-291, doi:https://doi.org/10.1016/j.geoforum.2013.07.005.
Boholm, Å. and M. Prutzer, 2017: Experts' understandings of drinking water risk management in a climate change scenario. *Climate Risk Management*, **16**, 133-144, doi:https://doi.org/10.1016/j.crm.2017.01.003.
Boisier, J. P., R. Rondanelli, R. D. Garreaud and F. Muñoz, 2016: Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile. *Geophysical Research Letters*, **43** (1), 413-421, doi:10.1002/2015GL067265.
Bolch, T. et al., 2019: Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region. In: The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer International Publishing, Cham, 209-255.
Bombelli, G. M., A. Soncini, A. Bianchi and D. Bocchiola, 2019: Potentially modified hydropower production under climate change in the Italian Alps. *Hydrological Processes*, **33** (17), 2355-2372, doi:https://doi.org/10.1002/hyp.13473.
Bond, M. J. and J. Carr, 2018: Permafrost thaw and implications for the fate and transport of tritium in the Canadian north. *Journal of Environmental Radioactivity*, **192**, 295-311, doi:https://doi.org/10.1016/j.jenvrad.2018.07.006.
Bond, M. O., B. J. Anderson, T. H. A. Henare and P. M. Wehi, 2019: Effects of climatically shifting species distributions on biocultural relationships. *People and Nature*, **1** (1), 87-102, doi:https://doi.org/10.1002/pan3.15.
Bonsal, B. et al., 2020: Western Canadian freshwater availability: current and future vulnerabilities. *Environmental Reviews*, **28** (4), 528-545, doi:10.1139/er-2020-0040.
Bonsal, B. R. et al., 2019: Changes in freshwater availability across Canada. In: Canada's Changing Climate Report, [Bush, E. and D. D. S. Lemmen (eds.)]. Government of Canada,, Ottawa, Ontario, 261-342.
Bonsch, M. et al., 2015: Environmental flow provision: Implications for agricultural water and land-use at the global scale. *Global Environmental Change*, **30**, 113-132, doi:https://doi.org/10.1016/j.gloenvcha.2014.10.015.
Boonwichai, S. et al., 2019: Evaluation of climate change impacts and adaptation strategies on rainfed rice production in Songkhram River Basin, Thailand. *Science of The Total Environment*, **652**, 189-201, doi:https://doi.org/10.1016/j.scitotenv.2018.10.201.
Boretti, A. and L. Rosa, 2019: Reassessing the projections of the World Water Development Report. *npj Clean Water*, **2** (1), 15, doi:10.1038/s41545-019-0039-9.
Borgomeo, E. et al., 2020: Impact of green water anomalies on global rainfed crop yields. *Environmental Research Letters*, **15** (12), 124030, doi:10.1088/1748-9326/abc587.
Borrelli, P. et al., 2020: Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences*, **117** (36), 21994, doi:10.1073/pnas.2001403117.

Bosmans, J. H. C., L. P. H. van Beek, E. H. Sutanudjaja and M. F. P. Bierkens, 2017: Hydrological impacts of global land cover change and human water use. *Hydrol. Earth Syst. Sci.*, **21** (11), 5603-5626, doi:10.5194/hess-21-5603-2017.
Bott, L.-M. and B. Braun, 2019: How do households respond to coastal hazards? A framework for accommodating strategies using the example of Semarang Bay, Indonesia. *International Journal of Disaster Risk Reduction*, **37**, 101177, doi:https://doi.org/10.1016/j.ijdrr.2019.101177.
Boudet, H. et al., 2020: Event attribution and partisanship shape local discussion of climate change after extreme weather. *Nature Climate Change*, **10** (1), 69-76, doi:10.1038/s41558-019-0641-3.
Bouwer, L. M., 2019: Observed and Projected Impacts from Extreme Weather Events: Implications for Loss and Damage. In: Loss and Damage from Climate Change: Concepts, Methods and Policy Options [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, 63-82.
Bower, L. M. et al., 2019: Effects of Hydrology on Fish Diversity and Assemblage Structure in a Texan Coastal Plains River. *Transactions of the American Fisheries Society*, **148** (1), 207-218, doi:https://doi.org/10.1002/tafs.10129.
Bowles, D. C., 2015: Climate Change and Health Adaptation: Consequences for Indigenous Physical and Mental Health. *Annals of Global Health*, **81** (3), 427-431, doi:https://doi.org/10.1016/j.aogh.2015.06.004.
Bowman, D. M. J. S. et al., 2017: Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology & Evolution*, **1** (3), 0058, doi:10.1038/s41559-016-0058.
Bradford, J. B. et al., 2017: Future soil moisture and temperature extremes imply expanding suitability for rainfed agriculture in temperate drylands. *Scientific Reports*, **7** (1), 12923, doi:10.1038/s41598-017-13165-x.
Brás, T. A., J. Seixas, N. Carvalhais and J. Jägermeyr, 2021: Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environmental Research Letters*, **16** (6), 065012, doi:10.1088/1748-9326/abf004.
Bring, A. et al., 2016: Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research: Biogeosciences*, **121** (3), 621-649, doi:10.1002/2015jg003131.
Briones, F., R. Vachon and M. Glantz, 2019: Local responses to disasters: recent lessons from zero-order responders. *Disaster Prevention and Management: An International Journal*, **28** (1), 119-125, doi:10.1108/DPM-05-2018-0151.
Brottem, L. and B. Brooks, 2018: Crops and livestock under the sun: Obstacles to rural livelihood adaptations to hotter 21st century temperatures in eastern Senegal. *Land Degradation & Development*, **29** (1), 118-126.
Brouziyne, Y. et al., 2018: Modeling sustainable adaptation strategies toward a climate-smart agriculture in a Mediterranean watershed under projected climate change scenarios. *Agricultural Systems*, **162**, 154-163.
Brown, T. C., V. Mahat and J. A. Ramirez, 2019: Adaptation to Future Water Shortages in the United States Caused by Population Growth and Climate Change. *Earth's Future*, **7** (3), 219-234, doi:10.1029/2018EF001091.
Brun, F. et al., 2017: A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nature Geoscience*, **10**, 668, doi:10.1038/ngeo2999
https://www.nature.com/articles/ngeo2999#supplementary-information.
Brunner, M. I. et al., 2019: Future shifts in extreme flow regimes in Alpine regions. *Hydrol. Earth Syst. Sci.*, **23** (11), 4471-4489, doi:10.5194/hess-23-4471-2019.
Brüssow, K., A. Faße and U. Grote, 2017: Implications of climate-smart strategy adoption by farm households for food security in Tanzania. *Food Security*, **9** (6), 1203-1218.
Budiyono, Y., J. C. J. H. Aerts, D. Tollenaar and P. J. Ward, 2016: River flood risk in Jakarta under scenarios of future change. *Nat. Hazards Earth Syst. Sci.*, **16** (3), 757-774, doi:10.5194/nhess-16-757-2016.
Buhaug, H., 2016: Climate Change and Conflict: Taking Stock. **22**, 331, doi:10.1515/peps-2016-0034.
Bunce, A. et al., 2016: Vulnerability and adaptive capacity of Inuit women to climate change: a case study from Iqaluit, Nunavut. *Natural Hazards*, **83** (3), 1419-1441, doi:10.1007/s11069-016-2398-6.
Burchfield, E. K. and J. Gilligan, 2016: Agricultural adaptation to drought in the Sri Lankan dry zone. *Applied Geography*, **77**, 92-100, doi:https://doi.org/10.1016/j.apgeog.2016.10.003.
Burek, P. et al., 2020: Development of the Community Water Model (CWatM v1.04) – a high-resolution hydrological model for global and regional assessment of integrated water resources management. *Geosci. Model Dev.*, **13** (7), 3267-3298, doi:10.5194/gmd-13-3267-2020.
Burgess, W. G. et al., 2010: Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic. *Nature Geoscience*, **3** (2), 83-87, doi:10.1038/ngeo750.
Burke, E. J., Y. Zhang and G. Krinner, 2020: Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change. *The Cryosphere*, **14** (9), 3155-3174.
Burke, M., S. M. Hsiang and E. Miguel, 2015: Climate and Conflict. *Annual Review of Economics*, **7** (1), 577-617, doi:10.1146/annurev-economics-080614-115430.
Burn, D. H., P. H. Whitfield and M. Sharif, 2016: Identification of changes in floods and flood regimes in Canada using a peaks over threshold approach. *Hydrological Processes*, **30** (18), 3303-3314.
Burn, S. et al., 2015: Desalination techniques — A review of the opportunities for desalination in agriculture. *Desalination*, **364**, 2-16, doi:https://doi.org/10.1016/j.desal.2015.01.041.
Bussière, E. M. S., L. G. Underhill and R. Altwegg, 2015: Patterns of bird migration phenology in South Africa suggest northern hemisphere climate as the most consistent driver of change. *Global Change Biology*, **21** (6), 2179-2190, doi:10.1111/gcb.12857.

Bustamante, M. et al., 2018: Chapter 4: Direct and indirect drivers of change in biodiversity and nature's contributions to people.
Buytaert, W. et al., 2016: Citizen Science for Water Resources Management: Toward Polycentric Monitoring and Governance? *Journal of Water Resources Planning and Management*, **142** (4), 01816002, doi:10.1061/(ASCE)WR.1943-5452.0000641.
Buytaert, W. et al., 2017: Glacial melt content of water use in the tropical Andes. *Environmental Research Letters*, **12** (11), 114014.
Buytaert, W. et al., 2014: Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, **2**, 26.
Byers, E. A., G. Coxon, J. Freer and J. W. Hall, 2020: Drought and climate change impacts on cooling water shortages and electricity prices in Great Britain. *Nature Communications*, **11** (1), 2239, doi:10.1038/s41467-020-16012-2.
Byers, E. A. et al., 2016: Water and climate risks to power generation with carbon capture and storage. *Environmental Research Letters*, **11** (2), 024011, doi:10.1088/1748-9326/11/2/024011.
Caillouet, L. et al., 2017: Ensemble reconstruction of spatio-temporal extreme low-flow events in France since 1871. *Hydrol. Earth Syst. Sci.*, **21** (6), 2923-2951, doi:10.5194/hess-21-2923-2017.
Caldera, U., D. Bogdanov, S. Afanasyeva and C. Breyer, 2018: Role of Seawater Desalination in the Management of an Integrated Water and 100% Renewable Energy Based Power Sector in Saudi Arabia. *Water*, **10** (1), doi:10.3390/w10010003.
Caldera, U. and C. Breyer, 2020: Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems. *Energy*, **200**, 117507, doi:https://doi.org/10.1016/j.energy.2020.117507.
Call, M. A., C. Gray, M. Yunus and M. Emch, 2017: Disruption, not displacement: environmental variability and temporary migration in Bangladesh. *Global Environmental Change*, **46**, 157-165.
Calliari, E., A. Staccione and J. Mysiak, 2019: An assessment framework for climate-proof nature-based solutions. Elsevier B.V., **656**, 691-700, doi:10.1016/j.scitotenv.2018.11.341.
Canadell, J. G. et al., 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Capodaglio, A. G., 2020: Fit-for-purpose urban wastewater reuse: Analysis of issues and available technologies for sustainable multiple barrier approaches. *Critical Reviews in Environmental Science and Technology*, 1-48, doi:10.1080/10643389.2020.1763231.
Caretta, M. A. and L. Börjeson, 2015: Local gender contract and adaptive capacity in smallholder irrigation farming: a case study from the Kenyan drylands. *Gender, Place & Culture*, **22** (5), 644-661, doi:10.1080/0966369X.2014.885888.
Caretta, M. A., R. Fernandez, N. Zegre and J. Shinn, 2021: Flooding Hazard and Vulnerability. An Interdisciplinary Experimental Approach for the Study of the 2016 West Virginia Floods. *Frontiers in Water*, **3** (60), doi:10.3389/frwa.2021.656417.
Carey, M. et al., 2017: Impacts of Glacier Recession and Declining Meltwater on Mountain Societies. *Annals of the American Association of Geographers*, **107** (2), 350-359, doi:10.1080/24694452.2016.1243039.
Carlisle, K. and R. L. Gruby, 2017: Polycentric Systems of Governance: A Theoretical Model for the Commons. *Policy Studies Journal*, **0** (0), doi:10.1111/psj.12212.
Carlton, E. J. et al., 2014: Heavy Rainfall Events and Diarrhea Incidence: The Role of Social and Environmental Factors. *American Journal of Epidemiology*, **179** (3), 344-352, doi:10.1093/aje/kwt279.
Carmichael, W. W. and G. L. Boyer, 2016: Health impacts from cyanobacteria harmful algae blooms: Implications for the North American Great Lakes. *Harmful Algae*, **54**, 194-212, doi:https://doi.org/10.1016/j.hal.2016.02.002.
Carr, E. R. and M. C. Thompson, 2014: Gender and Climate Change Adaptation in Agrarian Settings: Current Thinking, New Directions, and Research Frontiers. *Geography Compass*, **8** (3), 182-197, doi:10.1111/gec3.12121.
Carrão, H., G. Naumann and P. Barbosa, 2016: Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change*, **39**, 108-124, doi:https://doi.org/10.1016/j.gloenvcha.2016.04.012.
Carrão, H., G. Naumann and P. Barbosa, 2018: Global projections of drought hazard in a warming climate: a prime for disaster risk management. *Climate Dynamics*, **50** (5-6), 2137-2155.
Carratalà, A., V. Bachmann, T. R. Julian and T. Kohn, 2020: Adaptation of Human Enterovirus to Warm Environments Leads to Resistance against Chlorine Disinfection. *Environmental Science & Technology*, **54** (18), 11292-11300, doi:10.1021/acs.est.0c03199.
Carrivick, J. L. and T. Heckmann, 2017: Short-term geomorphological evolution of proglacial systems. *Geomorphology*, **287**, 3-28, doi:https://doi.org/10.1016/j.geomorph.2017.01.037.
Carter, J. G., J. Handley, T. Butlin and S. Gill, 2018: Adapting cities to climate change – exploring the flood risk management role of green infrastructure landscapes. *Journal of Environmental Planning and Management*, **61** (9), 1535-1552, doi:10.1080/09640568.2017.1355777.

Carter, L., 2019: He korowai o Matainaka / The cloak of Matainaka: Traditional ecological knowledge in climate change adaptation – Te Wai Pounamu, New Zealand. *New Zealand Journal of Ecology*, **43** (3), 3386, doi:https://dx.doi.org/10.20417/nzjecol.43.27.
Carvajal, P. E. et al., 2019: Large hydropower, decarbonisation and climate change uncertainty: Modelling power sector pathways for Ecuador. *Energy Strategy Reviews*, **23**, 86-99, doi:https://doi.org/10.1016/j.esr.2018.12.008.
Cashman, A., 2014: Water Security and Services in the Caribbean. *Water*, **6** (5), doi:10.3390/w6051187.
Cashman, A. and D. Yawson, 2019: Water, Livelihoods, and Migration in SIDS: Climate Change and Future Prospects for Carriacou, West Indies. *Resources*, **8** (4), doi:10.3390/resources8040174.
Cassin, J. and J. Matthews, 2021: Nature based solutions, water security and climate change: issues and opportunities. In: Nature-based Solutions and Water Security: An Agenda for the 21st Century [Cassin, J., J. Matthews and E. Lopez Gunn (eds.)]. Elsevier.
Castells-Quintana, D., M. d. P. Lopez-Uribe and T. K. J. McDermott, 2018: Adaptation to climate change: A review through a development economics lens. *World Development*, **104**, 183-196, doi:https://doi.org/10.1016/j.worlddev.2017.11.016.
Castleden, H. et al., 2017: Implementing Indigenous and Western Knowledge Systems (Part 2): "You Have to Take a Backseat" and Abandon the Arrogance of Expertise. *International Indigenous Policy Journal*, **8`**, doi:10.18584/iipj.2017.8.4.8.
Cattaneo, C. et al., 2019: Human migration in the era of climate change. *Review of Environmental Economics and Policy*, **13** (2), 189-206.
Cattaneo, C. and G. Peri, 2016: The migration response to increasing temperatures. *Journal of Development Economics*, **122**, 127-146, doi:https://doi.org/10.1016/j.jdeveco.2016.05.004.
Cave, K. and S. McKay, 2016: *Water Song: Indigenous Women and Water*. 64-73 pp.
CDP, 2018: *Treading Water, Corporate Responses to Rising Water Challenges (CDP Global Water Report). CDP Global Water Report 2018*. London, UK [Available at: https://6fefcbb86e61af1b2fc4-c70d8ead6ced550b4d987d7c03fcdd1d.ssl.cf3.rackcdn.com/cms/reports/documents/000/004/232/original/CDP_Global_Water_Report_2018.pdf?1554392583].
Ceola, S. et al., 2016: Adaptation of water resources systems to changing society and environment: a statement by the International Association of Hydrological Sciences. *Hydrological Sciences Journal*, **61** (16), 2803-2817, doi:10.1080/02626667.2016.1230674.
CERES, 2019: *Feeding Ourselves Thirsty, Tracking Food Company Progress Toward a Water-Smart Future, Executive Summary*. [Available at: https://feedingourselvesthirsty.ceres.org/].
Chadburn, S. E. et al., 2017: An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, **7**, 340, doi:10.1038/nclimate3262 https://www.nature.com/articles/nclimate3262#supplementary-information.
Chakraborty, J., T. W. Collins and S. E. Grineski, 2018: Exploring the Environmental Justice Implications of Hurricane Harvey Flooding in Greater Houston, Texas. *American Journal of Public Health*, **109** (2), 244-250, doi:10.2105/AJPH.2018.304846.
Chakraborty, J., S. E. Grineski and T. W. Collins, 2019: Hurricane Harvey and people with disabilities: Disproportionate exposure to flooding in Houston, Texas. *Social Science & Medicine*, **226**, 176-181, doi:https://doi.org/10.1016/j.socscimed.2019.02.039.
Chakraborty, R. and P. Y. Sherpa, 2021: From climate adaptation to climate justice: Critical reflections on the IPCC and Himalayan climate knowledges. *Climatic Change*, **167** (3), 49, doi:10.1007/s10584-021-03158-1.
Chambwera, M. et al., 2014: Economics of adaptation. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 945-977.
Chan, N. W., M. L. Tan, A. A. Ghani and N. A. Zakaria, 2019: Sustainable urban drainage as a viable measure of coping with heat and floods due to climate change. *IOP Conference Series: Earth and Environmental Science*, **257**, 012013, doi:10.1088/1755-1315/257/1/012013.
Chandra, A., K. E. McNamara and P. Dargusch, 2018: Climate-smart agriculture: perspectives and framings. *Climate Policy*, **18** (4), 526-541.
Chandra, A. et al., 2017: Gendered vulnerabilities of smallholder farmers to climate change in conflict-prone areas: A case study from Mindanao, Philippines. *Journal of Rural Studies*, **50**, 45-59, doi:https://doi.org/10.1016/j.jrurstud.2016.12.011.
Charan, D., M. Kaur and P. Singh, 2017: Customary Land and Climate Change Induced Relocation—A Case Study of Vunidogoloa Village, Vanua Levu, Fiji. In: Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life [Leal Filho, W. (ed.)]. Springer International Publishing, Cham, 19-33.
Chaturvedi, V. et al., 2015: Climate mitigation policy implications for global irrigation water demand. *Mitigation and Adaptation Strategies for Global Change*, **20** (3), 389-407, doi:10.1007/s11027-013-9497-4.
Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, **26** (11), 6134-6155, doi:https://doi.org/10.1111/gcb.15310.

Chen, B. et al., 2021: Dynamic Risk Assessment for Geologic CO2 Sequestration. In: *15th International Conference on Greenhouse Gas Control Technologies GHGT*, 15-18 March 2021, Abu Dhabi, UAE.
Chen, X. and S.-J. Jeong, 2018: Irrigation enhances local warming with greater nocturnal warming effects than daytime cooling effects. *Environmental Research Letters*, **13** (2), 024005, doi:10.1088/1748-9326/aa9dea.
Cheng, S., J. Huang, F. Ji and L. Lin, 2017: Uncertainties of soil moisture in historical simulations and future projections. *Journal of Geophysical Research: Atmospheres*, **122** (4), 2239-2253, doi:10.1002/2016jd025871.
Chesterman, N. S. et al., 2019: The effects of trainings in soil and water conservation on farming practices, livelihoods, and land-use intensity in the Ethiopian highlands. *Land Use Policy*, **87**, 104051.
Chiblow , S., 2019: Anishinabek Women's Nibi Giikendaaswin (Water Knowledge). *Water*, **11** (2), 209.
Chinwendu, O., S. Sadiku, A. Okhimamhe and J. Eichie, 2017: Households Vulnerability and Adaptation to Climate Variability Induced Water Stress on Downstream Kaduna River Basin. *American Journal of Climate Change*, **6**, 247-267, doi:10.4236/ajcc.2017.62013.
Choi, W., K. Nauth, J. Choi and S. Becker, 2016: Urbanization and Rainfall–Runoff Relationships in the Milwaukee River Basin. *The Professional Geographer*, **68** (1), 14-25, doi:10.1080/00330124.2015.1007427.
Cholibois, T., 2020: Electrifying the 'eighth continent': exploring the role of climate finance and its impact on energy justice and equality in Madagascar's planned energy transition. *Climatic Change*, **161** (2), 345-364, doi:10.1007/s10584-019-02644-x.
Christidis, N., R. A. Betts and P. A. Stott, 2019: The Extremely Wet March of 2017 in Peru. *Bulletin of the American Meteorological Society*, **100** (1), S31-S35, doi:10.1175/BAMS-D-18-0110.1.
Christidis, N., K. Manomaiphiboon, A. Ciavarella and P. A. Stott, 2018: The Hot and Dry April of 2016 in Thailand. *Bulletin of the American Meteorological Society*, **99** (1), S128-S132, doi:10.1175/BAMS-D-17-0071.1.
Chu, E. K., 2017: Urban climate adaptation and the reshaping of state–society relations: The politics of community knowledge and mobilisation in Indore, India. *Urban Studies*, **55** (8), 1766-1782, doi:10.1177/0042098016686509.
Chu, E. K. and C. E. B. Cannon, 2021: Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. *Current opinion in environmental sustainability*, **51**, 85-94, doi:https://doi.org/10.1016/j.cosust.2021.02.009.
Chui, T. F. M. and J. P. Terry, 2015: Groundwater salinisation on atoll islands after storm-surge flooding: modelling the influence of central topographic depressions. *Water and Environment Journal*, **29** (3), 430-438, doi:https://doi.org/10.1111/wej.12116.
CIESIN, 2018a: Documentation for the Gridded Population of the World, Version 4 (GPWv4), Revision 11 Data Sets. Palisades NY: NASA Socioeconomic Data and Applications Center (SEDAC). Center for International Eaerth Science Information Network (CIESIN), Columbia University, doi:https://doi.org/10.7927/H45Q4T5F.
CIESIN, 2018b: Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. NASA Socioeconomic Data and Applications Center (SEDAC). Center for International Earth Science Information Network (CIESIN), Columbia University, Palisades, NY, doi: https://doi.org/10.7927/H49C6VHW.
Ciplet, D., K. M. Adams, R. Weikmans and J. T. Roberts, 2018: The Transformative Capability of Transparency in Global Environmental Governance. *Global Environmental Politics*, **18** (3), 130-150, doi:10.1162/glep_a_00472.
Cipollina, A. et al., 2015: Renewable energy desalination: performance analysis and operating data of existing RES desalination plants. *Desalination and Water Treatment*, **55** (11), 3120-3140, doi:10.1080/19443994.2014.959734.
Ciscar, J. C. et al., 2018: *Climate impacts in Europe: Final report of the JRC PESETA III project, EUR 29427 EN*. Union, P. O. o. t. E., Luxembourg.
Cissé, G. et al., 2016: Vulnerabilities of water and sanitation at households and community levels in face of climate variability and change: trends from historical climate time series in a West African medium-sized town. *International Journal of Global Environmental Issues*, **15** (1-2), 81-99, doi:10.1504/IJGENVI.2016.074360.
Climate., C., 2019: *Record breaking temperatures for June*. [Available at: https://climate.copernicus.eu/record-breaking-temperatures-june].
Closas, A. and E. Rap, 2017: Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. **104**, 33-37, doi:10.1016/j.enpol.2017.01.035.
Coffel, E. D. and J. S. Mankin, 2020: Thermal power generation is disadvantaged in a warming world. *Environmental Research Letters*, doi:10.1088/1748-9326/abd4a8.
Cohen, A. S. et al., 2016: Climate warming reduces fish production and benthic habitat in Lake Tanganyika, one of the most biodiverse freshwater ecosystems. *Proceedings of the National Academy of Sciences*, **113** (34), 9563, doi:10.1073/pnas.1603237113.
Cole, D. H., 2015: Advantages of a polycentric approach to climate change policy. *Nature Climate Change*, **5**, 114, doi:10.1038/nclimate2490.
Collins, L. et al., 2017: Source Water Protection Planning for Ontario First Nations Communities: Case Studies Identifying Challenges and Outcomes. *Water*, **9** (7), doi:10.3390/w9070550.
Collins, M. et al., 2013: Long-term Climate Change: Projections, Com¬mitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Collins, S. M. et al., 2019a: 'I know how stressful it is to lack water!' Exploring the lived experiences of household water insecurity among pregnant and postpartum women in western Kenya. *Global Public Health*, **14** (5), 649-662, doi:10.1080/17441692.2018.1521861.
Collins, T. W., S. E. Grineski, J. Chakraborty and A. B. Flores, 2019b: Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research*, **179**, 108772, doi:https://doi.org/10.1016/j.envres.2019.108772.
Colón-González, F. J. et al., 2016: Assessing the effects of air temperature and rainfall on malaria incidence: an epidemiological study across Rwanda and Uganda. *Geospatial health*, **11** (s1), doi:10.4081/gh.2016.379.
Comberti, C. et al., 2019: Adaptation and Resilience at the Margins: Addressing Indigenous Peoples' Marginalization at International Climate Negotiations. *Environment: Science and Policy for Sustainable Development*, **61** (2), 14-30, doi:10.1080/00139157.2019.1564213.
Comprehensive Assessment of Water Management in Agriculture, 2007: *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Institute, I. W. M., London: Earthscan, and Colombo.
Comte, L. and G. Grenouillet, 2013: Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography*, **36** (11), 1236–1246, doi:https://doi.org/10.1111/j.1600-0587.2013.00282.x.
Comte, L. and J. D. Olden, 2017: Climatic vulnerability of the world's freshwater and marine fishes. *Nature Climate Change*, **7**, 718, doi:10.1038/nclimate3382
https://www.nature.com/articles/nclimate3382#supplementary-information.
CONAF, 2017: *Análisis de la Afectación y Severidad de los Incendios Forestales ocurridos en enero y febrero de 2017 sobre los usos de suelo y los ecosistemas naturales presentes entre las regiones de Coquimbo y Los Ríos de Chile*. Santiago, Chile [Available at: https://doi.org/https://doi.org/10.1002/ecs2.2171].
Condon, L. E., A. L. Atchley and R. M. Maxwell, 2020: Evapotranspiration depletes groundwater under warming over the contiguous United States. *Nature Communications*, **11** (1), 873, doi:10.1038/s41467-020-14688-0.
Conroy-Ben, O. and R. Richard, 2018: Disparities in Water Quality in Indian Country. *Journal of Contemporary Water Research & Education*, **163** (1), 31-44, doi:10.1111/j.1936-704X.2018.03268.x.
Constantine, K., M. Massoud, I. Alameddine and M. El-Fadel, 2017: The role of the water tankers market in water stressed semi-arid urban areas: Implications on water quality and economic burden. *Journal of environmental management*, **188**, 85-94.
Conway, D. et al., 2015: Climate and southern Africa's water–energy–food nexus. *Nature Climate Change*, **5**, 837, doi:10.1038/nclimate2735
https://www.nature.com/articles/nclimate2735#supplementary-information.
Cook, B. et al., 2020a: Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future*, **8** (6).
Cook, B. I. et al., 2020b: Divergent Regional Climate Consequences of Maintaining Current Irrigation Rates in the 21st Century. *Journal of Geophysical Research: Atmospheres*, **125** (14), e2019JD031814, doi:https://doi.org/10.1029/2019JD031814.
Cook, B. I., S. P. Shukla, M. J. Puma and L. S. Nazarenko, 2015: Irrigation as an historical climate forcing. *Climate Dynamics*, **44** (5), 1715-1730, doi:10.1007/s00382-014-2204-7.
Cook, W. D., K. Tone and J. Zhu, 2014: Data envelopment analysis: Prior to choosing a model. *Omega*, **44**, 1-4, doi:https://doi.org/10.1016/j.omega.2013.09.004.
Cooper, M. W. et al., 2019: Mapping the effects of drought on child stunting. *Proceedings of the National Academy of Sciences*, **116** (35), 17219-17224.
Cooper, R. C. et al., 2012: *Review of California's Water Recycling Criteria for Agricultural Irrigation. Recommendations of an NWRI Independent Advisory Panel*. National Water Research Institute, Institute, N. W. R. [Available at: https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/recharge/NWRI_AgPanelReportforCDPHFINAL-09-2012.pdf].
Cousins, S., 2020: COVID-19 has "devastating" effect on women and girls. *The Lancet*, **396** (10247), 301-302, doi:10.1016/S0140-6736(20)31679-2.
Craft, A., 2018: Navigating Our Ongoing Sacred Legal Relationship with Nibi (Water). In: UNDRIP Implementation: More Reflections on the Braiding of International, Domestic and Indigenous Laws. Centre for International Governance Innovation, Waterloo, ON, Canada, 53–62.
Crayton, A. et al., 2020: *Narratives and Needs: Analyzing Experiences of Cyclone Amphan Using Twitter Discourse*. [Available at: http://arxiv.org/abs/2009.05560].
CRED, 2019: *Disasters in Africa: 20 Year Review (2000-2019*)*. CRED Crunch [Available at: file:///Users/aditimukherji/Downloads/CredCrunch56 (1).pdf].
Creed, I. F. et al., 2019: Managing Forests for Both Downstream and Downwind Water. *Frontiers in Forests and Global Change*, **2**, 64.
Creed, I. F. and M. van Noordwijk, 2018: *Forest and Water on a Changing Planet: Vulnerability, Adaptation and Governance Opportunities. A Global Assessment Report*. IUFRO World Series **38**, Vienna, 192p.
Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, **7** (5), 916-944, doi:10.1111/gcbb.12205.

Cronin, J., G. Anandarajah and O. Dessens, 2018: Climate change impacts on the energy system: a review of trends and gaps. *Climatic Change*, **151** (2), 79-93, doi:10.1007/s10584-018-2265-4.
Cui, X. et al., 2014: Changes in soil total organic carbon after an experimental fire in a cold temperate coniferous forest: A sequenced monitoring approach. *Geoderma*, **226-227**, 260-269, doi:https://doi.org/10.1016/j.geoderma.2014.02.010.
Cunsolo, A. et al., 2020: "You can never replace the caribou": Inuit experiences of ecological grief from caribou declines. *American Imago*, **77** (1), 31-59, doi:10.1353/aim.2020.0002.
Currenti, R. et al., 2019: Adaptation to Climate Change in an Interior Pacific Island Village: a Case Study of Nawairuku, Ra, Fiji. *Human Ecology*, **47** (1), 65-80, doi:10.1007/s10745-019-0049-8.
Cuthbert, M. O. et al., 2019a: Global patterns and dynamics of climate–groundwater interactions. *Nature Climate Change*, **9** (2), 137-141, doi:10.1038/s41558-018-0386-4.
Cuthbert, M. O. et al., 2019b: Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. *Nature*, **572** (7768), 230-234, doi:10.1038/s41586-019-1441-7.
Cutter, S. et al., 2012: Managing the Risks from Climate Extremes at the Local Level. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C. B., V. Barros, T. F. Stocker, Q. Dahe, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 291-338.
Cutter, S. L. and M. Gall, 2015: Sendai targets at risk. *Nature Climate Change*, **5** (8), 707-709, doi:10.1038/nclimate2718.
D'Odorico, P. et al., 2014: Feeding humanity through global food trade. *Earth's Future*, **2** (9), 458-469, doi:https://doi.org/10.1002/2014EF000250.
D'Odorico, P. et al., 2018: The Global Food-Energy-Water Nexus. *Reviews of Geophysics*, **56** (3), 456-531, doi:10.1029/2017RG000591.
da Cunha, D. A., A. B. Coelho and J. G. Féres, 2015: Irrigation as an adaptive strategy to climate change: an economic perspective on Brazilian agriculture. *Environment and Development Economics*, **20** (1), 57-79, doi:10.1017/S1355770X14000102.
Dai, A., 2016: Historical and Future Changes in Streamflow and Continental Runoff. In: Terrestrial Water Cycle and Climate Change, 17-37.
Dai, C., X. S. Qin, W. T. Lu and Y. Huang, 2020: Assessing adaptation measures on agricultural water productivity under climate change: A case study of Huai River Basin, China. *Science of The Total Environment*, **721**, 137777, doi:https://doi.org/10.1016/j.scitotenv.2020.137777.
Daly-Hassen, H., M. Annabi and C. King-Okumu, 2019: Social and private profitability of tree-based adaptation options to climate change in a dryland area of Tunisia. *New Medit*, **18** (2), 89-104, doi:10.30682/nm1902f.
Damania, R. et al., 2017: *Uncharted Waters: The New Economics of Water Scarcity and Variability*. The World Bank, Washington DC [Available at: https://doi.org/10.1596/978-1-4648-1179-1].
Dang, L. Q., 2017: *Water Management through the Lenses of Gender, Ethnicity and Class: A Comparative Case Study of Upstream and Downstream Sites on the Mekong River in the Mekong Delta of Vietnam'*. ASEAN-Canada Working Paper Series, Centre for Non-Traditional Security Studies (NTS Centre), Singapore [Available at: https://think-asia.org/bitstream/handle/11540/7115/wp06-Ly-Quoc-Dang.pdf?sequence=1].
Darrah, S. E. et al., 2019: Improvements to the Wetland Extent Trends (WET) index as a tool for monitoring natural and human-made wetlands. *Ecological Indicators*, **99**, 294-298, doi:https://doi.org/10.1016/j.ecolind.2018.12.032.
Daryanto, S., L. Wang and P.-A. Jacinthe, 2017: Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. *Agricultural Water Management*, **179**, 18-33.
Das, A., P. Rokaya and K.-E. Lindenschmidt, 2020: Ice-Jam Flood Risk Assessment and Hazard Mapping under Future Climate. *Journal of Water Resources Planning and Management*, **146** (6), 04020029, doi:10.1061/(ASCE)WR.1943-5452.0001178.
Dasgupta, S. et al., 2013: River Salinity and Climate Change: Evidence from Coastal Bangladesh. In: World Scientific Reference on Asia and the World Economy. WORLD SCIENTIFIC, 205-242.
Dasgupta, S. et al., 2020: *Coping with Climate Change in the Sundarbans: Lessons from Multidisciplinary Studies*. World Bank, Bank, W., Washington, DC [Available at: https://openknowledge.worldbank.org/handle/10986/34770].
Davaze, L. et al., 2020: Region-wide annual glacier surface mass balance for the European Alps from 2000 to 2016. *Frontiers in Earth Science*, **8**.
Davenport, F. V., M. Burke and N. S. Diffenbaugh, 2021: Contribution of historical precipitation change to US flood damages. *Proceedings of the National Academy of Sciences*, **118** (4), e2017524118, doi:10.1073/pnas.2017524118.
David-Chavez, D. M. and M. C. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environmental Research Letters*, **13** (12), 123005, doi:10.1088/1748-9326/aaf300.
David, J. M. et al., 2014: Assessing multiple foodborne, waterborne and environmental exposures of healthy people to potential enteric pathogen sources: effect of age, gender, season, and recall period. *Epidemiology and infection*, **142** (1), 28-39, doi:10.1017/S0950268813000770.

Davidson, N., 2014: How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*, **65**, 936-941, doi:10.1071/MF14173.
Davidson, N. C. and C. M. Finlayson, 2018: Extent, regional distribution and changes in area of different classes of wetland. *Marine and Freshwater Research*, **69** (10), 1525-1533, doi:https://doi.org/10.1071/MF17377.
de Abreu, R. C. et al., 2019: Contribution of Anthropogenic Climate Change to April–May 2017 Heavy Precipitation over the Uruguay River Basin. *Bulletin of the American Meteorological Society*, **100** (1), S37-S41, doi:10.1175/BAMS-D-18-0102.1.
de Coninck, H. et al., 2018: Strengthening and implementing the global response. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V, M.-D. (ed.)].
de Graaf, I. E. M. et al., 2019: Environmental flow limits to global groundwater pumping. *Nature*, **574** (7776), 90-94, doi:10.1038/s41586-019-1594-4.
de Jong, P. et al., 2018: Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability. *Science of The Total Environment*, **634**, 1540-1553, doi:https://doi.org/10.1016/j.scitotenv.2018.03.256.
de Jong, S. M. and V. G. Jetten, 2007: Estimating spatial patterns of rainfall interception from remotely sensed vegetation indices and spectral mixture analysis. *International Journal of Geographical Information Science*, **21** (5), 529-545, doi:10.1080/13658810601064884.
de Juan, A., 2015: Long-term environmental change and geographical patterns of violence in Darfur, 2003–2005. *Political Geography*, **45**, 22-33, doi:https://doi.org/10.1016/j.polgeo.2014.09.001.
De Juan, A. and N. Hänze, 2020: Climate and cohesion: The effects of droughts on intra-ethnic and inter-ethnic trust. *Journal of Peace Research*, **58** (1), 151-167, doi:10.1177/0022343320974096.
de Kauwe, M. G. et al., 2013: Forest water use and water use efficiency at elevated CO2: a model-data intercomparison at two contrasting temperate forest FACE sites. *Global Change Biology*, **19** (6), 1759-1779, doi:10.1111/gcb.12164.
de Longueville, F. et al., 2020: Comparing climate change perceptions and meteorological data in rural West Africa to improve the understanding of household decisions to migrate. *Climatic Change*, 1-19.
de Roos, A. J. et al., 2017: Review of Epidemiological Studies of Drinking-Water Turbidity in Relation to Acute Gastrointestinal Illness. *Environmental Health Perspectives*, **125** (8), 086003-086003, doi:10.1289/EHP1090.
de Stefano, L. et al., 2017: Assessment of transboundary river basins for potential hydro-political tensions. *Global Environmental Change*, **45**, 35-46, doi:https://doi.org/10.1016/j.gloenvcha.2017.04.008.
de Vrese, P., S. Hagemann and M. Claussen, 2016: Asian irrigation, African rain: Remote impacts of irrigation. *Geophysical Research Letters*, **43** (8), 3737-3745, doi:10.1002/2016gl068146.
DeBeer, C. M., H. S. Wheater, S. K. Carey and K. P. Chun, 2016: Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a review and synthesis. *Hydrol. Earth Syst. Sci.*, **20** (4), 1573-1598, doi:10.5194/hess-20-1573-2016.
Debele, S. E. et al., 2019: Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases. Elsevier Inc., **179**, 108799, doi:10.1016/j.envres.2019.108799.
DEFRA, 2018: *The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting Making the country resilient to a changing climate*. Department for Environment, Food & Rural Affairs (DEFRA) [Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727252/national-adaptation-programme-2018.pdf].
Deitz, S. and K. Meehan, 2019: Plumbing Poverty: Mapping Hot Spots of Racial and Geographic Inequality in U.S. Household Water Insecurity. *Annals of the American Association of Geographers*, **109** (4), 1092-1109, doi:10.1080/24694452.2018.1530587.
Delany-Crowe, T. et al., 2019: Australian policies on water management and climate change: are they supporting the sustainable development goals and improved health and well-being? *Globalization and Health*, **15** (1), 68, doi:10.1186/s12992-019-0509-3.
Delaporte, I. and M. Maurel, 2018: Adaptation to climate change in Bangladesh. *Climate Policy*, **18** (1), 49-62.
Deligios, P. A. et al., 2019: Climate change adaptation and water saving by innovative irrigation management applied on open field globe artichoke. *Science of The Total Environment*, **649**, 461-472, doi:https://doi.org/10.1016/j.scitotenv.2018.08.349.
Dell, A. I., S. Pawar and V. M. Savage, 2014: Temperature dependence of trophic interactions are driven by asymmetry of species responses and foraging strategy. *Journal of Animal Ecology*, **83** (1), 70-84, doi:10.1111/1365-2656.12081.
Dellink, R., E. Lanzi and J. Chateau, 2019: The Sectoral and Regional Economic Consequences of Climate Change to 2060. *Environmental and Resource Economics*, **72** (2), 309-363, doi:10.1007/s10640-017-0197-5.
DeLong, S. B., A. M. Youberg, W. M. DeLong and B. P. Murphy, 2018: Post-wildfire landscape change and erosional processes from repeat terrestrial lidar in a steep headwater catchment, Chiricahua Mountains, Arizona, USA. *Geomorphology*, **300**, 13-30, doi:https://doi.org/10.1016/j.geomorph.2017.09.028.

Deng, C. and R. Bailey, 2019: A Modeling Approach for Assessing Groundwater Resources of a Large Coral Island under Future Climate and Population Conditions: Gan Island, Maldives. *Water*, **11** (10), doi:10.3390/w11101963.
Deng, H.-M., Q.-M. Liang, L.-J. Liu and L. D. Anadon, 2017: Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. *Environmental Research Letters*, **12** (12), 123001, doi:10.1088/1748-9326/aa98d2.
DeNicola, E. et al., 2015: Climate Change and Water Scarcity: The Case of Saudi Arabia. *Annals of Global Health*, **81** (3), 342-353, doi:https://doi.org/10.1016/j.aogh.2015.08.005.
Depietri, Y. and T. McPhearson, 2017: Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In: Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice [Kabisch, N., H. Korn, J. Stadler and A. Bonn (eds.)]. Springer International Publishing, Cham, 91-109.
Derner, J. et al., 2018: Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. *Climatic Change*, **146** (1-2), 19-32.
Deryng, D. et al., 2016: Regional disparities in the beneficial effects of rising CO2 concentrations on crop water productivity. *Nature Climate Change*, **6**, 786, doi:10.1038/nclimate2995
https://www.nature.com/articles/nclimate2995#supplementary-information.
Detges, A., 2016: Local conditions of drought-related violence in sub-Saharan Africa:The role of road and water infrastructures. *Journal of Peace Research*, **53** (5), 696-710, doi:10.1177/0022343316651922.
Devanand, A. et al., 2019: Choice of Irrigation Water Management Practice Affects Indian Summer Monsoon Rainfall and Its Extremes. *Geophysical Research Letters*, **46** (15), 9126-9135, doi:https://doi.org/10.1029/2019GL083875.
Devkota, R. P., G. Cockfield and T. N. Maraseni, 2014: Perceived community-based flood adaptation strategies under climate change in Nepal. *International Journal of Global Warming*, **6** (1), 113-124, doi:10.1504/IJGW.2014.058758.
Dewi, N., Kusnandar and E. S. Rahayu, 2018: Risk mitigation of climate change impacts on rice farming through crop insurance: An analysis of farmer's willingness to participate (a case study in Karawang Regency, Indonesia). *IOP Conference Series: Earth and Environmental Science*, **200** (1), doi:10.1088/1755-1315/200/1/012059.
Dey, N. C. et al., 2019: Effectiveness of a community-based water, sanitation, and hygiene (WASH) intervention in reduction of diarrhoea among under-five children: Evidence from a repeated cross-sectional study (2007–2015) in rural Bangladesh. *International journal of hygiene and environmental health*, **222** (8), 1098-1108, doi:10.1016/j.ijheh.2019.08.006.
Dey, P. and A. Mishra, 2017: Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *Journal of Hydrology*, **548**, 278-290, doi:https://doi.org/10.1016/j.jhydrol.2017.03.014.
Di Baldassarre, G. et al., 2013: Socio-hydrology: conceptualising human-flood interactions. *Hydrol. Earth Syst. Sci.*, **17** (8), 3295-3303, doi:10.5194/hess-17-3295-2013.
Diaz-Elsayed, N. et al., 2019: Wastewater-based resource recovery technologies across scale: A review. *Resources, Conservation and Recycling*, **145**, 94-112, doi:https://doi.org/10.1016/j.resconrec.2018.12.035.
Diaz, S. et al., 2019: Summary for policymakers of the global assessment report on biodiversity and ecosystem services. 1-56.
Dickin, S. et al., 2020: Sustainable sanitation and gaps in global climate policy and financing. *npj Clean Water*, **3** (1), 24, doi:10.1038/s41545-020-0072-8.
Dickin, S. K., C. J. Schuster-Wallace, M. Qadir and K. Pizzacalla, 2016: A Review of Health Risks and Pathways for Exposure to Wastewater Use in Agriculture. *Environmental Health Perspectives*, **124** (7), 900-909, doi:10.1289/ehp.1509995.
Dinar, S., D. Katz, L. De Stefano and B. Blankespoor, 2015: Climate change, conflict, and cooperation: Global analysis of the effectiveness of international river treaties in addressing water variability. *Political Geography*, **45**, 55-66, doi:https://doi.org/10.1016/j.polgeo.2014.08.003.
Dinar, S., D. Katz, L. De Stefano and B. Blankespoor, 2019: Do treaties matter? Climate change, water variability, and cooperation along transboundary river basins. *Political Geography*, **69**, 162-172, doi:https://doi.org/10.1016/j.polgeo.2018.08.007.
Diodato, N. et al., 2018: Climate-scale modelling of suspended sediment load in an Alpine catchment debris flow (Rio Cordon-northeastern Italy). *Geomorphology*, **309**, 20-28, doi:https://doi.org/10.1016/j.geomorph.2018.02.026.
Diver, S., 2018: Native Water Protection Flows Through Self-Determination: Understanding Tribal Water Quality Standards and "Treatment as a State". *Journal of Contemporary Water Research & Education*, **163** (1), 6-30, doi:10.1111/j.1936-704X.2018.03267.x.
Djoudi, H. et al., 2016: Beyond dichotomies: Gender and intersecting inequalities in climate change studies. *Ambio*, **45** (3), 248-262, doi:10.1007/s13280-016-0825-2.
Do, H. X., S. Westra and M. Leonard, 2017: A global-scale investigation of trends in annual maximum streamflow. *Journal of Hydrology*, **552**, 28-43, doi:https://doi.org/10.1016/j.jhydrol.2017.06.015.
Doblas-Reyes, F. J. et al., 2021: Linking Global to Regional Climate Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Chang [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen,

L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Döll, P. et al., 2018: Risks for the global freshwater system at 1.5 °C and 2 °C global warming. *Environmental Research Letters*, **13** (4), 044038, doi:10.1088/1748-9326/aab792.

Domec, J.-C., D. D. Smith and K. A. McCulloh, 2017: A synthesis of the effects of atmospheric carbon dioxide enrichment on plant hydraulics: implications for whole-plant water use efficiency and resistance to drought. *Plant, Cell & Environment*, **40** (6), 921-937, doi:10.1111/pce.12843.

Donat, M. G., O. Angélil and A. M. Ukkola, 2019: Intensification of precipitation extremes in the world's humid and water-limited regions. *Environmental Research Letters*, **14** (6), 065003, doi:10.1088/1748-9326/ab1c8e.

Donchyts, G. et al., 2016: Earth's surface water change over the past 30 years. *Nature Climate Change*, **6**, 810, doi:10.1038/nclimate3111.

Donohue, R. J., M. L. Roderick, T. R. McVicar and Y. Yang, 2017: A simple hypothesis of how leaf and canopy-level transpiration and assimilation respond to elevated CO2 reveals distinct response patterns between disturbed and undisturbed vegetation. *Journal of Geophysical Research: Biogeosciences*, **122** (1), 168-184, doi:10.1002/2016jg003505.

Doorn, N., 2021: Artificial intelligence in the water domain: Opportunities for responsible use. *Science of The Total Environment*, **755**, 142561, doi:https://doi.org/10.1016/j.scitotenv.2020.142561.

Dorber, M., A. Arvesen, D. Gernaat and F. Verones, 2020: Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection. *Scientific Reports*, **10** (1), 21777, doi:10.1038/s41598-020-78444-6.

Doswald, N. et al., 2014: Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, **6** (2), 185-201, doi:10.1080/17565529.2013.867247.

Dottori, F. et al., 2018: Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, **8** (9), 781-786, doi:10.1038/s41558-018-0257-z.

Douglas, I., 2018: The challenge of urban poverty for the use of green infrastructure on floodplains and wetlands to reduce flood impacts in intertropical Africa. *Landscape and Urban Planning*, **180**, 262-272, doi:https://doi.org/10.1016/j.landurbplan.2016.09.025.

Douville, H. et al., 2021: Water Cycle Changes. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Drenkhan, F. et al., 2015: The changing water cycle: climatic and socioeconomic drivers of water-related changes in the Andes of Peru. *Wiley Interdisciplinary Reviews: Water*, **2** (6), 715-733, doi:10.1002/wat2.1105.

Droppers, B. et al., 2020: Simulating human impacts on global water resources using VIC-5. *Geosci. Model Dev.*, **13** (10), 5029-5052, doi:10.5194/gmd-13-5029-2020.

du Bray, M. V. et al., 2017: Emotion, Coping, and Climate Change in Island Nations: Implications for Environmental Justice. *Environmental Justice*, **10** (4), 102-107, doi:10.1089/env.2016.0025.

Du, J., K. Wang and B. Cui, 2021: Attribution of the Extreme Drought-Related Risk of Wildfires in Spring 2019 over Southwest China. *Bulletin of the American Meteorological Society*, **102** (1), S83-S90, doi:10.1175/BAMS-D-20-0165.1.

Du, S. et al., 2020: Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. *Global Environmental Change*, **61**, 102037, doi:https://doi.org/10.1016/j.gloenvcha.2020.102037.

Dudley, R. W. et al., 2017: Trends in snowmelt-related streamflow timing in the conterminous United States. *Journal of Hydrology*, **547**, 208-221, doi:10.1016/j.jhydrol.2017.01.051.

Duffy Katharyn, A. et al., 2021: How close are we to the temperature tipping point of the terrestrial biosphere? *Science Advances*, **7** (3), eaay1052, doi:10.1126/sciadv.aay1052.

Dumenu, W. K. and E. A. Obeng, 2016: Climate change and rural communities in Ghana: Social vulnerability, impacts, adaptations and policy implications. *Environmental Science & Policy*, **55**, 208-217, doi:https://doi.org/10.1016/j.envsci.2015.10.010.

Dunn, R. J. H. et al., 2020: Development of an Updated Global Land In Situ-Based Data Set of Temperature and Precipitation Extremes: HadEX3. *Journal of Geophysical Research: Atmospheres*, **125** (16), e2019JD032263, doi:10.1029/2019JD032263.

Duran-Encalada, J. A., A. Paucar-Caceres, E. R. Bandala and G. H. Wright, 2017: The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region. *European Journal of Operational Research*, **256** (2), 567-581, doi:https://doi.org/10.1016/j.ejor.2016.06.016.

Durand, J.-L. et al., 2018: How accurately do maize crop models simulate the interactions of atmospheric CO2 concentration levels with limited water supply on water use and yield? *European Journal of Agronomy*, **100**, 67-75, doi:https://doi.org/10.1016/j.eja.2017.01.002.

Dussaillant, I. et al., 2019: Two decades of glacier mass loss along the Andes. *Nature Geoscience*, **12** (10), 802-808.

Duží, B. et al., 2017: Household measures for river flood risk reduction in the Czech Republic. *Journal of Flood Risk Management*, **10** (2), 253-266, doi:10.1111/jfr3.12132.

Dyer, F. et al., 2014: The effects of climate change on ecologically-relevant flow regime and water quality attributes. *Stochastic Environmental Research and Risk Assessment*, **28** (1), 67-82, doi:10.1007/s00477-013-0744-8.
Eakin, H. et al., 2016: Adapting to risk and perpetuating poverty: Household's strategies for managing flood risk and water scarcity in Mexico City. *Environmental Science & Policy*, **66**, 324-333, doi:https://doi.org/10.1016/j.envsci.2016.06.006.
Eakin, H. et al., 2020: Expressions of collective grievance as a feedback in multi-actor adaptation to water risks in Mexico City. *Regional Environmental Change*, **20** (1), 17, doi:10.1007/s10113-020-01588-8.
Earle, A. et al., 2015: *Transboundary Water Management and the Climate Change Debate*. Routledge, Abingdon and New York.
Ebrahim, S. H. et al., 2020: Forward planning for disaster-related mass gatherings amid COVID-19. *The Lancet Planetary Health*, **4** (9), e379-e380, doi:10.1016/S2542-5196(20)30175-3.
Eby, L. A., O. Helmy, L. M. Holsinger and M. K. Young, 2014: Evidence of Climate-Induced Range Contractions in Bull Trout Salvelinus confluentus in a Rocky Mountain Watershed, U.S.A. *PLOS ONE*, **9** (6), e98812, doi:10.1371/journal.pone.0098812.
EC, 2020: *Minimum requirements for water Re-use. 2020(March), 1689*. (EC), E. C. [Available at: http://data.consilium.europa.eu/doc/document/ST-15301-2019-REV-1/en/pdf].
Eekhout, J. P., J. E. Hunink, W. Terink and J. de Vente, 2018: Why increased extreme precipitation under climate change negatively affects water security. *Hydrology and Earth System Sciences*, **22** (11), 5935-5946.
Eekhout, J. P. C. and J. de Vente, 2019a: Assessing the effectiveness of Sustainable Land Management for large-scale climate change adaptation. *Science of The Total Environment*, **654**, 85-93, doi:https://doi.org/10.1016/j.scitotenv.2018.10.350.
Eekhout, J. P. C. and J. De Vente, 2019b: How soil erosion model conceptualization affects soil loss projections under climate change. *Progress in Physical Geography: Earth and Environment*, **44** (2), 212-232, doi:10.1177/0309133319871937.
Egbinola, C. N., H. D. Olaniran and A. C. Amanambu, 2017: Flood management in cities of developing countries: the example of Ibadan, Nigeria. *Journal of Flood Risk Management*, **10** (4), 546-554, doi:10.1111/jfr3.12157.
Eira, I. M. G., A. Oskal, I. Hanssen-Bauer and S. D. Mathiesen, 2018: Snow cover and the loss of traditional indigenous knowledge. *Nature Climate Change*, **8** (11), 928-931, doi:10.1038/s41558-018-0319-2.
Eisenack, K. et al., 2014: Explaining and overcoming barriers to climate change adaptation. *Nature Climate Change*, **4**, 867, doi:10.1038/nclimate2350.
Eisner, S. et al., 2017: An ensemble analysis of climate change impacts on streamflow seasonality across 11 large river basins. *Climatic Change*, **141** (3), 401-417.
Elias, E. et al., 2016: Climate Change, Agriculture and Water Resources in the Southwestern United States. *Journal of Contemporary Water Research & Education*, **158** (1), 46-61, doi:10.1111/j.1936-704X.2016.03218.x.
Elliott, J. et al., 2014: Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, **111** (9), 3239-3244, doi:10.1073/pnas.1222474110.
Elliott, M. et al., 2017: Multiple Household Water Sources and Their Use in Remote Communities With Evidence From Pacific Island Countries. *Water Resources Research*, **53** (11), 9106-9117, doi:https://doi.org/10.1002/2017WR021047.
Ellis, A. et al., 2016: WASH challenges to girls' menstrual hygiene management in Metro Manila, Masbate, and South Central Mindanao, Philippines. *Waterlines*, **35** (3), 306–323, doi:https://doi.org/10.3362/1756-3488.2016.022.
Ellison, D. et al., 2017: Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, **43**, 51-61.
Elum, Z. A., G. Nhamo and M. A. Antwi, 2018: Effects of climate variability and insurance adoption on crop production in select provinces of South Africa. *Journal of Water and Climate Change*, **9** (3), 500-511, doi:10.2166/wcc.2018.020.
Emanuel, K., 2017: Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences*, **114** (48), 12681, doi:10.1073/pnas.1716222114.
Emanuel, R. E., 2018: Climate Change in the Lumbee River Watershed and Potential Impacts on the Lumbee Tribe of North Carolina. *Journal of Contemporary Water Research & Education*, **163** (1), 79-93, doi:10.1111/j.1936-704X.2018.03271.x.
Emodi, N. V., T. Chaiechi and A. B. M. R. A. Beg, 2019: The impact of climate variability and change on the energy system: A systematic scoping review. *Science of The Total Environment*, **676**, 545-563, doi:https://doi.org/10.1016/j.scitotenv.2019.04.294.
Empinotti, V. L., J. Budds and M. Aversa, 2019: Governance and water security: The role of the water institutional framework in the 2013–15 water crisis in São Paulo, Brazil. *Geoforum*, **98**, 46-54, doi:https://doi.org/10.1016/j.geoforum.2018.09.022.
Emrich, C. T., E. Tate, S. E. Larson and Y. Zhou, 2020: Measuring social equity in flood recovery funding. *Environmental Hazards*, **19** (3), 228-250, doi:10.1080/17477891.2019.1675578.
Eriksen, S. et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383, doi:https://doi.org/10.1016/j.worlddev.2020.105383.

Ernst, K. M. and B. L. Preston, 2017: Adaptation opportunities and constraints in coupled systems: Evidence from the U.S. energy-water nexus. *Environmental Science & Policy*, **70**, 38-45, doi:https://doi.org/10.1016/j.envsci.2017.01.001.
Erwin, A. et al., 2021: Intersectionality shapes adaptation to social-ecological change. *World Development*, **138**, 105282, doi:https://doi.org/10.1016/j.worlddev.2020.105282.
Esteve, P., C. Varela-Ortega and T. E. Downing, 2018: A stakeholder-based assessment of barriers to climate change adaptation in a water-scarce basin in Spain. *Regional Environmental Change*, **18** (8), 2505-2517, doi:10.1007/s10113-018-1366-y.
Etongo, D., I. N. S. Djenontin, M. Kanninen and K. Fobissie, 2015: Smallholders' tree planting activity in the ziro province, southern burkina faso: Impacts on livelihood and policy implications. *Forests*, **6** (8), 2655-2677, doi:10.3390/f6082655.
Etter, S., N. Addor, M. Huss and D. Finger, 2017: Climate change impacts on future snow, ice and rain runoff in a Swiss mountain catchment using multi-dataset calibration. *Journal of Hydrology: Regional Studies*, **13**, 222-239, doi:https://doi.org/10.1016/j.ejrh.2017.08.005.
Eves, C. and S. Wilkinson, 2014: Assessing the immediate and short-term impact of flooding on residential property participant behaviour. *Natural Hazards*, **71** (3), 1519-1536.
Eyer, J. and C. J. Wichman, 2018: Does water scarcity shift the electricity generation mix toward fossil fuels? Empirical evidence from the United States. *Journal of Environmental Economics and Management*, **87**, 224-241, doi:https://doi.org/10.1016/j.jeem.2017.07.002.
Eyring, V. et al., 2021: Human Influence on the Climate System. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Fadul, E., I. Masih and C. De Fraiture, 2019: Adaptation strategies to cope with low, high and untimely floods: Lessons from the Gash spate irrigation system, Sudan. *Agricultural Water Management*, **217**, 212-225, doi:https://doi.org/10.1016/j.agwat.2019.02.035.
Falco, C., M. Galeotti and A. Olper, 2019: Climate change and migration: Is agriculture the main channel? *Global Environmental Change*, **59**, 101995, doi:https://doi.org/10.1016/j.gloenvcha.2019.101995.
Falkenmark, M., J. Lundqvist and C. Widstrand, 1989: Macro-scale water scarcity requires micro-scale approaches. *Natural Resources Forum*, **13** (4), 258-267, doi:10.1111/j.1477-8947.1989.tb00348.x.
Falkland, T. and I. White, 2020: *Freshwater availability under climate change*. Springer Climate, Springer.
Falkner, R., 2016: The Paris Agreement and the new logic of international climate politics. *International Affairs*, **92** (5), 1107-1125, doi:10.1111/1468-2346.12708.
Fallon, D. S. M. and C. A. Sullivan, 2014: Are We There Yet? NSW local governments' progress on climate change. *Australian Geographer*, **45** (2), 221-238, doi:10.1080/00049182.2014.899030.
Famiglietti, J. S., 2014: The global groundwater crisis. *Nature Climate Change*, **4**, 945, doi:10.1038/nclimate2425.
FAO, 2018a: *Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options.*, Food and Agriculture Organization of the United Nations (FAO) [Available at: http://www.fao.org/3/i9705en/i9705en.pdf].
FAO, 2018b: *World Food and Agriculture - Statistical Pocketbook 2018*. Rome, 254 [Available at: http://www.fao.org/3/CA1796EN/ca1796en.pdf].
Farinosi, F. et al., 2018: An innovative approach to the assessment of hydro-political risk: A spatially explicit, data driven indicator of hydro-political issues. *Global Environmental Change*, **52**, 286-313, doi:https://doi.org/10.1016/j.gloenvcha.2018.07.001.
Farinotti, D., A. Pistocchi and M. Huss, 2016: From dwindling ice to headwater lakes: could dams replace glaciers in the European Alps? *Environmental Research Letters*, **11** (5), 054022, doi:10.1088/1748-9326/11/5/054022.
Fasihi, M., O. Efimova and C. Breyer, 2019: Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production*, **224**, 957-980, doi:https://doi.org/10.1016/j.jclepro.2019.03.086.
Fauconnier, I. et al., 2018: *Women as change-makers in the governance of shared waters*. UN Water, Water, U., Gland, Switzerland, 50pp.
Fedele, G. et al., 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116-125, doi:https://doi.org/10.1016/j.envsci.2019.07.001.
Feng, H., 2016: Individual contributions of climate and vegetation change to soil moisture trends across multiple spatial scales. *Scientific Reports*, **6**, 32782, doi:10.1038/srep32782.
Feng, H. and M. Zhang, 2015: Global land moisture trends: drier in dry and wetter in wet over land. *Scientific Reports*, **5**, 18018, doi:10.1038/srep18018.
Feng, S. and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmos. Chem. Phys.*, **13** (19), 10081-10094, doi:10.5194/acp-13-10081-2013.
Fenton, A., J. Paavola and A. Tallontire, 2017a: Autonomous adaptation to riverine flooding in Satkhira District, Bangladesh: implications for adaptation planning. *Regional Environmental Change*, **17** (8), 2387-2396, doi:10.1007/s10113-017-1159-8.

Fenton, A., J. Paavola and A. Tallontire, 2017b: The Role of Microfinance in Household Livelihood Adaptation in Satkhira District, Southwest Bangladesh. *World Development*, **92**, 192-202, doi:https://doi.org/10.1016/j.worlddev.2016.12.004.
Ferchichi, I., S. Marlet and A. Zairi, 2017: How Farmers Deal with Water Scarcity in Community-Managed Irrigation SYSTEMS: A Case Study in Northern Tunisia. *Irrigation and Drainage*, **66** (4), 556-566, doi:10.1002/ird.2135.
Ferdous, M. R. et al., 2018: Socio-hydrological spaces in the Jamuna River floodplain in Bangladesh. *Hydrol. Earth Syst. Sci.*, **22** (10), 5159-5173, doi:10.5194/hess-22-5159-2018.
Ferdous, M. R. et al., 2019: The costs of living with floods in the Jamuna floodplain in Bangladesh. *Water*, **11** (6), 1238.
Ferdousi, F. et al., 2015: Identification of Essential Containers for Aedes Larval Breeding to Control Dengue in Dhaka, Bangladesh. *Tropical medicine and health*, **43** (4), 253-264, doi:10.2149/tmh.2015-16.
Fernández-Arévalo, T. et al., 2017: Quantitative assessment of energy and resource recovery in wastewater treatment plants based on plant-wide simulations. *Water Research*, **118**, 272-288, doi:https://doi.org/10.1016/j.watres.2017.04.001.
Fernández-Giménez, M. E., B. Batkhishig, B. Batbuyan and T. Ulambayar, 2015: Lessons from the dzud: Community-based rangeland management increases the adaptive capacity of Mongolian herders to winter disasters. *World Development*, **68**, 48-65.
Fezzi, C., A. R. Harwood, A. A. Lovett and I. J. Bateman, 2015: The environmental impact of climate change adaptation on land use and water quality. *Nature Climate Change*, **5**, 255, doi:10.1038/nclimate2525 https://www.nature.com/articles/nclimate2525#supplementary-information.
Ficklin, D. L. et al., 2018: Natural and managed watersheds show similar responses to recent climate change. *Proceedings of the National Academy of Sciences*, **115** (34), 8553-8557, doi:10.1073/pnas.1801026115.
Field, C. B. et al., 2014a: Technical Summary. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Aldunce, P., J. P. Ometto, N. Raholijao and K. Yasuhara (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 35-94.
Field, C. B., V. R. Barros, M. D. Mastrandrea and K. J. e. a. Mach, 2014b: Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability.Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press,, Cambridge, United Kingdom and New York, NY, USA, 1-32.
Filkova, M. et al., 2018: *Bonds and Climate Change: The State of the Market*. Climate Bonds Initiative [Available at: https://www.climatebonds.net/resources/reports/bonds-and-climate-change-state-market-2018].
Finlayson, C. M. et al., 2017: Policy considerations for managing wetlands under a changing climate. *Marine and Freshwater Research*, **68** (10), 1803-1815.
Finlayson, C. M. et al., 2006: Climate variability and change and other pressures on wetlands and waterbirds – Impacts and Adaptation In: Water Birds Around the World, Scottish Natural Heritage, [Boere, G., C. Gailbraith and D. Stroud (eds.)], Edinburgh, UK, 88-89.
Fitton, N. et al., 2019: The vulnerabilities of agricultural land and food production to future water scarcity. *Global Environmental Change*, **58**, 101944, doi:https://doi.org/10.1016/j.gloenvcha.2019.101944.
Fitzgerald, J. and J. Lenhart, 2016: Eco-districts: can they accelerate urban climate planning? *Environment and Planning C: Government and Policy*, **34** (2), 364-380, doi:10.1177/0263774X15614666.
Flores, A. B., T. W. Collins, S. E. Grineski and J. Chakraborty, 2020: Social vulnerability to Hurricane Harvey: Unmet needs and adverse event experiences in Greater Houston, Texas. *International Journal of Disaster Risk Reduction*, **46**, 101521, doi:https://doi.org/10.1016/j.ijdrr.2020.101521.
Flörke, M., C. Schneider and R. I. McDonald, 2018: Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, **1** (1), 51-58, doi:10.1038/s41893-017-0006-8.
Fluixá-Sanmartín, J., L. Altarejos-García, A. Morales-Torres and I. Escuder-Bueno, 2018: Review article: Climate change impacts on dam safety. *Nat. Hazards Earth Syst. Sci.*, **18** (9), 2471-2488, doi:10.5194/nhess-18-2471-2018.
Fluixá-Sanmartín, J., A. Morales-Torres, I. Escuder-Bueno and J. Paredes-Arquiola, 2019: Quantification of climate change impact on dam failure risk under hydrological scenarios: a case study from a Spanish dam. *Nat. Hazards Earth Syst. Sci.*, **19** (10), 2117-2139, doi:10.5194/nhess-19-2117-2019.
Flyen, C., L. Hauge Åshild, A.-J. Almås and L. Godbolt Åsne, 2018: Municipal collaborative planning boosting climate resilience in the built environment. *International Journal of Disaster Resilience in the Built Environment*, **9** (1), 58-69, doi:10.1108/IJDRBE-10-2016-0042.
Fodor, N. et al., 2017: Integrating Plant Science and Crop Modeling: Assessment of the Impact of Climate Change on Soybean and Maize Production. *Plant & cell physiology*, **58** (11), 1833-1847, doi:10.1093/pcp/pcx141.
Fontana, M. and D. Elson, 2014: Public policies on water provision and early childhood education and care (ECEC): do they reduce and redistribute unpaid work? *Gender & Development*, **22** (3), 459-474, doi:10.1080/13552074.2014.963320.

Forbes, B. C. et al., 2019: Changes in mountain birch forests and reindeer management: Comparing different knowledge systems in Sápmi, northern Fennoscandia. *Polar Record*, **55** (6), 507-521, doi:10.1017/S0032247419000834.
Ford, J. D. et al., 2019: Changing access to ice, land and water in Arctic communities. *Nature Climate Change*, **9** (4), 335-339, doi:10.1038/s41558-019-0435-7.
Ford, J. D. et al., 2020: The Resilience of Indigenous Peoples to Environmental Change. *One Earth*, **2** (6), 532-543, doi:10.1016/j.oneear.2020.05.014.
Ford, J. D. et al., 2017: Readiness for climate change adaptation in the Arctic: a case study from Nunavut, Canada. *Climatic Change*, **145** (1), 85-100, doi:10.1007/s10584-017-2071-4.
Ford, J. D., G. McDowell and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5** (12), 1046-1053, doi:10.1038/nclimate2723.
Ford, J. D. et al., 2016: Community-based adaptation research in the Canadian Arctic. *Wiley Interdisciplinary Reviews: Climate Change*, **7** (2), 175-191, doi:10.1002/wcc.376.
Formetta, G. and L. Feyen, 2019: Empirical evidence of declining global vulnerability to climate-related hazards. *Global Environmental Change*, **57**, 101920, doi:https://doi.org/10.1016/j.gloenvcha.2019.05.004.
Foster, S. et al., 2018: Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions. *Hydrogeology Journal*, **26** (8), 2781-2791, doi:10.1007/s10040-018-1830-2.
Fosu, B. O., S. Y. Simon Wang and J.-H. Yoon, 2016: The 2014/15 Snowpack Drought in Washington State and its Climate Forcing. *Bulletin of the American Meteorological Society*, **97** (12), S19-S24, doi:10.1175/BAMS-D-16-0154.1.
Fox-Kemper, B. et al., 2021: Ocean, Cryosphere and Sea Level Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Frame, D. J., M. F. Wehner, I. Noy and S. M. Rosier, 2020: The economic costs of Hurricane Harvey attributable to climate change. *Climatic Change*, **160** (2), 271-281, doi:10.1007/s10584-020-02692-8.
Francipane, A., S. Fatichi, V. Y. Ivanov and L. V. Noto, 2015: Stochastic assessment of climate impacts on hydrology and geomorphology of semiarid headwater basins using a physically based model. *Journal of Geophysical Research: Earth Surface*, **120** (3), 507-533, doi:10.1002/2014jf003232.
Franco-Torres, M., B. C. Rogers and R. Harder, 2020: Articulating the new urban water paradigm. *Critical Reviews in Environmental Science and Technology*, 1-47, doi:10.1080/10643389.2020.1803686.
François, B. et al., 2014: Integrating hydropower and intermittent climate-related renewable energies: a call for hydrology. *Hydrological Processes*, **28** (21), 5465–5468, doi:10.1002/hyp.10274.
Frank, D. C. et al., 2015: Water-use efficiency and transpiration across European forests during the Anthropocene. *Nature Climate Change*, **5**, 579, doi:10.1038/nclimate2614
https://www.nature.com/articles/nclimate2614#supplementary-information.
Frank, W., C. Bals and J. Grimm, 2019: The Case of Huaraz: First Climate Lawsuit on Loss and Damage Against an Energy Company Before German Courts. In: Loss and Damage from Climate Change: Concepts, Methods and Policy Options [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, 475-482.
French, A. and R. Mechler, 2017: *Managing El Niño Risks Under Uncertainty in Peru: Learning from the past for a more disaster-resilient future. Zurich*. [Available at: https://www.zurich.com/en/corporate-responsibility/flood-resilience/learning-from-post-flood-events].
French, A. et al., 2020: Root causes of recurrent catastrophe: The political ecology of El Niño-related disasters in Peru. *International Journal of Disaster Risk Reduction*, **47**, 101539, doi:https://doi.org/10.1016/j.ijdrr.2020.101539.
Frey, K. et al., 2021: Polycentric Water Governance in the Urban Global South. In: Sustainability in Natural Resources Management and Land Planning [Leal Filho, W., U. M. Azeiteiro and A. F. F. Setti (eds.)]. Springer International Publishing, Cham, 47-61.
Fricko, O. et al., 2016: Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, **11** (3), 034011, doi:10.1088/1748-9326/11/3/034011.
Frieler, K. et al., 2017a: Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geosci. Model Dev.*, **10** (12), 4321-4345, doi:10.5194/gmd-10-4321-2017.
Frieler, K. et al., 2017b: Understanding the weather signal in national crop-yield variability. *Earth's Future*, **5** (6), 605-616, doi:10.1002/2016ef000525.
Fritz, M., J. E. Vonk and H. Lantuit, 2017: Collapsing arctic coastlines. *Nature Climate Change*, **7** (1), 6-7.
Frolova, N. L. et al., 2017a: Recent changes of annual flow distribution of the Volga basin rivers. *Geography, Environment, Sustainability*, **10** (2), 28-39.
Frolova, N. L. et al., 2017b: Runoff fluctuations in the Selenga River Basin. *Regional Environmental Change*, **17** (7), 1965-1976, doi:10.1007/s10113-017-1199-0.

Frost, K. and I. Hua, 2019: "Quantifying spatiotemporal impacts of the interaction of water scarcity and water use by the global semiconductor manufacturing industry". *Water Resources and Industry*, **22**, 100115, doi:https://doi.org/10.1016/j.wri.2019.100115.
Fuchs, L. E., L. Orero, N. Namoi and H. Neufeldt, 2019: How to Effectively Enhance Sustainable Livelihoods in Smallholder Systems: A Comparative Study from Western Kenya. *Sustainability*, **11** (6), doi:10.3390/su11061564.
Fuhrman, J. et al., 2020: Food–energy–water implications of negative emissions technologies in a +1.5 °C future. *Nature Climate Change*, **10** (10), 920-927, doi:10.1038/s41558-020-0876-z.
Fujimori, S., N. Hanasaki and T. Masui, 2017: Projections of industrial water withdrawal under shared socioeconomic pathways and climate mitigation scenarios. *Sustainability Science*, **12** (2), 275-292, doi:10.1007/s11625-016-0392-2.
Funk, C. et al., 2018: Anthropogenic Enhancement of Moderate-to-Strong El Niño Events Likely Contributed to Drought and Poor Harvests in Southern Africa During 2016. *Bulletin of the American Meteorological Society*, **99** (1), S91-S96, doi:10.1175/BAMS-D-17-0112.1.
Funk, C. et al., 2019: Examining the Potential Contributions of Extreme "Western V" Sea Surface Temperatures to the 2017 March–June East African Drought. *Bulletin of the American Meteorological Society*, **100** (1), S55-S60, doi:10.1175/BAMS-D-18-0108.1.
Funk, C. et al., 2015: The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific Data*, **2** (1), 1-21.
Gabriel, A. and T. Mangahas, 2017: Indigenous People's Contribution to the Mitigation of Climate Variation, Their Perception, and Organizing Strategy for Sustainable Community Based Forest Resources Management in Caraballo Mountain, Philippines. *Open Journal of Ecology*, **7**, 85-100, doi:10.4236/oje.2017.72007.
Gadissa, T., M. Nyadawa, F. Behulu and B. Mutua, 2018: The Effect of Climate Change on Loss of Lake Volume: Case of Sedimentation in Central Rift Valley Basin, Ethiopia. *Hydrology*, **5** (4), doi:10.3390/hydrology5040067.
Gain, A. K., C. Giupponi and Y. Wada, 2016: Measuring global water security towards sustainable development goals. *Environmental Research Letters*, **11** (12), 124015, doi:10.1088/1748-9326/11/12/124015.
Ganguli, P., D. Kumar and A. R. Ganguly, 2017: US Power Production at Risk from Water Stress in a Changing Climate. *Scientific Reports*, **7** (1), 11983, doi:10.1038/s41598-017-12133-9.
Ganguly, D., P. J. Rasch, H. Wang and J.-h. Yoon, 2012: Fast and slow responses of the South Asian monsoon system to anthropogenic aerosols. *Geophysical Research Letters*, **39** (18), doi:10.1029/2012gl053043.
Gao, J. and B. F. Mills, 2018: Weather Shocks, Coping Strategies, and Consumption Dynamics in Rural Ethiopia. *World Development*, **101**, 268-283, doi:https://doi.org/10.1016/j.worlddev.2017.09.002.
Garbrecht, J. D. and X. C. Zhang, 2015: Soil Erosion from Winter Wheat Cropland under Climate Change in Central Oklahoma. *Applied Engineering in Agriculture*, **31** (3), 439-454, doi:https://doi.org/10.13031/aea.31.10998.
Garrick, D. et al., 2019: Rural water for thirsty cities: a systematic review of water reallocation from rural to urban regions. *Environmental Research Letters*, **14** (4), 043003, doi:10.1088/1748-9326/ab0db7.
Gawith, D., A. Daigneault and P. Brown, 2016: Does community resilience mitigate loss and damage from climaterelated disasters? Evidence based on survey data. *Journal of Environmental Planning and Management*, **59** (12), 2102-2123, doi:10.1080/09640568.2015.1126241.
GCA, 2019: *Adapt now: A global call for leadership on climate resilience*. Global Comission on Adaptation [Available at: https://www.wetlands.org/publications/adapt-now-a-global-call-for-leadership-on-climate-resilience/].
GCWDA, 2015: *H20 minus CO2: Concept paper.*, (GCWDA), G. C. W. D. A. [Available at: https://www.diplomatie.gouv.fr/IMG/pdf/global_water_desalination_alliance_1dec2015_cle8d61cb.pdf].
Geere, J.-A. L. and P. R. Hunter, 2020: The association of water carriage, water supply and sanitation usage with maternal and child health. A combined analysis of 49 Multiple Indicator Cluster Surveys from 41 countries. *International journal of hygiene and environmental health*, **223** (1), 238-247, doi:https://doi.org/10.1016/j.ijheh.2019.08.007.
Gelfan, A. et al., 2017: Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues. *Climatic Change*, **141** (3), 499-515.
Gemenne, F. and J. Blocher, 2017: How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *The Geographical Journal*, **183** (4), 336-347, doi:10.1111/geoj.12205.
Gericke, A., J. Kiesel, D. Deumlich and M. Venohr, 2019: Recent and Future Changes in Rainfall Erosivity and Implications for the Soil Erosion Risk in Brandenburg, NE Germany. *Water*, **11** (5), doi:10.3390/w11050904.
Gheuens, J., N. Nagabhatla and E. D. P. Perera, 2019: Disaster-Risk, Water Security Challenges and Strategies in Small Island Developing States (SIDS). *Water*, **11** (4), 637.
Giang, P. Q., L. T. Giang and K. Toshiki, 2017: Spatial and Temporal Responses of Soil Erosion to Climate Change Impacts in a Transnational Watershed in Southeast Asia. *Climate*, **5** (1), doi:10.3390/cli5010022.
Gibson, K., N. Haslam and I. Kaplan, 2019: Distressing encounters in the context of climate change: Idioms of distress, determinants, and responses to distress in Tuvalu. *Transcultural Psychiatry*, **56** (4), 667-696, doi:10.1177/1363461519847057.
Ginbo, T., L. Di Corato and R. Hoffmann, 2020: Investing in climate change adaptation and mitigation: A methodological review of real-options studies. *Ambio*, doi:10.1007/s13280-020-01342-8.

Gioli, G., T. Khan, S. Bisht and J. Scheffran, 2014: Migration as an adaptation strategy and its gendered implications: A case study from the Upper Indus Basin. *Mountain Research and Development*, **34** (3), 255-265.
Giordano, R. et al., 2020: Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. *Science of The Total Environment*, **713**, 136552, doi:https://doi.org/10.1016/j.scitotenv.2020.136552.
Giorgi, F., F. Raffaele and E. Coppola, 2019: The response of precipitation characteristics to global warming from climate projections. *Earth Syst. Dynam.*, **10** (1), 73-89, doi:10.5194/esd-10-73-2019.
Gleeson, T. et al., 2020: HESS Opinions: Improving the evaluation of groundwater representation in continental to global scale models. *Hydrol. Earth Syst. Sci. Discuss.*, **2020**, 1-39, doi:10.5194/hess-2020-378.
Gleick, P. H., 2014: Water, drought, climate change, and conflict in Syria. *Weather, Climate, and Society*, **6** (3), 331-340.
Gobiet, A. et al., 2014: 21st century climate change in the European Alps—a review. *Science of The Total Environment*, **493**, 1138-1151.
Goddard, F. G. B. et al., 2020: Faecal contamination of the environment and child health: a systematic review and individual participant data meta-analysis. *The Lancet Planetary Health*, **4** (9), e405-e415, doi:10.1016/S2542-5196(20)30195-9.
Godde, C. et al., 2019: Climate change and variability impacts on grazing herds: Insights from a system dynamics approach for semi-arid Australian rangelands. *Global Change Biology*, **25** (9), 3091-3109, doi:10.1111/gcb.14669.
Goderniaux, P. et al., 2015: Uncertainty of climate change impact on groundwater reserves – Application to a chalk aquifer. *Journal of Hydrology*, **528**, 108-121, doi:https://doi.org/10.1016/j.jhydrol.2015.06.018.
Gohar, A. A., A. Cashman and F. A. Ward, 2019: Managing food and water security in Small Island States: New evidence from economic modelling of climate stressed groundwater resources. *Journal of Hydrology*, **569**, 239-251, doi:https://doi.org/10.1016/j.jhydrol.2018.12.008.
Goharian, E., J. Burian Steven, T. Bardsley and C. Strong, 2016: Incorporating Potential Severity into Vulnerability Assessment of Water Supply Systems under Climate Change Conditions. *Journal of Water Resources Planning and Management*, **142** (2), 04015051, doi:10.1061/(ASCE)WR.1943-5452.0000579.
Golden, D. M., C. Audet and M. A. Smith, 2015: "Blue-ice": framing climate change and reframing climate change adaptation from the indigenous peoples' perspective in the northern boreal forest of Ontario, Canada. *Climate and Development*, **7** (5), 401-413, doi:10.1080/17565529.2014.966048.
Goldman, M. J., M. D. Turner and M. Daly, 2018: A critical political ecology of human dimensions of climate change: Epistemology, ontology, and ethics. *WIREs Climate Change*, **9** (4), e526, doi:10.1002/wcc.526.
Golosov, V. N. et al., 2018: Application of bomb- and Chernobyl-derived radiocaesium for reconstructing changes in erosion rates and sediment fluxes from croplands in areas of European Russia with different levels of Chernobyl fallout. *Journal of Environmental Radioactivity*, **186**, 78-89, doi:https://doi.org/10.1016/j.jenvrad.2017.06.022.
Gonda, N., 2016: Climate Change, "Technology" and Gender: "Adapting Women" to Climate Change with Cooking Stoves and Water Reservoirs. *Gender, Technology and Development*, **20** (2), 149-168, doi:10.1177/0971852416639786.
González-Zeas, D. et al., 2019: Linking global climate change to local water availability: Limitations and prospects for a tropical mountain watershed. *Science of The Total Environment*, **650**, 2577-2586, doi:https://doi.org/10.1016/j.scitotenv.2018.09.309.
González, M. E. et al., 2018: The 2010–2015 Megadrought and its influence on the fire regime in central and south-central Chile. *Ecosphere*, **9** (8), e02300, doi:10.1002/ecs2.2300.
González, M. E. et al., 2020: Incendios forestales en Chile: causas, impactos y resiliencia. Centro de Ciencia del Clima y la Resiliencia.
González Perea, R., E. Camacho Poyato, P. Montesinos and J. A. Rodríguez Díaz, 2018: Prediction of applied irrigation depths at farm level using artificial intelligence techniques. *Agricultural Water Management*, **206**, 229-240, doi:https://doi.org/10.1016/j.agwat.2018.05.019.
Good, S. P., D. Noone and G. Bowen, 2015: Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. *Science*, **349** (6244), 175, doi:10.1126/science.aaa5931.
Goodrich, C. G., A. Prakash and P. B. Udas, 2019: Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. *Environmental Development*, **31**, 1-8, doi:https://doi.org/10.1016/j.envdev.2019.01.001.
Gooré Bi, E., P. Gachon, M. Vrac and F. Monette, 2017: Which downscaled rainfall data for climate change impact studies in urban areas? Review of current approaches and trends. *Theoretical and Applied Climatology*, **127** (3), 685-699, doi:10.1007/s00704-015-1656-y.
Gosling, S. N. and N. W. Arnell, 2016: A global assessment of the impact of climate change on water scarcity. *Climatic Change*, **134** (3), 371-385, doi:10.1007/s10584-013-0853-x.
Gosling, S. N. et al., 2017: A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1 °C, 2 °C and 3 °C. *Climatic Change*, **141** (3), 577-595, doi:10.1007/s10584-016-1773-3.
Gotgelf, A., M. Roggero and K. Eisenack, 2020: Archetypical opportunities for water governance adaptation to climate change. *Ecology and Society*, **25** (4), doi:10.5751/ES-11768-250406.
Gould, G. K. et al., 2016: The effects of climate change and extreme wildfire events on runoff erosion over a mountain watershed. *Journal of Hydrology*, **536**, 74-91, doi:https://doi.org/10.1016/j.jhydrol.2016.02.025.

Grafton, R. Q., J. Williams and Q. Jiang, 2015: Food and water gaps to 2050: preliminary results from the global food and water system (GFWS) platform. *Food Security*, **7** (2), 209-220, doi:10.1007/s12571-015-0439-8.
Grafton, R. Q. et al., 2018: The paradox of irrigation efficiency. *Science*, **361** (6404), 748, doi:10.1126/science.aat9314.
Graham, N. T. et al., 2020a: Humans drive future water scarcity changes across all Shared Socioeconomic Pathways. *Environmental Research Letters*, **15** (1), 014007, doi:10.1088/1748-9326/ab639b.
Graham, N. T. et al., 2020b: Future changes in the trading of virtual water. *Nature Communications*, **11** (1), 3632, doi:10.1038/s41467-020-17400-4.
Grasham, C. F., M. Korzenevica and K. J. Charles, 2019: On considering climate resilience in urban water security: A review of the vulnerability of the urban poor in sub-Saharan Africa. *WIREs Water*, **6** (3), e1344, doi:10.1002/wat2.1344.
Graves, A. R. et al., 2015: The total costs of soil degradation in England and Wales. *Ecological Economics*, **119**, 399-413, doi:https://doi.org/10.1016/j.ecolecon.2015.07.026.
Gray, C. and E. Wise, 2016: Country-specific effects of climate variability on human migration. *Climatic Change*, **135** (3), 555-568, doi:10.1007/s10584-015-1592-y.
Green, T. R., 2016: Linking Climate Change and Groundwater. In: Integrated Groundwater Management: Concepts, Approaches and Challenges [Jakeman, A. J., O. Barreteau, R. J. Hunt, J.-D. Rinaudo and A. Ross (eds.)]. Springer International Publishing, Cham, 97-141.
Greve, P. et al., 2018: Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability*, **1** (9), 486-494, doi:10.1038/s41893-018-0134-9.
Greve, P. et al., 2014: Global assessment of trends in wetting and drying over land. *Nature Geoscience*, **7**, 716, doi:10.1038/ngeo2247
https://www.nature.com/articles/ngeo2247#supplementary-information.
Grey, D. and C. W. Sadoff, 2007: Sink or Swim? Water security for growth and development. *Water Policy*, **9** (6), 545-571, doi:10.2166/wp.2007.021.
Griego, A. L., A. B. Flores, T. W. Collins and S. E. Grineski, 2020: Social vulnerability, disaster assistance, and recovery: A population-based study of Hurricane Harvey in Greater Houston, Texas. *International Journal of Disaster Risk Reduction*, **51**, 101766, doi:https://doi.org/10.1016/j.ijdrr.2020.101766.
Griffith, A. W. and C. J. Gobler, 2020: Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. *Harmful Algae*, **91**, 101590, doi:https://doi.org/10.1016/j.hal.2019.03.008.
Grillakis, M. G., 2019: Increase in severe and extreme soil moisture droughts for Europe under climate change. *Science of The Total Environment*, **660**, 1245-1255, doi:https://doi.org/10.1016/j.scitotenv.2019.01.001.
Grossiord, C. et al., 2020: Plant responses to rising vapor pressure deficit. *New Phytologist*, **226** (6), 1550-1566, doi:https://doi.org/10.1111/nph.16485.
Gudmundsson, L. et al., 2021: Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, **371** (6534), 1159-1162, doi:10.1126/science.aba3996.
Gudmundsson, L., P. Greve and S. I. Seneviratne, 2016: The sensitivity of water availability to changes in the aridity index and other factors—A probabilistic analysis in the Budyko space. *Geophysical Research Letters*, **43** (13), 6985-6994, doi:10.1002/2016gl069763.
Gudmundsson, L. et al., 2019: Observed Trends in Global Indicators of Mean and Extreme Streamflow. *Geophysical Research Letters*, **46** (2), 756-766, doi:10.1029/2018gl079725.
Gudmundsson, L., S. I. Seneviratne and X. Zhang, 2017: Anthropogenic climate change detected in European renewable freshwater resources. *Nature Climate Change*, **7**, 813, doi:10.1038/nclimate3416
https://www.nature.com/articles/nclimate3416#supplementary-information.
Guermazi, E., M. Milano, E. Reynard and M. Zairi, 2019: Impact of climate change and anthropogenic pressure on the groundwater resources in arid environment. *Mitigation and Adaptation Strategies for Global Change*, **24** (1), 73-92, doi:10.1007/s11027-018-9797-9.
Guerreiro, S. B. et al., 2018: Future heat-waves, droughts and floods in 571 European cities. *Environmental Research Letters*, **13** (3), 034009, doi:10.1088/1748-9326/aaaad3.
Guimberteau, M., K. Laval, A. Perrier and J. Polcher, 2012: Global effect of irrigation and its impact on the onset of the Indian summer monsoon. *Climate Dynamics*, **39** (6), 1329-1348, doi:10.1007/s00382-011-1252-5.
Gulev, S. K. et al., 2021: Changing State of the Climate System. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Gunathilaka, R. P. D., J. C. R. Smart and C. M. Fleming, 2018: Adaptation to climate change in perennial cropping systems: Options, barriers and policy implications. *Environmental Science & Policy*, **82**, 108-116, doi:https://doi.org/10.1016/j.envsci.2018.01.011.
Güneralp, B., İ. Güneralp and Y. Liu, 2015: Changing global patterns of urban exposure to flood and drought hazards. *Global Environmental Change*, **31**, 217-225, doi:https://doi.org/10.1016/j.gloenvcha.2015.01.002.
Guo, Y. et al., 2020: Floods in China, COVID-19, and climate change. *The Lancet Planetary Health*, **4** (10), e443-e444, doi:10.1016/S2542-5196(20)30203-5.

Gupta, E., 2019: The impact of solar water pumps on energy-water-food nexus: Evidence from Rajasthan, India. *Energy Policy*, **129**, 598-609, doi:https://doi.org/10.1016/j.enpol.2019.02.008.
Gurdak, J. J., 2018: The Water-Energy-Food Nexus and California's Sustainable Groundwater Management Act. In: The Water-Energy-Food Nexus [A., E. and O. T. (eds.)]. Springer Singapore. , 145-155.
Gwenzi, W. et al., 2015: Water quality and public health risks associated with roof rainwater harvesting systems for potable supply: Review and perspectives. *Sustainability of Water Quality and Ecology*, **6**, 107-118, doi:https://doi.org/10.1016/j.swaqe.2015.01.006.
GWP, 2018: *Preparing to adapt : the untold story of water in climate change adaptation processes*. (GWP), G. W. P., 1-20 [Available at: https://www.gwp.org/globalassets/global/events/cop24/gwp-ndc-report.pdf].
H2020., 2014: Work Programme 2014 – 2015. European Commission Decision C (2014)4995 of 22 July 2014. European Commission.
Hagenlocher, M. et al., 2019: Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda. *Environmental Research Letters*, **14** (8), 083002, doi:10.1088/1748-9326/ab225d.
Hall, J. et al., 2014: Understanding flood regime changes in Europe: a state-of-the-art assessment. *Hydrol. Earth Syst. Sci.*, **18** (7), 2735-2772, doi:10.5194/hess-18-2735-2014.
Halladay, K. and P. Good, 2017: Non-linear interactions between CO2 radiative and physiological effects on Amazonian evapotranspiration in an Earth system model. *Climate Dynamics*, **49** (7), 2471-2490, doi:10.1007/s00382-016-3449-0.
Hallegatte, S. et al., 2018: *The Economics of (and Obstacles to) Aligning Development and Climate Change Adaptation: A World Bank Group Contribution to the Global Commission on Adaptation*. Rotterdam and Washington, DC [Available at: https://cdn.gca.org/assets/2018-10/18_WP_GCA_Economics_1001_final.pdf].
Hamilton, M. and M. Lubell, 2018: Collaborative Governance of Climate Change Adaptation Across Spatial and Institutional Scales. *Policy Studies Journal*, **46** (2), 222-247, doi:10.1111/psj.12224.
Hammond, J. C., F. A. Saavedra and S. K. Kampf, 2018: Global snow zone maps and trends in snow persistence 2001–2016. *International Journal of Climatology*, **38** (12), 4369-4383, doi:https://doi.org/10.1002/joc.5674.
Hanasaki, N., S. Yoshikawa, K. Kakinuma and S. Kanae, 2016: A seawater desalination scheme for global hydrological models. *Hydrol. Earth Syst. Sci.*, **20** (10), 4143-4157, doi:10.5194/hess-20-4143-2016.
Hanasaki, N., S. Yoshikawa, Y. Pokhrel and S. Kanae, 2018: A global hydrological simulation to specify the sources of water used by humans. *Hydrol. Earth Syst. Sci.*, **22** (1), 789-817, doi:10.5194/hess-22-789-2018.
Handmer, J. and J. Nalau, 2019: Understanding Loss and Damage in Pacific Small Island Developing States. In: Loss and Damage from Climate Change: Concepts, Methods and Policy Options [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, 365-381.
Handschuch, C. and M. Wollni, 2016: Improved production systems for traditional food crops: the case of finger millet in western Kenya. *Food Security*, **8** (4), 783-797.
Hannaford, J., 2015: Climate-driven changes in UK river flows:A review of the evidence. *Progress in Physical Geography: Earth and Environment*, **39** (1), 29-48, doi:10.1177/0309133314536755.
Hanrahan, M., 2017: Water (in) security in Canada: national identity and the exclusion of Indigenous peoples. *British Journal of Canadian Studies*, **30** (1), 69-90.
Hansen, J. G. and R. Antsanen, 2018: What Can Traditional Indigenous Knowledge Teach Us About Changing Our Approach to Human Activity and Environmental Stewardship in Order to Reduce the Severity of Climate Change? *International Indigenous Policy Journal*, **9** (3).
Hanzer, F., K. Förster, J. Nemec and U. Strasser, 2018: Projected cryospheric and hydrological impacts of 21st century climate change in the Ötztal Alps (Austria) simulated using a physically based approach. *Hydrol. Earth Syst. Sci.*, **22** (2), 1593-1614, doi:10.5194/hess-22-1593-2018.
Haque, M. et al., 2021: Wildfire in Australia during 2019-2020, Its Impact on Health, Biodiversity and Environment with Some Proposals for Risk Management: A Review. *Journal of Environmental Protection*, **12**, 391-414, doi:10.4236/jep.2021.126024.
Harmsworth, G., S. Awatere and M. Robb, 2016: Indigenous Māori values and perspectives to inform freshwater management in Aotearoa-New Zealand. *Ecology and Society*, **21**, doi:10.5751/ES-08804-210409.
Harp, R. D. et al., 2021: Interannual Climate Variability and Malaria in Mozambique. *GeoHealth*, **5** (2), e2020GH000322, doi:https://doi.org/10.1029/2020GH000322.
Harper, S. L., C. Wright, S. Masina and S. Coggins, 2020: Climate change, water, and human health research in the Arctic. *Water Security*, **10**, 100062, doi:https://doi.org/10.1016/j.wasec.2020.100062.
Harrington, L. J. and F. E. L. Otto, 2020: Reconciling theory with the reality of African heatwaves. *Nature Climate Change*, **10** (9), 796-798, doi:10.1038/s41558-020-0851-8.
Harrison, S. et al., 2018: Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere*, **12** (4), 1195-1209, doi:10.5194/tc-12-1195-2018.
Hartmann, A., T. Gleeson, Y. Wada and T. Wagener, 2017: Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. *Proceedings of the National Academy of Sciences*, **114** (11), 2842-2847, doi:10.1073/pnas.1614941114.
Hartmann, T. et al., 2019: Nature-based flood risk management on private land: Disciplinary perspectives on a multidisciplinary challenge.

Hattermann, F. F. et al., 2017: Cross-scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins. *Climatic Change*, **141** (3), 561-576, doi:10.1007/s10584-016-1829-4.
Havet, A. et al., 2014: Review of livestock farmer adaptations to increase forages in crop rotations in western France. *Agriculture, Ecosystems & Environment*, **190**, 120-127, doi:https://doi.org/10.1016/j.agee.2014.01.009.
Hawkins, E. et al., 2020: Observed Emergence of the Climate Change Signal: From the Familiar to the Unknown. *Geophysical Research Letters*, **47** (6), e2019GL086259, doi:10.1029/2019GL086259.
He, C. et al., 2021: Future global urban water scarcity and potential solutions. *Nature Communications*, **12** (1), 4667, doi:10.1038/s41467-021-25026-3.
Hedelin, B., 2016: The EU Floods Directive trickling down: tracing the ideas of integrated and participatory flood risk management in Sweden. *Water Policy*, **19** (2), 286-303, doi:10.2166/wp.2016.092.
Hegre, H. et al., 2016: Forecasting civil conflict along the shared socioeconomic pathways. *Environmental Research Letters*, **11** (5), 054002, doi:10.1088/1748-9326/11/5/054002.
Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205-226, doi:https://doi.org/10.1016/j.techfore.2013.05.006.
Hellin, J., B. D. Ratner, R. Meinzen-Dick and S. Lopez-Ridaura, 2018: Increasing social-ecological resilience within small-scale agriculture in conflict-affected Guatemala. *Ecology and Society*, **23** (3), 5, doi:https://doi.org/10.5751/ES-10250-230305.
Hendel, M. and L. Royon, 2015: The effect of pavement-watering on subsurface pavement temperatures. *Urban Climate*, **14**, 650-654, doi:https://doi.org/10.1016/j.uclim.2015.10.006.
Henderson, G. R., Y. Peings, J. C. Furtado and P. J. Kushner, 2018: Snow–atmosphere coupling in the Northern Hemisphere. *Nature Climate Change*, **8** (11), 954-963, doi:10.1038/s41558-018-0295-6.
Henley, B. J. et al., 2019: Amplification of risks to water supply at 1.5 °C and 2 °C in drying climates: a case study for Melbourne, Australia. *Environmental Research Letters*, **14** (8), 084028, doi:10.1088/1748-9326/ab26ef.
Henry, B. K., R. J. Eckard and K. A. Beauchemin, 2018: Review: Adaptation of ruminant livestock production systems to climate changes. *animal*, **12** (s2), s445-s456, doi:10.1017/S1751731118001301.
Herbert, C. and P. Döll, 2019: Global Assessment of Current and Future Groundwater Stress With a Focus on Transboundary Aquifers. *Water Resources Research*, **55** (6), 4760-4784, doi:10.1029/2018WR023321.
Hérivaux, C. and P. Le Coent, 2021: Introducing Nature into Cities or Preserving Existing Peri-Urban Ecosystems? Analysis of Preferences in a Rapidly Urbanizing Catchment. *Sustainability*, **13** (2), doi:10.3390/su13020587.
Herman-Mercer, N. M. et al., 2019: Vulnerability of Subsistence Systems Due to Social and Environmental Change. *Arctic*, **72** (3), 258-272, doi:https://doi.org/10.14430/arctic68867.
Hernández-Henríquez, M. A., S. J. Déry and C. Derksen, 2015: Polar amplification and elevation-dependence in trends of Northern Hemisphere snow cover extent, 1971–2014. *Environmental Research Letters*, **10** (4), 044010, doi:10.1088/1748-9326/10/4/044010.
Hernández-Sancho, F., B. Lamizana-Diallo, M. Mateo-Sagasta and M. Qadir, 2015: *Economic Valuation of Wastewater: The Cost of Action and the Cost of No Action*. (UNEP), U. N. E. P. [Available at: http://www.unep.org/ourplanet/december-2015/unep-publications/economic-valuation-wastewater-cost-action-and-cost-no-action%0Ahttp://unep.org/gpa/Documents/GWI/Wastewater Evaluation Report Mail.pdf].
Hewett, C. J. M., C. Simpson, J. Wainwright and S. Hudson, 2018: Communicating risks to infrastructure due to soil erosion: A bottom-up approach. *Land Degradation & Development*, **29** (4), 1282-1294, doi:10.1002/ldr.2900.
Hino, M., C. B. Field and K. J. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, **7**, 364, doi:10.1038/nclimate3252
https://www.nature.com/articles/nclimate3252#supplementary-information.
Hirabayashi, Y. et al., 2021a: Anthropogenic climate change has changed frequency of past flood during 2010-2013. *Progress in Earth and Planetary Science*, **8** (1), 36, doi:10.1186/s40645-021-00431-w.
Hirabayashi, Y. et al., 2021b: Global exposure to flooding from the new CMIP6 climate model projections. *Scientific Reports*, **11** (1), 3740, doi:10.1038/s41598-021-83279-w.
Hirpa, F. A. et al., 2018: Finding sustainable water futures in data-sparse regions under climate change: Insights from the Turkwel River basin, Kenya. *Journal of Hydrology: Regional Studies*, **19**, 124-135, doi:https://doi.org/10.1016/j.ejrh.2018.08.005.
Ho, T. T. and K. Shimada, 2019: The effects of climate smart agriculture and climate change adaptation on the technical efficiency of rice farming—An empirical study in the Mekong Delta of Vietnam. *Agriculture*, **9** (5), 99.
Hochman, Z., D. L. Gobbett and H. Horan, 2017a: Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology*, **23** (5), 2071-2081, doi:https://doi.org/10.1111/gcb.13604.
Hochman, Z. et al., 2017b: Smallholder farmers managing climate risk in India: 1. Adapting to a variable climate. *Agricultural Systems*, **150**, 54-66.
Hock, R. et al., 2019a: GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology*, **65** (251), 453-467, doi:10.1017/jog.2019.22.
Hock, R. et al., 2019b: High mountain areas.
Hodges, M. et al., 2014: Delays in reducing waterborne and water-related infectious diseases in China under climate change. *Nature Climate Change*, **4**, 1109, doi:10.1038/nclimate2428

https://www.nature.com/articles/nclimate2428#supplementary-information.
Hodgkins, G., R. Dudley, S. A. Archfield and B. Renard, 2019: Effects of climate, regulation, and urbanization on historical flood trends in the United States. *Journal of Hydrology*, **573**, 697-709.
Hoegh-Guldberg, O., D. et al., 2018: Impacts of 1.5°C of Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change [T. W. Masson-Delmotte, P. Z. V., H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], 175–311.
Hoell, A. et al., 2019: Anthropogenic Contributions to the Intensity of the 2017 United States Northern Great Plains Drought. *Bulletin of the American Meteorological Society*, **100** (1), S19-S24, doi:10.1175/BAMS-D-18-0127.1.
Holding, S. et al., 2016: Groundwater vulnerability on small islands. *Nature Climate Change*, **6**, 1100, doi:10.1038/nclimate3128
https://www.nature.com/articles/nclimate3128#supplementary-information.
Hong, N. B. and M. Yabe, 2017: Improvement in irrigation water use efficiency: a strategy for climate change adaptation and sustainable development of Vietnamese tea production. *Environment, Development and Sustainability*, **19** (4), 1247-1263, doi:10.1007/s10668-016-9793-8.
Hope, P., E.-P. Lim, H. Hendon and G. Wang, 2018: The Effect of Increasing CO2 on the Extreme September 2016 Rainfall Across Southeastern Australia. *Bulletin of the American Meteorological Society*, **99** (1), S133-S138, doi:10.1175/BAMS-D-17-0094.1.
Horn, L. M. et al., 2018: Association between Precipitation and Diarrheal Disease in Mozambique. *International Journal of Environmental Research and Public Health*, **15** (4), doi:10.3390/ijerph15040709.
Horney, J. A. et al., 2018: Comparing residential contamination in a Houston environmental justice neighborhood before and after Hurricane Harvey. *PLOS ONE*, **13** (2), e0192660, doi:10.1371/journal.pone.0192660.
Hovenden, M. J., P. C. D. Newton and K. E. Wills, 2014: Seasonal not annual rainfall determines grassland biomass response to carbon dioxide. *Nature*, **511**, 583, doi:10.1038/nature13281.
Howard, G., R. Calow, A. Macdonald and J. Bartram, 2016: Climate change and water and sanitation: likely impacts and emerging trends for action. *Annual Review of Environment and Resources*, **41**, 253-276.
Hoy, A. et al., 2016: Climatic changes and their impact on socio-economic sectors in the Bhutan Himalayas: an implementation strategy. *Regional Environmental Change*, **16** (5), 1401-1415.
Hsiang Solomon, M., M. Burke and E. Miguel, 2013: Quantifying the Influence of Climate on Human Conflict. *Science*, **341** (6151), 1235367, doi:10.1126/science.1235367.
Huang, J. et al., 2016a: Accelerated dryland expansion under climate change. *Nature Climate Change*, **6** (2), 166-171, doi:10.1038/nclimate2837.
Huang, L.-Y. et al., 2016b: Risk of Flood-Related Diseases of Eyes, Skin and Gastrointestinal Tract in Taiwan: A Retrospective Cohort Study. *PLOS ONE*, **11** (5), e0155166, doi:10.1371/journal.pone.0155166.
Huang M, M. et al., 2015: Change in terrestrial ecosystem water-use efficiency over the last three decades. *Global Change Biology*, **21** (6), 2366-2378, doi:10.1111/gcb.12873.
Huang, Y. et al., 2020: Nature-based solutions for urban pluvial flood risk management. *WIREs Water*, **7** (3), e1421, doi:10.1002/wat2.1421.
Huang, Z. et al., 2019: Global agricultural green and blue water consumption under future climate and land use changes. *Journal of Hydrology*, **574**, 242-256, doi:https://doi.org/10.1016/j.jhydrol.2019.04.046.
Huggel, C. et al., 2019: Loss and Damage in the mountain cryosphere. *Regional Environmental Change*, **19** (5), 1387-1399, doi:10.1007/s10113-018-1385-8.
Hugonnet, R. et al., 2021: Accelerated global glacier mass loss in the early twenty-first century. *Nature*, **592** (7856), 726-731, doi:10.1038/s41586-021-03436-z.
Hurlbert, M., 2014: Adaptive institutional design in agri-environmental programs. *International Journal of Climate Change Strategies and Management*, **6** (2), 145-165, doi:10.1108/IJCCSM-12-2012-0076.
Hurlbert, M., 2018: *Adaptive Governance of Disaster. Drought and Flood in Rural Areas,* . Springer.
Hurlbert, M. et al., 2019: Risk management and decision making in relation to sustainable development. In: IPCC SRCCL.
Hurlbert, M. and J. Pittman, 2014: Exploring adaptive management in environmental farm programs in Saskatchewan, Canada. *Journal of Natural Resources Policy Research*, **6** (2-3), 195-212.
Huss, M. et al., 2017: Toward mountains without permanent snow and ice. *Earth's Future*, **5** (5), 418-435, doi:10.1002/2016ef000514.
Huss, M. and M. Fischer, 2016: Sensitivity of Very Small Glaciers in the Swiss Alps to Future Climate Change. *Frontiers in Earth Science*, **4** (34), doi:10.3389/feart.2016.00034.
Huss, M. and R. Hock, 2018: Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, **8** (2), 135-140, doi:10.1038/s41558-017-0049-x.
Huynh, L. T. M. and L. C. Stringer, 2018: Multi-scale assessment of social vulnerability to climate change: An empirical study in coastal Vietnam. *Climate Risk Management*, **20**, 165-180.

Huynh, P. T. A. and B. P. Resurreccion, 2014: Women's differentiated vulnerability and adaptations to climate-related agricultural water scarcity in rural Central Vietnam. *Climate and Development*, **6** (3), 226-237, doi:10.1080/17565529.2014.886989.
IDA, 2020: *Desalination and Water Reuse by the Numbers*. (IDA), I. D. A. [Available at: idadesal.org/].
Ide, T., M. Brzoska, J. F. Donges and C.-F. Schleussner, 2020: Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk. *Global Environmental Change*, **62**, 102063, doi:https://doi.org/10.1016/j.gloenvcha.2020.102063.
IDMC., 2020: *2020 Global Report on Internal Displacement*.
Iglesias, A., D. Santillán and L. Garrote, 2018: On the Barriers to Adaption to Less Water under Climate Change: Policy Choices in Mediterranean Countries. *Water Resources Management: An International Journal, Published for the European Water Resources Association (EWRA)*, **32** (15), 4819-4832, doi:10.1007/s11269-018-2043-0.
IHA, 2020: *Hydropower Status Report 2020*. (IHA), I. H. A. [Available at: https://www.hydropower.org/publications/2020-hydropower-status-report].
Iizumi, T. and N. Ramankutty, 2016: Changes in yield variability of major crops for 1981–2010 explained by climate change. *Environmental Research Letters*, **11** (3), 034003.
Iizumi, T. et al., 2018: Crop production losses associated with anthropogenic climate change for 1981–2010 compared with preindustrial levels. *International Journal of Climatology*, **38** (14), 5405-5417.
Ikeda, N., C. Narama and S. Gyalson, 2016: Knowledge Sharing for Disaster Risk Reduction: Insights from a Glacier Lake Workshop in the Ladakh Region, Indian Himalayas. *Mountain Research and Development*, **36** (1), 31-40, 10.
Imran, M. A. et al., 2019: Impact of climate smart agriculture (CSA) through sustainable irrigation management on Resource use efficiency: A sustainable production alternative for cotton. *Land Use Policy*, **88**, 104113, doi:https://doi.org/10.1016/j.landusepol.2019.104113.
Ingty, T., 2017: High mountain communities and climate change: adaptation, traditional ecological knowledge, and institutions. *Climatic Change*, **145** (1), 41-55, doi:10.1007/s10584-017-2080-3.
IPBES, 2019: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.[Díaz, S., J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. R. Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis and C. N. Zayas (eds.)]. IPBES secretariat,, Bonn, Germany, 56 pages.
IPCC, 2018a: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. IPCC, Geneva, Switzerland, 616 pp.
IPCC, 2018b: Technical Summary. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], In press.
IPCC, 2019a: Summary for Policymakers. In: IPCC special report on the ocean and cryosphere in a changing climate [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)].
IPCC, 2019b: Summary to Policymakers (2). In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [Shukla, P. R., J. Skea, E. C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], 906.
IPCC, 2019c: Technical Summary. In: IPCC special report on the ocean and cryosphere in a changing climate [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], In press.
Iqbal, M. W., S. Donjadee, B. Kwanyuen and S.-y. Liu, 2018: Farmers' perceptions of and adaptations to drought in Herat Province, Afghanistan. *Journal of Mountain Science*, **15** (8), 1741-1756, doi:10.1007/s11629-017-4750-z.
Irannezhad, M., A.-K. Ronkanen and B. Kløve, 2016: Wintertime climate factors controlling snow resource decline in Finland. *International Journal of Climatology*, **36** (1), 110-131, doi:10.1002/joc.4332.
IRENA, 2012: *Water Desalination Using Renewable Energy ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME*. (IRENA), I. R. E. A., 1-28 [Available at: www.etsap.org-www.irena.org].
Ishak, E. H. et al., 2013: Evaluating the non-stationarity of Australian annual maximum flood. *Journal of Hydrology*, **494**, 134-145, doi:https://doi.org/10.1016/j.jhydrol.2013.04.021.

Islam, M. M., S. Sallu, K. Hubacek and J. Paavola, 2014: Migrating to tackle climate variability and change? Insights from coastal fishing communities in Bangladesh. *Climatic Change*, **124** (4), 733-746.
Islam, M. S. and M. E. Hoq, 2018: Vulnerability of Aquaculture-Based Fish Production Systems to the Impacts of Climate Change: Insights from Inland Waters in Bangladesh. In: Bangladesh I: Climate Change Impacts, Mitigation and Adaptation in Developing Countries [Islam, M. N. and A. van Amstel (eds.)]. Springer International Publishing, Cham, 67-97.
Islam, M. S., M. Z. Hossain and M. B. Sikder, 2019a: Drought adaptation measures and their effectiveness at Barind Tract in northwest Bangladesh: a perception study. *Natural Hazards*, **97** (3), 1253-1276.
Islam, S. U., C. L. Curry, S. J. Déry and F. W. Zwiers, 2019b: Quantifying projected changes in runoff variability and flow regimes of the Fraser River Basin, British Columbia. *Hydrology and Earth System Sciences*, **23** (2), 811-828.
Issaka, S. and M. A. Ashraf, 2017: Impact of soil erosion and degradation on water quality: a review. *Geology, Ecology, and Landscapes*, **1** (1), 1-11, doi:10.1080/24749508.2017.1301053.
Iticha, B. and A. Husen, 2019: Adaptation to climate change using indigenous weather forecasting systems in Borana pastoralists of southern Ethiopia. *Climate and Development*, **11** (7), 564-573, doi:10.1080/17565529.2018.1507896.
Iturbide, M. et al., 2020: An update of IPCC climate reference regions for subcontinental analysis of climate model data: definition and aggregated datasets. *Earth Syst. Sci. Data*, **12** (4), 2959-2970, doi:10.5194/essd-12-2959-2020.
IUCN, 2020: IUCN Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS: first edition. doi:10.2305/iucn.ch.2020.08.en.
Iza, A., 2019: *Gobernanza para la adaptación basada en ecosistemas*. IUCN, Gland, Switzerland, 156.
Jaakkola, J. J. K., S. Juntunen and K. Näkkäläjärvi, 2018: The Holistic Effects of Climate Change on the Culture, Well-Being, and Health of the Saami, the Only Indigenous People in the European Union. *Current Environmental Health Reports*, **5** (4), 401-417, doi:10.1007/s40572-018-0211-2.
Jaeger, K. L., J. D. Olden and N. A. Pelland, 2014: Climate change poised to threaten hydrologic connectivity and endemic fishes in dryland streams. *Proceedings of the National Academy of Sciences*, **111** (38), 13894-13899, doi:10.1073/pnas.1320890111.
Jaeger, W. K. et al., 2017: Finding water scarcity amid abundance using human–natural system models. *Proceedings of the National Academy of Sciences*, **114** (45), 11884-11889, doi:10.1073/pnas.1706847114.
Jagai, J. S. et al., 2015: Extreme Precipitation and Emergency Room Visits for Gastrointestinal Illness in Areas with and without Combined Sewer Systems: An Analysis of Massachusetts Data, 2003-2007. *Environmental Health Perspectives*, **123** (9), 873-879, doi:10.1289/ehp.1408971.
Jägermeyr, J. and K. Frieler, 2018: Spatial Variations in Crop Growing Seasons Pivotal to Reproduce Global Fluctuations in Maize and Wheat Yields. *Science Advances*, **4** (11), doi:https://doi.org/10.1126/sciadv.aat4517.
Jägermeyr, J. et al., 2015: Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrol. Earth Syst. Sci.*, **19** (7), 3073-3091, doi:10.5194/hess-19-3073-2015.
Jägermeyr, J., A. Pastor, H. Biemans and D. Gerten, 2017: Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. *Nature Communications*, **8** (1), 15900, doi:10.1038/ncomms15900.
Jain, M. et al., 2021: Groundwater depletion will reduce cropping intensity in India. *Science Advances*, **7** (9), eabd2849, doi:10.1126/sciadv.abd2849.
Jakob, M. and J. C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environmental Research Letters*, **11** (10), 104010, doi:10.1088/1748-9326/11/10/104010.
Jamero, M. L. et al., 2017: Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change*, **7** (8), 581-586, doi:10.1038/NCLIMATE3344.
James, H., 2019: Women, Water and 'Wicked Problems': Community Resilience and Adaptation to Climate Change in Northern Pakkoku, Myanmar. In: Population, Development, and the Environment: Challenges to Achieving the Sustainable Development Goals in the Asia Pacific [James, H. (ed.)]. Springer Singapore, Singapore, 215-225.
Jans, Y. et al., 2018: Biomass production in plantations: Land constraints increase dependency on irrigation water. *GCB Bioenergy*, **10** (9), 628-644, doi:https://doi.org/10.1111/gcbb.12530.
Jaramillo, M. F. and I. Restrepo, 2017: Wastewater Reuse in Agriculture: A Review about Its Limitations and Benefits. *Sustainability*, **9** (10), 1734.
Jaramillo, P. and A. Nazemi, 2018: Assessing urban water security under changing climate: Challenges and ways forward. *Sustainable Cities and Society*, **41**, 907-918, doi:https://doi.org/10.1016/j.scs.2017.04.005.
Jasechko, S. et al., 2021: Widespread potential loss of streamflow into underlying aquifers across the USA. *Nature*, **591** (7850), 391-395, doi:10.1038/s41586-021-03311-x.
Jat, H. S. et al., 2019: Re-designing irrigated intensive cereal systems through bundling precision agronomic innovations for transitioning towards agricultural sustainability in North-West India. *Scientific Reports*, **9** (1), 1-14.
Javadinejad, S. et al., 2019: The impact of future climate change and human activities on hydro-climatological drought, analysis and projections: using CMIP5 climate model simulations. *Water Conservation Science and Engineering*, **4** (2-3), 71-88.

Javeline, D., N. Dolšak and A. Prakash, 2019: Adapting to water impacts of climate change. *Climatic Change*, **152** (2), 209-213, doi:10.1007/s10584-018-2349-1.
Jenkins, K., J. Hall, V. Glenis and C. Kilsby, 2018: A Probabilistic Analysis of Surface Water Flood Risk in London. *Risk Analysis*, **38** (6), 1169-1182, doi:10.1111/risa.12930.
Jenny, J.-P. et al., 2016: Global spread of hypoxia in freshwater ecosystems during the last three centuries is caused by rising local human pressure. *Global Change Biology*, **22** (4), 1481-1489, doi:https://doi.org/10.1111/gcb.13193.
Jeppesen, E. et al., 2015: Ecological impacts of global warming and water abstraction on lakes and reservoirs due to changes in water level and related changes in salinity. *Hydrobiologia*, **750** (1), 201-227, doi:10.1007/s10750-014-2169-x.
Jezkova, T. and J. J. Wiens, 2016: Rates of change in climatic niches in plant and animal populations are much slower than projected climate change. *Proceedings of the Royal Society B: Biological Sciences*, **283** (1843), 20162104, doi:10.1098/rspb.2016.2104.
Jha, C. K., V. Gupta, U. Chattopadhyay and B. Amarayil Sreeraman, 2018a: Migration as adaptation strategy to cope with climate change: A study of farmers' migration in rural India. *International Journal of Climate Change Strategies and Management*, **10** (1), 121-141, doi:10.1108/IJCCSM-03-2017-0059.
Jha, C. K., V. Gupta, U. Chattopadhyay and B. A. Sreeraman, 2018b: Migration as adaptation strategy to cope with climate change. *International Journal of Climate Change Strategies and Management*.
Ji, P. et al., 2020: Anthropogenic Contributions to the 2018 Extreme Flooding over the Upper Yellow River Basin in China. *Bulletin of the American Meteorological Society*, **101** (1), S89-S94, doi:10.1175/BAMS-D-19-0105.1.
Jiang, L. and B. C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 193-199, doi:https://doi.org/10.1016/j.gloenvcha.2015.03.008.
Jiménez, B. and T. Asano, 2008: Water Reuse: An International Survey of current practice, issues and needs. IWA Publishing, doi:10.2166/9781780401881.
Jiménez Cisneros, B. E. et al., 2014: Freshwater resources. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change [C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.
Johnson, K. A. et al., 2020: A benefit–cost analysis of floodplain land acquisition for US flood damage reduction. *Nature Sustainability*, **3** (1), 56-62, doi:10.1038/s41893-019-0437-5.
Johnson, T. et al., 2018: Water. In: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, 145-173.
Jones, E. et al., 2019: The state of desalination and brine production: A global outlook. *Science of The Total Environment*, **657**, 1343-1356, doi:https://doi.org/10.1016/j.scitotenv.2018.12.076.
Jones, N. et al., 2020: Water, sanitation and hygiene risk factors for the transmission of cholera in a changing climate: using a systematic review to develop a causal process diagram. *Journal of water and health*, **18** (2), 145-158, doi:10.2166/wh.2020.088.
Jones Rena, R. et al., 2016: Nitrate from Drinking Water and Diet and Bladder Cancer Among Postmenopausal Women in Iowa. *Environmental Health Perspectives*, **124** (11), 1751-1758, doi:10.1289/EHP191.
Jongman, B., 2018: Effective adaptation to rising flood risk. *Nature Communications*, **9** (1), 1986, doi:10.1038/s41467-018-04396-1.
Jongman, B. et al., 2014: Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change*, **4** (4), 264-268, doi:10.1038/nclimate2124.
Jongman, B., P. J. Ward and J. C. J. H. Aerts, 2012: Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change*, **22** (4), 823-835, doi:https://doi.org/10.1016/j.gloenvcha.2012.07.004.
Jost, C. et al., 2016: Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, **8** (2), 133-144, doi:10.1080/17565529.2015.1050978.
Juhola, S., E. Glaas, B.-O. Linnér and T.-S. Neset, 2016: Redefining maladaptation. *Environmental Science & Policy*, **55**, 135-140, doi:https://doi.org/10.1016/j.envsci.2015.09.014.
Jung, T., J. Frandsen, D. Gordon and D. Mossop, 2016: Colonization of the Beaufort Coastal Plain by beaver (Castor canadensis): a response to shrubification of the tundra? *Canadian Field Naturalist*, **130**, 132-135, doi:10.22621/cfn.v130i4.1927.
Jurgilevich, A., A. Räsänen, F. Groundstroem and S. Juhola, 2017: A systematic review of dynamics in climate risk and vulnerability assessments. *Environmental Research Letters*, **12** (1), 013002, doi:10.1088/1748-9326/aa5508.
Kabir, M. J., R. Cramb, M. Alauddin and C. Roth, 2016: Farming adaptation to environmental change in coastal Bangladesh: shrimp culture versus crop diversification. *Environment, Development and Sustainability*, **18** (4), 1195-1216, doi:10.1007/s10668-015-9697-z.
Kaczan, D. J. and J. Orgill-Meyer, 2020: The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change*, **158** (3), 281-300.
Kahn, R. et al., 2019: Rapid Forecasting of Cholera Risk in Mozambique: Translational Challenges and Opportunities. *Prehospital and Disaster Medicine*, **34** (5), 557-562, doi:10.1017/S1049023X19004783.

Kahsay, K. D., S. M. Pingale and S. D. Hatiye, 2018: Impact of climate change on groundwater recharge and base flow in the sub-catchment of Tekeze basin, Ethiopia. *Groundwater for Sustainable Development*, **6**, 121-133, doi:https://doi.org/10.1016/j.gsd.2017.12.002.
Kakinuma, K. et al., 2020: Flood-induced population displacements in the world. *Environmental Research Letters*, **15** (12), 124029, doi:10.1088/1748-9326/abc586.
Kakumanu, K. R. et al., 2019: Adaptation to climate change: Impact of capacity building, India. *Irrigation and Drainage*, **68** (1), 50-58, doi:10.1002/ird.2275.
Kakumanu, K. R. et al., 2018: Building farm-level capacities in irrigation water management to adapt to climate change. *Irrigation and Drainage*, **67** (1), 43-54.
Kala, J. et al., 2016: Impact of the representation of stomatal conductance on model projections of heatwave intensity. *Scientific Reports*, **6**, 23418, doi:10.1038/srep23418 https://www.nature.com/articles/srep23418#supplementary-information.
Kalungu, J. W., W. L. Filho, D. O. Mbuge and H. K. Cheruiyot, 2021: Assessing the Impact of Rainwater HarvestingRainwater harvestingTechnology as Adaptation Strategy for Rural Communities in Makueni County, KenyaMakueni County. In: Handbook of Climate Change Adaptation [Leal Filho, W. (ed.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, 1-17.
Kam, J., S.-K. Min, P. Wolski and J.-S. Kug, 2021: CMIP6 Model-Based Assessment of Anthropogenic Influence on the Long Sustained Western Cape Drought over 2015–19. *Bulletin of the American Meteorological Society*, **102** (1), S45-S50, doi:10.1175/BAMS-D-20-0159.1.
Kamara, J. K., K. Agho and A. M. Renzaho, 2019: Understanding disaster resilience in communities affected by recurrent drought in Lesotho and Swaziland—A qualitative study. *PLOS ONE*, **14** (3), e0212994.
Kang, S. and E. A. B. Eltahir, 2019: Impact of Irrigation on Regional Climate Over Eastern China. *Geophysical Research Letters*, **46** (10), 5499-5505, doi:https://doi.org/10.1029/2019GL082396.
Kankwamba, H., M. Kadzamira and K. Pauw, 2018: How diversified is cropping in Malawi? Patterns, determinants and policy implications. *Food Security*, **10** (2), 323-338, doi:10.1007/s12571-018-0771-x.
Kapos, V. et al., 2020: Chapter 6: Nature based solutions In: Adaptation Gap Report 2020. UNEP, Nairobi.
Karamesouti, M. et al., 2016: Erosion rate predictions from PESERA and RUSLE at a Mediterranean site before and after a wildfire: Comparison & implications. *Geoderma*, **261**, 44-58, doi:https://doi.org/10.1016/j.geoderma.2015.06.025.
Karim, M. R. and A. Thiel, 2017: Role of community based local institution for climate change adaptation in the Teesta riverine area of Bangladesh. *Climate Risk Management*, **17**, 92-103, doi:10.1016/j.crm.2017.06.002.
Karnauskas, K. B., J. P. Donnelly and K. J. Anchukaitis, 2016: Future freshwater stress for island populations. *Nature Climate Change*, **6**, 720, doi:10.1038/nclimate2987 https://www.nature.com/articles/nclimate2987#supplementary-information.
Karnauskas, K. B., C.-F. Schleussner, J. P. Donnelly and K. J. Anchukaitis, 2018: Freshwater stress on small island developing states: population projections and aridity changes at 1.5 and 2 °C. *Regional Environmental Change*, **18** (8), 2273-2282, doi:10.1007/s10113-018-1331-9.
Kattumuri, R., D. Ravindranath and T. Esteves, 2017: Local adaptation strategies in semi-arid regions: study of two villages in Karnataka, India. *Climate and Development*, **9** (1), 36-49, doi:10.1080/17565529.2015.1067179.
Kawase, H. et al., 2020: The Heavy Rain Event of July 2018 in Japan Enhanced by Historical Warming. *Bulletin of the American Meteorological Society*, **101** (1), S109-S114, doi:10.1175/BAMS-D-19-0173.1.
Kawaye, F. P. and M. F. Hutchinson, 2018: Are Increases in Maize Production in Malawi Due to Favourable Climate or the Farm Input Subsidy Program (FISP)? In: Theory and practice of climate adaptation. Springer, 375-390.
Kayaga, S. and I. Smout, 2014: Tariff structures and incentives for water demand management. *Proceedings of the Institution of Civil Engineers: Water Management*, **167** (8), 448-456, doi:10.1680/wama.12.00120.
Keller, P. S., R. Marcé, B. Obrador and M. Koschorreck, 2021: Global carbon budget of reservoirs is overturned by the quantification of drawdown areas. *Nature Geoscience*, **14** (6), 402-408, doi:10.1038/s41561-021-00734-z.
Kelley, C. et al., 2017: Commentary on the Syria case: Climate as a contributing factor. *Political Geography*, **60**, 245-247, doi:https://doi.org/10.1016/j.polgeo.2017.06.013.
Kelley, C. P. et al., 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences*, **112** (11), 3241-3246, doi:10.1073/pnas.1421533112.
Kellner, E., C. Oberlack and J.-D. Gerber, 2019: Polycentric governance compensates for incoherence of resource regimes: The case of water uses under climate change in Oberhasli, Switzerland. *Environmental Science & Policy*, **100**, 126-135, doi:https://doi.org/10.1016/j.envsci.2019.06.008.
Keohane, R. O. and M. Oppenheimer, 2016: Paris: Beyond the Climate Dead End through Pledge and Review? *Politics and Governance*, **4** (3), 142-151, doi:http://dx.doi.org/10.17645/pag.v4i3.634.
Keohane, R. O. and D. G. Victor, 2016: Cooperation and discord in global climate policy. *Nature Climate Change*, **6** (6), 570-575, doi:10.1038/nclimate2937.
Keswani, B. et al., 2019: Adapting weather conditions based IoT enabled smart irrigation technique in precision agriculture mechanisms. *Neural Computing and Applications*, **31** (1), 277-292, doi:10.1007/s00521-018-3737-1.
Khalafzai, M.-A. K., T. K. McGee and B. Parlee, 2019: Flooding in the James Bay region of Northern Ontario, Canada: Learning from traditional knowledge of Kashechewan First Nation. *International Journal of Disaster Risk Reduction*, **36**, 101100.

Khan, M. et al., 2020: Twenty-five years of adaptation finance through a climate justice lens. *Climatic Change*, **161** (2), 251-269, doi:10.1007/s10584-019-02563-x.

Khan, S. J. et al., 2015: Extreme weather events: Should drinking water quality management systems adapt to changing risk profiles? *Water Research*, **85**, 124-136, doi:https://doi.org/10.1016/j.watres.2015.08.018.

Khanal, U., C. Wilson, V.-N. Hoang and B. L. Lee, 2019: Autonomous adaptations to climate change and rice productivity: a case study of the Tanahun district, Nepal. *Climate and Development*, **11** (7), 555-563, doi:10.1080/17565529.2018.1469965.

Khanal, U., C. Wilson, V. N. Hoang and B. Lee, 2018a: Farmers' Adaptation to Climate Change, Its Determinants and Impacts on Rice Yield in Nepal. *Ecological Economics*, **144** (July 2017), 139-147, doi:10.1016/j.ecolecon.2017.08.006.

Khanal, U., C. Wilson, B. L. Lee and V.-N. Hoang, 2018b: Climate change adaptation strategies and food productivity in Nepal: a counterfactual analysis. *Climatic Change*, **148** (4), 575-590.

Kher, J., S. Aggarwal and G. Punhani, 2015: Vulnerability of Poor Urban Women to Climate-linked Water Insecurities at the Household Level: A Case Study of Slums in Delhi. *Indian Journal of Gender Studies*, **22** (1), 15-40, doi:10.1177/0971521514556943.

Kibria, G., A. Y. Haroon and D. Nugegoda, 2017: Climate change impacts on tropical and temperate fisheries, aquaculture, and seafood security and implications-A review. *Livestock Research for Rural Development*, **29**.

Kim, B. F. et al., 2020: Country-specific dietary shifts to mitigate climate and water crises. *Global Environmental Change*, **62**, 101926, doi:https://doi.org/10.1016/j.gloenvcha.2019.05.010.

Kim, K. et al., 2015: Chemical and anatomical changes in Liquidambar styraciflua L. xylem after long term exposure to elevated CO_2. *Environmental Pollution*, **198**, 179-185, doi:https://doi.org/10.1016/j.envpol.2015.01.006.

Kim, W., T. Iizumi and M. Nishimori, 2019: Global Patterns of Crop Production Losses Associated with Droughts from 1983 to 2009. *Journal of Applied Meteorology and Climatology*, **58** (6), 1233-1244, doi:10.1175/JAMC-D-18-0174.1.

Kimaro, A. A. et al., 2016: Is conservation agriculture 'climate-smart' for maize farmers in the highlands of Tanzania? *Nutrient Cycling in Agroecosystems*, **105** (3), 217-228, doi:10.1007/s10705-015-9711-8.

Kimball, B. A. et al., 2019: Simulation of maize evapotranspiration: An inter-comparison among 29 maize models. *Agricultural and Forest Meteorology*, **271**, 264-284, doi:https://doi.org/10.1016/j.agrformet.2019.02.037.

King, J., L. Liu and M. Aspinwall, 2013: Chapter 9 - Tree and Forest Responses to Interacting Elevated Atmospheric CO_2 and Tropospheric O_3: A Synthesis of Experimental Evidence. In: Developments in Environmental Science [Matyssek, R., N. Clarke, P. Cudlin, T. N. Mikkelsen, J. P. Tuovinen, G. Wieser and E. Paoletti (eds.)]. Elsevier, **13**, 179-208.

Kingsborough, A., E. Borgomeo and J. W. Hall, 2016: Adaptation pathways in practice: Mapping options and trade-offs for London's water resources. *Sustainable Cities and Society*, **27**, 386-397, doi:https://doi.org/10.1016/j.scs.2016.08.013.

Kinoshita, Y., M. Tanoue, S. Watanabe and Y. Hirabayashi, 2018: Quantifying the effect of autonomous adaptation to global river flood projections: application to future flood risk assessments. *Environmental Research Letters*, **13** (1), 014006, doi:10.1088/1748-9326/aa9401.

Kirby, J. M. et al., 2016: The impact of climate change on regional water balances in Bangladesh. *Climatic Change*, **135** (3), 481-491, doi:10.1007/s10584-016-1597-1.

Kirby, M. et al., 2014: Sustainable irrigation: How did irrigated agriculture in Australia's Murray–Darling Basin adapt in the Millennium Drought? *Agricultural Water Management*, **145**, 154-162.

Kirchmeier-Young, M. C., H. Wan and X. Zhang, 2021: Anthropogenic Contribution to the Rainfall Associated with the 2019 Ottawa River Flood. *Bulletin of the American Meteorological Society*, **102** (1), S33-S38, doi:10.1175/BAMS-D-20-0191.1.

Kireeva, M. B. et al., 2020: Occasional Floods On The Rivers Of Russian Plain In The 20Th–21St Centuries. *Geography, Environment, Sustainability*, **13** (2), 84-95, doi: https://DOI-10.24057/2071-9388-2020-29

Kirshen, P. et al., 2018: Integrated urban water management applied to adaptation to climate change. *Urban Climate*, **24**, 247-263.

Klein Goldewijk, K., A. Beusen and P. Janssen, 2010: Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene*, **20** (4), 565-573.

Klein Goldewijk, K., A. Beusen, G. Van Drecht and M. De Vos, 2011: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography*, **20** (1), 73-86.

Klein, R. J. T. et al., 2014: Adaptation opportunities, constraints, and limits. In: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943.

Kloos, J. and F. G. Renaud, 2014: Organic cotton production as an adaptation option in north-west Benin. *Outlook on Agriculture*, **43** (2), 91-100, doi:10.5367/oa.2014.0166.

Klostermann, J. et al., 2018: Towards a framework to assess, compare and develop monitoring and evaluation of climate change adaptation in Europe. *Mitigation and Adaptation Strategies for Global Change*, **23** (2), 187-209, doi:10.1007/s11027-015-9678-4.
Kløve, B. et al., 2014: Climate change impacts on groundwater and dependent ecosystems. *Journal of Hydrology*, **518**, 250-266, doi:https://doi.org/10.1016/j.jhydrol.2013.06.037.
Knauer, J. et al., 2017: The response of ecosystem water-use efficiency to rising atmospheric CO2 concentrations: sensitivity and large-scale biogeochemical implications. *New Phytologist*, **213** (4), 1654-1666, doi:10.1111/nph.14288.
Knopp, J. A. et al., 2020: Systematic review of documented Indigenous Knowledge of freshwater biodiversity in the circumpolar Arctic. *Freshwater Biology*, **n/a** (n/a), doi:10.1111/fwb.13570.
Knouft, J. H. and D. L. Ficklin, 2017: The Potential Impacts of Climate Change on Biodiversity in Flowing Freshwater Systems. *Annual Review of Ecology, Evolution, and Systematics*, **48** (1), 111-133, doi:10.1146/annurev-ecolsys-110316-022803.
Kodirekkala, K. R., 2018: Cultural adaptation to climate change among indigenous people of South India. *Climatic Change*, **147** (1), 299-312, doi:10.1007/s10584-017-2116-8.
Kohlitz, J. P., J. Chong and J. Willetts, 2017: Climate change vulnerability and resilience of water, sanitation, and hygiene services: A theoretical perspective. *Journal of Water Sanitation and Hygiene for Development*, **7**, 181-195, doi:10.2166/washdev.2017.134.
Koirala, S., Y. Hirabayashi, R. Mahendran and S. Kanae, 2014: Global assessment of agreement among streamflow projections using CMIP5 model outputs. *Environmental Research Letters*, **9** (6), 064017, doi:10.1088/1748-9326/9/6/064017.
Koks, E. E. et al., 2019: The macroeconomic impacts of future river flooding in Europe. *Environmental Research Letters*, **14** (8), 084042, doi:10.1088/1748-9326/ab3306.
Konchar, K. M. et al., 2015: Adapting in the shadow of Annapurna: a climate tipping point. *Journal of Ethnobiology*, **35** (3), 449-471.
Kong, Y. and C.-H. Wang, 2017: Responses and changes in the permafrost and snow water equivalent in the Northern Hemisphere under a scenario of 1.5 °C warming. *Advances in Climate Change Research*, **8** (4), 235-244, doi:https://doi.org/10.1016/j.accre.2017.07.002.
Kontar, Y. Y. et al., 2015: Interdisciplinary approach to hydrological hazard mitigation and disaster response and effects of climate change on the occurrence of flood severity in central Alaska. *Proceedings of the International Association of Hydrological Sciences*, **369**, 13-17.
Kookana, R. S. et al., 2016: Groundwater scarcity impact on inclusiveness and women empowerment: Insights from school absenteeism of female students in two watersheds in India. *International Journal of Inclusive Education*, **20** (11), 1155-1171, doi:10.1080/13603116.2016.1155664.
Kooperman, G. J. et al., 2018: Plant Physiological Responses to Rising CO2 Modify Simulated Daily Runoff Intensity With Implications for Global-Scale Flood Risk Assessment. *Geophysical Research Letters*, **45** (22), 12,457-12,466, doi:10.1029/2018gl079901.
Kopytkovskiy, M., M. Geza and J. E. McCray, 2015: Climate-change impacts on water resources and hydropower potential in the Upper Colorado River Basin. *Journal of Hydrology: Regional Studies*, **3**, 473-493, doi:https://doi.org/10.1016/j.ejrh.2015.02.014.
Kormann, C., T. Francke, M. Renner and A. Bronstert, 2015: Attribution of high resolution streamflow trends in Western Austria–an approach based on climate and discharge station data. *Hydrology and Earth System Sciences*, **19** (3), 1225-1245.
Kosmowski, F., 2018: Soil water management practices (terraces) helped to mitigate the 2015 drought in Ethiopia. *Agricultural Water Management*, **204** (February), 11-16, doi:10.1016/j.agwat.2018.02.025.
Kostyla, C., R. Bain, R. Cronk and J. Bartram, 2015: Seasonal variation of fecal contamination in drinking water sources in developing countries: A systematic review. *Science of The Total Environment*, **514**, 333-343, doi:https://doi.org/10.1016/j.scitotenv.2015.01.018.
Kotchoni, D. O. V. et al., 2019: Relationships between rainfall and groundwater recharge in seasonally humid Benin: a comparative analysis of long-term hydrographs in sedimentary and crystalline aquifers. *Hydrogeology Journal*, **27** (2), 447-457, doi:10.1007/s10040-018-1806-2.
Kothari, K. et al., 2019: Potential climate change adaptation strategies for winter wheat production in the Texas High Plains. *Agricultural Water Management*, **225**, 105764.
Koubi, V., 2019: Climate Change and Conflict. *Annual Review of Political Science*, **22** (1), 343-360, doi:10.1146/annurev-polisci-050317-070830.
Koubi, V., S. Stoll and G. Spilker, 2016: Perceptions of environmental change and migration decisions. *Climatic Change*, **138** (3), 439-451, doi:10.1007/s10584-016-1767-1.
Koutroulis, A. G. et al., 2019: Global water availability under high-end climate change: A vulnerability based assessment. *Global and Planetary Change*, **175**, 52-63, doi:https://doi.org/10.1016/j.gloplacha.2019.01.013.
Kraaijenbrink, P. D. A., M. F. P. Bierkens, A. F. Lutz and W. W. Immerzeel, 2017: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, **549**, 257, doi:10.1038/nature23878
https://www.nature.com/articles/nature23878#supplementary-information.

Krakauer, N. Y., B. I. Cook and M. J. Puma, 2020: Effect of irrigation on humid heat extremes. *Environmental Research Letters*, **15** (9), 094010, doi:10.1088/1748-9326/ab9ecf.
Kreienkamp, F. et al., 2021: *Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021*. Attribution, W. W. [Available at: https://www.worldweatherattribution.org/heavy-rainfall-which-led-to-severe-flooding-in-western-europe-made-more-likely-by-climate-change/].
Krikken, F. et al., 2019: Attribution of the role of climate change in the forest fires in Sweden 2018. *Nat. Hazards Earth Syst. Sci. Discuss.*, **2019**, 1-24, doi:10.5194/nhess-2019-206.
Krishnamurthy, L., P. K. Krishnamurthy, I. Rajagopal and A. Peralta Solares, 2019: Can agroforestry systems thrive in the drylands? Characteristics of successful agroforestry systems in the arid and semi-arid regions of Latin America. *Agroforestry Systems*, **93** (2), 503-513, doi:10.1007/s10457-017-0143-0.
Krysanova, V. et al., 2017: Intercomparison of regional-scale hydrological models and climate change impacts projected for 12 large river basins worldwide—a synthesis. *Environmental Research Letters*, **12** (10), 105002, doi:10.1088/1748-9326/aa8359.
Kumar, S. N. et al., 2016: Adaptation of farming community to climatic risk: does adaptation cost for sustaining agricultural profitability? *Current Science*, 1216-1224.
Kumar, V. and S. Sen, 2018: Evaluation of spring discharge dynamics using recession curve analysis: a case study in data-scarce region, Lesser Himalayas, India. *Sustainable Water Resources Management*, **4** (3), 539-557, doi:10.1007/s40899-017-0138-z.
Kummu, M. et al., 2016: The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*, **6**, 38495, doi:10.1038/srep38495
https://www.nature.com/articles/srep38495#supplementary-information.
Kundzewicz, Z. W. et al., 2018: Uncertainty in climate change impacts on water resources. *Environmental Science & Policy*, **79**, 1-8, doi:https://doi.org/10.1016/j.envsci.2017.10.008.
Kundzewicz, Z. W. et al., 2017: Differences in flood hazard projections in Europe – their causes and consequences for decision making. *Hydrological Sciences Journal*, **62** (1), 1-14, doi:10.1080/02626667.2016.1241398.
Kusaka, H. et al., 2014: Mechanism of Precipitation Increase with Urbanization in Tokyo as Revealed by Ensemble Climate Simulations. *Journal of Applied Meteorology and Climatology*, **53** (4), 824-839, doi:10.1175/jamc-d-13-065.1.
Kusters, K. and N. Wangdi, 2013: The Costs of Adaptation: Changes in Water Availability and Farmers' Responses in Punakha District, Bhutan. *International Journal of Global Warming* **5**(4), 387-399, doi:https://doi.org/10.1504/IJGW.2013.057287.
Kuzdas, C. et al., 2016: Identifying the potential of governance regimes to aggravate or mitigate local water conflicts in regions threatened by climate change. *Local Environment*, **21** (11), 1387-1408.
Labbé, J., J. D. Ford, M. Araos and M. Flynn, 2017: The government-led climate change adaptation landscape in Nunavut, Canada. *Environmental Reviews*, **25** (1), 12-25, doi:10.1139/er-2016-0032.
Lafrenière, M. J. and S. F. Lamoureux, 2019: Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. *Earth-Science Reviews*, **191**, 212-223, doi:https://doi.org/10.1016/j.earscirev.2019.02.018.
Lall, U., L. Josset and T. Russo, 2020: A Snapshot of the World's Groundwater Challenges. *Annual Review of Environment and Resources*, **45** (1), 171-194, doi:10.1146/annurev-environ-102017-025800.
Lalou, R., B. Sultan, B. Muller and A. Ndonky, 2019: Does climate opportunity facilitate smallholder farmers' adaptive capacity in the Sahel? *Palgrave Communications*, **5** (1), 1-11.
Lambert, H. et al., 2020: COVID-19 as a global challenge: towards an inclusive and sustainable future. *The Lancet Planetary Health*, **4** (8), e312-e314, doi:10.1016/S2542-5196(20)30168-6.
Landauer, M. and S. Juhola, 2019: Loss and Damage in the Rapidly Changing Arctic. In: Loss and Damage from Climate Change: Concepts, Methods and Policy Options [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, 425-447.
Landsman, M. R. et al., 2019: Impacts of Hurricane Harvey on drinking water quality in two Texas cities. *Environmental Research Letters*, **14** (12), 124046, doi:10.1088/1748-9326/ab56fb.
Lange, S. et al., 2020: Projecting Exposure to Extreme Climate Impact Events Across Six Event Categories and Three Spatial Scales. *Earth's Future*, **8** (12), e2020EF001616, doi:https://doi.org/10.1029/2020EF001616.
Langhans, C. et al., 2016: A model for assessing water quality risk in catchments prone to wildfire. *Journal of Hydrology*, **534**, 407-426, doi:https://doi.org/10.1016/j.jhydrol.2015.12.048.
Larsen, J. N. et al., 2014: Polar Regions. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1567-1612.
Lashley, J. G. and K. Warner, 2015: Evidence of demand for microinsurance for coping and adaptation to weather extremes in the Caribbean. *Climatic Change*, **133** (1), 101-112, doi:10.1007/s10584-013-0922-1.
Leadley, P. et al., 2014: Interacting Regional-Scale Regime Shifts for Biodiversity and Ecosystem Services. *BioScience*, **64** (8), 665-679, doi:10.1093/biosci/biu093.

Leal Filho, W. et al., 2018: A Comparative Analysis of Climate-Risk and Extreme Event-Related Impacts on Well-Being and Health: Policy Implications. *International Journal of Environmental Research and Public Health*, **15** (2), doi:10.3390/ijerph15020331.

Lebel, L. et al., 2020: Aquaculture farmers' perceptions of climate-related risks in the Mekong Region. *Regional Environmental Change*, **20** (3), 95, doi:10.1007/s10113-020-01688-5.

Lee, S.-Y., A. F. Hamlet and E. E. Grossman, 2016: Impacts of climate change on regulated streamflow, hydrologic extremes, hydropower production, and sediment discharge in the Skagit River Basin. *Northwest Science*, **90** (1), 23-43.

Lei, Y. et al., 2017: Using government resettlement projects as a sustainable adaptation strategy for climate change. *Sustainability*, **9** (8), 1373.

Lemessa, S. D., M. D. Watebaji and M. A. Yismaw, 2019: Climate change adaptation strategies in response to food insecurity: The paradox of improved potato varieties adoption in eastern Ethiopia. *Cogent Food & Agriculture*, **5** (1), 1640835.

Lemordant, L. and P. Gentine, 2019: Vegetation Response to Rising CO2 Impacts Extreme Temperatures. *Geophysical Research Letters*, **46** (3), 1383-1392, doi:10.1029/2018gl080238.

Lemordant, L. et al., 2018: Critical impact of vegetation physiology on the continental hydrologic cycle in response to increasing CO₂. *Proceedings of the National Academy of Sciences*, **115** (16), 4093-4098, doi:10.1073/pnas.1720712115.

Leng, G. and J. Hall, 2019: Crop yield sensitivity of global major agricultural countries to droughts and the projected changes in the future. *Science of The Total Environment*, **654**, 811-821, doi:https://doi.org/10.1016/j.scitotenv.2018.10.434.

Leng, G., Q. Tang, M. Huang and L.-y. R. Leung, 2015: A comparative analysis of the impacts of climate change and irrigation on land surface and subsurface hydrology in the North China Plain. *Regional Environmental Change*, **15** (2), 251-263, doi:10.1007/s10113-014-0640-x.

Lequechane, J. D. et al., 2020: Mozambique's response to cyclone Idai: how collaboration and surveillance with water, sanitation and hygiene (WASH) interventions were used to control a cholera epidemic. *Infectious Diseases of Poverty*, **9** (1), 68, doi:10.1186/s40249-020-00692-5.

Lesk, C., P. Rowhani and N. Ramankutty, 2016: Influence of extreme weather disasters on global crop production. *Nature*, **529**, 84, doi:10.1038/nature16467 https://www.nature.com/articles/nature16467#supplementary-information.

Levis, S. et al., 2018: CLMcrop yields and water requirements: avoided impacts by choosing RCP 4.5 over 8.5. *Climatic Change*, **146** (3), 501-515, doi:10.1007/s10584-016-1654-9.

Levy, K., S. M. Smith and E. J. Carlton, 2018: Climate Change Impacts on Waterborne Diseases: Moving Toward Designing Interventions. *Current Environmental Health Reports*, **5** (2), 272-282, doi:10.1007/s40572-018-0199-7.

Levy, K., A. P. Woster, R. S. Goldstein and E. J. Carlton, 2016: Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. *Environmental Science & Technology*, **50** (10), 4905-4922.

Li, D., Z. Li, Y. Zhou and X. Lu, 2020a: Substantial Increases in the Water and Sediment Fluxes in the Headwater Region of the Tibetan Plateau in Response to Global Warming. *Geophysical Research Letters*, **47** (11), e2020GL087745, doi:https://doi.org/10.1029/2020GL087745.

Li, D. et al., 2021a: Air Temperature Regulates Erodible Landscape, Water, and Sediment Fluxes in the Permafrost-Dominated Catchment on the Tibetan Plateau. *Water Resources Research*, **57** (2), e2020WR028193, doi:https://doi.org/10.1029/2020WR028193.

Li, L. et al., 2020b: Global trends in water and sediment fluxes of the world's large rivers. *Science Bulletin*, **65** (1), 62-69.

Li, R. et al., 2021b: Anthropogenic Influences on Heavy Precipitation during the 2019 Extremely Wet Rainy Season in Southern China. *Bulletin of the American Meteorological Society*, **102** (1), S103-S109, doi:10.1175/BAMS-D-20-0135.1.

Li, X. and T. J. Troy, 2018: Changes in rainfed and irrigated crop yield response to climate in the western US. *Environmental Research Letters*, **13** (6), 064031, doi:10.1088/1748-9326/aac4b1.

Li, Y. et al., 2018: Effects of reservoir operation and climate change on thermal stratification of a canyon-shaped reservoir, in northwest China. *Water Science and Technology: Water Supply*, **18** (2), 418-429.

Li, Y. et al., 2014: Patterns and Potential Drivers of Dramatic Changes in Tibetan Lakes, 1972–2010. *PLOS ONE*, **9** (11), e111890, doi:10.1371/journal.pone.0111890.

Li, Y. et al., 2015: Local cooling and warming effects of forests based on satellite observations. *Nature Communications*, **6** (1), 6603, doi:10.1038/ncomms7603.

Liang, P. and Y. Ding, 2017: The long-term variation of extreme heavy precipitation and its link to urbanization effects in Shanghai during 1916–2014. *Advances in Atmospheric Sciences*, **34** (3), 321-334, doi:10.1007/s00376-016-6120-0.

Liljedahl, A. K. et al., 2017: Glacierized headwater streams as aquifer recharge corridors, subarctic Alaska. *Geophysical Research Letters*, **44** (13), 6876-6885, doi:https://doi.org/10.1002/2017GL073834.

Lillo-Ortega, G. et al., 2019: On the evaluation of adaptation practices: a transdisciplinary exploration of drought measures in Chile. *Sustainability Science*, **14** (4), 1057-1069.

Lin, H. et al., 2017: A decreasing glacier mass balance gradient from the edge of the Upper Tarim Basin to the Karakoram during 2000–2014. *Scientific Reports*, **7** (1), 6712, doi:10.1038/s41598-017-07133-8.
Lin, S.-h. and S.-m. Chen, 2016: The Localization of Actions for Climate Change Adaptation: A Case Study of Post-Morakot Reconstruction in Coastal Taiwan. *DEStech Transactions on Computer Science and Engineering*, (cmsam).
Lin, Y. et al., 2020: Water as an urban heat sink: Blue infrastructure alleviates urban heat island effect in mega-city agglomeration. *Journal of Cleaner Production*, **262**, 121411, doi:https://doi.org/10.1016/j.jclepro.2020.121411.
Lindoso, D. P. et al., 2018: Harvesting water for living with drought: Insights from the Brazilian Human Coexistence with Semi-Aridity approach towards achieving the sustainable development goals. *Sustainability (Switzerland)*, **10** (3), doi:10.3390/su10030622.
Lindsay, A., 2018: Social learning as an adaptive measure to prepare for climate change impacts on water provision in Peru. *Journal of Environmental Studies and Sciences*, **8** (4), 477-487, doi:10.1007/s13412-017-0464-3.
Ling, F. H. et al., 2015: Reducing flood risks in rural households: survey of perception and adaptation in the Mekong delta. *Climatic Change*, **132** (2), 209-222.
Link, P. M., J. Scheffran and T. Ide, 2016: Conflict and cooperation in the water-security nexus: a global comparative analysis of river basins under climate change. *Wiley Interdisciplinary Reviews: Water*, **3** (4), 495-515, doi:10.1002/wat2.1151.
Linke, A. M. et al., 2018a: The consequences of relocating in response to drought: human mobility and conflict in contemporary Kenya. *Environmental Research Letters*, **13** (9), 094014, doi:10.1088/1748-9326/aad8cc.
Linke, A. M. et al., 2018b: Drought, Local Institutional Contexts, and Support for Violence in Kenya. *Journal of Conflict Resolution*, **62** (7), 1544-1578, doi:10.1177/0022002717698018.
Liu-Helmersson, J., J. Rocklöv, M. Sewe and Å. Brännström, 2019: Climate change may enable Aedes aegypti infestation in major European cities by 2100. *Environmental Research*, **172**, 693-699, doi:https://doi.org/10.1016/j.envres.2019.02.026.
Liu, C., N. Hofstra and E. Franz, 2013: Impacts of climate change on the microbial safety of pre-harvest leafy green vegetables as indicated by Escherichia coli O157 and Salmonella spp. *International Journal of Food Microbiology*, **163** (2-3), 119-128.
Liu, J. et al., 2018a: Nexus approaches to global sustainable development. *Nature Sustainability*, **1** (9), 466-476, doi:10.1038/s41893-018-0135-8.
Liu, J., Q. Liu and H. Yang, 2016: Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality. *Ecological Indicators*, **60**, 434-441, doi:https://doi.org/10.1016/j.ecolind.2015.07.019.
Liu, J. et al., 2018b: Managing the energy-water-food nexus for sustainable development. *Applied Energy*, **210**, 377-381, doi:https://doi.org/10.1016/j.apenergy.2017.10.064.
Liu, J. et al., 2017a: Challenges in operationalizing the water–energy–food nexus. *Hydrological Sciences Journal*, **62** (11), 1714-1720, doi:10.1080/02626667.2017.1353695.
Liu, J. et al., 2017b: Water scarcity assessments in the past, present, and future. *Earth's Future*, **5** (6), 545-559, doi:10.1002/2016ef000518.
Liu J. and Z. D., 2020: Three-dimensional water scarcity assessment by considering water quantity, water quality, and environmental flow requirements: review and prospect. *Chinese Science Bulletin*, **65** (36), 4251-4261.
Liu, L. and M. B. Jensen, 2017: Climate resilience strategies of Beijing and Copenhagen and their links to sustainability. *Water Policy*, **19** (6), 997-1013, doi:10.2166/wp.2017.165.
Liu, L. and M. B. Jensen, 2018: Green infrastructure for sustainable urban water management: Practices of five forerunner cities. *Cities*, **74**, 126-133, doi:https://doi.org/10.1016/j.cities.2017.11.013.
Liu, Z. et al., 2018c: Association between floods and infectious diarrhea and their effect modifiers in Hunan province, China: A two-stage model. *Science of The Total Environment*, **626**, 630-637, doi:https://doi.org/10.1016/j.scitotenv.2018.01.130.
Livneh, B. and A. M. Badger, 2020: Drought less predictable under declining future snowpack. *Nature Climate Change*, **10** (5), 452-458.
Lobanova, A. et al., 2018: Hydrological impacts of moderate and high-end climate change across European river basins. *Journal of Hydrology: Regional Studies*, **18**, 15-30, doi:https://doi.org/10.1016/j.ejrh.2018.05.003.
Logan, T. M., S. D. Guikema and J. D. Bricker, 2018: Hard-adaptive measures can increase vulnerability to storm surge and tsunami hazards over time. *Nature Sustainability*, **1** (9), 526-530, doi:10.1038/s41893-018-0137-6.
Loiola, C., W. Mary and L. Pimentel da Silva, 2019: Hydrological performance of modular-tray green roof systems for increasing the resilience of mega-cities to climate change. *Journal of Hydrology*, **573**, 1057-1066, doi:https://doi.org/10.1016/j.jhydrol.2018.01.004.
Loiselle, D. et al., 2020: Projecting impacts of wildfire and climate change on streamflow, sediment, and organic carbon yields in a forested watershed. *Journal of Hydrology*, **590**, 125403, doi:https://doi.org/10.1016/j.jhydrol.2020.125403.
Lopez-Gunn, E. et al., 2021: Chapter 16: Maintstreaming Nature-based Solutions through Insurance: the Five "Hats" of the Insurance Sector In: Nature-based Solutions and Water Security: An Agenda for the 2Ist Century [Cassin, J., J. Matthews and E. Lopez Gunn (eds.)]. Elsevier.

Lowe, J. A. et al., 2018: *UKCP18 Science Overview Report*. UK Met Office [Available at: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf].
Lu, C. et al., 2021: Anthropogenic Influence on 2019 May–June Extremely Low Precipitation in Southwestern China. *Bulletin of the American Meteorological Society*, **102** (1), S97-S102, doi:10.1175/BAMS-D-20-0128.1.
Lu, P., 2016: Spatial planning to promote urban resilience in coping with climate change and flooding: Exploring two cases in Kaohsiung, Taiwan. 45-67.
Lucier, K. J. and M. Qadir, 2018: Gender and Community Mainstreaming in Fog Water Collection Systems. *Water*, **10** (10), doi:10.3390/w10101472.
Lukasiewicz, A., J. Pittock and M. Finlayson, 2016: Institutional challenges of adopting ecosystem-based adaptation to climate change. *Regional Environmental Change*, **16** (2), 487-499, doi:10.1007/s10113-015-0765-6.
Luo, Q., M. Bange, M. Braunack and D. Johnston, 2016: Effectiveness of agronomic practices in dealing with climate change impacts in the Australian cotton industry — A simulation study. *Agricultural Systems*, **147**, 1-9, doi:https://doi.org/10.1016/j.agsy.2016.05.006.
Lute, A. C., J. T. Abatzoglou and K. C. Hegewisch, 2015: Projected changes in snowfall extremes and interannual variability of snowfall in the western United States. *Water Resources Research*, **51** (2), 960-972, doi:10.1002/2014wr016267.
Lutz, A. F., W. W. Immerzeel, A. B. Shrestha and M. F. P. Bierkens, 2014: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, **4**, 587, doi:10.1038/nclimate2237
https://www.nature.com/articles/nclimate2237#supplementary-information.
Lyons, I. et al., 2019: Putting uncertainty under the cultural lens of Traditional Owners from the Great Barrier Reef Catchments. *Regional Environmental Change*, **19** (6), 1597-1610, doi:10.1007/s10113-019-01468-w.
Ma, X. et al., 2015: Sustainable Water Systems for the City of Tomorrow—A Conceptual Framework. *Sustainability*, **7** (9), doi:10.3390/su70912071.
Maavara, T. et al., 2020: River dam impacts on biogeochemical cycling. *Nature Reviews Earth & Environment*, **1** (2), 103-116, doi:10.1038/s43017-019-0019-0.
Macchi, M., A. M. Gurung and B. Hoermann, 2015: Community perceptions and responses to climate variability and change in the Himalayas. *Climate and Development*, **7** (5), 414-425, doi:10.1080/17565529.2014.966046.
MacDonald, A. M. et al., 2016: Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. *Nature Geoscience*, **9**, 762, doi:10.1038/ngeo2791
https://www.nature.com/articles/ngeo2791#supplementary-information.
MacDonald, M. C. et al., 2017: Temporal and thematic trends in water, sanitation and hygiene (WaSH) research in Pacific Island Countries: a systematic review. *Journal of Water, Sanitation and Hygiene for Development*, **7** (3), 352-368, doi:10.2166/washdev.2017.021.
MacDonald, M. C. et al., 2020: Mitigating drought impacts in remote island atolls with traditional water usage behaviors and modern technology. *Science of The Total Environment*, **741**, 140230, doi:https://doi.org/10.1016/j.scitotenv.2020.140230.
MacDonald, S. and S. J. Birchall, 2020: Climate change resilience in the Canadian Arctic: The need for collaboration in the face of a changing landscape. *The Canadian Geographer / Le Géographe canadien*, **64** (3), 530-534, doi:10.1111/cag.12591.
Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571** (7764), 193-197, doi:10.1038/s41586-019-1300-6.
MacMillan, G. A. et al., 2015: High Methylmercury in Arctic and Subarctic Ponds is Related to Nutrient Levels in the Warming Eastern Canadian Arctic. *Environmental Science & Technology*, **49** (13), 7743-7753, doi:10.1021/acs.est.5b00763.
Magesa, B. A. and N. M. Pauline, 2016: Analysis of adaptation strategies of water insecure coastal communities of Tanzania by gender: Case of Mlingotini village in Bagamoyo district. *Journal of the Geographical Association of Tanzania*, **39** (1), 118-141.
Magnan, A. K. et al., 2016: Addressing the risk of maladaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **7** (5), 646-665, doi:10.1002/wcc.409.
Magritsky, D., N. Frolova, M. Kireeva and O. Pakhomova, 2018: Long-term changes of river water inflow into the seas of the Russian Arctic sector. *Polarforschung*, **87**, 177-194.
Maharjan, A. et al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, **6** (1), 1-16, doi:10.1007/s40641-020-00153-z.
Maia-Silva, D., R. Kumar and R. Nateghi, 2020: The critical role of humidity in modeling summer electricity demand across the United States. *Nature Communications*, **11** (1), 1686, doi:10.1038/s41467-020-15393-8.
Majuru, B., M. Suhrcke and P. R. Hunter, 2016: How Do Households Respond to Unreliable Water Supplies? A Systematic Review. *International Journal of Environmental Research and Public Health*, **13** (12), 1222, doi:10.3390/ijerph13121222.
Makate, C. and M. Makate, 2019: Interceding role of institutional extension services on the livelihood impacts of drought tolerant maize technology adoption in Zimbabwe. *Technology in Society*, **56** (September), 126-133, doi:10.1016/j.techsoc.2018.09.011.

Makate, C., M. Makate, N. Mango and S. Siziba, 2019: Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa. *Journal of environmental management*, **231**, 858-868, doi:https://doi.org/10.1016/j.jenvman.2018.10.069.
Maldonado, J. K. and K. Peterson, 2018: A community-based model for resettlement: Lessons from coastal Louisiana. In: Routledge Handbook of Environmental Displacement and Migration. Routledge, 289-299.
Malek, K. et al., 2020: Water rights shape crop yield and revenue volatility tradeoffs for adaptation in snow dependent systems. *Nature Communications*, **11** (1), 3473, doi:10.1038/s41467-020-17219-z.
Malek, Ž. and P. H. Verburg, 2018: Adaptation of land management in the Mediterranean under scenarios of irrigation water use and availability. *Mitigation and Adaptation Strategies for Global Change*, **23** (6), 821-837, doi:10.1007/s11027-017-9761-0.
Mali, S. S., P. B. Shirsath and A. Islam, 2021: A high-resolution assessment of climate change impact on water footprints of cereal production in India. *Scientific Reports*, **11** (1), 8715, doi:10.1038/s41598-021-88223-6.
Mallakpour, I. and G. Villarini, 2015: The changing nature of flooding across the central United States. *Nature Climate Change*, **5**, 250, doi:10.1038/nclimate2516
https://www.nature.com/articles/nclimate2516#supplementary-information.
Mankin, J. S. et al., 2019: Mid-latitude freshwater availability reduced by projected vegetation responses to climate change. *Nature Geoscience*, **12** (12), 983-988, doi:10.1038/s41561-019-0480-x.
Mansourian, S., N. Doncheva, K. Valchev and D. Vallauri, 2019: Lessons learnt from 20 years of floodplain forest restoration in the Lower Danube Landscape. 1-40.
Mansur, A. V. et al., 2018: Adapting to urban challenges in the Amazon: flood risk and infrastructure deficiencies in Belém, Brazil. *Regional Environmental Change*, **18** (5), 1411-1426, doi:10.1007/s10113-017-1269-3.
Mantyka-Pringle, C. S. et al., 2014: Understanding and predicting the combined effects of climate change and land-use change on freshwater macroinvertebrates and fish. *Journal of Applied Ecology*, **51** (3), 572-581, doi:doi:10.1111/1365-2664.12236.
Manuamorn, O. P., R. Biesbroek and V. Cebotari, 2020: What makes internationally-financed climate change adaptation projects focus on local communities? A configurational analysis of 30 Adaptation Fund projects. *Global Environmental Change*, **61**, 102035, doi:https://doi.org/10.1016/j.gloenvcha.2020.102035.
Mao, J. et al., 2015: Disentangling climatic and anthropogenic controls on global terrestrial evapotranspiration trends. *Environmental Research Letters*, **10** (9), 094008, doi:10.1088/1748-9326/10/9/094008.
Mapfumo, P. et al., 2017: Pathways to transformational change in the face of climate impacts: an analytical framework. *Climate and Development*, **9** (5), 439-451.
Marjanac, S. and L. Patton, 2018: Extreme weather event attribution science and climate change litigation: an essential step in the causal chain? *Journal of Energy & Natural Resources Law*, **36** (3), 265-298, doi:10.1080/02646811.2018.1451020.
Markandya, A., 2017: *State of Knowledge on Climate Change, Water, and Economics. Discussion Paper*. The World Bank, Washington, DC. [Available at: https://openknowledge.worldbank.org/handle/10986/26491].
Märker, C., S. Venghaus and J.-F. Hake, 2018: Integrated governance for the food–energy–water nexus – The scope of action for institutional change. *Renewable and Sustainable Energy Reviews*, **97**, 290-300, doi:https://doi.org/10.1016/j.rser.2018.08.020.
Markkula, I., M. Turunen and S. Rasmus, 2019: A review of climate change impacts on the ecosystem services in the Saami Homeland in Finland. *Science of The Total Environment*, **692**, 1070-1085, doi:https://doi.org/10.1016/j.scitotenv.2019.07.272.
Marshall, A. M., J. T. Abatzoglou, T. E. Link and C. J. Tennant, 2019: Projected Changes in Interannual Variability of Peak Snowpack Amount and Timing in the Western United States. *Geophysical Research Letters*, **46** (15), 8882-8892, doi:https://doi.org/10.1029/2019GL083770.
Marshall, R. E. et al., 2018: Source water protection programs and Indigenous communities in Canada and the United States: A scoping review. *Journal of Hydrology*, **562**, 358-370.
Marson, M. and I. Savin, 2015: Ensuring Sustainable Access to Drinking Water in Sub Saharan Africa: Conflict Between Financial and Social Objectives. *World Development*, **76**, 26-39, doi:https://doi.org/10.1016/j.worlddev.2015.06.002.
Martínez-Alvarez, V. et al., 2018a: 14 - Seawater desalination for crop irrigation—Current status and perspectives. In: Emerging Technologies for Sustainable Desalination Handbook [Gude, V. G. (ed.)]. Butterworth-Heinemann, 461-492.
Martínez-Alvarez, V. et al., 2018b: Seawater desalination for crop irrigation—Current status and perspectives. In: Emerging Technologies for Sustainable Desalination Handbook [Gude, V. G. (ed.)]. Butterworth-Heinemann, 461-492.
Martínez-Alvarez, V., B. Martin-Gorriz and M. Soto-García, 2016: Seawater desalination for crop irrigation — A review of current experiences and revealed key issues. *Desalination*, **381**, 58-70, doi:https://doi.org/10.1016/j.desal.2015.11.032.
Martinez Moscoso, A., 2019: La normativa como alternativa para garantizar el derecho humano al agua frente al cambio climático. Regulación de las áreas de protección hídrica en el Ecuador. *Revista de Derecho Ambiental*, **12**, 135-159, doi:10.5354/0719-4633.2019.54152.

Martins, E. S. P. R. et al., 2018: A Multimethod Attribution Analysis of the Prolonged Northeast Brazil Hydrometeorological Drought (2012–16). *Bulletin of the American Meteorological Society*, **99** (1), S65-S69, doi:10.1175/BAMS-D-17-0102.1.
Marx, A. et al., 2018: Climate change alters low flows in Europe under global warming of 1.5, 2, and 3 °C. *Hydrol. Earth Syst. Sci.*, **22** (2), 1017-1032, doi:10.5194/hess-22-1017-2018.
Marzeion, B. et al., 2020: Partitioning the Uncertainty of Ensemble Projections of Global Glacier Mass Change. *Earth's Future*, e2019EF001470.
Mas-Pla, J. and A. Menció, 2019: Groundwater nitrate pollution and climate change: learnings from a water balance-based analysis of several aquifers in a western Mediterranean region (Catalonia). *Environmental Science and Pollution Research*, **26** (3), 2184-2202, doi:10.1007/s11356-018-1859-8.
Mashizha, T. M., 2019: Adapting to climate change: Reflections of peasant farmers in Mashonaland West Province of Zimbabwe. *Jàmbá: Journal of Disaster Risk Studies*, **11** (1), 1-8.
Masseroni, D. et al., 2020: 65-year changes of annual streamflow volumes across Europe with a focus on the Mediterranean basin. *Hydrology and Earth System Sciences Discussions*, 1-16.
Massey, E., R. Biesbroek, D. Huitema and A. Jordan, 2014: Climate policy innovation: The adoption and diffusion of adaptation policies across Europe. *Global Environmental Change*, **29**, 434-443, doi:https://doi.org/10.1016/j.gloenvcha.2014.09.002.
Mastrorillo, M. et al., 2016: The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change*, **39**, 155-169, doi:https://doi.org/10.1016/j.gloenvcha.2016.04.014.
Mathur, R. and K. AchutaRao, 2020: A modelling exploration of the sensitivity of the India's climate to irrigation. *Climate Dynamics*, **54** (3), 1851-1872, doi:10.1007/s00382-019-05090-8.
Matthew, R., 2014: Integrating climate change into peacebuilding. *Climatic Change*, **123** (1), 83-93, doi:10.1007/s10584-013-0894-1.
Matti, B., H. E. Dahlke and S. W. Lyon, 2016: On the variability of cold region flooding. *Journal of Hydrology*, **534**, 669-679, doi:https://doi.org/10.1016/j.jhydrol.2016.01.055.
Maxwell, R. M. and L. E. Condon, 2016: Connections between groundwater flow and transpiration partitioning. *Science*, **353** (6297), 377, doi:10.1126/science.aaf7891.
Mbow, C. et al., 2019: Chapter 5: Food Security. In: IPCC Special Report on Climate Change and Land [Benkeblia, N., A. Challinor, A. Khan and J. Porter (eds.)].
McCord, P., J. Dell'Angelo, E. Baldwin and T. Evans, 2017: Polycentric Transformation in Kenyan Water Governance: A Dynamic Analysis of Institutional and Social-Ecological Change. *Policy Studies Journal*, **45** (4), 633-658, doi:https://doi.org/10.1111/psj.12168.
McCracken, M. and C. Meyer, 2018: Monitoring of transboundary water cooperation: Review of Sustainable Development Goal Indicator 6.5.2 methodology. *Journal of Hydrology*, **563**, 1-12, doi:https://doi.org/10.1016/j.jhydrol.2018.05.013.
McDonough, L. K. et al., 2020: Changes in global groundwater organic carbon driven by climate change and urbanization. *Nature Communications*, **11** (1), 1279, doi:10.1038/s41467-020-14946-1.
McIver, L. et al., 2016: Health Impacts of Climate Change in Pacific Island Countries: A Regional Assessment of Vulnerabilities and Adaptation Priorities. *Environmental Health Perspectives*, **124** (11), 1707-1714, doi:doi:10.1289/ehp.1509756.
McKenna, O. P. and O. E. Sala, 2018: Groundwater recharge in desert playas: current rates and future effects of climate change. *Environmental Research Letters*, **13** (1), 014025, doi:10.1088/1748-9326/aa9eb6.
McKune, S. et al., 2018: Reaching the end goal: Do interventions to improve climate information services lead to greater food security? *Climate Risk Management*, **22**, 22-41.
McLeman, R., M. Opatowski, B. Borova and M. Walton-Roberts, 2016: *Environmental Migration and Displacement - What we know, and what we do not know*. [Available at: http://www.laurierenvironmentalmigration.com/wp-content/uploads/2015/11/WLU-Environmental-Migration-Background-Report.pdf].
McLeod, E. et al., 2018: Raising the voices of Pacific Island women to inform climate adaptation policies. *Marine Policy*, **93**, 178-185, doi:https://doi.org/10.1016/j.marpol.2018.03.011.
McLeod, E. et al., 2019: Lessons From the Pacific Islands – Adapting to Climate Change by Supporting Social and Ecological Resilience. *Frontiers in Marine Science*, **6** (289), doi:10.3389/fmars.2019.00289.
McMillan, H. et al., 2016: Panta Rhei 2013–2015: global perspectives on hydrology, society and change. *Hydrological Sciences Journal*, **61** (7), 1174-1191, doi:10.1080/02626667.2016.1159308.
McNamara, K. E., R. Westoby and A. Chandra, 2021: Exploring climate-driven non-economic loss and damage in the Pacific Islands. *Current opinion in environmental sustainability*, **50**, 1-11, doi:https://doi.org/10.1016/j.cosust.2020.07.004.
MCTI, 2020: *Fourth National Communication of Brazil to the UNFCCC*. Ministry of Science, T. a. I. M., Rio de Janeiro, Brazil [Available at: https://issuu.com/mctic/docs/fourth_national_communication_brazil_unfccc].
McVittie, A. et al., 2018: Ecosystem-based solutions for disaster risk reduction: Lessons from European applications of ecosystem-based adaptation measures. Elsevier Ltd, **32**, 42-54, doi:10.1016/j.ijdrr.2017.12.014.
Mechler, R., 2016: Reviewing estimates of the economic efficiency of disaster risk management: opportunities and limitations of using risk-based cost–benefit analysis. *Natural Hazards*, **81** (3), 2121-2147.

Mechler, R. et al., 2014: Managing unnatural disaster risk from climate extremes. *Nature Climate Change*, **4** (4), 235-237, doi:10.1038/nclimate2137.
Mechler, R. et al., 2019: *Loss and Damage from Climate Change : Concepts, Methods and Policy Options*. Springer Nature.
Mechler, R. et al., 2020: Loss and Damage and limits to adaptation: recent IPCC insights and implications for climate science and policy. *Sustainability Science*, **15** (4), 1245-1251, doi:10.1007/s11625-020-00807-9.
Medeiros, A. S. et al., 2017: Water security for northern peoples: review of threats to Arctic freshwater systems in Nunavut, Canada. *Regional Environmental Change*, **17** (3), 635-647, doi:10.1007/s10113-016-1084-2.
Medlyn, B. E. et al., 2015: Using ecosystem experiments to improve vegetation models. *Nature Climate Change*, **5**, 528, doi:10.1038/nclimate2621.
Meehl, G. A. et al., 2020: Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, **6** (26), eaba1981, doi:10.1126/sciadv.aba1981.
Mehdi, B. et al., 2015: Simulated impacts of climate change and agricultural land use change on surface water quality with and without adaptation management strategies. *Agriculture, Ecosystems & Environment*, **213**, 47-60, doi:https://doi.org/10.1016/j.agee.2015.07.019.
Mehran, A. et al., 2017: Compounding Impacts of Human-Induced Water Stress and Climate Change on Water Availability. *Scientific Reports*, **7** (1), 6282, doi:10.1038/s41598-017-06765-0.
Mehrazar, A. et al., 2020: Adaptation of Water Resources System to Water Scarcity and Climate Change in the Suburb Area of Megacities. *Water Resources Management*, **34** (12), 3855-3877, doi:10.1007/s11269-020-02648-8.
Meier, J., F. Zabel and W. Mauser, 2018: A global approach to estimate irrigated areas – a comparison between different data and statistics. *Hydrol. Earth Syst. Sci.*, **22** (2), 1119-1133, doi:10.5194/hess-22-1119-2018.
Meixner, T. et al., 2016: Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, **534**, 124-138, doi:https://doi.org/10.1016/j.jhydrol.2015.12.027.
Mekonnen, M. M. and A. Y. Hoekstra, 2016: Four billion people facing severe water scarcity. *Science Advances*, **2** (2), e1500323, doi:10.1126/sciadv.1500323.
Meng, Q. et al., 2016: Growing sensitivity of maize to water scarcity under climate change. *Scientific Reports*, **6**, 19605.
Meng, Y. et al., 2020: Hydropower Production Benefits More From 1.5 °C than 2 °C Climate Scenario. *Water Resources Research*, **56** (5), e2019WR025519, doi:10.1029/2019WR025519.
Meng, Y. et al., 2021: Undermined co-benefits of hydropower and irrigation under climate change. *Resources, Conservation and Recycling*, **167**, 105375, doi:https://doi.org/10.1016/j.resconrec.2020.105375.
Menounos, B. et al., 2019: Heterogeneous changes in western North American glaciers linked to decadal variability in zonal wind strength. *Geophysical Research Letters*, **46** (1), 200-209.
Mercer, N. and M. Hanrahan, 2017: "Straight from the heavens into your bucket": domestic rainwater harvesting as a measure to improve water security in a subarctic indigenous community. *International Journal of Circumpolar Health*, **76** (1), 1312223, doi:10.1080/22423982.2017.1312223.
Mercure, J. F. et al., 2019: System complexity and policy integration challenges: The Brazilian Energy- Water-Food Nexus. *Renewable and Sustainable Energy Reviews*, **105**, 230-243, doi:https://doi.org/10.1016/j.rser.2019.01.045.
Meredith, M. et al., 2019: Polar Regions. In: IPCC Special Report on Cryopshere and Oceans in a Changing Climate.
Mersha, A. A. and F. van Laerhoven, 2018: The interplay between planned and autonomous adaptation in response to climate change: Insights from rural Ethiopia. *World Development*, **107**, 87-97.
Mesquita, P. S. and M. Bursztyn, 2017: Food acquisition programs in the Brazilian semi-arid region: benefits to farmers and impacts of climate change. *Food Security*, **9** (5), 1041-1051.
Mfitumukiza, D. et al., 2020: Smallholder farmers' perceived evaluation of agricultural drought adaptation technologies used in Uganda: Constraints and opportunities. *Journal of Arid Environments*, **177**, 104137, doi:https://doi.org/10.1016/j.jaridenv.2020.104137.
Michael, H. A., C. J. Russoniello and L. A. Byron, 2013: Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems. *Water Resources Research*, **49** (4), 2228-2240, doi:10.1002/wrcr.20213.
Michalak, A. M., 2016: Study role of climate change in extreme threats to water quality. *Nature*, **535** (7612), 349-350, doi:10.1038/535349a.
Micheletti, N., C. Lambiel and S. N. Lane, 2015: Investigating decadal-scale geomorphic dynamics in an alpine mountain setting. *Journal of Geophysical Research: Earth Surface*, **120** (10), 2155-2175, doi:10.1002/2015jf003656.
Miletto, M., Caretta, M. A., Burchi, F. M. and Zanlucchi, G, 2017: *Migration and its interdependencies with water scarcity, gender and youth employment.* WWAP, UNESCO, Paris [Available at: https://unesdoc.unesco.org/ark:/48223/pf0000258968].
Miller, J. D., J. Vonk, C. Staddon and S. L. Young, 2020: Is household water insecurity a link between water governance and well-being? A multi-site analysis. *Journal of Water, Sanitation and Hygiene for Development*, **10** (2), 320-334, doi:10.2166/washdev.2020.165.
Miller, K. M. et al., 2014: Infectious disease, shifting climates, and opportunistic predators: cumulative factors potentially impacting wild salmon declines. *Evolutionary Applications*, **7** (7), 812-855, doi:10.1111/eva.12164.

Miller, M. M. and M. Shirzaei, 2019: Land subsidence in Houston correlated with flooding from Hurricane Harvey. *Remote Sensing of Environment*, **225**, 368-378, doi:https://doi.org/10.1016/j.rse.2019.03.022.
Milly, P. C. D. and K. A. Dunne, 2016: Potential evapotranspiration and continental drying. *Nature Climate Change*, **6**, 946, doi:10.1038/nclimate3046 https://www.nature.com/articles/nclimate3046#supplementary-information.
Milman, A. and Y. Arsano, 2014: Climate adaptation and development: Contradictions for human security in Gambella, Ethiopia. *Global Environmental Change*, **29**, 349-359, doi:https://doi.org/10.1016/j.gloenvcha.2013.11.017.
Milman, A. and K. Jagannathan, 2017: Conceptualization and implementation of ecosystems-based adaptation. *Climatic Change*, **142** (1), 113-127, doi:10.1007/s10584-017-1933-0.
Minayeva, T., A. Sirin, P. Kershaw and O. Bragg, 2018: Arctic Peatlands. In: The Wetland Book: II: Distribution, Description, and Conservation [Finlayson, C. M., G. R. Milton, R. C. Prentice and N. C. Davidson (eds.)]. Springer Netherlands, Dordrecht, 275-288.
Miralles, D. G., A. J. Teuling, C. C. van Heerwaarden and J. Vilà-Guerau de Arellano, 2014: Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nature Geoscience*, **7**, 345, doi:10.1038/ngeo2141 https://www.nature.com/articles/ngeo2141#supplementary-information.
Miranda, A. et al., 2020: Evidence-based mapping of the wildland-urban interface to better identify human communities threatened by wildfires. *Environmental Research Letters*, **15** (9), 094069, doi:10.1088/1748-9326/ab9be5.
Mirumachi, N., 2015: *Transboundary Water Politics in the Developing World*. Routledge, Abingdon and New York
Mirzabaev, A. et al., 2019: Chapter 3 (Desertification) In: IPCC SRCC.
Mishra, A., E. Bruno and D. Zilberman, 2021: Compound natural and human disasters: Managing drought and COVID-19 to sustain global agriculture and food sectors. *Science of The Total Environment*, **754**, 142210, doi:https://doi.org/10.1016/j.scitotenv.2020.142210.
Mishra, A. K. and N. Vanganuru, 2020: Monitoring a tropical super cyclone Amphan over Bay of Bengal and nearby region in May 2020. *Remote Sensing Applications: Society and Environment*, **20**, 100408, doi:https://doi.org/10.1016/j.rsase.2020.100408.
Mishra, V. et al., 2020: Moist heat stress extremes in India enhanced by irrigation. *Nature Geoscience*, **13** (11), 722-728, doi:10.1038/s41561-020-00650-8.
Mishra, V., A. R. Ganguly, B. Nijssen and D. P. Lettenmaier, 2015: Changes in observed climate extremes in global urban areas. *Environmental Research Letters*, **10** (2), 024005, doi:10.1088/1748-9326/10/2/024005.
Missirian, A. and W. Schlenker, 2017: Asylum applications respond to temperature fluctuations. *Science*, **358** (6370), 1610-1614, doi:10.1126/science.aao0432.
Moggridge, B. J. and R. M. Thompson, 2021: Cultural value of water and western water management: an Australian Indigenous perspective. *Australasian Journal of Water Resources*, **25** (1), 4-14, doi:10.1080/13241583.2021.1897926.
Mohamed, H., M. Elayah and L. Schuplen, 2017: *Yemen between the Impact of the Climate Change and the Ongoing Saudi-Yemen War: A Real Tragedy*. University, R. [Available at: www.ru.nl/publish/pages/871321/a_real_tragedy.pdf].
Mokadem, N. et al., 2018: Impact of climate change on groundwater and the extinction of ancient "Foggara" and springs systems in arid lands in North Africa: a case study in Gafsa basin (Central of Tunisia). *Euro-Mediterranean Journal for Environmental Integration*, **3** (1), 28, doi:10.1007/s41207-018-0070-0.
Momblanch, A. et al., 2019: Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system. *Science of The Total Environment*, **655**, 35-47, doi:https://doi.org/10.1016/j.scitotenv.2018.11.045.
Monterrey-Viña, A., A. Musicki-Savic, F. J. Díaz-Peña and B. Peñate-Suárez, 2020: Technical and Agronomical Assessment of the Use of Desalinated Seawater for Coastal Irrigation in an Insular Context. *Water*, **12** (1), doi:10.3390/w12010272.
Moomaw, W. R. et al., 2018: Wetlands In a Changing Climate: Science, Policy and Management. *Wetlands*, **38** (2), 183-205, doi:10.1007/s13157-018-1023-8.
Morán-Tejeda, E. et al., 2014: Streamflow timing of mountain rivers in Spain: Recent changes and future projections. *Journal of Hydrology*, **517**, 1114-1127, doi:https://doi.org/10.1016/j.jhydrol.2014.06.053.
Morecroft, M. D. et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. **366**, doi:10.1126/science.aaw9256.
Morel, A. C. et al., 2019: The structures underpinning vulnerability: examining landscape-society interactions in a smallholder coffee agroforestry system. *Environmental Research Letters*, **14** (7), 075006, doi:10.1088/1748-9326/ab2280.
Morera, S. B. et al., 2017: The impact of extreme El Niño events on modern sediment transport along the western Peruvian Andes (1968–2012). *Scientific Reports*, **7** (1), 11947, doi:10.1038/s41598-017-12220-x.
Morote, Á.-F., J. Olcina and M. Hernández, 2019: The Use of Non-Conventional Water Resources as a Means of Adaptation to Drought and Climate Change in Semi-Arid Regions: South-Eastern Spain. *Water*, **11** (1), 93.
Morrison, T. H. et al., 2017: Mitigation and adaptation in polycentric systems: sources of power in the pursuit of collective goals. *WIREs Climate Change*, **8** (5), e479, doi:https://doi.org/10.1002/wcc.479.

Motschmann, A. et al., 2020: Losses and damages connected to glacier retreat in the Cordillera Blanca, Peru. *Climatic Change*, **162** (2), 837-858, doi:10.1007/s10584-020-02770-x.

Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48-58, doi:https://doi.org/10.1016/j.envsci.2016.06.007.

Mpanga, I. K. and O. J. Idowu, 2021: A Decade of Irrigation Water use trends in Southwestern USA: The Role of Irrigation Technology, Best Management Practices, and Outreach Education Programs. *Agricultural Water Management*, **243**, 106438, doi:https://doi.org/10.1016/j.agwat.2020.106438.

Mu, C. et al., 2019: Carbon and mercury export from the Arctic rivers and response to permafrost degradation. *Water Research*, **161**, 54-60, doi:https://doi.org/10.1016/j.watres.2019.05.082.

Mudryk, L. et al., 2020: Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. *The Cryosphere*, **14** (7), 2495-2514.

Mudryk, L. R., P. J. Kushner, C. Derksen and C. Thackeray, 2017: Snow cover response to temperature in observational and climate model ensembles. *Geophysical Research Letters*, **44** (2), 919-926, doi:10.1002/2016gl071789.

Mueller, N. D. et al., 2016: Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, **6** (3), 317-322.

Mugambiwa, S. S., 2018: Adaptation measures to sustain indigenous practices and the use of indigenous knowledge systems to adapt to climate change in Mutoko rural district of Zimbabwe. *Jàmbá: Journal of Disaster Risk Studies*, **10** (1), 1-9.

Muis, S. et al., 2018: Influence of El Niño-Southern Oscillation on Global Coastal Flooding. *Earth's Future*, **6** (9), 1311-1322, doi:10.1029/2018ef000909.

Mukherjee, A., S. S. Babu and S. Ghosh, 2020: Thinking about water and air to attain Sustainable Development Goals during times of COVID-19 Pandemic. *Journal of Earth System Science*, **129** (1), 180, doi:10.1007/s12040-020-01475-0.

Mukherji, A., 2020: Sustainable Groundwater Management in India Needs a Water-Energy-Food Nexus Approach. *Applied Economic Perspectives and Policy*, **n/a** (n/a), doi:https://doi.org/10.1002/aepp.13123.

Mukherji, A. et al., 2021: *Effectiveness of water adaptation responses in reducing climate related risks : a meta review.* ACIAR, Canberra, Australia, 75 [Available at: https://www.aciar.gov.au/project/wac-2020-157].

Mukherji, A. et al., 2019: Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: a review. *Regional Environmental Change*, **19** (5), 1311-1326, doi:10.1007/s10113-019-01484-w.

Mullan, D. et al., 2019: Climate impacts on soil erosion and muddy flooding at 1.5 versus 2°C warming. *Land Degradation & Development*, **30** (1), 94-108, doi:10.1002/ldr.3214.

Muller, M., 2018: Cape Town's drought: Don't blame climate change. *Nature*, **559**, 174-176, doi:10.1038/d41586-018-05649-1.

Müller Schmied, H. et al., 2021: The global water resources and use model WaterGAP v2.2d: model description and evaluation. *Geosci. Model Dev.*, **14** (2), 1037-1079, doi:10.5194/gmd-14-1037-2021.

Munia, H. A. et al., 2020: Future Transboundary Water Stress and Its Drivers Under Climate Change: A Global Study. *Earth's Future*, **8** (7), e2019EF001321, doi:https://doi.org/10.1029/2019EF001321.

Muratori, M. et al., 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, **11** (9), 095004, doi:10.1088/1748-9326/11/9/095004.

Muricho, D. N., D. J. Otieno, W. Oluoch-Kosura and M. Jirström, 2019: Building pastoralists' resilience to shocks for sustainable disaster risk mitigation: Lessons from West Pokot County, Kenya. *International Journal of Disaster Risk Reduction*, **34** (December 2018), 429-435, doi:10.1016/j.ijdrr.2018.12.012.

Murphy, H. M., K. D. M. Pintar, E. A. McBean and M. K. Thomas, 2014: A systematic review of waterborne disease burden methodologies from developed countries. *Journal of water and health*, **12** (4), 634-655, doi:10.2166/wh.2014.049.

Murphy, S. F., J. H. Writer, R. B. McCleskey and D. A. Martin, 2015: The role of precipitation type, intensity, and spatial distribution in source water quality after wildfire. *Environmental Research Letters*, **10** (8), doi:10.1088/1748-9326/10/8/084007.

Murray-Tortarolo, G. N. and M. M. Salgado, 2021: Drought as a driver of Mexico-US migration. *Climatic Change*, **164** (3), 48, doi:10.1007/s10584-021-03030-2.

Musah-Surugu, I. J., A. Ahenkan, J. N. Bawole and S. A. Darkwah, 2018: Migrants' remittances: A complementary source of financing adaptation to climate change at the local level in Ghana. *International Journal of Climate Change Strategies and Management*, **10** (1), 178-196, doi:10.1108/IJCCSM-03-2017-0054.

Musselman, K. N. et al., 2018: Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, **8** (9), 808-812.

Mussetta, P., S. Turbay and A. J. Fletcher, 2016: Adaptive Strategies Building Resilience to Climate Variability in Argentina, Canada and Colombia. In: Climate Change Adaptation, Resilience and Hazards. Springer, 225-240.

Mustafa, D. and M. Usman Qazi, 2008: Karez versus tubewell irrigation: the comparative social acceptability and practicality of sustainable groundwater development in Balochistan, Pakistan. *Contemporary South Asia*, **16** (2), 171-195, doi:10.1080/09584930701733514.

Mustonen, T., 2015: Communal visual histories to detect environmental change in northern areas: Examples of emerging North American and Eurasian practices. *Ambio*, **44** (8), 766-777, doi:10.1007/s13280-015-0671-7.
Mustonen, T. and P. Feodoroff, 2018: Skolt Sámi and Atlantic Salmon Collaborative Management of Näätämö Watershed, Finland as a Case of Indigenous Evaluation and Knowledge in the Eurasian Arctic. *New Directions for Evaluation*, **2018** (159), 107-119, doi:10.1002/ev.20334.
Mustonen, T. et al., 2021: 2021 Compendium of Indigenous Knowledge and Local Knowledge: towards inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change. Snowchange Cooperative, Kontiolahti, Finland, doi:10.13140/RG.2.2.14498.76485.
Mustonen, T. and A. A. Lehtinen, 2020: Lived displacement among the Evenki of Yiengra. *International Journal of Critical Indigenous Studies*, **13** (1), 16-44.
Mustonen, T. and K. Mustonen, 2016: *Life in the cyclic world: a compendium of traditional knowledge from the Eurasian North*. Snowchange Cooperative, Finland, Kontiolahti.
Mutenje, M. J. et al., 2019: A cost-benefit analysis of climate-smart agriculture options in Southern Africa: Balancing gender and technology. *Ecological Economics*, **163**, 126-137, doi:https://doi.org/10.1016/j.ecolecon.2019.05.013.
Muyambo, F., Y. T. Bahta and A. J. Jordaan, 2017: The role of indigenous knowledge in drought risk reduction: A case of communal farmers in South Africa. *Jàmbá: Journal of Disaster Risk Studies*, **9**, 1-6.
Mycoo, M. A., 2014: Autonomous household responses and urban governance capacity building for climate change adaptation: Georgetown, Guyana. *Urban Climate*, **9**, 134-154, doi:https://doi.org/10.1016/j.uclim.2014.07.009.
Myers, B. J. E. et al., 2017: Global synthesis of the documented and projected effects of climate change on inland fishes. *Reviews in Fish Biology and Fisheries*, **27** (2), 339-361, doi:10.1007/s11160-017-9476-z.
Myhre, G. et al., 2019: Frequency of extreme precipitation increases extensively with event rareness under global warming. *Scientific Reports*, **9** (1), 16063, doi:10.1038/s41598-019-52277-4.
Naik, P. K., 2017: Water crisis in Africa: myth or reality? *International Journal of Water Resources Development*, **33** (2), 326-339, doi:10.1080/07900627.2016.1188266.
Najibi, N. and N. Devineni, 2018: Recent trends in the frequency and duration of global floods. *Earth Syst. Dynam.*, **9** (2), 757-783, doi:10.5194/esd-9-757-2018.
Nambi, A. A., S. Bahinipati Chandra, R. Raghunath and R. Nagendran, 2015: Farm household level adaptation metrics for agriculture and water sectors. *International Journal of Climate Change Strategies and Management*, **7** (1), 27-40, doi:10.1108/IJCCSM-04-2013-0048.
Nangombe, S., T. Zhou, L. Zhang and W. Zhang, 2020: Attribution Of The 2018 October–December Drought Over South Southern Africa. *Bulletin of the American Meteorological Society*, **101** (1), S135-S140.
Naqvi, S. M. K., D. Kumar, K. De and V. Sejian, 2015: Climate Change and Water Availability for Livestock: Impact on Both Quality and Quantity. In: Climate Change Impact on Livestock: Adaptation and Mitigation [Sejian, V., J. Gaughan, L. Baumgard and C. Prasad (eds.)]. Springer India, New Delhi, 81-95.
Narayan, S. et al., 2020: Local adaptation responses to coastal hazards in small island communities: insights from 4 Pacific nations. *Environmental Science & Policy*, **104**, 199-207, doi:https://doi.org/10.1016/j.envsci.2019.11.006.
Naskar, M. et al., 2018: Quantifying climate change induced threats to wetland fisheries: a stakeholder-driven approach. *Environment, Development and Sustainability*, **20** (6), 2811-2830, doi:10.1007/s10668-017-0018-6.
Naumann, G. et al., 2018: Global Changes in Drought Conditions Under Different Levels of Warming. *Geophysical Research Letters*, **45** (7), 3285-3296, doi:10.1002/2017gl076521.
Nawrotzki, R. J. and M. Bakhtsiyarava, 2017: International Climate Migration: Evidence for the Climate Inhibitor Mechanism and the Agricultural Pathway. *Population, Space and Place*, **23** (4), e2033, doi:10.1002/psp.2033.
Nazemi, A. and K. Madani, 2018: Urban water security: Emerging discussion and remaining challenges. *Sustainable Cities and Society*, **41**, 925-928, doi:https://doi.org/10.1016/j.scs.2017.09.011.
NCCARF, 2018: *Impacts on Indigenous Communities. National Landcare Program Phase Two 2018*. National Climate Change Adaptation Research Facility, A. G.
Neal, M. J., 2020: COVID-19 and water resources management: reframing our priorities as a water sector. *Water International*, **45** (5), 435-440, doi:10.1080/02508060.2020.1773648.
Nechifor, V. and M. Winning, 2019: Global crop output and irrigation water requirements under a changing climate. *Heliyon*, **5** (3), e01266, doi:https://doi.org/10.1016/j.heliyon.2019.e01266.
Nelson, G. L. et al., 2019: The Indigenous Practices and Climate Change Responses of Ati and Suludnon Farmers in Iloilo, Philippines. *Journal of Environmental Science and Management*, **22** (1).
Newell, R. and A. Dale, 2020: COVID-19 and climate change: an integrated perspective. *Cities & Health*, 1-5, doi:10.1080/23748834.2020.1778844.
Newsham, A. et al., 2018: Ecosystems-based adaptation: Are we being conned? Evidence from Mexico. *Global Environmental Change*, **49**, 14-26, doi:https://doi.org/10.1016/j.gloenvcha.2018.01.001.
Ng'ang'a, S. K. et al., 2016: Migration and Self-Protection Against Climate Change: A Case Study of Samburu County, Kenya. *World Development*, **84**, 55-68, doi:https://doi.org/10.1016/j.worlddev.2016.04.002.
Ngata, T., 2018: Wai māori. In: Mountains to Sea: Solving New Zealand's freshwater crisis [Joy, M. (ed.)]. BWB Texts, Wellington, 6-11.
Ngigi, M. W., U. Müller and R. Birner, 2018: Farmers' intrinsic values for adopting climate-smart practices in Kenya: empirical evidence from a means-end chain analysis. *Climate and Development*, **10** (7), 614-624.

Ngô, L. A., I. Masih, Y. Jiang and W. Douven, 2016: Impact of reservoir operation and climate change on the hydrological regime of the Sesan and Srepok Rivers in the Lower Mekong Basin. *Climatic Change*, **149**, 107-119.
Ngoran, S. D. and X. Xue, 2015: Addressing urban sprawl in Douala, Cameroon: Lessons from Xiamen integrated coastal management. *Journal of Urban Management*, **4** (1), 53-72, doi:https://doi.org/10.1016/j.jum.2015.05.001.
Nichols, G., I. Lake and C. Heaviside, 2018: Climate change and water-related infectious diseases. *Atmosphere*, **9** (10), 385.
Nie, X. et al., 2020: Big Data analytics and IoT in Operation safety management in Under Water Management. *Computer Communications*, **154**, 188-196, doi:https://doi.org/10.1016/j.comcom.2020.02.052.
Nilsson, C., L. E. Polvi and L. Lind, 2015: Extreme events in streams and rivers in arctic and subarctic regions in an uncertain future. *Freshwater Biology*, **60** (12), 2535-2546, doi:https://doi.org/10.1111/fwb.12477.
Nitze, I. et al., 2018: Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. *Nature Communications*, **9** (1), 5423, doi:10.1038/s41467-018-07663-3.
Niyogi, D. et al., 2017: Urbanization Impacts on the Summer Heavy Rainfall Climatology over the Eastern United States. *Earth Interactions*, **21** (5), 1-17, doi:10.1175/ei-d-15-0045.1.
Noble, I. R. et al., 2014: Adaptation needs and options. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 833-868.
Noori, R., R. Berndtsson, J. Franklin Adamowski and M. Rabiee Abyaneh, 2018: Temporal and depth variation of water quality due to thermal stratification in Karkheh Reservoir, Iran. *Journal of Hydrology: Regional Studies*, **19**, 279-286, doi:https://doi.org/10.1016/j.ejrh.2018.10.003.
Northey, S. A. et al., 2017: The exposure of global base metal resources to water criticality, scarcity and climate change. *Global Environmental Change*, **44**, 109-124, doi:https://doi.org/10.1016/j.gloenvcha.2017.04.004.
Norton-Smith, K. et al., 2016: *Climate change and indigenous peoples: a synthesis of current impacts and experiences*.
Nursey-Bray, M. and R. Palmer, 2018: Country, climate change adaptation and colonisation: insights from an Indigenous adaptation planning process, Australia. *Heliyon*, **4** (3), e00565.
Nüsser, M. and S. Schmidt, 2017: Nanga Parbat Revisited: Evolution and Dynamics of Sociohydrological Interactions in the Northwestern Himalaya. *Annals of the American Association of Geographers*, **107** (2), 403-415, doi:10.1080/24694452.2016.1235495.
Nyantakyi-Frimpong, H., 2020: Unmasking difference: intersectionality and smallholder farmers' vulnerability to climate extremes in Northern Ghana. *Gender, Place & Culture*, **27** (11), 1536-1554, doi:10.1080/0966369X.2019.1693344.
Nygren, M. et al., 2020: Changes in seasonality of groundwater level fluctuations in a temperate-cold climate transition zone. *Journal of Hydrology X*, **8**, 100062, doi:https://doi.org/10.1016/j.hydroa.2020.100062.
Nyima, Y. and K. A. Hopping, 2019: Tibetan Lake Expansion from a Pastoral Perspective: Local Observations and Coping Strategies for a Changing Environment. *Society & Natural Resources*, **32** (9), 965-982, doi:10.1080/08941920.2019.1590667.
Nyman, P. et al., 2015: Predicting sediment delivery from debris flows after wildfire. *Geomorphology*, **250**, 173-186, doi:https://doi.org/10.1016/j.geomorph.2015.08.023.
O'Reilly, C. M. et al., 2015: Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, **42** (24), 10,773-10,781, doi:https://doi.org/10.1002/2015GL066235.
Oberlack, C., 2017: Diagnosing institutional barriers and opportunities for adaptation to climate change. *Mitigation and Adaptation Strategies for Global Change*, **22** (5), 805-838, doi:10.1007/s11027-015-9699-z.
Oberlack, C. and K. Eisenack, 2018: Archetypical barriers to adapting water governance in river basins to climate change. *Journal of Institutional Economics*, **14** (3), 527-555, doi:10.1017/S1744137417000509.
Oberle, F. K. J., P. W. Swarzenski and C. D. Storlazzi, 2017: Atoll Groundwater Movement and Its Response to Climatic and Sea-Level Fluctuations. *Water*, **9** (9), doi:10.3390/w9090650.
Obokata, R., L. Veronis and R. McLeman, 2014: Empirical research on international environmental migration: a systematic review. *Population and Environment*, **36** (1), 111-135, doi:10.1007/s11111-014-0210-7.
Ocello, C., A. Petrucci, M. R. Testa and D. Vignoli, 2015: Environmental aspects of internal migration in Tanzania. *Population and Environment*, **37** (1), 99-108, doi:10.1007/s11111-014-0229-9.
Odell, S. D., A. Bebbington and K. E. Frey, 2018: Mining and climate change: A review and framework for analysis. *The Extractive Industries and Society*, **5** (1), 201-214, doi:https://doi.org/10.1016/j.exis.2017.12.004.
OECD, 2015: *Water: Fit to Finance?*, Organisation for Economic Cooperation and Development, Marseille, France [Available at: http://www.worldwatercouncil.org/en/publications/water-fit-finance].
Okereke, C., 2018: Equity and Justice in Polycentric Climate Governance. In: Governing Climate Change [Jordan, A., D. Huitema, H. v. Asselt and J. Forster (eds.)]. Cambridge University Press, Cambridge UK, 320-337.
Okunlola, J., D. Oke, V. Adekunle and K. Owolabi, 2019: Effects of climate change and coping strategies among crop farmers in South West, Nigeria. *Agroforestry Systems*, **93** (4), 1399-1408.
Olarinoye, T. et al., 2020: Exploring the future impacts of urbanization and climate change on groundwater in Arusha, Tanzania. *Water International*, **45** (5), 497-511, doi:10.1080/02508060.2020.1768724.

Olazabal, M. et al., 2019: A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, **14** (12), 124056, doi:10.1088/1748-9326/ab5532.
Oliva, M. and M. Fritz, 2018: Permafrost degradation on a warmer Earth: Challenges and perspectives. *Current Opinion in Environmental Science & Health*, **5**, 14-18.
Olsson, L. et al., 2020: Land degradation (Chapter 4). In: IPCC SRCCL.
Op de Hipt, F. et al., 2018: Modeling the impact of climate change on water resources and soil erosion in a tropical catchment in Burkina Faso, West Africa. *CATENA*, **163**, 63-77, doi:https://doi.org/10.1016/j.catena.2017.11.023.
Opie, S. et al., 2020: Climate-groundwater dynamics inferred from GRACE and the role of hydraulic memory. *Earth Syst. Dynam. Discuss.*, **2020**, 1-28, doi:10.5194/esd-2019-83.
Opiyo, F. et al., 2015: Drought Adaptation and Coping Strategies Among the Turkana Pastoralists of Northern Kenya. *International Journal of Disaster Risk Science*, **6** (3), 295-309, doi:10.1007/s13753-015-0063-4.
Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC special report on the ocean and cryosphere in a changing climate [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], In press.
Oral, H. V. et al., 2020: A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. *Blue-Green Systems*, **2** (1), 112-136, doi:10.2166/bgs.2020.932.
Orlove, B. et al., 2019: Framing climate change in frontline communities: anthropological insights on how mountain dwellers in the USA, Peru, and Italy adapt to glacier retreat. *Regional Environmental Change*, **19** (5), 1295-1309.
Ostrom, E., 2014: A Polycentric Approach for Coping with Climate Change. *Annals of Economics and Finance*, **15**, doi:10.2139/ssrn.1934353.
Otto, F. et al., 2015: Factors Other Than Climate Change, Main Drivers of 2014/15 Water Shortage in Southeast Brazil. *Bulletin of the American Meteorological Society*, **96**, S35-S40, doi:10.1175/BAMS-EEE_2014_ch8.1.
Otto, F. E. L. et al., 2020: Challenges to Understanding Extreme Weather Changes in Lower Income Countries. *Bulletin of the American Meteorological Society*, **101** (10), E1851-E1860, doi:10.1175/BAMS-D-19-0317.1.
Otto, F. E. L. et al., 2016: The attribution question. *Nature Climate Change*, **6** (9), 813-816, doi:10.1038/nclimate3089.
Otto, F. E. L. et al., 2018: Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. *Environmental Research Letters*, **13** (12), 124010, doi:10.1088/1748-9326/aae9f9.
Owain, E. L. and M. A. Maslin, 2018: Assessing the relative contribution of economic, political and environmental factors on past conflict and the displacement of people in East Africa. *Palgrave Communications*, **4** (1), 47, doi:10.1057/s41599-018-0096-6.
Padrón, R. S. et al., 2020: Observed changes in dry-season water availability attributed to human-induced climate change. *Nature Geoscience*, **13** (7), 477-481, doi:10.1038/s41561-020-0594-1.
Paerregaard, K., 2013: Bare Rocks and Fallen Angels: Environmental Change, Climate Perceptions and Ritual Practice in the Peruvian Andes. *Religions*, **4**, 290-305, doi:10.3390/rel4020290.
Paerregaard, K., 2018: Power in/of/as water: Revisiting the hydrologic cycle in the Peruvian Andes. *Wiley Interdisciplinary Reviews: Water*, **5** (2), e1270, doi:10.1002/wat2.1270.
Pagano, A. et al., 2019: Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: A participatory System Dynamics Model for benefits and co-benefits evaluation. **690**, 543-555, doi:10.1016/j.scitotenv.2019.07.059.
Page, E. A. and C. Heyward, 2016: Compensating for Climate Change Loss and Damage. *Political Studies*, **65** (2), 356-372, doi:10.1177/0032321716647401.
Page, R. and L. Dilling, 2020: How experiences of climate extremes motivate adaptation among water managers. *Climatic Change*, **161** (3), 499-516, doi:10.1007/s10584-020-02712-7.
Pahl-Wostl, C. and C. Knieper, 2014: The capacity of water governance to deal with the climate change adaptation challenge: Using fuzzy set Qualitative Comparative Analysis to distinguish between polycentric, fragmented and centralized regimes. *Global Environmental Change*, **29**, 139-154, doi:https://doi.org/10.1016/j.gloenvcha.2014.09.003.
Pahl-Wostl, C. et al., 2020: Enhancing the capacity of water governance to deal with complex management challenges: A framework of analysis. *Environmental Science & Policy*, **107**, 23-35, doi:https://doi.org/10.1016/j.envsci.2020.02.011.
Pak-Uthai, S. and N. Faysse, 2018: The risk of second-best adaptive measures: Farmers facing drought in Thailand. *International Journal of Disaster Risk Reduction*, **28**, 711-719.
Palmer, M. A. et al., 2015: Manage water in a green way. **349**, 584-585, doi:10.1126/science.aac7778.
Palomo, I. et al., 2021: Assessing nature-based solutions for transformative change. *One Earth*, **4** (5), 730-741, doi:10.1016/j.oneear.2021.04.013.
Paltiel, O. et al., 2016: Human Exposure to Wastewater-Derived Pharmaceuticals in Fresh Produce: A Randomized Controlled Trial Focusing on Carbamazepine. *Environmental Science & Technology*, **50** (8), 4476-4482, doi:10.1021/acs.est.5b06256.
Panagos, P. et al., 2018: Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. *Land Degradation & Development*, **29** (3), 471-484, doi:10.1002/ldr.2879.

Pande, S. and M. Sivapalan, 2017: Progress in socio-hydrology: a meta-analysis of challenges and opportunities. *Wiley Interdisciplinary Reviews: Water*, **4** (4), e1193, doi:10.1002/wat2.1193.
Pandey, R. et al., 2017: Agroecology as a Climate Change Adaptation Strategy for Smallholders of Tehri-Garhwal in the Indian Himalayan Region. *Small-scale forestry*, **16** (1), 53-63, doi:10.1007/s11842-016-9342-1.
Pandey, S. S., G. Cockfield and T. N. Maraseni, 2016: Assessing the roles of community forestry in climate change mitigation and adaptation: A case study from Nepal. *Forest Ecology and Management*, **360**, 400-407.
Parkinson, S. et al., 2019: Balancing clean water-climate change mitigation trade-offs. *Environmental Research Letters*, **14** (1), 014009, doi:10.1088/1748-9326/aaf2a3.
Parsons, L. A., 2020: Implications of CMIP6 Projected Drying Trends for 21st Century Amazonian Drought Risk. *Earth's Future*, **8** (10), e2020EF001608, doi:https://doi.org/10.1029/2020EF001608.
Parsons, M., J. Nalau and K. Fisher, 2017: *Alternative Perspectives on Sustainability: Indigenous Knowledge and Methodologies*. 2017.
Pastor, A. V. et al., 2014: Accounting for environmental flow requirements in global water assessments. *Hydrol. Earth Syst. Sci.*, **18** (12), 5041-5059, doi:10.5194/hess-18-5041-2014.
Patel, A. and J. Giri, 2019: Climate Change, Migration and Women: Analysing Construction Workers in Odisha. *Social Change*, **49** (1), 97-113, doi:10.1177/0049085718821756.
Patel, S. K., A. Sharma and G. S. Singh, 2020: Traditional agricultural practices in India: an approach for environmental sustainability and food security. *Energy, Ecology and Environment*, **5** (4), 253-271, doi:10.1007/s40974-020-00158-2.
Paterson, D. L., H. Wright and P. N. Harris, 2018: Health risks of flood disasters. *Clinical Infectious Diseases*, **67** (9), 1450-1454.
Patrick, R. J., K. Grant and L. Bharadwaj, 2019: Reclaiming Indigenous Planning as a Pathway to Local Water Security. *Water*, **11** (5), doi:10.3390/w11050936.
Patricola, C. M. and M. F. Wehner, 2018: Anthropogenic influences on major tropical cyclone events. *Nature*, **563** (7731), 339-346, doi:10.1038/s41586-018-0673-2.
Pauleit, S. et al., 2017: Nature-Based Solutions and Climate Change – Four Shades of Green. In: Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice [Kabisch, N., H. Korn, J. Stadler and A. Bonn (eds.)]. Springer International Publishing, Cham, 29-49.
Pauw, W. P. et al., 2018: Beyond headline mitigation numbers: we need more transparent and comparable NDCs to achieve the Paris Agreement on climate change. *Climatic Change*, **147** (1), 23-29, doi:10.1007/s10584-017-2122-x.
Paymard, P., M. Bannayan and R. S. Haghighi, 2018: Analysis of the climate change effect on wheat production systems and investigate the potential of management strategies. *Natural Hazards*, **91** (3), 1237-1255, doi:10.1007/s11069-018-3180-8.
Pearce, T., R. Currenti, A. Mateiwai and B. Doran, 2018: Adaptation to climate change and freshwater resources in Vusama village, Viti Levu, Fiji. *Regional Environmental Change*, **18** (2), 501-510, doi:10.1007/s10113-017-1222-5.
Pearson, A. L., J. D. Mayer and D. J. Bradley, 2015: Coping with Household Water Scarcity in the Savannah Today: Implications for Health and Climate Change into the Future. *Earth Interactions*, **19** (8), 1-14, doi:10.1175/EI-D-14-0039.1.
Pechlivanidis, I. G. et al., 2017: Analysis of hydrological extremes at different hydro-climatic regimes under present and future conditions. *Climatic Change*, **141** (3), 467-481, doi:10.1007/s10584-016-1723-0.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355** (6332), eaai9214, doi:10.1126/science.aai9214.
Peel, J. and H. M. Osofsky, 2020: Climate Change Litigation. *Annual Review of Law and Social Science*, **16** (1), 21-38, doi:10.1146/annurev-lawsocsci-022420-122936.
Pei, S. et al., 2020: Compound Risks of Hurricane Evacuation Amid the COVID-19 Pandemic in the United States. *GeoHealth*, **4** (12), e2020GH000319, doi:https://doi.org/10.1029/2020GH000319.
Pelling, M., K. O'Brien and D. Matyas, 2015: Adaptation and transformation. *Climatic Change*, **133** (1), 113-127, doi:10.1007/s10584-014-1303-0.
Penot, E., V. Fevre, P. Flodrops and H. M. Razafimahatratra, 2018: Conservation Agriculture to buffer and alleviate the impact of climatic variations in Madagascar: Farmers' perception. *Cahiers Agricultures*, **27** (2), doi:10.1051/cagri/2018009.
Perkins-Kirkpatrick, S. E. and S. C. Lewis, 2020: Increasing trends in regional heatwaves. *Nature Communications*, **11** (1), 3357, doi:10.1038/s41467-020-16970-7.
Petersen-Perlman, J. D., J. C. Veilleux and A. T. Wolf, 2017: International water conflict and cooperation: challenges and opportunities. *Water International*, **42** (2), 105-120, doi:10.1080/02508060.2017.1276041.
Petit, O. et al., 2017: Can agricultural groundwater economies collapse? An inquiry into the pathways of four groundwater economies under threat. *Hydrogeology Journal*, **25** (6), 1549-1564, doi:10.1007/s10040-017-1567-3.
Petroleum, B., 2020: *Statistical Review of World Energy*. British Petroleum (BP): London, UK.
Petzold, J., 2018: Social adaptability in ecotones: sea-level rise and climate change adaptation in Flushing and the Isles of Scilly, UK. *Island Studies Journal*, **13**, 101+.

Phalkey, R. K. et al., 2015: Systematic review of current efforts to quantify the impacts of climate change on undernutrition. *Proceedings of the National Academy of Sciences*, **112** (33), E4522-E4529.
Phan, L., S.-C. Jou and J.-H. Lin, 2019: Gender Inequality and Adaptive Capacity: The Role of Social Capital on the Impacts of Climate Change in Vietnam. *Sustainability*, **11**, 1257, doi:10.3390/su11051257.
Philipsborn, R., S. M. Ahmed, B. J. Brosi and K. Levy, 2016: Climatic Drivers of Diarrheagenic Escherichia coli Incidence: A Systematic Review and Meta-analysis. *The Journal of Infectious Diseases*, **214** (1), 6-15, doi:10.1093/infdis/jiw081.
Phillips, C. A. et al., 2020: Compound climate risks in the COVID-19 pandemic. *Nature Climate Change*, **10** (7), 586-588, doi:10.1038/s41558-020-0804-2.
Phiri, D., M. Simwanda and V. Nyirenda, 2020: Mapping the impacts of cyclone Idai in Mozambique using Sentinel-2 and OBIA approach. *South African Geographical Journal*, 1-22, doi:10.1080/03736245.2020.1740104.
Phuong, L. T. H. et al., 2018: Using a social learning configuration to increase Vietnamese smallholder farmers' adaptive capacity to respond to climate change. *Local Environment*, **23** (8), 879-897, doi:10.1080/13549839.2018.1482859.
Piggott-McKellar, A. E., K. E. McNamara, P. D. Nunn and S. T. Sekinini, 2019a: Moving People in a Changing Climate: Lessons from Two Case Studies in Fiji. *Social Sciences*, **8** (5), doi:10.3390/socsci8050133.
Piggott-McKellar, A. E., K. E. McNamara, P. D. Nunn and J. E. M. Watson, 2019b: What are the barriers to successful community-based climate change adaptation? A review of grey literature. *Local Environment*, **24** (4), 374-390, doi:10.1080/13549839.2019.1580688.
Pinto, P. J., G. M. Kondolf and P. L. R. Wong, 2018: Adapting to sea level rise: Emerging governance issues in the San Francisco Bay Region. *Environmental Science and Policy*, **90** (August), 28-37, doi:10.1016/j.envsci.2018.09.015.
Pistocchi, A. et al., 2020: Can seawater desalination be a win-win fix to our water cycle? *Water Research*, **182**, 115906, doi:https://doi.org/10.1016/j.watres.2020.115906.
Poddar, S., M. Mondal and S. Ghosh, 2020: *A Survey on Disaster: Understanding the After-effects of Super-cyclone Amphan and Helping Hand of Social Media*. [Available at: http://arxiv.org/abs/2007.14910].
Poesch, M. S. et al., 2016: Climate Change Impacts on Freshwater Fishes: A Canadian Perspective. *Fisheries*, **41** (7), 385-391, doi:10.1080/03632415.2016.1180285.
Pokhrel, Y. et al., 2021: Global terrestrial water storage and drought severity under climate change. *Nature Climate Change*, **11** (3), 226-233, doi:10.1038/s41558-020-00972-w.
Polyakov, V. O., M. N. Nichols and M. A. Nearing, 2017: Determining soil erosion rates on semi-arid watersheds using radioisotope-derived sedimentation chronology. *Earth Surface Processes and Landforms*, **42** (6), 987-993, doi:doi:10.1002/esp.4057.
Pommells, M., C. Schuster-Wallace, S. Watt and Z. Mulawa, 2018: Gender Violence as a Water, Sanitation, and Hygiene Risk: Uncovering Violence Against Women and Girls as It Pertains to Poor WaSH Access. *Violence Against Women*, **24** (15), 1851-1862, doi:10.1177/1077801218754410.
Popular, G. and T. Rik, 2016: Transhumant Pastoralism in the Context of Socioeconomic and Climate Change in the Mountains of Nepal. *Mountain Research and Development*, **36** (2), 173-182, doi:10.1659/MRD-JOURNAL-D-15-00011.1.
Porter, J. R. et al., 2014: Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability.
Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the
Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 485-533.
Post, V. E. A. et al., 2018: On the resilience of small-island freshwater lenses: Evidence of the long-term impacts of groundwater abstraction on Bonriki Island, Kiribati. *Journal of Hydrology*, **564**, 133-148, doi:https://doi.org/10.1016/j.jhydrol.2018.06.015.
Postigo, J. C., 2020: The role of social institutions in indigenous Andean Pastoralists' adaptation to climate-related water hazards. *Climate and Development*, 1-12, doi:10.1080/17565529.2020.1850409.
Potemkina, T. G. and V. L. Potemkin, 2015: Sediment load of the main rivers of Lake Baikal in a changing environment (east Siberia, Russia). *Quaternary International*, **380-381**, 342-349, doi:https://doi.org/10.1016/j.quaint.2014.08.029.
Poudel, D. D. and T. W. Duex, 2017: Vanishing Springs in Nepalese Mountains: Assessment of Water Sources, Farmers' Perceptions, and Climate Change Adaptation. *Mountain Research and Development*, **37** (1), 35-46, doi:10.1659/MRD-JOURNAL-D-16-00039.1.
Pouramin, P., N. Nagabhatla and M. Miletto, 2020: A Systematic Review of Water and Gender Interlinkages: Assessing the Intersection With Health. *Frontiers in Water*, **2** (6), doi:10.3389/frwa.2020.00006.
Pouyfaucon, A. B. and L. García-Rodríguez, 2018: Solar thermal-powered desalination: A viable solution for a potential market. *Desalination*, **435**, 60-69, doi:https://doi.org/10.1016/j.desal.2017.12.025.
Poveda, G. et al., 2020: High Impact Weather Events in the Andes. *Frontiers in Earth Science*, **8**, 162.
Pradhan, P., 2019: Antagonists to meeting the 2030 Agenda. Springer US, **2**, 171-172, doi:10.1038/s41893-019-0248-8.

Pralle, S., 2019: Drawing lines: FEMA and the politics of mapping flood zones. *Climatic Change*, **152** (2), 227-237, doi:10.1007/s10584-018-2287-y.
Pramanik, M. et al., 2021: Population health risks in multi-hazard environments: action needed in the Cyclone Amphan and COVID-19 – hit Sundarbans region, India. *Climate and Development*, 1-6, doi:10.1080/17565529.2021.1889948.
Preston, B. J., 2016: The Role of the Courts in facilitating Climate Change Adaptation.
Price, J. I., P. R. Lloyd-Smith, D. P. Dupont and W. L. Adamowicz, 2019: Floods and Water Service Disruptions: Eliciting Willingness-to-Pay for Public Utility Pricing and Infrastructure Decisions. *Water Economics and Policy*, **5** (02), 1850021.
Pritchard, B. and R. Thielemans, 2014: 'Rising Waters Don't Lift All Boats': a sustainable livelihood analysis of recursive cycles of vulnerability and maladaptation to flood risk in rural Bihar, India. *Australian Geographer*, **45** (3), 325-339, doi:10.1080/00049182.2014.930001.
Pritchard, H. D., 2019: Asia's shrinking glaciers protect large populations from drought stress. *Nature*, **569** (7758), 649-654.
Prudencio, L. and S. E. Null, 2018: Stormwater Management and Ecosystem Services: A Review. doi:10.1016/j.snb.2007.07.003.
Prudhomme, C. et al., 2014: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences*, **111** (9), 3262-3267, doi:10.1073/pnas.1222473110.
Prüss-Ustün, A. et al., 2019: Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: An updated analysis with a focus on low- and middle-income countries. *International journal of hygiene and environmental health*, **222** (5), 765-777, doi:https://doi.org/10.1016/j.ijheh.2019.05.004.
PUB, 2016: Industrial Water Solutions. In: Innovation in water conservation Singapore: An R&D publication of PUB, Singapore's National Water Agency **8**, 6–8.
Pulido-Bosch, A. et al., 2018: Impacts of agricultural irrigation on groundwater salinity. *Environmental Earth Sciences*, **77** (5), 197, doi:10.1007/s12665-018-7386-6.
Pulido-Velazquez, D., A.-J. Collados-Lara and F. J. Alcalá, 2018: Assessing impacts of future potential climate change scenarios on aquifer recharge in continental Spain. *Journal of Hydrology*, **567**, 803-819, doi:https://doi.org/10.1016/j.jhydrol.2017.10.077.
Pulliainen, J. et al., 2020: Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. *Nature*, **581** (7808), 294-298, doi:10.1038/s41586-020-2258-0.
Putra, M. P. I. F., P. Pradhan and J. P. Kropp, 2020: A systematic analysis of Water-Energy-Food security nexus: A South Asian case study. *Science of The Total Environment*, **728**, 138451, doi:https://doi.org/10.1016/j.scitotenv.2020.138451.
Pyne, M. I. and N. L. Poff, 2017: Vulnerability of stream community composition and function to projected thermal warming and hydrologic change across ecoregions in the western United States. *Global Change Biology*, **23** (1), 77-93, doi:10.1111/gcb.13437.
Qadir, M. et al., 2020: Global and regional potential of wastewater as a water, nutrient and energy source. **44**, 40-51, doi:10.1111/1477-8947.12187.
Qadir, M. et al., 2014: Economics of salt-induced land degradation and restoration. *Natural Resources Forum*, **38** (4), 282-295, doi:10.1111/1477-8947.12054.
Qian, Y. et al., 2020: Neglecting irrigation contributes to the simulated summertime warm-and-dry bias in the central United States. *npj Climate and Atmospheric Science*, **3** (1), 31, doi:10.1038/s41612-020-00135-w.
Qin, X. et al., 2018: Simulated adaptation strategies for spring wheat to climate change in a northern high latitude environment by DAYCENT model. **v. 95**.
Qin, Y. et al., 2020: Agricultural risks from changing snowmelt. *Nature Climate Change*, **10** (5), 459-465.
Qin, Y. et al., 2019: Flexibility and intensity of global water use. *Nature Sustainability*, **2** (6), 515-523, doi:10.1038/s41893-019-0294-2.
Qiu, J. et al., 2019: Impacts of climate change on watershed systems and potential adaptation through BMPs in a drinking water source area. *Journal of Hydrology*, **573**, 123-135, doi:https://doi.org/10.1016/j.jhydrol.2019.03.074.
Quan, S. et al., 2019: Adaptation to Climate Change and its Impacts on Wheat Yield: Perspective of Farmers in Henan of China. *Sustainability*, **11** (7), doi:10.3390/su11071928.
Quandt, A., H. Neufeldt and J. T. McCabe, 2019: Building livelihood resilience: what role does agroforestry play? *Climate and Development*, **11** (6), 485-500, doi:10.1080/17565529.2018.1447903.
Radić, V. et al., 2014: Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dynamics*, **42** (1), 37-58, doi:10.1007/s00382-013-1719-7.
Raghavendra, K. J. and A. Suresh, 2018: Risk management in rainfed agriculture: An analysis of strategies and adaptations followed by farmers in Madhya Pradesh. *Indian Journal of Agricultural Sciences*, **88** (6), 895-901.
Rahman, H. M. T. and G. M. Hickey, 2019: What Does Autonomous Adaptation to Climate Change Have to Teach Public Policy and Planning About Avoiding the Risks of Maladaptation in Bangladesh? *Frontiers in Environmental Science*, **7** (2), doi:10.3389/fenvs.2019.00002.

Rahman, M. H. and K. Alam, 2016: Forest Dependent Indigenous Communities' Perception and Adaptation to Climate Change through Local Knowledge in the Protected Area—A Bangladesh Case Study. *Climate*, **4** (1), 12.
Rahman, M. S. and J. Tosun, 2018: State Bureaucracy and the Management of Climate Change Adaptation in Bangladesh. *Review of Policy Research*, **35** (6), 835-858, doi:10.1111/ropr.12289.
Rahut, D. B. and A. Ali, 2017: Coping with climate change and its impact on productivity, income, and poverty: Evidence from the Himalayan region of Pakistan. *International Journal of Disaster Risk Reduction*, **24**, 515-525, doi:https://doi.org/10.1016/j.ijdrr.2017.05.006.
Rahut, D. B. and A. Ali, 2018: Impact of climate-change risk-coping strategies on livestock productivity and household welfare: empirical evidence from Pakistan. *Heliyon*, **4** (10), e00797, doi:https://doi.org/10.1016/j.heliyon.2018.e00797.
Rai, R. K. et al., 2019: Economics of climate adaptive water management practices in Nepal. *Heliyon*, **5** (5), e01668-e01668, doi:10.1016/j.heliyon.2019.e01668.
Rainato, R. et al., 2017: Three decades of monitoring in the Rio Cordon instrumented basin: Sediment budget and temporal trend of sediment yield. *Geomorphology*, **291**, 45, doi:10.1016/j.geomorph.2016.03.012.
Rajan, A., K. Ghosh and A. Shah, 2020: Carbon footprint of India's groundwater irrigation. *Carbon Management*, **11** (3), 265-280, doi:10.1080/17583004.2020.1750265.
Ramsar Convention, 2018: *Global Wetland Outlook: State of the world's wetlands and their services to people 2018*. Ramsar Convention Secretariat, Gland, Switzerland [Available at: https://www.ramsar.org/sites/default/files/flipbooks/ramsar_gwo_english_web.pdf].
Räsänen, T. A., O. Varis, L. Scherer and M. Kummu, 2018: Greenhouse gas emissions of hydropower in the Mekong River Basin. *Environmental Research Letters*, **13** (3), 034030, doi:10.1088/1748-9326/aaa817.
Rasmus, S. et al., 2020: Climate change and reindeer management in Finland: Co-analysis of practitioner knowledge and meteorological data for better adaptation. *Science of The Total Environment*, **710**, 136229, doi:https://doi.org/10.1016/j.scitotenv.2019.136229.
Rasul, G. and B. Sharma, 2016: The nexus approach to water–energy–food security: an option for adaptation to climate change. *Climate Policy*, **16** (6), 682-702, doi:10.1080/14693062.2015.1029865.
Rawlins, M., D. Yang and S. Ge, 2021: Regional and Basin Streamflow Regimes and Changes: Climate Impact and Human Effect. In: Arctic Hydrology, Permafrost and Ecosystems [Yang, D. and D. L. Kane (eds.)]. Springer International Publishing, Cham, 159-186.
Ray, D. K., J. S. Gerber, G. K. MacDonald and P. C. West, 2015: Climate variation explains a third of global crop yield variability. *Nature Communications*, **6** (1), 1-9.
Ray, D. K. et al., 2019: Climate change has likely already affected global food production. *PLOS ONE*, **14** (5), e0217148.
Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environment and Urbanization*, **29** (1), 159-182, doi:10.1177/0956247816677778.
Reckien, D. et al., 2018: How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *Journal of Cleaner Production*, **191**, 207-219, doi:https://doi.org/10.1016/j.jclepro.2018.03.220.
Reid, H., 2016: Ecosystem- and community-based adaptation: learning from community-based natural resource management. *Climate and Development*, **8** (1), 4-9, doi:10.1080/17565529.2015.1034233.
Reid, H. et al., 2019: *Is ecosystem-based adaptation effective? Perceptions and lessons learned from 13 project sites.* IIED Research Report, IIED, London.
Reinecke, R. et al., 2021: Uncertainty of simulated groundwater recharge at different global warming levels: a global-scale multi-model ensemble study. *Hydrol. Earth Syst. Sci.*, **25** (2), 787-810, doi:10.5194/hess-25-787-2021.
Remmington, G., 2018: Transforming tradition: The aflaj and changing role of traditional knowledge systems for collective water management. *Journal of Arid Environments*, **151**, 134-140, doi:https://doi.org/10.1016/j.jaridenv.2017.10.003.
Ren, X., Y. Lu, B. C. O'Neill and M. Weitzel, 2018a: Economic and biophysical impacts on agriculture under 1.5 °C and 2 °C warming. *Environmental Research Letters*, **13** (11), 115006, doi:10.1088/1748-9326/aae6a9.
Ren, X. et al., 2018b: Avoided economic impacts of climate change on agriculture: integrating a land surface model (CLM) with a global economic model (iPETS). *Climatic Change*, **146** (3), 517-531, doi:10.1007/s10584-016-1791-1.
Restrepo, J. D. and H. A. Escobar, 2018: Sediment load trends in the Magdalena River basin (1980–2010): Anthropogenic and climate-induced causes. *Geomorphology*, **302**, 76-91, doi:https://doi.org/10.1016/j.geomorph.2016.12.013.
Rets, E. P. et al., 2020: Past 'peak water' in the North Caucasus: deglaciation drives a reduction in glacial runoff impacting summer river runoff and peak discharges. *Climatic Change*, **163** (4), 2135-2151, doi:10.1007/s10584-020-02931-y.
Rets, E. P. et al., 2018: Recent Trends Of River Runoff In The North Caucasus. *Geography, Environment, Sustainability*, **11** (3), 61-70.
Revi, A. et al., 2014: Urban Areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir and

L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 535-612.
Rey, D., I. P. Holman and J. W. Knox, 2017: Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. *Regional Environmental Change*, **17** (5), 1527-1540, doi:10.1007/s10113-017-1116-6.
Ricciardi, V. et al., 2020: A scoping review of research funding for small-scale farmers in water scarce regions. *Nature Sustainability*, **3** (10), 836-844, doi:10.1038/s41893-020-00623-0.
Rice, J. and P. Westerhoff, 2017: High levels of endocrine pollutants in US streams during low flow due to insufficient wastewater dilution. *Nature Geoscience*, **10**, 587, doi:10.1038/ngeo2984 https://www.nature.com/articles/ngeo2984#supplementary-information.
Rice, J. L., J. Long and A. Levenda, 2021: Against climate apartheid: Confronting the persistent legacies of expendability for climate justice. *Environment and Planning E: Nature and Space*, 2514848621999286, doi:10.1177/2514848621999286.
Richardson, J. et al., 2019: Response of cyanobacteria and phytoplankton abundance to warming, extreme rainfall events and nutrient enrichment. *Global Change Biology*, **25** (10), 3365-3380, doi:https://doi.org/10.1111/gcb.14701.
Richmond, M., N. Upadhyaya and A. O. Pastor, 2021: *An Analysis of Urban Climate Adaptation Finance. A Report from the Cities Climate Finance Leadership Alliance*. [Available at: https://www.climatepolicyinitiative.org/publication/an-analysis-of-urban-climate-adaptation-finance/].
Richts, A. and J. Vrba, 2016: Groundwater resources and hydroclimatic extremes: mapping global groundwater vulnerability to floods and droughts. *Environmental Earth Sciences*, **75** (10), 926, doi:10.1007/s12665-016-5632-3.
Rigaud, K. et al., 2018: *Groundswell : Preparing for Internal Climate Migration*.
Rimi, R. H., K. Haustein, M. R. Allen and E. J. Barbour, 2019: Risks of pre-monsoon extreme rainfall events of Bangladesh: is anthropogenic climate change playing a role? *Bulletin of the American Meteorological Society*, **100** (1), S61-S65.
Risser, M. D. and M. F. Wehner, 2017: Attributable Human-Induced Changes in the Likelihood and Magnitude of the Observed Extreme Precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44** (24), 12,457-12,464, doi:10.1002/2017GL075888.
Risvoll, C. and G. K. Hovelsrud, 2016: Pasture access and adaptive capacity in reindeer herding districts in Nordland, Northern Norway. *The Polar Journal*, **6** (1), 87-111, doi:10.1080/2154896X.2016.1173796.
Ritchie, H. and M. Roser. "Clean Water". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/water-access' [Online Resource]. [Available at]
Robb, A. et al., 2019: Development Control And Vulnerable Coastal Lands: Examples Of Australian Practice. *Urban Policy and Research*, **37** (2), 199-214, doi:10.1080/08111146.2018.1489791.
Roberts, K. E. et al., 2017: Climate and permafrost effects on the chemistry and ecosystems of High Arctic Lakes. *Scientific Reports*, **7** (1), 13292, doi:10.1038/s41598-017-13658-9.
Robison, J. et al., 2018: Indigenous Water Justice. *Lewis &Clark Law Review*, **22** (3), 841-922.
Rockström, J. et al., 2014: *Water Resilience for Human Prosperity*. Cambridge University Press, Cambridge.
Rodell, M. et al., 2018: Emerging trends in global freshwater availability. *Nature*, **557** (7707), 651-659, doi:10.1038/s41586-018-0123-1.
Roderick, M. L., P. Greve and G. D. Farquhar, 2015: On the assessment of aridity with changes in atmospheric CO2. *Water Resources Research*, **51** (7), 5450-5463, doi:10.1002/2015wr017031.
Rodríguez-Blanco, M. L. et al., 2016: Potential Impact of Climate Change on Suspended Sediment Yield in NW Spain: A Case Study on the Corbeira Catchment. *Water*, **8** (10), doi:10.3390/w8100444.
Rodriguez-Lonebear, D., N. E. Barceló, R. Akee and S. R. Carroll, 2020: American Indian Reservations and COVID-19: Correlates of Early Infection Rates in the Pandemic. *Journal of Public Health Management and Practice*, **26** (4).
Rodríguez-Morata, C. et al., 2019: The anomalous 2017 coastal El Niño event in Peru. *Climate Dynamics*, **52** (9), 5605-5622, doi:10.1007/s00382-018-4466-y.
Rodríguez-Sinobas, L., S. Zubelzu, S. Perales-Momparler and S. Canogar, 2018: Techniques and criteria for sustainable urban stormwater management. The case study of Valdebebas (Madrid, Spain). *Journal of Cleaner Production*, **172**, 402-416, doi:https://doi.org/10.1016/j.jclepro.2017.10.070.
Rodriguez-Solorzano, C., 2014: Unintended outcomes of farmers' adaptation to climate variability: deforestation and conservation in Calakmul and Maya biosphere reserves. *Ecology and Society*, **19** (2).
Rohde, M. M., R. Froend and J. Howard, 2017: A Global Synthesis of Managing Groundwater Dependent Ecosystems Under Sustainable Groundwater Policy. *Groundwater*, **55** (3), 293-301, doi:10.1111/gwat.12511.
Rokaya, P., S. Budhathoki and K.-E. Lindenschmidt, 2018: Trends in the timing and magnitude of ice-jam floods in Canada. *Scientific Reports*, **8** (1), 1-9.
Rokaya, P. et al., 2019: Climatic effects on ice phenology and ice-jam flooding of the Athabasca River in western Canada. *Hydrological Sciences Journal*, **64** (11), 1265-1278.
Rolla, A. L., M. N. Nuñez, J. J. Ramayón and M. E. Ramayón, 2019: Impacts of climate change on bovine livestock production in Argentina. *Climatic Change*, **153** (3), 439-455.

Romankiewicz, C., M. Doevenspeck, M. Brandt and C. Samimi, 2016: Adaptation as by-product: migration and environmental change in Nguith, Senegal. *DIE ERDE–Journal of the Geographical Society of Berlin*, **147** (2), 95-108.
Romanovsky, V. et al., 2017: Terrestrial Permafrost. *Bulletin of the American Meteorological Society*, **98**, S265-S269, doi:10.1175/2017BAMSStateoftheClimate.1.
Roncoli, C. et al., 2019: Enough is enough: how West African farmers judge water sufficiency. *Regional Environmental Change*, **19** (2), 573-585, doi:10.1007/s10113-018-1426-3.
Rosa, L. et al., 2020a: Global agricultural economic water scarcity. *Science Advances*, **6** (18), eaaz6031, doi:10.1126/sciadv.aaz6031.
Rosa, L. et al., 2020b: Potential for sustainable irrigation expansion in a 3 °C warmer climate. *Proceedings of the National Academy of Sciences*, **117** (47), 29526, doi:10.1073/pnas.2017796117.
Rosa, L., J. A. Reimer, M. S. Went and P. D'Odorico, 2020c: Hydrological limits to carbon capture and storage. *Nature Sustainability*, **3** (8), 658-666, doi:10.1038/s41893-020-0532-7.
Rosenberger, L., J. Leandro, S. Pauleit and S. Erlwein, 2021: Sustainable stormwater management under the impact of climate change and urban densification. *Journal of Hydrology*, **596**, 126137, doi:https://doi.org/10.1016/j.jhydrol.2021.126137.
Rosenzweig, B. et al., 2019: Developing knowledge systems for urban resilience to cloudburst rain events. *Environmental Science & Policy*, **99**, 150-159, doi:https://doi.org/10.1016/j.envsci.2019.05.020.
Röser, F., O. Widerberg, N. Höhne and T. Day, 2020: Ambition in the making: analysing the preparation and implementation process of the Nationally Determined Contributions under the Paris Agreement. *Climate Policy*, **20** (4), 415-429, doi:10.1080/14693062.2019.1708697.
Rosinger, A. Y. and S. L. Young, 2020: The toll of household water insecurity on health and human biology: Current understandings and future directions. *WIREs Water*, **7** (6), e1468, doi:https://doi.org/10.1002/wat2.1468.
Rouabhi, A., M. Hafsi and P. Monneveux, 2019: Climate change and farming systems in the region of Setif (Algeria). *Journal of Agriculture and Environment for International Development (JAEID)*, **113** (1).
Rounce, D. R., R. Hock and D. E. Shean, 2020: Glacier Mass Change in High Mountain Asia Through 2100 Using the Open-Source Python Glacier Evolution Model (PyGEM). *Frontiers in Earth Science*, **7** (331), doi:10.3389/feart.2019.00331.
Roxy, M. K. et al., 2017: A threefold rise in widespread extreme rain events over central India. *Nature Communications*, **8** (1), 708, doi:10.1038/s41467-017-00744-9.
Roy, J. et al., 2018: Sustainable development, poverty eradication and reducing inequalities.
Roy, R., 2018: Evaluating the Suitability of Community-Based Adaptation: A Case Study of Bangladesh. In: Handbook of Climate Change Communication: Vol. 1. Springer, 39-59.
Roy, S., 2019: Sundarbans Forest and the Gendered Context of Cyclones: Sidr and Aila. In: Climate Change Impacts on Gender Relations in Bangladesh (SpringerBr) Springer, Singapore.
Rozenberg, J. and M. Fay, 2019: *Beyond the Gap: How Countries Can Afford the Infrastructure They Need while Protecting the Planet*. Sustainable Infrastructure, World Bank, Washington, DC [Available at: https://openknowledge.worldbank.org/handle/10986/31291].
Ruane, A. C., M. M. Phillips and C. Rosenzweig, 2018: Climate shifts within major agricultural seasons for +1.5 and +2.0 °C worlds: HAPPI projections and AgMIP modeling scenarios. *Agricultural and Forest Meteorology*, **259**, 329-344, doi:https://doi.org/10.1016/j.agrformet.2018.05.013.
Rubio-Aliaga, Á. et al., 2016: GIS based solar resource analysis for irrigation purposes: Rural areas comparison under groundwater scarcity conditions. *Solar Energy Materials and Solar Cells*, **156**, 128-139, doi:https://doi.org/10.1016/j.solmat.2016.06.045.
Rufat, S., E. Tate, C. G. Burton and A. S. Maroof, 2015: Social vulnerability to floods: Review of case studies and implications for measurement. *International Journal of Disaster Risk Reduction*, **14**, 470-486.
Ryan, C. and P. Elsner, 2016: The potential for sand dams to increase the adaptive capacity of East African drylands to climate change. *Regional Environmental Change*, **16** (7), 2087-2096.
Sabo, J. L., J. C. Finlay, T. Kennedy and D. M. Post, 2010: The Role of Discharge Variation in Scaling of Drainage Area and Food Chain Length in Rivers. *Science*, **330** (6006), 965-967, doi:10.1126/science.1196005
Sadoff, C. W., E. Borgomeo and S. Uhlenbrook, 2020: Rethinking water for SDG 6. *Nature Sustainability*, **3** (5), 346-347, doi:10.1038/s41893-020-0530-9.
Sahade, R. et al., 2015: Climate change and glacier retreat drive shifts in an Antarctic benthic ecosystem. *Science Advances*, **1** (10), e1500050, doi:10.1126/sciadv.1500050.
Sain, G. et al., 2017: Costs and benefits of climate-smart agriculture: The case of the Dry Corridor in Guatemala. *Agricultural Systems*, **151**, 163-173.
Salat, M. and B. Swallow, 2018: Resource Use Efficiency as a Climate Smart Approach: Case of Smallholder Maize Farmers in Nyando, Kenya. *Environments*, **5** (8), 93.
Salehyan, I. and C. S. Hendrix, 2014: Climate shocks and political violence. *Global Environmental Change*, **28**, 239-250, doi:https://doi.org/10.1016/j.gloenvcha.2014.07.007.
Salem, G. S. A., S. Kazama, S. Shahid and N. C. Dey, 2018: Groundwater-dependent irrigation costs and benefits for adaptation to global change. *Mitigation and Adaptation Strategies for Global Change*, **23** (6), 953-979, doi:10.1007/s11027-017-9767-7.

Salgot, M. and M. Folch, 2018: Wastewater treatment and water reuse. *Current Opinion in Environmental Science & Health*, **2**, 64-74, doi:https://doi.org/10.1016/j.coesh.2018.03.005.
Samuel, O. O. and T. S. Sylvia, 2019: Establishing the nexus between climate change adaptation strategy and smallholder farmers' food security status in South Africa: A bi-casual effect using instrumental variable approach. *Cogent Social Sciences*, **5** (1), 1656402, doi:10.1080/23311886.2019.1656402.
Sánchez, A. and M. Izzo, 2017: Micro hydropower: an alternative for climate change mitigation, adaptation, and development of marginalized local communities in Hispaniola Island. *Climatic Change*, **140** (1), 79-87, doi:10.1007/s10584-016-1865-0.
Sanderson, D. et al., 2015: Climate change and water at Stellat'en First Nation, British Columbia, Canada: Insights from western science and traditional knowledge. *The Canadian Geographer / Le Géographe canadien*, **59** (2), 136-150, doi:10.1111/cag.12142.
Sankey, J. B. et al., 2017: Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, **44** (17), 8884-8892, doi:10.1002/2017GL073979.
Santos, A. et al., 2018: Artificial lakes as a climate change adaptation strategy in drylands: evaluating the trade-off on non-target ecosystem services. *Mitigation and Adaptation Strategies for Global Change*, **23** (6), 887-906.
Sari, A. D. and N. Prayoga, 2018: Enhancing citizen engagement in the face of climate change risks: A case study of the flood early warning system and health information system in Semarang City, Indonesia. In: Climate Change in Cities. Springer, 121-137.
Sarkar, M. N. I. and H. R. Ghosh, 2017: Techno-economic analysis and challenges of solar powered pumps dissemination in Bangladesh. *Sustainable Energy Technologies and Assessments*, **20**, 33-46, doi:https://doi.org/10.1016/j.seta.2017.02.013.
Sarkar, S. et al., 2015: Assessing the potential of indigenous technological knowledge (ITK) for adaptation to climate change in the Himalayan and arid ecosystems. *Indian Journal of Traditional Knowledge*, **14** (2), 251-257.
Saroar, M. M., 2018: Ecosystem-Based Adaptation (EbA) for Coastal Resilience Against Water Related Disasters in Bangladesh. *Climate Change Management*, 187-205, doi:10.1007/978-3-319-70703-7_10.
Sartori, M. et al., 2019: A linkage between the biophysical and the economic: Assessing the global market impacts of soil erosion. *Land Use Policy*, **86**, 299-312, doi:https://doi.org/10.1016/j.landusepol.2019.05.014.
Satoh, Y. et al., 2021: A quantitative evaluation of the issue of drought definition: A source of disagreement in future drought assessments. *Environmental Research Letters*.
Satterthwaite, D. et al., 2020: Building Resilience to Climate Change in Informal Settlements. *One Earth*, **2** (2), 143-156, doi:10.1016/j.oneear.2020.02.002.
Saurí, D. and A. Arahuetes, 2019: Water reuse: A review of recent international contributions and an agenda for future research. *Documents d'Analisi Geografica*, **65** (2), 399–417, doi:https://doi.org/10.5565/rev/dag.534.
Savage, A., L. McIver and L. Schubert, 2020: Review: the nexus of climate change, food and nutrition security and diet-related non-communicable diseases in Pacific Island Countries and Territories. *Climate and Development*, **12** (2), 120-133, doi:10.1080/17565529.2019.1605284.
Savo, V. et al., 2016: Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change*, **6**, 462, doi:10.1038/nclimate2958
https://www.nature.com/articles/nclimate2958#supplementary-information.
Sayre, M., T. Stenner and A. Argumedo, 2017: You can't grow potatoes in the sky: building resilience in the face of climate change in the Potato Park of Cuzco, Peru. *Culture, Agriculture, Food and Environment*, **39** (2), 100-108.
Schaefli, B. et al., 2019: The role of glacier retreat for Swiss hydropower production. *Renewable Energy*, **132**, 615-627.
Schaer, C., 2015: Condemned to live with one's feet in water? A case study of community based strategies and urban maladaptation in flood prone Pikine/Dakar, Senegal. *International Journal of Climate Change Strategies and Management*, **7** (4), 534-551, doi:10.1108/IJCCSM-03-2014-0038.
Scheffers, B. R. et al., 2016: The broad footprint of climate change from genes to biomes to people. *Science*, **354** (6313), aaf7671, doi:10.1126/science.aaf7671.
Schellenberg, G., C. R. Donnelly, C. Holder and R. Ahsan, 2017: Dealing with sediment: Effects on dams and hydropower generation. *Hydro Review*, **2** (1).
Schembergue, A. et al., 2017: Sistemas agroflorestais como estratégia de adaptação aos desafios das mudanças climáticas no Brasil. *Revista de Economia e Sociologia Rural*, **55** (1), 9-30.
Schewe, J. et al., 2019: State-of-the-art global models underestimate impacts from climate extremes. *Nature Communications*, **10** (1), 1005, doi:10.1038/s41467-019-08745-6.
Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, **111** (9), 3245-3250, doi:10.1073/pnas.1222460110.
Schiefer, E. et al., 2018: Fluvial suspended sediment yields over hours to millennia in the High Arctic at proglacial Lake Linnévatnet, Svalbard. *Earth Surface Processes and Landforms*, **43** (2), 482-498, doi:doi:10.1002/esp.4264.
Schipper, E. L. F., 2020: Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, **3** (4), 409-414, doi:10.1016/j.oneear.2020.09.014.
Schleussner, C.-F. et al., 2018: Crop productivity changes in 1.5 °C and 2 °C worlds under climate sensitivity uncertainty. *Environmental Research Letters*, **13** (6), 064007, doi:10.1088/1748-9326/aab63b.
Schleussner, C. F. et al., 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth Syst. Dynam.*, **7** (2), 327-351, doi:10.5194/esd-7-327-2016.

Schmitter, P., K. S. Kibret, N. Lefore and J. Barron, 2018: Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa. *Applied Geography*, **94**, 41-57, doi:https://doi.org/10.1016/j.apgeog.2018.02.008.
Schneider, U. et al., 2020: GPCC Full Data Monthly Product Version 2020 at 1.0°: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historical Data. doi:10.5676/DWD_GPCC/FD_M_V2020_100.
Schneider, U. et al., 2017: Evaluating the Hydrological Cycle over Land Using the Newly-Corrected Precipitation Climatology from the Global Precipitation Climatology Centre (GPCC). *Atmosphere*, **8** (3), doi:10.3390/atmos8030052.
Schuler, T. V. et al., 2020: Reconciling Svalbard glacier mass balance. *Frontiers in Earth Science*, **8**, 156.
Schuster-Wallace, C. J., S. E. Dickson-Anderson, S. M. Paplexiou and A. El Ganzouri, 2021: Design and Application of the Tank Simulation Model (TSM): Assessing the Ability of Rainwater Harvesting to Meet Domestic Water Demand. *Journal of Environmental Informatics*, **In Press**.
Schuster, R. C. et al., 2020: "If there is no water, we cannot feed our children": The far-reaching consequences of water insecurity on infant feeding practices and infant health across 16 low- and middle-income countries. *American Journal of Human Biology*, **32** (1), e23357, doi:10.1002/ajhb.23357.
Schutte, S., J. Vestby, J. Carling and H. Buhaug, 2021: Climatic conditions are weak predictors of asylum migration. *Nature Communications*, **12** (1), 2067, doi:10.1038/s41467-021-22255-4.
Schuur, E. A. G. et al., 2015: Climate change and the permafrost carbon feedback. *Nature*, **520**, 171, doi:10.1038/nature14338.
Schwaab, J. et al., 2020: Increasing the broad-leaved tree fraction in European forests mitigates hot temperature extremes. *Scientific Reports*, **10** (1), 14153, doi:10.1038/s41598-020-71055-1.
Sclar, G. D. et al., 2018: Exploring the relationship between sanitation and mental and social well-being: A systematic review and qualitative synthesis. *Social Science & Medicine*, **217**, 121-134, doi:https://doi.org/10.1016/j.socscimed.2018.09.016.
Scoville-Simonds, M., 2018: Climate, the Earth, and God – Entangled narratives of cultural and climatic change in the Peruvian Andes. *World Development*, **110**, 345-359, doi:https://doi.org/10.1016/j.worlddev.2018.06.012.
Scovronick, N., S. J. Lloyd and R. S. Kovats, 2015: Climate and health in informal urban settlements. *Environment and Urbanization*, **27** (2), 657-678, doi:10.1177/0956247815596502.
Scussolini, P. et al., 2016: FLOPROS: an evolving global database of flood protection standards. *Nat. Hazards Earth Syst. Sci.*, **16** (5), 1049-1061, doi:10.5194/nhess-16-1049-2016.
Sebastian, A. et al., 2019: Disentangling the impacts of human and environmental change on catchment response during Hurricane Harvey. *Environmental Research Letters*, **14** (12), 124023, doi:10.1088/1748-9326/ab5234.
Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. **375**, doi:10.1098/rstb.2019.0120.
Sekhri, S., 2014: Wells, Water, and Welfare: The Impact of Access to Groundwater on Rural Poverty and Conflict. *American Economic Journal: Applied Economics*, **6** (3), 76-102, doi:10.1257/app.6.3.76.
Selby, J., 2019: Climate change and the Syrian civil war, Part II: The Jazira's agrarian crisis. *Geoforum*, **101**, 260-274, doi:https://doi.org/10.1016/j.geoforum.2018.06.010.
Selby, J., O. S. Dahi, C. Fröhlich and M. Hulme, 2017: Climate change and the Syrian civil war revisited. *Political Geography*, **60**, 232-244, doi:https://doi.org/10.1016/j.polgeo.2017.05.007.
Selby, J. and C. Hoffmann, 2014: Beyond scarcity: Rethinking water, climate change and conflict in the Sudans. *Global Environmental Change*, **29**, 360-370, doi:https://doi.org/10.1016/j.gloenvcha.2014.01.008.
Sen, S., 2020: Kolkata Greens, Post 'Amphan'. *International Journal of Research and Analytical Reviews*, **7** (2), 368-371.
Seneviratne, S. I. et al., 2010: Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, **99** (3), 125-161, doi:https://doi.org/10.1016/j.earscirev.2010.02.004.
Seneviratne, S. I. et al., 2012: Changes in Climate Extremes and their Impacts on the Natural Physical Environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C. B., V. Barros, T. F. Stocker, Q. Dahe, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 109-230.
Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Senthil Kumar, S. et al., 2020: Solar powered water pumping systems for irrigation: A comprehensive review on developments and prospects towards a green energy approach. *Materials Today: Proceedings*, **33**, 303-307, doi:https://doi.org/10.1016/j.matpr.2020.04.092.
Sepulveda-Jauregui, A. et al., 2018: Eutrophication exacerbates the impact of climate warming on lake methane emission. *Science of The Total Environment*, **636**, 411-419, doi:https://doi.org/10.1016/j.scitotenv.2018.04.283.

Serdeczny, O. et al., 2017: Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, **17** (6), 1585-1600, doi:10.1007/s10113-015-0910-2.
Settele, J. et al., 2014: Terrestrial and Inland Water Systems (Chapter 4). In: Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 1: Global and Sectoral Aspects [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir and L. L. … White (eds.)]. Cambridge University Press, Cambridge, **1**, 271-360.
Setty, K. E. et al., 2018: Time series study of weather, water quality, and acute gastroenteritis at Water Safety Plan implementation sites in France and Spain. *International journal of hygiene and environmental health*, **221** (4), 714-726.
Setzer, J. and L. C. Vanhala, 2019: Climate change litigation: A review of research on courts and litigants in climate governance. *WIREs Climate Change*, **10** (3), e580, doi:https://doi.org/10.1002/wcc.580.
Shaffril, H. A. M. et al., 2020: Systematic literature review on adaptation towards climate change impacts among indigenous people in the Asia Pacific regions. *Journal of Cleaner Production*, **258**, 120595.
Shah, A. A. et al., 2020: Factors affecting flood-induced household vulnerability and health risks in Pakistan: The case of Khyber Pakhtunkhwa (KP) Province. *International Journal of Disaster Risk Reduction*, **42**, 101341, doi:https://doi.org/10.1016/j.ijdrr.2019.101341.
Shah, T. et al., 2018: Solar pumps and South Asia’s energy-groundwater nexus: exploring implications and reimagining its future. *Environmental Research Letters*, **13** (11), 115003, doi:10.1088/1748-9326/aae53f.
Shahgedanova, M. et al., 2020: Emptying Water Towers? Impacts of Future Climate and Glacier Change on River Discharge in the Northern Tien Shan, Central Asia. *Water*, **12** (3), 627.
Shahsavari, F., F. Karandish and P. Haghighatjou, 2019: Potentials for expanding dry-land agriculture under global warming in water-stressed regions: a quantitative assessment based on drought indices. *Theoretical and Applied Climatology*, **137** (1), 1555-1567, doi:10.1007/s00704-018-2689-9.
Shamsudduha, M. et al., 2020: Multi-hazard Groundwater Risks to Water Supply from Shallow Depths: Challenges to Achieving the Sustainable Development Goals in Bangladesh. *Exposure and Health*, **12** (4), 657-670, doi:10.1007/s12403-019-00325-9.
Shamsudduha, M. and R. G. Taylor, 2020: Groundwater storage dynamics in the world's large aquifer systems from GRACE: uncertainty and role of extreme precipitation. *Earth Syst. Dynam.*, **11** (3), 755-774, doi:10.5194/esd-11-755-2020.
Shannon, S. et al., 2019: Global glacier volume projections under high-end climate change scenarios. *The Cryosphere*, **13** (1), 325-350, doi:10.5194/tc-13-325-2019.
Shaw, M. R., J. T. Overpeck and G. F. Midgley, 2014: Cross-Chapter Box on Ecosystem-Based Approaches to Adaptation—Emerging Opportunities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 101-103.
Sheldon, K. S., 2019: Climate Change in the Tropics: Ecological and Evolutionary Responses at Low Latitudes. *Annual Review of Ecology, Evolution, and Systematics*, **50** (1), 303-333, doi:10.1146/annurev-ecolsys-110218-025005.
Sherpa, A. M., T. Koottatep, C. Zurbrügg and G. Cissé, 2014: Vulnerability and adaptability of sanitation systems to climate change. *Journal of Water and Climate Change*, **5** (4), 487-495, doi:10.2166/wcc.2014.003.
Sherry, J. and A. Curtis, 2017: At the intersection of disaster risk and religion: interpretations and responses to the threat of Tsho Rolpa glacial lake. *Environmental Hazards*, **16** (4), 314-329, doi:10.1080/17477891.2017.1298983.
Sherwood, S. and Q. Fu, 2014: A Drier Future? *Science*, **343** (6172), 737-739, doi:10.1126/science.1247620.
Sherwood, S. C. et al., 2020: An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*, **58** (4), e2019RG000678, doi:10.1029/2019RG000678.
Shi, L. et al., 2016: Roadmap towards justice in urban climate adaptation research. *Nature Climate Change*, **6** (2), 131-137, doi:10.1038/nclimate2841.
Shi, X. et al., 2019: Changes in Major Global River Discharges Directed into the Ocean. *International Journal of Environmental Research and Public Health*, **16** (8), 1469.
Shrestha, B. B. et al., 2019a: Assessing flood disaster impacts in agriculture under climate change in the river basins of Southeast Asia. *Natural Hazards*, **97** (1), 157-192, doi:10.1007/s11069-019-03632-1.
Shrestha, P. et al., 2016: *Benefit Sharing and Sustainable Hydropower : Lessons from Nepal*.
Shrestha, R. P. and N. Nepal, 2016: An assessment by subsistence farmers of the risks to food security attributable to climate change in Makwanpur, Nepal. *Food Security*, **8** (2), 415-425, doi:10.1007/s12571-016-0554-1.
Shrestha, R. R. et al., 2021: Heterogeneous snowpack response and snow drought occurrence across river basins of northwestern North America under 1.0°C to 4.0°C global warming. *Climatic Change*, **164** (3), 40, doi:10.1007/s10584-021-02968-7.
Shrestha, R. R., A. J. Cannon, M. A. Schnorbus and F. W. Zwiers, 2017: Projecting future nonstationary extreme streamflow for the Fraser River, Canada. *Climatic Change*, **145** (3), 289-303, doi:10.1007/s10584-017-2098-6.

Shrestha, S., A. K. Anal, P. A. Salam and M. Van Der Valk, 2015: Managing water resources under climate uncertainty: Examples from Asia, Europe, Latin America, and Australia. 1-438.
Shrestha, S., P. S. Chapagain and M. Ghimire, 2019b: Gender Perspective on Water Use and Management in the Context of Climate Change: A Case Study of Melamchi Watershed Area, Nepal. *SAGE Open*, **9** (1), 2158244018823078, doi:10.1177/2158244018823078.
Shugar, D. H. et al., 2020: Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change*, **10** (10), 939-945.
Shukla, P. R. et al., 2019: Technical Summary. In: Climate Change and Land: an IPCC special report on climate change, desertification, land
degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [Shukla, P. R., J. Skea, E. C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. v. Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. P. Pereira, P. Vyas, E. Huntley, K. Kissick, B. M and J. Malley (eds.)].
Shultz, J. M., C. Fugate and S. Galea, 2020: Cascading Risks of COVID-19 Resurgence During an Active 2020 Atlantic Hurricane Season. *JAMA*, **324** (10), 935-936, doi:10.1001/jama.2020.15398.
Shumilova, O. et al., 2018: Global Water Transfer Megaprojects: A Potential Solution for the Water-Food-Energy Nexus? *Frontiers in Environmental Science*, **6** (150), doi:10.3389/fenvs.2018.00150.
Siddiqi, A. and J. L. Wescoat, 2013: Energy use in large-scale irrigated agriculture in the Punjab province of Pakistan. *Water International*, **38** (5), 571-586, doi:10.1080/02508060.2013.828671.
Siebert, S. et al., 2014: Impact of heat stress on crop yield—on the importance of considering canopy temperature. *Environmental Research Letters*, **9** (4), 044012, doi:10.1088/1748-9326/9/4/044012.
Simms, R., L. Harris, N. Joe and K. Bakker, 2016: Navigating the tensions in collaborative watershed governance: Water governance and Indigenous communities in British Columbia, Canada. *Geoforum*, **73**, 6-16, doi:https://doi.org/10.1016/j.geoforum.2016.04.005.
Singh, C. and R. Basu, 2020: Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural–urban continuum in India. *The Geographical Journal*, **186** (1), 87-102, doi:10.1111/geoj.12328.
Singh, C. et al., 2021: Interrogating 'effectiveness' in climate change adaptation: 11 guiding principles for adaptation research and practice. *Climate and Development*, 1-15, doi:10.1080/17565529.2021.1964937.
Singh, C., A. Rahman, A. Srinivas and A. Bazaz, 2018: Risks and responses in rural India: Implications for local climate change adaptation action. *Climate Risk Management*, **21**, 52-68, doi:https://doi.org/10.1016/j.crm.2018.06.001.
Singh, D., S. Ghosh, M. K. Roxy and S. McDermid, 2019: Indian summer monsoon: Extreme events, historical changes, and role of anthropogenic forcings. *Wiley Interdisciplinary Reviews: Climate Change*, **10** (2), e571, doi:10.1002/wcc.571.
Singh, N. and O. P. Singh, 2015: Climate change, water and gender: Impact and adaptation in North-Eastern Hills of India. *International Social Work*, **58** (3), 375-384, doi:10.1177/0020872814556826.
Singh, R. K. et al., 2014: Adaptation in rice-wheat based sodic agroecosystems: A case study on climate resilient farmers' practices. *Indian Journal of Traditional Knowledge*, **13** (2), 377-389.
Sinharoy, S. S. and B. A. Caruso, 2019: On World Water Day, gender equality and empowerment require attention. *The Lancet Planetary Health*, **3** (5), e202-e203, doi:https://doi.org/10.1016/S2542-5196(19)30021-X.
Siraw, Z., M. Adnew Degefu and W. Bewket, 2018: The role of community-based watershed development in reducing farmers' vulnerability to climate change and variability in the northwestern highlands of Ethiopia. *Local Environment*, **23** (12), 1190-1206.
Sishodia, R. P. et al., 2018: Future irrigation expansion outweigh groundwater recharge gains from climate change in semi-arid India. *Science of The Total Environment*, **635**, 725-740, doi:https://doi.org/10.1016/j.scitotenv.2018.04.130.
Siswanto et al., 2015: Trends in High-Daily Precipitation Events in Jakarta and the Flooding of January 2014. *Bulletin of the American Meteorological Society*, **96** (12), S131-S135, doi:10.1175/BAMS-D-15-00128.1.
Sivakumar, B., 2021: COVID-19 and water. *Stochastic Environmental Research and Risk Assessment*, **35** (3), 531-534, doi:10.1007/s00477-020-01837-6.
Sjerps, R. M. A., T. L. ter Laak and G. J. J. G. Zwolsman, 2017: Projected impact of climate change and chemical emissions on the water quality of the European rivers Rhine and Meuse: A drinking water perspective. *Science of The Total Environment*, **601-602**, 1682-1694, doi:https://doi.org/10.1016/j.scitotenv.2017.05.250.
Skinner, C. B. et al., 2017: The Role of Plant CO2 Physiological Forcing in Shaping Future Daily-Scale Precipitation. *Journal of Climate*, **30** (7), 2319-2340, doi:10.1175/jcli-d-16-0603.1.
Smith, A. J. et al., 2019a: Resilience of benthic macroinvertebrates to extreme floods in a Catskill Mountain river, New York, USA: Implications for water quality monitoring and assessment. *Ecological Indicators*, **104**, 107-115, doi:https://doi.org/10.1016/j.ecolind.2019.04.057.
Smith, B. A. et al., 2015: A risk modeling framework to evaluate the impacts of climate change and adaptation on food and water safety. *Food Research International*, **68**, 78-85, doi:https://doi.org/10.1016/j.foodres.2014.07.006.
Smith, K. A. et al., 2019b: A multi-objective ensemble approach to hydrological modelling in the UK: an application to historic drought reconstruction. *Hydrol. Earth Syst. Sci.*, **23** (8), 3247-3268, doi:10.5194/hess-23-3247-2019.

Smith, P. et al., 2008: Sectoral approaches to improve regional carbon budgets. *Climatic Change*, **88** (3), 209-249, doi:10.1007/s10584-007-9378-5.
Smith, R.-A. J. and K. Rhiney, 2016: Climate (in)justice, vulnerability and livelihoods in the Caribbean: The case of the indigenous Caribs in northeastern St. Vincent. *Geoforum*, **73**, 22-31, doi:https://doi.org/10.1016/j.geoforum.2015.11.008.
Solander, K. C., K. E. Bennett and R. S. Middleton, 2017: Shifts in historical streamflow extremes in the Colorado River Basin. *Journal of Hydrology: Regional Studies*, **12**, 363-377.
Solecki, W. and C. Rosenzweig, 2014: Climate Change, Extreme Events, and Hurricane Sandy: From Non-Stationary Climate to Non-Stationary Policy. *Journal of Extreme Events*, **01** (01), 1450008, doi:10.1142/S2345737614500080.
Somanje, A. N., O. Crespo and N. Zinyengere, 2017: Conservation Agriculture Among Farmers in Kalomo, Zambia: Potential for Productivity Under Climate Change. Elsevier Inc., 77-99.
Somerville, M., 2014: Developing relational understandings of water through collaboration with indigenous knowledges. *Wiley Interdisciplinary Reviews: Water*, **1** (4), 401-411, doi:10.1002/wat2.1030.
Sommer, C. et al., 2020: Rapid glacier retreat and downwasting throughout the European Alps in the early 21 st century. *Nature Communications*, **11** (1), 1-10.
Song, C. et al., 2018: Cradle-to-grave greenhouse gas emissions from dams in the United States of America. *Renewable and Sustainable Energy Reviews*, **90**, 945-956, doi:https://doi.org/10.1016/j.rser.2018.04.014.
Song, X. et al., 2019: Changes in precipitation extremes in the Beijing metropolitan area during 1960–2012. *Atmospheric Research*, **222**, 134-153, doi:https://doi.org/10.1016/j.atmosres.2019.02.006.
Sonneveld, M., Alfarra, Unver, 2018: Nature-Based Solutions for agricultural water management and food security.
Soriano, M. A. and S. Herath, 2020: Climate change and traditional upland paddy farming: a Philippine case study. *Paddy and Water Environment*, **18** (2), 317-330, doi:10.1007/s10333-019-00784-5.
Spalding-Fecher, R., B. Joyce and H. Winkler, 2017: Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wide impacts and policy implications. *Energy Policy*, **103**, 84-97, doi:https://doi.org/10.1016/j.enpol.2016.12.009.
Spekker, H. and J. Heskamp, 2017: Flood protection for the City of Beira: An exemplary climate adaptation project in Mozambique. *Bautechnik*, **94** (12), 872-874.
Springmann, M. et al., 2018: Options for keeping the food system within environmental limits. *Nature*, **562** (7728), 519-525, doi:10.1038/s41586-018-0594-0.
Staal, A. et al., 2018: Forest-rainfall cascades buffer against drought across the Amazon. *Nature Climate Change*, **8** (6), 539-543, doi:10.1038/s41558-018-0177-y.
Stacklin, C., 2012: *The Value of Wastewater: An Econometric Evaluation of Recoverable Resources in Wastewater for Reuse*. WEF Proceedings, New Orleans, La., New Orleans Morial Convention Center.
Stanley, A. C., D. Willms, C. Schuster-Wallace and S. Watt, 2017: From rhetoric to reality: an NGO's challenge for reaching the furthest behind. *Development in Practice*, **27** (7), 913-926, doi:10.1080/09614524.2017.1350258.
Stavenhagen, M., J. Buurman and C. Tortajada, 2018: Saving water in cities: Assessing policies for residential water demand management in four cities in Europe. *Cities*, **79**, 187-195, doi:https://doi.org/10.1016/j.cities.2018.03.008.
Stefanelli, R. D. et al., 2017: Experiences with integrative Indigenous and Western knowledge in water research and management: a systematic realist review of literature from Canada, Australia, New Zealand, and the United States. *Environmental Reviews*, **25** (3), 323-333, doi:10.1139/er-2016-0114.
Steffen, W. et al., 2015: Planetary boundaries: Guiding human development on a changing planet. *Science*, **347** (6223), 1259855, doi:10.1126/science.1259855.
Steiger, R. et al., 2019: A critical review of climate change risk for ski tourism. *Current Issues in Tourism*, **22** (11), 1343-1379.
Steinhoff-Knopp, B. and B. Burkhard, 2018: Soil erosion by water in Northern Germany: long-term monitoring results from Lower Saxony. *CATENA*, **165**, 299-309, doi:https://doi.org/10.1016/j.catena.2018.02.017.
Sterl, S. et al., 2021: Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam. *Nature Energy*, **6** (4), 407-418, doi:10.1038/s41560-021-00799-5.
Stoler, J. et al., 2021: Household water insecurity will complicate the ongoing COVID-19 response: Evidence from 29 sites in 23 low- and middle-income countries. *International journal of hygiene and environmental health*, **234**, 113715-113715, doi:10.1016/j.ijheh.2021.113715.
Storlazzi, C. D. et al., 2018: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, **4** (4), eaap9741, doi:10.1126/sciadv.aap9741.
Streletskiy, D. A. et al., 2019: Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. *Environmental Research Letters*, **14** (2), 025003.
Stults, M. and L. Larsen, 2018: Tackling Uncertainty in US Local Climate Adaptation Planning. *Journal of Planning Education and Research*, 0739456X18769134, doi:10.1177/0739456X18769134.
Su, Y. et al., 2017: Gendered Responses to Drought in Yunnan Province, China. *Mountain Research and Development*, **37**, 24-34, doi:10.1659/MRD-JOURNAL-D-15-00041.1.
Suhardiman, D., D. Wichelns, L. Lebel and S. S. Sellamuttu, 2014: Benefit sharing in Mekong Region hydropower: Whose benefits count? *Water Resources and Rural Development*, **4**, 3-11, doi:https://doi.org/10.1016/j.wrr.2014.10.008.

Sujakhu, N. M. et al., 2016: Farmers' perceptions of and adaptations to changing climate in the Melamchi Valley of Nepal. *Mountain Research and Development*, **36** (1), 15-30, doi:10.1659/MRD-JOURNAL-D-15-00032.1.

Sullivan-Wiley, K. A. and A. G. Short Gianotti, 2018: Pursuing productivity gains and risk reduction in a multi-hazard landscape: A case study from eastern Uganda. *Land Use Policy*, **79** (August), 671-683, doi:10.1016/j.landusepol.2018.08.035.

Sultan, B., D. Defrance and T. Iizumi, 2019: Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Scientific Reports*, **9** (1), 12834, doi:10.1038/s41598-019-49167-0.

Sultana, F., 2014: Gendering Climate Change: Geographical Insights. *The Professional Geographer*, **66** (3), 372-381, doi:10.1080/00330124.2013.821730.

Sultana, F., 2018: Gender and Water in a Changing Climate: Challenges and Opportunities. In: Water Security Across the Gender Divide [Fröhlich, C., G. Gioli, R. Cremades and H. Myrttinen (eds.)]. Springer International Publishing, Cham, 17-33.

Sultana, P. et al., 2019: Transforming local natural resource conflicts to cooperation in a changing climate: Bangladesh and Nepal lessons. *Climate Policy*, **19** (sup1), S94-S106, doi:10.1080/14693062.2018.1527678.

Sun, D. et al., 2018a: The effects of land use change on soil infiltration capacity in China: A meta-analysis. *Science of The Total Environment*, **626**, 1394-1401, doi:https://doi.org/10.1016/j.scitotenv.2018.01.104.

Sun, L. et al., 2018b: Wetland-atmosphere methane exchange in Northeast China: A comparison of permafrost peatland and freshwater wetlands. *Agricultural and Forest Meteorology*, **249**, 239-249, doi:https://doi.org/10.1016/j.agrformet.2017.11.009.

Sun, L. et al., 2019a: Impact of environmental change on runoff in a transitional basin: Tao River Basin from the Tibetan Plateau to the Loess Plateau, China. *Advances in Climate Change Research*, **10** (4), 214-224, doi:https://doi.org/10.1016/j.accre.2020.02.002.

Sun, Q. and C. Miao, 2018: Extreme Rainfall (R20mm, RX5day) in Yangtze–Huai, China, in June–July 2016: The Role of ENSO and Anthropogenic Climate Change. *Bulletin of the American Meteorological Society*, **99** (1), S102-S106, doi:10.1175/BAMS-D-17-0091.1.

Sun, Q. et al., 2020: A global, continental and regional analysis of changes in extreme precipitation. *Journal of Climate*, 1-52, doi:10.1175/JCLI-D-19-0892.1.

Sun, Y. et al., 2019b: Anthropogenic Influence on the Heaviest June Precipitation in Southeastern China since 1961. *Bulletin of the American Meteorological Society*, **100** (1), S79-S83, doi:10.1175/BAMS-D-18-0114.1.

Sutanudjaja, E. H. et al., 2018: PCR-GLOBWB 2: a 5 arcmin global hydrological and water resources model. *Geosci. Model Dev.*, **11** (6), 2429-2453, doi:10.5194/gmd-11-2429-2018.

Svoboda, V., M. Hanel, P. Máca and J. Kyselý, 2016: Projected changes of rainfall event characteristics for the Czech Republic. *Journal of Hydrology and Hydromechanics*, **64** (4), 415-425, doi:doi:10.1515/johh-2016-0036.

Swann, A. L. S., F. M. Hoffman, C. D. Koven and J. T. Randerson, 2016: Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences*, **113** (36), 10019-10024, doi:10.1073/pnas.1604581113.

Szekeres, P. et al., 2016: On the neglected cold side of climate change and what it means to fish. *Climate Research*, **69**, doi:10.3354/cr01404.

Szewrański, S. et al., 2018: Socio-Environmental Vulnerability Mapping for Environmental and Flood Resilience Assessment: The Case of Ageing and Poverty in the City of Wrocław, Poland. *Integrated Environmental Assessment and Management*, **14** (5), 592-597, doi:https://doi.org/10.1002/ieam.4077.

Tabari, H., 2020: Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports*, **10** (1), 1-10.

Taboada, C. et al., 2017: Can warmer be better? Changing production systems in three Andean ecosystems in the face of environmental change. *Journal of Arid Environments*, **147**, 144-154.

Tack, J., A. Barkley and N. Hendricks, 2017: Irrigation offsets wheat yield reductions from warming temperatures. *Environmental Research Letters*, **12** (11), 114027, doi:10.1088/1748-9326/aa8d27.

Tadgell, A., B. Doberstein and L. Mortsch, 2018: Principles for climate-related resettlement of informal settlements in less developed nations: a review of resettlement literature and institutional guidelines. *Climate and Development*, **10** (2), 102-115, doi:10.1080/17565529.2017.1291401.

Takakura, J. y. et al., 2019: Dependence of economic impacts of climate change on anthropogenically directed pathways. *Nature Climate Change*, **9** (10), 737-741, doi:10.1038/s41558-019-0578-6.

Takata, K. and N. Hanasaki, 2020: The effects of afforestation as an adaptation option: a case study in the upper Chao Phraya River basin. *Environmental Research Letters*, **15** (4), 044020, doi:10.1088/1748-9326/ab7462.

Tamura, M., N. Kumano, M. Yotsukuri and H. Yokoki, 2019: Global assessment of the effectiveness of adaptation in coastal areas based on RCP/SSP scenarios. *Climatic Change*, **152** (3), 363-377, doi:10.1007/s10584-018-2356-2.

Tan, Y. and X. Liu, 2017: Water shortage and inequality in arid Minqin oasis of northwest China: adaptive policies and farmers' perceptions. *Local Environment*, **22** (8), 934-951.

Tananaev, N. I., O. M. Makarieva and L. S. Lebedeva, 2016: Trends in annual and extreme flows in the Lena River basin, Northern Eurasia. *Geophysical Research Letters*, **43** (20), 10,764-10,772, doi:10.1002/2016gl070796.

Tanoue, M., Y. Hirabayashi and H. Ikeuchi, 2016: Global-scale river flood vulnerability in the last 50 years. *Scientific Reports*, **6**, 36021, doi:10.1038/srep36021
https://www.nature.com/articles/srep36021#supplementary-information.

Tanoue, M., R. Taguchi, H. Alifu and Y. Hirabayashi, 2021: Residual flood damage under intensive adaptation. *Nature Climate Change*, **In Press**.
Tapia, C. et al., 2017: Profiling urban vulnerabilities to climate change: An indicator-based vulnerability assessment for European cities. *Ecological Indicators*, **78**, 142-155, doi:https://doi.org/10.1016/j.ecolind.2017.02.040.
Taraz, V., 2017: Adaptation to climate change: historical evidence from the Indian monsoon. *Environment and Development Economics*, **22** (5), 517-545, doi:10.1017/S1355770X17000195.
Tarroja, B., A. AghaKouchak and S. Samuelsen, 2016: Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation. *Energy*, **111**, 295-305, doi:https://doi.org/10.1016/j.energy.2016.05.131.
Tauhid, F. A. and H. Zawani, 2018: Mitigating climate change related floods in urban poor areas: green infrastructure approach. *Journal of Regional and City Planning*, **29** (2), 98-112.
Taylor, R. G. et al., 2013a: Ground water and climate change. *Nature Climate Change*, **3** (4), 322-329, doi:10.1038/nclimate1744.
Taylor, R. G. et al., 2013b: Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. *Nature Climate Change*, **3** (4), 374-378, doi:10.1038/nclimate1731.
Teklewold, H., A. Mekonnen, G. Kohlin and S. Di Falco, 2017: Does adoption of multiple climate-smart practices improve farmers' climate resilience? Empirical evidence from the Nile Basin of Ethiopia. *Climate Change Economics*, **8** (1), doi:10.1142/S2010007817500014.
Tellman, B. et al., 2021: Satellite imaging reveals increased proportion of population exposed to floods. *Nature*, **596** (7870), 80-86, doi:10.1038/s41586-021-03695-w.
Telteu, C. E. et al., 2021: Understanding each other's models: an introduction and a standard representation of 16 global water models to support intercomparison, improvement, and communication. *Geosci. Model Dev.*, **14** (6), 3843-3878, doi:10.5194/gmd-14-3843-2021.
Tembata, K. and K. Takeuchi, 2018: Collective decision making under drought: An empirical study of water resource management in Japan. *Water Resources and Economics*, **22**, 19-31, doi:https://doi.org/10.1016/j.wre.2017.11.001.
Tengö, M. et al., 2014: Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. *Ambio*, **43** (5), 579-591.
Tengö, M. et al., 2017: Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. *Current opinion in environmental sustainability*, **26**, 17-25.
Tesfamariam, Y. and M. Hurlbert, 2017: Gendered adaptation of Eritrean dryland farmers. *International Journal of Climate Change Strategies and Management*, **9** (2), 207-224, doi:10.1108/IJCCSM-07-2016-0096.
Thackeray, C. W., C. Derksen, C. G. Fletcher and A. Hall, 2019: Snow and Climate: Feedbacks, Drivers, and Indices of Change. *Current Climate Change Reports*, **5** (4), 322-333, doi:10.1007/s40641-019-00143-w.
Thackeray, C. W., C. G. Fletcher, L. R. Mudryk and C. Derksen, 2016: Quantifying the Uncertainty in Historical and Future Simulations of Northern Hemisphere Spring Snow Cover. *Journal of Climate*, **29** (23), 8647-8663, doi:10.1175/jcli-d-16-0341.1.
Thebo, A. L., P. Drechsel, E. F. Lambin and K. L. Nelson, 2017: A global, spatially-explicit assessment of irrigated croplands influenced by urban wastewater flows. *Environmental Research Letters*, **12** (7), 074008, doi:10.1088/1748-9326/aa75d1.
Thiam, S. et al., 2017: Association between Childhood Diarrhoeal Incidence and Climatic Factors in Urban and Rural Settings in the Health District of Mbour, Senegal. *International Journal of Environmental Research and Public Health*, **14** (9), doi:10.3390/ijerph14091049.
Thiede, B., C. Gray and V. Mueller, 2016: Climate variability and inter-provincial migration in South America, 1970–2011. *Global Environmental Change*, **41**, 228-240, doi:https://doi.org/10.1016/j.gloenvcha.2016.10.005.
Thierfelder, C., R. Matemba-Mutasa and L. Rusinamhodzi, 2015: Yield response of maize (Zea mays L.) to conservation agriculture cropping system in Southern Africa. *Soil and Tillage Research*, **146**, 230-242.
Thiery, W. et al., 2020: Warming of hot extremes alleviated by expanding irrigation. *Nature Communications*, **11** (1), 290, doi:10.1038/s41467-019-14075-4.
Thomas, A. and L. Benjamin, 2018a: Management of loss and damage in small island developing states: implications for a 1.5 °C or warmer world. *Regional Environmental Change*, **18** (8), 2369-2378, doi:10.1007/s10113-017-1184-7.
Thomas, A. and L. Benjamin, 2018b: Policies and mechanisms to address climate-induced migration and displacement in Pacific and Caribbean small island developing states. *International Journal of Climate Change Strategies and Management*, **10** (1), 86-104, doi:10.1108/IJCCSM-03-2017-0055.
Thomas, B., A. Behrangi and J. Famiglietti, 2016: Precipitation Intensity Effects on Groundwater Recharge in the Southwestern United States. *Water*, **8**, doi:10.3390/w8030090.
Thorn, J., T. F. Thornton and A. Helfgott, 2015: Autonomous adaptation to global environmental change in peri-urban settlements: Evidence of a growing culture of innovation and revitalisation in Mathare Valley Slums, Nairobi. *Global Environmental Change*, **31**, 121-131, doi:https://doi.org/10.1016/j.gloenvcha.2014.12.009.
Thorslund, J. et al., 2017: Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management. **108**, 489-497, doi:10.1016/j.ecoleng.2017.07.012.
Tian, S. et al., 2019: Temporal variations of runoff and sediment load in the upper Yellow River, China. *Journal of Hydrology*, **568**, 46-56, doi:https://doi.org/10.1016/j.jhydrol.2018.10.033.

Tian, Z. et al., 2021: Searching for "Win-Win" solutions for food-water-GHG emissions tradeoffs across irrigation regimes of paddy rice in China. *Resources, Conservation and Recycling*, **166**, 105360, doi:https://doi.org/10.1016/j.resconrec.2020.105360.
Tigkas, D., H. Vangelis and G. Tsakiris, 2019: Drought characterisation based on an agriculture-oriented standardised precipitation index. *Theoretical and Applied Climatology*, **135** (3), 1435-1447, doi:10.1007/s00704-018-2451-3.
Tilleard, S. and J. Ford, 2016: Adaptation readiness and adaptive capacity of transboundary river basins. *Climatic Change*, **137** (3), 575-591, doi:10.1007/s10584-016-1699-9.
Tillman, F. D., S. Gangopadhyay and T. Pruitt, 2017: Changes in Projected Spatial and Seasonal Groundwater Recharge in the Upper Colorado River Basin. *Groundwater*, **55** (4), 506-518, doi:10.1111/gwat.12507.
Timmerman, J. et al., 2017: Improving governance in transboundary cooperation in water and climate change adaptation. *Water Policy*, **19** (6), 1014-1029, doi:10.2166/wp.2017.156.
Tobin, I. et al., 2018: Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming. *Environmental Research Letters*, **13** (4), 044024, doi:10.1088/1748-9326/aab211.
Tor-ngern, P. et al., 2015: Increases in atmospheric CO2 have little influence on transpiration of a temperate forest canopy. *New Phytologist*, **205** (2), 518-525, doi:10.1111/nph.13148.
Toreti, A., O. Cronie and M. Zampieri, 2019: Concurrent climate extremes in the key wheat producing regions of the world. *Scientific Reports*, **9** (1), 5493, doi:10.1038/s41598-019-41932-5.
Tormos-Aponte, F. and G. A. García-López, 2018: Polycentric struggles: The experience of the global climate justice movement. *Environmental Policy and Governance*, **28** (4), 284-294, doi:10.1002/eet.1815.
Torres-Slimming, P. A. et al., 2020: Climatic Changes, Water Systems, and Adaptation Challenges in Shawi Communities in the Peruvian Amazon. *Sustainability*, **12** (8), doi:10.3390/su12083422.
Tosun, J. and L. Leopold, 2019: Aligning Climate Governance with Urban Water Management: Insights from Transnational City Networks. *Water*, **11** (4), 701.
Touma, D. et al., 2015: A multi-model and multi-index evaluation of drought characteristics in the 21st century. *Journal of Hydrology*, **526**, 196-207, doi:https://doi.org/10.1016/j.jhydrol.2014.12.011.
Townsend, D. A., J. Sušnik and P. V. der Zaag, 2020: Domestic Water Supply Vulnerability to Climate Change and the Role of Alternative Water Sources in Kingston, Jamaica. *Atmosphere*, **11** (12), doi:10.3390/atmos11121314.
Tozer, C. R. et al., 2020: A 1-Day Extreme Rainfall Event in Tasmania: Process Evaluation and Long Tail Attribution. *Bulletin of the American Meteorological Society*, **101** (1), S123-S128, doi:10.1175/BAMS-D-19-0219.1.
Tram Vo, P. et al., 2014: A mini-review on the impacts of climate change on wastewater reclamation and reuse. *Science of The Total Environment*, **494-495**, 9-17, doi:https://doi.org/10.1016/j.scitotenv.2014.06.090.
Tramblay, Y., L. Mimeau, F. Vinet and E. Sauquet, 2019: Detection and attribution of flood trends in Mediterranean basins.
Traore, K., D. K. Sidibe, H. Coulibaly and J. Bayala, 2017: Optimizing yield of improved varieties of millet and sorghum under highly variable rainfall conditions using contour ridges in Cinzana, Mali. *Agriculture & Food Security*, **6** (1), 11, doi:10.1186/s40066-016-0086-0.
Tsang, S. W. and C. Y. Jim, 2016: Applying artificial intelligence modeling to optimize green roof irrigation. *Energy and Buildings*, **127**, 360-369, doi:https://doi.org/10.1016/j.enbuild.2016.06.005.
Tu, Y., R. Wang, Y. Zhang and J. Wang, 2018: Progress and Expectation of Atmospheric Water Harvesting. *Joule*, **2** (8), 1452-1475, doi:10.1016/j.joule.2018.07.015.
Tubi, A. and J. Williams, 2021: Beyond binary outcomes in climate adaptation: The illustrative case of desalination. *WIREs Climate Change*, **12** (2), e695, doi:https://doi.org/10.1002/wcc.695.
Turcotte, B., B. Morse and G. Pelchat, 2020: Impact of Climate Change on the Frequency of Dynamic Breakup Events and on the Risk of Ice-Jam Floods in Quebec, Canada. *Water*, **12** (10), doi:10.3390/w12102891.
Turner, P. A. et al., 2018: The global overlap of bioenergy and carbon sequestration potential. *Climatic Change*, **148** (1), 1-10, doi:10.1007/s10584-018-2189-z.
Turner, S. W. et al., 2019: A pathway of global food supply adaptation in a world with increasingly constrained groundwater. *Science of The Total Environment*, **673**, 165-176.
Turner, S. W. D., J. Y. Ng and S. Galelli, 2017: Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model. *Science of The Total Environment*, **590-591**, 663-675, doi:https://doi.org/10.1016/j.scitotenv.2017.03.022.
Turunen, M. T. et al., 2016: Coping with difficult weather and snow conditions: Reindeer herders' views on climate change impacts and coping strategies. *Climate Risk Management*, **11**, 15-36, doi:https://doi.org/10.1016/j.crm.2016.01.002.
Uhe, P. et al., 2021: Method-uncertainty is essential for reliable confidence statements of precipitation projections. *Journal of Climate.*, **34** (3), 1227–1240, doi:https://doi.org/10.1175/JCLI-D-20-0289.1.
Ukkola, A. M. et al., 2015: Reduced streamflow in water-stressed climates consistent with CO2 effects on vegetation. *Nature Climate Change*, **6**, 75, doi:10.1038/nclimate2831
https://www.nature.com/articles/nclimate2831#supplementary-information.
UN-Habitat, 2019: *The Strategic Plan 2020-2023*. Habitat, U., Paris [Available at: https://unhabitat.org/sites/default/files/documents/2019-09/strategic_plan_2020-2023.pdf].
UN, 2015: *Transforming our world: the 2030 Agenda for Sustainable Development*. 41 [Available at: sustainabledevelopment.un.org].

UN, 2019: *Global Sustainable Development Report 2019: The Future is Now – Science for Achieving Sustainable Development*. Independent Group of Scientists appointed by the Secretary-General (United Nations, N. Y., New York [Available at: https://sustainabledevelopment.un.org/content/documents/24797GSDR_report_2019.pdf].
UN Environment, 2019: *Global Environment Outlook – GEO-6: Healthy Planet, Healthy People*. Press, C. U., Cambridge, UK.
UN Water, 2017: *The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource*. UNESCO, Paris [Available at: www.unesco.org/ new/en/natural-sciences/environment/water/wwap/wwdr/2017-wastewater-the-untapped-resource/].
UN Water, 2018: *The United Nations world water development report 2018: Nature-Based Solutions for Water*. UNESCO, 1-139.
UN Water, 2020: *United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO, Paris [Available at: https://en.unesco.org/themes/water-security/wwap/wwdr/2020].
UN Water, 2021: *The United Nations World Water Development Report 2021: Valuing Water*. UNESCO, Paris.
UNEP, 2018: *The Adaptation Gap Report 2018*. United Nations Environment Programme (UNEP), Nairobi, Kenya [Available at: http://web.unep.org/ganadapt/publication/adaptation-gap-report-2018].
UNFCCC, 2017: *Adaptation planning, implementation and evaluation addressing ecosystems and areas such as water resources* **46**, United Nations Framework Convention on Climate Change, Bonn, Germany [Available at: http://unfccc.int/resource/docs/2017/sbsta/eng/03.pdf].
UNICEF, W., 2020: *Hygiene Baselines pre-COVID-19 Global Snapshot*. World Health Organization and UNICEF [Available at: www.washdata.org].
UNIDO, 2017: *Low-carbon and Climate Resilient Industrial Development in Africa*. (UNIDO), U. N. I. D. O., Vienna, Austria [Available at: https://www.unido.org/sites/default/files/files/2018-12/LCCR-Impact-Report.pdf].
UNISDR, 2004: Living with risk: A global review of disaster reduction initiatives: Version 1. In: Living with risk: A global review of disaster reduction initiatives: Version 1. UN. International Strategy for Disaster Reduction (ISDR). Secretariat; World ….
UNISDR, 2021: Terminology. United Nations International Strategy for Disaster Risk Reduction (UNISDR), Geneva.
UNISDR., 2015: Sendai Framework for Disaster Risk Reduction 2015–2030,. In: *Proceedings of the 3rd United Nations World Conference on Disasester Risk Reduction*, Sendai.
US EPA, 2017: *2017 Potable Reuse Compendium*. United States Environmental Protection Agency (US EPA), EPA), U. S. E. P. A. U. [Available at: https://www.epa.gov/sites/production/files/2018-01/documents/potablereusecompendium_3.pdf].
Uyttendaele, M. et al., 2015: Special issue on the impacts of climate change on food safety. *Food Research International*, (68), 1-6.
van der Geest, K. et al., 2019: The Impacts of Climate Change on Ecosystem Services and Resulting Losses and Damages to People and Society. In: Loss and Damage from Climate Change: Concepts, Methods and Policy Options [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, 221-236.
van der Geest, K. and M. Schindler, 2016: Brief communication: Loss and damage from a catastrophic landslide in Nepal. *Nat. Hazards Earth Syst. Sci.*, **16** (11), 2347-2350, doi:10.5194/nhess-16-2347-2016.
van der Geest, K. and K. Warner, 2015: *What the IPCC Fifth Assessment Report has to say about loss and damage*.
van der Kooij, S., M. Zwarteveen, H. Boesveld and M. Kuper, 2013: The efficiency of drip irrigation unpacked. *Agricultural Water Management*, **123**, 103-110, doi:https://doi.org/10.1016/j.agwat.2013.03.014.
van der Schalie, R. et al., 2021: ESA Climate Change Initiative Plus Soil Moisture Product User Guide (PUG) Supporting Product Version v06.1. ESA.
van der Sleen, P. et al., 2014: No growth stimulation of tropical trees by 150 years of CO2 fertilization but water-use efficiency increased. *Nature Geoscience*, **8**, 24, doi:10.1038/ngeo2313 https://www.nature.com/articles/ngeo2313#supplementary-information.
van der Wiel, K. et al., 2017: Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrol. Earth Syst. Sci.*, **21** (2), 897-921, doi:10.5194/hess-21-897-2017.
van Houtven, G. L., S. K. Pattanayak, F. Usmani and J.-C. Yang, 2017: What are households willing to pay for improved water access? Results from a meta-analysis. *Ecological Economics*, **136**, 126-135.
Van Lanen, H. A. J., N. Wanders, L. M. Tallaksen and A. F. Van Loon, 2013: Hydrological drought across the world: impact of climate and physical catchment structure. *Hydrol. Earth Syst. Sci.*, **17** (5), 1715-1732, doi:10.5194/hess-17-1715-2013.
van Leeuwen, C. J., S. H. A. Koop and R. M. A. Sjerps, 2016: City Blueprints: baseline assessments of water management and climate change in 45 cities. *Environment, Development and Sustainability*, **18** (4), 1113-1128, doi:10.1007/s10668-015-9691-5.
van Oldenborgh, G. J. et al., 2020: Attribution of the Australian bushfire risk to anthropogenic climate change. *Nat. Hazards Earth Syst. Sci. Discuss.*, **2020**, 1-46, doi:10.5194/nhess-2020-69.
van Oldenborgh, G. J., F. E. L. Otto, K. Haustein and K. AchutaRao, 2017a: The Heavy Precipitation Event of December 2015 in Chennai, India. *Bulletin of the American Meteorological Society*, **97** (12), S87-S91, doi:10.1175/BAMS-D-16-0129.1.

van Oldenborgh, G. J. et al., 2017b: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12** (12), 124009, doi:10.1088/1748-9326/aa9ef2.
van Vliet, M. T. H., M. Flörke and Y. Wada, 2017: Quality matters for water scarcity. *Nature Geoscience*, **10**, 800, doi:10.1038/ngeo3047
https://www.nature.com/articles/ngeo3047#supplementary-information.
van Vliet, M. T. H. et al., 2021: Global water scarcity including surface water quality and expansions of clean water technologies. *Environmental Research Letters*, **16** (2), 024020, doi:10.1088/1748-9326/abbfc3.
van Vliet, M. T. H., J. Sheffield, D. Wiberg and E. F. Wood, 2016a: Impacts of recent drought and warm years on water resources and electricity supply worldwide. *Environmental Research Letters*, **11** (12), 124021, doi:10.1088/1748-9326/11/12/124021.
van Vliet, M. T. H. et al., 2016b: Multi-model assessment of global hydropower and cooling water discharge potential under climate change. *Global Environmental Change*, **40**, 156-170, doi:https://doi.org/10.1016/j.gloenvcha.2016.07.007.
van Vliet, M. T. H., D. Wiberg, S. Leduc and K. Riahi, 2016c: Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, **6**, 375, doi:10.1038/nclimate2903
https://www.nature.com/articles/nclimate2903#supplementary-information.
van Weezel, S., 2019: On climate and conflict: Precipitation decline and communal conflict in Ethiopia and Kenya. *Journal of Peace Research*, **56** (4), 514-528, doi:10.1177/0022343319826409.
Vanmaercke, M., J. Poesen, J. Broeckx and J. Nyssen, 2014: Sediment yield in Africa. *Earth-Science Reviews*, **136**, 350-368, doi:https://doi.org/10.1016/j.earscirev.2014.06.004.
Vanmaercke, M., J. Poesen, G. Govers and G. Verstraeten, 2015: Quantifying human impacts on catchment sediment yield: A continental approach. *Global and Planetary Change*, **130**, 22-36, doi:https://doi.org/10.1016/j.gloplacha.2015.04.001.
Vano, J. A., B. Nijssen and D. P. Lettenmaier, 2015: Seasonal hydrologic responses to climate change in the P acific N orthwest. *Water Resources Research*, **51** (4), 1959-1976.
Vanschoenwinkel, J. and S. Van Passel, 2018: Climate response of rainfed versus irrigated farms: the bias of farm heterogeneity in irrigation. *Climatic Change*, **147** (1), 225-234, doi:10.1007/s10584-018-2141-2.
Vantas, K., E. Sidiropoulos and A. Loukas, 2020: Estimating Current and Future Rainfall Erosivity in Greece Using Regional Climate Models and Spatial Quantile Regression Forests. *Water*, **12** (3), doi:10.3390/w12030687.
Varadan, R. and P. Kumar, 2014: Indigenous knowledge about climate change: Validating the perceptions of dryland farmers in Tamil Nadu. *Indian Journal of Traditional Knowledge*, **13**, 390-397.
Vardakoulias, O. and N. Nicholles, 2015: A Socio-Economic Evaluation of Community-based Adaptation: A Case Study in Dakoro, Niger. In: Handbook of Climate Change Adaptation [Leal, W. (ed.)].
Vautard, R. et al., 2020: Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe. *Environmental Research Letters*, **15** (9), 094077, doi:10.1088/1748-9326/aba3d4.
Vegas-Vilarrúbia, T., E. Hernández, V. Rull and E. Rull Vegas, 2015: The Orinoco megadelta as a conservation target in the face of the ongoing and future sea level rise. *Science of The Total Environment*, **515-516**, 129-142, doi:https://doi.org/10.1016/j.scitotenv.2015.01.056.
Veldkamp, T. I. E. et al., 2017: Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nature Communications*, **8** (1), 15697, doi:10.1038/ncomms15697.
Venkataramanan, V. et al., 2020: In pursuit of 'safe' water: the burden of personal injury from water fetching in 21 low-income and middle-income countries. *BMJ Global Health*, **5** (10), e003328, doi:10.1136/bmjgh-2020-003328.
Vermeulen, S. J. et al., 2018: Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change. *Frontiers in Sustainable Food Systems*, **2**, 65.
Vestby, J., 2019: Climate variability and individual motivations for participating in political violence. *Global Environmental Change*, **56**, 114-123, doi:https://doi.org/10.1016/j.gloenvcha.2019.04.001.
Vetter, T. et al., 2017: Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. *Climatic Change*, **141** (3), 419-433, doi:10.1007/s10584-016-1794-y.
Vicente-Serrano, S. M. et al., 2019: Climate, Irrigation, and Land Cover Change Explain Streamflow Trends in Countries Bordering the Northeast Atlantic. *Geophysical Research Letters*, **46** (19), 10821-10833, doi:https://doi.org/10.1029/2019GL084084.
Villamayor-Tomas, S. and G. García-López, 2017: The influence of community-based resource management institutions on adaptation capacity: A large-n study of farmer responses to climate and global market disturbances. *Global Environmental Change*, **47**, 153-166, doi:https://doi.org/10.1016/j.gloenvcha.2017.10.002.
Vincent, A., S. Violette and G. Aðalgeirsdóttir, 2019: Groundwater in catchments headed by temperate glaciers: A review. *Earth-Science Reviews*, **188**, 59-76, doi:https://doi.org/10.1016/j.earscirev.2018.10.017.
Vinoj, V. and D. Swain, 2020: Did COVID-19 Lockdown Brew "Amphan" into a Super Cyclone? *Preprints 2020*, **2020070033**, doi:10.20944/preprints202007.0033.v1.
Viviroli, D. et al., 2020: Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, 1-12.
Vogel, E. et al., 2019: The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, **14** (5), 054010, doi:10.1088/1748-9326/ab154b.

von Lossow, T., 2016: The Rebirth of Water as a Weapon: IS in Syria and Iraq. *The International Spectator*, **51** (3), 82-99, doi:10.1080/03932729.2016.1213063.
von Uexkull, N., M. Croicu, H. Fjelde and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proceedings of the National Academy of Sciences*, **113** (44), 12391, doi:10.1073/pnas.1607542113.
von Uexkull, N., M. d'Errico and J. Jackson, 2020: Drought, Resilience, and Support for Violence: Household Survey Evidence from DR Congo. *Journal of Conflict Resolution*, **64** (10), 1994-2021, doi:10.1177/0022002720923400.
Vormoor, K. et al., 2016: Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway. *Journal of Hydrology*, **538**, 33-48.
Wada, Y., 2016: Modeling Groundwater Depletion at Regional and Global Scales: Present State and Future Prospects. *Surveys in Geophysics*, **37** (2), 419-451, doi:10.1007/s10712-015-9347-x.
Wada, Y. et al., 2016: Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. *Geosci. Model Dev.*, **9** (1), 175-222, doi:10.5194/gmd-9-175-2016.
Wada, Y. et al., 2017: Recent Changes in Land Water Storage and its Contribution to Sea Level Variations. *Surveys in Geophysics*, **38** (1), 131-152, doi:10.1007/s10712-016-9399-6.
Wagena, M. B. et al., 2018: Impact of climate change and climate anomalies on hydrologic and biogeochemical processes in an agricultural catchment of the Chesapeake Bay watershed, USA. *Science of The Total Environment*, **637-638**, 1443-1454, doi:https://doi.org/10.1016/j.scitotenv.2018.05.116.
Waha, K. et al., 2017: Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. *Regional Environmental Change*, **17** (6), 1623-1638, doi:10.1007/s10113-017-1144-2.
Wako, G., M. Tadesse and A. Angassa, 2017: Camel management as an adaptive strategy to climate change by pastoralists in southern Ethiopia. *Ecological Processes*, **6** (1), 26, doi:10.1186/s13717-017-0093-5.
Walch, C., 2019: Adaptive governance in the developing world: disaster risk reduction in the State of Odisha, India. *Climate and Development*, **11** (3), 238-252, doi:10.1080/17565529.2018.1442794.
Walker, A. P. et al., 2015: Predicting long-term carbon sequestration in response to CO2 enrichment: How and why do current ecosystem models differ? *Global Biogeochemical Cycles*, **29** (4), 476-495, doi:10.1002/2014gb004995.
Walsh, K. J. E. et al., 2019: Tropical cyclones and climate change assessment. *Tropical Cyclone Research and Review*, 240–250, doi:https://doi.org/DOI:10.6057/2019TCRR04.04.
Walters, G., J. Mair and B. Ritchie, 2015: Understanding the tourist's response to natural disasters: The case of the 2011 Queensland floods. *Journal of Vacation Marketing*, **21** (1), 101-113.
Wamsler, C. et al., 2016: Operationalizing ecosystem-based adaptation: Harnessing ecosystem services to buffer communities against climate change. *Ecology and Society*, **21** (1), doi:10.5751/ES-08266-210131.
Wanda, E. M. M. et al., 2017: Governing WASH for disaster risk reduction in Karonga Town, Malawi. *International Journal of Disaster Risk Reduction*, **26**, 69-77, doi:https://doi.org/10.1016/j.ijdrr.2017.09.034.
Wanders, N., Y. Wada and H. A. J. Van Lanen, 2015: Global hydrological droughts in the 21st century under a changing hydrological regime. *Earth Syst. Dynam.*, **6** (1), 1-15, doi:10.5194/esd-6-1-2015.
Wang, J., J. Feng and Z. Yan, 2018: Impact of Extensive Urbanization on Summertime Rainfall in the Beijing Region and the Role of Local Precipitation Recycling. *Journal of Geophysical Research: Atmospheres*, **123** (7), 3323-3340, doi:10.1002/2017jd027725.
Wang, J., Y. Yang, J. Huang and B. Adhikari, 2019a: Adaptive irrigation measures in response to extreme weather events: empirical evidence from the North China plain. *Regional Environmental Change*, **19** (4), 1009-1022, doi:10.1007/s10113-018-1442-3.
Wang, K. et al., 2021a: Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of mekong river delta. *Resources, Conservation and Recycling*, **167**, 105390, doi:https://doi.org/10.1016/j.resconrec.2020.105390.
Wang, S., J. Huang and X. Yuan, 2021b: Attribution of 2019 Extreme Spring–Early Summer Hot Drought over Yunnan in Southwestern China. *Bulletin of the American Meteorological Society*, **102** (1), S91-S96, doi:10.1175/BAMS-D-20-0121.1.
Wang, S. and L. Zhou, 2017: Glacial Lake Outburst Flood Disasters and Integrated Risk Management in China. *International Journal of Disaster Risk Science*, **8** (4), 493-497, doi:10.1007/s13753-017-0152-7.
Wang, Y. et al., 2019b: Vulnerability of existing and planned coal-fired power plants in Developing Asia to changes in climate and water resources. *Energy & Environmental Science*, **12** (10), 3164-3181, doi:10.1039/C9EE02058F.
Wang, Y. and X. Chen, 2018: Are farmers' adaptations enhancing food production? Evidence from China. *Regional Environmental Change*, **18** (7), 2183-2196, doi:10.1007/s10113-018-1410-y.
Ward Jones, M. K., W. H. Pollard and B. M. Jones, 2019: Rapid initialization of retrogressive thaw slumps in the Canadian high Arctic and their response to climate and terrain factors. *Environmental Research Letters*, **14** (5), 055006, doi:10.1088/1748-9326/ab12fd.
Ward, M. et al., 2020: Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology & Evolution*, **4** (10), 1321-1326, doi:10.1038/s41559-020-1251-1.
Ward, P. J. et al., 2017: A global framework for future costs and benefits of river-flood protection in urban areas. *Nature Climate Change*, **7** (9), 642-646, doi:10.1038/nclimate3350.

Ward, P. S. and S. Makhija, 2018: New modalities for managing drought risk in rainfed agriculture: Evidence from a discrete choice experiment in Odisha, India. *World Development*, **107**, 163-175, doi:https://doi.org/10.1016/j.worlddev.2018.03.002.
Warner, B. P., C. Kuzdas, M. G. Yglesias and D. L. Childers, 2015: Limits to adaptation to interacting global change risks among smallholder rice farmers in Northwest Costa Rica. *Global Environmental Change*, **30**, 101-112, doi:https://doi.org/10.1016/j.gloenvcha.2014.11.002.
Warner, K. and T. Afifi, 2014: Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. *Climate and Development*, **6** (1), 1-17, doi:10.1080/17565529.2013.835707.
Warner, K. and K. van der Geest, 2013: Loss and damage from climate change: Local-level evidence from nine vulnerable countries. *International Journal of Global Warming*, **5**, 367-386, doi:10.1504/IJGW.2013.057289.
Warren, J. M. et al., 2015: Carbon dioxide stimulation of photosynthesis in Liquidambar styraciflua is not sustained during a 12-year field experiment. *AoB PLANTS*, **7**, doi:10.1093/aobpla/plu074.
Warszawski, L. et al., 2014: The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. *Proceedings of the National Academy of Sciences*, **111** (9), 3228-3232, doi:10.1073/pnas.1312330110.
Watson, J., B. Zheng, S. Chapman and K. Chenu, 2017: Projected impact of future climate on water-stress patterns across the Australian wheatbelt. *Journal of experimental botany*, **68**, doi:10.1093/jxb/erx368.
WEF, 2015: *Global Risks 2015*. World Economic Forum, Geneva, Switzerland [Available at: http://www.weforum.org/risks].
WEF, 2016: *The Global Risks Report 2016* **1**, World Economic Forum, Geneva, Switzerland.
WEF, 2017: *The Global Risks Report 2017*. World Economic Forum [Available at: https://doi.org/10.1017/CBO9781107415324.004].
WEF, 2018: *The Global Risks Report 2018* **14**, World Economic Forum [Available at: http://www3.weforum.org/docs/WEF_GRR18_Report.pdf].
WEF, 2019: *The Global Risks Report 2019*. World Economic Forum.
WEF, 2020: *The Global Risks Report 2020*. Forum, T. W. E., Geneva, Switzerland [Available at: http://www3.weforum.org/docs/WEF_Global_Risk_Report_2020.pdf].
Wesselbaum, D., 2021: Revisiting the climate driver and inhibitor mechanisms of international migration. *Climate and Development*, **13** (1), 10-20, doi:10.1080/17565529.2020.1711700.
West Colin, T., C. Roncoli and P. Yaka, 2016: Climate Variability in West Africa: A Case Study in Vulnerability and Adaptation on the Northern Central Plateau, Burkina Faso. In: The Economics of Ecology, Exchange, and Adaptation: Anthropological Explorations. Emerald Group Publishing Limited, **36**, 57-76.
Weston, P., R. Hong, C. Kaboré and C. A. Kull, 2015: Farmer-Managed Natural Regeneration Enhances Rural Livelihoods in Dryland West Africa. *Environmental Management*, **55** (6), 1402-1417, doi:10.1007/s00267-015-0469-1.
WGMS, 2017: *Global Glacier Change Bulletin No. 2 (2014-2015)* [Zemp, M., S. U. Nussbaumer, I. Gärtner-Roer, J. Huber, H. Machguth, F. Paul and M. Hoelzle (eds.)]. ICSU(WDS) / IUGG(IACS)/ UNEP / UNESCO / WMO, W. G. M. S., Zurich, Switzerland, 244.
White, C. J., T. W. Tanton and D. W. Rycroft, 2014: The Impact of Climate Change on the Water Resources of the Amu Darya Basin in Central Asia. *Water Resources Management*, **28** (15), 5267-5281, doi:10.1007/s11269-014-0716-x.
White, I. et al., 2017: *Climate Change & Stormwater and Wastewater Systems* Motu Economic and Public Policy Research. Motu Economic and Public Policy Research.
Whitehead, P. et al., 2015: Impacts of climate change and socio-economic scenarios on flow and water quality of the Ganges, Brahmaputra and Meghna (GBM) river systems: low flow and flood statistics. *Environmental Science: Processes & Impacts*, **17** (6), 1057-1069.
WHO, 2006: *WHO Guidelines for the safe use of wastewater, excreta and greywater*. World Health Organization (WHO), (WHO), W. H. O. [Available at: https://www.who.int/water_sanitation_health/sanitation-waste/wastewater/wastewater-guidelines/en/].
WHO, 2014: *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s.* . World Health Organization. [Available at: https://apps.who.int/iris/handle/10665/134014].
WHO, 2017: *Potable reuse - Guidance for producing safe drinking-water*. World Health Organization (WHO), (WHO), W. H. O. [Available at: https://www.who.int/water_sanitation_health/publications/potable-reuse-guidelines/en/].
WHO, 2019: *Progress on household drinking water, sanitation and hygiene 2000-2017: special focus on inequalities*. World Health Organization.
WHO and UNICEF, 2019: *WASH in health care facilities: Global Baseline Report 2019*. WHO and UNICEF, Geneva.
WHO and UNICEF, 2021: *Progress on household drinking water, sanitation and hygiene 2000-2020. Five Years into the SDGs*. (WHO), U. N. C. s. F. U. a. W. H. O., New York.
Whyte, K., 2017: The Dakota access pipeline, environmental injustice, and US colonialism. *Red Ink: An International Journal of Indigenous Literature, Arts, & Humanities*, (19.1).
Whyte, K., 2018: Settler colonialism, ecology, and environmental injustice. *Environment and Society*, **9** (1), 125-144.
Whyte, K., 2020: Too late for indigenous climate justice: Ecological and relational tipping points. *WIREs Climate Change*, **11** (1), e603, doi:https://doi.org/10.1002/wcc.603.

Wiederkehr, C., M. Beckmann and K. Hermans, 2018: Environmental change, adaptation strategies and the relevance of migration in Sub-Saharan drylands. *Environmental Research Letters*, **13** (11), 113003, doi:10.1088/1748-9326/aae6de.
Wijaya, N., 2015: Climate Change Adaption Measures in the Coastal City of Semarang, Indonesia: Current Practices and Performance. *Journal of Regional and City Planning; Vol 26, No 1 (2015)*.
Wilder, M. O. et al., 2016: Desalination and water security in the US–Mexico border region: assessing the social, environmental and political impacts. *Water International*, **41** (5), 756-775, doi:10.1080/02508060.2016.1166416.
Wilkinson, M. E., S. Addy, P. F. Quinn and M. Stutter, 2019: Natural flood management: small-scale progress and larger-scale challenges. Taylor & Francis, **135**, 23-32, doi:10.1080/14702541.2019.1610571.
Williams, D. S. et al., 2019: Vulnerability of informal settlements in the context of rapid urbanization and climate change. *Environment and Urbanization*, **31** (1), 157-176, doi:10.1177/0956247818819694.
Williams, E., 2020: Attributing blame?—climate accountability and the uneven landscape of impacts, emissions, and finances. *Climatic Change*, **161** (2), 273-290, doi:10.1007/s10584-019-02620-5.
Williams, P. A. et al., 2021: Feasibility assessment of climate change adaptation options across Africa: an evidence-based review. *Environmental Research Letters*, **16** (7), 073004, doi:10.1088/1748-9326/ac092d.
Wilmsen, B. and M. Webber, 2015: What can we learn from the practice of development-forced displacement and resettlement for organised resettlements in response to climate change? *Geoforum*, **58**, 76-85, doi:https://doi.org/10.1016/j.geoforum.2014.10.016.
Wilson, N. et al., 2019: Water is Medicine: Reimagining Water Security through Tr'ondëk Hwëch'in Relationships to Treated and Traditional Water Sources in Yukon, Canada. *Water*, **11**, 19, doi:10.3390/w11030624.
Wilson, N. J., 2019: "Seeing Water Like a State?": Indigenous water governance through Yukon First Nation Self-Government Agreements. *Geoforum*, **104**, 101-113.
Winsemius, H. C. et al., 2016: Global drivers of future river flood risk. *Nature Climate Change*, **6**, 381, doi:10.1038/nclimate2893
https://www.nature.com/articles/nclimate2893#supplementary-information.
Winsemius, H. C. et al., 2018: Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, **23** (3), 328-348, doi:10.1017/S1355770X17000444.
Winter, J. M., H. Huang, E. C. Osterberg and J. S. Mankin, 2020: Anthropogenic Impacts on the Exceptional Precipitation of 2018 in the Mid-Atlantic United States. *Bulletin of the American Meteorological Society*, **101** (1), S5-S10, doi:10.1175/BAMS-D-19-0172.1.
Winter, J. M. et al., 2017: Representing water scarcity in future agricultural assessments. *Anthropocene*, **18**, 15-26, doi:https://doi.org/10.1016/j.ancene.2017.05.002.
Witmer, F. D. et al., 2017: Subnational violent conflict forecasts for sub-Saharan Africa, 2015–65, using climate-sensitive models. *Journal of Peace Research*, **54** (2), 175-192, doi:10.1177/0022343316682064.
WMO, 2020: *2020 State of Climate Services: Risk information and early warning systems*. World Meteorological Organization (WMO), Geneva, Switzerland. [Available at: https://library.wmo.int/doc_num.php?explnum_id=10385].
WMO, 2021: *Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970-2019)*. (WMO), W. M. O. [Available at: https://public.wmo.int/en/media/news/atlas-of-mortality-and-economic-losses-from-weather-climate-and-water-extremes-1970-2019].
Wolf, J. et al., 2018: Impact of drinking water, sanitation and handwashing with soap on childhood diarrhoeal disease: updated meta-analysis and meta-regression. *Tropical Medicine & International Health*, **23** (5), 508-525, doi:10.1111/tmi.13051.
Wong, P. P. et al., 2014: Coastal systems and low-lying areas. *Climate change*, **2104**, 361-409.
Wood, B. T., C. H. Quinn, L. C. Stringer and A. J. Dougill, 2017: Investigating Climate Compatible Development Outcomes and their Implications for Distributive Justice: Evidence from Malawi. *Environmental Management*, **60** (3), 436-453, doi:10.1007/s00267-017-0890-8.
Woodward, G., D. M. Perkins and L. E. Brown, 2010: Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365** (1549), 2093-2106, doi:doi:10.1098/rstb.2010.0055.
Woolway, R. I. et al., 2021: Phenological shifts in lake stratification under climate change. *Nature Communications*, **12** (1), 2318, doi:10.1038/s41467-021-22657-4.
Work, K., 2020: Not just an arid landscape problem: Springflow declines in a region with high rainfall. *Limnologica*, **82**, 125766, doi:https://doi.org/10.1016/j.limno.2020.125766.
Workman, C. L. and H. Ureksoy, 2017: Water insecurity in a syndemic context: Understanding the psycho-emotional stress of water insecurity in Lesotho, Africa. *Social Science & Medicine*, **179**, 52-60, doi:10.1016/j.socscimed.2017.02.026.
World Bank, 2016: *High and Dry: Climate Change, Water, and the Economy*. The World Bank, Washington, DC [Available at: http://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy].
World Bank, 2017: *Green Bond Impact Report*. The World Bank, Washington, DC [Available at: http://pubdocs.worldbank.org/en/790081576615720375/IBRD-Green-Bond-Impact-Report-FY-2019.pdf].

World Bank, 2019: *Financing Climate Change Adaptation in Transboundary Basins: Preparing Bankable Projects*. World Bank, Washington, DC [Available at: http://documents.worldbank.org/curated/en/172091548959875335/pdf/134236-WP-PUBLIC.pdf].
Wossen, T. et al., 2017: Measuring the impacts of adaptation strategies to drought stress: The case of drought tolerant maize varieties. *Journal of environmental management*, **203**, 106-113, doi:https://doi.org/10.1016/j.jenvman.2017.06.058.
Wossen, T., T. Berger, M. G. Haile and C. Troost, 2018: Impacts of climate variability and food price volatility on household income and food security of farm households in East and West Africa. *Agricultural Systems*, **163**, 7-15, doi:https://doi.org/10.1016/j.agsy.2017.02.006.
WRI, 2019: *Unaffordable and Undrinkable : Rethinking Urban Water Access in the Global South* Washington D.C. [Available at: https://wriorg.s3.amazonaws.com/s3fs-public/unaffordable-and-undrinkable.pdf].
Wu, Q., Y. Hou, H. Yun and Y. Liu, 2015: Changes in active-layer thickness and near-surface permafrost between 2002 and 2012 in alpine ecosystems, Qinghai–Xizang (Tibet) Plateau, China. *Global and Planetary Change*, **124**, 149-155, doi:https://doi.org/10.1016/j.gloplacha.2014.09.002.
Wu, W.-Y. et al., 2020: Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nature Communications*, **11** (1), 3710, doi:10.1038/s41467-020-17581-y.
Wutich, A., A. Brewis and A. Tsai, 2020: Water and mental health. *WIREs Water*, **7** (5), e1461, doi:https://doi.org/10.1002/wat2.1461.
WWAP, 2019: *The United Nations World Water Development Report 2019: Leaving no one behind.*, UNESCO, Paris.
Xenarios, S. et al., 2019: Climate change and adaptation of mountain societies in Central Asia: uncertainties, knowledge gaps, and data constraints. *Regional Environmental Change*, **19** (5), 1339-1352, doi:10.1007/s10113-018-1384-9.
Yadav, S. S. and R. Lal, 2018: Vulnerability of women to climate change in arid and semi-arid regions: The case of India and South Asia. *Journal of Arid Environments*, **149**, 4-17, doi:https://doi.org/10.1016/j.jaridenv.2017.08.001.
Yager, K. et al., 2019: Socio-ecological dimensions of Andean pastoral landscape change: bridging traditional ecological knowledge and satellite image analysis in Sajama National Park, Bolivia. *Regional Environmental Change*, **19** (5), 1353-1369, doi:10.1007/s10113-019-01466-y.
Yalew, S. G. et al., 2020: Impacts of climate change on energy systems in global and regional scenarios. *Nature Energy*, **5** (10), 794-802, doi:10.1038/s41560-020-0664-z.
Yamba, S., D. O. Appiah and L. P. Siaw, 2019: Smallholder farmers' perceptions and adaptive response to climate variability and climate change in southern rural Ghana. *Cogent Social Sciences*, **5** (1), doi:10.1080/23311886.2019.1646626.
Yang, D., X. Shi and P. Marsh, 2015a: Variability and extreme of Mackenzie River daily discharge during 1973–2011. *Quaternary International*, **380**, 159-168.
Yang, J., V. Owusu, E. Andriesse and A. Dziwornu Ablo, 2019a: In-Situ Adaptation and Coastal Vulnerabilities in Ghana and Tanzania. *The Journal of Environment & Development*, **28** (3), 282-308, doi:10.1177/1070496519852992.
Yang, J. et al., 2019b: Projection of 21st century irrigation water requirement across the Lower Mississippi Alluvial Valley. *Agricultural Water Management*, **217**, 60-72, doi:https://doi.org/10.1016/j.agwat.2019.02.033.
Yang L., J. Scheffran, H. Qin and Q. You, 2015: Climate-related flood risks and urban responses in the Pearl River Delta, China. *Regional Environmental Change*, **15** (2), 379-391, doi:10.1007/s10113-014-0651-7.
Yang, R. et al., 2020: Glacier mass and area changes on the Kenai Peninsula, Alaska, 1986–2016. *Journal of Glaciology*, **66** (258), 603-617.
Yang, X., B. Yu and Q. G. Zhu, 2015b: Climate change impacts on rainfall erosivity and hillslope erosion in NSW. *Proc. - 21st Int. Congr. Model. Simulation, MODSIM 2015*, 1572-1578, doi:10.36334/modsim.2015.g4.yang.
Yang, Y. et al., 2016: Water use efficiency and crop water balance of rainfed wheat in a semi-arid environment: sensitivity of future changes to projected climate changes and soil type. *Theoretical and Applied Climatology*, **123** (3), 565-579, doi:10.1007/s00704-015-1376-3.
Yasarer, L. M. W. et al., 2017: Climate Change Impacts on Runoff, Sediment, and Nutrient Loads in an Agricultural Watershedin the Lower Mississippi River Basin. *Applied Engineering in Agriculture*, **33** (3), 379-392, doi:https://doi.org/10.13031/aea.12047.
Yasarer, L. M. W. and B. S. M. Sturm, 2016: Potential impacts of climate change on reservoir services and management approaches. *Lake and Reservoir Management*, **32** (1), 13-26, doi:10.1080/10402381.2015.1107665.
Yates, O. E. T., S. Manuela, A. Neef and S. Groot, 2021: Reshaping ties to land: a systematic review of the psychosocial and cultural impacts of Pacific climate-related mobility. *Climate and Development*, 1-18, doi:10.1080/17565529.2021.1911775.
Yokohata, T. et al., 2020a: MIROC-INTEG-LAND version 1: a global biogeochemical land surface model with human water management, crop growth, and land-use change. *Geosci. Model Dev.*, **13** (10), 4713-4747, doi:10.5194/gmd-13-4713-2020.
Yokohata, T. et al., 2020b: Model improvement and future projection of permafrost processes in a global land surface model. *Progress in Earth and Planetary Science*, **7** (1), 69, doi:10.1186/s40645-020-00380-w.

Young, S. L. et al., 2019: The Household Water InSecurity Experiences (HWISE) Scale: development and validation of a household water insecurity measure for low-income and middle-income countries. *BMJ Global Health*, **4** (5), e001750, doi:10.1136/bmjgh-2019-001750.
Yu, Q.-y. et al., 2014: Interpretation of Climate Change and Agricultural Adaptations by Local Household Farmers: a Case Study at Bin County, Northeast China. *Journal of Integrative Agriculture*, **13** (7), 1599-1608, doi:https://doi.org/10.1016/S2095-3119(14)60805-4.
Yuan, X., S. Wang and Z.-Z. Hu, 2018: Do Climate Change and El Niño Increase Likelihood of Yangtze River Extreme Rainfall? *Bulletin of the American Meteorological Society*, **99** (1), S113-S117, doi:10.1175/BAMS-D-17-0089.1.
Yung, L. et al., 2015: Drought Adaptation and Climate Change Beliefs among Working Ranchers in Montana. *Weather, Climate, and Society*, **7** (4), 281-293, doi:10.1175/WCAS-D-14-00039.1.
Zaherpour, J. et al., 2018: Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts. *Environmental Research Letters*, **13** (6), 065015, doi:10.1088/1748-9326/aac547.
Zang, C. and J. Liu, 2013: Trend analysis for the flows of green and blue water in the Heihe River basin, northwestern China. *Journal of Hydrology*, **502**, 27-36, doi:https://doi.org/10.1016/j.jhydrol.2013.08.022.
Zarfl, C. et al., 2019: Future large hydropower dams impact global freshwater megafauna. *Scientific Reports*, **9** (1), 18531, doi:10.1038/s41598-019-54980-8.
Zarroca, M. et al., 2021: Natural acid rock drainage in alpine catchments: A side effect of climate warming. *Science of The Total Environment*, **778**, 146070, doi:https://doi.org/10.1016/j.scitotenv.2021.146070.
Zavaleta-Cortijo, C. et al., 2020: Climate change and COVID-19: reinforcing Indigenous food systems. *The Lancet Planetary Health*, **4** (9), e381-e382, doi:10.1016/S2542-5196(20)30173-X.
Zaveri, E. and D. B. Lobell, 2019: The role of irrigation in changing wheat yields and heat sensitivity in India. *Nature Communications*, **10** (1), 4144, doi:10.1038/s41467-019-12183-9.
Zaveri, E. et al., 2016: Invisible water, visible impact: groundwater use and Indian agriculture under climate change. *Environmental Research Letters*, **11** (8), 084005, doi:10.1088/1748-9326/11/8/084005.
Zehra, D. et al., 2019: Rapid flood risk assessment of informal urban settlements in Maputo, Mozambique: The case of Maxaquene A. *International Journal of Disaster Risk Reduction*, **40**, 101270, doi:https://doi.org/10.1016/j.ijdrr.2019.101270.
Zemp, M. et al., 2015: Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology*, **61** (228), 745-762, doi:10.3189/2015JoG15J017.
Zemp, M. et al., 2019: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, **568** (7752), 382-386, doi:10.1038/s41586-019-1071-0.
Zeng Z et al., 2018: Impact of Earth Greening on the Terrestrial Water Cycle. *Journal of Climate*, **31** (7), 2633-2650, doi:10.1175/jcli-d-17-0236.1.
Zeng, Z., L. Peng and S. Piao, 2018: Response of terrestrial evapotranspiration to Earth's greening. *Current opinion in environmental sustainability*, **33**, 9-25, doi:https://doi.org/10.1016/j.cosust.2018.03.001.
Zeng, Z. et al., 2017: Climate mitigation from vegetation biophysical feedbacks during the past three decades. *Nature Climate Change*, **7**, 432, doi:10.1038/nclimate3299
https://www.nature.com/articles/nclimate3299#supplementary-information.
Zeng, Z. et al., 2014: A worldwide analysis of spatiotemporal changes in water balance-based evapotranspiration from 1982 to 2009. *Journal of Geophysical Research: Atmospheres*, **119** (3), 1186-1202, doi:10.1002/2013jd020941.
Zevenbergen, C., J. Rijke, S. Van Herk and P. J. T. M. Bloemen, 2015: Room for the River: a stepping stone in Adaptive Delta Management. *International Journal of Water Governance*, **3** (3), 121-140, doi:10.7564/14-IJWG63.
Zhai, R. and F. Tao, 2017: Contributions of climate change and human activities to runoff change in seven typical catchments across China. *Science of The Total Environment*, **605-606**, 219-229, doi:https://doi.org/10.1016/j.scitotenv.2017.06.210.
Zhai, R. et al., 2020: Larger Drought and Flood Hazards and Adverse Impacts on Population and Economic Productivity Under 2.0 than 1.5°C Warming. *Earth's Future*, **8** (7), e2019EF001398, doi:https://doi.org/10.1029/2019EF001398.
Zhang, C. et al., 2016a: Revealing Water Stress by the Thermal Power Industry in China Based on a High Spatial Resolution Water Withdrawal and Consumption Inventory. *Environmental Science & Technology*, **50** (4), 1642-1652, doi:10.1021/acs.est.5b05374.
Zhang, F. et al., 2019: Water availability on the Third Pole: A review. *Water Security*, **7**, 100033, doi:https://doi.org/10.1016/j.wasec.2019.100033.
Zhang G. et al., 2020: Tropical cyclone motion in a changing climate. *Science Advances*, **6** (17), eaaz7610, doi:10.1126/sciadv.aaz7610.
Zhang, H., Y. Xu and T. Kanyerere, 2020a: A review of the managed aquifer recharge: Historical development, current situation and perspectives. *Physics and Chemistry of the Earth, Parts A/B/C*, **118-119**, 102887, doi:https://doi.org/10.1016/j.pce.2020.102887.
Zhang K et al., 2015: Vegetation Greening and Climate Change Promote Multidecadal Rises of Global Land Evapotranspiration. *Scientific Reports*, **5**, 15956, doi:10.1038/srep15956
https://www.nature.com/articles/srep15956#supplementary-information.

Zhang, L., J. Wang, G. Zhang and Q. Huang, 2016b: Impact of the methods of groundwater access on irrigation and crop yield in the North China Plain: Does climate matter? *China Agricultural Economic Review*, **8** (4), 613-633, doi:10.1108/CAER-12-2015-0177.
Zhang, Q., F. Zhang, S. Kang and Z. Cong, 2017: Melting glaciers: Hidden hazards. *Science*, **356** (6337), 495-495, doi:10.1126/science.aan4118.
Zhang, W. et al., 2020b: Anthropogenic Influence on 2018 Summer Persistent Heavy Rainfall in Central Western China. *Bulletin of the American Meteorological Society*, **101** (1), S65-S70, doi:10.1175/BAMS-D-19-0147.1.
Zhang W., G. Villarini, G. A. Vecchi and J. A. Smith, 2018: Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. *Nature*, **563** (7731), 384-388, doi:10.1038/s41586-018-0676-z.
Zhang Y et al., 2016: Multi-decadal trends in global terrestrial evapotranspiration and its components. *Scientific Reports*, **6**, 19124, doi:10.1038/srep19124
https://www.nature.com/articles/srep19124#supplementary-information.
Zhao F. et al., 2020: Materials for solar-powered water evaporation. *Nature Reviews Materials*, **5** (5), 388-401, doi:10.1038/s41578-020-0182-4.
Zhao, M. et al., 2020: Ecological restoration impact on total terrestrial water storage. *Nature Sustainability*, doi:10.1038/s41893-020-00600-7.
Zhao, T. and A. Dai, 2015: The Magnitude and Causes of Global Drought Changes in the Twenty-First Century under a Low–Moderate Emissions Scenario. *Journal of Climate*, **28** (11), 4490-4512, doi:10.1175/jcli-d-14-00363.1.
Zhao, X. et al., 2015: Physical and virtual water transfers for regional water stress alleviation in China. *Proceedings of the National Academy of Sciences*, **112** (4), 1031-1035, doi:10.1073/pnas.1404130112.
Zheng, H. et al., 2018: Closing water productivity gaps to achieve food and water security for a global maize supply. *Scientific Reports*, **8** (1), 14762, doi:10.1038/s41598-018-32964-4.
Zhou, C., K. Wang and D. Qi, 2018a: Attribution of the July 2016 Extreme Precipitation Event Over China's Wuhang. *Bulletin of the American Meteorological Society*, **99** (1), S107-S112, doi:10.1175/BAMS-D-17-0090.1.
Zhou, Q. et al., 2018b: Cooling Water Sufficiency in a Warming World: Projection Using an Integrated Assessment Model and a Global Hydrological Model. *Water*, **10** (7), 872.
Zhou, X. et al., 2021: Did water-saving irrigation protect water resources over the past 40 years? A global analysis based on water accounting framework. *Agricultural Water Management*, **249**, 106793, doi:https://doi.org/10.1016/j.agwat.2021.106793.
Zhou, Y. et al., 2020: Distinguishing the multiple controls on the decreased sediment flux in the Jialing River basin of the Yangtze River, Southwestern China. *CATENA*, **193**, 104593, doi:https://doi.org/10.1016/j.catena.2020.104593.
Zhu, Q. et al., 2020: Extreme rainfall, rainfall erosivity, and hillslope erosion in Australian Alpine region and their future changes. *International Journal of Climatology*, **40** (2), 1213-1227, doi:https://doi.org/10.1002/joc.6266.
Zhu Z et al., 2016: Greening of the Earth and its drivers. *Nature Climate Change*, **6** (8), 791-795, doi:10.1038/nclimate3004.
Zhuo, L. and A. Y. Hoekstra, 2017: The effect of different agricultural management practices on irrigation efficiency, water use efficiency and green and blue water footprint. *Front. Agr. Sci. Eng.*, **4** (2), 185-194, doi:10.15302/j-fase-2017149.
Zickgraf, C., 2018: Immobility. In: Routledge Handbook of Environmental Displacement and Migration. Routledge, 71-84.
Zipper, S. C., J. Qiu and C. J. Kucharik, 2016: Drought effects on US maize and soybean production: spatiotemporal patterns and historical changes. *Environmental Research Letters*, **11** (9), 094021.
Zografos, C., M. C. Goulden and G. Kallis, 2014: Sources of human insecurity in the face of hydro-climatic change. *Global Environmental Change*, **29**, 327-336, doi:https://doi.org/10.1016/j.gloenvcha.2013.11.002.
Zouabi, O., 2021: Climate change and climate migration: issues and questions around an in-transition Tunisian economy. *Climatic Change*, **164** (3), 32, doi:10.1007/s10584-021-03006-2.
Zougmoré, R. et al., 2016: Toward climate-smart agriculture in West Africa: a review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agriculture & Food Security*, **5** (1), 26, doi:10.1186/s40066-016-0075-3.
Zscheischler, J. et al., 2020: A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, **1** (7), 333-347, doi:10.1038/s43017-020-0060-z.
Zscheischler, J. et al., 2018: Future climate risk from compound events. *Nature Climate Change*, **8** (6), 469-477, doi:10.1038/s41558-018-0156-3.

Chapter 5: Food, Fibre, and other Ecosystem Products

Coordinating Lead Authors: Rachel Bezner Kerr (USA/Canada), Toshihiro Hasegawa (Japan), Rodel Lasco (Philippines)

Lead Authors: Indra Bhatt (India), Delphine Deryng (Germany/France), Aidan Farrell (Trinidad and Tobago/Ireland), Helen Gurney-Smith (Canada/United Kingdom), Hui Ju (China), Salvador Lluch-Cota (Mexico), Francisco Meza (Chile), Gerald Nelson (USA), Henry Neufeldt (Denmark/Germany), Philip Thornton (Kenya/United Kingdom)

Contributing Authors: Guleid Artan (Kenya/Somalia), Ayansina Ayanlade (Nigeria), Marta Baraibar (Kenya/Spain), Manuel Barange (South Africa/Italy), Mucahid Mustafa Bayrak (The Netherlands), Ermias A. Betemariam (Kenya/Ethiopia), Edwin Castellanos (Guatemala), William Cheung (Canada), Priscilla Claeys (Belgium), Jennifer Clapp (Canada), Verónica Crespo-Pérez (Ecuador), Shouro Dasgupta (Italy/Bangladesh), Deborah Delgado Pugley (Peru), Alice Favero (USA), Jennifer Franco (The Netherlands), Eranga Galappaththi (Canada/Sri Lanka), Amelie Gaudin (USA/France), Adugna Gemeda (Ethiopia), Patrick Gonzalez (USA), Jack Heinemann (New Zealand/USA), Ann Kingiri (Kenya), Xiaoyue Li (China), Ana Maria Loboguerrero (Colombia), Dianne Mayberry (Australia), Kenneth Kemucie Mwangi (Kenya), Christine Negra (USA), Kari Marie Norgaard (USA), Hanson Nyantakyi-Frimpong (USA/Ghana), Patricia Pinho (Brazil), Julio C. Postigo (USA/Peru), Bronwen Powell (Canada), Victoria Reyes-García (Spain), Marta Rivera-Ferre (Spain), Abubakr A.M. Salih (Kenya/Sudan), Arnim Scheidel (Spain/Austria), Matthew Schnurr (Canada), Anna Schlingmann (Spain/Germany), Rupert Seidl (Germany), Gudeta W. Sileshi (Tanzania), Doris Soto (Chile), Pete Smith (United Kingdom), Elizabeth Sprout (United Kingdom/USA), M. Cristina Tirado-von der Pahlen (USA/Spain), Hitomi Wakatsuki (Japan), Jennifer Vanos (Canada), Lewis Ziska (USA), Robert Zougmoré (Burkina Faso)

Review Editors: Pauline Dube (Botswana), James Morison (United Kingdom)

Chapter Scientists: Emily Baker (USA), Hitomi Wakatsuki (Japan), Elizabeth Sprout (United Kingdom/USA)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Current Impacts

Climate change impacts are stressing agriculture, forestry, fisheries, and aquaculture, increasingly hindering efforts to meet human needs (*high confidence*[1]). Human-induced warming has slowed growth of agricultural productivity over the past 50 years in mid- and low-latitudes (*medium confidence*). Crop yields are compromised by surface ozone (*high confidence*). Methane emissions have negatively impacted crop yields by increasing temperatures and surface ozone concentrations (*medium confidence*). Warming is negatively affecting crop and grassland quality and harvest stability (*high confidence*). Warmer and drier conditions have increased tree mortality and forest disturbances in many temperate and boreal biomes (*high confidence*), negatively impacting provisioning services (*medium confidence*). Ocean warming has decreased sustainable yields of some wild fish populations (*high confidence*). Ocean acidification and warming have already affected farmed aquatic species (*high confidence*). {5.2.1, 5.4.1, 5.5.1, 5.6.1, 5.7.1, 5.8.1, 5.9.1}

Warming has altered the distribution, growing area suitability and timing of key biological events, such as flowering and insect emergence, impacting food quality and harvest stability *(high confidence)*. It is *very likely*[2] that climate change is altering the distribution of cultivated, wild terrestrial, marine and freshwater species. At higher-latitudes warming has expanded potential area but has also altered phenology (*high confidence*), potentially causing plant-pollinator and pest mismatches (*medium confidence*). At low-latitude temperatures have crossed upper tolerance thresholds more frequently leading to heat stress (*high confidence*). {5.4.1, 5.7.4, 5.8.1, Cross-Chapter Box MOVING PLATE this Chapter , 5.12.3.4}

Climate-related extremes have affected the productivity of all agricultural and fishery sectors, with negative consequences for food security and livelihoods (*high confidence*). The frequency of sudden food production losses has increased since at least mid-20th century on land and sea *(medium evidence, high agreement)*. Droughts, floods, and marine heatwaves contribute to reduced food availability and increased food prices, threatening food security, nutrition, and livelihoods of millions *(high confidence)*. Droughts induced by the 2015-2016 El Niño, partially attributable to human influences (*medium confidence*), caused acute food insecurity in various regions, including eastern and southern Africa and the dry corridor of Central America (*high confidence*). In the northeast Pacific, a recent 5-year warm period impacted the migration, distribution, and abundance of key fish resources (*high confidence*). Increasing variability in grazing systems has negatively affected animal fertility, mortality, and herd recovery rates, reducing livestock keepers' resilience (*medium confidence*). {WGI AR6 Sections 11.2-11.8, 5.2.1, 5.4.1, 5.4.2, 5.5.2,5.8.1, 5.9.1, 5.12.1, 5.14.2, 5.14.6, Cross-Chapter Box MOVING PLATE this Chapter}

Climate change impacts everybody, but vulnerable groups, such as women, children, low-income households, Indigenous or other minority groups and small-scale producers, are often at higher risk of malnutrition, livelihood loss, rising costs and competition over resources (*high confidence*). Increasing competition for land, energy, and water, exacerbates impacts of climate change on food security (*high confidence)*. {5.4.2.2, 5.5.2.6; 5.8.2.2, 5.9.2.1, 5.12.2, 5.12.3.1; 5.12.3.2; 5.12.3.3; 5.13.1, 5.13.3, 5.13.4}

Projected Impacts

Climate change will make some current food production areas unsuitable (*high confidence*). Current global crop and livestock areas will increasingly become climatically unsuitable under a high emission scenario (*high confidence*) (e.g.,10% by 2050, over 30 % by 2100 under SSP-8.5 vs below 8% by 2100 under SSP1-2.6). Increased, potentially concurrent climate extremes will periodically increase simultaneous losses

---

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. This Report also uses the term 'likely range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

in major food-producing regions (*medium confidence*). {WGI Section 11.8, 5.2.2, 5.4.1, 5.4.3, 5.5.2, 5.5.3, Cross-Chapter Box MOVING PLATE in Chapter 5 this Chapter, Section 5.12.4}

Impacts on food availability and nutritional quality will increase the number of people at risk of hunger, malnutrition and diet-related mortality (*high confidence*). Climate change will increase the number of people at risk of hunger in mid-century, concentrated in Sub-Saharan Africa, South Asia and Central America (*high confidence*) (e.g. between 8 million under SSP1-6.0 to 80 million people under SSP3-6.0). Increased CO_2 concentrations will reduce nutrient density in some crops (*high confidence*). Climate change will increase loss of years of full health[3] by 10% in 2050 under RCP8.5 due to undernutrition and micronutrient deficiencies (*medium evidence, high agreement*). {5.2.2, 5.4.2, 5.4.3, 5.12.1.2, 5.12.4; Cross-Chapter Box MOVING PLATE this Chapter}

Climate change will increasingly expose outdoor workers and animals to heat stress, reducing labour capacity, animal health, and dairy and meat production (*high confidence*). The number of days with climatically stressful conditions for outdoor workers will increase by up to 250 workdays per year by century's end in some parts of South Asia, tropical sub-Saharan Africa and parts of Central and South America under SSP5-8.5, with negative consequences such as reduced food productivity, higher costs and prices (*medium confidence*). From early-to end-century, cattle, sheep, goats, pigs and poultry in the low latitudes will face 72-136 additional days per year of extreme stress from high heat and humidity under SSP5-8.5. Meat and milk productivity will be reduced (*medium confidence*). {5.5.3.4; 5.12.4}

Climate change will further increase pressures on terrestrial ecosystem services supporting global food systems (*high confidence*). Climate change will reduce the effectiveness of pollinator agents as species are lost from certain areas, or the coordination of pollinator activity and flower receptiveness is disrupted in some regions (*high confidence*). Greenhouse gas emissions will negatively impact air, soil, and water quality, exacerbating direct climatic impacts on yields (*high confidence)*. {5.4.3, Box5.3, Box5.4, 5.5.3.4; 5.7.1, 5.7.4, 5.10.3}

Climate change will significantly alter aquatic food provisioning services and water security with regional variances (*high confidence*). Climate change will reduce marine fisheries and aquaculture productivity, altering the species that will be fished or cultured, and reducing aquaculture habitat in tropical and sub-tropical areas (*high confidence*).. Global ocean animal biomass will decrease by 5 to 17% under RCP2.6 and 8.5 respectively from 1970 to 2100 with an average decline of 5% for every 1°C of warming, affecting food provisioning, revenue value and distribution, (*medium confidence*). Global marine aquaculture will decline under warming and acidification from 2020 to 2100, with potential short-term gains for temperate finfish and overall negative impacts on bivalve aquaculture from habitat reduction (50-100% for some countries in the Northern Hemisphere) (*medium confidence*). Changes in precipitation, sea level, temperature, and extreme climate events will affect food provisioning from inland and coastal aquatic systems (*high confidence*). Sea-level rise and altered precipitation will increase coastal inundation and water conflicts between water-dependent sectors, such as rice production, direct human use, and hydropower (*medium confidence*). {5.8.3, 5.9.3, 5.13, Cross-Chapter Box SLR in Chapter 3}.

The occurrence and distribution of pests, weeds and diseases, including zoonoses, in agricultural, forest and food systems (terrestrial and aquatic) will be altered and their control will become costlier (*medium confidence*). Changes in the rates of reproduction and distribution of weeds, insect pests, pathogens and disease vectors will increase biotic stress on crops, forests, and livestock, and will increase the risk of biodiversity loss and ecosystem degradation (*medium evidence, high agreement*). Risks will increase for climate-driven emerging zoonoses (*medium evidence, high agreement*). {5.4.1.3, 5.9.4, Cross-Chapter Box MOVING PLATE this Chapter}

Forest production systems will have variable responses to climate change across regions, with negative effects being more predominant in tropical forests (*high confidence*). In temperate and boreal regions, some productivity gains are projected, but tree mortality will increase in some areas (*high confidence*). In tropical forests, change in species composition and forest structure will lower production *(medium confidence*). Some models project a possible increase in global wood supply and lowering of average wood

[3] Disability-Adjusted Life Years or DALYs.

prices, but they do not account for the negative impacts of extreme events and thus possibly overestimate the wood supply (*medium confidence*). {5.6.2}

Climate change will negatively impact food safety (*high confidence*). Higher temperatures and humidity will favour toxigenic fungi, plant and animal-based pathogens, and harmful algal blooms (HABs) (*high confidence*). More frequent and intense flood events and increased melting of snow and ice will increase food contamination (*high confidence*). Incidence and severity of harmful algal blooms and water-borne diseases will increase, as will indirect effects from infrastructure damage during extreme events (*high confidence*). {5.4.3, 5.5.2.3, 5.8.1, 5.8.2, 5.8.3, 5.9.1, 5.11.1, 5.11.3, 5.12.3; Cross-Chapter Box ILLNESS in Chapter 2}

Adaptation

Many autonomous adaptation options have been implemented in both terrestrial and aquatic systems, but on-farm adaptations are insufficient to meet SDG2 (*high confidence*). Autonomous responses include livestock and farm management, switching varieties/species and altered timing of key farm activities such as planting or stocking (*high confidence*). However, because of limited adaptive capacities and non-climatic compounding drivers of food insecurity, SDG2 will not be met (*high confidence*). {Table 5.1, 5.4.4; 5.5.4, 5.9.4, 5.10.4; 5.12.4}

Various adaptation options are currently feasible and effective at reducing climate impacts in different socio-cultural, economic, and geographical contexts (*high confidence*) but some lack adequate economic or institutional feasibility or information on limits (*medium confidence*). Feasible and effective options include cultivar improvements, community-based adaptation, agricultural diversification, climate services, adaptive eco-management in fisheries and aquaculture. There is *limited evidence, medium agreement* on the institutional feasibility or cost effectiveness of adaptation activities, and the limits to such adaptations. {5.4.4, 5.5.4, 5.6.3, 5.8.4, 5.9.4, 5.10.4, 5.11.4, 5.12.4, 5.14.1}

Ecosystem-based approaches such as diversification, land restoration, agroecology, and agroforestry have the potential to strengthen resilience to climate change with multiple co-benefits but trade-offs and benefits vary with socio-ecological context (*high confidence*). Ecosystem-based approaches support long-term productivity and ecosystem services such as pest control, soil health, pollination and buffering of temperature extremes (*high confidence*), but potential and trade-offs vary by socio-economic context, ecosystem zone, species combinations and institutional support (*medium confidence*). {5.4.4.4, 5.6.3, 5.10.4, 5.14.1, Cross-Chapter Box NATURAL in Chapter 2; Cross-Working Group Box BIOECONOMY this Chapter}

Bio-based products as part of a circular bioeconomy have potential to support adaptation and mitigation, with sectoral integration, transparent governance and stakeholder involvement key to maximizing benefits and managing trade-offs (*high confidence*). A sustainable bioeconomy relying on bioresources will need to be supported by technology innovation and international cooperation and governance of global trade to disincentivize environmental and social externalities (*medium confidence*). {Cross-Working Group Box BIOECONOMY this Chapter}

Sustainable resource management in response to distribution shifts of terrestrial and aquatic species under climate change is an effective adaptation option to reduce food and nutritional risk, conflict and loss of livelihood (*medium confidence*). Adaptive transboundary governance and ecosystem-based management, livelihood diversification, capacity development and improved knowledge-sharing will reduce conflict and promote the fair distribution of sustainably-harvested wild products and revenues (*medium confidence*). Other options include shared quotas and access rights considering trade-offs, shifting livelihoods to follow target species, new markets for emerging species, and technology {Cross Chapter Box MOVING PLATE this Chapter, 5.8.4, 5.14.3.4}

Implemented adaptation in crop production will be insufficient to offset the negative effects of climate change (*high confidence*). Currently available management options have the potential to compensate global crop production losses due to climate change up to ~2-°C warming, but the negative impacts even with adaptation will grow substantially from the mid-century under high temperature change scenarios (*high* *confidence*). Regionally, the negative effects will prevail sooner where current temperatures are already higher as in lower latitudes (*high confidence)*. {5.2.2, 5.4.3, 5.4.4, 5.8.4, 5.9.4, 5.14.2.4}

Supportive public policies will enhance effectiveness and/or feasibility of adaptation in ecosystem provisioning services (*medium confidence*). Policies that support system transitions include shifting subsidies, removing perverse incentives, regulation and certification, green public procurement, investment in sustainable value chains, support for capacity-building, access to insurance premiums and payments for ecosystem services, social protection, among others (*medium confidence*). {5.4.4.3; 5.4.4.4; 5.10.4.4; 5.12.6; 5.13.4; 5.14.1.3; 5.14.2.4; Box 5.13, Cross-Working Group Box BIOECONOMY in Chapter 2}.

Harnessing youth innovation and vision alongside other SDGs such as gender equity, Indigenous knowledge, local knowledge, urban and rural livelihoods, will support effective climate change adaptation to ensure resilient economies in food systems (*high confidence*). Adaptation strategies that address power inequities lead to co-benefits in equity outcomes and resilience for vulnerable groups (*medium confidence*). Indigenous knowledge and local knowledge facilitate adaptation strategies for ecosystem provisioning, especially when combined with scientific knowledge using participatory and community-based approaches (*high confidence*). {5.4.4.3, Table 5.6, 5.6.3, 5.8.4, 5.9.2, 5.9.4.1, 5.9.5, 5.10.2.2, 5.12.7, 5.12.8, 5.13.4, 5.13.5, 5.14.1.1, 5.14.1.2, 5.14.1.4,5.14.2.1, Box 5.13, 5.14.2.2 }

Policy decisions related to climate change adaptation and mitigation that ignore or worsen risks of adverse effects for different groups and ecosystems increase vulnerability, negatively affect capacity to deal with climate impacts, and impede sustainable development (*medium confidence with robust evidence, medium agreement*). Lacking sufficient stakeholder participation, large-scale land acquisitions have had mostly negative implications for vulnerable groups and climate change adaptation (*high confidence*). Policy and program appraisal of adaptation options that consider the risks of adverse effects across different groups at different scales and use inclusive rights-based approaches help avoid maladaptation (*medium confidence*). Successful forest adaptation involves recognition of land rights and cooperation with Indigenous Peoples and other local communities who depend on forest resources (*high confidence*). {5.6.3; 5.12.3, 5.13.1; 5.13.2; 5.14.2.1}

Financial barriers limit implementation of adaptation options in agriculture, fisheries, aquaculture and forestry and vastly more public and private investment is required (*high confidence)*. Public-sector investment in adaptation of agriculture, forestry and fisheries has grown four-fold since 2010 but adaptation costs will be much higher to meet future adaptation needs (*medium confidence*). Expanding access to financial services and pooling climate risks will enable and incentivize climate change adaptation (*medium confidence*). {5.14.3, 5.14.5., Cross-Chapter Box FINANCE in Chapter 17}.

Climate-resilient development pathways offer a way forward to guide climate action in food system transitions, but operationalisation is hampered by limited indicators and analyses (*medium confidence*). Robust analyses are needed that detail plausible pathways to move towards more resilient, equitable and sustainable food systems in ways that are socially, economically and environmentally acceptable through time (*high confidence*). Appropriate monitoring and rapid feedback to food system actors will be critical to the success of many current and future adaptation actions (*high confidence*). {5.14.4}

5.1 Introduction

5.1.1 Scope of the Chapter

This chapter assesses the scientific literature produced after AR5 dealing with past, current, and future climate change effects on managed ecosystems that provide provisioning and cultural services. It spans low and high intensity production systems for food, feed, fibre, and other ecosystem products.

Climate change has already had global impacts, including high income countries. Special emphasis is placed on the assessment of vulnerabilities of particular groups that are context- and location-specific, such as Indigenous Peoples and other minorities, women and small-scale food producers. The report builds on the IPCC AR5 and recent Special Reports. This chapter combines food systems, fibre, wood, and other products from ecosystems previously detailed in separate chapters of AR5, with an increased focus on ecosystem services, including the long-term sustainability of the global food system (Figure 5.1). The chapter focuses on key climate risks, implementation and outcomes of adaptation solutions for different groups as well as limits to adaptation.

5.1.2 Starting Point: AR5 and Recent IPCC Special Reports

AR5 Chapter 7 reported with *high confidence* that food production systems were being negatively impacted by climate change, including both terrestrial and aquatic food species (Porter et al., 2014). Increased temperatures will have large negative impacts on the food production system under 2°C warming by late 20th century, with temperatures exceeding 4°C posing even greater risk to global food security (Porter et al., 2014). Adaptation options are needed to reduce the risk from climate change, but there was limited information of their effectiveness.

The 1.5°C Special Report concluded that climate-related risks to food security will rise under 1.5°C and will increase further under 2°C or higher. Above 1.5°C, currently available adaptation options will be much less effective and site-specific limits to adaptation will be reached for vulnerable regions and sectors. There was *high confidence* that limiting warming to 1.5°C will result in smaller net reductions in yields of major crops affecting food availability and nutrition, and that rising temperatures will adversely affect livestock via changes in feed quality, fertility, production, spread of diseases and water availability.

The SRCCL expanded beyond the 1.5°C report to provide more in-depth information on climate change interactions with food security, desertification, and degradation. There was *high confidence* that climate risks, both for slow changes and extreme events, are interlinked with ecosystem services, health, and food security, often cascading and potentially reinforcing effects. Climate change already affects all dimensions of food security, namely availability, access, utilization, and stability, by disrupting food production, quality, storage, transport, and retail. These effects exacerbate competition for land and water resources, leading to increased deforestation, biodiversity reduction and loss of wetlands. With *high certainty*, limiting global warming would lower future risks related to land, such as water scarcity, fire, vegetation shifts, degradation, desertification and food insecurity and malnutrition, particularly for those most vulnerable today: small-scale food producers in low-income countries, Indigenous communities, women, and the urban poor. SRCCL assessed a range of adaptation pathways to increase food resilience.

The SROCC identified climate change impacts of warming, deoxygenation and acidification of the ocean and reductions in snow, sea ice and glaciers as having major negative impacts on fisheries and crops watered from mountain runoff, agriculture. These impacts affect food provisioning of food and directly threatening livelihoods and food security of vulnerable coastal communities and glacier-fed river basins. Climate change impacts on fisheries will be particularly high in tropical regions, where reductions in catch are expected to be among the largest globally, leading to negative economic and social effects for fishing communities and with implications for the supply of fish and shellfish (*high confidence*). While specific impacts will depend on the level of global warming and mitigative action to improve fisheries and aquaculture management, some current management practices and extraction levels may not be viable in the future.

5.1.3 Chapter Framework

This chapter is taking a food systems approach similar to the food security chapter in SRCCL (Mbow et al., 2019), with close attention to food system linkages, interactions and impacts on ecosystem services and biodiversity (Steffen et al., 2015; Raworth, 2017; Gerten et al., 2020). Climate change directly affects food systems, and the impacts on terrestrial or aquatic food production will become increasingly negative, although regionally some changes may be beneficial in the near future (Porter et al., 2014). Current food system trajectories are leading to biodiversity loss, land and aquatic ecosystem degradation without delivering food security and nutrition, sustainable and healthy livelihoods to many (Steffen et al., 2015). Addressing climate change in isolation ignores these interconnections, which is why the chapter considers integrated adaptation solutions to allow humanity to thrive in the long term. At the same time, social foundations of equality, justice and political participation are crucial in order to move toward a safe operating space for humanity (Raworth, 2017). The SDGs provide the most comprehensive set of metrics of humanity's progress in achieving equitable and thriving socio-ecological systems. Therefore, while the focus of this chapter is climate change impacts, vulnerability and adaptation of food systems, feed, fibre and other ecosystem products, other environmental and social challenges are considered concomitantly.

Food system and natural systems interact via political, economic, social, cultural, and demographic factors in complex ways, leading to food security and sustainability outcomes. The food system has a supply (production) and demand (consumption) side, connected via processing, trade and retail, with loss and waste streams all along the food chain. Natural ecosystems provide multiple services (regulating, supporting, provisioning, cultural) to the food system. Food security and nutrition strongly depend on the driving forces connecting food and natural systems while at the same time positively or negatively influencing them. Climate change frequently exacerbates the effects of other drivers of change, further limiting the environment within which humanity can safely operate and thrive. The chapter assesses how climate change affects the four pillars of food security and nutrition and how these effects can be mediated by various factors, including our adaptation responses, social equity, underlying ecosystem services and governance (Figure 5.1). Adaptation solutions are a major emphasis of this chapter, including many ecosystem-based adaptation options (Table 5.1), which fall under the broader umbrella of nature-based solutions (Seddon et al., 2020).

Ecosystem-based adaptation, defined as the "use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change" (Campbell et al., 2009), has at its core the recognition that there are unexploited synergies in agricultural systems that can increase productivity and resilience. These can result from increasing biodiversity, adding organic matter to soils, integrating livestock and aquatic species, including aquaculture, into farming practices, broadening landscape practices to exploit crop-forestry synergies, supporting beneficial insect populations, and altering pest management practices that have unintended negative consequences. In addition, the chapter considers socio-economic strategies to build resilience in the food system, strengthening local and regional economies, building on Indigenous and local knowledge, addressing social inequity, inclusive, participatory and democratic governance of food systems (HLPE, 2019; Wezel et al., 2020).

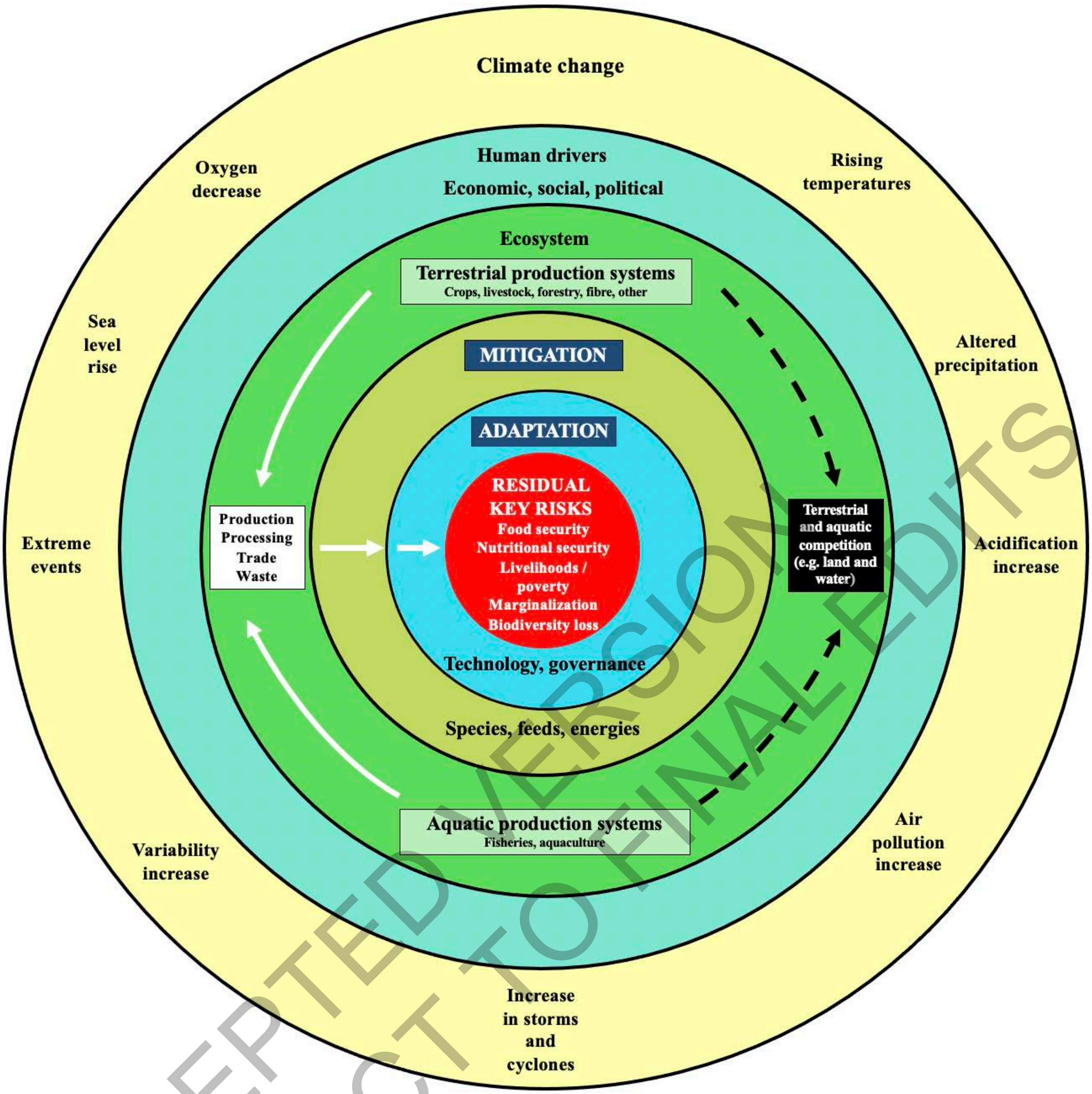


Figure 5.1: Conceptual framework of Chapter 5

Table 5.1: Adaptation strategies assessment in food, fibre, and other ecosystem provisioning services.

Adaptation strategies/options	Systems	Benefits	Constraints or enablers	Confidence	Relevant sections
• **Ecosystem-based integrated approaches such as agroecology that increase soil organic matter, enhance soil and water conservation, and diversify food production systems** • **Certain types of urban agriculture**	Crops	• Improve resilience of food systems • Provide mitigation measures and co-benefits in health, ecosystem services and other sustainable development goals	Secure tenure arrangements are often critical for delivering successful ecosystem-based adaptation.	*High*	(5.4.4.5, 5.6.3, 5.12.3, Cross-Chapter Box NATURAL in Chapter 2, 5.14.3.6, 5.14.3.11; Cross-Chapter Box HEALTH in Chapter 7)

		• Improve productivity and yield stability			
• **Increasing agroecosystem diversification through -expanding crop, animal, fish and other species genetic diversity -varying spatial and temporal arrangements including mixed planting, crop rotations, integrated crop, livestock and agroforestry systems**	Crops, Livestock, Aquaculture, Mixed, Agroforestry systems	• Increase resilience, productivity, and sustainability of farming systems under climate change.	Policies and technologies that support diversification at landscape and farm levels: programs that reward farmers for diversification practices, reduced incentives for intensified monocultures, extension support and market infrastructure for diverse crops, and productivity research on a greater variety of crops with support for post-harvest processing and regional markets	*High*	(5.4.4.4, 5.14.3.1, 5.14.3.6)
• **Changing the relative emphasis on crops and livestock** • **Changing crop varieties and livestock breeds and species**	Crops-livestock mixed system particularly in the tropics and subtropics	• Increase resilience	Gender inequalities can act as a risk multiplier	*Medium*	(5.5.4; 5.10.4)
• **Indigenous and local knowledge including participatory plant breeding or community-based adaptation**	Crops, Forestry, Fisheries	• Increase resilience and sustainability of food, fibre, forest, and small-scale fisheries production	Indigenous knowledge and local knowledge can facilitate adaptation when combined with scientific knowledge and utilized in management regimes.	*High*	(5.4.4.5, 5.6.3, 5.14.3)
• **Land restoration** • **Agroforestry** • **Silvo-pasture**	Forestry	• Improve resilience and productivity	Partnerships between key stakeholders such as researchers, forest managers, Indigenous and local forest dependent communities will facilitate sustainable forest management	*Medium*	(5.6.3)

• **Improved management practices that consider fish stocks and the ecosystem (ecosystem-based management, adaptive management, co-management, adaptive eco-management, and active adaptive management)** • **Adopting complementary productive activities to reduce economic dependence on fisheries** • **Developing capacity** • **Improving information flows in adaptive co-management transboundary resource management** • **Gear or vessel modifications**	Fisheries	• Promote sustainable harvesting and fair distribution of wild fish products and revenues • Proactive dynamic fisheries management and diversification based on scientific, Indigenous and local knowledge will facilitate adaptive fisheries planning and reduce conflict (national and international) over resources.		*Medium*	(5.14.3.4; Cross-Chapter Box MOVING PLATE this Chapter)
• **Adaptation options that incorporate ecological knowledge and risk into management decisions in the near- and long-term**	Aquacultur e	• Enhance sustainable aquaculture production	Governance that recognizes unexploited biological and socioeconomic food system synergies and equity would lead to positive adaptation strategy development and implementation, but options may be limited for those most at risk due to technological cost and low financial access	*High*	(5.14.3.5)
• **Effective linkage of freshwater aquatic food provisioning management to the adaptation plans of other water-using sectors, considering trade-offs of production with community nutritional needs**	Freshwater fisheries and aquaculture systems,	• Reduce the risk of food insecurity and livelihood loss for those reliant on freshwater for inland fisheries and aquaculture	Changing precipitation patterns will increase competition for limited freshwater supplies.	*Medium*	(5.8.4, 5.9.4.)

• **Agricultural production systems that integrate crops, livestock, forestry, fisheries, and aquaculture**	Mixed system	• Increase food production per unit of land • Reduce climate risks • Reduce GHG emission • Confer buffering capacity • Increasing household resilience though the benefits and challenges depend on local context.	Uncertainties exist concerning the scalability of integrated systems; their uptake face particular barriers around risk, land tenure, social inclusion, information and management skill, and the nature and timing of benefit flows.	*High*	(5.10.4)
• **Investments in improved humidity and temperature control in storage facilities for perishable items, and changes in public policy that control international trade and domestic market transactions**	Post-harvest	• Improve food utilization and access and thereby resilience to climate change.	The extent to which adaptation activities beyond harvest are cost-effective, and the limits to such adaptation, are location-specific and largely unknown	*Medium*	(5.11.4)
• **Integrated multisectoral food system adaptation approaches that address food production, consumption, and equity issues.** • **Nutrition and gender sensitive agriculture programs, adaptive social protection and disaster risk management are examples.**	Production and post-harvest	• Protect vulnerable groups against livelihood risks; • Enhance responsiveness to extreme events	Differentiated responses based on food security level and climate risk can be effective.	*Medium*	(5.12.4)
• **Rights-based approaches, including legislation, gender transformative approaches to agriculture, recognition of rights to land, seeds, fishing areas and other natural resources, and community-based adaptation.**	Production and post-harvest	• Improved food security and nutrition for marginalized groups; • Increased resilience through capacity-building of marginalized groups; • Address questions of access to resources for marginalized groups.	Focus on meaningful participation in governance, design, and implementation of adaptation strategies of those groups who are vulnerable including gender. Can be conflicts and tradeoffs, such as between addressing land rights or traditional fishing grounds.	*Medium*	(5.12.4)

• **Climate services**	Production	• Can support decision-makers i agriculture by providing tailored information that can inform the implementation o specific adaptatio options	For some high- and medium-income countries, evidence suggests that climate services have been underutilized. In low-income countries, use of climate services can increase yields, incomes and promote changes in farmers' practices, but *low confidence* that climate services are delivering on their potential, whether they are being accessed by the vulnerable, and how these services are contributing to food security and nutrition.	*Medium*	(5.14.1)

5.2 Observed Impacts and Key Risks

5.2.1 Detection and Attribution of Observed Impacts

Detection and attribution of climate change impacts on the food system remain challenging because many non-climate drivers are involved (Porter et al., 2014), but have been improved by recently developed climate model outputs tailored for impact attribution (Iizumi et al., 2018; Moore, 2020; Ortiz-Bobea et al., 2021).

Climate change has caused regionally different, but mostly negative, impacts on crop yields, quality, and marketability of products (*high confidence*) (see Section 5.4.1 for observed impacts). There is *medium evidence and high agreement* that the effects of human-induced climate warming since the pre-industrial era has had significantly negative effects on global crop production, acting as a drag on the growth of agricultural production (Iizumi et al., 2018; Moore, 2020; Ortiz-Bobea et al., 2021). One global study using an empirical model estimated the negative effect of anthropogenic warming trends from 1961 to 2017 to be on average 5.3 % for three staple crops (5.9% for maize, 4.9% for wheat, and 4.2 % for rice) (Moore, 2020). Another study using a process-based crop model found a yield loss of 4.1% (0.5-8.4%) for maize and 4.5% (0.5-8.4%) for soybean between 1981 and 2010 relative to the non-warming condition, even with CO_2 fertilisation effects (Iizumi et al., 2018). Human-induced warming trends since 1961 have also slowed down the growth of agricultural total factor productivity by 21% (Ortiz-Bobea et al., 2021). Regionally, heat and rainfall extremes intensified by human-induced warming in West Africa have reduced millet and sorghum yields by 10-20%, and 5-15 %, respectively (Sultan et al., 2019).

Methane emissions significantly impact crop yields by increasing temperatures as a GHG and surface ozone concentrations as a precursor (*medium confidence*) (Shindell, 2016; Van Dingenen, 2018; Shindell et al., 2019). Shindell (2016) estimated a net yield loss of 9.5±3.0% for four major crops due to anthropogenic emissions (1850-2010), after incorporation of the positive effect of CO_2 (6.5±1.0%) and the negative effects of warming (10.9±3.2%) and tropospheric ozone elevation (5.0±1.5%). Although these estimates were not linked with historical yield changes, more than half of the estimated yield loss is attributable to increasing temperature and ozone concentrations from methane emissions, suggesting the importance of methane mitigation in alleviating yield losses (*medium confidence*) (Section 5.4.1.4).

Climate change is already affecting livestock production (*high confidence)* (Section 5.5.1). The effects include direct impacts of heat stress on mortality and productivity, and indirect impacts have been observed on grassland quality, shifts in species distribution and range changes in livestock diseases (Sections 5.5.1.1 – 5.5.1.3). Quantitative assessment of observed impacts is still limited.

In aquatic systems, more evidence has accumulated since AR5 on warming-induced shifts (mainly poleward) of species (*high confidence*) (Section 5.8.1, Cross-Chapter Box MOVING PLATE this Chapter), causing significant challenges for resource allocation between different countries and fishing fleets. Quantitative assessments of climate change impacts on production are still limited, but (Free et al., 2019) estimated a 4.1% global loss of the maximum sustainable yield of several marine fish populations from 1930 to 2010 due to climate change. The effects of climate change on aquaculture are apparent but diverse, depending on the types and species of aquaculture (*high confidence*) (Section 5.9.1). Temperature increases, acidification, salt intrusion, oxygen deficiency, floods, and droughts have negatively impacted production via reduced growing suitability, mortalities, or damages to infrastructure (Section 5.9.1).

The impacts of climate change on food provisioning have cascading effects on key elements of food security, such as food prices, household income, food safety and nutrition of vulnerable groups (Peri, 2017; Ubilava, 2018; 5.11, 5.12). Climate extreme events are frequently causing acute food insecurity (Section 5.12.3, FSIN, 2021). There is growing evidence that human-induced climate warming has amplified climate extreme events (Seneviratne et al., 2021), but detection and attribution of food insecurity to anthropogenic climate change is still limited by a lack of long-term data and complexity of food systems (Phalkey et al., 2015; Cooper et al., 2019). A recent event attribution study by Funk (2018) demonstrated that anthropogenic enhancement of the 2015/16 El Niño increased drought-induced crop production losses in Southern Africa. Human-induced warming also exacerbated the 2007 drought in southern Africa, causing food shortages, price spikes, and acute food insecurity in Lesoto (Verschuur et al., 2021).

5.2.2 Key Risks

Key risks in this chapter are grouped into those related to food security, food safety and dietary health, livelihoods of people in related sectors and ecosystem services (Table 16.9). Determining when a risk is considered severe is challenging to quantify because of the complexity of the food system, uncertainty about the effects and ethical challenges.

Current levels of food insecurity are already high in some parts of the world, and often exacerbated by short-term food shortages and price spikes caused by weather extremes partly linked to climate change (Sections 5.2.1, 5.12.3, 16.5.2). Climate change will increase malnourished populations through direct impacts on food production and have cascading impacts on food prices and household incomes, all of which will reduce access to safe and nutritious food (*high confidence)* (Figure 5.2, 5.12).

Extreme climate events will become more frequent and force some of the current food production areas beyond the safe climatic space for production (*high confidence*) (Sections 5.4.3, 5.5.2). Globally, 10% of the currently suitable area for major crops and livestock are projected to be climatically unsuitable in mid-century and 31-34% by the end of the century under SSP5-8.5 (Kummu et al., 2021). Adverse effects of climate change on food production will become more severe when global temperatures rise by more than 2°C (Sections 5.4.4.1, 5.12.4.1). One study estimated that the heat stress from projected 3°C warming above baseline (1986-2005) would reduce labour capacity by 30-50% in Sub-Saharan Africa and southeast Asia, leading to an 5% increase in crop prices because of higher labour cost and production losses, thereby undermining food availability, access, and livelihood (de Lima et al., 2021). Thiault et al. (2019) projected that by 2100 climate change under RCP8.5 could have negative impacts on both agriculture and marine fisheries productivity in countries where 90% of the world population live. A global analysis of shellfish aquaculture estimated that habitat suitability will decline beyond 2060 globally, but much sooner in some Asian countries (Stewart-Sinclair et al., 2020; 5.9.1). These negative effects in the second half of the century will be much less under RCP2.6.

Climate change impacts will increase the number of people at risk of hunger in 2050 ranging from 8 million people under SSP1 to 80 million people under SSP3 scenarios (RCP6.0), compared to a world with no climate change (Mbow et al., 2019). Estimates also vary depending on the adaptation and mitigation assumptions (Hasegawa et al., 2018; Janssens et al., 2020). Geographically, nearly 80% of the population at risk of hunger are projected to occur in Africa and Asia (Nelson et al., 2018). Projections of risk of hunger beyond 2050 are limited, but it will grow from the mid-century toward the end of the century, with more people at risk under RCP8.5 compared to RCP4.5 (Richardson et al., 2018). Regional disparity is projected to increase, particularly under a high emission scenario.

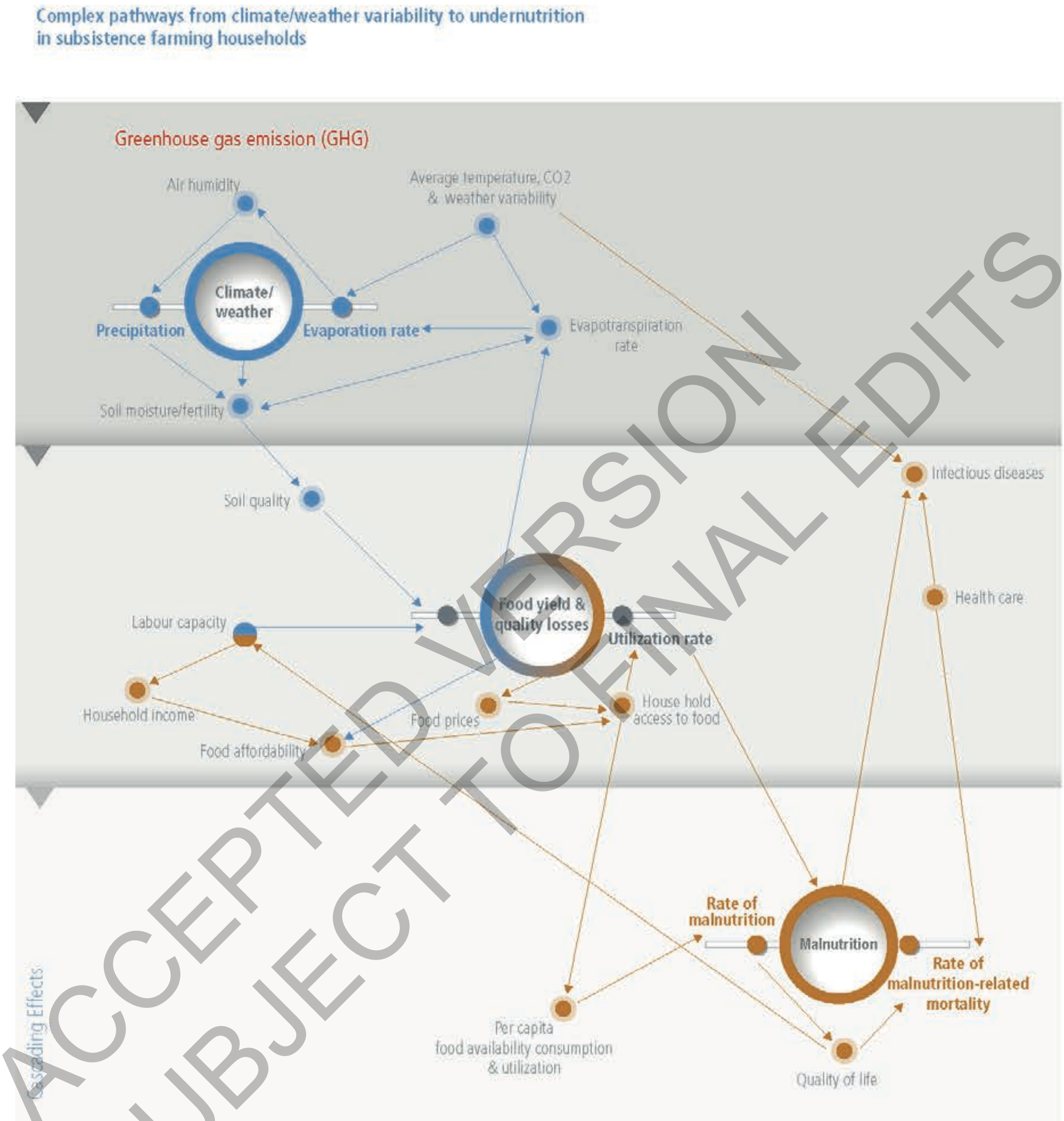


Figure 5.2: Complex pathways from climate/weather variability to malnutrition in subsistence farming households. The factors involved in and the probable impacts of weather variables on crop yields (blue arrows) and of production on malnutrition (red arrows). Adapted and revised from (Phalkey et al., 2015)

Climate change will increase the costs and management challenges of providing safe food. The safety challenges arise from contamination caused by increased prevalence of pathogens, harmful algal bloom, and toxic inorganic bioaccumulation (*high confidence*) (Sections 5.8, 5.9, 5.11, 5.12). Micronutrient deficiency is prevalent across many regions and will continue to be a problem at least during the first half of the century (Nelson et al., 2018), with significant implications for human health (Section 5.12.4).

Food security and healthy balanced diets will also be undermined by reduced livelihoods and health of people in agriculture and food-related sectors (Sections 5.12.3, 5.12.4), diminished ecosystem services provided by pollinators, the soil biome (Section 5.4.3), and water systems, and climate-mitigation related policies that solely focus on reducing GHG emissions without considering their potential to increase competition with food production for scarce land and water (Section 5.13.3).

5.3 Methodologies and Associated Uncertainties

Chapter text draws on previous IPCC reports, other reports (i.e., HLPE, FAO, IPBES, and Traffic), and literature published since 2014. This section highlights key trends in research topics and methods since AR5.

5.3.1 Methodologies for Assessing Impacts and Risks

Since AR5, there are more examples of observed impacts from past climate change in cropping systems (Section 5.4.1), pastoral systems (Section 5.5.1), forests (Section 5.6.1), fisheries (Section 5.8.1) and in mixed farming systems (Section 5.10.1). These assessments of observed impacts make use of historical data on climate, production area and yield to attribute the role of climate in driving changes in suitability, production, yield, food quality or Total Factor Productivity (Ortiz-Bobea et al., 2021). Observations across the global food-systems have been analysed (Cottrell et al., 2019), with the advantage that unexpected impacts due to changes in seasonality and biotic interactions can be detected. Quantitative analysis is only possible in places with adequate historical data, in many cases studies rely on qualitative assessments, often drawing on farmers perceptions of climate impacts.

Projecting future climate impacts relies on modelling that combines climate data with data from experimental studies testing how species respond to each climate factor. In cropping and forest systems, a network of experimental studies with plants exposed to elevated CO_2 concentrations, ozone and elevated temperature provides data on the fundamental responses to climate and atmospheric conditions (i.e., free-air carbon dioxide enrichment (FACE) and temperature free-air controlled enhancement (T-FACE) systems). FACE results have been combined and assessed more extensively since AR5 (Bishop et al., 2014; Haworth et al., 2016; Kimball, 2016; Ainsworth and Long, 2021; SM5.3). Field-based FACE studies have several advantages over more enclosed testing chambers, although results from more controlled experiments and coordination between different methods continue to give new insights into crop responses to climate change and variability (Drag et al., 2020; Ainsworth and Long, 2021; Sun et al., 2021). Experimental results have limitations and can be difficult to scale up (Porter et al., 2014; Haworth et al., 2016), but generally the conclusions follow known plant responses (Lemonnier and Ainsworth, 2018). As highlighted in AR5, there is a scarcity of FACE infrastructure in the tropics and subtropics (Leakey et al., 2012; Lemonnier and Ainsworth, 2018; Toreti et al., 2020). One area that has been further investigated is the negative impact of elevated CO_2 on crop nutritional value, which has important implications for human nutrition (Scheelbeek et al., 2018; Smith and Myers, 2018; Toreti et al., 2020; Ainsworth and Long, 2021). Increasingly, experimental studies seek to examine the interaction between climatic factors such as temperature, drought and ozone, or the responses of understudied food-systems, crop species, cultivars, and management interventions (Kimball, 2016; Ainsworth and Long, 2021). The use of experimental data to improve projections has also expanded in other systems. There has been an increased focus on the impact of warming on livestock health and productivity (5.5.2). Aquatic system studies have incorporated projected impacts on physiology, distribution, phenology, and productivity (5.8.3).

Modelling approaches differ widely and serve different purposes (Table 5.2; Porter et al., 2014; Jones, 2017a). The use of process-based and statistical modelling alongside remote sensing and other spatial data has grown. Projections increasingly draw on a combination of modelling approaches and coordinated efforts for model intercomparisons and ensemble techniques, using standardized emission scenarios (RCPs). For major crops, models of global yield impacts from CO_2 concentration, air temperature and precipitation, have been refined and compared (Challinor et al., 2014; Iizumi et al., 2017; Ruane et al., 2017; Zhao et al., 2017; Rojas et al., 2019). Despite advances since AR5, modelling is still constrained by limited data from field experiments (Ruane et al., 2017). Increasingly, studies attempt to incorporate effects of elevated CO_2, ozone, and climate extremes (Barlow et al., 2015; Schauberger et al., 2019a; Vogel et al., 2019), as well as attempts to incorporate more complex interactions with soil and crop management (Basso et al., 2018; Smith et al., 2020b). However, only a few models consider crop protein content and other quality factors (Nuttall et al., 2017; Asseng et al., 2019). Some models take account of the impacts of climate on the timing of key biological events (phenology) in the target species, however incorporating biotic interactions with pests, pathogens, and pollinators remains a challenge (Table 5.2; Sections 5.4.1, 5.4.2).

In addition to productivity projections, research also draws on climate suitability estimates (Table 5.2). These compare the known climate suitability of species and habitats with projected climate conditions across different locations. Such projections are useful especially for incorporating movement of pests and pathogens but cannot be applied in isolation if non-climate constraints are not considered. As different research groups use different assumptions and data inputs, more coordination is needed if suitability projections are to be compared globally (SM5.3).

Increasingly, projections look across different disciplines and across multiple components of the food-system, including livestock, fisheries and mixed farming systems (Campbell et al., 2016; Mbow et al., 2019). Major timber species have been modelled, with projected impacts on productivity, duration of rotation and distribution (i.e., climate suitability) (Albert et al., 2018). Livestock systems are influenced by plant productivity projections via their feedstock, e.g., rangeland cattle impacted by changes in net primary production (NPP) (Boone et al., 2018). Direct climate impacts on animals are also projected, using indices based on direct observations (Section 5.5.3). Since AR5, Fish-MIP has allowed for global intercomparisons and ensemble projections of marine fisheries (Fisheries and Marine Ecosystem Model Intercomparison Project), and projections capturing interactions from multiple food systems (e.g., Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP); Sections 5.8, 5.10).

Global simulations have uncovered important differences between regions (Deryng et al., 2016; Blanchard et al., 2017). Efforts to coordinate and combine regional and global modelling studies allow for greater insight into regional differences in climate change impacts, e.g., the Coordinated Global and Regional Assessments (CGRA) performed by the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Blanchard et al., 2017; Müller et al., 2017; Rosenzweig et al., 2018; Ruane et al., 2018; Lotze et al., 2019). Increasingly, multi-model intercomparisons are used to evaluate global gridded crop models' performance and sensitivity to temperature, water, nitrogen, and CO_2 within AgMIP, with the focus mostly on major annual crops (Valdivia et al., 2015; Ruane et al., 2017; Müller et al., 2021a). Differences in model type, structures and input data can result in large variation in projections, particularly for the response of crops to elevated CO_2 and temperature (5.4.3.1), methods for quantifying and minimizing this uncertainty have been developed, but improvement is still needed (Li et al., 2014b; Asseng et al., 2015; Zhao et al., 2017; Folberth et al., 2019; Tao et al., 2020; Müller et al., 2021a; Ruane et al., 2021). The use of multi-model intercomparisons has widened the range of uncertainties but has increased the robustness of impact assessments (Asseng et al., 2013; Challinor et al., 2014; Zhao et al., 2017). Model outputs are strongly influenced by decisions over which factors to include, e.g., including drought impacts can result in positive yield projections switching to neutral or negative values (Gray et al., 2016; Jin et al., 2018). Models are also limited in their ability to incorporate socio-economic drivers and extreme events (Porter et al., 2014; Campbell et al., 2016; Ruane et al., 2017; Jagermeyr and Frieler, 2018; Webber et al., 2018; Schewe et al., 2019).

For long-term projections and integrated assessments, a large component of uncertainty remains the ability to represent socio-economic responses to climate change and the degree to which these will mitigate or exacerbate climatic changes (Valdivia et al., 2015; Prestele et al., 2016; Arneth et al., 2019). This includes the potential adaptation responses of food producers. Models that incorporate alternative socio-economic responses offer one solution (e.g., AgMIP) (Nelson et al., 2014; Von Lampe et al., 2014; Wiebe et al., 2015; Rosenzweig et al., 2018; van Zeist et al., 2020). Another approach is the use of solution-oriented scenarios to compare the effectiveness of adaptation options (Le Mouël and Forslund, 2017; Arneth et al., 2019), or to quantify the time period in which adaptation responses will become essential (Challinor et al., 2016; Rojas et al., 2019). Others point to the necessity of managing food systems within the context of uncertainty (Campbell et al., 2016).

Table 5.2: A comparison of modelling approaches and their application in climate change impact projections. Model types are categorised by: food system, with labels representing the food systems from this chapter where each model type is used (**[CROP]**, **[TREE]**, **[LIVES]**, **[FISH]**, **[MIX]**, **[FOOD]**); scale over which each model type is usually applied (local [()], regional [( )], global [( )], or a combination of these); and sensitivity to climate change where the

colour intensity indicates the ability of each model type to incorporate each of the listed factors. After (Van Wijk et al., 2014; Kanter et al., 2018; Thornton, 2018). Integrated assessment models are discussed in the main text.

		Description	Applications for each food-system	Scale	Sensitivity to climate change factors and responses: Climate	CO2	Biotic	Adaptation	System responses
Empirical	Agroclimatic indices	Use simple equations to link agricultural performance to key climate factors, such as drought or heat stress, or summarising agricultural requirements using multiple environmental descriptors.	Comparing regions; matching crops to regions; early warning systems: e.g. Agro-ecological zones, Ecocrop, Palmer Drought Severity Index **{CROP}**.	(( ))					
	Statistical models	Use quantitative associations between agricultural performance and climate, based on past observations. Can include projections for biotic factors such as pest and disease.	Productivity and production area projections; annual climate variability; attribution: e.g. Traditional: regression, statistical emulators **{CROP} {TREE} {LIVES} {FISH}**; e.g. Spatial suitability models /niche models: MaxEnt, CLIMEX, Ecocrop **{CROP} {TREE} {FISH}**.	(( ))					
Process-based (dynamic simulation models)	Vegetation focused	Use combinations of land-surface energy and soil water balance models to simulate the growth of crop species along with natural vegetation, typically using plant and crop functional types.	Productivity projections; interactions with non-climate variables (e.g. CO2): e.g. PEGASUS, Agro-IBIS, DayCent, LPJmL, LPJ-GUESS, ORCHIDEE **{CROP} {TREE}**.	( )					
	Species focused	Use mechanistic models based on the known responses of species to key environmental descriptors over time. Typically based on detailed information for a particular species within a region, but also applied to mixed systems such as agroforestry and globally.	Productivity projections; matching tree species to locations; species interactions; interactions with non-climate variables (e.g.CO2); adaptation projections: e.g. point-based versions: APSIM, AquaCrop, DayCent, DSSAT, EPIC, Infocrop, SARRA-H, STICS **{CROP}** IBIS **{TREE}** LIVSIM, RUMINANT **{LIVES}** Fish-MIP **{FISH}** Yield-SAFE, WaNuLCAS, Hi-sAFe **{MIX}**; e.g. global gridded version: pDSSAT, pAPSIM, GEPIC, GLAM, MCWLA, PEGASUS, SARRA-O **{CROP}**.	(( ))					
Integrated models	Optimization methods	Mathematical representations of systems with regard to key indicators, constraints, and objectives. Allows prioritisation of different climate change response options using the defined indicators.	Adaptation projections; food security projections; livelihood projections; trade-offs; live cycle assessment: e.g. Global Timber Model **{TREE}** CSAP toolkit, FarmDESIGN **{CROP} {MIX} {FOOD}**	()					
	Economic (Econometric, Economic surplus,	Used to integrate the broad impacts of climate change with other economic drivers, to quantify the economic costs and assess the value of adaptation/mitigation interventions.	Adaptation projections; food security projections; livelihood projections: e.g. GFPM **{TREE}** FUND 3.8, DICE 2010, IMPACT **{FOOD}**	( )					
	Household and village models	Use detailed site-specific data to generate rules that describe the current behaviour of stakeholders such as households or villages. Can be integrated with other model approaches to consider climate response and adaptation interventions.	Adaptation projections (case specific); behavioural responses; trade-offs; participatory monitoring: e.g. DECUMA, PALM, MPMAS, MIDAS, TOA-MD **{LIVES} {MIX} {FOOD}**	(())					

5.3.2 Methodologies for Assessing Vulnerabilities and Adaptation

Methods for monitoring vulnerability and adaptation are under-researched but have increased since AR5. Increasingly, projections move from individual crops, to assessing risks across the food systems and the relative vulnerability of different systems (Campbell et al., 2016; Gil et al., 2017; Lipper et al., 2017; Richardson et al., 2018). Adaptation options can be considered as parameters in integrated models, such as those used in ISI-MIP, while others use systematic assessments of case studies, e.g., the application of agent-based household models to assessments of adaptation in livestock systems (Section 5.5.4). Quantitative studies are less common than qualitative assessments and there is a need to combine modelling and qualitative approaches more effectively (Beveridge et al., 2018a; Vermeulen et al., 2018).

The food system is dynamic with changes in management practices driven by many factors including climate adaptation (Iizumi, 2019; Iizumi et al., 2021a). Adaptation potential, such as expected advances in crop breeding, are often not explicitly accounted for in modelling studies, but more recent studies do quantify the potential for adaptation (Iizumi et al., 2017; Tao et al., 2017; Aggarwal et al., 2019; Minoli et al., 2019). To account for this complexity, case studies rely on data derived from the perception and practices of stakeholders who are engaged in adaptation (usually autonomous adaptation) (Hussain et al., 2016; Lipper et al., 2017; Ankrah, 2018; Sousa-Silva et al., 2018). Case studies use a range of different indicators to monitor climate response options, making quantitative comparisons more difficult (Gil et al., 2017; Vermeulen et al., 2018). However, systematic comparisons have provided valuable insights (Descheemaeker et al., 2018; Shaffril et al., 2018; Aggarwal et al., 2019; Bene et al., 2019), e.g., the sustainable livelihood framework has been applied widely to diverse aquatic systems (Bueno and Soto, 2017; Barange and Cochrane, 2018) and the Livelihood Vulnerability Index is well used across systems (Section 5.14). Coordinated efforts such as the AgMIP also provide systematic assessments (Blanchard et al., 2017; Lipper et al., 2017; Antle et al., 2018). Nonetheless, the full effectiveness of different adaptation options is difficult to assess given that many impacts have not yet occurred (due to the cumulative nature of impacts and the inertia in the climate system (Stocker et al., 2013; Zickfeld et al., 2013).

Transformation of the food system that addresses all dimensions of ecosystem services is discussed in this chapter, including risk management and the communication of uncertainties (Section 5.14). The focus is on flexible approaches to risk and uncertainty, assessing trends, drivers, and trade-offs under different future scenarios (Campbell et al., 2016).

5.4 Crop-based Systems

Crops such as cereals, vegetables, fruit, roots, tubers, oilseeds, and sugar account for about 80 % of the dietary energy supply (FAO, 2019f). Crops are a significant source of food and income for about 600 million farms in the world, 90 % of which are family farms (Lowder et al., 2019). Previous assessment reports focused on yields of staple crops such as maize, wheat and rice, but studies are emerging on climate change impacts on other crops.

5.4.1 Observed Impacts

5.4.1.1 Observed impacts on major crops

AR5 Chapter 7 stated with confidence that warmer temperatures have benefited agriculture in the high latitudes, and more evidence has been published to support the statement. Typical examples include pole-ward expansion of growing areas and reduction of cold stress in East Asia and North America (Table SM5.1).

Recent warming trends have generally shortened the life cycle of major crops (*high confidence*) (Zhang et al., 2014; Shen and Liu, 2015; Ahmed et al., 2018; Liu et al., 2018c; Tan et al., 2021). Some studies, however, observed prolonged crop growth duration despite the warming trends (Mueller et al., 2015; Tao et al., 2016; Butler et al., 2018; Zhu et al., 2018b) due to shifts in planting dates and/or adoption of longer-duration cultivars in mid to high latitudes. Conversely, in mid-to-low latitudes in Asia, a review study found that farmers favoured early maturing cultivars to reduce risks of damages due to drought, flood and/or heat (Shaffril et al., 2018), suggesting that region-specific adaptations are already occurring in different parts of the world *(high confidence)*.

Global yields of major crops per unit land area have increased 2.5 - 3-fold since 1960. Plant breeding, fertilisation, irrigation, and integrated pest management have been the major drivers, but many studies have found significant impacts from recent climate trends on crop yield (*high confidence*) (Figure 5.3; See Section 5.2.1 for the change attributable to anthropogenic climate change).

Climate impacts for the past 20-50 years differ by crops and regions. Positive effects have been identified for rice and wheat in Eastern Asia, and for wheat in Northern Europe. The effects are mostly negative in Sub-Saharan Africa, South America and Caribbean, Southern Asia, Western and Southern Europe. Climate factors that affected long-term yield trends also differ between regions. For example, in Western Africa, 1°C-warming above preindustrial climate has increased heat and rainfall extremes, and reduced yields by 10-20% for millet, and 5-15 % for sorghum (Sultan et al., 2019). In Australia, declined rainfall and increased temperatures reduced yield potential of wheat by 27%, accounting for the low yield growth between 1990 and 2015 (Hochman et al., 2017). In Southern Europe, climate warming has negatively impacted yields of almost all major crops, leading to recent yield stagnation (Moore and Lobell, 2015; Agnolucci and De Lipsis, 2020; Brás et al., 2021).

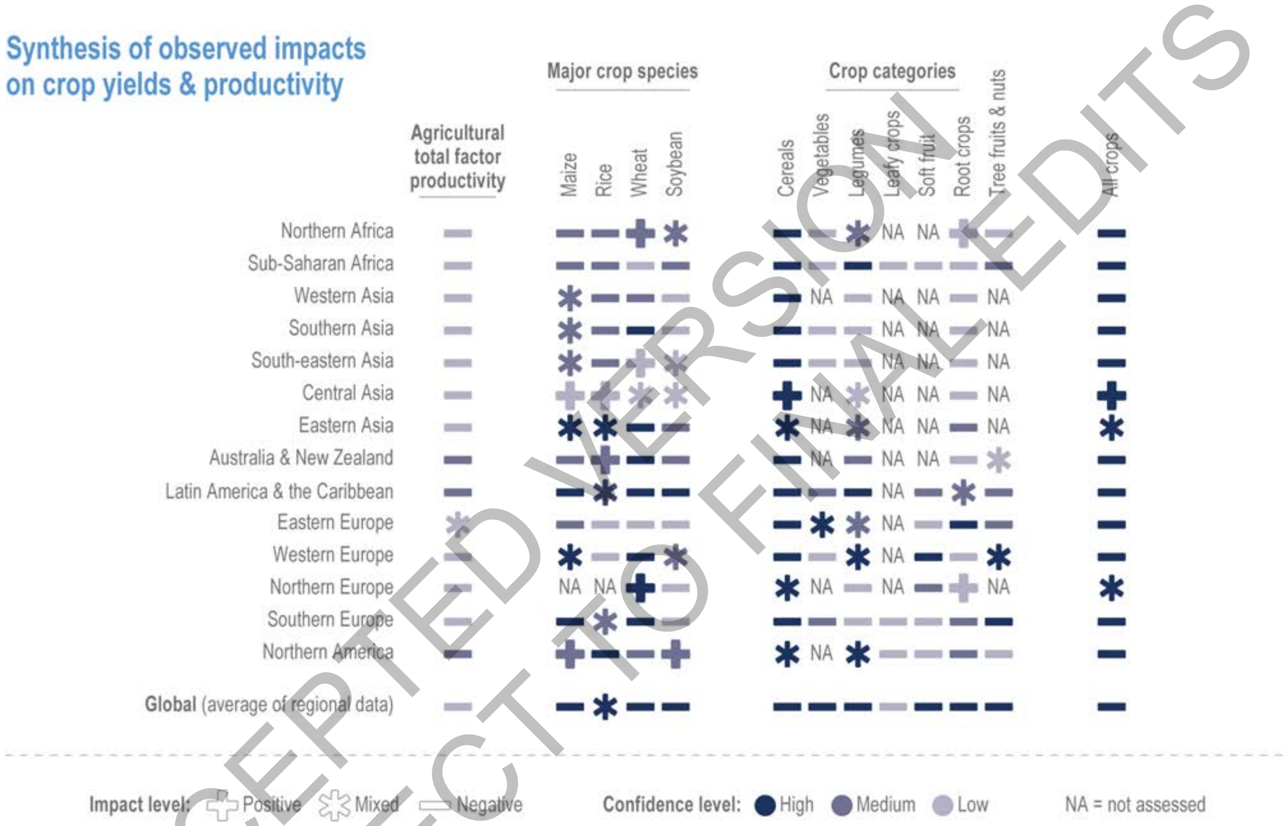


Figure 5.3: Synthesis of literature on observed impacts of climate change on productivity by crop type and region. The figure draws on >150 articles categorised by: agriculture total factor productivity including literature estimating all agricultural outputs in a region; major crop species including literature assessing yield changes in the four major crops; crop categories including productivity changes (yield, quality, and other perceived changes) in a range of crops with different growth habits. The assessment uses literature published since AR5, although the timespan often extends prior to 2014. The direction of the effect and the confidence are based on the reported impacts and attribution, and on the number of articles. See SM5.1 and SM5.2 for details.

Ortiz-Bobea et al. (2021) analysed agricultural Total Factor Productivity (TFP), defined as the ratio of all agricultural outputs to all agricultural inputs, and found that while TFP has increased between 1961 and 2015, the climate change trends reduced global TFP growth by a cumulative 21% over a 55-year period relative to TFP growth under counterfactual non-climate change conditions. Greater effects (30- 33%) were in Africa, Latin America and the Caribbean (Figure 5.3).

Climate variability is a major source of variation in crop production (Ray et al., 2015; Iizumi and Ramankutty, 2016; Frieler et al., 2017; Cottrell et al., 2019)(Table SM5.1). Weather signals in yield variability are generally stronger in productive regions than in the less productive regions (Frieler et al., 2017), where other yield constraints exist such as pests, diseases, and poor soil fertility (Mills et al., 2018;

5.2.2). Nevertheless, yield variability in less productive regions has severe impacts on local food availability and livelihood (*high confidence*) (FAO, 2021).

Climate-related hazards that cause crop losses are increasing (*medium evidence, high agreement*) (Cottrell et al., 2019; Mbow et al., 2019; Brás et al., 2021; FAO, 2021; Ranasinghe et al., 2021). Drought-related yield losses have occurred in about 75% of the global harvested area (Kim et al., 2019b) and increased in recent years (Lesk et al., 2016). Heatwaves have reduced yields of wheat (Zampieri et al., 2017) and rice (Liu et al., 2019b). The combined effects of heat and drought decreased global average yields of maize, soybeans, and wheat by 11.6, 12.4, and 9.2% (Matiu et al., 2017). In Europe, crop losses due to drought and heat have tripled over the last five decades (Brás et al., 2021), pointing to the importance of assessing multiple stresses. Globally, floods also increased in the past 50 years, causing direct damages to crops and indirectly reduced yields by delaying planting, which cost 4.5 billion USD in the 2010 flood in Pakistan and 572 million USD in the 2015 flood in Myanmar (FAO, 2021).

[START BOX 5.1 HERE]

Box 5.1: Evidence for Simultaneous Crop Failures due to Climate Change

Simultaneous yield losses across major producing regions can be a threat to food security but had not been quantified by the time of AR5. Large-scale sea surface temperature (SST) oscillations greatly influence global yield of major crops (*high confidence*) (Anderson et al., 2019b; Najafi et al., 2019; Ubilava and Abdolrahimi, 2019; Heino et al., 2020; Iizumi et al., 2021b) and food prices (Ubilava, 2018). Some studies showed that crop yields in different regions covaried with SST oscillations, suggesting occurrences of tele-connected yield failures (crop losses caused by related factors in distant regions; Table Box 5.1.1) (*medium confidence*). Evidence is still limited that synchronised crop failures are increasing with ongoing climate change.

Table Box 5.1.1: A summary of peer-review papers detecting synchronised yield losses

Regions/ Commodities	Period studied	Observed impacts	Climate driver	Evidence for multiple breadbasket failures	Evidence for increasing risks due to multiple breadbasket failures	Reference
Global breadbaskets for maize, rice, sorghum and soybean	1961-2013	Not only yields of each crop covaried in many countries, but also that of different crops, maize in particular, covaried with other crops.	Sea surface temperature anomalies (SST), atmospheric and oceanic indices, air temperature anomalies (AT) and Palmer Drought Severity Index (PDSI)	High	NA	Najafi et al. (2019)

Global breadbaskets for wheat, soybean, and maize		Climate modes (El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), tropical Atlantic variability (TAV), and the North Atlantic Oscillation (NAO)) account for 18, 7, and 6% of global maize, wheat, and soybean production variability. ENSO events sometimes offset yield reductions in some places by increases in other places (e.g., Soybean yields in the United States and southeast South America). Since 1961, ENSO in 1983 was the only climate mode that showed global synchronous crop failures.	Climate modes	Medium (1983)	NA	Anderson et al. (2019b)
Global breadbaskets for wheat, soybean, and maize		Climate modes induce yield variability in major breadbaskets. e.g. ENSO affects about half of maize and wheat areas. IOD and ENSO influence what in Australia. ENSO affects soybean in northern South America.	Climate modes	Medium	NA	Heino et al. (2020)
67 maize producing countries	1961-2017	SST anomalies from the 1980–2010 base period in the Niño3.4 region, a rectangular area bounded by 120◦W–170◦W and 5◦S–5◦ is used as a driver. Maize yields are tele-connected among the south-eastern tier of Sub-Saharan Africa, as well as Central America, South Asia, and Australia. A 1-degree increase in SST reduced maize yield by up to 20% in these countries.	Climate modes (Sea surface temperature), Precipitation	Medium	NA	Ubilava and Abdolrahimi (2019)
Global breadbasket (the United States, Argentina, Europe, Russia/Ukraine, China, India, Australia, Indonesia, and Brazil)	1967-2012	Likelihood of simultaneous climate risks increased from 1967-1990 to 1991-2012 in the global breadbasket (Lower 25th yield deviation percentile events at province level) for wheat, soybean maize, but not rice. Likelihood of simultaneous climate risks increased from 1967-1990 to 1991-2012 in China (Lower 25th yield deviation percentile events at province level)	Unspecified	medium	medium	Gaupp et al. (2020)

Global		Synchronous yield losses among major breadbaskets within each commodity, such as maize and soybean decreased between 1961 and 2008. In contrast, synchronous yield variation between crops has increased. Under a scenario of synchronization of all four crops, the global maximum production losses for rice, wheat, soybean, and maize are estimated to reach between −17% and −34%.	unspecified	medium	medium	Mehrabi and Ramankutty (2019)

[END BOX 5.1 HERE]

5.4.1.2 Observed impacts on other crops (vegetables, fruit, nut, and fibre)

The impact of climate change on these diverse crop types is under-researched and uncertain (Manners and van Etten, 2018; Alae-Carew et al., 2020), there are reports of positive impacts in some cases but overall, the observed impacts are negative across all crop categories (Figure 5.3).

Above-ground annual crops consumed as vegetables, fruits, or salad are essential for food security and nutrition (5.12). In temperate regions, climate change can result in higher yields (Potopová et al., 2017; Bisbis et al., 2018), while in subtropical/tropical regions, negative impacts from heat and drought take precedence (Scheelbeek et al., 2018). Different species have different sensitivities to heat and drought (Prasad et al., 2017; Scheelbeek et al., 2018) and to combinations of stresses (Zandalinas et al., 2018). Above-ground vegetables are especially vulnerable to heat and drought stress during pollination and fruit set, resulting in negitive impacts on yiled (Daryanto et al., 2017; Sita et al., 2017; Brás et al., 2021)and harvest quality (Mattos et al., 2014; Bisbis et al., 2018). Growers have already seen negative impacts from the expansion of pest and disease agents due to warming (Section 5.4.1.3; Figure 5.3).

Below-ground vegetables include starchy roots and tubers that form a regular diet in many parts of the tropics and sub-tropics. Warming and climate variability has altered the rate of tuber development with yield impacts varying by location, including yield increases in some cases (Shimoda et al., 2018; Ray et al., 2019). These crops are considered stress tolerant but are more sensitive to drought than cereals (Daryanto et al., 2017). Impacts on water supply are critical as root crops are water-demanding for long periods, and highly sensitive to drought and heat events during tuber initiation (Dua et al., 2013; Potopová et al., 2017; Brás et al., 2021).

Among perennial tree crops, only grapevine, olive, almond, apple, coffee, and cocoa have received significant research attention. Concerns about climate impacts on harvest quality are widespread (Figure 5.3) (Barnuud et al., 2014; Bonada et al., 2015). In higher-latitude regions, the primary concern is the effect of temperature variability on harvest stability, pests and diseases and phenology (including fulfilment of winter chill requirements and risks due to early emergence in spring), (El Yaacoubi et al., 2014; Ramírez and Kallarackal, 2015; Santos et al., 2017; Gitea et al., 2019). In lower-latitude regions, information is limited, but studies are focused on increased tree mortality and yield loss due to drought, heat, and impacts from variability in the timing of the wet and dry seasons (Glenn et al., 2013; Ramírez and Kallarackal, 2015); see Box 5.7). In fruit trees, warming and climate variability have already affected fruit quality, such as acidity and texture in apples, or skin colour in grape berries (Sugiura et al., 2013; Sugiura et al., 2018). The reliability and stability of harvests has been impacted by climate variability, changes in the distribution of pests and pathogens (Seidel, 2014; Bois et al., 2017), and by the mismatch of important phenological events (such as bud emergence and flowering) (Guo and Shen, 2015; Legave et al., 2015; Ito et al., 2018; Vitasse et al., 2018). Perennial crops are particularly vulnerable to these impacts as they are exposed throughout the year, with little potential for growers to adjust planting date or location. Negative impacts via disruption to phenology and pest dynamics are best studied in grapevine (see Box 5.2).

Among the fibre crops, cotton is particularly well studied. As cotton is heat tolerant and yield increases with extra plant growth, positive effects of increasing temperature are expected, but observed impacts have been mixed due to negative impacts on phenology and plant water status (Traore et al., 2013; Chen et al., 2015a; Cho and McCarl, 2017). Negative impacts of climate change due to proliferation of the pest cotton bollworm are widely reported (Ouyang et al., 2014; Huang and Hao, 2020).

The impacts of climate change on water availability (rainfall and irrigation supply) are an emerging issue. Increased occurrence of drought combined with limited access to irrigation water is already a key constraint, e.g., Californian almonds are predicted to increase their potential geographical range under climate warming (Parker, 2018), yet a trend of increasing drought has already resulted in trees being removed due to lack of access to irrigation water (Keppen and Dutcher, 2015; Kerr et al., 2018; Reisman, 2019).

5.4.1.3 Observed impacts on pests, diseases, and weeds

AR5 and SRCCL indicated that more frequent outbreaks and area expansion of pests and diseases are serious concerns under climate change but are under-researched because of the difficulties in assessing multi-species interactions (Porter et al., 2014; Mbow et al., 2019). High-quality historical and current observational data to detect changes in pests and diseases attributable to recent trends in climate are still limited.

Bebber (2013) found significant poleward expansions of many important groups of crop pests and pathogens since 1960, with an average shift of 2.7 km yr^{-1}. Different pest species populations respond differently to ongoing climate change, with some shifting, contracting, or expanding their current distribution range and others persisting or disappearing in their current range (*high confidence*). These asymmetric distribution changes can create novel species combinations or decouple existing ones (Pecl et al., 2017; Hobbs et al., 2018), but their consequences on future crop production and food security are hard to predict. Multi-species climate change experiments are rare (Bonebrake et al., 2018) but one study shows that under future climates, different pest assemblages of interacting species may alter levels of damage to crops compared to that by only one species (Crespo-Perez et al., 2015). Some studies highlight the importance of location-specific species interactions for more realistic projections of pest distribution, performance, and damage to crops, which in turn would allow more effective prevention and pest control strategies (Wilson et al., 2015; Carrasco et al., 2018).

Weeds are recognized as a primary constraint on crop production (Oerke, 2006), rangelands (DiTomaso et al., 2017) and forests (Webster et al., 2006). Climate change could favour the growth and development of weeds over crops with negative consequences for desired plants in managed systems (*medium evidence, high agreement*) (Peters et al., 2014; Ziska and McConnell, 2016). First, changes in temperature and precipitation alter the range, composition, and competitiveness of native and invasive weeds (Bradley et al., 2010). Second, rising concentrations of CO_2 enhance growth of C_3 species (~85% of plant species, including many weeds) (Ogren and Chollet, 1982; Ziska, 2003), and increase plant water use efficiency with potentially strong effects on invasive plant species establishment (Smith et al., 2000; Belote et al., 2004; Blumenthal et al., 2013).

Some invasive species within unmanaged areas will expand further, proliferate and be more competitive under climate change as they may benefit from increased resource ability (e.g., additional CO_2, enhanced precipitation) (Bradley et al., 2010; Kathiresan and Gualbert, 2016; Merow et al., 2017; Ramesh et al., 2017; Waryszak et al., 2018), which will make chemical weed-control more problematic (*medium evidence, high agreement*) (Waryszak et al., 2018; Ziska, 2020). The range of other invasive weeds may become static, or even decline (Bradley et al., 2016; Buckley and Csergo, 2017). A recent meta-analysis also supports that invasive plants respond more favourably to elevated CO_2 concentrations and elevated temperatures than native plants (Korres et al., 2016; Liu et al., 2017). Movement of invasive species into low fertility areas, however, could provide resource opportunities, especially if agriculture in those areas is limited (Randriambanona et al., 2019).

Rising CO_2 concentrations and climate change could reduce herbicide efficacy (*medium evidence, high agreement*). These reductions may be associated with physical environmental changes (precipitation, wind speed) that influence herbicide coverage (Ziska, 2016), as well as direct effects of CO_2 on plant biochemistry and herbicide resistance (Refatti et al., 2019). Increasing CO_2 levels and altered temperature and precipitation, are therefore projected to affect all aspects of weed biology (Peters et al., 2014; Ziska and McConnell, 2016), including establishment (Bradley et al., 2016), competition (Fernando et al., 2019), distribution, (Castellanos-Frías et al., 2016), and management (Waryszak et al., 2018).

A warmer climate increases the need for pesticides (Shakhramanyan et al., 2013; Ziska, 2014; Delcour et al., 2015; Zhang et al., 2018). Increases in temperature and CO_2 concentration may reduce pesticide efficiency by altering its metabolism, or accelerating detoxification (Matzrafi et al., 2016; Matzrafi, 2019). Intense rainfall also reduces persistence (Delcour et al., 2015). Invasive pests and pathogens impose an additional cost for the society (Bradshaw et al., 2016). Rapid and large-scale dispersal of pests is already a major threat to food security, as exemplified by the recent outbreak of desert locusts (see Box 5.8), indicating the importance of international cooperation. Taken together, the need for control of pests, disease and weeds will increase under climate change (*medium evidence, high agreement*). The use of toxic agricultural chemicals also has human health and environmental risks (Whitmee et al., 2015; IPBES, 2019). Surveillance for monitoring pest distribution and damages, climate-relevant pest-risk analysis, and climate-smart strategies for controlling pests with minimal impacts on human and environmental health are important tools in the face of climate change (IPPC Secretariat, 2021).

5.4.1.4 Observed impacts of ozone on crops

Tropospheric (i.e., the lowest 6–10 km of the atmosphere) ozone exacerbates negative impacts of climate change (*high confidence*) (Mattos et al., 2014; Chuwah et al., 2015; McGrath et al., 2015; Bisbis et al., 2018; Mills et al., 2018; Scheelbeek et al., 2018). Ozone is an air pollutant and short-lived greenhouse gas that affects air quality and global climate. It is a strong oxidant that reduces physiological functions, yield and quality of crops and animals. Surface ozone concentration has increased substantially since the late 19th century (Cooper et al., 2014; Forster et al., 2021; Gulev et al., 2021; Naik et al., 2021)and in some locations and times reaches levels that harm plants, animals, and human (*high confidence*) (Fleming et al., 2018).

Mills (2018) estimated global distributions of current yield losses of major crops due to ozone, pest and diseases, heat, and aridity (Figure 5.4). Ozone-induced yield losses in 2010-2012 averaged 12.4, 7.1, 4.4, and 6.1 % for soybean, wheat, rice, and maize, respectively. Spatial variation in yield losses is similar among different stresses; areas with a large loss due to ozone are also at high risk of yield losses due to pest and diseases and heat. Many vegetable crops are also susceptible to ozone, which will adversely impact quality and quantity (Mattos et al., 2014; Bisbis et al., 2018; Scheelbeek et al., 2018).

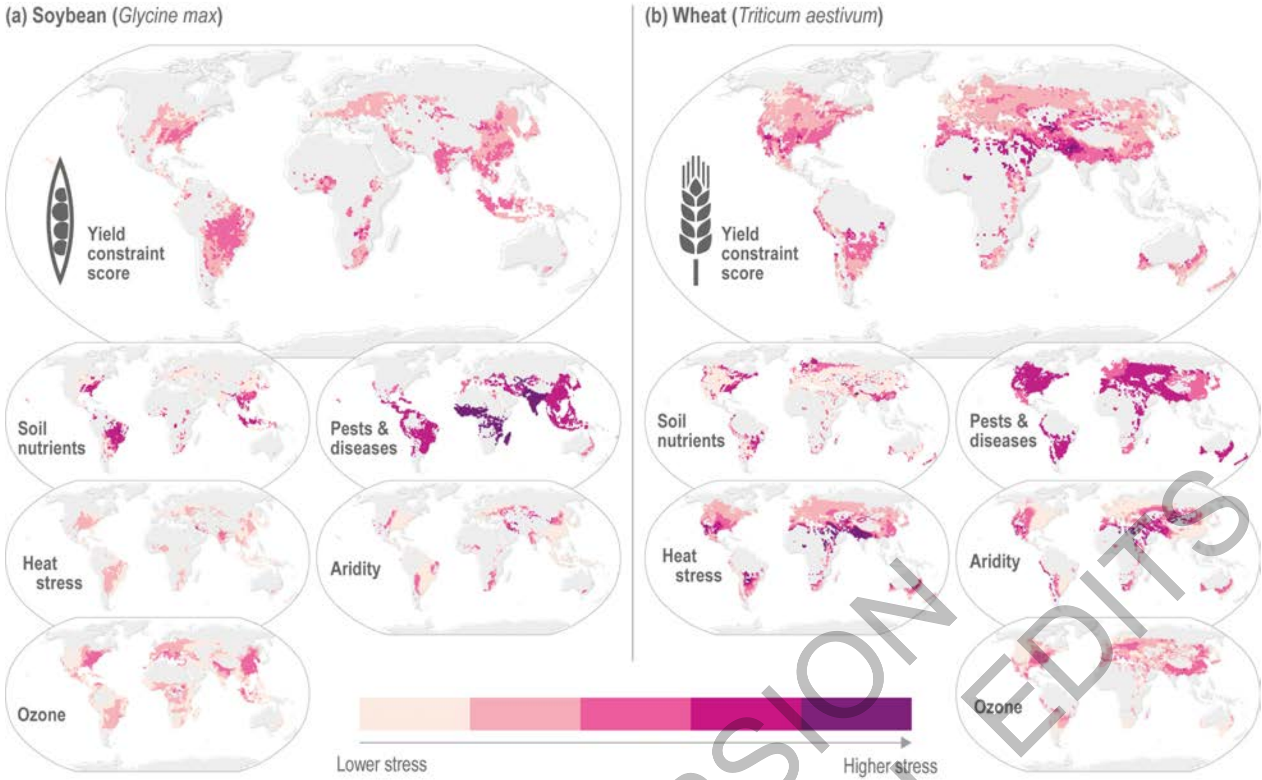


Figure 5.4: The global effects of five biotic and abiotic stresses on soybean and wheat. All data are presented for the 1 × 1° (latitude and longitude) grid squares where the mean production of soybean or wheat was >500 tonnes (0.0005 Tg). The effect of each stress on yield is presented as a Yield Constraint Score (YCS) on a scale of 1–5, where 5 is the highest level of stress from ozone, pests and diseases, heat stress and aridity (Mills et al., 2018). Data are available at Sharps et al.,(2020). See Annex I: Global to Regional Atlas for all four crops.

The estimated yield loss does not account for interactions with other climatic factors. Temperatures enhance not only ozone production but also ozone uptake by plants, exacerbating yield and quality damage. Burney (2014) estimated current yield losses due to the combined effects of ozone and heat in India at 36% for wheat and 20 % for rice. Schauberger et al. (2019a) found global yield losses, ranging from 2 to 10 % for soybean and 0 to 39 % for wheat with a model that accounts for temperature, water, and CO_2 concentration on ozone uptake.

5.4.2 Assessing Vulnerabilities within Production Systems

Since AR5, vulnerability assessment has become a pivotal component of risk analysis associated with climate hazards, climate change and climate variability (UNDRR, 2019). Vulnerability assessment can be sectoral or regional but involves social and ecological indicators. This section presents examples of vulnerability assessment to climatic hazards and social vulnerabilities.

5.4.2.1 Vulnerability to climatic hazards

Drought is a major risk component in cropping systems globally, with substantial economic loss (Kim et al., 2019b), livelihood impacts (Shiferaw et al., 2014; Miyan, 2015), and ultimately health risks such as malnutrition (Phalkey et al., 2015; Cooper et al., 2019). Vulnerability to drought can be estimated with a range of indicators (Hagenlocher et al., 2019). Meza (2020) showed that drought risks could be exacerbated or moderated by regional differences in vulnerability (Figure 5.5). For instance, high-level risks observed in southern Africa, western Asia, and central Asia result from high vulnerability (low coping capacity), whereas risk levels are relatively low despite the high exposure by relatively high adaptive capacity to drought in other regions.

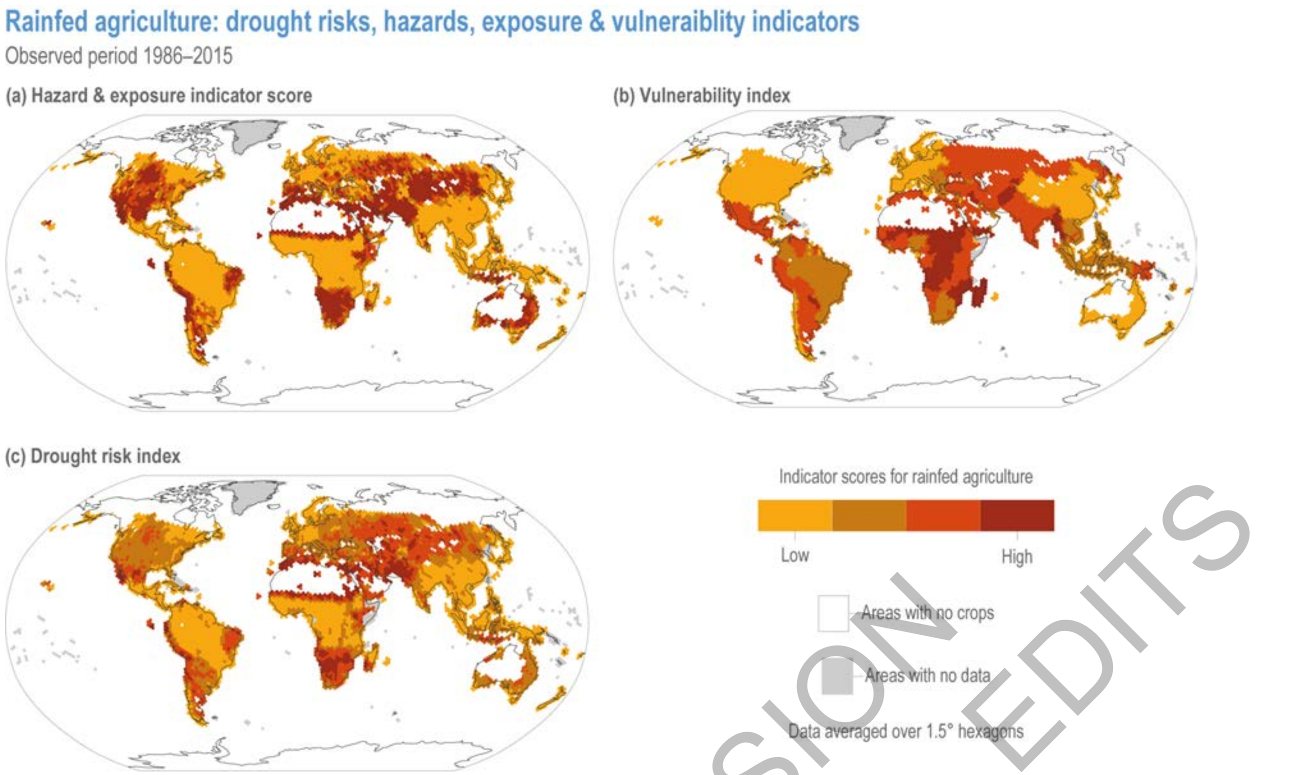


Figure 5.5: Hazard and exposure indicator score (a), vulnerability index (b) and drought risk index (c), for rainfed agricultural systems between 1986 and 2015. Drought hazard indicator is defined as the ratio of actual crop evapotranspiration to potential crop evapotranspiration, calculated for 24 crops. Vulnerability index is the country-scale weighted average of a total of 64 indicators including social and ecological susceptibility indicators, and coping capacity. Risk index is calculated by multiplying hazard/exposure indicator score and vulnerability index (Meza et al., 2020).

Regional-scale assessment also highlights the importance of adaptive capacity. For instance, rice and maize production in Viet Nam Mekong Delta has high exposure to multiple climate hazards such as flooding, sea-level rise, salinity intrusion, and drought (Parker et al., 2019). Risks can be moderated by a relatively high adaptive capacity because of infrastructure, resources, and high education levels (Parker et al., 2019). Another regional study demonstrated that erratic rains and high temperatures in southern and south-eastern Africa increased the vulnerability of agricultural soils, thereby exacerbating impacts of prolonged and frequent droughts (Sonwa et al., 2017a; See also Box 5.4).

Farm-scale assessment exemplifies context-sensitive vulnerability to climate hazards. Studies of coffee growers in Central America demonstrated that key vulnerability indicators varied greatly between regions and between farms, ranging from a lack of labour, postharvest infrastructure, conservation practices and transport that limits access to market, technical and financial assistance (Baca et al., 2014; Bouroncle et al., 2017). These region- and scale-specific vulnerability indicators assist in identifying ways to enhance resilience to climate hazards (*high confidence*).

5.4.2.2 Inequalities in cropping systems- other crops and regional disparities

While those working with major crops have benefited from the release of new cultivars, those growing other crops are typically reliant on a heritage cultivars or landraces. While Indigenous knowledge and local smallholder knowledge and practices play an important role in supporting agrobiodiversity which provides genetic diversity resistant to climate-related stresses, a global and national focus in international research, subsidies and support for a few crop species has contributed to an overall decline in agrobiodiversity (FAO, 2019e; Song et al., 2019) Similarly, there is a lack of agronomic innovation and research to service 'minor' crops (Moriondo et al., 2015; Manners and van Etten, 2018). Even some high value commodities grown outside high-income countries suffer from imbalances in the focus of available credit, research, and innovation (Section 5.4.4.3; Glover, 2014; Fischer, 2016; Farrell et al., 2018). There is a possibility that a lack of adaptive capacity and policy support will drive these growers to move away from these diverse crops, further reducing the resilience of food systems by increasing risk of crop loss from pests, disease and drought and potential loss of Indigenous or local knowledge (Section 5.13.5, Table Box 5.1.1). In the Andean Altiplano of Bolivia, for example, Indigenous farmers have traditionally managed a diverse set of native crops which are drought and frost-tolerant, using cultural practices of seed selection and exchange, but have faced an increase in pests and diseases and a decline of traditional crops due to climate change related stresses, out-migration and intensification drivers (Meldrum et al., 2018).

5.4.2.3 Gender and other social inequalities

Social inequalities such as gender, ethnicity, and income level, which vary by time and place and may overlap, can compound vulnerability to climate change for producers within cropping systems (*high confidence*) (Table 5.3, Arora-Jonsson, 2011; Djoudi et al., 2013; Carr and Thompson, 2014; Mbow et al., 2019; Rao et al., 2019a; Nyantakyi-Frimpong, 2020a). Rather than binary and static categories (i.e., men vs women), social vulnerabilities are dynamic and intersect; to understand vulnerability the specific socio-cultural identities, political and environmental context needs to be studied in relation to climate stress (Thompson-Hall et al., 2016; Rao et al., 2019a; Nyantakyi-Frimpong, 2020a).

Table 5.3: Examples of social inequalities in cropping systems that compound climate change vulnerability.

Social inequality	**How social inequality increases vulnerability to climate change in cropping systems**
Gender inequality can create and worsen social vulnerability to climate change impacts within cropping systems (*high confidence*) (Carr and Thompson, 2014; Sugden et al., 2014; Nyantakyi-Frimpong and Bezner-Kerr, 2015; Rao et al., 2019a; Ebhuoma et al., 2020; Nyantakyi-Frimpong, 2020a; see Cross-Chapter Box GENDER in Chapter 18).	• Men and women have different access to and decision-making control over resources such as seeds, systemic differences in land tenure and agricultural employment, and their responsibilities, workloads and response to climate stresses differ due to systemic gender inequities and socio-cultural norms, which intersect with other inequities (e.g., income level, ethnicity) to compound vulnerability (Rao et al., 2019a; Ebhuoma et al., 2020; Nyantakyi-Frimpong, 2020a). • In a study in northern Ghana, for example, poor widows with poor health had fewer resources to rely on during droughts than married women, particularly those married to local leaders; in contrast, due to gendered expectations, during floods low-income men suffered greater consequences (Nyantakyi-Frimpong, 2020a). • Adaptation strategies such as migration can compound that vulnerability, but importantly the specific gendered vulnerability intersects with other inequalities which are context specific (Sugden et al., 2014; Nyantakyi-Frimpong, 2020a; Cross-Chapter Box MIGRATE in Chapter 7).
Globally, **smallholder food producers** are more vulnerable than large-scale producers to climate change impacts (*high confidence*).	• In part because of limited policy, infrastructure and institutional support, low credit access, viable markets and limited political voice in policy debates (HLPE, 2013; Karttunen et al., 2017; Mbow et al., 2019; Nyantakyi-Frimpong, 2020a). • Smallholder producers' vulnerability may be increased by heavy reliance on one crop for income, particularly if the crop requires significant capital investments (*medium confidence*) (Toufique and Belton, 2014; Craparo et al., 2015; Ovalle-Rivera et al., 2015). • For example, smallholder coffee producers in southern Mexico and Central America are more vulnerable due to a range of factors, including unstable and low coffee prices, limited institutional support for small-scale producers, low negotiation capacity and access to markets, and heavy reliance on one crop for income (Economic Commission for Latin America and the Caribbean and System, 2014; Ovalle-Rivera et al., 2015; Ruiz Meza, 2015; Hannah et al., 2017; Bacon et al., 2021). Pest and disease outbreaks such as coffee leaf rust, extreme climatic events, ongoing conflict, poor governance, and low viability of livelihoods increased migration and high levels of food insecurity for this group (Robalino et al., 2015; Hannah et al., 2017; Donatti et al., 2019) which also varied by institutional and farm level responses, land size and income level (Quiroga et al., 2020; Bacon et al., 2021).
Farmworkers are another social group with heightened	• Farmworkers often experience job insecurity, food insecurity, poor working conditions, poverty, and social marginalization. Climate change impacts can compound their vulnerability, for example by worsening working conditions

vulnerability to climate change (*medium confidence*).	through increased temperatures and humidity (Section 5.12.3.1), or increase unreliability of work due to rainfall irregularity, flooding or drought, and can put them more at risk during climatic extreme events such as wildfires (Turhan et al., 2015; Greene, 2018; Mendez et al., 2020; Tigchelaar et al., 2020).

5.4.3 Projected Impacts

5.4.1.1 Advances in the characterisation of the effects of elevated atmospheric CO_2

Elevated CO_2 concentrations stimulate photosynthesis rates and biomass accumulation of C_3 crops, and enhance crop water use efficiency of various crop species including C_4 crops (*high confidence*) (Kimball, 2016; Toreti et al., 2020). Perennial crops and root crops may have a greater capacity for enhanced biomass under elevated CO_2 concentrations, although this does not always result in higher yields (Glenn et al., 2013; Kimball, 2016).

Recent FACE studies found that the effects of elevated CO_2 are greater under water-limited conditions (*medium confidence*) (Manderscheid et al., 2014; Fitzgerald et al., 2016; Kimball, 2016), which was generally reproduced by crop models (Deryng et al., 2016). However, drought sometimes negates the CO_2 effects (Jin et al., 2018).

There are significant interactions between CO_2, temperature, cultivars, nitrogen and phosphorous nutrients (Kimball, 2016; Toreti et al., 2020): Positive effects of rising CO_2 on yield are significantly reduced by higher temperatures for soybean, wheat and rice (*medium confidence*) (Ruiz-Vera et al., 2013; Cai et al., 2016; Gray et al., 2016; Hasegawa et al., 2016; Obermeier et al., 2016; Purcell et al., 2018; Wang et al., 2018). In aboveground vegetables, elevated CO_2 can in some cases reduce the impact of other climate stressors, while in others the negative impacts of other abiotic factors negate the potential benefit of elevated CO_2 (Bourgault et al., 2017; Bourgault et al., 2018; Parvin et al., 2018; Parvin et al., 2019). Significant variation exists among cultivars in yield response to elevated CO_2, which is positively correlated with yield potential in rice and soybean, suggesting the potential to develop cultivars for enhanced productivity under future elevated [CO_2] (Ainsworth and Long, 2021).

Elevated CO_2 reduces some important nutrients elements such as protein, iron, zinc, and some vitamins in the grains, fruit or vegetables to varying degrees depending on crop species and cultivars (*high confidence*) (Mattos et al., 2014; Myers et al., 2014; Dong et al., 2018; Scheelbeek et al., 2018; Zhu et al., 2018a; Jin et al., 2019; Ujiie et al., 2019). This is of particular relevance for fruit and vegetable crops given their importance in human nutrition (*high confidence*) (see Section 5.12.4 for potential impacts on nutrition; Nelson et al., 2018; Springmann et al., 2018). Recent experimental studies (Section 5.3.2), however, show some complex and counteracting interactions between CO_2 and temperature in wheat, soybean, and rice; heat stress negates the adverse effect of elevated CO_2 on some nutrient elements (Macabuhay et al., 2018; Kohler et al., 2019; Wang et al., 2019b). The CO_2 by temperature interaction for grain quality needs better quantitative understandings to predict food nutritional security in the future.

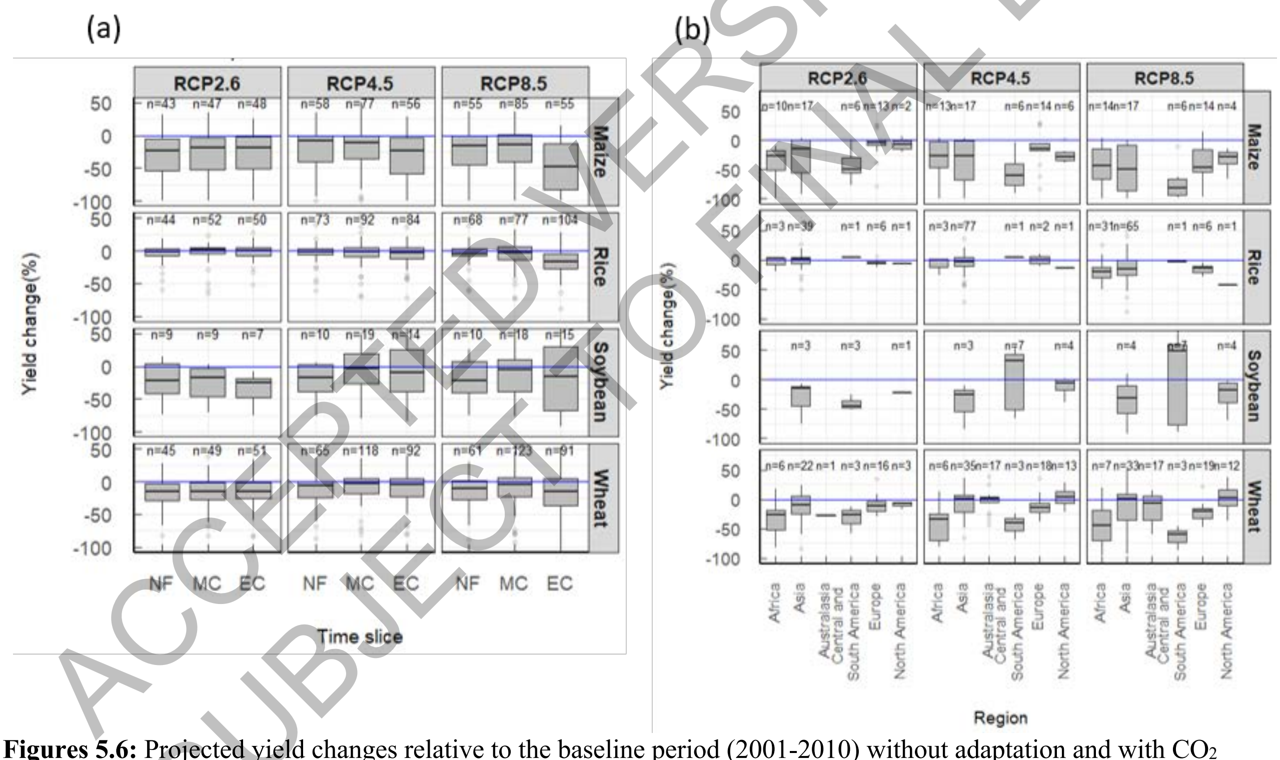
5.4.3.2 Projected impacts on major crop production

AR5 Chapter 7 estimated the crop yield reduction globally of about 1% per decade due to climate change (Porter et al., 2014), similar to that in the previous assessment reports (Porter et al., 2019). Additional research confirms that climate change will disproportionately affect crop yields among regions with more negative than positive effects being expected in most areas, especially in currently warm regions including Africa, Central and South America (*high confidence*).

A systematic literature search between 2014 and 2020 resulted in about 100 peer-reviewed papers that simulated crop yields of four major crops (maize, rice, soybean, and wheat) using CMIP5 data (Hasegawa et al., 2021b). Most studies focus on the relative change in crop yields due to climate change, but do not consider technological advances. Nevertheless, they provide useful insights into time-, scenario-, and warming-degree-dependent impacts of climate change.

The impact of climate change on crop yield without adaptation projected in the 21st century is generally negative even with the CO_2 fertilisation effects, with the overall median per-decade effect being −2.3% for maize, −3.3% for soybean, −0.7% for rice, and −1.3% for wheat, which are consistent with previous IPCC assessments (Porter et al., 2014). The effects vary greatly within each crop, timeframe, and RCP, but show a few common features across crops (Figure 5.6a**)**. Differences in the projected impacts between RCPs are not pronounced by mid-century. From then onward, the negative effect becomes more pronounced under RCP8.5, notably in maize. Rice yields show less variation across models than other crops presumably because simulations are mostly under irrigated conditions. A part of the uncertainty in the projection is due to regional differences (Figure 5. 6b). Negative impacts on cereals are projected in Africa and Central and South America at the end of the century, which agrees with the previous studies (Aggarwal et al., 2019; Porter et al., 2019).

The differences due to regions, RCPs, and timeframes are related to the current temperature level and degree of warming (Figure 5.7). The projected effects of climate change are positive where current annual mean temperatures (T_{ave}) are below 10 °C, but they become negative with T_{ave} above around 15 °C. At T_{ave}>20°C, even a small degree of warming could result in adverse effects. In maize, negative effects are apparent at almost all temperature zones. A new study using the latest climate scenarios (CMIP6) and global gridded crop model ensemble projected that climate change impacts on major crop yields appear sooner than previously anticipated, mainly because of warmer climate projections and improved crop model sensitivities (Jägermeyr et al., 2021).



Figures 5.6: Projected yield changes relative to the baseline period (2001-2010) without adaptation and with CO_2 fertilization effects (Hasegawa et al., 2021b). The box is the interquartile range (IQR) and the middle line in the box represents the median. The upper- and lower-end of whiskers are median 1.5 × IQR ± median. Open circles are values outside the 1.5 × IQR. (a) at different time periods (Near Future, NF, Baseline-2039; Mid Century, MC, 2040-2069; End of Century, EC, 2070-2100) under three representative concentration pathways (RCPs), and (b) at different regions at EC.

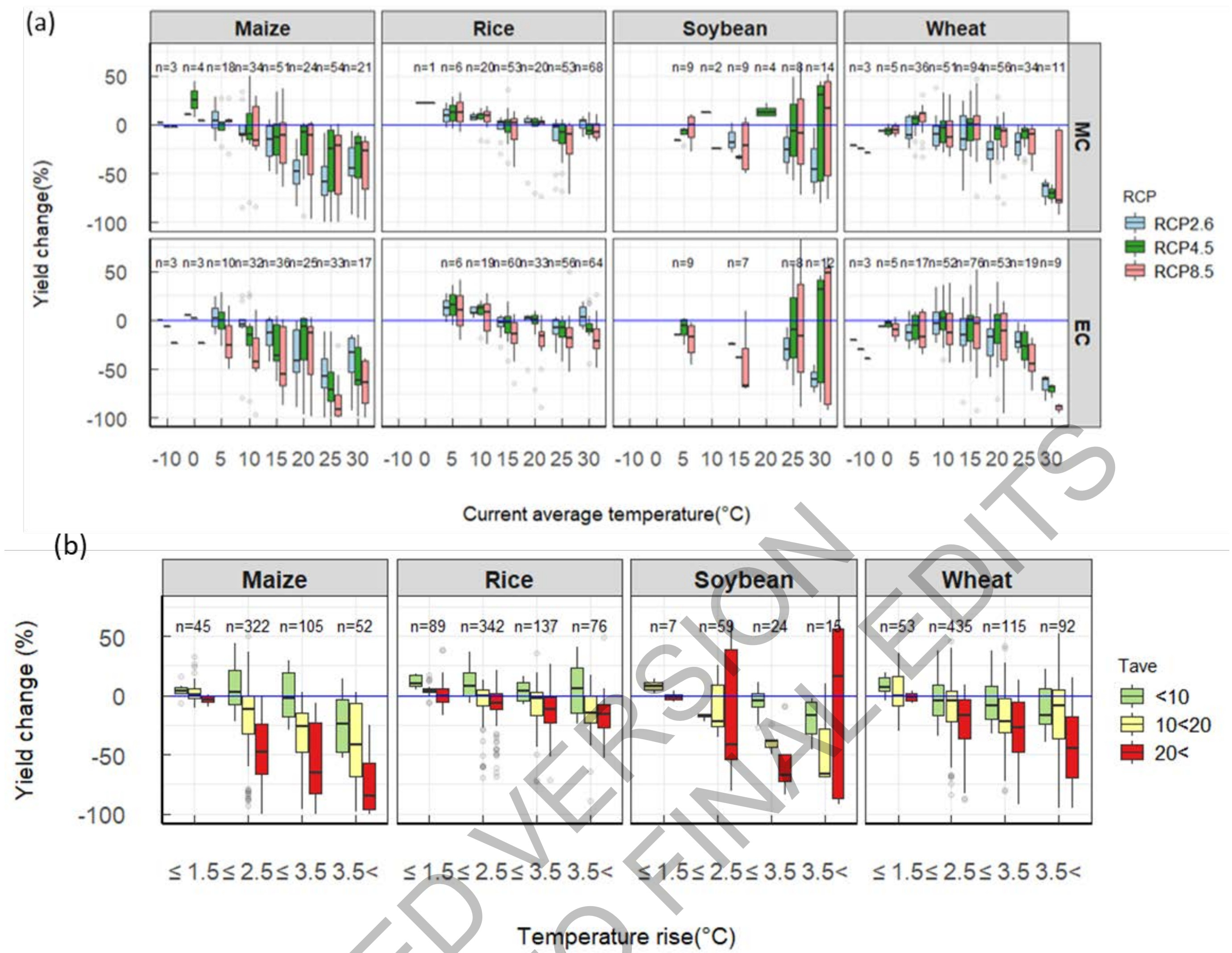


Figure 5.7: Projected yield changes relative to the baseline period (2001-2010) without adaptation and with CO_2 fertilization effects (Hasegawa et al., 2021b). (a) Mid-century (MC, 2040-2069) and end-century (EC, 2070-2100) projections under three RCP scenarios as a function of current annual temperature (T_{ave}), (b) as a function of global temperature rise from the baseline period by three T_{ave} levels. See Figure. 5.6 for legends.

As noted in Section 5.3.1, most simulations do not fully account for responses to pests, diseases, long-term change in soil, and some climate extremes (Rosenzweig et al., 2014), but studies are emerging to include some of these effects. For example, based on the temperature response of insect pest population and metabolic process, global yield losses of rice, maize, and wheat are projected to increase by 10 – 25 % per degree of warming (Deutsch et al., 2018). Rising temperatures reduce soil carbon and nitrogen, which in turn exacerbate the negative effects of + 3 °C warming on yield from 9 to 13 % in wheat and from 14 to 19 % in maize (Basso et al., 2018).

A few studies have examined possible occurrences of tele-connected yield losses (5.4.1.2) using future climate scenarios. Tigchelaar (2018) estimated that for the top four maize–exporting countries, the probability that simultaneous production losses greater than 10% occur in any given year increases from 0 to 7% under 2°C-warming and to 86% under 4 °C-warming. Gaupp (2019) estimated that risks of simultaneous failure in maize would increase from 6% to 40% at 1.5 °C and to 54% at 2 °C-warming, respectively, relative to the historical baseline climate. Large-scale changes in SST are the major factors causing simultaneous variation in climate extremes, which are projected to intensify under global warming (Cai et al., 2014; Perry et al., 2017). Consequently, risks of multi-breadbasket failures will also increase (*medium confidence*). Further examination is needed for the effects of spatial patterns of these extremes on breadbaskets in relation to SST anomalies under more extreme climate scenarios.

Future surface ozone concentration is highly uncertain (Fiore et al., 2012; Turnock et al., 2018); it is projected to increase under RCP8.5 and to decrease under other RCPs depending largely on different methane emission trajectories because methane is an important precursor of ozone. Methane, therefore, reduces crop yield both from climate warming and ozone increase (Avnery et al., 2013). Shindell (2016) estimated yield losses of four major crops (to be 25 ± 11% by 2100 under RCP8.5, as a net balance of the positive effect of CO_2 (15± 2%) and negative effects of warming (35 ± 10%) and ozone (4.0 ± 1.3%), and that 62% of the yield loss was attributable to methane. This points to the importance of reducing methane and other precursors of ozone as an effective adaptation strategy (*medium evidence, high agreement*).

5.4.3.3 Projected impacts on other crops

Yield projections for crops other than cereals indicate mostly negative impacts on production due to a range of climate drivers (*high confidence*), with yield reductions similar to that of cereals expected in tropical, subtropical and semi-arid areas (Mbow et al., 2019). Springmann et al. (2016), compared the projected global food availability for different food groups under the SSP2 2050 scenario and found reductions in availability were similar in cereals, fruit and vegetables, and root and tubers (with legumes and oilseed crops showing a smaller reduction).

Fruit and vegetables have not been subject to extensive or coordinated yield projections (Figure 5.8). Yield projections have been performed for individual crops and locations (Ruane, 2014; Adhikari et al., 2015; Awoye et al., 2017; Ramachandran et al., 2017); but more often crop suitability models have been used (SM5.3). Zhao(2019) introduced a modelling approach that could be used to generate yield projections for a wider range of annual crops. The discussion here also draws on reviews of more restricted experimental studies. Negative impacts of climate change on crop production are expected across many cropping systems (Figure 5.8). Apart from the direct effects of elevated carbon dioxide, most changes are expected to have negative effects on crop production. Changes in temperature and rainfall are most often mentioned as drivers of climate impacts, but expected changes in phenology, pests and diseases are also raising concerns. (Scheelbeek et al., 2018) synthesized projections for vegetables and legumes, based on their response to climate factors under experimental conditions; in most cases the magnitude of the changes is comparable to the RCP 8.5 2100 forecasts. Scheelbeek et al. (2018) projected yield changes of: +22.0% (+11.6% to +32.5%) for a 250 ppm increase in CO_2 concentration; −34.7% (−44.6% to −24.9%) for a 50 % reduction in water availability; −8.9% (−15.6% to −2.2%) for a 25 % increase in ozone concentration; −31.5% for a 4°C increase in temperature (in papers with a baseline temperature of >20°C). Overall, impacts are expected to be largely negative in regions where the temperature is currently above 20°C, while some yield gains are expected in cooler regions (provided that water availability and other conditions are maintained). Scheelbeek et al. (2018), did not consider changes in pest and disease pressure, which are projected to increase with warming (see SM5.3).

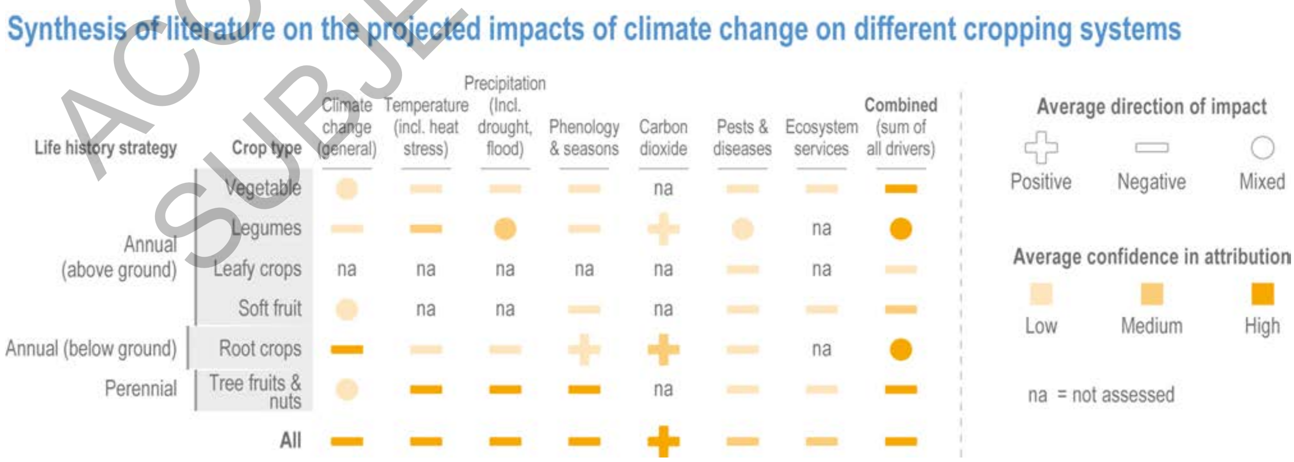


Figure 5.8: Synthesis of literature on the projected impacts of climate change on different cropping systems. The assessment includes projections of impacts on crop productivity over a range of emission scenarios and time periods. The projected impacts are disaggregated by the different climate and climate-related drivers. Impacts are reported as positive, negative or mixed. The assessment draws on >60 articles published since AR5. The confidence is based on the evidence given in individual articles and on the number of articles. See **SM5.2** information for details.

Systematic assessments of climate response for root crops as a group are lacking (Raymundo et al., 2014; Knox et al., 2016; Manners and van Etten, 2018). Climate suitability is projected to increase for tropical root crops (SM5.3) and some studies have found that root crops will be less negatively impacted than cereals, but there is no consensus on this (Brassard and Singh, 2008; Adhikari et al., 2015; Schafleitner, 2016; Manners et al., 2021). For potato, Raymundo et al. (2018) projected global yield reductions of 2-6% by 2055 under different RCPs, but with important differences among regions; tuber dry weight may experience reductions of 50 to 100% in marginal growing areas such as central Asia, while increases of up to 25% are expected in many high-yielding environments. Projections show yield increases of 6% per 100 ppm elevation in CO_2 but declines of 4.6% per °C and 2% per 10% decrease in rainfall (Fleisher et al., 2017). Jennings et al. (2020), projected an overall increase in global potato production, but only if widespread adoption of adaptation measures is achieved. Although increases in CO_2 could produce positive yield responses, the effects of temperature may offset these potential benefits (Dua et al., 2013; Raymundo et al., 2014). Warming offers the potential of longer growing seasons but can also have negative impacts through disrupted phenology and interactions with pests (Figure 5.8, Bebber, 2015; Pulatov et al., 2015).

Global yield modelling is lacking for woody perennial crops. Experimental studies suggest negative impacts on yields due to reduced water supply and increased soil salinity, as well as from warming and ozone (although evidence was limited for these) (Alae-Carew et al., 2020). Increasing CO_2 is expected to increase yields, but only where other factors, such as warming, do not become yield-limiting (Alae-Carew et al., 2020). Many local projections include large uncertainty because of a lack of observational data and reliable parametrization (Moriondo et al., 2015; Mosedale et al., 2016; Kerr et al., 2018; Mayer et al., 2019b). Most perennial crop models have found large negative impacts on yield and suitability, although CO_2 fertilisation and phenology are not always considered (Lobell and Field, 2011; Glenn et al., 2013). Perennial crops are often grown in dryland areas where rainfall or irrigation water can be critical (Mrabet et al., 2020). Valverde (2015) found that yield losses in the Mediterranean region were largely driven by reduced rainfall, with maximum estimated yield losses of 5.4% for grape, 14.9% for olive and 27.2% for almond under a relatively hot and dry scenario (by 2041–2070). Moriondo (2015) highlight the need for perennial crop models to incorporate phenology and extreme climate events. Equally challenging is the need to estimate the impact of biotic changes, particularly climate-driven movement of pests and diseases (Ponti et al., 2014; Bosso et al., 2016; Schulze-Sylvester and Reineke, 2019; Section 5.5.2.4).

For cotton, experimental studies suggest positive impacts from rising CO_2 and temperature (Zhang et al., 2017a; Jans et al., 2021), but projections show mixed impacts on yield, including large negative impacts in warmer regions due to heat, drought and the interaction of temperature with phenology (Yang et al., 2014; Williams et al., 2015; Adhikari et al., 2016; Rahman et al., 2018). Climate change is also expected to increase the demand for irrigation water, which will likely limit production (Jans et al., 2021). There are also concerns that fibre quality may deteriorate (e.g., air permeability of compressed cotton fibers) (Luo et al., 2016).

Higher temperatures and altered moisture levels are expected to present a food safety risk, particularly for above ground harvested vegetables (Figures 5.8; 5.10). Warmer and wetter weather is anticipated to increase fungal and microbial growth on leaves and fruit, while altered flooding regimes increase the risk of crop contamination (Liu et al., 2013; Uyttendaele et al., 2015). This is also true for perennial crops, e.g., warming and climate variability can increase fungal contamination of grapes including those associated with mycotoxins (Battilani, 2016; Paterson, 2018).

[START BOX 5.2 HERE]

Box 5.2: Case Study: Wine

Wine growing regions cover 7.4 million ha with a value of 35 billion USD in 2018 (OIV, 2019). Important regions (Italy, France, Spain, United States, Argentina, Australia, South Africa, Chile, Germany, China, Argentina) are located in areas where mean annual temperature roughly varies between 10 and 20 °C (Schultz and Jones, 2010; Mosedale et al., 2016).

Temperature is the primary determinant for vine development. Recent warming trends have advanced flowering, maturity, and harvest (*high confidence*) (Koufos et al., 2014; Cook and Wolkovich, 2016; Hall et al., 2016; Ruml et al., 2016; van Leeuwen and Destrac-Irvine, 2017; Koufos et al., 2020; Wang et al., 2020b; Wang and Li, 2020), and wine growing regions have expanded outside the normal temperature bounds of locally grown varieties (*limited evidence, high agreement*) (Kryza et al., 2015; Irimia et al., 2018). Milder winters have affected harvest in ice-wine growing regions (Pickering et al., 2015). Higher temperatures have mixed effects depending on site, but generally decreases grape quality (Barnuud et al., 2014; Morales et al., 2014; Sweetman et al., 2014; Kizildeniz et al., 2015; Kizildeniz et al., 2018). Warming increases sugar accumulation and decreases acidity (Leolini et al., 2019). Secondary metabolites are negatively affected (Biasi et al., 2019; Teslić et al., 2019). Developmental phases are projected to proceed faster in response to warming (*high confidence*) (Fraga et al., 2016a; Fraga et al., 2016b; García de Cortázar-Atauri et al., 2017; Costa et al., 2019; Molitor and Junk, 2019; Sánchez, 2019). However extreme high temperatures may have inhibitory effects on development (Cuccia et al., 2014).

In some cases, irrigation is required, and more frequent droughts are a key concern for yield and fruit quality (Morales et al., 2014; Bonada et al., 2015; Kizildeniz et al., 2015; Salazar-Parra, 2015; Kizildeniz et al., 2018; Funes et al., 2020). Water stress reduces shoot growth and berry size, and increases tannin and anthocyanin content (van Leeuwen and Darriet, 2016). However, controlled water stress produces positive impacts on wine quality, increasing skin phenolic compounds (van Leeuwen and Destrac-Irvine, 2017). The level of stress will depend on soil type, texture and organic matter content (Fraga et al., 2016a; Fraga et al., 2016b; Bonfante, 2017; García de Cortázar-Atauri et al., 2017; Leibar et al., 2017; Costa et al., 2019; Molitor and Junk, 2019; Sánchez, 2019). Increases in water demands with potential negative effects from increased soil salinity are among the most common effects of climate change in irrigated regions (*medium evidence, high agreement*) (Mirás-Avalos et al., 2018; Phogat et al., 2018).

Rising CO_2 will have mixed effects on vine growth and quality (*medium evidence, high agreement*) (Martínez-Lüscher et al., 2016; Edwards et al., 2017; van Leeuwen and Destrac-Irvine, 2017). Rising CO_2 concentrations will negatively affect wine quality by reducing anthocyanin concentration and colour intensity (Leibar et al., 2017).

Suitability responses to warming are region-specific. In regions where low temperature is a limiting factor, warming will enable growers to grow a wider range of varieties and obtain better-quality wines (*high confidence*) (Fuhrer et al., 2014; Mosedale et al., 2015; Mosedale et al., 2016; Meier et al., 2018; Jobin Poirier et al., 2019; Maciejczak and Mikiciuk, 2019). Subtropical and Mediterranean regions will experience major declines in fruit quality for high-quality wines (*high confidence*) (Resco et al., 2016; Lazoglou et al., 2018; Cardell et al., 2019; Fraga et al., 2019a; Fraga et al., 2019b; Teslić et al., 2019). These changes will also affect wine tourism (Nunes and Loureiro, 2016).

Impacts on suitability may reshape the geographical distribution of wine regions. Viability of the wine-growing regions will depend on the knowledge of local climatic variability (Neethling et al., 2019; Rességuier et al., 2020) and the implementation of adaptation strategies such as use of adapted plant material rootstocks, cultivars and clones, viticultural techniques (e.g., changing trunk height, leaf area to fruit weight ratio, timing of pruning), irrigation, enological interventions to control alcohol and acidity, as well as policy incentives and support (Callen et al., 2016; Ollat and Leeuwen, 2016; van Leeuwen and Destrac-Irvine, 2017; Merloni et al., 2018; Alikadic et al., 2019; del Pozo et al., 2019; Fraga et al., 2019b; Santillan et al., 2019; Morales-Castilla et al., 2020; Marín et al., 2021).

[END BOX 5.2 HERE]

[START BOX 5.3 HERE]

Box 5.3: Pollinators

Climate change will reduce the effectiveness of pollinator agents as species are lost from certain areas, or the coordination of pollinator activity and flower receptiveness is disrupted in some regions (*high confidence*)

(Potts et al., 2010; Gonzalez-Varo et al., 2013; Polce et al., 2014; Kerr et al., 2015; Potts et al., 2016; Settele et al., 2016; Giannini et al., 2017; Mbow et al., 2019). A modelling study estimates that complete removal of pollinators could reduce global fruit supply by 23%, vegetables by 16%, and nuts and seeds by 22%, leading to significant increases in nutrient-deficient population and malnutrition-related diseases (Smith and Haddad, 2015), highlighting the importance of this ecosystem service for human health.

Bees are an essential agricultural pollinator, widely recognized for their role in the fertilisation of many domesticated plants. The observed wide-spread decline in native bees and honeybee colony numbers, particularly in the U.S. and Europe, has been associated with a number of environmental stressors in addition to climate change, such as neonicotinoids and varroa mites, and has raised concerns regarding plant-pollinator networks, the stability of pollination services, global food production and the prevalence of malnutrition (Williams and Osborne, 2009; Potts et al., 2010; Chaplin-Kramer et al., 2014).

Any climatic influence on floral phenology or physiology could, potentially, alter bee biology. At present there is evidence that climate change induced asynchrony in pollen and pollinators can occur (Stemkovski et al., 2020). In addition, the nutritional composition of floral pollen may also affect the bee's health at the global level (*low evidence*). For example, the goldenrod (*Solidago* spp.), a ubiquitous pollen source for bees just prior to winter, has experienced a ~30% drop in protein since the onset of CO_2 emissions from the industrial revolution (Ziska et al., 2016).

Climate extremes could pose risks to pollinator when species tolerance is exceeded, with subsequent reduction in populations and potential extirpation (Nicholson and Egan, 2020; Soroye et al., 2020). The rate of climate change may induce potential mismatches in the timing of flowering and pollinator activity depending on the species (Bartomeus et al., 2011). For instance, Miller-Struttmann (2015) showed that long-tongued bumblebees may be at a disadvantage as warming temperatures are reducing their floral hosts, making generalist bumblebees more successful.

Overall, there is *medium confidence* that long-term mutualisms may be impacted directly by CO_2 increases in terms of nutrition, or by temperature and other climatic shifts that may alter floral emergence relative to pollinator life cycles. Additional research is needed to further our understanding of the biological basis for these effects, and their consequence for pollination services.

[END BOX 5.3 HERE]

5.4.3.4 Observed and projected impacts on cultural ecosystem service

Cultural ecosystem services (CES) are those non-material benefits, such as aesthetic experiences, recreation, spiritual enrichment, social relations, cultural identity, knowledge and other values (Millennium Ecosystem Assessment, 2005), which support physical and mental health and human well-being (Chan et al., 2012; Triguero-Mas et al., 2015). CES in agricultural and wild landscapes include recreational activities, access to wild or cultivated products, and cultural foods, spiritual rituals, heritage and memory dimensions, and aesthetic experiences (Daugstad et al., 2006; Calvet-Mir et al., 2012; Ruoso et al., 2015). Relative to other ecosystem services, CES in agricultural landscapes has had less research (Merlín-Uribe et al., 2012; Milcu et al., 2013; Bernues et al., 2014; Plieninger et al., 2014; van Berkel and Verburg, 2014; Ruoso et al., 2015; Quintas-Soriano et al., 2016). Agricultural heritage is a key aspect of CES and plays an important role in maintaining agrobiodiversity (Hanaček and Rodríguez-Labajos, 2018).

Climate change is projected to have negative impacts on Cultural ecosystem services (*medium confidence*) (Table 5.4). There is limited evidence that climate change has been the main driver affecting CES of agroecosystems confounded by other drivers such as migration and changing farming patterns (Hanaček and Rodríguez-Labajos, 2018; Dhakal and Kattel, 2019). Recent studies observed declines in CES in Alpine pastures and floodplains in Europe in part due to climate change impacts (Probstl-Haider et al., 2016; Schirpke et al., 2019). Another study estimated that the scenic beauty enjoyed by those who visit the vineyards in central Chile will decline by 18-28% by 2050 due to a combination of reduced precipitation, increased temperatures, and natural fire cycles (Martinez-Harms et al., 2017). More research is needed, however, particularly on cultural heritage, spiritually significant places, and in low-income countries.

Table 5.4: Projected Impacts on CES from Climate Change.

Region	CES	Climate Change Scenario	Projected impacts from climate change	References
Central Chile, South America	Aesthetic experience of scenic beauty in vine-growing region.	RCP 2.6 and 8.5.	Increased temperature, reduced precipitation and increased fires will damage scenic beauty of vineyards. Participatory scenario analysis estimated reduction in aesthetic experience from scenic beauty by 18-28% by 2050 for RCP 2.6, with greater impacts under RCP 8.5.	Martinez-Harms et al. (2017)
Mountainous regions of Austria	Cultural and aesthetic experiences in alpine pastures and diverse agricultural landscapes	Temperature + 1.5 °C from 2008 to 2040 and 4 precipitation scenarios (High, similar, seasonal *s*hift and Low*)*.	Some decline in CES, with tradeoffs between diversity and cultural ecosystem services and provisioning services depending upon the scenario.	Kirchner et al. (2015)
Forest and agricultural landscapes in southern Saxony-Anhalt in Germany	Recreation, scenic landscape beauty and spiritual value of agricultural landscapes and forests.	Regional scenarios, do not specify RCPs.	Not anticipated to be significantly changed by climate change under most scenarios, except for intensification scenario, which would lead to a decline in the forest cultural services as they provide important historical and cultural ties.	Gorn et al. (2018)
Northeast Austria floodplains (grasslands and wetlands)	Tourism, recreation, cultural heritage.	Increased temperature by 2050 and 2100 and seasonal shifts in precipitation.	Increased agricultural intensification due to shifts in climate and decline in CES is predicted, based on farmer interviews.	Probstl-Haider et al. (2016)
Mount Kenya, Kenya	Tourism, recreation, spiritual and cultural values.	Not specified	Glacier disappearance may lead to reduced mountain trekking and other tourism and recreational activities.	Evaristus (2014)
Philippines	Nature-based tourism in agri-tourism	Not specified	Risk of typhoon, drought and strong wind, grass fire, heavy rains. Anticipated to increase vulnerability in terms of human health services and energy use in tourism.	Hidalgo (2015)

[START BOX 5.4 HERE]

Box 5.4: Soil Health

Soil health, defined as an integrative property that reflects the capacity of soil to respond to land management, continues to support provisioning ecosystem services (Kibblewhite et al., 2008). Climate change will have significant impacts on soil health indicators such as soil organic matter (SOM). For example, precipitation extremes can reduce soil biological functions, and increase surface flooding, waterlogging, soil erosion and susceptibility to salinization (Herbert et al., 2015; Chen and Mueller, 2018; Akter et al., 2019; Sánchez-Rodríguez et al., 2019).

The most significant threat to soil health is the loss of SOM (FAO and ITPS, 2015). SOM holds a great proportion of the nutrients, and regulates important soil physical, chemical, and biological processes, such as cation exchange capacity, pH-buffering, soil structure, water-holding capacity, and microbial activity (FAO and ITPS, 2015). Soils also hold the largest terrestrial organic carbon stock, 3-4 times greater than the atmosphere (Stoorvogel et al., 2017). At the global scale, climate and vegetation are the main drivers of soil carbon (SOC) storage (Wiesmeier et al., 2019). While organic matter input is the primary driver of SOC stocks (Fujisaki et al., 2018), temperature and soil moisture play a key role in SOC storage at the local scale (Carvalhais et al., 2014; Doetterl et al., 2015). Soil type, land-use and management practices also play important roles at the local scale.

Increase in soil temperature will negatively impact SOC, but primarily in higher latitudes (*medium confidence*) (Carey et al., 2016; Qi et al., 2016; Feng et al., 2017; Gregorich et al., 2017; Hicks Pries et al., 2017; Melillo et al., 2017; Hicks Pries et al., 2018). Experiments have shown that warming can accelerate litter mass loss and soil respiration (Lu et al., 2013) and reduces the soil recalcitrant C pool (Chen et al., 2020). SOC losses may speed up soil structural degradation, changes in soil stoichiometry and function (Hakkenberg et al., 2008; Tamene et al., 2019), with downstream effects on aquatic ecosystems. The rate and extent of SOC losses vary greatly depending on the scale of measurement (local to global), soil properties, climate, land-use, and management practices (Sanderman et al., 2017; Wiesmeier et al., 2019).

Adoption of practices that build SOC can improve crop resilience to climate change-related stresses such as agricultural drought. Iizumi and Wagai (2019) found that a relatively small increase in topsoil (0–30 cm) SOC could reduce drought damages to crops over 70% of the global harvested area. The effects of increasing SOC are more positive in drylands due to more efficient use of rainwater, which can increase drought tolerance (Iizumi and Wagai, 2019). Similarly, Sun et al. (2020) found that relative to local conventional tillage, conservation agriculture has a win-win outcome of enhanced C sequestration and increased crop yield in arid regions. However, the impact of no-till may be minimal if not supplemented with residue cover and cover crops. As such this is a highly debated area where some authors argue that no-till has limited effect and the evidence outside drylands is weak. Furthermore, the use of crop residues is constrained by its alternative uses (e.g., fuel, livestock feed, etc.) in much of the developing world. Practices that build up SOC may encourage soil microbial populations, which in turn can increase yield stability under drought conditions (Prudent et al., 2020).

Soil C sequestration is an important strategy to improve crop and livestock production sustainably that could be applied at large scales and at a low cost, if there was adequate institutional support and labour, using agroforestry, conservation agriculture, mixed cropping, and targeted application of fertiliser and compost (*high confidence*) (Paustian et al., 2016; Kongsager, 2018; Nath et al., 2018; Woolf et al., 2018; Corbeels et al., 2019; Kuyah et al., 2019; Corbeels et al., 2020; Muchane et al., 2020; Sun et al., 2020; Nath et al., 2021). For example, a widespread adoption of agroforestry, conservation agriculture, mixed cropping, and balanced application of fertiliser and compost by India's small landholders could increase annual C sequestration by 70–130 Tg CO_2e (Nath et al., 2018; Nath et al., 2021).

[END BOX 5.4 HERE]

5.4.4 Adaptation Options

Adaptation strategies in crop production range from field and farm-level technical options such as crop management and cultivar/crop options to livelihood diversification and income protection such as index-based insurance. This section assesses crop management options for different crop types. Feasibility of adaptation options in various systems are addressed in Section 5.14.

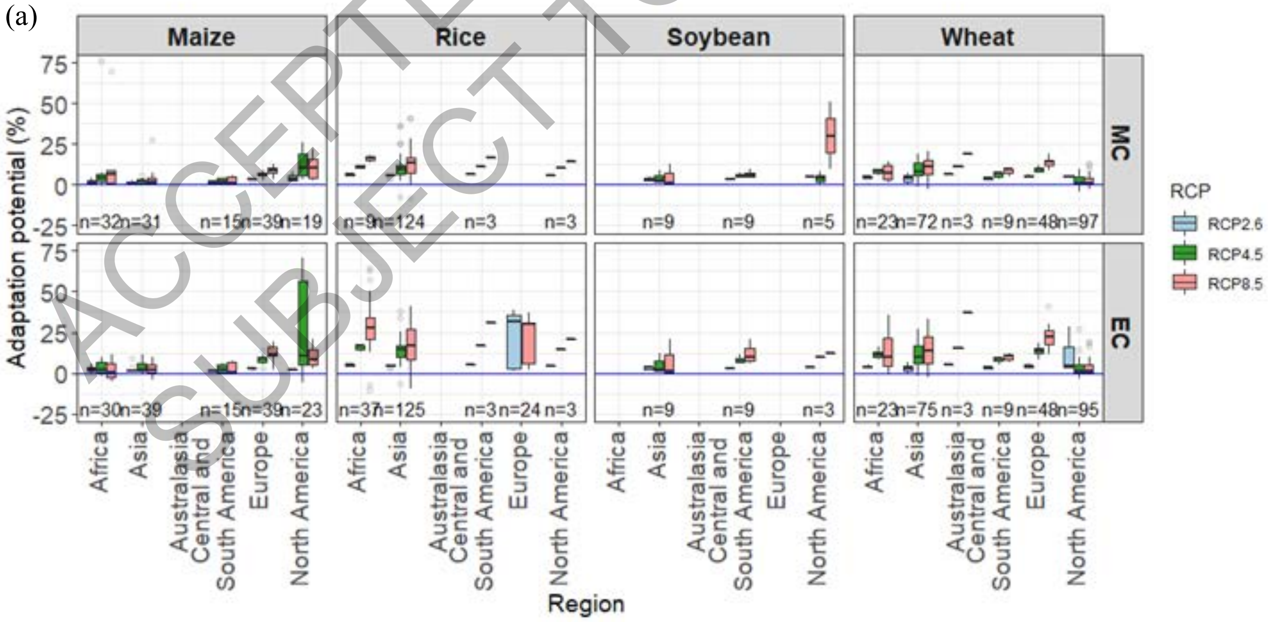
5.4.4.1 Adaptation options for major crops

Crop management practices are the most commonly studied adaptation measures (Shaffril et al., 2018; Hansen et al., 2019a; Muchuru and Nhamo, 2019), but quantitative assessments are mostly limited to existing agronomic options such as changes in planting schedules, cultivars, and irrigation (Beveridge et al., 2018a; Aggarwal et al., 2019). This section draws on the global dataset used in Sections 5.4.3.2 (Hasegawa et al., 2021b) to estimate adaptation potential, defined as the difference in simulated yields with and without adaptations. A caveat to the analysis is that the dataset includes management options if the literature treats them as adaptation. They include intensification measures such as fertilizer and water management, not allowing for physical and economic feasibility.

The overall adaptation potential of existing farm management practices to reduce yield losses averaged 8% in mid-century and 11% in end-century (Figure 5.9), which is insufficient to offset the negative impacts from climate change, particularly in currently warmer regions (Section 5.4.3.2). Emission scenarios, crop species, regions, or adaptation options do not show discernible differences. Combinations of two or more options do not necessarily have greater adaptation potential than a single option, though a fair comparison is difficult in the dataset from independent studies. One regional study in West Africa found that currently promising management would no longer be effective under future climate, suggesting the need to evaluate effectiveness under projected climate change.

A global-scale meta-analysis estimated a 3-7% yield loss per degree increase in temperature (Zhao et al., 2017). Two global-scale studies using multiple global gridded crop models found that growing-season adaptation through cultivar changes offsets global production losses up to 2°C of temperature increase (Minoli et al., 2019; Zabel et al., 2021). While these studies do not account for CO_2 fertilisation effects, another global-scale study with the CO_2 fertilisation effects (Iizumi et al., 2020) showed that residual damage (climate change impacts after adaptation) would start to increase almost exponentially from 2040 toward the end of the century under RCP 8.5. The cost required for adaptation and due to residual damage is projected to rise from US$63 billion at 1.5°C to US$80 billion at 2°C and to US$128 billion at 3°C (Iizumi et al., 2020). All these global studies project that risks and damages are greater in tropical and arid regions, where crops are exposed to heat and drought stresses more often than in temperate regions (Sun et al., 2019; Kummu et al., 2021; SM5.4). There are still large uncertainties in the crop model projections (Müller et al., 2021a), but these (Iizumi et al., 2020) multiple lines of evidence suggest that warming beyond +2 °C (projected to be reached by mid-century under high emission scenarios) will substantially increase the cost of adaptation and the residual damage to major crops (*high confidence*). The residual damage will prevail much sooner in currently warmer regions, where the effect of even a modest temperature increase is greater (Section 5.4.3.2).

(a)



(b)

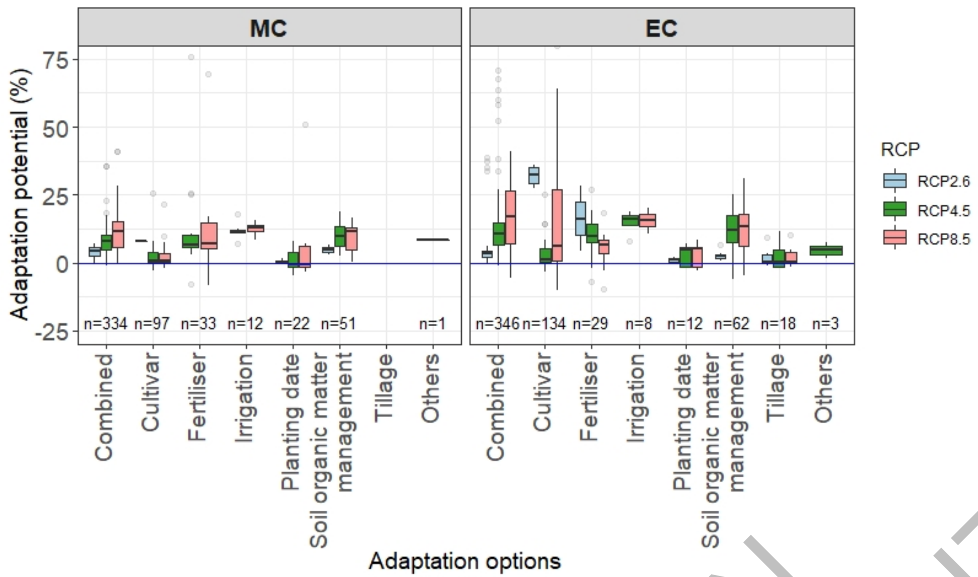


Figure 5.9: Adaptation potential, defined as the difference between yield impacts with and without adaptation in projected impacts (Hasegawa et al., 2021b). (a) projections under three RCP scenarios by regions and (b) by options at mid-century (MC, 2040-2069) and end-century (EC, 2070-2100). n is the number of simulations. See Figure 5.6 for legends.

Most crop modelling studies on adaptation are still limited to a handful of options for each crop type (Beveridge et al., 2018a). A range of other options are possible not just to reduce yield losses but to diversify risks to livelihoods, which are partially assessed in Sections 5.4.4.4 and 5.14.1. Current modelling approaches are not suited for the assessment of multiple dimensions of adaptation options. New studies are emerging that evaluate multiple options for productivity, sustainability, and greenhouse gas emission (Xin and Tao, 2019; Smith et al., 2020b), but local- and household-scale assessment, taking account of future climatic variability, needs to be enhanced (Beveridge et al., 2018a).

5.4.4.2 Adaptation options for other crops

Across this diverse group of cropping systems distinct adaptation options and adaptation limits have emerged (Figure 5. 10; Acevedo et al., 2020; Berrang-Ford et al., 2021b). Some crop types have already seen widescale implementation of climate adaptation (e.g., grapevines), while others show little evidence of preparation for climate change (e.g., leafy salad crops). Many adaptation responses are shared with the major crops, but prominent options such as plant breeding are under-utilized and there is a lack of evidence for assessing adaptation for many crops (Bisbis et al., 2018; Gunathilaka et al., 2018; Manners and van Etten, 2018). Figure 5.11 assesses several adaptation options based on the perceived importance of each in the literature. Fruit and vegetable crops tend to be more reliant on ecosystem services in the form of pollination, biocontrol, and other resources (water, nutrients, microbes, etc.), and ecosystem-based adaptation options are prominent. The range of crops means that there is great potential for crop switching, but cultural and economic barriers will make such options difficult to implement, with barriers to entry for production and marketing (Waha et al., 2013; Magrini et al., 2016; Kongsager, 2017; Rhiney et al., 2018). Perennial crops are exposed to a wide range of climate factors throughout the year and have significant barriers to implementing some of the common adaptation options, such as relocation or replacing tree species/cultivar, agronomic interventions on-farm are well used in high value tree crops and provide some climate resilience, but longer-term options will be needed (Glenn et al., 2013; Mosedale et al., 2016; Gunathilaka et al., 2018; Sugiura, 2019).

Many fruit and vegetable crops are water demanding, and adaptation responses relating to water management and access to irrigation water are crucial. Rainwater storage and deficit irrigation techniques are frequently mentioned as adaptation options and can minimise the burden on off-farm water supplies (Bisbis et al., 2018; Acevedo et al., 2020).

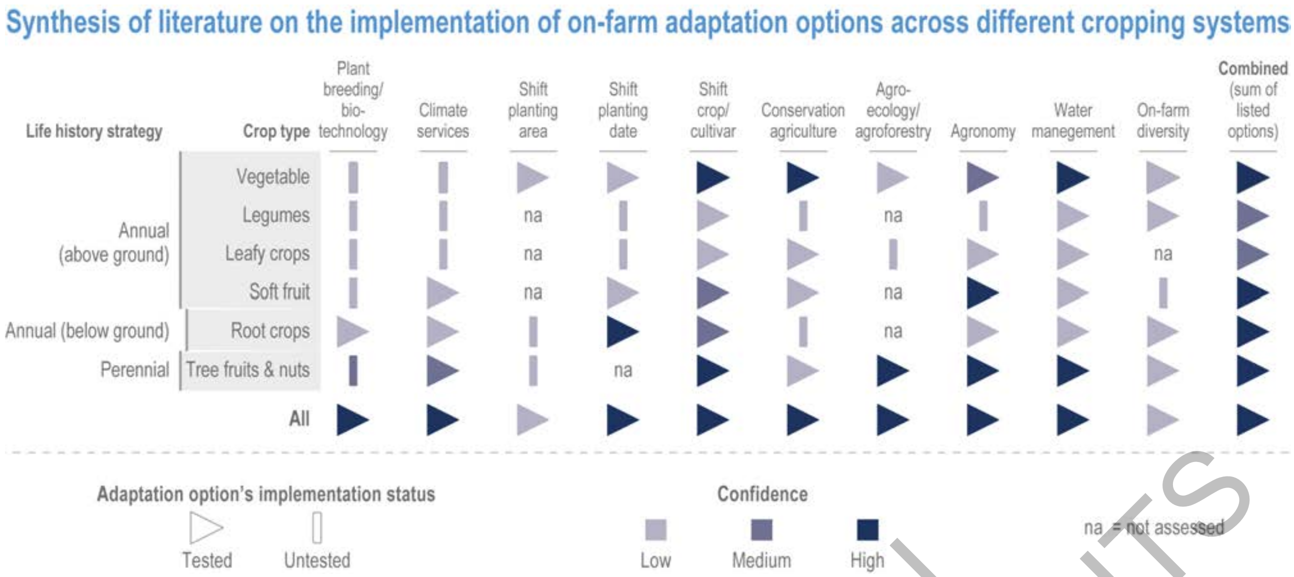


Figure 5.10: Synthesis of literature on the implementation of on-farm adaptation options across different cropping systems. Adaptation options that have been implemented by growers are considered 'tested', while those that have not are considered 'untested'. Untested options are those that appear in studies as suggestions by stakeholder or experts, but were not implemented within the study. The assessment draws on >200 articles published since AR5. The confidence is based on the evidence given in individual articles and on the number of articles. See SM5.2 for details.

5.4.4.3 Cultivar improvements

As stated in AR5, cultivar improvements are one effective countermeasure against climate change (Porter et al., 2014; Challinor et al., 2016; Atlin et al., 2017). Plant breeding biotechnology for climate change adaptation draws upon modern biotechnology and conventional breeding, with the latter often assisted by genomics and molecular markers. Plant breeding biotechnology will contribute to adaptation for large scale producers (*high confidence*). However, in addition to inconsistencies in meeting farmer expectations, a variety of socio-economic and political variables strongly influence, and limit, uptake of climate-resilient crops (Acevedo et al., 2020; Rhoné et al., 2020).

Genome sequencing significantly increases the rate and accuracy for identifying genes of agronomic traits that are relevant to climate change, including adaptation to stress from pests and disease, temperature, and water extremes (*high confidence*) (Brozynska et al., 2016; Scheben et al., 2016; Voss-Fels and Snowdon, 2016). Access to this information where it is needed and in practical timeframes, as well as the expertise to use it will limit the sharing of benefits by the most vulnerable groups and countries (*high agreement, limited evidence*) (Heinemann et al., 2018).

Genetic improvements for climate change adaptation using modern biotechnology have not reliably translated into the field (Hu and Xiong, 2014; Nuccio et al., 2018; Napier et al., 2019), but good progress has been made by conventional breeding. Desirable traits that adapt plants to environmental stress are inherited as a complex of genes each of which makes a small contribution to the trait (Negin and Moshelion, 2017). Adaptation by conventional breeding requires making rapid incremental changes in the best germplasm to keep pace with the environment (Millet et al., 2016; Atlin et al., 2017; Cobb et al., 2019). Further improvements would be difficult without in situ and ex situ conservation of plant genetic resources to maintain critical germplasm for breeding (Dempewolf et al., 2014; Castañeda-Álvarez et al., 2016).

Despite the advances in sequencing, phenotyping remains a significant bottleneck (Ghanem et al., 2015; Negin and Moshelion, 2017; Araus and Kefauver, 2018), the emergence of high-throughput phenotyping platforms may reduce this bottle neck in future. Emerging modern biotechnology such as gene/genome editing may in the future increase the ability to better translate genetic improvements into the field *(medium agreement, limited evidence)* (Puchta, 2017; Yamamoto et al., 2018; Friedrichs et al., 2019; Kawall, 2019; Zhang et al., 2019).

Other breeding approaches assisted by genomics have been making steady gains in introducing traits that adapt crops to climate change (*high confidence*). DNA sequence information is used to identify markers of desirable traits that can be enriched in breeding programs, as well as to quantify the genetic variability in species (Gepts, 2014; Brozynska et al., 2016; Voss-Fels and Snowdon, 2016). However, breeding for smallholder farmers and the stresses caused by climate change is unlikely to be addressed by the private sector and will require more public investment and adjusting to the local social-ecological system (Glover, 2014; Heinemann et al., 2014; Acevedo et al., 2020). Modern biotechnology has not demonstrated the scale neutrality needed to serve smallholder dominated agroecosystems, due to a combination of the kinds of traits and restrictions that come from the predominant intellectual property rights instruments used in their commercialization, as well as the focus on a small number of major crop species (*medium confidence)* (Fischer, 2016; Montenegro de Wit et al., 2020).

Globally, there is a notable lack of programs aimed specifically at breeding for climate resilience in fruits and vegetables, although there have been calls to begin this process (Kole et al., 2015). Breeding for climate resilience in vegetables has great potential given the range of crop species available. Tolerance to abiotic stress is reasonably advanced in pulses (Araújo et al., 2015; Varshney et al., 2018), but examples of translation to commercial cultivars are still limited (Varshney et al., 2018; Varshney et al., 2019). The infrastructure for germplasm collection, maintenance, testing, and breeding lags behind that of major crops (partly because of the large number of species involved) (Keatinge et al., 2016; Atlin et al., 2017).

Participatory plant breeding (PPB) facilitates interaction between Indigenous and local knowledge systems and scientific research and can be an effective adaptation strategy in generating varieties well adapted to the socio-ecological context and climate hazards (*high confidence*) (Table 5.5, Westengen and Brysting, 2014; Humphries et al., 2015; Anderson et al., 2016; Migliorini et al., 2016; Leitão et al., 2019; Ceccarelli and Grando, 2020; Singh et al., 2020).

Table 5.5: Participatory plant breeding as cultivar improvement adaptation method.

Region	Crop(s) used for breeding	Results
West Africa	Sorghum and pearl millet	• Released sorghum and millet varieties which were selected for climate variability (e.g., drought), low soil fertility, pest and disease resistance, gendered preferences for processing, and nutrition (Camacho-Henriquez et al., 2015; Weltzien et al., 2019). – • Farmers who adopted these varieties increased yield, income and food security, alongside increased technical knowledge of plant breeding, and increased breeders' understanding of local farmers' varietal requirements (Trouche et al., 2016). • Joint learning with scientists led to increased genetic gain both in terms of operational scale and focused breeding for diverse farmer priorities (Weltzien et al., 2019).
South America (Andes)	Potato	• PPB with Indigenous Quechua and Aymara farmers resulted in potato varieties with traits from wild relatives, with yield stability, higher yields under low input use and disease resistance under climate change impacts such as increased hail or frost events and upward expansion of pests and diseases (Camacho-Henriquez et al., 2015; Scurrah et al., 2019).
Asia (southwest China)	Maize	• PPB done primarily with women farmers, led to 1500 landraces safeguarded, 12 farmer-preferred varieties released and 30 landraces released, bred for improved yield (15-20% increases), drought resistance, taste, market potential and other priority traits (Song et al., 2019). • Studies suggest PPB improved farmer knowledge, income, and access to resilient seeds, and strengthened institutions

		such as women-led farmer cooperatives and a Farmer Seed Network of China (Song et al., 2019).

5.4.4.4 *Integrated approach to enhance agroecosystem resilience*

Diversifying agricultural systems is an adaptation strategy that can strengthen resilience to climate change, with socio-economic and environmental co-benefits, but tradeoffs and benefits vary by socio-ecological context (*high confidence*) (Table 5.6, M'Kaibi et al., 2015; Bellon et al., 2016; Jones, 2017b; Schulte et al., 2017; Jarecki et al., 2018; Jones et al., 2018; Luna-Gonzalez and Sorensen, 2018; Sibhatu and Qaim, 2018; Renard and Tilman, 2019; Rosa-Schleich et al., 2019; Bozzola and Smale, 2020; Mulwa and Visser, 2020). Crop diversification alongside livestock, fish and other species can be applied at various scales in a range of systems, from rainfed or irrigated to urban and home gardens in multiple spatial and temporal arrangements such as mixed planting, intercrops, crop rotation, diversified management of field margins, agroforestry (Section 5.10.1.3) and integrated crop livestock systems (Section 5.10.1.1, Isbell et al., 2017; Kremen and Merenlender, 2018; Dainese et al., 2019; Rosa-Schleich et al., 2019; Hussain et al., 2020; Renwick et al., 2020; Tamburini et al., 2020; Snapp et al., 2021; see Section 5.14 and Cross-Chapter Box NATURAL in Chapter 2).

Diversification improves regulating and supporting ecosystem services such as pest control, soil fertility and health, pollination, nutrient cycling, water regulation and buffering of temperature extremes (*high confidence*) (Barral et al., 2015; Prieto et al., 2015; Tiemann et al., 2015; Schulte et al., 2017; Beillouin et al., 2019a; Dainese et al., 2019; Kuyah et al., 2019; Tamburini et al., 2020), which can in turn mediate yield stability and reduced risk of crop loss according to socio-ecological contexts and time since adoption (*high confidence*) (Prieto et al., 2015; Roesch-McNally et al., 2018; Sida et al., 2018; Williams et al., 2018; Birthal and Hazrana, 2019; Degani et al., 2019; Amadu et al., 2020; Bowles et al., 2020; Li et al., 2020; Sanford et al., 2021).

Agroecosystem diversification often has variable impacts depending on crop combination, agro-ecological zone and soil types and rigorous assessments of adaptive gains with traditional and locally diversified systems and potential trade-offs still need to be conducted across socioecological contexts. The quantitative upstanding will assist in enhancing multiple benefits of diversification tailored for each condition (Table 5.6). Progress is also needed via breeding and/or agronomy to adapt underutilized as well as major food crops to diversified agroecosystems and optimize management of nutrients, pest and disease pressure and other socio-ecological constraints (Araújo et al., 2015; Foyer et al., 2016; Adams et al., 2018; Pang et al., 2018).

Managing for diversity and flexibility at multiple scales is central to developing adaptive capacity. Policies to support diversification include shifting subsidies towards diversified systems, public procurement for diverse foods for schools and other public institutions, investment in shorter value chains, lower insurance premiums and payments for ecosystem services that include diversification (Sorensen et al., 2015; Guerra et al., 2017; Nehring et al., 2017; Valencia et al., 2019). Integrated landscape approaches involving multiple stakeholders (Reed et al., 2016) including urban governments can support diversification at a regional scale through public and private sector investment in extension services, regional supply chains, agritourism and other incentives for diversified landscapes (Milder et al., 2014; Münke et al., 2015; Sorensen et al., 2015; Pérez-Marin et al., 2017; Caron et al., 2018; 5.14.1.5).

Table 5.6: Agroecosystem diversification practices, climate change adaptation mechanisms, tradeoffs, co-benefits and constraints to implementation.

Agroecosystem diversification practice and Mechanism for climate change adaptation	Benefits, tradeoffs and constraints to implementation with examples.
Crop diversification - Diversifying revenue streams and food supply (portfolio effect). - Can impact multiple plant and soil biological and physicochemical properties	• Crop diversification reduces cereal crop sensitivity to **precipitation variability**, yield losses and crop insurance payouts under **drought** (*high confidence*) (McDaniel et al., 2014; Williams et al., 2016; Iizumi and Wagai, 2019; Renwick et al., 2020; Huang et al., 2021; Kane et al., 2021)

associated with building soil organic matter, improving soil structure and water conservation	• For example, a study in Canada comparing diversified rotations to monoculture corn found significant positive yield impacts, yield stability and increased soil organic carbon under both RCP4.5 and RCP8.5 by 2100 (Jarecki et al., 2018). • Diverse agroecosystems with a range of native, neglected and introduced species, often maintained through Indigenous knowledge and farmer seed systems, offer adaptation opportunities in some regions (*medium evidence, high agreement*) (Bezner Kerr, 2014; Westengen and Brysting, 2014; Camacho-Henriquez et al., 2015; Ghosh-Jerath et al., 2015; Adhikari et al., 2017; Li and Siddique, 2018; Scurrah et al., 2019). • Diversified landscapes can also enhance cultural ecosystem services, by supporting cultural heritage crops, recreational and aesthetic experiences (*medium confidence*) (Novikova et al., 2017; Martínez-Paz et al., 2019; Alcon et al., 2020). • Diversified cropping systems often require new knowledge, equipment access to inputs and viable markets for new products (van Zonneveld et al., 2020). Barriers to diversification, or those which support agroecosystem simplification include environmental constraints such as elevation or soil type, along with institutional constraints such as low research investment, limited policy support, subsidies that encourage monocrops, poor market access, market instability and limited access to seeds (Kaushal and Muchomba, 2015; DeLonge et al., 2016; Burchfield and de la Poterie, 2018).
Legume diversification can be effective for both mitigation and adaptation, by reducing **use of nitrogen derived from fossil fuels**, and meat consumption, and providing ecosystem services through **nutrient cycling, increasing soil biological activity and erosion control** (Snapp et al., 2019).	• Can increase food security and nutrition by increasing cereal productivity and stability in intercropped systems, diversify diets, and increase income in crop sales (*high agreement, medium evidence*) (Snapp et al., 2019; Steward et al., 2019; Renwick et al., 2020), but legume production may be constrained by pest, disease, limited access to genetic material, market access and food preferences (Anders et al., 2020).
Organic amendments, no/low tillage or crop residue retention may increase diversity in soil biological organisms, which might be important in building resilience to multiple stresses such as **drought and pest pressure** (Furze et al., 2017; Blundell et al., 2020; de Vries et al., 2020; Stefan et al., 2021; Yang et al., 2021).	• Higher organic matter does not consistently improve soil hydraulic properties (Minasny and McBratney, 2018; Basche and DeLonge, 2019), • Can decrease **yield variability under dry conditions** and increase rainfed annual crop yield productivity (*high agreement*) (Pittelkow et al., 2014; Williams et al., 2016; Williams et al., 2018; Degani et al., 2019; Steward et al., 2019; Bowles et al., 2020; Marini et al., 2020; Sanford et al., 2021).
Livestock integration. Inclusion of legumes and other forage into crop rotation allows mixed crop and livestock operations to **mitigate farm-level risk and ecosystem buffering**	• Benefits to productivity and stability of annual crop yields in some contexts (see Section 5.10.3, *strong agreement, medium evidence*) (Stark et al., 2018; Peterson et al., 2020; de Albuquerque Nunes et al., 2021).
Traditional and locally adapted **mixed cropping and agroforestry practices** which include leguminous trees can improve soil fertility and microclimate (Sida et al., 2018; Amadu et al., 2020).	Benefits: Resilience to extreme events such as hurricanes can be promoted by supporting ecosystem functions to mitigate impacts and accelerate recovery (*high agreement, medium evidence*) (Altieri et al., 2015; Simelton et al., 2015; Sida et al., 2018; Perfecto et al., 2019).

	• Can increase food security, livelihoods, and productivity, but local context and resource availability must be considered to optimize species arrangement and benefits and can have considerable implementation barriers and costs (*high confidence*) (see Sections 5.10.3, 5.14 and Cross-Chapter Box NATURAL in Chapter 2). (Altieri et al., 2015; Simelton et al., 2015; Sida et al., 2018; Perfecto et al., 2019).

5.5 Livestock-based Systems

Livestock systems may be classified as industrial (monogastric, ruminant), grassland-based in which crop-based agriculture is absent or minimal (pastoralism, agro-pastoralism), mixed rainfed combining mostly rainfed cropping with livestock, and mixed irrigated systems with a significant proportion of irrigated cropping interspersed with livestock. Livestock systems are located widely across all regions of the world, and animal-sourced food provides humans with 39% of their protein and 18% of their calorie intake (FAO, 2019f). Some 400 million people depend on livestock for a substantial part of their livelihood (Robinson et al., 2011).

5.5.1 Observed Impacts

Climate change affects livestock productivity and production in many ways (Porter et al., 2014; Rojas-Downing et al., 2017). Evidence is accumulating that rising temperatures are increasing heat stress in domestic species and affecting productivity (*high confidence*) (Das et al., 2016b; Godde et al., 2021).

5.5.1.1 Pastoral systems

Many grassland-based livestock systems are vulnerable to climate change and increases in climate variability (*high confidence*) (Dasgupta et al., 2014; Sloat et al., 2018; Stanimirova et al., 2019). Decadal vegetation changes from warming and drying trends have been detected in North American grasslands, with implications for species composition, rangeland quality and economic viability of grazing livestock (Rondeau et al., 2018; Reeves et al., 2020). Feed quality in South Asian grasslands has been negatively affected, reducing food security (Rasul et al., 2019). Increased grassland degradation has been observed in parts of Inner Mongolia (Nandintsetseg et al., 2021). Changing seasonality, increasing frequency of drought and rising temperatures are affecting pastoral systems globally (*high confidence*). These and other drivers are reducing herd mobility, decreasing productivity, increasing incidence of vector borne diseases and parasites, and reducing access to water and feed (*high agreement, medium evidence*) (López-i-Gelats et al., 2016; Vidal-González and Nahhass, 2018; de Leeuw et al., 2020).

5.5.1.2 Livestock distribution and climate variability

There is *limited evidence* of observed distributional changes in livestock species because of climate changes. Asian buffalo and yak breeds in China over the past 50 years have shifted distribution due partly to increases in heat stress (Wu, 2015; Wu, 2016). Nepalese cattle numbers have declined, attributed to increases in the number of hot days (Koirala and Shrestha, 2017).

Climate variability has been identified as the primary cause of vegetation cover changes in Tibet since 2000 (Lehnert et al., 2016). Increasing inter-annual variability is a driver of farm extensification in Mediterranean dairy systems (Dono et al., 2016). In Australian rangelands (Godde et al., 2019) and dairy systems (Harrison et al., 2016; Harrison et al., 2017), increasing rainfall variability contributes more to stocking rate and profitability variability than changes in mean rainfall.

5.5.1.3 Diseases and disease vectors

Climate change is affecting the transmission of vector-borne diseases (Hutter et al., 2018; Semenza and Suk, 2018) and parasites (Rinaldi et al., 2015) in high latitudes (*high confidence*). Different processes link climate change and infectious diseases in domesticated livestock: some show a positive association between temperature and range expansion of arthropod vectors that spread the bluetongue virus. Others show a contraction, such as tsetse flies that transmit trypanosome parasites of several livestock species. Positive associations have been found between temperature and the spread of pathogens such as anthrax, and droughts and El Niño-Southern Oscillation (ENSO) weather patterns and Rift Valley fever outbreaks in East Africa (Bett et al., 2017). Observed range expansion of economically important tick disease vectors in North America (Sonenshine, 2018) and Africa (Nyangiwe et al., 2018) are presenting new public health threats to humans and livestock.

5.5.2 Assessing Vulnerabilities

5.5.2.1 Rising temperature and heat stress

Most domestic livestock have comfort zones in the range 10-30°C, depending on species and breed (Nardone et al., 2006). At higher temperatures, animals eat 3–5% less per additional degree of temperature, reducing their productivity and fertility. Heat stress suppresses the immune and endocrine system, enhancing susceptibility of the animal to disease (Das et al., 2016b). Recent stagnation in dairy production in West Africa and China may be associated with increased periods of high daily temperatures (*low confidence*) (Rahimi et al., 2020; Ranjitkar et al., 2020). Increases in the productive capacity of domestic animals can compromise thermal acclimation and plasticity creating further loss. Escalating demand for livestock products in LMICs may necessitate considerable adaptation in the face of new thermal environments (*medium confidence*) (Collier and Gebremedhin, 2015; Theusme et al., 2021). Heat effects on productivity have been summarised for pigs (da Fonseca de Oliveira et al., 2019), sheep and goats (Sejian et al., 2018), and cattle (Herbut et al., 2019). The direct effects of higher temperatures on the smaller ruminants (sheep and goats) are relatively muted, compared with large ruminants; goats are better able to cope with multiple stressors than sheep (Sejian et al., 2018). Under SSP5-8.5 to mid-century, land suitability for livestock production will decrease because of increased heat stress prevalence in mid and lower latitudes (*high confidence*) (Thornton et al., 2021).

5.5.2.2 Livestock water needs

Livestock production may account for 30 percent of all water (blue, green and grey) used in agriculture (Mekonnen and Hoekstra, 2010) and can negatively affect water quality. Cropland feed production accounts for 38% of crop water consumption (Weindl et al., 2017). High-input livestock systems may consume more water than grazing or mixed systems, though water used per kg beef produced, for example, depends on country, context, and system (Noya et al., 2019). In systems where feed production is rainfed, livestock and crop water productivity may be comparable (Haileslassie et al., 2009). Direct water consumption by livestock is <1-2% of global water consumption (Hejazi et al., 2014). Rising temperatures increase animal water needs, potentially affecting access of herders and livestock to drinking water sources (Flörke et al., 2018).

5.5.2.3 Rising temperatures and livestock disease

Climate change will have effects on future distribution, incidence, and severity of climate-sensitive infectious diseases of livestock (*high confidence*) (Bett et al., 2017). In an assessment of climate sensitivity of European human and domestic animal infectious pathogens, 63% were sensitive to rainfall and temperature, and zoonotic pathogens were more climate-sensitive than human- or animal-only pathogens (McIntyre et al., 2017). Over the last 75 years, >220 emerging zoonotic diseases, some associated with domesticated livestock, have been identified, several of which may be affected by climate change, particularly vector-borne diseases (Vaillancourt and Ogden, 2016; see Cross-Chapter Box ILLNESS in Chapter 2). Walsh et al. (2018) identified both temperature and rainfall as influential factors in predicting increasing anthrax outbreaks in northern latitudes. Growing infectious disease burdens in domesticated animals may have wide-ranging impacts on the vulnerability of rural livestock producers in the future, particularly related to human health and projected increases in zoonoses (*high confidence*) (Bett et al., 2017; Heffernan, 2018; Rushton et al., 2018; Meade et al., 2019).

5.5.2.4 Livestock and socio-economic vulnerability to climate change

There is *limited evidence* about the role of livestock in addressing socio-economic vulnerability. Although agriculture in parts of North America has become more sensitive to climate over the last 50 years, livestock have helped to moderate this effect, being less sensitive to increasing temperatures than some specialised crop systems (Ortiz-Bobea et al., 2018). Increasing frequency and severity of droughts will affect the future economic viability of grassland-based livestock production in the North American Great Plains (Briske et al., 2021). Purchasing more forage and selling more livestock have reduced household vulnerability in semi-arid parts of China over the last 35 years (Bai et al., 2019). A greater focus on sheep production away from cropping has increased the resilience of farming systems in Western Australia in low-rainfall years, although with mixed environmental effects (Ghahramani and Bowran, 2018). More insights are needed as to where and how livestock can affect the vulnerability of farmers and pastoralists.

5.5.2.5 Effects of climate on the health and vulnerability of livestock keepers

Vulnerability to the health impacts of climate change will be shaped by existing burdens of ill-health and is expected to be highest in poor and socio-economically marginalized populations (*high agreement, limited evidence*) (Labbé et al., 2016). As well as projected changes in infectious disease burdens, labour capacity in a warming climate is anticipated to decrease further, beyond the >5% drop estimated since 2000 (Watts et al., 2018). Loss of labour capacity may greatly increase the vulnerability of subsistence livestock keepers (*high agreement, limited evidence*).

5.5.2.6 Gender and other social inequalities

Vulnerability to climate change depends on demography and social roles (Mbow et al., 2019). Gender inequalities can act as a risk multiplier, with women being more vulnerable than men to climate change-induced food insecurity and related risks (*high confidence*) (Cross-Chapter Box GENDER in Chapter 18). Women and men often have differential and unequal control over different productive assets and the benefits they provide, such as income from livestock (Ngigi et al., 2017; Musinguzi et al., 2018). Indigenous livestock keepers can be more vulnerable to climate change, partly due to on-going processes of land fragmentation (Hobbs et al., 2008), historical land dispossession, discrimination, and colonialization, creating greater levels of poverty and marginalization (Stephen, 2018). Adaptation actions may also be affected by gender and other social inequalities (Balehey et al., 2018; Dressler et al., 2019). Men and women heads of household may access institutional support for adaptation in different ways (Assan et al., 2018). Further research is warranted to evaluate alternative gendered and equity-based approaches that can address differences in adaptive capacity within communities.

5.5.3 Projected Impacts

There is *limited evidence* on future impact of climate change on livestock production, particularly in LMICs (Rivera-Ferre et al., 2016).

5.5.3.1 Impacts on rangelands, feeds, and forages

Uncertainties persist regarding estimates of net primary productivity (NPP) in grazing lands (Fetzel et al., 2017; Chen et al., 2018b), so estimation of climate change impacts on grasslands is challenging. Mean global annual NPP is projected to decline 10 gC m^{-2} yr^{-1} in 2050 under RCP8.5, although herbaceous NPP is projected to increase slightly (Boone et al., 2018; see Figure 5.11). Similar estimates were made by (Havlik et al., 2014): large increases in projected NPP in higher northern latitudes (21% increase in the US and Canada) and large declines in western Africa (-46% in western Africa) and Australia (-17%). The cumulative effects of impacts on forage productivity globally are projected to result in 7-10% declines in livestock numbers by 2050 for warming of ~2°C, representing a loss of livestock assets ranging from USD 10 to 13 billion (Boone et al., 2018). Changes to African grassland productivity will have substantial, negative impacts on the livelihoods of >180 million people.

Increases in above-ground NPP, and woody cover at the expense of grassland, are projected in some of the tropical and subtropical drylands (Doherty et al., 2010; Ravi et al., 2010; Saki et al., 2018), in Mediterranean wood-pastures (Rolo and Moreno, 2019), and in the northern Great Plains of North America (Klemm et al., 2020). Godde et al. (2021) projected that woody encroachment would occur on 51% of global rangeland area by 2050 under RCP8.5. The future makeup of grasslands under climate change is uncertain, given the variation in responses of the component species; though this variation may provide a climate buffer (Jones, 2019) (*low confidence*). C4 grass species are regarded as less responsive to elevated carbon dioxide than C3 species, though this is not always the case (Reich et al., 2018).

There are other interactions between climate change and grazing effects on grasslands. Li (2018a) reported strong negative responses of NPP and species richness to 4°C warming, a 50% precipitation decrease, and high grazing intensity. Changes in grassland composition will inevitably change their suitability for different grazing animal species, with switches from herbaceous grazers such as cattle to goats and camels to take advantage of increases in shrubland (Kagunyu and Wanjohi, 2014). Rangeland feed quality may also be reduced via invasive species of lower quality than native species (Blumenthal et al., 2016).

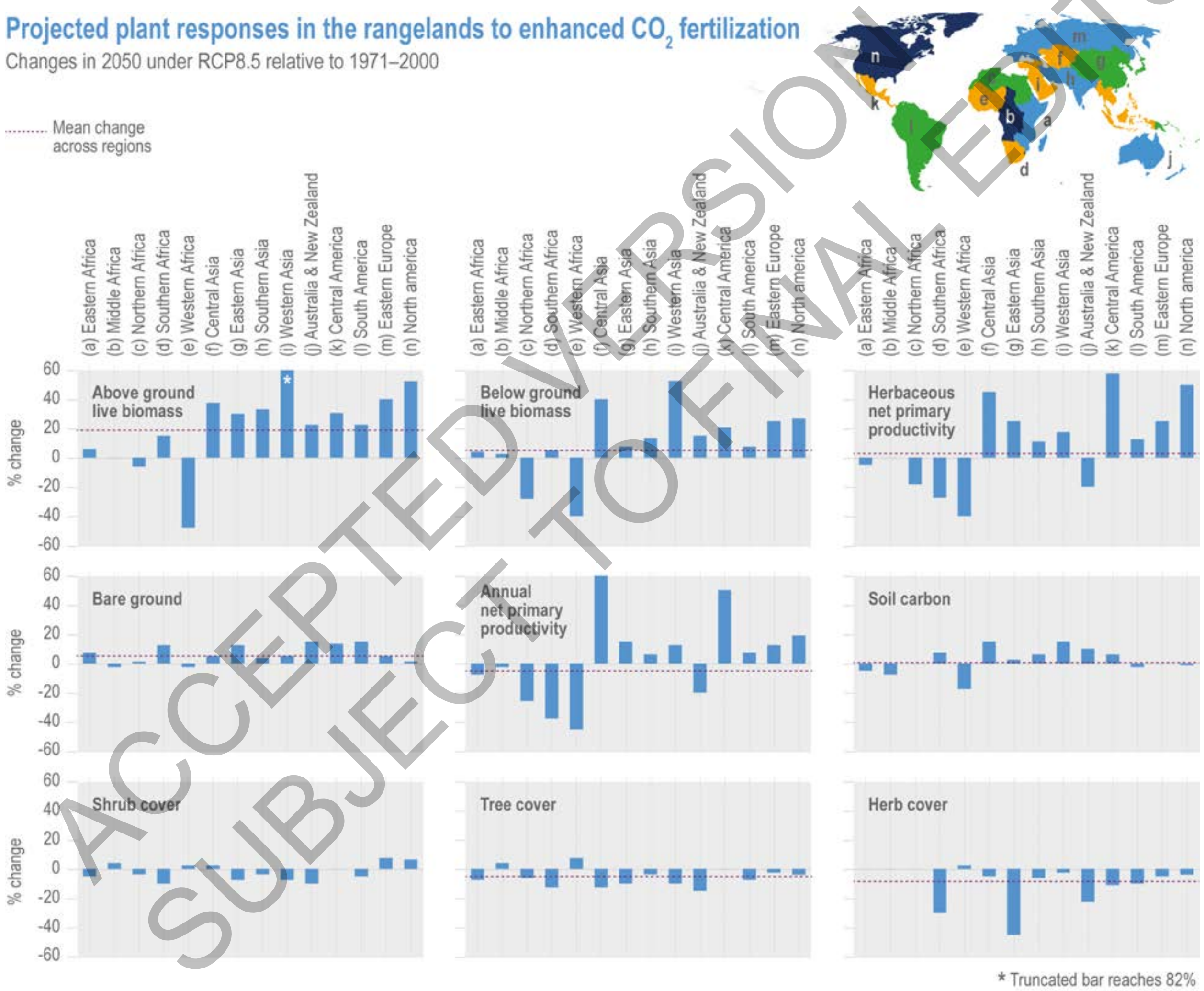


Figure 5.11: Regional percent changes in land cover and soil carbon from ensemble simulation results in 2050 under emissions scenario RCP8.5 compared with 1971-2000. Plant responses were enhanced by CO2 fertilization. The larger chart (lower left) shows mean changes for all rangelands, and all charts are scaled to -60 to +60 percent change. Shown are annual net primary productivity (ANPP), herbaceous net primary productivity (HNPP), bare ground, herbaceous (herb), shrub, and tree cover, soil organic carbon (soil carbon), aboveground live biomass (A. L. biomass), and belowground live biomass (B. L. biomass). Regions as defined by the United Nations Statistics Division. The bar for aboveground live biomass in Western Asia (*) is truncated and was 82%. (Boone et al., 2018).

Warming and water deficits impair the quality and digestibility of a C4 tropical forage grass, *Panicum maximum,* because of increases in leaf lignin (Habermann et al., 2019). A metanalysis Dellar (2018) of climate change impacts on European pasture yield and quality found an increase in above-ground dry weight under increased CO_2 concentrations for forbs, legumes, graminoids and shrubs with reductions in N concentrations in all plant functional groups. Temperature increases will increase yields in Alpine and northern areas (+82.6%) but reduce N concentrations for shrubs (−13.6%) and forbs (−18.5%).

Increased temperatures and CO_2 concentrations may increase herbaceous growth and favour legumes over grasses in mixed pastures (He et al., 2019). These effects may be modified by changes in rainfall patterns, plant competition, perennial growth habits, and plant–animal interactions. The cumulative effect of these factors is uncertain. Large, persistent declines in forage quality are projected, irrespective of warming, under elevated CO_2 conditions (600 ppm and +1.5°C day/3°C night temperature increases) in North American grasslands (Augustine et al., 2018). Rising CO_2 concentrations may result in losses of iron, zinc, and protein in plants by up to 8 percent by 2050 (Smith and Myers, 2018). Little information is available on possible impacts on carbon-based micronutrients, such as vitamins. About 57% of grasses globally are C3 plants and thus susceptible to CO_2 effects on their nutritional quality (Osborne et al., 2014). These impacts will result in greater nutritional stress in grazing animals as well as reduced meat and milk production (quality and quantity) (*high confidence, medium evidence*).

5.5.3.2 Impacts of increased temperature on livestock

Recent research confirms the seriousness of the heat stress issue (*medium evidence, high agreement*). Considerable increases are projected during this century in the number of "extreme stress" days per year for cattle, chicken, goat, pig and sheep populations with SSP5-8.5 but many fewer with SSP1-2.6 (Thornton et al., 2021: Figure 5.12; see Cross-Chapter Box MOVING PLATE in this Chapter). Resulting impacts on livestock production and productivity may be large, particularly for cattle throughout the tropics and subtropics and for goats in parts of Latin America and much of Africa and Asia. Pigs are projected to be particularly affected in the mid-latitudes of Europe, East Asia, and North America. (Lallo et al., 2018) estimated that global warming of 1.5°C and 2°C may exceed limits for normal thermo-regulation of livestock animals and result in persistent heat stress for animals in the Caribbean. Breed differences in heat stress resistance in dairy animals are now being quantified (Gantner et al., 2017), as are effects on sow reproductive performance in temperate climates (Wegner et al., 2016). Estimates of losses in milk production due to heat stress in parts of the USA, UK and West Africa to the end of the century range from 1-17% (Hristov et al., 2018; Fodor et al., 2018; Wreford and Topp, 2020; Rahimi et al., 2020). Much larger losses in dairy and beef production due to heat stress are projected for many parts of the tropics and subtropics: these could amount to USD 22 billion per year for dairy and USD 38 billion per for beef to end-century under SSP5-8.5, approximately 7% and 20% of the global value of production of these commodities in constant 2005 dollars.

In many LMICs, poultry contribute significantly to rural livelihoods including via modest improvements in nutritional outcomes of household children (de Bruyn et al., 2018). Rural poultry are generally assumed to be hardy and well adapted to stressful environments, but little information exists regarding their performance under warmer climates or interactions with other production challenges (Nyoni et al., 2019).

5.5.3.3 Impacts on livestock diseases

The impacts of climate change on livestock diseases remain highly uncertain (*medium evidence, high agreement*). Bett et al. (2017) showed positive associations between rising temperature and expansion of the geographical ranges of arthropod vectors such as *Culicoides imicola*, which transmits bluetongue virus. A 1-in-20-year bluetongue outbreak at present-day temperatures is projected to increase in frequency to 1-in-5- to 1-in-7 years by the 2050s, under RCP4.5 and RCP8.5, although animal movement restrictions can prevent devastating outbreaks (Jones et al., 2019).

The prevalence and occurrence of some livestock diseases are positively associated with extreme weather events (*high confidence*). There are high risks of future Rift Valley Fever (RVF) outbreaks under both RCP4.5 and RCP8.5 this century in East Africa and beyond (Taylor et al., 2016; Mweya et al., 2017).

Few studies explicitly consider the biotic and abiotic factors that interact additively, multiplicatively, or antagonistically to influence host-pathogen dynamics (Cable et al., 2017). Integrative concepts that aim to improve the health of people, animals, and the environment such as One Health may offer a framework for enhancing understanding of these complex interactions (Zinsstag et al., 2018). Much remains unknown concerning disease transmission dynamics under a warming climate (Heffernan, 2018), highlighting the need for effective monitoring of livestock disease (Brito et al., 2017; Hristov et al., 2018).

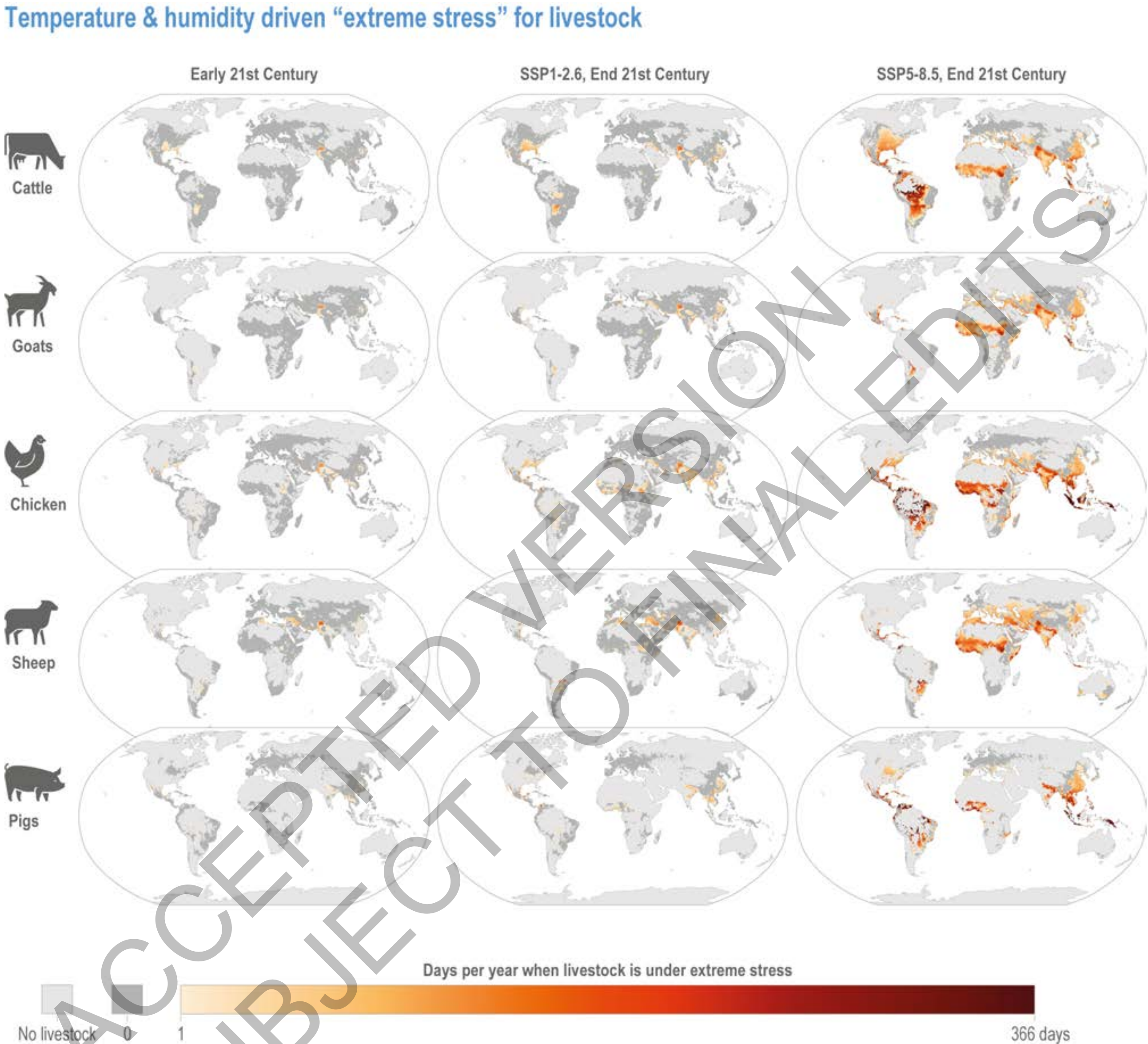


Figure 5.12: Change in the number of days per year above "extreme stress" values from 2000 to the 2090s for SSP5-8.5, estimated using the Temperature Humidity Index (THI). Mapped for species current global distribution (Gilbert et al., 2018) (grey areas, no change). (Thornton et al., 2021), Also see Annex 1: Global to Regional Atlas.

5.5.3.4 Impacts on livestock and water resources

Water resources for livestock may decrease in places because of increased runoff and reduced groundwater resources, as well as decreased groundwater availability in some environments (AR5). Increased temperatures will cause changes in river flow and the amount of water stored in basins, potentially leading to increased water stress in dry areas such as parts of the Volta River Basin (Mul et al., 2015). Toure (2017) estimated decreases in groundwater recharge rates of 49% and of stored groundwater by 24% to the 2030s in the Klela basin in Mali under both RCP4.5 and RCP8.5, with potentially serious consequences for water availability for livestock and irrigation.

Water intake by livestock is related to species, breed, animal size, age, diet, animal activity, temperature, and physiological status of animals (Henry et al., 2018). Direct water use by cattle may increase by 13% for a temperature increase of 2.7°C in a sub-tropical region (Harle et al., 2007). Changes in water availability may arise because of decreased supply or increased competition from other sectors. Availability changes may be accompanied by shifts in water quality, such as increased levels of microorganisms and algae, that can negatively affect livestock health (Naqvi et al., 2015). In arid lands, projected decreases in water availability will severely compromise reproductive performance and productivity in sheep (Naqvi et al., 2017). In higher-input livestock systems, water costs may increase substantially owing to increased competition for water (Rivera-Ferre et al., 2016).

5.5.3.5 Livestock and climate variability

Information on future climate variability changes on livestock system productivity does not exist yet. Increases in climate variability may increase food insecurity in the future, mediated through increased crop and livestock production variability (Thornton and Herrero, 2014) in LMICs. Rainfall variability increases in pastoral lands have been linked to declining cattle numbers (Megersa et al., 2014). Changes in future climate variability may have large negative impacts on livestock system outcomes (Sloat et al., 2018; Stanimirova et al., 2019); these effects can be larger than those associated with gradual climate change (*limited evidence, medium agreement*) (Godde et al., 2019). In grasslands, (Chang et al., 2017) (Europe) and Godde et al. (2020) (globally) projected increases in biomass inter-annual variability, the worst effects occurring in rangeland communities that are already vulnerable. Ways in which climate variability impacts have been addressed in the past, such as via herd mobility, may become increasingly unviable in the future (Hobbs et al., 2008).

5.5.3.6 Societal impacts within the production system

Livestock play important social (Kitalyi et al., 2005) and cultural (Gandini and Villa, 2003) roles in many societies. Climate change will negatively affect the provisioning of social benefits in many of the world's grasslands (*medium confidence*). Examples include moving to semi-private land ownership models, driven in part by climate change, that are changing social networks and limiting socio-ecological resilience in pastoral systems in East Africa (Kibet et al., 2016; Bruyere et al., 2018) and Asia (Cao et al., 2018a); altering traditional food, resource and medicine sharing mechanisms in West Africa (Boafo et al., 2016); and the limited ability of current livestock systems to satisfy societies' demand for cultural ecosystem services in Northwest Europe (Bengtsson et al., 2019). The societal impacts of climate change on livestock systems may interact with drivers of change and increase herders' vulnerability via processes of sedentarization and land fragmentation, both of which may result in decreased animal access to rangelands (Adhikari et al., 2015; Cross-Chapter Box MOVING PLATE this Chapter). Stronger linkages are needed between ecosystem service and food security research and policy to address these challenges (Gentle and Thwaites, 2016; Bengtsson et al., 2019).

5.5.4 Adaptation in Livestock-based Systems

Livestock adaptation options are increasingly being studied with methods such as agent-based household models (Hailegiorgis et al., 2018), household models that disaggregate climate scenarios as well as differentiating farms of varying types and farmer attributes (Descheemaeker et al., 2018), new meso-scale grassland models (Boone et al., 2018), and modelling approaches that capture decision making at the farm level for sample populations (Henderson et al., 2018).

Many grassland-based livestock systems have been highly resilient to past climate risk, providing a sound starting point for current and future climate change adaptation (Hobbs et al., 2008). These adaptations include more effective matching of stocking rates with pasture or other feed production; adjusting herd and watering point management to altered seasonal and spatial patterns of forage production; managing diet quality, which also helps reduce enteric fermentation in ruminants and thus greenhouse gas emissions (using diet supplements, legumes, choice of introduced pasture species and pasture fertility management); more effective use of silage, rotational grazing or other forms of pasture spelling; fire management to control woody thickening; using better-adapted livestock breeds and species; restoration of degraded pastureland; migratory pastoralist activities; and a wide range of biosecurity activities to monitor and manage the spread of pests, weeds, and diseases (Herrero et al., 2015; Godde et al., 2020). Combining adaptations can result in increases in benefits in terms of production and livelihoods over and above those attainable from single adaptations (*high confidence*) (Bonaudo et al., 2014; Thornton and Herrero, 2015; ul Haq et al., 2021).

The adaptations that livestock keepers have been undertaking in Asia (Hussain et al., 2016; Li et al., 2017) and Africa (Belay et al., 2017; Ouédraogo et al., 2017) are largely driven by their perceptions of climate change. Keeping two or more species of livestock simultaneously on the same farm can confer economic and sustainability benefits to European farmers (Martin et al., 2020). Some livestock producers are changing and diversifying management practices, improving access to water sources, increased uptake of off-farm activities, trading short-term profits for longer-term resilience benefits and migrating out of the area (Hussain et al., 2016; Berhe et al., 2017; Merrey et al., 2018; Thornton et al., 2018; Espeland et al., 2020). Others are adopting more climate-resilient livestock species such as camels (Watson et al., 2016a), using climate forecasts at differing time scales, and benefiting from innovative livestock insurance schemes, though challenges remain in their use at scale (Dayamba et al., 2018; Hansen et al., 2019a; Johnson et al., 2019).

In West Africa, cattle and small ruminant producers and traders are changing strategies in response to emerging market opportunities as well as to multiple challenges including climate change (Gautier et al., 2016; Ouédraogo et al., 2017). Niles (2017) found that reduced food insecurity in 12 countries was associated with livestock ownership, providing cash for food purchases. Livestock ownership or switching to smaller, local breeds does not automatically translate into positive nutrition outcomes for women and children, although it may if communities see such animals as suitable for husbandry by women (Chanamuto and Hall, 2015); the relationship is complex (Nyantakyi-Frimpong and Bezner-Kerr, 2015; Dumas et al., 2018).

Options for adapting domestic livestock systems to increased exposure to heat stress (Table 5.7) include breeding and crossbreeding strategies, species switching, low-cost shading alternatives and ventilation and building-design options (Chang-Fung-Martel et al., 2017; Godde et al., 2021). In utero exposure to heat stress may increase adaptive capacity in later life, though the underlying mechanisms are incompletely understood (Skibiel et al., 2018). For confined livestock systems in temperate regions, the economic consequences of adapting to heat stress are still being quantified.

New research is investigating the prospects for accelerating traditional and novel breeding processes for animal traits that may be effective in improving livestock adaptation as well as production (Stranden et al., 2019; Barbato et al., 2020). Even if the technical challenges of using new tools such as CRISPR-Cas9 for genome editing in livestock are overcome, the granting of societal approval to operate in this research space may be elusive (Herrero et al., 2020; Menchaca et al., 2020).

Table 5.7: Selected adaptations to heat stress in livestock systems.

Adaptation	Example	Reference
Breeding for heat stress tolerance	Sheep and cattle farming systems in southern Australia under SRES A2. Projected not to improve livestock productivity by 2070, even in drier locations.	Moore and Ghahramani (2014)
"Slick hair" breeding	In the Caribbean, introduction of a "slick hair" gene into Holstein cows by crossbreeding with Senepols to increase thermo-tolerance and productivity. An integrated approach to heat-stress adaptation will still be needed, including shading strategies, for example.	(Ortiz-Colón et al. (2018)
Crossbreeding	Crossbreeding with Indigenous sheep breeds as an adaptation option in Mongolia produced some benefits in productivity and improved adaptation to winter cold. Best combined with other improved management interventions. In general, effectiveness of crossbreeding as an adaptation strategy will be dependent on context.	Wilkes et al. (2017)

Species switching	Switching from large ruminants to more heat-resilient goats for dairy production in Mediterranean systems to adapt to increasing heat stress.	Silanikove and Koluman (2015)
	Switching from cattle to more heat- and drought-resilient camels in pastoral systems of southern Ethiopia as an adaptation to increasing drought.	Wako et al. (2017)
Shading, fanning, bathing	Low-capital relief strategies (shading with trees or different types of shed; bathing animals several times each day; installing electric fans in sheds) are effective at reducing heat stress impacts on household income in smallholder dairy systems in India.	York et al. (2017)
	Different tree arrangements in silvopastoral systems in Brazil were effective in reducing thermal loads by up to 22% for animals compared with full-sun pasture.	Pezzopane et al. (2019)
Ventilation & cooling systems	A wide range of different ventilation systems, cooling systems and building designs for confined and seasonally confined intensive livestock systems (pigs, poultry, beef, dairy) in temperate regions. Economic consequences and profitability of different options under different RCPs are still being assessed.	Vitt et al. (2017) Derner et al. (2018), Hempel and Menz (2019), Mikovits et al. (2019), Schauberger et al. (2019b)
In utero exposure to heat stress	Potential as an adaption option is uncertain, as there are different effects of *in utero* heat stress exposure and the mechanisms are not completely understood: • Cows may be better adapted to heat stress conditions at maturity via improved regulation of core body temperature. • Cow milk yield at first lactation was reduced • Nutrient partitioning and carcass composition were altered in pigs	Ahmed et al. (2017) Monteiro et al. (2016), Boddicker et al. (2014)

5.5.4.1 Contributions of Indigenous knowledge and local knowledge

Indigenous knowledge has a role to play in helping livestock keepers adapt (*medium confidence*), though the transferability of this knowledge is often unclear. Pastoralists' local knowledge of climate and ecological change can complement scientific research (Klein et al., 2014), and local knowledge can be mobilised to inform adaptation decision-making (Klenk et al., 2017). While Indigenous weather forecasting systems among pastoralists in Ethiopia (Balehegn et al., 2019; Iticha and Husen, 2019) and Uganda (Nkuba et al., 2020) are effective, synergies can be gained by combining traditional and modern knowledge to help pastoralists adapt. Sophisticated knowledge of feed resources among agro-pastoralists in West Africa is being used to increase system resilience (Naah and Braun, 2019). Understanding local knowledge for adaptation can present research challenges, for which new multi-disciplinary research methods may be needed (Reyes-Garcia et al., 2016; Roncoli et al., 2016). In particular, the complexities of knowledge, practice, power, local governance and politics need to be addressed (Hopping et al., 2016; Scoville-Simonds et al., 2020).

[START BOX 5.5 HERE]

Box 5.5: Alternative Sources of Protein for Food and Feed

Alternative protein sources for human food and livestock feed are receiving considerable attention. Laboratory or "clean meat" is one potential contributor to the human demand for protein in the future (SRCLL). Such technology may be highly disruptive to existing value chains but could lead to significant reduction in land use for pastures and crop-based animal feeds (Burton, 2019; Rosenzweig et al., 2020). The impacts on GHG emissions depend on the meat being substituted and the trade-off between industrial energy consumption and agricultural land requirements (Mattick et al., 2015; Alexander et al., 2017; Rubio et al., 2020b; Santo et al., 2020). Livestock feeds can make use of other protein sources: insects are generally rich in protein and can be a significant source of vitamins and minerals. Black soldier fly, yellow mealworm and the common housefly have been identified for potential use in feed products in the EU, for example (Henchion et al., 2017). Replacing land-based crops in livestock diets with some proportion of insect-derived protein may reduce the GHG emissions associated with livestock production, though these and other potential effects have not yet been quantified (Parodi et al., 2018; Section 5.13.2). Other sources are high-protein woody plants such as paper mulberry (Du et al., 2021) and algae, including seaweed. While microalgae and cyanobacteria are mainly sold as a dietary supplement for human consumption, they are also used as a feed additive for livestock and aquaculture, being nutritionally comparable to vegetable proteins. The potential for cultivated seaweed as a feed supplement may be even greater: some red and green seaweeds are rich in highly digestible protein. *Asparagopsis taxiformis*, for example, also decreases methane production in both cattle and sheep when used as a feed supplement (Machado et al., 2016; Li et al., 2018b). Novel protein sources may have considerable potential for sustainably delivering protein for food and feed alike, though their nutritional, environmental, technological, and socio-economic impacts at scale need to be researched and evaluated further.

[END BOX 5.5 HERE]

5.6 Forestry Systems

Forests play a vital role in the ecology of the planet, including climate regulation and provide a range of important ecosystem services within their local landscape. Moreover, they are essential to the well-being of millions of people around the world. Forests are sources of food contributing about 0.6% of global food consumption and provide important products, such as timber and non-timber forest products (NTFPs) (FAO, 2014). Indigenous Peoples and local communities are estimated to manage at least 17% of total carbon (or 293×10^9 Mg) stored in forest in sixty-four assessed countries (RRI, 2018a). While small in number, numerous local communities around the world are highly or entirely dependent on forests for their food supply (Karttunen et al., 2017). An estimated 9 percent of the world's rural population is lifted above the extreme poverty line because of income from forest resources (World Bank, 2016). Additionally, forest income plays a particularly important role in diversifying the income sources of poor households, reducing their vulnerability to loss from one source of income. This section covers an assessment of the impacts of climate change on forestry production systems and the adaptation options available. Non-timber forest products will be covered in the next section.

5.6.1 Observed Impacts

The IPCC AR5 stated that there is high confidence that numerous plants and animal species have already migrated, changed their abundance, and shifted their seasonal activities as a results of climate change (Settele et al., 2014). The report highlighted the widespread deaths of trees in many forested areas of the world. Forest dieback could significantly affect wood production among other impacts.

The Special Report on Climate Change and Land (SRCCL) (Barbosa et al., 2019) concluded that climate change will have positive and negative effects on forests, with varying regional and temporal patterns. For example, the SRCCL noted the increasing productivity in high latitude forests such as those in Siberia. In contrast, negative impacts are already being observed in other regions such as increasing tree mortality due to wildfires.

In the past years, tree mortality continued to increase in many parts of the world. Large pulses of tree mortality were consistently linked to warmer and drier than average conditions for forests throughout the temperate and boreal biomes (*high confidence*) (Sommerfeld et al., 2018; Seidl et al., 2020). Long-term monitoring of tropical forests indicates that climate change as begun to increase tree mortality and alter regeneration (Hubau et al., 2020; Sullivan et al., 2020). Climate related dieback has also been observed due to novel interactions between the life cycles of trees and pest species (Kurz et al., 2008; Lesk et al., 2017;

Sambaraju et al., 2019). A recent example of the impacts of climatic extremes is the European drought of 2018 (Buras et al., 2020), which led to a significant browning of the vegetation and resulted in widespread tree mortality (*high confidence*) (Brun et al., 2020; Schuldt et al., 2020). This brought markets for conifer timber close to a collapse in parts of Europe, posing considerable challenges for timber-based forestry and leading to cascading impacts on society (Hlásny et al., 2021). Overall, there is *robust evidence* and *medium agreement* that provisioning services of boreal and temperate forests are affected negatively by forest disturbances, while for cultural services only *limited evidence* with *medium agreement* exists (Thom and Seidl, 2016).

Increasingly, climate impacts on the recovery of forests after disturbance are observed: Using data from the past 20 years and 33 wildfires, it has been shown that post-fire regeneration of *Pinus ponderosa* and *Pseudotsuga menziesii* in the western United States has declined because of climate change and increased severity of fires (Davis et al., 2019). However, the observed patterns of post-disturbance recovery vary with region, with reduced tree regeneration reported for the Western US (Stevens-Rumann and Morgan, 2019; Turner et al., 2019) but robust recovery observed in Canada (White et al., 2017) and Central Europe (*medium confidence*) (Senf et al., 2019).

Also, the distribution and traits of trees are increasingly influenced by climate change, with impacts for local ecosystem service supply. In the United States, a study of 86 tree species/groups over the past three decades showed that more tree species have shifted westward (73%) than poleward (62%) in their abundance (Fei et al., 2017). This was due more to changes in moisture availability than to changes in temperature. As climate has warmed, trees are growing faster with longer growing seasons. However, a study of forests in Central Europe revealed that wood density has decreased since the 1870s (Pretzsch et al., 2018). This means that increasing tree growth might not directly translate to increased total biomass and carbon sequestration.

5.6.2 Projected Impacts

AR5 stated that other stressors such as human-driven land use change and pollution will continue to be the main causes of forest cover change in the next three decades (Settele et al., 2014). In the second half of this century, it was projected that climate change will be a strong stressor of change in forest ecosystems. Many forest species may not be able to move fast enough to adjust to new climate conditions. In some cases, a warmer climate could lead to extinction of species.

The SR15 concluded that limiting warming to 1.5°C will be more favourable to terrestrial ecosystems, including forests relative to a 2°C warming (Hoegh-Guldberg et al., 2018). In general, a 2°C warming could lead to two times more area of biome shifts compared to a 1.5°C warming. As a result, keeping a cooler average global temperature will lead to lower extinction risks. The special report supports the AR5 conclusion that a warmer planet will impact wide swaths of forests adversely. For example, higher temperatures will promote fire, drought, and insect disturbances. Consistent with AR5, SRCCL projected that tree mortality will increase with climate change (Barbosa et al., 2019). In addition, forests will be more exposed to extreme events such as extreme heat, droughts, and storms. The incidence of forest fires will likewise increase.

Additional evidence since the above reports were published supports their overall conclusions. For example, at the global scale, modelling the vulnerability of 387 forest ecoregions under future climate change (to 2080 using the average of five GCMs and RCP 4.5 and 8.5) across different biomes, biogeographical realms and conservation statuses showed that 8.8% of global forest ecoregions are highly vulnerable in a low-greenhouse-gas-concentration scenario, and 32.6% of the global forest ecoregions were highly vulnerable in the high-greenhouse-gas-concentration scenario (Wang et al., 2019a). Furthermore, a recent synthesis of the literature suggests that climate change will result in younger and shorter forests globally (McDowell et al., 2020). In Asia, a systematic review of climate change impacts on tropical forests revealed that future climate may lead to changes in species distribution, forest structure and composition as well as phenology (Deb et al., 2018).

Overall, studies indicate both negative and positive climate change impacts on forest production systems. Some forests in the US could benefit slightly from CO_2 fertilisation (using IGSM-CAM and MIROC3.2 till 2100) resulting in increased productivity especially for hardwoods (Beach et al., 2015). A study across

Europe showed that both productivity gains (mostly in Northern and Central Europe, up to +33%) and losses (predominately in Southern Europe, up to -37%) are possible until the end of the 21st century (Reyer et al., 2017). The study further indicated that disturbances would reduce gains and exacerbate losses of productivity throughout Europe under climate change (Reyer et al., 2017). For Central and Eastern Canada, decreasing biomass production is projected as a result of increasing disturbance from wildfire and drought (Brecka et al., 2020). Climate-induced disturbances could also reduce the temporal stability of ecosystem service supply (Albrich et al., 2018), increasing the volatility of timber markets (*medium confidence*). More broadly, climate change could lead to abrupt changes and the crossing of tipping points, resulting in profoundly altered future forest development trajectories (Turner et al., 2020). Some studies suggest that such threshold could already be crossed at relatively low warming levels of +2°C (Elkin et al., 2013; Albrich et al., 2020), with substantial implications for ecosystem service supply (*limited evidence, high agreement*).

Regional studies on the potential future effects of climate change on forest production systems indicate diverse impacts. In Germany, drier conditions in 2070 (RCP 8.5; GCMs INM-CM4, ECHAM6 and ACCESS1.0) are expected to benefit the mean annual increment at biological rotation age of Scots pine and oak, while beech might suffer losses of up to 3 $m^3ha^{-1}yr^{-1}$ depending on climate scenario and region (Albert et al., 2018). In India, 46% of the forest grid points were found to have high, very high, or extremely high vulnerability under future climate in the short term (2030s) under both RCP 4.5 and 8.5, increasing to 49 and 54%, respectively, in the long term (2080s) (Sharma et al., 2017). In addition, forests in the higher rainfall zones show lower vulnerability as compared to drier forests under future climate, which is in contrast to dry forests in Central and South America cited above. Warming and drying trends are projected to reduce timber production in the neotropics in some cases (Hiltner et al., 2021). Also in India, a study using CMIP (RCP4.5 and 8.5 with two time slices 2021–2050 and 2070–2099) shows how forests in five districts in Himachal Pradesh in Western Himalayan region are vulnerable to global warming (Upgupta et al., 2015). In the Guiana Shield, climate projections under RCP 2.5 and 8.5 led to decreasing the basal area, above-ground fresh biomass, quadratic diameter, tree growth and mortality rates of tropical forests (Aubry-Kientz et al., 2019). In Central Africa, projections under RCP 4.5 and 8.5 showed a general increase in growth, mortality and recruitment leading to a strong natural thinning effect, with different magnitudes across species (Claeys et al., 2019).

On a global and regional scale, there is *limited evidence* and *high agreement* (*medium confidence*) that climate change will increase global and regional supply of timber and other forest products. To date, there are eight studies assessing the total economic impacts of climate change on the forestry sector at the global level. Some of them have assumed only flow effects of climate change by using the projected changes in yields of forest types from integrated economic models (Perez-Garcia et al., 1997; Perez-Garcia et al., 2002; Buongiorno, 2015), while other studies have assumed both flow and stock effects by accounting for changes in forest yields, dieback effects and biomes migration (Sohngen et al., 2001; Lee and Lyon, 2004; Tian et al., 2016; Favero et al., 2018; Favero et al., 2021).

According to these studies, global timber supply will increase as the result of an increase in global forest growth under climate change scenarios (*medium confidence*). Some studies indicate that timber supply is projected to increase more in tropical and subtropical areas because of the assumed availability of short-rotation species which are likely to make adaptation easier for forest owners in these regions relative to others (Sohngen et al., 2001; Perez-Garcia et al., 2002; Tian et al., 2016) while others indicate that temperate areas will experience the largest increase in supply (Favero et al., 2018; Favero et al., 2021). The results are very sensitive to the climate change scenarios tested, the climate and vegetation models used and the climate drivers that are considered. For example, Tian et al.(2016) and Favero et al.(2018; 2021) used the same economic model (the global timber model) but different climate scenarios and vegetation models, obtaining different results.

The increasing supply induces lower global timber prices (*medium confidence*). Studies estimate that the prices are likely to decline between 1% to 38% in 2100 with respect to a no climate change scenario depending on the model and the climate change scenario assumed (climate change is represented as a change in greenhouse gas concentration, global average temperature or radiative forcing) (Favero et al., 2018; Favero et al., 2021). Clearly, further studies are needed considering a wider set of vegetation and climate models and incorporating the impacts of extreme events (such as droughts and wildfires).

There are a number of national and regional scale studies exploring the impact of climate change on yields and markets of wood products, with mixed results. In Finland, it is projected that timber yield in the north will increase in Scots pine and birch stands by 33–145% and 42–123%, compared to the current climate, depending on the GCM and thinning regime using a 90-year rotation (10 individual GCM projections under the RCP4.5 and RCP8.5 forcing scenarios) (ALRahahleh et al., 2018). However, in Norway spruce stands, yield could decline by up to 35%, under GFDL-CM3 RCP8.5 and increase by up to 39%, under CNRM-CM5 RCP8.5, compared to the current climate.

In Germany, timber harvest was projected to increase slightly (< 10%) in 2045 using the process-based forestry model (4C) driven by three management strategies (nature protection, biomass production and a baseline management) and an ensemble of regional climate scenarios (RCP2.6, RCP 4.5, RCP 8.5) (Gutsch et al., 2018). Similarly, average production of pulpwood in slash pine stands in the Southeastern United States are projected to increase by 7.5 m^3 ha^{-1} for all climatic scenarios using 3-PG forest growth model by 2100 (RCP4.5 and RCP8.5; CanESM2) (Susaeta and Lal, 2018).

5.6.3 Adaptation

AR5 notes that natural ecosystems have built-in adaptation ability (Settele et al., 2014). However, this capacity will not be enough to prevent loss of forest ecosystem services because of projected climate change in this century under RCP 6.0 and 8.5. Management actions could reduce the risks of impacts to forest ecosystems but only up to a certain point.

A systematic review of literature revealed that successful adaptation in forest management can be achieved if there are partnerships between key stakeholders such as researchers, forest managers, and local actors (Keenan, 2015). Such partnerships will lead to a shared understanding of climate-related challenges and more effective decisions. Forest managers in some countries of the world seem to have high awareness of climate change (van Gameren and Zaccai, 2015; Seidl et al., 2016; Sousa-Silva et al., 2016). However, they need more information on how they can adjust their practices in response to climate change. Institutional and policy context needs to be considered to facilitate adaptation by forest managers (Sousa-Silva et al., 2016; Andersson et al., 2017).

5.6.3.1 Adaptation measures in sustainable forest management

A wide range of measures exist to adapt sustainably managed forests of the boreal and temperate zone to climate change (Kolström et al., 2011; Gauthier et al., 2014; Keenan, 2015). Evidence emerging since the last assessment report further bolstered the notion that adapting the tree species composition to more warm-tolerant and less disturbance-prone species can significantly mitigate climate change impacts (*high confidence*) (Duveneck and Scheller, 2015; Seidl et al., 2018). Assisting the establishment of species in suitable habitats is one option to achieve climate-adapted tree species compositions (Benito-Garzón and Fernández-Manjarrés, 2015; Iverson et al., 2019). Furthermore, increasing the diversity of tree species within stands can have positive effects on tree growth and reduce disturbance impacts (*high confidence*) (Neuner et al., 2015; Jactel et al., 2018; Ammer, 2019). Some studies also suggest a positive effect of increased structural diversity, e.g., on forest resilience (*moderate confidence*) (Lafond et al., 2013; Koontz et al., 2020). Managing for continuous forest cover can also help to maintain the forest microclimate and buffer tree regeneration and the forest floor community against climate change (*high confidence*) (De Frenne et al., 2013; Zellweger et al., 2020). Reducing stocking levels e.g., through thinning has been found to effectively mitigate drought stress (Gebhardt et al., 2014; Elkin et al., 2015; Bottero et al., 2017), yet effects vary with species and ecological context (*robust evidence, medium agreement*) (Sohn et al., 2016; Castagneri et al., 2021). Also shortened rotation periods have been suggested in response to climate-induced increases in growth and disturbance (Jönsson et al., 2015; Schelhaas et al., 2015). However, recent evidence suggests that these measures diminish in efficiency under climate change and can have corollary effects on other important forest functions such as carbon storage and habitat quality (*medium confidence*) (Zimová et al., 2020). Also, measures targeting landscape structure and composition have proven effective for increasing the climate resilience of forest systems (*medium confidence*) (Aquilue et al., 2020; Honkaniemi et al., 2020). While an increasing number of adaptation measures exist for sustainably managed forests, many studies highlight that the lead times for adaptation in forestry are long and that some vulnerabilities might remain also after adaptation measures have been implemented. Furthermore, the costs and benefits of adaptation measures relative to other goals of sustainable forest management, such as the conservation of biological diversity, have to be considered (Felton et al., 2016; Zimová et al., 2020; see CCP7 5.3.1 Adaptation Response Options).

[START BOX5.6 HERE]

Box 5.6: Contributions of Indigenous and local knowledge: an example

Indigenous and local people have long histories of adaptation to climate hazards in forests (see Eriksen and Hankins, 2014; Neale et al., 2019; Bourke et al., 2020; Long et al., 2020; Williamson, 2021 for notable examples in Australia and North America). In this section we present a North American example of an indigenous adaptation practice developed by the Karuk Tribe in northern California. The Karuk Climate Adaptation Plan focuses on the use of cultural fire as climate adaptation, places a central importance on restoring human ecological caretaking responsibilities, and emphasizes the need for collaboration, public education, and policy advocacy to achieve these outcomes.

The Karuk Climate Adaptation Plan utilizes a combination of western science and Karuk traditional ecological knowledge. The plan centres on 22 focal species as **cultural indicators** as cues for human responsibilities and the particular techniques of fire application across seven habitat management zones (e.g., multiple forest types as well as riverine, riparian and montane systems). These adaptations range from specific prescriptions for the use of fire to lower river temperatures in acute scenarios (David et al., 2018), to protocols for treatment of grasslands and the use of high elevation meadows as fuel breaks. The plan also includes chapters on adaptations for tribal sovereignty, the mental and physical health effects of the changing climate and the protection of critical tribal infrastructure.

One aspect of Indigenous fire knowledge featured in the Karuk Climate Adaptation Plan is the culture-centric perspective on vegetation zones which are organized in relation to the elevation band in which smoke inversions occur (Figure Box 5.6.1). Within this system, burn timing follows a gradient that tracks the reproductive life cycles of season and elevational migrant species, the calving of elk as well as the nesting of birds. Within this system, elevational migrants are indicators of when to stop burning at one location and move upslope, following receding snows.

The plan also calls for the restoration of Indigenous fire science in emergency scenarios such as when rivers become too hot for salmon. With such fires localized, smoke inversions cool water temperatures through a variety of mechanisms including shading river systems and reducing evapo-transpiration thereby increasing stream flow (David et al., 2018).

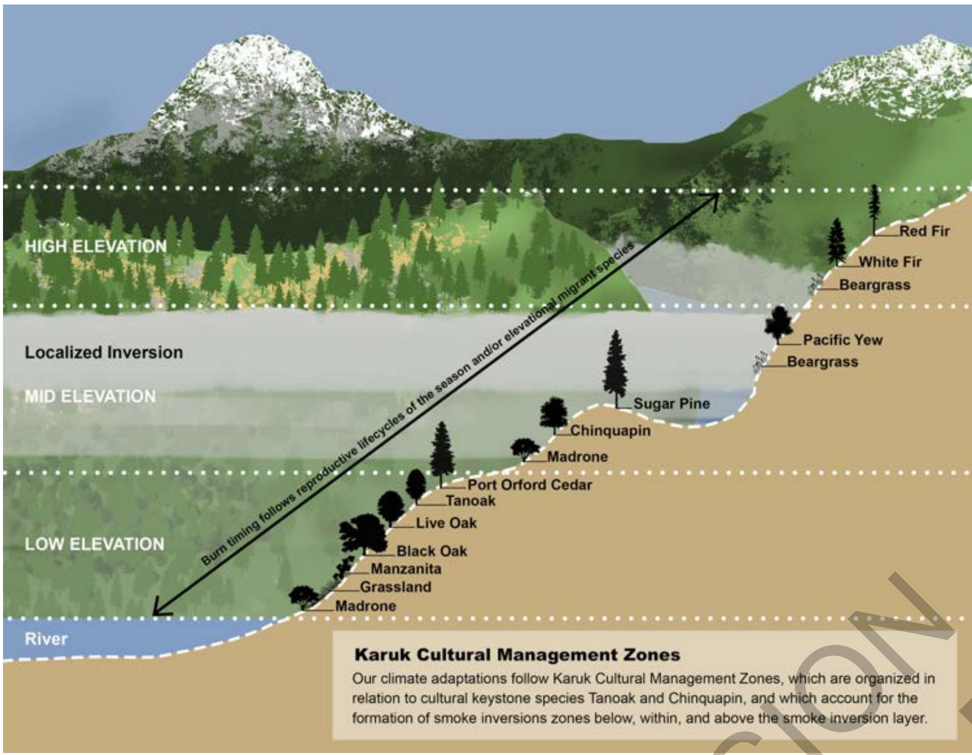


Figure Box 5.6.1: Seasonality and elevation dynamics of cultural indicators in Karuk Cultural Management Zones based in Karuk traditional ecological knowledge.

[END BOX 5.6 HERE]

5.6.3.2 Linking adaptation and mitigation through REDD+

Reducing Deforestation and Forest Degradation plus (REDD+) is a climate mitigation strategy which could also provide important climate change adaptation co-benefits, e.g., sustainable forest management could provide long term livelihoods to local communities and enhance resilience to climate risks (Turnhout et al., 2017), but with major challenges related to REDD+ implementation and forest use remain such that it has not been implemented successfully at scale (Table 5.8).

Table 5.8: Challenges and solutions for Reducing Deforestation and Forest Degradation (REDD+)

Challenges with REDD+ implementation	**Solutions for successful forest management**
Legal: lack of carbon rights in national legislations (Sunderlin et al., 2018; RRI, 2018b); unclear forestland tenure systems (Resosudarmo et al., 2014);.	There is *high confidence* that implementing social safeguards such as a Free Prior and Informed Consent (FPIC) is vital to adequately involving Indigenous Peoples and local communities in REDD+ (White, 2014; Raftopoulos and Short, 2019). Indigenous Peoples, consisting of at least 370 million people, manage or have tenure rights over a quarter of the world's land surface (around 38 million km^2) encompassing about 40% of the world's protected areas (Garnett et al., 2018; RRI, 2018a).
Food security and livelihoods: Negative impacts of REDD+ on food security, agroforestry and swidden agriculture (Fox et al., 2014; Holmes et al., 2017).	There is *high agreement* that REDD+ and other green adaptation and mitigation efforts need to cooperate with Indigenous Peoples and other local communities who depend on forest resources for their livelihoods and food security (Wallbott, 2014; Mccall, 2016; Brugnach et al., 2017; Vanclay, 2017; Garnett et al., 2018; Paneque-Galvez et al., 2018; Sunderlin et al., 2018; Schroeder and Gonzalez, 2019).

Political and socio-culural: land acquisition or 'green grabbing' (Asiyanbi, 2016; Corbera et al., 2017); (mis)communicating the concept of carbon (Kent and Hannay, 2020); and lack of influence of Indigenous and local communities' representation in global and national REDD+ negotiations (Wallbott, 2014; Dehm, 2016). In the absence of social and environmental safeguards, REDD+ could drive large-scale land acquisitions by states and corporations resulting in global land grabs (or green grabbing), negatively affecting the food security, livelihoods and tenure rights of Indigenous and local communities (*limited evidence, high agreement*) (Carter et al., 2017; Lund et al., 2017; Borras et al., 2020).	There is *low confidence* as to whether community forestry is compatible with REDD+ (Hajjar et al., 2021). This is mainly due to lack of carbon payments and the variety of approaches to REDD+. There is *high confidence* that restoring land access and rights via transfer of formal land titles to Indigenous and local communities improves biodiversity conservation and carbon sequestration.

5.7 Other Natural Products

Natural products such as medicinal plants, wild food (plants, animals, mushrooms) and resins (e.g., gum arabic and frankincense) have high commercial value and contribute an important source of livelihood in some regions. One in six persons globally live in or near forests and many depend on forest resources for some of their livelihood and needs, particularly in low- and middle-income countries (Vira et al., 2016; Newton et al., 2020). The FAO has estimated that in 2011 non-wood forest products, including medicinal plants, contributed over 88 billion USD to the global economy (FAO, 2014). Greater diversity in local knowledge and Indigenous knowledge of natural resources supports resilience in the face of hazards, especially in environments with high levels of uncertainty (Berkes et al., 2003; Blanco and Carriere, 2016).

5.7.1 Medicinal Plants

The World Health Organization lists traditional medicine as an essential component of culturally appropriate healthcare (WHO, 2013). Medicinal plants make up the primary source of medicine for 70 to 95% of people in low- and middle-income countries and are used widely in wealthier countries (Applequist et al., 2020). Continued use of medicinal plants ensures millions of rural people have access to effective treatments for day-to-day illness and infection and thus improves their health and resilience to climate change.

Indigenous Peoples largely depend on medicinal plants for their healthcare need in different parts of the world (de Boer and Cotingting, 2014; Silva et al., 2020). Medicinal and aromatic plants can support the economy and generate livelihood options for rural people through preparing and selling traditional medicine; collecting from wild; and trade for income generation (Fajinmi et al., 2017; Zahra et al., 2020). Income from medicinal plant collection increases livelihood diversification, which is widely accepted to improve resilience.

5.7.2 Resin and Gum

Resin and gum are economically important natural products: contributing 14-23% total household income in parts of Ethiopia and Sudan (Abtew et al., 2014; Fikir et al., 2016), Cambodia (Sakkhamduang et al.) and India (Tewari et al., 2017). They are an important source of raw material for many industries. For instance, in Africa, the genus *Boswellia* and *Commiphora,* which provide frankincense and myrrh resins, provide significant income generation and export value (Tilahun et al., 2015). Populations of many species that provide gums and resins are declining under pressure from unsustainable harvesting and deforestation and climate change may further threaten them.

In Sri Lanka, *Boswellia serrata* Roxb. is critically endangered or possibly extinct (Weerakoon and Wijesundara 2012). In India, *B. serrata* populations are 'vulnerable' (Chaubey et al., 2015; Brendler et al., 2018), and declining in the Western Ghats (Soumya et al., 2019). Invasion of *Lantana camara* and *Prosopis juliflora* has resulted in poor regeneration of *Commiphorawightii* in central India (Jain and Nadgauda, 2013). Other resin-producing species under threat include: *Daemonoropsdraco* (Dragon's blood resin) in Indonesia (Yetty et al., 2013; Widianingsih et al., 2019), *Pinus merkusii*(tusam) in Sumatra (Indonesia) (Hartiningtias et al., 2020), *Pinus pinaster* in Spain*, Pinus massoniana*in China*,* (Génova et al., 2014; Chen et al., 2015b), *Pistacia atlantica* in Iran (Yousefi et al., 2020).

5.7.3 Wild Foods

Wild foods can include both native and introduced species that are not cultivated or reared but may be under various degrees of management by humans and may include escapees of species that are cultivated in some contexts (Powell et al., 2015). Information on the use and importance of wild foods for nutrition is growing but remains limited (FAO, 2019e). The AR4 covered wild food briefly in the Polar Regions and noted the interrelated nature of climate change and Indigenous knowledge loss in reducing access to wild food (Anisimov et al., 2001). AR5 did not address wild foods and other natural products. There is large variation in the importance of wild foods (Powell et al., 2015; Rowland et al., 2017; Dop et al., 2020). A recent survey of 91 countries found that 15 reported regular use of wild foods by most of the population, and 26 reported regular use of wild foods by a subsection of the population (FAO, 2019e). While they contribute little to food energy intake, their contribution to nutrition can be significant because most wild and forest foods (vegetables, fruits, mushrooms, insects, and meat) are rich in proteins and micronutrients (Powell et al., 2015). The impacts of climate change on wild foods will vary in time, space, and among species.

5.7.4 Observed and Projected Impacts

5.7.4.1 Medicinal lants

Research is limited on the effects of climate change on the distribution, productivity, or availability of medicinal plants (Applequist et al., 2020), but some are facing threats due to climate change (Phanxay et al., 2015; Chirwa et al., 2017; Chitale et al., 2018). Climate change is projected to impact some medicinal plant species through changing temperature and precipitation, changes in pests and pathogens: unsustainable harvest of high value species will significantly exacerbate these impacts (*medium evidence; high agreement*) (Applequist et al., 2020). Table 5.9 highlights that climate change impacts on medicinal plant species will vary greatly by species. Medicinal plants that grow in arid environments are also highly susceptible to climate-induced change (Applequist et al., 2020). Arctic medicinal species may also be particularly at risk due to climate change (Cavaliere, 2009).

Changes in range distribution will interact with detailed local knowledge and Indigenous knowledge needed to harvest and use medicinal plants. Northward range shifts, for example, may mean certain plants still exist, but not where they have traditionally been important as medicine, and with protected areas, possibly moving suitable ranges outside of areas where plants species have sufficient protection (Kaky and Gilbert, 2017). Climate-induced phenological changes are already observed as a threat to some species (Gaira et al., 2014; Maikhuri et al., 2018). Other major climate-induced impacts on medicinal plants will be via the phytochemical content and pharmacological properties of medical plants (Gairola et al., 2010; Das et al., 2016a). Experimental trials have shown that drought stresses increase phytochemical content, either by decreasing biomass or increasing metabolites production (*high confidence*) (Selmar and Kleinwachter, 2013; Al-Gabbiesh et al., 2015).

Table 5.9: Observed and Predicted impacts of climate change on selected medicinal plant species.

Region	Species	Observed and Projected Impacts of Climate Change	Assessment of Evidence and level of agreement
Egypt, Sub-Saharan Africa, Spain, Central Himalaya, China, Nepal	General assessment of medicinal plants	Habitat suitability and/or range distribution will shift or may be lost (Munt et al., 2016; Yan et al., 2017; Brunette et al., 2018; Chitale et al., 2018; Zhao et al., 2018; Applequist et al., 2020) including in high elevation meadows which are home to some of the most threatened plant populations and contain a high number of and higher proportion of species used as medicine compared to lower elevation habitats (Salick et al., 2009; Brandt et al., 2013).	*medium confidence.*
Hindukush Himalaya	*Gynostemmapenta phyllum*	The elevated CO_2 and temperature can increase biomass, but the health-promoting	*medium confidence*

		properties such as total antioxidants, phenols, and flavonoids are expected to decrease (Chang et al., 2016).	
Arctic	Golden Root (*Rhodiola rosea)*	Population decline has been associated with drying of stream beds and alpine meadows, which are predicted to become more severe under climate change (Cavaliere, 2009; Brinkman et al., 2016)	*medium confidence*
North America	American ginseng (*Panax quinquefolius*)	Modelling of the combined impact of climate change (warming) and harvesting pressure indicates a non-linear increase in extinction risk (Souther and McGraw, 2014)	*medium confidence*
Asia	*Gentiana rigescens*	A model evaluating future climate impacts shows a westward range shift and major loss of highly suitable habitats. Modelling also shows a potential decline in quality (chemical concentration of iridoid glycoside, which is highest in highly suitable habitats) due to climate change (Shen et al., 2021)	*medium confidence*
Africa	*Alstoniaboonei*	Modelling indicates that the range for this species remains relatively stable with a possible modest expansion at the northern and southern margins of the range (Asase and Peterson, 2019).	*medium confidence*
Asia	*Homonoia riparia*	Modelling of future climate scenarios in Yanan province, China projects that habitat suitability improves (Yi et al., 2016). Modelling of future climate scenarios across the whole species range in China shows that both the suitable area and suitability of the habitat increase (Yi et al., 2018).	*medium confidence*
Asia	*Notopterygiuminc isum*	Modelling for future climate change shows areas of suitable habitat will significantly decrease, however, the area of marginally suitable habitat will remain relatively stable (Zhao et al., 2020).	*medium confidence*
Himalayas	Himalayan yew *Taxus wallichiana*	Modelling shows projected shrink in climatic niche of the species by 28% (RCP 4.5) and 31% (RCP 8.5) highlights the vulnerability to climate change impacts (Rathore et al., 2019).	*medium confidence*
Iran	*Daphne mucronata*	Modelling of future climate change projects disappearance of the species below 2000 m, significant change in distribution between 2000-3000m and no change above 3000 m (Abolmaali et al., 2018).	*medium confidence*
Central America	Pericón or Mexican Mint Marigold *Tagetes lucida*	Models predict range to contract somewhat and shift northward (Kurpis et al., 2019)	*medium confidence*
Africa	Rooibos tea *Aspalathus linearis*	Modelling of future climate scenarios shows substantial range contraction of both wild and cultivated tea with range shifts south-eastwards and upslope (Lotter and Maitre, 2014)	*medium confidence*
Himalayas	*Lilium polyphyllum*	Habitats of this species will shrink by 38–81% under future climate scenarios and shift towards the south-east region in western Himalaya, India (Dhyani et al., 2021).	*medium confidence*
Iran	*Fritillaria imperialis*	Modeling shows 18% and 16.5% of the habitats may be lost due to climate change by 2070 under RCP4.5 and RCP8.5, Further,	*medium confidence*

		it is observed that under the current climatic conditions, the suitable habitat may become unsuitable in the future resulting in local extinction (Naghipour Borj et al., 2019)	
Himalayas/ China	Snow lotus *(Saussurea spp.)*	Climate change is a significant threat to this species (Law and Salick, 2005). Laboratory and field trials show considerable plasticity and a wide thermal range for germination, which may help compensate for range reductions under climate change (Peng et al., 2019)	*medium confidence*
North Africa	Atlas cedar *Cedrusatlantica*	Modelling shows a significant and rapid contraction of distribution range, upward elevational range shift, increased fragmentation, and possible disappearance in many North African localities (Bouahmed et al., 2019)	*medium confidence*
Asia / South Korea	*Paeonia obovata*	Modelling of climate change scenarios shows significant loss of suitable habitat and possible disappearance of *P. obovata*in South Korea after 2080 (Jeon et al., 2020).	*medium confidence*
Iran	*Salvia hydrangea*	A projected loss of habitat in the south-east of the range will not be compensated by the northward or upward elevational range migration (Ardestani and Ghahfarrokhi, 2021)	*medium confidence*
Patagonian, Argentina	*Valerianacarnosa*	Modelling for future climate scenarios projects a 22% loss of the suitable habitat (Nagahama and Bonino, 2020)	*medium confidence*
Western Ghats, India	Kokum *Garcinia indica*	Predictions of Climate change impact on habitat suitability indicate drastic reduction in the suitability by over 10% under RCP 8.5 for the year 2050 and 2070 (Pramanik et al., 2018)	*medium confidence*
Himalaya	*Ophiocordyceps sinensis*	A decline of the species is largely due to over harvesting but ecological modelling indicates that climate warming is also contributing to this decline (Hopping et al., 2018)	*high confidence*
Pacific islands	noni (*Morindacitrifoli*), naupaka (*Scaevola spp*.), kukui (*Aleurites moluccana*), and milo (*Thespesia populnea*)	May be less susceptible to climate change as they are fast growing, have high reproduction rates, grow at sea-level (and are often salt-tolerant) and have significant room for range shifts (Cavaliere, 2009).	*Low confidence.*

5.7.4.2 Wild food

5.7.4.2.1 Wild Food in the Arctic, North America, and Europe

Changes to the availability, abundance, access, and storage of wild foods associated with changing climate are exacerbating high rates of food insecurity (*high confidence*) (Ford, 2009; Beaumier and Ford, 2010; Herman-Mercer et al., 2019). Wild foods are central to the food systems of communities throughout the Arctic and sub-Arctic (Kuhnlein et al., 1996; Ballew et al., 2006; Kuhnlein and Receveur, 2007; Johnson et al., 2009) and play an essential role in people's physical and emotional health (CCP 6.2.5; 2.8) (*high confidence*) (Loring and Gerlach, 2009; Cunsolo Willox et al., 2012). Wild foods consumed in the Arctic and Northern regions include animals and a wide variety of plant foods (Wein et al., 1996; Ballew et al., 2006; Kuhnlein and Receveur, 2007). Wild foods contribute most of important nutrients in the diets of Northern and Arctic people (Johnson et al., 2009; Wesche and Chan, 2010; Kenny et al., 2018). However, the use of traditional wild foods is declining across the region, lowering diet quality (Rosol et al., 2016). Indigenous communities in the Arctic perceive climate change related impacts on traditional wild foods, and availability and access to wild foods are forecast to continue to decline (Brinkman et al., 2016). Some communities hold positive views of the new opportunities a warmer climate will bring, seeing them as a favourable trade-off relative to the loss of some forms of subsistence hunting (Nuttall, 2009). Climate change is causing ecological changes that impact Arctic wild food availability and abundance in many different ways, including changes to breeding success, migration patterns, and food webs (Table 5.10, Markon et al., 2018).

Climate-change induced impacts of access to wild foods are also of concern in Arctic regions (*high confidence*). Coastal and inland communities of Alaska found that 60% of climate impacts on food security listed by hunters were related to access (Brinkman et al., 2016). Reduced duration, thickness and quality of sea ice are some of the most cited impacts of climate change on wild food consumption (Ford, 2009; Laidler et al., 2009; Downing and Cuerrier, 2011; Huntington et al., 2017; Nuttall, 2017; Fawcett et al., 2018; Ford et al., 2018; Markon et al., 2018). Lack of snowfall reduces and delays the ability to travel on the land using snowmobiles (Downing and Cuerrier, 2011), impacting safety of travel, time needed and costs of accessing wild foods (Cold et al., 2020).

Rising temperatures and humidity are also impacting wild food storage and increasing the risk of food-borne diseases (Cozzetto et al., 2013; Nuttall, 2017; Markon et al., 2018). Changes in air temperature and humidity can mean that whale and fish meat no longer dry properly, or meat may spoil before hunters can get it home (Downing and Cuerrier, 2011; Nuttall, 2017). Traditional permafrost ice cellars are no longer reliable (Downing and Cuerrier, 2011; Nyland et al., 2017; Herman-Mercer et al., 2019). Climate-related environmental change compounded with social, economic, cultural, and political change have had complex but overall negative impacts on wild foods (CCP 6.4, Lujan et al., 2018) .

Communities across other (non-Arctic) parts of North America and Europe also report declining availability of wild foods with climate change among the perceived drivers for decline (*medium confidence*) (Table 5.10, Serrasolses et al., 2016; Smith et al., 2019a). Even when climate change may not always be the primary driver of loss of these wild food resources, climate may interact with other stressors to exacerbate loss of wild foods (Lynn et al., 2013; Reo and Parker, 2013).

5.7.4.2.2 Wild food in the arid and semi-arid environments

Wild foods are also impacted by climate change in arid and semi-arid landscapes around the world (*medium evidence, high agreement*) (Table 5.10). A number of wild species are important traditional foods of Indigenous Peoples or local communities across arid regions of North America (Messer, 1972; Kuhnlein and Calloway, 1977; Santos-Fita et al., 2012; Vinyeta et al., 2016), South America (e.g. Argentina, Ladio and Lozada, 2004; Altrichter, 2006; Eyssartier et al., 2011), Australia (Scelza et al., 2014), the Mediterranean basin (Hadjichambis et al., 2008; Powell et al., 2014), India and the Himalayas (Pingle, 1975; Gupta and Sen, 1980; Delang, 2006; Bhatt et al., 2017).

Wild foods such as baobab, shea and nere from plants and animal make an important contribution to diets and nutrition in arid and semi-arid regions of African (Boedecker et al., 2014; Leßmeister et al., 2015; Bélanger and Pilling, 2019) and are being impacted by climate change (Moseley et al., 2015; Sango and Godwell, 2015; Hitchcock, 2016) (see Chapter 9). There has been little published research on the impacts on climate change on wild food in arid regions of Australia, although Aboriginal elders in one report suggested that climate related changes are impacting wild food (Memmott et al., 2013).

5.7.4.2.3 Wild Food in tropical humid environments

Wild foods are important to many communities that live in and adjacent to humid tropical forests, but climate change impacts are mixed (Table 5.10, Dounias et al., 2007; Colfer, 2008; Powell et al., 2015; Rowland et al., 2017; Reyes-García et al., 2019).. In some humid tropical forest regions, bushmeat is particularly important (Golden et al., 2011; Nasi et al., 2011; Fa et al., 2015; Powell et al., 2015; Rowland et al., 2017). In humid tropical regions the impact of climate change on wild food availability, access and consumption is currently unclear and research is limited. There are, however, important interrelationships between climate change and wild food use in humid forests. For example, the loss of large mammals to bushmeat consumption and global trade will likely slow the regeneration of tropical forests in which a large number of tree species are dependent on large mammals for seed dispersal (Brodie and Gibbs, 2009).

Conversely, others argue that bushmeat provides local communities with an important incentive to support local maintenance of forest cover and thus carbon sequestration (Bennett et al., 2007).

Table 5.10: Observed and Predicted impacts of climate change on selected wild food species.

Region	Species	Observed and Projected Impacts of Climate Change	Assessment of Evidence and level of agreement
Arctic region	Ringed Seals (*Pusahispida*)	Drastic declines in population size and major changes in population structure (Hammill, 2009; Reimer et al., 2019); habitat (dependent on snow cover or ice breathing holes for lairs) will decline by approximately 70%, and significantly reduce survival rates of pups (Freitas et al., 2008).	*high confidence*
Arctic region	Bearded seal (*Erignathus barbatus*)	Climate change affect the availability and stability of at least 11 ice-associated species including Bearded seal. Potential impacts due to climate change will reduce available habitat for birthing (Moore and Huntington, 2008; Fink, 2017).	*medium evidence, high agreement*
Arctic region	Walrus (*Odobenus rosmarus*)	Declines in the climate-vulnerable Pacific walrus populations, induced by overharvesting (Taylor et al., 2018); however, the species is considered highly vulnerable to loss of sea ice (Lydersen, 2018). Possible diet changes (related to climate-induced changes in food-web) raise concernsabout the health of the population (Clark et al., 2019).	*high confidence*
Arctic region	Narwhal (*Monodon monoceros*)	The impacts of climate change on other sea ice-associated marine mammals are somewhat less clear (Moor et al., 2017). Climate change may threaten narwhal given their vulnerability to ice entrapment (Laidre and Heide-Jorgensen, 2005) and the narrow range of prey in their diet (Heide-Jørgensen, 2018). In Greenland hunters report that narwhal now frequent fjords and other areas where manoeuvring a boat is difficult (Nuttall, 2017)	*low evidence, medium agreement*
Arctic region	Beluga (*Delphinapterus leucas*)	Belugas are thought to be less sensitive to climate change than some other sea mammals but can perish in large groups from ice entrapment. Climate impacts likely increased human activity (noise) (O'Corry-Crowe, 2009). Changes in migrating timing have been documented (Hsiang et al., 2017).	*low evidence, low agreement*
Arctic region	Bowhead (*Balaena mysticetus*)	The movements of some whale species are linked to sea surface temperatures (Moore and Huntington, 2008; Chambault et al., 2018). Some whale hunting communities are now reporting that whales pass by at a time of year when launching boats is impaired by rough weather and poor sea ice conditions (Noongwook et al., 2007; Huntington et al., 2017).	*medium confidence*
Artic region	Other sea ice associated marine mammals (harp seal, hooded seal)	The impacts of climate change on other sea ice associated marine mammals are somewhat less clear (Moor et al., 2017).	*low confidence*
Arctic and Northern regions	Reindeer and caribou (*Rangifer tarandus*)	Large herbivores are highly dependent on their food sources such as mosses, lichens and grasses which are sensitive to climate change (Istomin and Habeck, 2016). Combined impacts of climate change and other interrelated factors suggest significant declines in caribou and reindeer populations, although to varying extents from one population to another (Kenny et al., 2018; Mallory and Boyce, 2018).	*medium confidence*

		Warming has led to increased plant productivity and associated increases in body mass of some reindeer populations (Albon et al., 2017; Mallory and Boyce, 2018). Increasing primary production, warming will also change the plant composition, leading to increases in woody / shrubby vegetation which will have negative nutritional consequences for caribou and reindeer (Elmendorf et al., 2012; Mallory and Boyce, 2018). The loss of lichens, a key winter food source, due to increased wildfire or replacement by grasses and herbs that die back in the winter, may also be detrimental to caribou and reindeer, although there is not currently consensus on this among experts (Mallory and Boyce, 2018). Rain on snow and icing events during winter, which are predicted to become more frequent, have been documented to lead to large increases in arctic herbivore mortality because they create an ice barrier making access to food more difficult (Putkonen and Roe, 2003; Tyler, 2010; Stien et al., 2012; Hansen et al., 2013; Forbes et al., 2016). Rain on snow events may also impact reproductive success, although recent research suggests this relationship in not straight forward (Douhard et al., 2016). Increased summer insect harassment is also predicted to increase and further stress large herbivores both by the additional parasitic load and by decreasing the amount of time spent grazing as animals seek to outrun pests (Mallory and Boyce, 2018). Finally, many caribou and reindeer populations rely on sea and freshwater ice to facilitate their movement and migration: loss of ice may make some populations no longer viable (Mallory and Boyce, 2018).	
Arctic and Northern regions	Moose (*Alces alces*)	The distributional changes of Rangifer populations might be affected by the range expansions and the northward expansion of moose (Mallory and Boyce, 2018). This is due to increases in productivity on the tundra and more frequent wildfire activity resulted to improve habitat quality for moose in the northward.	*medium confidence*
North America	Geese (*Branta canadensis, Answer spp., Branta spp.*)	Phenological mismatch develops between the berries and migration timing may mean that Canadian geese no longer stop near some communities (Downing and Cuerrier, 2011).	*medium confidence*
Arctic and Northern regions	Berries (*Vaccinium spp., Rubus spp.* and others)	Berries are among the most important and widely consumed wild foods of plant origins in Arctic and northern regions (Vaara et al., 2013; Hupp et al., 2015; Boulanger-Lapointe et al., 2019). Berry production will be impacted by climate change, including snow cover, rainfall, soil moisture, air temperature, and availability of insect pollinators (Herman-Mercer et al., 2020) and possible risk from sea-level-rise associated soil salinization (Cozzetto et al., 2013). Increased growth of woody shrub vegetation, driven by increased temperatures, can also make moving across the land move difficult, impairing access to berry patches (Boulanger-Lapointe et al., 2019). Conversely, a recent modelling experiment suggested that the >2 °C warming experienced by Arctic communities over the past three	*high confidence*

		decades has had minimal impact on overall trail access (Ford et al., 2019). In Alaska, communities perceive berry abundance as declining and/ or becoming more variable (Kellogg et al., 2010; Hupp et al., 2015). In a Gwich'in community in Canada, Parlee and Berkes (2005) recorded that local women perceived climate change, especially extreme weather events as the greatest risk to traditional berry patches (cranberry, blueberry, and cloudberry). The expansion of trees and shrubs may cause shading and negatively impact the productivity of berry plants (Downing and Cuerrier, 2011; Lévesque et al., 2012). Berries are predicted to be increasingly susceptible to negative impacts of invasive species (which compete for pollinators) as climate change progresses (Spellman and Swenson, 2012) and infections (Turner and Clifton, 2009). Suitable area of Huckleberry (*Vaccinium membranaceum*) would shrink by 5–40% by the end of the 21st century (Prevéy et al., 2020). Phenological shifts are also important. Many communities report changes in phenology including failed ripening or "all of the berries are ripening at the same time" (Turner and Clifton, 2009; Herman-Mercer et al., 2020). Competition with growing populations of geese is viewed by many communities to be an important threat to berry harvesting. (Boulanger-Lapointe et al., 2019). In Labrador, Canada report that changes in permafrost, vegetation, water, and weather have had an impact on cloudberry (bakeapple) productivity, phenology, and patch fragmentation. Moreover, changes in summer settlement patterns (which are now farther from berry patches) are making it more difficult for people to respond to variations in growth and timing (Anderson et al., 2018). In Montana, USA, Crow Nation elders have noted that many of their important berry resources have been impacted by climate change, either because they bud earlier and are then vulnerable to cold snaps, or the timing of fruit production has changed (with many now ripening at the same time) (Doyle et al., 2013). Similarly, the Wabanaki Nations in Maine and Eastern Canada worry that climate change will impact berry resources already under pressure from dwindling territory and pollution (Lynn et al., 2013).	
North America (Washington State, USA)	Salmon (*Salmonidae*)	Indigenous communities in Washington State, USA report devastation of their salmon fishery due to loss of glacial run off and associated warming river and stream temperatures; potential damage to shellfish resources due to sea level rise and ocean acidification (Lynn et al., 2013). The Karuk people in California have also experienced losses in salmon (Lynn et al., 2013; Vinyeta et al., 2016).	*Medium confidence*
North America (California)	Acorns form oak trees (*Querus)*	In the arid south-west of the USA, wild foods are less widely consumed today, but their revitalization is important to identity and well-being of many Indigenous people. The Karuk people of the Klamath River in California have experienced an almost complete loss of two key traditional wild foods: salmon and acorns, foods which once made up 50 % of a traditional Karuk diet (Lynn et al., 2013; Vinyeta et al., 2016), as well as huckleberry (Vinyeta et al., 2016). Using regional climate models, Kueppers (2005) showed a	

		major reduction in the range of two species of oak in California that are used in traditional diets. Increasing frequency of severe fires in the western United States threaten a number of traditional wild food resources, especially acorns (Vinyeta et al., 2016).	
North America	Wild rice (*Zizania spp*.)	Significant reductions in wild rice area in Great lakes havebeen associated with mining, dams, and other activities but climate change may lead to further reductions (Cozzetto et al., 2013; Lynn et al., 2013)	*high confidence*
North America	Camas tuber (*Camassiaquamash*)	Historic changes in fire regimes, linked to changes in climate, are believed to have altered availability of the important Camas tuber (*Camassiaquamash*) (Lepofsky et al., 2005).	*medium confidence*
North America	Wapato tuber *(Sagittaria latifolia)*	The aquatic *Sagittaria latifolia* (the roots of which are consumed by Indigenous groups across North America) is vulnerable to both water salinity and temperature (Delesalle and Blum, 1994)	*medium confidence*
North America	Springbeauty *(Claytonia lanceolate)*	*Claytonia lanceolata* is particularly vulnerable to changes in snow melt and other climatic changes due to advancement in the flowering (Renner and Zohner, 2018).	*medium confidence*
North America	Seaweed (*Porphyraabbottiae;* among others)	In British Columbia, Canada, Gitga'at elders note that the ripening of an important edible seaweed (*Porphyraabbottiae*) rarely coincides with weather and needed to process in the traditional way (drying on rocks and then ripening and re-drying) (Turner and Clifton, 2009).	*low confidence*
Africa	Baobab (*Adansonia digitata*)	Baobab is thought to be vulnerable to climate change because it is long-lived, can take up to 23 years to start fruiting and leaf harvesting is often so intensive that it depresses fruit production. Modeling study using different records model shows the percentage of present distribution predicted to be suitable in the future ranged varied from 5% to 91% (Sanchez et al., 2011).	*low confidence*
Africa	Shea (*Vitellaria paradoxa*)	Shea (*Vitellaria paradoxa*), was expanded through human intervention and is linked to human migration; fruit traits such as fruit size and shape, pulp sweetness, and kernel fat content are determined both by temperature and rainfall, as well as human selection for preferred traits (Maranz and Wiesman, 2003). There is limited and conflicting evidence of the impacts of climatic conditions and future projected climate variations on *V. paradoxa* (Tom-Dery et al., 2018). Mixed evidence of the impact of climate and rainfall on fruit production and timing is reported (Tom-Dery et al., 2018). Fruit production was negatively correlated with mean annual temperature and positively correlated with annual rainfall (Bondé et al., 2019).	*Limited evidence, medium agreement*
North Africa (Morocco)	Argan (*Argania spinosa*)	Climate change projections suggest a 32% decrease in habitat suitable for *Argania spinosa* under some scenarios (Alba-Sánchez et al., 2015; Moukrim et al., 2019).	*medium confidence*
Asia (Nepal)	Fruit species and vegetables (e.g., *Asparagus racemosus, Urticadioica*).	In Nepal, Thapa (2015) report phenological changes in semi-domesticated fruit species, as well as decreased availability of a number of wild plants that can be consumed as vegetables.	*Limited evidence, medium agreement*
Worldwide, most important in Europe and Asia	Mushrooms	Wild mushrooms production (including truffles) is closely linked to climate factors including temperature and precipitation as well tree growth and carbohydrate production (Tahvanainen et al., 2016). Some species are sensitive to high temperatures (Büntgen et al., 2012; Le Tacon et al., 2014; Ágreda et al., 2015; Bradai et al., 2015; Taye et al., 2016; Alday et al., 2017; Karavani et al., 2018; Büntgen et al., 2019; Thomas and Buntgen, 2019). Models	*high confidence*

		for some varieties suggest "declines of 78–100% in European truffle production are likely for 2071–2100" (Thomas and Buntgen, 2019). For some species in norther Europe, the season is expanding (starting earlier and/or ending later), likely linked to warming (Büntgen et al., 2012; Le Tacon et al., 2014; Ágreda et al., 2015; Bradai et al., 2015; Taye et al., 2016; Alday et al., 2017; Karavani et al., 2018; Büntgen et al., 2019; Thomas and Buntgen, 2019). Matsutake mushroom (*Tricholoma matsutake*), highly prized in China, is sensitive to timing and amount of precipitation and temperature (Yang et al., 2012), and suitable habitat for this species is predicted to significantly decrease and highly suitable habitat would nearly disappear under various climate change scenarios (Guo et al., 2017).	
North America (California)	Acorns, nuts and berries and other fire-dependant wild foods	Low intensity traditional burning practices increased pyro-diversity (Vinyeta et al., 2016). Climate change will exacerbate the risks posed by exotic pathogens that attack oak species and further reduce access to acorns, as well as other foods founds in oak ecosystems (Voggesser et al., 2013).	*high confidence*
South America (Amazon region)	Aguaje, (*Mauritia felxuosa),* Brazilian nut (*Bertholletiaexcelsa*) fishing and hunting in general	Local communities perceived a lower yield of aguaje Hofmeijer et al. (2013) due to drought. Another study from the Colombian Amazon wild food use was reported to be vulnerable to extreme climate events which impact species migration patterns or restrict access to fishing and hunting rounds (Torres-Vitolas et al., 2019). In some humid regions the range of some wild food species may be extended by climate change, such as the Brazilian nut (*Bertholletiaexcelsa*) (Thomas et al., 2014).	
Small Islands (Papua New Guinea)	Sweet potato	Increases in the El Niño Southern Oscillation was associated with drought which increased sweet potato losses (Jacka, 2016) in highlands humid forest.	*Limited evidence, medium agreement*
Australasia (Australia)	General wild foods	Aboriginal communities in North Queensland, a humid tropical region of northern Australia reported some climate impacts on wild foods, however primarily for marine resources and those found in dry forest ecosystems (McIntyre-Tamwoy et al., 2013).	*Limited evidence, medium agreement*
Asia (Indonesia)	Sago (*Metroxylon sagu*)	People in a sago-dependent community in Papua Indonesia viewed climate variation as less important than other factors (logging, mining, infrastructure), but still expressed concerns about salinity of water supplies, floods, and reduced hunting success (Boissière et al., 2013).	*Limited evidence, medium agreement*

5.8 Ocean-based and Inland Fisheries Systems

The livelihoods of 10 to 12 percent of the world's population depend on fisheries and aquaculture (FAO, 2020c). Globally, fish provide more than 3.3 billion people with 20 % of their average per capita intake of animal proteins, reaching 50 % or more in countries such as Bangladesh, Cambodia, The Gambia, Ghana, Indonesia, Sierra Leone, Sri Lanka, and several Small Island Developing States (FAO, 2020c). Between 1961 and 2017, the average annual apparent global food fish consumption increased (3.1% per year; from 9.0 kg per person in 1961 to 20.5 kg in 2018), exceeding the rate of increase in consumption of meat from all terrestrial animals combined (2.1% annually, currently around 40 kg per person) (FAO, 2020d). Fish are a rich source of protein and specific vitamins and minerals (Khalili Tilami and Sampels, 2018), and are an essential food source in regions in need of nutritious, affordable food (Thilsted et al., 2016; FAO et al., 2018; Hicks et al., 2019; Cross-Chapter Box MOVING PLATE this Chapter).

Overall capture fishery production has remained relatively static since the 1990s, reaching 96.4 million tons in 2018, with over 87% of the production coming from marine environments and the rest from inland fisheries (FAO, 2020c). Finfish represent 85% of global marine seafood production, with small pelagic fishes (anchovies, sardines, and herrings) as the major contributor. Almost 60% of the total global marine catches come from China, Peru, Indonesia, the Russian Federation, the United States of America, India, Viet Nam, Japan, Norway, and Chile (FAO, 2020c). Inland fisheries are found on every continent other than Antarctica and provide 158 million people the equivalent of all dietary animal protein (McIntyre et al., 2016). Inland production accounted for 12 million tons in 2018, with nearly 70% of capture from low-income Asian and African countries (Harrod et al., 2018a).

The aquaculture and fisheries' share of GDP varies mostly from 0.01 to 10 percent (Cai et al., 2019), but the relative importance in countries' economies and welfare is greater in several low-income countries, especially in many African and Pacific Island states. Approximately 60 million people are directly employed along in fisheries value chains, from harvesting to distribution (Vannuccini et al., 2018), around 95% of those are in small-scale fisheries of low and middle-income countries, and almost half of them are women.

5.8.1 Observed Impacts

Ocean systems are already facing significant impacts of climate change. At the ocean surface, temperature has on average increased by 0.88 [0.68–1.01] °C from 1850–1900 to 2011–2020 (Fox-Kemper et al., 2021; Gulev et al., 2021). Marine heatwaves have increased in frequency over the 20th century, with an approximate doubling since the 1980s (*high confidence*), and their intensity and duration have also increased (*medium confidence*) (IPCC, 2021, Box 9.2). In the Northeast Pacific, for example, an intense and long-lasting marine heatwave during 2013 to 2015 bridged to the strong 2015-2016 El Niño (Tseng et al., 2017) resulted in over five years of warmer-than-normal temperatures affecting the migration, distribution and abundance of several marine species, including fisheries resources (Cornwall, 2019; Jiménez-Quiroz et al., 2019). The surface open ocean pH has declined globally over the last 40 years by 0.003–0.026 pH per decade (*virtually certain*), and a decline in the ocean interior pH has been observed in all ocean basins over the past 2–3 decades (*high confidence*) (Gulev et al., 2021). The ocean is losing dissolved oxygen (*very likely*) in the range of 0.5–3.3% between 1970 and 2010 for the 0–1000 m depth stratum (Bindoff et al., 2019; Canadell et al., 2021), salt content is being redistributed (*very likely*) (Liu et al., 2019a; Gulev et al., 2021), and vertical stratification is increasing (*virtually certain*) (HLPE, 2017a; Fox-Kemper et al., 2021; Ranasinghe et al., 2021). There is *high confidence* that all these new physical, chemical, and biological conditions affect marine organisms' physiology, distribution, and ecology, with an overall shift in biomass and species composition affecting ecosystem structure and function (Chapter 3). Under climate change, freshwater ecosystems are highly exposed to eutrophication, species invasion, and rising temperatures (Lynch et al., 2016; Hassan et al., 2020). Major threats to wetland fisheries include water stress, sedimentation, weed proliferation, sea-level rise, and loss of wetland connectivity (Naskar et al., 2018).

Changes in aquatic ecosystems directly affect humans by altering livelihood, cultural identity and sense of self, and seafood provision, quality, and safety. The state of marine fishery resources has continued to decline, with the proportion of fish stocks at biologically unsustainable levels of exploitation increasing from 10 percent in 1974 to 34.2 percent in 2017 (FAO, 2020d). There is *medium confidence* that fisheries production declines in different world regions can be partly attributed to climate change, along with overfishing and other socio-economic factors. It has been estimated that, from 1930 to 2010, the amount of fish that can be sustainably harvested from several marine fish populations has decreased by 4.1% globally due to ocean warming, with some regions (East Asian Marginal Seas, the North Sea, the Iberian Coast, and the Celtic-Biscay Shelf), experiencing losses of 15-35% (Free et al., 2019). There is regional variation such as redistribution of fishing grounds, due to climate-induced fish species migrations (Cross-Chapter Box MOVING PLATE this Chapter). In Tanzania, for example, most small-scale fishers (75 %) have reported shifting fishing grounds from nearshore to offshore areas during the last decade, due to perceived combined effects of overfishing and environmental impacts (Silas et al., 2020). Observed impacts in some inland aquatic systems indicate substantial productivity reductions (*medium confidence*). For example, sustained warming in Lake Tanganyika during the last ~150 years has affected the biological productivity by strengthening and shallowing stratification of the water column (Cohen et al., 2016). Still, over 60% of the published reports on directly observed impacts of climate change on freshwater biota are on salmonids in

North America and Europe, highlighting significant literature gaps for other fish species and regions (Myers et al., 2017a).

There is *low confidence* in climate change affecting the nutritious value of seafood. Contrasting evidence suggests that ocean warming and acidification could be altering the nutritional quality of commercial mollusks, primarily by reducing healthy fatty acids content (Tate et al., 2017; Ab Lah et al., 2018; Lemasson et al., 2019); but Coleman (2019) found no significant changes in a widely distributed coastal fish species.

In terms of food safety, there is *high confidence* that climate change increases the trends in seafood consumption related illnesses due to biological agents such as algae-produced toxins, Ciguatera, and *Vibrio* (Cross-Chapter Box ILLNESS in Chapter 2, Sections 5.11 and 5.12). Increased surface water warming changes the occurrence, intensity, species composition, and toxicity of marine and freshwater algae and bacteria, and expansion to areas where they had not been reported before (Botana, 2016; McCabe et al., 2016; Griffith et al., 2019). There is *limited evidence* suggesting that risks linked to the bioaccumulation of chemicals are also of concern, such as neurotoxic methilmercury (MeHg) and heavy metals, due to water quality and trophic changes induced by climate change (Shi et al., 2016; Schartup et al., 2019).

5.8.2 Assessing Vulnerabilities

In the absence of adaptive measures, climate-induced changes in the abundances and distributions of fish will impact the provision, nutrition, livelihood security of many people (*high confidence*) as well as regional and global trade patterns (*medium confidence*).

5.8.2.1 Food security: provision and nutrition

The importance of seafood in food security and nutrition is increasing, largely due to its contribution as high-quality food (*high confidence*) (Hicks et al., 2019), as seafood contains unique long-chain polyunsaturated fatty acids (LC-PUFAs) and highly bioavailable essential micronutrients—vitamins (A, B and D) and minerals (calcium, phosphorus, iodine, zinc, iron, and selenium). These compounds, often not readily available elsewhere in diets, have beneficial effects for adult health and child cognitive development (HLPE, 2014). Changes in marine and freshwater fish production can have significant consequences for human nutrition (Colombo et al., 2020). These changes are of particular concern in regions with few nutrition alternatives, such as low-income countries in Africa, Asia, Australasia, and Central and South America (*high confidence*) (Ding et al., 2017; Kibria et al., 2017).

Freshwater ecosystems that support most inland fisheries are under continuing threat from changes in land use, water availability and pollution and other pressures that will be exacerbated by climate change (*high confidence*) (Section 4.3.5). Declines in dissolved oxygen in freshwater are 2.75 to 9.3 times greater than observed in the world's oceans (Jane et al., 2021). These systems have a relatively low buffering capacity and are therefore more sensitive to climate-related shocks and variability (Harrod et al., 2018b). Freshwater faunae are projected to be highly vulnerable; in the tropics because organisms are closer to approaching their thermal physiological limits and in the northern hemisphere (30-50°N) because the rate of temperature change is faster (Comte and Olden, 2017). The worldwide spatial confluence of productive freshwater fisheries and low food security highlights the critical role of rivers and lakes in providing locally sourced, low-cost, nutritious food sources (McIntyre et al., 2016).

Deltas and other wetland fisheries are extremely vulnerable to climate change and home to a large and growing proportion of the world's population. In India, Ghana, and Bangladesh, where three of the most populated Deltaic systems are located, subsistence fisheries provide 12 to 60% of the animal protein in people´s diets (Lauria et al., 2018).

The concern over aquatic food products' safety due to climate change is increasing (*high confidence*). A strong positive relationship exists between specific bacterial growth rates and temperature, including pathogenic species of the genus *Vibrio, Listeria, Clostridium, Aeromonas, Salmonella, Escherichia,* and others, whose distributional area is expanding with changing climate conditions (Cross-Chapter Box ILLNESS in Chapter 2, Section 5.12.1).

5.8.2.2 Social vulnerabilities, including gender and marginalized groups and cultural services

There is *high confidence* that climate change is and will continue to be a threat to the livelihood of millions of fishers, with the most vulnerable being those with fewer opportunities and less income (Barange and Cochrane, 2018); Section 3.4.3. The social vulnerability can differ largely between locations, even between relatively close coastal or inland communities (Bennett et al., 2014; Maina et al., 2016; Ndhlovu et al., 2017; Martins et al., 2019) and among inhabitants within a location, depending on factors such as access to other economic activities, education, health, adults in the household, and political connections (*high confidence*) (Senapati and Gupta, 2017; Abu Samah et al., 2019; Lowe et al., 2019).

Indigenous coastal communities consume 1.5 million to 2.8 million metric tonnes of fish per year (about 2% of global yearly commercial marine catch), and reach a per capita consumption estimated to be 15 times greater than that of non-Indigenous country populations (Cisneros-Montemayor et al., 2016). There is *high confidence* that some Indigenous fishing communities are particularly vulnerable to climate change through a reduced capacity to conduct traditional harvests because of limited access to, or availability of, fish resources (Weatherdon et al., 2016), with consequences that include dietary shifts with significant nutritional and health implications (Marushka et al., 2019), displacement and loss of cultural identity (Sullivan and Rosenberg, 2018) and loss of social, economic, and cultural rights (Finkbeiner et al., 2018). Areas of high risk for Indigenous Peoples include the Arctic, coastal communities with a high dependency on marine and freshwater fisheries, and small island states and territories (Finkbeiner et al., 2018; Hanich et al., 2018, CCP6.2.5.1).

Women play a crucial role along the entire fisheries value chain, providing labour force in industrialized and small-scale fisheries all around the world (FAO, 2020d). For small-scale fisheries alone, women represent about 11% of the labour force, and their activity is generally in subsistence fisheries, highlighting their role in household food security (Harper et al., 2020). In general, gendered division of labour tend to cause lower salaries for women and different perception and experience of risk to climate change impacts (*high confidence*) (Lokuge and Hilhorst, 2017).

5.8.2.3 Management, economic and geopolitical vulnerabilities

Local, national, regional, and international fisheries are mostly underprepared for geographic shifts in marine animals driven by climate change over the coming decades (*high confidence*) (Pinsky et al., 2018; Oremus et al., 2020; Pinsky et al., 2020). With fisheries distribution changes, sometimes into areas dedicated to different historical uses or new ventures, the current management regimes will face constraining legal frameworks (Farady and Bigford, 2019; Pinsky et al., 2020), which will demand interventions in the form of policies, programs, and actions, at multiple scales.(Cross-Chapter Box MOVING PLATE this Chapter). Coordinated fisheries management can substantially expand capacity to respond to a changing climate (Pinsky et al., 2020), but a great deal of political will, capacity building, and collective action will be necessary (*high confidence*) (Teslic´ et al., 2017; Burden and Fujita, 2019; Section 5.8.4).

Today, approximately half the world's population (~4 billion out of 7.8 billion people) are assessed as being currently subject to severe water scarcity for at least one month per year (*medium confidence*) (Box 4.1), and freshwater inland fisheries are particularly vulnerable as they are given lower priority for water resources than other sectors (*high confidence*). In some cases, this situation results in the total loss of freshwater fisheries. Examples include diversion of water for agriculture, shifts from food provision to recreational fisheries, conserving biodiversity, and the requirement for high-quality water for drinking water supply (Section 5.13, Harrod et al., 2018a).

There is *high confidence* that climate change increases the risk of conflicts due to the redistribution of stocks and their abundance fluctuations, with subsequent impacts on resource sharing (Spijkers and Boonstra, 2017; Pinsky et al., 2018; Spijkers et al., 2018; Mendenhall et al., 2020; Pinsky et al., 2020). High vulnerability and lack of adaptive capacity to climate change impacts (including fisheries-dependent livelihoods, attachment to place, and pre-existing tensions) increase the risk of conflicts, including among fishery area users and authorities (Ndhlovu et al., 2017; Shaffril et al., 2017; Spijkers and Boonstra, 2017; Mendenhall et al., 2020). Similarly, shifts in the distribution of transboundary fish stocks under climate change alter the current sharing of resources between countries and create conflicts as well as new opportunities (Cross-Chapter Box MOVING PLATE this Chapter, Spijkers and Boonstra, 2017; Pinsky et al., 2018).

5.8.3 Projected Impacts

There is *medium confidence* that climate change will reduce global fisheries' productivity (Section 3.4.4.2.3), with more significant reductions in tropical and sub-tropical regions and gains in the poleward areas (Bindoff et al., 2019; Oremus et al., 2020). Through an ensemble of marine ecosystem models and earth system models, mean global animal biomass in the ocean has been estimated to decrease by 5% under the Representative Concentration Pathway (RCP)2.6 emissions scenario and 17% under RCP8.5 by 2100, with an average decline of 5% for every 1°C of warming (Lotze et al., 2019), affecting food provision, revenue distribution, and potentially hindering the rebuilding of depleted fish stocks (Britten et al., 2017). The projected declining rates result in a 5.3-7% estimated global decrease in marine fish catch potential by 2050 (Cheung et al., 2019), particularly accentuated in tropical marine ecosystems and affecting many low-income countries (Barange and Cochrane, 2018; Bindoff et al., 2019; Cross-Chapter Box MOVING PLATE this Chapter). Projections indicate that by 2060 the number of exclusive economic zones (EEZ) with new transboundary stocks will increase to 46 under strong mitigation RCP2.6, and up to 60 EEZs under the RCP8.5 greenhouse gas emissions scenario (Pinsky et al., 2018). Similarly, by combining six intercompared marine ecosystem models, (Bryndum-Buchholz et al., 2019) projected that under the RCP8.5 scenario a total marine animal biomass decline of 15%–30% would occur in the North and South Atlantic and Pacific, and the Indian Ocean by 2100. In contrast, polar ocean basins would experience a 20%–80% increase. In the eastern Bering Sea, simulations based on RCP8.5 predict declines of pollock (>70%) and cod (>35%) stocks by the end of the century (Holsman et al., 2020). Temperate tunas (albacore, Atlantic bluefin, and southern bluefin) and the tropical bigeye tuna are expected to decline in the tropics and shift poleward by the end of the century under RCP8.5, while skipjack and yellowfin tunas are projected to increase abundance in tropical areas of the eastern Pacific but decrease in the equatorial western Pacific (*medium confidence*) (Erauskin-Extramiana et al., 2019). In the western and central Pacific, redistribution of tropical tuna due to climate change is projected to affect license revenues from purse seine fishing and shift more fishing into high seas areas (Bell et al., 2018a; Table 15.5). For the east Atlantic, observational evidence indicates that not only will tuna distribution change with temperature anomalies, but also fishing effort distribution (Rubio et al., 2020a). There is *medium confidence* that climate change will create new fishing opportunities when exploited fish stocks shift their distribution into new fishing regions in enclosed seas, such as the Mediterranean and the Black Sea (Hidalgo et al., 2018; Pinsky et al., 2018). However, in general, where land barriers constrain the latitudinal shifts, the expected impacts of climate change are population declines and reduced productivity (*high confidence*) (Oxenford and Monnereau, 2018). Besides direct impacts on the abundance of fisheries-targeted species, climate-change-induced proliferation of invasive species could also affect fishery's productivity (*low confidence*) (Mellin et al., 2016; Goldsmith et al., 2019).

Shifting marine fisheries will affect national economies (*high confidence*) (Bindoff et al., 2019). It has been suggested that without government subsides, fishing is already non-profitable in 54% of the international waters (Sala et al., 2018). Projections are that Fishing Maximum revenue potential from landed catches will decrease further by 10.4% (±4.2%) by 2050 relative to 2000 under RCP8.5, close to 35% greater than the decrease projected for the global maximum catch potential (7.7% ±4.4%); (Lam et al., 2016). The global revenue potential loss for that period ranges from USD 6-15 billion (depending on the model), but impacts may be amplified at the regional scale for fisheries-dependent and low-income countries. The maximum revenue potential percentage decrease in the EEZ under RCP8.5 is estimated to be over 2.3 times larger than that of the high seas (Lam et al., 2016). Ocean acidification is also expected to drive large global economic impacts (*medium confidence*) (Cooley et al., 2015; Fernandes et al., 2017; Macko et al., 2017; Hansel et al., 2020), and there is *high confidence* that the integrated economic consequences of all interacting climate change-related factors would result in even larger losses. Changes in the frequency and intensity of extreme events will also alter marine ecosystems and productivity. Marine heatwaves can lead to severe and persistent impacts, from mass mortality of benthic communities to decline in fisheries catch (IPCC, 2021, Box 9.2). These events have *very likely* doubled in frequency between 1982 and 2016 and have also become more intense and longer (Smale et al., 2019; Laufkotter et al., 2020); for all future scenarios Earth System Models project even more frequent, intense, and longer-lasting marine heatwaves (Eyring et al., 2021; IPCC, 2021, Box9.2).

In addition to temperature and water availability stress, climate change will bring new water quality challenges in freshwater systems, including increased dissolved organic carbon and toxic metal loads (*high confidence*) (Chen et al., 2016). Harrod et al. (2018a) found that the two major inland fishery producers (China and India) will face significant stress in the future, a large group of countries that produce around 60 percent of total yield is projected to face medium stress, and a small group of 17 countries has the least severe repercussions (*medium confidence*). Climate warming may enhance northward colonization of water bodies of commercial freshwater species in the Arctic, where there are few ecological competitors (*medium confidence*) (Campana et al., 2020), but at the same time may also accentuate the age-truncation effect of harvesting, elevating the population's vulnerability to environmental perturbations (Smalås et al., 2019). Detailed information on many of the most important inland fisheries is limited.

In terms of food safety, major concerns linked to climate change include the continued trend of increasing Harmful Algal Blooms (HABs), and the quantity of pollutants reaching aquatic systems (Box 3.3; section 5.11).

5.8.4 Adaptation

Adaptation options in land and aquatic-based culturing food production systems include both governance actions and changes in the factors of production (Section 5.4.4, 5.5.4, Reverter et al., 2020). In contrast, adaptation options in fisheries are primarily concentrated in the socio-economic dimension, especially governance and management (Brander et al., 2018; Holsman et al., 2019), and given the scale of the problem, there are relatively few intentional, well-documented examples of implemented tactical responses (Bell et al., 2020).

The proportion of fisheries operating at levels that are considered biologically unsustainable by the FAO has increased from 10% in 1974 to 34.2% in 2017 (FAO, 2020d). There is *high confidence* that reducing stresses on marine ecosystems reduces vulnerability to climate change and augments resilience (Barange, 2019; Woodworth-Jefcoats et al., 2019; Ogier et al., 2020). Specifically, overfishing is the most critical non-climatic driver affecting the sustainability of fisheries, and therefore improving management could help rebuild fish stocks, reduce ecosystem impacts, and increase the adaptive capacity of fishing (*high confidence*); (Barange, 2019; Das et al., 2020). Pursuing sustainable fisheries practices under a low emissions scenario would decrease risk by 63%; in contrast, under the most extreme RCP 8.5, both profit and harvest decline relative to today even under the most optimistic assumptions about global fisheries management reforms (Gaines et al., 2018; Sumaila et al., 2019; Free et al., 2020).

One adaptation strategy in the fishing sector is developing the capacity to recognize and respond to new opportunities that might arise from climate change by establishing a policy and planning setting that augments the fishers' flexibility to change target species of fisheries or even engage in different productive activities. A key element would be the design and implementation of management schemes that consider flexible permits, sharing quotas, rethinking boundaries, and reference points in response to system changes (Brander et al., 2018; Cross-Chapter Box MOVING PLATE this Chapter). Large-scale distribution and productivity changes of commercial fish species will demand the ability to implement cooperative fishing strategies (Cisneros-Montemayor et al., 2020; Østhagen et al., 2020), and adjust multi-lateral treaties and other legal instruments used for managing shared transboundary ecosystems (Butler et al., 2019; Cross-Chapter Box MOVING PLATE this Chapter).

There is *high confidence* that making climate change and adaptive capacity a mainstream consideration in global, regional, environmental, and fisheries governance structures can improve the response capacity to ocean change (Gaines et al., 2018; Bindoff et al., 2019; Holsman et al., 2020; Ojea et al., 2020). For example, spatial management that includes strategies such as Territorial Use Rights for Fishing (TURFs), Locally Managed Marine Areas (LMMAs) and customary tenure is an approach that has climate change adaptation potential in small-scale fisheries but will require adjustments in governing and managing institutions that allow them to be more dynamic and flexible (Le Cornu et al., 2018). In regions where some of these measures have already been tested, institutional, legal, financial, and logistical barriers to successful adaptation have been encountered, such as market failures stemming from uncertainty around new or emerging species, or policy barriers derived from the fact that the creation of scientific information needed to change regulations is likely slower than the pace of changes in stocks (Peck and Pinnegar, 2018).

Adaptation capacity is limited by the financial capacity of some countries (Bindoff et al., 2019). For example, in West African fisheries, adaptation costs associated with replacing the loss of coastal ecosystems and productivity is estimated to require 5–10% of countries' Gross Domestic Product (Zougmoré et al., 2016). For Pacific Islands and Coastal Territories, fisheries adaptation will require significant investment from local governments and the private sector (Rosegrant et al., 2016), and reducing dependence on or finding alternatives to vulnerable marine resources (Johnson et al., 2020; Mabe and Asase, 2020).

Adaptive capacity is strongly associated with social capital (i.e., the networks, shared norms, values, and understandings that facilitate co-operation within or among groups) (*high confidence*) (Stoeckl et al., 2017; D'agata et al., 2020) and depends on to what extent are stakeholders aware of climate change and their perception of risk (Ankrah, 2018; Martins and Gasalla, 2018; Chen, 2020). Improving information flows allows for a more efficient co-management implementation (*medium confidence*) (Vasconcelos et al., 2020). Utilization of local and Indigenous knowledge has the potential to facilitate adaptation (Bindoff et al., 2019), not only because it represents actual experiences and autonomous adaptations, but also because it facilitates reaching shared understanding among stakeholders and adoption of solutions. Challenges to hybridizing local ecological knowledge and scientific knowledge include differences in stakeholder or governance perceptions about the validity of each knowledge set and issues of expertise and trust (Harrison et al., 2018). Engaging Indigenous Peoples and local communities as partners across climate research ensures this knowledge is utilized, enhancing the usefulness of assessments (Bindoff et al., 2019) and facilitating the co-construction and implementation of sustainable solutions (*medium confidence*); (Braga et al., 2020; Bulengela et al., 2020). Building climate resilience in the fishing sector also involves recognizing gender and other social inequities (Call and Sellers, 2019), and ensure that all stakeholders are equally involved in the adaptation plans, including their design and the capacity-building training programs.

There is *high confidence* that for the freshwater fisheries systems, the most immediate adaptation option is the effective linkage of fisheries management to the adaptation plans of other sectors, especially water management (hydropower, irrigation, and the commitment to maintaining environmental flows) (Harrod et al., 2018a; Kao et al., 2020). In some regions, organizations are already addressing this issue, for example The Office of Water (OW) in the USA is aimed at ensuring that drinking water is safe while ecosystem is conserved to provide healthy habitat for fish, plants and wildlife; however, success strongly depends on the possibility of integrating the jurisdictional framework of different agencies (Poesch et al., 2016), the implementation of effective monitoring programs (Paukert et al., 2016), and finding ways to incentivize the early restoration of degraded systems (Ranjan, 2020).

[START CROSS-CHAPTER BOX MOVING PLATE HERE]

Cross-Chapter Box: MOVING PLATE: Sourcing food when species distributions change

Authors: H. Gurney-Smith (Canada/United Kingdom), W. Cheung (Canada), S. Lluch Cota (Mexico), E. Ojea (Spain),C. Parmesan (France/United Kingdom/USA), J. Pinnegar (United Kingdom) P. Thornton (Kenya/United Kingdom), M-F. Racault (United Kingdom/France), G. Pecl (Australia), E.A. Nyboer (Canada), K. Holsman (USA), K. Miller (USA), J. Birkmann (Germany), G. Nelson (USA) and C. Möllmann (Germany)

This Cross-Chapter Box the 'moving plate' addresses climate-induced shifts and domesticated production suitability of food species consumed by people. Marine, freshwater, and terrestrial systems are already experiencing species shifts in response to climate change (*very high confidence*) (see also Sections 2.4.2.1.and 3.4.3., Figure Cross-Chapter Box MOVING PLATE.1), with subsequent impacts on food provisioning services, pests, and diseases (*high confidence*) (see Box 5.8 and Cross-Chapter Box ILLNESS in Chapter 2). This Box highlights food insecurity and malnutrition of vulnerable peoples under climate change for both wild and domesticated aquatic and terrestrial species, discusses challenges for adaptation, and the roles that management (transboundary and ecosystem-based) can play to enable food security, reduce conflicts, and prevent resource over-extraction.

Range contractions, shifts or extirpations are projected for terrestrial and aquatic species under warming with greater warming leading to larger shifts and losses, where mitigation would therefore benefit climate refugia and reduce projected biodiversity declines (Smith et al., 2018; Warren et al., 2018). Marine species are moving poleward faster than terrestrial and freshwater species, despite faster warming on land (Pecl et al., 2017; Lenoir et al., 2019; Woolway and Maberly, 2020), leading to new or exacerbated socio-economic conflicts within and between countries (see Figure Cross-Chapter Box MOVING PLATE.1, see Sections 13.5.2.2., 15.3.4.4., FAQ 15.3., Mendenhall et al., 2020). There is large variation in the magnitude and pattern of species shifts, even among similar species within a region, leading to changes in communities in a given region (Brown et al., 2016; Pecl et al., 2017). The number of extreme heat stress days are projected to increase for domesticated species like cattle (see Figure Cross-Chapter Box MOVING PLATE.1), leading to shifts in suitable habitat for raising livestock in the open with associated impacts in animal productivity and the costs of adapting in Africa, Asia, Central and South America (Thornton et al., 2021).

Nutritional dependency, cultural importance, livelihood, or economic reliance on shifting species will increase impacts of climate change, especially for small scale fishers (marine and freshwater), farmers, women, and communities highly dependent on local sources of food and nutrition (*high confidence*) (see Figures Cross-Chapter Box MOVING PLATE.1 and 3, Sections 3.5.3., 8.2.1.2. and 15.3.4.4, McIntyre et al., 2016; Blasiak et al., 2017; Kifani et al., 2018; Bindoff et al., 2019; Atindana et al., 2020; Hasselberg et al., 2020; Farmery et al., 2021). Micronutrient concentrations from marine fisheries vary with species, providing higher concentrations of calcium, iron and zinc in tropical regions and higher concentrations of omega-3 fatty acids in polar regions (Hicks et al., 2019). While consumption of smaller species rich in micronutrients may provide significant benefits against deficiencies in Asia and Africa, local dietary changes in fish consumption may be linked to food preferences, fish availability due to international trade or illegal fishing and competing usage of fish (see Figure Cross-Chapter Box MOVING PLATE.3, Hicks et al., 2019; Sumaila et al., 2020; Vianna et al., 2020). Industrial fleets are likely to switch target species (Belhabib et al., 2016) and inhibit small-scale fishers via illegal, unreported, or unregulated fishing in Exclusive Economic Zones (Belhabib et al., 2019; Belhabib et al., 2020). Extreme events can exacerbate issues, as fisheries are frequently increasingly exploited as a coping mechanism under times of crisis, increasing illegal fishing activities and conflict amongst maritime users (Pomeroy et al., 2016; Mazaris and Germond, 2018). Spatial conflicts between artisanal and commercial foreign fishing fleets are already occurring in Ghana (Penney et al., 2017), and from climate-induced tropical tuna shifts in the Western and Central Pacific Ocean Islands (see Section 15.3.4.4., (Bell et al., 2018a)). Properly managed small-scale fisheries can reduce poverty and improve localized food security and nutrition in low-incom countries but will likely require restriction in the number of fishers, boat size or fishing days (Purcell and Pomeroy, 2015; Hicks et al., 2019).

Shifting species have negative implications for the equitable distribution of food provisioning services, increasing the complexity of resolving sovereignty claims and climate justice (*high confidence*) (Allison and Bassett, 2015; Ayers et al., 2018; Baudron et al.; Ojea et al., 2020; Palacios-Abrantes et al., 2020). Higher latitude countries generally have higher GHG emissions and will benefit from poleward migrating resources from tropical poorer and lower-emitting GHG countries (Free et al., 2020). In this context, climate justice supporting fishing arrangements could offset socio-economic impacts from exiting species (Mills, 2018; Lam et al., 2020) and have negative implications particularly for small-scale operators (Farmery et al., 2021), However, considerations of climate justice have not been used by Regional Fisheries Management Organizations (RFMOs) allocation shares to date (Engler, 2020). Species shifting from one historical jurisdiction to another may result in an incentivized depletion of the resource by the country the stock is shifting away from; reforming management to allocate resource sharing of quotas and permits, or stock-unrelated side payments in bilateral or multilateral cooperative agreements may compensate or prevent loss (Diekert and Nieminen, 2017; Free et al., 2020; Ojea et al., 2020; Østhagen et al., 2020; Cross-Chapter Paper Polar 6.2.).

Strong governance, ecosystem-based and transboundary management are considered fundamental to ameliorate the impacts of climate change (*high confidence*) but may be limited in effectiveness by the magnitude of change projected under low or no mitigation scenarios (see Sections 2.6.2., 14.4.2.2. and 15.3.4.4., Harrod et al., 2018c; Pinsky et al., 2018; Holsman et al., 2020; Ojea et al., 2020). Flexible and rapid policy reform and management adaptation will help to meet sustainability targets (Nguyen et al., 2016; Pentz and Klenk, 2020), and may only be available for countries with the scientific, technical, and institutional capacity to implement these (*high confidence*) (Peck and Pinnegar, 2018; Figures Cross-Chapter

Box MOVING PLATE.2 and 3). Other adaptation options include 'follow the food' thereby migrating further (Belhabib et al., 2016), provision of alternative livelihoods (Thiault et al., 2019; Cross-Chapter Box MIGRATE in Chapter 7, Free et al., 2020), increasing ecosystem resilience by rebuilding coastal mangroves (Tanner et al., 2014; and Box 1.3) and riparian areas of freshwater ecosystems (Mantyka-Pringle et al., 2016) and autonomous adaptations, such as harvesting gear modifications to access new target species (Harrod et al., 2018c; Kifani et al., 2018), practice change, and early-warning systems (see Section 11.3.2.3; Pecl et al., 2019; Melbourne-Thomas et al., 2021). Adaptive capacity will change with country, region, scale (commercial, recreational, Indigenous) of fishery, jurisdiction and resource dependence (see Figure Cross-Chapter Box MOVING PLATE.2 for adaptation options for marine, freshwater, and terrestrial systems). Whilst shifting fishing fleets or herding may be an adaptation option to follow resources, limits to feasibility include institutional, legal, financial, and logistical barriers such as costs of sourcing food and operational economic viability (Belhabib et al., 2016); this could potentially lead to maladaptation through increased greenhouse gas emissions from fuel usage and cultural displacement from traditional fishing and herding lands. Overall, decreases in greenhouse gas emissions under future scenarios would reduce increases in global temperatures and limit species shifts, thereby lowering the likelihood of conflicts and food insecurity (*high confidence*).

Coastal regions of the Gulf of Guinea: Ghanian fisheries

Marine fisheries in Ghana are dominated by artisanal fishers with overfished stocks, high nutritional fish dependency, high illegal fishing, low governance capacity (-0.21 2018, (World Bank, 2019)) and low climate awareness in regional fisheries management (Figure Cross-Chapter Box MOVING PLATE.3, see Chapter 9; Nunoo et al., 2014; Belhabib et al., 2015; Belhabib et al., 2016; Kifani et al., 2018; Belhabib et al., 2019). Artisanal fishing plays a pivotal role in reducing poverty and food insecurity, and the impacts of climate change will risk developing poverty traps (see Section 8.4.5.6., (Kifani et al., 2018)). Climate change induced species redistribution is a large risk to Ghanian fisheries, with projections of over 20 commercial fish species exiting the region with no new species entering under RCP4.5 by 2100 (Oremus et al., 2020), and has already seen increases in warmer-water species with declining stocks. Adaptation options being applied are extending fishing ranges increasing fishing effort (and cost) to access declining fish (with government fuel incentives) (Kifani et al., 2018; Muringai et al., 2021), developing aquaculture for alternative livelihoods, implementation of fleet monitoring to reduce illegal fishing and developing a robust Fisheries Information and Management System that accounts for environmental and climate drivers (Johnson et al., 2014; FAO, 2016; Kassi et al., 2018). However, fisheries remain insufficiently regulated, there is a lack of a skilled workforce, and there is low access to credit; collectively these factors limit options for artisanal fishers to find alternative sustainable employment (FAO, 2016).

Shifting distributions of freshwater fishery resources: knowledge gaps

Freshwater fisheries provide the primary source of animal protein and essential micronutrients for an estimated 200 million people globally and are especially important in tropical developing nations (see Section 9.8, Lynch et al., 2017; Funge-Smith and Bennett, 2019.). There is evidence that freshwater fishes have undergone climate-induced distribution shifts (Comte and Grenouillet, 2015; see Section 9.8.5.1.), and further shifts are projected as water temperatures rise and hydrological regimes change, with the largest effects predicted for equatorial, subtropical, and semi-arid regions (Barbarossa et al., 2021). Currently, the effects of distribution shifts on local fishery catch potential, food security, and/or nutrition have not been quantified for any major inland fishery, representing a key knowledge gap for anticipating future adaptation needs for freshwater fishing societies. However, studies on fishers' perceptions of climate-induced changes in fishery catch rates have revealed that using local knowledge to adjust management practices (see Chapter 12 Central and South America this volume; Oviedo et al., 2016) and shifting gears, fishing grounds and target species (see Section 9.8.5.3.; Musinguzi et al., 2016) can be effective adaptation options.

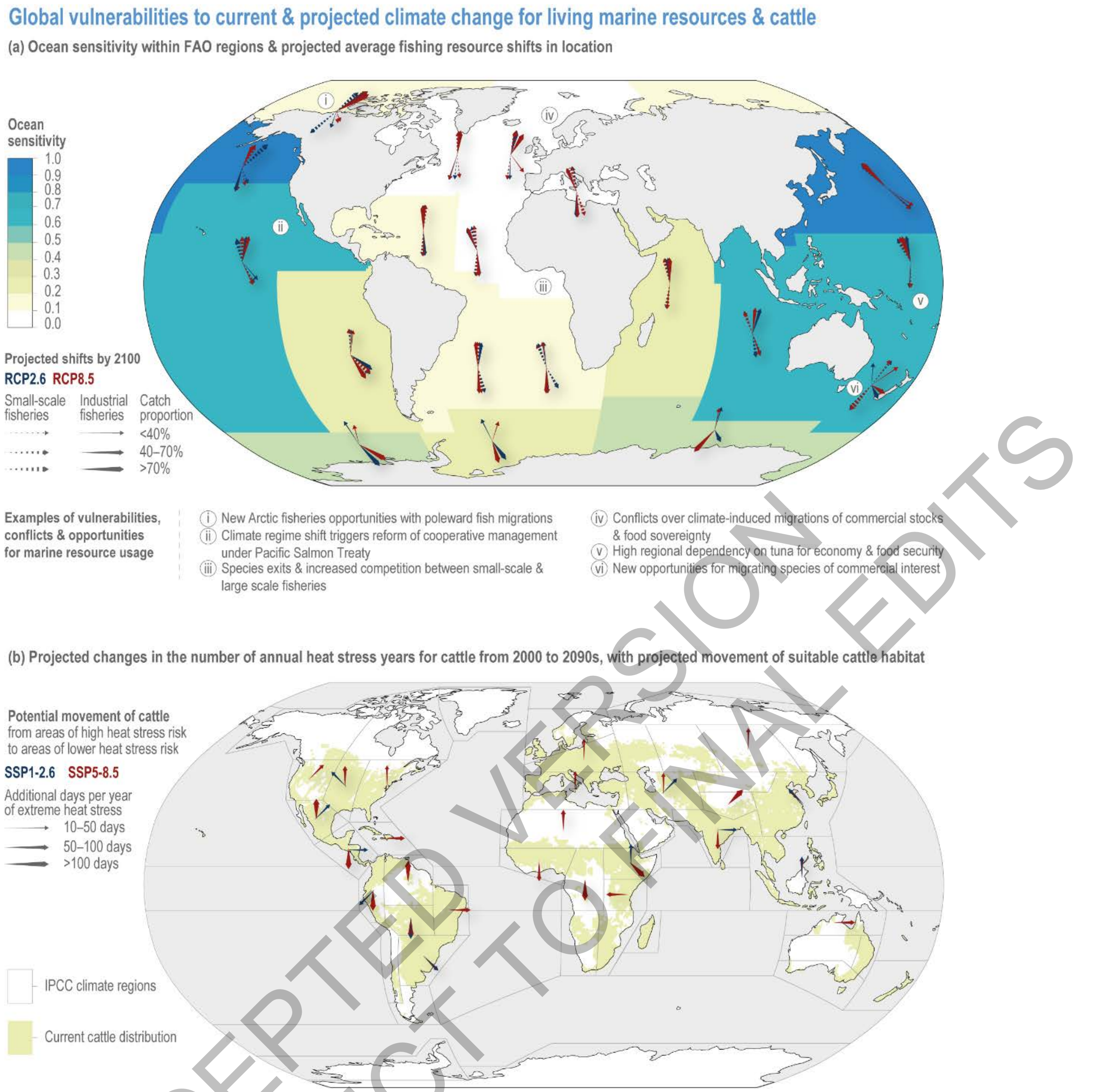


Figure Cross-Chapter Box MOVING PLATE.1: Global vulnerabilities to current and projected climate change for living marine resources and cattle. **a** - Ocean areas are delineated into FAO (Food and Agricultural Organization of the United Nations) regions. Ocean sensitivity is calculated from aggregated sensitivities from Blasiak et al. (2017) S1 country data based on number of fishers, fisheries exports, proportions of economically active population working as fishers, total fisheries landings and nutritional dependence, which was subsequently reanalyzed for each FAO region depicted here. Arrows denote projected average commercial (light blue) and artisanal (orange arrows) fishing resource shifts in location under RCP2.6 and under RCP8.5 (dark blue and red arrows respectively) scenarios by 2100. Text boxes highlight examples of vulnerabilities (Bell et al., 2018a), conflicts (Miller et al., 2013; Blasiak et al., 2017; Østhagen et al., 2020), or opportunities for marine resource usage (Robinson et al., 2015; Stuart-Smith et al., 2018; Meredith et al., 2019). **b** – Projected changes in the number of extreme heat stress days per year for cattle (*Bos taurus*, temperate sub-regions, grey background; *Bos indicus*, tropical sub-regions, orange background) from 2000 to the 2090s, shown as arrows rooted in the most affected area in each IPCC sub-region pointing to the nearest area of reduced or no extreme heat stress.. Arrows are shown only for sub-regions where > 1 million additional animals affected. Areas in green are those with >5000 animals per 0.5 degree grid cell (Thornton et al., 2021).

Terrestrial species shifts

There is *robust evidence* of shifts that terrestrial species have shifted poleward in high latitudes, with general declines of sea-ice dependent as well as some extreme-polar-adapted species (*high confidence*) (Arctic and Siberian Tundra, see Section 2.4.2.2., Cross-Chapter Paper 6), with often deleterious effects on the food security and traditional knowledge systems of Indigenous societies (Horstkotte et al., 2017; Pecl et al., 2017; Mallory and Boyce, 2018; Forbes et al., 2020). Recent decades have seen declines in Arctic reindeer and caribou (see Section 2.5.1., Cross-Chapter Paper 6) and adaptation responses include utilization of Indigenous knowledge with scientific sampling to maintain traditional management practices (Pecl et al., 2017; Barber et al.; Forbes et al., 2020). Preserving herder livelihoods will necessitate novel solutions (supplementary feeding, seasonal movements), where governance, ecological and socio-economic trade-offs will be balanced at the local level (Horstkotte et al., 2017; Pecl et al., 2017; Mallory and Boyce, 2018; Forbes et al., 2020). Wild meat consumption plays a critical, though not well understood, role in the diets and food security of several hundred million people (*medium evidence*), for example in lower latitudes such as central Africa and the Amazon basin (Bharucha and Pretty, 2010; Godfray et al., 2010; Nasi et al., 2011; Friant et al., 2020). Although illegal in many countries, wild meat hunting occurs either in places where there is no or limited domesticated livestock production, or in places where shock events such as droughts and floods that threaten food supply, forcing increased reliance on wild foods including bush meat (Mosberg and Eriksen, 2015; Bodmer et al., 2018). Appropriate management of wild meat for reliant peoples under projected climate change will necessitate incorporating social justice elements into conservation and public health strategies (see Cross-Chapter Box ILLNESS in Chapter 2, Cross-Chapter Box COVID in Chapter 7, Friant et al., 2020; Ingram, 2020; Pelling et al., 2021).

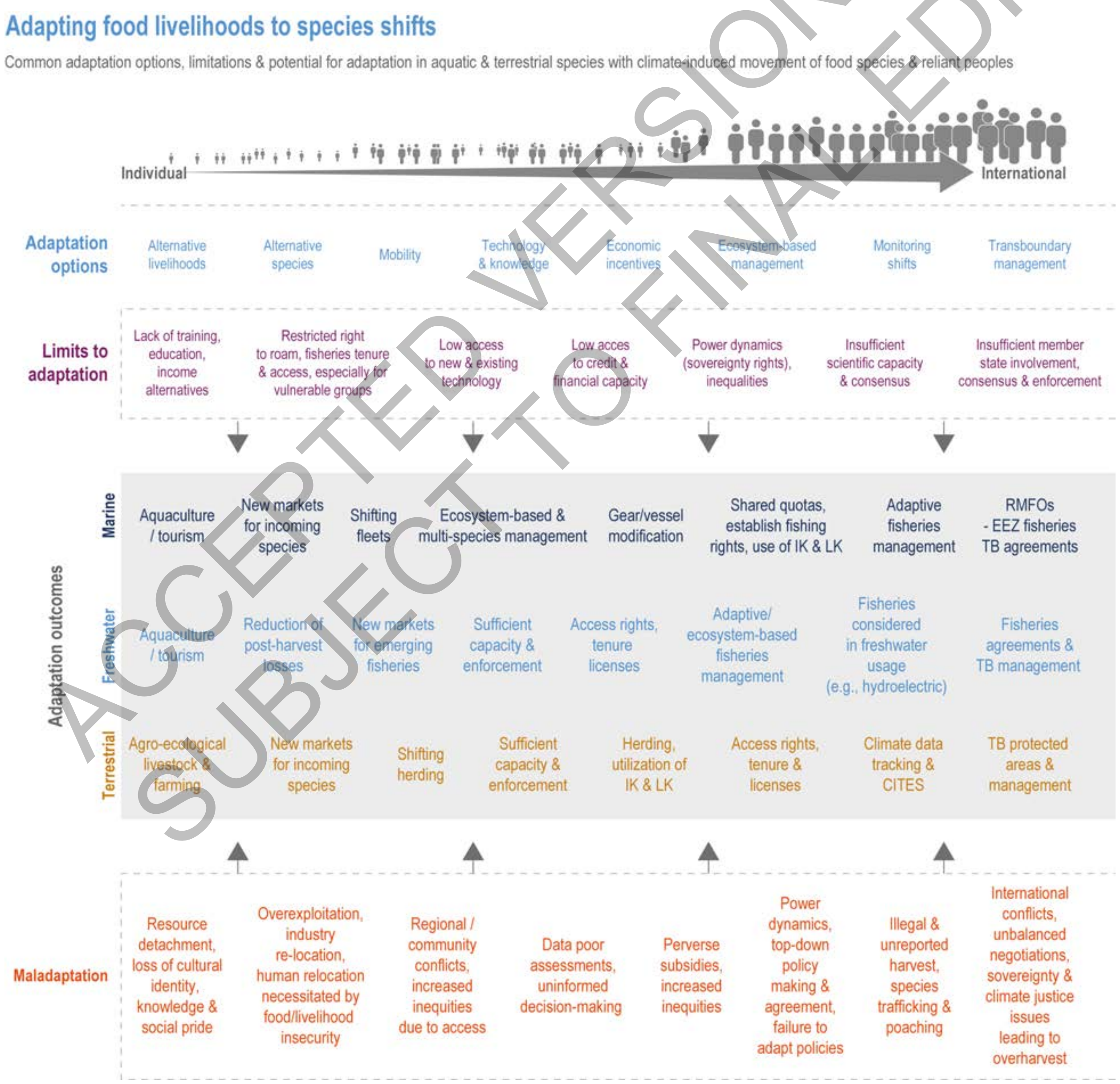


Figure Cross-Chapter Box MOVING PLATE.2: Common adaptation options, limitations, and potential for adaptation and maladaptation in aquatic and terrestrial species with climate-induced movement of food species and reliant peoples.

In terrestrial, marine, and freshwater systems human populations already impacted by poverty and hunger experience greater risk under climate change. Future food security will depend on access to other sustainable sources either via transnational agreements or resource / livelihood diversification. Sudden shocks across food production systems (Cottrell et al., 2019) can lead to increases in fisheries harvest and wild meat consumptions and following food species may result in community relocations or disruption and loss of access to historical places of attachment (*high confidence*) (Pecl et al., 2017; Lenoir et al., 2019; Meredith et al., 2019; Melbourne-Thomas et al., 2021; see Cross-Chapter Box MIGRATE in Chapter 7). Ecosystem based management approaches exist for terrestrial, marine and freshwater systems, but have proved successful only with early engagement of local small-scale, subsistence fishers / harvesters, utilizing Indigenous knowledge and local knowledge and needs, in addition to those of larger-scale operators (*high confidence*) (Huntington et al., 2015; McGrath and Costello, 2015; Huq and Stubbings, 2016; Huq et al., 2017; Raymond-Yakoubian et al., 2017; Nalau et al., 2018; Raymond-Yakoubian and Daniel, 2018; Pecl et al., 2019; Planque et al., 2019). Currently there is large regional differences in climate literacy in RFMOs (Sumby et al., 2021) which, when combined with low governance and GDP per capita, will limit adaptation capacity and increase vulnerabilities, particularly for tropical and sub-tropical regions already at increased risk due to poleward species migrations (see Figure Cross-Chapter Box MOVING PLATE.3). Trade will be an alternative to compensate for the moving plate but has specific risks that can amplify inequities and maladaptation (Asche et al., 2015; Vianna et al., 2020).

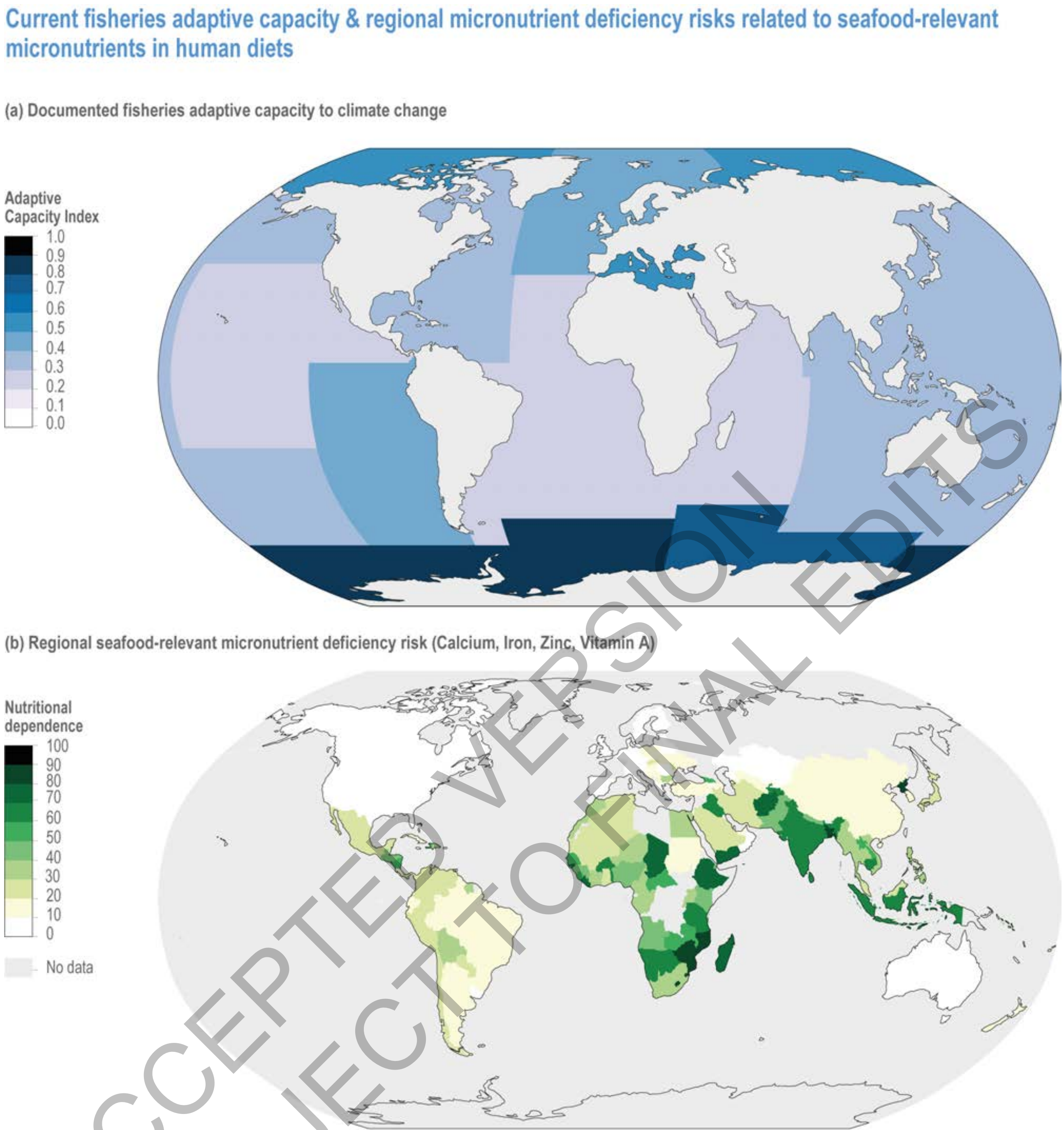


Figure Cross-Chapter Box MOVING PLATE.3: Global documented fisheries adaptive capacity to climate change and regional seafood micronutrient deficiency risk. Ocean areas are delineated into FAO (Food and Agricultural Organization of the United Nations) regions. Fisheries management adaptive capacity is a function of: averaged GDP World Development Indicators for 2018 (World Bank, 2020); climate awareness assessments of 30 of the FAO recognized most recent Regional Fisheries Management Organizations with direct fisheries linkages (see Supplementary Material SM5.5); governance effectiveness index based on six aggregate indicators (voice and accountability, political stability and absence of violence / terrorism, government effectiveness, regulatory quality, rule of law, control of corruption) from 2018 World Governance Indicator (World Bank, 2019) data, and; heterogeneity of countries within each FAO zone (highly heterogeneous regions are less likely to establish sustainable and efficient fisheries management for the entire FAO zone). Land area represents the percentage regional averaged seafood micronutrient deficiency risk of calcium, iron, zinc, and vitamin A from 2011 data (Beal et al., 2017).

[END CROSS-CHAPTER BOX MOVING PLATE HERE]

5.9 Ocean-based and Inland Aquaculture Systems

Global aquaculture provides more fish for human consumption than wild capture fisheries, with projected provisioning of 60% by 2030 (FAO, 2018c). Aquaculture can contribute to SDGs by reducing poverty and food insecurity, filling increasing aquatic food demand shortages from declining capture fisheries production, (*medium confidence*) (Figure 5.13a and c, World Bank, 2013; Béné et al., 2016; Hambrey, 2017; Beveridge et al., 2018b; Kalikoski et al., 2018; Belton et al., 2020), improving social inequities for poor rural communities (Béné et al., 2016; FAO, 2018c; Vannuccini et al., 2018; Pongthanapanic et al., 2019). Global aquaculture production reached 82 million tonnes (Mt) of food fish, crustaceans, molluscs, and other aquatic animals from inland (51 Mt) and marine (31 Mt) systems, and 32 Mt of aquatic plants in 2018 (FAO, 2020d). China, India, Indonesia, Vietnam, Bangladesh, Egypt, Norway and Chile are major production regions (FAO, 2020d). The range of species, farming methods and environments makes aquaculture the most diverse, long-standing farming practice in the world with an estimated global sectoral value of USD 250 billion in 2018 (Figure 5.13b and 5.14d, Bell et al., 2019; Harland, 2019; FAO, 2020d; Houston et al., 2020; Metian et al., 2020), but is dominated by 20 finfish, 9 mollusc and 6 crustacean species (FAO, 2020). Inland aquaculture in freshwater and coastal ponds accounts for 85-90% of farmed production (Beveridge et al., 2018b; Naylor et al., 2021). Globally 20.5 million people are engaged in aquaculture (FAO, 2020d), where marine finfish farming is primarily conducted by high-income countries and inland production is dominated by small-scale producers in lower-middle-income countries (Vannuccini et al., 2018).

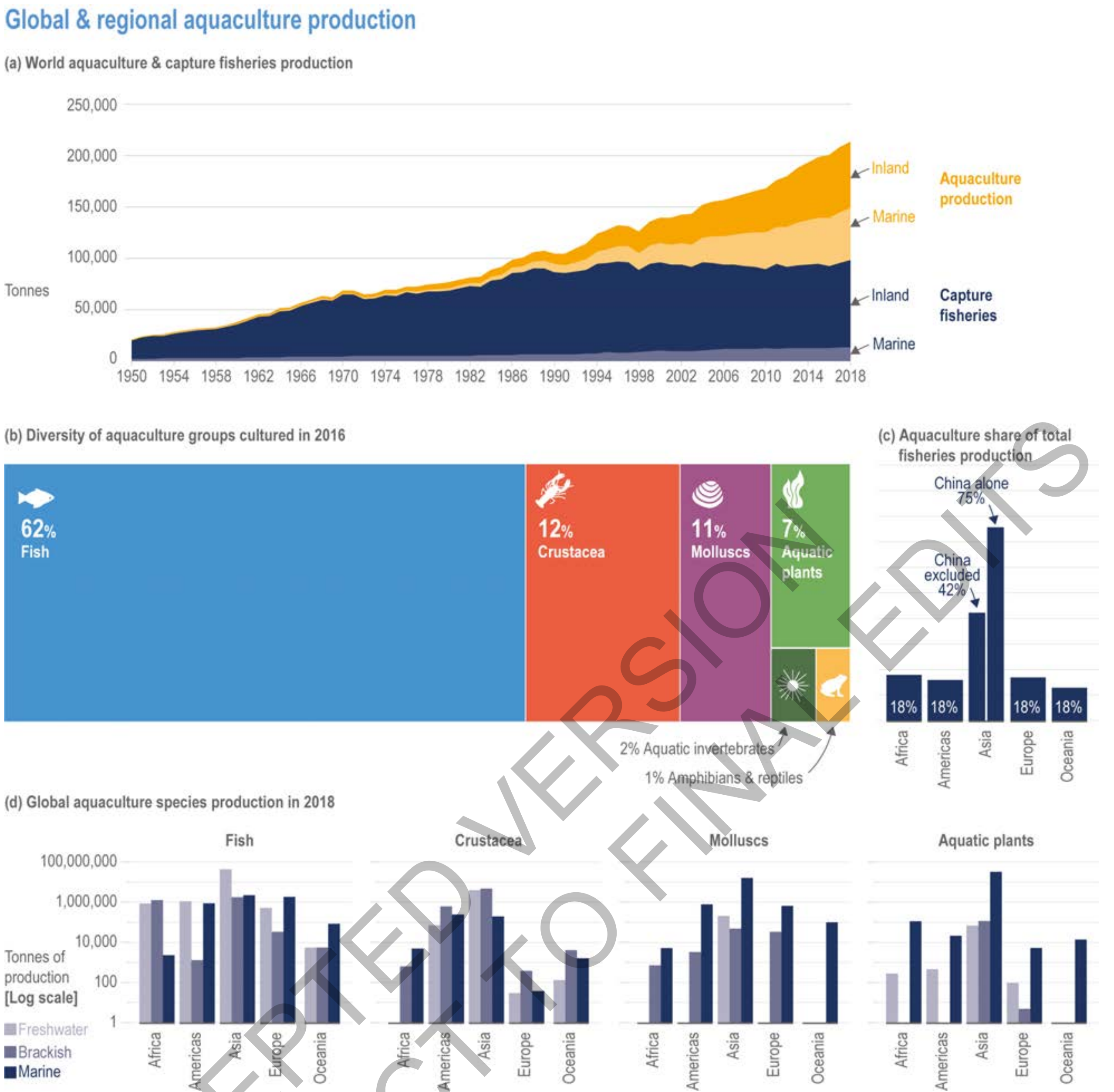


Figure 5.13: Global and regional aquaculture production a) world wild capture fisheries and aquaculture inland (freshwater and brackish) and marine production from 1950-2018, b) diversity of aquaculture groups cultured in 2016, and c) regional aquaculture share of total fisheries production, and d) global aquaculture species production in 2018 by region and type (freshwater, brackish, or marine) on a logged scale (FAO, 2018c; FAO, 2020c; FAO, 2020d).

5.9.1 Observed Impacts

Marine aquaculture food production is being impacted directly and indirectly by climate change (*high confidence*) (Bindoff et al., 2019). Ocean pH and oxygen levels are declining, whereas global warming, sea level rise and extreme events are increasing (Cross-Chapter Box SLR in Chapter 3, Canadell et al., 2021; Eyring et al., 2021; Fox-Kemper et al., 2021; Lee et al., 2021;). Marine heatwaves have been increasing in both incidence and longevity over the past century (Frolicher and Laufkotter, 2018; Oliver et al., 2018; Bricknell et al., 2021) with productivity consequences for marine aquaculture (mariculture), carbon sequestration and local species extinctions (*high confidence*) (Weatherdon et al., 2016; Smale et al., 2019). Temperature increases related to El Niño climatic oscillations have caused mass fish mortalities either through warming waters (e.g. Pacific threadfin in Hawaii (McCoy et al., 2017)), or associated harmful algal blooms (e.g. 12% loss of Atlantic salmon as well as other fish and shellfish in Chile in 2016 with estimated $800 million in losses (*high confidence*) (Clement et al., 2016; Apablaza et al., 2017; Leon-Munoz et al., 2018; Trainer et al., 2020)). Increases in sea lice parasite infestations on salmon are related to higher salinity and warmer waters (*medium confidence*) (Groner et al., 2016; Soto et al., 2019). Ocean acidification is having negative impacts on the sustainability of mariculture production (*high confidence*) (Bindoff et al., 2019) with observed impacts on shellfish causing significant production and economic losses for regions, estimated at losses of nearly USD $110 million by 2015 in the Pacific Northwest (Barton et al., 2015; Ekstrom et al., 2015; Waldbusser et al., 2015; Zhang et al., 2017b; Doney et al., 2020). Ocean oxygen levels are declining due to climate change (Hoegh-Guldberg et al., 2018; IPCC, 2021) and decreased oxygen (hypoxia) has negative impacts on fish physiology (Cadiz et al., 2018; Hvas and Oppedal, 2019; Martos-Sitcha et al., 2019; Perera et al., 2021), fish growth, behaviour and sensitivity to concurrent stressors (*high confidence*) (Stehfest et al., 2017; Abdel-Tawwab et al., 2019).

Observed impacts on inland systems have generally been site and region specific (*high confidence*) (Hoegh-Guldberg et al., 2018; Sainz et al., 2019; Lebel et al., 2020). Salinity intrusions into freshwater aquaculture systems have changed oxygen and water quality of inland ponds, resulting in mortalities in areas such as India and Bangladesh (*medium confidence*) (Dubey et al., 2017; Dabbadie et al., 2018). Rapid changes in temperature, precipitation, droughts, floods and erosion have created significant production losses for aquatic farmers in Cambodia, Laos, Myanmar, Thailand, Viet Nam and Ghana (*medium confidence*) (Asiedu et al., 2017; Pongthanapanic et al., 2019; Lebel et al., 2020). Algal blooming and inland lake browning related to warming was found to negatively affect fish biomass (van Dorst et al., 2018). Observed indirect effects of climate change on aquaculture include extreme weather events that damage coastal aquaculture infrastructure or enable flooding, both leading to animal escapees (e.g. fish, shrimp), damaged livelihoods and interactions with wild species (*high agreement, medium evidence*) (Beveridge et al., 2018b; Dabbadie et al., 2018; Kais and Islam, 2018; Pongthanapanic et al., 2019; Ju et al., 2020).

5.9.2 Assessing Vulnerabilities

Aquaculture vulnerability assessments have shown that countries from both high and low latitudes are highly vulnerable to climate change, where vulnerability is driven by particular exposures, economic reliance, type of production sector (freshwater, brackish, marine) and adaptive capacity (*high confidence*) (Handisyde et al., 2017; Soto et al., 2018). Regional aquaculture vulnerabilities and risk mitigation potentials for the major FAO reporting regions are shown in Figure 5.14. Best practice guidelines for assessments exist (Brugère et al., 2019; FAO, 2020d), but in practice most only cover some climatic drivers (*medium agreement, limited evidence*) (Soto et al., 2018). Holistic vulnerability assessments include ecosystem services (Custódio et al., 2020; Gentry et al., 2020) and farming practices which can exacerbate production pressures (stocking densities, eutrophication, fish stress) (Soto et al., 2018; Sainz et al., 2019). Common vulnerabilities to inland and marine aquaculture include increasing incidence and toxicity of harmful algal blooms related to warming waters, causing fish kills and product consumption risks, negatively impacting the productivity and stability of production sectors and reliant communities (*high confidence*) (Soto et al., 2018; Aoki et al., 2019) (Bannister et al., 2019).

There is *high confidence* that inland aquaculture in Southeast Asia is highly vulnerable to climate change, due to fluctuations in water resources either through climatic variability in precipitation, flooding or salinity inundation or through competition (Handisyde et al., 2017; Nguyen et al., 2018; Soto et al., 2018; Islam et al., 2019; Nguyen et al., 2019b; Prakoso et al., 2020). Studies in Bangladesh and Indonesia highlighted regional and species-specific vulnerabilities (Prakoso et al., 2020) and roles of governance in vulnerability reduction (Islam et al., 2019).

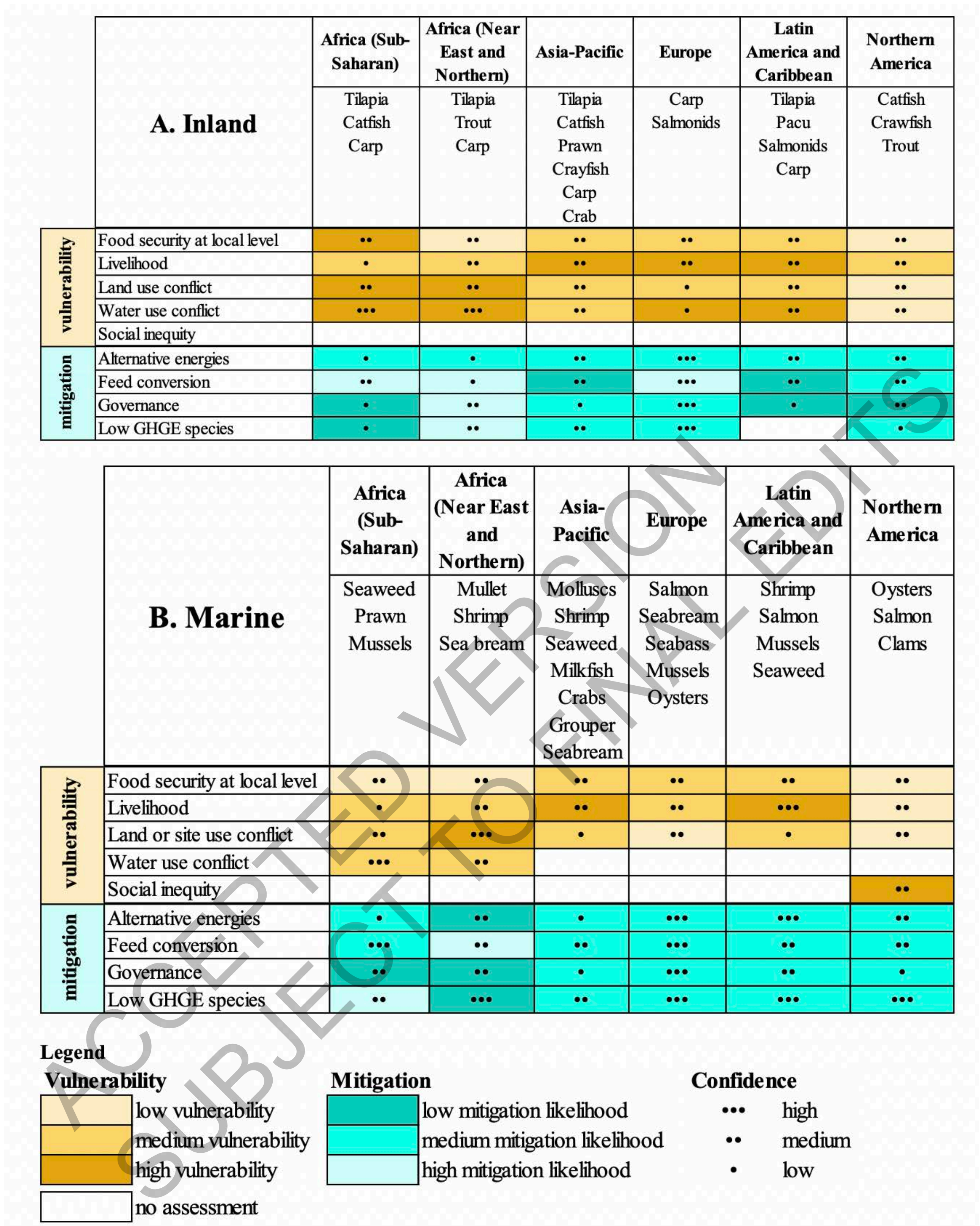


Figure 5.14: Assessment of a) inland freshwater and brackish aquaculture (salinities of <10ppm and / or no connection to the marine environment) b) marine aquaculture vulnerabilities and mitigation potential per major FAO production zones. See SM5.6 (Tables SM5.4, 5.5, 5.8,5.9) for assessment methodologies.

In the marine sector, vulnerability models (Brugère and De Young, 2015; Handisyde et al., 2017) have been adapted and applied to semi-quantitative spatial risk assessments for Chilean Atlantic salmon, where analysis of exposure threat coupled with mortality and temperature farm data could enhance salmon production (Soto et al., 2019). Vulnerability assessments in Korea (RCP8.5 temperature increase of 4-5°C by 2100) (Kim et al., 2019a) and the U.S. (ocean acidification, Barton et al., 2015; Ekstrom et al., 2015) found major exposure-related vulnerabilities for seaweeds and shellfish, with reduced vulnerabilities under higher production control and adaptive capacity. Global bivalve vulnerability assessments (RCP8.5 by 2100) show high vulnerabilities for major producing countries related to cyclones (China, Japan, South Korea, Thailand, Viet Nam, and North Korea), regional risk of high sensitivity and low adaptive capacity (Chile, Peru, Spain, Italy), with few major producers (France, the Netherland and U.S.) anticipated to remain moderately vulnerable by 2100 (Stewart-Sinclair et al., 2020).

Climate uncertainty and data limitations hinder vulnerability assessments (*high confidence*), so broader vulnerabilities and qualitative assessments can be used (Brugère and De Young, 2015; Soto et al., 2018; Brugère et al., 2019; Cochrane et al., 2019). Filling data gaps with monitoring (*high confidence*), increasing governmental support to assist particularly vulnerable small- and medium-scale farmers with increased costs associated with risk management and uncertainty (*medium confidence*) and the early inclusion of community stakeholders (*high agreement, medium evidence*) can reduce vulnerabilities (Handisyde et al., 2017; Dabbadie et al., 2018; Soto et al., 2018; Bindoff et al., 2019; Cochrane et al., 2019).

5.9.2.1 Gender and other social vulnerability and roles in aquaculture

There are regional differences in women's roles, responsibilities and involvement in adaptation strategies in the aquaculture sector. Women comprise 14% of the 2018 global aquaculture workforce of 20.5 million (FAO, 2020c), representing up to 42% of the salmon workforce in Chile (Chávez et al., 2019), predominantly in processing roles (Gopal et al., 2020). In the majority of lower-middle-income countries seaweed culture is dominated by women in family-owned businesses as in Zanzibar and the Philippines (Brugere et al., 2020; Ramirez et al., 2020), where women are not always paid directly but contribute to family incomes (*high confidence*) (Msuya and Hurtado, 2017; Brugere et al., 2020; Ramirez et al., 2020). In India women collect stocking juveniles and assist in pond construction, in Bangladesh women do the same tasks as men and in Ghana women undertake post-harvest fishing activities (Lauria et al., 2018). Women employed in aquaculture cooperatives gained adaptive capacity, which reduced gender inequities (*medium confidence*) (Farquhar et al., 2018; Gonzal et al., 2019), but lack of financial access for women can create gender inequality at larger commercial scales (Gurung et al., 2016; Call and Sellers, 2019).Women in aquaculture experience competing roles between employment, childcare and home duties (*high confidence*) (Morgan et al., 2015; Lauria et al., 2018; Chávez et al., 2019; see Cross-Chapter Box GENDER in Chapter 18), and differ from men in terms of perceptions of environmental risk, climate change, adaptation behaviour, with limited contributions to decision-making (*medium confidence*) (Barange and Cochrane, 2018). Therefore, effective climate aquaculture adaptation options need to address gender inequality e.g. suitable technology designs that fit with social norms and access to credit to facilitate independent uptake (*medium evidence, high agreement*) (Morgan et al., 2015; Oppenheimer et al., 2019). Generalized best practices for gender-sensitive approaches to adaptation are relevant for aquaculture (UNFCCC, 2013).

5.9.3 Projected Impacts

Projected impacts on regional inland and marine aquaculture production are summarized in Figure 5.15.

5.9.3.1 Inland freshwater and brackish aquaculture

Predicted sea level and temperature rise will result in coastal inundation into brackish and inland aquaculture systems (*high confidence*) (Mehvar et al., 2019; Nhung et al., 2019; Oppenheimer et al., 2019; IPCC AR6), with negative impacts on aquaculture production in Viet Nam, East Africa and Jamaica (*medium confidence*) (Lebel et al., 2018; Nguyen et al., 2018; Bornemann et al., 2019). Precipitation and temperature changes will cause drought and flooding, negatively affecting near-shore fishpond productivity (*limited evidence*) (Canevari-Luzardo et al., 2019), but provide competitive advantages to non-native shrimp in Australia (*limited evidence*) (Cerato et al., 2019). Warming and acidification will increase harmful algal bloom toxicity in freshwater systems, but responses may be strain-specific (Griffith and Gobler, 2020; Hennon and Dyhrman, 2020). As for molluscs in marine systems, projected climate change in freshwater and brackish systems may limit the availability of wild-sourced juveniles from fisheries (Beveridge et al., 2018). Projected impact studies for the inland and small-scale aquatic sectors are very limited (Halpern et al., 2019; Galappaththi et al., 2020b), therefore this is a noted knowledge gap.

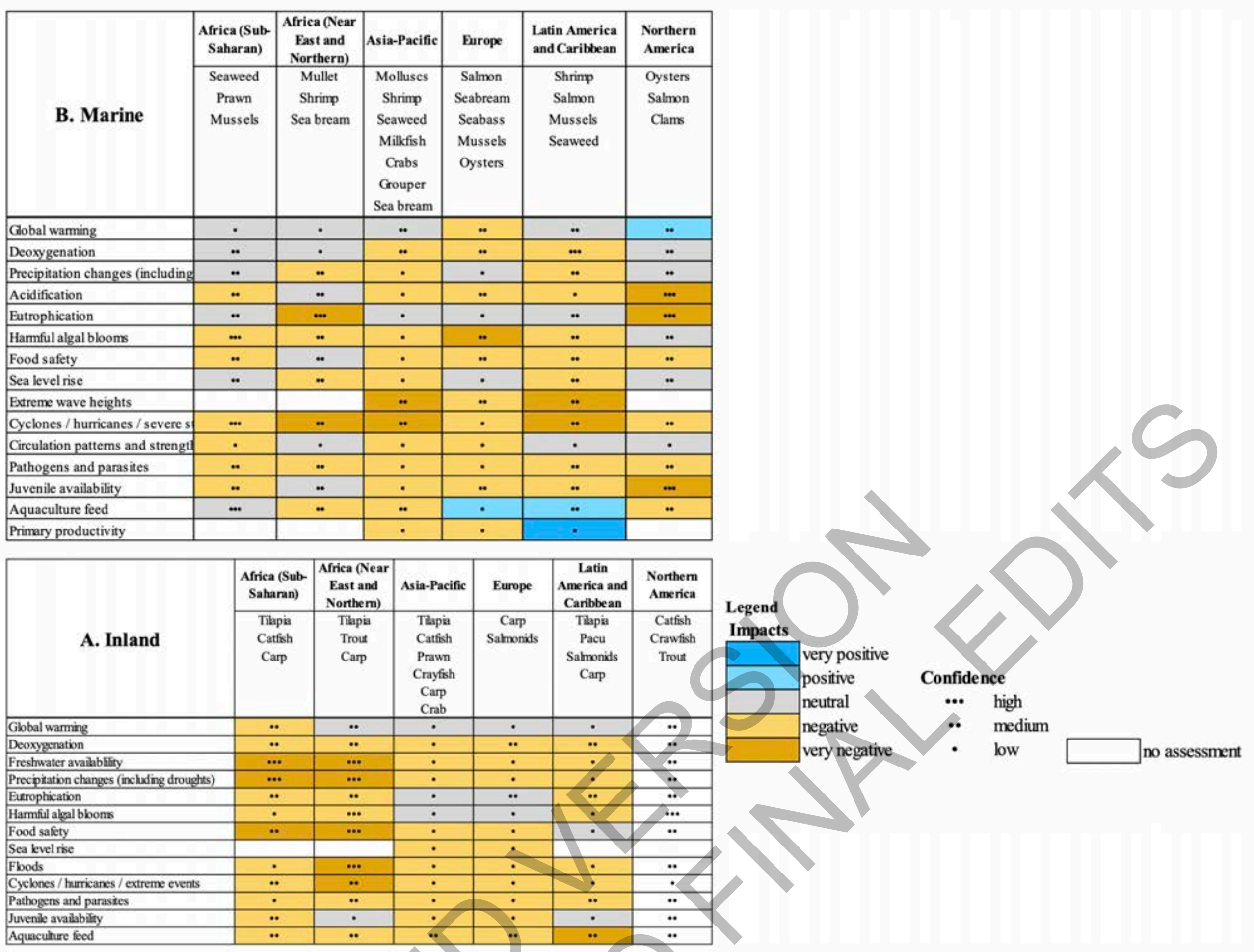


Figure 5.15: Assessment of projected impacts of climate change on a) inland freshwater and brackish aquaculture (salinities of <10ppm and / or no connection to the marine environment) b) marine aquaculture per major FAO production zones. See SM5.6 (Tables SM5.6, 5.10) for assessment methodologies.

5.9.3.2 Marine aquaculture

5.9.3.2.1 Finfish culture

Global projections of ocean warming, primary productivity and ocean acidification predict suitable habitat expansions and short-term growth benefits for finfish aquaculture for some regions (*medium confidence*) (see Figure 5.15) until thermal tolerances or productivity constraints are exceeded by 2090 (Beveridge et al., 2018b; Dabbadie et al., 2018; Froehlich et al., 2018a; Catalán et al., 2019; Thiault et al., 2019; Falconer et al., 2020a). Sensitivities for marine finfish may be high even under +1.5-2.0°C (*medium confidence*) (Gattuso et al., 2018), resulting in finfish farms moving northward to maintain productivity (e.g., Arctic (Troell et al., 2017). Downscaled projections of regionally specific tolerances (Klinger et al., 2017) may be particularly useful for management and planning; a 0.5°C rise is predicted for Chilean salmon aquaculture (Soto et al., 2019) and potential projected negative impacts on productivity in Norway by 2029 (*limited evidence*) (Falconer et al., 2020a). Marine heatwaves are predicted to increase in occurrence, intensity, and persistence under RCP4.5 or RCP8.5 by 2100 (Oliver et al., 2019; Bricknell et al., 2021) with risk partly mitigated by husbandry (*medium confidence*) (McCoy et al., 2017). Generally, negative impacts are predicted for marine species with residual risk increasing with level of exposure (Sara et al., 2018; Smale et al., 2019), where warming will affect oxygen solubility and reduce salmon culture capacity (*limited evidence*) (Aksnes et al., 2019, Chapter 3) and combine with increasing incidence of harmful algal blooms (*high confidence*) resulting in negative impacts for food security and nutrition and health (Oppenheimer et al., 2019; Colombo et al., 2020; Glibert, 2020; Raven et al., 2020). Climate change is predicted to affect the incidence, magnitude and virulence of finfish disease, e.g., *Vibriosis* (Barber et al., 2016; Mohamad et al., 2019a; Mohamad et al., 2019b), but specific host-pathogen-climate relationships are not yet established (*high confidence*) (Slenning, 2010; Marcogliese, 2016; Montanchez et al., 2019; Bandin and Souto, 2020; Behringer et al., 2020; Filipe et al., 2020; Montanchez and Kaberdin, 2020). Projected climate change will also increase competition for feed ingredients between aquatic and terrestrial animal production systems (see Section 5.13.2.).

5.9.3.2.2 Shellfish culture

Globally, there is overall *high confidence* that suitable shellfish aquaculture habitat will decline by 2100 under projected warming, ocean acidification and primary productivity changes, with significant negative impacts for some regions and species before 2100 (Table 5.9, Froehlich et al., 2018a; Ghezzo et al., 2018). Shellfish growth will increase with warming waters until tolerances are reached, e.g., through extreme El Niño events (*high confidence*) (Beveridge et al., 2018b; Dabbadie et al., 2018; Liu et al., 2018b; Liu et al., 2020). Rising temperatures and ocean acidification will result in losses of primary productivity and farmed species from tropical and subtropical regions, and gains in higher latitudes (*high confidence*) (Froehlich et al., 2018a; Aveytua-Alcazar et al., 2020; Chapman et al., 2020; Des et al., 2020; Oyinlola et al., 2020), but net marine production gains could be achieved under strong mitigation (Thiault et al., 2019). Shellfish *Vibrio* infections will increase with warming waters and extreme events, increasing shellfish mortalities (*medium confidence*) (Green et al., 2019; Montanchez et al., 2019) with ocean acidification impairing immune responses (*limited evidence*) (Cao et al., 2018b). Bivalve larvae are known to be highly vulnerable to ocean acidification (*high confidence*) (see Section 3.3, Bindoff et al., 2019), with projected regional and species-specific levels of impact (*high confidence*) (Ekstrom et al., 2015; Zhang et al., 2017b; Mangi et al., 2018) (Greenhill et al., 2020). Ocean acidification is also projected to weaken shells, affecting productivity and processing (*high confidence*) (Martinez et al., 2018; Cummings et al., 2019) and dependent livelihoods (Doney et al., 2020).

5.9.3.2.3 Aquatic plant culture

There is *medium confidence* that cultivated seaweeds are predicted to suffer habitat loss resulting in population declines and northward shifts (Table 5.11).

Table 5.11: Projected impacts of climate on specific inland, brackish, and marine culture systems and species.

Exposure	Scenario	Region	Production system	Species	Impact	Reference
Temperature increase	RCP4.5 and RCP8.5 by 2050	Northern Thailand	Inland	Nile tilapia	Reduced productivity	Lebel et al. (2018)
Precipitation change (drought, hurricane, heavy rainfall)	-	Jamaica	Inland	Tilapia	Reduced productivity, infrastructure damage	Canevari-Luzardo et al. (2019)
Temperature increase	4°C increase, B2, A1B by 2100	Australia	Inland	Freshwater shrimp	Increased production in non-native zones	Cerato et al. (2019)
Temperature increase, ocean acidification, primary productivity declines	CMIP5 RCP 8.5 in 20-year increments to 2090	Global	Marine	Finfish species	Increased suitable habitat expansion for regions (Russia, Norway, U.S. Alaska, Denmark, Canada). By 2100 reduction in productivity for major producers (Norway, China)	Froehlich et al. (2018a), Thiault et al. (2019)
Temperature increase	2-5°C increase under RCP8.5	Europe	Marine	Atlantic salmon	Increased growth	Catalán et al. (2019)

Temperature increase	RCP4.5 to 2029	Norway	Marine	Atlantic salmon	Growth threshold reached by 2029	Falconer et al. (2020a)
Temperature increase	Downscaled CM2.6 by 2050	Global	Marine	Atlantic salmon, cobia and sea bream	Increased or decreased growth rates depending on region	Klinger et al. (2017)
Temperature increase, ocean acidification, primary productivity declines	CMIP5 RCP 8.5 in 20-year increments to 2090	Global	Marine	Shellfish	Overall declines in suitable habitat globally, up to 50-100% reductions regions in China, Thailand, and Canada	Froehlich et al. (2018a)
Temperature increase	CMIP5 RCP8.5 by 2050, 2100	Italy	Marine	Clams	Negative impacts for juvenile timing, spatial distribution, and quality	Ghezzo et al. (2018)
Temperature increase	CMIP5 RCP2.6 and RCP8.5 by 2035, 2070	France	Marine	Oysters	Increase incidence of oyster mortality; increase by 2035 to annual occurrence by 2070	Thomas et al. (2018)
Temperature increase	RCP2.6 and RCP8.5 by 2050	Global	Marine	Shellfish	Species reduction (10-40%) in tropical and subtropical regions with increase (40%) in higher latitudes	Oyinlola et al. (2020)
Temperature increase, ocean acidification	Ecopath with RCP 8.5 by 2100 (2.8°C warming and pH 7.89)	U.S.	Marine	Shellfish	Reduction primary productivity and subsequent bivalve carrying capacity	Chapman et al. (2020)
Temperature increase, stratification change	RCP8.5 by 2088-2099	Spain	Marine	Mussels	Decline in mussel optimal culture conditions of 60% in upper and 30% in deeper waters by 2099	Des et al. (2020)
Temperature increase, ocean acidification	RCP2.6 and 8.5 by 2070-2090	Global	Marine	Shellfish	Under RCP8.5 a decline in shellfish production due to primary productivity reduction in tropical regions and gains in high latitudes. Under RCP2.6 marine production will have net gain	Thiault et al. (2019)
Temperature increase	4°C increase	Global	Marine	*Vibrio* spp. (mortality causative agent)	Increased virulence	Montanchez et al. (2019)
Temperature increase (marine heat wave)	5°C increase	Global	Marine	Oysters	Increased oyster mortality	Green et al. (2019)
Ocean acidification	~2000ppm CO_2	Global	Marine	Oysters	Impaired immune function	Cao et al. (2018b)
Ocean acidification	RCP8.5 in 20-year	U.S.	Marine	Shellfish	Regional projected vulnerabilities – Southern Alaska and	Ekstrom et al. (2015)

	increments to after 2099				Pacific Northwest at more immediate risk	
Ocean acidification	A1B and RCP8.5 by 2100	U.K.	Marine	Shellfish	Regional projected vulnerabilities - Wales and England at more immediate risk	Mangi et al. (2018)
Ocean acidification	RCP2.6 and RCP8.5 by 2300	East China	Marine	Shellfish	Carbonate saturation projected to decrease by 13% and 72% under RCP2.6 and RCP8.5 respectively, projecting decreased shellfish productivity	RCP2.6 and RCP8.5 by 2300 (Zhang et al., 2017b)
Increased temperature	RCP2.6 and RCP8.5 by 2100	North Sea	Marine	Seaweed	Northward population shift by 110-163km and 450-635km under RCP2.6 and RCP8.5 respectively	Westmeijer et al. (2019),
Increased temperature	RCP4.5 and RCP8.5 by 2090	Japan	Marine	Kelp	Habitat decline to 30-51% and 0-25% under RCP4.5 and RCP8.5 respectively	Sudo et al. (2020).

5.9.3.2.4 Societal impacts within the production system

Marine aquaculture provides distinct ecosystem services through provisioning (augmenting wild fishery catches), regulating (coastal protection, carbon sequestration, nutrient removal, improved water clarity), habitat and supporting (artificial habitat) and cultural (livelihoods and tourism) services (Gentry et al., 2020), which vary with species, location, and husbandry (Alleway et al., 2019). Projected thermal increases of 1.5°C will reduce ecosystem services, further reduced under 2°C warming, with associated increases in acidification, hypoxia, dead zones, flooding, and water restrictions (*medium confidence*) (Hoegh-Guldberg et al., 2018). Sudden production loses from extreme climate events can exacerbate food security challenges across production sectors, including aquaculture, increasing global hunger (*high confidence*) (Cottrell et al., 2019; Food Security Information Network, 2020). While aquaculture provides positive influences such as food security and livelihoods, there are negative concerns over environmental impacts (including high nutrient loads from sites) and socio-economic conflicts (Alleway et al., 2019; Soto et al., 2019) and adoption of ecosystem approaches are dependent on particular user groups and regions (Gentry et al., 2017; Brugère et al., 2019; Gentry et al., 2020). In coastal Bangladesh projected saline inundation to wetland ecosystem services will result in ecosystem services losses of raw materials and food provisioning, ranging from USD 0-20.0 million under RCP2.6 to RCP8.5 scenarios (Mehvar et al., 2019). Mangrove deforestation for shrimp farming in Asia negatively impacts ecosystem services and reduces climate resilience (*medium confidence*) (Mehvar et al., 2019; Nguyen and Parnell, 2019; Reid et al., 2019; Custódio et al., 2020), while mangrove reforestation efforts may have some effectiveness in recreating important nursery grounds for aquatic species (*low confidence)* (Gentry et al., 2017; Chiayarak et al., 2019; Hai et al., 2020). Families are highly vulnerable to climate change where nutritional needs are being met by self-production, e.g., Mozambique, Namibia (Villasante et al., 2015), Zambia (Kaminski et al., 2018) and Bangladesh (*high confidence*) (Pant et al., 2014). Climate change will therefore affect multiple ecosystem services where ultimately decisions on balance or trade-offs will vary with regional perceptions of service value (*high confidence*).

5.9.4 Aquaculture Adaptation

5.9.4.1 Adaptation planning

Aquaculture is often viewed as an adaptation option for fisheries declines, thereby alleviating food security from losses of other climate change impacts (Sowman and Raemaekers, 2018; Johnson et al., 2020) e.g., Pacific Islands freshwater aquaculture, Bangladesh crop-aquaculture systems, or Viet Nam rice-fish cultivations (Soto et al., 2018). Many adaptations are specific to regions, countries, or sector, implemented on a regional to national scale (FAO, 2018c; Galappaththi et al., 2020b). Adaptation likelihood (potential), effectiveness and risk of maladaptation was assessed per major FAO production region for inland, brackish, and marine aquaculture (Figure 5.16) production systems. Potential adaptation measures to reduce production loss can be built upon existing adaptation planning and guidelines, to reduce the risk of maladaptation including feedback loops (e. g. FAO, 2015; Bueno and Soto, 2017; Dabbadie et al., 2018; FAO, 2018c; Poulain et al., 2018; Brugère et al., 2019; Pham et al., 2021; Soto et al., 2021). Large climate change adaptation strategies for the aquaculture sector exist e.g. U.S. (Link et al., 2015), Australia (Hobday et al., 2017) and South Africa (Department of Environmental Affairs, 2016). Lower income countries often lack financial, technical, or institutional capacity for adaptation planning (Galappaththi et al., 2020b), but examples include Bangladesh and Myanmar (FAO, 2018c), with programs offering adaptation funding (Dabbadie et al., 2018). Early participation of stakeholders in adaptive planning has promoted action and ownership of results (*high confidence*) e.g. India and U.S. (Link et al., 2015; FAO, 2018c; Soto et al., 2018) Early outreach, education, and knowledge gap assessments raises awareness, where utilization of local knowledge and Indigenous knowledge and scientific involvement support informed adaptive planning and uptake for all stakeholders (*high confidence*) (Cooley et al., 2016; FAO, 2018c; Rybråten et al., 2018; Soto et al., 2018; McDonald et al., 2019; Galappaththi et al., 2020b), as perceptions of climate risk and capacity will vary (Tiller and Richards, 2018). Supporting the active involvement of women helps address gender inequity and perceived risk, particularly for smallholder farmers (*high confidence*) (Morgan et al., 2015; Barange and Cochrane, 2018; FAO, 2018c; Avila-Forcada et al., 2020). However, regional, and national political influences, financial and technical capacity, governance planning and policy development will ultimately support or hinder adaptation for aquaculture (*high confidence*) (Cooley et al., 2016; FAO, 2018c; Galappaththi et al., 2020b; Greenhill et al., 2020).

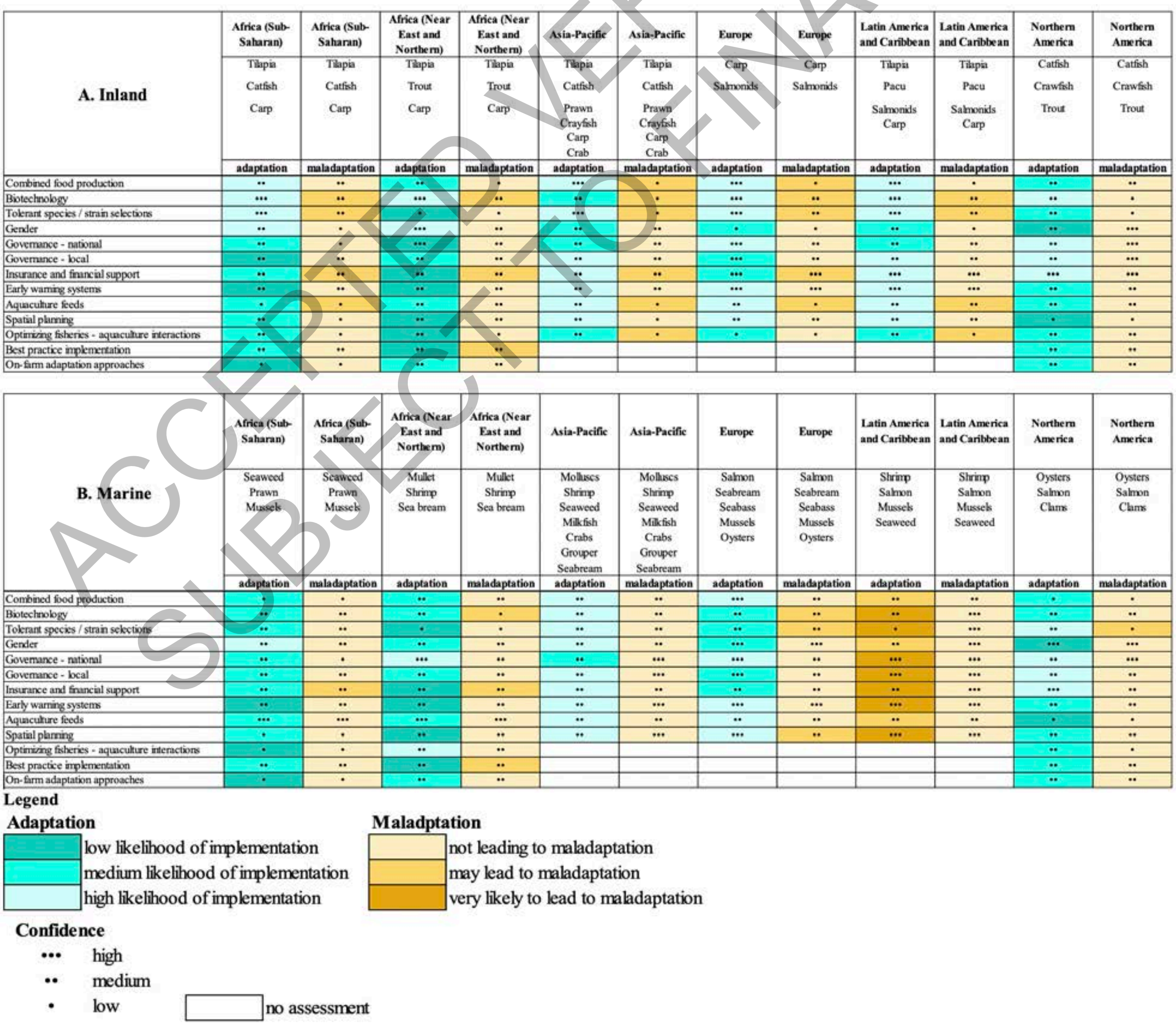


Figure 5.16: Assessment of the likelihood and effectiveness of a range of adaptation options for potential implementation in the near-term (next decade) for a) inland freshwater and brackish aquaculture (salinities of <10ppm and / or no connection to the marine environment) and b) marine aquaculture systems per major FAO production zone. See SM5.6 (Tables SM5.7, 5.11) for assessment methodologies.

5.9.4.2 Species selections and selective breeding

Adaptation options at the operational level include species selections, e.g., cultivation of brackish species (shrimp, crabs) during dry seasons, and rice-finfish in wetter seasons in Thailand (Chiayarak et al., 2019), use of salt-tolerant plants in Viet Nam (Nhung et al., 2019; Paik et al., 2020), converting inundated rice paddies into aquaculture, rotating shrimp, and rice culture (*high confidence*) (Chiayarak et al., 2019). Species diversification through co-culture, integrated aquaculture-agriculture (e.g. rice-fish) or integrated multi-trophic culture (e.g. shrimp-tilapia-seaweed or finfish-bivalve-seaweed) may maintain farm long-term performance and viability by: creating new aquaculture opportunities; promoting societal and environmental stability; reducing GHG emissions through reduced feed usage and waste, and; carbon sequestration (*medium confidence*) (see Section 5.10, Li et al., 2019; Galappaththi et al., 2020b; Prakoso et al., 2020; Tran et al., 2020) (Ahmed et al., 2017; Bunting et al., 2017; Gasco et al., 2018; Soto et al., 2018; Ahmed et al., 2019; Dubois et al., 2019; FAO, 2019c; Freed et al., 2020). In practice, most aquaculture operations concentrate on single-species systems (Metian et al., 2020) and barriers such as land availability, freshwater resources and lack of credit access may limit the uptake and success of integrated adaptation approaches to climate change (Ahmed et al., 2019; Tran et al., 2020; Kais and Islam, 2021).

Selective breeding can promote climate resilience (*medium confidence*) (Klinger et al., 2017; Fitzer et al., 2019) and operations have already intentionally, or unintentionally, selected for production traits for changing conditions (de Melo et al., 2016; Tan and Zheng, 2020). Exposure of broodstock to future climate conditions may or may not confer advantages to offspring (*moderate evidence, low agreement*) (Parker et al., 2015; Griffith and Gobler, 2017; Thomsen et al., 2017; Durland et al., 2019). Traditional pedigree developments require extensive phenotypic data, but genomic selections can rapidly select for robust climate-associated traits (Sae-Lim et al., 2017; Gutierrez et al., 2018; Zenger et al., 2018; Houston et al., 2020; Tan and Zheng, 2020). Genomic resources are available for salmon, rainbow trout, coho, carp, tilapia, seabass, bream, turbot, flounder, catfish, yellow drum, scallops, oysters and shrimp, but have been developed for disease and growth selections rather than climate resistance (Guo et al., 2018; Houston et al., 2020) (Dégremont et al., 2015a; Dégremont et al., 2015b; Abdelrahman et al., 2017; Gjedrem and Rye, 2018; Gutierrez et al., 2018; Liu et al., 2018a; FAO, 2019d), although bivalve selections for ocean acidification and warming resiliency are underway (Tan and Zheng, 2020). Targeted genome editing could modify phenotypes of major aquaculture species (Li et al., 2014a; Elaswad et al., 2018; Yu et al., 2019; Houston et al., 2020), but uptake is dependent upon national regulatory and public approvals. Local adaptations within species with higher climate resiliencies may assist in selections (Thomsen et al., 2017; Falkenberg et al., 2019; Scanes et al., 2020; Toomey et al., 2020), but highlights the need to consider specific farming environments for selective processes (Houston et al., 2020). Projections of climate on aquaculture production traits are not well understood (Lhorente et al., 2019), therefore genetic diversity needs to be maintained to ensure population fitness (*high confidence*) (Bitter et al., 2019; Lhorente et al., 2019; Visch et al., 2019; Houston et al., 2020; Mantri et al., 2020).

5.9.4.3 Farm site selection, infrastructure, and husbandry

Land-based aquaculture systems including hatcheries may reduce exposure to climatic extremes (due to better control of the culture environment), limit water usage, reduce juvenile reliance and buffer climate effects using optimal diets (*high confidence*) (Barton et al., 2015; Reid et al., 2019; Cominassi et al., 2020). However, land-based aquaculture requires large capital and operational costs, use of land increasing conflicts between land and water use, increased energy demands increasing GHG if fossil fuels are primary energy source, require necessary expertise and will not reduce outgrowing exposures (*high confidence*) (see Section 5.13, Beveridge et al., 2018b; Soto et al., 2018; Tillotson et al., 2019; Costello et al., 2020; Prakoso et al., 2020).

Geographical selection of marine farm sites may prevent climate productivity declines (*medium confidence*) (Froehlich et al., 2018a; Sainz et al., 2019; Oyinlola et al., 2020), particularly for temperature–related mortality hotspots (Garrabou et al., 2019), harmful algal bloom occurrences (Dabbadie et al., 2018) or extreme events (Liu et al., 2020; Wu et al., 2020). However, while downscaled climate forecasts facilitate localized adaptation planning (Falconer et al., 2020a), such projections are rare (Whitney et al., 2020). GIS can be used for climate adaptive planning along with routine site assessments (Falconer et al., 2020b; Galappaththi et al., 2020b; Jayanthi et al., 2020). Building coastal protection, stronger cages and mooring systems, deeper ponds and using sheltered bays can reduce escapees and mortalities related to flooding, increased storms and extreme events (*medium confidence*) (Dabbadie et al., 2018; Bricknell et al., 2021; Kais and Islam, 2021). Inshore aquaculture in low-lying areas prone to sea-level salinity intrusion (e.g. Mekong delta and Viet Nam) have already implemented adaptation measures, such as conversion of land to mixed plant-animal systems (Nguyen et al., 2019a), converting freshwater ponds to brackish or saline aquaculture (Galappaththi et al., 2020b), building of dams and dykes (Renaud et al., 2015) and intensification of shrimp or fish pond culture to reduce water and land usage (Nguyen et al., 2019b; Johnson et al., 2020). Other adaptation options for limited water supply are government equitable water allocations and water storage (*high confidence*) (Bunting et al., 2017; Galappaththi et al., 2020b).

Feed formulations and improved feed conversion can reduce climate-associated stress for freshwater species, significantly reducing waste and increase sustainability (*medium confidence*) (Chen and Villoria, 2019) (FAO, 2018c; Gasco et al., 2018). Projected decreases in fish meal and global targets of limiting warming to under 2°C may increase the ratio of plant-based diets, but reduce fish nutritional content (see Sections 5.10 and 5.13, Hasan and Soto, 2017; Johnson et al., 2020) (). Companies provide insurance in major production areas, but aquaculture is considered high risk with large levels of small claims (Secretan et al., 2007). Insurance covers natural disasters and disease, helping to reduce and cope with climate-induced risk, enabling faster livelihood recoveries and preventing poverty (*high agreement, limited evidence*) (Xinhua et al., 2017; Kalikoski et al., 2018; Soto et al., 2018). For example, small-scale shrimp farmers were willing to pay higher premiums to manage risk, after participation in government pilot insurance schemes, ensuring greater pay-outs if a mortality event occurred (Nyguyen and Pongthanapanic, 2016; Pongthanapanic et al., 2019). Technological innovations are more widely implemented in larger operations, with internet access promoting adoption at the farm site (Joffre et al., 2017; Salazar et al., 2018). Improved farm management is a key opportunity (*high confidence*) to reduce climate risks on aquaculture, where Best Management Practices can increase resiliency (Soto et al., 2018), lower additional risk from non-climatic stressors (Gattuso et al., 2018; Smith and Bernard, 2020), and decision-tree frameworks can provide adaptation choices when events occur (Nguyen et al., 2016).

5.9.4.4 Early warning and monitoring systems

Globally monitoring is increasing to fill scientific uncertainties (Goldsmith et al., 2019), but is not often at spatial scales which facilitate farm or regional adaptation management (Whitney et al., 2020) or data complexities prevent direct uptake by operators, resource managers and policymakers (*medium confidence*) (Soto et al., 2018; Gallo et al., 2019). Specialized industry portals (Pacific shellfish) and government-established monitoring programs (Chilean salmon) and other observational networks (e.g., GOA-ON) can provide real-time monitoring, early-warning event alerts and facilitate aquaculture decision-making (*medium confidence*) (Cross et al., 2019; Farcy et al., 2019; Soto et al., 2019; Bresnahan et al., 2020; Peck et al., 2020) (Tilbrook et al., 2019). Seasonal forecasting, downscaled models and early-warning systems provide valuable regional or farm site risk information (Hobday et al., 2018; Galappaththi et al., 2020b; Whitney et al., 2020), but monitoring will need to be useful for farmers, involve farmers, accurate, timely, cost-effective, reviewed and maintained in order to ensure uptake (*high confidence*) (Soto et al., 2018). Early warning systems for harmful algal blooms enable rapid decision-making and risk mitigation (*medium confidence*), e.g., ocean colour monitoring in South Africa (Smith and Bernard, 2020), where early harvesting and additional husbandry were used to minimize production and economic losses (Pitcher et al., 2019). New tools, strategies and observations are needed to predict harmful algal bloom occurrences and range shifts with changing climate (*high confidence*) (Schaefer et al., 2019; Tester et al., 2020), as there is uncertainty on drivers of incidence and toxicity (Wells et al., 2020).

5.9.5 Contributions of Indigenous, Traditional, and Local Knowledge

Indigenous mariculture practices, e.g., intertidal clam gardens, have been occurring for thousands of years, providing knowledge of traditional practices still applicable to mariculture (Deur et al., 2015; Jackley et al., 2016; Poulain et al., 2018; Bell et al., 2019; Toniello et al., 2019). Indigenous groups differ in opinions on aquaculture acceptability, implications for coastal management and territorial rights (*high confidence*) (Young et al., 2019). Such perceptions may determine culturally appropriate types and benefits of aquaculture (employment, food diversification, income, building autonomy and skillsets), e.g., Australia (Petheram et al., 2013) and Canada (Young and Liston, 2010). Marginalized people, like small-scale aquaculture farmers in lower-income and lower-middle-income countries, are often overlooked and are not represented at a governance level (Barange et al., 2014; Kalikoski et al., 2018). Therefore policy, economic, knowledge and other support needs to ensure representation with traditional and other stakeholder ecological knowledge at national, regional, and local levels to facilitate climate change adaptation and safeguard human rights for poor and vulnerable groups (*high confidence*) (Kalikoski et al., 2018; Poulain et al., 2018).

5.10 Mixed Systems

The food and livelihoods of many rural people depend on combinations of crops, livestock, forestry, and fisheries, and still information on these mixed systems is scarce. Rural households in low and middle-income countries earn almost 70% of their income through mixed production systems (Angelsen et al., 2014). These systems produce about half of the world's cereals, most of the fruits, vegetables, pulses, roots, and tubers, and most of the staple crops and livestock products consumed by poor people in lower-income countries (Herrero et al., 2017). They can help in adapting to climatic risks and reducing GHG emissions by improving nutrient flows and improving the recycling of nutrients within the production system and by increasing food production and diet quality per unit of land and diversifying income sources (Smith et al., 2019c). Indigenous groups often practice mixed production, integrating crops, animals, fisheries, forestry, and agroforestry through traditional ecological knowledge.

Some evidence exists of the buffering capacity that integrated systems can provide in the face of climate change (Gil et al., 2017). This buffering, often affecting the farming system as a whole rather than the individual agricultural enterprises involved, applies to some aquaculture-agriculture systems as well as to crop-livestock systems (Bunting et al., 2017; Stewart-Koster et al., 2017). In some situations, there may be tradeoffs and constraints at the household level that affect this resilience-conferring ability: for instance, mixed systems often need relatively high levels of management skill, and extra labour may be required (van Keulen and Schiere, 2004; Thornton and Herrero, 2015). The diversification of food production systems offers promise for enhanced resilience at the global level (Kremen and Merenlender, 2018; Dainese et al., 2019; section 5.4.4.4), though policies need to provide adequate incentives for resource efficiency, equity, and environmental protection (Havet et al., 2014; Thornton and Herrero, 2014; Troell et al., 2014).

5.10.1 Observed Impacts

5.10.1.1 Mixed crop-livestock systems

Overall, there is *high confidence* that farm strategies that integrate mixed crop-livestock systems can improve farm productivity and have positive sustainability outcomes (Havet et al., 2014; Thornton and Herrero, 2014; Herrero et al., 2015; Thornton and Herrero, 2015; HLPE, 2019). The scale of the improvement varies between regions and systems and is moderated by overall demand in specific food products and the policy context. Integrated crop-livestock systems present opportunities for the control of weeds, pests, and diseases. They can also provide a range of environmental benefits, such as increased soil carbon and soil water retention, increased biodiversity, and reduced need for inorganic fertilizers (Havet et al., 2014; Thornton and Herrero, 2014; Herrero et al., 2015; Thornton and Herrero, 2015; HLPE, 2019).

Research indicates that mixed crop-livestock systems are often more resilient to climate change *(medium confidence*). In the southern Afar region of Ethiopia, crop-livestock households were more resilient than livestock-only households to climate-induced shock (Mekuyie et al., 2018). However, the benefits of managing crop-livestock interactions in response to climate change depend on local context. For example, in higher-rainfall zones in Australia, Nie et al. (2016) found some yield reductions and difficulty in maintaining groundcover. The systematic review of Gil et al. (2017) concluded that the integration of crop and livestock enterprises as an adaptation measure can enhance resilience (FAQ 5.1).

Reconfiguring mixed farming systems is occurring. In semiarid eastern Senegal, Brottem and Brooks (2018) found increasing reliance on livestock production mostly because of changing climate conditions. Many poorer households are having to rely on migration to compensate for shortfalls in crop production arising from a changing climate. Some farmers have successfully shifted to crop-livestock systems in Australia, where they have allocated land and forage resources in response to climate and price trends (Bell et al., 2014).

Mixed livestock-crop systems may increase burdens on women, require managing competing uses of crop residues, and have higher requirements of capital and management skills. These factors can be challenging in many lower-income countries (Rufino et al., 2013; Thornton and Herrero, 2015; Jost et al., 2016; Thornton, 2018). The policy actions needed for the successful operation of mixed crop-livestock systems may be similar across widely different situations: good access to credit inputs and capacity-building needed to facilitate uptake (Hassen et al., 2017; Marcos-Martinez et al., 2017), and good levels of market infrastructure (Ouédraogo et al., 2017; Iiyama et al., 2018).

5.10.1.2 Mixed crop-aquatic systems

Households may have a mix of aquatic and land-based food production, contributing to food security and nutrition and income generation (Freed et al., 2020; see also discussion of aquaponics and hydroponics in Section 5.10.4.3. and combined rice-aquatic species production in Section 5.9.4). Failures in agricultural outputs due to climate-associated factors may result in diversification to fisheries as a way of alleviating food production shortfalls; for example, fisheries landings may dramatically increase after agricultural failures following hurricanes, which can subsequently create overfishing collapses (Cottrell et al., 2019). Where climatic impact drivers affect multiple sectors, adaptation may become more difficult because of the interacting challenges (Cottrell et al., 2019). One study of 12 countries with high food insecurity levels found that fish-reliant households utilized as much land as those not reliant on fish (Fisher et al., 2017). To meet food security requirements, most of these households needed to both farm and fish, illustrating the interdependence of aquatic-terrestrial food systems.

5.10.1.3 Agroforestry systems

Agroforestry is frequently mentioned as a strategy to adapt to and mitigate climate change and address food security ((de Coninck et al., 2018; Smith et al., 2019c). There is strong evidence of net positive biophysical and socioeconomic effects of agroforestry systems under both smallholder and large-scale mechanized production systems (Quandt et al., 2017; Hoegh-Guldberg et al., 2018; Sida et al., 2018; Wood and Baudron, 2018; Table 5.10; Cross-Chapter Box NATURAL in Chapter 2; Quandt et al., 2019). Many of these effects also reduce climate risk. At the same time, agroforestry systems are subject to impacts from climate change, potentially reducing the benefits they provide. Still, there is limited evidence of observed climate impacts on agroforestry systems, and modeling climate impacts is more complex for agroforestry than for single cropping systems (Luedeling et al., 2014).

5.10.2 Assessing Vulnerabilities

5.10.2.1 Assessing vulnerability in mixed systems

Important information gaps exist concerning the costs and benefits of many adaptation options in mixed systems, where the interactions between farming enterprises may be complex. Among communal crop-livestock farmers in Eastern Cape province of South Africa, Bahta (2016) reported high levels of vulnerability to drought and highlighted the need for more coordination between monitoring agencies in terms of reliable early warning information that can be communicated appropriately, between farmers' organizations and the private sector to facilitate adaptation options that can overcome feed shortages such as fodder purchases in times of drought, and between government departments at the national and provincial level that address the concerns and needs of affected communities. Nyamushamba (2017) reviewed the use of indigenous beef cattle breeds in smallholder mixed production systems in southern Africa. Some of these breeds exhibit adaptive traits such as drought and heat tolerance and resistance to tick-borne diseases. However, their adaptation potential in crossbreeding programs is essentially unknown, as most African cattle populations are still largely uncharacterized.

5.10.2.2 Social vulnerabilities

As in other production systems, Indigenous groups, gender, race, and other social categories can result in heightened vulnerability to climate change in mixed production systems due to historical and current marginalization and discrimination (*high confidence*) (Parraguez-Vergara et al., 2016; Baptiste and Devonish, 2019; Moulton and Machado, 2019; Popke and Rhiney, 2019; Fagundes et al., 2020). A study of the Mapuche Indigenous group in Chile found that marginalization and discrimination worsened their vulnerability and observed impacts of climate change because they had less access to services, lower incomes and were not as high a priority as other groups (Parraguez-Vergara et al., 2016). Among fisherfolk on Lake Wamala, Uganda, Musinguzi (2018) found evidence of considerable diversification to crop and livestock production as a means of increasing households' food security and income, but women had greater workloads and had less control over new income sources than men. Ngigi (2017) evaluated adaptation actions within households in rural Kenya and found that women tended to adopt adaptation strategies related to crops, men to livestock and agroforestry activities. Chingala (2017) found substantial gender- and age-related differences in control of access to animal feed, animal health, and water resources in beef producers in mixed crop-livestock systems in Malawi. In a review of agriculture-aquaculture systems in coastal Bangladesh, Hossain et al. (2018) showed that existing policies and adaptation mechanisms are not adequately addressing gender power imbalances, and women continue to be marginalized, leading to increasing feminization of food insecurity. Such studies highlight the need to consider gender and other social inequities when examining adaptation in mixed production systems, particularly in situations in which men and women have different levels of control over productive assets (Cross-Chapter Box GENDER in Chapter 18).

5.10.3 Projected Impacts

The impacts of climate change on risk in mixed farming systems are projected to be dependent on market, ecosystem, and policy context (*medium evidence, low agreement*). In mixed crop-livestock farms in a semiarid region of Zimbabwe, Descheemaeker (2018) found that feeding forages and grain could alleviate dry-season feed gaps to the 2050s, but their effectiveness depended on the household's livestock stocking density. In comparing different commercial production systems, Tibesigwa (2017) found that under South African conditions, climate change to the 2050s will reduce productivity across the agricultural sector, with the largest impacts occurring in specialized commercial crop farms owing to their relative lack of diversity. Mixed farming systems were the least vulnerable in terms of relative effects on farm output; this applied to commercial and subsistence sectors (Tibesigwa et al., 2017). Other studies suggest increased risk in mixed systems in semiarid conditions. In northern Burkina Faso, Rigolot (2017) examined different crop fertilization and animal supplementation levels under RCP8.5 to the 2050s. They found that although aggregate profits could be increased via moderate levels of inputs, the use of external inputs may increase risk because of marginal costs exceeding marginal benefits in lower rainfall years. In the Western Australian wheat belt, Thamo (2017) assessed climate-change-induced shifts in farm profitability to the 2050s. For most options, the adverse effects on profitability were greater than the advantageous effects, profit margins being much more sensitive to climate change than production levels. However, in the same system Ghahramani (2018) evaluated adaptation options to 2030 and found that a shift to a greater reliance on livestock could be profitable, even in years with low rainfall.

Risk management in integrated production systems may constitute a barrier to uptake of adaptation options (Rigolot et al., 2017). Watson (2018) highlighted the current lack of financial risk management tools that could be used in smallholder coastal communities. Alongside other risk management tools such as weather-based index insurance, risk pooling may find wide application in different farming systems as an effective adaptation measure (*medium agreement, limited evidence*) (Hansen et al., 2019a).

Climate change impacts on productivity of agroforestry systems are similar to individual perennial crops, although there is limited research on tree crops (see section 5.4.1.2). Impacts include increased temperature or water stress, an increase in pathogens affecting crops, changes to pollinator abundance, and changes in the nutrient content of one or more of the agroforestry components. Many tree products such as fruits and nuts are grown in agroforestry settings. The quality and nutrition of these products and other specialty crops are often negatively affected by rising temperatures, ambient CO_2 concentrations, and tropospheric ozone

(Ahmed and Stepp, 2016). There is also evidence that the fungus coffee rust will be positively affected by climate change (Avelino et al., 2015; Bebber et al., 2016), with adverse effects on coffee agroforestry systems.

While shade trees can ameliorate increasing stand temperatures that will significantly impact arabica coffee (Ovalle-Rivera et al., 2015; Schroth et al., 2015), the opposite can also be true. Comparing shade and full-sun coffee systems in Ghana, Abdulai (2018) concluded that the leguminous tree species providing shade and additional nitrogen led to soil water competition with the coffee trees during severe drought, resulting in enhanced coffee mortality. On the other hand, experimentally induced drought in a soybean-intercropping agroforestry system in eastern Canada led to crop losses in the monocropping system only, whereas N-fixation declined in both systems (Nasielski et al., 2015). Thus, balancing the synergies and tradeoffs of multiple component systems is necessary based on local context. While species diversification can enhance resilience to climate shocks, lack of water can constrain the implementation of agroforestry practices in arid locations (Apuri et al., 2018).

For people reliant on both agriculture and fisheries for food production, regional differences in productivity effects of climate change are expected; populations in LMICs that are already vulnerable will be most affected by simultaneous reductions in fisheries and agricultural productivity (Blanchard et al., 2017). Twelve out of 17 high-income countries in Europe showed projected increases in agricultural production where adaptive capacity is higher, and agricultural and food fisheries' dependence were lower. Some LMIC countries (Nigeria, Cameroon, Ghana, and Gabon) showed relative reductions in both fisheries and agricultural production, where food insecurity, human population growth, and fisheries overexploitation rates are high (Blanchard et al., 2017). Model projections under the RCP6.0 scenario show decrease in marine and terrestrial production to 2050 in 87 out of the 119 coastal countries studied, even though there is a wide variance in adaptive capacity and relative and combined dependencies on fisheries and agriculture (Blanchard et al., 2017). A projected 2050 move towards greater consumption of cultured seafood and less meat showed that aquaculture requires less feed crops and land, but was regionally dependent upon differing patterns of production, trade, and feed composition (Froehlich et al., 2018b).

[START BOX 5.7 HERE]

Box 5.7: Perspectives of crop and livestock farmers on observed changes in climate in the Sahel

The Sahel region of West Africa has experienced some of the most severe multi-decadal rainfall variations in the world: excessive rainfall in the 1950s–1960s followed by two decades of deficient rainfall, leading to a large negative trend until the mid-to-late 1980s with a decrease in annual rainfall of between 20 and 30%. Recently, there has been a partial recovery of annual rainfall amounts, more significant over the central than the western Sahel. This recovery is characterized by new rainfall features including false starts and early cessation of rainy seasons, increased frequency of rainy days, increased precipitation intensity, and more frequent and longer dry spells (Salack et al., 2015; Sanogo et al., 2015; Salack et al., 2016; Biasutti, 2019). The Sahel is experiencing a new era of rainfall extremes (Bichet and Diedhiou, 2018; Panthou et al., 2018), suggesting an intensification of the hydrological cycle (Doblas-Reyes et al., 2021).

The ways in which crop and livestock farmers in the Sahel have responded to climatic variability have been studied widely (Sissoko, 2011; Gonzalez et al., 2012; Jalloh et al., 2013; Gautier et al., 2016; Sultan and Gaetani, 2016; Zougmoré et al., 2016; Segnon, 2019). Local communities have developed an extensive Indigenous ecological knowledge system, enabling them to make use of ecosystem services to support their livelihoods and to survive environmental change (Nyong et al., 2007; Mertz et al., 2009; Lahmar et al., 2012; Segnon et al., 2015). These knowledge systems have been crucial in people's resilience to and recovery from major environmental change, such as the severe drought period experienced in the region in the 1970s and 1980s (Nyong et al., 2007; Lahmar et al., 2012; Segnon et al., 2015; Gautier et al., 2016; Zouré et al., 2019). As climate change became evident and a primary concern on the global agenda, interest in local people's knowledge and understanding of climate change has also increased (Mertz et al., 2009; Tambo and Abdoulaye, 2013; Traore et al., 2015; Kosmowski et al., 2016; Sanogo et al., 2017; Segnon, 2019).

There is no simple understanding of crop and livestock farmers' response in the Sahel to rainfall variability. Nielsen and Reenberg (2010) developed human-environment timelines for the period 1950-2008 for a small village in northern Burkina Faso, relating livelihood diversification and crop-livestock management changes that map closely to local rainfall variability, such as fields abandoned in dry years and intense animal manure use in wet years. Although they found a significant correlation between crop-livestock management practice changes and major climatic events, the climate is only one of many interacting factors that influence local adaptation strategies (Mortimore, 2010; Nielsen and Reenberg, 2010; Sendzimir et al., 2011). Robust attribution of observed changes to specific change drivers remains a challenge.

Crop and livestock farmers' knowledge and perceptions of increases in temperature and temperature-related stressors (heat waves, number of extreme hot or cold days) are consistent with the observed meteorological data (Mertz et al., 2009; Mertz, 2012; Tambo and Abdoulaye, 2013; Traore et al., 2015; Sanogo et al., 2017; Segnon, 2019). Their perceptions of changes in rainfall amounts have not always been consistent with the observational record (Mertz, 2012; Segnon, 2019). Nevertheless, their perception of increases in dry spell occurrence during the rainy season and changes in rainfall pattern (onset, cessation, rainfall intensity, and distribution) were consistent with the recent observations (Barbier et al., 2009; Ouédraogo et al., 2010; Tambo and Abdoulaye, 2013; Salack et al., 2015; Traore et al., 2015; Kosmowski et al., 2016; Salack et al., 2016; Segnon, 2019). Rainfall patterns within the season, rather than the total amounts of rainfall, matter more for crop and livestock farmers in the Sahel (Segnon, 2019).

Crop and livestock farmers in the Sahel have a sophisticated understanding of the local climate. There is considerable potential to harness this knowledge, coupled with an enabling institutional environment, in developing policies and adaptation plans (Rasmussen et al., 2018); the Sahel is a region where meteorological stations and observed data are scarce (Buytaert et al., 2012; Nkiaka et al., 2017). A deeper understanding of the resilience of local ecological knowledge systems, in light of the hydro-climatic intensification currently experienced in the region and future changes, may well provide further insights into their long-term effectiveness.

[END BOX 5.7 HERE]

5.10.4 Adaptation Strategies

5.10.4.1 Increasing integration and diversity within mixed systems

There is *medium confidence* in the effectiveness of changing the nature of the integration between crops and livestock as an adaptation: moving from crops to livestock, moving from livestock to crops, and moving from one species of livestock to others, for example (Roy et al., 2018). Such transitions that increase integration between farm enterprises may contribute to risk reduction and increased food security. In areas with adequate rainfall and relatively limited rainfall variability under climate change, where agricultural diversity is the greatest, transitions towards more diverse and integrated systems may bring substantial adaptation benefits (Waha et al., 2018).

Barriers to increasing integration and diversification include policies which support cereals and crop specialization, lack of markets, limited post-harvest processing, limited technical or biophysical research on implementation and poor market infrastructure (Keatinge et al., 2015; Bodin et al., 2016; Garibaldi et al., 2016; Bassett and Koné, 2017; Kongsager, 2017; Rhiney et al., 2018; Roesch-McNally et al., 2018; Clay and King, 2019; Ickowitz et al., 2019). Proactive policy and market development are needed to reduce these barriers (Clay and King, 2019; Ickowitz et al., 2019; See 5.14.3.8 for Insurance).

5.10.4.2 Agroforestry as an adaptation–mitigation strategy for mixed systems

Agroforestry, the purposeful integration of trees or shrubs with crop or livestock systems, increases resilience against climate risks through a range of biophysical and economic effects (*high confidence*). Traditional agroforestry has been practiced for millennia and provides prime examples of sustainable agroecological production systems meeting the production, income, and socio-cultural needs of farming communities within their ecological niches, but market forces have often led to their demise (McNeely and

Schroth, 2006; Plieninger and Schaar, 2008; García-Martínez et al., 2016; Krčmářová and Jeleček, 2016; Coq-Huelva et al., 2017; Paudel et al., 2017; Doddabasawa et al., 2018; Maezumi et al., 2018; Lincoln, 2020). The wide range of options to associate different trees with crops, livestock and aquaculture allow agroforestry to be practiced in most regions, including those with precipitation regimes ranging from semiarid to humid. While most agroforestry systems occur in smallholder settings, there are examples of successful industrial-scale mechanized agroforestry systems (Feliciano et al., 2018; Lovell et al., 2018). Agroforestry delivers medium to large benefits to all five land challenges described in the SRCCL - climate change mitigation, adaptation, desertification, land degradation, and food security - and is considered to have broad adaptation and moderate mitigation potential compared with other land challenges (Smith et al., 2019c). Agroforestry is also able to deliver multiple biophysical and socioeconomic benefits (Table 5.12).

Table 5.12: Some of the biophysical and socioeconomic benefits of agroforestry.

Contribution	Pathway	References
Increased food security and household income	Diversification of production, avoiding tradeoffs between crop and tree products	Nath et al. (2016), Coulibaly et al. (2017), Montagnini and Metzel (2017), Waldron et al. (2017), Blaser et al. (2018), Sida et al. (2018), Quandt et al. (2019), Amadou et al. (2020)
Increased productivity per unit of land	Introduction of multiple species leading to higher land equivalency ratios	van Noordwijk et al. (2018), Reppin et al. (2019)
Improved biophysical site properties	Via limiting soil erosion, facilitating water infiltration, increasing nutrient use efficiency, improving soil physical properties, improving crop nutritional quality, modifying the site micro-climate, and helping to buffer against extreme events	Nguyen et al. (2013); Carsan et al. (2014), Rosenstock et al. (2014), Quandt et al. (2017), Hoegh-Guldberg et al. (2018), Sida et al. (2018), Wood and Baudron (2018), de Leeuw et al. (2020), Muchane et al. (2020), Nyberg et al. (2020)
Enhanced biodiversity and supporting ecosystem services	Via integrating different perennial and annual species in different spatial or temporal associations, thereby providing greater habitat diversity for other species, including pollinators and predators	McNeely and Schroth (2006), Imbach et al. (2017), Isbell et al. (2017), Sonwa et al. (2017b), Tran and Brown (2019)
Enhanced cultural ecosystem services	Enhanced recreational, cultural and spiritual uses	Nyberg et al. (2020)
Carbon dioxide removal	Via enhanced above-ground carbon sequestration compared with most cropping or livestock systems, ranging from 2.6 -10 Mg C ha^{-1} yr^{-1} depending on regional and climatic conditions (> 0.7 Gt CO_2e yr^{-1} globally between 2000 and 2010)	Ramachandran Nair et al. (2009), Zomer et al. (2016), Rochedo et al. (2018), Wolz et al. (2018), Crous-Duran et al. (2019), Platis et al. (2019)
Enhanced gender balance	Via providing women with more diversified income sources	Kiptot et al. (2014), Ngigi et al. (2017), Benjamin et al. (2018)
Strengthened urban & peri-urban agricultural systems	Via provision of regulating and provisioning ecosystem services such as shade, water infiltration, new food and livelihood opportunities	Borelli et al. (2017) See Section 5.12

The adoption and maintenance of agroforestry practices require appropriate incentives or the removal of barriers (*high confidence*). Agroforestry adoption has been limited to date in both higher-income and lower-income countries. Several constraints need to be carefully addressed for successful scaling up of agroforestry systems, including costs of establishment, limited short-term benefits, lack of reliable financial support to incentivize longer-term returns on investments, land tenure, knowledge of and experience with trees and the management of multiple component systems, and inadequate market access, (Coulibaly et al., 2017; Iiyama et al., 2017; Jacobi et al., 2017; Kongsager, 2017; Hernández-Morcillo et al., 2018; Iiyama et al., 2018; Lincoln, 2019). Kongsager (2017) Roupsard et al. (2020) also highlight the need for vertical integration of measures from local to national scales to successfully address local barriers to adoption. Although there are few studies evaluating the long-term performance of agroforestry systems (Coe et al., 2014; Meijer et al., 2015; Brockington et al., 2016; Kongsager, 2017; Toth et al., 2017), the available results suggest that successful adoption of agroforestry practices depends strongly on the local enabling environment, including appropriate markets, technologies, and delivery systems (*medium evidence, high agreement*).

5.10.4.3 Links between crops and aquaponics-hydroponics as adaptation

Hydroponic systems produce plants in a soilless environment requiring mineral fertilizers to meet plant nutritional needs, whereas aquaponics combines an aquaculture production system with hydroponics, where fish waste provides nitrogen, phosphorous, and potassium for plant growth and nitrifying and mineralizing bacteria act as filters (Goddek et al., 2015; Pérez-Urrestarazu et al., 2019; Ghamkhar et al., 2020). The relative environmental impact of hydroponic systems is lower compared with conventional systems owing to the significant reductions in land use and fertilizer usage (*high confidence*) (Goddek et al., 2015; Datta et al., 2018; Pantanella, 2018; Suhl et al., 2018; El-Essawy et al., 2019; Jaeger et al., 2019; Monsees et al., 2019; Mupambwa et al., 2019; Pérez-Urrestarazu et al., 2019; Ghamkhar et al., 2020). While studies indicate that aquaponics and hydroponics have higher yields and a lower environmental footprint than conventional agriculture (*medium confidence*), aquaculture and heated greenhouse production (Pantanella, 2018; Romeo et al., 2018), aquaponic production may need to be coupled, decoupled, or have double-recirculation systems to meet the different requirements of farmed fish and crop species (Pantanella, 2018; Suhl et al., 2018; Mupambwa et al., 2019). Aquaponics and hydroponics are a promising adaptation option for urban agriculture, benefits including a protected growing environment from climate extremes, reduced GHG emissions related to food transportation, reduced food waste, rainwater harvesting and use of food waste (*medium agreement, limited evidence*) (Goddek et al., 2015; Al-Kodmany, 2018; Clinton et al., 2018; Weidner and Yang, 2020). Such systems show promise for reducing food production environmental footprints and increasing food security, particularly in arid or water-stressed environments (Doyle et al., 2018; Mupambwa et al., 2019). Barriers to aquaponics and hydroponics adoption include market acceptance of cultured fish species and desirability of plant crops, lack of expertise, legal constraints or high investment costs and financial feasibility (Bosma et al., 2017; Al-Kodmany, 2018; Datta et al., 2018; Pantanella, 2018; El-Essawy et al., 2019; Martin and Molin, 2019; Pérez-Urrestarazu et al., 2019; Specht et al., 2019). There is *high confidence* (*high agreement, medium evidence*) that a major barrier to hydroponic and aquaponics adoption is the requirement for skilled operators (Goddek et al., 2015; Bosma et al., 2017; Datta et al., 2018; McHunu et al., 2018; Pantanella, 2018), which could be mitigated by decoupling systems and disciplines (Pantanella, 2018). As yet, these systems are not widely implemented and information on their climate change impacts is limited.

5.10.4.4 Transitions in and between mixed systems as adaptation strategy

Transitions in and between the different elements of integrated agricultural systems can be an effective adaptation option *(medium confidence*). Havlik et al. (2014) projected that by 2030 market-driven autonomous transitions toward more efficient production systems would increase ruminant meat and milk productivity by up to 20% and decrease emissions by 736 $MtCO_2e \cdot y^{-1}$, most of this arising through avoided emissions from the conversion of 162 Mha of natural land. Weindl et al. (2015) assessed the implications of several climate projections on land use change to 2045 and found that shifts in livestock production towards mixed crop-livestock systems would represent a resource- and cost-efficient adaptation option, reducing global agricultural adaptation costs and abating deforestation by about 76 million ha globally. Both studies suggest that public policy support for transitioning livestock production systems to increase their efficiency could be an important lever for reducing adaptation costs and contributing to emissions reductions. This policy support could include modified regulatory and certification frameworks that incentivise livestock producers to adapt and mitigate (Weindl et al., 2015).

Recent reviews have summarised literature on production system transitions, driven at least partly by a changing climate or changing climate variability, that sometimes involves substantial shifts in enterprises and land configurations. These reviews found several cases of transitions affecting pastoral and mixed systems, with a range of responses including intensification, diversification, sedentarisation, as well as the abandonment of agriculture (see section 5.14.3.1, Vermeulen et al., 2018; Thornton et al., 2019). The consequences of these system transitions have been mixed; in some cases, the household level outcomes have been beneficial, while in others not. Policy environments, defined in terms of multi-level governance structures and institutions, are critical enablers of change. The vulnerability of many crop-livestock keepers to climate change is particularly affected by property and grazing rights (*high confidence*). Identifying the winners and losers from changes in land ownership and the use of communal lands in the coming decades is a key challenge for the research agenda, particularly as climate change impacts in the marginal lands intensify (Reid et al., 2014).

[START BOX 5.8 HERE]

Box 5.8: Climate Adaptation and Maladaptation in Cocoa and Coffee Production

Coffee and cocoa are important crops in low latitude regions where agriculture is projected to be heavily impacted by climate change. Both crops are at risk from climate change impacts by 2050 (Baca et al., 2014; Ovalle-Rivera et al., 2015; Chemura et al., 2016; Schroth et al., 2016; Bacon et al., 2017; Schreyer et al., 2018; de Sousa et al., 2019; Lahive et al., 2019; Pham et al., 2019; Cilas and Bastide, 2020). Chocolate and coffee are notable among foods in that their carbon footprint ranges from negative to high, as these industries include both low-input agroforestry systems that have many co-benefits, and high-input monoculture systems where crops are grown without shade, in some cases on sites that have been deforested (Poore and Nemecek, 2019). While the coffee industry in many countries has already transitioned from agroforestry to a full-sun production (Jha et al., 2014), the cocoa industry is at a turning point with many growers deciding whether to move to the potentially more productive ‘full-sun system', despite a general view that the agroforestry system is more resilient to climate change impacts (Rajab et al., 2016; Schroth et al., 2016; Farrell et al., 2018; Niether et al., 2020).

Shade-grown cocoa and coffee agroforestry systems provide an array of ecosystem services, including regulating pests and diseases, maintaining soil fertility, maintaining biodiversity and carbon sequestration (*high confidence*) (Jha et al., 2014; Rajab et al., 2016; Cerda et al., 2017; Pham et al., 2019). For example, a comparison of Indonesian cocoa stands found that total carbon stocks above and below ground were five times higher in multi-shade agroforestry stands compared to monoculture stands (57 compared to 11 Mg C ha^{-1}) and total net primary production was twice as high (18 compared to 9 Mg C ha^{-1} yr^{-1}). The extra carbon sequestration was achieved without any notable difference in cocoa yield (Rajab et al., 2016). At higher levels of shade there can be negative impacts on the yield of the understory crop, but careful management of shade trees allows for both crops to thrive (Andreotti et al., 2018; Blaser et al., 2018; Niether et al., 2020).

Cocoa grown under shade in some situations may be more resilient to climate change (Schwendenmann et al., 2010; Schroth et al., 2016). Schwendenmann et al. (2010) implemented drought experimentally in the field and found shade trees increased drought resilience. Shade trees insulate the understory crop from the warming and drying sun (Schroth et al., 2016). On the other hand, full-sun cocoa systems may be more climate resilient in some cases (Abdulai et al., 2018), as interactions between understory trees and shade trees are complex; in addition to shade effects, evapotranspiration and root interactions must be considered (Niether et al., 2017; Wartenberg et al., 2020). Moving to a full-sun system may also involve additional inputs in irrigation, fertiliser, and labour. Neither (2020) reviewed the literature comparing the two cocoa production systems and concluded that the agroforestry system was superior in terms of climate adaptation.

The choice of cropping-system will have wide-reaching consequences for climate vulnerability and climate justice. Coffee and cocoa are often a main source of income for small-scale producers who are among the most vulnerable to climate hazards (Bacon et al., 2014; Schroth et al., 2016). Most of their produce is exported by large corporations and sold to relatively better-off consumers. In the context of climate justice, underlying structural inequalities (socioeconomic, ethnicity, gender, caste), marginality, and poverty help to shape the vulnerabilities of small-scale farmers to climate hazards (Beckford and Rhiney, 2016; Schreyer et al., 2018). Climate change may compound their vulnerability, if for example the loss of pollination services leads to a reduction in productivity (Avelino et al., 2015). Adaptation needs to consider the inequalities associated with the commodity chain, and the adaptative capacity of producers as they seek to move into the more advanced processing stages of the commodity chain to realize higher returns from their exports (Ovalle-Rivera et al., 2015). Blue Mountain Coffee is a 'specialty' coffee associated with a Protected Area forest ecosystem that attracts a high price premium owing to its distinct flavour and aroma. The livelihoods of coffee farmers in this region are characterized by multiple socioeconomic, environmental, and institutional stressors related to climate change, pests, plant diseases and production costs. Some coping strategies employed by these coffee farmers have increased their susceptibility to future climate impacts (Guido et al., 2019). Davis (2017) showed that these coffee farmers' food security challenges could be alleviated by improved marketing of fruit tree products under shade coffee farming systems. Adaptation measures in such systems need to consider co-benefits and negative trade-offs, especially in vulnerable communities, to avoid widening further the inequalities, rural livelihood loss, migration, and marginalisation, and ensure progress towards the SDGs (*high confidence*).

[END BOX 5.8 HERE]

5.11 The Supply Chain from Postharvest to Food

The food system is more than just the production of food. It includes domestic and international transportation, storage, processing, market infrastructure and institutions that make up value chains, as well as the food environment in which consumers make food purchasing decisions (HLPE, 2017a). Climate change impacts along the value chain alter availability, access, and stability of food security. Nutrition-dense foods tend to be more perishable and are thus more vulnerable to limitations of food storage and transportation infrastructure (Ickowitz et al., 2019). Climate-change-related damage to food in storage (e.g., electricity failures and loss of cold storage) and transportation infrastructure (e.g., extreme weather events damaging roads and other infrastructure) could significantly decrease availability and increase the cost of highly perishable, nutritious foods such as fruits, vegetables, fish, meat, and dairy.

This discussion of the post–harvest food system (i.e., after production or catch) focuses on three key elements – food safety, storage, and domestic and international transactions – that could see significant climate change impacts, either directly or indirectly. Higher temperatures and humidity can increase post–harvest loss from pests and diseases, increase occurrence of food borne diseases and contamination, and raise the cost of refrigeration and other forms of preservation. Extreme weather events can cause disruptions to food transport networks and storage infrastructure. Changes in regional weather can cause production centres to shift locations, potentially requiring changes in storage and processing locations. Prices to producers and consumers will change although directions and magnitudes are determined by local conditions and policies.

Food *loss* is the harvest not used by industry or for food. Food *waste* is the subset of food loss that is potentially recoverable for food use. As a product moves in the postharvest chain to end users, post-harvest food loss from climate change can occur from improper handling to damage from microorganisms, insects, rodents, or birds. Post-harvest losses in quality can be the result of stresses and damage to a plant or animal before harvest, including from climate change (Hodges et al., 2011; Medina et al., 2015a). Food *waste* caused by climate change may occur at both retail units and homes because fresh ingredients and freshly prepared foods are vulnerable to quality reduction and spoilage from exposure to higher temperatures and humidity. Food waste also contributes to climate change by utilizing resources that emit GHGs (Galford et al., 2020).

5.11.1 Current and Future Climate Change Impacts on Food Safety

Emerging food safety risks from climate change include those posed by toxigenic fungi, plant and marine based bacterial pathogens, harmful algal blooms (HABs), increased use of chemicals (plant protection products, veterinary drugs) potentially leaving residues in food (European Food Safety Authority Panel on Plant Protection Products and their Residues et al., 2017; Deeb et al., 2018; Mbow et al., 2019; FAO et al., 2020).

Mycotoxins, produced by toxigenic fungi found on many crops, contaminate food and feed and cause a wide range of adverse impacts to human and animal health. Climate change can affect the growth and geographical expansion of these fungi (*high confidence)* (Wild et al., 2015; Battilani, 2016; FAO and WHO, 2016; Watson et al., 2016b; Alshannaq and Yu, 2017; Chen et al., 2018a; Avery et al., 2019; Milicevic et al., 2019; Van der Fels-Klerx et al., 2019; FAO, 2020a; FAO et al., 2020).

Aspergillus flavus is a fungus that infects a range of crops and can reduce grain quality. Several strains also produce aflatoxin, a particularly problematic mycotoxin. Increasing CO_2 and drought stress has little effect on growth of *Aspergillus* but significantly increases the production of aflatoxin (Medina et al., 2015b). In Europe one estimate is that the risk of aflatoxin contamination will increase in maize in a + 2°C temperature scenario in Europe with nearly 40% of Europe exceeding the current legal limits (Battilani and Toscano, 2016). In Malawi, maize aflatoxin levels above EU legal thresholds are possible for most of the country by mid-21st century (Warnatzsch and Reay, 2020). The occurrence of toxin-producing fungi will increase and expand from tropical and subtropical areas into new regions and where appropriate capacity for surveillance and risk management is lacking *(medium confidence)* (Miller, 2016). The increase in toxigenic fungi in crops, and consequent contamination of staple foods with mycotoxins, will increase the risks of human and animal exposure *(high confidence)* (Botana and Sainz, 2015; Rose and Wu, 2015; Battilani, 2016; Avery et al., 2019; Bosch et al., 2019; Milicevic et al., 2019; Moretti et al., 2019; Van der Fels-Klerx et al., 2019; FAO, 2020a).

In aquatic systems, mycotoxins produced by *Vibrio* during HABs also cause food safety problems (*high confidence*) (Botana, 2016; Estevez et al., 2019; section 5.8). Increased poleward expansion of Vibrios in coastal mid- to high-latitude areas has been observed (Baker-Austin et al., 2017). Vibrio-related mortalities from finfish consumption are expected to rise with climate change (water temperature, salinity, oxygen and pH) (*medium confidence*) (Mohamad et al., 2019a; Mohamad et al., 2019b). For shellfish species oxygen deficits (Mohamad et al., 2019b), sea-level rise (Deeb et al., 2018) and temperature (Green et al., 2019) will be most important for food safety.

Food safety is also anticipated to worsen from increased contaminant bioaccumulation under climate-induced warming (*high confidence*) (Sections 3.5.8, 3.5.9, 5.8, 5.9, Bindoff et al., 2019;), with changes in pathogen, parasite, fungi and virus abundance and virulence (Bondad-Reantaso et al., 2018). Coastal communities who depend on fisheries for livelihoods and nutrition are especially vulnerable (Hilmi et al., 2014; Golden et al., 2016; Bindoff et al., 2019).

Occurrence of bacterial pathogens such as Salmonella and Campylobacter will increase with rising temperatures (*high confidence*). Foodborne pathogen risks will increase through multiple mechanisms, though in general the impacts of climate change on different pathogens are uncertain (Akil et al., 2014; Hellberg and Chu, 2016; Lake and Barker, 2018). Even species within a genus can be affected differently. For example, higher CO_2 levels depress the growth rate of *F. graminearum*, an economically important pathogen on barley but have little effect on *F. verticillioides*, which is the most reported fungal species infecting maize.

Increases in rainfall intensity will have some effect on the transport of heavy metals by enhancing run-off from soil and increasing the leaching of heavy metals into water systems with magnitudes dependent on local conditions (*high confidence*) (Joris et al., 2014; Wijngaard et al., 2017). Methyl mercury (MeHg) is highly neurotoxic and nephrotoxic and bioaccumulates and biomagnifies through the food web via dietary uptake (fish, seafood, mammals) (Fort et al., 2016). Ocean warming facilitates methylation of mercury, and the subsequent uptake of methyl mercury in fish and mammals has been found to increase by 3–5% for each 1°C rise in water temperature (Booth and Zeller, 2005; FAO, 2020a). A changing climate will release mercury from snow and ice, raising the amount of mercury in aquatic ecosystems although its importance relative to industrial sources is unknown (Morrissey et al., 2005).

Increased frequency of inland floods has been associated with contamination of food with toxic and fat-soluble persistent organic pollutants (POPS), polychlorinated biphenyls (PCBs) and dioxins (Lake et al., 2014; Tirado, 2015; Alava et al., 2017). Exposure to POPs can lead to serious health effects including certain cancers, birth defects, and impairments to the immune, reproductive, and neurological systems.

Climate change–contaminant interactions may alter the bioaccumulation and biomagnification of POPs and PCBs as well as (MeHg) (Alava et al., 2017). Of particular concern is the pollution risk influenced by climate change in Arctic ecosystems and because of the bioamplification of POPs and MeHg in seafoods resulting in long-term contamination of traditional foods in Indigenous communities (Tirado, 2015; Alava et al., 2017).

The high risk associated with emerging zoonoses (animal diseases that can infect humans) and alterations in the distribution, survival and transmission of vectors and associated pathogens and parasites, could lead to an increased use of veterinary drugs and more rapid development of microbial resistance (European Food Safety Authority et al., 2020; FAO, 2020a) and higher veterinary drug residues in food of animal origin, potentially posing health issues for humans (Beyene et al., 2015; FAO et al., 2018; European Food Safety Authority et al., 2020). These outcomes will depend, at least in part, on the extent of changes in current regulatory systems for veterinary drugs. Preharvest stress on animals can increase the contamination of meat products with zoonoses. Climate change may also increase rodent populations and rodent-born zoonoses (Naicker, 2011). Extreme weather events that cause flooding, such as hurricanes or extreme rain events, increase the chance of inundating areas that contain waste from animal farms where antibiotics are used for production, increasing the spread of antibiotic-resistant bacteria into the surrounding environment (FAO, 2020a).

5.11.2 Current and Future Climate Change Impacts on Food Loss in Storage, Distribution and Processing

The potential for climate-change-based food losses exists in all parts of the food system – post-harvest storage, distribution, and processing – with the potential for impacts in one part of the system to be passed on to other elements (Davis et al., 2021). Storing a product destined for food use makes it available in times other than immediately after harvest, especially important for products with a pronounced seasonal availability or are not available from other regions with different seasons. Storage of fresh products (meat, fish, fruits, and vegetables) even with the best cold storage technology results in some quality loss relatively quickly. Higher temperatures increase the cost of maintaining quality. One estimate is that an increase in outdoor temperature from 17°C to 25°C increases cold storage power consumption by about 11% (James and James, 2010). Post–harvest storage of roots and cereals is subject to physical and quality losses from damage by mice, rats, and birds and by microorganisms such as the toxigenic fungi discussed above, all of which are expected to increase in warmer and more humid conditions.

The higher temperatures and humidity will generally raise storage costs and lower the quantity and quality of stored product, reducing producer incomes and raising consumer prices (*high agreement, medium evidence*) (Mbow et al., 2019). For example, in the US state of Michigan, climate change will shorten the period of reliably cold local storage of potato by 11-17 days and 14–20 days further south by mid-century and by 15–29 days and 31–35 days, respectively by late century. These changes would increase future demand for ventilation and/or refrigeration immediately after harvest and again in spring and early summer (Winkler et al., 2018).

Insects are a main source of food loss. Climate change can alter insect damage in at least two ways – increases in reproductive rate from temperature increases and changes in pheromone effectiveness (*high confidence*). Increasing temperature up to about 40°C raises the rates of insect food digestion and reproduction (Deutsch et al., 2018), but temperatures above that level are fatal for many insects (Neven, 2000). Most insects rely on pheromones to facilitate reproduction. Higher temperatures, but also increases in atmospheric CO_2 and O_3 levels, can affect this process. Insect species that rely on long-range chemical signals (such as ladybirds, aphids, bark beetles and fruit flies) will be most impacted, because these signals suffer from longer exposure to processes that reduce pheromone effectiveness (Medina et al., 2015b; Moses et al., 2015; Boullis et al., 2016; Verheecke-Vaessen et al., 2019).

There are several potential pathways for climate change impacts on processing that would negatively affect quality and appearance, but with limited research to date. For example, some studies have indicated that recent increases in temperature have decreased the appearance and milling quality of rice in the US and East Asia, owing to increased occurrence of chalky grains (Lyman et al., 2013; Morita et al., 2016; Masutomi et al., 2019; Ishigooka et al., 2021). Impacts on quality of perennial crops and annual fruits and vegetables are discussed above (Section 5.4.3 and Box 5.2).

5.11.3 Current and Projected Impacts on Transportation and Distribution: Domestic and International Trade

Regional differences in resource availability are a key underlying driver of domestic and international trade. Climate change can change resource availability, both in quantity and quality terms, altering trade flows, prices, and incomes of producers. Climate change can also affect food access and its stability can be affected through climate change driven disruption of infrastructure (FAO et al., 2018; Mbow et al., 2019). Extreme events are expected to become more common as climate change progresses. Recent examples illustrate the potential for trade disruptions. In March 2019, Cyclone Idai affected 1.7 million people in Mozambique and 920,000 in neighbouring Malawi, according to UN officials. The World Food Program reported that satellite imagery of flooding in central Mozambique showed an 'inland ocean' the size of Luxembourg with potentially large impacts on distribution of existing supplies, and uncertain effects on future food production and availability. The extreme rainfall events in the US state of Iowa in spring 2019 destroyed large numbers of well-built grain silos. In addition, major road and bridge damage required rebuilding.

Trade plays a sizeable role in global food supplies. More than 1 billion people relied on international food trade in the early 21st century (Fader et al., 2013; Pradhan, 2014). Domestic and international trade flows can be dramatically affected by climate change impacts *(medium evidence, high confidence)* (Nelson et al., 2014; Pradhan, 2014; Wiebe et al., 2015). Since the impacts of climate change will not be uniform, profitable locations for exports production will change. In addition, the effects of increasing local weather variability caused by climate change means increasing variability of food availability for domestic use and international trade. Finally, extreme events driven by climate change can disrupt transportation along the food value chain. Countries more at risk of natural hazards that disrupt transportation and distribution, and with less extensive routes, are more vulnerable to climate change impacts. A global multi-hazard risk assessment (Koks et al., 2019) suggests surface and river flooding, which are projected to increase in a warmer climate, are the main hazards for road and railway infrastructure, increasingly disrupting international and domestic transportation of agricultural commodities.

Climate change impacts will increase most global prices relative to early 21st levels with varying effects on the cost of food imports *(high confidence)* (Nelson et al., 2014; Wiebe et al., 2015; Fujimori et al., 2018; Lee et al., 2018). For example, analysis using results from one study (using CMIP5 data for RCP8.5 and SSP2) found that net food importing countries in the early 21st century would see expenditures on food imports decrease by USD 36 billion in mid-century in real terms with climate change over a no climate change scenario. (Table 5.13).

Table 5.13: Net exports of agricultural products, by net exporting and net importing countries, 2010 and 2050 (billion constant parity US dollars), based on analysis in Beach et al. (2019)

	2010	2050
Net importers in 2010		
No climate change	-301	-838
Climate change	-301	-802

Global economic models with a focus on agriculture provide a perspective on the range of potential changes in market outcomes because of climate change. In one study comparing several SSPs to a future with no climate change to one with impacts from RCP8.5, 2050 yields with climate changes impacts are 17% smaller on average than those without climate change. Adaptation by farmers reduce that to an 11% decline. The change in 2050 prices of all crops and regions after climate change impacts and farm level adaptation is a mean 20% increase (Nelson et al., 2014). Substantial differences arise from both the heterogeneous impacts of climate change over crops and geography and the diversity of modelling approaches in the GCM and crop models. A later study with more socio-economic scenarios and fewer models got roughly similar results (Wiebe et al., 2015) as did a modelling study focused on food security in South Asian countries (Cai et al., 2016).

Most climate scenario modelling to date does not incorporate increasing variability nor the use of storage, a critical tool to manage variability. Two recent studies are exceptions. In one, climate change generally reduces mean yields and increases their variability in the Midwestern U.S. and causes modest increases in price volatility (Thompson et al., 2018). A second study (Chen and Villoria, 2019) focuses on maize net importers across Africa, Asia, and Latin America during 2000–2015. A 1% increase in the ratio of imports to total consumption reduces domestic price variability by 0.29%. A 1% increase in stocks at the beginning of the season is correlated with a 0.22% reduction in the coefficient of variation.

5.11.4 Adaptation in the Post-harvest Supply Chain

The SRCCL (Mbow et al., 2019) findings on adaptation support targeting food value chains and intervention types to the needs of specific locations. Furthermore, adaptation choices will need to be dynamic as climate change impacts are expected to worsen over time.

As discussed above and in section 6.2.5, climate change is expected to cause increasingly severe effects on infrastructure needed for food security: roads and harbours for transport, water storage facilities for irrigation and storage facilities able to withstand climate-related damage. Three categories of adaptation could be considered – adoption of technologies already in use elsewhere, including indigenous and local knowledge, or available or near ready that become profitable as impacts become more severe, development of new technologies, and taking advantage of changing comparative advantage across regions. Specific examples of post-harvest technical adaptation options that are already available but could be more widely adopted include solar driers, cold storage facilities and transport and use of ultrasonic humidification of selected fruits and vegetables, a technology that has been shown in Europe to reduce losses in each post–harvest stage by 20% or more (Fabbri et al., 2018). Hermetic storage containers using community-based farmer research networks to scale out (Singano et al., 2020; Wenndt et al., 2021) also show promise. Another innovation is to introduce Aspergillus fungi that do not produce aflatoxins in biocontrol formulations, such as being undertaken in the Aflasafe project in Kenya (Bandyopadhyay et al., 2016).

International trade changes are a potentially important adaptation mechanism for both the short-term effects of climate variability and long-term changes in comparative advantage with globally substantial benefits but that are distributed unevenly (Mosnier et al., 2014; Baldos and Hertel, 2015; Fuss et al., 2015; Costinot et al., 2016; Hertel and Baldos, 2016; Gouel and Laborde, 2021). One estimate is that with a reduction in tariffs as well as institutional and infra-structural barriers, the negative impacts of climate change globally would be reduced by 64%, with hunger-affected import-dependent regions seeing the greatest benefit. However, in hunger-affected export-oriented regions, partial trade integration might lead to increased exports at the expense of domestic food availability (Janssens et al., 2020). It is possible for policy changes that result in increased trade flows to also increase the potential for maladaptation, for example by encouraging conversion of environmentally sensitive areas to agriculture (Fuchs et al., 2020; 5.13.3).

As discussed in section 5.4, climate change is expected to increase variability in yields. As long as the variability is not correlated across regions, trade flows within a year can partially compensate, with in-period exports from countries less affected to those that are. Alterations in trade flow patterns to accommodate these impacts will reduce the negative effects so long as this variability is not correlated across regions (UK, 2015; Janetos et al., 2017).

In terms of food safety impacts, (Lake and Barker, 2018) highlight a range of approaches to enhance preparedness for more serious foodborne disease effects from climate change: adoption of novel surveillance methods to speed up detection and improve intervention in foodborne outbreaks; genotype–based approaches to surveillance of food pathogens to enhance spatiotemporal resolution in tracing and tracking of illness; improving integration of plant, animal and human surveillance systems under the rubric of One Health, increased commitment to cross–border and global information initiatives; improved clarity regarding the governance of complex societal issues such as the conflict between food safety and food waste and strong user–centric (social) communications strategies to engage diverse stakeholder groups.

The range of potential adaptation approaches from production to transportation to reduce food loss and waste is captured in Figure 5.17 (Galford et al., 2020).

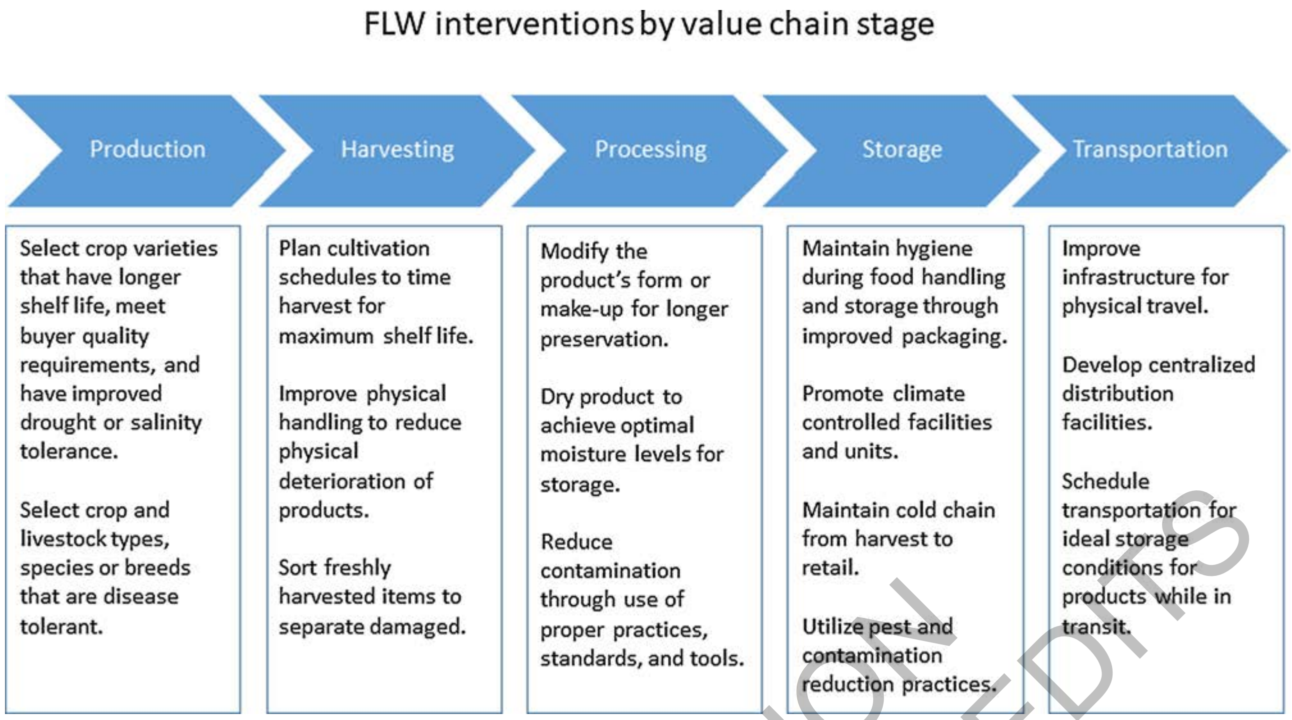


Figure 5.17: Examples of food loss and waste (FLW) interventions at five stages in the food value change (Galford et al., 2020).

The importance of reducing food loss and waste due to climate change is widely recognized, but literature on cost-effective reductions is sparse, particularly in low-income countries (Parfitt et al., 2010). A list of farm and post-harvest methods to reduce food loss (Sheahan and Barrett, 2017) includes potential farm interventions such as varietal choice, education in harvest and post-harvest handling, hermetic storage technologies (see above), chemical sprays and integrated pest management techniques in storage. The evidence on their effectiveness, especially in the face of increased climate change impacts, is limited.

5.12 Food Security, Consumption and Nutrition

5.12.1 Introduction

Food security and nutrition are key desired outcomes of food systems. Climate change is already contributing to reduced food security and nutrition and will continue to do so (*high confidence*) (Sections 5.4, 5.5, 5.8, 5.9, 5.10). Climate change impacts affect all four dimensions of food security: availability, access, utilization, and stability (Table 5.14) through both direct and indirect pathways.

Global food security improved dramatically in the 20th century even as global population increased from 2 to 6 billion. While some may assume that global food security is primarily provided by large-scale producers, research since AR5 has shown the sizeable role of small and mid-sized food producers in Asia, Africa and Latin America contributing to global food security and nutrition, while being highly vulnerable to climate change impacts on food security (Samberg et al., 2016; Herrero et al., 2017; FAO et al., 2018; Ricciardi et al., 2018).

In 2019 more than 750 million people in the world, almost 1 in 10 people, suffered from severe food insecurity, a figure which has risen since 2014 in every region except North America and Europe (FAO et al., 2020). Overnutrition, a result of high-calorie unbalanced diets, is also rising, with over 2 billion adults overweight or obese (FAO et al., 2018; Swinburn et al., 2019; FAO et al., 2020; Venkatesh Mannar et al., 2020; WHO, 2021). Many low and middle-income countries now have both high under- and overnutrition rates (FAO et al., 2018).

There are multiple drivers of food security including changing dietary patterns, urbanization and population growth (HLPE, 2017b; FAO et al., 2018; Swinburn et al., 2019). Vulnerability to climate change impacts on food insecurity and malnutrition is worsened by other underlying causes, including poverty, multiple forms of inequality (e.g., gender, racial, income), low access to water and sanitation, macroeconomic shocks, and conflict (Smith and Haddad, 2015; Clay et al., 2018; FAO et al., 2018; Cook et al., 2019). Climate change frequently acts to compound these drivers of food insecurity (Table 5.14).

The covid-19 pandemic has increased vulnerability to food insecurity and malnutrition of particular groups and sectors in the food system, including low-income households, farmworkers, food service workers, informal food market sellers, and low-income countries dependent on food imports (Cross-Chapter Box COVID in Chapter 7). Climate change will compound pandemic vulnerabilities in the food system (*high agreement, low evidence*) (HLPE, 2020; UNDRR (United Nations Office for Disaster Risk Reduction - Regional Office for Asia and Pacific), 2020; WFP-FSIN, 2020). The pandemic may also increase coordination among sectors and a willingness to address food system weaknesses made visible by the impacts of COVID-19 (Blay-Palmer et al., 2020; Cohen, 2020; Ramos et al., 2020).

Ecosystem services, the provisioning, supporting, and regulating mechanisms we all depend on for food security and nutrition, are also undermined by climate change impacts (Section 5.4.3). Even in the absence of climate change, our current food system threatens to exceed planetary, regional, or local boundaries of long-term sustainable development (Campbell et al., 2017). Climate change will make efforts to reduce this threat more difficult to achieve (*medium confidence)* though many solutions to enhancing food security are also potential climate change adaptation responses (Sections 5.4, 5.6, 5.8, 5.10, 5.14).

5.12.2 Mechanisms for Climate Change Impacts on Food Security

Climate change is increasing the number of people experiencing food insecurity through greater incidence and severity of climatic impact drivers (CIDs), (Seneviratne et al., 2021) such as extreme heat, drought, and floods. Increasing CO_2 concentrations have positive effects on food and forage crops by enhancing photosynthesis and alleviating drought stresses (5.4.3.1, 5.5.3.1), but have negative effects on nutrient concentrations in food crops. Ocean acidification is also caused by increasing CO_2, causing negative impacts on aquatic systems. Tropospheric ozone concentrations already hinder crop production (Section 5.4.1.4). Several CIDs increase the number of people experiencing food insecurity (*high confidence*) (SROCC 2019, FAO et al., 2018; Mbow et al., 2019; Baker and Anttila-Hughes, 2020; Table 5.12).

Vulnerability to climate impacts on food security and nutrition vary by region and group. Countries that experience CIDs such as extreme heat, severe drought or floods and have a large proportion of the population dependent on rainfed agriculture or livestock for their livelihoods and food supply have experienced rising food insecurity due to climate change impacts (FAO et al., 2018; Cooper et al., 2019; Mbow et al., 2019). Children in Sub-Saharan Africa are particularly at risk of undernutrition and mortality from increasing temperatures (Belesova et al., 2019; Baker and Anttila-Hughes, 2020). An additional estimated 5.9 million children became underweight due to rising temperatures in 51 countries affected by El Niño Southern Oscillation intensity in 2015-2016 (Anttila-Hughes et al., 2021). Low-income urban households and marginalized groups such as landless and ethnic minorities are at risk of increased food insecurity due in part to climate change extreme events such as extended drought, floods or cyclones that interrupt supply chains and impact livelihoods (Rodriguez-Llanes et al., 2016; FAO et al., 2018; Algur et al., 2021). A systematic review in India found that women often experience greater workloads and stress during drought events (Algur et al., 2021).

In the subsequent sections, the four dimensions of food security will be discussed in relation to observed and projected impacts and vulnerabilities (Table 5.14).

Table 5.14: Impacts from climate change drivers on the four dimensions of food security. Adapted from Table 5.1 in SRCCL

Climatic impact drivers and mechanism for food security impacts	**Examples of regions and groups most affected**	**References**
Food security dimension: Availability		

Increased heat and drought reduce crop and animal productivity and soil fertility and increase land degradation for some regions and crops.	Countries in which a large proportion relies on agriculture for livelihoods. Food production systems that rely on rainfed agriculture and pastoral rangeland. Urban populations and the poor.	FAO et al. (2018), Dury et al. (2019), Mbow et al. (2019), Section 5.4 and 5.5).
Extreme heat affects crop productivity. Combined with high humidity reduces agricultural labour capacity and animal productivity.	Countries and sectors that rely extensively on outdoor manual agricultural labor and experience high temperatures and humidity	Zander et al. (2015), Kjellstrom et al. (2016), Ioannou et al. (2017), Mitchell et al. (2017), FAO et al. (2018), Flouris et al. (2018), Kjellstrom et al. (2018), Levi et al. (2018).
Increasing temperatures and precipitation changes increase and shift crop and livestock pests and diseases	East African pastoral groups who experienced increased livestock morbidity and mortality from Rift Valley Fever in El Niño years.	Bebber (2015), FAO et al. (2018), Mbow et al. (2019), Sections 5.4.1.3 and 5.5.1.3
Increasing temperatures and drought stress has led to higher post-harvest losses due to mycotoxins.	Tropical and sub-tropic regions with limited food safety surveillance	Miller (2016), FAO et al. (2018), Section 5.11
Rising ocean temperatures, marine heatwaves and ocean acidity has reduced availability of fish in coastal communities.	Coastal people and coastal areas of tropical countries with high dependence on fisheries e.g., West African coastal communities	Hilmi et al. (2014), Golden et al. (2016), Bindoff et al. (2019), Section 5.8 and 5.9
Increased number and intensity of extreme events such as cyclones lead to reduced food production and distribution from crop damage, increased pest incidence and transportation disruption.	Delta regions where there are high populations and are often important food production regions. E.g., Cyclone Nargis in Myanmar estimated to reduce crop production by 19%, production declined for subsequent 3 years.	Omori et al. (2020)
Increased atmospheric CO_2 concentrations increase total plant biomass and plant sugar content, which can increase crops as well as pests and weeds. High CO^2 also reduces transpiration during drought which can increase plant drought resistance.	All regions are anticipated to have increased atmospheric CO^2 concentrations, but due to impacts of other CIDs (e.g., drought, heat stress, pests), the impacts on crop growth, forage, and subsequent food availability are mixed.	Iizumi et al. (2018); Canadell et al. (2021), Ranasinghe et al. (2021), Cross-Chapter Box MOVING PLATE this Chapter)
Food security dimension: Access		
Increased **drought** and **flood events** and increased pests and disease from **rising temperatures** lead to loss of agricultural income due to reduced yields, and higher costs of production inputs such as water. Reduced ability to purchase food leads to lower dietary diversity and consumption levels.	Low-income smallholder farmers and pastoralists in Ethiopia, Mali, Niger, Malawi, Zambia, and Tanzania.	Saronga et al. (2016), Giannini et al. (2017), FAO et al. (2018) Mbow et al. (2019) Omori et al. (2020)
Increase in number and intensity of **extreme weather events (e.g droughts, floods**) lead to increased food prices, which often leads to lower dietary diversity as well as lower consumption levels.	Low-income consumers. Women and girls.	FAO et al. (2018), Mbow et al. (2019), Ilboudo Nébié et al. (2021)
Extreme events (e.g. floods) disrupt food storage and transport networks, reducing access and availability of food supplies.	Countries dependent on food imports e.g Small Island Developing States. Poor households living in flash flood and saline zones in Bangladesh who rely on monocropped rice. Women and children may experience greater impacts from extreme events.	Toufique and Belton (2014), FAO et al. (2018), Hickey and Unwin (2020), Algur et al. (2021)
Food security dimension: Utilization (food quality and safety)		
Increased temperatures reduce food safety caused by microorganisms, including increased mycotoxins in food and feed.	Countries with limited food safety surveillance systems.	FAO et al. (2018), Mbow et al. (2019), Section 5.11

Climate change **extreme events** make fruits and vegetables relatively unaffordable compared to less nutrient dense foods.	Urban low-income households and rural households who purchase the majority of their food. Children in regions such as West Africa, with lower access to diverse food types as a result of climate impact drivers e.g. drought.	An et al. (2018), Algur et al. (2021), Baker and Anttila-Hughes (2020), Niles et al. (2021)
Rising air temperatures, **ocean warming, and high CO_2 conditions** increase risk of food poisoning and pollutant contamination of food through increased prevalence of pathogens (e.g., mycotoxins), harmful algal bloom, and increased contaminant bioaccumulation and threaten human health.	Low-income tropical countries where current ability to reduce and monitor mycotoxin contamination is limited. Coastal Indigenous Peoples and other poor populations in coastal areas of tropical countries with high dependence on fisheries e.g., west African coastal communities	Golden et al. (2016), Bindoff et al. (2019), Sections 5.7, 5.8, 5.9, 5.11
Increased atmospheric CO_2 concentrations reduce nutritional quality of grains, some fruits, and vegetables.	Low-income households who have limited access to range of diverse foods.	Mbow et al. (2019), Section 5.4
Rising ocean temperatures, marine heatwaves and ocean acidity reduce fish populations, which reduce consumption of fish high in iron, zinc, omega-3 fatty acids and vitamins in areas where fish populations decline.	Coastal areas of tropical countries; coastal Indigenous Peoples and other groups who rely on fisheries.	Golden et al. (2016); Bindoff et al., 2019; Section 5.7, 5.8, 5.9
Food security dimension: Stability		
Increased frequency and severity of extreme events (e.g., **droughts** and **heatwaves)** lead to greater instability of supply through production losses and disruption to food transport.	Landlocked countries; low-income countries reliant on imports; lo- income households in areas prone to floods.	Toufique and Belton (2014), FAO et al. (2018), Algur et al. (2021), Section 5.11
Increased drought and **flood events** and increased pests and disease from **rising temperatures** lead to unstable incomes from agriculture and fisheries.	Small-scale producers (crops and livestock) and fishers	Ruiz Meza, (2015), FAO et al. (2018), Sections 5.8, 5.9
Climate change **extreme events** increase food prices due to climate shocks.	Low-income countries reliant on imports; Urban low-income households and rural households who purchase the majority of their food.	Bene et al. (2015), Peri (2017), Mbow et al. (2019), Section 5.11
Increased drought and **flood events** and increased pests and disease from **rising temperatures** cause widespread crop failure. **Rising ocean temperatures, marine heatwaves, and ocean acidity** lead to dramatic decline in fisheries contributing to migration and conflict.	Coastal communities in West Africa, SE Asia, and other tropical countries highly dependent on fisheries.	Golden et al. (2016), Bindoff et al. (2019) Mbow et al. (2019)
Reduced frost days and snow days will increase stability of food security in some temperate regions since there will be less loss of food crops to frost damage and a longer growing season. However, they also raise pest and disease risks due to increased range and overwintering.	Australia, most Asian regions, Europe, Central and South America, North America The benefits of yield gains at high latitudes may be tempered by greater risks of pests and pathogen damages.	Jones and Barbetti (2012), IPPC Secretariat (2021), Ranasinghe et al. (2021)

5.12.3 Observed Impacts

5.12.3.1 Impacts on food availability

All food production systems (crops, livestock, marine, fish, mixed, aquaculture) have been undermined by climate change and are expected to experience larger impacts in the future as described in earlier sections (see Sections 5.4.1, 5.5, 5.8, 5.9, 5.10). In addition, sudden production losses from extreme climate events can reduce food security (FAO et al., 2018; Cottrell et al., 2019; FAO et al., 2020; Anttila-Hughes et al., 2021). For example, a 2007 drought-induced crop failure in southern Africa led to severe food insecurity in

Lesotho because of the land-locked country's dependence on imports from South Africa that aggravated food availability and access under conditions of declining food production and land degradation (Verschuur et al., 2021). Pest and disease outbreaks in both crops and livestock due to climate change (Sections 5.4.1, 5.5.1) have also impacted food availability and access (see Box 5.8 Desert Locust case study). Loss in labour productivity from climate change-related heat stress is a growing problem.

[START BOX 5.9 HERE]

Box 5.9: Desert Locust Case Study: Climate as Compounding Effect on Food Security

At the end of 2019, desert locust swarms infested Eastern Africa and caused widespread damage to crops and pastures, threatening food security and livelihoods (Kimathi et al., 2020; Salih et al., 2020). The FAO estimates that over 200,000 ha of crop and pastureland were damaged, rendering 2 million people in the region acutely food insecure (IGAD, 2020). The desert locust infestation was facilitated by two tropical cyclones that created desert lakes in a usually dry region of Saudi Arabia. Moist soils, warm temperatures and ample vegetation provided a suitable environment for desert locust breeding and migration to Yemen and Somalia, where the pest remained uncontrolled due to conflict and spread to neighbouring countries. A series of political and socioeconomic weaknesses such as armed conflict, limited financial resources, and lack of early actions compounded the impact of the current invasion and made it the most damaging in 70 years (Meynard et al., 2020; Salih et al., 2020).

Although desert locusts have been here for centuries, this recent outbreak can be linked to a unique feature of the positive Indian Ocean Dipole event (IOD), in part caused by long-term trends in sea surface temperatures (Wang et al., 2020a). The warming of the western Indian Ocean has increased frequency and intensity of severe weather, including tropical cyclones (Roxy et al., 2014; Murakami H, 2017; Roxy et al., 2017). Under a 1.5° C warmer climate, extreme positive IODs are anticipated to occur twice as often, which could also increase the occurrence of pest outbreaks (Cai et al., 2018).

Climate change increases the need for robust adaptation measures, such as transnational early warning systems, biological control mechanisms, crop diversification, and further technological innovations in areas of sound and light stimulants, remote sensing, and modeling for tracking and forecasting of movement (Maeno and Ould Babah Ebbe, 2018; Peng et al., 2020). The desert locust outbreak and the role of the Indian Ocean warming show that the impacts of climate change extend can increase unpredictable events. Extreme weather events act as a compounding effect, exacerbated further by weak governance systems, political instability, limited financial resources, and poor early warning systems (Meynard et al., 2020).

[END BOX 5.9 HERE]

Climate change affects agricultural labour productivity through increased intensity and frequency of heat stress events, with those performing physical labour in high humidity and ambient temperatures most vulnerable to heat stress (*high confidence*) (Hsiang et al.; FAO et al., 2018; Kjellström et al., 2019; Antonelli et al., 2020; Shayegh et al., 2020). Labour capacity, supply, and productivity loss in moderate outdoor work due to heat stress is estimated between 2% and 14% depending on the location and indicator (Ioannou et al., 2017; Kjellstrom et al., 2018), with an overall estimate of 5.3% loss in productivity for outdoor work between 2000 and 2015 (*medium confidence*) (Watts et al., 2018) but as high as 14% in low-income tropical countries (Antonelli et al., 2020; Shayegh et al., 2020). Highly vulnerable occupation groups affected by heat stress include farmers, farmworkers and livestock keepers working outdoors in low-income tropical countries (*high confidence*) (Zander et al., 2015; Kjellstrom et al., 2016; Flouris et al., 2018; Kjellstrom et al., 2018; Levi et al., 2018). Farmworkers and small-scale food producers in high- and middle-income countries involved in outdoor labour are also affected by heat stress (Zander et al., 2015; Gosling et al., 2018; Szewczyk et al., 2018; Watts et al., 2021). There is also evidence that heat stress is affecting labour supply through variation in nutrition intake (Antonelli et al., 2020).

5.12.3.2 Impacts on food access (physical, economic, and socio-cultural) and vulnerabilities

Increased extreme events (e.g., droughts, floods, and tropical storms, (Seneviratne et al., 2021) due to climate change are key drivers of recent rises in food insecurity rates and severe food crises in some regions (*high confidence*) (Section 5.4.1, Yeni and Alpas, 2017; FAO et al., 2018; Cooper et al., 2019; Baker and Anttila-Hughes, 2020; Bogdanova et al., 2021; Ilboudo Nébié et al., 2021). Extreme weather events reduce physical and economic access to food, increase food prices, and compound underlying conditions of food insecurity and malnutrition such as low access to diverse healthy foods, and safe water (FAO et al., 2018; Niles et al., 2021). Increased incidence of severe drought conditions since 2005 are contributing to food insecurity in affected regions, including Africa, Asia, and the Pacific (Chapter 7, Phalkey et al., 2015; FAO et al., 2018; Cooper et al., 2019; Ilboudo Nébié et al., 2021; Verschuur et al., 2021;). In Arctic western Siberia, high temperatures, melting ice and forest and tundra fires have degraded reindeer pastures; Indigenous Peoples have reduced traditional diets and increased purchased food with increases in hypertension and related health impacts (Bogdanova et al., 2021).

There is growing evidence that anthropogenic climate warming has already intensified climate extreme events induced by large-scale sea surface temperature oscillations such as ENSO (Herring et al., 2018; Seneviratne et al., 2021). For example, the 2015-2016 El Niño, the strongest for the past 145 years, induced severe droughts in southeast Asia, eastern and southern Africa, some intensified by anthropogenic warming (Funk et al., 2018). As a result, 20.5 million people faced acute food insecurity in 2016 (FSIN, 2017) and an estimated additional 5.9 million children became underweight (Anttila-Hughes et al., 2021).

Weather extreme events increased food prices and food price volatility (Peri, 2017), thereby worsening food insecurity (Shiferaw et al., 2014; Bene et al., 2015; Miyan, 2015; FAO et al., 2018; Ilboudo Nébié et al., 2021). Rising food prices can affect conflict, political instability, and migration (Bush and Martiniello, 2017) but the relationship between climate change, political instability and conflict is often mediated by other underlying factors such as poor governance (Chapter 7.2.7, Mach et al., 2019; Selby, 2019).

Low-income urban and rural households who are net food buyers are particularly affected by food price increases, with reduction of consumption of diverse food groups (*high confidence*) (Green et al., 2013; Villasante et al., 2015; FAO et al., 2018). Depending on the context, particular groups, including women, ethnic and religious minorities will be more vulnerable to worsening food insecurity from climate change impacts (Clay et al., 2018; Jantarasami et al., 2018; Nature climate change Editorials, 2019; Algur et al., 2021 and see Cross-Chapter Box GENDER in Chapter 18). Indigenous Peoples are often more vulnerable to climate change, due to conditions of poverty, limited resources, discrimination, and marginalization (*high confidence*) (Smith and Rhiney, 2016; Vinyeta et al., 2016; Jantarasami et al., 2018). Indigenous Peoples may experience loss of culturally significant foods and declining traditional ecological knowledge (Dounias and Ichikawa, 2017; Ross and Mason, 2020; 5.7).

5.12.3.3 Impacts on food utilization and vulnerabilities

Food utilization refers to the way the body most effectively uses food, and includes food preparation, food quality, and intra-household distribution. Food utilization is affected by climate change in several ways: food safety, dietary diversity, and food quality (Aberman and Tirado, 2014).

Climate change hazards have increased food safety risks (*high confidence*) including animal diseases (5.5), harmful algal blooms and marine toxins (Section 5.8, 5.9) and mycotoxins (Section 5.11). Other foodborne and waterborne infectious diseases such as cholera are further covered in Chapter 7.

Weather variability and extreme events (Seneviratne et al., 2021) have reduced availability and access to diverse foods to sell and to purchase in rural markets, thereby reducing access to affordable, diverse foods for both rural small-scale producers and net consumers, particularly for landlocked and low-income countries (*high confidence*) (Pant et al., 2014; Villasante et al., 2015; Alston and Akhter, 2016; FAO et al., 2018; Park et al., 2019; Niles et al., 2021) and otherwise marginalised communities (Algur et al., 2021). One study of 87 countries and 150 extreme events estimated that low-income food deficit and landlocked countries had reduced nutrient supply ranging from -1.6 to -7.6% of average supply, a significant portion of a healthy child's average dietary intake (Park et al., 2019).

Rural children in low-income countries are at particular risk of undernutrition from climate change impacts, due to a combination of factors: potential reduction in food quantity and quality from heat impacts; greater exposure from outdoor play and agricultural activities, and increased likelihood of heat exhaustion, vector borne and diarrheal diseases (Oppenheimer and Anttila-Hughes, 2016). A study of child growth data in 30 countries in Africa between 1993-2012 found that increased temperature was significantly related to children's wasting (Baker and Anttila-Hughes, 2020). Another study examined 30 years of climate data and child dietary diversity outcomes in 19 countries, and found that higher-than-average annual temperatures correlated with declines in child diet diversity at levels equal to or greater than other factors which often are the focus of policy, such as market access or education (Niles et al., 2021).

5.12.3.4 Impacts on food stability

Climate change has already changed the start and duration of the growing season and increased variability of rainfall in some places with impacts on food intake and nutritional status and income for low-income and small-scale producers (*medium evidence, high agreement*, (FAO et al., 2018; Cooper et al., 2019). Evidence to date suggests that climate change has negative impacts on the stability of food supply over the medium to long term, thereby affecting food stability (Myers et al., 2017b). Increasing number and intensity of adverse weather events, driven by climate change (Seneviratne et al., 2021), are important factors decreasing food stability, through reduced availability, increased local price volatility, reduced livelihoods for food producers and disruption to food transport (Toufique and Belton, 2014; Verma et al., 2014; Ruiz Meza, 2015; Clay et al., 2018; FAO et al., 2018; Mbow et al., 2019).

5.12.4 Projected Impacts on Food Security

5.12.4.1 Food availability and access

Climate change will have negative effects on food security and nutrition in 2050 (*high agreement, medium evidence*) (Amjath-Babu et al., 2016; Springmann et al., 2016; Lloyd et al., 2018; Richardson et al., 2018; see Chapter 7; Hasegawa et al., 2021a). How many people are affected will depend considerably on non-climatic drivers of food security (van Dijk et al., 2021), but modelling studies agreed that climate change would increase the risk of food insecurity. For example, one study comparing an RCP8.5 scenario with one that has zero climate impacts estimates 65 million additional people (10% increase) will experience food insecurity due to climate change impacts in 2050 (modelling results in Nelson et al. (2018)). Another study accounting for climate extreme events estimates that by 2050, the number of people at risk of hunger will increase by 20% and 11 % under high and low emission scenarios, respectively, owing to a once-per-100-year extreme climate event (Hasegawa et al., 2021a). Sub-Saharan Africa and South Asia in this study were projected to be at the greatest risk, with triple the amount of South Asia's current food reserves needed to offset such an extreme event. Models suggest that food security and malnutrition impacts will be much more severe from 2050 onwards relative to pre-2050, but the scale and extent of the impacts will strongly depend on the greenhouse gas emission scenario (FAO, 2018a; Richardson et al., 2018). Due to climatic impact drivers and non-climate drivers of food insecurity, Sub Saharan Africa is projected to be the hardest hit, followed by south Asia and Central and South America, but contingent on adaptation level (Richardson et al., 2018; Hasegawa et al., 2021a).

Without adaptive measures, heat stress impacts on agricultural labour will increase with climate change (*high confidence*) (Im et al., 2017; Levy and Roelofs, 2019; Hertel and de Lima, 2020). Climate-change-related heat stress will reduce outdoor physical work capacity on a global scale. Depending on greenhouse gas concentrations, some regions will experience losses of 200 to 250 outdoor workdays per year at century's end. Using results from one study reporting experimental procedures to assess loss of work capacity (Foster et al., 2021) regions hardest hit in an SSP5-8.5 scenario include much of South Asia, tropical Sub-Saharan Africa and parts of Central and South America (Figure 5.18) de Lima et al. (2021) projected that negative impacts of warming on crop yields and labour capacity would affect crop production and cost for workers and labour-saving mechanisation, raising food price by 5 % at +3° from the baseline period (1986-2005) globally, with significant implications for vulnerable regions (sub-Saharan Africa and Southeast Asia). Large uncertainties, however, exist around population diversity and adaptive capacity (Vanos et al., 2019). Agricultural labour productivity impacts of heat attributed to climate change are expected to be worse in low- and middle-income countries (Kjellstrom et al., 2016). Adaptation options needed to protect agricultural worker productivity outdoors and reduce occupational heat illnesses and deaths include cooled working environments, improved surveillance systems and education about the need to monitor (*high confidence)* (Xiang et al., 2016; Quiller et al., 2017; Flouris et al., 2018; Day et al., 2019; Vanos et al., 2019). Currently available options, however, are more difficult to achieve in lower-income economies (Kjellstrom et al., 2016; Im et al., 2017).

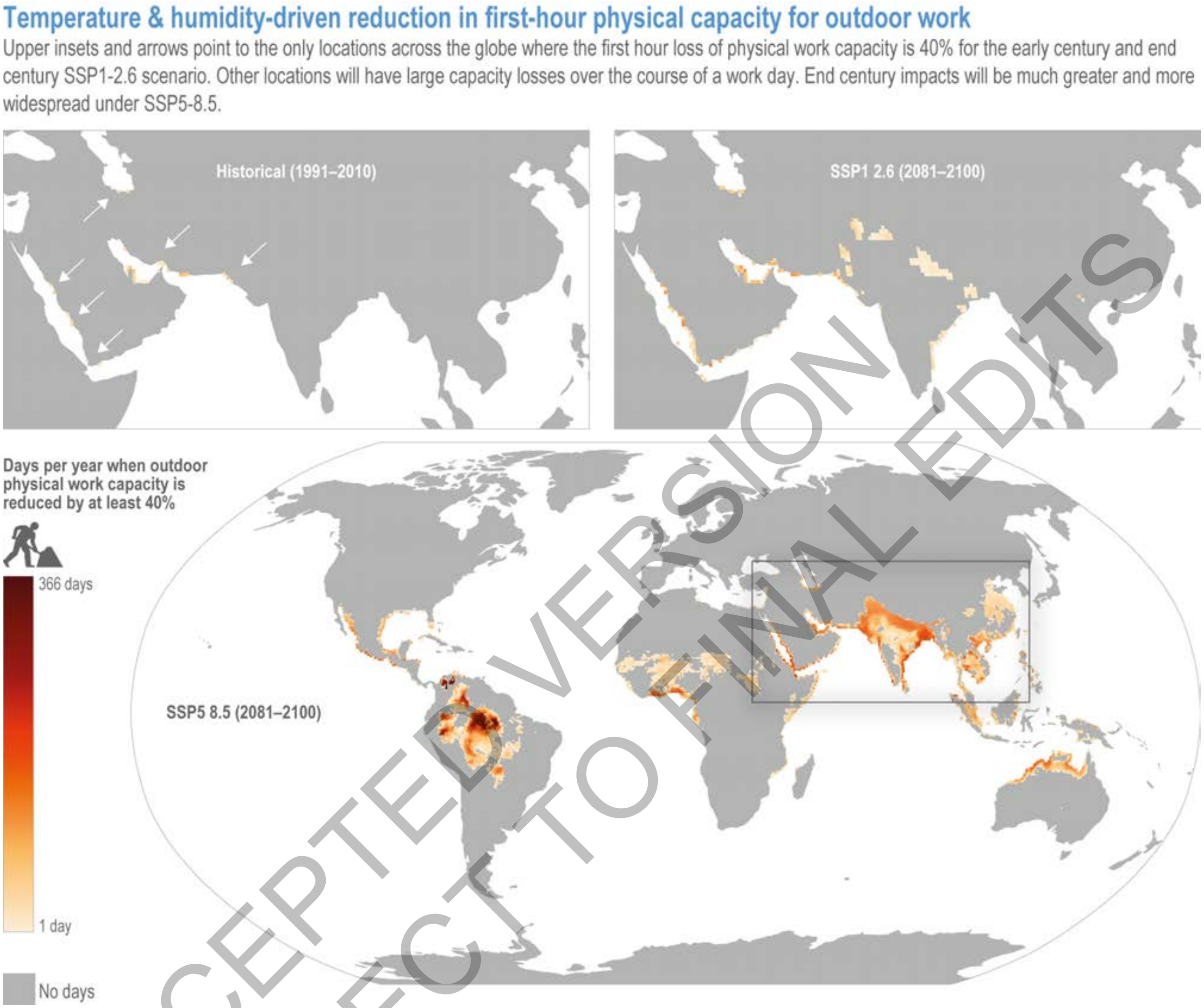


Figure 5.18: The number of days per year where physical work capacity (PWC) is less than 50% based on average daily air temperature and relative humidity (Foster et al., 2021). PWC is defined as the maximum physical work output that can be reasonably expected from an individual performing moderate to heavy work in a 'cool' reference environment of 15oC. Values plotted are from the early (A) and end of century (B) for SSP 585 using ensemble means from the ISIMIP CMIP6 data set. See SM5.4 for detail.

Under higher emission scenarios, food availability will be further reduced after 2050, due to the potential for widespread crop failure, and decline in livestock and fisheries stocks (Mbow et al., 2014; Kelley et al., 2017; Challinor et al., 2018; Hendrix, 2018; Bindoff et al., 2019). At +3° from the preindustrial era, all food production sectors will experience greater, and pronounced, losses due to climate change compared to +1.5° or +2° (see Sections 5.2, 5.4.3, 5.8.3 and 5.9.3).

Food insecurity from food price spikes due to reduced agricultural production associated with climate impact drivers such as drought can lead to both domestic and international conflict, including political instability (Abbott et al., 2017; Bush and Martiniello, 2017; WEF, 2017; D'Odorico et al., 2018; de Amorim et al., 2018;Chapter 7.2.7). While climate change impacts, including drought impacts on food security are important risk factors for conflict, other key drivers are often more influential, including low socioeconomic development, limited state capacity, weak governance, intergroup inequities, and recent histories of conflict (*medium confidence*) (Mach et al., 2019; Selby, 2019; Chapter 7.2.7). The interaction between extreme weather events, conflict and human migration may increase vulnerability of particular communities of low-income countries (WEF, 2017; D'Odorico et al., 2018; de Amorim et al., 2018; Chapter 7). Further research is needed to better understand how increased drought-risk under future climate change might affect food prices and water availability (Abbott et al., 2017).

5.12.4.2 Projected impacts on food safety and quality

Increasing levels of CO_2 directly contribute to reduced food quality by reducing levels of protein, iron, zinc and some vitamins, varying by crop species and cultivars (*high confidence*) (Section 5.4.3, Myers et al., 2014; Smith and Haddad, 2015; Bisbis et al., 2018; Scheelbeek et al., 2018; Weyant et al., 2018; Zhu et al., 2018a). Higher levels of CO_2 are predicted to lead to 5-10% reductions in a wide range of minerals and nutrients (Loladze, 2014). Climate warming will also reduce food quality of seafood, by changing the long-chain polyunsaturated fatty acid content in phytoplankton (Section 5.8; Hixson and Arts, 2016).

[START BOX 5.10 HERE]

Box 5.10: Food Safety Interactions with Food Security and Malnutrition

Climate change significantly increases the future food safety risks (*high confidence*) (Sections 5.8.2, 5.8.3, 5.11.1, Box 5.9). Increasing temperatures and drought stress are expected to lead to greater aflatoxin contamination of food crops. Aflatoxins, a major foodborne hazard, contaminate staple crops and are associated with various health risks including stunting in children and cancer (Koshiol et al., 2017). In LICs, children with high exposure to aflatoxins were found to be more likely to suffer from micronutrient (zinc and vitamin A) deficiencies (Watson et al., 2016b). Climate change is expected to cause decreases in micro- and macronutrient content of foods, leading to an increased burden of infectious diseases, diarrhea and anaemia, with an estimated 10 % increase in disability-adjusted life years (DALYs) by 2050 associated with undernutrition and micronutrient deficiencies (Aberman and Tirado, 2014; Smith and Myers, 2018; Weyant et al., 2018; Zhu et al., 2018a; Ebi and Loladze, 2019; FAO, 2020a; Sulser et al., 2021b).

Children in low-income countries will be at greater risk of undernutrition from these multiple climate change impacts, including lower food availability, lower food quality, food safety and risk of diarrheal disease (*high confidence*) (Aberman and Tirado, 2014). One study of 30 countries in Africa estimated that by 2100, increased temperatures under RCP8.5 could increase children's wasting in western Africa by 37% and 25% in southern Africa (Baker and Anttila-Hughes, 2020).

The combination of climate change and the presence of arsenic in paddy rice fields is expected to increase the toxic heavy metal content of rice and reduce production by 2100, threatening food security and food safety mainly in low-income countries where rice is the main staple (Neumann et al., 2017; Muehe et al., 2019; Farhat et al., 2021).

[END BOX 5.10 HERE]

5.12.4.3 Reaching SDG2

Current projections indicate that it is *highly likely* that the UN SDG 2 ('Zero Hunger') by 2030 will not be achieved, with climate impacts one of several drivers on food security and nutrition preventing this goal including in Africa, Small Island States and South Asia (*high confidence)* (FAO et al., 2018; Otekunrin et al., 2019; Singh et al., 2019; Atukunda et al., 2021; Kumar et al., 2021; Vogliano et al., 2021). Integrated policy strategies that consider synergies and tradeoffs between different food system components would strengthen the likelihood of meeting SDG2 goals (Dyngeland et al., 2020; Lipper et al., 2020; Vogliano et al., 2021) (Grosso et al., 2020). Adaptation options which address climate risks for food security and nutrition are discussed below.

5.12.5 Adaptation Options for Food Security and Nutrition

Since AR5 there has been increased research on adaptation options that address climate risks for food security and nutrition. In this section cultivar improvements, urban and peri-urban agriculture, changing dietary patterns, integrated multisectoral approaches and rights-based approaches are assessed for their potential as an adaptation option that addresses food security and nutrition. Feasibility and effectiveness assessment of several options is in section 5.14.

5.12.5.1 Potential, barriers, and challenges for genetically modified crops to address food security and nutrition

While biotechnology can be used as an adaptation strategy (Section 5.4.4.3), there is low confidence that genetically modified (GM) crops can increase food security and nutrition in smallholder farming systems relative to alternative agronomic strategies (National Academies of Sciences Engineering and Medicine, 2016; Qaim, 2016). Some underline their potential in building resilience to changing climatic conditions, in the form of enhanced drought/heat tolerance, pest/disease protection and/or reduced land usage, thus serving to bolster food security and nutrition (Sainger et al., 2015; Muzhinji and Ntuli, 2021). Others suggest that the empirical evidence supporting GM crops as a climate-resilience strategy remains thin (Leonelli, 2018). Technical and social barriers and potential solutions are summarized in Table 5.15.

Table 5.15: Barriers, challenges and potential solutions for GM crops

Barriers and challenges	Examples and potential solutions to barriers
Major challenges as a food security and nutrition adaptation include the introgression of GM traits into host varieties (Dowd-Uribe, 2014), and confusion around proper growing practices that can accelerate resistance (Iversen et al., 2014; Fischer et al., 2015). The combination of the kinds of traits and restrictions that come from the predominant intellectual property rights instruments used in their commercialization, and concentration of plant and animal breeding industry (Bonny, 2017) mean that benefits from released GM crops tend to be captured disproportionately by farmers with more land, wealth and education (Afidchao et al., 2014; Ali and Rahut, 2018; Azadi et al., 2018) but also increase debt levels for growers (Dowd-Uribe, 2014; Leguizamón, 2014). Underlying gender inequities also play a critical role in shaping food security and nutrition outcomes associated with the introduction of GM crops in part due to unequal control over income and agricultural decision-making; in some cases women reported decreased workload and enhanced decision-making power (Gouse et al., 2016), while in others the introduction of GM crops could increase workload and devalue womens' role as seed savers.(Carro-Ripalda and Astier, 2014; Addison and Schnurr, 2016). Major hurdles for genetically modified crops include translating promising research results into real-world farming systems and consumer trust in the food product. Experimental programs have been dogged by issues including complications with the introgression of genetically modified traits into high-performing varieties (Dowd-Uribe and Schnurr, 2016; Stone and Glover, 2017), strict management regimes that clash with the realities of smallholder agricultural systems (Iversen et al., 2014; Whitfield et al., 2015), and a lack of attention to farmer decision-making (Schnurr, 2019).	One case study is the Water Efficient Maize for Africa program (WEMA), a Public Private Partnership that transplants a cold shock protein B, known as Droughtgard, into maize in order to mitigate yield losses from drought. Proponents suggest that this GM venture, which will be distributed free to smallholder farmers, represents the best strategy for ensuring stable yields in the face of climatic change across Africa (Kyetere et al., 2019). Critics argue that WEMA maize is not a good fit with the smallholder farming systems it is designed to benefit, with particular concerns around how farmers will access the extra inputs, credit, and labour that WEMA maize requires in order to be successful (Schnurr, 2019). Emergent genome edited crops are considered a more precise, accessible and accelerated means of targeting stressors that matter to poor farmers, but evidence is limited (Kole et al., 2015; Haque et al., 2018; Zaidi et al., 2019). A more iterative and flexible adaptation approach beyond just genomic improvement to tackle the multiplicity of factors limiting smallholder production is anticipated to increase the likelihood that these promising technologies can enhance food security and nutrition (*medium confidence*) (Giller et al., 2017; Stone, 2017; Montenegro de Wit, 2019). To address food security and nutrition, future breeding needs to move from just enhancing agronomic traits of a single crop to improving multiple traits of multiple crops suited to local conditions that will increase climate resilience of farming systems. To make breeding technologies scale-neutral, the policy structure is needed to support and protect smallholders *(medium confidence)*.

5.12.5.2 Urban and peri-urban agriculture, vertical and horizontal

Urban areas have more than half of the global population and consume about 70 % of the total food supply (FAO, 2019b). The urban population is projected to grow further to about 70 % of the global population by 2050 (UN, 2018). Direct evidence supporting climate resilience of UPA is limited and contextual, but there is *medium confidence* of multifunctional benefits from UPA, depending on regions and types of UPA (Artmann and Sartison, 2018; Kareem et al., 2020). UPA takes different forms of production, and can be broadly classified into four categories, depending on operating characteristics and capital inputs (Table 5.16) (Goldstein et al., 2016). Controlled environments can protect crops, livestock, and fish from extreme weather events or pest and disease outbreak (Mohareb et al., 2017). Innovative indoor farming such as vertical farming can be highly productive with minimal water and nutrient supply but can be capital intensive with high energy demand (O'Sullivan et al., 2019) and those with aquaponics can be water demanding (Love et al., 2015). Currently, commodities are often limited to crops with short growing seasons such as leafy vegetables. Vertically grown crops are more expensive than field-grown produce, and thus not accessible for low-income urban dwellers (Al-Kodmany, 2018). Community and institutional unconditioned (outdoor) farms and gardens are better positioned to provide increased access to healthy food to those who need it (Eigenbrod and Gruda, 2015; Goodman and Minner, 2019).

Many UPA farmers are migrant workers or other socially marginalized racial and ethnic groups and often limited by access to land (Lawanson et al., 2014; Horst et al., 2017). There is *high agreement* that proactive policies for urban design accounting for food-energy-nexus and social inclusion including addressing questions of governance and rights to green urban spaces are necessary to enhance food provisioning and to gain multiple functions of UPA (Lwasa et al., 2014; Horst et al., 2017; Mohareb et al., 2017; Siegner et al., 2018; O'Sullivan et al., 2019; Titz and Chiotha, 2019; Halvey et al., 2020).

Table 5.16: Urban agriculture classifications based on operating characteristics and capital inputs (Goldstein et al., 2016; O'Sullivan et al., 2019), and a summary of literature search on positive and negative aspects.

Summary of adaptation option and evidence for improved food security and nutrition		
Urban agriculture has two components – vertical (e.g., grown on or in buildings) and horizontal (grown on land within urban boundaries, in backyards and marginal spaces). The horizontal component of urban and peri-urban agriculture (UPA) has gained attention because of multiple functions that could improve food systems and ecosystem services under climate change (Revi et al., 2014; Artmann and Sartison, 2018; FAO, 2019b; Mbow et al., 2019; Chapter 6). UPA cannot fully feed urban dwellers within its boundaries but can make an important contribution to local food security and nutrition (*medium confidence*) (Martellozzo et al., 2014; Badami and Ramankutty, 2015; Algert et al., 2016; Mohareb et al., 2017; Clinton et al., 2018; Kriewald et al., 2019). UPA is also expected to play important roles in ecosystem functions in addition to alleviating food shocks caused by natural disasters and reducing food mileage.		
***Categories* and Description**	**Synergies**	**Tradeoffs**
Ground-based Unconditioned Traditional, peri-urban field farms, market gardens, community farms, community gardens, home gardens. *Building-integrated Unconditioned* Rooftop gardens, balcony agriculture, and green wall, but production quantity is small.	- Multi-species cropping can increase access to diverse healthy foods and reduce food costs for low-income households (Algert et al., 2016; Horst et al., 2017). -Green cover helps to attenuate heat island effects, reduce run-off and flood risks (Lwasa et al., 2015; Di Leo et al., 2016; Gondhalekar and Ramsauer, 2017; Artmann and Sartison, 2018; Small et al., 2019). -Green garden spaces can reduce vulnerability to heat stress and food insecurity for low-income neighborhoods and address racial inequities in access to green spaces if UA governance addresses equity concerns (Horst et al., 2017; Titz and Chiotha, 2019; Halvey et al., 2020; Hoffman et al., 2020)	- Can increase the value of land and thereby push out lower income households via gentrification (Horst et al., 2017). -unconditioned UPA is under strong pressure from other lucrative land-use demands and can be difficult to maintain without addressing urban social inequities, (Martellozzo et al., 2014; Horst et al., 2017; White and Bunn, 2017). -Yields are lower than conventional, rural production and water demand is high (Goldstein et al., 2016; Bisaga et al., 2019). - Air, soil and water quality in urban areas, can disturb crop production and reduce food safety (Eigenbrod and Gruda, 2015; Titz and Chiotha, 2019), and create health

	-Multi-species cropping helps to conserve biodiversity (Lovell, 2010; Goldstein et al., 2016). -Skill building and job opportunities (Lovell, 2010; Mok et al., 2014; Horst et al., 2017), sometimes in regions and for groups that have been socially and economically disadvantaged (Horst et al., 2017). - cultural ecosystem service benefits through cultivation of specific crops, cultural learning, sharing culinary and garden knowledge and strengthening social networks for socially marginalized ethnic, racial groups (Horst et al., 2017; Nadeau et al., 2019). -UPA provides social and health co-benefits such as increased social interaction, physical and mental health benefits (Horst et al., 2017; White and Bunn, 2017). -can divert organic waste produced in cities as compost, to reduce water contamination and input costs (Menyuka et al., 2020)	risks from contamination (Mok et al., 2014) which causes mixed or even negative public perceptions against the produce (Specht et al., 2019; Menyuka et al., 2020). Trace metal contamination in soils and plants is an increased risk in outdoor UPA (Eigenbrod and Gruda, 2015; Titz and Chiotha, 2019). -May provide limited job and income opportunities in low income urban areas (Daftary-Steel et al., 2015; Biewener, 2016) - outdoor fields are exposed to rising temperatures and urban heat islands (Chapman et al., 2017). Low water availability may be another limit for UPA as a form of adaptation (Kareem et al., 2020; Tankari, 2020). In coastal cities, sea level rise and flooding from climate change impacts may make significant portions of cities unuseable for UPA (Algert et al., 2016; Kareem et al., 2020).
Ground-based Conditioned Horticultural farms using glasshouses or polyhouses. Often exist on the city fringes. Aquaponics that grow fish in aquaculture systems and reuse nutrient-rich wastewater. One of the few options that provide proteins in urban farms. *Building integrated Conditioned* Rooftop glasshouses, fully indoor, artificially lit plant factories. Recent advancements include production using vertical stacks to produce more food per land area. Indoor aquaculture is also included.	-Controlled environments can protect crops, livestock, and fish from extreme weather events or pest and disease outbreak (Mohareb et al., 2017). -Some building integrated conditioned farms can utilise wastewater and waste heat from buildings or other urban source (De Zeeuw et al., 2011; Thomaier et al., 2015; Mohareb et al., 2017). - Innovative indoor farming such as vertical farming (VF) is highly productive with minimal water and nutrient supply, but highly energy-demanding (O'Sullivan et al., 2019). - Some initiatives combine with social justice goals and use abandoned buildings in low income neighbourhoods to grow diverse food types for addressing food security of low income groups (Thomaier et al., 2015; Horst et al., 2017).	-Power outages and/or system failure can easily destroy the production system (Small et al., 2019). -Initial costs and energy requirements, particularly are substantially higher than unconditioned farms (Goodman and Minner, 2019; O'Sullivan et al., 2019). -Greenhouse gas emissions may be higher than conventional rural agriculture (Santo et al., 2016) and full mitigation potential only realized with low energy systems (WGIII, 12.4) -Commodities are often limited to short-cycled crops such as leafy vegetables and herbs and the produce is more expensive, which are difficult for the urban poor to access (O'Sullivan et al., 2019).

5.12.6 Changing Dietary Patterns

Dietary change in regions with excess consumption of calories and animal-sourced foods to a higher share of plant-based foods with greater dietary diversity and reduced consumption of animal-sourced foods and unhealthy foods (as defined by scientific panels such as EAT-Lancet), has both mitigation and adaptation benefits along with reduced mortality from diet related non-communicable diseases, health, biodiversity and other environmental co-benefits (*high confidence*) (Springmann et al., 2016; Springmann et al., 2018; Branca et al., 2019; Henry et al., 2019; Searchinger et al., 2019; Swinburn et al., 2019; Willett et al., 2019; Rosenzweig et al., 2020; Chapter 7.4.2.1.3 and WGIII Chapter 12). Reducing food waste, especially of environment- and climate- costly foods would further extend these benefits (Rosenzweig et al., 2020 and see section 5.11).

Dietary behaviour is complex: shaped by the broader food system (HLPE, 2017a), the food environment (Herforth and Ahmed, 2015; Turner et al., 2018) and socio-cultural factors (Fischler, 1988). Since most food-related decisions are made at a subconscious level (Marteau et al., 2012), achieving dietary change for personal health reasons has proven difficult: it seems unlikely that dietary change for climate will be achieved without careful attention to the factors that shape dietary choice and behaviour. Food environments, defined as "the physical, economic, political and socio-cultural context in which consumers engage with the food system to make their decisions about acquiring, preparing and consuming food" (HLPE, 2017a): 28), include food availability, accessibility, price/ affordability, food characteristics, desirability, convenience, and marketing.

There are a range of options to change dietary patterns, but more research is needed in this area, adjusted to the regional, socio-economic, and cultural context. Studies of policy instruments to change diets include changes in subsidies, taxes, marketing regulation and efforts to change the retail physical environment. Subsidies directed at staple foods and animal sourced foods could be shifted towards diversified production of plant-based foods in order to change the relative price of foods and thus dietary choice (Franck et al., 2013; Harris et al., 2021). Taxes on animal-sourced foods that are climate-costly and unhealthy, as defined by scientific panels such as the EAT-Lancet report, could similarly impact relative price (Mbow et al., 2019; Willett et al., 2019). Regulation of marketing could change desirability of climate-unfriendly and unhealthy foods (Willett et al., 2019). Many of the same strategies used to increase sales by conventional food marketing efforts hold potential to change the desirability and people's preferences for plant foods which are strongly shaped by social-cultural norms. Studies have shown that changes to the number, placing, or prevalence vegetarian options on a menu (Bacon and Krpan, 2018; Kurz, 2018; Garnett et al., 2019; Gravert and Kurz, 2019), the relative price of vegetarian options (Garnett et al., 2021)and the "access" (order and distance) to vegetarian options in the retail physical environment (Garnett et al., 2020) can all increase consumption of plant-based foods and decrease meat consumption (Bianchi et al., 2018). Studies on food environment 'nudging' methods found that making the vegetarian meal option the default during conference registration or on a meal plan significantly reduced meat consumption (Campbell-Arvai et al., 2012; Hansen et al., 2019b). Studies simply educating people about the negative health and environmental/ climate outcomes of meat consumption have been found to have very little impact (Byerly et al., 2018). More research is needed to understand the potential for motivational crowding in shaping pro-climate dietary choice, as has been demonstrated in development (Agrawal et al., 2015) and conservation interventions (Rode et al., 2015).

5.12.7 Integrated Multisectoral Food Security and Nutrition Adaptation Options

Integrated multisectoral strategies that incorporate social protection are effective adaptation responses (*high confidence*) (Gros et al., 2019; Ulrichs et al., 2019; Medina Hidalgo et al., 2020; Daron et al., 2021; Ilboudo Nébié et al., 2021; Verschuur et al., 2021; 7.4.2, Cross-Chapter Box-GENDER in Chapter 18). Social protection programmes, such as cash transfers, weather index insurance and asset-building activities such as well construction, can support short-term responses to acute food insecurity in response to extreme events, but can also build adaptive capacity longer-term (Table 5.16, Costella et al., 2017; Ulrichs et al., 2019). An assessment of an adaptive social protection programme in the Sahel found that tailored seasonal forecasting can improve responsiveness to climate-related extreme events, but investment in capacity building and dialogue between forecasters, community groups and humanitarian organizations is needed (Daron et al., 2021). Forecast-based financing, which automatically disperses funds when threshold forecasts are reached for an extreme event (Coughlan de Perez et al., 2016), used in Bangladesh prior to a 2017 flood event allowed low-income, flood-prone communities to access better quality food in the short term without accruing debt (Gros et al., 2019).

Differentiated responses based on food security level and climate risk can be effective. A study of drought impacts on food security in Senegal between 1997-2016 recommended different adaptation strategies based on whether the region was a higher risk of acute short-term food insecurity and/or faced higher risk of drought (Table 5.16; Ilboudo Nébié et al., 2021).Given identified linkages between higher temperatures and extreme events with declines in child dietary diversity, safeguarding diverse diets is one important adaptation priority (Niles et al., 2021). Humanitarian responses are appropriate for short-term acute hunger, while in the medium term, home-grown school feeding programmes with diverse foods can support child nutrition and learning, and with local procurement can also increase income and food security of smallholder farmers (Ilboudo Nébié et al., 2021). Farmer associations can manage regional staple food storehouses, in which farmers store their harvest and receive credit, and can sell their harvest later in the season and pay back the credit with interest, strengthening local supplies and farmer income (Ilboudo Nébié et al., 2021).

A study in Lesotho examined the extent to which climate change increased the likelihood of an acute drought in 2007, and a related food crisis (Verschuur et al., 2021). Given land degradation, reliance on rainfed agriculture and food imports from neighbouring South Africa, the study recommended crop diversification, increased use of drought tolerant crop varieties and expanded trade partners in the medium to long term, to both strengthen regional food production, reduce risk of crop failure, and the likelihood of climate-induced drought from trade partners reducing food imports (Verschuur et al., 2021). A longitudinal study of smallholder coffee farmers in Nicaragua found that crop diversification, alongside crop management and varietal improvement, would help farmers strengthen food security long term in the face of climate hazards such as drought and coffee leaf rust (Bacon et al., 2021). Another medium to long-term adaptation response is to address systemic gender, land tenure and other social inequalities as part of an inclusive approach (Bezner Kerr et al., 2019; Khatri-Chhetri et al., 2020; Bacon et al., 2021). This long-term strategy could be part of a human-rights-based approach (HRBA, 5.12.8)

Table 5.17: Examples of adaptation responses to drought and floods by food security level and time frame. Adapted from Ilboudo Nébié et al. (2021) Table 4, with information from (Bahadur et al., 2015; Costella et al., 2017; Gros et al., 2019; Ulrichs et al., 2019; Medina Hidalgo et al., 2020; Bacon et al., 2021; Verschuur et al., 2021).

	Food insecurity level and time frame of adaptation			
Adaptation response to drought or floods	**Acute, short-term**	**Moderate, medium term**	**Chronic, long-term**	**Resilience type**
Forecast-based financing (provides unconditional cash in advance of extreme event)	X			*Anticipatory*: people and systems are better prepared for climate shock by reduced exposure or vulnerability.
Early warning systems / climate services and education for disaster preparation	X	X	X	
Social protection programmes with regular provisions which allow for asset building e.g., savings, build informal networks, purchase of livestock	X	X		
Humanitarian food aid and malnutrition treatment	X	X		*Absorptive capacity*: people or systems cope with climate-related shocks or systems while and immediately after they occur.
Home grown nutrition-sensitive school feeding programmes		X	X	
Social protection programmes with short-term targeted response e.g., short-term cash transfers, food assistance for asset building e.g., wells	X			
Weather index insurance program	X	X	X	
Regional grain banks run by farmer associations		X	X	*Adaptive capacity*: can adjust to long-term climate risks and disasters reduce vulnerability to future shocks.
Savings, credit and local food procurement support for smallholder farmers		X	X	
Agroecosystem diversification, other agroecological practices to strengthen ecosystem services in long-term (see Box 5.10)		X	X	

Rainwater evacuation infrastructure combined with flood management and waste collection and urban gardening		X	X	
Drought or flood resistant crop varieties		X	X	
Expand trade partners beyond climactically connected partners		X	X	
Gender transformative or responsive agriculture programs		X	X	

5.12.8 Incorporating Human Rights-based Approaches into Food Systems

A human rights-based approach (HRBA), endorsed by the United Nations, is one strategy for addressing core inequities that are key drivers for food insecurity and malnutrition of particular groups such as low-income consumers, children, women, small-scale producers and different regions of the world (FAO, 2013; Claeys and Delgado Pugley, 2017; Caron et al., 2018; Le Mouël et al., 2018; Springmann et al., 2018; Tramel, 2018; HLPE, 2019; Willett et al., 2019). Climate change impacts, mitigation and adaptation approaches can also worsen inequities (Eastin, 2018; Borras et al., 2020). HRBA includes core principles of participation, accountability, non-discrimination, transparency, human rights, empowerment, and rule of law, which can be integrated into policymaking and implementation as part of transforming the food system (FAO, 2013; Caron et al., 2018; Toussaint and Martínez Blanco, 2020). The right to wellbeing can serve as the overarching umbrella of HRBA to addressing climate change within food systems and includes a right to health, right to food, cultural rights, the rights of the child and the right to healthy environment (Swinburn et al., 2019). A HRBA has a specific focus on those groups who are vulnerable due to poverty, discrimination and historical inequities and involves meaningful participation of vulnerable groups in governance, design and implementation of adaptation and mitigation strategies, including gender-responsiveness and integration of Indigenous Peoples' knowledge (UNHRC 2017; Caron et al., 2018; Mills, 2018). There can be conflicts and trade-offs, such as between addressing land rights or traditional fishing grounds, the right to food, and addressing climate justice concerns (Mills, 2018; Borras et al., 2020; section 5.13). Adaptation strategies that incorporate HRBA include legislation, programmes that address gender inequities in agriculture, agroecology, recognition of rights to land, fishing areas and other natural resources, protection of culturally significant seeds, and community-based adaptation that explicitly involves marginalized groups in governance (Mills, 2018; Tramel, 2018; Huyer et al., 2019; Borras et al., 2020; section 5.14).

5.13 Climate Change Triggered Competition, Trade-offs and Nexus Interactions in Land and Ocean

This section presents information about the impacts generated by competition and trade-offs in food systems and discusses opportunities and challenges associated with the use of the Nexus framework.

5.13.1 Impacts of Global Land Deals on Land Use, Vulnerable Groups, and Adaptation to Climate Change

Land deals, also known as large-scale land acquisitions (LSLAs), describe recent changes in access to land globally (Borras et al., 2011). Since 2000, at least 160 million hectares have been under negotiation (Land Matrix, 2021). Land deals surged after the 2007-2008 food price crisis and farmland investment boom (Fairbairn, 2014), with a diverse range of drivers (Arezki et al., 2015; Zoomers and Otsuki, 2017; Conigliani et al., 2018) including land-based climate change interventions (Dunlap and Fairhead, 2014; Davis et al., 2015a; Hunsberger et al., 2017; Franco and Borras, 2019). Examples are the expansion of biofuel crops (e.g. Yengoh and Armah, 2016; Aha and Ayitey, 2017), Afforestation and Reforestation (A/R) projects (Olwig et al., 2016; Richards and Lyons, 2016; Scheidel and Work, 2018), REDD+ (Bayrak and Marafa, 2016; Ingalls et al., 2018), conservation areas (Lunstrum, 2016; Schleicher et al., 2019), renewable energy installations (e.g. Sovacool, 2021), or natural disaster management (e.g. Uson, 2017).

Land deals raise important social justice questions (Franco et al., 2017; Hunsberger et al., 2017; Borras and Franco, 2018b; Borras et al., 2020; Sekine, 2021) (*high confidence*). Specific impacts of land deals vary according to their purpose, location, actors, land use history, and procedural aspects. However, multi-case analyses identify severe adverse impacts (Table 5.18). LSLAs are a significant driver of tropical forest loss

(Davis et al., 2020) increasing emissions through deforestation (Liao et al., 2021) and industrialization of agriculture (Rosa et al., 2021). LSLAs entail large water appropriations (Breu et al., 2016; Chiarelli et al., 2016; Adams et al., 2019) affecting local populations' access to water and food security (Dell'Angelo et al., 2018; Veldwisch et al., 2018). By increasing exported crops, and limiting local populations' access to land, LSLAs produce food security risks (Marselis et al., 2017; Müller et al., 2021b). Negative livelihoods impacts arise through enclosure of assets, elite capture (Oberlack et al., 2016), crowding out of small farmers (Nolte and Ostermeier, 2017) and reducing local populations' access to commons (Dell'Angelo et al., 2016; Giger et al., 2019). Indigenous People are affected facing high levels of violence in land acquisition conflicts (Dell'Angelo et al., 2021). The social burdens of land deals tend to be gendered (e.g. Fonjong et al., 2016; Nyantakyi-Frimpong and Bezner Kerr, 2017; Atuoye et al., 2021).

Local populations can experience declining access to livelihood resources and deteriorating food security, increasing gendered vulnerabilities (Yengoh et al., 2015; Faye and Ribot, 2017; Atuoye et al., 2021). Vulnerable groups displaced by land deals may face higher exposure to climate change (Dell'Angelo et al., 2017). LSLAs affecting common-pool resources governed by Indigenous institutions jeopardize the resilience and adaptive capacity of local socio-ecological systems (Dell'Angelo et al., 2016; D'Odorico et al., 2017; Hak et al., 2018; Haller, 2019; Haller et al., 2020). Growing land tenure insecurity may force farmers to engage in unsustainable farming and forestry practices (Aha and Ayitey, 2017; Gabay and Alam, 2017) and hinder agroecological innovations to manage climate risks (Nyantakyi-Frimpong, 2020b). Social justice concerns and vulnerability of local populations can be addressed by promoting land redistribution and recognition, particularly for customary lands of Indigenous and ethnic minorities; and land restitution to those who were forcibly displaced (Franco et al., 2015; Borras and Franco, 2018a).

Table 5.18: Adverse social and ecological risks and impacts of agricultural land deals on land use and vulnerable groups.

Land use dimensions	**Impacts and implications**	**References (2014- present)**
Forestry	Direct and indirect land use change provoked by LSLAs accelerate deforestation of tropical forests globally.	*Multi-case analyses* Davis et al. (2020) *Case study examples* Davis et al. (2015b) Scheidel and Work (2018), Magliocca et al. (2020)
Energy use and access	Expected land use changes provoked by agricultural LSLAs have high fossil-energy footprints. LSLAs may adversely affect local population' access to energy resources.	*Multi-case analyses* Rosa et al. (2021)
Carbon emissions	LSLAs have high carbon footprints resulting from deforestation and industrialization of agriculture.	*Multi-case analyses* Liao et al. (2021) Rosa et al. (2021) *Case study examples* Johansson et al. (2020) Liao et al. (2020)
Water use and access	LSLAs frequently involve water appropriations, which may affect access to water, traditional agriculture, and the human right to food of local populations.	*Multi-case analyses* Breu et al. (2016) Chiarelli et al. (2016) Dell'Angelo et al. (2018) *Case study examples* Adams et al. (2019) Tejada and Rist (2018)
Food security and nutrition	LSLAs pose food security risks by re-orienting crop production to nutrient-poor crops predominantly destined for export,	*Multi-case analyses* Cristina Rulli and D'Odorico (2014) Mechiche-Alami et al. (2021) Marselis et al. (2017)

	and/or excluding local populations from agricultural land.	Müller et al. (2021b) *Conceptual studies* Häberli and Smith (2014) *Case study examples* Shete and Rutten (2015) Mabe et al. (2019) Bruna (2019) Hules and Singh (2017) Moreda (2018) Atuoye et al. (2021)
Livelihoods	LSLAs frequently provoke adverse livelihood impacts and increased livelihood vulnerability of local populations.	*Multi-case analyses* Davis et al. (2014) Oberlack et al. (2016) Nolte and Ostermeier, 2017) Vandergeten et al. (2016) Schoneveld (2017) *Conceptual studies* Zoomers and Otsuki (2017) *Case study examples* Richards and Lyons (2016) Shete and Rutten (2015) Yengoh and Armah (2016) Mabe et al. (2019) Gyapong (2020)
Indigenous People and commons	LSLAs have adverse impacts on Indigenous peoples and lands, including land encroachment, dispossession, and displacement. Land deals frequently target common land and may increase the vulnerability of customary, traditional, and Indigenous systems common property, while reducing their adaptive capacity.	*Multi-case analyses* Dell'Angelo et al. (2016) Giger et al. (2019) Dell'Angelo et al. (2021) *Conceptual studies* Haller et al. (2020) *Case study examples* Olwig et al. (2016) Moreda (2017) Montefrio (2017) Scheidel and Work (2018) Konforti (2018) Pietilainen and Otero (2019) Mingorría (2018) Bukari and Kuusaana (2018) Haller (2019) Hak et al. (2018) Gabay and Alam (2017) Imbong (2021)
Gender	Impacts and implications of land deals are frequently suffered in different ways among genders.	*Case study examples* Tsikata and Yaro (2014) Yengoh et al. (2015) Fonjong et al. (2016) Nyantakyi-Frimpong and Bezner Kerr (2017) Elmhirst et al. (2017) Bottazzi et al. (2018) Ndi (2019) Osabuohien et al. (2019) Porsani et al. (2019) Atuoye et al. (2021)
Impacts on other climate	LSLAs may undermine mitigation and adaptation initiatives and other land uses	*Multi-case analyses* Carter et al. (2017)

change mitigation and adaptation initiatives	relevant for climate change mitigation and adaptation	*Case study examples* Borras et al. (2020) Gabay and Alam (2017) Nyantakyi-Frimpong (2020b) Scheidel and Work (2018) Rodríguez-de-Francisco et al. (2021)
Other environmental impacts	LSLAs expected to provoke lasting global environmental change (Lazarus, 2014); LSLAs are a potential driver of slope instability (Chiarelli et al., 2021); LSLAs affect natural habitats such as tiger landscapes (Debonne et al., 2019); LSLAs jeopardize biodiversity (Balehegn, 2015).	

5.13.2 Trade-offs Generated by Agricultural Intensification and Expansion

Agricultural intensification seeks to increase agricultural productivity per input unit, reducing the pressure on land use, generating positive impacts in greenhouse gas emissions (Mbow et al., 2019), but valuing the final effect requires common metrics in terms of carbon capture or emission reductions (Searchinger et al., 2018). It has been suggested to address multiple Sustainable Development Goals (SDG2, SDG13, SDG15), but only occasionally leads to simultaneous positive ecosystem service and well-being outcomes (Rasmussen et al., 2018). When the process relies only on increasing input use there is a risk of generating adverse outcomes that may override positive effects, such as CO_2 emissions, (McGill et al., 2018); NOx emissions (Hickman et al., 2017), soil salinization and groundwater depletion (Doody et al., 2015; Daliakopoulos et al., 2016; Fragaszy and Closas, 2016; Foster et al., 2018; Flörke et al., 2019). Agricultural intensification could meet short-term food security and livelihood goals, but reduces biological and landscape diversity, and ecosystem services (*high confidence*) (Campbell et al., 2017; Balmford et al., 2018; Springmann et al., 2018; Ickowitz et al., 2019; Mbow et al., 2019). Agricultural intensification can also affect livelihoods of small-scale producers, compromising food security. It can increase low-waged casual farm work, increasing gender and income inequality (Bigler et al., 2017; Clay and King, 2019; Table 5.18).

Table 5.19: Case studies of trade-offs and negative outcomes associated with Agricultural Intensification on biodiversity and ecosystem services.

Ecosystem service	**Trade-offs / Negative Outcomes**	**References**
Provisioning: Water quality	Negative impacts on ephemeral wetlands	Dalu et al. (2017)
Provisioning: Water availability	Contribution to water scarcity	Satgé et al. (2019)
Supporting: Soil	Increasing erosion risk	Govers et al. (2017)
Regulating: Climate	Reduced soil organic carbon sequestration	Olsen et al. (2019)
Regulating: Pest control	Reduced level of biological control of pests: Reduced number of insectivorous birds	Emmerson et al. (2016)
Cultural: Recreational	Reduction on river wildlife	DeBano et al. (2016)
Biodiversity	Reduced global biodiversity	Newbold et al. (2015), Egli et al. (2018), Beckmann et al. (2019)
Biodiversity	Reduction of taxonomic diversity	Jeliazkov et al., (2016), Kehoe et al. (2017), Banerjee et al. (2019)
Biodiversity	Negative impacts on mean population stability	Olivier et al. (2020)

Land available for provisioning ecosystem services is declining in many places because of agricultural expansion, bioenergy crops and reforestation for mitigation (Kongsager, 2018), with adverse climate impacts

(Froese and Schilling, 2019). Cropland expansion can deteriorate biodiversity (Delzeit et al., 2017), water quality (Ayala et al., 2016) and carbon storage (Goldstein et al., 2012) and increase water demands (Yokohata et al., 2020).

A systems-based perspective on land use is needed to address climate change impacts on nutrition security, and ecosystem services (Springmann et al., 2018; IPCC, 2019b; Willett et al., 2019). Land sparing sets aside some land for conservation purposes and intensifies production on farmland (Balmford et al., 2018; Benton et al., 2018; IPCC, 2019b) with potential to offset greenhouse gas emissions (Lamb et al., 2016). Alternatively 'land sharing' approach, through principles such as minimizing fossil-fuel based inputs, maximizing synergies, addressing both climate change mitigation and adaptation and biodiversity (Kremen and Miles, 2012; Kremen, 2015; Kremen and Merenlender, 2018; HLPE, 2019; section 5.14, Box on Agroecology). Community-managed initiatives can address biodiversity and ecosystem conservation, livelihoods, food provisioning and other ecosystem services (Kremen and Merenlender, 2018; HLPE, 2019).

The concept of sustainable intensification has emerged, looking for enhancements in environmental outcomes, while maintaining or increasing agricultural systems performance. There is a potential to find synergies between agricultural production and landscape systems if systems are design to operate within planetary boundaries (Rockström et al., 2017; Liao and Brown, 2018; Pretty, 2018; Pretty et al., 2018).

5.13.3 Competition Between Food Systems in Land and Ocean

Livestock and aquaculture feeds utilize crops such as soyabean and maize, with food conversion efficiencies similar in chicken and Atlantic salmon, and higher in pigs and cattle (Troell et al., 2014; Fry et al., 2018b; Fry et al., 2018a). Use of wild fish meal and oil has been decreasing, partly due to concerns regarding vulnerable small pelagic fish stocks (Bindoff et al., 2019). The instability of wild fish stocks has increased terrestrial crop feed components (Troell et al., 2014; Blanchard et al., 2017; FAO, 2017; Cottrell et al., 2018). The use of wild fish in fish feeds that may have been directly consumed may put low-income households at risk of food insecurity (Troell et al., 2014). An increasing demand for aquaculture products intensifies competition for feed supplies (*medium confidence*) (Troell et al., 2014; Blanchard et al., 2017). Increases in demands for animal protein and shifts to pescatarian diets will increase the existing competition for land resources, particularly in low and medium income countries, with negative impacts on food security (Makkar, 2018), but may be mitigated by dietary changes, novel feeds and food waste usage for aquatic systems (Berners-Lee et al., 2018; Hua et al., 2019; Cottrell et al., 2020).

Competition over use of major aquaculture feed crops (Fry et al., 2016) with terrestrial livestock (Troell et al., 2014), and fish use by terrestrial livestock, will also place pressure on fish and crop resources (*medium confidence*) (Cottrell et al., 2018). Increases in feed prices will affect fish and meat prices (Troell et al., 2014), and changes in agriculture will be needed to satisfy aquaculture demands (Blanchard et al., 2017). Aquaculture and livestock dietary components may also compromise crops and forage fish that provide essential nutrients for low-income households increasing nutritional insecurity, in regions of sub-Saharan Africa, Asia and Latin America (Troell et al., 2014). Waste fish products can supplement fish meal and oil to reduce competition for feed, as well as reducing use of fish that could go to human consumption (*medium confidence*) (Little et al., 2016; Shepherd et al., 2017; Dave and Routray, 2018; Naylor et al., 2021). Use of algae, bacteria, yeast and insect diets could replace fishmeal for aquaculture (Cohen et al., 2018; Hua et al., 2019; Cottrell et al., 2020), not affecting nutritional profiles (Campanaro et al., 2019) and fish could be reared on waste by-products of other food production systems (Bava et al., 2019). Complete fish oil substitutions with microalgae may be possible without compromising omega-3 contents, but energy usage in diet production should be considered Cottrell et al. (2020). Substitutions of plant-based and alternative feeds may decrease food conversion efficiencies (Cottrell et al., 2020), affect omega-3 content of farmed seafood (Fry et al., 2016; Shepherd et al., 2017), be problematic for the fish themselves (Little et al., 2016; Naylor et al., 2021) and lead to reduced productivity (Shepherd et al., 2017).

Competition will be heightened by other climate impacts, such as changes in water availability. Water usage is relatively high in animal production (Abraham et al., 2014; Sultana et al., 2014; de Miguel et al., 2015; Palhares and Pezzopane, 2015; Weindl et al., 2017). In some areas, increased demand for plant-based animal feeds will be affected by sea level rise and competing usage of available freshwater with other users, and ecosystem needs (Karttunen et al., 2017).

5.13.3.1 Agricultural and river run-off

Flooding on agricultural land will enhance nutrient run-off, creating eutrophication and increasing hamr phytoplankton blooms, affecting fisheries and aquaculture, human health and ecosystem biodiversity. Changes in precipitation, monsoons, run-off and flood potential combine with deforestation and poor sewage treatment, resulting in larger volumes of nutrients and freshwater reaching coastal ecosystems (Jin et al., 2018; Nasonova et al., 2018; Tamm et al., 2018). Rising surface temperatures, ocean acidification and eutrophication will increase pathogenic *Vibrio* bacterial loads in marine organisms with potential transfer to humans (Hernroth and Baden, 2018). Shallow and microtidal estuaries will be more vulnerable to changing river runoffs and saltwater intrusions, eutrophication, and hypoxia (*high confidence*) (IPCC, 2019c).

5.13.4 Maladaptation Responses and sustainable solutions

Maladaptation can result in three types of outcomes (Juhola et al., 2016) 1) *Rebounding vulnerability*: short term adaptations that decrease adaptive capacity and hinder future choices; 2) *Shifting vulnerability*: larger-scale adaptation actions that produce spill-over effects in other locations; 3) *Eroding sustainable development*: adaptation strategies which increase emissions, deteriorate environmental conditions and/or social and economic values (Tables 5.20 and 5.21).

Existing climate policies do not adequately consider tradeoffs, adaptive limits, cumulative costs and potential risks of maladaptation (*robust evidence and medium agreement*) (Dovie, 2017; Holsman et al., 2019; IPCC, 2019b; Work et al., 2019; Thomas, 2020: Table 5.19). Government policies are seldom coordinated across scales and often focused on regional short-term risks (*medium evidence, medium agreement*) (Dovie, 2017; Holsman et al., 2019; Rahman and Hickey, 2019; Butler et al., 2020). Past development trajectories and dominant political economic structures may narrow adaptation pathways, be restrictive and increase the vulnerability of particular groups (Paprocki, 2018; Quan et al., 2019; Rahman and Hickey, 2019; Work et al., 2019).

Case Studies of Maladaptation

Large-scale irrigation project in Navarre, Spain

Many small-scale producers could not afford the irrigation investment and had to sell or rent their land to those who joined the irrigation project. Many large-scale farmers using irrigation switched to corn and forage and dropped crops with high labour costs. Water costs are now paid to a private company, and small-scale farmers lost access to communal water rights. The project increased inequity, land concentration and lowered crop diversity, with small scale producers more vulnerable to climate change. Large-scale intensive farmers are more exposed to crop price volatility than to climate vulnerability but have greater access to subsidies and water rights (Albizua et al., 2019).

Constraining adaptation: previous agricultural development pathways in India

Government policies in colonial and postcolonial India, invested in infrastructure, export production and synthetic input use (Gupta, 1998; Davis, 2001), setting the stage for current development trajectories, closing out other adaptive options. Although such policies increased national food production, they failed to address high levels of malnutrition, worsening regional inequalities, degraded natural resources, and an agrarian debt crisis (Singh, 2000; Gupta et al., 2016; Gajjar et al., 2019). Agricultural livelihoods are increasingly considered unviable, with lower adaptive capacity of farmers, high debt levels (Gupta et al., 2016), Indigenous and local knowledge loss and denigration (Kumar, 2016) alongside lower crop diversification (Srivastava et al., 2016). Government institutions aimed at infrastructure often lack adaptive capacity needed to address rural livelihoods (Singh et al., 2017; Gajjar et al., 2019).

Table 5.20: Summary of the emerging literature on potential risks of maladaptation.

Description of adaptation strategy	Potential Negative impacts	Maladaptation Typology (1= Rebounding vulnerability, 2= shifting or 3=eroding SDGs)	Regions and countries affected	Groups affected	References
Agricultural intensification to increase productivity, in places with heavy rainfall events or rising pest/disease incidence	Increases GHG emissions, water pollution, possible insect resistance and costs to farmers, possibly increased inequities. May constrain adaptation policy options for development pathways due to lock-ins and trade-offs which entrench inequities.	1,2,3	United States, Africa, Asia (India, China), Europe	Farmers, pastoralists / nearby communities who rely on water; small-scale farmers who cannot afford inputs; Policymakers.	Gajjar et al. (2019), Guodaar et al. (2019), Houser and Stuart (2019), Neset et al. (2019b), Quan et al. (2019), Young and Ismail (2019)
Livelihood diversification into charcoal production	Increases GHG emissions and deforestation rates	1,3	Africa (Northern Ghana), South America (Peru)	Small-scale food producers; Indigenous communities	Antwi-Agyei et al. (2018), Zavaleta et al. (2018), Young and Ismail (2019)
Irrigation projects or programs either large-scale and/or that rely on groundwater	Reduces long term potential for hydropower and groundwater availability, can increase salinization and cost of water. Can increase cost of farming and debt levels of farmers, squeezing out small-scale producers. Can reduce water availability for aquaculture.	1,2 and 3	Northern China; India; Mediterranean areas; Europe; United States	Food producers who rely on irrigation; consumers who rely on hydropower or groundwater; Small-scale diversified producers who cannot afford irrigation; Aquaculture.	Doody et al. (2015), Herbert et al. (2015), Barik et al. (2016), Daliakopoulos et al. (2016) Fragaszy and Closas (2016) Dalin et al. (2017), Foster et al. (2018) Hanaček and Rodríguez-Labajos (2018), Albizua et al. (2019), Flörke et al. (2019) Gajjar et al. (2019), Xu et al. (2019)
Investment in improved cultivars or shift to different crops	May displace local varieties, reduces diversity if too much policy/extension emphasis falls on a few varieties; may increase risk of crop loss from pests, disease, drought if reliant on a few varieties; may increase fertilizer use; may lead to loss of Indigenous or local knowledge	1, 3	South America (Bolivia); Pacific Islands; Asia	Small scale food producers; Indigenous communities	Mcleod et al. (2018), Meldrum et al. (2018), Neset et al. (2019b) Rahman and Hickey (2019)
Migration	Can increase the workload of people left behind (often women), worsen rural livelihoods and food insecurity; can lead to worsened living conditions, food security and	1,3	Asia, Africa, Central and South America	Small-scale low-income food producers or rural workers; women	Bettini et al. (2017), Paprocki (2018), Chen et al. (2019), Jacobson et al.

	poverty in precarious urban conditions, may increase vulnerability to flooding in urban locations. May affect mental health by disrupting eisting social ties				(2019), Michael et al. (2019), Young and Ismail (2019), Singh and Basu (2020), Torres and Casey (2017)
Coastal sea walls, embankments, canals, riverbed draining and dikes to reduce flood risk	Can degrade coastal mangroves, deplete open freshwater fisheries, sedimentation of rivers, reduce fish diversity and increase flooding risk for particular vulnerable groups; may divert funds from other more sustainable measures.	1,2,3	Asia, South Pacific Islands, west Africa	Coastal communities dependent on mangroves and fisheries; low-income rural households with seasonal dependence on inland fisheries	Dovie (2017), Owusu-Daaku (2018), Freduah et al. (2019), IPCC (2019c), Rahman and Hickey (2019), Nunn et al. (2020) Seddon et al. (2020), Thomas (2020)
River regulation for hydropower	May have negative impacts on inland fisheries.	2,3	Global	Small-scale inland fisheries and low-income rural households with seasonal dependence on inland fisheries	FAO (2018c)
Government policies to manage coastal fisheries which promote overcapitalization of fisheries, including index insurance	Government confiscation of fishing nets to prevent rapid decline of fish population can worsen livelihoods for small scale fishers; Subsidies of pre-mixed fuel to allow fishers to stay out longer due to shifting fish populations may increase total number of fishers and total fish catch. Insurance payments may benefit larger-scale fishing fleets and push out small-scale fishers.	1,3	West Africa	Coastal small-scale fishery communities	FAO (2018b), Freduah et al. (2019), Holsman et al. (2019), Sainsbury et al. (2019)
Consultative stakeholder systems in fisheries or flood management	May encourage inertia in the system due to a few powerful stakeholders participating in the consultative process.	2	North America; Asia	Coastal fisheries	Holsman et al. (2019), Rahman and Hickey (2019)
Climate services	May reinforce existing inequalities if climate services are attuned to powerful stakeholders in industry, services are privatized, there are limited ways to get input from vulnerable groups and planning budgets that use climate services are constrained.	1,2,3	North America	Coastal fisheries, Farming	Furman et al. (2014), Webber (2017), Nost (2019)
Nature-based solutions mitigation and adaptation	Can displace local communities' access to land for food production and other ecosystem services, have negative impacts	2,3	Africa, Asia, and South America	Indigenous communities; small-scale producers and	Lunstrum et al. (2016), Work et al. (2019),

strategies such as reforestation or afforestation	on Indigenous rights, reduce biodiversity and may not reduce GHG as much as conserving natural forests and wetlands or agroecological systems such as agroforestry or other means to increase soil C.		e.g., Indonesia, Amazon, west-central Africa	forest dependent communities	Seddon et al. (2020), Cross-Working Group Box BIOECONOMY this Chapter)
Social safety nets provide funds which increases consumption of processed, purchased food and erodes Indigenous knowledge	Decline in Indigenous knowledge of and collective approaches to seasonal adaptation strategies in hunting, fishing, and food production; shift in dietary patterns to more processed and non-local foods; reduction in farming. Reduced capacity to respond to hazards through dispersed settlement e.g. hunting, fishing, wild food collection. Increased population density increases deforestation and vulnerability.	1,3	South America (Amazonian region of Peru); Africa (South Africa)	Indigenous communities	Lemos et al. (2016), Zavaleta et al. (2018)
Community-based adaptation strategies	Local gender and other social inequities can lead to 'elite capture' that reinforces inequality; power dynamics between the funding agency and local participants can make local community involvement tokenistic. There may be inadequate attention to socio-cultural preferences and structural factors which foster maladaptation such as inappropriate crops or animals used.	1,3	Pacific Islands; Africa; Asia	Small scale food producers; Indigenous communities, other vulnerable groups such as women and low caste groups	McNamara and Buggy (2017) Jamero et al. (2018), Singh (2018) Bezner Kerr et al. (2019) Piggott-McKellar et al. (2020), Westoby et al. (2020)
Digital agriculture for increased precision and efficient use of fertilizers, pesticides, water	Could lead to net job losses, particularly for those with lower levels of education; increased surveillance and employer scrutiny of lower-skilled workers in fields, greenhouses and processing plants and warehouses; separate workers from employees and companies who collect data. Overall increased racial, income inequities and unequal working conditions.	2,3	North America, South America, Europe, Asia, parts of Africa.	Farmworkers; small-scale food producers who cannot afford digital technologies; rural communities.	(Furman et al. (2014), Rotz et al. (2019)
Increased credit access for livelihood diversification	High interest rates, tight return policies could increase debt loads for low-income households, which could rebound vulnerability. Household may invest in livelihood strategies which are vulnerable to climate change impacts, or which increase GHG.	1,3	Asia (Bangladesh)	Low-income landless people or small-scale producers	Rahman et al. (2018)
Aquaculture	Large-scale coastal aquaculture can increase soil salinization and reduce land available for other food production and can increase migration	2,3	Asia (Bangladesh)	Small-scale mixed systems including rice production and other rural livelihoods	Paprocki (2018), Paprocki and Huq (2018)

Adaptation options that consider adverse effects for different groups reduce the risk increasing vulnerability, negatively affecting socio-economic factors to deal with climate impacts, or impeding efforts to implement sustainable development goals (*high confidence*) (Juhola et al., 2016; Antwi-Agyei et al., 2018; Paprocki and Huq, 2018; Holsman et al., 2019; IPCC, 2019b; Stringer et al., 2020). Adaptation methods considering historical roots of current vulnerabilities can identify viable solutions, which are difficult to undertake because of path dependencies (*high confidence*) (Ribot, 2014; Albizua et al., 2019; Gajjar et al., 2019; Paprocki, 2019; Thomas, 2020). Planning techniques that model outcomes for different groups from different adaptation options could be put in place to diminish maladaptation risks (Rodríguez et al., 2019).

Inclusive planning initiatives such as community-based anticipatory adaptation combined with 'two-way learning' that considers future scenarios and different adaptation pathways, can prevent maladaptation (*high confidence*) (Dovie, 2017; Bezner Kerr et al., 2019; Neset et al., 2019a; Rahman and Hickey, 2019; Work et al., 2019; Butler et al., 2020; Nunn et al., 2020; Piggott-McKellar et al., 2020; Westoby et al., 2020; Table 5.20). Promising policy management tools combine temporal scales, mitigation-adaptation interactions, consider political dynamics, socio-economic impacts and trade-offs for vulnerable groups, long-term support for policy leaders, efforts to establish livelihood 'niches' and ongoing participatory evaluation (Dovie, 2017; Holsman et al., 2019; Rahman and Hickey, 2019; Work et al., 2019; Butler et al., 2020). A focus on the most disadvantaged groups can help small-scale producers at higher risk to prevent maladaptation (FAO, 2018c). Governance mechanisms have emerged that consider food security, socio-cultural factors, land and water rights, using participatory, inclusive 'two-way learning' methods that involve vulnerable people alongside government (IPCC, 2018; Holsman et al., 2019; IPCC, 2019b; Rahman and Hickey, 2019; Butler et al., 2020).

Table 5.21: Strategies to avoid maladaptation (adapted from (Magnan, 2014; Lim-Camacho et al., 2015; Sovacool et al., 2015; FAO, 2018b; Paprocki and Huq, 2018; Sainsbury et al., 2019).

Type of maladaptation	Strategies
Environmental	1. Prevent negative effects on ecosystem services in situ (e.g., habitat degradation, pollution) that increases exposure to climate hazards. 2. Avoid increasing pressure on other socio-ecological systems. 3. Ensure ecosystems' protective role as natural buffer zones is sustained against current and future climate-related hazards, such as storms, floods, and sea level rise. 4. Provide some duplication and ensure flexibility of adaptation strategies to reduce risk because of uncertainties about climate change impacts and ecosystem response (e.g., agrobiodiversity to reduce pest outbreaks).
Socio-cultural	1. Consider local social characteristics and cultural values that could affect risks and environmental dynamics. 2. Support local skills and knowledge related to climate-related hazards. 3. Support capacity-building for new skills needed by local communities.
Political-Economic	1. Consider the political dynamics and power imbalances and create inclusive processes to involve the most vulnerable and disadvantaged groups in decisions. 2. Work to reduce socio-economic inequalities, poverty, and food insecurity. 3. Support livelihood diversification. 4. Focus on the impacts of adaptation on the poorest, structurally disadvantaged, and vulnerable groups, and take power imbalances into account. 5. Work across the full supply chain to consider linkages and possible ripple effects.

5.13.5 Climate Change and Climate Response Impacts on Indigenous People

Indigenous people and ethnic minorities, many of them having special cultural associations to local foods, are particularly vulnerable to climate change due to changes in the availability of wild foods, crop failure and food production loses or via increased food prices (Norton-Smith et al., 2016; Otto et al., 2017).

Changes in sea level rise or coastal erosion can reduce ecosystem services to a point where either subsidies are used to enable human populations to remain in their place of attachment, or ultimately to displace coastal residents thereby removing connections to places of intrinsic value. For example, the United Houma Nation in Louisiana is experiencing coastal land loss, sea level rise and strong Gulf hurricanes, which leads to the relocation of some tribes causing loss of Houma identity (Sullivan and Rosenberg, 2018). Another example is the relocation of Alaska Native communities due to climate change (Hamilton et al., 2016)

Expansion of agriculture can bring distress to Indigenous communities because of environmental deterioration and the stress associated with relocation or displacement (Otto et al., 2017). Afforestation and reforestation (A/R) programs can also bring inequalities to Indigenous communities (Godden and Tehan, 2016) and even violent displacement with tragic results (Celentano et al., 2017). A/R programs can negatively affect a range of substantial and procedural Indigenous Peoples' rights entrenched in international human rights law (Table 5.22) and their potential for climate change adaptation (*high confidence*).

A significant proportion of land targeted for A/R projects is inhabited and used by Indigenous Peoples and local communities (Cagalanan, 2016). Indigenous Peoples have rights to and/ or manage at least 37.9 million km^2 of land and influence land management across at least 28.1% of the land area (Garnett et al., 2018). At least a quarter of the global land area is traditionally owned, managed, used or occupied by Indigenous Peoples overlapping 35 to 40 per cent of the area that is formally protected (Garnett et al., 2018; Brondizio et al., 2019). In many cases, A/R is implemented in areas where tenure rights are insecure and Indigenous Peoples' rights are in risk of being disregarded (Naughton-Treves and Wendland, 2014; Kohler and Brondizio, 2017; Garnett et al., 2018) (*medium evidence, high agreement*). Many projects are also found in areas where complex socio-political contexts challenge management (Jurjonas and Seekamp, 2019). It is anticipated that A/R projects will create huge pressures on existing land uses and generate further land use conflicts (Aggarwal, 2014; Robinson et al., 2014; Paul et al., 2016; Brancalion and Chazdon, 2017; Pye et al., 2017; Bond et al., 2019). In addition, many afforestation projects are conducted in regions that are not bio-climatically suitable, leading to the degradation of ecosystems that are key to local livelihoods (Veldman et al., 2015; Robinson et al., 2016b).

Table 5.22: Indigenous rights recognized in international human rights law negatively affected by A/R projects.

Negative impacts of monoculture plantations (and other A/R projects)	Indigenous Peoples' rights affected	Degree of certainty	References
Local community not informed, not adequately consulted, not provided means for meaningful participation in project design, implementation, and monitoring (with specific attention to women and poor households); disruption or non-recognition of local or traditional institutions; elite capture; no access to third-party grievance mechanisms.	Right to self-determination; consultation and free, prior and informed consent (FPIC); participation	*Medium evidence, high agreement*	Aggarwal (2014), Maraseni et al. (2014), Ravikumar et al. (2015), Bayrak and Marafa (2016), Loaiza et al. (2016), Vijge et al. (2016), Pye et al. (2017), Ryngaert (2017), Wolde et al. (2016), Brancalion and Chazdon (2017), Seddon et al. (2020)
Evictions and displacement; dispossession; livelihood precarity; and criminalization of forest-dwelling people	Right not to be forcibly removed	*Medium evidence, high agreement*	Mingorría (2014), Richards and Lyons (2016), Witasari (2016), Corbera et al. (2017), Pye et al. (2017), Sarmiento Barletti et al. (2020), Brancalion and Chazdon (2017)
Loss, transfer or acquisition of land. A/R projects involve changes in land use for medium to long term and often lack consideration for local dynamics including land tenure and competition with agriculture or conservation.	Rights to land and territory	*Limited evidence, high agreement*	Aggarwal (2014), Robinson et al. (2014), Bayrak and Marafa (2016), Pye et al. (2017), Bond et al. (2019)
A/R projects exacerbate conflicts, accentuate uneven power relations,	Rights to land and territory	*Limited evidence,*	Aggarwal (2014)

increase existing inequalities within communities, exclude the poor and deepen structural injustices including racism and stigmatization.		*low agreement*	
Forest expansion intensifies already acute land shortages for growing food and forces villagers to take their animals for grazing to new areas as a result of forests being fenced off.	Rights to land and territory (with implications for food security)	*Limited evidence, high agreement*	Lyons et al. (2014), Wolde et al. (2016), Brancalion and Chazdon (2017), Mousseau and Teare (2019)
Decreased stream flows and water yields; exacerbated water scarcity.	Right to water	*Robust evidence, high agreement*	Veldman et al. (2015), Aitken and Bemmels (2016), Brancalion and Chazdon (2017), Pye et al. (2017), Bond et al. (2019), Seddon et al. (2020)
Pollution of lakes with agrochemicals; heavy chemical use including the spread of pesticides, herbicides and fertilizers by aircraft and other means causing runoff into rivers	Right to a healthy environment	*Medium evidence, high agreement*	Richards and Lyons (2016), Johansson and Isgren (20179, Pye et al. (2017)
Encroachment on other ecosystems with devastating impacts on biodiversity; pressures on ecologically sensitive ecosystems such as wetlands; reduction in seed-dispersing animals; planted tree species becoming invasive, introducing pests and diseases	Right to a healthy environment, right to food	*Medium evidence, high agreement*	Richards and Lyons (2016), Holmes et al. (2017), Seddon et al. (2020), Ennos et al. (2019)
Loss of habitat, degradation of savannas, native grasslands (grassy biomes) or mangroves wrongly characterized as degraded land suitable for afforestation	Right to a healthy environment, right to food	*Robust evidence, high agreement*	Veldman et al: (2015), Cormier-Salem and Panfili (2016), Brancalion and Chazdon (2017), Bond et al. (2019), Seddon et al. (2020)
Direct negative health impacts; loss of traditional medicine	Right to health	*Limited evidence, medium agreement*	Dotchamou et al. (2016), Johansson and Isgren (2017)
A/R projects affect burial sites as for many communities, the forest is also the resting place for deceased ancestors	Right to cultural identity and to main and control their traditional knowledge	*Limited evidence, high agreement*	Lyons et al. (2014), Gabriel and Mangahas (2017), Mousseau and Teare (2019)
Loss of traditional or Indigenous ecological knowledge and forest management practices	Right to cultural identity and traditional knowledge	*Limited evidence, medium agreement*	Bayrak and Marafa (2016)
Increased labor burden. Benefit sharing by direct cash transfer or in-kind modalities tends to not compensate lost income opportunities. Some projects bring employment opportunities, but these are short term and limited and rarely viable if the opportunity cost of land and labour is considered. Poor farmers may drop out in order to regain access to their land for uses that provide cash returns in the shorter term.	Right to an adequate standard of living; right to decent work; right to benefit-sharing	*Medium evidence, medium agreement*	Boyd et al. (2007), Aggarwal (2014), Cagalanan (2016), Witasari (2016), Corbera et al. (2017), Pye et al. (2017)

Until 2010, most A/F projects had technical, carbon-related goals and did not consider issues of livelihoods, community involvement or broader ecosystem impacts (Wolde et al., 2016). New strategies such as Nature-based Solutions (Seddon et al., 2020) and Forest and Landscape Restoration (Brancalion and Chazdon, 2017) integrate a larger set of social and environmental objectives. Indigenous Peoples enjoy a range of co-benefits of A/F initiatives such as improved habitat, fire management or protection from climatic shocks such as drought (Robinson et al., 2016b; Seddon et al., 2020) provided they are able to manage carbon funds collectively, meet the monitoring and reporting requirements, and protect forests from illicit uses and natural disasters (Wolde et al., 2016).

Policies and safeguards attached to specific A/R initiatives determine their impact (*high confidence*) (Talor, 2015; West, 2016; Brancalion and Chazdon, 2017). In countries where there is a great level of devolution of rights to Indigenous Peoples there is a risk that the A/R agenda will lead to recentralization (*limited evidence, medium agreement*) (Bayrak and Marafa, 2016). Some A/R initiatives specify the need to respect the rights of Indigenous Peoples and local communities and protect biodiversity (*medium evidence, high agreement*) (Seddon et al., 2020).

Local communities' ability to participate in project design, implementation and monitoring is directly linked to the autonomy and independence of local institutions (Pye et al., 2017), their ability to formulate by-laws (Wolde et al., 2016) and handle funds in a transparent way (*medium evidence, high agreement*) (Witasari, 2016). It is further dependent on cohesion in the community (Cagalanan, 2016), the existence of clear rules delineating community membership and the presence of elders and community members with relevant local knowledge (Robinson et al., 2016b) as well as gender and out-migration dynamics affecting participation structures (*robust evidence, medium agreement*) (Cormier-Salem and Panfili, 2016; Witasari, 2016; Wolde et al., 2016; Jurjonas and Seekamp, 2019).

5.13.6 Increased Presence of Financial Actors in the Agrifood System

Financial actors, markets, institutions, and incentives have gained importance in agricultural commodities and farmland markets in the past two decades (Clapp and Isakson, 2018; Fairbairn, 2020).New types of investment vehicles such as commodity index funds that track prices of commodities and farmland have emerged and the use of older vehicles such as forward and futures markets has increased (Schmidt and Pearson, 2016; Clapp and Isakson, 2018). These trends are connected to climate change as financial investments are influenced by the likelihood that climate change will increase commodity and farmland price variability (*medium confidence*) (Cotula, 2012; Isakson, 2014; Tadesse et al.).

Financial investors pool their investments through intermediaries, alongside other dynamic forces in the global economy, making unambiguous assessments of their effect difficult (Clapp, 2014; Clapp, 2017). However, assessment of the broader trends at the interface of financial investment, food system dynamics, and climate change shows potential connections.

Climate-induced variability in food production has the potential to introduce a new level of uncertainty into food and farmland markets, encouraging financial investment into products to capitalize on price volatility and to hedge risks. The new financial instruments enable investors to speculate more easily on the direction of food and land prices, especially when they are volatile (Ouma, 2014; Baines, 2017).

5.13.7 Climate Change Interactions with other Drivers – Food-Water-Health-Energy-Security Nexus

Linkages between food security and nutrition with water and energy as well as other important socio-environmental issues are increasingly being described within a nexus framework (see also Chapters 3, 4, 6, and 7) with food systems frequently located at the centre of nexus concepts (Caron et al., 2018).

Climate change will affect the food-energy-water (FEW) nexus, commonly in the form of risk multiplier (*high confidence*) (e.g. Conway et al., 2015; Barik et al., 2016; Keairns et al., 2016; Abbott et al., 2017; Ebhuoma and Simatele, 2017; Caron et al., 2018; D'Odorico et al., 2018; de Amorim et al., 2018; Mpandeli et al., 2018; Nhamo et al., 2018; Soto Golcher and Visseren-Hamakers, 2018; Yang et al., 2018; Amjath-Babu et al., 2019; Froese and Schilling, 2019; Mercure et al., 2019; Momblanch et al., 2019; Pastor et al., 2019; Xu et al., 2019). Xu et al. (2019) assessed the need for an increase in irrigation water to sustain maize production in Northeast China. As droughts will become more frequent, this could lead to groundwater depletion and other environmental knock-on effects. Barik et al. (2016) described how the growing demand for food in India has led to more irrigation with a reduction in groundwater levels in some regions.

Increasing demands for food, energy and water can lead to domestic and international conflict, including political instability and migration, often in the context of drought (*high confidence)* (Abbott et al., 2017; Bush and Martiniello, 2017; WEF, 2017; D'Odorico et al., 2018; de Amorim et al., 2018). de Amorim et al. (2018) conclude that the WEF nexus is susceptible to many global risks, including extreme weather events and human migrations and predominantly endanger vulnerable communities of less developed countries. There is emerging evidence that food and water insecurity enhance social conflicts, including protests and violent riots, at least partially, by accelerating existing grievances (Heslin, 2021; Koren et al., 2021). Closer coordination at global, regional, and national levels could be recommended to manage these risks.

Meeting growing demands for food, water, and energy under a changing climate require technical solutions and behavioural change as well as greater coordination across multilateral institutions and governance. Supply-side solutions focus on enhancing production, reducing food waste and loss or lowering water demand through both technological approaches (e.g., breeding, improved irrigation) and agroecological approaches, such as agroforestry, underutilized and more adapted crops, and transition toward a circular economy (Alexander et al., 2015; Obersteiner et al., 2016; D'Odorico et al., 2018; Nhamo et al., 2018; Soto Golcher and Visseren-Hamakers, 2018). Demand-side solutions focus primarily on changes in consumer behaviour toward healthier diets with lower carbon footprints, particularly reduction of meat consumption (Alexander et al., 2015; Obersteiner et al., 2016). Improving the coordination of multilateral organizations could result in improved cross-boundary management of natural resources, particularly related to water (Conway et al., 2015; Nhamo et al., 2018; Soto Golcher and Visseren-Hamakers, 2018).

As relationships between individual subsystems are systemic, integrated solutions would result in better outcomes across the FEW nexus (*strong agreement*). Obersteiner et al. (2016) concluded that single-sector policies can create strong trade-offs with other policy targets and SDGs, whereas strategies that reduce pressure on food production systems diminish trade-offs between FEW nexus components. This suggests that achieving multiple SDGs will require balancing societal demands in the context of finite natural resources (Jägermeyr et al., 2017; Amjath-Babu et al., 2019; Momblanch et al., 2019).

Despite concluding that integrated solutions addressing the systemic connections between the FEW nexus would improve development and environmental outcomes, there are limitations of integrating multiple frameworks, both in terms of describing the complexities and in finding solutions (Leck et al., 2015; Weitz et al., 2017; Wichelns, 2017; Shannak et al., 2018). Leck et al. (2015) and Weitz et al. (2017) indicate that evidence of successful implementation and improved outcomes based on the application of nexus concepts is rare.

5.14 Implementation Pathways to Adaptation and Co-benefits

5.14.1 State of Adaptation of Food, Feed, Fibre, and Other Ecosystem Products

Since AR5, several adaptation reviews have been done (Ford et al., 2015; Lesnikowski et al., 2016). In a review of 1159 peer-reviewed sources, Berrang-Ford et al. (2021b) found that observed adaptations in food, fibre and other ecosystem products has consisted mainly in changes in autonomous behaviour changes, such as changing planting time, followed by technological/infrastructure and ecosystem-based adaptation approaches, the majority of which have occurred in Africa and Asia (Figures 5.20-5.21, Table 5.22). Several adaptation options addressed multiple SDGs (e.g. 2, 6 8, 12) (Figure 5.21).

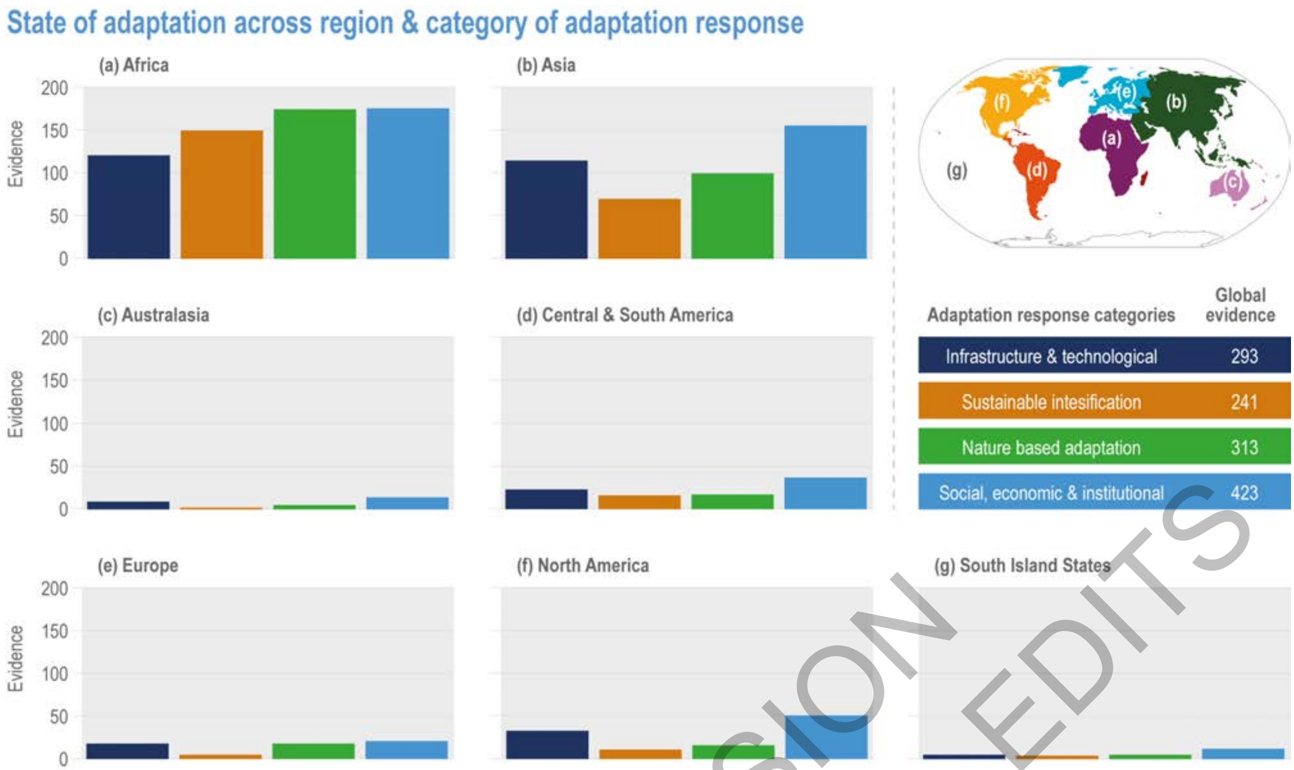


Figure 5.19: State of adaptation by region and type of response (based on 1159 peer-reviewed references that addressed adaptation in food, fibre, and other ecosystem products sector; source: Global Adaptation Mapping Initiative (GAMI) database (Berrang-Ford et al., 2021a). The bars indicate the number of evidence for the category x region.

Table 5.23: State of adaptation in food, fibre and other ecosystem products by actor and vulnerability (planned and targeted) (source: Global Adaptation Mapping Initiative (GAMI) database (Berrang-Ford et al., 2021a)).

Actors	N (%)	Equity/justice	Planned – N (%)	Targeted – N (%)
International or multinational governance institutions	72 (6%)	*Women*	134 (12%)	118 (10%)
National government	264 (23%)	*Youth*	22 (2%)	24 (2%)
Local government	267 (23%)	*Elderly*	31 (3%)	28 (2%)
Sub-national government	89 (8%)	*Low-income*	201 (17%)	258 (22%)
Private sector corporations	56 (5%)	*Disabled*	2 (0%)	3 (0%)
Private sector SMEs	80 (7%)	*Migrants*	12 (1%)	18 (2%)
Civil Society-international/multinational/national	117 (10%)	*Indigenous*	95 (8%)	85 (7%)
Civil Society- sub-national or local	257 (22%)	*Ethnic minorities*	32 (3%)	32 (3%)
Individuals or households	1087 (94%)			

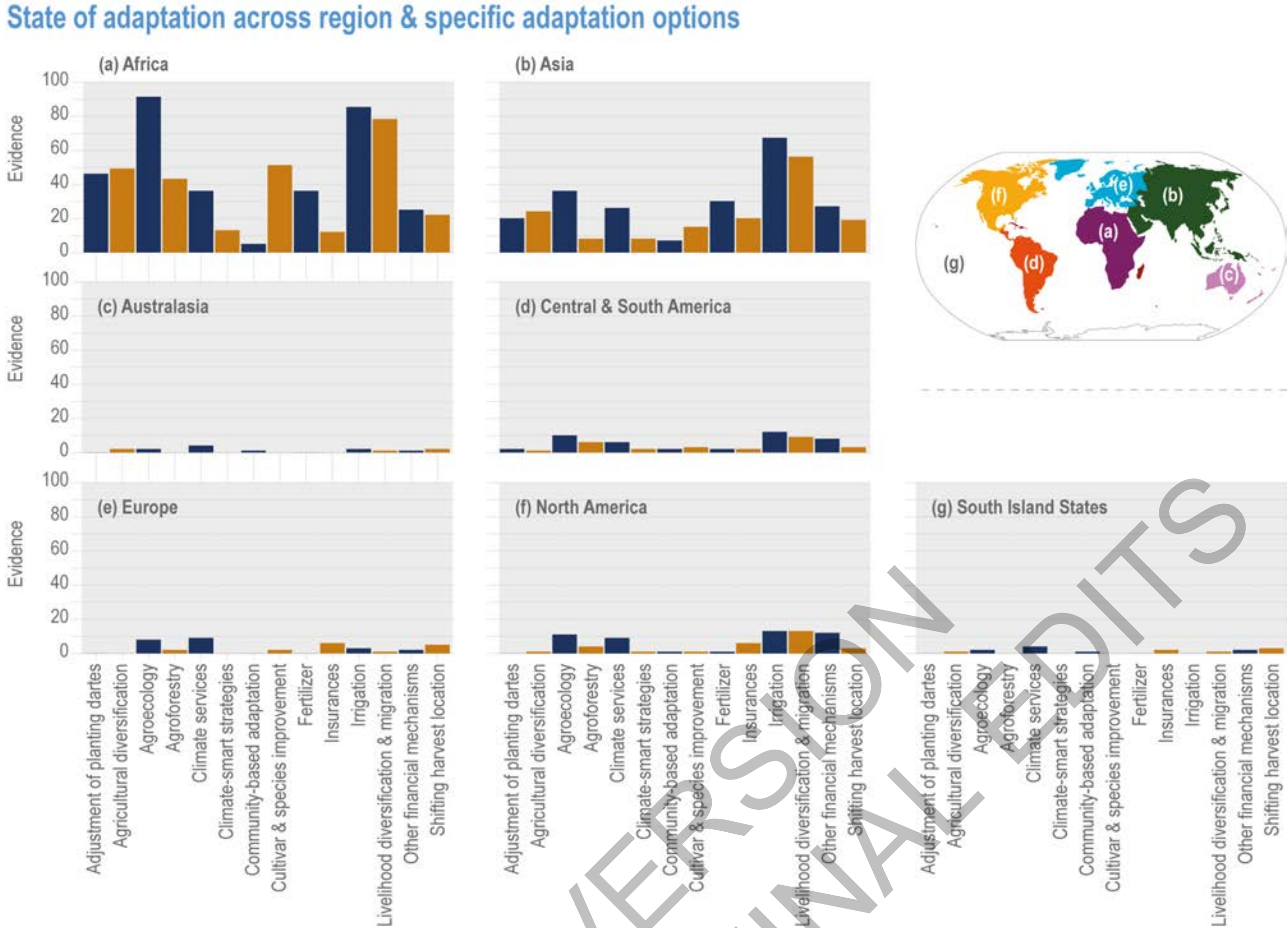


Figure 5.20: Observed adaptation across regions in food, fibre, and other ecosystem products. Stage of implementation; Type of adaptation; Inclusion of Indigenous knowledge and local knowledge (IK and LK) based on Global Adaptation Mapping Initiative (GAMI) database – (Berrang-Ford et al., 2021a). The bars indicate the number of evidence for the options x region.

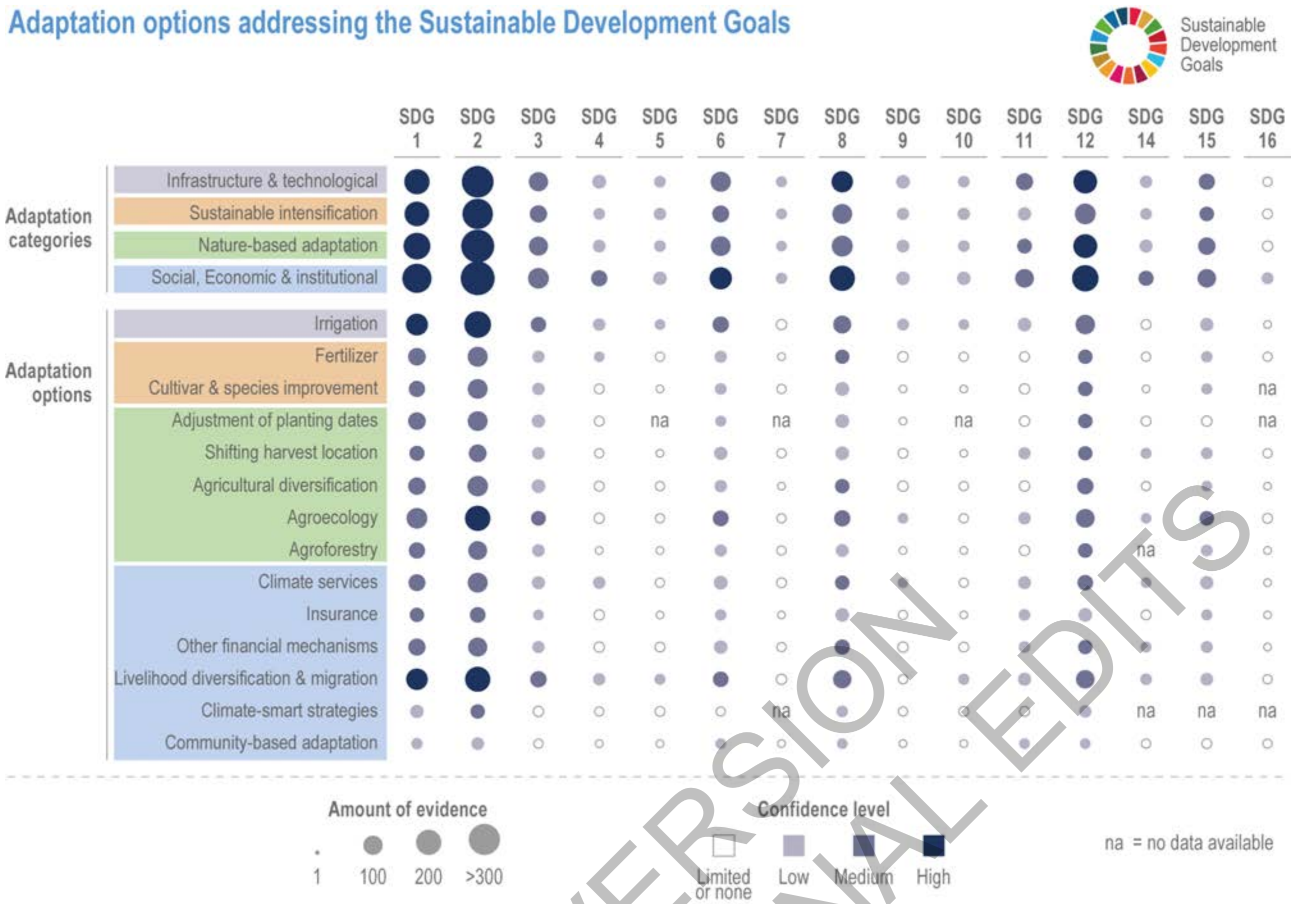


Figure 5.21: How different response types address the SDGs based on GAMI

Assessment of adaptation options was done for 15 potential options for land and ecosystem transitions (SM5.7, Figure 5.22a). Several adaptation options have high to medium feasibility, with *robust evidence, high agreement* about the adaptive capacity resilience building potential of options in relation to climate change impact drivers (*high confidence*). Policy and planning and production shifts have limited evidence for feasibility. Most options are technically and physically feasible, with generally high political and social acceptability and environmental feasibility, but have limited evidence for institutional feasibility. Most adaptation options have medium to high microeconomic feasibility (*high confidence*), but *limited evidence* for macroeconomic viability.

Among five effectiveness indicators (SM5.7, Figure 5.22b), most options have *robust evidence* of reduced risk vulnerability to climate change, with low scores for local governance, substitution of plant or animal type, community forest management, livelihood diversification and climate services. Higher scored options to reduce risk included increasing biodiversity (at landscape and field level), community seed banks, conventional breeding (plant and animals), mixed systems and agroecological approaches (*medium confidence*), suggesting multiple co-benefits of these options. Most options have high scores for enhancing social well-being, economic and environmental benefits (*medium confidence*) but limited evidence for strengthening institutions for most options. There were low scores for potential maladaptation (*medium confidence*).

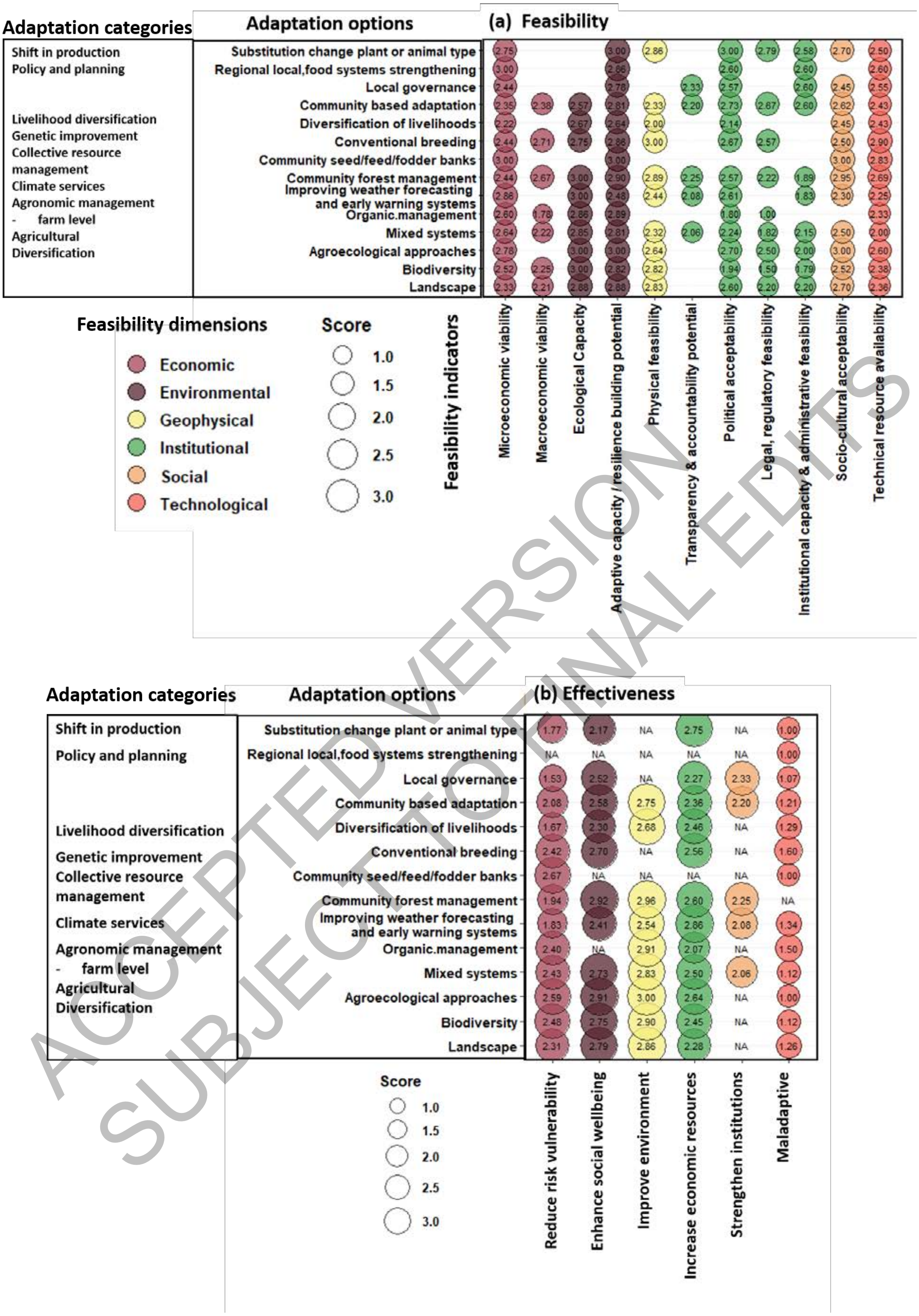


Figure 5.22: Assessment of 11 feasibility indicators (six categories) (a) and five effectiveness indicators and maladaptation (b) of adaptation options based on 287 peer-reviewed papers. See SM5.7 for methods and data. Scores ranging from 1 (low) to 3 (high) were obtained by averaging five or more papers for each option and indicator.

5.14.1.1 Nature-based solutions or ecosystem-based adaptation

There is growing evidence that nature-based solutions (NBS), which emphasise ecological approaches and biodiversity conservation (Chapter 1), have high potential to transform land and aquatic systems into climate-resilient systems *(medium evidence, high agreement*) (Albert et al., 2017; Brugère et al., 2019; Galappaththi et al., 2020b; Snapp et al., 2021; Cross-Working Group Box BIOECO; Cross-Chapter Box - NATURAL in Chapter 2).

[START BOX 5.11 HERE]

Box 5.11: Agroecology as a Transformative Climate Change Adaptation Approach

Agroecological approaches can increase food system resilience (*robust evidence, medium agreement*), while some agroecological practices such as agroforestry can provide mitigation measures (*medium confidence*) (Section 5.10.4.2, Table Box 5.11.1, Altieri et al., 2015; Martin and Willaume, 2016; HLPE, 2019; Bezner Kerr et al., 2021; Snapp et al., 2021). Studies testing agroecological approaches have shown *robust evidence, medium agreement* of increasing adaptation effectiveness through reducing risk, improving food security, yield stability, reducing input costs, and other supporting and provisioning ecosystem services (Section 5.4.4.4 Diacono et al., 2017; Pandey et al., 2017; Schulte et al., 2017; Calderón, 2018; Bezner Kerr et al., 2019; Côte et al., 2019; Rosa-Schleich et al., 2019; Bezner Kerr et al., 2021; Snapp et al., 2021). Effective locally relevant agroecological approaches involves participatory processes, co-creation of knowledge with farmers and attention to social inequities (Bezner Kerr et al., 2021; Santoso et al., 2021; Snapp et al., 2021). To address smallholder vulnerability to climate change impacts, however, additional policy support beyond agroecology will be needed that is context specific; for example, addressing farmer capacity, limited political power to access land, water, seeds and other key natural resources, structural gender inequalities, policy and market disincentives that support large-scale monocultures (*high confidence*) (Anderson et al., 2019a; HLPE, 2019; Holt-Giménez et al., 2021; Snapp et al., 2021).

Table Box 5.11.1: Dimensions of agroecological transitions as a transformative climate change adaptation strategy, benefits, tradeoffs and constraints to implementation

Different dimensions of agroecological transitions as a transformative climate change adaptation strategy	**Links to climate change impacts, benefits, tradeoffs and constraints to implementation with examples.**
Environmental: Agroecology can support long-term productivity and resilience of food systems by sustaining ecosystem services such as pollination, soil organic carbon, pest and weed control, soil microbial activity, crop yield stability, water quality and biodiversity (*high confidence,* see Section 5.4.4.4, Cross-Working Group Box BIOECONOMY this chapter and Cross-Chapter Box NATURAL in Chapter 2). (Isbell et al., 2017; Kremen and Merenlender, 2018; LaCanne and Lundgren, 2018; Beillouin et al., 2019b; Dainese et al., 2019; Rosa-Schleich et al., 2019; Snapp et al., 2021).	• Biodiversity of functional species groups and responses to climate hazards play an important role in building stability and productivity in agroecological systems (5.4.4.4). A 5-year study, for example, in Asia, Africa and Latin America found that smallholder farmers (< 2 ha) increased yields by 25% through promoting pollination (Garibaldi et al., 2016). • Landscape complexity is an important feature of agroecology which can increase resilience to extreme events, such as pest and disease outbreaks or floods, and provide multipurpose benefits (Sections 5.4.4; 5.10.4.2) (Paolotti et al., 2016; Reed et al., 2016; Kremen and Merenlender, 2018; LaCanne and Lundgren, 2018; Rosa-Schleich et al., 2019; Holt-Giménez et al., 2021). • Context-specific: some agroecological systems and practices have lower average crop productivity than conventional systems, while others can have higher overall crop productivity and farm profitability (LaCanne and Lundgren, 2018; Barbieri et al., 2019; Rosa-Schleich et al., 2019).
Socio-cultural: Effective locally relevant agroecological approaches involves participatory processes, co-creation of knowledge with farmers and attention to	• Agroecology can emphasize social justice concerns, including gender inequities, considered crucial for climate change adaptations in food production to have positive impacts on food

social inequities, in doing so building farmer capacity (HLPE, 2019; Bharucha et al., 2020; Holt-Giménez et al., 2021; Snapp et al., 2021).	security and nutrition (Cross-Chapter Box GENDER in Chapter 18; (Smith and Haddad, 2015; HLPE, 2019; Sylvester and Little, 2020). • In some contexts, agroecological systems can draw on and support Indigenous knowledge, farming systems, networks and socio-cultural values(Catacora-Vargas et al., 2017).
Food security and nutrition: Agroecological practices can increase household food security and nutrition for producer households, with more evidence in low- and medium-income countries *(high confidence*) (Darrouzet-Nardi, 2016; Demeke et al., 2017; Jones, 2017a; Kangmennaang et al., 2017; Pandey et al., 2017; Luna-Gonzalez and Sorensen, 2018; Bezner Kerr et al., 2019; Boedecker et al., 2019; Mulwa and Visser, 2020; Bezner Kerr et al., 2021; Santoso et al., 2021).	• Combinations of practices, such as intercropping, crop rotation and crop diversification, often outperform individual practices for yield and food security outcomes (Beillouin et al., 2019b; Bezner Kerr et al., 2021). • Agroecological systems more effectively support food security and nutrition when complemented by nutrition and health education, participatory research and other public policies and programs which address access to knowledge (*high confidence;* (HLPE, 2019; Bezner Kerr et al., 2021; 7.4).
Economic: Agroecology can support socio-economic resilience, through reducing reliance on purchased inputs, enhancing local and regional economies (HLPE, 2019; Bharucha et al., 2020; Holt-Giménez et al., 2021).	• Multi-level policies and programs that support urban and peri-urban networks with agroecological producers, including farmers' markets, public procurement (e.g.school meals, hospitals), incentives for short food value chains, and participatory guarantee certification schemes which build producer-consumer networks are all ways to support agroecological transitions by consumers (*high confidence*) (Catacora-Vargas et al., 2017; Pérez-Marin et al., 2017; Mier y Terán Giménez Cacho et al., 2018; Anderson et al., 2019a; HLPE, 2019; Borsatto et al., 2020; González de Molina, 2020). • Transitions to agroecology at a global scale, however, may require considerable dietary shifts which vary by region, have implications for total food production and farm level revenues, especially in the short term (medium confidence, (Muller et al., 2017; Seufert and Ramakutty, 2017; Barbieri et al., 2019; Rosa-Schleich et al., 2019; Smith et al., 2019b; Smith et al., 2020a). • To address smallholder vulnerability to climate change impacts additional policy support beyond agroecology will be needed that is context specific; for example addressing farmer capacity, limited political power to access land, water, seeds and other key natural resources, structural gender inequalities, policy and market disincentives that support large-scale monocultures (Anderson et al., 2019a; Holt-Giménez et al., 2021; Snapp et al., 2021).
Long-term investment: Timeframes are an important consideration, as an agroecological transition involves multiple overlapping stages, of reducing chemical inputs, experimenting with and applying new agroecological practices and adjusting them, redesigning the farm, strengthening short value chains and producer networks (Gliessman, 2014; Padel et al., 2020).	• In the short term, without policy support the costs of implementing agroecological practices at the farm scale can outweigh ecological and adaptation benefits, although the timeframe required is context-specific (Padel et al., 2020). • In the long-term, implementing agroecological practices can increase yields, yield stability, farm profitability, reduce risks and build resilience alongside ecological, health and social co-benefits, but impacts are context-specific (Section 5.4.4.4, Rosa-Schleich et al., 2019; Bezner Kerr et al., 2021; Snapp et al., 2021).

	• In Malawi, for example, studies indicate that smallholder producers using agroecological practices improved food security and nutrition, livelihoods and provisioning ecosystem services after 2 years (Kangmennaang et al., 2017; Bezner Kerr et al., 2019; Kansanga et al., 2021), while in the UK, farmers transitioning to agroecological practices took 3 or more years to realize benefits (Padel et al., 2020).
Policy tools: Investment in agroecological approaches that are designed for socio-ecological context, farmer-led schools, co-learning platforms, and networks of farmers, scientists, private sector and civil society can support agroecological transitions at a regional scale (*high confidence*) (Coe et al., 2014; Catacora-Vargas et al., 2017; Pérez-Marin et al., 2017; Mier y Terán Giménez Cacho et al., 2018; Anderson et al., 2019a; González de Molina, 2020; Lampkin et al., 2020; Padel et al., 2020; Snapp et al., 2021). Policies can provide incentives (e.g., price premiums, access to credit, extension service, taxes, regulation) to support agroecological transitions by producers (HLPE, 2019; Rosa-Schleich et al., 2019; Gerard et al., 2020; SAPEA, 2020).	• Farm scale and landscape diversity can affect the capacity for producers to implement agroecological systems. Small to mid-sized farms can more effectively integrate agroecological methods such as increasing landscape diversity, on-farm diversity and intercrops (*medium confidence)* (Garibaldi et al., 2016; Herrero et al., 2017; HLPE, 2019). Barriers to adopting agroecological practices for small to mid-sized farms include limited market options, subsidy and policy disincentives, lack of extension support, knowledge and insecure land tenure (Jacobi et al., 2017; Kongsager, 2017; Hernández-Morcillo et al., 2018; Iiyama et al., 2018; Anderson et al., 2019a; Gerard et al., 2020). • Barriers for large farms to transition to agroecological practices include knowledge gaps, cost, significant infrastructure and farm design changes, labour, psycho-social adjustments, policy disincentives and market lock-ins (Hill, 2014; Rosa-Schleich et al., 2019; Lampkin et al., 2020). • Some policies and initiatives support large-sized farms to transition to agroecology (Zhou et al., 2014; Liebman and Schulte, 2015; Ajates Gonzalez et al., 2018; Bellon and Ollivier, 2018; Lampkin et al., 2020; Padel et al., 2020)
Other drivers of agroecological transitions can include crises (environmental, economic, or social), social movements, changing socio-cultural values, addressing social inequities, and discourse (Pérez-Marin et al., 2017; Mier y Terán Giménez Cacho et al., 2018; Anderson et al., 2019a).	Further research could provide context-specific information about economic and ecological benefits of some practices and combinations, with effective policies to support their implementation (*high confidence*) (HLPE, 2019; Rosa-Schleich et al., 2019; Snapp et al., 2021). Institutional support to monitor the ecosystem services climate change mitigation and adaptation impact of agroecological systems can inform policy, using systematic methods and indicators (e.g. Barrios et al., 2020; Mottet et al., 2020) including annual reporting to the UNFCCC (Snapp et al., 2021).

5.14.1.2 Climate services

Climate services, understood as the production, translation, communication and use of climate information in decision-making processes, can contribute to adaptation efforts in agricultural systems (*medium agreement, low evidence*). Climate services can support decision-makers in agriculture by providing tailored information that can inform the implementation of specific adaptation options (Vaughan, 2018; Buontempo et al., 2019; Dobardzic et al., 2019; Hank et al., 2019).

For some high- and medium-income countries, evidence suggests that climate services have been underutilized (Mase and Prokopy, 2014), with *limited evidence* in these countries of the impact of climate services on yields, income, and food security and nutrition. In low-income countries, use of climate services can increase yields, incomes and promote changes in farmers' practices (*low confidence*) (Roudier et al., 2014; Roudier et al., 2016; Tarchiani et al., 2017; Ouedraogo et al., 2018). There is *low confidence* that climate services are delivering on their potential, whether they are being accessed by the vulnerable, and how these services are contributing to food security and nutrition (Ouedraogo et al., 2018; Vaughan et al., 2019).

Improved design and delivery of climate services can enhance effectiveness (*medium confidence*). Ways to enhance the impact of climate services include integrating information from multiple sources at different scales (Bouroncle et al., 2019), participatory collection and analysis of climate information (Loboguerrero AM, 2018; Tesfaye et al., 2019; Rossa, 2020), and making forecast information available in local languages and as verbal communications for farmers who cannot read (Nkiaka et al., 2019).

In countries with limited climate data, crowd sourcing (outsourcing data collection to the public) (Minet et al., 2017) and digital tools present an opportunity for addressing climate risk (*medium confidence*) (Osgood et al., 2018; Thornton, 2018; Partey et al., 2020; Sotelo et al., 2020). Bundling additional services such as market information with climate information may be effective at plugging information gaps (*low confidence*) (Chatuphale and Armstrong, 2018; Dalberg, 2019; Tesfaye et al., 2019)

There may be inequality in access to climate services; their use may tend to benefit large-scale operations and disadvantage small-and medium-scale farmers and others who face issues of access due to social and economic inequity; also some groups such as pastoralists have not yet benefitted from climate services (*high confidence*) (Furman et al., 2014; Muema et al., 2018; Awazi et al., 2019; Nyantakyi-Frimpong, 2019; Paudyal et al., 2019; Vaughan et al., 2019; Nidumolu et al., 2020; Partey et al., 2020). Other challenges include technology ignorance, data privacy and security, data access permissions, software and system compatibility, and understanding how to use and derive value from accessed data (Chatuphale and Armstrong, 2018; Drewry et al., 2019). More work is needed to understand the factors that prevent farmers and fishers from benefiting from this new information. Recent assessments suggest that access to, and value of, climate and weather information can be enhanced by the development of digital tools (including radio, text messages, etc.) appropriate to the specific needs of different vulnerable groups, as well as by including these groups in their development and building their capacity (*medium confidence*) (Camacho and Conover, 2019; Gumucio et al., 2020; Sultan et al., 2020).

5.14.1.3 Insurance as a climate impact risk management tool

Insurance is a financial adaptation strategy increasingly used in agriculture and aquaculture. A relatively new approach to agricultural insurance risk is the use of financial derivative products, such as index-based agricultural insurance (IBAI), marketed by financial institutions to farmers to help them deal with weather-related production risks (Isakson, 2015; Jensen and Barrett, 2017). The basic idea is to rely on easily observed weather indices, such as precipitation or temperature, that co-vary with farm production. Insurance payments are received when the metric trigger for a region is reached, eliminating the need to collect farm-specific information. Proponents of index insurance argue that it can resolve the information costs and incentive problems inherent in rural financial markets, such as adverse selection, and allow provision of insurance coverage at a fraction of the costs of loss-based polices (Jensen and Barrett, 2017). Buyers of index policies do not have to prove their ownership of assets with weather-related losses. This lowers transactions costs and makes it more affordable to insure small plots of land.

The creation of index insurance requires significant prior research and extensive data that may not be available or sufficient in lower income countries, including identifying the most appropriate farm and climate variables to include and financial and regulatory support from the public sector (Economic Commission for Latin America and the Caribbean and Central American Agricultural Council of the Central American Integration System, 2013; Economic Commission for Latin America and the Caribbean and System, 2014). Some insurance providers bundle it with other services, such as fertilizer use or seeds that may not be useful to particular farmers and can increase their overall capital costs (Isakson, 2015). Although proponents see IBAI as a way to mitigate farmers' risks associated with more variable weather patterns (Greatrex et al., 2015), critics argue that derivative-based insurance products tend to benefit wealthier farmers and fail in assisting the poorest and most marginalized farmers (Isakson, 2015; Taylor, 2016). Thus far, there is *low agreement and medium evidence* regarding the adaptation potential of derivatives-based insurance products, signaling a need for further research in this area.

5.14.1.4 Community-based adaptation approaches

Community-based adaptation (CbA) strategies, which involve locally-driven, place-based adaptation approaches, can help build adaptive capacity to climate change impacts, but require explicit attention to power dynamics, respect for local and Indigenous knowledge systems, adequate resources, future climatic trends and coordination at multiple levels of governance to be effective (*high confidence*) (Spires et al., 2014; Fernández-Giménez et al., 2015; Nagoda, 2015; Ashley et al., 2016; Berner et al., 2016; Ensor et al., 2016; Avtar et al., 2019; Lam et al., 2019; Silwal et al., 2019; McNamara et al., 2020; Piggott-McKellar et al., 2020; Rossa, 2020; Uchiyama et al., 2020). Since AR5, there is strong evidence that participation of local stakeholders in adaptation planning and implementation improve communities' capacity to monitor and respond to climate change impacts on food, fibre, and forestry systems, provided that adequate resources and local knowledge on climate change exist. Participatory monitoring of climate change impacts, and participatory scenario development to develop community action plans are examples, which can help strengthen community preparation for and response to climate impacts.

Community-based monitoring of forests, coral reefs, seagrass and mangroves are examples of local natural resource assessment that can support food security and livelihoods while informing regional and national climate change planning tools (Carter et al., 2014; Gevaña et al., 2018; Avtar et al., 2019). Negotiation amongst many stakeholders at multiple scales, including inclusive mechanisms to address power inequities in governance structures and communities, may be needed for CbA to be effective (Avtar et al., 2019; McNamara et al., 2020). Indigenous knowledge and community-based management of fisheries and aquaculture in the Arctic and Asia (Roux et al., 2019; Chen and Cheng, 2020; Galappaththi et al., 2020a; Schott et al., 2020; Galappaththi et al., 2021) provide adaptive strategies for sustainable use. (Iticha and Husen, 2019). Community-based climate services in the Andes (managed through a collaboration of smallholder producers and an international partnership) built capacity and knowledge of climate change dynamics as well as trust in local climate institutions, providing meaningful information for regional responses to climate change impacts (Rossa, 2020). Community-based participatory scenario planning can help identify multiple climate stressors and vulnerabilities to develop effective adaptation plans (Fernández-Giménez et al., 2015; Bennett et al., 2016; Cross-Chapter Box MOVING PLATE this Chapter).

An assessment of 32 different CbA initiatives in the Pacific Islands, including addressing risks to food security, found high performing projects had 6 key entry points: effective methods to improve adaptive capacity, appropriate to the local context, which moved beyond narrow geographical definitions of community to consider equity of impact, and ecosystem-based approaches, jointly addressing climatic and non-livelihood pressures and consideration of future climatic trends (McNamara et al., 2020). Low-performing initiatives, in contrast, were not sustained; these overlooked future climatic trends in their initiatives, such as beehive susceptibility to climate extremes, and had dependent, unequal relationships that lacked genuine local approval or ownership and did not fit local values and context (Spires et al., 2014; McNamara et al., 2020; Piggott-McKellar et al., 2020). CbA initiatives can also suffer from not having adequate local knowledge of potential strategies to address future climatic scenarios, and may lead to maladaptation, increasing socio-economic inequities in communities (Nagoda, 2015). Addressing inequity in power dynamics and building technical adaptive capacity of local people are some of the ways that CbA initiatives can support more resilient food systems (McNamara et al., 2020).

5.14.1.5 Local and regional food systems' strengthening and food sovereignty

Food sovereignty brings together adaptation options based on agroecological methods, access to resources, collective and CbA (HLPE, 2019). Addressing food security and nutrition in light of climate change impacts and vulnerabilities is considered to arise from a mixture of globalised supply chains and local production, not one or the other (Blesh et al., 2019; Stringer et al., 2020). Evidence on strengthening local and regional food systems with a food sovereignty approach, in terms of access to resources (land, seeds, water), shortened food chains and CbA strategies suggest that these strategies can positively contribute to climate change adaptation in many contexts (*medium confidence)*(SRCCL) but can also lead to conflict especially regarding management of mobile resources such as fisheries (Section 5.8, Cross-Chapter Box MOVING PLATE this Chapter). All these options can build adaptation through actions that strengthen local capacities and the power to act within food systems. Securing and recognising tenure for Indigenous Peoples (Hurlbert et al., 2019) and local communities (Oates et al., 2020) can improve their ability to adapt by increasing the incentive to invest in resilient infrastructure and sustainable land management practices. Community seed banks and networks strengthen local seed systems and realize farmers' rights favouring access to a variety of local genetic resources, with landraces often more adapted to the local social, cultural, and ecological environment and needs, and better adapted to harsh environments without external inputs (Mousseau, 2015; Bisht et al., 2018; Maharjan and Maharjan, 2018; Otieno et al., 2018; Mbow et al., 2019). This plays a key role in participatory plant breeding (section 5.4.4.5; FAO, 2019e). The integration of informal and formal seed system elements is important for the adaptive capacity of smallholder farmers (Westengen and Brysting, 2014; Westengen and Berg, 2016; FAO, 2019e).

Strengthening both local and regional food systems is a strategy to increase resilience (Schipanski et al., 2016; Palmer et al., 2017)resource use efficiency (Mu et al., 2019) and self-reliance (*medium evidence, low agreement*) (Griffin et al., 2015; Chapin et al., 2016; Karg et al., 2016). Collective trademarks (Quiñones-Ruiz et al., 2015) and participatory guarantee systems (Niederle et al., 2020) are examples of innovative institutional strategies to strengthen local and regional food systems. In the urban context, the city-region food system (CRFS) approach is motivated by reducing dependence on international trade and associated instability and to facilitate local decision-making (Karg et al., 2016). CRFS includes a network within a regional landscape around one urban center and surrounding peri-urban and rural regions (Blay-Palmer et al., 2018). Urban and peri-urban agriculture are promoted as effective strategies to adapt to climate change in different contexts (see Section 5.12.5.3, Dubbeling, 2015; Lwasa et al., 2015). In order to cope with the effects of climate change, strengthening regional food systems is becoming an explicit part of urban and regional policy, being tested in many different cities worldwide (Dubbeling et al., 2017; Blay-Palmer et al., 2018; Berner et al., 2019; Sellberg et al., 2020; van der Gaast et al., 2020). Strengthening both local and regional food systems has to be balanced against limitations and tradeoffs, since modelling exercises of regionalization scenarios show urban agriculture cannot achieve food security in areas with rapid population growth (Le Mouël et al., 2018). Furthermore, international trade can compensate in cases where the regional system fails due to extreme events or other related climate shocks (Section 5.11.8).

5.14.2 Enabling Conditions for Implementing Adaptation

5.14.2.1 Addressing social inequalities in food systems

Addressing gender and other social inequalities (e.g., racial, ethnicity, age, income, geographic location) in markets, governance and control over resources is a key enabling condition for climate resilient transitions in land and aquatic ecosystems (*high confidence*) (Pearse, 2017; Vermeulen et al., 2018; Blesh et al., 2019; Rao et al., 2019b; Cross-Chapter Box GENDER in Chapter 18, Section 5,13,1; Tavenner et al., 2019). Adaptation strategies can have negative impacts on marginalized social groups and worsen socio-economic inequities unless explicit efforts are made to address unequal power dynamics and differences in access to resources in agricultural, fisheries, aquaculture, livestock and forestry systems (*high confidence*) (Glemarec, 2017; Haji and Legesse, 2017; Nagoda and Nightingale, 2017; Nightingale, 2017; Rao et al., 2019b; Huyer and Partey, 2020; Mikulewicz, 2020; Taylor and Bhasme, 2020; Eriksen et al., 2021). Technical approaches to adaptation that ignore inequities can worsen them, see for example the case study on Climate Smart Agriculture (Box 5.12). Enabling environments support inclusive decision-making, capacity-building, shifts in social rules, norms and behaviours and access to resources for marginalized groups for climate change adaptation (e.g., Tschakert et al., 2016; Ziervogel, 2019; Eriksen et al., 2021; Garcia et al., 2021).

[START BOX 5.12 HERE]

Box 5.12: Is Climate-smart Agriculture Overlooking Gender and Power Relations?

Climate-smart agriculture (CSA) is an approach that aims to increase agricultural productivity, enhance food security, adapt to climate change and, where possible, reduce GHG emissions. The effective implementation of climate-smart practices is conceptually linked to an enabling environment in which policies, institutions and finance can reorient agricultural systems, thereby supporting development and enhancing food security in a changing climate (Lipper et al., 2014; Karttunen et al., 2017). However, the concept has received criticism based on the absence of conceptual clarity of the interrelations between productivity, food security, adaptation and mitigation (Arenas-Sanchez et al., 2019) and because of limited evidence on the efficacy of

CSA for achieving adaptation and mitigation outcomes at a global scale (Arslan et al., 2015; Lamanna et al., 2016; Chandra et al., 2018). Some argue that CSA operates within an apolitical framework that tends to minimize issues concerning power, inequality, and access, and is overly focused on technical approaches (Taylor, 2017; HLPE, 2019). CSA is explicitly referenced by more than 30 countries in their Intended Nationally Determined Contributions (INDCs) (Ross et al., 2016), but measuring the degree of its implementation still represents a challenge.

There is *low agreement, medium evidence* on the relationship between CSA and equity (Allen, 2018; Karlsson et al., 2018). CSA can potentially benefit women if they are able to take advantage of improvements in productivity, food security and adaptation decision making as a result of the implementation of CSA practices. Nevertheless, these advantages can be unequally realized given male domination in receiving information and extension services, as well as financial or resource access (Jost et al., 2016). Some argue that CSA may undermine gender equity (Collins, 2018), entrench and solidify power (Haapala, 2018), and result in the disproportional allocation of new labour-intensive activities to women (Jost et al., 2016). Uptake of some climate-smart technologies can further marginalize the most disadvantaged local groups (Roncoli et al., 2009; Haapala, 2018). Unequal sharing of benefits and burdens with respect to emission reduction costs among different agricultural groups have also been observed (Budiman, 2019).

In contrast, emerging research points to the potential of CSA as a supporting condition for gender equity, provided that equity and power concerns are explicitly included in the approach (Chanana-Nag and Aggarwal, 2020). Some CSA technologies and practices, such as direct seeding, green manuring, and laser land levelling, can have a significant role in reducing the gender gap in labour burden for women in agriculture, (Khatri-Chhetri et al., 2020). The use of participatory approaches can facilitate community-based adaptation of gender-sensitive CSA practices (Rosimo, 2018). CSA may also empower both men and women: in two villages in India, CSA adoption empowered both sexes in decision making and use and control of income (Hariharan et al., 2018).

In general CSA programs have tended to overlook questions of inequity (*medium confidence)*, including limited attention to social conditions that promote business-as-usual pathways, although this is now changing. Addressing questions of rights, social injustice, unequal power relations and inequality would help make CSA-related policy responses more effective in addressing vulnerability (Chandra et al., 2017; Clapp and Isakson, 2018; Karlsson et al., 2018; Westengen et al., 2018; Ellis and Tschakert, 2019; Eriksen et al., 2019; Westengen et al., 2019).

[END BOX 5.12 HERE]

[START BOX 5.13 HERE]

Box 5.13: Supporting youth adaptation in food systems

Young people are key agents in agri-food systems: both a vulnerable group, and one that can foster systemic change (*high confidence*) (Brooks et al., 2019; Figure X; IFAD, 2019; Flynn and Sumberg, 2021; HLPE, 2021). Food systems are the largest source of employment for young people, but do not always provide adequate livelihoods or decent working conditions (HLPE, 2021). Regions with more youthful populations – such as Sub-Saharan Africa, South Asia, and Central America - are both highly vulnerable to climate change impacts, and reliant on agriculture, forestry, aquaculture, and fisheries for livelihoods (Brooks et al., 2019; IFAD, 2019; HLPE, 2021). Rural youth in these sectors are particularly vulnerable, often with less access to land, water, capital, and other resources, shaped by family and social relations, and fewer opportunities (*high confidence*) (Chingala et al., 2017; Ricker-Gilbert and Chamberlin, 2018; IFAD, 2019; Yeboah et al., 2020; Flynn and Sumberg, 2021; Nhat Lam Duyen, 2021). In these vulnerable regions, climate change compounds other drivers such as poverty to increase youth out-migration to urban areas or other regions (*medium confidence*) (Zin et al., 2019; Weinreb et al., 2020; HLPE, 2021; Stoltz et al., 2021; Voss, 2021), which can further worsen rural economies. Young low-income rural women may be particularly marginalized and vulnerable due to systemic gender inequities in access to land, credit, employment, institutions, and other resources (*medium confidence*) (Sah Akwen, 2017; IFAD, 2019; Flynn and Sumberg, 2021).

Youth play a critical role in all sectors of the food system (HLPE, 2021; Figure Box 5.13.1) and some are actively pursuing work and innovation in agri-food systems (*medium confidence*) (Sah Akwen, 2017; 2019; Yeboah et al., 2020; Flynn and Sumberg, 2021). Climate change impacts may reduce youth employment options in food systems in some regions, while they are often politically marginalized (Brooks et al., 2019; IFAD, 2019; HLPE, 2021). At the same time, due to heightened awareness about climate change, youth may be more willing to apply climate adaptation strategies (*medium confidence*) (Ali and Erenstein, 2017; Jiri et al., 2017; Sah Akwen, 2017; Chamberlin and Sumberg, 2021; Doherty et al., 2021). Agri-food policy implementation of adaptation strategies could increase inclusive participation of youth to meet their needs (HLPE, 2021). Inclusive investments in water management, infrastructure, agri-food science, and policies that increase youth access to land, credit, knowledge, education, skills, and other crucial resources can support dignified and rewarding agri-food employment (Ahsan and Mitra, 2016; Brooks et al., 2019; HLPE, 2021). Digital technologies can support agrifood adaptations, but digital divides must be overcome to avoid worsening inequities (HLPE, 2021). Initiatives which protect and strengthen youth engagement and employment in the all points of the food system, including recognition of youth's critical role and agency through rights-based approaches, can support sustainable food transitions (HLPE, 2021). Harnessing youth innovation and vision to address climate change alongside other SDGs such as gender inequity and rural poverty, will be a crucial strategy to ensure resilient economies in food systems (*high confidence*) (Laube, 2016; Brooks et al., 2019; IFAD, 2019; Abay et al., 2021; HLPE, 2021).

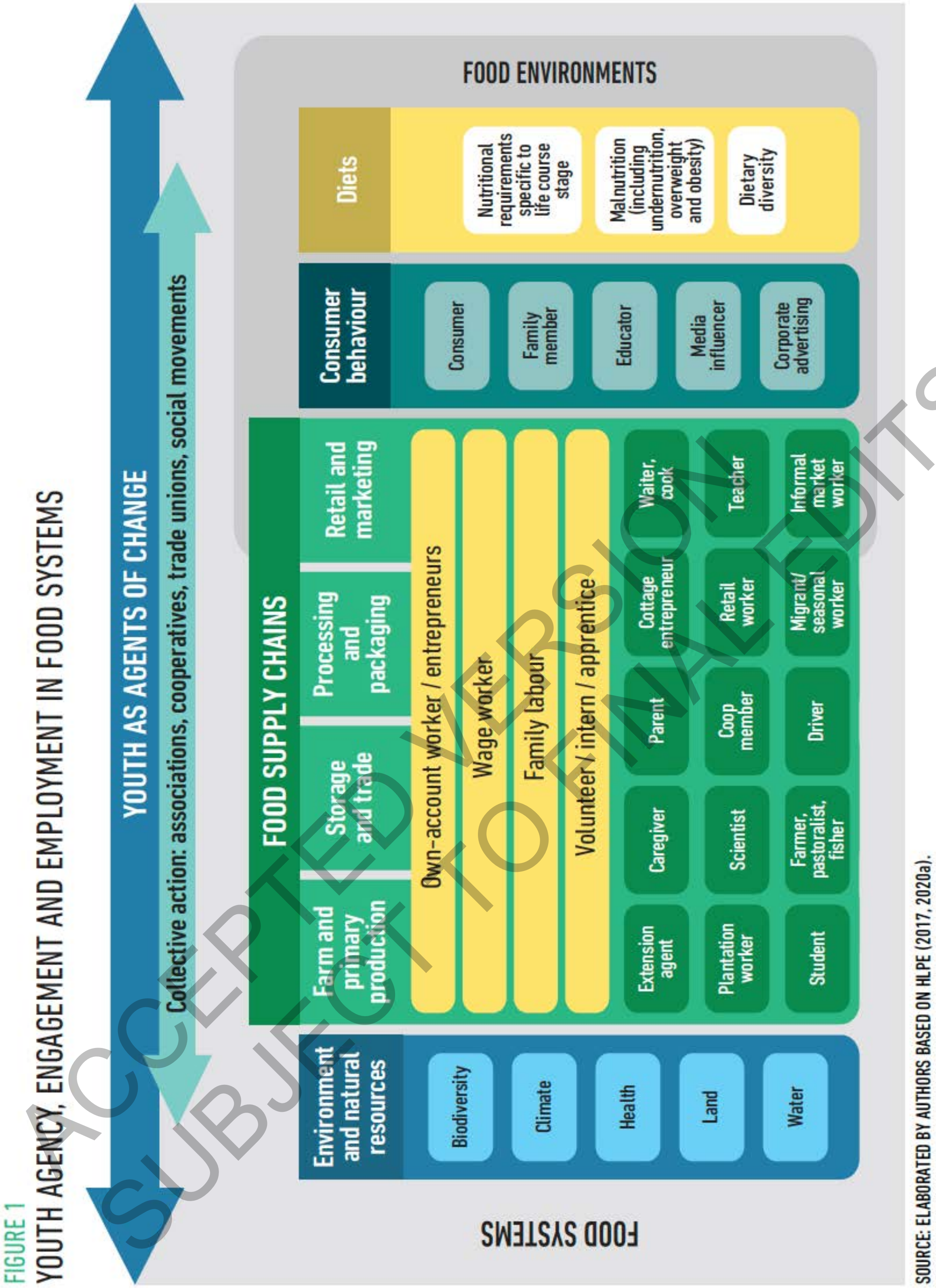


Figure Box 5.13.1: Youth agency, engagement, and employment in food system (HLPE, 2021)

[END BOX 5.13 HERE]

5.14.2.2 Incorporating Indigenous knowledge and local knowledge

Indigenous knowledge (IK) and local knowledge (LK), while an important component of many adaptation strategies (Reyes-García, 2014; Roue, 2018), continues to be marginalized in food systems; greater integration will increase effectiveness (*high confidence*) (Ford et al., 2015; Brugnach et al., 2017; Figueroa-Helland et al., 2018). Where Indigenous Peoples have access to and control over their lands and natural resources, food systems can potentially be more sustainably managed and more resilient (*high confidence*) (Rumbach and Foley, 2014; O'Connell-Milne, 2015; Camacho et al., 2016; Janhiainen, 2017; Kihila, 2018). For example, Solomon Islands, community-based adaptation combining with IK-informed community mapping helped boost agricultural yields sustainably (Leon et al., 2015), and in China people living in rich plant resource regions have used their wild plants IK to complement the decrease of crop yields during extreme droughts to ensure food security (Zhang et al., 2016). These cases have led scientists and local communities to call for more practical actions to bridge local knowledge, Indigenous knowledge, and formal science (Borquez et al., 2017; Klenk et al., 2017; Mukhopadhyay, 2017; Olorunfemi, 2017; Reyes-Garcia et al., 2019). Despite this increased public and scientific recognition, Indigenous knowledge is often not acknowledged or used.

Effective adaptation requires a more holistic approach that includes the recognition of Indigenous rights, governance systems and laws (*high confidence*) (Robinson et al., 2016a; Brugnach et al., 2017; Magni, 2017; McMillen et al., 2017; McNeeley, 2017; Pearce et al., 2018), and to couple IK with proactive and regionally coherent adaptation plans, actions, and cooperation (Shaffer, 2014; Melvin et al., 2017; Forbis Jr. and Hayhoe, 2018; Makondo and Thomas, 2018).

Supporting Indigenous groups' knowledge and other excluded social groups can help preserve and harness underutilized resources to enhance nutritional and economic security, with careful measures in protecting Indigenous intellectual rights and avoiding commodification exploitation (Nakashima et al., 2012; Nandal and Bhardwaj, 2014; Ghosh-Jerath et al., 2015; Ebert, 2017). In some regions there has been a loss of Indigenous knowledge about food systems, reducing adaptive capacity (Richards et al., 2019; Panikkar and Lemmond, 2020). Knowledge exchange between Indigenous elders and youth can support adaptive capacity (Osterhoudt, 2018; Richards et al., 2019; Zin et al., 2019). Education utilizing Indigenous knowledge and local knowledge can help prevent maladaptation options (*high confidence*) (Melvin et al., 2017; Taremwa, 2017; Forbis Jr. and Hayhoe, 2018; Narayan et al., 2020). There are examples of integrating IK and LK into resource management systems, school curricula and in local institutions with existing decision-making process to strengthen their capacity to address climate change (Huaman and Valdiviezo, 2014; McNamara and Prasad, 2014; Abah et al., 2015; Mistry and Berardi, 2016; Tschakert et al., 2017; McNeeley et al., 2018; McNeeley et al., 2020). However, there are limitations of IK and LK to address future climate impacts. Therefore, it is important that science-based knowledge and other knowledge coalesce to produce solutions that are sustainable and viable in the face of projected impacts of climate change. Community-based adaptation approaches can integrate IK and LK and more formal knowledge systems, provided efforts to establish relationships of respect, trust and common understanding between different stakeholders involved (Herath et al., 2015; Camacho et al., 2016; Fidelman et al., 2017; Inaotombi and Mahanta, 2019; Lam et al., 2019).

5.14.2.3 System transformation and policy enablers

Recent literature highlights the future challenges of producing the quantities of food needed to feed a growing world population in a way that satisfies nutritional needs, benefits everyone equally and equitably, and minimises the negative impacts of food systems on the environment and the natural resource base. There is broad agreement that current trajectories towards the SDGs and countries' commitments under the Paris Agreement are slow and that transformation of food systems is needed (*medium agreement, robust evidence*) (Campbell et al., 2018; Brondizio et al., 2019; Dury et al., 2019; EAT-LANCET, 2019; FAO, 2019f; Food and Land Use Coalition, 2019; Sachs et al., 2019; Searchinger, 2019a; Searchinger T, 2019b; Loboguerrero et al., 2020; Meridian Institute, 2020; Steiner A, 2020).

Recent reviews have summarised literature on production system transformations, driven at least in part by a changing climate or changing climate variability. Such transformations may involve sometimes substantial shifts in farm and livelihood enterprises and land configurations, including intensification, diversification, sedentarisation, as well as abandonment of agriculture (Vermeulen et al., 2018; Thornton et al., 2019). Relevant literature is summarised in Table 5.24, showing reported farmers' perceptions of the drivers of change and the different outcomes of these changes. The consequences of these production system transitions have been mixed; in about 40% of cases, the outcomes at household level have been unequivocally beneficial. In the other cases, there were detrimental effects on livelihoods, or a mixture of positive and negative effects. The effects on nutritional security reported in these studies were limited. Different enablers of change appear critical if transitions are to have positive outcomes. Policy environments, defined in terms of multi-level governance structures and institutions, are a key driver of systems change, as well as being enablers of and barriers to adaptation responses (Xu et al., 2008; Namgay et al., 2014; Galvin et al., 2015; Schmidt and Pearson, 2016; Liao and Fei, 2017). Policies around property and grazing rights are directly linked to small-scale food producer vulnerability, and land ownership changes will pose a key challenge as climate change impacts in the marginal lands intensify (Reid et al., 2014). Collective action at multiple scales and effective governance structures are also a key enabler of transformational change, for helping community initiatives overcome economic, social, and technical barriers, and to strengthen social capital and farmer knowledge (Haglund et al., 2011; Reed et al., 2017; Vermeulen et al., 2018; Fedele et al., 2019). Market development has been shown to be a critical factor for successful adaptation at scale in sub-Saharan Africa (Ouédraogo et al., 2017; Iiyama et al., 2018; Totin et al., 2018). At the same time, financing mechanisms may be a crucial enabler for different food system actors: de-risking agricultural production and food system investments for producers and input suppliers, for example, that address core market failures and compensate actors for extra short-term costs that can lead to longer-term benefits, particularly for small-scale producers and businesses with comparatively low access to technologies and services (Vermeulen et al., 2018; Millan, 2019; see Section 5.14.2.5).

The examples in Table 5.24 highlight the uneven impact of adaptation programs and projects in general, due in part to differences in institutional support and failure of policies to take into account inequalities (Clay and King, 2019; Nightingale et al., 2020). Focusing on transformational adaptation, Vermeulen(2018) suggested the need to expand the remit of adaptation planning to consider the multi-functionality of agriculture and a system-wide view of food production and consumption. Several authors argue that transformational change must address the personal, practical, and political spheres, in view of the role of power relations and worldviews in shaping practices, food security and inequity (O'Brien, 2015; Nightingale, 2017; O'Brien, 2018; Eriksen et al., 2019; Gosnell et al., 2019). If it involves new or unfamiliar technology, transformation may also be highly disruptive, and the added vulnerabilities of food system actors at risk will need to be addressed (Herrero et al., 2020; see Box5.5).

"Transformation", defined by IPCC (2019a) as 'b a change in the fundamental attributes of natural and human systems', is defined here as a redistribution of at least a third in the primary factors of production (land, labor, capital) and/or the outputs and outcomes of production (the types and amounts of production and consumption of goods and services arising from multifunctional agricultural systems) (Vermeulen et al., 2018; Thornton et al., 2019).

Table 5.24: Agricultural and livelihood system transformations from systematic searches of the literature, which are at least partially attributable to climatic factors and that involve increased or decreased system integration, and major consequences of the change. Information in the table is from the references cited. Sources: updated from (Vermeulen et al., 2018; Thornton et al., 2019).

Underlying Production System	Primary Drivers of Change as Stated	Major Processes of Change as Reported	Consequences of Change, if Reported	Reference
Extensive grassland-based systems				
Extensive grassland-based, NW China	Government policy, climate	Sedentarisation Diversification (crops, wages)	Income decline, asset holding decline	Liao and Fei, (2017)
Extensive grassland-based, Peruvian Andes	Multiple climatic and non-climatic drivers	Diversification (wages, livestock assets, land) Extensification	Livestock accumulation in wealthy households, asset diversification in poorer households	López-i-Gelats et al., (2015)

Extensive grassland-based, Bhutan	Government policy, labour constraints, climate	Sedentarisation Diversification (crops) Exit	Increased risk, loss of cultural identity, improved market access, livelihood "lock-in" (inability to change rapidly)	Namgay et al., (2014)
Extensive grassland-based, Borana, Ethiopia	Increase in climate variability, resource degradation	Livestock herd diversification (more small stock and camels, fewer cattle)	Enhanced household resilience	Megersa et al., (2014)
Extensive grassland-based, Tibet	Government policy, climate	Sedentarisation Diversification (crops, off-farm wages, trade)	Increased food production, increased disease burden	Xu et al. (2008)
Extensive grassland-based, Afar, Ethiopia	Government policy, climate	Sedentarisation Diversification (crops)	Weakened institutions and cultural practices, deteriorating natural resources	Schmidt and Pearson (2016)
Extensive grassland-based, Kajiado, Kenya	Government policy, climate, population growth	Sedentarisation Diversification (crops, wages, remittances) Intensification	Nutritional status remains poor	Galvin et al. (2015)
Extensive grassland-based, Mongolian Altai	Government policy, climate	Sedentarisation Diversification (cashmere sales, forest products)	Fodder shortages, forest over-use, unsustainable land-use system	Lkhagvadorj et al. (2013)
Extensive grassland based, Mongolia	Increasing drought, grassland degradation	Diversification (decreases in sheep and goats, increases in cattle, decreases in grain production, increases in fruit and vegetable production) Exit from agriculture	Increased household income from off-farm employment, more diverse diets	Du et al. (2016)
Extensive grassland-based, northern Kenya	Climate change and variability	Diversification (crops, wages, migration)	Decreasing adaptive capacity, over-dependence on local knowledge for adaptation	Ogalleh et al. (2012)
Extensive systems with crops				
Extensive with crops, Eastern Cape, South Africa	Multiple	Intensification (richer households) Exit and abandonment (poorer households) Livelihood diversification	Wildlife conflicts, loss of cultural identity	Shackleton et al. (2013)
Extensive with crops, Peruvian highlands	Economic globalisation, climate change	Diversification (dairy production, wage migration) Conversion (away from staple crops to feed production) Intensification (feed production)	Reduced vulnerability to climate change, but potential loss of both agrobiodiversity and food self-sufficiency identified by the author	Lennox (2015)
Extensive with crops, East Africa	Climate	Diversification (crops, livestock, wages) Intensification (crops, intercrops)	Increasing household vulnerability	Rufino et al. (2013)
Extensive with crops, Ghana	Climate variability, temperature change	Diversification (off-farm activities)	Reduced vulnerability	Antwi-Agyei et al. (2018)

Extensive smallholder cropping, Nepal	Annual and seasonal warming. Increased precipitation with changes in patterns.	Diversification and integration (from growing buckwheat and barley to vegetables and fruit trees)	Increased household resilience owing to diversification of production	Konchar et al. (2015)
Extensive smallholder mixed system, Niger	Droughts and famines, and land degradation	Large-scale regeneration of native trees and shrubs in the arable landscape	Increased household income, effects on household food security not yet know	Haglund et al. (2011)
Other mixed coastal and forest systems				
Coastal rice-based, Bangladesh	Increased salinity due to reduced dry season flows from rivers in India, use of groundwater for irrigation	Diversification (from rice cultivation to aquaculture of shrimp and prawn)	Increased household income, increased engagement of women, increased human disease vulnerability	Faruque et al. (2017)
Smallholder cropping systems, coastal Bangladesh	Increasing frequency and severity of floods since 2008	Diversification (reallocation of land from crops to aquaculture) Exit (migration away from village)	Mixed impacts on household incomes and seasonal migration frequency	Fenton et al. (2017)
Smallholder mixed cropping in forested landscapes in Indonesia	Floods, drought, crop and livestock disease	Diversification (reallocation of land from forests to rubber plantations and rice) Intensification (agroforestry) Extensification (reforestation, forest protection)	Locally, increased household incomes in general; more widely, some trade-offs with biodiversity, water, carbon stocks	Fedele et al. (2018)

5.14.2.4 Finance needs and strategies for adaptation

Current understanding of finance flows and needs for adaptation in crop agriculture, livestock, fisheries, aquaculture, and forest products relies primarily on top-down projections, with limited data (UNFCCC, 2018; Buchner et al., 2019; Jachnik et al., 2019). By one estimate, in 2017/2018, agriculture, forestry, and land use received 24% of public adaptation finance (totaling USD 7 billion; half via multilateral development finance institutions and one-quarter from governments) and 35% of international grants (with 71% used for adaptation) (Buchner et al., 2019). According to data from OECD (2020), finance flows for agriculture, forestry and fisheries have risen fairly linearly from ca. USD 1.46 billion in 2010 (the year the Rio marker on climate change adaptation was introduced) to ca. 5.5 billion in 2018. Over the entire tracked period the three subsectors combined received a total of USD 29.82 billion for activities with principal and significant adaptation components.[4] However, the dataset only includes climate-related development finance from bilateral, multilateral, and private philanthropic sources, whereas private sector finance flows are not captured as this is notoriously difficult to track (UNEP, 2016; OECD, 2020; cross-ref to Cross-Chapter Box FINANCE in Chapter 17). Most of the funding (85%) was directed towards agriculture with forestry (12%) and fisheries (3%) receiving significantly less, but across the subsectors, there is consistency in the sense that policy and administrative management and development receive the lion's share of support, which is predominantly given in the form of grants (72%) while debt instruments (26%) and equity and shares in collective investment vehicles (2%) contribute less. From a regional perspective, 80% were directed to Africa (47%), Asia-Pacific (27%), and Latin America and Caribbean States (7%), whereas Eastern Europe and Western Europe and Other States received (2%) each and 17% were destined for 'developing countries'

[4] For reference, the SEI Aid-Atlas (https://aid-atlas.org) only reports flows where adaptation is the principal objective, and therefore adaptation spending on agriculture, forestry and fisheries for the same period is significantly lower with USD 16.52 billion, i.e., 21.4% of total adaptation spending.

without regional tags. Finally, it is noteworthy that 38% of adaptation finance in agriculture, forestry and fisheries is marked as also having mitigation benefits and roughly a quarter of funding is reported as having principal or significant gender objectives.

Whether current levels of growth in adaptation finance for agriculture, forestry and fisheries is keeping up with estimated needs cannot be assessed because of the large uncertainties that surround adaptation cost estimates (Cross-Chapter Box FINANCE in Chapter 17). There is hence high agreement that better assessment of adaptation costs of climate impacts requires considerably more research (Watkiss, 2015; Diaz and Moore, 2017). A recent study focusing on investments needed to offset the effects of climate change on the prevalence of hunger concludes that investments in agricultural R+D have to increase from USD 1.62 billion to USD 2.77 billion per year between 2015 and 2050 (Sulser et al., 2021a). In addition to agricultural R+D, significant investment increases in water and infrastructure in the range of USD 12.7 billion and USD 10.8 billion are required, respectively, a considerable portion of which is relevant to the food system. In total, Sulser et al. (2021a) estimate that annual investment between USD 21.47 billion and USD 29.8 billion are needed to avoid sliding back from climate-change related increases in the prevalence of hunger but recognize the shortcomings of their approach and acknowledge that "a full analysis of adaptation to climate change in agriculture would require including many other social, economic, and environmental dimensions". For comparison, World Bank (2010) estimated global costs of USD 70-100 billion per year for agriculture, forestry and fisheries, infrastructure, water resources, health, ecosystem services, coastal zones, and extreme weather events to adapt to an approximately 2°C warmer world between 2010 and 2050. While the World Bank includes more sectors, more recent publications consider the resulting figures to be significantly too low (Baarsch et al., 2015; UNEP, 2016; Rossi and Miola, 2017; Hallegatte et al., 2018; Markandya and González-Eguino, 2019; Chapagain et al., 2020; cross-ref to WGII Cross-Chapter Box FINANCE in Chapter 17). Therefore, despite the methodological and data challenges, further efforts are needed to better capture the economic risks of climate change and provide estimates of adaptation costs at global to national scales as well as across sectors (Watkiss, 2015; Diaz and Moore, 2017).

Financial barriers limit implementation of adaptation options in agriculture, fisheries, aquaculture, and forestry (*high confidence*) (Shukla et al., 2019; FAO et al., 2020). Finance strategies can contribute to adaptation in these sectors in different ways (Table 5.25) and to different degrees. Standardized strategies have not yet been developed for specific adaptation needs and, in current practice, finance strategies are opportunistically deployed, with developing countries facing particular challenges due to under-developed financial mechanisms (Omari-Motsumi et al., 2019).

Table 5.25: Potential adaptation finance strategies for categories of climate-related risks in the agriculture, fisheries, aquaculture, and forestry sectors.

Finance strategies	Reduced food availability	Low food safety / dietary health	Diminished livelihoods	Declining ecosystem services
Reduce vulnerability	▪ *Avoid staple failure:* Vouchers to producers for improved production inputs	▪ *Diversify production strategies:* Invest in alternative crops / species / harvest methods	▪ *Increase producer capacity:* Fund technical assistance programs	▪ *Incentivize improved management:* Improved access to credit based on environmental performance
Anticipate / minimize impacts	▪ *Minimize impact of extreme weather:* Fund early warning systems	▪ *Diversify products in supply chains:* Finance processing equipment for alternative food products	▪ *Moderate food price spikes:* National food reserves	▪ *Minimize resource depletion:* Subsidize micro-lending for water-efficient technologies
Steer capital toward climate resilience	▪ *Develop climate-resilient production technologies:* Fund	▪ *Build nutrition-sensitive food systems:* Finance early-stage	▪ *Increase resilience of supply chain infrastructure:* Finance improved	▪ *Disincentivize low-resilience production:* Screen investments based

Finance strategies	Reduced food availability	Low food safety / dietary health	Diminished livelihoods	Declining ecosystem services
	R&D for improved genetics (crops, fish, livestock) and management	market building for diversified food products	storage and transport facilities	on climate risk disclosures
Pool climate-related risks	▪ *Distribute climate-related risks:* Securitize investments in production systems	▪ *De-risk diversified food supply chains:* Invest in producer aggregation to improve supply chain efficiency	▪ *Insure against supply chain risks:* Subsidized index insurance programs	▪ *Detect high-risk production systems:* Invest in supply chain monitoring / traceability mechanisms
Compensate for climate-related impacts	▪ *Compensate for production losses:* Financial transfers to affected producers	▪ *Avoid food shortages:* Subsidize food importation	▪ *Avoid selling off productive assets:* Fund social support for low-income households	▪ *Ecological restoration:* Direct development aid to land rehabilitation projects

Many types of financial instruments are employed by diverse actors (Table 5.26) guided by their mandates (e.g., development, commerce), capacity (investor, intermediary, donor), and risk appetite. Actors within a sector or local production area can coordinate their financial strategies toward common objectives (e.g., reduced supply chain loss) or participate in joint financial action such as blended finance structures that combine commercial and concessionary finance to catalyze additional private investment, enrich the pipeline of bankable projects, and test business models (FAO, 2020b).

Table 5.26: Potential adaptation finance objectives for major actors in agriculture, fisheries, aquaculture, and forestry sectors.

Actors	Potential adaptation finance objectives
Private sector –Focused on capturing positive externalities (i.e., lower risks or costs) from adaptation investments (Woodard et al., 2019). Major considerations include fiduciary responsibilities; expected rates of return (i.e., risk-adjusted; benchmarked to comparable investments); investment characteristics (e.g., liquidity, structure, size) and contribution to investor portfolio; material business risks (e.g., supply chain reliability; stranded assets); cost control (e.g., product losses; insurance); legal compliance; and sectoral requirements (e.g., climate risk disclosure) (Havemann et al., 2020).	
Production companies or cooperatives	▪ Supply chain transactions (e.g., trade finance) ▪ Sustainable agricultural infrastructure (e.g., capital investment in storage or processing facilities to reduce exposure to climate risks) ▪ Developing or accessing advisory services (weather data; agronomic information) (Orchard, 2019) ▪ Risk management (e.g., insurance / reinsurance; budget reserves)
Financial investors and intermediaries (e.g. banks, asset managers, venture capital; non-bank financial institutions)	▪ Ownership shares in established companies (i.e., private equity) or large publicly traded companies (i.e., listed equities) ▪ Debt issuance (e.g., working capital; catastrophe bonds; emergency loans) ▪ Real estate investment ▪ Financial derivatives ▪ Technological research and development ▪ (Impact investors) Bespoke non-financial sustainability objectives (e.g., fairtrade products; financial inclusion) (Havemann et al., 2020)
Public sector – Encompassing nearly-commercial (e.g., specialized commodity boards; bond issuances), partially subsidized (e.g., low-interest loans), and fully subsidized (e.g., R&D; grants) investments. Major considerations include avoiding negative impacts to citizens (e.g., food price spikes) and specific constituencies (e.g., catastrophic losses to producers) and maintaining / enhancing public revenues (i.e., taxes from economic activity in agriculture, fisheries, aquaculture, and forestry).	

Actors	Potential adaptation finance objectives
Government agencies and multilateral institutions	▪ Strengthen enabling environments for sustainable production and ecosystem protection (e.g., price transparency; information exchange; international coordination) ▪ Support demonstration projects for sustainable land and resource management (e.g., grants) ▪ Disaster risk reduction (e.g., national disaster funds; social protection programs; contingent credit lines; sovereign / subsovereign insurance (Global Commission on Adaptation, 2019) ▪ Increase resilience through early warning systems, infrastructure, and capacity building (e.g., climate change adaptation funds) ▪ Increase revenues for adaptation activities (e.g., income / luxury taxes) ▪ Reduce production risks (e.g., agricultural subsidies) ▪ Promote advanced technology implementation (e.g., tax incentives) ▪ Coordinate and align donor funding with national priorities (e.g., multi-donor national climate change funds) ▪ Incentivize and de-risk commercial investments (e.g., interest rate reduction programs, structured financing, guarantee funds) (Woodard et al., 2019)

Expanding access to financial services and pooling climate risks can enable and incentivize climate change adaptation (*medium confidence*) (Shukla et al., 2019). To mobilize financial instruments (Table 5.27) toward adaptation needs, individual actors can apply an adaptation lens to existing or new activities, accounting for investment characteristics (e.g., development stage; cash flow profile), requirements (e.g., amount; risk-return), and context (e.g., regulatory landscape) (Havemann et al., 2020). Risk-layering can match financial instruments to severity and probability climate risks (Chatterjee, 2019).

Table 5.27: Major types of financial instruments suitable to adaptation finance in agriculture, fisheries, aquaculture, and forestry sectors (adapted from (Havemann et al., 2020))

Financial instrument	Description
Equity – Ownership stake in a company (e.g., agricultural technology company; processing company) or collective investment vehicle (e.g., agriculture fund; Timber Investment Management Organization; commodity index fund) providing returns (via dividends and / or sale of equity shares) corresponding to business-related risk (e.g., higher return for higher risk and / or lower liquidity)	
Listed equities	Ownership of shares in a company listed in a public market
Private equity	Ownership of shares in a company or other assets
Junior or risk-absorbing equity	Ownership of lower-tier shares in a company (e.g., Common stock) or collective investment vehicle (e.g., first-loss tranche)
Debt – Capital provided directly or indirectly (via banks or other third-party institutions) to users with defined repayment terms (i.e. timeframe, interest rate); more likely to deliver adaptation benefits when coupled with capacity building (e.g. technical assistance, education, analytics) (Woodard et al., 2019)	
Loan, bond, note, credit line	Direct or indirect provision of capital (e.g., operating loans; dedicated credit line for agricultural trade); concessionary loans may allow for below-market interest rates
Soft loan	Direct interest-free loan (e.g., funds provided in advance of good / service delivery)
Emergency loan	Lending in response to climate risks or impacts with repayment terms (e.g., return period) that consider necessary relief, recovery, and reconstruction
Catastrophe bond	Risk transfer instrument in which insurers or reinsurers provide high interest payments to investors in exchange for a payout (and repayment deferment or forgiveness) activated by specific events (e.g., extreme weather)
Impact bond	Subsidized investment providing capital upfront or based on defined outcomes
Subordinated loan	Concessionary capital with a junior position (i.e., accepting higher risk of non-repayment and / or lower rate of return on investment) relative to other investors
Securitized investments	Aggregation of equity or debt to offer marketable securities to a wider pool of investors with different risk-return appetites
Guarantees – Commercial and concessionary guarantees that provide compensation for losses due to specified risks (e.g., political risk, performance risk); more likely to deliver adaptation benefits when linked to robust underwriting standards and verification protocols (Woodard et al., 2019)	

Financial instrument	Description
Credit guarantee	Compensation for specified losses incurred by agricultural lenders
Payment, performance, surety bonds	De-risking mechanism for transactions between providers and buyers of goods / services; may be used in trade finance and other forms of intermediation
Insurance – Policies and other financial instruments that provide compensation for losses based on defined terms and conditions.	
Production insurance	Compensation for specified losses related to production (e.g., insurance indexed to specific weather events) or supply chains (e.g., shipping insurance)
Market and price insurance	Compensation for specified market-related losses (e.g., price or currency fluctuation)
Grants – Concessionary funding provided by public or philanthropic entities to support climate adaptation costs or outcomes (no expectation of repayment)	
Direct support	Funding for provision of goods (e.g., fertilizer, seeds, nursery stock) or services (e.g., technical assistance; product storage) to producers, local companies, or intermediaries (e.g., for agronomic or business management expertise); can reduce credit risk when part of blended finance arrangements
Performance-based grants	Grants or other concessionary funding contingent on achievement of defined adaptation outcomes (with possible third-party verification requirement); may support development and testing of new approaches (i.e., design funding; challenges / prizes)
Governmental instruments –	
Policy incentives	Public policies designed to stimulate adaptation action among targeted groups (e.g., producers; consumers; agri-businesses; financiers) including direct or indirect subsidies (e.g., producer payments; tax breaks; health insurance), procurement policies (e.g., low carbon and sustainability criteria; nutrition-sensitive school feeding programs) and other fiscal measures (e.g., infrastructure development; funding R&D in climate-resilient practices or technologies) (Shukla et al., 2019)
Development aid	International or domestic programs that directly or indirectly fund adaptation actions including financial transfers (e.g., producer support or anti-poverty programs) and subsidized credit (*medium confidence*) (Shukla et al., 2019)
Planning grants	Financial support to governments for adaptation planning (e.g., via readiness programs)
Other instruments –	
Fintech	Data analytics and risk analysis models used to better assess borrowers' repayment risk (e.g., due to crop failure) and reduce transaction costs (e.g., streamlined lending processes); applications may include financial inclusion (e.g. micro-financing; lending to small- and mid-size operators), alternative repayment programs (e.g., for larger capital borrowing), insurance (e.g., more granular risk assessment), or digital strategies (e.g., crowdfunding; smallholder credit) (Agyekumhene et al., 2018)
Payment for Ecosystem Services (PES)	Funds delivered to land and resource managers in exchange for compliance with specified sustainability practices or environmental outcomes; PES depends on willing payers (i.e., direct and indirect beneficiaries of ecosystem services such as governments, companies, conservation groups, philanthropies)

5.14.2.5 Constraints on adaptation finance for food, feed, fibre, and other ecosystem products

Flow of adaptation finance in the agriculture, fisheries, aquaculture, and forestry sectors is impeded by weak measurement and benchmarking of financial and resilience outcomes (Kramer et al., 2019; Negra et al., 2020), and challenges in assessing repayment capacity of investee producers and companies (*medium confidence*). Immature information systems (e.g., weak analytics; fragmented standards) (Woodard et al., 2019; Negra et al., 2020) inhibit effective due diligence and impact assessment, contributing to uncertainty and low investor confidence (Havemann et al., 2020; NGFS, 2020). Improved characterization of adaptation finance strategies (e.g., insurance, subsidies, blended finance) requires increased transaction volume (Millan et al., 2019) and analysis of financial (e.g., risk-return profile; investor demand) and resilience (e.g., reduced vulnerability) effects.

Use of climate-resilient financial strategies and instruments is limited by weak incentives, which commonly take the form of high upfront costs (Verdolini et al., 2018), high transaction and intermediation costs

(Havemann et al., 2020), and relatively long pay-off time. Tenant producers may not experience benefits from adaptation investments (Woodard et al., 2019). Investors seek low-risk, liquid investments, and credit-worthy counterparties (Havemann et al., 2020) yet small- and medium-sized producers and supply chain actors often lack access to formal credit. Given limited experience and weak information for adaptation finance, sub-optimal outcomes may include imbalanced allocation of public and private finance (e.g., to less vulnerable regions and producers; to lower-resilience investments; to short-term benefits) as well as inequitable division of risks and returns (e.g., within blended finance structures) (Clapp, 2017; World Bank, 2018; Attridge and Engen, 2019). Additionally, while risk-sharing finance strategies can deliver adaptation benefits, they do not inherently reduce overall risk and commonly cover only specified types of risks (Kellett and Peters, 2014; Watson et al., 2015).

Methods to strengthen adaptation finance include updating regulations and policies to support adaptation finance instruments (e.g., climate accounting standards), requiring climate-risk disclosure, improved information-sharing among public and private sector actors and devolving funding to local actors (*medium confidence*) (Global Commission on Adaptation, 2019; Millan et al., 2019).

5.14.3 Climate-resilient Development Pathways

Climate-resilient development pathways (CRDPs) introduced in AR5 (Denton, 2014) can briefly be described as “development trajectories that integrate adaptation and mitigation to realize the goal of sustainable development” (see IPCC (2019a)) for a more extensive definition). Several characteristics were proposed in SR1.5 by which such CRDPs could be identified: consistency with principles of sustainable development; ability to deliver poverty reduction; ability to enhance social, gender, racial, ethnic, and intergenerational equity; ability to deliver resilience to climate change and other shocks and stresses; and ability to protect species, biodiversity, and ecosystem goods and services. There is an increasing literature, assessed in SR1.5, on adaptation pathways approaches, generally for specific regions, locations, and subsectors.

Two recent examples directly related to agriculture and food are the following: sustaining agrarian livelihoods to mid-century of Nicaraguan small-scale coffee producers using analyses of suitability and coffee quality changes under a SRES A2 emissions scenario (Läderach et al., 2017); and development of participatory pathways to mid-century under RCPs 4.5 and 8.5 support regional adaptation planning in Hawke’s Bay, New Zealand for agricultural producers and rural communities (Cradock-Henry et al., 2020). CRDPs mentioned in SROCC include shifting from providing coastal defences to adapting to seawater inundation in coastal regions (Renaud et al., 2015) and retreating coastal megacities (Solecki et al., 2017). Pathways frameworks continue to be used to frame the broad-scale challenges of development and climate change, thereby linking different types of food system actor with different responses through time using a variety of approaches, top down and participatory, qualitative, and quantitative (Butler et al., 2016; Antle et al., 2017; Thornton and Comberti, 2017; Collste et al., 2019; Loboguerrero et al., 2020; Stringer et al., 2020).

While there is consensus that the concept of CRDPs is useful, there are major challenges in identifying, operationalising, monitoring, and evaluating them (Lin et al., 2017; Bloemen et al., 2018). Management approaches seldom integrate across spatio-temporal scales and may be unable to address unidirectional change and extreme events (Holsman et al., 2019). The socio-economic complexities and implications of pursuing integrated outcomes make it difficult to evaluate synergies and trade-offs associated with different actions in local contexts through time (Thornton and Comberti, 2017; Ellis and Tschakert, 2019; Holsman et al., 2019; Orchard, 2019). Case studies by Lo (2019) of transformation in a fishing town in south China and by Gajjar (2019) on undesirable path dependencies in development trajectories in urban and rural India show that overall adaptive capacity of populations may be decreased though politicization and entrenchment of existing inequalities, severely limiting the possibilities for future adaptation. A further challenge of implementation is timely detection of tipping points and abrupt exposure events in both climate and environmental systems (Lenton et al., 2019; Trisos et al., 2020), which may alter the efficacy of current and planned adaptation actions, necessitating a switch to other, more transformational strategies; in such cases, re-energizing food system actors’ commitment to adaptation action may well be needed (Bloemen et al., 2018).

Integrated modelling of CRDPs will increasingly be needed to throw light on key SDG synergies and trade-offs into the future (Bleischwitz et al., 2018). In investigating possible future pressures on land under the Shared Socio-economic Pathways (SSP), Doelman (2018) projected that the largest changes take place in sub-Saharan Africa in SSP3 and SSP4, mostly because of continued high population growth coupled with (projected) sluggish increases in agricultural efficiency, among other things, leading to expansion of agricultural land for crop and livestock production and reduced food security. Lassaletta (2019) evaluated global pig production in the SSPs and concluded that the future sustainability of pig systems will depend on production efficiency improvements coupled with other factors such as use of alternative feed sources and use of slurries on cropland. Such studies will be increasingly important for quantifying the potential trade-offs and synergies between different SDGs, to guide adaptation (and mitigation) action along CRDPs in the future. The current lack of widely accepted and simple-to-measure indicators for tracking progress in adaptation is a significant hurdle to overcome. There is a large literature on the desirable characteristics of future global food systems, but much less on robust analysis that explicitly addresses and evaluates the pathways towards these desired futures. Gerten (2020) estimate that 10.2 billion people can be supported within key planetary boundaries via spatially redistributed cropland and dietary changes, among other actions. There are few if any analyses for detailing the plausible pathways to move towards such a future in ways that are socially, economically, and environmentally acceptable through time; whether such pathways could indeed be made climate-resilient is unknown. Appropriate monitoring and rapid feedback to food system actors on what is working and why, will be critical to the successful operationalisation of adaptation actions within CRDPs (Bosomworth and Gaillard, 2019).

[START CROSS-WORKING GROUP BOX BIOECONOMY HERE]

Cross-Working Group Box BIOECONOMY: Mitigation and Adaptation via the Bioeconomy

Authors: Henry Neufeldt (Denmark/Germany), Göran Berndes (Sweden), Almut Arneth (Germany), Rachel Bezner Kerr (USA/Canada), Luisa F Cabeza (Spain), Donovan Campbell (Jamaica), Jofre Carnicer Cols (Spain), Annette Cowie (Australia), Vassilis Daioglou (Greece), Joanna House (UK), Adrian Leip (Italy/Germany), Francisco Meza (Chile), Michael Morecroft (UK), Gert-Jan Nabuurs (Netherlands), Camille Parmesan (UK/USA), Julio C Postigo (USA/Peru), Marta G. Rivera-Ferre (Spain), Raphael Slade (UK), Maria Cristina Tirado von der Pahlen (USA/Spain), Pramod K. Singh (India), Peter Smith (UK)

Summary statement

The growing demand for biomass offers both opportunities and challenges to mitigate and adapt to climate change and natural resource constraints (high confidence). Increased technology innovation, stakeholder integration and transparent governance structures and procedures at local to global scales are key to successful bioeconomy deployment maximizing benefits and managing trade-offs (high confidence).

Limited global land and biomass resources accompanied by growing demands for food, feed, fibre, and fuels, together with prospects for a paradigm shift towards phasing out fossil fuels, set the frame for potentially fierce competition for land[5] and biomass to meet burgeoning demands even as climate change increasingly limits natural resource potentials (*high confidence*).

Sustainable agriculture and forestry, technology innovation in biobased production within a circular economy and international cooperation and governance of global trade in products to reflect and disincentivize their environmental and social externalities, can provide mitigation and adaptation via bioeconomy development that responds to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize synergies while limiting trade-offs (*high confidence*).

Background

[5] For lack of space the focus is on land only although the bioeconomy also includes sea-related bioresources.

There is *high confidence* that climate change, population growth and changes in per capita consumption will increase pressures on managed as well as natural and semi-natural ecosystems, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (Conijn et al., 2018; IPCC, 2018; IPCC, 2019b; Lade et al., 2020). At the same time, many global mitigation scenarios presented in IPCC assessment reports rely on large GHG emissions reduction in the AFOLU sector and concurrent deployment of reforestation/afforestation and biomass use in a multitude of applications (Rogelj et al., 2018; Hanssen et al., 2020; AR6 WGIII Chapter 3 and Chapter 7; Canadell et al., 2021; Lee et al., 2021)

Given the finite availability of natural resources, there are invariably trade-offs that complicate land-based mitigation unless land productivity can be enhanced without undermining ecosystem services (e.g.,Obersteiner et al., 2016; Campbell et al., 2017; Caron et al., 2018; Conijn et al., 2018; Heck et al., 2018; WRI, 2018; Smith et al., 2019c). Management intensities can often be adapted to local conditions with consideration of other functions and ecosystem services, but at a global scale the challenge remains to avoid further deforestation and degradation of intact ecosystems, in particular biodiversity-rich systems (cross-ref to Cross-Chapter Box on NBS-NATURAL in Chapter 2), while meeting the growing demands. Further, increased land-use competition can affect food prices and impact food security and livelihoods (To and Grafton, 2015; Chakravorty et al., 2017), with possible knock-on effects related to civil unrest (Abbott et al., 2017; D'Odorico et al., 2018).

Developing new biobased solutions while mitigating overall biomass demand growth

Many existing biobased products have significant mitigation potential. Increased use of wood in buildings can reduce GHG emissions from cement and steel production while providing carbon storage (Churkina et al., 2020). Substitution of fossil fuels with biomass in manufacture of cement and steel can reduce GHG emissions where these materials are difficult to replace. Dispatchable power based on biomass can provide power stability and quality as the contribution from solar and wind power increases (cross-ref WGIII-Chapter 6), and biofuels can contribute to reducing fossil fuel emissions in the transport and industry sectors (cross-ref WGIII-Chapter10 and Chapter11). The use of biobased plastics, chemicals and packaging could be increased, and biorefineries can achieve high resource-use efficiency in converting biomass into food, feed, fuels, and other biobased products (Aristizábal-Marulanda and Cardona Alzate, 2019; Schmidt et al., 2019). There is also scope for substituting existing biobased products with more benign products. For example, cellulose-based textiles can replace cotton, which requires large amounts of water, chemical fertilizers, and pesticides to ensure high yields.

While increasing and diversified use of biomass can reduce the need for fossil fuels and other GHG-intensive products, unfavourable GHG balances may limit the mitigation value. Growth in biomass use may in the longer term also be constrained by the need to protect biodiversity and ecosystems' capacity to support essential ecosystem services. Biomass use may also be constrained by water scarcity and other resource scarcities, and/or challenges related to public perception and acceptance due to impacts caused by biomass production and use. Energy conservation and efficiency measures and deployment of technologies and systems that do not rely on carbon, e.g., carbon-free electricity supporting, inter alia, electrification of transport as well as industry processes and residential heating (IPCC, 2018; UNEP, 2019), can constrain the growth in biomass demand when countries seek to phase out fossil fuels and other GHG-intensive products while providing an acceptable standard of living. Nevertheless, demand for biobased products may become high where full decoupling from carbon is difficult to achieve (e.g., aviation, biobased plastics, and chemicals) or where carbon storage is an associated benefit (e.g., wood buildings, BECCS, biochar for soil amendments), leading to challenging trade-offs (e.g., food security, biodiversity) that need to be managed in environmentally sustainable and socially just ways.

Changes on the demand side as well as improvements in resource-use efficiencies within the global food and other bio-based systems can also reduce pressures on the remaining land resources. For example, dietary changes toward more plant-based food (where appropriate) and reduced food waste can provide climate change mitigation along with health benefits (Cross-ref WGIII-Chapter 7.4 and 12.4, Willett et al., 2019) and other co-benefits with regard to food security, adaptation and land use (Mbow et al., 2019; Smith et al., 2019c; cross-ref WGII chapter 5). Advancements in the provision of novel food and feed sources (e.g., cultured meat, insects, grass-based protein feed and cellular agriculture) can also limit the pressures on finite natural resources (WGIII Chapter 12.4, Parodi et al., 2018; Zabaniotou, 2018).

[START BOX CROSS-WORKING GROUP BOX BIOECONOMY.1 HERE]

Box Cross-Working Group Box BIOECONOMY.1: Circular bioeconomy

Circular economy approaches (Cross ref WGIII-12.6) are commonly depicted by two cycles, where the biological cycle focuses on regeneration in the biosphere and the technical cycle focuses on reuse, refurbishment, and recycling to maintain value and maximize material recovery (Mayer et al., 2019a). Biogenic carbon flows and resources are part of the biological carbon cycle, but carbon-based products can be included in, and affect, both the biological and the technical carbon cycles (Kirchherr et al., 2017; Winans et al., 2017; Velenturf et al., 2019). The integration of circular economy and bioeconomy principles has been discussed in relation to organic waste management (Teigiserova et al., 2020), societal transition and policy development (Directorate-General for Research Innovation, 2018; Bugge et al., 2019) as well as COVID-19 recovery strategies (Palahi et al., 2020). To maintain the natural resource base, circular bioeconomy emphasizes sustainable land use and the return of biomass and nutrients to the biosphere when it leaves the technical cycle.

Biomass scarcity is an argument for adopting circular economy principles for the management of biomass as for non-renewable resources. This includes waste avoidance, product reuse and material recycling, which keep down resource use while maintaining product and material value. However, reuse and recycling is not always feasible, e.g., when biofuels are used for transport and biobased biodegradable chemicals are used to reduce ecological impacts where losses to the environment are unavoidable. A balanced approach to management of biomass resources could take departure in the carbon cycle from a value-preservation perspective and the possible routes that can be taken for biomass and carbon, considering a carbon budget defined by the Paris Agreement, principles for sustainable land use and natural ecosystem protection.

[END BOX CROSS-WORKING GROUP BOX BIOECONOMY.1 HERE]

Land use opportunities and challenges in the bioeconomy

Analyses of synergies and trade-offs between adaptation and mitigation in the agriculture and forestry sectors show that outcomes depend on context, design, and implementation, so actions have to be tailored to the specific conditions to minimize adverse effects (Kongsager, 2018). This is supported in literature analyzing the nexus between land, water, energy, and food in the context of climate change which consistently concludes that addressing these different domains together rather than in isolation would enhance synergies and reduce trade-offs (Obersteiner et al., 2016; D'Odorico et al., 2018; Soto Golcher and Visseren-Hamakers, 2018; Froehse and Schilling, 2019; Momblanch et al., 2019).

Nature-based solutions addressing climate change can provide opportunities for sustainable livelihoods as well as multiple ecosystem services, such as flood risk management through floodplain restoration, saltmarshes, mangroves or peat renaturation (Cross-Chapter Box NATURAL in Chapter 2; UNEP, 2021). Climate-smart agriculture can increase productivity while enhancing resilience and reducing GHG emissions inherent to production (Lipper et al., 2014; Nabuurs et al., 2018; Verkerk et al., 2020; Singh and Chudasama, 2021). Similarly, climate-smart forestry considers the whole value chain and integrates climate objectives into forest sector management through multiple measures (from strict reserves to more intensively managed forests) providing mitigation and adaptation benefits (WGIII Section 7.3).

Agroecological approaches can be integrated into a wide range of land management practices to support a sustainable bioeconomy and address equity considerations (HLPE, 2019). Relevant land-use practices, such as agroforestry, intercropping, organic amendments, cover crops and rotational grazing, can provide mitigation and support adaption to climate change via food security, livelihoods, biodiversity and health co-benefits (Ponisio et al., 2015; Garibaldi et al., 2016; D'Annolfo et al., 2017; Bezner Kerr et al., 2019; Clark et al., 2019; Córdova et al., 2019; HLPE, 2019; Mbow et al., 2019; Renard and Tilman, 2019; Sinclair et al., 2019; Bharucha et al., 2020; Bezner Kerr et al., 2021;WGII Cross-Chapter Box NATURAL in Chapter 2). Strategic integration of appropriate biomass production systems into agricultural landscapes can provide biomass for bioenergy and other biobased products while providing co-benefits such as enhanced landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, climate regulation, flood regulation, pollination and biological pest and disease control (WGIII Chapter12 Box on UNCCD-LDN, Christen and Dalgaard, 2013; Asbjornsen et al., 2014; Holland et al., 2015; Ssegane et al., 2015; Dauber and Miyake, 2016; Milner et al., 2016; Ssegane and Negri, 2016; Styles et al., 2016; Zumpf et al., 2017; Cacho et al., 2018; Alam and Dwivedi, 2019; Cubins et al., 2019; HLPE, 2019; Olsson et al., 2019; Zalesny et al., 2019; Englund et al., 2020). Such approaches can help limit environmental impacts from intensive agriculture while maintaining or increasing land productivity and biomass output.

Figure Cross-Working Group Box BIOECONOMY.1: Left: High-input intensive agriculture, aiming for high yields of a few crop species, with large fields and no semi-natural habitats. Right: Agroecological agriculture, supplying a range of ecosystem services, relying on biodiversity and crop and animal diversity instead of external inputs, and integrating plant and animal production, with smaller fields and presence of semi-natural habitats. Credit: Jacques Baudry (left); Valérie Viaud (right), published in van der Werf et al. (2020)

Transitions from conventional to new biomass production and conversion systems include challenges related to cross-sector integration and limited experience with new crops and land use practices, including needs for specialized equipment (WGII Chapter 5.10, Thornton and Herrero, 2015; HLPE, 2019). Introduction of agroecological approaches and integrated biomass/food crop production can result in lower food crop yields per hectare, particularly during transition phases, potentially causing indirect land use change, but can also support higher and more stable yields, reduce costs, and increase profitability under climate change (Muller et al., 2017; Seufert and Ramakutty, 2017; Barbieri et al., 2019; HLPE, 2019; Sinclair et al., 2019; Smith et al., 2019c; Smith et al., 2020a). Crop diversification, organic amendments, and biological pest control (HLPE, 2019) can reduce input costs and risks of occupational pesticide exposure and food and water contamination (Gonzalez-Alzaga et al., 2014; European Food Safety Authority Panel on Plant Protection Products and their Residues et al., 2017; Mie et al., 2017), reduce farmers' vulnerability to climate change (e.g., droughts and spread of pests and diseases affecting plant and animal health (Delcour et al., 2015; FAO, 2020a)) and enhance provisioning and sustaining ecosystem services, such as pollination (D'Annolfo et al., 2017; Sinclair et al., 2019).

Barriers toward wider implementation include absence of policies that compensate landowners for providing enhanced ecosystem services and other environmental benefits, which can help overcome short term losses during the transition from conventional practices before longer term benefits can accrue. Other barriers include limited access to markets, knowledge gaps, financial, technological, or labour constraints, lack of extension support and insecure land tenure (Jacobi et al., 2017; Kongsager, 2017; Hernández-Morcillo et al., 2018; Iiyama et al., 2018; HLPE, 2019). Regional-level agroecology transitions may be facilitated by co-learning platforms, farmer networks, private sector, civil society groups, regional and local administration, and other incentive structures (e.g., price premiums, access to credit, regulation) (Coe et al., 2014; Pérez-Marin et al., 2017; Mier y Terán Giménez Cacho et al., 2018; HLPE, 2019; Valencia et al., 2019; SAPEA, 2020). With the right incentives, improvements can be made with regard to profitability, making alternatives more attractive to landowners.

Governing the solution space

Literature analyzing the synergies and trade-offs between competing demands for land suggest that solutions are highly contextualized in terms of their environmental, socioeconomic, and governance-related characteristics, making it difficult to devise generic solutions (Haasnoot et al., 2020). Aspects of spatial and temporal scale can further enhance the complexity, for instance where transboundary effects across jurisdictions or upstream-downstream characteristics need to be considered, or where climate change trajectories might alter relevant biogeophysical dynamics (Postigo and Young, 2021). Nonetheless, there is broad agreement that taking the needs and perspectives of multiple stakeholders into account in a transparent process during negotiations improves the chances of achieving outcomes that maximize synergies while limiting trade-offs (Ariti et al., 2018; Metternicht, 2018; Favretto et al., 2020; Kopáček, 2021; Muscat et al., 2021). Yet differences in agency and power between stakeholders or anticipated changes in access to or control of resources can undermine negotiation results even if there is a common understanding of the overarching benefits of more integrated environmental agreements and the need for greater coordination and cooperation to avoid longer-term losses to all (Aarts and Leeuwis, 2010; Weitz et al., 2017). There is also the risk that strong local participatory processes can become disconnected from broader national plans, and thus fail to support the achievement of national targets. Thus, connection between levels is needed to ensure that ambition for transformative change is not derailed at local level (Aarts and Leeuwis, 2010; Postigo and Young, 2021).

Decisions on land uses between biomass production for food, feed, fibre, or fuel, as well as nature conservation or restoration and other uses (e.g., mining, urban infrastructure), depend on differences in perspectives and values. Because the availability of land for diverse biomass uses is invariably limited, setting priorities for land-use allocations therefore first depends on making the perspectives underlying what is considered as 'high-value' explicit (Fischer et al., 2007; Garnett et al., 2015; de Boer and van Ittersum, 2018; Muscat et al., 2020). Decisions can then be made transparently based on societal norms, needs and the available resource base. Prioritization of land-use for the common good therefore requires societal consensus-building embedded in the socioeconomic and cultural fabric of regions, societies, and communities. Integration of local decision-making with national planning ensures local actions complement national development objectives.

International trade in the global economy today provides important opportunities to connect producers and consumers, effectively buffering price volatilities and potentially offering producers in low-income countries access to global markets, which can be seen as an effective adaptation measure (Baldos and Hertel, 2015; Costinot et al., 2016; Hertel and Baldos, 2016; Gouel and Laborde, 2021; WGII Section 5.11). But there is also clear evidence that international trade and the global economy can enhance price volatility, lead to food price spikes and affect food security due to climate and other shocks, as seen recently due to the COVID-19 pandemic (WGII Chapter 5.12, Cottrell et al., 2019; WFP-FSIN, 2020; Verschuur et al., 2021). The continued strong demand for food and other biobased products, mainly from high- and middle-income countries, therefore, requires better cooperation between nations and global governance of trade to more accurately reflect and disincentivize their environmental and social externalities. Trade in agricultural and extractive products driving land-use change in tropical forest and savanna biomes is of major concern because of the biodiversity impacts and GHG emissions incurred in their provision (CCP7, Hosonuma et al., 2012; Forest Trends, 2014; Henders et al., 2015; Curtis et al., 2018; Pendrill et al., 2019; Seymour and Harris, 2019; Kissinger et al., 2021).

In summary, there is significant scope for optimizing use of land resources to produce more biomass while reducing adverse effects (*high confidence*). Context-specific prioritization, technology innovation in biobased production, integrative policies, coordinated institutions and improved governance mechanisms to enhance synergies and minimize trade-offs can mitigate the pressure on managed as well as natural and semi-natural ecosystems (*medium confidence*). Yet, energy conservation and efficiency measures, and deployment of technologies and systems that do not rely on carbon-based energy and materials, are essential for mitigating biomass demand growth as countries pursue ambitious climate goals (*high confidence*).

[END CROSS-WG BOX BIOECONOMY HERE]

[START FAQ5.1 HERE]

FAQ5.1: How is climate change (already) affecting people's ability to have enough nutritious food?

Climate change has already made feeding the world's people more difficult. Climate related hazards have become more common, disrupting the supply of crops, meat, and fish. Rapid changes in weather patterns have put financial strain on producers, while also raising prices and limiting the choices and quality of produce available to consumers.

Most of our food comes from crops, livestock, aquaculture, and fisheries. Global food supply increased dramatically in the last century, but ongoing climate change has begun to slow that growth, reducing the gains that would have been expected without climate change. Regionally, negative effects are apparent in regions closer to the equator, with some positive effects further north and south.

Climate impacts are also negatively affecting the quality of produce, from changes in micronutrient content to texture, colour, and taste changes that reduce marketability. With warmer and more humid condition, many food pests thrive, food decays more quickly and food contains more toxic compounds produced by fungi and bacteria.

Warming of the oceans has reduced potential fish catch. The increased carbon dioxide in the atmosphere has led to ocean acidification, which is already impacting the production of farmed fish and shellfish. Changes in local climate have forced producers to shift to new locations, change what they grow or where they work (e.g., pole-ward shifting fishing grounds).

Climate hazards have increased over the past 50 years and are the major cause of sudden losses of production (food production shocks). Food shocks occur following droughts, heatwaves, floods, storms, and outbreaks of climate-related pests and combine to cause multiplying impacts. Climate hazards sometimes disrupt food storage and transport, which impairs the food supply.

All of these negative impacts can lead to increased food prices, and reduced income for producers and retailers as there are fewer products to sell. Together, these impacts threaten to reduce the supply of varied, nutrient-rich foods to poor populations that already suffer ill health.

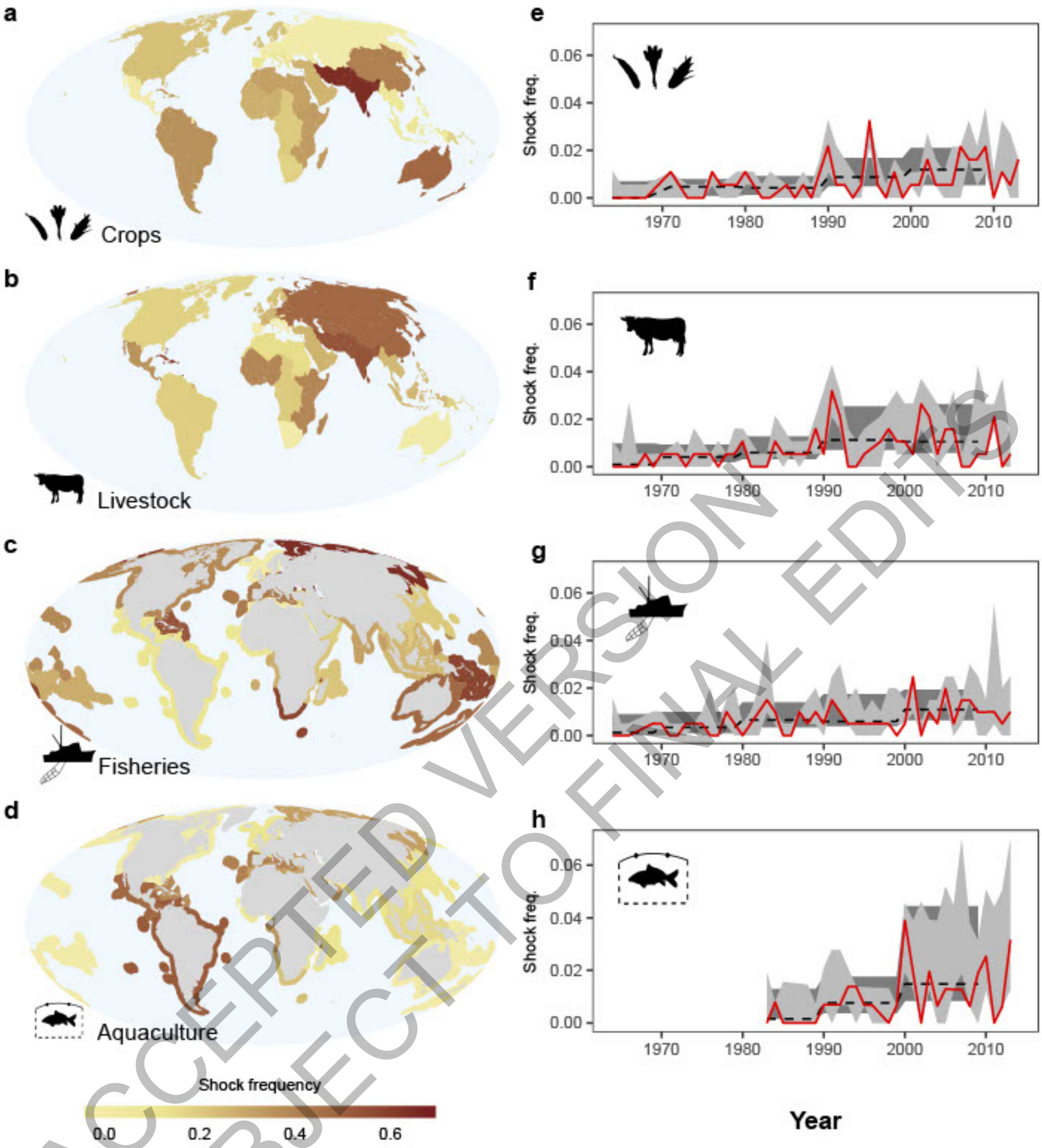


Figure FAQ 5.1.1: Trends in food production shocks in different food supply sectors from 1961-2-13 (Cottrell et al., 2019). The red lines in the time series are the annual shock frequency and the dashed line is the decadal mean.

[END FAQ5.1 HERE]

[START FAQ5.2 HERE]

FAQ5.2: How will climate change impact food availability by mid and late century and who will suffer most?

Climate change impacts will worsen over time with the period after mid-century seeing more rapid growth in negative impact than in the early part of this century. The impacts will be global but people with fewer resources, and those who live in regions where impacts will worsen more rapidly, will be hurt the most.

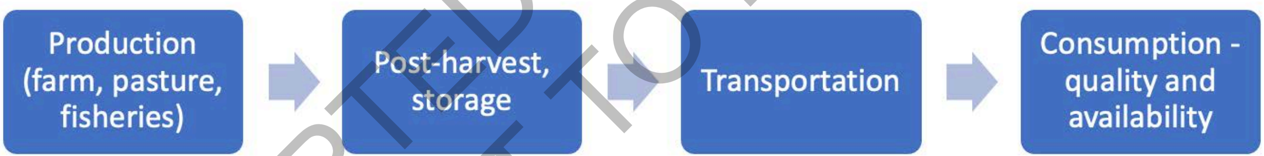
Climate change impacts will worsen over time, but the extent depends on how rapidly greenhouse gas emissions grow. If the current rate of emissions continues, the impacts will worsen, especially after mid-century with rapid growth in the number and severity of extreme weather events. Yields of plants, animals and aquaculture will decline in most places and marine and inland fisheries will suffer. Food production in some regions will become impossible, either because the crops or livestock there can't survive in the new climatic conditions, or it is too hot and humid for farm workers to be in the fields.

After harvest, agricultural production passes through the agricultural value chain, supplying animal feeds, industrial uses, and international markets, with some stored for use in the future. Each of these transitions will be affected by climate change. Food storage facilities will face more challenges in dealing with spoilage. Transportation of perishable fruits, vegetables, and meats will become costlier to maintain quality. Households and food services will need to spend more on food preservation.

Low-income countries and poor people are at higher risk, as they have limited social safety nets, suffer more from rising food prices, and an unstable food supply. But large famers will also be hurt. Rural communities, especially smallholder farmers, pastoralists, and fishers, are extremely vulnerable because their livelihoods mainly depend on their production. The urban poor will have to spend more on food.

A flood, for example, may force low-income families out of their homes, affect their employment and reduce their access to food supplies, with prices often rising after natural disasters. Families will have less access to safe water supplies, and this combination of lower food supplies, uncertain employment, displacement from home and rising food costs will increase the number of children who are undernourished.

Yields reduced Producer income falls	Pests and disease damage reduce quality and quantity	Losses of perishable items to higher temperatures/humidity More expense to marketing system	More spoilage, reduced availability Impacts in other sectors reduce income available



Examples [take from individual sections of ch 5]

Maize yields fall by 23 % in the 21st century with high GHG emissions (SSP5-8.5)	aflatoxin contamination will increase in maize in a + 2°C temperature scenario in Europe.	Increase in temperature from 17 °C to 25°C increases cold storage power consumption by about 11%	Uptake of methyl mercury in fish and mammals has been found to increase by 3–5% for each 1°C rise in water temperature

Figure FAQ5.2.1: Impacts of climate change in the food system

[END FAQ5.2 HERE]

[START FAQ5.3 HERE]

FAQ5.3: Land is going to be an important resource for mitigating climate change: How is the increasing competition for land threatening global food security and who will be affected the most?

Climate change will affect food production. To meet future food needs requires greater land shares unless we change what we eat and how we grow food. Additionally, large scale land projects that aim to mitigate *climate change will increase land competition. Less land will then be available for food production, increasing food insecurity. People at greater risk from land competition are smallholder farmers, Indigenous Peoples, and low-income groups.*

Why is land important?

Land is a limited resource on which humans and ecosystems depend on to grow plants, which capture carbon dioxide and release oxygen, provide food, timber, and other products. We also have cultural, recreational, and spiritual connections to land.

Why will climate change affect land use?

Climate change results in more frequent heat waves, extreme rainfall, drought, and rising sea levels, which negatively affect crop yields. More land is thus needed to grow crops, increasing land competition with other food systems that use crops to feed their animals (e.g., livestock, fish). Where land will be flooded, humans cannot grow crops, but food production could be adapted to grow seafood instead. Extensive land allocations aiming at reducing carbon emissions e.g., afforestation, reduce land availability for food. Unless carefully managed, competition for land will increase food prices and food security.

Solutions to reduce land competition and protect food security

Sustainable land management allows land to remain productive and support key functions. Other land practices include growing cover crops to improve soil quality. Governments can provide incentives to producers to grow alternative foods and use sustainable practices. Making sure that vulnerable groups (e.g. low-income communities, Indigenous people, and small-scale producers) strengthen land tenure rights will help protect food security.

Food by-products used as alternative food sources and other products reduce waste and increase sustainability. Dietary changes are another important solution. People that eat high amounts of meat or unhealthy foods could reduce consumption of these foods and have more diverse diets. These dietary changes will benefit their health and reduce pressure on land. Regulated labelling, education and other policies which encourage healthy diets can support these shifts.

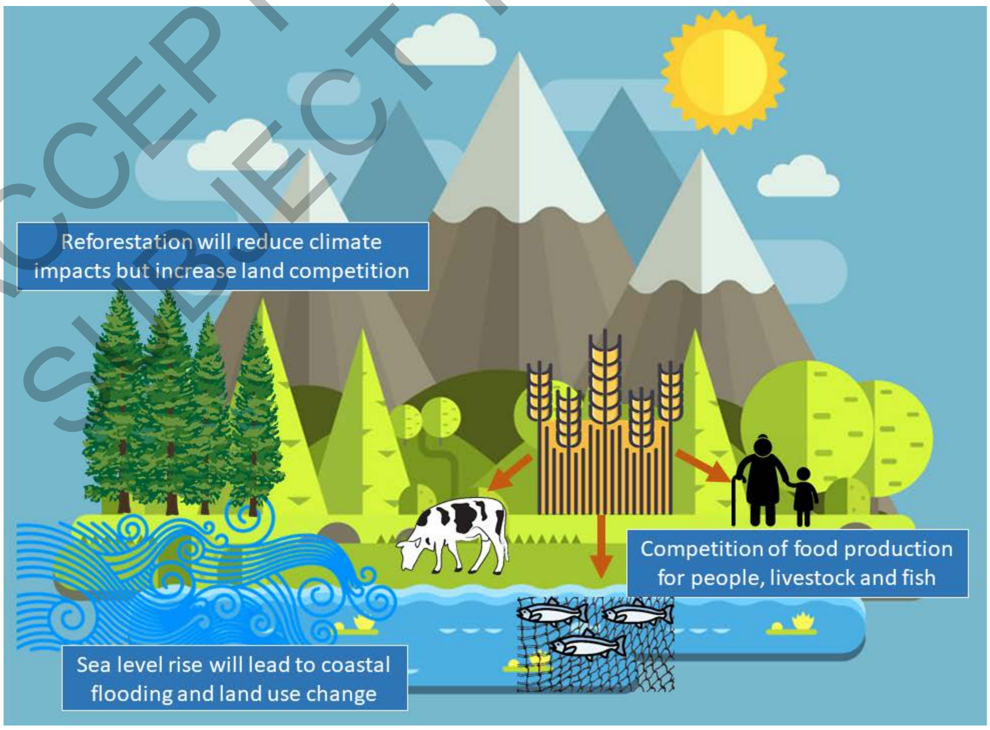


Figure FAQ5.3.1: Climate impacts will increase competition for land use reducing coastal land for crops, affecting food security for vulnerable groups. Adaptation methods like coastal aquaculture and mangrove reforestation reduce climate effects but may increase land competition.

[END FAQ5.3 HERE]

[START FAQ5.4 HERE]

FAQ5.4: What are effective adaptation strategies for improving food security in a warming world?

A variety of adaptation options exist to improve food security in a warming world. Examples of adaptation for crop production include crop management and livelihood diversification. For livestock-based systems, an example is matching number of animals with the production capacity of pastures. For fisheries, eliminating overfishing is an effective adaptation practice. For mixed cropping and nature-based systems, an appropriate adaptation is agroforestry.

Adaptation strategies to enhance food security vary from farm-level interventions to national policies and international agreements. They cover the following dimensions of food security: availability, access, utilization (food quality and safety), and stability.

For the production of crops, adaptation strategies include field and farm-level options such as crop management, livelihood diversification, and social protection such as crop insurance. The most common field management options are changes in planting schedules, crop varieties, fertilisers, and irrigation. For example, farmers can shift their planting schedules in response to the early or late onset of the rainy season. Moreover, there are new crop insurance schemes that are based on changes in weather patterns.

For livestock-based systems, adaptation options include matching the number of animals with the production capacity of pastures; adjusting water management based on seasonal and spatial patterns of forage production; managing animal diet; more effective use of fodder, rotational grazing; fire management to control woody thickening of grass; using more suitable livestock breeds or species; migratory pastoralist activities; and activities to monitor and manage the spread of pests, weeds, and diseases.

For ocean and inland fisheries, adaptation options are primarily concentrated in the socio-economic dimension and governance and management. In general, eliminating overfishing could help rebuild fish stocks, reduce ecosystem impacts, and increase fishing's adaptive capacity. Aquaculture is often viewed as an adaptation option for fisheries declines. However, there are adaptation strategies specific to aquaculture such as proper species selections at the operational level, such as the cultivation of brackish species (shrimp, crabs) in inland ponds during dry seasons and rice-freshwater finfish in wetter seasons.

For so-called mixed farming systems that produce a combination of crops, livestock, fish, and trees, these systems' inherent diversity provides a solid platform for adaptation. A good example is agroforestry, the purposeful integration of trees or shrubs with crop or livestock systems, increases resilience against climate risks.

Overall, nature-based systems or ecosystem-based strategies in food systems, such as agroecology, can be a useful adaptation method to increase wild and cultivated food sources. Agroecological practices include agroforestry, intercropping, increasing biodiversity, crop and pasture rotation, adding organic amendments, integration of livestock into mixed systems, cover crops and minimizing toxic and synthetic inputs with adverse health and environmental impacts.

[END FAQ5.4 HERE]

[START FAQ5.5 HERE]

FAQ5.5: Climate change is not the only factor threatening global food security: other than climate action, what other actions are needed to end hunger and ensure access by all people to nutritious and sufficient food all year round?

Our food systems depend on many factors other than climate change, such as food production, water, land, energy, and biodiversity. People's access to healthy food can be also be affected by factors such as poverty and physical insecurity. We are all stakeholders in food systems, whether as producers or consumers, and we can all contribute to the goal of a food-secure world by the choices we make in our everyday lives.

Today more than 820 million people are hungry, and hunger is on the rise in Africa. Two billion people experience moderate or severe food shortages and another 2 billion suffer from overnutrition, a state of obesity or being overweight from unbalanced diets, with related health impacts such as diabetes and heart disease. The changing climate is already affecting food production. These effects are worsening, affecting food production from crops, livestock, fish, and forests in many places where people already don't have enough to eat. Food prices will be affected as a result, with increasing risk that poorer people will not be able to buy enough for their families. Food quality will increasingly be affected too.

Our ability to grow and consume food depends on many factors other than climate change. There are tight connections between food production, water, land, energy, and biodiversity, for example. Other factors like gender inequality, poverty, political exclusion, remoteness from urban centres and physical insecurity can all affect people's access to healthy food.

Food systems are complicated **(**Figure FAQ5.5). To improve food production, supply, and distribution, we need to make changes throughout the food supply chain. For instance: improving the way farmers access the inputs needed to grow food; improving the ways in which food is grown, with climate and market information, training and technical know-how, water-saving and water-harvesting technologies; adopting new low-cost and less carbon-intensive storage and processing methods; and creating local networks of producers and processors For food consumers, we could consider shifts to different diets that are healthier and make more efficient use of natural resources; depending on context, these could involve rebalancing consumption of meat and highly processed foods, reducing food loss and waste, and preparing food in more energy-efficient ways. Policy makers can enable such actions through appropriate price and trade policies, implementing policies for sustainable and low-emission agriculture, providing safety nets where needed, and empowering women, youth, and other socially disadvantaged groups.

Our food systems need to be robust and sustainable, otherwise we won't be able to manage the additional pressures imposed on them by climate change. We can all contribute to this goal.

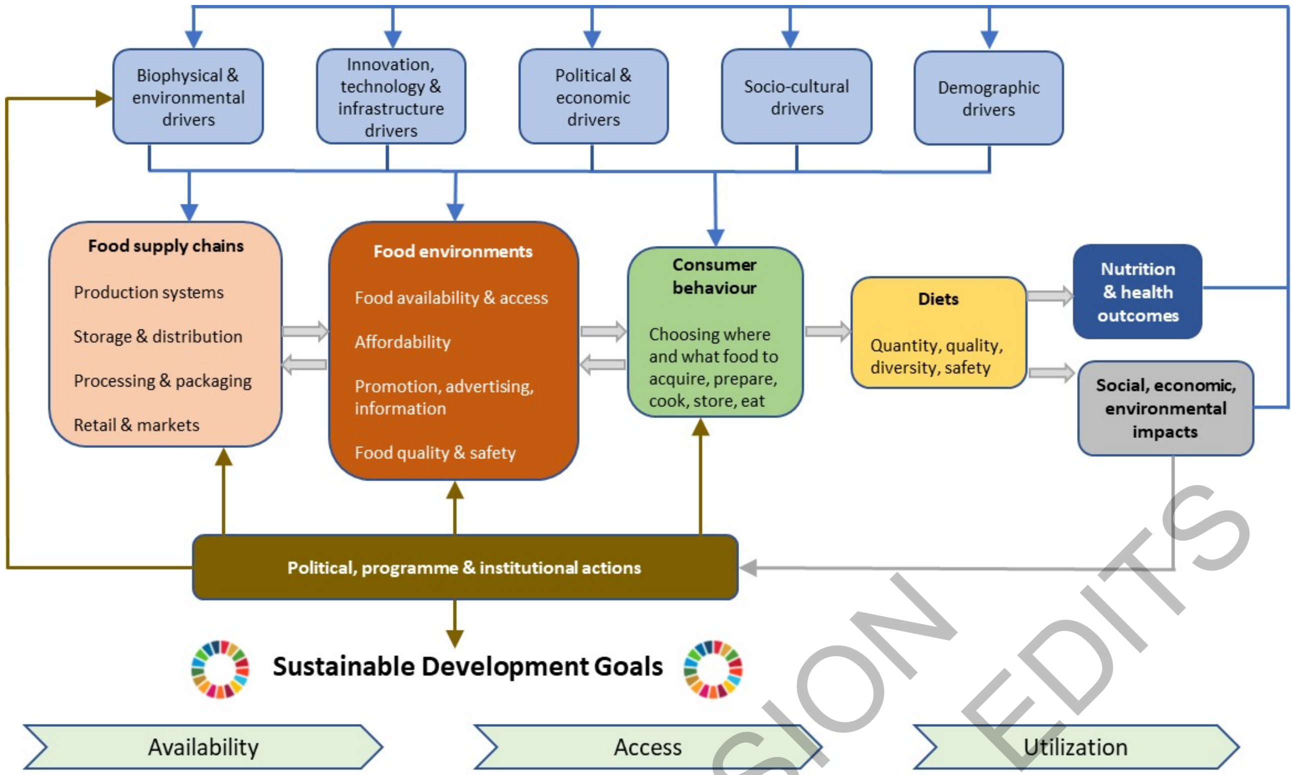


Figure FAQ5.5.1: Conceptual framework of food systems for diets and nutrition (modified from (HLPE, 2017a)

[END FAQ5.5 HERE]

References

Aarts, N. and C. Leeuwis, 2010: Participation and power: reflections on the role of government in land use planning and rural development. *J. Agric. Educ. Ext.*, **16**(2), 131-145, doi:10.1080/13892241003651381.

Ab Lah, R., B. P. Kelaher, D. Bucher and K. Benkendorff, 2018: Ocean warming and acidification affect the nutritional quality of the commercially-harvested turbinid snail Turbo militaris. *Mar. Environ. Res.*, **141**, 100-108, doi:10.1016/j.marenvres.2018.08.009.

Abah, J., P. Mashebe and D. D. Denuga, 2015: Prospect of integrating African indigenous knowledge systems into the teaching of sciences in Africa. *Am. J. Educ. Res.*, **3**(6), 668-673, doi:10.12691/education-3-6-1.

Abay, K. A. et al., 2021: Landscapes of opportunity: patterns of young people's engagement with the rural economy in sub-Saharan Africa. *J Dev.Stud.*, **57**(4), 594--613, doi:10.1080/00220388.2020.1808195.

Abbott, M., M. Bazilian, D. Egel and H. H. Willis, 2017: Examining the food-energy-water and conflict nexus. *Curr. Opin. Chem. Eng.*, **18**, 55-60, doi:10.1016/j.coche.2017.10.002.

Abdel-Tawwab, M., M. N. Monier, S. H. Hoseinifar and C. Faggio, 2019: Fish response to hypoxia stress: growth, physiological, and immunological biomarkers. *Fish Physiol. Biochem.*, **45**(3), 997-1013, doi:10.1007/s10695-019-00614-9.

Abdelrahman, H. et al., 2017: Aquaculture genomics, genetics and breeding in the United States: current status, challenges, and priorities for future research. *BMC Genomics*, **18**(1), 191, doi:10.1186/s12864-017-3557-1.

Abdulai, I. et al., 2018: Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. *Glob Chang Biol*, **24**(1), 273-286, doi:10.1111/gcb.13885.

Aberman, N.-L. and C. Tirado, 2014: Impacts of Climate Change on Food Utilization. Springer Netherlands, Dordrecht, pp. 717-724.

Abolmaali, S. M.-R., M. Tarkesh and H. Bashari, 2018: MaxEnt modeling for predicting suitable habitats and identifying the effects of climate change on a threatened species, Daphne mucronata, in central Iran. *Ecol. Inform.*, **43**, 116-123, doi:10.1016/j.ecoinf.2017.10.002.

Abraham, B. et al., 2014: The system of crop intensification: reports from the field on improving agricultural production, food security, and resilience to climate change for multiple crops. *Agric. Food Secur.*, **3**, 4, doi:10.1186/2048-7010-3-4.

Abtew, A. A., J. Pretzsch, L. Secco and T. E. Mohamod, 2014: Contribution of small-scale gum and resin commercialization to local livelihood and rural economic development in the drylands of eastern Africa. *Forests*, **5**(5), 952-977, doi:10.3390/f5050952.

Abu Samah, A., H. A. M. Shaffril, A. Hamzah and B. Abu Samah, 2019: Factors affecting small-scale fishermen’s adaptation toward the impacts of climate change: Reflections from Malaysian fishers. *SAGE Open*, **9**(3), doi:10.1177/2158244019864204.

Acevedo, M. et al., 2020: A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nat. Plants*, **6**(10), 1231-1241, doi:10.1038/s41477-020-00783-z.

Adams, E. A., E. D. Kuusaana, A. Ahmed and B. B. Campion, 2019: Land dispossessions and water appropriations: Political ecology of land and water grabs in Ghana. *Land Use Policy*, **87**(June 2018), doi:10.1016/j.landusepol.2019.104068.

Adams, M. A. et al., 2018: Crops, nitrogen, water: Are legumes friend, foe, or misunderstood ally? *Trends Plant Sci.*, **23**(6), 539-550, doi:10.1016/j.tplants.2018.02.009.

Addison, L. and M. Schnurr, 2016: Growing burdens? Disease-resistant genetically modified bananas and the potential gendered implications for labor in Uganda. *Agric. Hum. Values*, **33**, 967-978, doi:10.1007/s10460-015-9655-2.

Adhikari, L., A. Hussain and G. Rasul, 2017: Tapping the potential of neglected and underutilized food crops for sustainable nutrition security in the mountains of Pakistan and Nepal. *Sustainability*, **9**(2), 291, doi:10.3390/su9020291.

Adhikari, P. et al., 2016: Simulating future climate change impacts on seed cotton yield in the Texas High Plains using the CSM-CROPGRO-Cotton model. *Agric. Water Manage.*, **164**, 317-330, doi:10.1016/j.agwat.2015.10.011.

Adhikari, U., A. P. Nejadhashemi and S. A. Woznicki, 2015: Climate change and eastern Africa: a review of impact on major crops. *Food Energy Secur.*, **4**(2), 110-132, doi:10.1002/fes3.61.

Afidchao, M. M. et al., 2014: Analysing the farm level economic impact of GM corn in the Philippines. *NJAS-Wageningen Journal of Life Sciences*, **70-71**, 113-121, doi:10.1016/j.njas.2014.05.008.

Aggarwal, A., 2014: How sustainable are forestry clean development mechanism projects?—A review of the selected projects from India. *Mitig. Adapt. Strateg. Glob. Change*, **19**(1), 73-91, doi:10.1007/s11027-012-9427-x.

Aggarwal, P., S. Vyas, P. Thornton and B. M. Campbell, 2019: How much does climate change add to the challenge of feeding the planet this century? *Environ. Res. Lett.*, **14**(4), 043001, doi:10.1088/1748-9326/aafa3e.

Agnolucci, P. and V. De Lipsis, 2020: Long-run trend in agricultural yield and climatic factors in Europe. *Clim. Change*, **159**(3), 385-405, doi:10.1007/s10584-019-02622-3.

Agrawal, A., A. Chhatre and E. R. Gerber, 2015: Motivational crowding in sustainable development interventions. *Am. Political Sci. Rev.*, **109**(3), 470-487, doi:10.1017/S0003055415000209.

Ágreda, T. et al., 2015: Increased evapotranspiration demand in a Mediterranean climate might cause a decline in fungal yields under global warming. *Global Change Biol.*, **21**(9), 3499-3510, doi:10.1111/gcb.12960.

Agyekumhene, C. et al., 2018: Digital platforms for smallholder credit access: The mediation of trust for cooperation in maize value chain financing. *NJAS - Wagening. J. Life. Sci.*, **86-87**, 77-88, doi:10.1016/j.njas.2018.06.001.

Aha, B. and J. Z. Ayitey, 2017: Biofuels and the hazards of land grabbing: Tenure (in)security and indigenous farmers' investment decisions in Ghana. *Land Use Policy*, **60**, 48-59, doi:10.1016/j.landusepol.2016.10.012.

Ahmed, B. M. S. et al., 2017: Cows exposed to heat stress during fetal life exhibit improved thermal tolerance. *J. Anim. Sci.*, **95**(8), 3497-3497, doi:10.2527/jas2016.1298.

Ahmed, I. et al., 2018: Assessing the impact of climate variability on maize using simulation modeling under semi-arid environment of Punjab, Pakistan. *Environ Sci Pollut Res Int*, **25**(28), 28413-28430, doi:10.1007/s11356-018-2884-3.

Ahmed, N., S. Thompson and M. Glaser, 2019: Global aquaculture productivity, environmental sustainability, and climate change adaptability. *Environ Manage*, **63**(2), 159-172, doi:10.1007/s00267-018-1117-3.

Ahmed, S. and J. R. Stepp, 2016: Beyond yields: climate change effects on specialty crop quality and agroecological management. *Elementa: Sci. Anthropocene*, **4**, 1-16, doi:10.12952/journal.elementa.000092.

Ahsan, N. and D. Mitra, 2016: *Can the Whole be Greater than the Sum of Its Parts? Lessons from India's Growing Economy and its Evolving Structure*. International Food Policy Research Institute, 38--46 pp. Available at: https://ebrary.ifpri.org/digital/collection/p15738coll2/id/131168.

Ainsworth, E. A. and S. P. Long, 2021: 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Glob Chang Biol*, **27**(1), 27-49, doi:10.1111/gcb.15375.

Aitken, S. N. and J. B. Bemmels, 2016: Time to get moving: assisted gene flow of forest trees. *Evol Appl*, **9**(1), 271-290, doi:10.1111/eva.12293.

Ajates Gonzalez, R., J. Thomas and M. Chang, 2018: Translating agroecology into policy: The case of France and the United Kingdom. *Sustainability*, **10**(8), 2930, doi:10.3390/su10082930.

Akil, L., H. A. Ahmad and R. S. Reddy, 2014: Effects of climate change on Salmonella infections. *Foodborne Pathog Dis*, **11**(12), 974-980, doi:10.1089/fpd.2014.1802.

Aksnes, D. L. et al., 2019: Multi-decadal warming of Atlantic water and associated decline of dissolved oxygen in a deep fjord. *Estuar. Coast. Shelf Sci.*, **228**, 106392, doi:10.1016/j.ecss.2019.106392.

Akter, R. et al., 2019: The dominant climate change event for salinity intrusion in the GBM delta. *Climate*, **7**(5), 69, doi:10.3390/cli7050069.

Al-Gabbiesh, A., M. Kleinwächter and D. Selmar, 2015: Influencing the contents of secondary metabolites in spice and medicinal plants by deliberately applying drought stress during their cultivation. *Jordan J. Biol. Sci.*, **8**(1), 1-10, doi:10.12816/0026941.

Al-Kodmany, K., 2018: The vertical farm: A review of developments and implications for the vertical city. *Buildings*, **8**(2), 24, doi:10.3390/buildings8020024.

Alae-Carew, C. et al., 2020: The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: a systematic review. *Environ. Res. Lett.*, **15**(2), 023002, doi:10.1088/1748-9326/ab5cc0.

Alam, A. and P. Dwivedi, 2019: Modeling site suitability and production potential of carinata-based sustainable jet fuel in the southeastern United States. *J. Clean. Prod.*, **239**, 117817-117817, doi:10.1016/J.JCLEPRO.2019.117817.

Alava, J. J., W. W. L. Cheung, P. S. Ross and U. R. Sumaila, 2017: Climate change-contaminant interactions in marine food webs: toward a conceptual framework. *Glob Chang Biol*, **23**(10), 3984-4001, doi:10.1111/gcb.13667.
Alba-Sánchez, F., J. A. López-Sáez, D. Nieto-Lugilde and J.-C. Svenning, 2015: Long-term climate forcings to assess vulnerability in North Africa dry argan woodlands. *Applied vegetation science*, **18**(2), 283-296, doi:10.1111/avsc.12133.
Albert, C., J. H. Spangenberg and B. Schroter, 2017: Nature-based solutions: criteria. *Nature*, **543**(7645), 315, doi:10.1038/543315b.
Albert, M., R. V. Nagel, J. Sutmoller and M. Schmidt, 2018: Quantifying the effect of persistent dryer climates on forest productivity and implications for forest planning: a case study in northern Germany. *For. Ecosyst.*, **5**, 33, doi:10.1186/s40663-018-0152-0.
Albizua, A., E. Corbera and U. Pascual, 2019: Farmers' vulnerability to global change in Navarre, Spain: large-scale irrigation as maladaptation. *Reg. Environ. Change*, **19**(4), 1147-1158, doi:10.1007/s10113-019-01462-2.
Albon, S. D. et al., 2017: Contrasting effects of summer and winter warming on body mass explain population dynamics in a food-limited Arctic herbivore. *Glob Chang Biol*, **23**(4), 1374-1389, doi:10.1111/gcb.13435.
Albrich, K., W. Rammer and R. Seidl, 2020: Climate change causes critical transitions and irreversible alterations of mountain forests. *Glob Chang Biol*, **26**(7), 4013-4027, doi:10.1111/gcb.15118.
Albrich, K., W. Rammer, D. Thom and R. Seidl, 2018: Trade-offs between temporal stability and level of forest ecosystem services provisioning under climate change. *Ecol. Appl.*, **28**(7), 1884-1896, doi:10.1002/eap.1785.
Alcon, F. et al., 2020: Valuing diversification benefits through intercropping in Mediterranean agroecosystems: A choice experiment approach. *Ecol. Econ.*, **171**, 106593-106593, doi:10.1016/j.ecolecon.2020.106593.
Alday, J. G. et al., 2017: Record breaking mushroom yields in Spain. *Fungal Ecology*, **26**, 144-146, doi:10.1016/j.funeco.2017.01.004.
Alexander, P. et al., 2017: Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Glob. Food Secur.*, **15**, 22-32, doi:10.1016/j.gfs.2017.04.001.
Alexander, P. et al., 2015: Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. *Glob. Environ. Change*, **35**, 138-147, doi:10.1016/j.gloenvcha.2015.08.011.
Algert, S. J. et al., 2016: Vegetable output, cost savings, and nutritional value of low-income families' home gardens in San Jose, CA. *Journal of Hunger & Environmental Nutrition*, **11**(3), 328-336, doi:10.1080/19320248.2015.1128866.
Algur, K. D., S. K. Patel and S. Chauhan, 2021: The impact of drought on the health and livelihoods of women and children in India: A systematic review. *Children and Youth Services Review*, **122**(C), S0190740920323318.
Ali, A. and O. Erenstein, 2017: Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Clim. Risk Manag.*, **16**, 183--194, doi:10.1016/j.crm.2016.12.001.
Ali, A. and D. B. Rahut, 2018: Farmers willingness to grow GM food and cash crops: empirical evidence from Pakistan. *Gm Crops & Food-Biotechnology in Agriculture and the Food Chain*, **9**(4), 199-210, doi:10.1080/21645698.2018.1544831.
Alikadic, A. et al., 2019: The impact of climate change on grapevine phenology and the influence of altitude: A regional study. *Agric. For. Meteorol*, **271**, 73-82, doi:10.1016/j.agrformet.2019.02.030.
Allen, M. R., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, and K. Zickfeld. , 2018: Framing and context. In: *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (ed.)].
Alleway, H. K. et al., 2019: The ecosystem services of marine aquaculture: valuing benefits to people and nature. *Bioscience*, **69**(1), 59-68, doi:10.1093/biosci/biy137.
Allison, E. H. and H. R. Bassett, 2015: Climate change in the oceans: Human impacts and responses. *Science*, **350**(6262), 778-782, doi:10.1126/science.aac8721.

ALRahahleh, L. et al., 2018: Effects of CMIP5 projections on volume growth, carbon stock and timber yield in managed Scots pine, Norway spruce and silver birch stands under southern and northern boreal conditions. *Forests*, **9**(4), 208, doi:10.3390/f9040208.
Alshannaq, A. and J. H. Yu, 2017: Occurrence, toxicity, and analysis of major mycotoxins in food. *Int J Environ Res Public Health*, **14**(6), 632, doi:10.3390/ijerph14060632.
Alston, M. and B. Akhter, 2016: Gender and food security in Bangladesh: the impact of climate change. *Gend. Place Cult.*, **23**(10), 1450-1464, doi:10.1080/0966369x.2016.1204997.
Altieri, M. A., C. I. Nicholls, A. Henao and M. A. Lana, 2015: Agroecology and the design of climate change-resilient farming systems. *Agron. Sustain. Dev.*, **35**(3), 869-890, doi:10.1007/s13593-015-0285-2.
Altrichter, M., 2006: Wildlife in the life of local people of the semi-arid Argentine Chaco. *Biodivers. Conserv.*, **15**(8), 2719-2736, doi:10.1007/s10531-005-0307-5.
Amadou, I., M. Soulé and A. Salé, 2020: An overview on the importance of acacia nilotica (L.) willd. ex del.: A review. *Asian J. Res. in agricultur for.*, 12-18, doi:10.9734/ajraf/2020/v5i330085.
Amadu, F. O., D. C. Miller and P. E. McNamara, 2020: Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: evidence from southern Malawi. *Ecol. Econ.*, **167**, 106443, doi:10.1016/j.ecolecon.2019.106443.
Amjath-Babu, T. S. et al., 2016: Climate change and indicators of probable shifts in the consumption portfolios of dryland farmers in Sub-Saharan Africa: implications for policy. *Ecol. Indic.*, **67**, 830-838, doi:10.1016/j.ecolind.2016.03.030.
Amjath-Babu, T. S. et al., 2019: Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. *Appl. Energy*, **239**, 494-503, doi:10.1016/j.apenergy.2019.01.147.
Ammer, C., 2019: Diversity and forest productivity in a changing climate. *New Phytol.*, **221**(1), 50-66, doi:10.1111/nph.15263.
An, R., M. Ji and S. Zhang, 2018: Global warming and obesity: a systematic review. *Obes Rev*, **19**(2), 150-163, doi:10.1111/obr.12624.
Anders, E. J., L. C. Zulu and E. R. Jambo, 2020: Limits to grain-legume technology integration by smallholder farmers: The case of time-sensitive labor demands and food security primacy in Malawi. *Agric. Syst.*, **184**, 102879, doi:10.1016/j.agsy.2020.102879.
Anderson, C. R. et al., 2019a: From Transition to Domains of Transformation: Getting to Sustainable and Just Food Systems through Agroecology. *Sustainability*, **11**(19), 5272-5272, doi:10.3390/su11195272.
Anderson, D., J. D. Ford and R. G. Way, 2018: The impacts of climate and social changes on cloudberry (bakeapple) picking: a case study from southeastern Labrador. *Hum Ecol Interdiscip J*, **46**(6), 849-863, doi:10.1007/s10745-018-0038-3.
Anderson, W., C. Johansen and K. H. M. Siddique, 2016: Addressing the yield gap in rainfed crops: a review. *Agron. Sustain. Dev.*, **36**(1), doi:10.1007/s13593-015-0341-y.
Anderson, W. B. et al., 2019b: Synchronous crop failures and climate-forced production variability. *Sci Adv*, **5**(7), eaaw1976, doi:10.1126/sciadv.aaw1976.
Andersson Djurfeldt, A., A. Kalindi, K. Lindsjö and M. Wamulume, 2019: Yearning to farm – Youth, agricultural intensification and land in Mkushi, Zambia. *J. Rural Stud.*, **71**, 85-93, doi:10.1016/j.jrurstud.2019.08.010.
Andersson, E., E. C. H. Keskitalo and A. Lawrence, 2017: Adaptation to climate change in forestry: a perspective on forest ownership and adaptation responses. *Forests*, **8**(12), 493, doi:10.3390/f8120493.
Andreotti, F. et al., 2018: Exploring management strategies to enhance the provision of ecosystem services in complex smallholder agroforestry systems. *Ecol. Indic.*, **94**, 257-265, doi:10.1016/j.ecolind.2018.06.048.
Angelsen, A. et al., 2014: Environmental income and rural livelihoods: A global-comparative analysis. *World Dev*, **64**(Suppl 1), S12-S28, doi:10.1016/j.worlddev.2014.03.006.
Anisimov, O. et al., 2001: Polar regions (arctic and antarctic). *Climate change*, 801-841.
Ankrah, J., 2018: Climate change impacts and coastal livelihoods; an analysis of fishers of coastal Winneba, Ghana. *Ocean Coast. Manage.*, **161**, 141-146, doi:10.1016/j.ocecoaman.2018.04.029.
Antle, J. M. et al., 2018: Using AgMIP regional integrated assessment methods to evaluate vulnerability, resilience and adaptive capacity for climate smart agricultural systems. In: *Climate Smart*

Agriculture: Building Resilience to Climate Change [Lipper, L., N. McCarthy, D. Zilberman, S. Asfaw and G. Branca (eds.)]. Springer, Cham, Switzerland, pp. 307-333. ISBN 9783319611938.

Antle, J. M. et al., 2017: Design and use of representative agricultural pathways for integrated assessment of climate change in US Pacific Northwest cereal-based systems. *Front. Ecol. Evol.*, **5**, 99, doi:10.3389/fevo.2017.00099.

Antonelli, C. et al., 2020: Climate impacts on nutrition and labor supply disentangled – an analysis for rural areas of Uganda. *Environ. Dev. Econ.*, 1-26, doi:10.1017/s1355770x20000017.

Anttila-Hughes, J., A. Jina and G. McCord, 2021: ENSO Impacts Child Undernutrition in the Global Tropics. *Nat. Commun.*, **in press**.

Antwi-Agyei, P., A. J. Dougill, L. C. Stringer and S. N. A. Codjoe, 2018: Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Clim. Risk Manag.*, **19**, 83-93, doi:10.1016/j.crm.2017.11.003.

Aoki, K. et al., 2019: Exceptional red-tide of fish-killing dinoflagellate Karenia mikimotoi promoted by typhoon-induced upwelling. *Estuar. Coast. Shelf Sci.*, **219**, 14-23, doi:10.1016/j.ecss.2019.01.014.

Apablaza, P. et al., 2017: Primary isolation and characterization of Tenacibaculum maritimum from Chilean Atlantic salmon mortalities associated with a Pseudochattonella spp. algal bloom. *J. Aquat. Anim. Health*, **29**(3), 143-149, doi:10.1080/08997659.2017.1339643.

Applequist, W. L. et al., 2020: Scientists' warning on climate change and medicinal plants. *Planta Medica*, **86**(1), 10-18, doi:10.1055/a-1041-3406.

Apuri, I., K. Peprah and G. T. W. Achana, 2018: Climate change adaptation through agroforestry: the case of Kassena Nankana West District, Ghana. *Environ. Dev.*, **28**, 32-41, doi:10.1016/j.envdev.2018.09.002.

Aquilue, N. et al., 2020: Evaluating forest resilience to global threats using functional response traits and network properties. *Ecol. Appl.*, **30**(5), e02095, doi:10.1002/eap.2095.

Araújo, S. S. et al., 2015: Abiotic stress responses in legumes: strategies used to cope with environmental challenges. *Crit. Rev. Plant Sci.*, **34**(1-3), 237-280, doi:10.1080/07352689.2014.898450.

Araus, J. L. and S. C. Kefauver, 2018: Breeding to adapt agriculture to climate change: affordable phenotyping solutions. *Curr. Opin. Plant Biol.*, **45**(Pt B), 237-247, doi:10.1016/j.pbi.2018.05.003.

Ardestani, E. G. and Z. Ghahfarrokhi, Heidari, 2021: Ensembpecies distribution modeling of Salvia hydrangea under future climate change scenarios in Central Zagros Mountains, Iran. *Glob. Ecol. Conserv.*, **26**, e01488, doi:10.1016/j.gecco.2021.e01488.

Arenas-Sanchez, A. et al., 2019: Effects of increased temperature, drought, and an insecticide on freshwater zooplankton communities. *Environ. Toxicol. Chem.*, **38**(2), 396-411, doi:10.1002/etc.4304.

Arezki, R., K. Deininger and H. Selod, 2015: What drives the global "land rush"? *World Bank Economic Review*, **29**(2), 207-233, doi:10.1093/wber/lht034.

Aristizábal ‐ Marulanda, V. and C. A. Cardona Alzate, 2019: Methods for designing and assessing biorefineries: Review. *Biofuels, Bioproducts and Biorefining*, **13**(3), 789-808, doi:10.1002/bbb.1961.

Ariti, A. T., J. van Vliet and P. H. Verburg, 2018: Farmers' participation in the development of land use policies for the Central Rift Valley of Ethiopia. *Land Use Policy*, **71**, 129-137, doi:10.1016/J.LANDUSEPOL.2017.11.051.

Arneth, A. et al., 2019: Framing and context. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change (IPCC), pp. 1-98.

Arora-Jonsson, S., 2011: Virtue and vulnerability: Discourses on women, gender and climate change. *Glob. Environ. Change*, **21**(2), 744-751, doi:10.1016/j.gloenvcha.2011.01.005.

Arslan, A. et al., 2015: Climate smart agriculture? Assessing the adaptation implications in Zambia. *J. Agric. Econ.*, **66**(3), 753-780, doi:10.1111/1477-9552.12107.

Artmann, M. and K. Sartison, 2018: The role of urban agriculture as a nature-based solution: a review for developing a systemic assessment framework. *Sustainability*, **10**(6), 1937, doi:10.3390/su10061937.

Asase, A. and A. T. Peterson, 2019: Predicted impacts of global climate change on the geographic distribution of an invaluable African medicinal plant resource, Alstonia boonei De Wild. *J. Appl. Res. Med. Aromat. Plants*, **14**, 100206, doi:10.1016/j.jarmap.2019.100206.

Asbjornsen, H. et al., 2014: Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renew. Agric. Food Syst.*, **29**(2), 101-125, doi:10.1017/S1742170512000385.

Asche, F. et al., 2015: Fair enough? Food security and the international trade of seafood. *World Dev.*, **67**, 151-160.

Ashley, L., M. Zhumanova, A. Isaeva and C. Dear, 2016: Examining changes in local adaptive capacity resulting from climate change adaptation programming in rural Kyrgyzstan. *Clim. Dev.*, **8**(3), 281-287, doi:10.1080/17565529.2015.1034230.
Asiedu, B., F. K. E. Nunoo and S. Iddrisu, 2017: Prospects and sustainability of aquaculture development in Ghana, West Africa. *Cogent Food Agric.*, **3**(1), 1349531, doi:10.1080/23311932.2017.1349531.
Asiyanbi, A. P., 2016: A political ecology of REDD plus : property rights, militarised protectionism, and carbonised exclusion in Cross River. *Geoforum*, **77**, 146-156, doi:10.1016/j.geoforum.2016.10.016.
Assan, E., M. Suvedi, L. S. Olabisi and A. Allen, 2018: Coping with and adapting to climate change: a gender perspective from smallholder farming in Ghana. *Environments*, **5**(8), 86, doi:10.3390/environments5080086.
Asseng, S. et al., 2015: Rising temperatures reduce global wheat production. *Nat. Clim. Change*, **5**(2), 143-147.
Asseng, S. et al., 2013: Uncertainty in simulating wheat yields under climate change. *Nat. Clim. Change*, **3**(9), 827-832, doi:10.1038/Nclimate1916.
Asseng, S. et al., 2019: Climate change impact and adaptation for wheat protein. *Glob Chang Biol*, **25**(1), 155-173, doi:10.1111/gcb.14481.
Atindana, S. A. et al., 2020: Coping with climate variability and non-climate stressors in the West African Oyster (Crassostrea tulipa) fishery in coastal Ghana. *Marit. Stud.*, **19**(1), 81-92, doi:10.1007/s40152-019-00132-7.
Atlin, G. N., J. E. Cairns and B. Das, 2017: Rapid breeding and varietal replacement are critical to adaptation of cropping systems in the developing world to climate change. *Glob Food Sec*, **12**, 31-37, doi:10.1016/j.gfs.2017.01.008.
Attridge, S. and L. Engen, 2019: *Blended finance in the poorest countries: The need for a better approach*. Overseas Development Institute, London. Available at: https://cdn.odi.org/media/documents/12666.pdf.
Atukunda, P. et al., 2021: Unlocking the potential for achievement of the UN Sustainable Development Goal 2 – 'Zero Hunger' – in Africa: targets, strategies, synergies and challenges. *Food & Nutrition Research*, **65**, doi:10.29219/fnr.v65.7686.
Atuoye, K. N., I. Luginaah, H. Hambati and G. Campbell, 2021: Who are the losers? Gendered-migration, climate change, and the impact of large scale land acquisitions on food security in coastal Tanzania. *Land Use Policy*, **101**(August 2020), 105154-105154, doi:10.1016/j.landusepol.2020.105154.
Aubry-Kientz, M. et al., 2019: Temperature rising would slow down tropical forest dynamic in the Guiana Shield. *Sci Rep*, **9**(1), 10235, doi:10.1038/s41598-019-46597-8.
Augustine, D. J. et al., 2018: Elevated CO2 induces substantial and persistent declines in forage quality irrespective of warming in mixedgrass prairie. *Ecol. Appl.*, **28**(3), 721-735, doi:10.1002/eap.1680.
Avelino, J. et al., 2015: The coffee rust crises in Colombia and Central America (2008-2013): impacts, plausible causes and proposed solutions. *Food Secur.*, **7**(2), 303-321, doi:10.1007/s12571-015-0446-9.
Avery, S. V., I. Singleton, N. Magan and G. H. Goldman, 2019: The fungal threat to global food security. *Fungal Biol*, **123**(8), 555-557, doi:10.1016/j.funbio.2019.03.006.
Aveytua-Alcazar, L., D. M. Canu, V. F. Camacho-Ibar and C. Solidoro, 2020: Changes in upwelling regimes in a Mediterranean-type lagoon: a model application. *Ecol. Model.*, **418**, 108908, doi:10.1016/j.ecolmodel.2019.108908.
Avila-Forcada, S., A. L. Martinez-Cruz, R. Rodriguez-Ramirez and E. Sanjurjo-Rivera, 2020: Transitioning to alternative livelihoods: the case of PACE-Vaquita. *Ocean Coast. Manage.*, **183**, 104984, doi:10.1016/j.ocecoaman.2019.104984.
Avnery, S., D. L. Mauzerall and A. M. Fiore, 2013: Increasing global agricultural production by reducing ozone damages via methane emission controls and ozone-resistant cultivar selection. *Glob Chang Biol*, **19**(4), 1285-1299, doi:10.1111/gcb.12118.
Avtar, R., K. Tsusaka and S. Herath, 2019: REDD+ implementation in community-based muyong forest management in Ifugao, Philippines. *Land*, **8**(11), 164, doi:10.3390/land8110164.
Awazi, N. P., M. N. Tchamba and T. M. Avana, 2019: Climate change resiliency choices of small-scale farmers in Cameroon: determinants and policy implications. *J Environ Manage*, **250**, 109560, doi:10.1016/j.jenvman.2019.109560.
Awoye, O. H. R., F. Pollinger, E. K. Agbossou and H. Paeth, 2017: Dynamical-statistical projections of the climate change impact on agricultural production in Benin by means of a cross-validated linear

model combined with Bayesian statistics. *Agric. For. Meteorol*, **234**, 80-94, doi:10.1016/j.agrformet.2016.12.010.

Ayala, L. M. et al., 2016: Impact of agricultural expansion on water footprint in the Amazon under climate change scenarios. *Sci. Total Environ.*, **569**, 1159-1173, doi:10.1016/j.scitotenv.2016.06.191.

Ayers, A. L., J. N. Kittinger and M. B. Vaughan, 2018: Whose right to manage? Distribution of property rights affects equity and power dynamics in comanagement. *Ecol. Soc.*, **23**(2), 37, doi:10.5751/es-10124-230237.

Azadi, H., F. Taube and F. Taheri, 2018: Co-existence of GM, conventional and organic crops in developing countries: main debates and concerns. *Crit Rev Food Sci Nutr*, **58**(16), 2677-2688, doi:10.1080/10408398.2017.1322553.

Büntgen, U. et al., 2012: Drought-induced decline in Mediterranean truffle harvest. *Nat. Clim. Change*, **2**(12), 827-829, doi:10.1038/nclimate1733.

Büntgen, U. et al., 2019: Black truffle winter production depends on Mediterranean summer precipitation. *Environ. Res. Lett.*, **14**(7), 074004, doi:10.1088/1748-9326/ab1880.

Baarsch, F. et al., 2015: Impacts of Low Aggregate INDCs Ambition: Research commissioned by Oxfam. Climate Analytics.

Baca, M. et al., 2014: An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in Mesoamerica. *PLoS One*, **9**(2), e88463, doi:10.1371/journal.pone.0088463.

Bacon, C. M. et al., 2014: Explaining the 'hungry farmer paradox': Smallholders and fair trade cooperatives navigate seasonality and change in Nicaragua's corn and coffee markets. *Glob. Environ. Change*, **25**, 133-149, doi:10.1016/j.gloenvcha.2014.02.005.

Bacon, C. M., W. A. Sundstrom, I. T. Stewart and D. Beezer, 2017: Vulnerability to cumulative hazards: coping with the coffee leaf rust outbreak, drought, and food insecurity in Nicaragua. *World Dev.*, **93**, 136-152, doi:10.1016/j.worlddev.2016.12.025.

Bacon, C. M. et al., 2021: Towards smallholder food and water security: Climate variability in the context of multiple livelihood hazards in Nicaragua. *World Dev.*, **143**, 105468-105468, doi:10.1016/j.worlddev.2021.105468.

Bacon, L. and D. Krpan, 2018: (Not) eating for the environment: the impact of restaurant menu design on vegetarian food choice. *Appetite*, **125**, 190-200, doi:10.1016/j.appet.2018.02.006.

Badami, M. G. and N. Ramankutty, 2015: Urban agriculture and food security: a critique based on an assessment of urban land constraints. *Global Food Security-Agriculture Policy Economics and Environment*, **4**, 8-15, doi:10.1016/j.gfs.2014.10.003.

Bahadur, A. et al., 2015: *The 3As: tracking resilience across BRACED*. London, UK, 57-57 pp. Available at: https://cdn.odi.org/media/documents/9812.pdf.

Bahta, Y. T., A. Jordaan and F. Muyambo, 2016: Communal farmers' perception of drought in South Africa: policy implication for drought risk reduction. *Int. J. Disaster Risk Reduct.*, **20**, 39-50, doi:10.1016/j.ijdrr.2016.10.007.

Bai, Y. et al., 2019: Does climate adaptation of vulnerable households to extreme events benefit livestock production? *J. Clean. Prod.*, **210**, 358-365, doi:10.1016/j.jclepro.2018.10.250.

Baines, J., 2017: Accumulating through food crisis? Farmers, commodity traders and the distributional politics of financialization. *Rev. Int. Political Econ.*, **24**(3), 497-537, doi:10.1080/09692290.2017.1304434.

Baker-Austin, C., J. Trinanes, N. Gonzalez-Escalona and J. Martinez-Urtaza, 2017: Non-cholera vibrios: the microbial barometer of climate change. *Trends Microbiol.*, **25**(1), 76-84, doi:10.1016/j.tim.2016.09.008.

Baker, R. E. and J. Anttila-Hughes, 2020: Characterizing the contribution of high temperatures to child undernourishment in Sub-Saharan Africa. *Sci. Rep.*, **10**(1), 18796-18796, doi:10.1038/s41598-020-74942-9.

Baldos, U. L. C. and T. W. Hertel, 2015: The role of international trade in managing food security risks from climate change. *Food Secur.*, **7**(2), 275-290, doi:10.1007/s12571-015-0435-z.

Balehegn, M., 2015: Unintended Consequences: The Ecological Repercussions of Land Grabbing in Sub-Saharan Africa. *Environment: Science and Policy for Sustainable Development*, **57**(2), 4-21, doi:10.1080/00139157.2015.1001687.

Balehegn, M., S. Balehey, C. Fu and W. Liang, 2019: Indigenous weather and climate forecasting knowledge among Afar pastoralists of north eastern Ethiopia: role in adaptation to weather and climate variability. *Pastoralism*, **9**, 8, doi:10.1186/s13570-019-0143-y.

Balehey, S., G. Tesfay and M. Balehegn, 2018: Traditional gender inequalities limit pastoral women's opportunities for adaptation to climate change: evidence from the Afar pastoralists of Ethiopia. *Pastoralism*, **8**, 23, doi:10.1186/s13570-018-0129-1.
Ballew, C., A. R. Tzilkowski, K. Hamrick and E. D. Nobmann, 2006: The contribution of subsistence foods to the total diet of Alaska natives in 13 rural communities. *Ecol. Food Nutr.*, **45**(1), 1-26, doi:10.1080/03670240500408302.
Balmford, A. et al., 2018: The environmental costs and benefits of high-yield farming. *Nat Sustain*, **1**(9), 477-485, doi:10.1038/s41893-018-0138-5.
Bandin, I. and S. Souto, 2020: Betanodavirus and VER disease: a 30-year research review. *Pathogens*, **9**(2), doi:10.3390/pathogens9020106.
Bandyopadhyay, R. et al., 2016: Biological control of aflatoxins in Africa: current status and potential challenges in the face of climate change. *World Mycotoxin J.*, **9**(5), 771-789, doi:10.3920/wmj2016.2130.
Banerjee, S. et al., 2019: Agricultural intensification reduces microbial network complexity and the abundance of keystone taxa in roots. *ISME J*, **13**(7), 1722-1736, doi:10.1038/s41396-019-0383-2.
Bannister, W. et al., 2019: Potential anthropogenic regime shifts in three freshwater lakes in Tropical East Asia. *Freshw. Biol.*, **64**(4), 708-722, doi:10.1111/fwb.13256.
Baptiste, A. K. and H. Devonish, 2019: The Manifestation of Climate Injustices: The Post-Hurricane Irma Conflicts Surrounding Barbuda's Communal Land Tenure. *J. Extreme Events*, **06**(01), 1940002, doi:10.1142/S2345737619400025.
Barange, M., 2019: Avoiding misinterpretation of climate change projections of fish catches. *ICES J. Mar. Sci.*, **76**(6), 1390-1392, doi:10.1093/icesjms/fsz061.
Barange, M. and K. Cochrane, 2018: Impacts of climate change on fisheries and aquaculture: conclusions. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 611-628. ISBN 9789251306079.
Barange, M. et al., 2014: Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nat. Clim. Change*, **4**(3), 211-216, doi:10.1038/Nclimate2119.
Barbarossa, V. et al., 2021: Threats of global warming to the world's freshwater fishes. *Nat. Commun.*, **12**(1), 1-10.
Barbato, M. et al., 2020: Adaptive introgression from indicine cattle into white cattle breeds from Central Italy. *Sci. Rep.*, **10**(1), 1-11, doi:10.1038/s41598-020-57880-4.
Barber, I., B. W. Berkhout and Z. Ismail, 2016: Thermal change and the dynamics of multi-host parasite life cycles in aquatic ecosystems. *Integr. Comp. Biol.*, **56**(4), 561-572, doi:10.1093/icb/icw025.
Barber, Q. E. et al., 2018: Potential impacts of climate change on the habitat of boreal woodland caribou. *Ecosphere*, **9**(10), e02472, doi:10.1002/ecs2.2472.
Barbier, B. et al., 2009: Human vulnerability to climate variability in the Sahel: farmers' adaptation strategies in northern Burkina Faso. *Environ Manage*, **43**(5), 790-803, doi:10.1007/s00267-008-9237-9.
Barbieri, P., S. Pellerin, V. Seufert and T. Nesme, 2019: Changes in crop rotations would impact food production in an organically farmed world. *Nat. Sustain.*, **2**(5), 378-385, doi:10.1038/s41893-019-0259-5.
Barbosa, V. et al., 2019: Paralytic shellfish toxins and ocean warming: bioaccumulation and ecotoxicological responses in juvenile gilthead seabream (Sparus aurata). *Toxins*, **11**(7), 408, doi:10.3390/toxins11070408.
Barik, B. et al., 2016: Water-food-energy nexus: changing scenarios in India during recent decades. *Hydrology and Earth System Sciences Discussions*, **21**, 3041-3060, doi:10.5194/hess-2016-647.
Barlow, K. et al., 2015: Simulating the impact of extreme heat and frost events on wheat crop production: A review. *Field Crops Res.*, **171**, 109-119.
Barnuud, N. N., A. Zerihun, M. Gibberd and B. Bates, 2014: Berry composition and climate: responses and empirical models. *Int J Biometeorol*, **58**(6), 1207-1223, doi:10.1007/s00484-013-0715-2.
Barral, M. P., J. M. Rey Benayas, P. Meli and N. O. Maceira, 2015: Quantifying the impacts of ecological restoration on biodiversity and ecosystem services in agroecosystems: a global meta-analysis. *Agriculture, Ecosystems & Environment*, **202**, 223-231, doi:10.1016/j.agee.2015.01.009.
Barrios, E. et al., 2020: The 10 Elements of Agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. *Ecosystems and People*, **16**(1), 230-247, doi:10.1080/26395916.2020.1808705.

Bartomeus, I. et al., 2011: Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proc Natl Acad Sci U S A*, **108**(51), 20645-20649, doi:10.1073/pnas.1115559108.
Barton, A. et al., 2015: Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography*, **28**(2), 146-159, doi:10.5670/oceanog.2015.38.
Basche, A. D. and M. S. DeLonge, 2019: Comparing infiltration rates in soils managed with conventional and alternative farming methods: a meta-analysis. *PLoS One*, **14**(9), e0215702-e0215702, doi:10.1371/journal.pone.0215702.
Bassett, T. J. and M. Koné, 2017: Peanuts for cashews? Agricultural diversification and the limits of adaptability in Côte d'Ivoire. In: *Other Geographies:The Influences of Michael Watts* [Chari, S., S. Friedberg, V. Gidwani, J. Ribot and W. Wolford (eds.)]. Wiley Blackwell, Hoboken, NJ, USA and Chichester, United Kingdom, pp. 79-96. ISBN 9781119184775.
Basso, B. et al., 2018: Soil organic carbon and nitrogen feedbacks on crop yields under climate change. *Agric. Environ. Lett.*, **3**(1), 180026, doi:10.2134/ael2018.05.0026.
Battilani, P., 2016: Recent advances in modeling the risk of mycotoxin contamination in crops. *Curr. Opin. Food Sci.*, **11**, 10-15, doi:10.1016/j.cofs.2016.08.009.
Battilani, P. and P. a. Toscano, 2016: Aflatoxin B1 contamination in maize in Europe increases due to climate change. *Sci. Rep.*, **6**(1), 24328, doi:10.1038/srep24328.
Baudron, A. R. et al., 2020: Changing fish distributions challenge the effective management of European fisheries. *Ecography*, **43**(4), 494-505.
Bava, L. et al., 2019: Rearing of Hermetia illucens on different organic by-products: influence on growth, waste reduction, and environmental impact. *Animals*, **9**(6), 289, doi:10.3390/ani9060289.
Bayrak, M. M. and L. M. Marafa, 2016: Ten years of REDD plus : a critical review of the impact of REDD plus on forest-dependent communities. *Sustainability*, **8**(7), 620, doi:10.3390/su8070620.
Beach, R. H. et al., 2015: Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environ. Res. Lett.*, **10**(9), 095004, doi:10.1088/1748-9326/10/9/095004.
Beach, R. H. et al., 2019: Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. *The Lancet Planetary Health*, **3**(7), e307--e317, doi:10.1016/s2542-5196(19)30094-4.
Beal, T. et al., 2017: Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PLoS One*, **12**(4), e0175554, doi:10.1371/journal.pone.0175554.
Beaumier, M. C. and J. D. Ford, 2010: Food insecurity among Inuit women exacerbated by socio-economic stresses and climate change. *Can. J. Public Health*, **101**(3), 196-201, doi:10.1007/Bf03404373.
Bebber, D. P., 2015: Range-expanding pests and pathogens in a warming world. *Annu. Rev. Phytopathol.*, **53**(1), 335-356, doi:10.1146/annurev-phyto-080614-120207.
Bebber, D. P., A. D. Castillo and S. J. Gurr, 2016: Modelling coffee leaf rust risk in Colombia with climate reanalysis data. *Philos Trans R Soc Lond B Biol Sci*, **371**(1709), 20150458, doi:10.1098/rstb.2015.0458.
Bebber, D. P., M. A. T. Ramotowski and S. J. Gurr, 2013: Crop pests and pathogens move polewards in a warming world. *Nat. Clim. Change*, **3**(11), 985-988, doi:10.1038/Nclimate1990.
Beckford, C. L. and K. Rhiney, 2016: Future of food and agriculture in the Caribbean in the context of climate change and globalization: where do we go from here? In: *Globalization, Agriculture and Food in the Caribbean: Climate Change, Gender, and Geography* [Beckford, C. L. a. R., K (ed.)]. Palgrave Macmillian, London, United Kingdom, pp. 267-295. ISBN 9781137538376.
Beckmann, M. et al., 2019: Conventional land-use intensification reduces species richness and increases production: A global meta-analysis. *Glob Chang Biol*, **25**(6), 1941-1956, doi:10.1111/gcb.14606.
Behringer, D. C., C. L. Wood, M. Krkosek and D. Bushek, 2020: Disease in fisheries and aquaculture. *Mar. Dis. Ecol.*, 183-209, doi:10.1093/oso/9780198821632.003.0010.
Beillouin, D., T. Ben-Ari and D. Makowski, 2019a: A dataset of meta-analyses on crop diversification at the global scale. *Data Br.*, **24**, 103898, doi:10.1016/j.dib.2019.103898.
Beillouin, D., T. Ben-Ari and D. Makowski, 2019b: Evidence map of crop diversification strategies at the global scale. *Environ. Res. Lett.*, **14**(12), 123001-123001, doi:10.1088/1748-9326/ab4449.
Bélanger, J. and D. Pilling (eds.), 2019: *The State of the World's Biodiversity for Food and Agriculture*, FAO Commission on Genetic Resources for Food and Agriculture Assessments, Rome.
Belay, A., J. W. Recha, T. Woldeamanuel and J. F. Morton, 2017: Smallholder farmers' adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. *Agric. Food Secur.*, **6**(1), doi:10.1186/s40066-017-0100-1.

Belesova, K. et al., 2019: Drought exposure as a risk factor for child undernutrition in low- and middle-income countries: A systematic review and assessment of empirical evidence. *Environ. Int.*, **131**, 104973-104973, doi:10.1016/j.envint.2019.104973.
Belhabib, D. et al., 2020: Catching industrial fishing incursions into inshore waters of Africa from space. *Fish Fish.*, **21**(2), 379-392, doi:10.1111/faf.12436.
Belhabib, D., V. W. Y. Lam and W. W. L. Cheung, 2016: Overview of West African fisheries under climate change: impacts, vulnerabilities and adaptive responses of the artisanal and industrial sectors. *Mar. Policy*, **71**, 15-28, doi:10.1016/j.marpol.2016.05.009.
Belhabib, D., U. R. Sumaila and P. Le Billon, 2019: The fisheries of Africa: exploitation, policy, and maritime security trends. *Mar. Policy*, **101**, 80-92, doi:10.1016/j.marpol.2018.12.021.
Belhabib, D., U. R. Sumaila and D. Pauly, 2015: Feeding the poor: contribution of West African fisheries to employment and food security. *Ocean Coast. Manage.*, **111**, 72-81, doi:10.1016/j.ocecoaman.2015.04.010.
Bell, D., L. Molloy, J. Prpic and M. Tomko, 2019: A new World Heritage site for Aboriginal engineering. *Nature*, **572**, 32, doi:10.1038/d41586-019-02315-y.
Bell, J. D. et al., 2018a: Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 305-324. ISBN 9789251306079.
Bell, L. W., A. D. Moore and J. A. Kirkegaard, 2014: Evolution in crop-livestock integration systems that improve farm productivity and environmental performance in Australia. *Eur J Agron*, **57**, 10-20, doi:10.1016/j.eja.2013.04.007.
Bell, P. et al., 2018b: A Practical Guide to Climate-Smart Agriculture Technologies in Africa, Wageningen.
Bell, R. J., J. Odell, G. Kirchner and S. Lomonico, 2020: Actions to promote and achieve climate-ready fisheries: summary of current practice. *Mar. Coast. Fish.*, **12**(3), 166-190, doi:10.1002/mcf2.10112.
Bellon, M. R., G. D. Ntandou-Bouzitou and F. Caracciolo, 2016: On-farm diversity and market participation are positively associated with dietary diversity of rural mothers in Southern Benin, West Africa. *PLoS One*, **11**(9), e0162535, doi:10.1371/journal.pone.0162535.
Bellon, S. and G. Ollivier, 2018: Institutionalizing agroecology in France: social circulation changes the meaning of an idea. *Sustainability*, **10**(5), 1380, doi:10.3390/su10051380.
Belote, R. T., J. F. Weltzin and R. J. Norby, 2004: Response of an understory plant community to elevated [CO2] depends on differential responses of dominant invasive species and is mediated by soil water availability. *New Phytol.*, **161**(3), 827-835, doi:10.1111/j.1469-8137.2004.00977.x.
Belton, B. et al., 2020: Farming fish in the sea will not nourish the world. *Nat. Commun.*, **11**(1), 5804, doi:10.1038/s41467-020-19679-9.
Béné, C. et al., 2016: Contribution of fisheries and aquaculture to food security and poverty reduction: assessing the current evidence. *World Dev.*, **79**, 177-196, doi:10.1016/j.worlddev.2015.11.007.
Bene, C. et al., 2015: Feeding 9 billion by 2050 - putting fish back on the menu. *Food Secur.*, **7**(2), 261-274, doi:10.1007/s12571-015-0427-z.
Bene, C. et al., 2019: Global map and indicators of food system sustainability. *Sci Data*, **6**(1), 279, doi:10.1038/s41597-019-0301-5.
Bengtsson, J. et al., 2019: Grasslands-more important for ecosystem services than you might think. *Ecosphere*, **10**(2), e02582-e02582, doi:10.1002/ecs2.2582.
Benito-Garzón, M. and J. F. Fernández-Manjarrés, 2015: Testing scenarios for assisted migration of forest trees in Europe. *New Forests*, **46**(5-6), 979-994, doi:10.1007/s11056-015-9481-9.
Benjamin, E. O., O. Ola and G. Buchenrieder, 2018: Does an agroforestry scheme with payment for ecosystem services (PES) economically empower women in sub-Saharan Africa? *Ecosyst. Serv.*, **31**, 1-11, doi:10.1016/j.ecoser.2018.03.004.
Bennett, E. L. et al., 2007: Hunting for consensus: reconciling bushmeat harvest, conservation, and development policy in West and Central Africa. *Conserv. Biol.*, **21**(3), 884-887, doi:10.1111/j.1523-1739.2006.00595.x.
Bennett, N. J., P. Dearden, G. Murray and A. Kadfak, 2014: The capacity to adapt?: communities in a changing climate, environment, and economy on the northern Andaman coast of Thailand. *Ecol. Soc.*, **19**(2), 5, doi:10.5751/es-06315-190205.

Bennett, N. J., A. Kadfak and P. Dearden, 2016: Community-based scenario planning: a process for vulnerability analysis and adaptation planning to social-ecological change in coastal communities. *Environment Development and Sustainability*, **18**(6), 1771-1799, doi:10.1007/s10668-015-9707-1.
Benton, T. G. et al., 2018: Designing sustainable landuse in a 1.5 degrees C world: the complexities of projecting multiple ecosystem services from land. *Curr. Opin. Environ. Sustain.*, **31**, 88-95, doi:10.1016/j.cosust.2018.01.011.
Berhe, M. et al., 2017: The effects of adaptation to climate change on income of households in rural Ethiopia. *Pastoralism*, **7**(1), doi:10.1186/s13570-017-0084-2.
Berkes, F., J. Colding and C. Folke (eds.), 2003: *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*, Cambridge University Press, Cambridge, United Kingdom. ISBN 9780521815924.
Berner, J. et al., 2016: Adaptation in Arctic circumpolar communities: food and water security in a changing climate. *Int J Circumpolar Health*, **75**(1), 33820, doi:10.3402/ijch.v75.33820.
Berner, S. et al., 2019: Roadmapping to enhance local food supply: case study of a city-region in Austria. *Sustainability*, **11**(14), 3876, doi:10.3390/su11143876.
Berners-Lee, M., C. Kennelly, R. Watson and C. N. Hewitt, 2018: Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. *Elementa: Sci. Anthropocene*, **6**(1), 52, doi:10.1525/elementa.310.
Bernues, A., T. Rodriguez-Ortega, R. Ripoll-Bosch and F. Alfnes, 2014: Socio-cultural and economic valuation of ecosystem services provided by Mediterranean mountain agroecosystems. *PLoS One*, **9**(7), e102479, doi:10.1371/journal.pone.0102479.
Berrang-Ford, L. et al., 2021a: The Global Adaptation Mapping Initiative (GAMI): Part 1 – Introduction and overview of methods. *protocolexchange*, doi:10.21203/rs.3.pex-1240/v1.
Berrang-Ford, L. et al., 2021b: A systematic global stocktake of evidence on human adaptation to climate change. *Nat. Clim. Change*,(in press).
Bett, B. et al., 2017: Effects of climate change on the occurrence and distribution of livestock diseases. *Prev Vet Med*, **137**(Pt B), 119-129, doi:10.1016/j.prevetmed.2016.11.019.
Bettini, G., S. L. Nash and G. Gioli, 2017: One step forward, two steps back? The fading contours of (in)justice in competing discourses on climate migration. *Geogr. J.*, **183**(4), 348-358, doi:10.1111/geoj.12192.
Beveridge, L., S. Whitfield and A. Challinor, 2018a: Crop modelling: towards locally relevant and climate-informed adaptation. *Clim. Change*, **147**(3-4), 475-489, doi:10.1007/s10584-018-2160-z.
Beveridge, M. C. M. et al., 2018b: Climate change and aquaculture: interactions with fisheries and agriculture. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 491-516. ISBN 9789251306079.
Beyene, T., D. Endalamaw, Y. Tolossa and A. Feyisa, 2015: Evaluation of rational use of veterinary drugs especially antimicrobials and anthelmintics in Bishoftu, Central Ethiopia. *BMC Research Notes*, **8**, 482, doi:10.1186/s13104-015-1466-4.
Bezner Kerr, R., 2014: Lost and Found Crops: Agrobiodiversity, Indigenous Knowledge, and a Feminist Political Ecology of Sorghum and Finger Millet in Northern Malawi. *Annals of the Association of American Geographers*, **104**(3), 577-593.
Bezner Kerr, R. et al., 2019: Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agriculture, Ecosystems & Environment*, **279**, 109-121, doi:10.1016/j.agee.2019.04.004.
Bezner Kerr, R. et al., 2021: Can agroecology improve food security and nutrition? A review. *Glob. Food Secur.*, **29**, 100540-100540, doi:10.1016/j.gfs.2021.100540.
Bharucha, Z. and J. Pretty, 2010: The roles and values of wild foods in agricultural systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**(1554), 2913-2926.
Bharucha, Z. P., S. B. Mitjans and J. Pretty, 2020: Towards redesign at scale through zero budget natural farming in Andhra Pradesh, India*. *Int. J. Agric. Sustain.*, **18**(1), 1-20, doi:10.1080/14735903.2019.1694465.
Bhatt, I. D., S. Rawat, A. Badhani and R. S. Rawal, 2017: Nutraceutical potential of selected wild edible fruits of the Indian Himalayan region. *Food Chem.*, **215**, 84-91, doi:10.1016/j.foodchem.2016.07.143.

Bianchi, F. et al., 2018: Restructuring physical micro-environments to reduce the demand for meat: a systematic review and qualitative comparative analysis. *Lancet Planet Health*, **2**(9), e384-e397, doi:10.1016/S2542-5196(18)30188-8.
Biasi, R., E. Brunori, C. Ferrara and L. Salvati, 2019: Assessing impacts of climate change on phenology and quality traits of Vitis vinifera L.: the contribution of local knowledge. *Plants*, **8**(5), 121, doi:10.3390/plants8050121.
Biasutti, M., 2019: Rainfall trends in the African Sahel: Characteristics, processes, and causes. *Wiley Interdiscip Rev Clim Change*, **10**(4), e591, doi:10.1002/wcc.591.
Bichet, A. and A. Diedhiou, 2018: West African Sahel has become wetter during the last 30 years, but dry spells are shorter and more frequent. *Clim. Res.*, **75**(2), 155-162, doi:10.3354/cr01515.
Biewener, C., 2016: Paid work, unpaid work, and economic viability in alternative food initiatives: reflections from three Boston urban agriculture endeavors. *J. Agric. Food Syst. Community Dev.*, 1-19, doi:10.5304/jafscd.2016.062.019.
Bigler, C., M. Amacker, C. Ingabire and E. Birachi, 2017: Rwanda's gendered agricultural transformation: A mixed-method study on the rural labour market, wage gap and care penalty. *Womens Stud. Int. Forum*, **64**, 17-27, doi:10.1016/j.wsif.2017.08.004.
Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Crysosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. VMasson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. 447-587.
Birthal, P. S. and J. Hazrana, 2019: Crop diversification and resilience of agriculture to climatic shocks: evidence from India. *Agric. Syst.*, **173**, 345-354, doi:10.1016/j.agsy.2019.03.005.
Bisaga, I., P. Parikh and C. Loggia, 2019: Challenges and opportunities for sustainable urban farming in South African low-income settlements: a case study in Durban. *Sustainability*, **11**(20), 5660, doi:10.3390/su11205660.
Bisbis, M. B., N. Gruda and M. Blanke, 2018: Potential impacts of climate change on vegetable production and product quality - A review. *J. Clean. Prod.*, **170**, 1602-1620, doi:10.1016/j.jclepro.2017.09.224.
Bishop, K. A., A. D. B. Leakey and E. A. Ainsworth, 2014: How seasonal temperature or water inputs affect the relative response of C-3 crops to elevated [CO2]: a global analysis of open top chamber and free air CO2 enrichment studies. *Food Energy Secur.*, **3**(1), 33-45, doi:10.1002/fes3.44.
Bisht, I. S. et al., 2018: Farmers' rights, local food systems, and sustainable household dietary diversification: A case of Uttarakhand Himalaya in north-western India. *Agroecol. Sustain. Food Syst.*, **42**(1), 77-113, doi:10.1080/21683565.2017.1363118.
Bitter, M. C., L. Kapsenberg, J. P. Gattuso and C. A. Pfister, 2019: Standing genetic variation fuels rapid adaptation to ocean acidification. *Nat Commun*, **10**(1), 5821, doi:10.1038/s41467-019-13767-1.
Blanchard, J. L. et al., 2017: Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nat Ecol Evol*, **1**(9), 1240-1249, doi:10.1038/s41559-017-0258-8.
Blanco, J. and S. M. Carriere, 2016: Sharing local ecological knowledge as a human adaptation strategy to arid environments: Evidence from an ethnobotany survey in Morocco. *J. Arid Environ.*, **127**, 30-43, doi:10.1016/j.jaridenv.2015.10.021.
Blaser, W. J. et al., 2018: Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nat. Sustain.*, **1**(5), 234-239, doi:10.1038/s41893-018-0062-8.
Blasiak, R. et al., 2017: Climate change and marine fisheries: Least developed countries top global index of vulnerability. *PLoS One*, **12**(6), e0179632, doi:10.1371/journal.pone.0179632.
Blay-Palmer, A., R. Carey, E. Valette and M. R. Sanderson, 2020: Post COVID 19 and food pathways to sustainable transformation. *Agric Human Values*, **37**(3), 1-3, doi:10.1007/s10460-020-10051-7.
Blay-Palmer, A. et al., 2018: Validating the city region food system approach: enacting inclusive, transformational city region food systems. *Sustainability*, **10**(5), 1680, doi:10.3390/su10051680.
Bleischwitz, R. et al., 2018: Resource nexus perspectives towards the United Nations Sustainable Development Goals. *Nat. Sustain.*, **1**(12), 737-743, doi:10.1038/s41893-018-0173-2.
Blesh, J. et al., 2019: Development pathways toward "zero hunger". *World Dev.*, **118**, 1-14, doi:10.1016/j.worlddev.2019.02.004.
Bloemen, P. et al., 2018: Lessons learned from applying adaptation pathways in flood risk management and challenges for the further development of this approach. *Mitig. Adapt. Strateg. Glob. Change*, **23**(7), 1083-1108, doi:10.1007/s11027-017-9773-9.
Blumenthal, D. M. et al., 2016: Cheatgrass is favored by warming but not CO2 enrichment in a semi-arid grassland. *Global Change Biol.*, **22**(9), 3026-3038, doi:10.1111/gcb.13278.

Blumenthal, D. M. et al., 2013: Invasive forb benefits from water savings by native plants and carbon fertilization under elevated CO2 and warming. *New Phytol.*, **200**(4), 1156-1165, doi:10.1111/nph.12459.
Blundell, R. et al., 2020: Organic management promotes natural pest control through altered plant resistance to insects. *Nat. Plants*, **6**(5), 483-491, doi:10.1038/s41477-020-0656-9.
Boafo, Y. A. et al., 2016: Provisioning ecosystem services-sharing as a coping and adaptation strategy among rural communities in Ghana's semi-arid ecosystem. *Ecosyst. Serv.*, **19**, 92-102, doi:10.1016/j.ecoser.2016.05.002.
Boddicker, R. L. et al., 2014: Gestational Heat Stress Alters Postnatal Offspring Body Composition Indices and Metabolic Parameters in Pigs. *PLoS One*, **9**(11), e110859-e110859, doi:10.1371/journal.pone.0110859.
Bodin, P., S. Olin, T. A. M. Pugh and A. Arneth, 2016: Accounting for interannual variability in agricultural intensification: The potential of crop selection in Sub-Saharan Africa. *Agric. Syst.*, **148**, 159-168, doi:10.1016/j.agsy.2016.07.012.
Bodmer, R. et al., 2018: Major shifts in Amazon wildlife populations from recent intensification of floods and drought. *Conserv. Biol.*, **32**(2), 333-344, doi:10.1111/cobi.12993.
Boedecker, J. et al., 2019: Participatory farm diversification and nutrition education increase dietary diversity in Western Kenya. *Matern Child Nutr*, **15**(3), e12803, doi:10.1111/mcn.12803.
Boedecker, J. et al., 2014: Dietary contribution of wild edible plants to women's diets in the buffer zone around the Lama forest, Benin - an underutilized potential. *Food Secur.*, **6**(6), 833-849, doi:10.1007/s12571-014-0396-7.
Bogdanova, E. et al., 2021: The Impact of Climate Change on the Food (In)security of the Siberian Indigenous Peoples in the Arctic: Environmental and Health Risks. *Sustainability*, **13**(5), doi:10.3390/su13052561.
Bois, B., S. Zito and A. Calonnec, 2017: Climate vs grapevine pests and diseases worldwide : the first results of a global survey. *Oeno One*, **51**(2), 133-139, doi:10.20870/oeno-one.2016.0.0.1780.
Boissière, M. et al., 2013: Local perceptions of climate variability and change in tropical forests of Papua, Indonesia. *Ecol. Soc.*, **18**(4), 13, doi:10.5751/ES-05822-18041.
Bonada, M. et al., 2015: Impact of elevated temperature and water deficit on the chemical and sensory profiles of B arossa S hiraz grapes and wines. *Australian journal of grape and wine research*, **21**(2), 240-253, doi:10.1111/ajgw.12142.
Bonaudo, T. et al., 2014: Agroecological principles for the redesign of integrated crop-livestock systems. *Eur J Agron*, **57**, 43-51, doi:10.1016/j.eja.2013.09.010.
Bond, W. J., N. Stevens, G. F. Midgley and C. E. R. Lehmann, 2019: The trouble with trees: afforestation plans for Africa. *Trends Ecol. Evol.*, **34**(11), 963-965, doi:10.1016/j.tree.2019.08.003.
Bondad-Reantaso, M. G., E. Garrido-Gamarro and S. E. McGladdery, 2018: Climate change-driven hazards on food safety and aquatic animal health. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 517-533. ISBN 9789251306079.
Bondé, L. et al., 2019: Variability and estimating in fruiting of shea tree (Vitellaria paradoxa CF Gaertn) associated to climatic conditions in West Africa: implications for sustainable management and development. *Plant Production Science*, **22**(2), 143-158, doi:10.1080/1343943X.2018.1541712.
Bonebrake, T. C. et al., 2018: Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science. *Biol. Rev. Camb. Philos. Soc.*, **93**(1), 284-305, doi:10.1111/brv.12344.
Bonfante, A. e. a., 2017: Evaluation of the effects of future climate change on grape quality through a physically based model application: a case study for the Aglianico grapevine in Campania region, Italy. *Agric. Syst.*, **152**, 100-109, doi:10.1016/j.agsy.2016.12.009.
Bonny, S., 2017: Corporate concentration and technological change in the global seed industry. *Sustainability*, **9**(9), 1632, doi:10.3390/su9091632.
Boone, R. B. et al., 2018: Climate change impacts on selected global rangeland ecosystem services. *Glob Chang Biol*, **24**(3), 1382-1393, doi:10.1111/gcb.13995.
Booth, S. and D. Zeller, 2005: Mercury, food webs, and marine mammals: implications of diet and climate change for human health. *Environ. Health Perspect.*, **113**(5), 521-526, doi:10.1289/ehp.7603.

Borelli, S., M. Conigliaro, S. Quaglia and F. Salbitano, 2017: Urban and peri-urban agroforestry as multifunctional land use. In: *Agroforestry: Anecdotal to Modern Science* [Dagar, J. C. and V. P. Tewari (eds.)]. Springer Nature Singapore, Singapore, pp. 705-724. ISBN 9789811076497.
Bornemann, F. J. et al., 2019: Future changes and uncertainty in decision-relevant measures of East African climate. *Clim. Change*, **156**(3), 365-384, doi:10.1007/s10584-019-02499-2.
Borquez, R., P. Aldunce and C. Adler, 2017: Resilience to climate change: from theory to practice through co-production of knowledge in Chile. *Sustain. Sci.*, **12**(1), 163-176, doi:10.1007/s11625-016-0400-6.
Borras and J. C. Franco, 2018a: The challenge of locating land-based climate change mitigation and adaptation politics within a social justice perspective : towards an idea of agrarian climate justice. *Third World Q.*, **6597**, 1-18, doi:10.1080/01436597.2018.1460592.
Borras, J. and J. C. Franco, 2018b: Agrarian climate justice: Imperative and opportunity. *Amsterdam: Transnational Institute*.
Borras, S. M., J. C. Franco and Z. Nam, 2020: Climate change and land: Insights from Myanmar. *World Dev.*, **129**, 104864-104864, doi:10.1016/j.worlddev.2019.104864.
Borras, S. M. et al., 2011: Towards a better understanding of global land grabbing: an editorial introduction. *The Journal of Peasant Studies*, **38**(2), 209-216, doi:10.1080/03066150.2011.559005.
Borsatto, R. S., M. A. Altieri, H. C. Duval and J. Perez-Cassarino, 2020: Public procurement as strategy to foster organic transition: insights from the Brazilian experience. *Renew. Agric. Food Syst.*, **35**(6), 688-696, doi:10.1017/S174217051900036X.
Bosch, G. et al., 2019: Conversion of organic resources by black soldier fly larvae: legislation, efficiency and environmental impact. *J. Clean. Prod.*, **222**, 355-363, doi:10.1016/j.jclepro.2019.02.270.
Bosma, R. H. et al., 2017: The financial feasibility of producing fish and vegetables through aquaponics. *Aquac Eng*, **78**, 146-154, doi:10.1016/j.aquaeng.2017.07.002.
Bosomworth, K. and E. Gaillard, 2019: Engaging with uncertainty and ambiguity through participatory 'Adaptive Pathways' approaches: scoping the literature. *Environ. Res. Lett.*, **14**(9), 093007, doi:10.1088/1748-9326/ab3095.
Bosso, L. et al., 2016: Shedding light on the effects of climate change on the potential distribution of Xylella fastidiosa in the Mediterranean basin. *Biol. Invasions*, **18**(6), 1759-1768, doi:10.1007/s10530-016-1118-1.
Botana, L. M., 2016: Toxicological perspective on climate change: aquatic toxins. *Chem. Res. Toxicol.*, **29**(4), 619-625, doi:10.1021/acs.chemrestox.6b00020.
Botana, L. M. and M. J. Sainz (eds.), 2015: *Climate Change and Mycotoxins*, De Gruyter, Berlin, Germany, München, Germany, and Boston, MA, USA, 185 pp. ISBN 9783110333053.
Bottazzi, P., D. Crespo, L. O. Bangura and S. Rist, 2018: Evaluating the livelihood impacts of a large-scale agricultural investment: Lessons from the case of a biofuel production company in northern Sierra Leone. *Land Use Policy*, **73**, 128-137, doi:10.1016/j.landusepol.2017.12.016.
Bottero, A. et al., 2017: Density-dependent vulnerability of forest ecosystems to drought. *J. Appl. Ecol.*, **54**(6), 1605-1614, doi:10.1111/1365-2664.12847.
Bouahmed, A. et al., 2019: Modeling Cedrus atlantica potential distribution in North Africa across time: new putative glacial refugia and future range shifts under climate change. *Reg. Environ. Change*, **19**(6), 1667-1682, doi:10.1007/s10113-019-01503-w.
Boulanger-Lapointe, N. et al., 2019: Berry plants and berry picking in Inuit Nunangat: traditions in a changing socio-ecological landscape. *Hum. Ecol.*, **47**(1), 81-93, doi:10.1007/s10745-018-0044-5.
Boullis, A., C. Detrain, F. Francis and F. J. Verheggen, 2016: Will climate change affect insect pheromonal communication? *Curr Opin Insect Sci*, **17**, 87-91, doi:10.1016/j.cois.2016.08.006.
Bourgault, M. et al., 2017: Yield, growth and grain nitrogen response to elevated CO2 in six lentil (Lens culinaris) cultivars grown under Free Air CO2 Enrichment (FACE) in a semi-arid environment. *Eur J Agron*, **87**, 50-58, doi:10.1016/j.eja.2017.05.003.
Bourgault, M. et al., 2018: Effect of a heat wave on lentil grown under free-air CO2 enrichment (FACE) in a semi-arid environment. *Crop Sci.*, **58**, 803-812, doi:0.2135/cropsci2017.09.0565.
Bourke, M., A. Atkinson and T. Neale, 2020: Putting Country back together: a conversation about collaboration and Aboriginal fire management. *Postcolonial Studies*, **23**(4), 546-551, doi:10.1080/13688790.2020.1751909.
Bouroncle, C. et al., 2017: Mapping climate change adaptive capacity and vulnerability of smallholder agricultural livelihoods in Central America: ranking and descriptive approaches to support adaptation strategies. *Clim. Change*, **141**(1), 123-137, doi:10.1007/s10584-016-1792-0.

Bouroncle, C. et al., 2019: A systematic approach to assess climate information products applied to agriculture and food security in Guatemala and Colombia. *Clim. Serv.*, **16**, 100137, doi:A10.1016/j.cliser.2019.100137.

Bowles, T. M. et al., 2020: Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth*, **2**(3), 284-293, doi:10.1016/j.oneear.2020.02.007.

Boyd, E., M. Gutierrez and M. Y. Chang, 2007: Small-scale forest carbon projects: adapting CDM to low-income communities. *Glob. Environ. Change*, **17**(2), 250-259, doi:10.1016/j.gloenvcha.2006.10.001.

Bozzola, M. and M. Smale, 2020: The welfare effects of crop biodiversity as an adaptation to climate shocks in Kenya. *World Dev.*, **135**, 105065, doi:10.1016/j.worlddev.2020.105065.

Bradai, L., S. Bissati, H. Chenchouni and K. Amrani, 2015: Effects of climate on the productivity of desert truffles beneath hyper-arid conditions. *Int J Biometeorol*, **59**(7), 907-915, doi:10.1007/s00484-014-0891-8.

Bradley, B. A., D. M. Blumenthal, D. S. Wilcove and L. H. Ziska, 2010: Predicting plant invasions in an era of global change. *Trends Ecol. Evol.*, **25**(5), 310-318, doi:10.1016/j.tree.2009.12.003.

Bradley, B. A., C. A. Curtis and J. C. Chambers, 2016: Bromus response to climate and projected changes with climate change. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications* [Germino, M. J., J. C. Chambers and C. S. Brown (eds.)]. Springer, Cham, Switzerland, pp. 257-274. ISBN 9783319249285.

Bradshaw, C. J. et al., 2016: Massive yet grossly underestimated global costs of invasive insects. *Nat Commun*, **7**, 12986, doi:10.1038/ncomms12986.

Braga, H. O. et al., 2020: The role of local ecological knowledge for the conservation and sustainable fisheries of the sea lamprey (Petromyzon marinus Linnaeus, 1758) in the Iberian Peninsula. *Ocean Coast. Manage.*, **198**, 105345, doi:10.1016/j.ocecoaman.2020.105345.

Branca, F. et al., 2019: Transforming the food system to fight non-communicable diseases. *BMJ*, **364**, l296, doi:10.1136/bmj.l296.

Brancalion, P. H. S. and R. L. Chazdon, 2017: Beyond hectares: four principles to guide reforestation in the context of tropical forest and landscape restoration. *Restor. Ecol.*, **25**(4), 491-496, doi:10.1111/rec.12519.

Brander, K., K. Cochrane, M. Barange and D. Soto, 2018: Climate change implications for fisheries and aquaculture. In: *Climate Change Impacts on Fisheries and Aquaculture* [Phillips, B. F. and M. Pérez-Ramírez (eds.)]. Wiley Blackwell,, Hoboken, NJ, USA and Chichester, United Kingdom, pp. 45-62. ISBN 9781119154044.

Brandt, J. S. et al., 2013: Regime shift on the roof of the world: alpine meadows converting to shrublands in the southern Himalayas. *Biol. Conserv.*, **158**, 116-127, doi:10.1016/j.biocon.2012.07.026.

Brás, T. A., J. Seixas, N. Carvalhais and J. Jägermeyr, 2021: Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environ. Res. Lett.*, **16**, 065012, doi:10.1088/1748-9326/abf004.

Brassard, J. P. and B. Singh, 2008: Impacts of climate change and CO2 increase on agricultural production and adaptation options for Southern Quebec, Canada. *Mitig. Adapt. Strateg. Glob. Change*, **13**(3), 241-265, doi:10.1007/s11027-007-9109-2.

Brecka, A. F. J. et al., 2020: Sustainability of Canada's forestry sector may be compromised by impending climate change. *For. Ecol. Manag.*, **474**, 118352, doi:10.1016/j.foreco.2020.118352.

Brendler, T., J. A. Brinckmann and U. Schippmann, 2018: Sustainable supply, a foundation for natural product development: The case of Indian frankincense (Boswellia serrata Roxb. ex Colebr.). *J. Ethnopharmacol.*, **225**, 279-286, doi:10.1016/j.jep.2018.07.017.

Bresnahan, P. J. et al., 2020: Equipping smart coasts with marine water quality IoT sensors. *Results Eng.*, **5**, doi:10.1016/j.rineng.2019.100087.

Breu, T. et al., 2016: Large-scale land acquisition and its effects on the water balance in investor and host countries. *PLoS One*, **11**(3), 1-18, doi:10.1371/journal.pone.0150901.

Bricknell, I. R. et al., 2021: Resilience of cold water aquaculture: a review of likely scenarios as climate changes in the Gulf of Maine. *Rev. Aquac.*, **13**(1), 460-503, doi:10.1111/raq.12483.

Brinkman, T. J. et al., 2016: Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Clim. Change*, **139**, 413-427, doi:10.1007/s10584-016-1819-6.

Briske, D. D. et al., 2021: Future climate variability will challenge rangeland beef cattle production in the Great Plains. *Rangelands*, **43**(1), 29-36, doi:10.1016/j.rala.2020.11.001.

Brito, B. P. et al., 2017: Review of the global distribution of foot-and-mouth disease virus from 2007 to 2014. *Transbound Emerg Dis*, **64**(2), 316-332, doi:10.1111/tbed.12373.
Britten, G. L., M. Dowd, L. Kanary and B. Worm, 2017: Extended fisheries recovery timelines in a changing environment. *Nat Commun*, **8**, 15325, doi:10.1038/ncomms15325.
Brockington, J. D., I. M. Harris and R. M. Brook, 2016: Beyond the project cycle: a medium-term evaluation of agroforestry adoption and diffusion in a south Indian village. *Agroforestry Systems*, **90**(3), 489-508, doi:10.1007/s10457-015-9872-0.
Brodie, J. F. and H. K. Gibbs, 2009: Bushmeat hunting as climate threat. *Science*, **326**(5951), 364-365, doi:10.1126/science.326_364b.
Brondizio, E. S., J. Settele, S. Diaz and H. T. Ngo (eds.), 2019: *Global Assessment Report on Biodiversity and Ecosystem Services*, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 1148 pp. ISBN 9783947851201.
Brooks, K. et al., 2019: *Climate and Jobs for Rural Young People*. IFAD, 40 pp.
Brottem, L. and B. Brooks, 2018: Crops and livestock under the sun: obstacles to rural livelihood adaptations to hotter 21st century temperatures in eastern Senegal. *Land Degradation & Development*, **29**(1), 118-126, doi:10.1002/ldr.2844.
Brown, C. J. et al., 2016: Ecological and methodological drivers of species' distribution and phenology responses to climate change. *Global Change Biol.*, **22**(4), 1548-1560, doi:10.1111/gcb.13184.
Brozynska, M., A. Furtado and R. J. Henry, 2016: Genomics of crop wild relatives: expanding the gene pool for crop improvement. *Plant Biotechnol. J.*, **14**, 1070-1085, doi:10.1111/pbi.12454.
Brugère, C., J. Aguilar-Manjarrez, M. C. M. Beveridge and D. Soto, 2019: The ecosystem approach to aquaculture 10 years on - a critical review and consideration of its future role in blue growth. *Rev. Aquac.*, **11**(3), 493-514, doi:10.1111/raq.12242.
Brugère, C. and C. De Young, 2015: *Assessing Climate Change Vulnerability in Fisheries and Aquaculture: Available Methodologies and Their Relevance for the Sector*. FAO Fisheries and Aquaculture Technical Paper, Food and Agriculture Organization of the United Nations,, Rome, Italy, 86 pp. ISBN 9789251089460.
Brugere, C. et al., 2020: Can innovation empower? Reflections on introducing tubular nets to women seaweed farmers in Zanzibar. *Gender, Technology and Development*, **24**(1), 89-109, doi:10.1080/09718524.2019.1695307.
Brugnach, M., M. Craps and A. Dewulf, 2017: Including indigenous peoples in climate change mitigation: addressing issues of scale, knowledge and power. *Clim. Change*, **140**(1), 19-32, doi:10.1007/s10584-014-1280-3.
Brun, P. et al., 2020: Large-scale early-wilting response of Central European forests to the 2018 extreme drought. *Glob Chang Biol*, **26**(12), 7021-7035, doi:10.1111/gcb.15360.
Bruna, N., 2019: Land of plenty, land of misery: Synergetic resource grabbing in Mozambique. *Land*, **8**(8), doi:10.3390/land8080113.
Brunette, M., R. Bourke, M. Hanewinkel and R. Yousefpour, 2018: Adaptation to climate change in forestry: a multiple correspondence analysis (MCA). *Forests*, **9**(1), 20, doi:10.3390/f9010020.
Bruyere, B. L. et al., 2018: Paired comparison of visions for the future among young pastoralists and students in Samburu, Kenya. *Pastoralism*, **8**, 21, doi:10.1186/s13570-018-0127-3.
Bryndum-Buchholz, A. et al., 2019: Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. *Glob Chang Biol*, **25**(2), 459-472, doi:10.1111/gcb.14512.
Buchner, B. et al., 2019: *Global Landscape of Climate Finance 2019*. Climate Policy Initiative,, London, United Kingdom, 36 pp. Available at: https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2019/ (accessed 19/07/2021).
Buckley, Y. M. and A. M. Csergo, 2017: Predicting invasion winners and losers under climate change. *Proc Natl Acad Sci U S A*, **114**(16), 4040-4041, doi:10.1073/pnas.1703510114.
Budiman, I., 2019: Climate-smart agriculture policy and (in)justice for smallholders in developing countries. *Future Food: J. Food Agric. Soc.*, **7**(1), 31-41, doi:10.17170/kobra-2018122074.
Bueno, P. B. and D. Soto, 2017: *Adaptation Strategies of the Aquaculture Sector to the Impacts of Climate Change*. FAO Fisheries and Aquaculture Circular, Food and Agriculture Organization of the United Nations,, Rome, Italy, 28 pp. ISBN 9789251096864.
Bugge, M. M., S. Bolwig, T. Hansen and A. N. Tanner, 2019: Theoretical perspectives on innovation for waste valorisation in the bioeconomy. In: *From Waste to Value* [Klitkou, A., A. M. Fevolden and M. Capasso (eds.)]. Routledge, London, pp. 51-70. ISBN 9780429460289.

Bukari, K. N. and E. D. Kuusaana, 2018: Impacts of large-scale land holdings on Fulani pastoralists' in the Agogo Traditional Area of Ghana. *Land Use Policy*, **79**(November 2016), 748-758, doi:10.1016/j.landusepol.2018.09.018.
Bulengela, G. et al., 2020: "Bring fishermen at the center": the value of local knowledge for understanding fisheries resources and climate-related changes in Lake Tanganyika. *Environment Development and Sustainability*, **22**(6), 5621-5649, doi:10.1007/s10668-019-00443-z.
Bunting, S. W., N. Kundu and N. Ahmed, 2017: Evaluating the contribution of diversified shrimp-rice agroecosystems in Bangladesh and West Bengal, India to social-ecological resilience. *Ocean Coast. Manage.*, **148**, 63-74, doi:10.1016/j.ocecoaman.2017.07.010.
Buongiorno, J., 2015: Modeling some long-term implications of CO2 fertilization for global forests and forest industries. *For. Ecosyst.*, **2**, 29, doi:10.1186/s40663-015-0054-3.
Buontempo, C. et al., 2019: Fostering the development of climate services through Copernicus Climate Change Service (C3S) for agriculture applications. *Weather Clim. Extrem.*, **27**, 100226, doi:10.1016/j.wace.2019.100226.
Buras, A., A. Rammig and C. S. Zang, 2020: Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences*, **17**(6), 1655-1672, doi:10.5194/bg-17-1655-2020.
Burchfield, E. K. and A. T. de la Poterie, 2018: Determinants of crop diversification in rice-dominated Sri Lankan agricultural systems. *J. Rural Stud.*, **61**, 206-215, doi:10.1016/j.jrurstud.2018.05.010.
Burden, M. and R. Fujita, 2019: Better fisheries management can help reduce conflict, improve food security, and increase economic productivity in the face of climate change. *Mar. Policy*, **108**, 103610, doi:10.1016/j.marpol.2019.103610.
Burney, J. and V. Ramanathan, 2014: Recent climate and air pollution impacts on Indian agriculture. *Proc Natl Acad Sci U S A*, **111**(46), 16319-16324, doi:10.1073/pnas.1317275111.
Burton, R. J. F., 2019: The potential impact of synthetic animal protein on livestock production: the new "war against agriculture"? *J. Rural Stud.*, **68**, 33-45, doi:10.1016/j.jrurstud.2019.03.002.
Bush, R. and G. Martiniello, 2017: Food riots and protest: agrarian modernizations and structural crises. *World Dev.*, **91**, 193-207, doi:10.1016/j.worlddev.2016.10.017.
Butler, E. E., N. D. Mueller and P. Huybers, 2018: Peculiarly pleasant weather for US maize. *Proc Natl Acad Sci U S A*, **115**(47), 11935-11940, doi:10.1073/pnas.1808035115.
Butler, J. R. A. et al., 2020: Adapting scenarios for climate adaptation: practitioners' perspectives on a popular planning method. *Environ. Sci. Policy*, **104**, 13-19, doi:10.1016/j.envsci.2019.10.014.
Butler, J. R. A., S. Busilacchi and T. Skewes, 2019: How resilient is the Torres Strait Treaty (Australia and Papua New Guinea) to global change? A fisheries governance perspective. *Environ. Sci. Policy*, **91**, 17-26, doi:10.1016/j.envsci.2018.10.005.
Butler, J. R. A. et al., 2016: Priming adaptation pathways through adaptive co-management: design and evaluation for developing countries. *Clim. Risk Manag.*, **12**, 1-16, doi:10.1016/j.crm.2016.01.001.
Buytaert, W., J. Friesen, J. Liebe and R. Ludwig, 2012: Assessment and management of water resources in developing, semi-arid and arid regions. *Water Resour. Manage.*, **26**(4), 841-844, doi:10.1007/s11269-012-9994-3.
Byerly, H. et al., 2018: Nudging pro-environmental behavior: evidence and opportunities. *Front. Ecol. Environ.*, **16**(3), 159-168, doi:10.1002/fee.1777.
Cable, J. et al., 2017: Global change, parasite transmission and disease control: lessons from ecology. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **372**(1719), 20160088, doi:10.1098/rstb.2016.0088.
Cacho, J. F., M. C. Negri, C. R. Zumpf and P. Campbell, 2018: Introducing perennial biomass crops into agricultural landscapes to address water quality challenges and provide other environmental services. *Wiley Interdisciplinary Reviews: Energy and Environment*, **7**(2), e275-e275, doi:10.1002/wene.275.
Cadiz, L. et al., 2018: Moderate hypoxia but not warming conditions at larval stage induces adverse carry-over effects on hypoxia tolerance of European sea bass (Dicentrarchus labrax) juveniles. *Mar. Environ. Res.*, **138**, 28-35.
Cagalanan, D., 2016: Public-private partnerships for improved reforestation outcomes in the Philippines. *World Dev. Perspect.*, **3**, 32-34, doi:10.1016/j.wdp.2016.11.004.
Cai, J. N., H. Huang and P. S. Leung, 2019: *Understanding and measuring the contribution of aquaculture and fisheries to gross domestic product (GDP)*. FAO Fisheries and Aquaculture Technical Paper, vol. No.606, FAO, Rome, Italy. ISBN 978-92-5-131280-3.

Cai, W. et al., 2018: Stabilised frequency of extreme positive Indian Ocean Dipole under 1.5 degrees C warming. *Nat Commun*, **9**(1), 1419, doi:10.1038/s41467-018-03789-6.
Cai, W. J. et al., 2014: Increasing frequency of extreme El Nino events due to greenhouse warming. *Nat. Clim. Change*, **4**(2), 111-116, doi:10.1038/Nclimate2100.
Cai, Y. Y., J. S. Bandara and D. Newth, 2016: A framework for integrated assessment of food production economics in South Asia under climate change. *Environ. Model. Software*, **75**, 459-497, doi:10.1016/j.envsoft.2015.10.024.
Calderón, C. I. e. a., 2018: Agroecology-based farming provides grounds for more resilient livelihoods among smallholders in Western Guatemala. *Agroecol. Sustain. Food Syst.*, **42**, 1128-1169, doi:10.1080/21683565.2018.1489933.
Call, M. and S. Sellers, 2019: How does gendered vulnerability shape the adoption and impact of sustainable livelihood interventions in an era of global climate change? *Environ. Res. Lett.*, **14**(8), doi:10.1088/1748-9326/ab2f57.
Callen, S. T., L. L. Klein and A. J. Miller, 2016: Climatic niche characterization of 13 North American Vitis species. *American Journal of Enology and Viticulture*, **67**(3), 339-349, doi:10.5344/ajev.2016.15110.
Calvet-Mir, L., E. Gomez-Baggethun and V. Reyes-Garcia, 2012: Beyond food production: ecosystem services provided by home gardens. A case study in Vall Fosca, Catalan Pyrenees, Northeastern Spain. *Ecol. Econ.*, **74**, 153-160, doi:10.1016/j.ecolecon.2011.12.011.
Camacho-Henriquez, A. et al., 2015: Decentralized collaborative plant breeding for utilization and conservation of neglected and underutilized crop genetic resources. In: *Advances in Plant Breeding Strategies: Breeding, Biotechnology and Molecular Tools* [Al-Khayri, J. M., S. M. Jain and D. V. Johnson (eds.)]. Springer, Cham, Switzerland, pp. 25-61. ISBN 978-3-319-22520-3.
Camacho, A. and E. Conover, 2019: The impact of receiving SMS price and weather information on small scale farmers in Colombia. *World Dev.*, **123**, 104596, doi:10.1016/j.worlddev.2019.06.020.
Camacho, L. D., D. T. Gevaña, A. P. Carandang and S. C. Camacho, 2016: Indigenous knowledge and practices for the sustainable management of Ifugao forests in Cordillera, Philippines. *International Journal of Biodiversity Science, Ecosystem Services and Management*, **12**, 5-13, doi:10.1080/21513732.2015.1124453.
Campana, S. E. et al., 2020: Arctic freshwater fish productivity and colonization increase with climate warming. *Nat. Clim. Change*, **10**(5), 428-433, doi:10.1038/s41558-020-0744-x.
Campanaro, A. et al., 2019: DNA barcoding to promote social awareness and identity of neglected, underutilized plant species having valuable nutritional properties. *Food Res. Int.*, **115**, 1-9, doi:10.1016/j.foodres.2018.07.031.
Campbell-Arvai, V., J. Arvai and L. Kalof, 2012: Motivating Sustainable Food Choices: The Role of Nudges, Value Orientation, and Information Provision. *Environment and Behavior*, **46**(4), 453-475, doi:10.1177/0013916512469099.
Campbell, B. M. et al., 2017: Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.*, **22**(4), 8, doi:10.5751/Es-09595-220408.
Campbell, B. M. et al., 2018: Urgent action to combat climate change and its impacts (SDG 13): transforming agriculture and food systems. *Curr. Opin. Environ. Sustain.*, **34**, 13-20, doi:10.1016/j.cosust.2018.06.005.
Campbell, B. M. et al., 2016: Reducing risks to food security from climate change. *Global Food Security-Agriculture Policy Economics and Environment*, **11**, 34-43, doi:10.1016/j.gfs.2016.06.002.
Canadell, J. G. et al., 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Canevari-Luzardo, L. M., F. Berkhout and M. Pelling, 2019: A relational view of climate adaptation in the private sector: how do value chain interactions shape business perceptions of climate risk and adaptive behaviours? *Bus. Strategy Environ.*, **29**(2), 432-444, doi:10.1002/bse.2375.
Cao, J. J. et al., 2018a: Can individual land ownership reduce grassland degradation and favor socioeconomic sustainability on the Qinghai-Tibetan Plateau? *Environ. Sci. Policy*, **89**, 192-197, doi:10.1016/j.envsci.2018.08.003.

Cao, R. et al., 2018b: CO2-induced ocean acidification impairs the immune function of the Pacific oyster against Vibrio splendidus challenge: an integrated study from a cellular and proteomic perspective. *Sci. Total Environ.*, **625**, 1574-1583, doi:10.1016/j.scitotenv.2018.01.056.

Cardell, M. F., A. Amengual and R. Romero, 2019: Future effects of climate change on the suitability of wine grape production across Europe. *Reg. Environ. Change*, **19**(8), 2299-2310, doi:10.1007/s10113-019-01502-x.

Carey, J. C. et al., 2016: Temperature response of soil respiration largely unaltered with experimental warming. *Proc Natl Acad Sci U S A*, **113**(48), 13797-13802, doi:10.1073/pnas.1605365113.

Caron, P. et al., 2018: Food systems for sustainable development: proposals for a profound four-part transformation. *Agron Sustain Dev*, **38**(4), 41, doi:10.1007/s13593-018-0519-1.

Carr, E. R. and M. C. Thompson, 2014: Gender and climate change adaptation in agrarian settings: current thinking, new directions, and research frontiers. *Geogr. Compass*, **8**(3), 182-197, doi:10.1111/gec3.12121.

Carrasco, D. et al., 2018: With or without you: Effects of the concurrent range expansion of an herbivore and its natural enemy on native species interactions. *Glob Chang Biol*, **24**(2), 631-643, doi:10.1111/gcb.13836.

Carro-Ripalda, S. and M. Astier, 2014: Silenced voices, vital arguments: smallholder farmers in the Mexican GM maize controversy. *Agric. Hum. Values*, **31**(4), 655-663, doi:10.1007/s10460-014-9533-3.

Carsan, S. et al., 2014: Can agroforestry option values improve the functioning of drivers of agricultural intensification in Africa? *Curr. Opin. Environ. Sustain.*, **6**, 35-40, doi:10.1016/j.cosust.2013.10.007.

Carter, B. et al., 2014: Coral reef, water quality status and community understanding of threats in the eastern gulf of Thailand. *APN Sci. Bull.*,(4), 76-78.

Carter, S. et al., 2017: Large scale land acquisitions and REDD plus : a synthesis of conflicts and opportunities. *Environ. Res. Lett.*, **12**(3), doi:10.1088/1748-9326/aa6056.

Carvalhais, N. et al., 2014: Global covariation of carbon turnover times with climate in terrestrial ecosystems. *Nature*, **514**(7521), 213-217, doi:10.1038/nature13731.

Castagneri, D. et al., 2021: Meta-analysis reveals different competition effects on tree growth resistance and resilience to drought. *Ecosystems*, In press, doi:10.1007/s10021-021-00638-4.

Castañeda-Álvarez, N. P. et al., 2016: Global conservation priorities for crop wild relatives. *Nat. Plants*, **2**(4), 16022, doi:10.1038/nplants.2016.22.

Castellanos-Frías, E., D. G. De León, F. Bastida and J. L. González-Andújar, 2016: Predicting global geographical distribution of Lolium rigidum (rigid ryegrass) under climate change. *J. Agric. Sci.*, **154**(5), 755-764, doi:10.1017/S0021859615000799.

Catacora-Vargas, G. et al., 2017: Brief historical review of agroecology in Bolivia. *Agroecol. Sustain. Food Syst.*, **41**(3-4), 429-447, doi:10.1080/21683565.2017.1290732.

Catalán, I. A. et al., 2019: Critically examining the knowledge base required to mechanistically project climate impacts: a case study of Europe's fish and shellfish. *Fish Fish.*, **20**(3), 501-517, doi:10.1111/faf.12359.

Cavaliere, C., 2009: The effects of climate change on medicinal and aromatic plants. *Herbal Gram*, **81**, 44-57.

Ceccarelli, S. and S. Grando, 2020: Participatory plant breeding: who did it, who does it and where? *Exp. Agric.*, **56**(1), 1-11, doi:10.1017/s0014479719000127.

Celentano, D. et al., 2017: Land Use Policy Towards zero deforestation and forest restoration in the Amazon region of Maranhão state , Brazil. *Land Use Policy*, **68**(July), 692-698, doi:10.1016/j.landusepol.2017.07.041.

Cerato, S., A. R. Davis, D. Coleman and M. Y. L. Wong, 2019: Reversal of competitive dominance between invasive and native freshwater crayfish species under near-future elevated water temperature. *Aquat. Invasions*, **14**(3), 518-530, doi:10.3391/ai.2019.14.3.10.

Cerda, R. et al., 2017: Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. *Eur J Agron*, **82**, 308-319, doi:10.1016/j.eja.2016.09.019.

Chakravorty, U., M. H. Hubert, M. Moreaux and L. Nøstbakken, 2017: Long-Run Impact of Biofuels on Food Prices. *Scand. J. Econ.*, **119**(3), 733-767, doi:10.1111/sjoe.12177.

Challinor, A. et al., 2014: Making the most of climate impacts ensembles. *Nat. Clim. Change*, **4**(2), 77-80, doi:10.1038/nclimate2117.

Challinor, A. J. et al., 2018: Transmission of climate risks across sectors and borders. *Philos Trans A Math Phys Eng Sci*, **376**, 20170301, doi:10.1098/rsta.2017.0301.

Challinor, A. J. et al., 2016: Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nat. Clim. Change*, **6**(10), 954-958, doi:10.1038/Nclimate3061.

Chambault, P. et al., 2018: Sea surface temperature predicts the movements of an Arctic cetacean: the bowhead whale. *Sci Rep*, **8**(1), 9658, doi:10.1038/s41598-018-27966-1.

Chamberlin, J. and J. Sumberg, 2021: Are young people transforming the rural economy?, 92--124, doi:10.1079/9781789245011.0006.

Chan, K. M. A., T. Satterfield and J. Goldstein, 2012: Rethinking ecosystem services to better address and navigate cultural values. *Ecol. Econ.*, **74**, 8-18, doi:10.1016/j.ecolecon.2011.11.011.

Chanamuto, N. J. C. and S. J. G. Hall, 2015: Gender equality, resilience to climate change, and the design of livestock projects for rural livelihoods. *Gender and Development*, **23**(3), 515-530, doi:10.1080/13552074.2015.1096041.

Chanana-Nag, N. and P. K. Aggarwal, 2020: Woman in agriculture, and climate risks: hotspots for development. *Clim. Change*, **158**(1), 13-27, doi:10.1007/s10584-018-2233-z.

Chandra, A., K. E. McNamara and P. Dargusch, 2017: The relevance of political ecology perspectives for smallholder climate-smart agriculture: a review. *J. Political Ecol.*, **24**, 821-842, doi:10.2458/v24i1.20969.

Chandra, A., K. E. McNamara and P. Dargusch, 2018: Climate-smart agriculture: perspectives and framings. *Clim. Policy*, **18**(4), 526-541, doi:10.1080/14693062.2017.1316968.

Chang-Fung-Martel, J. et al., 2017: The impact of extreme climatic events on pasture-based dairy systems: a review. *Crop and Pasture Science*, **68**(12), 1158-1158, doi:10.1071/cp16394.

Chang, J. et al., 2017: Future productivity and phenology changes in European grasslands for different warming levels: Implications for grassland management and carbon balance. *Carbon Balance and Management*, **12**(1), doi:10.1186/s13021-017-0079-8.

Chang, J. D. et al., 2016: Effects of elevated CO2 and temperature on Gynostemma pentaphyllum physiology and bioactive compounds. *J. Plant Physiol.*, **196-197**, 41-52, doi:10.1016/j.jplph.2016.02.020.

Chapagain, D., F. Baarsch, M. Schaeffer and S. D'Haen, 2020: Climate change adaptation costs in developing countries: insights from existing estimates. *Clim. Dev.*, **12**(10), 934-942, doi:10.1080/17565529.2020.1711698.

Chapin, F. S. et al., 2016: Community-empowered adaptation for self-reliance. *Curr. Opin. Environ. Sustain.*, **19**, 67-75, doi:10.1016/j.cosust.2015.12.008.

Chaplin-Kramer, R. et al., 2014: Global malnutrition overlaps with pollinator-dependent micronutrient production. *Proc Biol Sci*, **281**(1794), 20141799, doi:10.1098/rspb.2014.1799.

Chapman, E. J. et al., 2020: Effects of climate change on coastal ecosystem food webs: Implications for aquaculture. *Mar. Environ. Res.*, **162**, 105103, doi:10.1016/j.marenvres.2020.105103.

Chapman, S. et al., 2017: The impact of urbanization and climate change on urban temperatures: a systematic review. *Landsc. Ecol.*, **32**(10), 1921-1935, doi:10.1007/s10980-017-0561-4.

Chatterjee, A., 2019: *Disaster Risk Financing Options for Enhancing Resilience*. Available at: <Go to WoS>://WOS:000448839600017.

Chatuphale, P. and L. Armstrong, 2018: Indian mobile agricultural services using big data and internet of things (IoT). In: *Intelligent Systems Design and Applications. 17th International Conference on Intelligent Systems Design and Applications*, 14-16 December 2017, New Delhi, India, [Abraham, A., P. K. Muhuri, A. K. Muda and N. Gandhi (eds.)], Springer, Cham, Switzerland, **736**, pp. 1028-1037, doi:10.1007/978-3-319-76348-4.

Chaubey, O. P., A. Sharma and G. Krishnamurthy, 2015: Ex-situ conservation of indigenous, threatened and ethno-medicinal diversity of forest species. *Int. J. Biosci. Bio-technology*, **7**(3), 9-22.

Chávez, C., J. Dresdner, Y. Figueroa and M. Quiroga, 2019: Main issues and challenges for sustainable development of salmon farming in Chile: a socio‐economic perspective. *Rev. Aquac.*, **11**(2), 403-421, doi:10.1111/raq.12338.

Chemura, A., D. Kutywayo, P. Chidoko and C. Mahoya, 2016: Bioclimatic modelling of current and projected climatic suitability of coffee (Coffea arabica) production in Zimbabwe. *Reg. Environ. Change*, **16**(2), 473-485, doi:10.1007/s10113-015-0762-9.

Chen, B. W. and N. B. Villoria, 2019: Climate shocks, food price stability and international trade: evidence from 76 maize markets in 27 net-importing countries. *Environ. Res. Lett.*, **14**(1), 014007, doi:10.1088/1748-9326/aaf07f.

Chen, C. et al., 2018a: Exposure to aflatoxin and fumonisin in children at risk for growth impairment in rural Tanzania. *Environ. Int.*, **115**, 29-37, doi:10.1016/j.envint.2018.03.001.

Chen, C., Y. M. Pang, X. B. Pan and L. Z. Zhang, 2015a: Impacts of climate change on cotton yield in China from 1961 to 2010 based on provincial data. *J. Meteorol. Res.*, **29**(3), 515-524, doi:10.1007/s13351-014-4082-7.
Chen, J.-L., 2020: Fishers' perceptions and adaptation on climate change in northeastern Taiwan. *Environment, Development and Sustainability*, **23**(1), 611-634, doi:10.1007/s10668-020-00598-0.
Chen, J. et al., 2020: Soil carbon loss with warming: New evidence from carbon-degrading enzymes. *Glob Chang Biol*, doi:10.1111/gcb.14986.
Chen, J., K. Kosec and V. Mueller, 2019: Moving to despair? Migration and well-being in Pakistan. *World Dev.*, **113**, 186-203, doi:10.1016/j.worlddev.2018.09.007.
Chen, J. and V. Mueller, 2018: Coastal climate change, soil salinity and human migration in Bangladesh. *Nat. Clim. Change*, **8**(11), 981-985, doi:10.1038/s41558-018-0313-8.
Chen, T.-L. and H.-W. Cheng, 2020: Applying traditional knowledge to resilience in coastal rural villages. *Int. J. Disaster Risk Reduct.*, **47**, 101564-101564, doi:10.1016/j.ijdrr.2020.101564.
Chen, Y. S., A. S. Todd, M. H. Murphy and G. Lomnicky, 2016: Anticipated water quality changes in response to climate change and potential consequences for inland fishes. *Fisheries*, **41**(7), 413-416, doi:10.1080/03632415.2016.1182509.
Chen, Y. Z. et al., 2018b: Great uncertainties in modeling grazing impact on carbon sequestration: a multi-model inter-comparison in temperate Eurasian Steppe. *Environ. Res. Lett.*, **13**(7), 075005, doi:10.1088/1748-9326/aacc75.
Chen, Z., H. Shang, J. X. Cao and H. Yu, 2015b: Effects of ambient ozone concentrations on contents of nonstructural carbohydrates in Phoebe bournei and Pinus massoniana seedlings in subtropical China. *Water Air and Soil Pollution*, **226**(9), 310, doi:10.1007/s11270-015-2555-7.
Cheung, W. W. L., B. J and B. M, 2019: Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century. *Impacts of climate change on fisheries and aquaculture*, 63.
Chiarelli, D. D. et al., 2021: Large-scale land acquisition as a potential driver of slope instability. *Land Degrad Dev*, **32**(4), 1773-1785, doi:10.1002/ldr.3826.
Chiarelli, D. D., K. F. Davis, M. C. Rulli and P. D'Odorico, 2016: Climate change and large-scale land acquisitions in Africa: Quantifying the future impact on acquired water resources. *Advances in Water Resources*, **94**, 231-237, doi:10.1016/j.advwatres.2016.05.016.
Chiayarak, B., G. Tattiyakul and N. Kamsunthad, 2019: *Climate Change Vulnerability Assessment Bang Pakong River Wetland, Thailand*. **X**, International Union of Conservation of Nature and Natural Resources,, International Union of Conservation of Nature and Natural Resources Asia Regional Office, Bangkok, Thailand, 73 pp. Available at: https://www.iucn.org/sites/dev/files/climate_change_vulnerability_assessment_bang_pakong_river_wetland_thailand.pdf (accessed 19/07/2021).
Chingala, G. et al., 2017: Determinants of smallholder farmers' perceptions of impact of climate change on beef production in Malawi. *Clim. Change*, **142**(1-2), 129-141, doi:10.1007/s10584-017-1924-1.
Chirwa, P. W., L. Mahamane and G. Kowero, 2017: Forests, people and environment: some African perspectives. *South. For.*, **79**(2), 79-85, doi:10.2989/20702620.2017.1295347.
Chitale, V., R. Silwal and M. Matin, 2018: Assessing the impacts of climate change on distribution of major non-timber forest plants in Chitwan Annapurna Landscape, Nepal. *Resources*, **7**(4), 66, doi:10.3390/resources7040066.
Cho, S. J. and B. A. McCarl, 2017: Climate change influences on crop mix shifts in the United States. *Sci Rep*, **7**, 40845, doi:10.1038/srep40845.
Christen, B. and T. Dalgaard, 2013: Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation. *Biomass Bioenergy*, **55**, 53-67, doi:10.1016/j.biombioe.2012.09.053.
Churkina, G. et al., 2020: Buildings as a global carbon sink. *Nat. Sustain.*, **3**(4), 269-276, doi:10.1038/s41893-019-0462-4.
Chuwah, C. et al., 2015: Global impacts of surface ozone changes on crop yields and land use. *Atmos. Environ.*, **106**, 11-23, doi:10.1016/j.atmosenv.2015.01.062.
Cilas, C. and P. Bastide, 2020: Challenges to Cocoa Production in the Face of Climate Change and the Spread of Pests and Diseases. *Agronomy*, **10**(9), doi:10.3390/agronomy10091232.
Cisneros-Montemayor, A. M., G. Ishimura, G. R. Munro and U. R. Sumaila, 2020: Ecosystem-based management can contribute to cooperation in transboundary fisheries: the case of pacific sardine. *Fish. Res.*, **221**, 105401, doi:10.1016/j.fishres.2019.105401.

Cisneros-Montemayor, A. M., D. Pauly, L. V. Weatherdon and Y. Ota, 2016: A global estimate of seafood consumption by coastal indigenous peoples. *PLoS One*, **11**(12), e0166681, doi:10.1371/journal.pone.0166681.
Claeys, F. et al., 2019: Climate change would lead to a sharp acceleration of Central African forests dynamics by the end of the century. *Environ. Res. Lett.*, **14**(4), doi:10.1088/1748-9326/aafb81.
Claeys, P. and D. Delgado Pugley, 2017: Peasant and indigenous transnational social movements engaging with climate justice. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, **38**(3), 325-340, doi:10.1080/02255189.2016.1235018.
Clapp, J., 2014: Financialization, distance and global food politics. *J. Peasant Stud.*, **41**(5), 797-814, doi:10.1080/03066150.2013.875536.
Clapp, J., 2017: Responsibility to the rescue? Governing private financial investment in global agriculture. *Agric. Hum. Values*, **34**(1), 223-235, doi:10.1007/s10460-015-9678-8.
Clapp, J. and S. R. Isakson, 2018: Risky returns: the implications of financialization in the food system. *Dev. Change*, **49**(2), 437-460, doi:10.1111/dech.12376.
Clark, M. A., M. Springmann, J. Hill and D. Tilman, 2019: Multiple health and environmental impacts of foods. *Proc Natl Acad Sci U S A*, **116**(46), 23357-23362, doi:10.1073/pnas.1906908116.
Clay, L. A., M. A. Papas, K. B. Gill and D. M. Abramson, 2018: Factors associated with continued food insecurity among households recovering from Hurricane Katrina. *Int J Environ Res Public Health*, **15**(8), 1647, doi:10.3390/ijerph15081647.
Clay, N. and B. King, 2019: Smallholders' uneven capacities to adapt to climate change amid Africa's 'green revolution': case study of Rwanda's crop intensification program. *World Dev*, **116**, 1-14, doi:10.1016/j.worlddev.2018.11.022.
Clement, A. et al., 2016: Exceptional summer conditions and HABs of Pseudochattonella in Southern Chile create record impacts on salmon farms. *Harmful Algae News*, **53**, 1-3.
Clinton, N. et al., 2018: A global geospatial ecosystem services estimate of urban agriculture. *Earths Future*, **6**(1), 40-60, doi:10.1002/2017ef000536.
Cobb, J. N. et al., 2019: Enhancing the rate of genetic gain in public-sector plant breeding programs: lessons from the breeder's equation. *Theor. Appl. Genet.*, **132**(3), 627-645, doi:10.1007/s00122-019-03317-0.
Cochrane, K. L. et al., 2019: Tools to enrich vulnerability assessment and adaptation planning for coastal communities in data-poor regions: application to a case study in Madagascar. *Front. Mar. Sci.*, **5**, 505, doi:10.3389/fmars.2018.00505.
Coe, R., F. Sinclair and E. Barrios, 2014: Scaling up agroforestry requires research 'in' rather than 'for' development. *Curr. Opin. Environ. Sustain.*, **6**, 73-77, doi:10.1016/j.cosust.2013.10.013.
Cohen, A. et al., 2018: Combined fish and lettuce cultivation: an aquaponics life cycle assessment. In: *25th CIRP Life Cycle Engineering (LCE) Conference*, 30 April - 2 May 2018, Copenhagen, Denmark, [Laurent, A., A. Leclerc, M. Niero, Y. Dong, S. I. Olsen, M. Owsianiak, N. Bey, M. Ryberg and M. Z. Hauschild (eds.)], Elsevier, **69**, pp. 551-556, doi:10.1016/j.procir.2017.11.029.
Cohen, A. S. et al., 2016: Climate warming reduces fish production and benthic habitat in Lake Tanganyika, one of the most biodiverse freshwater ecosystems. *Proc Natl Acad Sci U S A*, **113**(34), 9563-9568, doi:10.1073/pnas.1603237113.
Cohen, M. J., 2020: Does the COVID-19 outbreak mark the onset of a sustainable consumption transition? *Sustainability: Science, Practice and Policy*, **16**(1), 1-3, doi:10.1080/15487733.2020.1740472.
Cold, H. S. et al., 2020: Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska. *Ecol. Soc.*, **25**(1), 20, doi:10.5751/Es-11426-250120.
Coleman, M. A. et al., 2019: Climate change does not affect the seafood quality of a commonly targeted fish. *Glob Chang Biol*, **25**(2), 699-707, doi:10.1111/gcb.14513.
Colfer, C. J. P. (ed.), 2008: *The Longhouse of the Tarsier: Changing Landscape, Gender, and Well Being in Borneo*, Monograph Series, vol. 10, Borneo Research Council, Phillips, ME, USA, 418 pp. ISBN 9781929900104.
Collier, R. J. and K. G. Gebremedhin, 2015: Thermal biology of domestic animals. *Annu Rev Anim Biosci*, **3**(1), 513-532, doi:10.1146/annurev-animal-022114-110659.
Collins, A., 2018: Saying all the right things? Gendered discourse in climate-smart agriculture. *J. Peasant Stud.*, **45**, 175-191, doi:10.1080/03066150.2017.1377187.
Collste, D. et al., 2019: A cross-scale participatory approach to discuss pathways to the 2030 Agenda SDGs: the example of The World In 2050 African Dialogues. A Methodology paper on the The Three Horizons Framework for the SDGs (3H4SDG). doi:10.31235/osf.io/uhskb.

Colombo, S. M. et al., 2020: Projected declines in global DHA availability for human consumption as a result of global warming. *Ambio*, **49**(4), 865-880, doi:10.1007/s13280-019-01234-6.
Cominassi, L. et al., 2020: Food availability modulates the combined effects of ocean acidification and warming on fish growth. *Sci Rep*, **10**(1), 2338, doi:10.1038/s41598-020-58846-2.
Comte, L. and G. Grenouillet, 2015: Distribution shifts of freshwater fish under a variable climate: comparing climatic, bioclimatic and biotic velocities. *Divers. Distrib.*, **21**(9), 1014-1026.
Comte, L. and J. D. Olden, 2017: Climatic vulnerability of the world's freshwater and marine fishes. *Nat. Clim. Change*, **7**(10), 718-722, doi:10.1038/Nclimate3382.
Conigliani, C., N. Cuffaro and G. D'Agostino, 2018: Large-scale land investments and forests in Africa. *Land Use Policy*, **75**(February 2017), 651-660, doi:10.1016/j.landusepol.2018.02.005.
Conijn, J. G., P. S. Bindraban, J. J. Schröder and R. E. E. Jongschaap, 2018: Can our global food system meet food demand within planetary boundaries? *Agriculture, Ecosystems & Environment*, **251**, 244-256, doi:10.1016/j.agee.2017.06.001.
Conway, D. et al., 2015: Climate and southern Africa's water-energy-food nexus. *Nat. Clim. Change*, **5**(9), 837-846, doi:10.1038/Nclimate2735.
Cook, B. I. and E. M. Wolkovich, 2016: Climate change decouples drought from early wine grape harvests in France. *Nat. Clim. Change*, **6**(7), 715-719, doi:10.1038/Nclimate2960.
Cook, N. J., T. Grillos and K. P. Andersson, 2019: Gender quotas increase the equality and effectiveness of climate policy interventions. *Nat. Clim. Change*, **9**(4), 330-334, doi:10.1038/s41558-019-0438-4.
Cooley, S. R., C. R. Ono, S. Melcer and J. Roberson, 2016: Community-level actions that can address ocean acidification. *Front. Mar. Sci.*, **2**, 128, doi:10.3389/fmars.2015.00128.
Cooley, S. R. et al., 2015: An integrated assessment model for helping the United States sea scallop (Placopecten magellanicus) fishery plan ahead for ocean acidification and warming. *PLoS One*, **10**(5), e0124145, doi:10.1371/journal.pone.0124145.
Cooper, M. W. et al., 2019: Mapping the effects of drought on child stunting. *Proc Natl Acad Sci U S A*, **116**(35), 17219-17224, doi:10.1073/pnas.1905228116.
Cooper, O. R. et al., 2014: Global distribution and trends of tropospheric ozone: an observation-based review. *Elementa: Sci. Anthropocene*, **2**, 000029, doi:10.12952/journal.elementa.000029.
Coq-Huelva, D. et al., 2017: Co-evolution and bio-social construction: the Kichwa agroforestry systems (Chakras) in the Ecuadorian Amazonia. *Sustainability*, **9**(10), 1920, doi:10.3390/su9101920.
Corbeels, M. et al., 2019: The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. *Soil and Tillage Research*, **188**, 16-26, doi:10.1016/j.still.2018.02.015.
Corbeels, M. et al., 2020: Carbon sequestration potential through conservation agriculture in Africa has been largely overestimated comment on: "Meta-analysis on carbon sequestration through conservation agriculture in Africa". *Soil & Tillage Research*, **196**, 104300, doi:10.1016/j.still.2019.104300.
Corbera, E., C. Hunsberger and C. Vaddhanaphuti, 2017: Climate change policies, land grabbing and conflict: perspectives from Southeast Asia. *Can. J. Dev. Stud.*, **38**(3), 297-304, doi:10.1080/02255189.2017.1343413.
Córdova, R., N. J. Hogarth and M. Kanninen, 2019: Mountain Farming Systems' Exposure and Sensitivity to Climate Change and Variability: Agroforestry and Conventional Agriculture Systems Compared in Ecuador's Indigenous Territory of Kayambi People. *Sustainability*, **11**(9), doi:10.3390/su11092623.
Cormier-Salem, M. C. and J. Panfili, 2016: Mangrove reforestation: greening or grabbing coastal zones and deltas? Case studies in Senegal. *Afr. J. Aquat. Sci.*, **41**(1), 89-98, doi:10.2989/16085914.2016.1146122.
Cornwall, W., 2019: In hot water: Five years ago, a marine heat wave began to wash across Pacific ecosystems. Researchers fear it is a preview of the oceans' future. *Science*, **363**(6426), 442-445, doi:10.1126/science.363.6426.442.
Costa, R. et al., 2019: Grapevine phenology of cv. Touriga Franca and Touriga Nacional in the Douro wine region: modelling and climate change projections. *Agronomy*, **9**(4), 210, doi:10.3390/agronomy9040210.
Costella, C. et al., 2017: Scalable and Sustainable: How to Build Anticipatory Capacity into Social Protection Systems. *IDS Bulletin*, **48**(4), doi:10.19088/1968-2017.151.
Costello, C. et al., 2020: The future of food from the sea. *Nature*, **588**(7836), 95-100, doi:10.1038/s41586-020-2616-y.

Costinot, A., D. Donaldson and C. Smith, 2016: Evolving comparative advantage and the impact of climate change in agricultural markets: evidence from 1.7 million fields around the world. *J. Political Econ.*, **124**(1), 205-248, doi:10.1086/684719.
Côte, F.-X. et al., 2019: *The agroecological transition of agricultural systems in the Global South*. éditions Quae. ISBN 9782759230570.
Cottrell, R. S. et al., 2020: Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nat. Food*, **1**(5), 301-308, doi:10.1038/s43016-020-0078-x.
Cottrell, R. S. et al., 2018: Considering land-sea interactions and trade-offs for food and biodiversity. *Glob Chang Biol*, **24**(2), 580-596, doi:10.1111/gcb.13873.
Cottrell, R. S. et al., 2019: Food production shocks across land and sea. *Nat. Sustain.*, **2**(2), 130-137, doi:10.1038/s41893-018-0210-1.
Cotula, L., 2012: The international political economy of the global land rush: a critical appraisal of trends, scale, geography and drivers. *J. Peasant Stud.*, **39**(3-4), 649-680, doi:10.1080/03066150.2012.674940.
Coughlan de Perez, E. et al., 2016: Action-based flood forecasting for triggering humanitarian action. *Hydrol. Earth Syst. Sci.*, **20**(9), 3549-3560, doi:10.5194/hess-20-3549-2016.
Coulibaly, J. Y., B. Chiputwa, T. Nakelse and G. Kundhlande, 2017: Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agric. Syst.*, **155**, 52-69, doi:10.1016/j.agsy.2017.03.017.
Cozzetto, K. et al., 2013: Climate change impacts on the water resources of American Indians and Alaska Natives in the US. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Action* [Maldonado, J. K., B. Colombi and R. Pandya (eds.)]. Springer, Cham, Switzerland, pp. 61-76. ISBN 9783319052656.
Cradock-Henry, N. A. et al., 2020: Climate adaptation pathways for agriculture: Insights from a participatory process. *Environ. Sci. Policy*, **107**, 66-79, doi:10.1016/j.envsci.2020.02.020.
Craparo, A. C. W. et al., 2015: Coffea arabica yields decline in Tanzania due to climate change: Global implications. *Agric. For. Meteorol*, **207**, 1-10, doi:10.1016/j.agrformet.2015.03.005.
Crespo-Perez, V. et al., 2015: Changes in the distribution of multispecies pest assemblages affect levels of crop damage in warming tropical Andes. *Glob Chang Biol*, **21**(1), 82-96, doi:10.1111/gcb.12656.
Cristina Rulli, M. and P. D'Odorico, 2014: Food appropriation through large scale land acquisitions. *Environ. Res. Lett.*, **9**(6), doi:10.1088/1748-9326/9/6/064030.
Cross, J. N. et al., 2019: Building the knowledge-to-action pipeline in North America: connecting ocean acidification research and actionable decision support. *Front. Mar. Sci.*, **6**, 356, doi:10.3389/fmars.2019.00356.
Crous-Duran, J. et al., 2019: Assessing food sustainable intensification potential of agroforestry using a carbon balance method. *iForest - Biogeosciences For.*, **12**(1), 85-91, doi:10.3832/ifor2578-011.
Cubins, J. A. et al., 2019: Management of pennycress as a winter annual cash cover crop. A review. *Agron. Sustain. Dev.*, **39**(5), 1-11, doi:10.1007/S13593-019-0592-0.
Cuccia, C. et al., 2014: Phenological model performance to warmer conditions: application to Pinot noir in Burgundy. *Oeno One*, **48**(3), doi:10.20870/oeno-one.2014.48.3.1572.
Cummings, V. J. et al., 2019: Effect of reduced pH on physiology and shell integrity of juvenile Haliotis iris (paua) from New Zealand. *PeerJ*, **7**(9), e7670, doi:10.7717/peerj.7670.
Cunsolo Willox, A. et al., 2012: "From this place and of this place:" climate change, sense of place, and health in Nunatsiavut, Canada. *Soc. Sci. Med.*, **75**(3), 538-547, doi:10.1016/j.socscimed.2012.03.043.
Curtis, P. G. et al., 2018: Classifying drivers of global forest loss. *Science*, **361**(6407), 1108-1111, doi:10.1126/science.aau3445.
Custódio, M., S. Villasante, R. Calado and A. I. Lillebø, 2020: Valuation of ecosystem services to promote sustainable aquaculture practices. *Rev. Aquac.*, **12**(1), 392-405, doi:10.1111/raq.12324.
D'agata, S. et al., 2020: Multiscale determinants of social adaptive capacity in small-scale fishing communities. *Environ. Sci. Policy*, **108**, 56-66, doi:10.1016/j.envsci.2020.03.006.
D'Annolfo, R., B. Gemmill-Herren, B. Graeub and L. A. Garibaldi, 2017: A review of social and economic performance of agroecology. *Int. J. Agric. Sustain.*, **15**(6), 632-644, doi:10.1080/14735903.2017.1398123.
D'Odorico, P. et al., 2018: The global food-energy-water nexus. *Rev. Geophys.*, **56**(3), 456-531, doi:10.1029/2017rg000591.

D'Odorico, P., M. C. Rulli, J. Dell'Angelo and K. F. Davis, 2017: New frontiers of land and water commodification: socio-environmental controversies of large-scale land acquisitions. *Land Degrad Dev*, **28**(7), 2234-2244, doi:10.1002/ldr.2750.
da Fonseca de Oliveira, A. C. et al., 2019: Impacts on performance of growing-finishing pigs under heat stress conditions: a meta-analysis. *Vet. Res. Commun.*, **43**(1), 37-43, doi:10.1007/s11259-018-9741-1.
Dabbadie, L. et al., 2018: Effects of climate change on aquaculture: drivers, impacts and policies. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 449-463. ISBN 9789251306079.
Daftary-Steel, S., H. Herrera and C. M. Porter, 2015: The unattainable trifecta of urban agriculture. *Journal of Agriculture Food Systems and Community Development*, **6**(1), 19-32, doi:10.5304/jafscd.2015.061.014.
Dainese, M. et al., 2019: A global synthesis reveals biodiversity-mediated benefits for crop production. *Sci Adv*, **5**(10), eaax0121, doi:10.1126/sciadv.aax0121.
Dalberg, A., 2019: *The Digitalisation of African Agriculture Report 2018 - 2019*. The Netherlands.
Daliakopoulos, I. N. et al., 2016: The threat of soil salinity: a European scale review. *Sci. Total Environ.*, **573**, 727-739, doi:10.1016/j.scitotenv.2016.08.177.
Dalin, C., Y. Wada, T. Kastner and M. J. Puma, 2017: Groundwater depletion embedded in international food trade. *Nature*, **543**(7647), 700-704, doi:10.1038/nature21403.
Dalu, T., R. J. Wasserman and M. T. B. Dalu, 2017: Agricultural intensification and drought frequency increases may have landscape-level consequences for ephemeral ecosystems. *Global Change Biol.*, **23**(3), 983-985, doi:10.1111/gcb.13549.
Daron, J. et al., 2021: Integrating seasonal climate forecasts into adaptive social protection in the Sahel. *Clim. Dev.*, **13**(6), 543-550, doi:10.1080/17565529.2020.1825920.
Darrouzet-Nardi, e. a., 2016: Child dietary quality in rural Nepal: effectiveness of a community-led development initiative. *Food Policy*, **61**, 185-197.
Daryanto, S., L. X. Wang and P. A. Jacinthe, 2017: Global synthesis of drought effects on cereal, legume, tuber and root crops production: a review. *Agric. Water Manage.*, **179**, 18-33, doi:10.1016/j.agwat.2016.04.022.
Das, I. et al., 2020: Effects of climate change and management policies on marine fisheries productivity in the north-east coast of India. *Sci. Total Environ.*, **724**, 138082, doi:10.1016/j.scitotenv.2020.138082.
Das, M., V. Jain and S. K. Malhotra, 2016a: Impact of climate change on medicinal and aromatic plants: Review. *Indian J. Agric. Sci.*, **86**(11), 1375-1382.
Das, R. et al., 2016b: Impact of heat stress on health and performance of dairy animals: a review. *Vet World*, **9**(3), 260-268, doi:10.14202/vetworld.2016.260-268.
Dasgupta, P. et al., 2014: Rural Areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 613-657. ISBN 9781107058071.
Datta, S. et al., 2018: Aquaponics: a green and sustainable eco-tech for environmental cum economic benefits through integration of fish and edible crop cultivation. In: *Wastewater Management Through Aquaculture* [Jana, B. B., R. N. Mandal and P. Jayasankar (eds.)]. Springer Nature, Singapore, Singapore, pp. 207-224. ISBN 9789811072475.
Dauber, J. and S. Miyake, 2016: To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. *Energy, Sustainability and Society*, **6**(1), 25-25, doi:10.1186/s13705-016-0089-5.
Daugstad, K., K. Rønningen and B. Skar, 2006: Agriculture as an upholder of cultural heritage? Conceptualizations and value judgements—a Norwegian perspective in international context. *J. Rural Stud.*, **22**(1), 67-81, doi:10.1016/j.jrurstud.2005.06.002.
Dave, D. and W. Routray, 2018: Current scenario of Canadian fishery and corresponding underutilized species and fishery byproducts: a potential source of omega-3 fatty acids. *J. Clean. Prod.*, **180**, 617-641, doi:10.1016/j.jclepro.2018.01.091.

David, A. T., J. E. Asarian and F. K. Lake, 2018: Wildfire Smoke Cools Summer River and Stream Water Temperatures. *Water Resources Research*, **54**(10), 7273-7290, doi:10.1029/2018wr022964.
Davis, H. et al., 2017: The economic potential of fruit trees as shade in blue mountain coffee agroecosystems of the Yallahs River watershed, Jamaica W.I. *Agroforestry Systems*, **93**(2), 581-589, doi:10.1007/s10457-017-0152-z.
Davis, K. F., P. D'Odorico and M. C. Rulli, 2014: Land grabbing: a preliminary quantification of economic impacts on rural livelihoods. *Population and Environment*, **36**(2), 180-192, doi:10.1007/s11111-014-0215-2.
Davis, K. F., S. Downs and J. A. Gephart, 2021: Towards food supply chain resilience to environmental shocks. *Nat. Food*, **2**(1), 54-65, doi:10.1038/s43016-020-00196-3.
Davis, K. F. et al., 2020: Tropical forest loss enhanced by large-scale land acquisitions. *Nat. Geosci.*, **13**(7), 482-488, doi:10.1038/s41561-020-0592-3.
Davis, K. F., M. C. Rulli and P. D'Odorico, 2015a: The global land rush and climate change. *Earth's Future*, **3**(8), 298-311, doi:10.1002/2014EF000281.
Davis, K. F. et al., 2015b: Accelerated deforestation driven by large-scale land acquisitions in Cambodia. *Nat. Geosci.*, **8**(10), 772-+, doi:10.1038/Ngeo2540.
Davis, K. T. et al., 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proc Natl Acad Sci U S A*, **116**(13), 6193-6198, doi:10.1073/pnas.1815107116.
Davis, M., 2001: *Late Victorian Holocausts: El Niño Famines and the Making of the Third World*. Verso, London, United Kingdom, and Brooklyn, NY, USA. ISBN 9781781680612.
Day, E. et al., 2019: Upholding labour productivity under climate change: an assessment of adaptation options. *Clim Policy*, **19**(3), 367-385, doi:10.1080/14693062.2018.1517640.
Dayamba, D. S. et al., 2018: Assessment of the use of participatory integrated climate services for agriculture (PICSA) approach by farmers to manage climate risk in Mali and Senegal. *Clim. Serv.*, **12**, 27-35, doi:10.1016/j.cliser.2018.07.003.
de Albuquerque Nunes, P. A. et al., 2021: Livestock integration into soybean systems improves long-term system stability and profits without compromising crop yields. *Sci. Rep.*, **11**(1), 1649, doi:10.1038/s41598-021-81270-z.
de Amorim, W. S. et al., 2018: The nexus between water, energy, and food in the context of the global risks: an analysis of the interactions between food, water, and energy security. *Environ. Impact Assess. Rev.*, **72**, 1-11, doi:10.1016/j.eiar.2018.05.002.
de Boer, H. J. and C. Cotingting, 2014: Medicinal plants for women's healthcare in southeast Asia: a meta-analysis of their traditional use, chemical constituents, and pharmacology. *J. Ethnopharmacol.*, **151**(2), 747-767, doi:10.1016/j.jep.2013.11.030.
de Boer, I. J. M. and M. K. van Ittersum, 2018: *Circularity in Agricultural Production*. Wageningen University and Research,, 74 pp. Available at: https://library.wur.nl/WebQuery/wurpubs/fulltext/470625 (accessed 20/07/2021).
de Bruyn, J. et al., 2018: Does village chicken-keeping contribute to young children's diets and growth? A longitudinal observational study in rural Tanzania. *Nutrients*, **10**(11), 1799, doi:10.3390/nu10111799.
de Coninck, H. et al., 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
De Frenne, P. et al., 2013: Microclimate moderates plant responses to macroclimate warming. *Proc Natl Acad Sci U S A*, **110**(46), 18561-18565, doi:10.1073/pnas.1311190110.
de Leeuw, J. et al., 2020: The pastoral farming system: balancing between tradition and transition. In: *Farming Systems and Food Security in Africa: Priorities for Science and Policy under Global Change* [Dixon, J., D. P. Garrity, J.-M. Boffa, T. O. Williams, T. Amede, C. Auricht, R. Lott and G. Mburathi (eds.)]. Routledge, Oxon, United Kingdom, and New York, NY, USA, pp. 318-353. ISBN 9781138963351.

de Lima, C. Z. et al., 2021: Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environ. Res. Lett.*, **16**(4), 044020, doi:10.1088/1748-9326/abeb9f.
de Melo, C. M. R., E. Durland and C. Langdon, 2016: Improvements in desirable traits of the Pacific oyster, Crassostrea gigas, as a result of five generations of selection on the West Coast, USA. *Aquaculture*, **460**, 105-115, doi:10.1016/j.aquaculture.2016.04.017.
de Miguel, Á., A. Y. Hoekstra and E. García-Calvo, 2015: Sustainability of the water footprint of the Spanish pork industry. *Ecol. Indic.*, **57**, 465-474, doi:10.1016/j.ecolind.2015.05.023.
de Sousa, K. et al., 2019: The future of coffee and cocoa agroforestry in a warmer Mesoamerica. *Sci Rep*, **9**(1), 8828, doi:10.1038/s41598-019-45491-7.
de Vries, F. T. et al., 2020: Harnessing rhizosphere microbiomes for drought-resilient crop production. *Science*, **368**(6488), 270-274, doi:10.1126/science.aaz5192.
De Zeeuw, H., R. Van Veenhuizen and M. Dubbeling, 2011: The role of urban agriculture in building resilient cities in developing countries. *J. Agric. Sci.*, **149**(S1), 153-163, doi:10.1017/s0021859610001279.
Deb, J. C., S. Phinn, N. Butt and C. A. McAlpine, 2018: Climate change impacts on tropical forests: identifying risks for tropical Asia. *Journal of Tropical Forest Science*, **30**(2), 182-194, doi:10.26525/jtfs2018.30.2.182194.
DeBano, S. J. et al., 2016: Interactive influences of climate change and agriculture on aquatic habitat in a Pacific Northwestern watershed. *Ecosphere*, **7**(6), e01357, doi:10.1002/ecs2.1357.
Debonne, N., J. van Vliet and P. Verburg, 2019: Future governance options for large-scale land acquisition in Cambodia: Impacts on tree cover and tiger landscapes. *Environ Sci Policy*, **94**(December 2018), 9-19, doi:10.1016/j.envsci.2018.12.031.
Deeb, R. et al., 2018: Impact of climate change on Vibrio vulnificus abundance and exposure risk. *Estuaries Coasts*, **41**(8), 2289-2303, doi:10.1007/s12237-018-0424-5.
Degani, E. et al., 2019: Crop rotations in a climate change scenario: short-term effects of crop diversity on resilience and ecosystem service provision under drought. *Agriculture, Ecosystems & Environment*, **285**, 106625, doi:10.1016/j.agee.2019.106625.
Dégremont, L. et al., 2015a: New insight for the genetic evaluation of resistance to ostreid herpesvirus infection, a worldwide disease, in Crassostrea gigas. *PLoS One*, **10**(6), e0127917, doi:10.1371/journal.pone.0127917.
Dégremont, L., M. Nourry and E. Maurouard, 2015b: Mass selection for survival and resistance to OsHV-1 infection in Crassostrea gigas spat in field conditions: response to selection after four generations. *Aquaculture*, **446**, 111-121, doi:10.1016/j.aquaculture.2015.04.029.
Dehm, J., 2016: Indigenous peoples and REDD+ safeguards: rights as resistance or as disciplinary inclusion in the green economy? *J. Hum. Rights Environ.*, **7**(2), 170-217, doi:10.4337/jhre.2016.02.01.
del Pozo, A. et al., 2019: Climate change impacts and adaptation strategies of agriculture in Mediterranean-climate regions (MCRs). *Sustainability*, **11**(10), 2769-2769, doi:10.3390/su11102769.
Delang, C. O., 2006: Not just minor forest products: the economic rationale for the consumption of wild food plants by subsistence farmers. *Ecol. Econ.*, **59**(1), 64-73, doi:10.1016/j.ecolecon.2005.10.006.
Delcour, I., P. Spanoghe and M. Uyttendaele, 2015: Literature review: impact of climate change on pesticide use. *Food Res. Int.*, **68**, 7-15, doi:10.1016/j.foodres.2014.09.030.
Delesalle, V. A. and S. Blum, 1994: Variation in germination and survival among families of Sagittaria-Latifolia in response to salinity and temperature. *Int. J. Plant Sci.*, **155**(2), 187-195, doi:Doi 10.1086/297158.
Dell'Angelo, J., P. D'Odorico and M. C. Rulli, 2017: Threats to sustainable development posed by land and water grabbing. *Curr. Opin. Environ. Sustain.*, **26-27**(June), 120-128, doi:10.1016/j.cosust.2017.07.007.
Dell'Angelo, J., M. C. Rulli and P. D'Odorico, 2018: The global water grabbing syndrome. *Ecol. Econ.*, **143**, 276-285, doi:10.1016/j.ecolecon.2017.06.033.
Dell’Angelo, J., P. D’Odorico, M. C. Rulli and P. Marchand, 2016: The Tragedy of the Grabbed Commons: Coercion and Dispossession in the Global Land Rush. *World Dev.*, **xx**, doi:10.1016/j.worlddev.2016.11.005.
Dell’Angelo, J. et al., 2021: Commons grabbing and agribusiness : Violence , resistance and social mobilization. *Ecol. Econ.*, **184**, 107004-107004, doi:10.1016/j.ecolecon.2021.107004.
Dellar, M., C. F. E. Topp, G. Banos and E. Wall, 2018: A meta-analysis on the effects of climate change on the yield and quality of European pastures. *Agric. Ecosyst. Environ.*, **265**, 413-420, doi:10.1016/j.agee.2018.06.029.

DeLonge, M. S., A. Miles and L. Carlisle, 2016: Investing in the transition to sustainable agriculture. *Environ. Sci. Policy*, **55**, 266-273, doi:10.1016/j.envsci.2015.09.013.
Delzeit, R., F. Zabel, C. Meyer and T. Václavík, 2017: Addressing future trade-offs between biodiversity and cropland expansion to improve food security. *Reg. Environ. Change*, **17**(5), 1429-1441, doi:10.1007/s10113-016-0927-1.
Demeke, M. et al., 2017: *Linking Farm Diversification to Household Diet Diversification: Evidence from a Sample of Kenyan Ultrapoor Farmers.* ESA Working Paper, Food and Agriculture Organisation of the United Nations,, Rome, Italy, 27 pp. Available at: http://www.fao.org/3/i6852e/i6852e.pdf (accessed 22/07/2021).
Dempewolf, H. et al., 2014: Adapting Agriculture to Climate Change: A Global Initiative to Collect, Conserve, and Use Crop Wild Relatives. *Agroecol. Sustain. Food Syst.*, **38**(4), 369-377, doi:10.1080/21683565.2013.870629.
Denton, F., T.J. Wilbanks, A.C. Abeysinghe, I. Burton, Q. Gao, M.C. Lemos, T. Masui, K.L. O'Brien, and K. Warner, 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.
Department of Environmental Affairs, 2016: *South Africa National Adaptation Strategy (draft)*. Department of Environmental Affairs, Republic of South Africa, 122 pp. Available at: <Go to WoS>://WOS:000423707600003 (accessed 15/06/2021).
Derner, J. et al., 2018: Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. *Clim. Change*, **146**(1-2), 19-32, doi:10.1007/s10584-017-2029-6.
Deryng, D. et al., 2016: Regional disparities in the beneficial effects of rising CO 2 concentrations on crop water productivity. *Nat. Clim. Change*, **6**(8), 786, doi:10.1038/nclimate2995.
Des, M. et al., 2020: How can ocean warming at the NW Iberian Peninsula affect mussel aquaculture? *Sci. Total Environ.*, **709**, 136117, doi:10.1016/j.scitotenv.2019.136117.
Descheemaeker, K. et al., 2018: Effects of climate change and adaptation on the livestock component of mixed farming systems: a modelling study from semi-arid Zimbabwe. *Agric. Syst.*, **159**, 282-295, doi:10.1016/j.agsy.2017.05.004.
Deur, D., A. Dick, K. Recalma-Clutesi and N. J. Turner, 2015: Kwakwaka'wakw "clam gardens". *Hum. Ecol.*, **43**(2), 201-212.
Deutsch, C. A. et al., 2018: Increase in crop losses to insect pests in a warming climate. *Science*, **361**(6405), 916-919, doi:10.1126/science.aat3466.
Dhakal, B. and R. R. Kattel, 2019: Effects of global changes on ecosystems services of multiple natural resources in mountain agricultural landscapes. *Sci. Total Environ.*, **676**, 665-682, doi:10.1016/j.scitotenv.2019.04.276.
Dhyani, A., R. Kadaverugu, B. P. Nautiyal and M. C. Nautiyal, 2021: Predicting the potential distribution of a critically endangered medicinal plant Lilium polyphyllum in Indian Western Himalayan Region. *Reg. Environ. Change*, **21**(2), 30, doi:10.1007/s10113-021-01763-5.
Di Leo, N., F. J. Escobedo and M. Dubbeling, 2016: The role of urban green infrastructure in mitigating land surface temperature in Bobo-Dioulasso, Burkina Faso. *Environment, Development and Sustainability*, **18**(2), 373-392, doi:10.1007/s10668-015-9653-y.
Diacono, M. et al., 2017: Agro-ecology for potential adaptation of horticultural systems to climate change: agronomic and energetic performance evaluation. *Agronomy*, **7**(2), 35, doi:10.3390/agronomy7020035.
Diaz, D. and F. Moore, 2017: Quantifying the economic risks of climate change. *Nat. Clim. Change*, **7**(11), 774-782, doi:10.1038/nclimate3411.
Diekert, F. K. and E. Nieminen, 2017: International fisheries agreements with a shifting stock. *Dyn. Games Appl.*, **7**(2), 185-211, doi:10.1007/s13235-016-0184-4.
Ding, Q., X. J. Chen, R. Hilborn and Y. Chen, 2017: Vulnerability to impacts of climate change on marine fisheries and food security. *Mar. Policy*, **83**, 55-61, doi:10.1016/j.marpol.2017.05.011.
Directorate-General for Research Innovation, 2018: *Sustainable & circular bioeconomy, the European way Outcome report*. Brussels.

DiTomaso, J. M., T. A. Monaco, J. J. James and J. Firn, 2017: Invasive Plant Species and Novel Rangeland Systems. In: *Rangeland Systems: Processes, Management and Challenges* [Briske, D. D. (ed.)]. Springer International Publishing, Cham, pp. 429-465. ISBN 978-3-319-46709-2.
Djoudi, H., M. Brockhaus and B. Locatelli, 2013: Once there was a lake: vulnerability to environmental changes in northern Mali. *Reg. Environ. Change*, **13**(3), 493-508, doi:10.1007/s10113-011-0262-5.
Dobardzic, S. et al., 2019: *2019 State of Climate Services: Agriculture and Food Security*. World Meteorological Organization (WMO), Geneva, Switzerland, 44 pp. ISBN 9789263112422.
Doblas-Reyes, F. J. et al., 2021: Linking Global to Regional Climate Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Chang* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Doddabasawa, B. M. Chittapur and M. M. Murthy, 2018: Traditional agroforestry systems and biodiversity conservation. *Bangladesh Journal of Botany*, **47**(4), 927-935, doi:10.3329/bjb.v47i4.47388.
Doelman, J. C. et al., 2018: Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation. *Glob. Environ. Change*, **48**, 119-135, doi:10.1016/j.gloenvcha.2017.11.014.
Doetterl, S. et al., 2015: Soil carbon storage controlled by interactions between geochemistry and climate. *Nat. Geosci.*, **8**(10), 780-783, doi:10.1038/Ngeo2516.
Doherty, E. et al., 2021: A discrete choice experiment exploring farmer preferences for insurance against extreme weather events. *J. Environ. Manag.*, **290**, 112607, doi:10.1016/j.jenvman.2021.112607.
Doherty, R. M. et al., 2010: Implications of future climate and atmospheric CO2content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biol.*, **16**(2), 617-640, doi:10.1111/j.1365-2486.2009.01997.x.
Donatti, C. I. et al., 2019: Vulnerability of smallholder farmers to climate change in Central America and Mexico: current knowledge and research gaps. *Clim. Dev.*, **11**(3), 264-286, doi:10.1080/17565529.2018.1442796.
Doney, S. C., D. S. Busch, S. R. Cooley and K. J. Kroeker, 2020: The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. *Annual Review of Environment and Resources*, **45**(1), 83-112, doi:10.1146/annurev-environ-012320-083019.
Dong, Z. Q. et al., 2018: A quantitative method for risk assessment of agriculture due to climate change. *Theoretical and Applied Climatology*, **131**(1-2), 653-659, doi:10.1007/s00704-016-1988-2.
Dono, G. et al., 2016: Winners and losers from climate change in agriculture: insights from a case study in the Mediterranean basin. *Agric. Syst.*, **147**, 65-75, doi:10.1016/j.agsy.2016.05.013.
Doody, D. G., C. A. Augustenborg, P. J. A. Withers and S. Crosse, 2015: A systematic map protocol: what evidence exists to link agricultural practices with ecological impacts for Irish waterbodies? *Environ. Evid.*, **4**(1), 14, doi:10.1186/s13750-015-0040-9.
Dop, M. C. et al., 2020: Identification and frequency of consumption of wild edible plants over a year in central Tunisia: a mixed-methods approach. *Public Health Nutr*, **23**(5), 782-794, doi:10.1017/S1368980019003409.
Dotchamou, F. T., G. Atindogbe, A. I. Sode and H. N. Fonton, 2016: Density and spatial distribution of Parkia biglobosa pattern in Benin under climate change. *Journal of Agriculture and Environment for International Development*, **110**, doi:10.12895/jaeid.20161.447.
Douhard, M. et al., 2016: The influence of weather conditions during gestation on life histories in a wild Arctic ungulate. *Proc Biol Sci*, **283**(1841), 20161760, doi:10.1098/rspb.2016.1760.
Dounias, E. and M. Ichikawa, 2017: Seasonal Bushmeat Hunger in the Congo Basin. *EcoHealth*, **14**(3), 575-590, doi:10.1007/s10393-017-1252-y.
Dounias, E., A. Selzner, M. Koizumi and P. Levang, 2007: From sago to rice, from forest to town: the consequences of sedentarization for the nutritional ecology of Punan former hunter-gatherers of Borneo. *Food Nutr Bull*, **28**(2 Suppl), S294-S302, doi:10.1177/15648265070282S208.
Dovie, D. B. K., 2017: A communication framework for climatic risk and enhanced green growth in the eastern coast of Ghana. *Land Use Policy*, **62**, 326-336, doi:10.1016/j.landusepol.2017.01.008.
Dowd-Uribe, B., 2014: Engineering yields and inequality? How institutions and agro-ecology shape Bt cotton outcomes in Burkina Faso. *Geoforum*, **53**, 161-171.
Dowd-Uribe, B. and M. A. Schnurr, 2016: Briefing: Burkina Faso's reversal on genetically modified cotton and the implications for Africa. *African Affairs*, **115**(458), 161-172, doi:10.1093/afraf/adv063.

Downing, A. and A. Cuerrier, 2011: A synthesis of the impacts of climate change on the First Nations and Inuit of Canada. *Indian. J. Tradit. Knowl.*, **10**(1), 57-70.
Doyle, J. T., M. H. Redsteer and M. J. Eggers, 2013: Exploring effects of climate change on Northern Plains American Indian health. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions* [Maldonado, J. K., B. Colombi and R. Pandya (eds.)]. Springer, Cham, Switzerland, Heidelberg , Germany, New York, NY, USA, Dordrecht, The Netherlands, London, United Kingdom, pp. 135-147. ISBN 9783319052656.
Doyle, L., L. Oliver and C. Whitworth, 2018: Design of a climate smart farming system in East Africa. In: *GHTC 2018 IEEE Global Humanitarian Technology Conference*, 18 - 21 October 2018, San Jose, CA, USA, Institute of Electrical and Electronics Engineers Xplore, Piscataway, NJ, USA, pp. 1 - 6, doi:10.1109/GHTC.2018.8601553.
Drag, D. W. et al., 2020: Soybean photosynthetic and biomass responses to carbon dioxide concentrations ranging from pre-industrial to the distant future. *J. Exp. Bot.*, **71**(12), 3690-3700.
Dressler, G. et al., 2019: Polarization in (post)nomadic resource use in Eastern Morocco: insights using a multi-agent simulation model. *Reg. Environ. Change*, **19**(2), 489-500, doi:10.1007/s10113-018-1412-9.
Drewry, J. L. et al., 2019: Assessment of digital technology adoption and access barriers among crop, dairy and livestock producers in Wisconsin. *Comput. Electron. Agric.*, **165**, 104960, doi:10.1016/j.compag.2019.104960.
Du, B. Z., L. Zhen, H. M. Yan and R. de Groot, 2016: Effects of government grassland conservation policy on household livelihoods and dependence on local grasslands: evidence from Inner Mongolia, China. *Sustainability*, **8**(12), 1314, doi:10.3390/su8121314.
Du, Z. et al., 2021: Exploring microbial community structure and metabolic gene clusters during silage fermentation of paper mulberry, a high-protein woody plant. *Anim. Feed Sci. Technol.*, **275**, 114766-114766, doi:10.1016/j.anifeedsci.2020.114766.
Dua, V. K. et al., 2013: Impact of climate change on potato productivity in Punjab - a simulation study. *Curr. Sci.*, **105**(6), 787-794, doi:10.2307/24097516.
Dubbeling, M., 2015: *Integrating Urban Agriculture and Forestry into Climate Change Action Plans: Lessons from Western Province, Sri Lanka and Rosario, Argentina*. Resource Centers on Urban Agriculture & Food Security Foundation,, 18 pp. Available at: https://cdkn.org/wp-content/uploads/2015/02/SriLanka_Argentina_BackgroundPaper_FINAL_WEB.pdf (accessed 22/07/2021).
Dubbeling, M. et al., 2017: Assessing and planning sustainable city region food systems: insights from two Latin American Cities. *Sustainability*, **9**(8), 1455, doi:10.3390/su9081455.
Dubey, S. K. et al., 2017: Farmers' perceptions of climate change, impacts on freshwater aquaculture and adaptation strategies in climatic change hotspots: a case of the Indian Sundarban delta. *Environ. Dev.*, **21**, 38-51, doi:10.1016/j.envdev.2016.12.002.
Dubois, M. J. et al., 2019: Integrating fish into irrigation infrastructure projects in Myanmar: rice-fish what if…? *Marine and Freshwater Research*, **70**(9), 1229-1240, doi:10.1071/MF19182.
Dumas, S. E., L. Kassa, S. L. Young and A. J. Travis, 2018: Examining the association between livestock ownership typologies and child nutrition in the Luangwa Valley, Zambia. *PLoS One*, **13**(2), e0191339, doi:10.1371/journal.pone.0191339.
Dunlap, A. and J. Fairhead, 2014: The Militarisation and Marketisation of Nature: An Alternative Lens to 'Climate-Conflict'. *Geopolitics*, **19**(4), 937-961, doi:10.1080/14650045.2014.964864.
Durland, E., G. Waldbusser and C. Langdon, 2019: Comparison of larval development in domesticated and naturalized stocks of the Pacific oyster Crassostrea gigas exposed to high pCO2 conditions. *Mar. Ecol. Prog. Ser.*, **621**, 107-125, doi:10.3354/meps12983.
Dury, S. et al. (eds.), 2019: *Food Systems at Risk: New Trends and Challenges*, FAO-CIRAD-European Commission, Rome, Italy, Montpellier, France, and Brussels, Belgium, 130 pp. ISBN 9782876147515.
Duveneck, M. J. and R. M. Scheller, 2015: Climate-suitable planting as a strategy for maintaining forest productivity and functional diversity. *Ecol. Appl.*, **25**(6), 1653-1668, doi:10.1890/14-0738.1.
Dyngeland, C., J. A. Oldekop and K. L. Evans, 2020: Assessing multidimensional sustainability: Lessons from Brazil's social protection programs. *Proceedings of the National Academy of Sciences*, **117**(34), 20511--20519, doi:10.1073/pnas.1920998117.
Eastin, J., 2018: Climate change and gender equality in developing states. *World Dev.*, **107**, 289-305, doi:10.1016/j.worlddev.2018.02.021.

EAT-LANCET, 2019: *Healthy Diets from Sustainable Food Systems. Summary Report of the EAT-Lancet Commission.*, Lancet, 32 pp. Available at: https://eatforum.org/content/uploads/2019/01/EAT-Lancet_Commission_Summary_Report.pdf (accessed 22/07/2021).
Ebert, A. W., 2017: Vegetable Production, Diseases, and Climate Change. In: *World Agricultural Resources and Food Security: International Food Security* [Schmitz, A., P. L. Kennedy and T. G. Schmitz (eds.)]. Emerald, Bingley, United Kingdom, pp. 103-124. ISBN 9781787145160.
Ebhuoma, E. and D. Simatele, 2017: Defying the odds: climate variability, asset adaptation and food security nexus in the Delta State of Nigeria. *Int. J. Disaster Risk Reduct.*, **21**, 231-242, doi:10.1016/j.ijdrr.2016.12.017.
Ebhuoma, E. E. et al., 2020: Subsistence farmers' differential vulnerability to drought in Mpumalanga province, South Africa: Under the political ecology spotlight. *Cogent Social Sciences*, **6**(1), 1792155-1792155, doi:10.1080/23311886.2020.1792155.
Ebi, K. L. and I. Loladze, 2019: Elevated atmospheric CO2 concentrations and climate change will affect our food's quality and quantity. *Lancet Planet. Health*, **3**(7), E283-E284, doi:10.1016/S2542-5196(19)30108-1.
Economic Commission for Latin America and the Caribbean and Central American Agricultural Council of the Central American Integration System, 2013: *Impactos Potenciales del Cambio Climático sobre los Granos Básicos en Centroamérica*. Economic Commission for Latin America and the Caribbean,, Mexico City, Mexico, 137 pp. Available at: https://www.cepal.org/es/publicaciones/27171-impactos-potenciales-cambio-climatico-granos-basicos-centroamerica (accessed 17/08/2021).
Economic Commission for Latin America and the Caribbean and C. A. A. C. o. t. C. A. I. System, 2014: *Impactos Potenciales del Cambio Climático sobre el Café en Centroamérica*. Economic Commission for Latin America and the Caribbean,, México City, Mexico, 129 pp. Available at: https://www.cepal.org/es/publicaciones/37456-impactos-potenciales-cambio-climatico-cafe-centroamerica (accessed 17/08/2021).
Edwards, E. J., D. Unwin, R. Kilmister and M. Treeby, 2017: Multi-seasonal effects of warming and elevated CO2 on the physiology, growth and production of mature, field grown, Shiraz grapevines. *Oeno One*, **51**(2), 127-132, doi:10.20870/oeno-one.2016.0.0.1586.
Egli, L. et al., 2018: Winners and losers of national and global efforts to reconcile agricultural intensification and biodiversity conservation. *Glob Chang Biol*, **24**(5), 2212-2228, doi:10.1111/gcb.14076.
Eigenbrod, C. and N. Gruda, 2015: Urban vegetable for food security in cities. A review. *Agron. Sustain. Dev.*, **35**(2), 483-498, doi:10.1007/s13593-014-0273-y.
Ekstrom, J. A. et al., 2015: Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nat. Clim. Change*, **5**(3), 207-214, doi:10.1038/Nclimate2508.
El-Essawy, H., P. Nasr and H. Sewilam, 2019: Aquaponics: a sustainable alternative to conventional agriculture in Egypt - a pilot scale investigation. *Environ Sci Pollut Res Int*, **26**(16), 15872-15883, doi:10.1007/s11356-019-04970-0.
El Yaacoubi, A. et al., 2014: Global warming impact on floral phenology of fruit trees species in Mediterranean region. *Sci. Hortic.*, **180**, 243-253.
Elaswad, A. et al., 2018: Microinjection of CRISPR/Cas9 protein into channel catfish, Ictalurus punctatus, embryos for gene editing. *J Vis Exp*,(131), e56275, doi:10.3791/56275.
Elkin, C., A. Giuggiola, A. Rigling and H. Bugmann, 2015: Short- and long-term efficacy of forest thinning to mitigate drought impacts in mountain forests in the European Alps. *Ecol. Appl.*, **25**(4), 1083-1098, doi:10.1890/14-0690.1.
Elkin, C. et al., 2013: A 2 degrees C warmer world is not safe for ecosystem services in the European Alps. *Glob Chang Biol*, **19**(6), 1827-1840, doi:10.1111/gcb.12156.
Ellis, N. R. and P. Tschakert, 2019: Triple-wins as pathways to transformation? A critical review. *Geoforum*, **103**, 167-170, doi:10.1016/j.geoforum.2018.12.006.
Elmendorf, S. C. et al., 2012: Global assessment of experimental climate warming on tundra vegetation: heterogeneity over space and time. *Ecol. Lett.*, **15**(2), 164-175, doi:10.1111/j.1461-0248.2011.01716.x.
Elmhirst, R., M. Siscawati, B. S. Basnett and D. Ekowati, 2017: Gender and generation in engagements with oil palm in East Kalimantan, Indonesia: insights from feminist political ecology. *J. Peasant Stud.*, **44**(6), 1137-1159, doi:10.1080/03066150.2017.1337002.
Emmerson, M. et al., 2016: How agricultural intensification affects biodiversity and ecosystem services. In: *Large-Scale Ecology: Model Systems to Global Perspectives* [Dumbrell, A. J., R. L. Kordas and G.

Woodward (eds.)]. Academic, London, United Kingdom, Oxford, United Kingdom, San Diego, CA, USA, and Cambridge, MA, USA, pp. 43-97. ISBN 9780081009352.
Engler, C., 2020: Transboundary fisheries, climate change, and the ecosystem approach: taking stock of the international law and policy seascape. *Ecol. Soc.*, **25**(4), doi:10.5751/ES-11988-250443.
Englund, O. et al., 2020: Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. *Global Environ. Change*, **60**, 101990-101990, doi:10.1016/j.gloenvcha.2019.101990.
Ensor, J. E. et al., 2016: Can community-based adaptation increase resilience? *Clim. Dev.*, **10**(2), 134-151, doi:10.1080/17565529.2016.1223595.
Erauskin-Extramiana, M. et al., 2019: Large-scale distribution of tuna species in a warming ocean. *Glob Chang Biol*, **25**(6), 2043-2060, doi:10.1111/gcb.14630.
Eriksen, C. and D. L. Hankins, 2014: The Retention, Revival, and Subjugation of Indigenous Fire Knowledge through Agency Fire Fighting in Eastern Australia and California. *Soc. Nat. Resour.*, **27**(12), 1288-1303, doi:10.1080/08941920.2014.918226.
Eriksen, S. et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Dev.*, **141**, 105383-105383, doi:10.1016/j.worlddev.2020.105383.
Eriksen, S. H., L. K. Cramer, I. Vetrhus and P. Thornton, 2019: Can climate interventions open up space for transformation? Examining the case of climate-smart agriculture (CSA) in Uganda. *Front. Sustain. Food Syst.*, **3**, doi:10.3389/fsufs.2019.00111.
Espeland, E. K., L. Schreeg and L. M. Porensky, 2020: Managing risks related to climate variability in rangeland-based livestock production: what producer driven strategies are shared and prevalent across diverse dryland geographies? *J Environ Manage*, **255**, 109889, doi:10.1016/j.jenvman.2019.109889.
Estevez, P. et al., 2019: Emerging marine biotoxins in seafood from European coasts: incidence and analytical challenges. *Foods*, **8**(5), 149, doi:10.3390/foods8050149.
European Food Safety Authority et al., 2020: Climate change as a driver of emerging risks for food and feed safety, plant, animal health and nutritional quality. *EFSA Support. Publ.*, **17**(6), EN-1881, doi:10.2903/sp.efsa.2020.EN-1881.
European Food Safety Authority Panel on Plant Protection Products and their Residues et al., 2017: Scientific Opinion of the PPR Panel on the follow-up of the findings of the External Scientific Report 'Literature review of epidemiological studies linking exposure to pesticides and health effects'. *EFSA Journal*, **15**(10), e05007, doi:10.2903/j.efsa.2017.5007.
Evaristus, I., 2014: Global change and sustainable mountain tourism: the case of Mount Kenya. In: *Impact of Global Changes on Mountains: Responses and Adaptation* [Grover, V. I., A. Bordorf, J. Breuste, P. Chandra Tiwari and F. Witkowski Frangetto (eds.)]. CRC Press, Boca Raton, FL, USA, pp. 197-217. ISBN 9780429172915.
Eyring, V. et al., 2021: Human Influence on the Climate System. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Eyssartier, C., A. H. Ladio and M. Lozada, 2011: Horticultural and gathering practices complement each other: a case study in a rural population of northwestern Patagonia. *Ecol. Food Nutr.*, **50**(5), 429-451, doi:10.1080/03670244.2011.604587.
Fa, J. E. et al., 2015: Disentangling the relative effects of bushmeat availability on human nutrition in central Africa. *Sci Rep*, **5**, 8168, doi:10.1038/srep08168.
Fabbri, S., S. I. Olsen and M. Owsianiak, 2018: Improving environmental performance of post-harvest supply chains of fruits and vegetables in Europe: potential contribution from ultrasonic humidification. *J. Clean. Prod.*, **182**, 16-26, doi:10.1016/j.jclepro.2018.01.157.
Fader, M. et al., 2013: Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.*, **8**(1), 14046, doi:10.1088/1748-9326/8/1/014046.
Fagundes, C. et al., 2020: Ecological costs of discrimination: racism, red cedar and resilience in farm bill conservation policy in Oklahoma. *Renew. Agric. Food Syst.*, **35**(4), 420--434, doi:10.1017/S1742170519000322.

Fairbairn, M., 2014: 'Like gold with yield': evolving intersections between farmland and finance. *J. Peasant Stud.*, **41**(5), 777-795, doi:10.1080/03066150.2013.873977.
Fairbairn, M., 2020: *Fields of Gold: Financing the Global Land Rush*. Cornell University Press.
Fajinmi, O. O., O. O. Olarewaju and J. Van Staden, 2017: Traditional use of medicinal and aromatic plants in Africa. In: *Medicinal and Aromatic Plants of the World - Africa* [Neffati, M., H. Najjaa and Á. Máthé (eds.)]. Springer Science + Business, Dordrecht , The Netherlands, pp. 61-76.
Falconer, L. et al., 2020a: The importance of calibrating climate change projections to local conditions at aquaculture sites. *Aquaculture*, **514**, 734487, doi:10.1016/j.aquaculture.2019.734487.
Falconer, L. et al., 2020b: Use of geographic information systems for aquaculture and recommendations for development of spatial tools. *Rev. Aquac.*, **12**(2), 664-677, doi:10.1111/raq.12345.
Falkenberg, L. J., C. A. Styan and J. N. Havenhand, 2019: Sperm motility of oysters from distinct populations differs in response to ocean acidification and freshening. *Sci Rep*, **9**(1), 7970, doi:10.1038/s41598-019-44321-0.
FAO, 2013: *The Human Right to Adequate Food in the Global Strategic Framework for Food Security and Nutrition: A Global Consensus*. Rome, 26-26 pp. Available at: http://www.fao.org/3/i3546e/i3546e.pdf.
FAO, 2014: *State of the World's Forests: Enhancing the Socioeconomic Benefits from Forests*. The State of the World, Food and Agriculture Organization of the United Nations,, Rome, Italy, 119 pp. ISBN 978925108269.
FAO, 2015: *Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication*. Food and Agriculture Organization of the United Nations,, Rome, Italy, 18 pp. ISBN 9789251087046.
FAO, 2016: Fisheries and Aquaculture Country Profiles: Ghana (2016). Country Profile Fact Sheets. FAO, Rome.
FAO, 2017: *Adaptation Strategies of the Aquaculture Sector to the Impacts of Climate Change*. FAO Fisheries and Aquaculture Circular, vol. 1142, Food and Agriculture Organization of the United Nations,, Rome, Italy, 28 pp. ISBN 9789251096864.
FAO, 2018a: *The Future of Food and Agriculture – Alternative Pathways to 2050*. Future of Food and Agriculture, vol. 2, Food and Agriculture Organization of the United Nations,, Rome, Italy, 202 pp. ISBN 9789251301586.
FAO, 2018b: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options*. Food and Agriculture Organization of the United Nations,, Rome.
FAO, 2018c: *The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals*. The State of the World, Food and Agriculture Organization of the United Nations,, Rome, Italy, 210 pp. ISBN 9789551305621.
FAO, 2019a: *Climate-smart agriculture and the Sustainable Development Goals:Mapping interlinkages, synergies and trade-offs and guidelines for integrated implementation*. Rome, 1-144 pp. Available at: http://www.fao.org/climate-smart-agriculture/resources/publications/en/.
FAO, 2019b: *FAO Framework for the Urban Food Agenda. Leveraging Sub-National and Local Government Action to Ensure Sustainable Food Systems and Improved Nutrition.*, Food and Agriculture Organization of the United Nations,, Rome, Italy, 41 pp. ISBN 9789251312742.
FAO, 2019c: *Report of the Special Session on Advancing Integrated Agriculture Aquaculture through Agroecology, Montpellier, France, 25 August 2018.* FAO Fisheries and Aquaculture Report **1286**, Rome, 254 pp. Available at: https://agritrop.cirad.fr/594534/1/ID594534.pdf.
FAO, 2019d: *The State of the World's Aquatic Genetic Resources for Food and Agriculture.* FAO Commission on Genetic Resources for Food and Agriculture assessments, FAO, Rome, 251 pp. Available at: http://www.fao.org/3/ca5256en/CA5256EN.pdf.
FAO, 2019e: *The State of the World's Biodiversity for Food and Agriculture* [Bélanger, J. and D. Pilling (eds.)]. FAO Commission on Genetic Resources for Food and Agriculture Assessment,, Rome, Italy, 572 pp. ISBN 9789251312704.
FAO, 2019f: *World Food and Agriculture - Statistical Pocketbook 2019*. Food and Agriculture Organization of the United Nations,, Rome, Italy, 248 pp. ISBN 9 789251318492.
FAO, 2020a: *Climate Change: Unpacking the Burden on Food Safety*. Food Safety and Quality Series, Food and Agriculture Organization of the United States,, Rome, Italy, 154 pp. ISBN 9789251322932.
FAO, 2020b: *Farmers and agribusinesses at risk under COVID-19;What role for blended finance funds?*, FAO, Rome, Italy, 11 pp.

FAO, 2020c: *Fisheries and Aquaculture Statistics: Global aquaculture and fisheries production 1950-2018 (FishstatJ)*. [(online)., F. F. a. A. D. (ed.)]. Available at: www.fao.org/fishery/statistics/software/fishstatj/en.
FAO, 2020d: *The State of World Fisheries and Aquaculture 2020. Sustainability in Action*. The State of the World, Food and Agriculture Organization of the United Nations,, Rome, Italy, 206 pp. ISBN 9789251326923.
FAO, 2021: *The Impact of Disasters and Crises on Agriculture and Food Security*. FAO,, Rome, Italy, 143 pp. ISBN 9789251340714.
FAO et al., 2018: *The State of Food Security and Nutrition in the World 2018. Building Climate Resilience for Food Security and Nutrition*. The State of the World, Food and Agriculture Organization of the United Nations,, Rome, Italy, 181 pp. ISBN 9789251305713.
FAO et al., 2020: *The State of Food Security and Nutrition in the World 2020*. FAO, IFAD, UNICEF, WFP and WHO, Rome, 320-320 pp. ISBN 978-92-5-132901-6.
FAO and ITPS, 2015: *Status of the World's Soil Resources - Main Report*. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils,, Rome, Italy. ISBN 9789251090046.
FAO and WHO, 2016: *Evaluation of certain contaminants in food. Eighty-third report of the Joint FAO/WHO Expert Committee on Food Additives*. WHO Technical Report, World Health Organization and the Food and Agriculture Organization of the United Nations,, Malta, 166 pp. ISBN 9789241210027.
Farady, S. E. and T. E. Bigford, 2019: Fisheries and climate change: legal and management implications. *Fisheries*, **44**(6), 270-275, doi:10.1002/fsh.10263.
Farcy, P. et al., 2019: Toward a European coastal observing network to provide better answers to science and to societal challenges; the JERICO research infrastructure. *Front. Mar. Sci.*, **6**, 529, doi:10.3389/fmars.2019.00529.
Farhat, Y. A. et al., 2021: Altered arsenic availability, uptake, and allocation in rice under elevated temperature. *Sci. Total Environ.*, **763**, 143049-143049, doi:10.1016/j.scitotenv.2020.143049.
Farmery, A. K. et al., 2021: Food for all: designing sustainable and secure future seafood systems. *Rev. Fish Biol. Fish.*, doi:10.1007/s11160-021-09663-x.
Farquhar, S. D. et al., 2018: Socio-economic impacts of the women in aquaculture (WiA) project in Nepal. *Kasetsart J. Soc. Sci.*, **40**(2), 289-295, doi:10.1016/j.kjss.2017.12.014.
Farrell, A. D., K. Rhiney, A. Eitzinger and P. Umaharan, 2018: Climate adaptation in a minor crop species: is the cocoa breeding network prepared for climate change? *Agroecol. Sustain. Food Syst.*, **42**(7), 812-833, doi:10.1080/21683565.2018.1448924.
Faruque, G. et al., 2017: The evolution of aquatic agricultural systems in Southwest Bangladesh in response to salinity and other drivers of change. *Int. J. Agric. Sustain.*, **15**(2), 185-207, doi:10.1080/14735903.2016.1193424.
Favero, A., R. Mendelsohn and B. Sohngen, 2018: Can the global forest sector survive 11° C warming? *Agric. Econ. Res. Rev.*, **47**, 388-413, doi:10.1017/age.2018.15.
Favero, A., R. Mendelsohn, B. Sohngen and B. D. Stocker, 2021: Assessing the long-term interactions of climate change and timber markets on forest land and carbon storage. *Environ. Res. Lett.*, **16**(1), 014051, doi:10.1088/1748-9326/abd589.
Favretto, N. et al., 2020: Delivering Climate-Development Co-Benefits through Multi-Stakeholder Forestry Projects in Madagascar: Opportunities and Challenges. *Land*, **9**(5), 157-157, doi:10.3390/LAND9050157.
Fawcett, D. et al., 2018: Inuit adaptability to changing environmental conditions over an 11-year period in Ulukhaktok, Northwest Territories. *Polar Rec.*, **54**(2), 119-132, doi:10.1017/S003224741800027x.
Faye, P. and J. Ribot, 2017: Causes for adaptation: Access to forests, markets and representation in Eastern Senegal. *Sustainability (Switzerland)*, **9**(2), 1-20, doi:10.3390/su9020311.
Fedele, G. et al., 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environ. Sci. Policy*, **101**, 116-125, doi:10.1016/j.envsci.2019.07.001.
Fedele, G., B. Locatelli, H. Djoudi and M. J. Colloff, 2018: Reducing risks by transforming landscapes: cross-scale effects of land-use changes on ecosystem services. *PLoS One*, **13**(4), e0195895, doi:10.1371/journal.pone.0195895.
Fei, S. et al., 2017: Divergence of species responses to climate change. *Sci Adv*, **3**(5), e1603055, doi:10.1126/sciadv.1603055.

Feliciano, D., A. Ledo, J. Hillier and D. R. Nayak, 2018: Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? *Agriculture, Ecosystems & Environment*, **254**, 117-129, doi:10.1016/j.agee.2017.11.032.
Felton, A. et al., 2016: How climate change adaptation and mitigation strategies can threaten or enhance the biodiversity of production forests: Insights from Sweden. *Biol. Conserv.*, **194**, 11-20, doi:10.1016/j.biocon.2015.11.030.
Feng, W. et al., 2017: Enhanced decomposition of stable soil organic carbon and microbial catabolic potentials by long-term field warming. *Glob Chang Biol*, **23**(11), 4765-4776, doi:10.1111/gcb.13755.
Fenton, A., J. Paavola and A. Tallontire, 2017: Autonomous adaptation to riverine flooding in Satkhira District, Bangladesh: implications for adaptation planning. *Reg. Environ. Change*, **17**(8), 2387-2396, doi:10.1007/s10113-017-1159-8.
Fernandes, J. A. et al., 2017: Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. *Fish Fish.*, **18**(3), 389-411, doi:10.1111/faf.12183.
Fernández-Giménez, M. E., B. Batkhishig, B. Batbuyan and T. Ulambayar, 2015: Lessons from the Dzud: community-based rangeland management increases the adaptive capacity of Mongolian herders to winter disasters. *World Dev.*, **68**(1), 48-65, doi:10.1016/j.worlddev.2014.11.015.
Fernando, N. et al., 2019: Annual ryegrass (Lolium rigidum Gaud) competition altered wheat grain quality: a study under elevated atmospheric CO2 levels and drought conditions. *Food Chem.*, **276**, 285-290, doi:10.1016/j.foodchem.2018.09.145.
Fetzel, T. et al., 2017: Quantification of uncertainties in global grazing systems assessment. *Glob. Biogeochem. Cycles*, **31**(7), 1089-1102, doi:10.1002/2016gb005601.
Fidelman, P., T. V. Tuyen, K. Nong and M. Nursey-Bray, 2017: The institutions-adaptive capacity nexus: Insights from coastal resources co-management in Cambodia and Vietnam. *Environ. Sci. Policy*, **76**, 103-112, doi:10.1016/j.envsci.2017.06.018.
Figueroa-Helland, L., C. Thomas and A. P. Aguilera, 2018: Decolonizing food systems: food sovereignty, indigenous revitalization, and agroecology as counter-hegemonic movements. *Perspect. Glob. Dev. Technol.*, **17**(1-2), 173-201, doi:10.1163/15691497-12341473.
Fikir, D., W. Tadesse and A. Gure, 2016: Economic contribution to local livelihoods and households dependency on dry land forest products in Hammer District, Southeastern Ethiopia. *Int. J. For. Res.*, **2016**, 5474680, doi:10.1155/2016/547468.
Filipe, J. F. et al., 2020: Floods, hurricanes, and other catastrophes: a challenge for the immune system of livestock and other animals. *Front Vet Sci*, **7**, 16, doi:10.3389/fvets.2020.00016.
Fink, S., 2017: Loss of habitat: impacts on pinnipeds and their welfare. In: *Marine Mammal Welfare: Human Induced Change in the Marine Environment and its Impacts on Marine Mammal Welfare* [Butterworth, A. (ed.)]. Springer International Publishing, Cham, Switzerland, pp. 241-252. ISBN 9783319469935.
Finkbeiner, E. M. et al., 2018: Exploring trade-offs in climate change response in the context of Pacific Island fisheries. *Mar. Policy*, **88**, 359-364, doi:10.1016/j.marpol.2017.09.032.
Fiore, A. M. et al., 2012: Global air quality and climate. *Chem Soc Rev*, **41**(19), 6663-6683, doi:10.1039/c2cs35095e.
Fischer, J. et al., 2007: Mind the sustainability gap. *Trends Ecol. Evol.*, **22**(12), 621-624, doi:10.1016/j.tree.2007.08.016.
Fischer, K., 2016: Why new crop technology is not scale-neutral - a critique of the expectations for a crop-based African Green Revolution. *Res. Policy*, **45**(6), 1185-1194, doi:10.1016/j.respol.2016.03.007.
Fischer, K., J. Van den Berg and C. Mutengwa, 2015: Is Bt maize effective in improving South African smallholder agriculture? *S. Afr. J. Sci.*, **111**(1/2), a0092, doi:10.17159/sajs.2015/a0092.
Fischler, C., 1988: Food, self and identity. *Soc. Sci. Inf.*, **27**(2), 275-292, doi:10.1177/053901888027002005.
Fisher, B. et al., 2017: Integrating fisheries and agricultural programs for food security. *Agric. Food Secur.*, **6**(1), 1, doi:10.1186/s40066-016-0078-0.
Fitzer, S. C. et al., 2019: Selectively bred oysters can alter their biomineralization pathways, promoting resilience to environmental acidification. *Glob Chang Biol*, **25**(12), 4105-4115, doi:10.1111/gcb.14818.
Fitzgerald, G. J. et al., 2016: Elevated atmospheric [CO2] can dramatically increase wheat yields in semi-arid environments and buffer against heat waves. *Glob Chang Biol*, **22**(6), 2269-2284, doi:10.1111/gcb.13263.

Fleisher, D. H. et al., 2017: A potato model intercomparison across varying climates and productivity levels. *Global Change Biol.*, **23**(3), 1258-1281, doi:10.1111/gcb.13411.
Fleming, Z. L. et al., 2018: Tropospheric ozone assessment report: present-day ozone distribution and trends relevant to human health. *Elementa: Sci. Anthropocene*, **6**, 12, doi:10.1525/elementa.273.
Flörke, M. et al., 2019: Analysing trade-offs between SDGs related to water quality using salinity as a marker. *Curr. Opin. Environ. Sustain.*, **36**, 96-104, doi:10.1016/j.cosust.2018.10.005.
Flörke, M., C. Schneider and R. I. McDonald, 2018: Water competition between cities and agriculture driven by climate change and urban growth. *Nat. Sustain.*, **1**, 51-58, doi:10.1016/j.cosust.2018.10.005.
Flouris, A. D. et al., 2018: Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *Lancet Planet Health*, **2**(12), e521-e531, doi:10.1016/S2542-5196(18)30237-7.
Flynn, J. and J. Sumberg, 2021: Are Africa's rural youth abandoning agriculture?, 43--57, doi:10.1079/9781789245011.0003.
Fodor, N. et al., 2018: Spatially explicit estimation of heat stress-related impacts of climate change on the milk production of dairy cows in the United Kingdom. *PLoS One*, **13**(5), e0197076, doi:10.1371/journal.pone.0197076.
Folberth, C. et al., 2019: Parameterization-induced uncertainties and impacts of crop management harmonization in a global gridded crop model ensemble. *PLoS One*, **14**(9), e0221862.
Fonjong, L., I. Sama-Lang, L. Fombe and C. Abonge, 2016: Land governance and women's rights in large-scale land acquisitions in Cameroon. *Dev. Pract.*, **26**(4), 420-430, doi:10.1080/09614524.2016.1162285.
Food and Land Use Coalition, 2019: *Growing Better: Ten Critical Transitions to Transform Food and Land Use. The Global Consultation Report of the Food and Land Use Coalition*. Food and Land Use Coalition, 237 pp. Available at: <Go to WoS>://WOS:000376696800043 (accessed 26/07/2021).
Food Security Information Network, 2020: *2020 Global report on food crises: Joint analysis for better decisions.*, Food and Agriculture Organization (FAO); World Food Programme (WFP); and International Food Policy Research Institute (IFPRI). Rome, Italy and Washington DC, 233 pp. Available at: https://www.fsinplatform.org/global-report-food-crises-2020.
Forbes, B. C. et al., 2016: Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. *Biol. Lett.*, **12**(11), 20160466, doi:10.1098/rsbl.2016.0466.
Forbes, B. C. et al., 2020: Changes in mountain birch forests and reindeer management: comparing different knowledge systems in Sápmi, northern Fennoscandia. *Polar Rec.*, **55**(6), 507-521, doi:10.1017/s0032247419000834.
Forbis Jr., R. and K. Hayhoe, 2018: Does Arctic governance hold the key to achieving climate policy targets? *Environ. Res. Lett.*, **13**, 1-4, doi:10.1088/1748-9326/aaa359.
Ford, J. D., 2009: Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. *Reg. Environ. Change*, **9**(2), 83-100, doi:10.1007/s10113-008-0060-x.
Ford, J. D. et al., 2015: The status of climate change adaptation in Africa and Asia. *Reg. Environ. Change*, **15**(5), 801-814, doi:10.1007/s10113-014-0648-2.
Ford, J. D. et al., 2019: Changing access to ice, land and water in Arctic communities. *Nat. Clim. Change*, **9**(4), 335-339, doi:10.1038/s41558-019-0435-7.
Ford, J. D., N. Couture, T. Bell and D. G. Clark, 2018: Climate change and Canada's north coast: research trends, progress, and future directions. *Environ. Rev.*, **26**(1), 82-92, doi:10.1139/er-2017-0027.
Forest Trends, 2014: *Consumer goods and deforestation: An analysis of the extent and nature of illegality in forest conversation for agriculture and timber plantations*. Forest Trade and Finance Series, Washington, D.C.
Forster, P. et al., 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Fort, J. et al., 2016: Does temporal variation of mercury levels in Arctic seabirds reflect changes in global environmental contamination, or a modification of Arctic marine food web functioning? *Environ. Pollut.*, **211**, 382-388, doi:10.1016/j.envpol.2015.12.061.

Foster, J. et al., 2021: An advanced empirical model for quantifying the impact of heat and climate change on human physical work capacity. *Int J Biometeorol*, **65**(7), 1215-1229, doi:10.1007/s00484-021-02105-0.

Foster, S. et al., 2018: Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions. *Hydrogeol. J.*, **26**(8), 2781-2791, doi:10.1007/s10040-018-1830-2.

Fox-Kemper, B. et al., 2021: Ocean, Cryosphere and Sea Level Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Fox, J., J. C. Castella and A. D. Ziegler, 2014: Swidden, rubber and carbon: can REDD+ work for people and the environment in Montane Mainland Southeast Asia? *Global Environ. Change*, **29**, 318-326, doi:10.1016/j.gloenvcha.2013.05.011.

Foyer, C. H. et al., 2016: Neglecting legumes has compromised human health and sustainable food production. *Nat Plants*, **2**, 16112, doi:10.1038/nplants.2016.112.

Fraga, H., I. Garcia de Cortazar Atauri, A. C. Malheiro and J. A. Santos, 2016a: Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Glob Chang Biol*, **22**(11), 3774-3788, doi:10.1111/gcb.13382.

Fraga, H., N. Guimaraes and J. A. Santos, 2019a: Future changes in rice bioclimatic growing conditions in Portugal. *Agronomy*, **9**(11), 674, doi:10.3390/agronomy9110674.

Fraga, H., J. G. Pinto and J. A. Santos, 2019b: Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: a multi-model assessment. *Clim. Change*, **152**(1), 179-193, doi:10.1007/s10584-018-2337-5.

Fraga, H. et al., 2016b: Climatic suitability of Portuguese grapevine varieties and climate change adaptation. *Int. J. Climatol.*, **36**(1), 1-12, doi:10.1002/joc.4325.

Fragaszy, S. and A. Closas, 2016: Cultivating the desert: irrigation expansion and groundwater abstraction in Northern State, Sudan. *Water Altern.*, **9**(1), 139-161.

Franck, C., S. M. Grandi and M. J. Eisenberg, 2013: Agricultural subsidies and the American obesity epidemic. *Am. J. Prev. Med.*, **45**(3), 327-333, doi:10.1016/j.amepre.2013.04.010.

Franco, J., C. M. Y. Park and R. Herre, 2017: Just standards: international regulatory instruments and social justice in complex resource conflicts. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, **0**(0), 1-19, doi:10.1080/02255189.2017.1298520.

Franco, J. C. and S. M. Borras, 2019: Grey areas in green grabbing: subtle and indirect interconnections between climate change politics and land grabs and their implications for research. *Land Use Policy*, **84**(October 2018), 192-199, doi:10.1016/j.landusepol.2019.03.013.

Franco, J. C., S. Monsalve and S. M. Borras, 2015: Democratic land control and human rights. *Curr. Opin. Environ. Sustain.*, **15**, 66-71, doi:10.1016/j.cosust.2015.08.010.

Freduah, G., P. Fidelman and T. F. Smith, 2019: Adaptive capacity of small-scale coastal fishers to climate and non-climate stressors in the Western region of Ghana. *Geogr. J.*, **185**(1), 96-110, doi:10.1111/geoj.12282.

Free, C. M. et al., 2020: Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLoS One*, **15**(3), e0224347, doi:10.1371/journal.pone.0224347.

Free, C. M. et al., 2019: Impacts of historical warming on marine fisheries production. *Science*, **363**(6430), 979-983, doi:10.1126/science.aau1758.

Freed, S. et al., 2020: Maintaining Diversity of Integrated Rice and Fish Production Confers Adaptability of Food Systems to Global Change. *Front. Sustain. Food Syst.*, **4**, doi:10.3389/fsufs.2020.576179.

Freitas, C. et al., 2008: Ringed seal post-moulting movement tactics and habitat selection. *Oecologia*, **155**(1), 193-204, doi:10.1007/s00442-007-0894-9.

Friant, S. et al., 2020: Eating bushmeat improves food security in a biodiversity and infectious disease "hotspot". *EcoHealth*, **17**(1), 125-138, doi:10.1007/s10393-020-01473-0.

Friedrichs, S. et al., 2019: Meeting report of the OECD conference on "Genome editing: applications in agriculture-implications for health, environment and regulation". *Transgenic Res.*, **28**(3-4), 419-463, doi:10.1007/s11248-019-00154-1.

Frieler, K. et al., 2017: Understanding the weather signal in national crop-yield variability. *Earths Future*, **5**(6), 605-616, doi:10.1002/2016EF000525.

Froehlich, H. E., R. R. Gentry and B. S. Halpern, 2018a: Global change in marine aquaculture production potential under climate change. *Nat Ecol Evol*, **2**(11), 1745-1750, doi:10.1038/s41559-018-0669-1.
Froehlich, H. E. et al., 2018b: Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc Natl Acad Sci U S A*, **115**(20), 5295-5300, doi:10.1073/pnas.1801692115.
Froehse and Schilling, 2019: The nexus of climate change, land use, and conflicts. *Curr. Clim. Change Rep.*
Froese, R. and J. Schilling, 2019: The nexus of climate change, land use, and conflicts. *Curr. Clim. Change Rep.*, **5**(1), 24-35, doi:10.1007/s40641-019-00122-1.
Frolicher, T. L. and C. Laufkotter, 2018: Emerging risks from marine heat waves. *Nat Commun*, **9**(1), 650, doi:10.1038/s41467-018-03163-6.
Fry, J. P. et al., 2016: Environmental health impacts of feeding crops to farmed fish. *Environ. Int.*, **91**, 201-214, doi:10.1016/j.envint.2016.02.022.
Fry, J. P. et al., 2018a: Corrigendum: Feed conversion efficiency in aquaculture: do we measure it correctly? (2018 Environ. Res. Lett. 13 024017). *Environ. Res. Lett.*, **13**(7), 079502, doi:10.1088/1748-9326/aad007.
Fry, J. P. et al., 2018b: Feed conversion efficiency in aquaculture: do we measure it correctly? *Environ. Res. Lett.*, **13**(2), 024017, doi:10.1088/1748-9326/aaa273.
FSIN, 2017: *Global Report on Food Crises 2017*. Rome, Italy, 145-145 pp.
FSIN, 2021: *2021 Global Report on Food Crises: Joint analysis for better decisions* DC. Food and Agriculture Organization (FAO); World Food Programme (WFP); and International Food Policy Research Institute (IFPRI), Rome, Italy; and Washington, DO. . Available at: https://www.fsinplatform.org/global-report-food-crises-2021.
Fuchs, R., C. Brown and M. Rounsevell, 2020: Europe's Green Deal offshores environmental damage to other nations. *Nature*, **586**(7831), 671-673, doi:10.1038/d41586-020-02991-1.
Fuhrer, J., P. Smith and A. Gobiet, 2014: Implications of climate change scenarios for agriculture in alpine regions--a case study in the Swiss Rhone catchment. *Sci. Total Environ.*, **493**, 1232-1241, doi:10.1016/j.scitotenv.2013.06.038.
Fujimori, S. et al., 2018: Macroeconomic impacts of climate change driven by changes in crop yields. *Sustainability*, **10**, 3673, doi:10.3390/su10103673.
Fujisaki, K. et al., 2018: Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. *Agriculture, Ecosystems & Environment*, **259**, 147-158, doi:10.1016/j.agee.2017.12.008.
Funes, I. et al., 2020: Soil water availability as a tool for adapting viticulture to climate change. *Quaderns Agraris*, **49**, 35-52, doi:10.2436/20.1503.01.116.
Funge-Smith, S. and A. Bennett, 2019: A fresh look at inland fisheries and their role in food security and livelihoods. *Fish Fish.*, **20**(6), 1176-1195.
Funk, C. et al., 2018: Anthropogenic enhancement of moderate-to-strong el nino events likely contributed to drought and poor harvests in Southern Africa during 2016. *Bull. Am. Meterol. Soc.*, **99**(1), S91-S96, doi:10.1175/Bams-D-17-0112.1.
Furman, C. et al., 2014: Social justice in climate services: engaging African American farmers in the American South. *Clim. Risk Manag.*, **2**, 11-25, doi:10.1016/j.crm.2014.02.002.
Furze, J. R. et al., 2017: Resistance and resilience of root fungal communities to water limitation in a temperate agroecosystem. *Ecology and Evolution*, **7**(10), 3443-3454, doi:10.1002/ece3.2900.
Fuss, S. et al., 2015: Global food security & adaptation under crop yield volatility. *Technol. Forecast. Soc. Change*, **98**, 223-233, doi:10.1016/j.techfore.2015.03.019.
Gabay, M. and M. Alam, 2017: Community forestry and its mitigation potential in the Anthropocene: The importance of land tenure governance and the threat of privatization. *For Policy Econ*, **79**, 26-35, doi:10.1016/j.forpol.2017.01.011.
Gabriel, A. G. and T. L. S. Mangahas, 2017: Indigenous people's contribution to the mitigation of climate variation, their perception, and organizing strategy for sustainable community based forest resources management in Caraballo mountain, Philippines. *Open J. Ecol.*, **7**(2), 85-100, doi:10.4236/oje.2017.72007.
Gaines, S. D. et al., 2018: Improved fisheries management could offset many negative effects of climate change. *Sci Adv*, **4**(8), eaao1378, doi:10.1126/sciadv.aao1378.
Gaira, K. S., R. S. Rawal, B. Rawat and I. D. Bhatt, 2014: Impact of climate change on the flowering of Rhododendron arboreum in central Himalaya, India. *Curr. Sci.*, **106**(12), 1735-1738.

Gairola, S., N. M. Shariff, A. Bhatt and C. P. Kala, 2010: Influence of climate change on production of secondary chemicals in high altitude medicinal plants: issues needs immediate attention. *J. Med. Plants Res.*, **4**(18), 1825-1829, doi:10.5897/JMPR10.354.
Gajjar, S. P., C. Singh and T. Deshpande, 2019: Tracing back to move ahead: a review of development pathways that constrain adaptation futures. *Clim. Dev.*, **11**(3), 223-237, doi:10.1080/17565529.2018.1442793.
Galappaththi, E. K., J. D. Ford and E. M. Bennett, 2020a: Climate change and adaptation to social-ecological change: the case of indigenous people and culture-based fisheries in Sri Lanka. *Clim. Change*, **162**(2), 279-300, doi:10.1007/s10584-020-02716-3.
Galappaththi, E. K., J. D. Ford, E. M. Bennett and F. Berkes, 2021: Adapting to climate change in small-scale fisheries: Insights from indigenous communities in the global north and south. *Environ. Sci. Policy*, **116**, 160-170, doi:10.1016/j.envsci.2020.11.009.
Galappaththi, E. K. et al., 2020b: Climate change adaptation in aquaculture. *Rev. Aquac.*, **12**(4), 2160-2176, doi:10.1111/raq.12427.
Galford, G. L. et al., 2020: Agricultural development addresses food loss and waste while reducing greenhouse gas emissions. *Sci. Total Environ.*, **699**, 134318-134318, doi:10.1016/j.scitotenv.2019.134318.
Gallo, N. D. et al., 2019: Bridging from monitoring to solutions-based thinking: lessons from CalCOFI for understanding and adapting to marine climate change Impacts. *Front. Mar. Sci.*, **6**, 695, doi:10.3389/fmars.2019.00695.
Galvin, K. A., T. A. Beeton, R. B. Boone and S. B. BurnSilver, 2015: Nutritional status of Maasai pastoralists under change. *Hum Ecol Interdiscip J*, **43**(3), 411-424, doi:10.1007/s10745-015-9749-x.
Gandini, G. C. and E. Villa, 2003: Analysis of the cultural value of local livestock breeds: a methodology. *J. Anim. Breed. Genet.*, **120**(1), 1-11, doi:10.1046/j.1439-0388.2003.00365.x.
Gantner, V. et al., 2017: The differences in heat stress resistance due to dairy cattle breed. *Mljekarstvo*, **67**(2), 112-122, doi:10.15567/mljekarstvo.2017.0203.
García-Martínez, Y. G. et al., 2016: Traditional agroecosystems and global change implications in Mexico. *Bulg. J. Agric. Sci.*, **22**(4), 548-565.
García de Cortázar-Atauri, I. et al., 2017: Grapevine phenology in France: from past observations to future evolutions in the context of climate change. *Oeno One*, **51**(2), 115-126, doi:10.20870/oeno-one.2017.51.2.1622.
Garcia, A. et al., 2021: Emancipatory spaces: Opportunities for (re)negotiating gendered subjectivities and enhancing adaptive capacities. *Geoforum*, **119**, 190-205, doi:10.1016/j.geoforum.2020.09.018.
Garibaldi, L. A. et al., 2016: Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science*, **351**(6271), 388-391, doi:10.1126/science.aac7287.
Garnett, E. E. et al., 2021: Price of change: does a small alteration to the price of meat and vegetarian options affect their sales? *Journal of Environmental Psychology*, 101589, doi:10.1016/j.jenvp.2021.101589.
Garnett, E. E. et al., 2019: Impact of increasing vegetarian availability on meal selection and sales in cafeterias. *Proc Natl Acad Sci U S A*, **116**(42), 20923-20929, doi:10.1073/pnas.1907207116.
Garnett, E. E. et al., 2020: Order of meals at the counter and distance between options affect student cafeteria vegetarian sales. *Nat. Food*, **1**(8), 485-488, doi:10.1038/s43016-020-0132-8.
Garnett, S. T. et al., 2018: A spatial overview of the global importance of Indigenous lands for conservation. *Nat. Sustain.*, **1**, 369-374, doi:10.1038/s41893-018-0100-6.
Garnett, T., E. Röös and D. Little, 2015: *Lean, green, mean, obscene...? What is efficiency? And is it sustainable? Animal production and consumption reconsidered*. Available at: https://www.fcrn.org.uk/sites/default/files/fcrn_lmgo.pdf.
Garrabou, J. et al., 2019: Collaborative database to track mass mortality events in the Mediterranean Sea. *Front. Mar. Sci.*, **6**, 707, doi:10.3389/fmars.2019.00707.
Gasco, L. et al., 2018: Fishmeal Alternative Protein Sources for Aquaculture Feeds. In: *Feeds for the Aquaculture Sector: Current Situation and Alternative Sources*. Springer International Publishing, Cham, pp. 1-28. ISBN 978-3-319-77941-6.
Gattuso, J. P. et al., 2018: Ocean solutions to address climate change and its effects on marine ecosystems. *Front. Mar. Sci.*, **5**, 337, doi:10.3389/fmars.2018.00337.
Gaupp, F., J. Hall, S. Hochrainer-Stigler and S. Dadson, 2020: Changing risks of simultaneous global breadbasket failure. *Nat. Clim. Change*, **10**(1), 54-57, doi:10.1038/s41558-019-0600-z.
Gaupp, F., J. Hall, D. Mitchell and S. Dadson, 2019: Increasing risks of multiple breadbasket failure under 1.5 and 2 degrees C global warming. *Agric. Syst.*, **175**, 34-45, doi:10.1016/j.agsy.2019.05.010.

Gauthier, S. et al., 2014: Climate change vulnerability and adaptation in the managed Canadian boreal forest. *Environ. Rev.*, **22**(3), 256-285, doi:10.1139/er-2013-0064.
Gautier, D., B. Locatelli, C. Corniaux and V. Alary, 2016: Global changes, livestock and vulnerability: the social construction of markets as an adaptive strategy. *Geogr. J.*, **182**(2), 153-164, doi:10.1111/geoj.12115.
Gebhardt, T. et al., 2014: The more, the better? Water relations of Norway spruce stands after progressive thinning. *Agric. For. Meteorol*, **197**, 235-243, doi:10.1016/j.agrformet.2014.05.013.
Génova, M., L. Caminero and J. Dochao, 2014: Resin tapping in Pinus pinaster: effects on growth and response function to climate. *Eur. J. For. Res.*, **133**, 323-333, doi:10.1007/s10342-013-0764-4.
Gentle, P. and R. Thwaites, 2016: Transhumant pastoralism in the context of socioeconomic and climate change in the mountains of Nepal. *Mountain Research and Development*, **36**(2), 173-182, doi:10.1659/Mrd-Journal-D-15-00011.1.
Gentry, R. R. et al., 2020: Exploring the potential for marine aquaculture to contribute to ecosystem services. *Rev. Aquac.*, **12**(2), 499-512, doi:10.1111/raq.12328.
Gentry, R. R. et al., 2017: Offshore aquaculture: spatial planning principles for sustainable development. *Ecol Evol*, **7**(2), 733-743, doi:10.1002/ece3.2637.
Gepts, P., 2014: The contribution of genetic and genomic approaches to plant domestication studies. *Curr. Opin. Plant Biol.*, **18**, 51-59, doi:10.1016/j.pbi.2014.02.001.
Gerard, F., F. Affholder, N. F. Mane and M. Sali, 2020: Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le Bassin arachidier du Sénégal. *AFD Research Papers*.
Gerten, D. et al., 2020: Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat. Sustain.*, **3**, 200-208, doi:10.1038/s41893-019-0465-1.
Gevaña, D. T., L. D. Camacho and J. M. Pulhin, 2018: Conserving mangroves for their blue carbon: insights and prospects for community-based mangrove management in southeast Asia. In: *Threats to Mangrove Forests: Hazards, Vulnerability, and Management* [Makowski, C. and C. W. Finkl (eds.)]. Springer, Cham, Switzerland, pp. 579-588. ISBN 9783319730158.
Ghahramani, A. and D. Bowran, 2018: Transformative and systemic climate change adaptations in mixed crop livestock farming systems. *Agric. Syst.*, **164**, 236-251, doi:10.1016/j.agsy.2018.04.011.
Ghamkhar, R., C. Hartleb, F. Wu and A. Hicks, 2020: Life cycle assessment of a cold weather aquaponic food production system. *J. Clean. Prod.*, **244**, 118767, doi:10.1016/j.jclepro.2019.118767.
Ghanem, M. E., H. Marrou and T. R. Sinclair, 2015: Physiological phenotyping of plants for crop improvement. *Trends Plant Sci.*, **20**, 139-144, doi:10.1016/j.tplants.2014.11.006.
Ghezzo, M. et al., 2018: Natural resources and climate change: a study of the potential impact on Manila clam in the Venice lagoon. *Sci. Total Environ.*, **645**, 419-430, doi:10.1016/j.scitotenv.2018.07.060.
Ghosh-Jerath, S. et al., 2015: Traditional knowledge and nutritive value of indigenous foods in the Oraon tribal community of Jharkhand: An exploratory cross-sectional study. *Ecol Food Nutr*, **54**(5), 493-519, doi:10.1080/03670244.2015.1017758.
Giannini, T. C. et al., 2017: Projected climate change threatens pollinators and crop production in Brazil. *PLoS One*, **12**(8), e0182274, doi:10.1371/journal.pone.0182274.
Giger, M. et al., 2019: Impacts of large-scale land acquisitions on common-pool resources. [Haller, T., T. Breu, T. De Moor, C. Rohr and H. Znoj (eds.)]. Routledge, Abingdon, pp. 257-279. ISBN ISBN 978-1-138-48481-8.
Gil, J. D. B. et al., 2017: The resilience of integrated agricultural systems to climate change. *Wiley Interdiscip. Rev.: Clim. Change*, **8**(4), e461, doi:10.1002/wcc.461.
Gilbert, M. et al., 2018: Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Sci Data*, **5**, 180227, doi:10.1038/sdata.2018.227.
Giller, K. E., J. A. Andersson, J. Sumberg and J. Thompson, 2017: "A golden age for agronomy?". In: *Agronomy for Development: The Politics of Knowledge in Agricultural Research* [Sumberg, J. (ed.)]. Routledge, Oxon, United Kingdom, and New York, NY, USA, pp. 150-160. ISBN 9781138240278.
Gitea, M. A. et al., 2019: Orchard management under the effects of climate change: implications for apple, plum, and almond growing. *Environ Sci Pollut Res Int*, **26**(10), 9908-9915, doi:10.1007/s11356-019-04214-1.
Gjedrem, T. and M. Rye, 2018: Selection response in fish and shellfish: a review. *Rev. Aquac.*, **10**(1), 168-179, doi:10.1111/raq.12154.
Glemarec, Y., 2017: Addressing the gender differentiated investment risks to climate-smart agriculture. *AIMS Agric. Food*, **2**(1), 56-74, doi:10.3934/agrfood.2017.1.56.

Glenn, D. M., S. H. Kim, J. Ramirez-Villegas and P. Laderach, 2013: Response of perennial horticultural crops to climate change. In: *Horticultural Reviews* [Janick, J. (ed.)]. Wiley-Blackwell, pp. 47-130. ISBN 9781118707371.
Glibert, P. M., 2020: Harmful algae at the complex nexus of eutrophication and climate change. *Harmful Algae*, **91**, 101583, doi:10.1016/j.hal.2019.03.001.
Gliessman, S., 2014: *Agroecology: The Ecology of Sustainable Food Systems*, 3rd ed., CRC Press, Boca Raton.
Global Commission on Adaptation, 2019: *Adapt Now: A Global Call for Leadership on Climate Resilience*. Global Center on Adaptation,, Rotterdam, The Netherlands, 81 pp. Available at: <Go to WoS>://WOS:000336116500020 (accessed 30/07/2021).
Glover, D., 2014: Of yield gaps and yield ceilings: making plants grow in particular places. *Geoforum*, **53**, 184-194, doi:10.1016/j.geoforum.2013.06.001.
Godde, C. et al., 2019: Climate change and variability impacts on grazing herds: insights from a system dynamics approach for semi-arid Australian rangelands. *Glob Chang Biol*, **25**(9), 3091-3109, doi:10.1111/gcb.14669.
Godde, C. M. et al., 2020: Global rangeland production systems and livelihoods at threat under climate change and variability. *Environ. Res. Lett.*, **15**(4), 44021-44021, doi:10.1088/1748-9326/ab7395.
Godde, C. M. et al., 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Glob Food Sec*, **28**, 100488, doi:10.1016/j.gfs.2020.100488.
Goddek, S. et al., 2015: Challenges of sustainable and commercial aquaponics. *Sustainability*, **7**(4), 4199-4224, doi:10.3390/su7044199.
Godden, L. and M. Tehan, 2016: REDD+: climate justice and indigenous and local community rights in an era of climate disruption. *J. Energy Nat. Resour. Law*, **34**(1), 95-108, doi:10.1080/02646811.2016.1121620.
Godfray, H. C. et al., 2010: The future of the global food system. *Philos Trans R Soc Lond B Biol Sci*, **365**(1554), 2769-2777, doi:10.1098/rstb.2010.0180.
Golden, C. D. et al., 2016: Nutrition: fall in fish catch threatens human health. *Nature*, **534**(7607), 317-320, doi:10.1038/534317a.
Golden, C. D. et al., 2011: Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. *Proc Natl Acad Sci U S A*, **108**(49), 19653-19656, doi:10.1073/pnas.1112586108.
Goldsmith, K. A. et al., 2019: Scientific considerations for acidification monitoring in the U.S. Mid-Atlantic Region. *Estuarine, Coastal and Shelf Science*, **225**, 106189, doi:10.1016/j.ecss.2019.04.023.
Goldstein, B., M. Hauschild, J. Fernandez and M. Birkved, 2016: Urban versus conventional agriculture, taxonomy of resource profiles: a review. *Agron. Sustain. Dev.*, **36**(1), 9, doi:10.1007/s13593-015-0348-4.
Goldstein, J. H. et al., 2012: Integrating ecosystem-service tradeoffs into land-use decisions. *Proc Natl Acad Sci U S A*, **109**(19), 7565-7570, doi:10.1073/pnas.1201040109.
Gondhalekar, D. and T. Ramsauer, 2017: Nexus city: operationalizing the urban water-energy-food nexus for climate change adaptation in Munich, Germany. *Urban Clim.*, **19**, 28-40, doi:10.1016/j.uclim.2016.11.004.
Gonzal, A., T. Pongthanapanic and P. Bueno, 2019: *Strengthening Small Aquaculture Entrepreneurs: The Case of a Women's Association in the Philippines.* FAO Fisheries and Aquaculture Circular, Food and Agricultural Organization of the United Nations,, Rome, Italy, 26 pp. ISBN 9789251315446.
Gonzalez-Alzaga, B. et al., 2014: A systematic review of neurodevelopmental effects of prenatal and postnatal organophosphate pesticide exposure. *Toxicol. Lett.*, **230**(2), 104-121, doi:10.1016/j.toxlet.2013.11.019.
Gonzalez-Varo, J. P. et al., 2013: Combined effects of global change pressures on animal-mediated pollination. *Trends Ecol. Evol.*, **28**(9), 524-530, doi:10.1016/j.tree.2013.05.008.
González de Molina, M., 2020: Strategies for scaling up Agroecological experiences in Europe. *International Journal of Agriculture and Natural Resources*, **47**(3), 187-203, doi:10.7764/ijanr.v47i3.2257.
Gonzalez, P., C. J. Tucker and H. Sy, 2012: Tree density and species decline in the African Sahel attributable to climate. *J. Arid Environ.*, **78**, 55-64, doi:10.1016/j.jaridenv.2011.11.001.
Goodman, W. and J. Minner, 2019: Will the urban agricultural revolution be vertical and soilless? A case study of controlled environment agriculture in New York City. *Land Use Policy*, **83**, 160-173, doi:10.1016/j.landusepol.2018.12.038.
Gopal, N. et al., 2020: Expanding the horizons for women in fisheries and aquaculture. *Gender, Technology and Development*, **24**(1), 1-9, doi:10.1080/09718524.2020.1736353.

Gorn, L., J. Kleemann and C. Fürst, 2018: Improving the matrix-assessment of ecosystem services provision—the case of regional land use planning under climate change in the region of Halle, Germany. *Land*, **7**(2), 76, doi:10.3390/land7020076.

Gosling, S., J. Zaherpour and D. Ibarreta, 2018: *PESETA III: Climate change impacts on labour productivity*. Joint Research Centre (Seville site). Available at: https://ideas.repec.org/p/ipt/iptwpa/jrc113740.html.

Gosnell, H., N. Gill and M. Voyer, 2019: Transformational adaptation on the farm: processes of change and persistence in transitions to 'climate-smart' regenerative agriculture. *Glob. Environ. Change*, **59**, 101965, doi:10.1016/j.gloenvcha.2019.101965.

Gouel, C. and D. Laborde, 2021: The crucial role of domestic and international market-mediated adaptation to climate change. *J. Environ. Econ. Manage.*, **106**, doi:10.1016/j.jeem.2020.102408.

Gouse, M., D. Sengupta, P. Zambrano and J. F. Zepeda, 2016: Genetically modified maize: less drudgery for her, more maize for him? Evidence from smallholder maize farmers in South Africa. *World Dev.*, **83**, 27-38, doi:10.1016/j.worlddev.2016.03.008.

Govers, G., R. Merckx, B. van Wesemae and K. Van Oost, 2017: Soil conservation in the 21st century: why we need smart agricultural intensification. *Soil*, **3**(1), 45-59, doi:10.5194/soil-3-45-2017.

Gravert, C. and V. Kurz, 2019: Nudging à la carte: a field experiment on climate-friendly food choice. *Behav. Public Policy*, **5**(3), 378-395, doi:10.1017/bpp.2019.11.

Gray, S. B. et al., 2016: Intensifying drought eliminates the expected benefits of elevated carbon dioxide for soybean. *Nat Plants*, **2**(9), 16132, doi:10.1038/nplants.2016.132.

Greatrex, H. et al., 2015: *Scaling Up Index Insurance for Smallholder Farmers: Recent Evidence and Insights*. CCAFS Report, CGIAR Research Program on Climate Change, Agriculture and Food Security,, Copenhagen, Denmark, 32 pp. Available at: https://hdl.handle.net/10568/53101 (accessed 30/07/2021).

Green, R. et al., 2013: The effect of rising food prices on food consumption: systematic review with meta-regression. *BMJ*, **346**, f3703, doi:10.1136/bmj.f3703.

Green, T. J. et al., 2019: Simulated marine heat wave alters abundance and structure of Vibrio populations associated with the Pacific oyster resulting in a mass mortality event. *Microb. Ecol.*, **77**(3), 736-747, doi:10.1007/s00248-018-1242-9.

Greene, C., 2018: Broadening understandings of drought - the climate vulnerability of farmworkers and rural communities in California (USA). *Environ. Sci. Policy*, **89**, 283-291, doi:10.1016/j.envsci.2018.08.002.

Greenhill, L., J. O. Kenter and H. Dannevig, 2020: Adaptation to climate change-related ocean acidification: An adaptive governance approach. *Ocean Coast. Manage.*, **191**, 105176, doi:10.1016/j.ocecoaman.2020.105176.

Gregorich, E. G. et al., 2017: Litter decay controlled by temperature, not soil properties, affecting future soil carbon. *Glob Chang Biol*, **23**(4), 1725-1734, doi:10.1111/gcb.13502.

Griffin, T. et al., 2015: Regional self-reliance of the Northeast food system. *Renew. Agric. Food Syst.*, **30**(4), 349-363, doi:10.1017/S1742170514000027.

Griffith, A. W., O. M. Doherty and C. J. Gobler, 2019: Ocean warming along temperate western boundaries of the Northern Hemisphere promotes an expansion of Cochlodinium polykrikoides blooms. *Proceedings of the Royal Society B: Biological Sciences*, **286**(1904), 20190340, doi:10.1098/rspb.2019.0340.

Griffith, A. W. and C. J. Gobler, 2017: Transgenerational exposure of North Atlantic bivalves to ocean acidification renders offspring more vulnerable to low pH and additional stressors. *Sci Rep*, **7**(1), 11394, doi:10.1038/s41598-017-11442-3.

Griffith, A. W. and C. J. Gobler, 2020: Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. *Harmful Algae*, **91**, 101590-101590, doi:10.1016/j.hal.2019.03.008.

Groner, M. L. et al., 2016: Quantifying the influence of salinity and temperature on the population dynamics of a marine ectoparasite. *Can. J. Fish. Aquat. Sci.*, **73**(8), 1281-1291, doi:10.1139/cjfas-2015-0444.

Gros, C. et al., 2019: Household-level effects of providing forecast-based cash in anticipation of extreme weather events: Quasi-experimental evidence from humanitarian interventions in the 2017 floods in Bangladesh. *Int. J. Disaster Risk Reduct.*, **41**, 101275-101275, doi:10.1016/j.ijdrr.2019.101275.

Grosso, G. et al., 2020: Nutrition in the context of the Sustainable Development Goals. *Eur. J. Public Health*, **30**(Supplement_1), i19--i23, doi:10.1093/eurpub/ckaa034.

Guerra, J., J. Blesh, A. L. Schmitt and H. Wittman, 2017: Pathways to agroecological management through mediated markets in Santa Catarina, Brazil. *Elementa: Sci. Anthropocene*, **5**, 67, doi:10.1525/elementa.248.
Guido, Z., C. Knudson, D. Campbell and J. Tomlinson, 2019: Climate information services for adaptation: what does it mean to know the context? *Clim. Dev.*, 1-13, doi:10.1080/17565529.2019.1630352.
Gulev, S. K. et al., 2021: Changing State of the Climate System. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Gumucio, T., J. Hansen, S. Huyer and T. van Huysen, 2020: Gender-responsive rural climate services: a review of the literature. *Clim. Dev.*, **12**(3), 241-254, doi:10.1080/17565529.2019.1613216.
Gunathilaka, R. P. D., J. C. R. Smart and C. M. Fleming, 2018: Adaptation to climate change in perennial cropping systems: options, barriers and policy implications. *Environ. Sci. Policy*, **82**, 108-116, doi:10.1016/j.envsci.2018.01.011.
Guo, H. B. et al., 2018: Estimating realized heritability for growth in Zhikong scallop (Chlamys farreri) using genome-wide complex trait analysis. *Aquaculture*, **497**, 103-108, doi:10.1016/j.aquaculture.2018.07.046.
Guo, Y. et al., 2017: Prediction of the potential geographic distribution of the ectomycorrhizal mushroom Tricholoma matsutake under multiple climate change scenarios. *Sci Rep*, **7**, 46221, doi:10.1038/srep46221.
Guo, Y. and Y. J. Shen, 2015: Quantifying water and energy budgets and the impacts of climatic and human factors in the Haihe River Basin, China: 2. Trends and implications to water resources. *J. Hydrol.*, **527**, 251-261, doi:10.1016/j.jhydrol.2015.04.071.
Guodaar, L. et al., 2019: How do climate change adaptation strategies result in unintended maladaptive outcomes? Perspectives of tomato farmers. *Int. J. Veg. Sci.*, **26**(1), 15-31, doi:10.1080/19315260.2019.1573393.
Gupta, A., 1998: *Postcolonial Developments: Agriculture in the Making of Modern India*. Duke University Press, Durham, NC, USA, 432 pp. ISBN 9780822322139.
Gupta, P. and N. Sen, 1980: Food consumption and nutrition of regional tribes of India. *Ecol. Food Nutr.*, **9**(2), 93-108, doi:10.1080/03670244.1980.9990587.
Gupta, R., E. Somanathan and S. Dey, 2016: Global warming and local air pollution have reduced wheat yields in India. *Clim. Change*, **140**(3-4), 593-604, doi:10.1007/s10584-016-1878-8.
Gurung, K., H. Bhandari and T. Paris, 2016: Transformation from Rice Farming to Commercial Aquaculture in Bangladesh: Implications for Gender, Food Security, and Livelihood. *Gender, Technology and Development*, **20**(1), 49-80, doi:10.1177/0971852415618747.
Gutierrez, A. P., O. Matika, T. P. Bean and R. D. Houston, 2018: Genomic selection for growth traits in Pacific oyster (Crassostrea gigas): potential of low-density Marker Panels for breeding value prediction. *Front Genet*, **9**, 391, doi:10.3389/fgene.2018.00391.
Gutsch, M. et al., 2018: Balancing trade-offs between ecosystem services in Germany's forests under climate change. *Environ. Res. Lett.*, **13**(4), 45012, doi:10.1088/1748-9326/aab4e5.
Gyapong, A. Y., 2020: How and why large scale agricultural land investments do not create long-term employment benefits: A critique of the 'state' of labour regulations in Ghana. *Land Use Policy*, **95**(April), 104651-104651, doi:10.1016/j.landusepol.2020.104651.
Haapala, A., 2018: A feminist analysis of oppressive and emancipatory potentialities within technology-prioritized climate change adaptation intervention: a case study from Phailom community in Laos. In: *Gender dimension of climate change research in agriculture (Case studies in Southeast Asia)* [Paris, T. R. and M. E. Rola-Rubzen (eds.)]. Southeast Asian Regional Center for Graduate Study and Research in Agriculture,

CGIAR Research Program on Climate Change, Agriculture, and Food Security,, Laguna, Philippines and Wageningen, the Netherlands, pp. 123 - 140. ISBN 9789715602716.
Haasnoot, M. et al., 2020: Defining the solution space to accelerate climate change adaptation. *Reg. Environ. Change*, **20**(2), doi:10.1007/s10113-020-01623-8.

Häberli, C. and F. Smith, 2014: Food Security and Agri-Foreign Direct Investment in Weak States: Finding the Governance Gap to Avoid 'Land Grab'. *Mod. Law Rev.*, **77**(2), 189-222, doi:10.1111/1468-2230.12062.
Habermann, E. et al., 2019: Warming and water deficit impact leaf photosynthesis and decrease forage quality and digestibility of a C4 tropical grass. *Physiol. Plant.*, **165**(2), 383-402, doi:10.1111/ppl.12891.
Hadjichambis, A. et al., 2008: Wild and semi-domesticated food plant consumption in seven circum-Mediterranean areas. *Int. J. Food Sci. Nutr.*, **59**(5), 383-414, doi:10.1080/09637480701566495.
Hagenlocher, M. et al., 2019: Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda. *Environ. Res. Lett.*, **14**(8), doi:10.1088/1748-9326/ab225d.
Haglund, E., J. Ndjeunga, L. Snook and D. Pasternak, 2011: Dry land tree management for improved household livelihoods: farmer managed natural regeneration in Niger. *J Environ Manage*, **92**(7), 1696-1705, doi:10.1016/j.jenvman.2011.01.027.
Hai, N. T., B. Dell, V. T. Phuong and R. J. Harper, 2020: Towards a more robust approach for the restoration of mangroves in Vietnam. *Annals of Forest Science*, **77**(1), 18, doi:10.1007/s13595-020-0921-0.
Hailegiorgis, A., A. Crooks and C. Cioffi-Revilla, 2018: An agent-based model of rural households' adaptation to climate change. *J. Artif. Soc. Soc. Simul.*, **21**(4), doi:10.18564/jasss.3812.
Haileslassie, A. et al., 2009: Livestock water productivity in mixed crop-livestock farming systems of the Blue Nile basin: assessing variability and prospects for improvement. *Agric. Syst.*, **102**(1-3), 33-40, doi:10.1016/j.agsy.2009.06.006.
Haji, J. and B. Legesse, 2017: Impact of sedentarization program on the livelihood and food security of Ethiopian pastoralists. *J. Arid Environ.*, **136**, 45-53, doi:10.1016/j.jaridenv.2016.10.007.
Hajjar, R., G. Engbring and K. Kornhauser, 2021: The impacts of REDD plus on the social-ecological resilience of community forests. *Environ. Res. Lett.*, **16**(2), doi:10.1088/1748-9326/abd7ac.
Hak, S., J. McAndrew and A. Neef, 2018: Impact of government policies and corporate land grabs on indigenous people's access to common lands and livelihood resilience in Northeast Cambodia. *Land*, **7**(4), doi:10.3390/land7040122.
Hakkenberg, R. et al., 2008: Temperature sensitivity of the turnover times of soil organic matter in forests. *Ecol. Appl.*, **18**(1), 119-131, doi:10.1890/06-1034.1.
Hall, A., A. J. Mathews and B. P. Holzapfel, 2016: Potential effect of atmospheric warming on grapevine phenology and post-harvest heat accumulation across a range of climates. *Int J Biometeorol*, **60**(9), 1405-1422, doi:10.1007/s00484-016-1133-z.
Hallegatte, S. et al., 2018: *The Economics of (and Obstacles to) Aligning Development and Climate Change Adaptation*. Global Center on Adaptation, Rotterdam and Washington, DC. Available at: www.gca.org.
Haller, T., 2019: The different meanings of land in the age of neoliberalism: Theoretical reflections on commons and resilience grabbing from a social anthropological perspective. *Land*, **8**(7), doi:10.3390/land8070104.
Haller, T., F. Käser and M. Ngutu, 2020: Does commons grabbing lead to resilience grabbing? The anti-politics machine of neo-liberal agrarian development and local responses. *Land*, **9**(7), doi:10.3390/land9070220.
Halpern, B. S. et al., 2019: Putting all foods on the same table: achieving sustainable food systems requires full accounting. *Proc Natl Acad Sci U S A*, **116**(37), 18152-18156, doi:10.1073/pnas.1913308116.
Halvey, M. R. et al., 2020: Beyond backyard chickens: A framework for understanding municipal urban agriculture policies in the United States. *Food Policy*, 102013-102013, doi:10.1016/j.foodpol.2020.102013.
Hambrey, J., 2017: *The 2030 Agenda and the Sustainable Development Goals: The Challenge for Aquaculture Development and Management.* FAO Fisheries and Aquaculture Circular, vol. 1141, Food and Agriculture Organization of the United Nations,, Rome, Italy, 62 pp. ISBN 978925109928.
Hamilton, L. C. et al., 2016: Alaska. *Population and Environment*, **38**(2), 115-133, doi:10.1007/s11111-016-0259-6.
Hammill, M. O., 2009: Ringed seal: Pusa hispida. In: *Encyclopedia of Marine Mammals*, 2 ed. [Perrin, W. F., B. Würsig and J. G. M. Thewissen (eds.)]. Academic, Burlington, MA, USA, pp. 972-974. ISBN 97801237355539.
Hanaček, K. and B. Rodríguez-Labajos, 2018: Impacts of land-use and management changes on cultural agroecosystem services and environmental conflicts—a global review. *Global Environ. Change*, **50**, 41-59, doi:10.1016/j.gloenvcha.2018.02.016.

Handisyde, N., T. C. Telfer and L. G. Ross, 2017: Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish Fish.*, **18**(3), 466-488, doi:10.1111/faf.12186.
Hanich, Q. et al., 2018: Small-scale fisheries under climate change in the Pacific Islands region. *Mar. Policy*, **88**, 279-284, doi:10.1016/j.marpol.2017.11.011.
Hank, T. B. et al., 2019: Spaceborne imaging spectroscopy for sustainable agriculture: contributions and challenges. *Surv. Geophys.*, **40**(3), 515-551, doi:10.1007/s10712-018-9492-0.
Hannah, L. et al., 2017: Regional modeling of climate change impacts on smallholder agriculture and ecosystems in Central America. *Clim. Change*, **141**(1), 29-45, doi:10.1007/s10584-016-1867-y.
Hansel, M. C. et al., 2020: Ocean warming and acidification may drag down the commercial Arctic cod fishery by 2100. *PLoS One*, **15**(4), e0231589, doi:10.1371/journal.pone.0231589.
Hansen, B. B. et al., 2013: Climate events synchronize the dynamics of a resident vertebrate community in the high Arctic. *Science*, **339**(6117), 313-315, doi:10.1126/science.1226766.
Hansen, J. et al., 2019a: Climate risk management and rural poverty reduction. *Agric. Syst.*, **172**, 28-46, doi:10.1016/j.agsy.2018.01.019.
Hansen, P. G., M. Schilling and M. S. Malthesen, 2019b: Nudging healthy and sustainable food choices: three randomized controlled field experiments using a vegetarian lunch-default as a normative signal. *J. Public Health*, **43**(2), 392-397, doi:10.1093/pubmed/fdz154.
Hanssen, S. V. et al., 2020: The climate change mitigation potential of bioenergy with carbon capture and storage. *Nat. Clim. Change*, **10**(11), 1023-1029, doi:10.1038/s41558-020-0885-y.
Haque, E. et al., 2018: Application of CRISPR/Cas9 genome editing technology for the improvement of crops cultivated in tropical climates: recent progress, prospects, and challenges. *Front Plant Sci*, **9**, 617, doi:10.3389/fpls.2018.00617.
Hariharan, V. K. et al., 2018: Does climate-smart village approach influence gender equality in farming households? A case of two contrasting ecologies in India. *Clim. Change*, **158**(1), 77-90, doi:10.1007/s10584-018-2321-0.
Harland, J., 2019: The origins of aquaculture. *Nat Ecol Evol*, **3**(10), 1378-1379, doi:10.1038/s41559-019-0966-3.
Harle, K. J., S. M. Howden, L. P. Hunt and M. Dunlop, 2007: The potential impact of climate change on the Australian wool industry by 2030. *Agric. Syst.*, **93**(1-3), 61-89, doi:10.1016/j.agsy.2006.04.003.
Harper, S. et al., 2020: Valuing invisible catches: Estimating the global contribution by women to small-scale marine capture fisheries production. *PLoS One*, **15**(3), e0228912, doi:10.1371/journal.pone.0228912.
Harris, J. et al., 2021: *Fruits and Vegetables for Healthy Diets: Priorities for Food System Research and Action*. Food Systems Summit Briefs, The Scientific Group for the Food Systems Summit,, 11 pp. Available at: <Go to WoS>://WOS:000442732300001 (accessed 03/08/2021).
Harrison, H. L., S. Rybraten and O. Aas, 2018: Hatching knowledge: a case study on the hybridization of local ecological knowledge and scientific knowledge in small-scale Atlantic salmon (Salmo salar) cultivation in Norway. *Hum. Ecol.*, **46**(4), 449-459, doi:10.1007/s10745-018-0001-3.
Harrison, M. T., B. R. Cullen and D. Armstrong, 2017: Management options for dairy farms under climate change: Effects of intensification, adaptation and simplification on pastures, milk production and profitability. *Agric. Syst.*, **155**, 19-32, doi:10.1016/j.agsy.2017.04.003.
Harrison, M. T., B. R. Cullen and R. P. Rawnsley, 2016: Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. *Agric. Syst.*, **148**, 135-148, doi:10.1016/j.agsy.2016.07.006.
Harrod, C., A. Ramírez, J. Valbo-Jørgensen and S. Funge-Smith, 2018a: Current anthropogenic stress and projected effect of climate change on global inland fisheries. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agricultural Organization of the United Nations,, Rome, Italy, pp. 393-448. ISBN 9789251306079.
Harrod, C., A. Ramírez, J. Valbo-Jørgensen and S. Funge-Smith, 2018b: How climate change impacts inland fisheries. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 375-392. ISBN 9789251306079.
Harrod, C., F. Simmance, S. Funge-Smith and J. Valbo-Jørgensen, 2018c: Options and opportunities for supporting inland fisheries to cope with climate change adaptation in other sectors. In: *Impacts of*

climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options [Barange, M., T. Bahri, M. C. M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. FAO, Rome, pp. 567-584.

Hartiningtias, D., P. Z. Fulé and A. A. Gunawan, 2020: Wildfire effects on forest structure of Pinus merkusii in Sumatra, Indonesia. *For. Ecol. Manag.*, **457**, doi:10.1016/j.foreco.2019.117660.

Hasan, M. R. and S. Soto, 2017: *Improving Feed Conversion Ratio and Its Impact on Reducing Greenhouse Gas Emissions in Aquaculture*. Food and Agriculture Organization of the United Nations,, Rome, Italy, 33 pp. ISBN 9789251098868.

Hasegawa, T. et al., 2018: Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Change*, **8**(8), 699-703, doi:10.1038/s41558-018-0230-x.

Hasegawa, T. et al., 2016: Rice free-air carbon dioxide enrichment studies to improve assessment of climate change effects on rice agriculture. In: *Improving Modeling Tools to Assess Climate Change Effects on Crop Response* [Hatfield, J. L. and D. Fleisher (eds.)]. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America,, Madison, WI, USA, pp. 45-68. ISBN 9780891183518.

Hasegawa, T. et al., 2021a: Extreme climate events increase risk of global food insecurity and adaptation needs. *Nat. Food*, **2**(8), 587-595, doi:10.1038/s43016-021-00335-4.

Hasegawa, T. et al., 2021b: A global dataset for the projected impacts of climate change on four major crops. *Biorxiv*, doi:10.1101/2021.05.27.444762.

Hassan, B. et al., 2020: Impact of climate change on freshwater ecosystem and its sustainable management. In: *Fresh Water Pollution Dynamics and Remediation* [Qadri, H., R. A. Bhat, M. A. Mehmood and G. H. Dar (eds.)]. Springer Nature, Singapore, Singapore. ISBN 9789811382785.

Hasselberg, A. E. et al., 2020: Fish for food and nutrition security in Ghana: challenges and opportunities. *Global Food Security-Agriculture Policy Economics and Environment*, **26**, 100380, doi:10.1016/j.gfs.2020.100380.

Hassen, A. et al., 2017: Potential use of forage-legume intercropping technologies to adapt to climate-change impacts on mixed crop-livestock systems in Africa: a review. *Reg. Environ. Change*, **17**(6), 1713-1724, doi:10.1007/s10113-017-1131-7.

Havemann, T., C. Negra and F. Werneck, 2020: Blended finance for agriculture: exploring the constraints and possibilities of combining financial instruments for sustainable transitions. *Agric Human Values*, **1**, 1-12, doi:10.1007/s10460-020-10131-8.

Havet, A. et al., 2014: Review of livestock farmer adaptations to increase forages in crop rotations in western France. *Agric. Ecosyst. Environ.*, **190**, 120-127, doi:10.1016/j.agee.2014.01.009.

Havlik, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proc Natl Acad Sci U S A*, **111**(10), 3709-3714, doi:10.1073/pnas.1308044111.

Haworth, M., Y. Hoshika and D. Killi, 2016: Has the impact of rising CO2 on plants been exaggerated by meta-analysis of free air CO2 enrichment studies? *Front Plant Sci*, **7**, 1153, doi:10.3389/fpls.2016.01153.

He, W. et al., 2019: Assessing alfalfa production under historical and future climate in eastern Canada: DNDC model development and application. *Environ. Model. Software*, **122**, 104540-104540, doi:10.1016/j.envsoft.2019.104540.

Heck, V., D. Gerten, W. Lucht and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat. Clim. Change*, **8**(2), 151-155, doi:10.1038/s41558-017-0064-y.

Heffernan, C., 2018: Climate change and multiple emerging infectious diseases. *Vet. J.*, **234**, 43-47, doi:10.1016/j.tvjl.2017.12.021.

Heide-Jørgensen, M. P., 2018: Narwhal: Monodon monoceros. In: *Encyclopedia of Marine Mammals*, 2 ed. [Perrin, W. F., B. Würsig and J. G. M. Thewissen (eds.)]. Academic, Burlington, MA, USA, pp. 627-631. ISBN 97801237355539.

Heinemann, J., D. S. Coray and D. S. Thaler, 2018: *Exploratory fact-finding scoping study on "digital sequence information" on genetic resources for food and agriculture*. Background Study Paper, **No. 68**, UN FAO Rome.

Heinemann, J. A. et al., 2014: Sustainability and innovation in staple crop production in the US Midwest. *Int. J. Agric. Sustain.*, **12**(1), 71-88, doi:10.1080/14735903.2013.806408.

Heino, M. et al., 2020: A multi-model analysis of teleconnected crop yield variability in a range of cropping systems. *Earth Syst. Dyn.*, **11**, 113-128, doi:10.5194/esd-11-113-2020.

Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technol. Forecast. Soc. Change*, **81**, 205-226, doi:10.1016/j.techfore.2013.05.006.

Hellberg, R. S. and E. Chu, 2016: Effects of climate change on the persistence and dispersal of foodborne bacterial pathogens in the outdoor environment: A review. *Crit. Rev. Microbiol.*, **42**(4), 548-572, doi:10.3109/1040841X.2014.972335.

Hempel, S. and C. Menz, 2019: Indoor climate projections for European cattle barns, V1. *Mendeley Data*. Available at: https://doi.org/10.17632/tjp8h523p7.1 (accessed 03/08/2021).

Henchion, M. et al., 2017: Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. *Foods*, **6**(7), 53, doi:10.3390/foods6070053.

Henders, S., U. M. Persson and T. Kastner, 2015: Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. *Environ. Res. Lett.*, **10**(12), 125012, doi:10.1088/1748-9326/10/12/125012.

Henderson, B. et al., 2018: The economic potential of residue management and fertilizer use to address climate change impacts on mixed smallholder farmers in Burkina Faso. *Agric. Syst.*, **167**, 195-205, doi:10.1016/j.agsy.2018.09.012.

Hendrix, C. S., 2018: Searching for climate-conflict links. *Nat. Clim. Change*, **8**(3), 190-191, doi:10.1038/s41558-018-0083-3.

Hennon, G. M. M. and S. T. Dyhrman, 2020: Progress and promise of omics for predicting the impacts of climate change on harmful algal blooms. *Harmful Algae*, **91**, 101587-101587, doi:10.1016/j.hal.2019.03.005.

Henry, B. K., R. J. Eckard and K. A. Beauchemin, 2018: Review: Adaptation of ruminant livestock production systems to climate changes. *Animal*, **12**(s2), s445-s456, doi:10.1017/S1751731118001301.

Henry, R. C. et al., 2019: The role of global dietary transitions for safeguarding biodiversity. *Global Environ. Change*, **58**, 101956-101956, doi:10.1016/j.gloenvcha.2019.101956.

Herath, S., K. Tsusaka and J. Diwa, 2015: *Assessment on the Feasibility of REDD+ in Nagacadan Rice Terraces of Ifugao and Its Muyong Forest*. Rice Terrace Farming Systems Working Paper Series, United Nations University Institute for the Advanced Study of Sustainability, Tokyo, Japan, 8 pp. Available at: <Go to WoS>://WOS:000364024300035 (accessed 03/08/2021).

Herbert, E. R. et al., 2015: A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. *Ecosphere*, **6**(10), 206, doi:10.1890/Es14-00534.1.

Herbut, P., S. Angrecka, D. Godyń and G. Hoffmann, 2019: The Physiological and Productivity Effects of Heat Stress in Cattle: A Review. *Annals of Animal Science*, **19**(3), 579-593, doi:10.2478/aoas-2019-0011.

Herforth, A. and S. Ahmed, 2015: The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Secur.*, **7**(3), 505-520, doi:10.1007/s12571-015-0455-8.

Herman-Mercer, N. M. et al., 2019: Vulnerability of subsistence systems due to social and environmental change: a case study in the Yukon-Kuskokwim Delta, Alaska. *Arctic*, **72**(3), 258-272, doi:10.14430/arctic68867.

Herman-Mercer, N. M., R. A. Loehman, R. C. Toohey and C. Paniyak, 2020: Climate- and disturbance-driven changes in subsistence berries in coastal Alaska: indigenous knowledge to inform ecological inference. *Hum. Ecol.*, **48**(1), 85-99, doi:10.1007/s10745-020-00138-4.

Hernández-Morcillo, M. et al., 2018: Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environ. Sci. Policy*, **80**, 44-52, doi:10.1016/j.envsci.2017.11.013.

Hernroth, B. E. and S. P. Baden, 2018: Alteration of host-pathogen interactions in the wake of climate change - Increasing risk for shellfish associated infections? *Environ. Res.*, **161**, 425-438, doi:10.1016/j.envres.2017.11.032.

Herrero, M. et al., 2020: Innovation can accelerate the transition towards a sustainable food system. *Nat. Food*, **1**(5), 266-272, doi:10.1038/s43016-020-0074-1.

Herrero, M. et al., 2017: Farming and the geography of nutrient production for human use: a transdisciplinary analysis. *Lancet Planet. Health*, **1**(1), E33-E42, doi:10.1016/s2542-5196(17)30007-4.

Herrero, M. et al., 2015: Livestock and the environment: what have we learned in the past decade? *Annual Review of Environment and Resources*, **40**(1), 177-202, doi:10.1146/annurev-environ-031113-093503.

Herring, S. C. et al., 2018: Explaining Extreme Events of 2016 from a Climate Perspective. *Bull. Am. Meterol. Soc.*, **99**(1), S1-S157, doi:10.1175/BAMS-ExplainingExtremeEvents2016.1.
Hertel, T. W. and U. L. C. Baldos, 2016: Attaining food and environmental security in an era of globalization. *Glob. Environ. Change*, **41**, 195-205, doi:10.1016/j.gloenvcha.2016.10.006.
Hertel, T. W. and C. Z. de Lima, 2020: Viewpoint: climate impacts on agriculture: searching for keys under the streetlight. *Food Policy*, **95**, doi:10.1016/j.foodpol.2020.101954.
Heslin, A., 2021: Riots and resources: How food access affects collective violence. *Journal of Peace Research*, **58**(2), 199-214, doi:10.1177/0022343319898227.
Hickey, G. M. and N. Unwin, 2020: Addressing the triple burden of malnutrition in the time of COVID-19 and climate change in small island developing states: what role for improved local food production? *Food Secur*, **12**, 1-5, doi:10.1007/s12571-020-01066-3.
Hickman, J. E. et al., 2017: Nonlinear response of nitric oxide fluxes to fertilizer inputs and the impacts of agricultural intensification on tropospheric ozone pollution in Kenya. *Glob Chang Biol*, **23**(8), 3193-3204, doi:10.1111/gcb.13644.
Hicks, C. C. et al., 2019: Harnessing global fisheries to tackle micronutrient deficiencies. *Nature*, **574**(7776), 95-98, doi:10.1038/s41586-019-1592-6.
Hicks Pries, C. E. et al., 2018: Response to comment on "The whole-soil carbon flux in response to warming". *Science*, **359**(6378), eaao0457, doi:10.1126/science.aao0457.
Hicks Pries, C. E., C. Castanha, R. C. Porras and M. S. Torn, 2017: The whole-soil carbon flux in response to warming. *Science*, **355**(6332), 1420-1423, doi:10.1126/science.aal1319.
Hidalgo, H. A., 2015: Vulnerability assessment of agri-ecotourism communities as influenced by climate change. *International Journal on Advanced Science, Engineering and Information Technology*, **5**(6), 379, doi:10.18517/ijaseit.5.6.553.
Hidalgo, M., V. Mihneva, M. Vasconcellos and M. Bernal, 2018: Climate change impacts, vulnerabilities and adaptations: Mediterranean Sea and the Black Sea marine fisheries. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 139-158. ISBN 9789251306079.
Hill, S., 2014: Considerations for enabling the ecological redesign of organic and conventional agriculture: A social ecology and psychosocial perspective. [Bellon, S. and S. Penvern (eds.)]. Springer Science+Business Media, Dordrecht, pp. 401-422.
Hilmi, N. et al., 2014: Exposure of Mediterranean countries to ocean acidification. *Water*, **6**(6), 1719-1744, doi:10.3390/w6061719.
Hiltner, U. et al., 2021: Climate change alters the ability of neotropical forests to provide timber and sequester carbon. *For. Ecol. Manag.*, **492**, 119166, doi:10.1016/j.foreco.2021.119166.
Hitchcock, R., 2016: From Local to Global: Perceptions and Realities of Environmental Change Among Kalahari San. In: *Anthropology and Climate Change: From Encounters to Actions* [Crate, S. A. and M. Nuttall (eds.)]. Routledge, Oxon, United Kingdom and New York, NY, USA, pp. 250-262. ISBN 9781598743333.
Hixson, S. M. and M. T. Arts, 2016: Climate warming is predicted to reduce omega-3, long-chain, polyunsaturated fatty acid production in phytoplankton. *Glob Chang Biol*, **22**(8), 2744-2755, doi:10.1111/gcb.13295.
Hlásny, T. et al., 2021: Devastating outbreak of bark beetles in the Czech Republic: drivers, impacts, and management implications. *For. Ecol. Manag.*, **490**, doi:10.1016/j.foreco.2021.119075.
HLPE, 2013: *Investing in Smallholder Agriculture for Food Security*. HLPE Report, High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security,, Rome, Italy, 112 pp. Available at: <Go to WoS>://WOS:000406485000003 (accessed 03/08/2021).
HLPE, 2014: *Sustainable Fisheries and Aquaculture for Food Security and Nutrition*. HLPE Report, High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, , Rome, Italy, 119 pp. Available at: http://www.fao.org/3/i3844e/i3844e.pdf (accessed 03/08/2021).
HLPE, 2017a: *Nutrition and Food Systems*. HLPE Report, High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security,, 152 pp. Available at: http://www.fao.org/3/i7846e/i7846e.pdf (accessed 03/08/2021).
HLPE, 2017b: *Sustainable Forestry for Food Security and Nutrition*. HLPE Report, High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security,, Rome, Italy, 137 pp. Available at: http://www.fao.org/3/i7395e/i7395e.pdf (accessed 03/08/2021).

HLPE, 2019: *Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems that Enhance Food Security and Nutrition*. HLPE Report, High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security,, Rome, Italy, 163 pp. Available at: http://www.fao.org/3/ca5602en/ca5602en.pdf (accessed 03/08/2021).
HLPE, 2020: *Impacts of COVID-19 on Food Security and Nutrition: Developing Effective Policy Responses to Address the Hunger and Malnutrition Pandemic*. HLPE Issues Paper, High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security,, Rome, Italy, 22 pp. Available at: https://doi.org/10.4060/cb1000en (accessed 03/08/2021).
HLPE, 2021: *Promoting youth engagement and employment in agriculture and food systems*. High Level Panel of Experts (HLPE) of UN Committee for World Food Security Food and Agrcultural Organization (FAO).
Hobbs, N. T. et al., 2008: Fragmentation of rangelands: implications for humans, animals, and landscapes. *Glob. Environ. Change*, **18**(4), 776-785, doi:10.1016/j.gloenvcha.2008.07.011.
Hobbs, R. J., L. E. Valentine, R. J. Standish and S. T. Jackson, 2018: Movers and stayers: novel assemblages in changing environments. *Trends Ecol. Evol.*, **33**(2), 116-128, doi:10.1016/j.tree.2017.11.001.
Hobday, A. J. et al., 2017: *National climate change adaptation research plan marine biodiversity and resources: update 2017.*, National Climate Change Adaptation Research Facility, Gold Coast, 75 pp.
Hobday, A. J. et al., 2018: A framework for combining seasonal forecasts and climate projections to aid risk management for fisheries and aquaculture. *Front. Mar. Sci.*, **5**, doi:10.3389/fmars.2018.00137.
Hochman, Z., D. L. Gobbett and H. Horan, 2017: Climate trends account for stalled wheat yields in Australia since 1990. *Glob Chang Biol*, **23**(5), 2071-2081, doi:10.1111/gcb.13604.
Hodges, R. J., J. C. Buzby and B. Bennett, 2011: Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. *J. Agric. Sci.*, **149**, 37-45, doi:10.1017/S0021859610000936.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)].
Hoffman, J. S., V. Shandas and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: a study of 108 US urban areas. *Climate*, **8**(1), 12, doi:10.3390/cli8010012.
Hofmeijer, I. et al., 2013: Community vulnerability to the health effects of climate change among indigenous populations in the Peruvian Amazon: a case study from Panaillo and Nuevo Progreso. *Mitig. Adapt. Strateg. Glob. Change*, **18**(7), 957-978, doi:10.1007/s11027-012-9402-6.
Holland, R. A. et al., 2015: A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews*, **46**, 30-40, doi:10.1016/j.rser.2015.02.003.
Holmes, I., K. R. Kirby and C. Potvin, 2017: Agroforestry within REDD plus : experiences of an indigenous Embera community in Panama. *Agroforestry Systems*, **91**(6), 1181-1197, doi:10.1007/s10457-016-0003-3.
Holsman, K. K. et al., 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nat Commun*, **11**(1), 4579, doi:10.1038/s41467-020-18300-3.
Holsman, K. K. et al., 2019: Towards climate resiliency in fisheries management. *ICES J. Mar. Sci.*, **76**(5), 1368-1378, doi:10.1093/icesjms/fsz031.
Holt-Giménez, E., A. Shattuck and I. Van Lammeren, 2021: Thresholds of resistance: agroecology, resilience and the agrarian question. *The Journal of Peasant Studies*, **48**(4), 715-733, doi:10.1080/03066150.2020.1847090.
Honkaniemi, J., W. Rammer and R. Seidl, 2020: Norway spruce at the trailing edge: the effect of landscape configuration and composition on climate resilience. *Landsc Ecol*, **35**(3), 591-606, doi:10.1007/s10980-019-00964-y.
Hopping, K. A., S. M. Chignell and E. F. Lambin, 2018: The demise of caterpillar fungus in the Himalayan region due to climate change and overharvesting. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(45), 11489-11494, doi:10.1073/pnas.1811591115.

Hopping, K. A., C. R. Yangzong and J. A. Klein, 2016: Local knowledge production, transmission, and the importance of village leaders in a network of Tibetan pastoralists coping with environmental change. *Ecol. Soc.*, **21**(1), 25, doi:10.5751/Es-08009-210125.
Horst, M., N. McClintock and L. Hoey, 2017: The intersection of planning, urban agriculture, and food justice: a review of the literature. *Journal of the American Planning Association*, **83**(3), 277-295, doi:10.1080/01944363.2017.1322914.
Horstkotte, T. et al., 2017: Human-animal agency in reindeer management: Sami herders' perspectives on vegetation dynamics under climate change. *Ecosphere*, **8**(9), e01931, doi:10.1002/ecs2.1931.
Hosonuma, N. et al., 2012: An assessment of deforestation and forest degradation drivers in developing countries. *Environ. Res. Lett.*, **7**(4), 044009, doi:10.1088/1748-9326/7/4/044009.
Hossain, M. A. R., M. Ahmed, E. Ojea and J. A. Fernandes, 2018: Impacts and responses to environmental change in coastal livelihoods of south-west Bangladesh. *Sci. Total Environ.*, **637-638**, 954-970, doi:10.1016/j.scitotenv.2018.04.328.
Houser, M. and D. Stuart, 2019: An accelerating treadmill and an overlooked contradiction in industrial agriculture: climate change and nitrogen fertilizer. *J. Agrar. Change*, **20**(2), 215-237, doi:10.1111/joac.12341.
Houston, R. D. et al., 2020: Harnessing genomics to fast-track genetic improvement in aquaculture. *Nat. Rev. Genet.*, **21**(7), 389-409, doi:10.1038/s41576-020-0227-y.
Hristov, A. N. et al., 2018: Climate change effects on livestock in the Northeast US and strategies for adaptation. *Clim. Change*, **146**(1-2), 33-45, doi:10.1007/s10584-017-2023-z.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356**(6345), 1362-1369, doi:10.1126/science.aal4369.
Hu, H. and L. Xiong, 2014: Genetic engineering and breeding of drought-resistant crops. *Annu. Rev. Plant Biol.*, **65**(1), 715-741, doi:10.1146/annurev-arplant-050213-040000.
Hua, K. et al., 2019: The Future of Aquatic Protein: Implications for Protein Sources in Aquaculture Diets. *One Earth*, **1**(3), 316-329, doi:10.1016/j.oneear.2019.10.018.
Huaman, E. S. and L. A. Valdiviezo, 2014: Indigenous knowledge and education from the Quechua community to school: beyond the formal/non-formal dichotomy. *Int. J. Qual. Stud. Educ.*, **27**(1), 65-87, doi:10.1080/09518398.2012.737041.
Huang, J. and H. Hao, 2020: Effects of climate change and crop planting structure on the abundance of cotton bollworm, Helicoverpa armigera (Hubner) (Lepidoptera: Noctuidae). *Ecol Evol*, **10**(3), 1324-1338, doi:10.1002/ece3.5986.
Huang, J., A. E. Hartemink and C. J. Kucharik, 2021: Soil-dependent responses of US crop yields to climate variability and depth to groundwater. *Agric. Syst.*, **190**, 103085, doi:10.1016/j.agsy.2021.103085.
Hubau, W. et al., 2020: Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, **579**(7797), 80-87, doi:10.1038/s41586-020-2035-0.
Hules, M. and S. J. Singh, 2017: India's land grab deals in Ethiopia: Food security or global politics? *Land Use Policy*, **60**, 343-351, doi:10.1016/j.landusepol.2016.10.035.
Humphries, S. et al., 2015: Synergies at the interface of farmer–scientist partnerships: agricultural innovation through participatory research and plant breeding in Honduras. *Agric. Food Secur.*, **4**(1), 1-17, doi:10.1186/s40066-015-0046-0.
Hunsberger, C. et al., 2017: Climate change mitigation, land grabbing and conflict: towards a landscape-based and collaborative action research agenda. *Can. J. Dev. Stud.*, **38**(3), 305-324, doi:10.1080/02255189.2016.1250617.
Huntington, H. P. et al., 2015: Vessels, risks, and rules: planning for safe shipping in Bering Strait. *Mar. Policy*, **51**, 119-127, doi:10.1016/j.marpol.2014.07.027.
Huntington, H. P., L. T. Quakenbush and M. Nelson, 2017: Evaluating the effects of climate change on indigenous marine mammal hunting in northern and western Alaska using traditional knowledge. *Front. Mar. Sci.*, **4**, 319, doi:10.3389/fmars.2017.00319.
Hupp, J., M. Brubaker, K. Wilkinson and J. Williamson, 2015: How are your berries? Perspectives of Alaska's environmental managers on trends in wild berry abundance. *Int J Circumpolar Health*, **74**, 28704, doi:10.3402/ijch.v74.28704.
Huq, N., A. Bruns, L. Ribbe and S. Huq, 2017: Mainstreaming ecosystem services based climate change adaptation (EbA) in Bangladesh: status, challenges and opportunities. *Sustainability*, **9**(6), 926, doi:10.3390/su9060926.

Huq, N. and A. Stubbings, 2016: How is the role of ecosystem services considered in local level flood management policies: case study in Cumbria, England. *Journal of Environmental Assessment Policy and Management*, **17**(04), 1550032, doi:10.1142/s1464333215500325.

Hurlbert, M. et al., 2019: Risk management and decision-making in relation to sustainable development. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)].

Hussain, A., G. Rasul, B. Mahapatra and S. Tuladhar, 2016: Household food security in the face of climate change in the Hindu-Kush Himalayan region. *Food Secur.*, **8**(5), 921-937, doi:10.1007/s12571-016-0607-5.

Hussain, M. I., M. Farooq, A. Muscolo and A. Rehman, 2020: Crop diversification and saline water irrigation as potential strategies to save freshwater resources and reclamation of marginal soils-a review. *Environ Sci Pollut Res Int*, **27**(23), 28695-28729, doi:10.1007/s11356-020-09111-6.

Hutter, S. E. et al., 2018: Assessing changing weather and the El Nino Southern Oscillation impacts on cattle rabies outbreaks and mortality in Costa Rica (1985-2016). *BMC Vet Res*, **14**(1), 285, doi:10.1186/s12917-018-1588-8.

Huyer, S. et al., 2019: *Learning and action for gender-transformative climate-smart agriculture*. Wageningen, The Netherlands, 26-26 pp.

Huyer, S. and S. Partey, 2020: Weathering the storm or storming the norms? Moving gender equality forward in climate-resilient agriculture Introduction to the Special Issue on Gender Equality in Climate-Smart Agriculture: Approaches and Opportunities. *Clim. Change*, **158**(1), 1-12, doi:10.1007/s10584-019-02612-5.

Hvas, M. and F. Oppedal, 2019: Physiological responses of farmed Atlantic salmon and two cohabitant species of cleaner fish to progressive hypoxia. *Aquaculture*, **512**, 734353, doi:10.1016/j.aquaculture.2019.734353.

Ickowitz, A. et al., 2019: Agricultural intensification, dietary diversity, and markets in the global food security narrative. *Global Food Security-Agriculture Policy Economics and Environment*, **20**, 9-16, doi:10.1016/j.gfs.2018.11.002.

IFAD, 2019: *Creating opportunities for rural youth. 2019 Rural Development Report*. International Fund for Agricultural Development. Available at: https://www.ifad.org/documents/38714170/41133075/RDR_report.pdf/7282db66-2d67-b514-d004-5ec25d9729a0.

IGAD, 2020: *Food Security and Nutrition Response Strategy*. Intergovernmental Authority on Development,, 62 pp. Available at: <Go to WoS>://WOS:000398922100006 (accessed 05/08/2021).

Iiyama, M. et al., 2017: Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. *Agroforestry Systems*, **91**(2), 271-293, doi:10.1007/s10457-016-9926-y.

Iiyama, M. et al., 2018: Addressing the paradox - the divergence between smallholders' preference and actual adoption of agricultural innovations. *Int. J. Agric. Sustain.*, **16**(6), 472-485, doi:10.1080/14735903.2018.1539384.

Iizumi, T., 2019: Emerging adaptation to climate change in agriculture. In: *Adaptation to Climate Change in Agriculture: Research and Practices* [Iizumi, T., R. Hirata and R. Matsuda (eds.)]. Springer Nature, Singapore, Singapore, pp. 3-16. ISBN 9789811392344.

Iizumi, T. et al., 2021a: Rising temperatures and increasing demand challenge wheat supply in Sudan. *Nat. Food*, **2**(1), 19-27, doi:10.1038/s43016-020-00214-4.

Iizumi, T. et al., 2017: Responses of crop yield growth to global temperature and socioeconomic changes. *Sci Rep*, **7**(1), 7800, doi:10.1038/s41598-017-08214-4.

Iizumi, T. and N. Ramankutty, 2016: Changes in yield variability of major crops for 1981-2010 explained by climate change. *Environ. Res. Lett.*, **11**(3), 034003, doi:10.1088/1748-9326/11/3/034003.

Iizumi, T. et al., 2020: Climate change adaptation cost and residual damage to global crop production. *Clim. Res.*, **80**(3), 203-218, doi:10.3354/cr01605.

Iizumi, T. et al., 2018: Crop production losses associated with anthropogenic climate change for 1981-2010 compared with preindustrial levels. *Int. J. Climatol.*, **38**(14), 5405-5417, doi:10.1002/joc.5818.

Iizumi, T. et al., 2021b: Global within-season yield anomaly prediction for major crops derived using seasonal forecasts of large-scale climate indices and regional temperature and precipitation. *Weather Forecast.*, **36**(1), 285-299, doi:10.1175/waf-d-20-0097.1.

Iizumi, T. and R. Wagai, 2019: Leveraging drought risk reduction for sustainable food, soil and climate via soil organic carbon sequestration. *Sci. Rep.*, **9**, 19744, doi:10.1038/s41598-019-55835-y.

Ilboudo Nébié, E. K., D. Ba and A. Giannini, 2021: Food security and climate shocks in Senegal: Who and where are the most vulnerable households? *Glob. Food Secur.*, **29**, 100513-100513, doi:10.1016/j.gfs.2021.100513.

Im, E. S., J. S. Pal and E. A. B. Eltahir, 2017: Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Sci Adv*, **3**(8), e1603322, doi:10.1126/sciadv.1603322.

Imbach, P. et al., 2017: Coupling of pollination services and coffee suitability under climate change. *Proc Natl Acad Sci U S A*, **114**(39), 10438-10442, doi:10.1073/pnas.1617940114.

Imbong, J. D., 2021: "Bungkalan" and the Manobo-Pulangihon tribe's resistance to corporate land-grab in Bukidnon, Mindanao. *AlterNative*, **17**(1), 23-31, doi:10.1177/1177180120967724.

Inaotombi, S. and P. C. Mahanta, 2019: Pathways of socio-ecological resilience to climate change for fisheries through indigenous knowledge. *Hum. Ecol. Risk Assess.*, **25**(8), 2032-2044, doi:10.1080/10807039.2018.1482197.

Ingalls, M. L. et al., 2018: The transboundary displacement of deforestation under REDD+: Problematic intersections between the trade of forest-risk commodities and land grabbing in the Mekong region. *Global Environ. Change*, **50**(November 2017), 255-267, doi:10.1016/j.gloenvcha.2018.04.003.

Ingram, D. J., 2020: Wild meat in changing times. *Journal of Ethnobiology*, **40**(2), 117-130, doi:10.2993/0278-0771-40.2.117.

Ioannou, L. G. et al., 2017: Time-motion analysis as a novel approach for evaluating the impact of environmental heat exposure on labor loss in agriculture workers. *Temperature*, **4**(3), 330-340, doi:10.1080/23328940.2017.1338210.

IPBES, 2019: *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* [Díaz, S., J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis and C. N. Zayas (eds.)]. IPBES secretariat, Bonn, Germany.

IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

IPCC, 2019a: Annex I: Glossary [van Diemen, R. (ed.)]. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.

IPCC, 2019b: *Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. S., E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley (ed.)].

IPCC, 2019c: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O. (ed.)].

IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

IPPC Secretariat, 2021: *Scientific review of the impact of climate change on plant pests- A global challenge to prevent and mitigate plant pest risks in agriculture, forestry and ecosystems*. FAO on behalf of the IPPC Secretariat, Rome, Italy. ISBN 978-92-5-134435-4.

Irimia, L. M., C. V. Patriche and O. C. Murariu, 2018: The impact of climate change on viticultural potential and wine grape varieties of a temperate wine growing region. *Appl. Ecol. Environ. Res.*, **16**(3), 2663-2680, doi:10.15666/aeer/1603_26632680.

Isakson, S. R., 2014: Food and finance: the financial transformation of agro-food supply chains. *J. Peasant Stud.*, **41**(5), 749-775, doi:10.1080/03066150.2013.874340.

Isakson, S. R., 2015: Derivatives for development? Small-farmer vulnerability and the financialization of climate risk management. *J. Agrar. Change*, **15**(4), 569-580, doi:10.1111/joac.12124.

Isbell, F. et al., 2017: Benefits of increasing plant diversity in sustainable agroecosystems. *J. Ecol.*, **105**(4), 871-879, doi:10.1111/1365-2745.12789.

Ishigooka, Y. et al., 2021: Revision of estimates of climate change impacts on rice yield and quality in Japan by considering the combined effects of temperature and CO2 concentration. *J. Agric. Meteorol*, **77**(2), 139--149, doi:10.2480/agrmet.D-20-00038.

Islam, M. M. et al., 2019: Vulnerability of inland and coastal aquaculture to climate change: evidence from a developing country. *Aquaculture and Fisheries*, **4**(5), 183-189, doi:10.1016/j.aaf.2019.02.007.

Istomin, K. V. and J. O. Habeck, 2016: Permafrost and indigenous land use in the northern Urals: Komi and Nenets reindeer husbandry. *Polar Science*, **10**(3), 278-287, doi:10.1016/j.polar.2016.07.002.

Iticha, B. and A. Husen, 2019: Adaptation to climate change using indigenous weather forecasting systems in Borana pastoralists of southern Ethiopia. *Clim. Dev.*, **11**(7), 564-573, doi:10.1080/17565529.2018.1507896.

Ito, A. et al., 2018: Comparative phenology of dormant Japanese pear (Pyrus pyrifolia) flower buds: a possible cause of 'flowering disorder'. *Tree Physiol*, **38**(6), 825-839, doi:10.1093/treephys/tpx169.

Iversen, M. et al., 2014: Detection of transgenes in local maize varieties of small-scale farmers in eastern cape, South Africa. *PLoS One*, **9**(12), e116147, doi:10.1371/journal.pone.0116147.

Iverson, L. R., A. M. Prasad, M. P. Peters and S. N. Matthews, 2019: Facilitating adaptive forest management under climate change: a spatially specific synthesis of 125 species for habitat changes and assisted migration over the eastern United States. *Forests*, **10**(11), 989, doi:10.3390/f10110989.

Jachnik, R., R. M. Mirabile and A. Dobrinevski, 2019: *Tracking Finance Flows Towards Assessing their Consistency with Climate Objectives*. OECD Environment Working Papers, Organization for Economic Co-operation and Development,, Paris, France, 42 pp. Available at: <Go to WoS>://WOS:000462897600010 (accessed 05/08/2021).

Jacka, J. K., 2016: Correlating local knowledge with climatic data: Porgeran experiences of climate change in Papua New Guinea. In: *Anthropology and Climate Change: From Actions to Transformations, 2nd Edition*, 2 ed. [Crate, S. A. and M. Nuttall (eds.)]. Routledge, New York, NY, USA and Oxon, United Kingdom, pp. 186-199. ISBN 9781629580005.

Jackley, J., L. Gardner, A. F. Djunaedi and A. K. Salomon, 2016: Ancient clam gardens, traditional management portfolios, and the resilience of coupled human-ocean systems. *Ecol. Soc.*, **21**(4).

Jacobi, J., S. Rist and M. A. Altieri, 2017: Incentives and disincentives for diversified agroforestry systems from different actors' perspectives in Bolivia. *Int. J. Agric. Sustain.*, **15**(4), 365-379, doi:10.1080/14735903.2017.1332140.

Jacobson, C., S. Crevello, C. Chea and B. Jarihani, 2019: When is migration a maladaptive response to climate change? *Reg. Environ. Change*, **19**(1), 101-112, doi:10.1007/s10113-018-1387-6.

Jactel, H. et al., 2018: Positive biodiversity-productivity relationships in forests: climate matters. *Biol. Lett.*, **14**(4), 20170747, doi:10.1098/rsbl.2017.0747.

Jaeger, C. et al., 2019: Mass balanced based LCA of a common carp-lettuce aquaponics system. *Aquac Eng*, **84**, 29-41, doi:10.1016/j.aquaeng.2018.11.003.

Jagermeyr, J. and K. Frieler, 2018: Spatial variations in crop growing seasons pivotal to reproduce global fluctuations in maize and wheat yields. *Sci Adv*, **4**(11), eaat4517, doi:10.1126/sciadv.aat4517.

Jägermeyr, J. et al., 2021: Climate change signal in global agriculture emerges earlier in new generation of climate and crop models". *Nat. Food*, **in press**, doi:10.21203/rs.3.rs-101657/v1.

Jägermeyr, J., A. Pastor, H. Biemans and D. Gerten, 2017: Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. *Nat Commun*, **8**, 15900, doi:10.1038/ncomms15900.

Jain, N. and R. S. Nadgauda, 2013: Commiphora wight (Arnott) Bhandari—a natural source of guggulsterone: facing a high risk of extinction in its natural habitat. *Am. J. Plant Sci.*, **4**(6), 57-68, doi:10.4236/ajps.2013.46A009.

Jalloh, A. et al., 2013: *West African agriculture and climate change: A comprehensive analysis*. IFPRI Issue Brief, International Food Policy Research Institute, Washington, DC, USA, 4 pp. Available at: <Go to WoS>://WOS:000450572900007 (accessed 06/08/2021).

Jamero, M. L., M. Onuki, M. Esteban and N. Tan, 2018: Community-based adaptation in low-lying islands in the Philippines: challenges and lessons learned. *Reg. Environ. Change*, **18**(8), 2249-2260, doi:10.1007/s10113-018-1332-8.

James, S. J. and C. James, 2010: The food cold-chain and climate change. *Food Res. Int.*, **43**(7), 1944-1956, doi:10.1016/j.foodres.2010.02.001.

Jane, S. F. et al., 2021: Widespread deoxygenation of temperate lakes. *Nature*, **594**(7861), 66--70, doi:10.1038/s41586-021-03550-y.

Janetos, A. et al., 2017: *The Risks of Multiple Breadbasket Failures in the 21st Century: A Science Research Agenda.* [The Frederick S. Pardee Center for the Study of the Longer-Range Future (ed.)]. Pardee Center Research Report, Boston University, Boston, MA, USA, 22 pp. ISBN 9781936727148.

Janhiainen, J. S., and Lauri Hooli, 2017: Indigenous knowledge and developing countries' innovation systems: the case of Namibia. *Int. J. Innov. Stud.*, **1**, 89-106, doi:10.3724/SP.J.1440.101007.

Jans, Y., W. von Bloh, S. Schaphoff and C. Muller, 2021: Global cotton production under climate change - Implications for yield and water consumption. *Hydrol. Earth Syst. Sci.*, **25**(4), 2027-2044, doi:10.5194/hess-25-2027-2021.

Janssens, C. et al., 2020: Global hunger and climate change adaptation through international trade. *Nat Clim Chang*, **10**, 829-835, doi:10.1038/s41558-020-0847-4.

Jantarasami, L. et al., 2018: *Chapter 15 : Tribal and Indigenous Communities. Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II*. Washington, DC. Available at: https://nca2018.globalchange.gov/chapter/15/.

Jarecki, M. et al., 2018: Long-term Trends in Corn Yields and Soil Carbon under Diversified Crop Rotations. *Journal of Environmental Quality*, **47**(4), 635-643, doi:10.2134/jeq2017.08.0317.

Jayanthi, M. et al., 2020: Assessment of land and water ecosystems capability to support aquaculture expansion in climate-vulnerable regions using analytical hierarchy process based geospatial analysis. *J. Environ. Manag.*, **270**, 110952, doi:10.1016/j.jenvman.2020.110952.

Jeliazkov, A. et al., 2016: Impacts of agricultural intensification on bird communities: new insights from a multi-level and multi-facet approach of biodiversity. *Agriculture, Ecosystems & Environment*, **216**, 9-22, doi:10.1016/j.agee.2015.09.017.

Jennings, S. A. et al., 2020: Global Potato Yields Increase Under Climate Change With Adaptation and CO2 Fertilisation. *Front. Sustain. Food Syst.*, **4**, 248.

Jensen, N. and C. Barrett, 2017: Agricultural index insurance for development. *Appl. Econ. Perspect. Policy*, **39**(2), 199-219, doi:10.1093/aepp/ppw022.

Jeon, J.-Y., P. Adhikari and C. Seo, 2020: Impact of climate change on potential dispersal of Paeonia obovata (paeoniaceae), a critically endangered medicinal plant of South Korea. *Eco Env Cons*, **26**, S145-S155.

Jha, S. et al., 2014: Shade coffee: update on a disappearing refuge for biodiversity. *Bioscience*, **64**(5), 416-428, doi:10.1093/biosci/biu038.

Jiménez-Quiroz, M. d. C. et al., 2019: Impact of "The Blob" and "El Niño" in the SW Baja California Peninsula: Plankton and Environmental Variability of Bahia Magdalena. *Front. Mar. Sci.*, **6**, 25.

Jin, J., R. Armstrong and C. Tang, 2019: Impact of elevated CO2 on grain nutrient concentration varies with crops and soils - A long-term FACE study. *Sci. Total Environ.*, **651**(Pt 2), 2641-2647, doi:10.1016/j.scitotenv.2018.10.170.

Jin, Z., E. A. Ainsworth, A. D. B. Leakey and D. B. Lobell, 2018: Increasing drought and diminishing benefits of elevated carbon dioxide for soybean yields across the US Midwest. *Glob Chang Biol*, **24**(2), e522-e533, doi:10.1111/gcb.13946.

Jiri, O., P. L. Mafongoya and P. Chivenge, 2017: Building climate change resilience through adaptation in smallholder farming systems in semi-arid Zimbabwe. *Int. J. Clim. Change Strateg. Manag.*, **9**(2), 151--165, doi:10.1108/IJCCSM-07-2016-0092.

Jobin Poirier, E., G. Pickering and R. Plummer, 2019: Doom, gloom, or boom? Perceptions of climate change among Canadian winegrowers. *Int. J. Wine Res.*, **11**, 1-11, doi:10.2147/ijwr.S188787.

Joffre, O. M., L. Klerkx, M. Dickson and M. Verdegem, 2017: How is innovation in aquaculture conceptualized and managed? A systematic literature review and reflection framework to inform analysis and action. *Aquaculture*, **470**, 129-148, doi:10.1016/j.aquaculture.2016.12.020.

Johansson, E., S. Olin and J. Seaquist, 2020: Foreign demand for agricultural commodities drives virtual carbon exports from Cambodia. *Environ. Res. Lett.*, **15**(6), doi:10.1088/1748-9326/ab8157.

Johansson, E. L. and E. Isgren, 2017: Local perceptions of land-use change: using participatory art to reveal direct and indirect socioenvironmental effects of land acquisitions in Kilombero Valley, Tanzania. *Ecol. Soc.*, **22**(1), doi:10.5751/Es-08986-220103.

Johnson, A., K. Koranteng, S. Petersen and M. Tandstad, 2014: *Establishing a Baseline for the Implementation of an Ecosystem Approach to Marine Fisheries Management in West and Central Africa*. FAO-EAF-Nansen Project Report, Food and Agriculture Organization of the United Nations,, Rome, Italy, 44 pp. Available at: http://www.fao.org/fishery/docs/DOCUMENT/eaf_nansen/Reports/EAF-NansenReportNo20_en.pdf (accessed 06/08/2021).

Johnson, J. E. et al., 2020: Impacts of climate change on marine resources in the Pacific Island region. In: *Climate Change and Impacts in the Pacific* [Kumar, L. (ed.)]. Springer Nature, Cham, Switzerland, pp. 359-402. ISBN 9783030328771.

Johnson, J. S., E. D. Nobmann, E. Asay and A. P. Lanier, 2009: Dietary intake of Alaska Native people in two regions and implications for health: the Alaska Native dietary and subsistence food assessment project. *Int J Circumpolar Health*, **68**(2), 109-122, doi:10.3402/ijch.v68i2.18320.

Johnson, L., B. Wandera, N. Jensen and R. Banerjee, 2019: Competing expectations in an index-based livestock insurance project. *J. Dev. Stud.*, **55**(6), 1221-1239, doi:10.1080/00220388.2018.1453603.

Jones, A. D., 2017a: Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. *Nutr. Rev.*, **75**(10), 769-782, doi:10.1093/nutrit/nux040.

Jones, A. D., 2017b: On-farm crop species richness is associated with household diet diversity and quality in subsistence- and market-oriented farming households in Malawi. *J. Nutr.*, **147**(1), 86-96, doi:10.3945/jn.116.235879.

Jones, A. D. et al., 2018: Farm-level agricultural biodiversity in the Peruvian Andes is associated with greater odds of women achieving a minimally diverse and micronutrient adequate diet. *J. Nutr.*, **148**(10), 1625-1637, doi:10.1093/jn/nxy166.

Jones, A. E. et al., 2019: Bluetongue risk under future climates. *Nat. Clim. Change*, **9**(2), 153-157, doi:10.1038/s41558-018-0376-6.

Jones, M. B., 2019: Projected climate change and the global distribution of grasslands. In: *Grasslands and Climate Change* [Gibson, D. and J. Newman (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 67-81. ISBN 9781107195264.

Jones, R. A. C. and M. Barbetti, 2012: Influence of climate change on plant disease infections and epidemics caused by viruses and bacteria. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, **7**(022), doi:10.1079/pavsnnr20127022.

Jönsson, A. M., F. Lagergren and B. Smith, 2015: Forest management facing climate change - an ecosystem model analysis of adaptation strategies. *Mitig. Adapt. Strateg. Glob. Change*, **20**(2), 201-220, doi:10.1007/s11027-013-9487-6.

Joris, I., J. Bronders, B. van der Grift and P. Seuntjens, 2014: Model-based scenario analysis of the impact of remediation measures on metal leaching from soils contaminated by historic smelter emissions. *J Environ Qual*, **43**(3), 859-868, doi:10.2134/jeq2013.07.0287.

Jost, C. et al., 2016: Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Clim. Dev.*, **8**(2), 133-144, doi:10.1080/17565529.2015.1050978.

Ju, R. T. et al., 2020: Emerging risks of non‐native species escapes from aquaculture: call for policy improvements in China and other developing countries. *J. Appl. Ecol.*, **57**(1), 85-90, doi:10.1111/1365-2664.13521.

Juhola, S., E. Glaas, B. O. Linner and T. S. Neset, 2016: Redefining maladaptation. *Environ. Sci. Policy*, **55**, 135-140, doi:10.1016/j.envsci.2015.09.014.

Jurjonas, M. and E. Seekamp, 2019: Balancing carbon dioxide: a case study of forest preservation, out-migration, and afforestation in the Pueblos Mancomunados of Oaxaca, Mexico. *J. Sustain. For.*, **38**(7), 697-714, doi:10.1080/10549811.2019.1602058.

Kagunyu, A. W. and J. Wanjohi, 2014: Camel rearing replacing cattle production among the Borana community in Isiolo County of Northern Kenya, as climate variability bites. *Pastoralism*, **4**(1), 13, doi:10.1186/s13570-014-0013-6.
Kais, S. M. and M. S. Islam, 2018: Impacts of and resilience to climate change at the bottom of the shrimp commodity chain in Bangladesh: a preliminary investigation. *Aquaculture*, **493**, 406-415, doi:10.1016/j.aquaculture.2017.05.024.
Kais, S. M. and M. S. Islam, 2021: Resilience to Climate Change in Industrial Shrimping in Bangladesh: Assessing the Comparative Role of the Stakeholders. *Sustainability*, **13**(1), 307.
Kaky, E. and F. Gilbert, 2017: Predicting the distributions of Egypt's medicinal plants and their potential shifts under future climate change. *PLoS One*, **12**(11), e0187714, doi:10.1371/journal.pone.0187714.
Kalikoski, D. C. et al., 2018: Understanding the impacts of climate change for fisheries and aquaculture: applying a poverty lens. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 19-39. ISBN 9789251306079.
Kaminski, A. M., S. Genschick, A. S. Kefi and F. Kruijssen, 2018: Commercialization and upgrading in the aquaculture value chain in Zambia. *Aquaculture*, **493**, 355-364, doi:10.1016/j.aquaculture.2017.12.010.
Kane, D. A. et al., 2021: Soil organic matter protects US maize yields and lowers crop insurance payouts under drought. *Environ. Res. Lett.*, **16**(4), 044018, doi:10.1088/1748-9326/abe492.
Kangmennaang, J. et al., 2017: Impact of a participatory agroecological development project on household wealth and food security in Malawi. *Food Secur.*, **9**(3), 561-576, doi:10.1007/s12571-017-0669-z.
Kansanga, M. M. et al., 2021: Does participatory farmer-to-farmer training improve the adoption of sustainable land management practices? *Land Use Policy*, **108**, 105477-105477, doi:10.1016/j.landusepol.2021.105477.
Kanter, D. R. et al., 2018: Evaluating agricultural trade-offs in the age of sustainable development. *Agric. Syst.*, **163**, 73-88, doi:10.1016/j.agsy.2016.09.010.
Kao, Y. C. et al., 2020: Effects of climate and land-use changes on fish catches across lakes at a global scale. *Nat Commun*, **11**(1), 2526, doi:10.1038/s41467-020-14624-2.
Karavani, A. et al., 2018: Effect of climatic and soil moisture conditions on mushroom productivity and related ecosystem services in Mediterranean pine stands facing climate change. *Agric. For. Meteorol*, **248**, 432-440, doi:10.1016/j.agrformet.2017.10.024.
Kareem, B. et al., 2020: Pathways for resilience to climate change in African cities. *Environ. Res. Lett.*, **15**(7), 073002, doi:10.1088/1748-9326/ab7951.
Karg, H. et al., 2016: Foodsheds and city region food systems in two West African cities. *Sustainability*, **8**(12), 1175, doi:10.3390/su8121175.
Karlsson, L., L. O. Naess, A. Nightingale and J. Thompson, 2018: "Triple wins' or "triple faults'? Analysing the equity implications of policy discourses on climate-smart agriculture (CSA). *J. Peasant Stud.*, **45**(1), 150-174, doi:10.1080/03066150.2017.1351433.
Karttunen, K., J. Wolf, C. Garcia and A. Meybeck, 2017: *Addressing Agriculture, Forestry and Fisheries in National Adaptation Plans [Supplementary Guidelines]*. Food and Agriculture Organization of the United Nations,, Rome, Italy, 104 pp. ISBN 9789251097557.
Kassi, J. B. et al., 2018: Remotely sensing the biophysical drivers of Sardinella aurita wariability in Ivorian waters. *Remote Sens.*, **10**(5), 785, doi:10.3390/rs10050785.
Kathiresan, R. and G. Gualbert, 2016: Impact of climate change on the invasive traits of weeds. *Weed Biol. Manag.*, **16**(2), 59-66, doi:10.1111/wbm.12096.
Kaushal, N. and F. M. Muchomba, 2015: How consumer price subsidies affect nutrition. *World Dev.*, **74**, 25-42, doi:10.1016/j.worlddev.2015.04.006.
Kawall, K., 2019: New possibilities on the horizon: genome editing makes the whole genome accessible for changes. *Front Plant Sci*, **10**, 525, doi:10.3389/fpls.2019.00525.
Keairns, D. L., R. C. Darton and A. Irabien, 2016: The energy-water-food nexus. *Annu Rev Chem Biomol Eng*, **7**, 239-262, doi:10.1146/annurev-chembioeng-080615-033539.
Keatinge, J. D. H. et al., 2016: Assessing air temperature trends in Mesoamerica and their implications for the future of horticulture. *European Journal of Horticultural Science*, **81**(2), 63-77, doi:10.17660/eJHS.2016/81.2.1.
Keatinge, J. D. H. et al., 2015: Indigenous vegetables worldwide: their importance and future development. *Acta Hortic.*,(1102), 1-20, doi:10.17660/ActaHortic.2015.1102.1.

Keenan, R. J., 2015: Climate change impacts and adaptation in forest management: a review. *Annals of Forest Science*, **72**(2), 145-167, doi:10.1007/s13595-014-0446-5.
Kehoe, L. et al., 2017: Biodiversity at risk under future cropland expansion and intensification. *Nat. Ecol. Evol.*, **1**(8), 1129-1135, doi:10.1038/s41559-017-0234-3.
Kellett, J. and K. Peters, 2014: *Dare to Prepare: Taking Risk Seriously. Financing Emergency Preparedness: From Fighting Crisis to Managing Risk.*, Overseas Development Institute, London, United Kingdom, 133 pp. Available at: <Go to WoS>://WOS:000412260400023 (accessed 06/08/2021).
Kelley, C. et al., 2017: Commentary on the Syria case: climate as a contributing factor. *Political Geogr.*, **60**, 245-247, doi:10.1016/j.polgeo.2017.06.013.
Kellogg, J. et al., 2010: Alaskan wild berry resources and human health under the cloud of climate change. *J. Agric. Food Chem.*, **58**(7), 3884-3900, doi:10.1021/jf902693r.
Kenny, T. A. et al., 2018: Caribou (Rangifer tarandus) and Inuit nutrition security in Canada. *EcoHealth*, **15**(3), 590-607, doi:10.1007/s10393-018-1348-z.
Kent, R. and R. Hannay, 2020: Explaining "carbon" in community sequestration projects: a key element in the creation of local carbon knowledges. *Environ. Commun.*, **14**(3), 364-377, doi:10.1080/17524032.2019.1673459.
Keppen, D. and T. Dutcher, 2015: The 2014 drought and water management policy impacts on California’s Central Valley food production. *Journal of Environmental Studies and Sciences*, **5**(3), 362-377, doi:10.1007/s13412-015-0283-3.
Kerr, A. et al., 2018: Vulnerability of California specialty crops to projected mid-century temperature changes. *Clim. Change*, **148**(3), 419-436, doi:10.1007/s10584-017-2011-3.
Kerr, J. T. et al., 2015: Climate change impacts on bumblebees converge across continents. *Science*, **349**(6244), 177-180, doi:10.1126/science.aaa7031.
Khalili Tilami, S. and S. Sampels, 2018: Nutritional value of fish: lipids, proteins, vitamins, and minerals. *Rev. Fish. Sci. Aquac.*, **26**(2), 243-253, doi:10.1080/23308249.2017.1399104.
Khatri-Chhetri, A., P. P. Regmi, N. Chanana and P. K. Aggarwal, 2020: Potential of climate-smart agriculture in reducing women farmers' drudgery in high climatic risk areas. *Clim. Change*, **158**(1), 29-42, doi:10.1007/s10584-018-2350-8.
Kibblewhite, M. G., K. Ritz and M. J. Swift, 2008: Soil health in agricultural systems. *Philos Trans R Soc Lond B Biol Sci*, **363**(1492), 685-701, doi:10.1098/rstb.2007.2178.
Kibet, S., M. Nyangito, L. MacOpiyo and D. Kenfack, 2016: Tracing innovation pathways in the management of natural and social capital on Laikipia Maasai Group Ranches, Kenya. *Pastoralism*, **6**, doi:10.1186/s13570-016-0063-z.
Kibria, G., A. K. Haroon and D. Nugegoda, 2017: Climate change impacts on tropical and temperate fisheries, aquaculture, and seafood security and implications - A review. *Livest. Res. Rural Dev.*, **29**(1).
Kifani, S. et al., 2018: Climate change impacts, vulnerabilities and adaptations: Eastern Central Atlantic marine fisheries. In: *Impacts of Climate Change on Fisheries and Aquaculture: synthesis of Current Knowledge, Adaptation and Mitigation Options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 159-184. ISBN 9789251306079.
Kihila, J. M., 2018: Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review. *Clim. Dev.*, **10**(5), 406-416, doi:10.1080/17565529.2017.1318739.
Kim, B. T., C. L. Brown and D. H. Kim, 2019a: Assessment on the vulnerability of Korean aquaculture to climate change. *Mar. Policy*, **99**, 111-122, doi:10.1016/j.marpol.2018.10.009.
Kim, W., T. Iizumi and M. Nishimori, 2019b: Global patterns of crop production losses associated with droughts from 1983 to 2009. *J. Appl. Meteorol. Climatol.*, **58**(6), 1233-1244, doi:10.1175/Jamc-D-18-0174.1.
Kimathi, E. et al., 2020: Prediction of breeding regions for the desert locust Schistocerca gregaria in East Africa. *Sci Rep*, **10**(1), 11937, doi:10.1038/s41598-020-68895-2.
Kimball, B. A., 2016: Crop responses to elevated CO2 and interactions with H2O, N, and temperature. *Curr. Opin. Plant Biol.*, **31**, 36-43, doi:10.1016/j.pbi.2016.03.006.
Kiptot, E., S. Franzel and A. Degrande, 2014: Gender, agroforestry and food security in Africa. *Curr. Opin. Environ. Sustain.*, **6**, 104-109, doi:10.1016/j.cosust.2013.10.019.

Kirchherr, J., D. Reike and M. Hekkert, 2017: Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, **127**, 221-232, doi:10.1016/j.resconrec.2017.09.005.

Kirchner, M. et al., 2015: Ecosystem services and economic development in Austrian agricultural landscapes - the impact of policy and climate change scenarios on trade-offs and synergies. *Ecol. Econ.*, **109**, 161-174, doi:10.1016/j.ecolecon.2014.11.005.

Kissinger, G., M. Brockhaus and S. R. Bush, 2021: Policy integration as a means to address policy fragmentation: Assessing the role of Vietnam's national REDD+ action plan in the central highlands. *Environ. Sci. Policy*, **119**, 85-92, doi:10.1016/j.envsci.2021.02.011.

Kitalyi, A. et al., 2005: Why keep livestock if you are poor. In: *Livestock and Wealth Creation. Improving the Husbandry of Animals Kept by Resource-Poor People in Developing Countries* [Owen, E., A. Kitalyi, N. Jayasuriya and T. Smith (eds.)]. Nottingham University Press, Nottingham, United Kingdom, pp. 13-27. ISBN 9781904761327.

Kizildeniz, T., J. J. Irigoyen, I. Pascual and F. Morales, 2018: Simulating the impact of climate change (elevated CO2 and temperature, and water deficit) on the growth of red and white Tempranillo grapevine in three consecutive growing seasons (2013-2015). *Agric. Water Manage.*, **202**, 220-230, doi:10.1016/j.agwat.2018.02.006.

Kizildeniz, T. et al., 2015: Effects of climate change including elevated CO2 concentration, temperature and water deficit on growth, water status, and yield quality of grapevine (Vitis vinifera L.) cultivars. *Agric. Water Manage.*, **159**, 155-164, doi:10.1016/j.agwat.2015.06.015.

Kjellstrom, T. et al., 2016: Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. *Annu. Rev. Public Health*, **37**(1), 97-112, doi:10.1146/annurev-publhealth-032315-021740.

Kjellstrom, T. et al., 2018: Estimating population heat exposure and impacts on working people in conjunction with climate change. *Int J Biometeorol*, **62**(3), 291-306, doi:10.1007/s00484-017-1407-0.

Kjellström, T. et al., 2019: *Working on a Warmer Planet : The Effect of Heat Stress on Labour Productivity and Decent Work*, 1st ed., International Labor Organization,, Geneva, Switzerland, 97 pp. ISBN 9789221329671.

Klein, J. A. et al., 2014: Unexpected climate impacts on the Tibetan Plateau: Local and scientific knowledge in findings of delayed summer. *Glob. Environ. Change*, **28**, 141-152, doi:10.1016/j.gloenvcha.2014.03.007.

Klemm, T., D. D. Briske and M. C. Reeves, 2020: Vulnerability of rangeland beef cattle production to climate-induced NPP fluctuations in the US Great Plains. *Global Change Biol.*, **26**(9), 4841-4853, doi:10.1111/gcb.15202.

Klenk, N., A. Fiume, K. Meehan and C. Gibbes, 2017: Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co-production. *Wiley Interdiscip. Rev.: Clim. Change*, **8**(5), e475, doi:10.1002/wcc.475.

Klinger, D. H., S. A. Levin and J. R. Watson, 2017: The growth of finfish in global open-ocean aquaculture under climate change. *Proc Biol Sci*, **284**(1864), doi:10.1098/rspb.2017.0834.

Knox, J., A. Daccache, T. Hess and D. Haro, 2016: Meta-analysis of climate impacts and uncertainty on crop yields in Europe. *Environ. Res. Lett.*, **11**(11), 113004, doi:10.1088/1748-9326/11/11/113004.

Kohler, F. and E. S. Brondizio, 2017: Considering the needs of indigenous and local populations in conservation programs. *Conserv. Biol.*, **31**(2), 245-251, doi:10.1111/cobi.12843.

Kohler, I. H., S. C. Huber, C. J. Bernacchi and I. R. Baxter, 2019: Increased temperatures may safeguard the nutritional quality of crops under future elevated CO2 concentrations. *Plant J.*, **97**(5), 872-886, doi:10.1111/tpj.14166.

Koirala, A. and K. B. Shrestha, 2017: Effects of climate change on the livestock population in Mustang District, Nepal. *Asian Journal of Agriculture and Development*, **14**(1), 37-49, doi:10.22004/ag.econ.259247.

Koks, E. E. et al., 2019: A global multi-hazard risk analysis of road and railway infrastructure assets. *Nat Commun*, **10**(1), 2677, doi:10.1038/s41467-019-10442-3.

Kole, C. et al., 2015: Application of genomics-assisted breeding for generation of climate resilient crops: progress and prospects. *Front Plant Sci*, **6**, 563, doi:10.3389/fpls.2015.00563.

Kolström, M. et al., 2011: Reviewing the science and implementation of climate change adaptation measures in European forestry. *Forests*, **2**(4), 961-982, doi:10.3390/f2040961.

Konchar, K. M. et al., 2015: Adapting in the shadow of Annapurna: a climate tipping point. *Journal of Ethnobiology*, **35**(3), 449-471, doi:10.2993/0278-0771-35.3.449.
Konforti, L., 2018: Ungovernable? Indigenous Campesino Resistance to Land Grabbing in Guatemala's Polochic Valley. *Latin American Perspectives*, **XX**(Xxx), 1-18, doi:10.1177/0094582X18813565.
Kongsager, R., 2017: Barriers to the adoption of alley cropping as a climate-smart agriculture practice: lessons from maize cultivation among the Maya in southern Belize. *Forests*, **8**(7), 260, doi:10.3390/f8070260.
Kongsager, R., 2018: Linking Climate Change Adaptation and Mitigation: A Review with Evidence from the Land-Use Sectors. *Land*, **7**(4), doi:10.3390/land7040158.
Koontz, M. J. et al., 2020: Local forest structure variability increases resilience to wildfire in dry western U.S. coniferous forests. *Ecol. Lett.*, **23**(3), 483-494, doi:10.1111/ele.13447.
Kopáček, M., 2021: Land-Use Planning and the Public: Is There an Optimal Degree of Civic Participation? *Land 2021*, **10**(1), 90-90, doi:10.3390/LAND10010090.
Koren, O., B. E. Bagozzi and T. S. Benson, 2021: Food and water insecurity as causes of social unrest : Evidence from geolocated Twitter data. *Journal of Peace Research*, doi:10.1177/0022343320975091.
Korres, N. E. et al., 2016: Cultivars to face climate change effects on crops and weeds: a review. *Agron. Sustain. Dev.*, **36**(1), 12, doi:10.1007/s13593-016-0350-5.
Koshiol, J. et al., 2017: Association of aflatoxin and gallbladder cancer. *Gastroenterology*, **153**(2), 488-494 e481, doi:10.1053/j.gastro.2017.04.005.
Kosmowski, F., A. Leblois and B. Sultan, 2016: Perceptions of recent rainfall changes in Niger: a comparison between climate-sensitive and non-climate sensitive households. *Clim. Change*, **135**, 227-241, doi:10.1007/s10584-015-1562-4.
Koufos, G. et al., 2014: Viticulture-climate relationships in Greece: the impacts of recent climate trends on harvest date variation. *Int. J. Climatol.*, **34**(5), 1445-1459, doi:10.1002/joc.3775.
Koufos, G. C., T. Mavromatis, S. Koundouras and G. V. Jones, 2020: Adaptive capacity of winegrape varieties cultivated in Greece to climate change : current trends and future projections.(December), 1201-1219, doi:10.20870/oeno-one.2020.54.4.3129.
Kramer, B. et al., 2019: *Building Resilience Through Climate Risk Insurance: Insights from Agricultural Research for Development*. CCAFS Working Paper, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Wageningen, the Netherlands, 38 pp. Available at: https://hdl.handle.net/10568/106171 (accessed 16/08/2021).
Krčmářová, J. and L. Jeleček, 2016: Czech traditional agroforestry: historic accounts and current status. *Agroforestry Systems*, **91**(6), 1087-1100, doi:10.1007/s10457-016-9985-0.
Kremen, C., 2015: Reframing the land-sparing/land-sharing debate for biodiversity conservation. *Ann. N. Y. Acad. Sci.*, **1355**, 52-76, doi:10.1111/nyas.12845.
Kremen, C. and A. M. Merenlender, 2018: Landscapes that work for biodiversity and people. *Science*, **362**(6412), eaau6020, doi:10.1126/science.aau6020.
Kremen, C. and A. Miles, 2012: Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecol. Soc.*, **17**(4), 40, doi:10.5751/Es-05035-170440.
Kriewald, S. et al., 2019: Hungry cities: how local food self-sufficiency relates to climate change, diets, and urbanisation. *Environ. Res. Lett.*, **14**(9), 94007, doi:10.1088/1748-9326/ab2d56.
Kryza, M. et al., 2015: Observed changes in SAT and GDD and the climatological suitability of the Poland-Germany-Czech Republic transboundary region for wine grapes cultivation. *Theoretical and Applied Climatology*, **122**(1-2), 207-218, doi:10.1007/s00704-014-1296-7.
Kueppers, L. M. et al., 2005: Modeled regional climate change and California endemic oak ranges. *Proc Natl Acad Sci U S A*, **102**(45), 16281-16286, doi:10.1073/pnas.0501427102.
Kuhnlein, H. V. and D. H. Calloway, 1977: Contemporary Hopi food-intake patterns. *Ecol. Food Nutr.*, **6**(3), 159-173, doi:10.1080/03670244.1977.9990495.
Kuhnlein, H. V. and O. Receveur, 2007: Local cultural animal food contributes high levels of nutrients for Arctic Canadian Indigenous adults and children. *J. Nutr.*, **137**(4), 1110-1114, doi:10.1093/jn/137.4.1110.
Kuhnlein, H. V., R. Soueida and O. Receveur, 1996: Dietary nutrient profiles of Canadian Baffin Island Inuit differ by food source, season, and age. *J. Am. Diet. Assoc.*, **96**(2), 155-162, doi:10.1016/S0002-8223(96)00045-4.
Kumar, P. et al., 2021: Agricultural sustainability in Indian Himalayan Region: Constraints and potentials. *Indian J. Ecol.*, **48**(3), 649--662.

Kumar, R., 2016: The perils of productivity: making 'good farmers' in Malwa, India. *J. Agrar. Change*, **16**(1), 70-93, doi:10.1111/joac.12084.
Kummu, M. et al., 2021: Climate change risks pushing one-third of global food production outside the safe climatic space. *One Earth*, doi:10.1016/j.oneear.2021.04.017.
Kurpis, J., M. A. Serrato-Cruz and T. P. F. Arroyo, 2019: Modeling the effects of climate change on the distribution of Tagetes lucida Cav. (Asteraceae). *Glob. Ecol. Conserv.*, **20**, e00747, doi:10.1016/j.gecco.2019.e00747.
Kurz, V., 2018: Nudging to reduce meat consumption: Immediate and persistent effects of an intervention at a university restaurant. *J. Environ. Econ. Manage.*, **90**, 317-341, doi:10.1016/j.jeem.2018.06.005.
Kurz, W. A. et al., 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452**(7190), 987-990, doi:10.1038/nature06777.
Kuyah, S. et al., 2019: Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agron. Sustain. Dev.*, **39**(5), 47, doi:10.1007/s13593-019-0589-8.
Kyetere, D. et al., 2019: The Role and Contribution of Plant Breeding and Plant Biotechnology to Sustainable Agriculture in Africa. *Afr. Focus*, **32**(2), 83-108, doi:10.21825/af.v32i2.15772.
Labbé, J. et al., 2016: Vulnerability to the health effects of climate variability in rural southwestern Uganda. *Mitig. Adapt. Strateg. Glob. Change*, **21**(6), 931-953, doi:10.1007/s11027-015-9635-2.
LaCanne, C. E. and J. G. Lundgren, 2018: Regenerative agriculture: merging farming and natural resource conservation profitably. *PeerJ*, **6**, e4428-e4428, doi:10.7717/peerj.4428.
Lade, S. J. et al., 2020: Human impacts on planetary boundaries amplified by Earth system interactions. *Nat. Sustain.*, **3**(2), 119-128, doi:10.1038/s41893-019-0454-4.
Läderach, P. et al., 2017: Climate change adaptation of coffee production in space and time. *Clim. Change*, **141**(1), 47-62, doi:10.1007/s10584-016-1788-9.
Ladio, A. H. and M. Lozada, 2004: Patterns of use and knowledge of wild edible plants in distinct ecological environments: a case study of a Mapuche community from northwestern Patagonia. *Biodivers. Conserv.*, **13**(6), 1153-1173, doi:10.1023/B:Bioc.0000018150.79156.50.
Lafond, V., G. Lagarrigues, T. Cordonnier and B. Courbaud, 2013: Uneven-aged management options to promote forest resilience for climate change adaptation: effects of group selection and harvesting intensity. *Annals of Forest Science*, **71**(2), 173-186, doi:10.1007/s13595-013-0291-y.
Lahive, F., P. Hadley and A. J. Daymond, 2019: The physiological responses of cacao to the environment and the implications for climate change resilience. A review. *Agron. Sustain. Dev.*, **39**(1), 5, doi:10.1007/s13593-018-0552-0.
Lahmar, R. et al., 2012: Tailoring conservation agriculture technologies to West Africa semi-arid zones: building on traditional local practices for soil restoration. *Field Crops Res.*, **132**, 158-167, doi:10.1016/j.fcr.2011.09.013.
Laidler, G. J. et al., 2009: Travelling and hunting in a changing Arctic: assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. *Clim. Change*, **94**(3-4), 363-397, doi:10.1007/s10584-008-9512-z.
Laidre, K. L. and M. P. Heide-Jorgensen, 2005: Arctic sea ice trends and narwhal vulnerability. *Biol. Conserv.*, **121**(4), 509-517, doi:10.1016/j.biocon.2004.06.003.
Lake, I. R. and G. C. Barker, 2018: Climate change, foodborne pathogens and illness in higher-income countries. *Curr Environ Health Rep*, **5**(1), 187-196, doi:10.1007/s40572-018-0189-9.
Lake, I. R. et al., 2014: The effects of river flooding on dioxin and PCBs in beef. *Sci. Total Environ.*, **491-492**, 184-191, doi:10.1016/j.scitotenv.2014.01.080.
Lallo, C. H. O. et al., 2018: Characterizing heat stress on livestock using the temperature humidity index (THI)prospects for a warmer Caribbean. *Reg. Environ. Change*, **18**(8), 2329-2340, doi:10.1007/s10113-018-1359-x.
Lam, S. et al., 2019: Community-based monitoring of Indigenous food security in a changing climate: global trends and future directions. *Environ. Res. Lett.*, **14**(7), 073002, doi:10.1088/1748-9326/ab13e4.
Lam, V. W., W. W. Cheung, G. Reygondeau and U. R. Sumaila, 2016: Projected change in global fisheries revenues under climate change. *Sci Rep*, **6**, 32607, doi:10.1038/srep32607.
Lam, V. W. Y. et al., 2020: Climate change, tropical fisheries and prospects for sustainable development. *Nat. Rev. Earth Environ.*, **1**(9), 440-454, doi:10.1038/s43017-020-0071-9.
Lamanna, C. et al., 2016: *Evidence-based opportunities for out-scaling climate-smart agriculture in East Africa*. CCAFS Working Paper, Copenhagen, Denmark, 63 pp. Available at: https://hdl.handle.net/10568/77180 (accessed 16/08/2021).
Lamb, A. et al., 2016: The potential for land sparing to o set greenhouse gas emissions from agriculture.(February), doi:10.1038/NCLIMATE2910.

Lampkin, N., G. Schwarz and S. Bellon, 2020: Policies for agroecology in Europe, building on experiences in France, Germany and the United Kingdom. *LANDBAUFORSCH · J Sustainable Organic Agric Syst*, **70**(2), 103-112, doi:10.3220/LBF1611684471000.
Land Matrix, 2021: The Land Matrix. Available at: https://landmatrix.org.
Lassaletta, L. et al., 2019: Future global pig production systems according to the Shared Socioeconomic Pathways. *Sci. Total Environ.*, **665**, 739-751, doi:10.1016/j.scitotenv.2019.02.079.
Laube, W., 2016: Climate Change Adaptation, Education, and Rural Transformation in Northern Ghana. Moving Beyond an Agricultural Focus. 121--145, doi:10.1007/978-3-319-31499-0_8.
Laufkotter, C., J. Zscheischler and T. L. Frolicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science*, **369**(6511), 1621-1625, doi:10.1126/science.aba0690.
Lauria, V. et al., 2018: Importance of fisheries for food security across three climate change vulnerable deltas. *Sci. Total Environ.*, **640-641**, 1566-1577, doi:10.1016/j.scitotenv.2018.06.011.
Law, W. and J. Salick, 2005: Human-induced dwarfing of Himalayan snow lotus, Saussurea laniceps (Asteraceae). *Proceedings of the National Academy of Sciences*, **102**(29), 10218-10220, doi:10.1073/pnas.0502931102.
Lawanson, T., O. Orelaja and M. Simire, 2014: Effects of climate change on a peri-urban farming community in Lagos, Nigeria. *Afr. J. Sci. Technol. Dev.*, **6**(6), 511-517, doi:10.1080/20421338.2014.976990.
Lazarus, E. D., 2014: Land grabbing as a driver of environmental change. *Area*, **46**(1), 74-82, doi:10.1111/area.12072.
Lazoglou, G., C. Anagnostopoulou and S. Koundouras, 2018: Climate change projections for Greek viticulture as simulated by a regional climate model. *Theoretical and Applied Climatology*, **133**(1-2), 551-567, doi:10.1007/s00704-017-2198-2.
Le Cornu, E. et al., 2018: Spatial management in small-scale fisheries: A potential approach for climate change adaptation in Pacific Islands. *Mar. Policy*, **88**, 350-358, doi:10.1016/j.marpol.2017.09.030.
Le Mouël, C., M. De Lattre-Gasquet and O. Mora (eds.), 2018: *Land Use and Food Security in 2050: A Narrow Road*, Éditions Quae, Versailles, France, 400 pp. ISBN 9782759228805.
Le Mouël, C. and A. Forslund, 2017: How can we feed the world in 2050? A review of the responses from global scenario studies. *European Review of Agricultural Economics*, **44**(4), 541-591, doi:10.1093/erae/jbx006.
Le Tacon, F. et al., 2014: Climatic variations explain annual fluctuations in French Périgord black truffle wholesale markets but do not explain the decrease in black truffle production over the last 48 years. *Mycorrhiza*, **24**(1), 115-125.
Leakey, A. D., K. A. Bishop and E. A. Ainsworth, 2012: A multi-biome gap in understanding of crop and ecosystem responses to elevated CO2. *Curr. Opin. Plant Biol.*, **15**(3), 228-236, doi:10.1016/j.pbi.2012.01.009.
Lebel, L. et al., 2018: Managing the risks from the water-related impacts of extreme weather and uncertain climate change on inland aquaculture in Northern Thailand. *Water Int.*, **43**(2), 257-280, doi:10.1080/02508060.2017.1416446.
Lebel, L. et al., 2020: Aquaculture farmers' perceptions of climate-related risks in the Mekong Region. *Reg. Environ. Change*, **20**(3), 95, doi:10.1007/s10113-020-01688-5.
Leck, H., D. Conway, M. Bradshaw and J. Rees, 2015: Tracing the water-energy-food nexus: description, theory and practice. *Geogr. Compass*, **9**(8), 445-460, doi:10.1111/gec3.12222.
Lee, D. M. and K. S. Lyon, 2004: Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios. *South. Econ. J.*, **70**, 467-489, doi:10.1088/1748-9326/aa63fc.
Lee, H. L., Y. P. Lin and J. R. Petway, 2018: Global agricultural trade pattern in a warming world: regional realities. *Sustainability*, **10**(8), 2763, doi:10.3390/su10082763.
Lee, J. Y. et al., 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Legave, J. M. et al., 2015: Differentiated responses of apple tree floral phenology to global warming in contrasting climatic regions. *Front Plant Sci*, **6**, 1054, doi:10.3389/fpls.2015.01054.

Leguizamón, A., 2014: Modifying Argentina: GM soy and socio-environmental change. *Geoforum*, **53**, 149-160, doi:10.1016/j.geoforum.2013.04.001.
Lehnert, L. W. et al., 2016: Climate variability rather than overstocking causes recent large scale cover changes of Tibetan pastures. *Sci Rep*, **6**, 24367, doi:10.1038/srep24367.
Leibar, U. et al., 2017: Grape yield and quality responses to simulated year 2100 expected climatic conditions under different soil textures. *J. Sci. Food Agric.*, **97**(8), 2633-2640, doi:10.1002/jsfa.8086.
Leitão, S. T. et al., 2019: Maize open-pollinated populations physiological improvement: validating tools for drought response participatory selection. *Sustainability*, **11**(21), doi:10.3390/su11216081.
Lemasson, A. J., J. M. Hall-Spencer, V. Kuri and A. M. Knights, 2019: Changes in the biochemical and nutrient composition of seafood due to ocean acidification and warming. *Mar. Environ. Res.*, **143**, 82-92, doi:10.1016/j.marenvres.2018.11.006.
Lemonnier, P. and E. A. Ainsworth, 2018: Crop responses to rising atmospheric [CO2] and global climate change. In: *Food Security and Climate Change* [Yadav, S. S., R. J. Redden, J. L. Hatfield, A. A. Ebert and D. Hunter (eds.)]. Wiley Blackwell,, Hoboken, NJ, USA and Chichester, United Kingdom, pp. 51-69. ISBN 9781119180647.
Lemos, M. C. et al., 2016: Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil. *Glob. Environ. Change*, **39**, 170-179, doi:10.1016/j.gloenvcha.2016.05.001.
Lennox, E., 2015: Double exposure to climate change and globalization in a Peruvian highland community. *Soc. Nat. Resour.*, **28**(7), 781-796, doi:10.1080/08941920.2015.1024364.
Lenoir, J. et al., 2019: Species better track the shifting isotherms in the oceans than on lands. *bioRxiv*, 765776, doi:10.1101/765776.
Lenton, T. M. et al., 2019: Climate tipping points - too risky to bet against. *Nature*, **575**(7784), 592-595, doi:10.1038/d41586-019-03595-0.
Leolini, L. et al., 2019: Modelling sugar and acid content in Sangiovese grapes under future climates: an Italian case study. *Clim. Res.*, **78**(3), 211-224, doi:10.3354/cr01571.
Leon-Munoz, J., M. A. Urbina, R. Garreaud and J. L. Iriarte, 2018: Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016). *Sci Rep*, **8**(1), 1330, doi:10.1038/s41598-018-19461-4.
Leon, J. X. et al., 2015: Supporting local and traditional knowledge with science for adaptation to climate change: lessons learned from participatory three-dimensional modeling in BoeBoe, Solomon Islands. *Coast. Manage.*, **43**(4), 424-438, doi:10.1080/08920753.2015.1046808.
Leonelli, G. C., 2018: GMO risks, food security, climate change and the entrenchment of neo-liberal legal narratives. *Transnatl. Leg. Theory*, **9**, 302-315, doi:10.1080/20414005.2018.1572313.
Lepofsky, D., K. Lertzman, D. Hallett and R. Mathewes, 2005: Climate change and culture change on the southern coast of British Columbia 2400-1200 CAL. BP: an hypothesis. *Am. Antiq.*, **70**(2), 267-293, doi:10.2307/40035704.
Lesk, C. et al., 2017: Threats to North American forests from southern pine beetle with warming winters. *Nat Clim Chang*, **7**, 713-717, doi:10.1038/nclimate3375.
Lesk, C., P. Rowhani and N. Ramankutty, 2016: Influence of extreme weather disasters on global crop production. *Nature*, **529**(7584), 84-87, doi:10.1038/nature16467.
Lesnikowski, A. et al., 2016: National-level progress on adaptation. *Nat. Clim. Change*, **6**(3), 261- 264, doi:10.1038/Nclimate2863.
Leßmeister, A. et al., 2015: Substitution of the most important and declining wild food species in southeast Burkina Faso. *Flora Veg. Sudano-Sambesica*, **18**, 11-20, doi:10.21248/fvss.18.29.
Lévesque, E. et al., 2012: Trends in vegetation dynamics and impacts on berry productivity. In: *Nunavik and Nunatsiavut: From Science to Policy. An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization.* [Allard, M. and M. Lemay (eds.)]. ArcticNet, Quebec City, Canada, pp. 223-247.
Levi, M., T. Kjellstrom and A. Baldasseroni, 2018: Impact of climate change on occupational health and productivity: a systematic literature review focusing on workplace heat. *Med Lav*, **109**(3), 163-179, doi:10.23749/mdl.v109i3.6851.
Levy, B. S. and C. Roelofs, 2019: Impacts of climate change on workers' health and safety. In: *Oxford Research Encyclopedia of Global Public Health*, doi:10.1093/acrefore/9780190632366.013.39.
Lhorente, J. P., M. Araneda, R. Neira and J. M. Yanez, 2019: Advances in genetic improvement for salmon and trout aquaculture: the Chilean situation and prospects. *Rev. Aquac.*, **11**(2), 340-353, doi:10.1111/raq.12335.

Li, C. et al., 2020: Syndromes of production in intercropping impact yield gains. *Nat Plants*, **6**(6), 653-660, doi:10.1038/s41477-020-0680-9.
Li, F. B. et al., 2019: Effects of rice-fish co-culture on oxygen consumption in intensive aquaculture pond. *Rice Sci.*, **26**(1), 50-59, doi:10.1016/j.rsci.2018.12.004.
Li, M. et al., 2014a: Efficient and heritable gene targeting in tilapia by CRISPR/Cas9. *Genetics*, **197**(2), 591-599, doi:10.1534/genetics.114.163667.
Li, T. et al., 2014b: Crop-model ensembles reduce uncertainty in predicting rice yield under climate change. *Proc. Roy. Soc. B: Biol. Sci*.
Li, W. H. et al., 2018a: Ecosystem structure, functioning and stability under climate change and grazing in grasslands: current status and future prospects. *Curr. Opin. Environ. Sustain.*, **33**, 124-135, doi:10.1016/j.cosust.2018.05.008.
Li, X. et al., 2018b: Asparagopsis taxiformis decreases enteric methane production from sheep. *Anim. Prod. Sci.*, **58**(4), 681-681, doi:10.1071/an15883.
Li, X. and K. H. M. Siddique (eds.), 2018: *Future Smart Food: Rediscovering Hidden Treasures of Neglected and Underutilized Species for Zero Hunger in Asia*, Food and Agriculture Organization of the United Nations,, Bangkok, Thailand, 216 pp. ISBN 9789251304952.
Li, X. L. et al., 2017: Patterns of herders' adaptation to changes in social-ecological systems across northern China's grasslands over the past three decades. *Rangel. J.*, **39**(4), 317-328, doi:10.1071/Rj16070.
Liao, C. and D. G. Brown, 2018: ScienceDirect Assessments of synergistic outcomes from sustainable intensification of agriculture need to include smallholder livelihoods with food production and ecosystem services. *Curr. Opin. Environ. Sustain.*, **32**(December 2017), 53-59, doi:10.1016/j.cosust.2018.04.013.
Liao, C. and D. Fei, 2017: Sedentarization as constrained adaptation: evidence from pastoral regions in far Northwestern China. *Hum. Ecol.*, **45**(1), 23-35, doi:10.1007/s10745-016-9872-3.
Liao, C., S. Jung, D. G. Brown and A. Agrawal, 2020: Spatial patterns of large-scale land transactions and their potential socio-environmental outcomes in Cambodia, Ethiopia, Liberia, and Peru. *Land Degrad Dev*, **31**(10), 1241-1251, doi:10.1002/ldr.3544.
Liao, C. et al., 2021: Carbon emissions from the global land rush and potential mitigation. *Nat. Food*, **2**(1), 15-18, doi:10.1038/s43016-020-00215-3.
Liebman, M. and L. A. Schulte, 2015: Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems. *Elementa: Sci. Anthropocene*, **3**, 000041, doi:10.12952/journal.elementa.000041.
Lim-Camacho, L. et al., 2015: Facing the wave of change: stakeholder perspectives on climate adaptation for Australian seafood supply chains. *Reg. Environ. Change*, **15**(4), 595-606, doi:10.1007/s10113-014-0670-4.
Lin, B. B. et al., 2017: Adaptation pathways in coastal case studies: lessons learned and future directions. *Coast. Manage.*, **45**(5), 384-405, doi:10.1080/08920753.2017.1349564.
Lincoln, N. K., 2019: Learning from indigenous agriculture. *Nat. Sustain.*, **2**(3), 167-168, doi:10.1038/s41893-019-0234-1.
Lincoln, N. K., 2020: Agroforestry form and ecological adaptation in ancient Hawai'i: Extent of the pakukui swidden system of Hamakua, Hawai'i Island. *Agric. Syst.*, **181**, 102808, doi:10.1016/j.agsy.2020.102808.
Link, J. S., R. Griffis and S. Busch (eds.), 2015: *NOAA Fisheries Climate Science Strategy*, NOAA Technical Memorandum NMFS-F/SPO-155, U.S. Dept. of Commerce, Silver Spring, MD,USA, 70 pp.
Lipper, L., R. DeFries and L. Bizikova, 2020: Shedding light on the evidence blind spots confounding the multiple objectives of SDG 2. *Nat. Plants*, **6**(10), 1203--1210, doi:10.1038/s41477-020-00792-y.
Lipper, L. et al. (eds.), 2017: *Climate Smart Agriculture: Building Resilience to Climate Change*, Natural Resource Management and Policy, Springer Nature, Cham, Switzerland, 630 pp. ISBN 9783319611938.
Lipper, L. et al., 2014: Climate-smart agriculture for food security. *Nat. Clim. Change*, **4**(12), 1068-1072, doi:10.1038/Nclimate2437.
Little, D. C., R. W. Newton and M. C. Beveridge, 2016: Aquaculture: a rapidly growing and significant source of sustainable food? Status, transitions and potential. *Proc Nutr Soc*, **75**(3), 274-286, doi:10.1017/S0029665116000665.

Liu, C., N. Hofstra and E. Franz, 2013: Impacts of climate change on the microbial safety of pre-harvest leafy green vegetables as indicated by Escherichia coli O157 and Salmonella spp. *Int. J. Food Microbiol.*, **163**(2-3), 119-128, doi:10.1016/j.ijfoodmicro.2013.02.026.

Liu, C. et al., 2019a: Vertical redistribution of salt and layered changes in global ocean salinity. *Nat Commun*, **10**(1), 3445, doi:10.1038/s41467-019-11436-x.

Liu, S. et al., 2018a: Retrospective evaluation of marker-assisted selection for resistance to bacterial cold water disease in three generations of a commercial rainbow trout breeding population. *Front Genet*, **9**(286), 286, doi:10.3389/fgene.2018.00286.

Liu, S. L. et al., 2019b: Extreme stress threatened double rice production in Southern China during 1981-2010. *Theoretical and Applied Climatology*, **137**(3-4), 1987-1996, doi:10.1007/s00704-018-2719-7.

Liu, Y. et al., 2017: Do invasive alien plants benefit more from global environmental change than native plants? *Glob Chang Biol*, **23**(8), 3363-3370, doi:10.1111/gcb.13579.

Liu, Y. et al., 2018b: Impact of short-term climate effects and sea ice coverage variation on Japanese scallop aquaculture in Saroma Lake, Japan. *Aquac. Res.*, **49**(5), 1752-1767, doi:10.1111/are.13630.

Liu, Y. et al., 2020: Impact of climate extremes on suitability dynamics for Japanese scallop aquaculture in Shandong, China and Funka Bay, Japan. *Sustainability*, **12**(3), 833, doi:10.3390/su12030833.

Liu, Y. J. et al., 2018c: Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China. *Agric. For. Meteorol*, **248**, 518-526, doi:10.1016/j.agrformet.2017.09.008.

Lkhagvadorj, D., M. Hauck, C. Dulamsuren and J. Tsogtbaatar, 2013: Pastoral nomadism in the forest-steppe of the Mongolian Altai under a changing economy and a warming climate. *J. Arid Environ.*, **88**, 82-89, doi:10.1016/j.jaridenv.2012.07.019.

Lloyd, S. J. et al., 2018: A global-level model of the potential impacts of climate change on child stunting via income and food price in 2030. *Environ. Health Perspect.*, **126**(9), 97007, doi:10.1289/EHP2916.

Lo, A. Y., S. Liu, L. T. O. Cheung and F. K. S. Chan, 2019: Contested transformations: sustainable economic development and capacity for adapting to climate change. *Ann. Am. Assoc. Geogr.*, **110**(1), 223-241, doi:10.1080/24694452.2019.1625748.

Loaiza, T., U. Nehren and G. Gerold, 2016: REDD+ implementation in the Ecuadorian Amazon: Why land configuration and common-pool resources management matter. *For Policy Econ*, **70**, 67-79, doi:10.1016/j.forpol.2016.05.016.

Lobell, D. B. and C. B. Field, 2011: California perennial crops in a changing climate. *Clim. Change*, **109**, 317-333, doi:10.1007/s10584-011-0303-6.

Loboguerrero AM, B. F., Leon G, Martinez-Baron D, Giraldo D, Recaman L, Diaz E, Cock J., 2018: Bridging the gap between climate science and farmers in Colombia. *Clim. Risk Manag.*, **22**.

Loboguerrero, A. M. et al., 2020: Perspective article: actions to reconfigure food systems. *Glob Food Sec*, **26**, 100432, doi:10.1016/j.gfs.2020.100432.

Lokuge, G. and D. Hilhorst, 2017: Outside the net: intersectionality and inequality in the fisheries of Trincomalee, Sri Lanka. *Asian J. Women's Stud.*, **23**(4), 473-497, doi:10.1080/12259276.2017.1386839.

Loladze, I., 2014: Hidden shift of the ionome of plants exposed to elevated CO2 depletes minerals at the base of human nutrition. *Elife*, **3**, e02245, doi:10.7554/eLife.02245.

Long, J. W., R. W. Goode and F. K. Lake, 2020: Recentering ecological restoration with tribal perspectives. *Fremontia*, **48**(1), 14-19.

López-i-Gelats, F. et al., 2015: Adaptation strategies of Andean pastoralist households to both climate and non-climate changes. *Hum. Ecol.*, **43**(2), 267-282, doi:10.1007/s10745-015-9731-7.

López-i-Gelats, F., E. D. G. Fraser, J. F. Morton and M. G. Rivera-Ferre, 2016: What drives the vulnerability of pastoralists to global environmental change? A qualitative meta-analysis. *Global Environ. Change*, **39**, 258-274, doi:10.1016/j.gloenvcha.2016.05.011.

Loring, P. A. and S. C. Gerlach, 2009: Food, culture, and human health in Alaska: an integrative health approach to food security. *Environ. Sci. Policy*, **12**(4), 466-478, doi:10.1016/j.envsci.2008.10.006.

Lotter, D. and D. Maitre, 2014: Modelling the distribution of Aspalathus linearis (Rooibos tea): implications of climate change for livelihoods dependent on both cultivation and harvesting from the wild. *Ecol Evol*, **4**(8), 1209-1221, doi:10.1002/ece3.985.

Lotze, H. K. et al., 2019: Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proc Natl Acad Sci U S A*, **116**(26), 12907-12912, doi:10.1073/pnas.1900194116.

Love, D. C., M. S. Uhl and L. Genello, 2015: Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States. *Aquac Eng*, **68**, 19-27, doi:10.1016/j.aquaeng.2015.07.003.
Lovell, S. T., 2010: Multifunctional urban agriculture for sustainable land use planning in the United States. *Sustainability*, **2**(8), 2499-2522, doi:10.3390/su2082499.
Lovell, S. T. et al., 2018: Temperate agroforestry research: considering multifunctional woody polycultures and the design of long-term field trials. *Agroforestry Systems*, **92**(5), 1397-1415, doi:10.1007/s10457-017-0087-4.
Lowder, S. K., M. V. Sánchez and R. Bertini, 2019: *Farms, Family Farms, Farmland Distribution and Farm Labour: What do we Know Today?* FAO Agricultural Development Economics Working Paper, Food and Agriculture Organization of the United Nations,, 17/08/2021, 70 pp. ISBN 9789251319703.
Lowe, B. S. et al., 2019: Adapting to change in inland fisheries: analysis from Lake Tanganyika, East Africa. *Reg. Environ. Change*, **19**(6), 1765-1776, doi:10.1007/s10113-019-01516-5.
Lu, M. et al., 2013: Responses of ecosystem carbon cycle to experimental warming: a meta-analysis. *Ecology*, **94**(3), 726-738, doi:10.1890/12-0279.1.
Luedeling, E., R. Kindt, N. I. Huth and K. Koenig, 2014: Agroforestry systems in a changing climate—challenges in projecting future performance. *Curr. Opin. Environ. Sustain.*, **6**, 1-7, doi:10.1016/j.cosust.2013.07.013.
Lujan, E. et al., 2018: *Climate Change in Port Heiden, Alaska-Strategies for Community Health*. Alaska Native Tribal Health Consortium, 59 pp. Available at: https://anthc.org/wp-content/uploads/2018/10/ANTHC-Port-Heiden_Final.pdf (accessed 17/08/2021).
Luna-Gonzalez, D. V. and M. Sorensen, 2018: Higher agrobiodiversity is associated with improved dietary diversity, but not child anthropometric status, of Mayan Achi people of Guatemala. *Public Health Nutr*, **21**(11), 2128-2141, doi:10.1017/S1368980018000617.
Lund, J. F., E. Sungusia, M. B. Mabele and A. Scheba, 2017: Promising Change, Delivering Continuity: REDD plus as Conservation Fad. *World Dev.*, **89**, 124-139, doi:10.1016/j.worlddev.2016.08.005.
Lunstrum, E., 2016: Green grabs, land grabs and the spatiality of displacement: Eviction from Mozambique's Limpopo National Park. *Area*, **48**(2), 142-152, doi:10.1111/area.12121.
Lunstrum, E., P. Bose and A. Zalik, 2016: Environmental displacement: the common ground of climate change, extraction and conservation. *Area*, **48**(2), 130-133, doi:10.1111/area.12193.
Luo, Q. Y., M. Bange and D. Johnston, 2016: Environment and cotton fibre quality. *Clim. Change*, **138**(1-2), 207-221, doi:10.1007/s10584-016-1715-0.
Lwasa, S. et al., 2014: Urban and peri-urban agriculture and forestry: transcending poverty alleviation to climate change mitigation and adaptation. *Urban Clim.*, **7**, 92-106, doi:10.1016/j.uclim.2013.10.007.
Lwasa, S. et al., 2015: A meta-analysis of urban and peri-urban agriculture and forestry in mediating climate change. *Curr. Opin. Environ. Sustain.*, **13**, 68-73, doi:10.1016/j.cosust.2015.02.003.
Lydersen, C., 2018: Walrus: Odobenus rosmarus. In: *Encyclopedia of Marine Mammals*, 3 ed. [Würsig, B., J. G. M. Thewissen and K. M. Kovacs (eds.)]. Academic, London, United Kingdom, San Diego, CA, USA, Cambridge, MA, USA, and Oxford, United Kingdom, pp. 1045-1048, doi:10.1016/B978-0-12-804327-1.00020-0.
Lyman, N. B. et al., 2013: Neglecting rice milling yield and quality underestimates economic losses from high-temperature stress. *PLoS One*, **8**(8), e72157, doi:10.1371/journal.pone.0072157.
Lynch, A. J. et al., 2017: Inland fisheries–Invisible but integral to the UN Sustainable Development Agenda for ending poverty by 2030. *Global Environ. Change*, **47**, 167-173.
Lynch, A. J. et al., 2016: Climate change effects on North American inland fish populations and assemblages. *Fisheries*, **41**(7), 346-361, doi:10.1080/03632415.2016.1186016.
Lynn, K. et al., 2013: The impacts of climate change on tribal traditional foods. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions* [Maldonado, J. K., B. Colombi and R. Pandya (eds.)]. Springer, Cham, Switzerland, pp. 37-48. ISBN 9783319052656.
Lyons, K., C. Richards and P. Westoby, 2014: *The Darker Side of Green Plantation Forestry and Carbon Violence in Uganda: The Case of Green Resources' Forestry-Based Carbon Markets*. The Oakland Institute,, Oakland, CA, 19 pp. Available at: https://www.oaklandinstitute.org/sites/oaklandinstitute.org/files/Report_DarkerSideofGreen_hirez.pdf (accessed 05/08/2021).
M'Kaibi, F. K., N. P. Steyn, S. Ochola and L. Du Plessis, 2015: Effects of agricultural biodiversity and seasonal rain on dietary adequacy and household food security in rural areas of Kenya. *BMC Public Health*, **15**, 422, doi:10.1186/s12889-015-1755-9.

Müller, C. et al., 2017: Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications. *Geosci. Model Dev.*, **10**(4), 1403-1422.
Müller, C. et al., 2021a: Exploring uncertainties in global crop yield projections in a large ensemble of crop models and CMIP5 and CMIP6 climate scenarios. *Environ. Res. Lett.*, **16**(3), doi:10.1088/1748-9326/abd8fc.
Müller, M. F. et al., 2021b: Impact of transnational land acquisitions on local food security and dietary diversity. *Proceedings of the National Academy of Sciences*, **118**(4), e2020535118-e2020535118, doi:10.1073/pnas.2020535118.
Münke, C. et al., 2015: Wild ideas in food. In: *The Routledge Handbook on Sustainable Food and Gastronomy* [Sloan, P., W. Legrand and C. Hindley (eds.)]. Routledge, Abingdon, United Kingdom, and New York, NY, USA, pp. 206-213. ISBN 9780415702553.
Mabe, F. N. and A. Asase, 2020: Climate change adaptation strategies and fish catchability: The case of inland artisanal fishers along the Volta Basin in Ghana. *Fish. Res.*, **230**, 105675, doi:10.1016/j.fishres.2020.105675.
Mabe, F. N., S. Nashiru, E. Mummuni and V. F. Boateng, 2019: The nexus between land acquisition and household livelihoods in the Northern region of Ghana. *Land Use Policy*, **85**(April 2018), 357-367, doi:10.1016/j.landusepol.2019.03.043.
Macabuhay, A. et al., 2018: Can elevated CO2 buffer the effects of heat waves on wheat in a dryland cropping system? *Environ. Exp. Bot.*, **155**, 578-588, doi:10.1016/j.envexpbot.2018.07.029.
Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-197, doi:10.1038/s41586-019-1300-6.
Machado, L. et al., 2016: Dose-response effects of Asparagopsis taxiformis and Oedogonium sp. on in vitro fermentation and methane production. *J. Appl. Phycol.*, **28**(2), 1443-1452, doi:10.1007/s10811-015-0639-9.
Maciejczak, M. and J. Mikiciuk, 2019: Climate change impact on viticulture in Poland. *Int. J. Clim. Change Strateg. Manag.*, **11**(2), 254-264, doi:10.1108/Ijccsm-02-2018-0021.
Macko, S. A., C. Fantasia and G. J. Xue, 2017: Potential global economic impacts of ocean acidification. In: *International Marine Economy: Law and Policy* [Nordquist, M. H., J. N. Moore and R. Long (eds.)]. Brill Nijhoff, Leiden, the Netherlands and Boston, MA, USA, pp. 79-97. ISBN 9789004323438.
Maeno, K. O. and M. A. Ould Babah Ebbe, 2018: Aggregation Site Choice by Gregarious Nymphs of the Desert Locust, Schistocerca gregaria, in the Sahara Desert of Mauritania. *Insects*, **9**(3), 99-99, doi:10.3390/insects9030099.
Maezumi, S. Y. et al., 2018: The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. *Nat Plants*, **4**(8), 540-547, doi:10.1038/s41477-018-0205-y.
Magliocca, N. R., Q. V. Khuc, A. De Bremond and E. A. Ellicott, 2020: Direct and indirect land-use change caused by large-scale land acquisitions in Cambodia. *Environ. Res. Lett.*, **15**(2), 24010-24010, doi:10.1088/1748-9326/ab6397.
Magnan, A. K., 2014: Avoiding maladaptation to climate change: towards guiding principles. *S.A.P. I. EN. S.*, **7**(1).
Magni, G., 2017: Indigenous knowledge and implications for the sustainable development agenda. *European Journal of Education*, **52**(4), 437-447, doi:10.1111/ejed.12238.
Magrini, M.-B. et al., 2016: Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. *Ecol. Econ.*, **126**, 152-162, doi:10.1016/j.ecolecon.2016.03.024.
Maharjan, S. and K. Maharjan, 2018: Roles and contributions of community seed banks in climate adaptation in Nepal. *Dev. Pract.*, **28**(2), 292-302, doi:10.1080/09614524.2018.1418838.
Maikhuri, R. K. et al., 2018: Assessment of climate change impacts and its implications on medicinal plants-based traditional healthcare system in Central Himalaya, India. *Iranian Journal of Science and Technology, Transactions A: Science*, **42**(A4), 1827-1835, doi:10.1007/s40995-017-0354-2.
Maina, J. et al., 2016: Integrating social-ecological vulnerability assessments with climate forecasts to improve local climate adaptation planning for coral reef fisheries in Papua New Guinea. *Reg. Environ. Change*, **16**(3), 881-891, doi:10.1007/s10113-015-0807-0.
Makkar, H. P. S., 2018: Review: feed demand landscape and implications of food-not feed strategy for food security and climate change. *Animal*, **12**(8), 1744-1754, doi:10.1017/S175173111700324X.
Makondo, C. C. and D. S. G. Thomas, 2018: Climate change adaptation: linking indigenous knowledge with western science for effective adaptation. *Environ. Sci. Policy*, **88**, 83-91, doi:10.1016/j.envsci.2018.06.014.

Mallory, C. D. and M. S. Boyce, 2018: Observed and predicted effects of climate change on Arctic caribou and reindeer. *Environ. Rev.*, **26**(1), 13-25, doi:10.1139/er-2017-0032.
Manderscheid, R., M. Erbs and H. J. Weigel, 2014: Interactive effects of free-air CO2 enrichment and drought stress on maize growth. *Eur J Agron*, **52**, 11-21, doi:10.1016/j.eja.2011.12.007.
Mangi, S. C. et al., 2018: The economic impacts of ocean acidification on shellfish fisheries and aquaculture in the United Kingdom. *Environ. Sci. Policy*, **86**, 95-105, doi:10.1016/j.envsci.2018.05.008.
Manners, R. and J. van Etten, 2018: Are agricultural researchers working on the right crops to enable food and nutrition security under future climates? *Global Environ. Change*, **53**, 182-194.
Manners, R. et al., 2021: Suitability of root, tuber, and banana crops in Central Africa can be favoured under future climates. *Agric. Syst.*, **193**, 103246, doi:10.1016/j.agsy.2021.103246.
Mantri, V. A., M. G. Kavale and M. A. Kazi, 2020: Seaweed biodiversity of India: reviewing current knowledge to identify gaps, challenges, and opportunities. *Diversity*, **12**(1), 13, doi:10.3390/d12010013.
Mantyka-Pringle, C. S. et al., 2016: Prioritizing management actions for the conservation of freshwater biodiversity under changing climate and land-cover. *Biol. Conserv.*, **197**, 80-89, doi:10.1016/j.biocon.2016.02.033.
Maranz, S. and Z. Wiesman, 2003: Evidence for indigenous selection and distribution of the shea tree, Vitellaria paradoxa, and its potential significance to prevailing parkland savanna tree patterns in sub-Saharan Africa north of the equator. *J. Biogeogr.*, **30**(10), 1505-1516, doi:10.1046/j.1365-2699.2003.00892.x.
Maraseni, T. N., P. R. Neupane, F. Lopez-Casero and T. Cadman, 2014: An assessment of the impacts of the REDD+ pilot project on community forests user groups (CFUGs) and their community forests in Nepal. *J Environ Manage*, **136**, 37-46, doi:10.1016/j.jenvman.2014.01.011.
Marcogliese, D. J., 2016: The distribution and abundance of parasites in aquatic ecosystems in a changing climate: more than just temperature. *Integr. Comp. Biol.*, **56**(4), 611-619, doi:10.1093/icb/icw036.
Marcos-Martinez, R., B. A. Bryan, J. D. Connor and D. King, 2017: Agricultural land-use dynamics: assessing the relative importance of socioeconomic and biophysical drivers for more targeted policy. *Land Use Policy*, **63**, 53-66, doi:10.1016/j.landusepol.2017.01.011.
Marín, D., J. Armengol, J. M. Escalona and D. Gramaje, 2021: Challenges of viticulture adaptation to global change : tackling the issue from the roots. *Australian Journal of Grape and Wine Research*, 8-25, doi:10.1111/ajgw.12463.
Marini, L. et al., 2020: Crop rotations sustain cereal yields under a changing climate. *Environ. Res. Lett.*, **15**(12), 124011-124011, doi:10.1088/1748-9326/abc651.
Markandya, A. and M. González-Eguino, 2019: Integrated Assessment for Identifying Climate Finance Needs for Loss and Damage: A Critical Review. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, pp. 343-362. ISBN 978-3-319-72026-5.
Markon, C. et al., 2018: Alaska. In: *In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. US Global Change Research Program, Washington, DC, USA, pp. 1185–1241.
Marselis, S. M. et al., 2017: Agricultural land displacement and undernourishment. *J. Clean. Prod.*, **161**, 619-628, doi:10.1016/j.jclepro.2017.05.125.
Marteau, T. M., G. J. Hollands and P. C. Fletcher, 2012: Changing human behavior to prevent disease: the importance of targeting automatic processes. *Science*, **337**(6101), 1492-1495, doi:10.1126/science.1226918.
Martellozzo, F. et al., 2014: Urban agriculture: a global analysis of the space constraint to meet urban vegetable demand. *Environ. Res. Lett.*, **9**(6), 64025, doi:10.1088/1748-9326/9/6/064025.
Martínez-Lüscher, J. et al., 2016: Sensitivity of grapevine phenology to water availability, temperature and CO2 concentration. *Front. Environ. Sci.*, **4**, doi:10.3389/fenvs.2016.00048.
Martínez-Paz, J. M., I. Banos-González, J. Martínez-Fernández and M. Á. Esteve-Selma, 2019: Assessment of management measures for the conservation of traditional irrigated lands: The case of the Huerta of Murcia (Spain). *Land Use Policy*, **81**, 382-391, doi:10.1016/j.landusepol.2018.10.050.
Martin, G. et al., 2020: Potential of multi-species livestock farming to improve the sustainability of livestock farms: a review. *Agric. Syst.*, **181**, 102821, doi:10.1016/j.agsy.2020.102821.

Martin, G. and M. Willaume, 2016: A diachronic study of greenhouse gas emissions of French dairy farms according to adaptation pathways. *Agric. Ecosyst. Environ.*, **221**, 50-59, doi:10.1016/j.agee.2016.01.027.
Martin, M. and E. Molin, 2019: Environmental assessment of an urban vertical hydroponic farming system in Sweden. *Sustainability (Switzerland)*, **11**(15), doi:10.3390/su11154124.
Martinez-Harms, M. J. et al., 2017: Scenarios for land use and ecosystem services under global change. *Ecosyst. Serv.*, **25**, 56-68, doi:10.1016/j.ecoser.2017.03.021.
Martinez, M. et al., 2018: Measuring the effects of temperature rise on Mediterranean shellfish aquaculture. *Ecol. Indic.*, **88**, 71-78, doi:10.1016/j.ecolind.2018.01.002.
Martins, I. M., L. C. Gammage, A. Jarre and M. A. Gasalla, 2019: Different but similar? Exploring vulnerability to climate change in Brazilian and South African small-scale fishing communities. *Hum. Ecol.*, **47**(4), 515-526, doi:10.1007/s10745-019-00098-4.
Martins, I. M. and M. A. Gasalla, 2018: Perceptions of climate and ocean change impacting the resources and livelihood of small-scale fishers in the South Brazil bight. *Clim. Change*, **147**(3-4), 441-456, doi:10.1007/s10584-018-2144-z.
Martos-Sitcha, J. A. et al., 2019: Tissue-Specific Orchestration of Gilthead Sea Bream Resilience to Hypoxia and High Stocking Density. *Frontiers in Physiology*, **10**(840), doi:10.3389/fphys.2019.00840.
Marushka, L. et al., 2019: Potential impacts of climate-related decline of seafood harvest on nutritional status of coastal First Nations in British Columbia, Canada. *PLoS One*, **14**(2), e0211473, doi:10.1371/journal.pone.0211473.
Mase, A. S. and L. S. Prokopy, 2014: Unrealized potential: a review of perceptions and use of weather and climate information in agricultural decision making. *Weather Clim. Soc.*, **6**(1), 47-61, doi:10.1175/Wcas-D-12-00062.1.
Masutomi, Y. et al., 2019: Rice grain quality degradation and economic loss due to global warming in Japan. *Environ. res. commun.*, **1**(12), 121003, doi:10.1088/2515-7620/ab52e7.
Matiu, M., D. P. Ankerst and A. Menzel, 2017: Interactions between temperature and drought in global and regional crop yield variability during 1961-2014. *PLoS One*, **12**(5), e0178339, doi:10.1371/journal.pone.0178339.
Mattick, C. S., A. E. Landis, B. R. Allenby and N. J. Genovese, 2015: Anticipatory Life Cycle Analysis of In Vitro Biomass Cultivation for Cultured Meat Production in the United States. *Environ. Sci. Technol.*, **49**(19), 11941-11949, doi:10.1021/acs.est.5b01614.
Mattos, L. M. et al., 2014: Climate Changes and Potential Impacts on Quality of Fruit and Vegetable Crops. In: *Emerging Technologies and Management of Crop Stress Tolerance* [Ahmad, P. and S. Rasool (eds.)]. Academic, San Diego, CA, USA, London, United Kingdom, and Waltham, MA, USA, pp. 467-486. ISBN 9780128008768.
Matzrafi, M., 2019: Climate change exacerbates pest damage through reduced pesticide efficacy. *Pest Manag Sci*, **75**(1), 9-13, doi:10.1002/ps.5121.
Matzrafi, M. et al., 2016: Climate change increases the risk of herbicide-resistant weeds due to enhanced detoxification. *Planta*, **244**(6), 1217-1227, doi:10.1007/s00425-016-2577-4.
Mayer, A. et al., 2019a: Measuring Progress towards a Circular Economy: A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. *Journal of Industrial Ecology*, **23**(1), 62-76, doi:10.1111/jiec.12809.
Mayer, D. G., K. A. Chandra and J. R. Burnett, 2019b: Improved crop forecasts for the Australian macadamia industry from ensemble models. *Agric. Syst.*, **173**, 519-523, doi:10.1016/j.agsy.2019.03.018.
Mazaris, A. D. and B. Germond, 2018: Bridging the gap between climate change and maritime security: Towards a comprehensive framework for planning. *Sci. Total Environ.*, **635**, 1076-1080, doi:10.1016/j.scitotenv.2018.04.136.
Mbow, C. et al., 2019: Food security. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.
Mbow, C. et al., 2014: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr. Opin. Environ. Sustain.*, **6**, 8-14, doi:10.1016/j.cosust.2013.09.002.

McCabe, R. M. et al., 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophys. Res. Lett.*, **43**(19), 10,366-310,376, doi:10.1002/2016GL070023.
Mccall, M. K., 2016: Beyond "landscape" in REDD plus : the imperative for "territory". *World Dev.*, **85**, 58-72, doi:10.1016/j.worlddev.2016.05.001.
McCoy, D. et al., 2017: Large-scale climatic effects on traditional Hawaiian fishpond aquaculture. *PLoS One*, **12**(11), e0187951, doi:10.1371/journal.pone.0187951.
McDaniel, M. D., L. K. Tiemann and A. S. Grandy, 2014: Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecol. Appl.*, **24**(3), 560-570, doi:10.1890/13-0616.1.
McDonald, K. S. et al., 2019: Proactive, reactive, and inactive pathways for scientists in a changing world. *Earths Future*, **7**(2), 60-73, doi:10.1029/2018ef000990.
McDowell, N. G. et al., 2020: Pervasive shifts in forest dynamics in a changing world. *Science*, **368**(6494), doi:10.1126/science.aaz9463.
McGill, B. M., S. K. Hamilton, N. Millar and G. P. Robertson, 2018: The greenhouse gas cost of agricultural intensification with groundwater irrigation in a Midwest U.S. row cropping system. *Glob Chang Biol*, **24**(12), 5948-5960, doi:10.1111/gcb.14472.
McGrath, D. and L. Costello, 2015: Integrating fishers' ecological knowledge and the ecosystem based mangement of tropical inland fisheries: an Amazon case study. In: *Fishers' knowledge and the ecosystem approach to fisheries: applications, experiences and lessons in Latin America.* [Fischer, J., J. Jorgensen, H. Josupeit, D. Kalikoski and C. M. Lucas (eds.)]. FAO, Rome, pp. 127-148.
McGrath, J. M. et al., 2015: An analysis of ozone damage to historical maize and soybean yields in the United States. *Proc Natl Acad Sci U S A*, **112**(46), 14390-14395, doi:10.1073/pnas.1509777112.
McHunu, N., G. Lagerwall and A. Senzanje, 2018: Aquaponics in South Africa: Results of a national survey. *Aquaculture Reports*, **12**, 12-19, doi:10.1016/j.aqrep.2018.08.001.
McIntyre-Tamwoy, S., M. Fuary and A. Buhrich, 2013: Understanding climate, adapting to change: indigenous cultural values and climate change impacts in North Queensland. *Local Environ.*, **18**(1), 91-109, doi:10.1080/13549839.2012.716415.
McIntyre, K. M. et al., 2017: Systematic assessment of the climate sensitivity of important human and domestic animals pathogens in Europe. *Sci Rep*, **7**(1), 7134, doi:10.1038/s41598-017-06948-9.
McIntyre, P. B., C. A. Reidy Liermann and C. Revenga, 2016: Linking freshwater fishery management to global food security and biodiversity conservation. *Proc Natl Acad Sci U S A*, **113**(45), 12880-12885, doi:10.1073/pnas.1521540113.
Mcleod, E. et al., 2018: Raising the voices of Pacific Island women to inform climate adaptation policies. *Mar. Policy*, **93**, 178-185, doi:10.1016/j.marpol.2018.03.011.
McMillen, H., T. Ticktin and H. K. Springer, 2017: The future is behind us: traditional ecological knowledge and resilience over time on Hawai'i Island. *Reg. Environ. Change*, **17**(2), 579-592, doi:10.1007/s10113-016-1032-1.
McNamara, K. E. and L. Buggy, 2017: Community-based climate change adaptation: a review of academic literature. *Local Environ.*, **22**(4), 443-460, doi:10.1080/13549839.2016.1216954.
McNamara, K. E. et al., 2020: An assessment of community-based adaptation initiatives in the Pacific Islands. *Nat. Clim. Change*, **10**(7), 628-639, doi:10.1038/s41558-020-0813-1.
McNamara, K. E. and S. S. Prasad, 2014: Coping with extreme weather: communities in Fiji and Vanuatu share their experiences and knowledge. *Clim. Change*, **123**(2), 121-132, doi:10.1007/s10584-013-1047-2.
McNeeley, S. M., 2017: Sustainable Climate Change Adaptation in Indian Country. *Weather, Climate, and Society*, **9**(3), 393-404, doi:10.1175/WCAS-D-16-0121.1.
McNeeley, S. M. et al., 2018: Anatomy of an interrupted irrigation season: Micro-drought at the Wind River Indian Reservation. *Clim. Risk Manag.*, **19**, 61-82, doi:10.1016/j.crm.2017.09.004.
McNeeley, S. M., J. M. Friedman, T. A. Beeton and R. D. Thaxton, 2020: *Cottonwoods, Water, and People-Integrating Analysis of Tree Rings with Observations of Elders from the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation*. Wyoming.
McNeely, J. A. and G. Schroth, 2006: Agroforestry and biodiversity conservation - traditional practices, present dynamics, and lessons for the future. *Biodivers. Conserv.*, **15**(2), 549-554, doi:10.1007/s10531-005-2087-3.
Meade, E., M. A. Slattery and M. Garvey, 2019: Zoonotic antimicrobial resistance as a result of iatrogenic disease in companion animals - case study reports. *J Infect Dis Epidemiol*, **5**, 073, doi:10.23937/2474-3658/1510073.

Mechiche-Alami, A., J. Yagoubi and K. A. Nicholas, 2021: Agricultural land acquisitions unlikely to address the food security needs of African countries. *World Dev.*, **141**, doi:10.1016/j.worlddev.2020.105384.
Medina, A., A. Rodriguez and N. Magan, 2015a: Climate change and mycotoxigenic fungi: impacts on mycotoxin production. *Curr. Opin. Food Sci.*, **5**, 99-104, doi:10.1016/j.cofs.2015.11.002.
Medina, A., A. Rodriguez, Y. Sultan and N. Magan, 2015b: Climate change factors and Aspergillus flavus: effects on gene expression, growth and aflatoxin production. *World Mycotoxin J.*, **8**(2), 171-179, doi:10.3920/Wmj2014.1726.
Medina Hidalgo, D. et al., 2020: Sustaining healthy diets in times of change: linking climate hazards, food systems and nutrition security in rural communities of the Fiji Islands. *Reg. Environ. Change*, **20**(3), 73-73, doi:10.1007/s10113-020-01653-2.
Megersa, B. et al., 2014: Impacts of climate change and variability on cattle production in southern Ethiopia: Perceptions and empirical evidence. *Agric. Syst.*, **130**, 23-34, doi:10.1016/j.agsy.2014.06.002.
Mehrabi, Z. and N. Ramankutty, 2019: Synchronized failure of global crop production. *Nat Ecol Evol*, **3**(5), 780-786, doi:10.1038/s41559-019-0862-x.
Mehvar, S. et al., 2019: Climate change-driven losses in ecosystem services of coastal wetlands: A case study in the West coast of Bangladesh. *Ocean Coast. Manage.*, **169**, 273-283, doi:10.1016/j.ocecoaman.2018.12.009.
Meier, M., J. Fuhrer and A. Holzkamper, 2018: Changing risk of spring frost damage in grapevines due to climate change? A case study in the Swiss Rhone Valley. *Int J Biometeorol*, **62**(6), 991-1002, doi:10.1007/s00484-018-1501-y.
Meijer, S. S. et al., 2015: The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. *Int. J. Agric. Sustain.*, **13**(1), 40-54, doi:10.1080/14735903.2014.912493.
Mekonnen, M. M. and A. Y. Hoekstra, 2010: A global and high-resolution assessment of the green, blue and grey water footprint of wheat. *Hydrol. Earth Syst. Sci.*, **14**(7), 1259-1276, doi:10.5194/hess-14-1259-2010.
Mekuyie, M., A. Jordaan and Y. Melka, 2018: Understanding resilience of pastoralists to climate change and variability in the Southern Afar Region, Ethiopia. *Clim. Risk Manag.*, **20**, 64-77, doi:10.1016/j.crm.2018.02.004.
Melbourne-Thomas, J. et al., 2021: Poleward bound: adapting to climate-driven species redistribution. *Rev. Fish Biol. Fish.*, doi:10.1007/s11160-021-09641-3.
Meldrum, G. et al., 2018: Climate change and crop diversity: farmers' perceptions and adaptation on the Bolivian Altiplano. *Environment Development and Sustainability*, **20**(2), 703-730, doi:10.1007/s10668-016-9906-4.
Melillo, J. M. et al., 2017: Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. *Science*, **358**(6359), 101-105, doi:10.1126/science.aan2874.
Mellin, C. et al., 2016: Forecasting marine invasions under climate change: Biotic interactions and demographic processes matter. *Biol. Conserv.*, **204**, 459-467, doi:10.1016/j.biocon.2016.11.008.
Melvin, A. M. et al., 2017: Estimating wildfire response costs in Alaska's changing climate. *Clim. Change*, **141**(4), 783-795, doi:10.1007/s10584-017-1923-2.
Memmott, P. et al., 2013: *Aboriginal Responses to Climate Change in Arid Zone Australia: Regional Understandings and Capacity Building for Adaptation*. National Climate Change Adaptation Research Facility,, Gold Coast, Australia.
Menchaca, A., P. C. Dos Santos-Neto, A. P. Mulet and M. Crispo, 2020: CRISPR in livestock: from editing to printing. *Theriogenology*, **150**, 247-254, doi:10.1016/j.theriogenology.2020.01.063.
Mendenhall, E. et al., 2020: Climate change increases the risk of fisheries conflict. *Mar. Policy*, **117**, doi:10.1016/j.marpol.2020.103954.
Mendez, M., G. Flores-Haro and L. Zucker, 2020: The (in)visible victims of disaster: understanding the vulnerability of undocumented Latino/a and indigenous immigrants. *Geoforum*, **116**, 50-62, doi:10.1016/j.geoforum.2020.07.007.
Menyuka, N. N., M. Sibanda and U. Bob, 2020: Perceptions of the challenges and opportunities of utilising organic waste through urban agriculture in the Durban South Basin. *Int J Environ Res Public Health*, **17**(4), doi:10.3390/ijerph17041158.
Mercure, J. F. et al., 2019: System complexity and policy integration challenges: the Brazilian energy-water-food nexus. *Renew. Sustain. Energy Rev.*, **105**, 230-243, doi:10.1016/j.rser.2019.01.045.
Meredith, M. et al., 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Crysosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Vmasson-Delmotte, P. Zhai, M. Tignor, E.

Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. 203-320.

Meridian Institute, 2020: *Food Systems of the Future: A Synthesis of Reports on Food Systems Transformation*. Global Alliance for the Future of Food, 31 pp. Available at: https://futureoffood.org/wp-content/uploads/2020/03/GA-Meridian-Synthesis-Reports-FINAL-2020-03-16.pdf?fbclid=IwAR1QWVm77pNWD02MDZ6G2Jq3ayNw2LQyH0GuJLe46ZfXuCkirtCm37wJLaQ (accessed 05/08/2021).

Merlín-Uribe, Y. et al., 2012: Environmental and socio-economic sustainability of chinampas(raised beds) in Xochimilco, Mexico City. *Int. J. Agric. Sustain.*, **11**(3), 216-233, doi:10.1080/14735903.2012.726128.

Merloni, E., L. Camanzi, L. Mulazzani and G. Malorgio, 2018: Adaptive capacity to climate change in the wine industry: a Bayesian network approach. *Wine Econ. Policy*, **7**(2), 165-177, doi:10.1016/j.wep.2018.11.002.

Merow, C. et al., 2017: Climate change both facilitates and inhibits invasive plant ranges in New England. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(16), E3276-E3284, doi:10.1073/pnas.1609633114.

Merrey, D. J. et al., 2018: Evolving high altitude livelihoods and climate change: a study from Rasuwa District, Nepal. *Food Secur.*, **10**(4), 1055-1071, doi:10.1007/s12571-018-0827-y.

Mertz, O., A. Mbow, A. Reenberg and A. Diouf, 2009: Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environ. Manag.*, **45**, 804-816.

Mertz, O. e. a., 2012: Climate variability and environmental stress in the Sudan-Sahel zone of West Africa. *Ambio*, **41**, 380-392.

Messer, E., 1972: Patterns of "wild" plant consumption in Oaxaca, Mexico. *Ecol. Food Nutr.*, **1**(4), 325-332.

Metian, M. et al., 2020: Mapping diversity of species in global aquaculture. *Rev. Aquac.*, **12**(2), 1090-1100, doi:10.1111/raq.12374.

Metternicht, G., 2018: *Land Use and Spatial Planning*. SpringerBriefs in Earth Sciences, Springer International Publishing, Cham.

Meynard, C. N., M. Lecoq, M. P. Chapuis and C. Piou, 2020: On the relative role of climate change and management in the current desert locust outbreak in East Africa. *Glob Chang Biol*, **26**(7), 3753-3755, doi:10.1111/gcb.15137.

Meza, I. et al., 2020: Global-scale drought risk assessment for agricultural systems. *Nat. Hazards Earth Syst. Sci.*, **20**(2), 695-712, doi:10.5194/nhess-20-695-2020.

Michael, K., T. Deshpande and G. Ziervogel, 2019: Examining vulnerability in a dynamic urban setting: the case of Bangalore's interstate migrant waste pickers. *Clim. Dev.*, **11**(8), 667-678, doi:10.1080/17565529.2018.1531745.

Mie, A. et al., 2017: Human health implications of organic food and organic agriculture: a comprehensive review. *Environ. Health*, **16**, 1-22, doi:10.1186/s12940-017-0315-4.

Mier y Terán Giménez Cacho, M. et al., 2018: Bringing agroecology to scale: key drivers and emblematic cases. *Agroecol. Sustain. Food Syst.*, **42**(6), 637-665, doi:10.1080/21683565.2018.1443313.

Migliorini, P. et al., 2016: Agronomic and quality characteristics of old, modern and mixture wheat varieties and landraces for organic bread chain in diverse environments of northern Italy. *Eur J Agron*, **79**, 131-141, doi:10.1016/j.eja.2016.05.011.

Mikovits, C. et al., 2019: Impacts of global warming on confined livestock systems for growing-fattening pigs: simulation of heat stress for 1981 to 2017 in Central Europe. *Int J Biometeorol*, **63**(2), 221-230, doi:10.1007/s00484-018-01655-0.

Mikulewicz, M., 2020: Disintegrating labour relations and depoliticised adaptation to climate change in rural São Tomé and Príncipe. *Area*, area.12630-area.12630, doi:10.1111/area.12630.

Milcu, A. I., J. Hanspach, D. Abson and J. Fischer, 2013: Cultural ecosystem services: a literature review and prospects for future research. *Ecol. Soc.*, **18**(3), 44, doi:10.5751/Es-05790-180344.

Milder, J. C. et al., 2014: Integrated landscape initiatives for African agriculture, development, and conservation: a region-wide assessment. *World Dev.*, **54**, 68-80, doi:10.1016/j.worlddev.2013.07.006.

Milicevic, D. et al., 2019: Impact of climate change on aflatoxin M1 contamination of raw milk with special focus on climate conditions in Serbia. *J. Sci. Food Agric.*, **99**(11), 5202-5210, doi:10.1002/jsfa.9768.

Millan, A., B. Limketkai and S. Guarnaschelli, 2019: *Financing the Transformation of Food Systems Under a Changing Climate*. CGIAR Research Program on Climate Change, Agriculture and Food Security, Wageningen, the Netherlands, 32 pp. Available at: <Go to WoS>://WOS:000412300200003 (accessed 16/08/2021).

Millan, A., Limketkai B, Guarnaschelli S. , 2019: *Financing the Transformation of Food Systems Under a Changing Climate*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, the Netherlands. Available at: https://hdl.handle.net/10568/101132

Millennium Ecosystem Assessment, 2005: *Ecosystems and Human Well-being: Synthesis*. Press Island, Washington, D.C., USA, 137 pp. ISBN 1597260401.

Miller-Struttmann, N. E. et al., 2015: Functional mismatch in a bumble bee pollination mutualism under climate change. *Science*, **349**(6255), 1541-1544, doi:10.1126/science.aab0868.

Miller, J. D., 2016: Mycotoxins in food and feed: a challenge for the twenty-first century. In: *Biology of Microfungi* [Li, D. W. (ed.)]. Springer, Cham, Switzerland, pp. 469-493. ISBN 9783319291352.

Miller, K. A., G. R. Munro, U. R. Sumaila and W. W. L. Cheung, 2013: Governing marine fisheries in a changing climate: a game-theoretic perspective. *Can. J. Agric. Econ.*, **61**(2), 309-334, doi:10.1111/cjag.12011.

Millet, E. J. et al., 2016: Genome-wide analysis of yield in Europe: allelic effects vary with drought and heat scenarios. *Plant Physiol.*, **172**(2), 749-764, doi:10.1104/pp.16.00621.

Mills, E. N., 2018: Implicating "fisheries justice' movements in food and climate politics. *Third World Q.*, **39**(7), 1270-1289, doi:10.1080/01436597.2017.1416288.

Mills, G. et al., 2018: Closing the global ozone yield gap: quantification and cobenefits for multistress tolerance. *Glob Chang Biol*, **24**(10), 4869-4893, doi:10.1111/gcb.14381.

Milner, S. et al., 2016: Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *GCB Bioenergy*, **8**(2), 317-333, doi:10.1111/gcbb.12263.

Minasny, B. and A. B. McBratney, 2018: Limited effect of organic matter on soil available water capacity. *Eur. J. Soil Sci.*, **69**, 39-47, doi:10.1111/ejss.12475.

Minet, J. et al., 2017: Crowdsourcing for agricultural applications: a review of uses and opportunities for a farmsourcing approach. *Comput. Electron. Agric.*, **142**, 126-138, doi:10.1016/j.compag.2017.08.026.

Mingorría, S., 2018: Violence and visibility in oil palm and sugarcane conflicts: the case of Polochic Valley, Guatemala. *J. Peasant Stud.*, **45**(7), 1314-1340, doi:10.1080/03066150.2017.1293046.

Mingorría, S. G., G.; Martín, B; and Corbera, E. , 2014: The oil palm boom: socio-economic implications for Q'eqchi' households in the Polochic Valley, Guatemala. *Environment Development and Sustainability*, **16**, 841-871, doi:10.1007/s10668-014-9530-0

Minoli, S. et al., 2019: Global response patterns of major rainfed crops to adaptation by maintaining current growing periods and irrigation. *Earths Future*, **7**(12), 1464-1480, doi:10.1029/2018ef001130.

Mirás-Avalos, J. M., D. Uriarte, A. N. Lakso and D. S. Intrigliolo, 2018: Modeling grapevine performance with 'VitiSim', a weather-based carbon balance model: water status and climate change scenarios. *Sci. Hortic.*, **240**, 561-571, doi:10.1016/j.scienta.2018.06.065.

Mistry, J. and A. Berardi, 2016: Bridging indigenous and scientific knowledge. *Science*, **352**(6291), 1274-1275, doi:10.1126/science.aaf1160.

Mitchell, D. C. et al., 2017: Recruitment, methods, and descriptive results of a physiologic assessment of Latino farmworkers: the California heat illness prevention study. *J. Occup. Environ. Med.*, **59**(7), 649-658, doi:10.1097/JOM.0000000000000988.

Miyan, M. A., 2015: Droughts in Asian least developed countries: vulnerability and sustainability. *Weather Clim. Extrem.*, **7**, 8-23, doi:10.1016/j.wace.2014.06.003.

Mohamad, N. et al., 2019a: Vibriosis in cultured marine fishes: a review. *Aquaculture*, **512**, 734289, doi:10.1016/j.aquaculture.2019.734289.

Mohamad, N. et al., 2019b: Environmental factors associated with the presence of Vibrionaceae in tropical cage-cultured marine fishes. *J. Aquat. Anim. Health*, **31**(2), 154-167, doi:10.1002/aah.10062.

Mohareb, E. et al., 2017: Considerations for reducing food system energy demand while scaling up urban agriculture. *Environ. Res. Lett.*, **12**(12), 125004, doi:10.1088/1748-9326/aa889b.

Mok, H.-F. et al., 2014: Strawberry fields forever? Urban agriculture in developed countries: a review. *Agron. Sustain. Dev.*, **34**(1), 21-43, doi:10.1007/s13593-013-0156-7.

Molitor, D. and J. Junk, 2019: Climate change is implicating a two-fold impact on air temperature increase in the ripening period under the conditions of the Luxembourgish grape growing region. *Oeno One*, **53**(3), 409-422, doi:10.20870/oeno-one.2019.53.3.2329.

Momblanch, A. et al., 2019: Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system. *Sci. Total Environ.*, **655**, 35-47, doi:10.1016/j.scitotenv.2018.11.045.

Monsees, H. et al., 2019: Lettuce (Lactuca sativa, variety Salanova) production in decoupled aquaponic systems: same yield and similar quality as in conventional hydroponic systems but drastically reduced greenhouse gas emissions by saving inorganic fertilizer. *PLoS One*, **14**(6), e0218368, doi:10.1371/journal.pone.0218368.

Montagnini, F. and R. Metzel, 2017: The contribution of agroforestry to Sustainable Development Goal 2: end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. In: *Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty* [Montagnini, F. (ed.)]. Springer, Cham, Switzerland, pp. 11-45. ISBN 9783319693705.

Montanchez, I. and V. R. Kaberdin, 2020: Vibrio harveyi: a brief survey of general characteristics and recent epidemiological traits associated with climate change. *Mar. Environ. Res.*, **154**, 104850, doi:10.1016/j.marenvres.2019.104850.

Montanchez, I. et al., 2019: Analysis of Vibrio harveyi adaptation in sea water microcosms at elevated temperature provides insights into the putative mechanisms of its persistence and spread in the time of global warming. *Sci Rep*, **9**(1), 289, doi:10.1038/s41598-018-36483-0.

Montefrio, M. J. F., 2017: Land control dynamics and social-ecological transformations in upland Philippines. *J. Peasant Stud.*, **44**(4), 770-790, doi:10.1080/03066150.2016.1257988.

Monteiro, A. P. A., S. Tao, I. M. T. Thompson and G. E. Dahl, 2016: In utero heat stress decreases calf survival and performance through the first lactation. *J. Dairy Sci.*, **99**(10), 8443-8450, doi:10.3168/jds.2016-11072.

Montenegro de Wit, M., 2019: Gene driving the farm: who decides, who owns, and who benefits? *Agroecol. Sustain. Food Syst.*, **43**(9), 1054-1074, doi:10.1080/21683565.2019.1591566.

Montenegro de Wit, M., A. R. Kapuscinski and E. Fitting, 2020: Democratizing CRISPR? Stories, practices, and politics of science and governance on the agricultural gene editing frontier. *Elementa: Sci. Anthropocene*, **8**, doi:10.1525/elementa.405.

Moor, M. A. et al., 2017: Individual and community factors contributing to anemia among women in rural Baja California, Mexico. *PLoS One*, **12**(11), e0188590, doi:10.1371/journal.pone.0188590.

Moore, A. D. and A. Ghahramani, 2014: Climate change and broadacre livestock production across southern Australia. 3. Adaptation options via livestock genetic improvement. *Anim. Prod. Sci.*, **54**(2), 111-124, doi:10.1071/An13052.

Moore, F., 2020: The Fingerprint of Anthropogenic Warming on Global Agriculture. *EarthArXiv*, doi:10.31223/x5q30z.

Moore, F. C. and D. B. Lobell, 2015: The fingerprint of climate trends on European crop yields. *Proc Natl Acad Sci U S A*, **112**(9), 2670-2675, doi:10.1073/pnas.1409606112.

Moore, S. E. and H. P. Huntington, 2008: Arctic marine mammals and climate change: impacts and resilience. *Ecol. Appl.*, **18**(2 Suppl), s157-165, doi:10.1890/06-0571.1.

Morales-Castilla, I. et al., 2020: Diversity buffers winegrowing regions from climate change losses. *Proc Natl Acad Sci U S A*, **117**(6), 2864-2869, doi:10.1073/pnas.1906731117.

Morales, F. et al., 2014: Methodological advances: using greenhouses to simulate climate change scenarios. *Plant Sci.*, **226**, 30-40, doi:10.1016/j.plantsci.2014.03.018.

Moreda, T., 2017: Large-scale land acquisitions, state authority and indigenous local communities: insights from Ethiopia. *Third World Q.*, **38**(3), 698-716, doi:10.1080/01436597.2016.1191941.

Moreda, T., 2018: The right to food in the context of large-scale land investment in Ethiopia. *Third World Q.*, **39**(7), 1326-1347, doi:10.1080/01436597.2018.1460199.

Moretti, A., M. Pascale and A. F. Logrieco, 2019: Mycotoxin risks under a climate change scenario in Europe. *Trends Food Sci. Technol.*, **84**, 38-40, doi:10.1016/j.tifs.2018.03.008.

Morgan, M. et al., 2015: *Understanding the Gender Dimensions of Adopting Climate-Smart Smallholder Aquaculture Innovations*. Working Paper, CGIAR Research Program on Aquatic Agricultural Systems,, Penang, Malaysia, 43 pp. Available at: <Go to WoS>://WOS:000361906400033 (accessed 19/08/2021).

Moriondo, M. et al., 2015: Modelling olive trees and grapevines in a changing climate. *Environ. Model. Software*, **72**, 387-401, doi:10.1016/j.envsoft.2014.12.016.

Morita, S., H. Wada and Y. Matsue, 2016: Countermeasures for heat damage in rice grain quality under climate change. *Plant Production Science*, **19**(1), 1-11, doi:10.1080/1343943x.2015.1128114.

Morrissey, M. T., R. Rasmussen and T. Okada, 2005: Mercury Content in Pacific Troll-Caught Albacore Tuna (Thunnus alalunga). *J. Aquat. Food Prod. Technol.*, **13**(4), 41-52, doi:10.1300/J030v13n04_04.

Mortimore, M., 2010: Adapting to drought in the Sahel: lessons for climate change. *Wiley Interdiscip. Rev.: Clim. Change*, **1**(1), 134-143, doi:10.1002/wcc.25.
Mosberg, M. and S. H. Eriksen, 2015: Responding to climate variability and change in dryland Kenya: the role of illicit coping strategies in the politics of adaptation. *Glob. Environ. Change*, **35**, 545-557, doi:10.1016/j.gloenvcha.2015.09.006.
Mosedale, J. R. et al., 2016: Climate change impacts and adaptive strategies: lessons from the grapevine. *Glob Chang Biol*, **22**(11), 3814-3828, doi:10.1111/gcb.13406.
Mosedale, J. R., R. J. Wilson and I. M. Maclean, 2015: Climate change and crop exposure to adverse weather: changes to frost risk and grapevine flowering conditions. *PLoS One*, **10**(10), e0141218, doi:10.1371/journal.pone.0141218.
Moseley, W., M. Schnurr and R. B. Kerr, 2015: Interrogating the technocratic (neoliberal) agenda for agricultural development and hunger alleviation in Africa. *Afr. Geogr. Rev.*, **34**(1), 1-7, doi:10.1080/19376812.2014.1003308.
Moses, J. A., D. S. Jayas and K. Alagusundaram, 2015: Climate change and its implications on stored food grains. *Agricultural Research*, **4**(1), 21-30, doi:10.1007/s40003-015-0152-z.
Mosnier, A. et al., 2014: Global food markets, trade and the cost of climate change adaptation. *Food Secur.*, **6**(1), 29-44, doi:10.1007/s12571-013-0319-z.
Mottet, A. et al., 2020: Assessing Transitions to Sustainable Agricultural and Food Systems: A Tool for Agroecology Performance Evaluation (TAPE). *Front. Sustain. Food Syst.*, **4**, doi:10.3389/fsufs.2020.579154.
Moukrim, S. et al., 2019: Climate change impacts on potential distribution of multipurpose agro-forestry species: Argania spinosa (L.) Skeels as case study. *Agroforestry Systems*, **93**(4), 1209-1219.
Moulton, A. A. and M. R. Machado, 2019: Bouncing Forward After Irma and Maria: Acknowledging Colonialism, Problematizing Resilience and Thinking Climate Justice. *J. Extreme Events*, **06**(01), doi:10.1142/s2345737619400037.
Mousseau, F., 2015: The untold success story of agroecology in Africa. *Development*, **58**, 341-345, doi:10.1057/s41301-016-0026-0.
Mousseau, F. and E. Teare, 2019: *Evicted for Carbon Credits: Norway, Sweden, and Finland Displace Ugandan Farmers for Carbon Trading*. The Oakland Institute,, Oakland, CA, 15 pp. Available at: https://www.oaklandinstitute.org/evicted-carbon-credits-green-resources (accessed 05/08/2021).
Mpandeli, S. et al., 2018: Climate change adaptation through the water-energy-food nexus in Southern Africa. *Int J Environ Res Public Health*, **15**(10), 2306, doi:10.3390/ijerph15102306.
Mrabet, R. et al., 2020: Food. In: *Climate and Environmental Change in the Mediterranean Basin- Current Situation and Risks fo the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 237-264.
Msuya, F. E. and A. Q. Hurtado, 2017: The role of women in seaweed aquaculture in the Western Indian Ocean and South-East Asia. *Eur. J. Phycol.*, **52**(4), 482-494, doi:10.1080/09670262.2017.1357084.
Mu, J. E., J. M. Antle and J. T. Abatzoglou, 2019: Representative agricultural pathways, climate change, and agricultural land uses: an application to the Pacific Northwest of the USA. *Mitig. Adapt. Strateg. Glob. Change*, **24**(5), 819-837, doi:10.1007/s11027-018-9834-8.
Muchane, M. N. et al., 2020: Agroforestry boosts soil health in the humid and sub-humid tropics: a meta-analysis. *Agric. Ecosyst. Environ.*, **295**, 106899, doi:10.1016/j.agee.2020.106899.
Muchuru, S. and G. Nhamo, 2019: A review of climate change adaptation measures in the African crop sector. *Clim. Dev.*, **11**(10), 873-885, doi:10.1080/17565529.2019.1585319.
Muehe, E. M. et al., 2019: Rice production threatened by coupled stresses of climate and soil arsenic. *Nat Commun*, **10**(1), 4985, doi:10.1038/s41467-019-12946-4.
Mueller, B. et al., 2015: Lengthening of the growing season in wheat and maize producing regions. *Weather Clim. Extrem.*, **9**, 47-56, doi:10.1016/j.wace.2015.04.001.
Muema, E., J. Mburu, J. Coulibaly and J. Mutune, 2018: Determinants of access and utilisation of seasonal climate information services among smallholder farmers in Makueni County, Kenya. *Heliyon*, **4**(11), e00889, doi:10.1016/j.heliyon.2018.e00889.
Mukhopadhyay, R., and S.B. Roy, 2017: Traditional knowledge for biodiversity conservation, maintain ecosystem services and livelihood security in the context of climate change: case studies from West Bengal, India. *J. Biodivers.*, **6**, 22-29, doi:10.1080/09766901.2015.11884752.
Mul, M. et al., 2015: *Water Resources Assessment of the Volta River Basin*. IWMI Working Paper, International Water Management Institute,, Colombo, Sri Lanka. ISBN 9789290908296.

Muller, A. et al., 2017: Strategies for feeding the world more sustainably with organic agriculture. *Nat Commun*, **8**(1), 1290, doi:10.1038/s41467-017-01410-w.
Mulwa, C. K. and M. Visser, 2020: Farm diversification as an adaptation strategy to climatic shocks and implications for food security in northern Namibia. *World Dev.*, **129**, 104906, doi:10.1016/j.worlddev.2020.104906.
Munt, D. D., P. Munoz-Rodriguez, I. Marques and J. C. M. Saiz, 2016: Effects of climate change on threatened Spanish medicinal and aromatic species: predicting future trends and defining conservation guidelines. *Isr. J. Plant Sci.*, **63**(4), 309-319, doi:10.1080/07929978.2016.1258257.
Mupambwa, H. A., M. K. Hausiku, A. D. Nciizah and E. Dube, 2019: The unique Namib desert-coastal region and its opportunities for climate smart agriculture: a review. *Cogent Food Agric.*, **5**(1), 1645258, doi:10.1080/23311932.2019.1645258.
Murakami H, V. G., Underwood S., 2017: Increasing frequency of extremely severe cyclonic storms over the Arabian Sea. *Nat. Clim. Change*, **7**, 885-889, doi:10.1038/s41558-017-0008-6.
Muringai, R. T., P. L. Mafongoya and R. Lottering, 2021: Climate Change and Variability Impacts on Sub-Saharan African Fisheries: A Review. *Rev. Fish. Sci. Aquac.*, 1-21, doi:10.1080/23308249.2020.1867057.
Muscat, A., E. M. de Olde, I. J. M. de Boer and R. Ripoll-Bosch, 2020: The battle for biomass: A systematic review of food-feed-fuel competition. *Glob. Food Secur.*, **25**, 100330-100330, doi:10.1016/j.gfs.2019.100330.
Muscat, A. et al., 2021: Food, energy or biomaterials? Policy coherence across agro-food and bioeconomy policy domains in the EU. *Environ. Sci. Policy*, **123**, 21-30, doi:10.1016/J.ENVSCI.2021.05.001.
Musinguzi, L. et al., 2016: Fishers' perceptions of climate change, impacts on their livelihoods and adaptation strategies in environmental change hotspots: A case of Lake Wamala, Uganda. *Environment, Development and Sustainability*, **18**(4), 1255-1273.
Musinguzi, L., V. Natugonza, J. Efitre and R. Ogutu-Ohwayo, 2018: The role of gender in improving adaptation to climate change among small-scale fishers. *Clim. Dev.*, **10**(6), 566-576, doi:10.1080/17565529.2017.1372262.
Muzhinji, N. and V. Ntuli, 2021: Genetically modified organisms and food security in Southern Africa: conundrum and discourse. *GM Crops Food*, **12**(1), 25-35, doi:10.1080/21645698.2020.1794489.
Mweya, C. N., L. E. G. Mboera and S. I. Kimera, 2017: Climate Influence on emerging risk areas for Rift Valley fever epidemics in Tanzania. *Am. J. Trop. Med. Hyg.*, **97**(1), 109-114, doi:10.4269/ajtmh.16-0444.
Myers, B. J. E. et al., 2017a: Global synthesis of the documented and projected effects of climate change on inland fishes. *Rev. Fish Biol. Fish.*, **27**(2), 339-361, doi:10.1007/s11160-017-9476-z.
Myers, S. S. et al., 2017b: Climate change and global food systems: potential impacts on food security and undernutrition. *Annu. Rev. Public Health*, **38**(1), 259-277, doi:10.1146/annurev-publhealth-031816-044356.
Myers, S. S. et al., 2014: Increasing CO2 threatens human nutrition. *Nature*, **510**(7503), 139-142, doi:10.1038/nature13179.
Naah, J. S. N. and B. Braun, 2019: Local agro-pastoralists' perspectives on forage species diversity, habitat distributions, abundance trends and ecological drivers for sustainable livestock production in West Africa. *Sci Rep*, **9**(1), 1707, doi:10.1038/s41598-019-38636-1.
Nabuurs, G.-J. et al., 2018: *Climate-Smart Forestry: Mitigation Impacts in Three European Regions* [European Forest Institute (ed.)]. From Science to Policy. ISBN 9789525980530.
Nadeau, A., G. Cloutier, C. Poitras and A. Aylett, 2019: Racines citoyennes: la communauté locale au coeur de la transition écologique l'impact des initiatives climatiques locales et citoyennes à Montréal. *Can. J. Urban Res.*, **28**(2), 16-31.
Nagahama, N. and M. F. Bonino, 2020: Modeling the potential distribution of Valeriana carnosa Sm. in Argentinean Patagonia: a proposal for conservation and in situ cultivation considering climate change projections. *J. Appl. Res. Med. Aromat. Plants*, **16**, 100240, doi:10.1016/j.jarmap.2020.100240.
Naghipour Borj, A. A., Z. Ostovar and E. Asadi, 2019: The influence of climate change on distribution of an endangered medicinal plant (Fritillaria Imperialis L.) in Central Zagros. *J. Rangel. Sci.*, **9**(2), 159-171.
Nagoda, S., 2015: New discourses but same old development approaches? Climate change adaptation policies, chronic food insecurity and development interventions in northwestern Nepal. *Global Environ. Change*, **35**, 570-579, doi:10.1016/j.gloenvcha.2015.08.014.

Nagoda, S. and A. J. Nightingale, 2017: Participation and Power in Climate Change Adaptation Policies: Vulnerability in Food Security Programs in Nepal. *World Dev.*, **100**, 85-93, doi:10.1016/j.worlddev.2017.07.022.
Naicker, P. R., 2011: The impact of climate change and other factors on zoonotic diseases. *Arch. Clin. Microbiol.*, **2**(6), doi:10:3823/226.
Naik, V. et al., 2021: Short-Lived Climate Forcers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Najafi, E., I. Pal and R. Khanbilvardi, 2019: Climate drives variability and joint variability of global crop yields. *Sci. Total Environ.*, **662**, 361-372, doi:10.1016/j.scitotenv.2019.01.172.
Nakashima, D. J. et al., 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation* [United Nations Educational Scientific and Cultural Organization (ed.)]. United Nations Educational Scientific and Cultural Organization and United Nations University-Traditional Knowledge Initiative,, Paris, France and Darwin, Australia, 120 pp. ISBN 9789230010683.
Nalau, J., S. Becken and B. Mackey, 2018: Ecosystem-based adaptation: a review of the constraints. *Environ. Sci. Policy*, **89**, 357-364, doi:10.1016/j.envsci.2018.08.014.
Namgay, K., J. E. Millar, R. S. Black and T. Samdup, 2014: Changes in transhumant agro-pastoralism in Bhutan: a disappearing livelihood? *Hum. Ecol.*, **42**(5), 779-792, doi:10.1007/s10745-014-9684-2.
Nandal, U. and R. L. Bhardwaj, 2014: The role of underutilized fruits in nutritional and economic security of tribals: a review. *Crit Rev Food Sci Nutr*, **54**(7), 880-890, doi:10.1080/10408398.2011.616638.
Nandintsetseg, B. et al., 2021: Risk and vulnerability of Mongolian grasslands under climate change. *Environ. Res. Lett.*, **16**(3), 34035-34035, doi:10.1088/1748-9326/abdb5b.
Napier, J. A., R. P. Haslam, M. Tsalavouta and O. Sayanova, 2019: The challenges of delivering genetically modified crops with nutritional enhancement traits. *Nat Plants*, **5**(6), 563-567, doi:10.1038/s41477-019-0430-z.
Naqvi, S. M. K., K. De, D. Kumar and V. Sejian, 2017: Climate changes, water use and survival during severe water deprivation. In: *Sheep Production Adapting to Climate Change* [Sejian, V., R. Bhatta, J. Gaughan, P. K. Malik, S. M. K. Naqvi and R. Lal (eds.)]. Springer Singapore, Singapore, pp. 173-187. ISBN 9789811047138.
Naqvi, S. M. K., D. Kumar, K. De and V. Sejian, 2015: Climate change and water availability for livestock: impact on both quality and quantity. In: *Climate Change Impact on Livestock: Adaptation and Mitigation* [Sejian, V., J. Gaughan, L. Baumgard and C. Prasad (eds.)]. Springer India, New Delhi, pp. 81-95.
Narayan, S. et al., 2020: Local adaptation responses to coastal hazards in small island communities: insights from 4 Pacific nations. *Environ. Sci. Policy*, **104**, 199-207, doi:10.1016/j.envsci.2019.11.006.
Nardone, A., B. Ronchi, N. Lacetera and U. Bernabucci, 2006: Climatic Effects on Productive Traits in Livestock. *Vet. Res. Commun.*, **30**(S1), 75-81, doi:10.1007/s11259-006-0016-x.
Nasi, R., A. Taber and N. Van Vliet, 2011: Empty forests, empty stomachs? Bushmeat and livelihoods in the Congo and Amazon Basins. *Int. For. Rev.*, **13**(3), 355-368, doi:10.1505/146554811798293872.
Nasielski, J. et al., 2015: Agroforestry promotes soybean yield stability and N2-fixation under water stress. *Agron. Sustain. Dev.*, **35**(4), 1541-1549, doi:10.1007/s13593-015-0330-1.
Naskar, M. et al., 2018: Quantifying climate change induced threats to wetland fisheries: a stakeholder-driven approach. *Environment Development and Sustainability*, **20**(6), 2811-2830, doi:10.1007/s10668-017-0018-6.
Nasonova, O. N., Y. M. Gusev, E. M. Volodin and E. E. Kovalev, 2018: Application of the land surface model SWAP and global climate model INMCM4.0 for projecting runoff of northern Russian rivers. 1. Historical simulations. *Water Resour.*, **45**, S73-S84, doi:10.1134/S009780781806026x.
Nath, A. J., R. Lal, G. W. Sileshi and A. K. Das, 2018: Managing India's small landholder farms for food security and achieving the "4 per Thousand" target. *Sci. Total Environ.*, **634**, 1024-1033, doi:10.1016/j.scitotenv.2018.03.382.
Nath, A. J. et al., 2021: Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. *J. Clean. Prod.*, **281**, doi:10.1016/j.jclepro.2020.124831.

Nath, T. K. et al., 2016: The sustainable intensification of agroforestry in shifting cultivation areas of Bangladesh. *Agroforest Syst*, **90**, 405-416, doi:10.1007/s10457-015-9863-1.

National Academies of Sciences Engineering and Medicine, 2016: *Genetically Engineered Crops: Experiences and Prospects*. National Academies Press, Washington, D.C., 420 pp. ISBN 9780309437387.

Nature climate change Editorials, 2019: Gender in conservation and climate policy. *Nat. Clim. Change*, **9**(4), 255-255, doi:10.1038/s41558-019-0448-2.

Naughton-Treves, L. and K. Wendland, 2014: Land tenure and tropical forest carbon management. *World Dev.*, **55**, 1-6, doi:10.1016/j.worlddev.2013.01.010.

Naylor, R. L. et al., 2021: A 20-year retrospective review of global aquaculture. *Nature*, **591**(7851), 551-563, doi:10.1038/s41586-021-03308-6.

Ndhlovu, N., O. Saito, R. Djalante and N. Yagi, 2017: Assessing the sensitivity of small-scale fishery groups to climate change in Lake Kariba, Zimbabwe. *Sustainability*, **9**(12), 2209, doi:10.3390/su9122209.

Ndi, F. A., 2019: Land grabbing: A gendered understanding of perceptions and reactions from affected communities in Nguti Subdivision of South West Cameroon. *Dev. Policy Rev.*, **37**(3), 348-366, doi:10.1111/dpr.12351.

Neale, T., R. Carter, T. Nelson and M. Bourke, 2019: Walking together: a decolonising experiment in bushfire management on Dja Dja Wurrung country. *Cult. Geogr.*, **26**(3), 341-359, doi:10.1177/1474474018821419.

Neethling, E., G. Barbeau, C. Coulon-leroy and H. Quénol, 2019: Agricultural and Forest Meteorology Spatial complexity and temporal dynamics in viticulture : A review of climate-driven scales. *Agric. For. Meteorol*, **276-277**(June), 107618-107618, doi:10.1016/j.agrformet.2019.107618.

Negin, B. and M. Moshelion, 2017: The advantages of functional phenotyping in pre-field screening for drought-tolerant crops. *Funct. Plant Biol.*, **44**, 107-118, doi:10.1071/FP16156.

Negra, C. et al., 2020: Sustainable agri-food investments require multi-sector co-development of decision tools. *Ecol. Indic.*, **110**, 105851, doi:10.1016/j.ecolind.2019.105851.

Nehring, R., A. Miranda and A. Howe, 2017: Making the case for institutional demand: supporting smallholders through procurement and food assistance programmes. *Global Food Security-Agriculture Policy Economics and Environment*, **12**, 96-102, doi:10.1016/j.gfs.2016.09.003.

Nelson, G. et al., 2018: Income growth and climate change effects on global nutrition security to mid-century. *Nat. Sustain.*, **1**(12), 773-781, doi:10.1038/s41893-018-0192-z.

Nelson, G. C. et al., 2014: Climate change effects on agriculture: economic responses to biophysical shocks. *Proc Natl Acad Sci U S A*, **111**(9), 3274-3279, doi:10.1073/pnas.1222465110.

Neset, T. S., T. Asplund, J. Kayhko and S. Juhola, 2019a: Making sense of maladaptation: Nordic agriculture stakeholders' perspectives. *Clim. Change*, **153**(1-2), 107-121, doi:10.1007/s10584-019-02391-z.

Neset, T. S. et al., 2019b: Maladaptation in Nordic agriculture. *Clim. Risk Manag.*, **23**, 78-87, doi:10.1016/j.crm.2018.12.003.

Neumann, R. B., A. L. Seyfferth, J. Teshera-Levye and J. Ellingson, 2017: Soil Warming Increases Arsenic Availability in the Rice Rhizosphere. *Agric. Environ. Lett.*, **2**(1), doi:10.2134/ael2017.02.0006.

Neuner, S. et al., 2015: Survival of Norway spruce remains higher in mixed stands under a dryer and warmer climate. *Glob Chang Biol*, **21**(2), 935-946, doi:10.1111/gcb.12751.

Neven, L. G., 2000: Physiological responses of insects to heat. *Postharvest Biol. Technol.*, **21**(1), 103-111, doi:Doi 10.1016/S0925-5214(00)00169-1.

Newbold, T. et al., 2015: Global effects of land use on local terrestrial biodiversity. *Nature*, **520**(7545), 45-50, doi:10.1038/nature14324.

Newton, P. et al., 2020: The number and spatial distribution of forest-proximate people globally. *One Earth*, **3**(3), 363-370.

NGFS, 2020: *Overview of Environmental Risk Analysis by Financial Institutions*. Network for Greening the Financial System / Banque de France. Available at: https://www.ngfs.net/en/communique-de-presse/ngfs-promotes-environmental-risk-analysis-financial-industry.

Ngigi, M. W., U. Mueller and R. Birner, 2017: Gender differences in climate change adaptation strategies and participation in group-based approaches: An Intra-household analysis from rural Kenya. *Ecol. Econ.*, **138**, 99-108, doi:10.1016/j.ecolecon.2017.03.019.

Nguyen, H. Q. et al., 2019a: Farmer adoptability for livelihood transformations in the Mekong Delta: a case in Ben Tre province. *J. Environ. Plan. Manag.*, **62**(9), 1603-1618, doi:10.1080/09640568.2019.1568768.

Nguyen, L. A. et al., 2018: Impact of Climate Change on the Technical Efficiency of Striped Catfish, Pangasianodon hypophthalmus, Farming in the Mekong Delta, Vietnam. *J. World Aquacult. Soc.*, **49**(3), 570-581, doi:10.1111/jwas.12488.
Nguyen, L. A. et al., 2016: A decision tree analysis to support potential climate change adaptations of striped catfish farming in the Mekong Delta, Vietnam. *Tropicultura* **34**, 105-115.
Nguyen, Q., M. H. Hoang, I. Oborn and M. van Noordwijk, 2013: Multipurpose agroforestry as a climate change resiliency option for farmers: an example of local adaptation in Vietnam. *Clim. Change*, **117**(1-2), 241-257, doi:10.1007/s10584-012-0550-1.
Nguyen, T. A. T., K. A. T. Nguyen and C. Jolly, 2019b: Is Super-Intensification the Solution to Shrimp Production and Export Sustainability? *Sustainability*, **11**(19), doi:10.3390/su11195277.
Nguyen, T. P. and K. E. Parnell, 2019: Coastal land use planning in Ben Tre, Vietnam: constraints and recommendations. *Heliyon*, **5**(4), e01487, doi:10.1016/j.heliyon.2019.e01487.
Nhamo, L. et al., 2018: The Water-Energy-Food Nexus: Climate Risks and Opportunities in Southern Africa. *Water*, **10**(5), 567, doi:10.3390/w10050567.
Nhat Lam Duyen, T., 2021: A comparative analysis of gender and youth issues in rice production in North, Central, and South Vietnam. *Clim. Dev.*, **13**(2), 115--127, doi:10.1080/17565529.2020.1734771.
Nhung, T. T., P. V. Vo, V. V. Nghi and H. Q. Bang, 2019: Salt intrusion adaptation measures for sustainable agricultural development under climate change effects: A case of Ca Mau Peninsula, Vietnam. *Clim. Risk Manag.*, **23**, 88-100, doi:10.1016/j.crm.2018.12.002.
Nicholson, C. C. and P. A. Egan, 2020: Natural hazard threats to pollinators and pollination. *Glob Chang Biol*, **26**(2), 380-391, doi:10.1111/gcb.14840.
Nidumolu, U. et al., 2020: Linking climate forecasts to rural livelihoods: Mapping decisions, information networks and value chains. *Weather Clim. Extrem.*, **27**, doi:10.1016/j.wace.2018.06.001.
Nie, Z. N. et al., 2016: Benefits, challenges and opportunities of integrated crop-livestock systems and their potential application in the high rainfall zone of southern Australia: A review. *Agric. Ecosyst. Environ.*, **235**, 17-31, doi:10.1016/j.agee.2016.10.002.
Niederle, P., A. Loconto, S. Lemeilleur and C. Dorville, 2020: Social movements and institutional change in organic food markets: Evidence from participatory guarantee systems in Brazil and France. *J. Rural Stud.*, **78**, 282-291, doi:10.1016/j.jrurstud.2020.06.011.
Nielsen, J. O. and A. Reenberg, 2010: Cultural barriers to climate change adaptation: A case study from Northern Burkina Faso. *Glob. Environ. Change*, **20**(1), 142-152, doi:10.1016/j.gloenvcha.2009.10.002.
Niether, W. et al., 2020: Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. *Environ. Res. Lett.*, **15**(10), doi:10.1088/1748-9326/abb053.
Niether, W. et al., 2017: Spatial-temporal soil moisture dynamics under different cocoa production systems. *Catena*, **158**, 340-349, doi:10.1016/j.catena.2017.07.011.
Nightingale, A. J., 2017: Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, **84**, 11-20, doi:10.1016/j.geoforum.2017.05.011.
Nightingale, A. J. et al., 2020: Beyond Technical Fixes: climate solutions and the great derangement. *Clim. Dev.*, **12**(4), 343-352, doi:10.1080/17565529.2019.1624495.
Niles, M. T. and M. E. Brown, 2017: A multi-country assessment of factors related to smallholder food security in varying rainfall conditions. *Sci Rep*, **7**(1), 16277, doi:10.1038/s41598-017-16282-9.
Niles, M. T. et al., 2021: Climate impacts associated with reduced diet diversity in children across nineteen countries. *Environ. Res. Lett.*, **16**(1), 015010, doi:10.1088/1748-9326/abd0ab.
Nkiaka, E., N. R. Nawaz and J. C. Lovett, 2017: Evaluating Global Reanalysis Datasets as Input for Hydrological Modelling in the Sudano-Sahel Region. *Hydrology*, **4**(1), doi:10.3390/hydrology4010013.
Nkiaka, E. et al., 2019: Identifying user needs for weather and climate services to enhance resilience to climate shocks in sub-Saharan Africa. *Environ. Res. Lett.*, **14**(12), doi:10.1088/1748-9326/ab4dfe.
Nkuba, M. R. et al., 2020: Indigenous Knowledge Systems and Indicators of Rain: Evidence from Rwenzori Region, Western Uganda. *Weather Clim. Soc.*, **12**(2), 213-234, doi:10.1175/Wcas-D-19-0027.1.
Nolte, K. and M. Ostermeier, 2017: Labour Market Effects of Large-Scale Agricultural Investment: Conceptual Considerations and Estimated Employment Effects. *World Dev.*, **98**(2016), 430-446, doi:10.1016/j.worlddev.2017.05.012.
Noongwook, G., H. P. Huntington, J. C. George and N. V. Savoonga, 2007: Traditional knowledge of the bowhead whale (Balaena mysticetus) around St. Lawrence Island, Alaska. *Arctic*, **60**(1), 47-54.

Norton-Smith, K. et al., 2016: *Climate Change and Indigenous Peoples : A Synthesis of Current Impacts and Experiences*. 1-142 pp.
Nost, E., 2019: Climate services for whom? The political economics of contextualizing climate data in Louisiana's coastal Master Plan. *Clim. Change*, **157**(1), 27-42, doi:10.1007/s10584-019-02383-z.
Novikova, A., L. Rocchi and V. Vitunskienė, 2017: Assessing the benefit of the agroecosystem services: Lithuanian preferences using a latent class approach. *Land Use Policy*, **68**, 277-286, doi:10.1016/j.landusepol.2017.07.051.
Noya, I. et al., 2019: Water Footprint of Livestock Farming. In: *Environmental Water Footprints*, pp. 21-54. ISBN 978-981-13-2507-6

978-981-13-2508-3.
Nuccio, M. L. et al., 2018: Where are the drought tolerant crops? An assessment of more than two decades of plant biotechnology effort in crop improvement. *Plant Sci.*, **273**, 110-119, doi:10.1016/j.plantsci.2018.01.020.
Nunes, P. A. L. D. and M. L. Loureiro, 2016: Economic valuation of climate-change-induced vinery landscape impacts on tourism flows in Tuscany. *Agric. Econ.*, **47**(4), 365-374, doi:10.1111/agec.12236.
Nunn, P. D. et al., 2020: Adaptation to Climate Change: Contemporary Challenges and Perspectives. In: *Climate Change and Impacts in the Pacific* [Kumar, L. (ed.)]. Springer International Publishing, Cham, pp. 499-524. ISBN 978-3-030-32877-1

978-3-030-32878-8.
Nunoo, F. K. E. et al., 2014: Marine Fisheries Catches in Ghana: Historic Reconstruction for 1950 to 2010 and Current Economic Impacts. *Rev. Fish. Sci. Aquac.*, **22**(4), 274-283, doi:10.1080/23308249.2014.962687.
Nuttall, J. G. et al., 2017: Models of grain quality in wheat-A review. *Field Crops Res.*, **202**, 136-145, doi:10.1016/j.fcr.2015.12.011.
Nuttall, M., 2009: Living in a world of movement: human resilience to environmental instability in Greenland. In: *Anthropology and climate change: from encounters to actions* [Crate, S. A. and M. Nuttall (eds.)]. Routledge, Oxon, England, pp. 292-310.
Nuttall, M., 2017: *Climate, Society and Subsurface Politics in Greenland: Under the Great Ice*. Taylor & Francis.
Nyamushamba, G. B. et al., 2017: Conservation of indigenous cattle genetic resources in Southern Africa's smallholder areas: turning threats into opportunities - A review. *Asian-Australas J Anim Sci*, **30**(5), 603-621, doi:10.5713/ajas.16.0024.
Nyangiwe, N., M. Yawa and V. Muchenje, 2018: Driving forces for changes in geographic range of cattle ticks (Acari: Ixodidae) in Africa: A review. *S. Afr. J. Anim. Sci.*, **48**(5), 829-841, doi:10.4314/sajas.v48i5.4.
Nyantakyi-Frimpong, H., 2019: Combining feminist political ecology and participatory diagramming to study climate information service delivery and knowledge flows among smallholder farmers in northern Ghana. *Appl. Geogr.*, **112**, doi:10.1016/j.apgeog.2019.102079.
Nyantakyi-Frimpong, H., 2020a: Unmasking difference: intersectionality and smallholder farmers' vulnerability to climate extremes in Northern Ghana. *Gender, Place & Culture*, **27**(11), 1536-1554, doi:10.1080/0966369X.2019.1693344.
Nyantakyi-Frimpong, H., 2020b: What lies beneath: Climate change, land expropriation, and zaï agroecological innovations by smallholder farmers in Northern Ghana. *Land Use Policy*, **92**(December 2019), 104469-104469, doi:10.1016/j.landusepol.2020.104469.
Nyantakyi-Frimpong, H. and R. Bezner-Kerr, 2015: The relative importance of climate change in the context of multiple stressors in semi-arid Ghana. *Glob. Environ. Change*, **32**, 40-56, doi:10.1016/j.gloenvcha.2015.03.003.
Nyantakyi-Frimpong, H. and R. Bezner Kerr, 2017: Land grabbing, social differentiation, intensified migration and food security in northern Ghana. *J. Peasant Stud.*, **44**(2), 421-444, doi:10.1080/03066150.2016.1228629.
Nyberg, Y., J. Wetterlind, M. Jonsson and I. Oborn, 2020: The role of trees and livestock in ecosystem service provision and farm priorities on smallholder farms in the Rift Valley, Kenya. *Agric. Syst.*, **181**, 102815-102815, doi:10.1016/j.agsy.2020.102815.
Nyguyen, K. A. T. and T. Pongthanapanic, 2016: *Aquaculture Insurance in Viet Nam: Experiences from the pilot program*. FAO Fisheries and Aquaculture Circular, **1133**, FAO, Rome, 20 pp.

Nyland, K. E. et al., 2017: Traditional Inupiat Ice Cellars (Sigluaq) in Barrow, Alaska: Characteristics, Temperature Monitoring, and Distribution. *Geographical Review*, **107**(1), 143-158, doi:DOI 10.1111/j.1931-0846.2016.12204.x.
Nyong, A., F. Adesina and B. Osman Elasha, 2007: The value of Indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitig. Adapt. Strateg. Glob. Change*, **12**, 787-797.
Nyoni, N. M. B., S. Grab and E. R. M. Archer, 2019: Heat stress and chickens: climate risk effects on rural poultry farming in low-income countries. *Clim. Dev.*, **11**(1), 83-90, doi:10.1080/17565529.2018.1442792.
O'Corry-Crowe, G. M., 2009: Beluga whale: Delphinapterus leucas. In: *Encyclopedia of marine mammals*. Elsevier, pp. 108-112.
O'Sullivan, C. A. et al., 2019: Strategies to improve the productivity, product diversity and profitability of urban agriculture. *Agric. Syst.*, **174**(December 2018), 133-144, doi:10.1016/j.agsy.2019.05.007.
O'Brien, K., 2018: Is the 1.5 C target possible? Exploring the three spheres of transformation. *Curr. Opin. Environ. Sustain.*, **31**, 153-160.
O'Brien, K., Eriksen, S. E. H., Inderberg, T. H., and Sygna, L. , 2015: Climate change and development: adaptation through transformation. In: *Climate Change Adaptation and Development: Transforming Paradigms and Practices* [T. H. Inderberg, S. H. E. E., K. O'Brien, and L. Sygna (ed.)]. Routledge, New York, NY, pp. 273-289.
O'Connell-Milne, S. A., and Christopher D. Hepburn, 2015: A harvest method informed by traditional knowledge maximises yield and regeneration post harvest for karengo (Bangiaceae). *J. Appl. Phycol.*, **27**(447-454).
Oates, L., R. Gillard, A. Sudmant and A. Gouldson, 2020: *Secure and equal access to land for all: Lessons on land governance and climate resilience from Dar es Salaam, Tanzania*. University of Leeds.
Oberlack, C. et al., 2016: Sustainable livelihoods in the global land rush? Archetypes of livelihood vulnerability and sustainability potentials. *Global Environ. Change*, **41**, 153-171, doi:10.1016/j.gloenvcha.2016.10.001.
Obermeier, W. A. et al., 2016: Reduced CO2 fertilization effect in temperate C3 grasslands under more extreme weather conditions. *Nat. Clim. Change*, **7**(2), 137-141, doi:10.1038/nclimate3191.
Obersteiner, M. et al., 2016: Assessing the land resource-food price nexus of the Sustainable Development Goals. *Sci Adv*, **2**(9), e1501499, doi:10.1126/sciadv.1501499.
OECD, 2020: *Climate Change: OECD DAC External Development Finance Statistics*. Available at: https://www.oecd.org/dac/financing-sustainable-development/development-finance-topics/climate-change.htm
Oerke, E. C., 2006: Crop losses to pests. *J. Agric. Sci.*, **144**, 31-43, doi:10.1017/S0021859605005708.
Ogalleh, S. A., C. R. Vogl, J. Eitzinger and M. Hauser, 2012: Local Perceptions and Responses to Climate Change and Variability: The Case of Laikipia District, Kenya. *Sustainability*, **4**(12), 3302-3325, doi:10.3390/su4123302.
Ogier, E. et al., 2020: Responding to Climate Change: Participatory Evaluation of Adaptation Options for Key Marine Fisheries in Australia's South East. *Front. Mar. Sci.*, **7**, doi:10.3389/fmars.2020.00097.
Ogren, W. L. and R. Chollet, 1982: Photorespiration. In: *Photosynthesis* [Govindjee (ed.)]. Academic Press, Cambridge, MA, pp. 191-232.
OIV (ed.), OIV Statistical Report on World Vitiviniculture. 2018 World Vitiviniculture Situation, 1-26 pp. ISBN 0008-5472 (Print).
Ojea, E., S. E. Lester and D. Salgueiro-Otero, 2020: Adaptation of Fishing Communities to Climate-Driven Shifts in Target Species. *One Earth*, **2**(6), 544-556, doi:10.1016/j.oneear.2020.05.012.
Oliver, E. C. J. et al., 2019: Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Front. Mar. Sci.*, **6**, doi:10.3389/fmars.2019.00734.
Oliver, E. C. J. et al., 2018: Longer and more frequent marine heatwaves over the past century. *Nat Commun*, **9**(1), 1324, doi:10.1038/s41467-018-03732-9.
Olivier, T. et al., 2020: Urbanization and agricultural intensification destabilize animal communities differently than diversity loss. *Nat Commun*, **11**(1), 2686, doi:10.1038/s41467-020-16240-6.
Ollat, N. and C. V. Leeuwen, 2016: Climate Change Impacts and Adaptations : New Challenges for the Wine Industry * The challenging issue of climate change for sustainable grape and wine production.(May), 2016-2018, doi:10.1017/jwe.2016.3.

Olorunfemi, F., Mayowa Fasona, Grace Oloukoi, Peter Elias, and Vide Adedayo, 2017: Traditional Knowledge in the Use and Management of Forest Ecosystem for Livelihoods and Food Security in Nigerian Savanna. *J. Hum. Ecol.*, **53**, 167-175.
Olsen, E. et al., 2019: Ecological Effects and Ecosystem Shifts Caused by Mass Mortality Events on Early Life Stages of Fish. *Front. Mar. Sci.*, **6**, doi:10.3389/fmars.2019.00669.
Olsson, L. et al., 2019: Land degradation. [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press-In press.
Olwig, M. F., C. Noe, R. Kangalawe and E. Luoga, 2016: Inverting the moral economy : the case of land acquisitions for forest plantations in Tanzania. *Third World Q.*, **6597**(January), doi:10.1080/01436597.2015.1078231.
Omari-Motsumi, K., M. Barnett and L. Schalatek, 2019: *Broken Connections and Systemic Barriers; Overcoming the Challenge of the "Missing Middle" in Adaptation Finance.* . Global Commission on Adaptation Background Paper Global Center on Adaptation.
Omori, K. et al., 2020: Assessment of paddy fields' damage caused by Cyclone Nargis using MODIS time-series images (2004–2013). *Paddy Water Environ.*, doi:10.1007/s10333-020-00829-0.
Oppenheimer, M. and J. K. Anttila-Hughes, 2016: The Science of Climate Change. *Future Child.*, **26**(1), 11-30.
Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. VMasson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. 321-445.
Orchard, B., 2019: *Rethinking Climate Finance - Taking Action against Climate Change. Opportunities and Challenges for Financial Players*. BlueOrchard, , Zurich, Switzerland. Available at: https://www.blueorchard.com/rethinking-climate-finance-taking-action-climate-change-opportunities-challenges-financial-players/.
Oremus, K. L. et al., 2020: Governance challenges for tropical nations losing fish species due to climate change. *Nat. Sustain.*, **3**(4), 277-280, doi:10.1038/s41893-020-0476-y.
Ortiz-Bobea, A. et al., 2021: Anthropogenic climate change has slowed global agricultural productivity growth. *Nat. Clim. Change*, **11**(4), 306-312, doi:10.1038/s41558-021-01000-1.
Ortiz-Bobea, A., E. Knippenberg and R. G. Chambers, 2018: Growing climatic sensitivity of U.S. agriculture linked to technological change and regional specialization. *Sci Adv*, **4**(12), eaat4343, doi:10.1126/sciadv.aat4343.
Ortiz-Colón, G. et al., 2018: Assessing climate vulnerabilities and adaptive strategies for resilient beef and dairy operations in the tropics. *Clim. Change*, **146**(1-2), 47-58, doi:10.1007/s10584-017-2110-1.
Osabuohien, E. S., U. R. Efobi, R. T. Herrmann and C. M. W. Gitau, 2019: Female labor outcomes and large-scale agricultural land investments: Macro-micro evidencefrom Tanzania. *Land Use Policy*, **82**, 716-728, doi:10.1016/j.landusepol.2019.01.005.
Osborne, C. P. et al., 2014: A global database of C4 photosynthesis in grasses. *New Phytol.*, **204**(3), 441-446, doi:10.1111/nph.12942.
Osgood, D. et al., 2018: Farmer Perception, Recollection, and Remote Sensing in Weather Index Insurance: An Ethiopia Case Study. *Remote Sens.*, **10**(12), doi:10.3390/rs10121887.
Osterhoudt, S., 2018: Remembered resilience: oral history narratives and community resilience in agroforestry systems. *Renew. Agric. Food Syst.*, **33**(3), 252--255, doi:10.1017/S1742170517000679.
Østhagen, A., J. Spijkers and O. A. Totland, 2020: Collapse of cooperation? The North-Atlantic mackerel dispute and lessons for international cooperation on transboundary fish stocks. *Marit. Stud.*, **19**(2), 155-165, doi:10.1007/s40152-020-00172-4.
Otekunrin, O. A., O. A. Otekunrin, S. Momoh and I. A. Ayinde, 2019: How far has Africa gone in achieving the zero hunger target? Evidence from Nigeria. *Glob. Food Secur.*, **22**, 1--12, doi:10.1016/j.gfs.2019.08.001.
Otieno, G. et al., 2018: *Social Seed Networks for Climate Change Adaptation in Uganda: Strategies to Improve Access to Genetic Diversity and Information*. CCAFS Info note, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, Netherlands.
Otto, I. M. et al., 2017: Social vulnerability to climate change: a review of concepts and evidence. *Reg. Environ. Change*, **17**(6), 1651-1662, doi:10.1007/s10113-017-1105-9.

Ouedraogo, I. et al., 2018: Closing the Gap between Climate Information Producers and Users: Assessment of Needs and Uptake in Senegal. *Climate*, **6**(1), doi:10.3390/cli6010013.
Ouédraogo, M., Y. Dembélé and L. Somé, 2010: Perceptions et stratégies d'adaptation aux changements des précipitations: cas des paysans du Burkina Faso. *Science et changements planétaires/Sécheresse*, **21**, 87-96.
Ouédraogo, M. et al., 2017: Markets and climate are driving rapid change in farming practices in Savannah West Africa. *Reg. Environ. Change*, **17**(2), 437-449, doi:10.1007/s10113-016-1029-9.
Ouma, S., 2014: Situating global finance in the Land Rush Debate: A critical review. *Geoforum*, **57**, 162-166, doi:10.1016/j.geoforum.2014.09.006.
Ouyang, F. et al., 2014: Weakening density dependence from climate change and agricultural intensification triggers pest outbreaks: a 37-year observation of cotton bollworms. *Ecol Evol*, **4**(17), 3362-3374, doi:10.1002/ece3.1190.
Ovalle-Rivera, O. et al., 2015: Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. *PLoS One*, **10**(4), e0124155, doi:10.1371/journal.pone.0124155.
Oviedo, A. F., S. Mitraud, D. G. McGrath and M. Bursztyn, 2016: Implementing climate variability adaptation at the community level in the Amazon floodplain. *Environ. Sci. Policy*, **63**, 151-160.
Owusu-Daaku, K. N., 2018: (Mal)Adaptation opportunism: when other interests take over stated or intended climate change adaptation objectives (and their unintended effects). *Local Environ.*, **23**(9), 934-951, doi:10.1080/13549839.2018.1505836.
Oxenford, H. A. and I. Monnereau, 2018: Climate change impacts, vulnerabilities and adaptations: Western Central Atlantic marine fisheries. In: *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options*. Food and Agriculture Organization of the United Nations,, Rome, Italy, pp. 185-206. ISBN 9789251306079.
Oyinlola, M. A., G. Reygondeau, C. C. C. Wabnitz and W. W. L. Cheung, 2020: Projecting global mariculture diversity under climate change. *Glob Chang Biol*, doi:10.1111/gcb.14974.
Padel, S., L. Levidow and B. Pearce, 2020: UK farmers' transition pathways towards agroecological farm redesign: evaluating explanatory models. *Agroecol. Sustain. Food Syst.*, **44**(2), 139-163, doi:10.1080/21683565.2019.1631936.
Paik, S., D. T. P. Le, L. T. Nhu and B. F. Mills, 2020: Salt-tolerant rice variety adoption in the Mekong River Delta: Farmer adaptation to sea-level rise. *PLoS One*, **15**(3), e0229464, doi:10.1371/journal.pone.0229464.
Palacios-Abrantes, J., G. Reygondeau, C. C. C. Wabnitz and W. W. L. Cheung, 2020: The transboundary nature of the world's exploited marine species. *Sci Rep*, **10**(1), 17668, doi:10.1038/s41598-020-74644-2.
Palahi, M. et al., 2020: Investing in Nature to Transform the Post COVID-19 Economy : A 10-point Action Plan to create a circular bioeconomy devoted to sustainable wellbeing. *The Solutions Journal*, **11**(2).
Palhares, J. C. P. and J. R. M. Pezzopane, 2015: Water footprint accounting and scarcity indicators of conventional and organic dairy production systems. *J. Clean. Prod.*, **93**, 299-307, doi:10.1016/j.jclepro.2015.01.035.
Palmer, A. et al., 2017: Between Global and Local: Exploring Regional Food Systems from the Perspectives of Four Communities in the U.S. Northeast. *J. Agric. Food Syst. Community Dev.*, 187-205, doi:10.5304/jafscd.2017.074.017.
Pandey, R. et al., 2017: Agroecology as a Climate Change Adaptation Strategy for Smallholders of Tehri-Garhwal in the Indian Himalayan Region. ʺ **16**(1), 53-63, doi:10.1007/s11842-016-9342-1.
Paneque-Galvez, J. et al., 2018: High overlap between traditional ecological knowledge and forest conservation found in the Bolivian Amazon. *Ambio*, **47**(8), 908-923, doi:10.1007/s13280-018-1040-0.
Pang, J., M. H. Ryan, H. Lambers and K. H. Siddique, 2018: Phosphorus acquisition and utilisation in crop legumes under global change. *Curr. Opin. Plant Biol.*, **45**(Pt B), 248-254, doi:10.1016/j.pbi.2018.05.012.
Panikkar, B. and B. Lemmond, 2020: Being on Land and Sea in Troubled Times: Climate Change and Food Sovereignty in Nunavut. *Land*, **9**(12), 508, doi:10.3390/land9120508.
Pant, J. et al., 2014: Can aquaculture benefit the extreme poor? A case study of landless and socially marginalized Adivasi (ethnic) communities in Bangladesh. *Aquaculture*, **418-419**, 1-10, doi:10.1016/j.aquaculture.2013.09.027.

Pantanella, E., 2018: Aquaponics Production, Practices and Opportunities. In: *SUSTAINABLE AQUACULTURE* [Hai, F. I., C. Visvanathan and R. Boopathy (eds.)], pp. 191-248. ISBN 978-3-319-73257-2 978-3-319-73256-5.
Panthou, G. et al., 2018: Rainfall intensification in tropical semi-arid regions: the Sahelian case. *Environ. Res. Lett.*, **13**(6), doi:10.1088/1748-9326/aac334.
Paolotti, L. et al., 2016: Combining livestock and tree crops to improve sustainability in agriculture: a case study using the Life Cycle Assessment (LCA) approach. *J. Clean. Prod.*, **131**, 351-363, doi:10.1016/j.jclepro.2016.05.024.
Paprocki, K., 2018: Threatening Dystopias: Development and Adaptation Regimes in Bangladesh. *Ann. Am. Assoc. Geogr.*, **108**(4), 955-973, doi:10.1080/24694452.2017.1406330.
Paprocki, K., 2019: All That Is Solid Melts into the Bay: Anticipatory Ruination and Climate Change Adaptation. *Antipode*, **51**(1), 295-315, doi:10.1111/anti.12421.
Paprocki, K. and S. Huq, 2018: Shrimp and coastal adaptation: on the politics of climate justice. *Clim. Dev.*, **10**(1), 1-3, doi:10.1080/17565529.2017.1301871.
Parfitt, J., M. Barthel and S. Macnaughton, 2010: Food waste within food supply chains: quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**(1554), 3065-3081, doi:10.1098/rstb.2010.0126.
Park, C. S. et al., 2019: The global effect of extreme weather events on nutrient supply: a superposed epoch analysis. *Lancet Planet Health*, **3**(10), e429-e438, doi:10.1016/S2542-5196(19)30193-7.
Parker, L., C. Bourgoin, A. Martinez-Valle and P. Laderach, 2019: Vulnerability of the agricultural sector to climate change: The development of a pan-tropical Climate Risk Vulnerability Assessment to inform sub-national decision making. *PLoS One*, **14**(3), e0213641, doi:10.1371/journal.pone.0213641.
Parker, L. M. et al., 2015: Persistence of Positive Carryover Effects in the Oyster, Saccostrea glomerata, following Transgenerational Exposure to Ocean Acidification. *PLoS One*, **10**(7), e0132276, doi:10.1371/journal.pone.0132276.
Parker, R., 2018: Implications of high animal by-product feed inputs in life cycle assessments of farmed Atlantic salmon. *Int. J. Life Cycle Assess.*, **23**(5), 982-994, doi:10.1007/s11367-017-1340-9.
Parlee, B. and F. Berkes, 2005: Health of the land, health of the people: a case study on Gwich'in berry harvesting in northern Canada. *EcoHealth*, **2**(2), 127-137.
Parodi, A. et al., 2018: The potential of future foods for sustainable and healthy diets. *Nat. Sustain.*, **1**(12), 782-789, doi:10.1038/s41893-018-0189-7.
Parraguez-Vergara, E., J. R. Barton and G. Raposo-Quintana, 2016: Impacts of Climate Change in the Andean Foothills of Chile: Economic and Cultural Vulnerability of Indigenous Mapuche Livelihoods. *J. Dev. Soc.*, **32**(4), 454-483, doi:10.1177/0169796x16667874.
Partey, S. T. et al., 2020: Gender and climate risk management: evidence of climate information use in Ghana. *Clim. Change*, **158**(1), 61-75, doi:10.1007/s10584-018-2239-6.
Parvin, S. et al., 2018: Water availability moderates N2 fixation benefit from elevated [CO2]: A 2-year free-air CO2 enrichment study on lentil (Lens culinaris MEDIK.) in a water limited agroecosystem. *Plant Cell Environ*, **41**(10), 2418-2434, doi:10.1111/pce.13360.
Parvin, S. et al., 2019: Grain mineral quality of dryland legumes as affected by elevated CO2 and drought: a FACE study on lentil (Lens culinaris) and faba bean (Vicia faba). *Crop & Pasture Science*, **70**(3), 244-253, doi:10.1071/CP18421.
Pastor, A. V. et al., 2019: The global nexus of food-trade-water sustaining environmental flows by 2050. *Nat. Sustain.*, **2**(6), 499-507, doi:10.1038/s41893-019-0287-1.
Paterson, R. R. M. e. a., 2018: Predominant mycotoxin, mycotoxigenic fungi and climate change related to wine. *Food Res. Int.*, **103**, 478-491.
Paudel, D., K. R. Tiwari, R. M. Bajracharya and N. Raut, 2017: Agroforestry system: an opportunity for carbon sequestration and climate change adaptation in the mid-hills of Nepal *Octa Journal of Environmental Research*, **5**(1).
Paudyal, B. R. et al., 2019: Gender Integration in Climate Change and Agricultural Policies: The Case of Nepal. *Front. Sustain. Food Syst.*, **3**, doi:10.3389/fsufs.2019.00066.
Paukert, C. P. et al., 2016: Adapting Inland Fisheries Management to a Changing Climate. *Fisheries*, **41**(7), 374-384, doi:10.1080/03632415.2016.1185009.
Paul, K. I. et al., 2016: Managing reforestation to sequester carbon, increase biodiversity potential and minimize loss of agricultural land. *Land Use Policy*, **51**, 135-149, doi:10.1016/j.landusepol.2015.10.027.
Paustian, K. et al., 2016: Climate-smart soils. *Nature*, **532**(7597), 49-57, doi:10.1038/nature17174.

Pearce, W., M. Mahony and S. Raman, 2018: Science advice for global challenges: Learning from trade-offs in the IPCC. *Environ. Sci. Policy*, **80**, 125-131, doi:10.1016/j.envsci.2017.11.017.
Pearse, R., 2017: Gender and climate change. *WIREs Climate Change*, **8**(2), doi:10.1002/wcc.451.
Peck, M. and J. K. Pinnegar, 2018: Climate change impacts, vulnerabilities and adaptations: North Atlantic and Atlantic Arctic marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. FAO, Rome, pp. 87-112.
Peck, M. A. et al., 2020: *Climate Change and European Fisheries and Aquaculture: CERES Project Synthesis Report*. University of Hamburg. Available at: http://doi.org/10.25592/uhhfdm.804.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355**(6332), eaai9214, doi:10.1126/science.aai9214.
Pecl, G. T. et al., 2019: Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot. *Ambio*, **48**(12), 1498-1515, doi:10.1007/s13280-019-01186-x.
Pelling, M. et al., 2021: Synergies Between COVID-19 and Climate Change Impacts and Responses. *J. Extreme Events*.
Pendrill, F. et al., 2019: Agricultural and forestry trade drives large share of tropical deforestation emissions. *Glob. Environ. Change*, **56**, 1-10, doi:10.1016/j.gloenvcha.2019.03.002.
Peng, D. L. et al., 2019: Species distribution modelling and seed germination of four threatened snow lotus (Saussurea), and their implication for conservation. *Glob. Ecol. Conserv.*, **17**, e00565, doi:10.1016/j.gecco.2019.e00565.
Peng, W. et al., 2020: A review of historical and recent locust outbreaks: Links to global warming, food security and mitigation strategies. *Environ. Res.*, **191**, 110046-110046, doi:10.1016/j.envres.2020.110046.
Penney, R., G. Wilson and L. Rodwell, 2017: Managing sino-ghanaian fishery relations: A political ecology approach. *Mar. Policy*, **79**, 46-53, doi:10.1016/j.marpol.2017.02.008.
Pentz, B. and N. Klenk, 2020: Understanding the limitations of current RFMO climate change adaptation strategies: the case of the IATTC and the Eastern Pacific Ocean. *Int. Environ. Agreem.: Politics Law Econ.*, **20**(1), 21-39, doi:10.1007/s10784-019-09452-9.
Perera, E. et al., 2021: Effects of genetics and early-life mild hypoxia on size variation in farmed gilthead sea bream (Sparus aurata). *Fish Physiol. Biochem.*, **47**(1), 121-133, doi:10.1007/s10695-020-00899-1.
Perez-Garcia, J., L. A. Joyce, A. D. McGuire and X. M. Xiao, 2002: Impacts of climate change on the global forest sector. *Clim. Change*, **54**(4), 439-461, doi:Doi 10.1023/A:1016124517309.
Pérez-Marin, A. M. et al., 2017: Agroecological and Social Transformations for Coexistence with Semi-Aridity in Brazil. *Sustainability*, **9**(6), doi:10.3390/su9060990.
Pérez-Urrestarazu, L., J. Lobillo-Eguíbar, R. Fernández-Cañero and V. M. Fernández-Cabanás, 2019: Suitability and optimization of FAO's small-scale aquaponics systems for joint production of lettuce (Lactuca sativa) and fish (Carassius auratus). *Aquac Eng*, **85**, 129-137, doi:10.1016/j.aquaeng.2019.04.001.
Perez‐Garcia, J., L. A. Joyce, C. S. Binkley and A. D. McGuire, 1997: Economic impacts of climatic change on the global forest sector: An integrated ecological/economic assessment. *Crit. Rev. Environ. Sci. Technol.*, **27**, 123-138.
Perfecto, I. et al., 2019: Response of Coffee Farms to Hurricane Maria: Resistance and Resilience from an Extreme Climatic Event. *Sci. Rep.*, **9**(1), 15668-15668, doi:10.1038/s41598-019-51416-1.
Peri, M., 2017: Climate variability and the volatility of global maize and soybean prices. *Food Secur.*, **9**(4), 673-683, doi:10.1007/s12571-017-0702-2.
Perry, S. J., S. McGregor, A. Sen Gupta and M. H. England, 2017: Future Changes to El Nino-Southern Oscillation Temperature and Precipitation Teleconnections. *Geophys. Res. Lett.*, **44**(20), 10608-10616, doi:10.1002/2017gl074509.
Peters, K., L. Breitsameter and B. Gerowitt, 2014: Impact of climate change on weeds in agriculture: a review. *Agron. Sustain. Dev.*, **34**(4), 707-721, doi:10.1007/s13593-014-0245-2.
Peterson, C. A., L. W. Bell, P. C. d. F. Carvalho and A. C. M. Gaudin, 2020: Resilience of an Integrated Crop–Livestock System to Climate Change: A Simulation Analysis of Cover Crop Grazing in Southern Brazil. *Front. Sustain. Food Syst.*, **4**, 222-222.
Petheram, L., A. E. Fleming, N. Stacey and A. Perry, 2013: *Indigenous women's preferences for climate change adaptation and aquaculture development to build capacity in the Northern Territory*. National Climate Change Adaptation Research Facility Gold Coast. ISBN 1925039552.

Pezzopane, J. R. M. et al., 2019: Animal thermal comfort indexes in silvopastoral systems with different tree arrangements. *J. Therm. Biol.*, **79**, 103-111, doi:10.1016/j.jtherbio.2018.12.015.
Phalkey, R. K. et al., 2015: Systematic review of current efforts to quantify the impacts of climate change on undernutrition. *Proc Natl Acad Sci U S A*, **112**(33), E4522-4529, doi:10.1073/pnas.1409769112.
Pham, T. T. T. et al., 2021: Guidelines for co-creating climate adaptation plans for fisheries and aquaculture. *Clim. Change*, **164**(3), 62, doi:10.1007/s10584-021-03041-z.
Pham, Y., K. Reardon-Smith, S. Mushtaq and G. Cockfield, 2019: The impact of climate change and variability on coffee production: a systematic review. *Clim. Change*, **156**(4), 609-630, doi:10.1007/s10584-019-02538-y.
Phanxay, I., H. Isao and Y. Satoshi, 2015: Access to Livelihood Assets under the Influence of a Climate Event in Upland Northern Laos. *Geographical review of Japan series B*, **87**(2), 131-145, doi:10.4157/geogrevjapanb.87.131.
Phogat, V., J. W. Cox and J. Simunek, 2018: Identifying the future water and salinity risks to irrigated viticulture in the Murray-Darling Basin, South Australia. *Agric. Water Manage.*, **201**, 107-117, doi:10.1016/j.agwat.2018.01.025.
Pickering, K., R. Plummer, T. Shaw and G. Pickering, 2015: Assessing the adaptive capacity of the Ontario wine industry for climate change adaptation. 13-27.
Pietilainen, E. P. and G. Otero, 2019: Power and dispossession in the neoliberal food regime: oil palm expansion in Guatemala. *J. Peasant Stud.*, **46**(6), 1142-1166, doi:10.1080/03066150.2018.1499093.
Piggott-McKellar, A. E., K. E. McNamara and P. D. Nunn, 2020: Who defines "good" climate change adaptation and why it matters: a case study from Abaiang Island, Kiribati. *Reg. Environ. Change*, **20**(2), doi:10.1007/s10113-020-01614-9.
Pingle, U., 1975: Some Studies in Two Tribal Groups of Central India: Part 2: Nutritive importance of foods consumed in two different seasons. *Plant foods for Man*, **1**(3-4), 195-208.
Pinsky, M. L. et al., 2020: Fish and fisheries in hot water: What is happening and how do we adapt? *Popul. Ecol.*, **63**(1), 17-26, doi:10.1002/1438-390x.12050.
Pinsky, M. L. et al., 2018: Preparing ocean governance for species on the move. *Science*, **360**(6394), 1189-1191, doi:10.1126/science.aat2360.
Pitcher, G. C. et al., 2019: Devastating farmed abalone mortalities attributed to yessotoxin-producing dinoflagellates. *Harmful Algae*, **81**, 30-41, doi:10.1016/j.hal.2018.11.006.
Pittelkow, C. M. et al., 2014: Productivity limits and potentials of the principles of conservation agriculture. *Nature*, doi:10.1038/nature13809.
Planque, B. et al., 2019: A participatory scenario method to explore the future of marine social-ecological systems. *Fish Fish.*, **20**(3), 434-451, doi:10.1111/faf.12356.
Platis, D. P. et al., 2019: Energy analysis, and carbon and water footprint for environmentally friendly farming practices in agroecosystems and agroforestry. *Sustainability*, **11**(6), 1664-1664, doi:10.3390/su11061664.
Plieninger, T. and M. Schaar, 2008: Modification of land cover in a traditional agroforestry system in spain: processes of tree expansion and regression. *Ecol. Soc.*, **13**(2), art25, doi:10.5751/ES-02521-130225.
Plieninger, T., D. van der Horst, C. Schleyer and C. Bieling, 2014: Sustaining ecosystem services in cultural landscapes. *Ecol. Soc.*, **19**(2), art59, doi:10.5751/Es-06159-190259.
Poesch, M. S. et al., 2016: Climate Change Impacts on Freshwater Fishes: A Canadian Perspective. *Fisheries*, **41**(7), 385-391, doi:10.1080/03632415.2016.1180285.
Polce, C. et al., 2014: Climate-driven spatial mismatches between British orchards and their pollinators: increased risks of pollination deficits. *Glob Chang Biol*, **20**(9), 2815-2828, doi:10.1111/gcb.12577.
Pomeroy, R., J. Parks, K. L. Mrakovcich and C. LaMonica, 2016: Drivers and impacts of fisheries scarcity, competition, and conflict on maritime security. *Mar. Policy*, **67**, 94-104, doi:10.1016/j.marpol.2016.01.005.
Pongthanapanic, T., K. A. T. Nguyen and C. M. Jolli, 2019: *Risk management practices of small intensive shrimp farmers in the Mekong Delta of Viet Nam.* FAO Fisheries and Aquaculture Circular, **1194**, FAO, Rome, 1-20 pp.
Ponisio, L. C. et al., 2015: Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences*, **282**(1799), 20141396-20141396, doi:10.1098/rspb.2014.1396.
Ponti, L., A. P. Gutierrez, P. M. Ruti and A. Dell'Aquila, 2014: Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers. *Proc Natl Acad Sci U S A*, **111**(15), 5598-5603, doi:10.1073/pnas.1314437111.

Poore, J. and T. Nemecek, 2019: Reducing food's environmental impacts through producers and consumers (vol 363, eaaw9908, 2019). *Science*, **363**(6430), 939-939.
Popke, J. and K. Rhiney, 2019: Introduction to Special Issue on The Caribbean after Irma and Maria: Climate, Development & the Post-Hurricane Context. *J. Extreme Events*, **06**(01), doi:10.1142/s2345737619020019.
Porsani, J., M. A. Caretta and K. Lehtilä, 2019: Large-scale land acquisitions aggravate the feminization of poverty: findings from a case study in Mozambique. *GeoJournal*, **84**(1), 215-236, doi:10.1007/s10708-017-9836-1.
Porter, J. R. et al., 2019: Invited review: Intergovernmental Panel on Climate Change, agriculture, and food-A case of shifting cultivation and history. *Glob Chang Biol*, **25**(8), 2518-2529, doi:10.1111/gcb.14700.
Porter, J. R. et al., 2014: Food Security and Food Production Systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533. ISBN 9781107058071.
Postigo, J. C. and K. R. Young, 2021: Preparing for a diminished cryosphere. *Sustainability Science 2021*, 1-4, doi:10.1007/S11625-021-01023-9.
Potopová, V. et al., 2017: The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014. *Int. J. Climatol.*, **37**(3), 1648-1664, doi:10.1002/joc.4807.
Potts, S. G. et al., 2010: Global pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.*, **25**(6), 345-353, doi:10.1016/j.tree.2010.01.007.
Potts, S. G. et al., 2016: Safeguarding pollinators and their values to human well-being. *Nature*, **540**(7632), 220-229, doi:10.1038/nature20588.
Poulain, F., A. Himes-Cornell and C. Shelton, 2018: Chapter 35: Methods and tools for climate change adaptation in fisheries and aquaculture. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. FAO, Rome, pp. 535-566.
Powell, B. et al., 2014: Wild leafy vegetable use and knowledge across multiple sites in Morocco: a case study for transmission of local knowledge? *Journal of Ethnobiology and Ethnomedicine*, **10**(1), 34.
Powell, B. et al., 2015: Improving diets with wild and cultivated biodiversity from across the landscape. *Food Secur.*, **7**(3), 535-554, doi:10.1007/s12571-015-0466-5.
Pradhan, P. e. a., 2014: Food self-sufficiency across scales: how local can we go? *Environ. Sci. Technol.*, **48**, 9463-9470.
Prakoso, V. et al. (eds.), Risk assessment on the vulnerability of freshwater aquaculture to climate change: a case study from West Java, Indonesia. IOP Conference Series: Earth and Environmental Science, IOP Publishing, 012029 pp. ISBN 1755-1315.
Pramanik, M. et al., 2018: Predicting climate change impacts on the distribution of the threatened Garcinia indica in the Western Ghats, India. *Clim. Risk Manag.*, **19**, 94-105, doi:10.1016/j.crm.2017.11.002.
Prasad, P. V. V., R. Bheemanahalli and S. V. K. Jagadish, 2017: Field crops and the fear of heat stress-Opportunities, challenges and future directions. *Field Crops Res.*, **200**, 114-121, doi:10.1016/j.fcr.2016.09.024.
Prestele, R. et al., 2016: Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. *Glob Chang Biol*, **22**(12), 3967-3983, doi:10.1111/gcb.13337.
Pretty, J., 2018: Intensification for redesigned and sustainable agricultural systems. *Science*, **362**(6417), eaav0294, doi:10.1126/science.aav0294.
Pretty, J. et al., 2018: for sustainable intensification. *Nat. Sustain.*, **1**(August), 441-446, doi:10.1038/s41893-018-0114-0.
Pretzsch, H. et al., 2018: Wood density reduced while wood volume growth accelerated in Central European forests since 1870. *For. Ecol. Manag.*, **429**, 589-616, doi:10.1016/j.foreco.2018.07.045.
Prevéy, J. S. et al., 2020: Climate change shifts in habitat suitability and phenology of huckleberry (Vaccinium membranaceum). *Agric. For. Meteorol*, **280**, 107803.
Prieto, I. et al., 2015: Complementary effects of species and genetic diversity on productivity and stability of sown grasslands. *Nat Plants*, **1**(4), 15033, doi:10.1038/nplants.2015.33.

Probstl-Haider, U. et al., 2016: Farmers' Preferences for Future Agricultural Land Use Under the Consideration of Climate Change. *Environ Manage*, **58**(3), 446-464, doi:10.1007/s00267-016-0720-4.
Prudent, M. et al., 2020: The diversity of soil microbial communities matters when legumes face drought. *Plant Cell Environ*, **43**(4), 1023-1035, doi:10.1111/pce.13712.
Puchta, H., 2017: Applying CRISPR/Cas for genome engineering in plants: the best is yet to come. *Curr. Opin. Plant Biol.*, **36**, 1-8, doi:10.1016/j.pbi.2016.11.011.
Pulatov, B., M. L. Linderson, K. Hall and A. M. Jonsson, 2015: Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe. *Agric. For. Meteorol*, **214**, 281-292, doi:10.1016/j.agrformet.2015.08.266.
Purcell, C. et al., 2018: Increasing stomatal conductance in response to rising atmospheric CO2. *Ann. Bot.*, **121**(6), 1137-1149, doi:10.1093/aob/mcx208.
Purcell, S. W. and R. S. Pomeroy, 2015: Driving small-scale fisheries in developing countries. *Front. Mar. Sci.*, **2**(44), doi:10.3389/fmars.2015.00044.
Putkonen, J. and G. Roe, 2003: Rain-on-snow events impact soil temperatures and affect ungulate survival. *Geophys. Res. Lett.*, **30**(4), doi:10.1029/2002gl016326.
Pye, O., I. Radjawali and Julia, 2017: Land grabs and the river: eco-social transformations along the Kapuas, Indonesia. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, **38**(3), 378-394, doi:10.1080/02255189.2017.1298518.
Qaim, M., 2016: *Genetically modified crops and agricultural development*. Palgrave Macmillan, New York City, New York.
Qi, R. M. et al., 2016: Temperature effects on soil organic carbon, soil labile organic carbon fractions, and soil enzyme activities under long-term fertilization regimes. *Applied Soil Ecology*, **102**, 36-45, doi:10.1016/j.apsoil.2016.02.004.
Quan, S. P. et al., 2019: Adaptation to Climate Change and its Impacts on Wheat Yield: Perspective of Farmers in Henan of China. *Sustainability*, **11**(7), doi:10.3390/su11071928.
Quandt, A., H. Neufeldt and J. T. McCabe, 2017: The role of agroforestry in building livelihood resilience to floods and drought in semiarid Kenya. *Ecol. Soc.*, **22**(3), art10, doi:10.5751/Es-09461-220310.
Quandt, A., H. Neufeldt and J. T. McCabe, 2019: Building livelihood resilience: what role does agroforestry play? *Clim. Dev.*, **11**(6), 485-500, doi:10.1080/17565529.2018.1447903.
Quiller, G. et al., 2017: Heat exposure and productivity in orchards: Implications for climate change research. *Arch Environ Occup Health*, **72**(6), 313-316, doi:10.1080/19338244.2017.1288077.
Quiñones-Ruiz, X. F., M. Penker, C. R. Vogl and L. F. Samper-Gartner, 2015: Can origin labels re-shape relationships along international supply chains? – The case of Café de Colombia. *International Journal of the Commons*, **9**(1), 416-416, doi:10.18352/ijc.529.
Quintas-Soriano, C., A. J. Castro, H. Castro and M. Garcia-Llorente, 2016: Impacts of land use change on ecosystem services and implications for human well-being in Spanish drylands. *Land Use Policy*, **54**, 534-548, doi:10.1016/j.landusepol.2016.03.011.
Quiroga, S., C. Suárez, J. Diego Solís and P. Martinez-Juarez, 2020: Framing vulnerability and coffee farmers' behaviour in the context of climate change adaptation in Nicaragua. *World Dev.*, **126**, 104733-104733, doi:10.1016/j.worlddev.2019.104733.
Raftopoulos, M. and D. Short, 2019: Implementing free prior and informed consent: the United Nations Declaration on the Rights of Indigenous Peoples (2007), the challenges of REDD+ and the case for the precautionary principle. *International Journal of Human Rights*, **23**(1-2), 87-103, doi:10.1080/13642987.2019.1579990.
Rahimi, J. et al., 2020: Will dairy cattle production in West Africa be challenged by heat stress in the future? *Clim. Change*, **161**(4), 665-685, doi:10.1007/s10584-020-02733-2.
Rahman, A., M. A. Mojid and S. Banu, 2018: Climate change impact assessment on three major crops in the north-central region of Bangladesh using DSSAT. *International Journal of Agricultural and Biological Engineering*, **11**(4), 135-143, doi:10.25165/j.ijabe.20181104.3331.
Rahman, H. M. T. and G. M. Hickey, 2019: What Does Autonomous Adaptation to Climate Change Have to Teach Public Policy and Planning About Avoiding the Risks of Maladaptation in Bangladesh? *Front. Environ. Sci.*, **7**, doi:10.3389/fenvs.2019.00002.
Rajab, Y. A. et al., 2016: Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses. *PLoS One*, **11**(2), e0149949.

Ramachandran, A. et al., 2017: Spatiotemporal analysis of projected impacts of climate change on the major C3 and C4 crop yield under representative concentration pathway 4.5: Insight from the coasts of Tamil Nadu, South India. *PLoS One*, **12**(7), e0180706, doi:10.1371/journal.pone.0180706.
Ramachandran Nair, P. K., B. Mohan Kumar and V. D. Nair, 2009: Agroforestry as a strategy for carbon sequestration. *J. Plant Nutr. Soil Sci.*, **172**(1), 10-23, doi:10.1002/jpln.200800030.
Ramírez, F. and J. Kallarackal, 2015: *Responses of fruit trees to global climate change*. Springer. ISBN 3319142003.
Ramesh, K. et al., 2017: Weeds in a Changing Climate: Vulnerabilities, Consequences, and Implications for Future Weed Management. *Front Plant Sci*, **8**, 95, doi:10.3389/fpls.2017.00095.
Ramirez, P. J. B., T. A. Narvaez and E. J. Santos-Ramirez, 2020: Gender-inclusive value chains: the case of seaweed farming in Zamboanga Peninsula, Philippines. *Gender Technology & Development*, **24**(1), 110-130, doi:10.1080/09718524.2020.1728810.
Ramos, A. K. et al., 2020: Invisible No More: The Impact of COVID-19 on Essential Food Production Workers. *J. Agromed.*, **25**(4), 378-382, doi:10.1080/1059924X.2020.1814925.
Ranasinghe, R. et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Randriambanona, H., J. R. Randriamalala and S. M. Carrière, 2019: Native forest regeneration and vegetation dynamics in non-native Pinus patula tree plantations in Madagascar. *For. Ecol. Manag.*, **446**, 20-28, doi:10.1016/j.foreco.2019.05.019.
Ranjan, R., 2020: Protecting warming lakes through climate-adaptive PES mechanisms. *Ecol. Econ.*, **177**, doi:10.1016/j.ecolecon.2020.106782.
Ranjitkar, S. et al., 2020: Will heat stress take its toll on milk production in China? . *Climate Change*, 1-16, doi:10.1007/s10584-020-02688-4
Rao, N. et al., 2019a: Gendered vulnerabilities to climate change: insights from the semi-arid regions of Africa and Asia. *Clim. Dev.*, **11**(1), 14-26, doi:10.1080/17565529.2017.1372266.
Rao, N. et al., 2019b: A qualitative comparative analysis of women's agency and adaptive capacity in climate change hotspots in Asia and Africa. *Nat. Clim. Change*, **9**(12), 964-971, doi:10.1038/s41558-019-0638-y.
Rasmussen, L. V. et al., 2018: Social-ecological outcomes of agricultural intensification. *Nat. Sustain.*, **1**(6), 275-282, doi:10.1038/s41893-018-0070-8.
Rasul, G. et al., 2019: Food and Nutrition Security in the Hindu Kush Himalaya: Unique Challenges and Niche Opportunities. In: *The Hindu Kush Himalaya Assessment*. Springer International Publishing, Cham, pp. 301-338.
Rathore, P., A. Roy and H. Karnatak, 2019: Modelling the vulnerability of Taxus wallichiana to climate change scenarios in South East Asia. *Ecol. Indic.*, **102**, 199-207, doi:10.1016/j.ecolind.2019.02.020.
Raven, J. A., C. J. Gobler and P. J. Hansen, 2020: Dynamic CO2 and pH levels in coastal, estuarine, and inland waters: Theoretical and observed effects on harmful algal blooms. *Harmful Algae*, **91**, 101594, doi:10.1016/j.hal.2019.03.012.
Ravi, S., D. D. Breshears, T. E. Huxman and P. D'Odorico, 2010: Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, **116**(3-4), 236-245, doi:10.1016/j.geomorph.2009.11.023.
Ravikumar, A. et al., 2015: Multilevel governance challenges in transitioning towards a national approach for REDD plus : evidence from 23 subnational REDD plus initiatives. *International Journal of the Commons*, **9**(2), 909-931, doi:10.18352/ijc.593.
Raworth, K., 2017: A Doughnut for the Anthropocene: humanity's compass in the 21st century. *Lancet Planet Health*, **1**(2), e48-e49, doi:10.1016/S2542-5196(17)30028-1.
Ray, D. K., J. S. Gerber, G. K. MacDonald and P. C. West, 2015: Climate variation explains a third of global crop yield variability. *Nat Commun*, **6**, 5989, doi:10.1038/ncomms6989.
Ray, D. K. et al., 2019: Climate change has likely already affected global food production. *PLoS One*, **14**(5), e0217148, doi:10.1371/journal.pone.0217148.
Raymond-Yakoubian, J. and R. Daniel, 2018: An Indigenous approach to ocean planning and policy in the Bering Strait region of Alaska. *Mar. Policy*, **97**, 101-108, doi:10.1016/j.marpol.2018.08.028.

Raymond-Yakoubian, J., B. Raymond-Yakoubian and C. Moncrieff, 2017: The incorporation of traditional knowledge into Alaska federal fisheries management. *Mar. Policy*, **78**, 132-142, doi:10.1016/j.marpol.2016.12.024.
Raymundo, R., S. Asseng, D. Cammarano and R. Quiroz, 2014: Potato, sweet potato, and yam models for climate change: A review. *Field Crops Res.*, **166**, 173-185, doi:10.1016/j.fcr.2014.06.017.
Raymundo, R. et al., 2018: Climate change impact on global potato production. *Eur J Agron*, **100**, 87-98, doi:10.1016/j.eja.2017.11.008.
Reed, J., J. van Vianen, J. Barlow and T. Sunderland, 2017: Have integrated landscape approaches reconciled societal and environmental issues in the tropics? *Land Use Policy*, **63**, 481-492, doi:10.1016/j.landusepol.2017.02.021.
Reed, J. et al., 2016: Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. *Glob Chang Biol*, **22**(7), 2540-2554, doi:10.1111/gcb.13284.
Reeves, M. C. et al., 2020: An Assessment of Production Trends on the Great Plains from 1984 to 2017. *Rangeland Ecol. Manage.*, doi:10.1016/j.rama.2020.01.011.
Refatti, J. P. et al., 2019: High [CO2] and Temperature Increase Resistance to Cyhalofop-Butyl in Multiple-Resistant Echinochloa colona. *Front Plant Sci*, **10**, 529, doi:10.3389/fpls.2019.00529.
Reich, P. B., S. E. Hobbie, T. D. Lee and M. A. Pastore, 2018: Unexpected reversal of C3 versus C4 grass response to elevated CO2 during a 20-year field experiment. *Science*, **360**(6386), 317-320.
Reid, G. K. et al., 2019: Climate change and aquaculture: considering biological response and resources. *Aquaculture Environment Interactions*, **11**, 569-602, doi:10.3354/aei00332.
Reid, R. S., M. E. Fernandez-Gimenez and K. A. Galvin, 2014: Dynamics and Resilience of Rangelands and Pastoral Peoples Around the Globe. *Annual Review of Environment and Resources, Vol 39*, **39**, 217-242, doi:10.1146/annurev-environ-020713-163329.
Reimer, J. R., H. Caswell, A. E. Derocher and M. A. Lewis, 2019: Ringed seal demography in a changing climate. *Ecol. Appl.*, **29**(3), e01855, doi:10.1002/eap.1855.
Reisman, E., 2019: The great almond debate: A subtle double movement in California water. *Geoforum*, **104**, 137-146, doi:10.1016/j.geoforum.2019.04.021.
Renard, D. and D. Tilman, 2019: National food production stabilized by crop diversity. *Nature*, **571**(7764), 257-260, doi:10.1038/s41586-019-1316-y.
Renaud, F. G. et al., 2015: Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta. *Clim. Change*, **133**(1), 69-84, doi:10.1007/s10584-014-1113-4.
Renner, S. S. and C. M. Zohner, 2018: Climate Change and Phenological Mismatch in Trophic Interactions Among Plants, Insects, and Vertebrates. *Annual Review of Ecology, Evolution, and Systematics, Vol 49*, **49**, 165-182, doi:10.1146/annurev-ecolsys-110617-062535.
Renwick, L. L. R. et al., 2020: Maize-Pigeonpea Intercropping Outperforms Monocultures Under Drought. *Front. Sustain. Food Syst.*, **4**, 253-253.
Reo, N. J. and A. K. Parker, 2013: Re-thinking colonialism to prepare for the impacts of rapid environmental change. In: *Climate Change and Indigenous Peoples in the United States*. Springer, pp. 163-174.
Reppin, S. et al., 2019: Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. *Agroforestry Systems*, **94**(1), 203-220, doi:10.1007/s10457-019-00383-7.
Resco, P., A. Iglesias, I. Bardaji and V. Sotes, 2016: Exploring adaptation choices for grapevine regions in Spain. *Reg. Environ. Change*, **16**(4), 979-993, doi:10.1007/s10113-015-0811-4.
Resosudarmo, I. A. P. et al., 2014: Does tenure security lead to REDD+ project effectiveness? Reflections from five emerging sites in Indonesia. *World Dev.*, **55**, 68-83, doi:10.1016/j.worlddev.2013.01.015
Rességuier, L. D., S. Mary, R. L. Roux and T. Petitjean, 2020: Temperature Variability at Local Scale in the Bordeaux Area . Relations With Environmental Factors and Impact on Vine Phenology. **11**(May), 1-20, doi:10.3389/fpls.2020.00515.
Reverter, M. et al., 2020: Moving towards more sustainable aquaculture practices: a meta‐analysis on the potential of plant‐enriched diets to improve fish growth, immunity and disease resistance. *Rev. Aquac.*, **13**(1), 537-555, doi:10.1111/raq.12485.
Revi, A. et al., 2014: Urban Areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)].

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612. ISBN 9781107058071.
Reyer, C. P. O. et al., 2017: Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environ Res Lett*, **12**(3), 034027, doi:10.1088/1748-9326/aa5ef1.
Reyes-García, V., L Aceituno-Mata, L Calvet-Mir, T Garnatje, E Gómez-Baggethun, J J Lastra, R Ontillera, 2014: Resilience of traditional knowledge systems. *Global Environ. Change*, **24**, 223-231.
Reyes-García, V. et al., 2019: Dietary transitions among three contemporary hunter-gatherers across the tropics. *Food Secur.*, **11**(1), 109-122.
Reyes-Garcia, V. et al., 2016: Local indicators of climate change: The potential contribution of local knowledge to climate research. *Wiley Interdiscip Rev Clim Change*, **7**(1), 109-124, doi:10.1002/wcc.374.
Reyes-Garcia, V. et al., 2019: A collaborative approach to bring insights from local observations of climate change impacts into global climate change research. *Curr. Opin. Environ. Sustain.*, **39**(1-8), 1-8, doi:10.1016/j.cosust.2019.04.007.
Rhiney, K., A. Eitzinger, A. D. Farrell and S. D. Prager, 2018: Assessing the implications of a 1.5 degrees C temperature limit for the Jamaican agriculture sector. *Reg. Environ. Change*, **18**(8), 2313-2327, doi:10.1007/s10113-018-1409-4.
Rhoné, B. et al., 2020: Pearl millet genomic vulnerability to climate change in West Africa highlights the need for regional collaboration. *Nat. Commun.*, **11**(1), 5274, doi:10.1038/s41467-020-19066-4.
Ribot, J., 2014: Cause and response: vulnerability and climate in the Anthropocene. *J. Peasant Stud.*, **41**(5), 667-705, doi:10.1080/03066150.2014.894911.
Ricciardi, V. et al., 2018: How much of the world's food do smallholders produce? *Glob. Food Secur.*, **17**(June), 64-72, doi:10.1016/j.gfs.2018.05.002.
Richards, C. and K. Lyons, 2016: The new corporate enclosures: Plantation forestry, carbon markets and the limits of financialised solutions to the climate crisis. *Land Use Policy*, **56**, 209-216, doi:10.1016/j.landusepol.2016.05.013.
Richards, G., J. Frehs and E. a. Myers, 2019: Commentary - The Climate Change and Health Adaptation Program: Indigenous Climate Leaders' Championing Adaptation Efforts. *Health Promotion and Chronic Disease Prevention in Canada*, **39**(4), 127--130, doi:10.24095/hpcdp.39.4.03.
Richardson, K. J. et al., 2018: Food security outcomes under a changing climate: impacts of mitigation and adaptation on vulnerability to food insecurity. *Clim. Change*, **147**(1-2), 327-341, doi:10.1007/s10584-018-2137-y.
Ricker-Gilbert, J. and J. Chamberlin, 2018: Transaction Costs, Land Rental Markets, and Their Impact on Youth Access to Agriculture in Tanzania. *Land Economics*, **94**(4), 541--555, doi:10.3368/le.94.4.541.
Rigolot, C. et al., 2017: Interactions between intervention packages, climatic risk, climate change and food security in mixed crop-livestock systems in Burkina Faso. *Agric. Syst.*, **151**, 217-224, doi:10.1016/j.agsy.2015.12.017.
Rinaldi, L. et al., 2015: Sheep and Fasciola hepatica in Europe: the GLOWORM experience. *Geospat Health*, **9**(2), 309-317, doi:10.4081/gh.2015.353.
Rivera-Ferre, M. G. et al., 2016: Re-framing the climate change debate in the livestock sector: mitigation and adaptation options. *Wiley Interdiscip. Rev.: Clim. Change*, **7**(6), 869-892, doi:10.1002/wcc.421.
Robalino, J., J. Jimenez and A. Chacon, 2015: The Effect of Hydro-Meteorological Emergencies on Internal Migration. *World Dev.*, **67**, 438-448, doi:10.1016/j.worlddev.2014.10.031.
Robinson, B. E., M. B. Holland and L. Naughton-Treves, 2014: Does secure land tenure save forests? A meta-analysis of the relationship between land tenure and tropical deforestation. *Glob. Environ. Change*, **29**, 281-293, doi:10.1016/j.gloenvcha.2013.05.012.
Robinson, C. et al., 2016a: Participatory mapping to negotiate indigenous knowledge used to assess environmental risk. *Sustain. Sci.*, **11**(1), 115-126, doi:10.1007/s11625-015-0292-x.
Robinson, C. J. et al., 2016b: Indigenous benefits and carbon offset schemes: An Australian case study. *Environ. Sci. Policy*, **56**, 129-134, doi:10.1016/j.envsci.2015.11.007.
Robinson, L. M. et al., 2015: Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions. *Glob. Environ. Change*, **31**, 28-37, doi:10.1016/j.gloenvcha.2014.12.003.
Robinson, T. P. et al., 2011: *Global livestock production systems*. FAO and ILRI.

Rochedo, P. R. R. et al., 2018: The threat of political bargaining to climate mitigation in Brazil. *Nat. Clim. Change*, **8**(8), 695-+, doi:10.1038/s41558-018-0213-y.
Rockström, J. et al., 2017: Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, **46**(1), 4-17, doi:10.1007/s13280-016-0793-6.
Rode, J., E. Gomez-Baggethun and T. Krause, 2015: Motivation crowding by economic incentives in conservation policy: A review of the empirical evidence. *Ecol. Econ.*, **117**, 270-282, doi:10.1016/j.ecolecon.2014.11.019.
Rodríguez-de-Francisco, J. C. et al., 2021: Post-conflict transition and REDD+ in Colombia: Challenges to reducing deforestation in the Amazon. *For Policy Econ*, **127**(August 2019), 102450-102450, doi:10.1016/j.forpol.2021.102450.
Rodríguez, A. et al., 2019: Agricultural and Forest Meteorology Implications of crop model ensemble size and composition for estimates of adaptation e ff ects and agreement of recommendations. **264**(March 2018), 351-362, doi:10.1016/j.agrformet.2018.09.018.
Rodriguez-Llanes, J. M., S. Ranjan-Dash, A. Mukhopadhyay and D. Guha-Sapir, 2016: Flood-Exposure is Associated with Higher Prevalence of Child Undernutrition in Rural Eastern India. *Int J Environ Res Public Health*, **13**(2), 210, doi:10.3390/ijerph13020210.
Roesch-McNally, G. E., J. G. Arbuckle and J. C. Tyndall, 2018: Barriers to implementing climate resilient agricultural strategies: The case of crop diversification in the U.S. Corn Belt. *Global Environ. Change*, **48**, 206-215, doi:10.1016/j.gloenvcha.2017.12.002.
Rogelj, J. et al., 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press-In press. ISBN 9789291691517.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Clim. Risk Manag.*, **16**, 145-163, doi:10.1016/j.crm.2017.02.001.
Rojas, M., F. Lambert, J. Ramirez-Villegas and A. J. Challinor, 2019: Emergence of robust precipitation changes across crop production areas in the 21st century. *Proc Natl Acad Sci U S A*, **116**(14), 6673-6678, doi:10.1073/pnas.1811463116.
Rolo, V. and G. Moreno, 2019: Shrub encroachment and climate change increase the exposure to drought of Mediterranean wood-pastures. *Sci. Total Environ.*, **660**, 550-558, doi:10.1016/j.scitotenv.2019.01.029.
Romeo, D., E. B. Vea and M. Thomsen (eds.), Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. Procedia CIRP, 2018, 540-545 pp.
Roncoli, C. et al., 2009: From accessing to assessing forecasts: an end-to-end study of participatory climate forecast dissemination in Burkina Faso (West Africa). *Clim. Change*, **92**(3-4), 433-460, doi:10.1007/s10584-008-9445-6.
Roncoli, C., A. C. Tod and O. Ben, 2016: Fielding climate change in cultural anthropology. *Climate and Culture*, 87-115.
Rondeau, R. J., K. L. Decker and G. A. Doyle, 2018: Potential Consequences of Repeated Severe Drought for Shortgrass Steppe Species. *Rangeland Ecol. Manage.*, **71**(1), 91-97, doi:10.1016/j.rama.2017.07.002.
Rosa-Schleich, J., J. Loos, O. Musshoff and T. Tscharntke, 2019: Ecological-economic trade-offs of Diversified Farming Systems - A review. *Ecol. Econ.*, **160**, 251-263, doi:10.1016/j.ecolecon.2019.03.002.
Rosa, L. et al., 2021: Energy implications of the 21st century agrarian transition. *Nat. Commun.*, **12**(1), 2319-2319, doi:10.1038/s41467-021-22581-7.
Rose, J. B. and F. Wu, 2015: Waterborne and Foodborne Diseases. In: *Climate Change and Public Health*. Oxford University Press, pp. 157-172.
Rosegrant, M. W., M. M. Dey, R. Valmonte-Santos and O. L. Chen, 2016: Economic impacts of climate change and climate change adaptation strategies in Vanuatu and Timor-Leste. *Mar. Policy*, **67**, 179-188, doi:10.1016/j.marpol.2015.12.010.
Rosenstock, T. S. et al., 2014: Agroforestry with N2-fixing trees: sustainable development's friend or foe? *Curr. Opin. Environ. Sustain.*, **6**, 15-21, doi:10.1016/j.cosust.2013.09.001.

Rosenzweig, C. et al., 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc Natl Acad Sci U S A*, **111**(9), 3268-3273, doi:10.1073/pnas.1222463110.

Rosenzweig, C. et al., 2020: Climate change responses benefit from a global food system approach. *Nat. Food*, **1**(2), 94-97, doi:10.1038/s43016-020-0031-z.

Rosenzweig, C. et al., 2018: Coordinating AgMIP data and models across global and regional scales for 1.5 degrees C and 2.0 degrees C assessments. *Philos Trans A Math Phys Eng Sci*, **376**(2119), 20160455, doi:10.1098/rsta.2016.0455.

Rosimo, M., Dalusag, J., Gonsalves, J. and Vidallo, R. , 2018: Incorporating a Gender Dimension in a Participatory Community-Based Project: A Case Study in Guinayangan Quezon Province, Philippines. In: *Gender dimension of climate change research in agriculture (Case studies in Southeast Asia)* [Rola-Rubzen, T. R. P. a. M. (ed.)]. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, the Netherlands, pp. 157-179.

Rosol, R., S. Powell-Hellyer and H. M. Chan, 2016: Impacts of decline harvest of country food on nutrient intake among Inuit in Arctic Canada: impact of climate change and possible adaptation plan. *Int J Circumpolar Health*, **75**, 31127, doi:10.3402/ijch.v75.31127.

Ross, N., A. Agostini and M. Frick, 2016: *Agricultural sectors in nationally determined contributions (NDCs): priority areas for international support*. FAO. Available at: FAO: http://www.fao.org/3/a-i6400e.pdf.

Ross, P. and C. W. Mason, 2020: "We Hardly Have Any Moose Around Here Anymore": Climate Change and the Barriers to Food Security in the Dehcho Region, Northwest Territories. *Arctic*, **73**(3), 368-385, doi:10.14430/arctic71082.

Rossa, A., Flubacher, M., Cristobal, L., Ramos, H., & Lechthaler, F. , 2020: Towards More Resilient Food Systems for Smallholder Farmers in the Peruvian Altiplano: The Potential of Community-Based Climate Services. In: *Handbook of Climate Services*. Springer, Cham., pp. 327-351.

Rossi, R. and A. Miola, 2017: *Adaptation measures in Intended Nationally Determined Contributions from Small Island Developing States and Least Developed Countries - An analysis of communicated costs and information exhaustiveness*. Publications Office of the European Union, Luxembourg.

Rotz, S. et al., 2019: Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. *J. Rural Stud.*, **68**, 112-122, doi:10.1016/j.jrurstud.2019.01.023.

Roudier, P. et al., 2016: Assessing the benefits of weather and seasonal forecasts to millet growers in Niger. *Agric. For. Meteorol*, **223**, 168-180, doi:10.1016/j.agrformet.2016.04.010.

Roudier, P. et al., 2014: The role of climate forecasts in smallholder agriculture: Lessons from participatory research in two communities in Senegal. *Clim. Risk Manag.*, **2**, 42-55, doi:10.1016/j.crm.2014.02.001.

Roue, M. a. N., D., 2018: Indigenous and local knowledge and science: from validation to knowledge coproduction. *The International Encyclopedia of Anthropology*, 1-11.

Roupsard, O. et al., 2020: How far does the tree affect the crop in agroforestry? New spatial analysis methods in a Faidherbia parkland. *Agriculture, Ecosystems & Environment*, **296**, doi:10.1016/j.agee.2020.106928.

Roux, M.-J., R. F. Tallman and Z. A. Martin, 2019: Small-scale fisheries in Canada's Arctic: Combining science and fishers knowledge towards sustainable management. *Mar. Policy*, **101**, 177-186, doi:10.1016/j.marpol.2018.01.016.

Rowland, D. et al., 2017: Forest foods and healthy diets: quantifying the contributions. *Environ. Conserv.*, **44**(2), 102-114, doi:10.1017/S0376892916000151.

Roxy, M. et al., 2017: A threefold rise in widespread extreme rain events over central India. Nature communications. *Nat. Commun.*, **3**(1), 1-1.

Roxy, M. K., K. Ritika, P. Terray and S. Masson, 2014: The Curious Case of Indian Ocean Warming. *J. Clim.*, **27**(22), 8501-8509, doi:10.1175/Jcli-D-14-00471.1.

Roy, J. et al., 2018: Sustainable Development, Poverty Eradication and Reducing Inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

RRI, 2018a: *A global baseline of carbon storage in collective lands: Indigenous and local community contributions to climate change mitigation*. RRI, Washington, DC, USA, 12 pp.

RRI, 2018b: *Uncertainty and opportunity: The status of forest carbon rights and governance frameworks in over half of the world's tropical forests*. RRI, Washington, DC, USA, 23 pp.
Ruane, A. C., 2014: Carbon-Temperature-Water change analysis for peanut production under climate change: A prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3 MP). *Global Change Biol.*, **20**, 394-407.
Ruane, A. C. et al., 2018: Biophysical and economic implications for agriculture of +1.5 degrees and +2.0 degrees C global warming using AgMIP Coordinated Global and Regional Assessments. *Clim. Res.*, **76**(1), 17-39, doi:10.3354/cr01520.
Ruane, A. C. et al., 2021: Strong regional influence of climatic forcing datasets on global crop model ensembles. *Agric. For. Meteorol*, **300**, 108313.
Ruane, A. C. et al., 2017: An AgMIP framework for improved agricultural representation in IAMs. *Environ Res Lett*, **12**(12), 125003, doi:10.1088/1748-9326/aa8da6.
Rubio, I., U. Ganzedo, A. J. Hobday and E. Ojea, 2020a: Southward re-distribution of tropical tuna fisheries activity can be explained by technological and management change. *Fish Fish (Oxf)*, **21**(3), 511-521, doi:10.1111/faf.12443.
Rubio, N. R., N. Xiang and D. L. Kaplan, 2020b: Plant-based and cell-based approaches to meat production. *Nat. Commun.*, **11**(1), doi:10.1038/s41467-020-20061-y.
Rufino, M. C. et al., 2013: Transitions in agro-pastoralist systems of East Africa: Impacts on food security and poverty. *Agric. Ecosyst. Environ.*, **179**, 215-230, doi:10.1016/j.agee.2013.08.019.
Ruiz-Vera, U. M. et al., 2013: Global warming can negate the expected CO2 stimulation in photosynthesis and productivity for soybean grown in the Midwestern United States. *Plant Physiol.*, **162**(1), 410-423, doi:10.1104/pp.112.211938.
Ruiz Meza, L. E., 2015: Adaptive capacity of small-scale coffee farmers to climate change impacts in the Soconusco region of Chiapas, Mexico. *Clim. Dev.*, **7**(2), 100-109, doi:10.1080/17565529.2014.900472.
Rumbach, A. and D. Foley, 2014: Indigenous Institutions and Their Role in Disaster Risk Reduction and Resilience: Evidence from the 2009 Tsunami in American Samoa. *Ecol. Soc.*, **19**(1), 1-10, doi:10.5751/Es-06189-190119.
Ruml, M. et al., 2016: Response of grapevine phenology to recent temperature change and variability in the wine-producing area of Sremski Karlovci, Serbia. *J. Agric. Sci.*, **154**(2), 186-206, doi:10.1017/S0021859615000453.
Ruoso, L. E. et al., 2015: Reading Ecosystem Services at the Local Scale through a Territorial Approach: the Case of Peri-Urban Agriculture in the Thau Lagoon, Southern France. *Ecol. Soc.*, **20**(3), art11, doi:10.5751/Es-07694-200311.
Rushton, J. et al., 2018: *Interactions between intensifying livestock production for food and nutrition security, and increased vulnerability to AMR and zoonoses*. CGIAR Independent Science & Partnership Council (ISPC) Secretariat, Rome.
Rybråten, S., M. Bjørkan, G. K. Hovelsrud and B. P. Kaltenborn, 2018: Sustainable coasts? Perceptions of change and livelihood vulnerability in Nordland, Norway. *Local Environ.*, **23**(12), 1156-1171, doi:10.1080/13549839.2018.1533931.
Ryngaert, C., 2017: Climate Change Mitigation Techniques and International Law: Assessing the Externalities of Reforestation and Geoengineering. *Ratio Juris*, **30**(3), 273-289, doi:10.1111/raju.12154.
Sachs, J. D. et al., 2019: Six Transformations to achieve the Sustainable Development Goals. *Nat. Sustain.*, **2**(9), 805-814, doi:10.1038/s41893-019-0352-9.
Sae-Lim, P., A. Kause, H. A. Mulder and I. Olesen, 2017: Breeding and genetics symposium: Climate change and selective breeding in aquaculture. *J. Anim. Sci.*, **95**(4), 1801-1812, doi:10.2527/jas.2016.1066.
Sah Akwen, N., 2017: Chapter 10 - "Not Migrating After All": Young Farmers and Climate Change Adaptation in Cameroon. In: *Beyond Agricultural Impacts* [Zinyengere, N., T. F. Theodory, M. Gebreyes and C. I. Speranza (eds.)]. Academic Press, pp. 193-220. ISBN 978-0-12-812624-0.
Sainger, M. et al., 2015: GM crops for developing world in the era of climate change: For increase of farmer's income, poverty alleviation, nutrition and health. In: *Genetic Manipulation in Plants for Mitigation of Climate Change* [P., J., S. R. and D. O. (eds.)], Springer, New Delhi.
Sainsbury, N. C. et al., 2019: The challenges of extending climate risk insurance to fisheries. *Nat. Clim. Change*, **9**(12), 896-897, doi:10.1038/s41558-019-0645-z.

Sainz, J. F. et al., 2019: Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in Southern California. *Front. Mar. Sci.*, **6**(JUN), 253-253, doi:10.3389/fmars.2019.00253.
Saki, M., M. Tarkesh Esfahani and S. Soltani, 2018: A scenario-based modeling of climate change impacts on the aboveground net primary production in rangelands of central Iran. *Environmental Earth Sciences*, **77**(19), doi:10.1007/s12665-018-7864-x.
Sakkhamduang, J., K. Miwa and M. Mihara, 2017: Resin trees: A vital source of the Phnong people's livelihood in transition in Cambodia. *Satoyama Initiative Thematic Review*, **3**, 58.
Sala, E. et al., 2018: The economics of fishing the high seas. *Sci Adv*, **4**(6), eaat2504, doi:10.1126/sciadv.aat2504.
Salack, S. et al., 2016: Global warming induced hybrid rainy seasons in the Sahel. *Environ. Res. Lett.*, **11**(10), doi:10.1088/1748-9326/11/10/104008.
Salack, S. et al., 2015: Crop-climate ensemble scenarios to improve risk assessment and resilience in the semi-arid regions of West Africa. *Clim. Res.*, **65**, 107-121, doi:10.3354/cr01282.
Salazar-Parra, C. e. a., 2015: Carbon balance, partitioning and photosynthetic acclimation in fruit-bearing grapevine (Vitis vinifera L. cv. Tempranillo) grown under simulated climate change (elevated CO2, elevated temperature and moderate drought) scenarios in temperature gradient gre. *J. Plant Physiol.*, **174**, 97-109.
Salazar, C., M. Jaime, Y. Figueroa and R. Fuentes, 2018: Innovation in small-scale aquaculture in Chile. *Aquacult. Econ. Manage.*, **22**(2), 151-167, doi:10.1080/13657305.2017.1409293.
Salick, J., Z. D. Fang and A. Byg, 2009: Eastern Himalayan alpine plant ecology, Tibetan ethnobotany, and climate change. *Glob. Environ. Change*, **19**(2), 147-155, doi:10.1016/j.gloenvcha.2009.01.008.
Salih, A. A. M., M. Baraibar, K. K. Mwangi and G. Artan, 2020: Climate change and locust outbreak in East Africa. *Nat. Clim. Change*, **10**(7), 584-585, doi:10.1038/s41558-020-0835-8.
Sambaraju, K. R., A. L. Carroll and B. H. Aukema, 2019: Multiyear weather anomalies associated with range shifts by the mountain pine beetle preceding large epidemics. *For. Ecol. Manag.*, **438**, 86-95, doi:10.1016/j.foreco.2019.02.011.
Samberg, L. H. et al., 2016: Subnational distribution of average farm size and smallholder contributions to global food production. *Environ. Res. Lett.*, **11**(12), doi:10.1088/1748-9326/11/12/124010.
Sánchez-Rodríguez, A. R. et al., 2019: Extreme flood events at higher temperatures exacerbate the loss of soil functionality and trace gas emissions in grassland. *Soil Biol. Biochem.*, **130**, 227-236, doi:10.1016/j.soilbio.2018.12.021.
Sanchez, A. C., P. E. Osborne and N. Haq, 2011: Climate change and the African baobab (Adansonia digitata L.): the need for better conservation strategies. *Afr. J. Ecol.*, **49**(2), 234-245, doi:10.1111/j.1365-2028.2011.01257.x.
Sánchez, Y., 2019: Index for the calculation of future wine areas according to climate change application to the protected designation of origin "Sierra de Salamanca" (Spain). *Ecol. Indic.*
Sanderman, J., T. Hengl and G. J. Fiske, 2017: Soil carbon debt of 12,000 years of human land use. *Proc Natl Acad Sci U S A*, **114**(36), 9575-9580, doi:10.1073/pnas.1706103114.
Sanford, G. R. et al., 2021: Perenniality and diversity drive output stability and resilience in a 26-year cropping systems experiment. *Field Crops Res.*, **263**, doi:10.1016/j.fcr.2021.108071.
Sango, I. and N. Godwell, 2015: Climate change trends and environmental impacts in the Makonde Communal Lands, Zimbabwe. *S. Afr. J. Sci.*, **111**(7-8), 78-83.
Sanogo, K. et al., 2017: Farmers' perceptions of climate change impacts on ecosystem services delivery of parklands in southern Mali. *Agroforestry Systems*, **91**(2), 345-361, doi:10.1007/s10457-016-9933-z.
Sanogo, S. et al., 2015: Spatio-temporal characteristics of the recent rainfall recovery in West Africa. *Int. J. Climatol.*, **35**(15), 4589-4605, doi:10.1002/joc.4309.
Santillan, D. et al., 2019: Vineyards in transition: A global assessment of the adaptation needs of grape producing regions under climate change. *Sci. Total Environ.*, **657**, 839-852, doi:10.1016/j.scitotenv.2018.12.079.
Santo, R. E. et al., 2020: Considering Plant-Based Meat Substitutes and Cell-Based Meats: A Public Health and Food Systems Perspective. *Front. Sustain. Food Syst.*, **4**, doi:10.3389/fsufs.2020.00134.
Santo, R. E., A. Palmer and B. Kim, 2016: *Vacant Lots to Vibrant Plots: A review of the benefits and limitations of urban agriculture*. Baltimore, MD, USA, 35-35 pp.
Santos-Fita, D., E. J. Naranjo and J. L. Rangel-Salazar, 2012: Wildlife uses and hunting patterns in rural communities of the Yucatan Peninsula, Mexico. *J Ethnobiol Ethnomed*, **8**(1), 38, doi:10.1186/1746-4269-8-38.

Santos, J. A., R. Costa and H. Fraga, 2017: Climate change impacts on thermal growing conditions of main fruit species in Portugal. *Clim. Change*, **140**(2), 273-286, doi:10.1007/s10584-016-1835-6.
Santoso, M. V. et al., 2021: A Nutrition-Sensitive Agroecology Intervention in Rural Tanzania Increases Children's Dietary Diversity and Household Food Security But Does Not Change Child Anthropometry: Results from a Cluster-Randomized Trial. *The Journal of Nutrition*, doi:10.1093/jn/nxab052.
SAPEA, 2020: *A sustainable food system for the European Union*.
Sara, G. et al., 2018: Predicting shifting sustainability trade-offs in marine finfish aquaculture under climate change. *Glob Chang Biol*, **24**(8), 3654-3665, doi:10.1111/gcb.14296.
Sarmiento Barletti, J. P., A. M. Larson, C. Hewlett and D. Delgado, 2020: Designing for engagement: A Realist Synthesis Review of how context affects the outcomes of multi-stakeholder forums on land use and/or land-use change. *World Dev.*, **127**, doi:10.1016/j.worlddev.2019.104753.
Saronga, N. J. et al., 2016: "I eat two meals per day" impact of climate variability on eating habits among households in Rufiji district, Tanzania: a qualitative study. *Agric. Food Secur.*, **5**(1), 14, doi:10.1186/s40066-016-0064-6.
Satgé, F. et al., 2019: Unraveling the impacts of droughts and agricultural intensification on the Altiplano water resources. *Agric. For. Meteorol*, **279**(April), 107710-107710, doi:10.1016/j.agrformet.2019.107710.
Scanes, E. et al., 2020: Heatwaves alter survival of the Sydney rock oyster, Saccostrea glomerata. *Mar. Pollut. Bull.*, **158**, 111389, doi:10.1016/j.marpolbul.2020.111389.
Scelza, B. A., D. W. Bird and R. B. Bird, 2014: Bush tucker, shop tucker: production, consumption, and diet at an Aboriginal outstation. *Ecol Food Nutr*, **53**(1), 98-117, doi:10.1080/03670244.2013.772513.
Schaefer, A. M., M. D. Hanisak, M. McFarland and J. M. Sullivan, 2019: Integrated observing systems: An approach to studying harmful algal blooms in south Florida. *Journal of Operational Oceanography*, **12**(sup2), S187-S198, doi:10.1080/1755876x.2019.1606879.
Schafleitner, R., 2016: Adaptation Of Potato (Solanum Tuberosum) and Tomato (S. Lycopersicum) to Climate Change. In: *Applied Mathematics and Omics to Assess Crop Genetic Resources for Climate Change Adaptive Traits*. CRC Press. ISBN 9781315369006.
Schartup, A. T. et al., 2019: Climate change and overfishing increase neurotoxicant in marine predators. *Nature*, **572**(7771), 648-650, doi:10.1038/s41586-019-1468-9.
Schauberger, B., S. Rolinski, S. Schaphoff and C. Müller, 2019a: Global historical soybean and wheat yield loss estimates from ozone pollutino considering water and temperature as modifying effects. *Agric. For. Meteorol*, **265**, 1-15.
Schauberger, G. et al., 2019b: Global warming impact on confined livestock in buildings: efficacy of adaptation measures to reduce heat stress for growing-fattening pigs. *Clim. Change*, **156**(4), 567-587, doi:10.1007/s10584-019-02525-3.
Scheben, A., Y. Yuan and D. Edwards, 2016: Advances in genomics for adapting crops to climate change. *Current Plant Biology*, **6**, 2-10, doi:10.1016/j.cpb.2016.09.001.
Scheelbeek, P. F. D. et al., 2018: Effect of environmental changes on vegetable and legume yields and nutritional quality. *Proc Natl Acad Sci U S A*, **115**(26), 6804-6809, doi:10.1073/pnas.1800442115.
Scheidel, A. and C. Work, 2018: Forest plantations and climate change discourses: New powers of 'green' grabbing in Cambodia. *Land Use Policy*, **77**, 9-18, doi:10.1016/j.landusepol.2018.04.057.
Schelhaas, M.-J. et al., 2015: Alternative forest management strategies to account for climate change-induced productivity and species suitability changes in Europe. *Reg. Environ. Change*, **15**(8), 1581-1594, doi:10.1007/s10113-015-0788-z.
Schewe, J. et al., 2019: State-of-the-art global models underestimate impacts from climate extremes. *Nat Commun*, **10**(1), 1005, doi:10.1038/s41467-019-08745-6.
Schipanski, M. E. et al., 2016: Realizing Resilient Food Systems. *Bioscience*, **66**(7), 600-610, doi:10.1093/biosci/biw052.
Schirpke, U., A. Alizinger, G. Leitinger and E. Tasser, 2019: Change from agricultural to touristic use: Effects on the aesthetic value of landscapes over the last 150 years. *Landscape Urban Plann.*, **187**, 23-35, doi:10.1016/j.landurbplan.2019.03.004.
Schleicher, J. et al., 2019: Protecting half of the planet could directly affect over one billion people. *Nat. Sustain.*, **2**(12), 1094-1096, doi:10.1038/s41893-019-0423-y.
Schmidt, L. M. et al., 2019: The Biorefinery Approach. [Kaltschmitt, M. (ed.)]. Springer New York, New York, NY, pp. 1383-1412. ISBN 978-1-4939-7813-7.

Schmidt, M. and O. Pearson, 2016: Pastoral livelihoods under pressure: Ecological, political and socioeconomic transitions in Afar (Ethiopia). *J. Arid Environ.*, **124**, 22-30, doi:10.1016/j.jaridenv.2015.07.003.
Schnurr, M., 2019: *Africa's gene revolution: Genetically modified crops and the future of african agriculture*. McGill-Queen's University Press.
Schoneveld, G. C., 2017: Host country governance and the African land rush: 7 reasons why large-scale farmland investments fail to contribute to sustainable development. *Geoforum*, **83**, 119-132, doi:10.1016/j.geoforum.2016.12.007.
Schott, S. et al., 2020: Operationalizing knowledge coevolution: towards a sustainable fishery for Nunavummiut. *Arctic Science*, **6**(3), 208-228, doi:10.1139/as-2019-0011.
Schreyer, F., C. Bunn and F. Castro-Llanos, 2018: *The economic case for climate action in West-African cocoa production. Adapting cocoa production in Ghana to climate change is a smart investment. Inaction will result in income losses to farmers and the economy*.
Schroeder, H. and N. C. Gonzalez, 2019: Bridging knowledge divides: The case of indigenous ontologies of territoriality and REDD. *For Policy Econ*, **100**, 198-206, doi:10.1016/j.forpol.2018.12.010.
Schroth, G. et al., 2015: Winner or loser of climate change? A modeling study of current and future climatic suitability of Arabica coffee in Indonesia. *Reg. Environ. Change*, **15**(7), 1473-1482, doi:10.1007/s10113-014-0713-x.
Schroth, G. et al., 2016: Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation. *Sci. Total Environ.*, **556**, 231-241, doi:10.1016/j.scitotenv.2016.03.024.
Schuldt, B. et al., 2020: A first assessment of the impact of the extreme 2018 summer drought on Central European forests. *Basic Appl. Ecol.*, **45**, 86-103, doi:10.1016/j.baae.2020.04.003.
Schulte, L. A. et al., 2017: Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn-soybean croplands. *Proc Natl Acad Sci U S A*, **114**(42), 11247-11252, doi:10.1073/pnas.1620229114.
Schultz, H. R. and G. V. Jones, 2010: This article was downloaded by : [Schultz , Hans] Climate Change and Viticulture : Research Needs for Facing the Future.(June 2014), doi:10.1080/09571264.2010.530098.
Schulze-Sylvester, M. and A. Reineke, 2019: Elevated CO2 levels impact fitness traits of vine mealybug (Planococcus ficus Signoret), but not its parasitoid Leptomastix dactylopii Howard. *Agronomy*, **9**, 326.
Schwendenmann, L. et al., 2010: Effects of an experimental drought on the functioning of a cacao agroforestry system, Sulawesi, Indonesia. *Global Change Biol.*, **16**(5), 1515-1530, doi:10.1111/j.1365-2486.2009.02034.x.
Scoville-Simonds, M., H. Jamali and M. Hufty, 2020: The Hazards of Mainstreaming: Climate change adaptation politics in three dimensions. *World Dev.*, **125**, 104683, doi:10.1016/j.worlddev.2019.104683.
Scurrah, M., R. Ccanto and M. Bonierbale, 2019: Participatory varietal selection in the Andes;Farmer involvement in selecting potatoes with traits from wild relatives. In: *Farmers and Plant Breeding* [Westengen, O. T. and T. Winge (eds.)]. Routledge, London. ISBN 9780429507335.
Searchinger T, B. M., Campbell B, Carter R, Thornton P. , 2019b: Food security and livelihoods of small-scale producers. In: *Adapt Now: A Global Call for Leadership on Climate Resilience*. GCA, Rotterdam.
Searchinger, T. et al., 2019: *Creating a Sustainable Food Future*. World Resources Institute, Washington, DC, 556-556 pp.
Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., & Matthews, E, 2019a: *Creating a sustainable food future: a menu of solutions to feed nearly 10 billion people by 2050*. World Resources Institute. Available at: https://wrr-food.wri.org/.
Searchinger, T. D., S. Wirsenius, T. Beringer and P. Dumas, 2018: Assessing the efficiency of changes in land use for mitigating climate change. *Nature*, **564**(7735), 249-253, doi:10.1038/s41586-018-0757-z.
Secretan, P. A. D. et al., 2007: Guidelines to meet insurance and other risk management needs in developing aquaculture in Asia. In: *FAO Fisheries Technical Paper*. FAO, Rome, pp. 53-78.
Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos Trans R Soc Lond B Biol Sci*, **375**(1794), 20190120, doi:10.1098/rstb.2019.0120.

Segnon, A., 2019: Exploring agrobiodiversity-based climate change adaptation in semi-arid areas of West Africa: a case study in Mali. University of Ghana, Accra, Ghana.

Segnon, A. C., E. G. Achigan-Dako, O. G. Gaoue and A. Ahanchede, 2015: Farmer's Knowledge and Perception of Diversified Farming Systems in Sub-Humid and Semi-Arid Areas in Benin. *Sustainability*, **7**(6), 6573-6592, doi:10.3390/su7066573.

Seidel, P., 2014: Extreme weather and plant pests: extreme knowledge gap. *Gesunde Pflanzen*, **66**, 93-101.

Seidl, R. et al., 2016: The sensitivity of current and future forest managers to climate-induced changes in ecological processes. *Ambio*, **45**(4), 430-441, doi:10.1007/s13280-015-0737-6.

Seidl, R., K. Albrich, D. Thom and W. Rammer, 2018: Harnessing landscape heterogeneity for managing future disturbance risks in forest ecosystems. *J Environ Manage*, **209**, 46-56, doi:10.1016/j.jenvman.2017.12.014.

Seidl, R. et al., 2020: Globally consistent climate sensitivity of natural disturbances across boreal and temperate forest ecosystems. *Ecography*, **43**(7), 967-978, doi:10.1111/ecog.04995.

Sejian, V. et al., 2018: Review: Adaptation of animals to heat stress. *Animal*, **12**(s2), s431-s444, doi:10.1017/S1751731118001945.

Sekine, Y., 2021: Emerging 'agrarian climate justice' struggles in Myanmar. *J. Peasant Stud.*, doi:10.1080/03066150.2020.1839054.

Selby, J., 2019: Climate change and the Syrian civil war, Part II: The Jazira's agrarian crisis. *Geoforum*, **101**, 260-274, doi:10.1016/j.geoforum.2018.06.010.

Sellberg, M. M., A. V. Norström, G. D. Peterson and L. J. Gordon, 2020: Using local initiatives to envision sustainable and resilient food systems in the Stockholm city-region. *Glob. Food Secur.*, **24**, 100334-100334, doi:10.1016/j.gfs.2019.100334.

Selmar, D. and M. Kleinwachter, 2013: Influencing the product quality by deliberately applying drought stress during the cultivation of medicinal plants. *Industrial Crops and Products*, **42**, 558-566, doi:10.1016/j.indcrop.2012.06.020.

Semenza, J. C. and J. E. Suk, 2018: Vector-borne diseases and climate change: a European perspective. *FEMS Microbiol. Lett.*, **365**(2), doi:10.1093/femsle/fnx244.

Senapati, S. and V. Gupta, 2017: Vulnerability to Climate Change. In: *Natural Resources Management*, pp. 1393-1416. ISBN 9781522508038

9781522508045.

Sendzimir, J., C. P. Reij and P. Magnuszewski, 2011: Rebuilding Resilience in the Sahel: Regreening in the Maradi and Zinder Regions of Niger. *Ecol. Soc.*, **16**(3), doi:10.5751/Es-04198-160301.

Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Senf, C., J. Müller and R. Seidl, 2019: Post-disturbance recovery of forest cover and tree height differ with management in Central Europe. *Landsc. Ecol.*, **34**(12), 2837-2850, doi:10.1007/s10980-019-00921-9.

Serrasolses, G. et al., 2016: A Matter of taste: local explanations for the consumption of wild food pants in the Catalan pyrenees and the Balearic islands. *Econ. Bot.*, **70**(2), 176-189, doi:10.1007/s12231-016-9343-1.

Settele, J., J. Bishop and S. G. Potts, 2016: Climate change impacts on pollination. *Nat Plants*, **2**(7), 16092, doi:10.1038/nplants.2016.92.

Settele, J. et al., 2014: Terrestrial and inland water systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Pt A: Global and Sectoral Aspects*, 271-359, doi:10.1017/CBO9781107415379.009.

Seufert, V. and N. Ramakutty, 2017: Many shades of gray - The context-dependent perfornance of organic agriculture. *Science Advances*, **3**(e1602638).

Seymour, F. and N. L. Harris, 2019: Reducing tropical deforestation. *Science*, **365**(6455), 756-757, doi:10.1126/science.aax8546.

Shackleton, R., C. Shackleton, S. Shackleton and J. Gambiza, 2013: Deagrarianisation and forest revegetation in a biodiversity hotspot on the Wild Coast, South Africa. *PLoS One*, **8**(10), e76939, doi:10.1371/journal.pone.0076939.

Shaffer, L. J., 2014: Making sense of local climate change in rural Tanzania through knowledge co-production. *Journal of Ethnobiology*, **34**(3), 315-334, doi:10.2993/0278-0771-34.3.315.
Shaffril, H. A. M., A. Abu Samah and J. L. D'Silva, 2017: Climate change: Social adaptation strategies for fishermen. *Mar. Policy*, **81**, 256-261, doi:10.1016/j.marpol.2017.03.031.
Shaffril, H. A. M., S. E. Krauss and S. F. Samsuddin, 2018: A systematic review on Asian's farmers' adaptation practices towards climate change. *Sci. Total Environ.*, **644**, 683-695, doi:10.1016/j.scitotenv.2018.06.349.
Shakhramanyan, N. G., U. A. Schneider and B. A. McCarl, 2013: US agricultural sector analysis on pesticide externalities - the impact of climate change and a Pigovian tax. *Clim. Change*, **117**(4), 711-723, doi:10.1007/s10584-012-0585-3.
Shannak, S. d., D. Mabrey and M. Vittorio, 2018: Moving from theory to practice in the water–energy–food nexus: An evaluation of existing models and frameworks. *Water-Energy Nexus*, **1**(1), 17-25, doi:10.1016/j.wen.2018.04.001.
Sharma, J. et al., 2017: Vulnerability of Forests in India: A National Scale Assessment. *Environ Manage*, **60**(3), 544-553, doi:10.1007/s00267-017-0894-4.
Sharps, K. et al., 2020: Yield Constraint Score (YCS) for the effect of five crop stresses on global production of four staple food crops, NERC Environmental Information Data Centre. Available at: https://doi.org/10.5285/d347ed22-2b57-4dce-88e3-31a4d00d4358.
Shayegh, S., V. Manoussi and S. Dasgupta, 2020: Climate change and development in South Africa: the impact of rising temperatures on economic productivity and labour availability. *Clim. Dev.*, 1-11, doi:10.1080/17565529.2020.1857675.
Sheahan, M. and C. B. Barrett, 2017: Review: Food loss and waste in Sub-Saharan Africa. *Food Policy*, **70**, 1-12, doi:10.1016/j.foodpol.2017.03.012.
Shen, T., H. Yu and Y. Z. Wang, 2021: Assessing the impacts of climate change and habitat suitability on the distribution and quality of medicinal plant using multiple information integration: Take Gentiana rigescens as an example. *Ecol. Indic.*, **123**, 107376, doi:10.1016/j.ecolind.2021.107376.
Shen, Y. L. and X. G. Liu, 2015: Phenological changes of corn and soybeans over U.S. by bayesian change-point model. *Sustainability*, **7**(6), 6781-6803, doi:10.3390/su7066781.
Shepherd, C. J., O. Monroig and D. R. Tocher, 2017: Future availability of raw materials for salmon feeds and supply chain implications: The case of Scottish farmed salmon. *Aquaculture*, **467**, 49-62, doi:10.1016/j.aquaculture.2016.08.021.
Shete, M. and M. Rutten, 2015: Impacts of large-scale farming on local communities' food security and income levels - Empirical evidence from Oromia Region, Ethiopia. *Land Use Policy*, **47**, 282-292, doi:10.1016/j.landusepol.2015.01.034.
Shi, W. et al., 2016: Ocean acidification increases cadmium accumulation in marine bivalves: a potential threat to seafood safety. *Sci Rep*, **6**, 20197, doi:10.1038/srep20197.
Shiferaw, B. et al., 2014: Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather Clim. Extrem.*, **3**, 67-79, doi:10.1016/j.wace.2014.04.004.
Shimoda, S., H. Kanno and T. Hirota, 2018: Time series analysis of temperature and rainfall-based weather aggregation reveals significant correlations between climate turning points and potato (Solanum tuberosum L) yield trends in Japan. *Agric. For. Meteorol*, **263**, 147-155, doi:10.1016/j.agrformet.2018.08.005.
Shindell, D., G. Faluvegi, P. Kasibhatla and R. Van Dingenen, 2019: Spatial patterns of crop yield change by emitted pollutant. *Earths Future*, **7**(2), 101-112, doi:10.1029/2018EF001030.
Shindell, D. T., 2016: Crop yield changes induced by emissions of individual climate-altering pollutants. *Earths Future*, **4**(8), 373-380, doi:10.1002/2016ef000377.
Shukla, R. et al., 2019: Climate change perception: an analysis of climate change and risk perceptions among farmer types of Indian Western Himalayas. *Clim. Change*, **152**(1), 103-119, doi:10.1007/s10584-018-2314-z.
Sibhatu, K. T. and M. Qaim, 2018: Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. *Food Policy*, **77**, 1-18, doi:10.1016/j.foodpol.2018.04.013.
Sida, T. S., F. Baudron, H. Kim and K. E. Giller, 2018: Climate-smart agroforestry: Faidherbia albida trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agric. For. Meteorol*, **248**, 339-347, doi:10.1016/j.agrformet.2017.10.013.

Siegner, A., J. Sowerwine and C. Acey, 2018: Does Urban Agriculture Improve Food Security? Examining the Nexus of Food Access and Distribution of Urban Produced Foods in the United States: A Systematic Review. *Sustainability*, **10**(9), 8-12, doi:10.3390/su10092988.
Silanikove, N. and N. Koluman, 2015: Impact of climate change on the dairy industry in temperate zones: Predications on the overall negative impact and on the positive role of dairy goats in adaptation to earth warming. *Small Rumin. Res.*, **123**(1), 27-34, doi:10.1016/j.smallrumres.2014.11.005.
Silas, M. O. et al., 2020: Adaptive capacity and coping strategies of small-scale coastal fisheries to declining fish catches: Insights from Tanzanian communities. *Environ. Sci. Policy*, **108**, 67-76, doi:10.1016/j.envsci.2020.03.012.
Silva, J. G. et al., 2020: Are medicinal plants an alternative to the use of synthetic pharmaceuticals in animal healthcare in the Brazilian semi-arid? *Ethnobotany Research and Applications*, **19**, 1-20.
Silwal, P., L. Roberts, H. G. Rennie and M. J. Lexer, 2019: Adapting to climate change: an assessment of local adaptation planning processes in forest-based communities in Nepal. *Clim. Dev.*, **11**(10), 886-898, doi:10.1080/17565529.2019.1586634.
Simelton, E., B. V. Dam and D. Catacutan, 2015: Trees and agroforestry for coping with extreme weather events: experiences from northern and central Viet Nam. *Agroforestry Systems*, **89**(6), 1065-1082, doi:10.1007/s10457-015-9835-5.
Sinclair, F. et al., 2019: *The Contribution of Agroecological Approaches to Realizing Climate-Resilient Agriculture*. Available at: www.gca.org.
Singano, C. D. et al., 2020: What does global warming mean for stored-grain protection? Options for Prostephanus truncatus (Horn) control at increased temperatures. *J. Stored Prod. Res.*, **85**, 101532-101532, doi:10.1016/j.jspr.2019.101532.
Singh, C., 2018: Is participatory watershed development building local adaptive capacity? Findings from a case study in Rajasthan, India. *Environ. Dev.*, **25**, 43-58, doi:10.1016/j.envdev.2017.11.004.
Singh, C. and R. Basu, 2020: Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural-urban continuum in India. *Geogr. J.*, **186**(1), 87-102, doi:10.1111/geoj.12328.
Singh, G. G., N. Hilmi and J. R. a. Bernhardt, 2019: Climate impacts on the ocean are making the Sustainable Development Goals a moving target travelling away from us. *People and Nature*, **1**(3), 317--330, doi:10.1002/pan3.26.
Singh, K. et al., 2017: Mapping regional risks from climate change for rainfed rice cultivation in India. *Agric Syst*, **156**, 76-84, doi:10.1016/j.agsy.2017.05.009.
Singh, P. K. and H. Chudasama, 2021: Pathways for climate change adaptations in arid and semi-arid regions. *J. Clean. Prod.*, **284**, 124744-124744, doi:10.1016/J.JCLEPRO.2020.124744.
Singh, R. B., 2000: Environmental consequences of agricultural development: a case study from the Green Revolution state of Haryana, India. *Agric. Ecosyst. Environ.*, **82**(1-3), 97-103, doi:10.1016/S0167-8809(00)00219-X.
Singh, R. P. et al., 2020: Varietal replacement rate: Prospects and challenges for global food security. *Global Food Security-Agriculture Policy Economics and Environment*, **25**, doi:10.1016/j.gfs.2019.100324.
Sissoko, K. e. a., 2011: Agriculture, livelihoods and climate change in teh West African Sahel. *Reg. Environ. Change*, **11**, 119-125.
Sita, K. et al., 2017: Food Legumes and Rising Temperatures: Effects, Adaptive Functional Mechanisms Specific to Reproductive Growth Stage and Strategies to Improve Heat Tolerance. *Front Plant Sci*, **8**, 1658, doi:10.3389/fpls.2017.01658.
Skibiel, A. L. et al., 2018: In Utero Heat Stress Alters the Offspring Epigenome. *Sci Rep*, **8**(1), 14609, doi:10.1038/s41598-018-32975-1.
Slenning, B. D., 2010: Global climate change and implications for disease emergence. *Vet. Pathol.*, **47**(1), 28-33, doi:10.1177/0300985809354465.
Sloat, L. L. et al., 2018: Increasing importance of precipitation variability on global livestock grazing lands. *Nat. Clim. Change*, **8**(3), 214-+, doi:10.1038/s41558-018-0081-5.
Smalås, A. et al., 2019: Climate warming is predicted to enhance the negative effects of harvesting on high‐latitude lake fish. *J. Appl. Ecol.*, **57**(2), 270-282, doi:10.1111/1365-2664.13535.
Smale, D. A. et al., 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Change*, **9**(4), 306-+, doi:10.1038/s41558-019-0412-1.
Small, G. E., R. McDougall and G. S. Metson, 2019: Would a sustainable city be self-sufficient in food production? *International Journal of Design & Nature and Ecodynamics*, **14**(3), 178-194, doi:10.2495/dne-v14-n3-178-194.

Smith, E. et al., 2019a: Contribution of wild foods to diet, food security, and cultural values amidst climate change. *Journal of Agriculture Food Systems and Community Development*, **9**(B), 191-214, doi:10.5304/jafscd.2019.09B.011.
Smith, L. C. and L. Haddad, 2015: Reducing Child Undernutrition: Past Drivers and Priorities for the Post-MDG Era. *World Dev.*, **68**, 180-204, doi:10.1016/j.worlddev.2014.11.014.
Smith, L. G., G. J. D. Kirk, P. J. Jones and A. G. Williams, 2019b: The greenhouse gas impacts of converting food production in England and Wales to organic methods. *Nat Commun*, **10**(1), 4641, doi:10.1038/s41467-019-12622-7.
Smith, M. E. and S. Bernard, 2020: Satellite Ocean Color Based Harmful Algal Bloom Indicators for Aquaculture Decision Support in the Southern Benguela. *Front. Mar. Sci.*, **7**, doi:10.3389/fmars.2020.00061.
Smith, M. R. and S. S. Myers, 2018: Impact of anthropogenic CO2 emissions on global human nutrition. *Nat. Clim. Change*, **8**(9), 834-+, doi:10.1038/s41558-018-0253-3.
Smith, P. et al., 2020a: Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Glob Chang Biol*, **26**(3), 1532-1575, doi:10.1111/gcb.14878.
Smith, P. et al., 2019c: IPCC SRCCL Chapter 6: Interlinkages between Desertification, Land Degradation, Food Security and GHG fluxes: synergies, trade-offs and Integrated Response Options. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
Smith, P. et al., 2018: Impacts on terrestrial biodiversity of moving from a 2 C to a 1.5 C target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160456.
Smith, R. A. J. and K. Rhiney, 2016: Climate (in)justice, vulnerability and livelihoods in the Caribbean: The case of the indigenous Caribs in northeastern St. Vincent. *Geoforum*, **73**, 22-31, doi:10.1016/j.geoforum.2015.11.008.
Smith, S. D. et al., 2000: Elevated CO2 increases productivity and invasive species success in an arid ecosystem. *Nature*, **408**(6808), 79-82, doi:10.1038/35040544.
Smith, W. et al., 2020b: Towards an improved methodology for modelling climate change impacts on cropping systems in cool climates. *Sci. Total Environ.*, **728**, 138845, doi:10.1016/j.scitotenv.2020.138845.
Snapp, S. S., C. M. Cox and B. G. Peter, 2019: Multipurpose legumes for smallholders in sub-Saharan Africa: Identification of promising 'scale out' options. *Global Food Security-Agriculture Policy Economics and Environment*, **23**, 22-32, doi:10.1016/j.gfs.2019.03.002.
Snapp, S. S. et al., 2021: *Agroecology and climate change rapid evidence review: Performance of agroecological approaches in low- and middle- income countries*. Wageningen, The Netherlands, 63-63 pp.
Sohn, J. A., S. Saha and J. Bauhus, 2016: Potential of forest thinning to mitigate drought stress: A meta-analysis. *For. Ecol. Manag.*, **380**, 261-273, doi:10.1016/j.foreco.2016.07.046.
Sohngen, B., R. Mendelsohn and R. Sedjo, 2001: A global model of climate change impacts on timber markets. *J. Agric. Resour. Econ.*, **26**(2), 326-343.
Solecki, W., M. Pelling and M. Garschagen, 2017: Transitions between risk managemetn regimes in cities. *Ecol. Soc.*, **22**.
Sommerfeld, A. et al., 2018: Patterns and drivers of recent disturbances across the temperate forest biome. *Nat. Commun.*, **9**.
Sonenshine, D. E., 2018: Range Expansion of Tick Disease Vectors in North America: Implications for Spread of Tick-Borne Disease. *Int J Environ Res Public Health*, **15**(3), 478, doi:10.3390/ijerph15030478.
Song, Y. et al., 2019: A 20-year journey: Participatory breeding of maize in South-West China. [Westengen, O. T. and T. Winge (eds.)]. Routledge, London and New York, pp. 119-134.
Sonwa, D. J. et al., 2017a: Drivers of climate risk in African agriculture. *Clim. Dev.*, **9**(5), 383-398, doi:10.1080/17565529.2016.1167659.
Sonwa, D. J. et al., 2017b: Structure and composition of cocoa agroforests in the humid forest zone of Southern Cameroon. *Agroforestry Systems*, **91**(3), 451-470, doi:10.1007/s10457-016-9942-y.
Sorensen, N. N., A. D. Lassen, H. Loje and I. Tetens, 2015: The Danish Organic Action Plan 2020: assessment method and baseline status of organic procurement in public kitchens. *Public Health Nutr*, **18**(13), 2350-2357, doi:10.1017/S1368980015001421.

Soroye, P., T. Newbold and J. Kerr, 2020: Climate change contributes to widespread declines among bumble bees across continents. *Science*, **367**(6478), 685-688, doi:10.1126/science.aax8591.
Sotelo, S. et al., 2020: Pronosticos AClimateColombia: A system for the provision of information for climate risk reduction in Colombia. *Comput. Electron. Agric.*, **174**, doi:10.1016/j.compag.2020.105486.
Soto, D. et al., 2019: Salmon farming vulnerability to climate change in southern Chile: understanding the biophysical, socioeconomic and governance links. *Rev. Aquac.*, **11**(2), 354-374, doi:10.1111/raq.12336.
Soto, D. et al., 2021: Scientific warnings could help to reduce farmed salmon mortality due to harmful algal blooms. *Mar. Policy*, **132**, 104705, doi:10.1016/j.marpol.2021.104705.
Soto, D. et al., 2018: Chapter 21: Climate change and aquaculture: vulnerability and adaptation options. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options.* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. FAO, Rome pp. 465-490.
Soto Golcher, C. and I. J. Visseren-Hamakers, 2018: Framing and integration in the global forest, agriculture and climate change nexus. *Environment and Planning C: Politics and Space*, **36**(8), 1415-1436, doi:10.1177/2399654418788566.
Soumya, K. V., C. M. Shackleton and S. R. Setty, 2019: Impacts of gum-resin harvest and Lantana camara invasion on the population structure and dynamics of Boswellia serrata in the Western Ghats, India. *For. Ecol. Manag.*, **453**, 117618, doi:10.1016/j.foreco.2019.117618.
Sousa-Silva, R. et al., 2016: Adaptation of forest management to climate change as perceived by forest owners and managers in Belgium. *For. Ecosyst.*, **3**(1), 22, doi:10.1186/s40663-016-0082-7.
Sousa-Silva, R. et al., 2018: Adapting forest management to climate change in Europe: Linking perceptions to adaptive responses. *For Policy Econ*, **90**, 22-30, doi:10.1016/j.forpol.2018.01.004.
Souther, S. and J. B. McGraw, 2014: Synergistic effects of climate change and harvest on extinction risk of American ginseng. *Ecol. Appl.*, **24**(6), 1463-1477, doi:10.1890/13-0653.1.
Sovacool, B. K., 2021: Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Research & Social Science*, **73**, 101916, doi:10.1016/j.erss.2021.101916.
Sovacool, B. K., B. O. Linner and M. E. Goodsite, 2015: COMMENTARY: The political economy of climate adaptation. *Nat. Clim. Change*, **5**(7), 616-618, doi:10.1038/nclimate2665.
Sowman, M. and S. Raemaekers, 2018: Socio-ecological vulnerability assessment in coastal communities in the BCLME region. *J. Mar. Syst.*, **188**, 160-171, doi:10.1016/j.jmarsys.2018.01.008.
Specht, K. et al., 2019: How Will We Eat and Produce in the Cities of the Future? From Edible Insects to Vertical Farming—A Study on the Perception and Acceptability of New Approaches. *Sustainability*, **11**(16), 1-22, doi:10.3390/su11164315.
Spellman, K. V. and N. Y. Swenson, 2012: Assessing the vulnerability of Western Alaska ecosystems and subsistence resources to nonnative plant invasion. *Report for University of Alaska Fairbanks Contribution to Western Alaska LCC Cooperative Project*, **23**.
Spijkers, J. and W. J. Boonstra, 2017: Environmental change and social conflict: the northeast Atlantic mackerel dispute. *Reg. Environ. Change*, **17**(6), 1835-1851, doi:10.1007/s10113-017-1150-4.
Spijkers, J. et al., 2018: Marine fisheries and future ocean conflict. *Fish Fish.*, **19**(5), 798-806, doi:10.1111/faf.12291.
Spires, M., S. Shackleton and G. Cundill, 2014: Barriers to implementing planned community-based adaptation in developing countries: a systematic literature review. *Clim. Dev.*, **6**(3), 277-287, doi:10.1080/17565529.2014.886995.
Springmann, M. et al., 2018: Options for keeping the food system within environmental limits. *Nature*, **562**(7728), 519-525, doi:10.1038/s41586-018-0594-0.
Springmann, M. et al., 2016: Global and regional health effects of future food production under climate change: a modelling study. *Lancet*, **387**(10031), 1937-1946, doi:10.1016/S0140-6736(15)01156-3.
Srivastava, P., R. Singh, S. Tripathi and A. S. Raghubanshi, 2016: An urgent need for sustainable thinking in agriculture - An Indian scenario. *Ecol. Indic.*, **67**, 611-622, doi:10.1016/j.ecolind.2016.03.015.
Ssegane, H. and M. C. Negri, 2016: An Integrated Landscape Designed for Commodity and Bioenergy Crops for a Tile-Drained Agricultural Watershed. *Journal of Environmental Quality*, **45**(5), 1588-1596, doi:10.2134/jeq2015.10.0518.
Ssegane, H., M. C. Negri, J. Quinn and M. Urgun-Demirtas, 2015: Multifunctional landscapes: Site characterization and field-scale design to incorporate biomass production into an agricultural system. *Biomass Bioenergy*, **80**, 179-190, doi:10.1016/j.biombioe.2015.04.012.

Stanimirova, R. et al., 2019: Sensitivity of Global Pasturelands to Climate Variation. *Earths Future*, **7**(12), 1353-1366, doi:10.1029/2019ef001316.
Stark, F. et al., 2018: Crop-livestock integration determines the agroecological performance of mixed farming systems in Latino-Caribbean farms. *Agron. Sustain. Dev.*, **38**(1), 4-4, doi:10.1007/s13593-017-0479-x.
Stefan, L. et al., 2021: Positive Effects of Crop Diversity on Productivity Driven by Changes in Soil Microbial Composition. *Frontiers in Microbiology*, **12**, 808-808.
Steffen, W. et al., 2015: Sustainability. Planetary boundaries: guiding human development on a changing planet. *Science*, **347**(6223), 1259855, doi:10.1126/science.1259855.
Stehfest, K. M. et al., 2017: Response of Atlantic salmon Salmo salar to temperature and dissolved oxygen extremes established using animal-borne environmental sensors. *Sci Rep*, **7**(1), 4545, doi:10.1038/s41598-017-04806-2.
Steiner A, A. G., Andersen I, Bomba K, Bonilla JP, Campbell A, Dongyu Q, Echeverria R, Gandhi R, Hedegaard C, Holdorf D, Ishii N, Quinn K, Ruter B, Sunga I, Sukhdev P, Verghese S, Voegele J, Winters P, Campbell B, Dinesh D, Huyer S, Jarvis A, Loboguerrero Rodriguez AM, Millan A, Thornton P, Wollenberg L, Zebiak S. , 2020: *Actions to transform food systems under climate change*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, The Netherlands.
Stemkovski, M. et al., 2020: Bee phenology is predicted by climatic variation and functional traits. *Ecol. Lett.*, **23**(11), 1589-1598, doi:10.1111/ele.13583.
Stephen, K., 2018: Societal Impacts of a Rapidly Changing Arctic. *Curr. Clim. Change Rep.*, **4**(3), 223-237, doi:10.1007/s40641-018-0106-1.
Stevens-Rumann, C. S. and P. Morgan, 2019: Tree regeneration following wildfires in the western US: a review. *Fire Ecology*, **15**(1), doi:10.1186/s42408-019-0032-1.
Steward, P. R., C. Thierfelder, A. J. Dougill and I. Ligowe, 2019: Conservation agriculture enhances resistance of maize to climate stress in a Malawian medium-term trial. *Agriculture, Ecosystems & Environment*, **277**, 95-104, doi:10.1016/J.AGEE.2018.07.009.
Stewart-Koster, B. et al., 2017: Expert based model building to quantify risk factors in a combined aquaculture-agriculture system. *Agric. Syst.*, **157**, 230-240, doi:10.1016/j.agsy.2017.08.001.
Stewart-Sinclair, P. J., K. S. Last, B. L. Payne and T. A. Wilding, 2020: A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecol Evol*, **10**(7), 3518-3534, doi:10.1002/ece3.6149.
Stien, A. et al., 2012: Congruent responses to weather variability in high arctic herbivores. *Biol. Lett.*, **8**(6), 1002-1005, doi:10.1098/rsbl.2012.0764.
Stocker, T. F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115. ISBN 9781107057991.
Stoeckl, N. et al., 2017: Socioeconomic Impacts of Changes to Marine Fisheries and Aquaculture that are Brought About Through Climate Change. In: *Climate Change Impacts on Fisheries and Aquaculture*. John Wiley & Sons, Ltd, Chichester, UK, pp. 925-958. ISBN 9781119154051

9781119154044.
Stoltz, A. D., M. Shivlani and R. Glazer, 2021: Fishing Industry Perspectives on Sea-Level Rise Risk and Adaptation. *Water*, **13**(8), 1124, doi:10.3390/w13081124.
Stone, G., 2017: Dreading CRISPR: GMO's, honest brokers, and mertonian transgressions. *Geographical Review*, **107**, 584-591.
Stone, G. D. and D. Glover, 2017: Disembedding grain: Golden Rice, the Green Revolution, and heirloom seeds in the Philippines. *Agric. Hum. Values*, **34**(1), 87-102, doi:10.1007/s10460-016-9696-1.
Stoorvogel, J. J., M. Bakkenes, B. J. E. Brink and A. J. A. M. Temme, 2017: To what extent did we change our soils? A global comparison of natural and current conditions. *Land Degradation & Development*, **28**(7), 1982-1991, doi:10.1002/ldr.2721.
Stranden, I. et al., 2019: Genomic selection strategies for breeding adaptation and production in dairy cattle under climate change. *Heredity (Edinb)*, **123**(3), 307-317, doi:10.1038/s41437-019-0207-1.
Stringer, L. C. et al., 2020: Adaptation and development pathways for different types of farmers. *Environ. Sci. Policy*, **104**, 174-189, doi:10.1016/j.envsci.2019.10.007.

Stuart-Smith, J. et al., 2018: Southernmost records of two Seriola species in an Australian ocean-warming hotspot. *Marine Biodiversity*, **48**(3), 1579-1582, doi:10.1007/s12526-016-0580-4.
Styles, D. et al., 2016: Climate regulation, energy provisioning and water purification: Quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessment. *Ambio*, **45**(8), 872-884, doi:10.1007/s13280-016-0790-9.
Sudo, K., K. Watanabe, N. Yotsukura and M. Nakaoka, 2020: Predictions of kelp distribution shifts along the northern coast of Japan. *Ecol. Res.*, **35**(1), 47-60, doi:10.1111/1440-1703.12053.
Sugden, F. et al., 2014: Agrarian stress and climate change in the Eastern Gangetic Plains: Gendered vulnerability in a stratified social formation. *Glob. Environ. Change*, **29**, 258-269, doi:10.1016/j.gloenvcha.2014.10.008.
Sugiura, T., 2019: Three climate change adaptation strageties for fruit production In: *Climate Smart Agriculture for the Small-Scale Farmers in the Asian and Pacific Region* [Shirato, Y. and A. Hasebe (eds.)]. National Agriculture and Food Research Organization (NARO) Tsukuba, Japan pp. 277. ISBN 9784908914027.
Sugiura, T., H. Ogawa, N. Fukuda and T. Moriguchi, 2013: Changes in the taste and textural attributes of apples in response to climate change. *Sci Rep*, **3**, 2418, doi:10.1038/srep02418.
Sugiura, T., M. Shiraishi, S. Konno and A. Sato, 2018: Prediction of Skin Coloration of Grape Berries from Air Temperature. *Horticulture Journal*, **87**(1), 18-25, doi:10.2503/hortj.OKD-061.
Suhl, J. et al., 2018: An innovative suction filter device reduces nitrogen loss in double recirculating aquaponic systems. *Aquac Eng*, **82**, 63-72, doi:10.1016/j.aquaeng.2018.06.008.
Sullivan, J. and B. Rosenberg, 2018: "Losing Your Land You Feel Like You're Losing Your Identity, Like You're Experiencing Slow Death": An Interview With Chief Thomas Dardar-Houma Nation. *New Solut*, **28**(3), 501-514, doi:10.1177/1048291118795155.
Sullivan, M. J. P. et al., 2020: Long-term thermal sensitivity of Earth's tropical forests. *Science*, **368**(6493), 869, doi:10.1126/science.aaw7578.
Sulser, T. et al., 2021a: *Climate change and hunger: Estimating costs of adaptation in the agrifood system*. Food policy report, International Food Policy Research Institute (IFPRI), (IFPRI), I. F. P. R. I., Washington, DC
Sulser, T. B. et al., 2021b: Disability-adjusted life years due to chronic and hidden hunger under food system evolution with climate change and adaptation to 2050. *The American Journal of Clinical Nutrition*, doi:10.1093/ajcn/nqab101.
Sultan, B., D. Defrance and T. Iizumi, 2019: Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Sci Rep*, **9**(1), 12834, doi:10.1038/s41598-019-49167-0.
Sultan, B. and M. Gaetani, 2016: Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation. *Front Plant Sci*, **7**, 1262, doi:10.3389/fpls.2016.01262.
Sultan, B. et al., 2020: Current needs for climate services in West Africa: Results from two stakeholder surveys. *Clim. Serv.*, **18**, 100166-100166, doi:10.1016/j.cliser.2020.100166.
Sultana, M. N., M. M. Uddin, B. G. Ridoutt and K. J. Peters, 2014: Comparison of water use in global milk production for different typical farms. *Agric. Syst.*, **129**, 9-21, doi:10.1016/j.agsy.2014.05.002.
Sumaila, U. R. et al., 2019: Benefits of the Paris Agreement to ocean life, economies, and people. *Sci Adv*, **5**(2), eaau3855, doi:10.1126/sciadv.aau3855.
Sumaila, U. R. et al., 2020: Illicit trade in marine fish catch and its effects on ecosystems and people worldwide. *Science Advances*, **6**(9), eaaz3801, doi:10.1126/sciadv.aaz3801.
Sumby, J., M. Haward, E. A. Fulton and G. T. Pecl, 2021: Hot fish: The response to climate change by regional fisheries bodies. *Mar. Policy*, **123**, 104284, doi:10.1016/j.marpol.2020.104284.
Sun, Q. et al., 2019: Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. *Environ. Int.*, **128**, 125-136, doi:10.1016/j.envint.2019.04.025.
Sun, T. et al., 2021: Current rice models underestimate yield losses from short - term heat stresses. *Global Change Biol.*, **27**(2), 402-416.
Sun, W. et al., 2020: Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. *Glob Chang Biol*, **26**(6), 3325-3335, doi:10.1111/gcb.15001.
Sunderlin, W. D., A. M. Larson and J. P. S. Barletti, 2018: Land and carbon tenure. In: *Transforming REDD+: Lessons and new directions* [Angelsen, A., C. Martius, V. De Sy, A. E. Duchelle, A. M. Larson and T. T. Pham (eds.)]. CIFOR, Bogor, Indonesia, pp. 93-102.

Susaeta, A. and P. Lal, 2018: Impacts of Climate Change and Bioenergy Markets on the Profitability of Slash Pine Pulpwood Production in the Southeastern United States. *Forests*, **9**(10), 656, doi:10.3390/f9100656.
Sweetman, C. et al., 2014: Metabolic effects of elevated temperature on organic acid degradation in ripening Vitis vinifera fruit. *J. Exp. Bot.*, **65**(20), 5975-5988, doi:10.1093/jxb/eru343.
Swinburn, B. A. et al., 2019: The global syndemic of obesity, undernutrition, and cliamte change: The Lancet Commission report. *The Lancet*, **393**, 791-846.
Sylvester, O. and M. Little, 2020: "I came all this way to receive training, am I really going to be taught by a woman?" Factors that support and hinder women's participation in agroecology in Costa Rica. *Agroecol. Sustain. Food Syst.*, 1-24, doi:10.1080/21683565.2020.1811830.
Szewczyk, W., J. C. C. Martinez, I. Mongelli and A. S. Ramirez, 2018: *JRC PESETA III Project: Economic integration and spillover analysis*. Joint Research Centre (Seville site). Available at: https://ideas.repec.org/p/ipt/iptwpa/jrc113810.html.
Tadesse, G., B. Algieri, M. Kalkuhl and J. von Braun, 2014: Drivers and triggers of international food price spikes and volatility. *Food Policy*, **47**, 117-128, doi:10.1016/j.foodpol.2013.08.014.
Tahvanainen, V., J. Miina, M. Kurttila and K. Salo, 2016: Modelling the yields of marketed mushrooms in Picea abies stands in eastern Finland. *For. Ecol. Manag.*, **362**, 79-88, doi:10.1016/j.foreco.2015.11.040.
Talor, K., 2015: Improving substantive and procedural protections for indigenous rights in REDD projects: Possible lessons from Brazil. *Journal of Sustainable Development Law and Policy*, **5**.
Tambo, J. A. and T. Abdoulaye, 2013: Smallholder farmers' perceptions of and adaptations to climate change in the Nigerian savanna. *Reg. Environ. Change*, **13**(2), 375-388, doi:10.1007/s10113-012-0351-0.
Tamburini, G. et al., 2020: Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, **6**(45), eaba1715-eaba1715, doi:10.1126/sciadv.aba1715.
Tamene, L. et al., 2019: Soil structural degradation and nutrient limitations across land use categories and climatic zones in Southern Africa. *Land Degradation & Development*, **30**(11), 1288-1299, doi:10.1002/ldr.3302.
Tamm, O., S. Maasikamae, A. Padari and T. Tamm, 2018: Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model. *Catena*, **167**, 78-89, doi:10.1016/j.catena.2018.04.029.
Tan, K. and H. Zheng, 2020: Ocean acidification and adaptive bivalve farming. *Sci. Total Environ.*, **701**, 134794, doi:10.1016/j.scitotenv.2019.134794.
Tan, Q., Y. Liu, L. Dai and T. Pan, 2021: Shortened key growth periods of soybean observed in China under climate change. *Sci Rep*, **11**(1), 8197, doi:10.1038/s41598-021-87618-9.
Tankari, M. R., 2020: Rainfall variability and farm households' food insecurity in Burkina Faso: nonfarm activities as a coping strategy. *Food Secur.*, **12**(3), 567-578, doi:10.1007/s12571-019-01002-0.
Tanner, T. et al., 2014: Political Economy of Climate Compatible Development: Artisanal Fisheries and Climate Change in Ghana. *IDS Working Papers*, **2014**(446), 1-30, doi:10.1111/j.2040-0209.2014.00446.x.
Tao, F. et al., 2020: Why do crop models diverge substantially in climate impact projections? A comprehensive analysis based on eight barley crop models. *Agric. For. Meteorol*, **281**, 107851.
Tao, F. et al., 2017: Designing future barley ideotypes using a crop model ensemble. *Eur J Agron*, **82**, 144-162, doi:10.1016/j.eja.2016.10.012.
Tao, F. et al., 2016: Historical data provide new insights into response and adaptation of maize production systems to climate change/variability in China. *Field Crops Res.*, **185**, 1-11, doi:10.1016/j.fcr.2015.10.013.
Tarchiani, V. et al., 2017: Smallholder Farmers Facing Climate Change in West Africa: Decision-Making between Innovation and Tradition. *J. Innov. Econ.*, **3**(24), 151-176, doi:10.3917/jie.pr1.0013.
Taremwa, N. K., Damascene Gashumba, Anastase Butera, and Thimmaiyah Ranganathan, 2017: Climate Change Adaptation in Rwanda through Indigenous Knowledge Practice. *Journal of Social Sciences*, **46**, 165-175.
Tate, R. D., K. Benkendorff, R. Ab Lah and B. P. Kelaher, 2017: Ocean acidification and warming impacts the nutritional properties of the predatory whelk, Dicathais orbita. *J. Exp. Mar. Biol. Ecol.*, **493**, 7-13, doi:10.1016/j.jembe.2017.03.006.
Tavenner, K. et al., 2019: Intensifying Inequality? Gendered Trends in Commercializing and Diversifying Smallholder Farming Systems in East Africa. *Front. Sustain. Food Syst.*, **3**, doi:10.3389/fsufs.2019.00010.

Taye, Z. M. et al., 2016: Meteorological conditions and site characteristics driving edible mushroom production in Pinus pinaster forests of Central Spain. *Fungal Ecology*, **23**, 30-41, doi:10.1016/j.funeco.2016.05.008.
Taylor, D. et al., 2016: Environmental change and Rift Valley fever in eastern Africa: projecting beyond HEALTHY FUTURES. *Geospat Health*, **11**(1 Suppl), 387, doi:10.4081/gh.2016.387.
Taylor, M., 2016: Risky Ventures: Financial Inclusion, Risk Management and the Uncertain Rise of Index-Based Insurance. In: *Pisking Capitalism, Research in Political Economy* pp. 237-266.
Taylor, M., 2017: Climate-smart agriculture: what is it good for? *The Journal of Peasant Studies*, **45**(1), 89-107, doi:10.1080/03066150.2017.1312355.
Taylor, M. and S. Bhasme, 2020: Between deficit rains and surplus populations: The political ecology of a climate-resilient village in South India. *Geoforum*, doi:10.1016/j.geoforum.2020.01.007.
Taylor, R. L. et al., 2018: Demography of the Pacific walrus (Odobenus rosmarus divergens) in a changing Arctic. *Mar. Mamm. Sci.*, **34**(1), 54-86, doi:10.1111/mms.12434.
Teigiserova, D. A., L. Hamelin and M. Thomsen, 2020: Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy. *Sci. Total Environ.*, **706**, 136033, doi:10.1016/j.scitotenv.2019.136033.
Tejada, L. and S. Rist, 2018: Seeing land deals through the lens of the 'land–water nexus': the case of biofuel production in Piura, Peru. *J. Peasant Stud.*, **45**(7), 1247-1271, doi:10.1080/03066150.2016.1259220.
Tesfaye, A. et al., 2019: Estimating the economic value of climate services for strengthening resilience of smallholder farmers to climate risks in Ethiopia: A choice experiment approach. *Ecol. Econ.*, **162**, 157-168, doi:10.1016/j.ecolecon.2019.04.019.
Teslić, N. et al., 2019: Future climatic suitability of the Emilia-Romagna (Italy) region for grape production. *Reg. Environ. Change*, **19**(2), 599-614, doi:10.1007/s10113-018-1431-6.
Teslic´, N. et al., 2017: Climatic shifts in high quality wine production areas, Emilia Romagna, Italy, 1961-2015. *Clim. Res.*, **73**(3), 195-206, doi:10.3354/cr01468.
Tester, P. A., R. W. Litaker and E. Berdalet, 2020: Climate change and harmful benthic microalgae. *Harmful Algae*, **91**, 101655, doi:10.1016/j.hal.2019.101655.
Tewari, J. C., K. Pareek, K. Shiran and M. M. Roy, 2017: Non timber tree products: alternative source of livelihood in man-crop/grasslivestock-tree/shrub continuum of arid regions. *MOJ Ecology & Environmental Science*, **2**, 1-7.
Thamo, T. et al., 2017: Climate change impacts and farm-level adaptation: Economic analysis of a mixed cropping-livestock system. *Agric. Syst.*, **150**, 99-108, doi:10.1016/j.agsy.2016.10.013.
Thapa, L. B., H. Thapa and B. G. Magar, 2015: Perception, trends and impacts of climate change in Kailali District, Far West Nepal. *International Journal of Environment*, **4**, 62-76.
Theusme, C. et al., 2021: Climate change vulnerability of confined livestock systems predicted using bioclimatic indexes in an arid region of Mexico. *Sci. Total Environ.*, **751**, 141779, doi:10.1016/j.scitotenv.2020.141779.
Thiault, L. et al., 2019: Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. *Sci Adv*, **5**(11), eaaw9976, doi:10.1126/sciadv.aaw9976.
Thilsted, S. H. et al., 2016: Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy*, **61**, 126-131, doi:10.1016/j.foodpol.2016.02.005.
Thom, D. and R. Seidl, 2016: Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biol. Rev. Camb. Philos. Soc.*, **91**(3), 760-781, doi:10.1111/brv.12193.
Thomaier, S. et al., 2015: Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renew. Agric. Food Syst.*, **30**(1), 43-54, doi:10.1017/S1742170514000143.
Thomas, E., C. Alcázar Caicedo, J. Loo and R. Kindt, 2014: The distribution of the Brazil nut (Bertholletia excelsa) through time: from range contraction in glacial refugia, over human-mediated expansion, to anthropogenic climate change. *Bol do Mus Para Emílio Goeldi Ciências Nat*, **9**, 267-291.
Thomas, K. A., 2020: Shifting baselines of disaster mitigation. *Clim. Dev.*, **12**(2), 147-150, doi:10.1080/17565529.2019.1605875.
Thomas, P. and U. Buntgen, 2019: A risk assessment of Europe's black truffle sector under predicted climate change. *Sci. Total Environ.*, **655**, 27-34, doi:10.1016/j.scitotenv.2018.11.252.
Thomas, Y., C. Cassou, P. Gernez and S. Pouvreau, 2018: Oysters as sentinels of climate variability and climate change in coastal ecosystems. *Environ. Res. Lett.*, **13**(10), doi:10.1088/1748-9326/aae254.

Thompson-Hall, M., E. R. Carr and U. Pascual, 2016: Enhancing and expanding intersectional research for climate change adaptation in agrarian settings. *Ambio*, **45**(S3), 373-382, doi:10.1007/s13280-016-0827-0.
Thompson, W. et al., 2018: Automatic Responses of Crop Stocks and Policies Buffer Climate Change Effects on Crop Markets and Price Volatility. *Ecol. Econ.*, **152**, 98-105, doi:10.1016/j.ecolecon.2018.04.015.
Thomsen, J. et al., 2017: Naturally acidified habitat selects for ocean acidification-tolerant mussels. *Sci Adv*, **3**(4), e1602411, doi:10.1126/sciadv.1602411.
Thornton, P. et al., 2018: Agriculture in a changing climate: Keeping our cool in the face of the hothouse. *Outlook on Agriculture*, **47**(4), 283-290, doi:10.1177/0030727018815332.
Thornton, P. e. a., 2018: Is agricultural adaptation to global change in lower—income countries on track to meet the future food production challenge? . *Global Environ. Change*, **52**, 37-48.
Thornton, P. K. and M. Herrero, 2014: Climate change adaptation in mixed crop -livestock systems in developing countries. *Global Food Security-Agriculture Policy Economics and Environment*, **3**(2), 99-107, doi:10.1016/j.gfs.2014.02.002.
Thornton, P. K. and M. Herrero, 2015: Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nat. Clim. Change*, **5**(9), 830-836, doi:10.1038/Nclimate2754.
Thornton, P. K., M. Herrero and R. B. Boone, 2019: *Altered grazing systems: Pastoralism to conventional agriculture*. Cambridge University Press, 257-275 pp.
Thornton, P. K., G. C. Nelson, D. Mayberry and M. Herrero, 2021: Increases in extreme heat stress in domesticated livestock species during the twenty-first century. *Global Change Biol.*, doi:10.1111/gcb.15825.
Thornton, T. F. and C. Comberti, 2017: Synergies and trade-offs between adaptation, mitigation and development. *Clim. Change*, **140**(1), 5-18, doi:10.1007/s10584-013-0884-3.
Tian, X. et al., 2016: Global Climate Change Impacts on Forests and Markets. *Environ. Res. Lett.*, **11**(035011).
Tibesigwa, B., M. Visser and J. Turpie, 2017: Climate change and South Africa's commercial farms: an assessment of impacts on specialised horticulture, crop, livestock and mixed farming systems. *Environment Development and Sustainability*, **19**(2), 607-636, doi:10.1007/s10668-015-9755-6.
Tiemann, L. K. et al., 2015: Crop rotational diversity enhances belowground communities and functions in an agroecosystem. *Ecol. Lett.*, **18**(8), 761-771, doi:10.1111/ele.12453.
Tigchelaar, M., D. S. Battisti and J. T. Spector, 2020: Work Adaptations Insufficient to Address Growing Heat Risk for U.S. Agricultural Workers. *Environ Res Lett*, **15**(9), 094035-094035, doi:10.1088/1748-9326/ab86f4.
Tilahun, M. et al., 2015: Rural Households' Demand for Frankincense Forest Conservation in Tigray, Ethiopia: A Contingent Valuation Analysis. *Land Degradation & Development*, **26**(7), 642-653, doi:10.1002/ldr.2207.
Tilbrook, B. et al., 2019: An Enhanced Ocean Acidification Observing Network: From People to Technology to Data Synthesis and Information Exchange. *Front. Mar. Sci.*, **6**(JUN), doi:10.3389/fmars.2019.00337.
Tiller, R. and R. Richards, 2018: Ocean futures: Exploring stakeholders' perceptions of adaptive capacity to changing marine environments in Northern Norway. *Mar. Policy*, **95**, 227-238, doi:10.1016/j.marpol.2018.04.001.
Tillotson, M. D. et al., 2019: Artificial selection on reproductive timing in hatchery salmon drives a phenological shift and potential maladaptation to climate change. *Evol Appl*, **12**(7), 1344-1359, doi:10.1111/eva.12730.
Tirado, C., 2015: Addressing the challenges of climate change to food security, safety, and nutrition. In: *Global Climate Change and Human Health: From Science to Practice* [Sons, J. W. (ed.)], pp. 267.
Titz, A. and S. S. Chiotha, 2019: Pathways for Sustainable and Inclusive Cities in Southern and Eastern Africa through Urban Green Infrastructure? *Sustainability*, **11**(10), 2729-2729, doi:10.3390/su11102729.
To, H. and R. Q. Grafton, 2015: Oil prices, biofuels production and food security: past trends and future challenges. *Food Secur.*, **7**(2), 323-336, doi:10.1007/s12571-015-0438-9.
Tom-Dery, D., F. Eller, C. Reisdorff and K. Jensen, 2018: Shea (Vitellaria paradoxa CF Gaertn.) at the crossroads: current knowledge and research gaps. *Agroforestry Systems*, **92**(5), 1353-1371.

Toniello, G. et al., 2019: 11,500 y of human-clam relationships provide long-term context for intertidal management in the Salish Sea, British Columbia. *Proc Natl Acad Sci U S A*, **116**(44), 22106-22114, doi:10.1073/pnas.1905921116.
Toomey, L., P. Fontaine and T. Lecocq, 2020: Unlocking the intraspecific aquaculture potential from the wild biodiversity to facilitate aquaculture development. *Rev. Aquac.*, **12**(4), 2212-2227, doi:10.1111/raq.12430.
Toreti, A. et al., 2020: Narrowing uncertainties in the effects of elevated CO2 on crops. *Nat. Food*, **1**(12), 775-782, doi:10.1038/s43016-020-00195-4.
Torres-Vitolas, C. A. et al., 2019: The Socio-Ecological Dynamics of Food Insecurity among Subsistence-Oriented Indigenous Communities in Amazonia: a Qualitative Examination of Coping Strategies among Riverine Communities along the Caqueta River, Colombia. *Hum. Ecol.*, **47**(3), 355-368, doi:10.1007/s10745-019-0074-7.
Torres, J. M. and J. A. Casey, 2017: The centrality of social ties to climate migration and mental health. *BMC Public Health*, **17**(1), 600, doi:10.1186/s12889-017-4508-0.
Toth, G. G. et al., 2017: Malawi's energy needs and agroforestry: adoption potential of woodlots. *Hum. Ecol.*, **45**(6), 735-746, doi:10.1007/s10745-017-9944-z.
Totin, E. et al., 2018: Institutional Perspectives of Climate-Smart Agriculture: A Systematic Literature Review. *Sustainability*, **10**(6), 1990, doi:10.3390/su10061990.
Toufique, K. A. and B. Belton, 2014: Is Aquaculture Pro-Poor? Empirical Evidence of Impacts on Fish Consumption in Bangladesh. *World Dev.*, **64**, 609-620, doi:10.1016/j.worlddev.2014.06.035.
Toure, A., B. Diekkruger, A. Mariko and A. S. Cisse, 2017: Assessment of Groundwater Resources in the Context of Climate Change and Population Growth: Case of the Klela Basin in Southern Mali. *Climate*, **5**(3), 45-45, doi:10.3390/cli5030045.
Toussaint, P. and A. Martínez Blanco, 2020: A human rights-based approach to loss and damage under the climate change regime. *Clim. Policy*, **20**(6), 743-757, doi:10.1080/14693062.2019.1630354.
Trainer, V. L. et al., 2020: Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae*, **91**, 101591, doi:10.1016/j.hal.2019.03.009.
Tramel, S., 2018: Convergence as political strategy: social justice movements, natural resources and climate change. *Third World Q.*, **39**(7), 1290-1307, doi:10.1080/01436597.2018.1460196.
Tran, L. and K. Brown, 2019: The importance of ecosystem services to smallholder farmers in climate change adaptation: learning from an ecosystem-based adaptation pilot in Vietnam. *Agroforestry Systems*, **93**(5), 1949-1960, doi:10.1007/s10457-018-0302-y.
Tran, N. et al., 2020: Profitability and perceived resilience benefits of integrated shrimp-tilapia-seaweed aquaculture in North Central Coast, Vietnam. *Mar. Policy*, **120**, 104153, doi:10.1016/j.marpol.2020.104153.
Traore, B. et al., 2013: Effects of climate variability and climate change on crop production in southern Mali. *Eur J Agron*, **49**, 115-125, doi:10.1016/j.eja.2013.04.004.
Traore, B. et al., 2015: Climate Variability and Change in Southern Mali: Learning from Farmer Perceptions and on-Farm Trials. *Exp. Agric.*, **51**(4), 615-634, doi:10.1017/S0014479714000507.
Triguero-Mas, M. et al., 2015: Natural outdoor environments and mental and physical health: relationships and mechanisms. *Environ. Int.*, **77**, 35-41, doi:10.1016/j.envint.2015.01.012.
Trisos, C. H., C. Merow and A. L. Pigot, 2020: The projected timing of abrupt ecological disruption from climate change. *Nature*, **580**(7804), 496-501, doi:10.1038/s41586-020-2189-9.
Troell, M. et al., 2017: Seafood from a changing Arctic. *Ambio*, **46**(Suppl 3), 368-386, doi:10.1007/s13280-017-0954-2.
Troell, M. et al., 2014: Does aquaculture add resilience to the global food system? *Proc Natl Acad Sci U S A*, **111**(37), 13257-13263, doi:10.1073/pnas.1404067111.
Trouche, G., K. Vom Brocke, L. Temple and M. Guillet, 2016: *Analyse de l'impact des programmes de sélection participative du sorgo conduits au Burkina Faso de 1995 à 2015*. Montpellier, France, 205.-205. pp. Available at: http://agritrop.cirad.fr/5809.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdiscip. Rev.: Clim. Change*, **8**(5), 1-19, doi:10.1002/wcc.476.
Tschakert, P. et al., 2016: Micropolitics in collective learning spaces for adaptive decision making. *Global Environ. Change*, **40**, 182-194, doi:10.1016/j.gloenvcha.2016.07.004.
Tseng, Y.-H., R. Ding and X.-m. Huang, 2017: The warm Blob in the northeast Pacific—the bridge leading to the 2015/16 El Niño. *Environ. Res. Lett.*, **12**(5), 054019, doi:10.1088/1748-9326/aa67c3.

Tsikata, D. and J. A. Yaro, 2014: When a Good Business Model is Not Enough: Land Transactions and Gendered Livelihood Prospects in Rural Ghana. *Feminist Economics*, **20**(1), 202-226, doi:10.1080/13545701.2013.866261.
Turhan, E., C. Zografos and G. Kallis, 2015: Adaptation as biopolitics: Why state policies in Turkey do not reduce the vulnerability of seasonal agricultural workers to climate change. *Global Environ. Change*, **31**, 296-306, doi:10.1016/j.gloenvcha.2015.02.003.
Turner, C. et al., 2018: Concepts and critical perspectives for food environment research: A global framework with implications for action in low- and middle-income countries. *Global Food Security-Agriculture Policy Economics and Environment*, **18**, 93-101, doi:10.1016/j.gfs.2018.08.003.
Turner, M. G., K. H. Braziunas, W. D. Hansen and B. J. Harvey, 2019: Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proc Natl Acad Sci U S A*, **116**(23), 11319-11328, doi:10.1073/pnas.1902841116.
Turner, M. G. et al., 2020: Climate change, ecosystems and abrupt change: science priorities. *Philos Trans R Soc Lond B Biol Sci*, **375**(1794), 20190105, doi:10.1098/rstb.2019.0105.
Turner, N. J. and H. Clifton, 2009: "It's so different today": Climate change and indigenous lifeways in British Columbia, Canada. *Glob. Environ. Change*, **19**(2), 180-190, doi:10.1016/j.gloenvcha.2009.01.005.
Turnhout, E. et al., 2017: Envisioning REDD plus in a post-Paris era: between evolving expectations and current practice. *Wiley Interdiscip. Rev.: Clim. Change*, **8**(1), e425, doi:10.1002/wcc.425.
Turnock, S. T. et al., 2018: The impact of future emission policies on tropospheric ozone using a parameterised approach. *Atmospheric Chemistry and Physics*, **18**(12), 8953-8978, doi:10.5194/acp-18-8953-2018.
Tyler, N. J. C., 2010: Climate, snow, ice, crashes, and declines in populations of reindeer and caribou (Rangifer tarandus L.). *Ecol. Monogr.*, **80**(2), 197-219, doi:Doi 10.1890/09-1070.1.
Ubilava, D., 2018: The Role of El Nino Southern Oscillation in Commodity Price Movement and Predictability. *Am. J. Agric. Econ.*, **100**(1), 239-263, doi:10.1093/ajae/aax060.
Ubilava, D. and M. Abdolrahimi, 2019: The El Nino impact on maize yields is amplified in lower income teleconnected countries. *Environ. Res. Lett.*, **14**(5), doi:10.1088/1748-9326/ab0cd0.
Uchiyama, T., F. J. Mueter and G. H. Kruse, 2020: Multispecies biomass dynamics models reveal effects of ocean temperature on predation of juvenile pollock in the eastern Bering Sea. *Fish. Oceanogr.*, **29**(1), 10-22, doi:10.1111/fog.12433.
Ujiie, K. et al., 2019: How elevated CO2 affects our nutrition in rice, and how we can deal with it. *PLoS One*, **14**(3), e0212840, doi:10.1371/journal.pone.0212840.
UK, T. G. F. S. P., 2015: *Extreme weather and resilience of the global food system*. Final Project Report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience, London, UK. .
ul Haq, S., I. Boz and P. Shahbaz, 2021: Adoption of climate-smart agriculture practices and differentiated nutritional outcome among rural households: a case of Punjab province, Pakistan. *Food Secur.*, doi:10.1007/s12571-021-01161-z.
Ulrichs, M., R. Slater and C. Costella, 2019: Building resilience to climate risks through social protection: from individualised models to systemic transformation. *Disasters*, **43**(S3), S368-S387, doi:10.1111/disa.12339.
UN, 2018: *The World's Cities in 2018 - Data Booklet (ST/ESA/SER.A/417)*. United Nations.
UNDRR, 2019: *United Nations Office for Disaster Risk Reduction* 472-472 pp. ISBN 9789210041805.
UNDRR (United Nations Office for Disaster Risk Reduction - Regional Office for Asia and Pacific), 2020: *COVID-19 Brief: Combating the dual challenges of climate-related disasters and COVID-19*. Available at: https://www.undrr.org/publication/undrr-asia-pacific-covid-19-brief-combating-dual-challenges-climate-related-disasters.
UNEP, 2016: *The Adaptation Finance Gap Report*. UNEP,, Programme, U. N. E., Nairobi, Kenya Available at: https://climateanalytics.org/media/agr2016.pdf.
UNEP, 2019: *Emissions Gap Report 2019*. Nairobi. Available at: https://www.unenvironment.org/resources/emissions-gap-report-2019.
UNEP, 2021: *Adaptation Gap Report 2020*. Nairobi. Available at: https://www.unep.org/resources/adaptation-gap-report-2020.
UNFCCC, 2013: *Best Practices and Available Tools for the Use of Indigenous and Traditional Knowledge and Practices for Adaptation, and the Application of Gender-Sensitive Approaches and Tools for Understanding and Assessing Impacts, Vulnerability and Adaptation to Climate Change*. United Nations, 62 pp. Available at: https://unfccc.int/documents/7927 (accessed 26/07/2021).

UNFCCC, 2018: *Summary and recommendations by the Standing Committee on Finance on the 2018 Biennial Assessment and Overview of Climate Finance Flows*. Available at: https://unfccc.int/sites/default/files/resource/51904 - UNFCCC BA 2018 - Summary Final.pdf.
UNHRC, 2017: Human Rights and Climate Change.
Upgupta, S. et al., 2015: Climate change impact and vulnerability assessment of forests in the Indian Western Himalayan region: A case study of Himachal Pradesh, India. *Clim. Risk Manag.*, **10**, 63-76, doi:10.1016/j.crm.2015.08.002.
Uson, M. A. M., 2017: Natural disasters and land grabs: the politics of their intersection in the Philippines following super typhoon Haiyan. *Can. J. Dev. Stud.*, **38**(3), 414-430, doi:10.1080/02255189.2017.1308316.
Uyttendaele, M., C. Liu and N. Hofstra, 2015: Special issue on the impacts of climate change on food safety. *Food Res. Int.*, **68**, 1-6, doi:10.1016/j.foodres.2014.09.001.
Vaara, M., O. Saastamoinen and M. Turtiainen, 2013: Changes in wild berry picking in Finland between 1997 and 2011. *Scand. J. For. Res.*, **28**(6), 586-595, doi:10.1080/02827581.2013.786123.
Vaillancourt, J. P. and N. H. Ogden, 2016: Emergence of infectious diseases associated with climate change: rural and urban challenges. *Environnement Risques & Sante*, **15**(4), 312-316, doi:10.1684/ers.2016.0889.
Valdivia, R. O. et al., 2015: Representative agricultural pathways and scenarios for regional integrated assessment of climate change impacts, vulnerability, and adaptation. *Handbook of Climate Change and Agroecosystems*, **3**, 101-156.
Valencia, V., H. Wittman and J. Blesh, 2019: Structuring markets for resilient farming systems. *Agron. Sustain. Dev.*, **39**(2), 25-25, doi:10.1007/s13593-019-0572-4.
Valverde, P. et al., 2015: Climate change impacts on irrigated agriculture in the Guadiana river basin (Portugal). *Agric. Water Manage.*, **152**, 17-30, doi:10.1016/j.agwat.2014.12.012.
van Berkel, D. B. and P. H. Verburg, 2014: Spatial quantification and valuation of cultural ecosystem services in an agricultural landscape. *Ecol. Indic.*, **37**, 163-174, doi:10.1016/j.ecolind.2012.06.025.
Van der Fels-Klerx, H. J., L. C. Vermeulen, A. K. Gavai and C. Liu, 2019: Climate change impacts on aflatoxin B1 in maize and aflatoxin M1 in milk: A case study of maize grown in Eastern Europe and imported to the Netherlands. *PLoS One*, **14**(6), e0218956, doi:10.1371/journal.pone.0218956.
van der Gaast, K., E. van Leeuwen and S. Wertheim-Heck, 2020: City-Region Food Systems and Second Tier Cities: From Garden Cities to Garden Regions. *Sustainability*, **12**(6), doi:10.3390/su12062532.
van der Werf, H. M. G., M. T. Knudsen and C. Cederberg, 2020: Towards better representation of organic agriculture in life cycle assessment. *Nat. Sustain.*, **3**(6), 419-425, doi:10.1038/s41893-020-0489-6.
van Dijk, M., T. Morley, M. L. Rau and Y. Saghai, 2021: A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat. Food*, **2**(7), 494-501, doi:10.1038/s43016-021-00322-9.
Van Dingenen, R. C., M; Janssens-Maenhout, G; Guizzardi, D; Dentener, F, 2018: *Global trends of methane emissions and their impacts on ozone concentrations*. JRC Science for Policy Report, Office for Official Publications of the European Union, Luxembourg.
van Dorst, R. M. et al., 2018: Warmer and browner waters decrease fish biomass production. *Glob Chang Biol*, **25**(4), 1395-1408, doi:10.1111/gcb.14551.
van Gameren, V. and E. Zaccai, 2015: Private forest owners facing climate change in Wallonia: Adaptive capacity and practices. *Environ. Sci. Policy*, **52**, 51-60, doi:10.1016/j.envsci.2015.05.004.
van Keulen, H. and H. Schiere (eds.), New Directions for a Diverse Planet. 4th Int. Crop Science Congress, Brisbane, Australia, Crop Science Society of America. ISBN 9781920842215.
van Leeuwen, C. and P. Darriet, 2016: The impact of climate change on viticulture and wine quality. *Journal of Wine Economics*, **11**, 150-167.
van Leeuwen, C. and A. Destrac-Irvine, 2017: Modified grape composition under climate change conditions requires adaptations in the vineyard. *Oeno One*, **51**, 147.
van Noordwijk, M. et al., 2018: SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry? *Curr. Opin. Environ. Sustain.*, **34**, 33-42, doi:10.1016/j.cosust.2018.09.003.
Van Wijk, M. et al., 2014: Farm household models to analyse food security in a changing climate: A review. *Glob. Food Secur.*, **3**(2), 77-84.
van Zeist, W.-J. et al., 2020: Are scenario projections overly optimistic about future yield progress? *Global Environ. Change*, **64**, doi:10.1016/j.gloenvcha.2020.102120.

van Zonneveld, M., M.-S. Turmel and J. Hellin, 2020: Decision-Making to Diversify Farm Systems for Climate Change Adaptation. *Front. Sustain. Food Syst.*, **4**, doi:10.3389/fsufs.2020.00032.
Vanclay, F., 2017: Principles to gain a social licence to operate for green initiatives and biodiversity projects. *Curr. Opin. Environ. Sustain.*, **29**, 48-56, doi:10.1016/j.cosust.2017.11.003.
Vandergeten, E. et al., 2016: Agricultural outsourcing or land grabbing: a meta-analysis. *Landsc. Ecol.*, **31**(7), 1395-1417, doi:10.1007/s10980-016-0365-y.
Vannuccini, S. et al., 2018: Chapter 3: Understanding the impacts of climate change for fisheries and aquaculture: global and regional supply and demand trends and prospects. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options.* [Kalikoski, D. C., S. Jentoft, A. Charles, D. Salazar Herrera, K. Cook, C. Béne and E. H. Allison (eds.)]. FAO, Rome, pp. 41-61.
Vanos, J., D. J. Vecellio and T. Kjellstrom, 2019: Workplace heat exposure, health protection, and economic impacts: A case study in Canada. *Am. J. Ind. Med.*, **62**(12), 1024-1037, doi:10.1002/ajim.22966.
Varshney, R. K., C. Ojiewo and E. Monyo, 2019: A decade of Tropical Legumes projects: Development and adoption of improved varieties, creation of market-demand to benefit smallholder farmers and empowerment of national programmes in sub-Saharan Africa and South Asia. *Plant Breed*, **138**(4), 379-388, doi:10.1111/pbr.12744.
Varshney, R. K. et al., 2018: Can genomics deliver climate-change ready crops? *Curr. Opin. Plant Biol.*, **45**(Pt B), 205-211, doi:10.1016/j.pbi.2018.03.007.
Vasconcelos, V. V., P. M. Hannam, S. A. Levin and J. M. Pacheco, 2020: Coalition-structured governance improves cooperation to provide public goods. *Sci Rep*, **10**(1), 9194, doi:10.1038/s41598-020-65960-8.
Vaughan, C., Dessai, S., & Hewitt, C. , 2018: Surveying climate services: What can we learn from a bird's-eye view? . *Weather, Climate, and Society*, **10**, 373-395.
Vaughan, C. et al., 2019: Evaluating agricultural weather and climate services in Africa: Evidence, methods, and a learning agenda. *Wiley Interdiscip. Rev.: Clim. Change*, **10**(4), doi:10.1002/wcc.586.
Veldman, J. W. et al., 2015: Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *Bioscience*, **65**(10), 1011-1018, doi:10.1093/biosci/biv118.
Veldwisch, G. J., J. Franco and L. Mehta, 2018: Water grabbing: Practices of contestation and appropriation of water resources in the context of expanding global capital. *Water Justice*, 59-70, doi:10.1017/9781316831847.004.
Velenturf, A. P. M. et al., 2019: Circular economy and the matter of integrated resources. *Sci. Total Environ.*, **689**, 963-969, doi:10.1016/j.scitotenv.2019.06.449.
Venkatesh Mannar, M. G., R. Micha and I. E. Group, 2020: *2020 Global Nutrition Report: Action on equity to end malnutrition*. Bristol, UK.
Verdolini, E., C. Bak, J. Ruet and A. Venkatachalam, 2018: Innovative green-technology SMEs as an opportunity to promote financial de-risking. *Economics-the Open Access Open-Assessment E-Journal*, **12**, doi:10.5018/economics-ejournal.ja.2018-14.
Verheecke-Vaessen, C. et al., 2019: Interacting climate change environmental factors effects on Fusarium langsethiae growth, expression of Tri genes and T-2/HT-2 mycotoxin production on oat-based media and in stored oats. *Fungal Biol*, **123**(8), 618-624, doi:10.1016/j.funbio.2019.04.008.
Verkerk, P. J. et al., 2020: Climate-Smart Forestry: the missing link. Elsevier B.V., 102164-102164 pp.
Verma, M., T. Hertel and N. Diffenbaugh, 2014: Market-oriented ethanol and corn-trade policies can reduce climate-induced US corn price volatility. *Environ. Res. Lett.*, **9**(6), 064028, doi:10.1088/1748-9326/9/6/064028.
Vermeulen, S. J. et al., 2018: Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change. *Front. Sustain. Food Syst.*, **2**, doi:10.3389/fsufs.2018.00065.
Verschuur, J., S. Li, P. Wolski and F. E. L. Otto, 2021: Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. *Sci. Rep.*, **11**(1), 3852-3852, doi:10.1038/s41598-021-83375-x.
Vianna, G. M. S., D. Zeller and D. Pauly, 2020: Fisheries and Policy Implications for Human Nutrition. *Curr Environ Health Rep*, **7**(3), 161-169, doi:10.1007/s40572-020-00286-1.
Vidal-González, P. and B. Nahhass, 2018: The use of mobile phones as a survival strategy amongst nomadic populations in the Oriental region (Morocco). *GeoJournal*, **83**, 1079-1090, doi:10.1007/s10708-017-9823-6

Vijge, M. J., M. Brockhaus, M. Di Gregorio and E. Muharrom, 2016: Framing national REDD plus benefits, monitoring, governance and finance: A comparative analysis of seven countries. *Glob. Environ. Change*, **39**, 57-68, doi:10.1016/j.gloenvcha.2016.04.002.
Villasante, S. et al., 2015: Are provisioning ecosystem services from rural aquaculture contributing to reduce hunger in Africa? *Ecosyst. Serv.*, **16**, 365-377, doi:10.1016/j.ecoser.2015.07.003.
Vinyeta, K., F. K. Lake and K. Norgaard, 2016: *Vulnerabilities of Traditional Foods and Cultural Use Species*.
Vira, B., C. Wildburger and S. Mansourian, 2016: *Forests and Food: Addressing Hunger and Nutrition Across Sustainable Landscapes*. Open Book Publishers. ISBN 978-1-78374-193-9

978-1-78374-194-6

978-1-78374-195-3

978-1-78374-196-0

978-1-78374-197-7.
Visch, W. et al., 2019: Underpinning the Development of Seaweed Biotechnology: Cryopreservation of Brown Algae (Saccharina latissima) Gametophytes. *Biopreserv Biobank*, **17**(5), 378-386, doi:10.1089/bio.2018.0147.
Vitasse, Y. et al., 2018: Increase in the risk of exposure of forest and fruit trees to spring frosts at higher elevations in Switzerland over the last four decades. *Agric. For. Meteorol*, **248**, 60-69, doi:10.1016/j.agrformet.2017.09.005.
Vitt, R. et al., 2017: Modelled performance of energy saving air treatment devices to mitigate heat stress for confined livestock buildings in Central Europe. *Biosys. Eng.*, **164**, 85-97, doi:10.1016/j.biosystemseng.2017.09.013.
Vogel, E. et al., 2019: The effects of climate extremes on global agricultural yields. *Environ. Res. Lett.*, **14**(5), doi:10.1088/1748-9326/ab154b.
Voggesser, G. et al., 2013: Cultural impacts to tribes from climate change influences on forests. In: *Climate change and indigenous peoples in the United States*. Springer, pp. 107-118.
Vogliano, C. et al., 2021: Progress towards SDG 2: Zero hunger in melanesia – A state of data scoping review. *Glob. Food Secur.*, **29**, 100519, doi:10.1016/j.gfs.2021.100519.
Von Lampe, M. et al., 2014: Why do global long‐term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. *Agric. Econ.*, **45**(1), 3-20.
Voss-Fels, K. and R. J. Snowdon, 2016: Understanding and utilizing crop genome diversity via high-resolution genotyping. *Plant Biotechnol. J.*, **14**, 1086-1094, doi:10.1111/pbi.12456.
Voss, R. C., 2021: On- and non-farm adaptation in Senegal: understanding differentiation and drivers of farmer strategies. *Clim. Dev.*, 1--15, doi:10.1080/17565529.2021.1881424.
Waha, K. et al., 2013: Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. *Glob. Environ. Change*, **23**(1), 130-143, doi:10.1016/j.gloenvcha.2012.11.001.
Waha, K. et al., 2018: Agricultural diversification as an important strategy for achieving food security in Africa. *Glob Chang Biol*, **24**(8), 3390-3400, doi:10.1111/gcb.14158.
Wako, G., M. Tadesse and A. Angassa, 2017: Camel management as an adaptive strategy to climate change by pastoralists in southern Ethiopia. *Ecological Processes*, **6**, 26, doi:10.1186/s13717-017-0093-5.
Waldbusser, G. G. et al., 2015: Ocean Acidification Has Multiple Modes of Action on Bivalve Larvae. *PLoS One*, **10**(6), e0128376, doi:10.1371/journal.pone.0128376.
Waldron, A. et al., 2017: Agroforestry can enhance food security while meeting other sustainable development goals. *Trop. Conserv. Sci*, **10**, 194008291772066-194008291772066, doi:10.1177/1940082917720667.
Wallbott, L., 2014: Indigenous Peoples in UN REDD plus Negotiations: "Importing Power" and Lobbying for Rights through Discursive Interplay Management. *Ecol. Soc.*, **19**(1), doi:10.5751/Es-06111-190121.
Walsh, M. G., A. W. de Smalen and S. M. Mor, 2018: Climatic influence on anthrax suitability in warming northern latitudes. *Sci Rep*, **8**(1), 9269, doi:10.1038/s41598-018-27604-w.
Wang, C. J., Z. X. Zhang and J. Z. Wan, 2019a: Vulnerability of global forest ecoregions to future climate change. *Glob. Ecol. Conserv.*, **20**, e00760, doi:10.1016/j.gecco.2019.e00760.

Wang, G. J. et al., 2020a: A Unique Feature of the 2019 Extreme Positive Indian Ocean Dipole Event. *Geophys. Res. Lett.*, **47**(18), doi:10.1029/2020GL088615.
Wang, J. et al., 2019b: Changes in grain protein and amino acids composition of wheat and rice under short-term increased [CO2] and temperature of canopy air in a paddy from East China. *New Phytol.*, **222**(2), 726-734, doi:10.1111/nph.15661.
Wang, J. et al., 2020b: Global warming effects on climate zones for wine grape in Ningxia region, China. *Theoretical and Applied Climatology*, **140**(3-4), 1527-1536, doi:10.1007/s00704-020-03170-y.
Wang, W. L. et al., 2018: Elevated CO2 cannot compensate for japonica grain yield losses under increasing air temperature because of the decrease in spikelet density. *Eur J Agron*, **99**, 21-29, doi:10.1016/j.eja.2018.06.005.
Wang, X. and H. Li, 2020: Assessing grapevine phenological models under Chinese climatic conditions Assessing grapevine phenological models under Chinese climatic conditions.(April 2021), doi:10.20870/oeno-one.2020.54.3.3195.
Warnatzsch, E. A. and D. S. a. Reay, 2020: Climate Change Impact on Aflatoxin Contamination Risk in Malawi's Maize Crops. *Front. Sustain. Food Syst.*, **4**, doi:10.3389/fsufs.2020.591792.
Warren, R. et al., 2018: The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Clim. Change*, **147**(3), 395-409, doi:10.1007/s10584-018-2158-6.
Wartenberg, A. C. et al., 2020: Soil fertility and Theobroma cacao growth and productivity under commonly intercropped shade-tree species in Sulawesi, Indonesia. *Plant Soil*, **453**(1), 87-104.
Waryszak, P., T. I. Lenz, M. R. Leishman and P. O. Downey, 2018: Herbicide effectiveness in controlling invasive plants under elevated CO2: Sufficient evidence to rethink weeds management. *J Environ Manage*, **226**, 400-407, doi:10.1016/j.jenvman.2018.08.050.
Watkiss, P., 2015: *A review of the economics of adaptation and climate-resilient development*. Working Paper, **No. 205**, Grantham Research Institute on Climate Change and the Environment
Watson, C. et al., 2015: *Finance for reducing disaster risk: 10 things to know*. Available at: http://www.undp.org/content/undp/en/.
Watson, E. E., H. H. Kochore and B. H. Dabasso, 2016a: Camels and Climate Resilience: Adaptation in Northern Kenya. *Hum. Ecol.*, **44**(6), 701-713, doi:10.1007/s10745-016-9858-1.
Watson, J. R., F. Armerin, D. H. Klinger and B. Belton, 2018: Resilience through risk management: cooperative insurance in small-holder aquaculture systems. *Heliyon*, **4**(9), e00799, doi:10.1016/j.heliyon.2018.e00799.
Watson, S. et al., 2016b: Dietary exposure to aflatoxin and micronutrient status among young children from Guinea. *Mol. Nutr. Food Res.*, **60**(3), 511-518, doi:10.1002/mnfr.201500382.
Watts, N. et al., 2021: The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *Lancet*, **397**(10269), 129-170, doi:10.1016/S0140-6736(20)32290-X.
Watts, N. et al., 2018: The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *Lancet*, **391**(10120), 581-630, doi:10.1016/S0140-6736(17)32464-9.
Weatherdon, L. V. et al., 2016: Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. *Front. Mar. Sci.*, **3**(APR), doi:10.3339/fmars.2076.00048.
Webber, H. et al., 2018: Diverging importance of drought stress for maize and winter wheat in Europe. *Nat Commun*, **9**(1), 4249, doi:10.1038/s41467-018-06525-2.
Webber, S., 2017: Circulating climate services: Commercializing science for climate change adaptation in Pacific Islands. *Geoforum*, **85**(November 2016), 82-91, doi:10.1016/j.geoforum.2017.07.009.
Webster, C. R., M. A. Jenkins and S. Jose, 2006: Woody invaders and the challenges they pose to forest ecosystems in the eastern United States. *J. For.*, **104**(7), 366-374, doi:10.1093/jof/104.7.366.
Weerakoon, D. K. and S. Wijesundara (eds.), 2012: *The National Red List 2012 of Sri Lanka; Conservation Status of the Fauna and Flora*, Ministry of the Environment,, Colombo, Sri Lanka, 452 pp. ISBN 9789550033553.
WEF, 2017: *The Global Risks Report 2017*. World Economic Forum, 78 pp.
Wegner, K. et al., 2016: Effects of temperature and temperature-humidity index on the reproductive performance of sows during summer months under a temperate climate. *Anim Sci J*, **87**(11), 1334-1339, doi:10.1111/asj.12569.

Weidner, T. and A. D. Yang, 2020: The potential of urban agriculture in combination with organic waste valorization: Assessment of resource flows and emissions for two european cities. *J. Clean. Prod.*, **244**, doi:10.1016/j.jclepro.2019.118490.
Wein, E. E., M. M. R. Freeman and J. C. Makus, 1996: Use of and preference for traditional foods among the Belcher Island Inuit. *Arctic*, **49**(3), 256-264.
Weindl, I. et al., 2017: Livestock production and the water challenge of future food supply: Implications of agricultural management and dietary choices. *Glob. Environ. Change*, **47**, 121-132, doi:10.1016/j.gloenvcha.2017.09.010.
Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environ. Res. Lett.*, **10**(9), 094021, doi:10.1088/1748-9326/10/9/094021.
Weinreb, A., G. Stecklov and A. Arslan, 2020: Effects of changes in rainfall and temperature on age- and sex-specific patterns of rural-urban migration in sub-Saharan Africa. *Population and Environment*, **42**(2), 219--254, doi:10.1007/s11111-020-00359-1.
Weitz, N., C. Strambo, E. Kemp-Benedict and M. Nilsson, 2017: Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Glob. Environ. Change*, **45**, 165-173, doi:10.1016/j.gloenvcha.2017.06.006.
Wells, M. L. et al., 2020: Future HAB science: Directions and challenges in a changing climate. *Harmful Algae*, **91**, 101632, doi:10.1016/j.hal.2019.101632.
Weltzien, E. et al., 2019: Long-term collaboration between farmers' organizations and plant breeding programmes: Sorghum and pearl millet in West Africa. [Westengen, O. T. and T. Winge (eds.)]. Routledge, London and New York, pp. 29-48.
Wenndt, A. J., H. K. Sudini, P. Pingali and R. Nelson, 2021: Farmer research networks enable community-based mycotoxin management in rural Indian villages. *Agric. Syst.*, **192**, 103192, doi:10.1016/j.agsy.2021.103192.
Wesche, S. D. and H. M. Chan, 2010: Adapting to the impacts of climate change on food security among Inuit in the Western Canadian Arctic. *EcoHealth*, **7**(3), 361-373, doi:10.1007/s10393-010-0344-8.
West, T. A. P., 2016: Indigenous community benefits from a de-centralized approach to REDD plus in Brazil. *Clim. Policy*, **16**(7), 924-939, doi:10.1080/14693062.2015.1058238.
Westengen, O. T. and T. Berg, 2016: Crop Adaptation to Climate Change in SSA: The Role of Genetic Resources and Seed Systems. In: *Climate Change and Multi-Dimensional Sustainability in African Agriculture*. Springer International Publishing, Cham, pp. 327-343.
Westengen, O. T. and A. K. Brysting, 2014: Crop adaptation to climate change in the semi-arid zone in Tanzania: the role of genetic resources and seed systems. *Agric. Food Secur.*, **3**(1), 3-3, doi:10.1186/2048-7010-3-3.
Westengen, O. T., R. Haug, P. Guthiga and E. Macharia, 2019: Governing Seeds in East Africa in the Face of Climate Change: Assessing Political and Social Outcomes. *Front. Sustain. Food Syst.*, **3**, doi:10.3389/fsufs.2019.00053.
Westengen, O. T. et al., 2018: A climate for commerce: the political agronomy of conservation agriculture in Zambia. *Agric. Hum. Values*, **35**(1), 255-268, doi:10.1007/s10460-017-9820-x.
Westmeijer, G. et al., 2019: Mechanistic niche modelling to identify favorable growth sites of temperate macroalgae. *Algal Research-Biomass Biofuels and Bioproducts*, **41**, doi:10.1016/j.algal.2019.101529.
Westoby, R., K. E. McNamara, R. Kumar and P. D. Nunn, 2020: From community-based to locally led adaptation: Evidence from Vanuatu. *Ambio*, **49**(9), 1466-1473, doi:10.1007/s13280-019-01294-8.
Weyant, C. et al., 2018: Anticipated burden and mitigation of carbon-dioxide-induced nutritional deficiencies and related diseases: A simulation modeling study. *PLoS Med*, **15**(7), e1002586, doi:10.1371/journal.pmed.1002586.
WFP-FSIN, 2020: *Global Report on Food Crises: Joint Analysis for Better Decisions*. United Nations World Food Programme, Food Security Information Network.
White, D., 2014: A perfect storm? Indigenous rights within a national REDD+ readiness process in Peru. *Mitig. Adapt. Strateg. Glob. Change*, **19**, 657-676, doi:10.1007/s11027-013-9523-6
White, J. C. et al., 2017: A nationwide annual characterization of 25 years of forest disturbance and recovery for Canada using Landsat time series. *Remote Sens. Environ.*, **194**, 303-321, doi:10.1016/j.rse.2017.03.035.
White, J. T. and C. Bunn, 2017: Growing in Glasgow: Innovative practices and emerging policy pathways for urban agriculture. *Land Use Policy*, **68**(August), 334-344, doi:10.1016/j.landusepol.2017.07.056.

Whitfield, S., J. L. Dixon, B. P. Mulenga and H. Ngoma, 2015: Conceptualising farming systems for agricultural development research: Cases from Eastern and Southern Africa. *Agric. Syst.*, **133**, 54-62, doi:10.1016/j.agsy.2014.09.005.
Whitmee, S. et al., 2015: Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. *The Lancet*, **386**(10007), 1973-2028, doi:10.1016/s0140-6736(15)60901-1.
Whitney, C. K., T. Conger, N. C. Ban and R. McPhie, 2020: Synthesizing and communicating climate change impacts to inform coastal adaptation planning. *FACETS*, **5**(1), 704-737, doi:10.1139/facets-2019-0027.
WHO, 2013: *WHO traditional medicine strategy: 2014-2023*. World Health Organization. ISBN 9241506091.
WHO, 2021: The Global Health Observatory.
Wichelns, D., 2017: The water-energy-food nexus: Is the increasing attention warranted, from either a research or policy perspective? *Environ. Sci. Policy*, **69**, 113-123, doi:10.1016/j.envsci.2016.12.018.
Widianingsih, N. N., L. H. Schmidt and I. Theilade, 2019: Jernang (Daemonorops spp.) commercialization and its role for rural incomes and livelihoods in Southern Sumatra, Indonesia. *Forests, Trees and Livelihoods*, **28**(3), 143-159.
Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environ. Res. Lett.*, **10**(8), 085010, doi:10.1088/1748-9326/10/8/085010.
Wiesmeier, M. et al., 2019: Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma*, **333**, 149-162, doi:10.1016/j.geoderma.2018.07.026.
Wijngaard, R. R. et al., 2017: The Impact of Climate Change on Metal Transport in a Lowland Catchment. *Water Air Soil Pollut*, **228**(3), 107, doi:10.1007/s11270-017-3261-4.
Wild, C. P., J. D. Miller and J. D. Groopman (eds.), 2015: *Mycotoxin Control in Low- and Middle-Income Countries*, IARC World Group Reports, International Agency for Research on Cancer,, Lyon, France, 66 pp. ISBN 9789283225102.
Wilkes, A. et al., 2017: Is cross-breeding with indigenous sheep breeds an option for climate-smart agriculture? *Small Rumin. Res.*, **147**, 83-88, doi:10.1016/j.smallrumres.2016.12.036.
Willett, W. et al., 2019: Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet*, **393**(10170), 447-492, doi:10.1016/S0140-6736(18)31788-4.
Williams, A. et al., 2016: Soil Water Holding Capacity Mitigates Downside Risk and Volatility in US Rainfed Maize: Time to Invest in Soil Organic Matter? *PLoS One*, **11**(8), e0160974-e0160974, doi:10.1371/journal.pone.0160974.
Williams, A. et al., 2018: A regionally-adapted implementation of conservation agriculture delivers rapid improvements to soil properties associated with crop yield stability. *Sci. Rep.*, **8**(1), 8467-8467, doi:10.1038/s41598-018-26896-2.
Williams, A. et al., 2015: Quantifying the response of cotton production in eastern Australia to climate change. *Clim. Change*, **129**(1-2), 183-196, doi:10.1007/s10584-014-1305-y.
Williams, P. H. and J. L. Osborne, 2009: Bumblebee vulnerability and conservation world-wide. *Apidologie*, **40**(3), 367-387, doi:10.1051/apido/2009025.
Williamson, B., 2021: *Cultural Burning in NSW: Challenges and Opportunities for Policy Makers and Aboriginal Peoples*. CAEPR Working Paper, Canberra, ACT: Australian National University, Centre for Aboriginal Economic Policy Research (CAEPR).
Wilson, M. J. et al., 2015: Invasive slug pests and their parasites-temperature responses and potential implications of climate change. *Biol. Fertil. Soils*, **51**(6), 739-748, doi:10.1007/s00374-015-1022-3.
Winans, K., A. Kendall and H. Deng, 2017: The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, **68**, 825-833, doi:10.1016/j.rser.2016.09.123.
Winkler, J. A. et al., 2018: Potential impacts of climate change on storage conditions for commercial agriculture: an example for potato production in Michigan. *Clim. Change*, **151**(2), 275-287, doi:10.1007/s10584-018-2301-4.
Witasari, A. I., 2016: Trust Building to Coordinate Collective Action in Reforestation Program. *Manajemen Hutan Tropika*, **22**(3), 192-201, doi:10.7226/jtfm.22.3.192.
Wolde, A., T. Amsalu and M. M. Alemu, 2016: Social and Economic Impacts of Community Managed Reforestation and Natural Regeneration of Forestry Development, the Case of Humbo District, Ethiopia. *Environment and Natural Resources Research*, **6**(4), 36, doi:10.5539/enrr.v6n4p36.

Wolz, K. J. et al., 2018: Frontiers in alley cropping: Transformative solutions for temperate agriculture. *Glob Chang Biol*, **24**(3), 883-894, doi:10.1111/gcb.13986.
Wood, S. A. and F. Baudron, 2018: Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture. *Agric. Ecosyst. Environ.*, **266**, 100-108, doi:10.1016/j.agee.2018.07.025.
Woodard, J. D., B. Sherrick, J. Coppess and D. J. Muth, 2019: *The Role of the Banking and Financing Sector in Encouraging Conservation Practices and Organic Transitions* Meridian Institute. Available at: https://foodandagpolicy.org/wp-content/uploads/sites/4/2019/09/2019-March-Role-of-Banking-and-Finance-in-Encouraging-Conservation-Practices.pdf.
Woodworth-Jefcoats, P. A., J. L. Blanchard and J. C. Drazen, 2019: Relative Impacts of Simultaneous Stressors on a Pelagic Marine Ecosystem. *Front. Mar. Sci.*, **6**, doi:10.3389/fmars.2019.00383.
Woolf, D., D. Solomon and J. Lehmann, 2018: Land restoration in food security programmes: synergies with climate change mitigation. *Clim. Policy*, **18**(10), 1260-1270, doi:10.1080/14693062.2018.1427537.
Woolway, R. I. and S. C. Maberly, 2020: Climate velocity in inland standing waters. *Nat. Clim. Change*, **10**(12), 1124-1129, doi:10.1038/s41558-020-0889-7.
Work, C., V. Rong, D. Song and A. Scheidel, 2019: Maladaptation and development as usual? Investigating climate change mitigation and adaptation projects in Cambodia. *Clim. Policy*, **19**(sup1), S47-S62, doi:10.1080/14693062.2018.1527677.
World Bank, 2010: *Economics of adaptation to climate change - Synthesis report*. World Bank Washington, D.C. Available at: http://documents.worldbank.org/curated/en/646291468171244256/Economics-of-adaptation-to-climate-change-Synthesis-report.
World Bank, 2013: *Fish to 2030: Prospects for Fisheries and Aquaculture*. Agriculture and Environmental Services Discussion Paper No. 3, **1**, World Bank,, World Bank Group, Washington DC, USA, 80 pp. Available at: http://documents.worldbank.org/curated/en/458631468152376668/Fish-to-2030-prospects-for-fisheries-and-aquaculture (accessed 14/06/2021).
World Bank, 2016: *Forest Action Plan Fy16-20*. **1**, World Bank,, World Bank Group, Washington D.C., USA, 89 pp. Available at: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/240231467291388831/forest-action-plan-fy16-20 (accessed 14/06/2021).
World Bank, 2018: *Realigning Agricultural Support to Promote Climate-Smart Agriculture.* Agriculture Global Practice Note, **1**, World Bank,, World Bank Group, Washington D.C., USA, 4 pp. Available at: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/734701543906677048/realigning-agricultural-support-to-promote-climate-smart-agriculture (accessed 14/06/2021).
World Bank, 2019: *The World Governance Indicators*. Available at: https://info.worldbank.org/governance/wgi/.
World Bank, 2020: *The World Development Indicators: GDP (current US$)*. Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD.
Wreford, A. and C. F. E. Topp, 2020: Impacts of climate change on livestock and possible adaptations: A case study of the United Kingdom. *Agric. Syst.*, **178**, 102737, doi:10.1016/j.agsy.2019.102737.
WRI, 2018: *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. World Resources Institute. Available at: https://www.wri.org/publication/creating-sustainable-food-future.
Wu, J., 2016: The distributions of Chinese yak breeds in response to climate change over the past 50 years. *Anim Sci J*, **87**(7), 947-958, doi:10.1111/asj.12526.
Wu, J. G., 2015: The response of the distributions of Asian buffalo breeds in China to climate change over the past 50 years. *Livestock Science*, **180**, 65-77, doi:10.1016/j.livsci.2015.07.005.
Wu, K. S., Y. R. He, Q. J. Chen and Y. M. Zheng, 2020: Analysis on the damage and recovery of typhoon disaster based on UAV orthograph. *Microelectronics Reliability*, **107**, doi:10.1016/j.microrel.2019.06.029.
Xiang, J., A. Hansen, D. Pisaniello and P. Bi, 2016: Workers' perceptions of climate change related extreme heat exposure in South Australia: a cross-sectional survey. *BMC Public Health*, **16**, 549, doi:10.1186/s12889-016-3241-4.
Xin, Y. and F. Tao, 2019: Optimizing genotype-environment-management interactions to enhance productivity and eco-efficiency for wheat-maize rotation in the North China Plain. *Sci. Total Environ.*, **654**, 480-492, doi:10.1016/j.scitotenv.2018.11.126.
Xinhua, Y. et al., 2017: *Fishery and aquaculture insurance in China.* FAO Fisheries and Aquaculture Circular, **1139**, FAO, Rome, 1-30 pp.

Xu, H. Q. et al., 2019: Future increases in irrigation water requirement challenge the water-food nexus in the northeast farming region of China. *Agric. Water Manage.*, **213**, 594-604, doi:10.1016/j.agwat.2018.10.045.
Xu, J. et al., 2008: Understanding land use, livelihoods, and health transitions among Tibetan nomads: a case from Gangga Township, Dingri County, Tibetan Autonomous Region of China. *EcoHealth*, **5**(2), 104-114, doi:10.1007/s10393-008-0173-1.
Yamamoto, T. et al., 2018: Application and development of genome editing technologies to the Solanaceae plants. *Plant Physiol. Biochem.*, **131**, 37-46, doi:10.1016/j.plaphy.2018.02.019.
Yan, Y. J. et al., 2017: Range shifts in response to climate, change of Ophiocordyceps sinensis, a fungus endemic to the Tibetan Plateau. *Biol. Conserv.*, **206**, 143-150, doi:10.1016/j.biocon.2016.12.023.
Yang, G., J. Roy, S. D. Veresoglou and M. C. Rillig, 2021: Soil biodiversity enhances the persistence of legumes under climate change. *New Phytol.*, **229**(5), 2945-2956, doi:10.1111/nph.17065.
Yang, J. et al., 2018: Quantifying the Sustainability of Water Availability for the Water-Food-Energy-Ecosystem Nexus in the Niger River Basin. *Earths Future*, **6**(9), 1292-1310, doi:10.1029/2018EF000923.
Yang, X. F. et al., 2012: Climate change effects fruiting of the prize matsutake mushroom in China. *Fungal Diversity*, **56**(1), 189-198, doi:10.1007/s13225-012-0163-z.
Yang, Y. M. et al., 2014: Prediction of cotton yield and water demand under climate change and future adaptation measures. *Agric. Water Manage.*, **144**, 42-53, doi:10.1016/j.agwat.2014.06.001.
Yeboah, T. et al., 2020: Hard work and hazard: Young people and agricultural commercialisation in Africa. *J. Rural Stud.*, **76**, 142--151, doi:10.1016/j.jrurstud.2020.04.027.
Yengoh, G. T. and F. A. Armah, 2016: Land access constraints for communities affected by large-scale land acquisition in Southern Sierra Leone. *GeoJournal*, **81**(1), 103-122, doi:10.1007/s10708-014-9606-2.
Yengoh, G. T., F. A. Armah and K. Steen, 2015: Women's Bigger Burden: Disparities in Outcomes of Large Scale Land Acquisition in Sierra Leone. *Gender Issues*, **32**(4), 221-244, doi:10.1007/s12147-015-9140-7.
Yeni, F. and H. Alpas, 2017: Vulnerability of global food production to extreme climatic events. *Food Res. Int.*, **96**(27-39), 27-39, doi:10.1016/j.foodres.2017.03.020.
Yetty, Y., B. Hariyadi and P. Murni, 2013: Studi Etnobotani Jernang (Daemonorops spp.) pada Masyarakat Desa Lamban Sigatal dan Sepintun Kecamatan Pauh Kabupaten Sarolangun Jambi. *Biospecies*, **6**(1).
Yi, Y. J., X. Cheng, Z. F. Yang and S. H. Zhang, 2016: Maxent modeling for predicting the potential distribution of endangered medicinal plant (H. riparia Lour) in Yunnan, China. *Ecol. Eng.*, **92**, 260-269, doi:10.1016/j.ecoleng.2016.04.010.
Yi, Y. J. et al., 2018: The influence of climate change on an endangered riparian plant species: The root of riparian Homonoia. *Ecol. Indic.*, **92**, 40-50, doi:10.1016/j.ecolind.2017.05.004.
Yokohata, T. et al., 2020: MIROC-INTEG-LAND version 1 : a global biogeochemical land surface model with human water management , crop growth , and land-use change. 4713-4747.
York, L., C. Heffernan, C. Rymer and N. Panda, 2017: A deterministic evaluation of heat stress mitigation and feed cost under climate change within the smallholder dairy sector. *Animal*, **11**(5), 900-909, doi:10.1017/S1751731116002706.
Young, H. and M. A. Ismail, 2019: Complexity, continuity and change: livelihood resilience in the Darfur region of Sudan. *Disasters*, **43 Suppl 3**(S3), S318-S344, doi:10.1111/disa.12337.
Young, N. and M. Liston, 2010: (Mis)managing a risk controversy: the Canadian salmon aquaculture industry's responses to organized and local opposition. *J. Risk Res.*, **13**(8), 1043-1065, doi:10.1080/13669877.2010.514429.
Young, T. et al., 2019: Adaptation strategies of coastal fishing communities as species shift poleward. *ICES J. Mar. Sci.*, **76**(1), 93-103, doi:10.1093/icesjms/fsy140.
Yousefi, A. et al., 2020: Biometric indices of wild pistachio (Pistacia atlantica Desf.) trees under resin extraction in Western Iran. *Agroforestry Systems*, **94**(5), 1977-1988.
Yu, H. et al., 2019: Targeted Gene Disruption in Pacific Oyster Based on CRISPR/Cas9 Ribonucleoprotein Complexes. *Mar Biotechnol (NY)*, **21**(3), 301-309, doi:10.1007/s10126-019-09885-y.
Zabaniotou, A., 2018: Redesigning a bioenergy sector in EU in the transition to circular waste-based Bioeconomy-A multidisciplinary review. *J. Clean. Prod.*, **177**, 197-206, doi:10.1016/j.jclepro.2017.12.172.
Zabel, F. et al., 2021: Large potential for crop production adaptation depends on available future varieties. *Glob Chang Biol*, doi:10.1111/gcb.15649.

Zahra, W. et al., 2020: Economic Importance of Medicinal Plants in Asian Countries. In: *Bioeconomy for Sustainable Development*. Springer, pp. 359-377.
Zaidi, S. S. et al., 2019: New plant breeding technologies for food security. *Science*, **363**(6434), 1390-1391, doi:10.1126/science.aav6316.
Zalesny, R. S. et al., 2019: Positive water linkages of producing short rotation poplars and willows for bioenergy and phytotechnologies. *Wiley Interdisciplinary Reviews: Energy and Environment*, **8**(5), doi:10.1002/wene.345.
Zampieri, M., A. Ceglar, F. Dentener and A. Toreti, 2017: Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environ. Res. Lett.*, **12**(6), doi:10.1088/1748-9326/aa723b.
Zandalinas, S. I. et al., 2018: Plant adaptations to the combination of drought and high temperatures. *Physiol. Plant.*, **162**(1), 2-12, doi:10.1111/ppl.12540.
Zander, K. K. et al., 2015: Heat stress causes substantial labour productivity loss in Australia. *Nat. Clim. Change*, **5**(7), 647-+, doi:10.1038/Nclimate2623.
Zavaleta, C. et al., 2018: Multiple non-climatic drivers of food insecurity reinforce climate change maladaptation trajectories among Peruvian Indigenous Shawi in the Amazon. *PLoS One*, **13**(10), e0205714, doi:10.1371/journal.pone.0205714.
Zellweger, F. et al., 2020: Forest microclimate dynamics drive plant responses to warming. *Science*, **368**(6492), 772-775, doi:10.1126/science.aba6880.
Zenger, K. R. et al., 2018: Genomic Selection in Aquaculture: Application, Limitations and Opportunities With Special Reference to Marine Shrimp and Pearl Oysters. *Front Genet*, **9**(693), 693, doi:10.3389/fgene.2018.00693.
Zhang, L. et al., 2016: Ethnobotanical study of traditional edible plants used by the Naxi people during droughts. *J Ethnobiol Ethnomed*, **12**(1), 39, doi:10.1186/s13002-016-0113-z.
Zhang, S., F. L. Tao and Z. Zhang, 2014: Rice reproductive growth duration increased despite of negative impacts of climate warming across China during 1981-2009. *Eur J Agron*, **54**, 70-83, doi:10.1016/j.eja.2013.12.001.
Zhang, S. Z. et al., 2017a: Effects of elevated CO2 concentration and temperature on some physiological characteristics of cotton (Gossypium hirsutum L.) leaves. *Environ. Exp. Bot.*, **133**, 108-117, doi:10.1016/j.envexpbot.2016.10.001.
Zhang, Y., A. A. Malzahn, S. Sretenovic and Y. Qi, 2019: The emerging and uncultivated potential of CRISPR technology in plant science. *Nat Plants*, **5**(8), 778-794, doi:10.1038/s41477-019-0461-5.
Zhang, Y., Y. Wang and H. Niu, 2017b: Spatio-temporal variations in the areas suitable for the cultivation of rice and maize in China under future climate scenarios. *Sci. Total Environ.*, **601-602**, 518-531, doi:10.1016/j.scitotenv.2017.05.232.
Zhang, Y. Q. W., B. A. McCarl, Y. B. Luan and U. Kleinwechter, 2018: Climate change effects on pesticide usage reduction efforts: a case study in China. *Mitig. Adapt. Strateg. Glob. Change*, **23**(5), 685-701, doi:10.1007/s11027-017-9755-y.
Zhao, C. et al., 2017: Temperature increase reduces global yields of major crops in four independent estimates. *Proc Natl Acad Sci U S A*, **114**(35), 9326-9331, doi:10.1073/pnas.1701762114.
Zhao, C. et al., 2019: A SIMPLE crop model. *Eur J Agron*, **104**, 97-106, doi:10.1016/j.eja.2019.01.009.
Zhao, Q. et al., 2018: Modeling impacts of climate change on the geographic distribution of medicinal plant <i>Fritillaria cirrhosa</i> D. Don. *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology*, **152**, 349-355, doi:10.1080/11263504.2017.1289273.
Zhao, Z. et al., 2020: Potential distribution of Notopterygium incisum Ting ex H. T. Chang and its predicted responses to climate change based on a comprehensive habitat suitability model. *Ecol Evol*, **10**(6), 3004-3016, doi:10.1002/ece3.6117.
Zhou, X. et al., 2014: Nutrient removal by prairie filter strips in agricultural landscapes. *Journal of Soil and Water Conservation*, **69**(1), 54-64, doi:10.2489/jswc.69.1.54.
Zhu, C. et al., 2018a: Carbon dioxide (CO2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. *Sci Adv*, **4**(5), eaaq1012, doi:10.1126/sciadv.aaq1012.
Zhu, P. et al., 2018b: The important but weakening maize yield benefit of grain filling prolongation in the US Midwest. *Glob Chang Biol*, **24**(10), 4718-4730, doi:10.1111/gcb.14356.
Zickfeld, K. et al., 2013: Long-Term Climate Change Commitment and Reversibility: An EMIC Intercomparison. *J. Clim.*, **26**(16), 5782-5809, doi:10.1175/Jcli-D-12-00584.1.

Ziervogel, G., 2019: Building transformative capacity for adaptation planning and implementation that works for the urban poor: Insights from South Africa. *Ambio*, **48**(5), 494-506, doi:10.1007/s13280-018-1141-9.
Zimová, S. et al., 2020: Reducing rotation age to address increasing disturbances in Central Europe: Potential and limitations. *For. Ecol. Manag.*, **475**, doi:10.1016/j.foreco.2020.118408.
Zin, W. Y. L., P. Teartisup and P. Kerdseub, 2019: Evaluating Traditional Knowledge on Climate Change (TKCC): A Case Study in the Central Dry Zone of Myanmar. *Environment and Natural Resources Journal*, **17**(2), 1--29, doi:10.32526/ennrj.17.2.2019.09.
Zinsstag, J. et al., 2018: Climate change and One Health. *FEMS Microbiol. Lett.*, **365**(11), doi:10.1093/femsle/fny085.
Ziska, L. H., 2003: Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. *J. Exp. Bot.*, **54**(381), 395-404, doi:10.1093/jxb/erg027.
Ziska, L. H., 2014: Increasing minimum daily temperatures are associated with enhanced pesticide use in cultivated soybean along a latitudinal gradient in the mid-western United States. *PLoS One*, **9**(2), e98516, doi:10.1371/journal.pone.0098516.
Ziska, L. H., 2016: The role of climate change and increasing atmospheric carbon dioxide on weed management: Herbicide efficacy. *Agric. Ecosyst. Environ.*, **231**, 304-309, doi:10.1016/j.agee.2016.07.014.
Ziska, L. H., 2020: Climate Change and the Herbicide Paradigm: Visiting the Future. *Agronomy*, **10**(12), doi:10.3390/agronomy10121953.
Ziska, L. H. and L. L. McConnell, 2016: Climate Change, Carbon Dioxide, and Pest Biology: Monitor, Mitigate, Manage. *J. Agric. Food Chem.*, **64**(1), 6-12, doi:10.1021/jf506101h.
Ziska, L. H. et al., 2016: Rising atmospheric CO2 is reducing the protein concentration of a floral pollen source essential for North American bees. *Proc Biol Sci*, **283**(1828), 20160414, doi:10.1098/rspb.2016.0414.
Zomer, R. J. et al., 2016: Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Sci Rep*, **6**, 29987, doi:10.1038/srep29987.
Zoomers, E. B. and K. Otsuki, 2017: Addressing the impacts of large-scale land investments: Re-engaging with livelihood research. *Geoforum*, **83**, 164-171, doi:10.1016/j.geoforum.2017.01.009.
Zougmoré, R. et al., 2016: Toward climate-smart agriculture in West Africa: a review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agric. Food Secur.*, **5**(1), doi:10.1186/s40066-016-0075-3.
Zouré, C. et al., 2019: Modelling the water balance on farming practices at plot scale: Case study of Tougou watershed in Northern Burkina Faso. *CATENA*, **173**, 59-70, doi:10.1016/j.catena.2018.10.002.
Zumpf, C. et al., 2017: Yield and Water Quality Impacts of Field-Scale Integration of Willow into a Continuous Corn Rotation System. *Journal of Environmental Quality*, **46**(4), 811-818, doi:10.2134/jeq2017.02.0082.

Chapter 6: Cities, Settlements and Key Infrastructure

Coordinating Lead Authors: David Dodman (Jamaica/United Kingdom); Bronwyn Hayward (New Zealand); Mark Pelling (United Kingdom)

Lead Authors: Vanesa Castán Broto (United Kingdom/Spain); Winston Chow (Singapore); Eric Chu (USA/Hong Kong, Special Administrative Region, China); Richard Dawson (United Kingdom); Luna Khirfan (Canada); Timon McPhearson (USA); Anjal Prakash (India); Yan Zheng (China); Gina Ziervogel (South Africa)

Contributing Authors: Diane Archer (Australia/France), Chiara Bertolin (Italy), Shauna Brail (Canada), Anton Cartwright (South Africa), Mikhail Chester (USA), Sarah Colenbrander (Australia/Switzerland), Tapan Dhar (Bangladesh), Barbara Evans (United Kingdom), Sudharto P. Hadi (Indonesia), Wiwandari Handayani (Indonesia), David Hondula (USA), Twan van Hooff (The Netherlands), Sirkku Juhola (Finland), Christine Kirchhoff (USA), Sari Kovats (United Kingdom), Hayley Leck (South Africa/United Kingdom), Pablo Méndez Lázaro (Puerto Rico), Tischa Muñoz-Erickson (USA), Vishal Narain (India), Marta Olazabal (Spain), Luis Ortiz (Puerto Rico), Angelica Ospina (Colombia/Canada), Emmanuel Osuteye (Ghana), Chao Ren (China), Rukuh Setiadi (Indonesia), Shalini Sharma (India), Wan-Yu Shih (Taiwan, Province of China), Gilbert Siame (Zambia), Faith Taylor (United Kingdom), Jennifer Vanos (Canada), J. Jason West (USA), Linda Westman (Sweden)

Review Editors: Gian-Carlo Delgado-Ramos (Mexico); Patricia Romero-Lankao (USA/Mexico)

Chapter Scientist: Linda Westman (Sweden)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

In all cities and urban areas, the risk faced by people and assets from hazards associated with climate change has increased (*high confidence*[1]). Urban areas are now home to 4.2 billion people, the majority of the world's population. Urbanization processes generate vulnerability and exposure which combine with climate change hazards to drive urban risk and impacts (high confidence). Globally, the most rapid growth in urban vulnerability and exposure has been in cities and settlements where adaptive capacity is limited – especially in unplanned and informal settlements in low- and middle-income nations and in smaller and medium-sized urban centres (high confidence). Between 2015 and 2020, urban populations globally grew by more than 397 million people, with more than 90 percent of this growth taking place in Less Developed Regions. {Box 6.1; 6.1.4; 6.2.1; 6.3.2; 6.3.3.4; 6.2.2.2; 6.4.4}

The documentation of climate related events and observed human and economic losses have increased since AR5 for urban areas and human settlements. Observed losses arise from single, compound, cascading and systemic events (*medium evidence, high agreement*). Losses from single events include the direct impact of heat stress on human health. Compound event losses arise from the interaction of single climate hazards with at least one other hazard driver such as heat with poor air quality (e.g. from traffic fumes or wildfire), flooding with poor water quality (e.g. from contaminated run-off and flood water), or land subsidence. Cascading impacts are observed when damages in one place or system reduce resilience and generate impacts elsewhere (e.g. when flood waters damage energy infrastructure causing blackouts and knock on financial and human impacts). Losses become systemic when affecting entire systems and can even jump from one system to another (e.g. drought impacting on rural food production contributing to urban food insecurity) (medium confidence). In some cases, maladaptive responses to hazards have exacerbated inequality in the distribution of impacts, for example shifting risk from one community to another. {Figure 6.2; 6.2.6; 6.3.4.1; 6.4.5; Cross-Chapter Paper 2; Cross-Working Group Box URBAN in Chapter 6}

Evidence from urban and rural settlements is unequivocal; climate impacts are felt disproportionately in urban communities with the most economically and socially marginalized, most affected (*high confidence*). Vulnerabilities are shaped by drivers of inequality - including gender, class, race, ethnic origin, age, level of ability, sexuality and nonconforming gender orientation - framed by cultural norms, diverse values, and practices (high confidence). Intersections between these drivers shape unique experiences of vulnerability and risk and the adaptive capacities of groups and individuals. Robust adaptation plans are those developed in inclusive ways. However, few adaptation plans for urban areas and infrastructure are being developed through consultation and coproduction with diverse and marginalized urban communities. The concerns and capacities of marginalised communities are rarely considered in planning (medium confidence). {Box 6.3, Box 6.4; 6.4.3.1; 6.4.5.2, Case study 6.7; Cross-Working Group Box URBAN in Chapter 6}.

The COVID-19 pandemic has had a substantial impact on urban communities and climate adaptation (*medium evidence, high agreement*). The pandemic has revealed both systemic underinvestment resulting in multiple, persistent health related vulnerabilities (many of which also exacerbate climate change risk) and co-benefits for urban interventions to reduce future pandemic and climate change risk. The COVID-19 pandemic is estimated to have pushed an additional 119 to 124 million people into poverty in 2020, with South Asia and Sub-Saharan Africa each contributing roughly two-fifths of this total (medium confidence). At city level, community groups, NGOs and local governments face challenges to bring agencies already working on social and economic development into coordinated action to reduce urban vulnerabilities and manage risks. COVID-19 and climate change impacts are exacerbated by widening social inequality. Addressing the causes of social vulnerability creates opportunity for transformative adaptation. {Box 6.4; 6.1.4; 6.2.2.4; 6.2.5; 6.4.1.3; case study 6.4; Cross-Chapter Box COVID in Chapter 7}

The number of people expected to live in urban areas highly exposed to climate change impacts has increased substantially (*high confidence*). An additional 2.5 billion people are projected to be living in

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

urban areas by 2050, with up to 90 percent of this increase concentrated in the regions of Asia and Africa. Projections of the number of people expected to live in urban areas highly exposed to climate change impacts have increased. Sea level increase and increases in tropical cyclone storm surge and rainfall intensity will increase the probability of coastal city flooding, with more than a billion people located in low-lying cities and settlements expected to be at risk from coastal-specific climate hazards by 2050 (*high confidence*). Sea level rise, increases in tropical cyclone storm surge, and more frequent and intense extreme precipitation will increase the number of people, area of urban land, and damages from flood hazard (*high confidence*). The main driver for increased heat exposure is the combination of global warming and population growth in already-warm centres, and the majority of the population exposed to heatwaves will live in urban centres. An additional 350 million people living in urban areas are estimated be exposed to water scarcity from severe droughts at 1.5°C warming, and 410.7 million at 2°C warming. {6.1; 6.2.2; CCP2}

Many more cities have developed adaptation plans since AR5, but only a limited number of these have been implemented (*medium confidence*). Many of these plans focus narrowly on climate risk reduction, missing opportunities to advance co-benefits of climate mitigation and sustainable development, compounding inequality and reducing wellbeing (*medium confidence*). However, an increasing array of adaptation options are available. Nature-based solutions are now mainstream urban adaptation options and there remains considerable scope for their wider application. Social policy based adaptation, including education and the adaptation of health systems offers considerable future scope. Options of adapting physical infrastructure are similarly advancing though at times constrained by existing infrastructure design and location. The greatest gaps between policy and action are in failures to manage adaptation of social infrastructure (community facilities, services and networks) and failure to address complex interconnected risks for example in the food-energy-water-health nexus or the inter-relationships of air quality and climate risk (*medium confidence*). Barriers to implementing plans include lack of political will and management capacity, limited financial means and mechanisms (especially for smaller urban settlements) and competing priorities (*limited evidence, high agreement*). {6.3.1, 6.4.3; 6.4.5; 6.4.5.1; 6.4.5.2; Figure 6.5}

The shift from urban planning to action in ways that identify and advance synergies and co-benefits of mitigation, adaptation and Sustainable Development Goals (SDGs) has occurred slowly and unevenly (*high confidence*). While there is ambition for joined up policy, action and research, this is still the exception. One area of sustained effort is community-based adaptation planning and resilience actions which have potential to be better integrated to enhance wellbeing and create synergies with the Sustainable Development Goal ambitions of leaving no-one behind. Complex trade-offs and gaps in alignment between mitigation and adaptation over scale and across policy areas where sustainable development is hindered or reversed also remain. {6.1.1, Table 6.2; 6.1.5; 6.4.1.4; 6.4.3; 6.4.4}

Urban adaptation gaps exist in all world regions and for all hazard types, although exposure to the limits to adaptation are unevenly distributed. Governance capacity, financial support and the legacy of past urban infrastructure investment constrain how all cities and settlements are able to adapt (*high confidence*). Critical capacity gaps exist at city and community levels that hinder adaptation. These include the limited ability to identify social vulnerability and community strengths; the absence of integrated planning to protect communities; and the lack of access to innovative funding arrangements and limited capability to manage finance and commercial insurance (medium confidence). These can be addressed through enhanced locally accountable decision-making with sufficient access to science, technology and local knowledge to support widespread application of adaptation solutions. {6.3.1, 6.4.3; 6.4.5; 6.4.5.1; 6.4.5.2; Figure 6.4; Figure 6.5}

Slow uptake of monitoring and evaluation frameworks constrains potential for developing climate resilient urban development pathways (*medium confidence*). A lack of agreement on metrics and indices to measure urban adaptation investment, impacts and outcomes, reduces the scope for sharing lessons and joined-up action across interconnected sectors and places in the face of compound and systemic risks. These constraints affect the potential for climate resilient development pathways. Limits to adaptation are often most pronounced in rapidly growing towns and cities and smaller settlements including those without dedicated local government. At the same time, legacy infrastructure in large and mega-cities, designed without taking climate change risk into account, constrains innovation leading to stranded assets and with increasing numbers of people unable to avoid harm, including heat stress and flooding, without transformative adaptation. {6.2.5; 6.3.3.3; 6.3.7; Figure 6.4; 6.4.4; 6.4.6 FAQ6.5}

City and local governments are key amongst multiple actors facilitating climate change adaptation in cities and settlements (*medium confidence*). City and local governments can invest directly and work in partnership with community, private sector and national agencies to address climate risk. Private and business investment in key infrastructure, housing construction and through insurance requirements can also drive widespread adaptive action, though at times excluding the priorities of the poor (*medium confidence*). Networked community actions can also go beyond neighbourhood-scale improvements to address widespread vulnerability. Such actions include fostering roles of intermediaries and multiple spaces for networked governance across scales of decision making, improving development processes through an understanding of social and economic systems, foresight, experimentation and embedded solutions, and social learning. Transnational networks of local government can also enhance city level capacity, share lessons and advocacy (medium confidence). {Table 6.2, 6.3.3.4; 6.3.3.5; 6.4.1; 6.4.1.1; case study 6.2; FAQ6.5}

Globally, decisions about key infrastructure systems and urban expansion drive risk creation and potential action on climate change (*high confidence*). Urban infrastructure concentrates and connects populations, physical assets and energy use. Urban expansion and the compromising of green infrastructure and ecosystem services reduces adaptive capacity and can increase risk: the urban heat island – a product of expansion – can add 2°C to local warming. How settlements and key infrastructure are planned, designed and maintained determines patterns of exposure, social and physical vulnerability and capacity for resilience. Unplanned rapid urbanization including peri-urban development is a major driver of risk, particularly where cities and settlements are expanding into land that is prone to coastal flooding or landslides, or where there is inadequate water to meet the needs of growing populations. Urban decision-making processes equally shape how far low- and zero-carbon development can meet social needs – enhancing wellbeing while enabling climate change mitigation and advancing the Sustainable Development Goals. {6.1.3; 6.2.3; 6.2.4; 6.3.3; 6.3.4; 6.3.5; 6.4.6; Cross-Working Group Box URBAN in Chapter 6}

Investment in urban adaptation has not kept pace with innovations in policy and practice (*medium confidence*). Knowledge transfer and innovation in adaptation has broadened advances in social and ecological infrastructures including disaster risk management, social policy and green/blue infrastructure, especially where these are integrated with grey/physical infrastructure (medium evidence, high agreement). Innovation has also taken pace at the interface of difference systems, for example ICT and water or energy although financial investment has been slow to recognize and support these activities. Adaption finance continues to be directed at large-scale grey/physical engineering projects, neglecting maintenance and reproducing risk of stranded assets if climate change risk accelerates beyond planned-for levels. Finance deployed at the interface of multiple, integrated adaptation measures can support climate resilient development (high confidence). Access to finance is most difficult for city, local and non-state actors and in conditions where governance is fragile. {6.3.3; 6.3.4; 6.3.6; 6.4.5; 6.4.5.2; Table 6.10; Table 6.11; Box 6.8; case study 6.2; case study 6.3; case study 6.5}

Global urbanization offers a time-limited opportunity to work towards widespread and transformational adaptation and Climate Resilient Development (*high confidence*). Current dominant models of energy intensive and market-led urbanization build high carbon dependency and high vulnerability into cities, but this need not be the case. Integrated development planning that connects innovation and investment in social, ecological and grey/physical infrastructures can significantly increase the adaptive capacity of urban settlements and cities. Transitioning cities to low carbon development and equitable resilience may lead to trade-offs with dominant models of economic growth based on housing and infrastructure investment. Integrated planning approaches are important for Climate Resilient Development to enable planning and monitoring of interactions between development, mitigation and adaptation. Urban adaptation measures can offer a considerable contribution to Climate Resilient Development. This potential is realised by adaptations that extend predominant physical infrastructure approaches to also deploy nature based solutions and social interventions. The most consistent limit for all infrastructure types is in risk transfer. Current adaptation approaches in cities, settlements and key infrastructure have a tendency to move risk form one sector or place to others. Multi-level leadership, institutional capacity together with financial resources (including climate finance) to support inclusive and sustainable adaptation in the context of multiple pressures and interconnected risks, can help to ensure that global urbanization of an additional 2.5 billion people by 2050; reduces rather than generates climate risk (medium confidence). {Table 6.7; Table 6.5; 6.1.3; 6.3.6; 6.3.5.2; 6.4.7; Box 6.5; Cross-Working Group Box URBAN in Chapter 6; CCP2}

Intersectional, gender-responsive and inclusive action can accelerate transformative climate change adaptation. The greatest gains in wellbeing in urban areas can be achieved by prioritising investment to reduce climate risk for low-income and marginalised residents and targeting informal settlements (*high confidence*). These approaches can advance equity and environmental justice over the long term in ways more likely to lead to outcomes that reduce vulnerability for all urban residents. Participatory planning for infrastructure provision and risk management to address climate change and underlying drivers of risk in informal and underserviced neighbourhoods, the inclusion of Indigenous Knowledge and Local Knowledge, communication and efforts to build local leadership especially amongst women and youth are examples of inclusive approaches with co-benefits for equity. Providing opportunities for marginalised people, including women, to take on leadership and participation in local projects can enhance climate governance and its outcomes (high confidence). Since AR5, social movements in many cities, including movements led by youth, Indigenous and ethnic communities have also heightened public awareness about the need for urgent, inclusive action to achieve adaptation that can also enhance wellbeing. {6.1.5; 6.3.5; 6.4.1.2; 6.4.7; Box 6.6, case studies 6.2; 6.4 FAQ6.3}

City and infrastructure planning approaches that integrate adaptation into everyday decision-making are supported by the 2030 Agenda (the Paris Agreement, the Sustainable Development Goals, the New Urban Agenda and the Sendai Framework for Disaster Risk Reduction) (*high confidence*). The 2030 Agenda provides a global framework for city and community level action to be points of alignment between Nationally Determined Contributions, National Adaptation Plans of Action, and the Sustainable Development Goals. City and local action can complement – and at times go further than national and international interventions. Similarly, the Convention on Biological Diversity offers a global agreement through which nature-based solutions can be viewed as benefits for biodiversity, social justice and climate resilience. However, there is no specific global agreement that addresses informality and city level climate adaptation. More comprehensive and clearly articulated global ambitions for city and community adaptation will contribute to inclusive urbanization, by addressing the root causes of social and economic inequalities that drive social exclusion and marginalization, so that adaptation can directly support the 2030 Sustainable Development Agenda (high confidence). {6.1.1; Table 6.2; 6.2.3.2; 6.4.1.4; case study 6.4}

6.1 Introduction and Points of Departure

6.1.1 Background and Chapter Outline

Cities and urbanising areas are currently home to over half the world's population. What happens in cities is crucial to successful adaptation (Grafakos et al., 2019). By 2050 over two thirds of the world's population is expected to be urban, many living in unplanned and informal settlements and in smaller urban centres in Africa and Asia (*high confidence*) (UNDESA, 2018). Between 2015 and 2020, urban populations globally have grown by about 397 million people, with more than 90 percent of this growth taking place in Less Developed Countries (UNDESA, 2018). Projections of the number of people expected to live in urban areas highly exposed to climate change impacts have also increased, exacerbating future risks under a range of climate scenarios. Rates of population growth are most pronounced in smaller and medium sized settlements of up to 1 million people (UNDESA, 2018).

Since AR5 there has been increasing understanding of the interdependence of meta-regions, large, small and rural settlements which may be connected through key infrastructure (Lichter and Ziliak, 2017) including national and trans-national infrastructure investments (Hanakata and Gasco, 2018). Almost all the world's non-urban population and its provisioning ecosystems are impacted by urban systems through connecting infrastructure and family and kinship ties, remittances and trade arrangements that influence flows of water, food, fibre, energy, waste and people (Trundle, 2020; McIntyre-Mills and Wirawan, 2018; Zhang et al., 2019; Nerini et al., 2019; Friend and Thinphanga, 2018). Many rural places are so deeply connected to urban systems that risks are observed to cascade from one to the other – for example when drought in arable zones leads to food insecurity in cities, or where flood damage to urban transport infrastructure leads to prolonged isolation of small towns and rural settlements (Friend and Thinphanga, 2018; McIntyre-Mills and Wirawan, 2018). A focus of this chapter is the experience of a range of urban settlements, from small to large, and the connecting infrastructure and formal and informal networks and systems that join them to each other. There are close synergies with chapters 7 (Health, wellbeing and the changing structure of communities) and 8 (Poverty, livelihoods and sustainable development). There are further important synergies with Working Group III Chapter 8 (Urban systems and other settlements) and the Cross-Chapter Paper 2: Cities and Settlements by the Sea.

Well planned climate adaptation can have far reaching co-benefits for sustainable development, and community wellbeing (Nerini et al., 2019; Tonmoy et al., 2020). However the varied success of cities' responses to the global COVID-19 pandemic underscores how social and economic conditions, built environments and local planning can exacerbate or reduce vulnerability and long term sustainable, community wellbeing (Megahed and Ghoneim, 2020; Plastrik et al., 2020; Hepburn et al., 2020; Sarkis et al., 2020).

Many of the significant sustainable development initiatives that have been proposed and implemented in the last five years recognise the critical importance of cities, settlements and key infrastructure in responding to the crisis of climate change (Zhang et al., 2019; Nerini et al., 2019). There is widespread acceptance of the need for far-reaching responses by actors from the local to the global scales to make human settlements and infrastructure more resilient (UNDP, 2021). There is recognition also of the considerable capacity in settlements to meet climate change challenges, if the governance, financial and social conditions are in place (Carter et al., 2015; MINURVI, 2016). And yet the implementation of climate adaptation planning lags behind climate mitigation efforts in urban communities (Sharifi, 2020; Grafakos et al., 2019; Nagendra et al., 2018).

Since the publication of AR5, there has been rapid expansion in policy, practice and research related to climate change and human settlements. The 2030 Agenda for Sustainable Development (the Sustainable Development Goals) agreed in September 2015, was preceded by the Sendai Framework for Disaster Risk Reduction 2015-30 and followed shortly afterwards by the Paris Agreement (December 2015) (United Nations, 2015b). These make explicit mention of "mainstreaming of disaster risk assessments into land-use policy development and implementation, including urban planning" (Sendai Framework) (UNISDR, 2015). The agreements identify "sustainable cities and communities" (SDG11) and "cities and subnational authorities" (Paris Agreement) as important actors in integrating climate and development goals (Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018). However not all urban SDGs have measurable targets yet, or data particularly in regard to children and youth, the elderly and disabled (Klopp and Petretta, 2017; Reckien et al., 2017; Nissen et al., 2020). Clear procedures for linking climate adaptation in communities at all scales to the SDGs is lacking (Major, Lehmann and Fitton, 2018; Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018).

The New Urban Agenda (NUA) (October 2016), with its focus on housing and sustainable urban development, commits its signatories to building resilient and responsive cities that foster climate change mitigation and adaptation (United Nations, 2016b). This agreement followed the Geneva UN Charter on Sustainable Housing, endorsed by 56 member states of the United Nations Economic Commission for Europe (United Nations, 2015d). The NUA aims to ensure access to decent, adequate, affordable and healthy housing for all while reducing the impact of the housing sector on the environment and increasing resilience to extreme weather events (United Nations, 2016b). Voluntary, networked action led by cities was also illustrated by a November 2019 call to Mayors and youth climate activists to sign a voluntary pledge in a "Race to Zero" ahead of the Conference of the Parties 26, which included endorsing principles of a New Green Deal (C40, 2019). Other voluntary, global, urban efforts have been led by the scientific community including the Research and Action Agenda on Cities and Climate Change Science which aims to promote research and reports (Prieur-Richard, Walsh and Craig, 2019).

These collaborative global changes are reflected in the bodies of literature assessed for this report. In AR5, the section on 'human settlements, industry, and infrastructure' contained three chapters: urban areas; rural areas; and key economic sectors and services. This chapter covers the full range of human settlements: from small settlements in predominantly rural areas, to large metropolises in both high-income and low-income countries. It also assesses evidence of climate change impacts, vulnerability and adaptation on a range of urban infrastructures including infrastructure that incorporates socio-economic, and ecosystem dimensions (see 6.1.3).

This assessment also considers new literature about how enabling environments can support adaptation in ways that are also sensitive to Indigenous knowledge and local knowledge (see below 6.1), social justice (6.4.3.d) and climate mitigation (6.3.5.2). It builds on the findings of AR5 which highlighted the concentration of global climate risks in urban areas, the complex causal chains that mediate climate impacts for smaller settlements and rural areas, and the multiple issues shaping and influencing economic sectors and infrastructure. This integrated chapter enables a more detailed analysis of the inter-connected drivers of risk that affect urban people and settlements of different sizes. This discussion also highlights the inter-connections within and between urban areas, and between different types of infrastructure and how these complex relationships accentuate or limit the effects of climate change and the institutional structures that play a critical role in mediating and govern these relationships.

This chapter has five main sections. The first elaborates on changes in the international policy context since 2014, highlighting the implications that this has for responses to climate change in cities, settlements and key infrastructure. Section 6.2 is focused on observed and projected climate risks, paying particular attention to the ways in which these are created through processes of urbanization and infrastructural investment. Section 6.3 takes an integrated and holistic approach to an assessment of adaptive actions relevant to key infrastructures (those that form the material basis for resilience in cities and settlements, drive economies, and are essential for human wellbeing). Section 6.4 assesses the enabling conditions and leadership qualities associated with adaptation processes that can also meet the equity agenda of the Sustainable Development Goals – to leave no-one behind including the role of governance, finance, institutions and emerging literature around the limits of urban adaptation.

Case studies highlight how climate and other issues interrelate to create (or reduce) urban risk within and between scales of decision-making. They illustrate how multiple levels of governance and formal and informal decision-making sectors influence how risk production/reduction plays out across a range of urban contexts and networks.

6.1.2 Points of Departure

The AR5 conceptualised cities and settlements as complex interdependent systems that could be engaged in supporting climate change adaptation (Revi et al., 2014 8.8.2). Effective municipal governance systems and cooperative multilevel governance supported adaptation action. The AR5 report expressed *medium confidence* that governance interventions can help develop synergies across geographical and institutional scales. Urban areas face challenges of infrastructure investment and maintenance, land use management, livelihood creation, and ecosystem services protection. AR5 also considered how urban localities can encourage incremental and transformative adaptation, build resilience and support sustainable development. The assessment identified the need for multi-level and multi-partner action in rapidly growing cities where institutions and infrastructure are still not established to meet the growing demands of the cities. However, there was only *medium confidence* that adaptation action was happening in the AR5 review period.

The framing of 'key economic sectors and services' in AR5 focused primarily on three infrastructural areas (energy, water services, transport) and on primary and secondary economic activities (including recreation and tourism, insurance and financial services). Cities, settlements and key infrastructure are also referred to in the IPCC special reports released since AR5. The Special Report on Global Warming of 1.5°C examines impacts of global warming on urban systems and infrastructure in the context of advancing sustainable development and eradicating poverty. It highlights the risks facing residents of unplanned and informal urban settlements, many of which are exposed to a range of climate-related hazards (Sections 3.4.8 and 4.4.1.3). The Special Report on Global Warming of 1.5°C also identifies green infrastructure, sustainable land use and planning, and sustainable water management as key adaptation options that can reduce risks in urban areas (SPM C2.4; C. 2.5), and highlights "urban and infrastructure" as one of four system transitions required to limit warming to 1.5°C to create an enabling environment for adaptation (Section 4.3.3). Innovative governance arrangements that go beyond formal 'government' and political arrangements and that include non-state actors, networks and informal institutions were identified as important in addressing climate change and implementing responses to 1.5°C-consistent pathways (Special Report on Global Warming of 1.5°C (Section 4.4.1 and 5.6.2). In addition, the Special Report on Global Warming of 1.5°C mentions, with *high confidence*, the climate related health effects of urban heat islands, urban heatwaves and increasing risks from some vector-borne diseases (illnesses caused by pathogens and parasites in human populations) (SPM B 5.2). The report also notes both trade-offs and important co-benefits of sustainable development in pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (SPM D6).

The Special Report on Oceans and Cryosphere (SROCC) similarly emphasises the role governance plays in reducing disaster risk, through planning, and zoning. It identifies vulnerability factors such as poverty, which can undermine resilience and sustainable development in urban communities (SPM C31, Section 2.3.2.3; pp. 135; 164). The SROCC report shows that the emerging climate related challenges are impacting the accessibility and availability of vital resources and blurring the public and private boundaries of risk and responsibility (Cross-Chapter Box 3 p 99). According to the SROCC report, new governance arrangements are emerging to address these challenges, including participatory and networked structures, and institutions linking formal and informal networks involving state, private sector, Indigenous and civil society actors (Cross-Chapter Box 3 p 99). The SROCC report calls for place-specific action because there is no single climate governance panacea for the ocean, coasts, and cryosphere Cross Chapter box 3 p 99). The SROCC report highlights evidence of the importance of inclusivity, fairness, deliberation, reflexivity, responsiveness, social learning, the co-production of knowledge, and respect for ethical and cultural diversity in climate related urban decision-making (Cross-Chapter Box 3). In addition, the Special Report on Climate Change and Land notes that urbanisation can intensify extreme rainfall events over the city or downwind of urban areas and have can significant consequences for heat island effects loss of food production posing additional risks to the food system (SPM A5.3 and Cross-Chapter Box 4 in Chapter 2).

An additional research bridge between AR5 and AR6 was the IPCC Cities and Climate Change Science conference in Edmonton, Canada March 2018. This generated a 'Global Research and Action Agenda on Cities and Climate Change Science' (Prieur-Richard, Walsh and Craig, 2019), which highlights six topical research areas where more evidence is needed to inform action: finance; informality; uncertainty; urban planning and design; built and green/blue infrastructure; and sustainable consumption and production. These areas are addressed in specific sections of this chapter or as cross-cutting themes. The Cross-Working Group Box provides a linkage with perspectives from Working Group III.

6.1.3 Terminology and Definitions

This chapter covers both 'cities and settlements' and 'key infrastructure'.

Definitions of 'urban' have become more nuanced since the AR5 review with the publication of the OECD report 'A new perspective on urbanisation' (OECD and European Commission, 2020). This report presents two new global definitions of urbanisation reflecting the degree of urbanisation on a continuum of cities, towns & semi-dense areas, and rural areas. The OECD estimates almost half the world's population (48%) live in cities, while just 24% live in rural areas and 28% live in towns & semi-dense areas (28%). In addition, the OECD report defines metropolitan areas as functional urban areas together with their surrounding commuting zones 'to capture the full extent' of a city's working population. Metropolitan areas account for 54% of total world population, with the OECD estimating that commuting zones representing 17% of the overall metropolitan population, rising to 31% in high-income countries. In the context of these global definitions, this chapter identifies 'cities and settlements' as concentrated human habitation centres (along a dynamic continuum from rural to urban (Murali et al., 2019; Ward and Shackleton, 2016) (Figure 6.1) and that are fundamentally inter-connected to other urban centres and rural areas as nodes within broader networks.

Key infrastructure is used here to refer to 'critical nodes and arteries' that comprise urban energy, food, water, sewerage, health, transport and communication systems (Steele and Legacy, 2017; Maxwell et al., 2018; Bassolas et al., 2019). Key or critical infrastructure provides much of the material basis of cities and settlements, as well as the mechanisms for enabling flows of people, goods, data, waste, energy (through urban metabolism processes of consumption and production) and capital, between urban regions and rural areas (Blay-Palmer et al., 2018; Dijst et al., 2018). An overview of this process of 'planetary' urbanization is provided in Box 6.1. The balance of accumulated scientific knowledge on climate risks, impact and adaptation has been generated from studies in large and medium sized cities of 1 million or more. While these larger cities continue to grow rapidly (UNDESA 2018), settlements of more than 5 million people contain less than a quarter of the world's urban population, and more than half of the world's urban residents live in settlements of 1 million or less (Table 6.1). There is a key gap in knowledge, especially concerning urban enabling environments and how smaller settlements can be supported to accelerate equitable and sustainable adaptation in the face of financial and governance constraints (Birkmann et al., 2016; Shi et al., 2016; Dulal, 2019; Rosenzweig et al., 2018b).

Table 6.1: Proportion of the urban population in different size class urban areas (UN-DESA 2018). Each column indicates the percentage of urban residents in that region living in cities of that size class.

Proportion (by region) of urban population living in cities with population size:	Africa	Asia	Latin America and the Caribbean	Europe	Northern America	Oceania	World
10 million +	8	15	17	4	10	0	13
5-10 million	6	9	3	5	17	0	8
1-5 million	22	22	25	16	30	60	22
500,000-1 million	9	10	8	11	13	2	10
300,000-500,000	6	6	6	8	7	11	6
Under 300,000	48	38	40	57	24	27	41

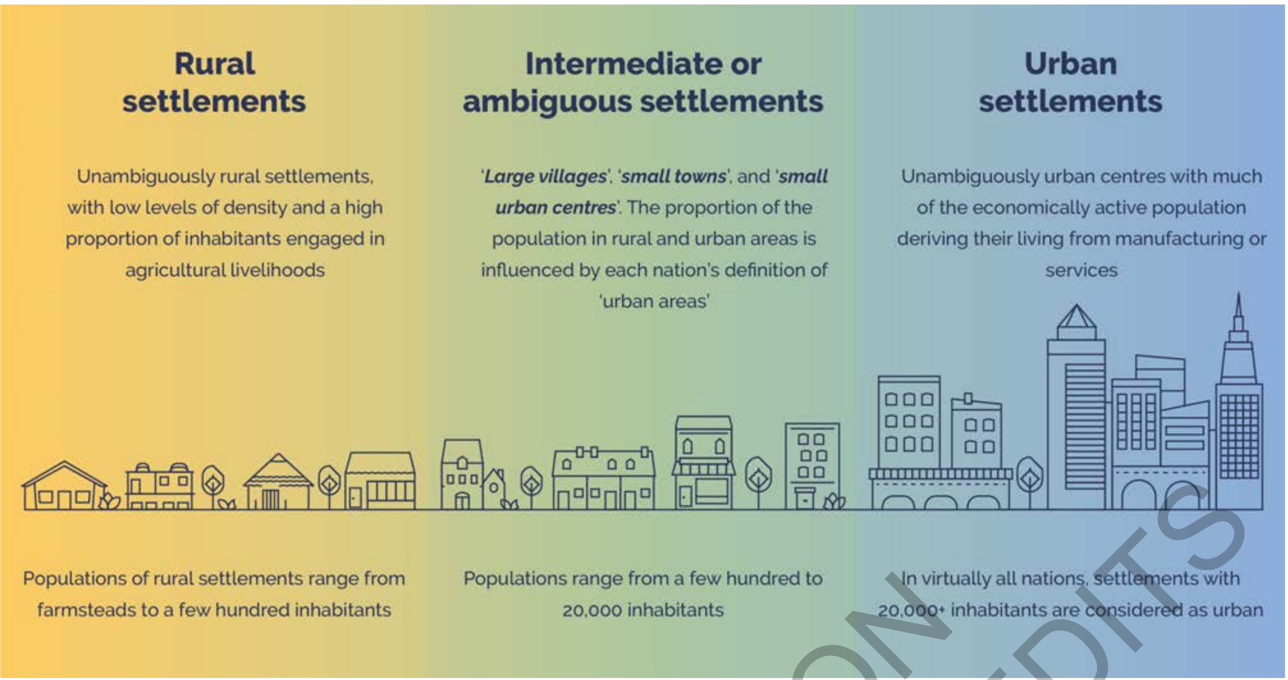


Figure 6.1: Defining 'urban' and 'rural' in relation to cities and settlements

The chapter takes a comprehensive approach to understanding 'key infrastructure' as expressed in social, nature-based and physical infrastructure. Social infrastructure includes the social, cultural, and financial activities and institutions as well as associated property, buildings and artefacts and policy domains such as social protection, health and education that support wellbeing, public life (Frolova et al., 2016; Latham and Layton, 2019). Nature-based infrastructure focusses on solutions to risk applying natural assets such as trees or open water, physical infrastructure describes engineering approaches. Grey/physical infrastructure refers to engineered assets that provide one or multiple services required by society, such as transportation or wastewater treatment ((IISD, N.D.); see also IPCC glossary).

This approach is based on a framing of cities and settlements as complex systems where social, ecological and physical processes interact in planned and unplanned ways. The chapter therefore builds on the AR5 chapter 10 conception of key economic sectors and services (e.g. energy, water, transport, waste, sanitation and drainage) by positioning these within three major categories of infrastructure: social, nature-based and physical (see Section 6.3). Where adaptation challenges can be responded to by more than one approach, sometimes working together, this is noted (see also Chapter 17.2; 17.4). This approach allows an understanding of adaptation that is not constrained to the administrative boundaries of cities and settlements, but that includes the networks and flows that connect peri-urban communities, metropolitan regions, suburban settlements and more rural places (See Box 6.1). Both formal provision of infrastructure services by government and informal provision by communities and individuals are considered at risk from climate change as are existing adaptation pathways and actions.

Cities are complex entities where social, ecological and physical systems interact in planned and unplanned ways (Markolf et al., 2018). The complexity of cities, settlements and key infrastructure (Figure 6.2) where multiple functional systems continuously interact, makes it difficult to distinguish risks (Box 6.1). The literature often resolves this by offering discrete assessments for specific sectors (see Section 6.3). This fragmented approach to understanding climate change associated impacts and risks is then reflected also in siloed approaches to risk management and adaptation financing (see Section 6.4). Recent literature notes that resilience planning has begun to overcome this tendency by presenting climate change impacts, losses and damages, and urban processes, as unfolding together in interacting and cascading pathways (Fraser et al., 2020; Eriksen et al., 2020) (Figure 6.2). The chapter reflects this change in the literature by presenting climate change impacts through a series of risk assessments, including by hazard type, through indirect impacts on: health or food security, key infrastructure systems, land-use and human mobility; water flows and on structural conditions, like poverty and justice in the city (see Sections 6.3 and 6.4). In a departure from AR5 we also consider the consequential interactions of climate risks, impacts, adaptation and climate mitigation (see also Cross Working Group Box URBAN in Chapter 6).

The IPCC 1.5°C Special Report commented that “The extent of risk depends on human vulnerability and the effectiveness of adaptation for regions (coastal and non-coastal), informal settlements, and infrastructure sectors (energy, water, and transport) (*high confidence*)” (Masson-Delmotte and Waterfield, 2018).We take this statement as a starting point for assessing the risks to cities, settlements and key infrastructure, with infrastructure extended as noted above. Risks from climate change are understood as the product of climate change associated hazards impacting on exposed and vulnerable people and assets (including biodiversity). Adaptation can in some cases reduce exposure and susceptibility and enable recovery and scope for transformation towards long-term equitable and sustainable development. Risks describe both present conditions and also future prospects. Direct attribution of hazards to climate change remains limited to temperature extremes and sea-level rise, though we consider all hydrometeorological hazards as systems associated with climate change processes.

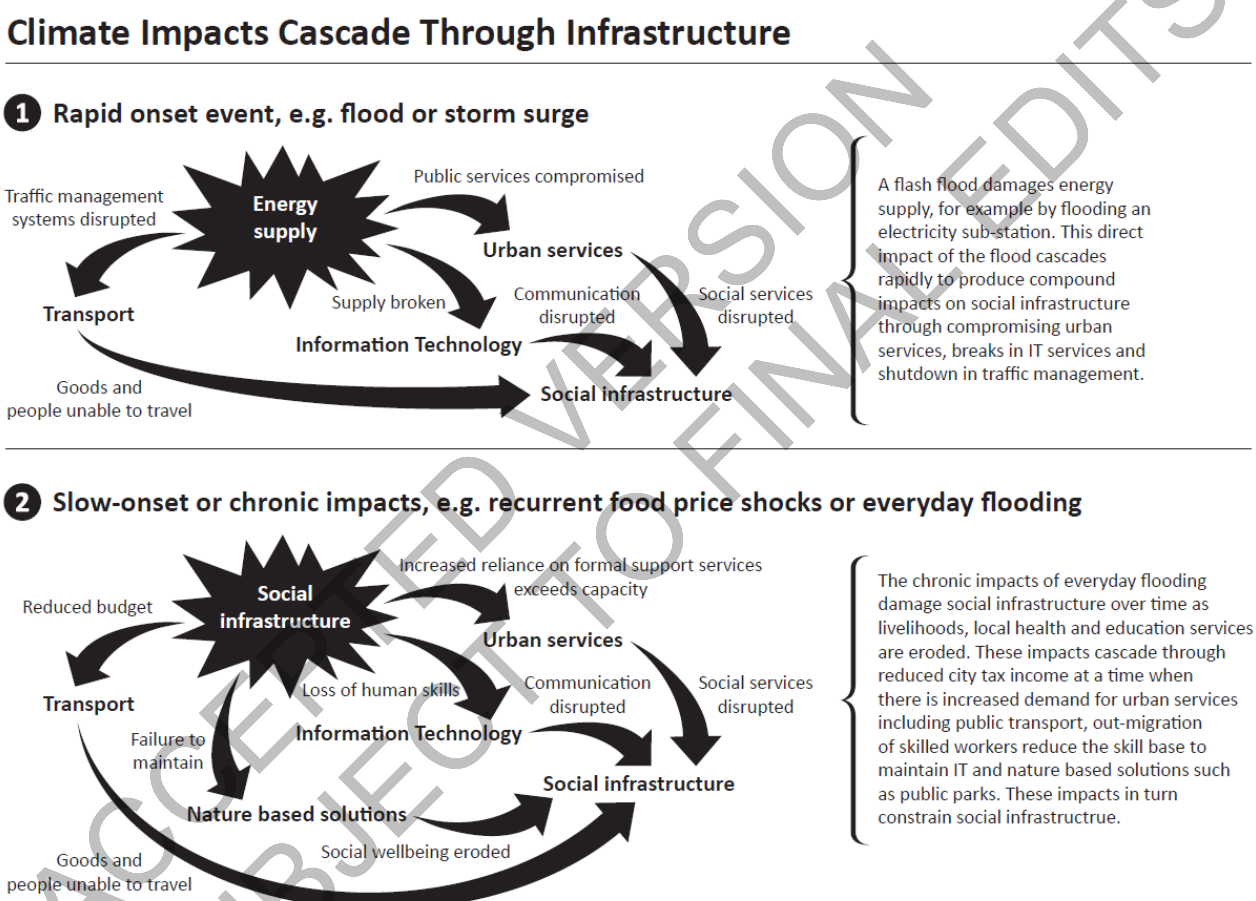


Figure 6.2: The interconnected nature of cities, settlements and infrastructure.

The chapter also assesses conditions supporting incremental and transformative adaptation (6.4). Incremental and transformative adaptation are both important but serve distinct roles in the interaction of urban systems, climate risk and risk management and in advancing social justice, just-transitions and climate resilient development (see 6.4). Climate resilient development pathways are an emerging concept in literature since the AR5 (Schipper et al., 2020). Climate resilient development is an iterative process of systemic change that integrates both mitigation and adaptation efforts (see Glossary). Initial studies highlight the way rapid urbanization and precarious urban housing and land tenure can undermine climate resilient development while human settlements that are managed to protect housing tenancy and land tenure rights, can advance land-use planning and social learning while reducing inequalities, and vulnerability, and enhancing resilient development (Mitchell, Enemark and Van der Molen, 2015; Bellinson and Chu, 2019; Ürge-Vorsatz et al., 2018). The benefits of integrating decision-making across scales for climate resilient development is also highlighted in 6.4. How households engage with communities and neighbourhoods and larger units within cities and how cities (both formal and informal) interact with sub national and national actors is also discussed as is the role of finance, and CBOs/NGOs in the governance process.

6.1.4 Global Urban Trends

Since AR5, many cities and other settlements, particularly unplanned and/or informal in Asia and Africa, have continued to grow at rapid rates (van den Berg , Otto and Fikresilassie 2021). Elsewhere, in Latin America in particular, while growth is less rapid, inequality persists. As a result, cities and settlements are crucial both as sites of potential action on climate change, and sites of increased exposure to risk (medium evidence, high agreement).

Patterns and trends for urban population growth were described in detail in AR5. Between 2015 and 2020, urban populations globally have grown by more than 397 million people, with more than 90 percent of this growth taking place in Less Developed Regions (UNDESA, 2018). The latest population projections from UNDESA (2018) reinforce the trends identified previously, with even higher estimates for global urban populations. The 2012 data used in AR5 projected a global urban population of 4,984 million in 2030 and 6,252 million in 2050; the 2018 revisions project 5,167 million and 6,680 million respectively. Particularly noteworthy is the higher projection provided for sub-Saharan Africa's urban population: increasing from 596 million to 666 million in 2030, and from 1,069 million to 1,258 million in 2050. These figures highlight the continued trend towards larger urban populations, and the particular significance of this in areas which currently have relatively small proportions of their populations living in towns and cities – this is also true in some Small Island States (e.g. Solomon Islands) (McEvoy et al., 2020). The proportion of the global urban population living in megacities (with populations of more than 10 million people) is expected to continue growing slowly (to 16% of the urban total, or 862 million people, living in 48 agglomerations) by 2035 (UNDESA, 2018). The size and form of these megacities presents particular challenges with climate change impacts, in areas including air quality (Baklanov, Luisa and Molina, 2016), flooding (Januriyadi et al., 2018), and temperature increase (Darmanto et al., 2019) (see 6.2.3).

While there are few analyses of urban trends at the global scale, an additional 2.5 billion people are projected to be living in urban areas by 2050, with up to 90 percent of this increase concentrated in the regions of Asia and Africa, particularly in India, China and Nigeria where 35 percent of this urban growth is projected to occur (UNDESA, 2018). Growth rates are slowing down in North America, South America and Europe (UNDESA, 2018). Much global growth continues to outstrip the ability of governments or the private sector to plan, fund and provide for sustainable urban infrastructure and this is most marked in low-income and informal settlements (Angel et al., 2016). Rural migration as a driver of urbanisation is discussed in 6.2.4.3, and literature has documented the way urban expansion, and the conversion of agricultural land is also driven by investment incentives and weak planning policies (Colsaet, Laurans and Levrel, 2018; Woodworth and Wallace, 2017). At the same time, early evidence suggests that – at least in some locations – out-migration from cities occurred as a result of the COVID-19 pandemic (Rajan, Sivakumar and Srinivasan, 2020) but the evidence is not clear and in some cases may have increased migration to other megacities (Chow et al., 2021). There is also growing recognition that poor planning has exacerbated the concentrated of deprivation in specific locations deepening a cycle of exclusion and marginalization (UNDESA, 2020).

One critical element of global urban trends, which has received growing attention is informality (see also Prieur-Richard, Walsh and Craig, 2019). Informality is one of the key defining features of cities and settlements in the Global South (See Glossary; Banks, Lombard and Mitlin, 2020; Myers, 2021; UNHABITAT, 2016). In almost all nations in the Global South, more than half the urban workforce work in informal employment; the proportions are particularly high in South Asia (82 percent in informal employment) and sub-Saharan Africa (66 percent) (Chen, Roever and Skinner, 2016; Chen, 2014). The term 'informal settlement' refers to urban settlements or neighbourhoods that developed outside the formal system that is meant to record land ownership and tenure and without meeting a range of regulations relating to planning and land use, built structures and health and safety. Informality is a broader concept than 'slums', which are usually defined using measures of housing quality, provision of services and overcrowding. While most countries do not generate formal statistics on the number of people living in informal settlements, UN Habitat provides regional and global estimates of the number of urban households that are 'slum' households and therefore likely to include most residents of informal settlements. These estimates suggest that there were 1034 million slum dwellers in 2018, including some 56 per cent of the urban population in sub-Saharan Africa and more than 30 percent of the urban population of South Asia (UN-Habitat, 2020). Informality is particularly important in understanding climate risks and responses in cities and settlements, and also in relation to key infrastructure (Trundle, 2020; Taylor et al., 2021).

Evidence since AR5 confirms that occupants of informal settlements are particularly exposed to climate events given low-quality housing, limited capacity to adapt, and limited or no risk-reducing infrastructure (*high confidence*) (Melore and Nel, 2020; Twinomuhangi et al., 2021; Satterthwaite et al., 2020; Patel et al., 2020a)(see 6.2 and case study). The impacts of COVID-19 are also increasingly impacting high-density informal and slum settlements where social distancing and access to water for handwashing are limited (Bhide, 2020; Pinchoff et al., 2021; Tagliacozzo, Pisacane and Kilkey, 2021; Wilkinson, 2020). This compounds pre-existing vulnerability to climate change associated hazards. Box 6.1 expands on trends in informality as part of global urbanism, peri-urbanization and suburbanization with implications for the global distribution of climate risks and adaptive capacity.

[START BOX 6.1 HERE]

Box 6.1: Planetary Urbanisation and Climate Risk

The scale, reach, and complexity of contemporary urbanization compounds climate risks and conditions adaptation (*high confidence*) (Miller and Hutchins, 2017; Rosenzweig et al., 2018b). Urbanization manifests as a heterogeneous and plural process with varied spatial manifestations (Oswin, 2018) that extends beyond cities and settlements, defining actions elsewhere in what has been called 'planetary urbanization' (Brenner, 2014b). While the concept of Planetary urbanisation is contested for example for a predominantly Eurocentric focus (Vegliò, 2021) the concept has reflected human urbanisation as a mega-trend of urban expansion and landuse intensification (Capon, 2017; Lauermann, 2018). Three dimensions of planetary urbanization are currently shaping adaptation actions: the new forms and scales of urbanization, the blurring of boundaries around clearly demarcated territories, and the fragmentation of the urban hinterland into units that serve productive functions for the reproduction of urban space under capitalism (Brenner and Schmid, 2017).

Planetary scale urbanization challenges current understandings of spatial settlements and how risk affects urban communities (*limited evidence, medium agreement*) (Ruddick et al., 2018). Massive urbanization manifests in large agglomerations such as metropolitan areas and urban regions, conurbations with unique risk challenges, particularly when interacting with other drivers of vulnerability (Adetokunbo and Emeka, 2015; Maragno, Pozzer and Musco, 2021). Experiences of regional collaboration to scale adaptation to metropolitan areas have shown to be effective, particularly facilitating information and technology exchanges and institutional cooperation (Shi, 2019; Lundqvist, 2016), but may face challenges such as addressing administrative and fiscal requirements and enrolling local populations in a meaningful participation process (Shi, 2019). For example, the coordination of planning policies in the Vienna-Bratislava metropolitan region, further divided by an international border, demonstrates that institutional coordination alone is not sufficient to deliver effective spatial governance: instead, meaningful spatial policies required the involvement of multiple actors (Patti, 2017). In addition to institutional coordination, adaptation in rapidly urbanizing areas requires understanding how these processes magnify risk and condition urban responses (see also 6.3).

Urban expansion processes affect human settlements everywhere, regardless of their size. Figure 6.1 represents a continuum of settlements from high to low-density areas (Ward and Shackleton, 2016). Urban and rural areas are not always clearly differentiated (Brenner, 2014a; Brenner and Schmid, 2017). For example, in 2010/2011, drought-exacerbated wildfires across Russia's agricultural hinterland not only led to increased air pollution in Moscow and other large cities in the region it also disrupted global supply chains of wheat and caused skyrocketing global food prices (Zscheischler et al., 2018). Floods in Bangkok, Thailand, in 2011 destroyed many foreign-owned factories, leading to a global shortfall in different types of IT equipment (Levermann, 2014).

Rural areas provide ecosystem services that benefit cities directly including thorugh reducing hazard (run-off, and temperature) and thorugh carbon storage – and can be maintained through urban markets and other inputs (Gebre and Gebremedhin, 2019). Most urban areas extend into dispersive peri-urban areas where urban and rural land uses coexist (Simon, 2016) and/or suburban areas which are lower density and primarily residential in function. Moreover, the urban and rural differentiation creates normative expectations at the heart of planning conflicts and constraints urban governance (Taylor, Butt and Amati, 2017). Expanding peri-urban areas pose specific structural constraints to addressing risks. In Bogotá, Colombia, a study found marked inequalities as more impoverished families had restricted access to peri-urban forests, trees, and tree services (Escobedo et al., 2015). Factors like limited land ownership and tenure insecurity in peri-urban areas hinder people's ability to invest in permanent infrastructure to buffer themselves from flood events, as witnessed in the slums in Nairobi (Thorn, Thornton and Helfgott, 2015). Building resilience and adaptation via community mobilization may not be effective in peri-urban areas shaped by migration, agricultural intensification, and industrialization (Wandl and Magoni, 2017).

At the same time, actions to improve access to peri-urban services almost always improve resilience (Simon, 2016) Evidence from Kampala, Addis Ababa, Dar es Salaam, Douala, Ibadan, Nairobi, Dakar and Accra shows that urban and peri-urban agriculture and forestry can support adaptation (Lwasa et al., 2014). In the metropolitan area of Milan, multifunctional agriculture supports a local, more sustainable food chain (Magoni and Colucci, 2017). Since communities in peri-urban areas are often transitory, efforts towards creating social capital by promoting civic engagement are crucial to facilitate collective action (Narain et al., 2017). For example, adaptation actions can help to build the capacity of the community to engage with service providers (Harris, Chu and Ziervogel, 2018; Ziervogel et al., 2017), as demonstrated in parts of peri-urban Kolkata, India, and Khulna, and Bangladesh (Gomes and Hermans, 2018; Gomes, Hermans and Thissen, 2018).

Urbanization on an immense scale blurs the boundaries that previously defined cities and settlements (Arboleda, 2016a; Shaw, 2015; Brenner, 2014a; OECD and European Commission, 2020; Schmid, 2018; Davidson et al., 2019; Wu and Keil, 2020). For example, peri-urban areas typically extend over multiple government jurisdictions (Wandl and Magoni, 2017). Adaptation actions can be difficult to plan, coordinate, implement and evaluate in these transboundary contexts (Solecki et al., 2018; Srivastava, 2020; Fünfgeld, 2015; Rukmana, 2020; Carter et al., 2018). In Medellín, Colombia, a 46-mile-long green belt is being built to stop urban expansion while also protecting urban forests, providing access to green spaces, and reducing urban heat island effects (Anguelovski et al., 2016). However, large-scale infrastructure projects like this one require coordination between regional transport authorities and the different municipalities in charge of housing and public services, in addition to consulting communities on their social impact (Chu, Anguelovski and Roberts, 2017). Local and regional authorities have competing mandates – such as a competition for taxpaying residents in peri-urban, commuting zones – and different infrastructure investment logics, political drivers, and constituent needs. Smaller discrete infrastructure projects that actively engage local populations may provide better opportunities to build resilience across fragmented spaces (Santos, 2017; Kamalipour and Dovey, 2020).

Suburbanization follows a gradual movement of citizens from high-density urban centres to the suburbs (Pieretti, 2014). Suburbanization generates new ways of appropriating space where, again, inequality (both in terms of limited access to access and limited capacity to respond to external changes) seems to be the main driver and a magnifier of its impacts (Keil and Macdonald, 2016). The development of enclaves for higher-income people, that appropriate resources and constraint the access to those resources for disadvantaged populations has been recorded in places as distant as Santiago de Chile, People's Republic of China, India, Indonesia, or the Philippines (Calvet and Castán Broto, 2016; Phelps, Miao and Zhang, 2020; Bulkeley, Castán Broto and Edwards, 2014; Buchori et al., 2021; Kleibert, 2018). The appropriation of land and resources in enclaves defends exclusive, privileged communities at the expense of everyone else. Enclaves exacerbate inequalities because those who cannot afford to live in the enclave suffer the fragmentation of public services, restrictions in access to resources, and greater exposure to climate risks (Hodson, 2010; Haase et al., 2017a). Moreover, suburbanization is linked to the privatization of public spaces and the decline of public infrastructures, collective spaces, and green projects (Long and Rice, 2019; North, Nurse and Barker, 2017). Climate gentrification, whereby vulnerable communities are displaced from urban areas with lower climate risks (UN-Habitat, 2020), reconfigures urban areas, for example, as higher-income populations move away from the city centers, as shown in North American cities that have already suffered climate-related impacts such as Miami, Philadelphia and New Orleans (Keenan, Hill and Gumber, 2018; Shokry, Connolly and Anguelovski, 2020; De Koning and Filatova, 2020; Aune, Gesch and Smith, 2020).

Urbanization leads to the spatial fragmentation of the hinterland, divided alongside functional units to serve the demands of the capitalist urban economy (Brenner and Schmid, 2017). Urbanization is thus linked to new intensities of resource exploitation that threaten vulnerable land and ecosystems, as shown in the Amazon and that extend across scales (Arboleda, 2016b; Wilson, 2018). The fragmentation of the hinterland for extractivist purposes depletes ecosystem services and further exacerbates cascading risks (*high confidence)* (Section 6.2.6).

[END BOX 6.1 HERE]

Adaptation and related concepts of urban climate resilience are also concerns for the broader agenda of sustainable development (Wachsmuth, Cohen and Angelo, 2016). Urban areas can play a positive role in advancing sustainability, but the pace and scale of urban development can also undermine progress in SDGs (Barnett and Parnell, 2016; Maes et al., 2019; Anarfi, Hill and Shiel, 2020) (*high confidence*). With careful planning, urbanization can be a transformative force, enhancing equity and wellbeing through co-benefits and synergies between climate change adaptation, equitable urban development and mitigation (*medium evidence, medium agreement*) (Parnell, 2016a; Solecki et al., 2015; Sharifi, 2020). Cities can be effective change agents when supported by networked local and national institutions including professional bodies (*high confidence*) (Andonova, Hale and Roger, 2017; Brandtner and Suárez, 2021; Heidrich et al., 2016; Kern, 2019; Farzaneh and Wang, 2020). Low Emission Development Strategies (LEDS) have developed effective science-policy interaction to support energy system, environmental, and economic development planning strategies in the city of Shanghai, China (Farzaneh and Wang, 2020). New literature is emerging about how adaptive changes at the urban level could integrate both far reaching rapid emission reduction and community protection in transformative ways (Wamsler and Raggers, 2018; Rosenzweig and Solecki, 2018; UN-Habitat, 2020; Ziervogel, 2019a). There is an increasing consensus about the need for integrated governance of urban areas within and across regions, so that urban risk management and adaptation happen hand in hand with more general processes of transition towards more sustainable urban regions (Simon, 2016; UN-Habitat, 2020).

Since AR5 there has also been increasing recognition of the contribution of diverse knowledges including local and Indigenous knowledge in contributing to the development and interpretation of urban relevant climate change data and policy for effective action (Klenk et al., 2017; Hosen, Nakamura and Hamzah, 2020; Makondo and Thomas, 2018). Indigenous and local knowledge inform coping strategies in urban adaptation planning and new directions for action (Nakashima, Krupnik and Rubis, 2018; Abudu Kasei, Dalitso Kalanda-Joshua and Tutu Benefor, 2019). Indigenous and local knowledge is also found to shape perceptions about urban climate risk awareness, its acceptable limits, causation and preferences for adaptation (see also Pyhälä et al., 2016 for a review; see Jaakkola, Juntunen and Näkkäläjärvi, 2018 for impacts on Indigenous peoples in the EU; Saboohi et al., 2019). Local perceptions about climate change in turn influence adaptation behaviours in settlements and urban communities (Lee et al., 2015; Larcom, She and van Gevelt, 2019). Engagement with Indigenous and local knowledge is an enabling condition for planning community-appropriate climate adaptation responses (Fernández-Llamazares et al., 2015). Urban decision-making that includes Indigenous and local knowledge has co-benefits for addressing Indigenous dispossession, historical inequities and marginalization of Indigenous values that occurred (Parsons et al., 2019; Carter, 2019; Maldonado et al., 2016; Orlove et al., 2014; Pearce et al., 2015). Indigenous and local knowledge can help deliver culturally appropriate strategies and local choices for urban risk management through, for example community-based observation networks (Alessa et al., 2016), integrating ecosystem-based adaptation strategies in institutional structures (Nalau et al., 2018), using Multiple Evidence-Based Approaches (Tengö et al., 2014), and adopting forms of governance that centre Indigenous peoples in urban adaptation and decision making (Horn, 2018; Parsons, Fisher and Nalau, 2016).

6.1.5 Changes in the Global Enabling Environment

This section reports on changes in global enabling environment – the architecture of international agreements available to inform policy for national governments and others on urbanization and climate adaptation, since the AR5.

Six new international agreements and initiatives have been achieved, each of which has far-reaching implications for the management of rapid urbanization and climate change: the Paris Climate Agreement (United Nations, 2015b); the 2030 Agenda for Sustainable Development including the Sustainable Development Goals (United Nations, 2015c); the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015); the New Urban Agenda (United Nations, 2016a); Addis Ababa Action Agenda (July 2015) and the World Humanitarian Summit (May 2016). Table 6.2 summarises these.

Table 6.2: International policy agreements with implications for urbanization and climate adaptation

Agreement (date of agreement)	Scope of agreement	Relevance for cities, settlements and infrastructure	Relevance for addressing climate change risk
Sendai Framework for Disaster Risk Reduction (March 2015)	Global agreement for reducing disaster risks in all countries and at all levels. Highlights urbanization as a key driver of risk and resilience.	Identifies rapid urbanization as a key underlying risk factor for disasters and driver of resilience. Promotes shift from disaster response to disaster risk management & reduction through cooperation between national and local governments. Limited focus on the role of civil society.	Highlights the need to respond to systemic risk, including compound and cascading risks and impacts from natural, technological and biological hazards. Includes focus on chronic stressors and sudden shocks through governance, planning, disaster response, post-event recovery.
Addis Ababa Action Agenda (July 2015)	Global agreement arising from the International Conference on Financing for Development (United Nations, 2015a) emphasized the need for adequate financing at all levels of government, especially sub-national and local, to support sustainable development, infrastructure and climate mitigation (UN-Habitat, 2016b).	Includes general comments on the importance of local actors and recognises the need for strengthening capacities of municipal and local governments. Commits to "support" local governments to "mobilise revenues as appropriate". Offers little on how to get finance to support local governments addressing these commitments.	Financing a critical element of risk reduction in cities and settlements (see section 6.4). Underlying variability of institutional arrangements inhibits development of universal framework.
Transforming our world: the 2030 Agenda for Sustainable Development (September 2015)	Global agreement adopted by 193 governments that includes the 17 Sustainable Development Goals (SDGs)	SDG11 speaks explicitly to making cities "inclusive, safe, resilient and sustainable". Extensive reference to universal provision of basic services in other SDGs which will require substantial efforts in cities; equality and governance are also stressed. Focuses on national goals and national monitoring with insufficient recognition of key roles of local and regional governments and urban civil society in addressing most of the SDGs.	SDG13 on climate action requires action in cities and settlements. Integrated approach can address underlying drivers of risk.
The Paris Agreement (December 2015)	Global agreement under UN Framework Convention on Climate Change: signed by 194 and ratified by 189 member states (05/01/21)	References the role of the local or sub-national levels of government and cities as non-state actors.	Encourages cities to develop specific agendas for climate action (mitigation and adaptation).

The World Humanitarian Summit (May 2016)	Not an agreement, but a summit of 180 member states generating over 3,500 commitments to action & addressing the role of non-state actors in reducing risk of climate change related forced-displacement of people	Includes five agreed 'core responsibilities' with relevance for urban areas, and commitments were made by professional associations, non-governmental organizations and networks of local authorities to address these in towns and cities.	Climate change likely to shape flows of refugees and migrants who are likely to live in highly exposed areas, particularly in low-income cities. However "meagre funding for collaboration, poor data collection and sharing" (Acuto, 2016) limits commitment effectiveness (Speckhard, 2016).
The New Urban Agenda (October 2016)	Global agenda adopted at UN Conference on Housing and Sustainable Urban Development (Habitat III) Envisioned national urban policies and adaptation plans as a central device to inform subnational governments addressing sustainable development.	Intended as the global guideline for sustainable urban development for 20 years, seeking to provide coherence with other agreements. Focus on national policy and action. Limited recognition of urban governments or civil society as initiators and drivers of change. .	Clearly frames roles for cities within national and international systems in contributing to sustainability (including low-carbon development) and resilience (including adaptation). Frames the role for cities within national and international systems, including an ongoing assessment of their contribution to sustainability and resilience (Kaika, 2017; Valencia et al., 2019)

Alongside new international agreements are a series of new landmark global stocktake reports: three IPCC special reports including the IPCC 1.5 report (Pörtner et al., 2019; Shukla et al., 2019; Hoegh-Guldberg et al., 2018), the UN Environment GEO6 (UN Environment, 2019), IPBES 2019 (Brondizio et al., 2019), and UNDRR 2019 (UNDRR, 2019), each have argued for urgent action on climate mitigation and to invest in inclusive strategies for adaptation if the Sustainable Development Goals are to be met. These findings are comprehensively evidenced and do not need to be revisited here. Our starting point then is to assess the science on how inclusive, sustainable development can be delivered through enhanced adaptation to climate change risks.

As a blueprint for advancing human dignity, the Sustainable Development Goals emphasize the need to consider how to achieve a better and more sustainable future while 'leaving no one behind.' In doing so, they highlight an agenda focused on wellbeing, equality and justice. The objective for SDG11 is defined as: "Make cities and human settlements inclusive, safe, resilient and sustainable" with ten associated targets including ensuring access for all to adequate, safe and affordable housing and basic services; participatory planning; safeguarding heritage features; reducing disasters particularly water related disasters and economic impacts on the poor; and promoting resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement plans, in line with the Sendai Framework for Disaster Risk Reduction. Similarly SDG9 aims to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation, with associated targets. The IPCC 1.5 special report emphasized that there are often cobenefits in pursuit of SDGs and adaptation strategies where "well-designed mitigation and adaptation responses can support poverty alleviation, food security, healthy ecosystems, equality and other dimensions of sustainable development" (Masson-Delmotte et al., 2018 FAQ 5.1). However there may also be negative trade-offs for example between pursuit of growth and reducing climate change risk (International Council for Science, 2017; Masson-Delmotte et al., 2018 Executive Summary; Roy et al., 2018).

The Paris Agreement also envisioned a significantly more active role for cities and other non-state actors in facilitating policy change (Hale, 2016) including through participation in Nationally Determined Contributions (NDCs), although there is little systematic review of the contributions made by cities to NDCs (Hsu et al., 2020; Bäckstrand and Kuyper, 2017). Over two-thirds – 113 out of 164 – of initial Intended Nationally Determined Contributions, prior to ratification, had referenced urban responses in the context of sustainable development, climate mitigation and adaptation (UN-Habitat, 2016a). Analysis of those INDCs revealed 58 focused on urban climate adaptation, 17 focused on both adaptation and mitigation, and 4 focused on mitigation (UN-Habitat, 2017). Simultaneously, multiple efforts have emerged to align the actions of nation states with those of other actors, including the UNFCC 2014 Global Climate Action Portal (Hsu, Weinfurter and Xu, 2017). While significant optimism has been gathered around the possibility to intervene at subnational level, the most difficult challenge has been to establish a coherent view of the overall contribution that cities and settlements are making (Hale, 2016; Chan et al., 2015b). Although meeting the Paris goals will require staying within a 'carbon budget', supporting rapidly developing urban areas in the Global South to the same infrastructure level as developed cities, may consume significant proportions of that budget (Bai et al., 2018).

There is increasing international effort amongst non-Party stakeholders to the Paris Climate Agreement to collaborate to meet the Paris Climate goals (Data Driven Yale New Climate Institute PBL, 2018; Chan et al., 2015a). A review of contributions by non-state actors in 2019 by the EU Covenant of Mayors identified 10427 cities with climate commitments, while the Global Covenant of Mayors included 10543 cities representing a population of 969 million citizens (Palermo et al., 2020; Peduzzi et al., 2020). International efforts also include the United Nations Framework Convention on Climate Change (UNFCCC) Non-State Actor Zone for Climate Action (Data Driven Yale New Climate Institute PBL, 2018). There is also a proliferation of new non-governmental and public-private actors that address both adaptation and mitigation in cities and settlements, including: the C40 Cities Climate Leadership Group, 100 Resilient Cities; the Global Resilient Cities Network, We Mean Business, and We Are Still In (Ireland and Clausen, 2019) and the Global Alliance for Buildings and Construction (Dean et al., 2016). However, there is as yet limited research into the effectiveness of these initiatives in enhancing medium and small city adaptation and limited documentation of climate adaptation actions by non-traditional agents, particularly in the Global South (Lamb et al., 2019).

New urban activists and stakeholders including youth, and Indigenous and minority communities and Non-Governmental Organizations alongside business groups have also been visible in the global urban climate debate, pressing for faster, more far reaching change (Frantzeskaki et al., 2016; O'Brien, Selboe and Hayward, 2018; Alves, Campos and Penha-Lopes, 2019; Smith and Patterson, 2018; Crnogorcevic, 2019; Campos et al., 2016; Hayward, 2021). Emergent urban social movements for climate justice often build on established international networks including local activists such as Shack and Slum Dwellers International while others are inspired by indigenous movements and are focused on human rights, indigenous sovereignty and land claims, and access to water, intergenerational justice, and gender and youth movements coordinated on social media (Agyeman et al., 2016; Cohen, 2018; Ulloa, 2017; Hayward, 2021; Prendergast et al., 2021). The emergence of climate justice movements in urban communities has the potential to reframe policy discussion in cities in ways that also bring inequality and climate justice to the fore (Sheller and Urry, 2016) underscoring growing public calls for more far-reaching, transformative changes towards socially just urban transformations (Akbulut et al., 2019; Foran, 2019; Vandepitte, Vandermoere and Hustinx, 2019; Smith and Patterson, 2018).

This section demonstrates the consistency with which urban processes and places have been rising to the top of international agreements and agendas in the last 10 years (Bulkeley, 2015; van der Heijden et al., 2018; Knieling, 2016). However, many cities, particularly smaller cities and informal settlements in the Global South where development is rapid, need greater support for local governance, more information, and more diverse sources of finance to meet the vision of global climate agreements (Greenwalt, Raasakka and Alverson, 2018; Cohen, 2019). Moreover, the response of many cities to climate change is often constrained by wider political, social and economic structures, development path dependences and high carbon lock-in (Princeti, 2016; Johnson, 2018; Jordan et al., 2015).

6.2 Impacts and Risks

This section assesses the impacts of hazards associated with climate change that will affect cities, settlements and key infrastructure, particularly how climate systems and urban systems interact to produce patterns of risk and loss. The conclusions of the IPCC Special Report on Global Warming of 1.5°C noted that "Global warming of 2°C is expected to pose greater risks to urban areas than global warming of 1.5°C (*medium confidence*)."

This section commences with a review of scenarios and pathways linking urban and infrastructural development with climate change; then assesses the key risks (with a focus on those for which there is a greater degree of evidence or confidence since AR5) and how these risks are created in urban settings. It then assesses evidence on the differentiated nature of human vulnerability and the risks affecting key infrastructure. Finally, this discussion reviews compound and cascading risks, and risks created by adaptation actions.

6.2.1 Risk Creation in cities, settlements, and infrastructure

In addition to direct climate impacts, interactions between changing urban form, exposure and vulnerability can create climate change-induced risks and losses for cities and settlements. Climate change already interacts with on-going global trends in urbanization to create regionally specific impacts and risk profiles. Through demographic change and encroachment into natural and agricultural lands and coastal zones, rapidly expanding urban settlements can place new physical assets and people in locations with high exposure (Tessler et al., 2015; Arnell and Gosling, 2016; Kundzewicz et al., 2014). Increasing rates of global urbanization will pose additional challenges to areas that have high levels of poverty, unemployment, informality, and housing and service backlogs (Jiang and O'Neill, 2017; Williams et al., 2019). There is some evidence to suggest that climate change impacts themselves are increasing urbanization rates generating a challenging feedback loop. In Sub-Saharan Africa, for example, manufacturing towns have experienced growth due to population movement following droughts in agricultural hinterlands (Henderson, Storeygard and Deichmann, 2017). The rapid rate of urbanization therefore presents a time-limited opportunity to work towards risk reduction and transformational adaptation in towns and cities. The following sections explore these dynamic interactions between urban systems and climate change, and how these shape risk for people and for key infrastructures.

Examining projected climate change impacts and resulting risks in cities, settlements and key infrastructures requires the prerequisite development of scenarios which are plausible descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces, (e.g., rate of technological change, prices and relationships) and pathways or the temporal evolution of natural and/or human systems, such as demographic and urban land cover change, towards a future state or states ((Gao and O'Neill, 2020; Gao and O'Neill, 2019); see also 6.1.5).

Climate change research creates scenarios integrating emissions and development pathways dimensions (Ebi et al., 2014; van Vuuren et al., 2017b; van Vuuren et al., 2017a) and Representative Concentration Pathways (RCPs) (Riahi et al., 2017). For risk reduction at regional scales, scenarios require urban-relevant climate projections e.g. downscaling from global and regional climate models of variables such as temperature, precipitation, air pollutants, and sea level rise that are analyzed usually for mid- or end-21st Century timeframes (e.g. Mika et al., 2018; Kusaka et al., 2016; Masson et al., 2014b). These data are needed to ascertain likely ranges of climate change impacts within city and settlement boundaries, and to quantify physical exposure when developing pathways for risk reduction. Consideration of current and projected future growth pathways of multiple urban sectors and key infrastructure e.g. transport, energy, and buildings, are also needed to estimate probabilities of risk outcomes and damages within and across urban systems (O'Neill et al., 2015)(WGIII AR6 Chapter 8).

The challenges of managing these risks are amplified by the complex interactions between climate and urban scenarios, due to the smaller spatial-temporal scales of urban areas in climate change modelling relative to Global Climate Models (GCM) and Shared Socioeconomic Pathways (SSP); geographical or geomorphological variations in city location; uncertainties arising from incomplete assumptions about socio-economic pathways at urban scales affecting urban demographics e.g. fertility rates and life expectancies, or increased rural-urban migration; and challenges in modelling the urban climate and in developing urban climate observational networks in cities (WGI Box 10.3; (Kamei, Hanaki and Kurisu, 2016; Yu, Jiang and Zhai, 2016; Jiang and O'Neill, 2017; Baklanov et al., 2018). Additionally, carbon-intensive economic growth, increasing inequalities, global pandemics, and uncontrolled or unmanaged urbanization will exacerbate the exposure and vulnerability of urban systems modelled in existing climate scenarios and pathways *(high confidence*) (Phillips et al., 2020a; Jackson, 2021; Raworth, 2017; Moraci et al., 2020). Mitigating these outcomes requires new forms of urban governance for climate adaptation, disaster risk reduction, and building resilience (see Section 6.4).

Strong connections exist between climate change scenarios and urban climate-related risks. In some cases, the linkage is direct as climate change is associated with more frequent and more intense extreme weather and climate events as assessed in Section 6.2.3. In other contexts, the connection is mediated by urban developmental pathways arising from local-scale environmental stresses and degradation, and access to adaptation options as reviewed in Section 6.2.4.

6.2.2 Dynamic Interaction of Urban Systems with Climate

Urban systems interact with climate systems in multiple, dynamic and complex ways (Section 6.1.1, WG1 Box 10.3). Climate change can have direct impacts on the functioning of urban systems, while the nature of those systems plays a substantial role in modifying the effects of climate change (*high confidence*) (Frank, Delano and Caniglia, 2017; Smid and Costa, 2018). An example of this urban system-climate nexus is the urban heat island effect (discussed in in section 6.2.3.1) (Susca and Pomponi, 2020). Assessing the inter-relationships between multiple systems and a range of hazards is particularly important, as many cities are presently exposed to multiple climate-related hazards: more than 100 cities analyzed as part of a 571 city study in Europe were deemed vulnerable to two or more climate impacts (Guerreiro et al., 2018). Rapid expansion of urban areas increases the exposure of urban populations to various hazards independent of global climate change. Huang et al. (2019) project that urban land areas will expand by 0.6–1.3 million km^2 between 2015 and 2050, an increase of 78%–171% over the urban footprint in 2015. Specifically in relation to floods and droughts, Güneralp et al (2015a) calculate that even without accounting for climate change, the extent of urban areas exposed to flood hazards will increase 2.7 times between 2000 and 2030, the extent exposed to drought hazards will approximately double during this period, and urban land exposed to both floods and droughts will increase more than 2.5 times.

This section assesses observed and expected impacts from the main hazards identified for cities, settlements and infrastructure – temperature extremes (and the urban heat island), flooding (including sea-level rise), water scarcity and security – as well as other hazards that are either less well-studied and/or likely to affect only a limited number of locations. The data assessed in this section are limited by uneven coverage. Despite improvements since AR5, data continue to be more complete for extreme events than for chronic hazards and everyday risks - which may have high aggregate impacts and disproportionately erode the wellbeing of urban poor households, especially for the most vulnerable, including women, children the aged, disabled and homeless (van Wesenbeeck, Sonneveld and Voortman, 2016; Kinay et al., 2019; Connelly et al., 2018). Data coverage is also less comprehensive for smaller settlements in poorer countries – the locations where urban growth is often high and adaptive capacities are often low (e.g. Rufat et al., 2015). Thus, data gaps frequently coincide with highly vulnerable populations (Rufat et al., 2015; Satterthwaite and Bartlett, 2017). Here, even small changes in livelihoods, health, or representation and voice can rapidly bring households into positions of risk, even when hazard conditions are relatively stable (Ziervogel et al., 2017). These structural limits in available data are discussed also in chapters 7 (Health, wellbeing and the changing structure of communities) and 8 (Poverty, livelihoods and sustainable development), and WGI Box 10.3. There are implications also for Adaptation (Section 6.3) where the greater availability of evidence on exposure driven risk can limit resilience building interventions that focus on the reduction of vulnerability.

6.2.2.1 Temperatures and the Urban Heat Island

Higher temperatures associated with climate change, through warmer global average temperatures and regional heat wave episodes, will interact with urban systems in a variety of ways (WG1 Box 10.3). Future urbanization will amplify projected local air temperature increase, particularly by strong influence on minimum temperatures, which is approximately comparable in magnitude to global warming (*high confidence*) (WG1 Box TS14). Within cities exposure to heat island effects is uneven with some populations disproportionately exposed to risk including low income communities, children, the elderly, disabled, and ethnic minorities ((Quintana-Talvac et al., 2021; Sabrin et al., 2020; Chambers, 2020) and see later in this section).

The risks to cities, settlements and infrastructure from heat waves will worsen (*high confidence*) (Leal Filho et al., 2021) see also 6.2.5; 6.3.3.1, WG1 Box TS14). Depending on the RCP, between half (RCP2.6) to three-quarters (RCP8.5) of human population could be exposed to periods of life-threatening climatic conditions arising from coupled impacts of extreme heat and humidity by 2100 (Figure 6.3; (Mora et al., 2017b; Zhao et al., 2021)). Cities in mid-latitudes are potentially subject to twice the levels of heat stress compared to their rural surroundings under all RCP scenarios by 2050 e.g. Belgian cities (Wouters et al., 2017). A disproportionate level of exposure exists in subtropical cities subject to year-round warm temperatures and higher humidity, requiring less warming to exceed "dangerous" thresholds e.g. Nairobi (Scott et al., 2017) and São Paulo (Diniz, Gonçalves and Sheridan, 2020). It is expected that more than 90% of the 300 million people who will exposed to super- and ultra-extreme heatwaves in the Middle East and North Africa will live in urban centres (Zittis et al., 2021), while the major driver for increased heat exposure is the combination of global warming and population growth in already-warm cities in regions including Africa, India and the Middle East (Klein and Anderegg, 2021).

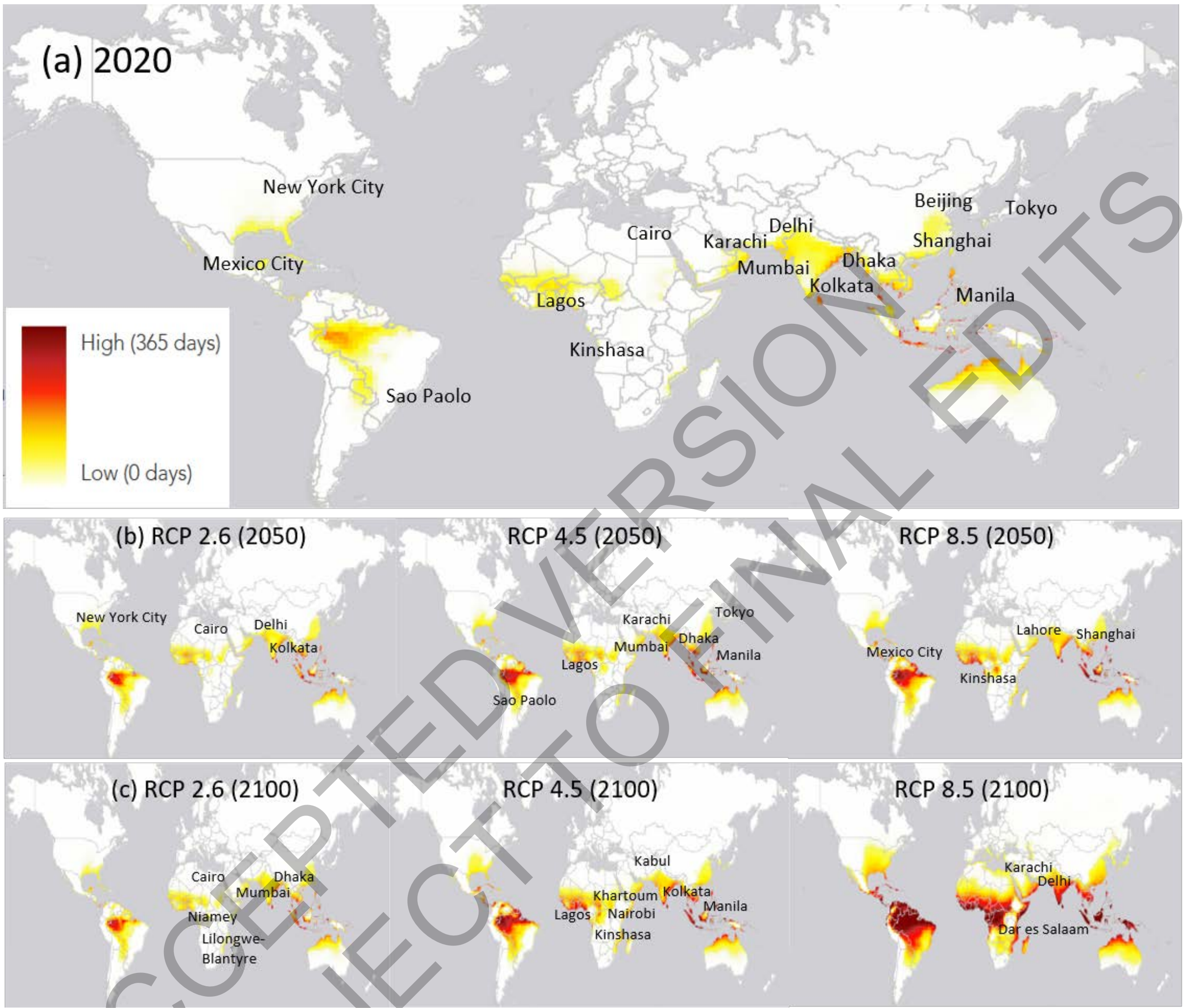


Figure 6.3 Global distribution of population exposed to hyperthermia from extreme heat for the present (a), and projections from selected Representative Concentration Pathways in (b.) mid-21st Century, and (c.) end 21st Century. Shading indicates projected number of days in a year in which conditions of air temperature and humidity surpass a common threshold beyond which climate conditions turned deadly and pose a risk of death (Mora et al., 2017b). Named cities are top fifteen urban areas by population size during 2020, 2050, and 2100 respectively as projected by Hoornweg and Pope (2017)

Locally, the urban heat island also elevates temperatures within cities relative to their surroundings. It is caused by physical changes to the surface energy balance of the pre-urban site from urbanization, resulting from the thermal characteristics and spatial arrangement of the built environment, and anthropogenic heat release ((Oke et al., 2017; Chow et al., 2014; Susca and Pomponi, 2020); WGI FAQ10.1). A considerable body of evidence exists on how the multi-scale impacts and consequent risks arise when local elevated temperatures within settlements are enhanced by climate change, with specific elements of this affecting megacities (Darmanto et al., 2019). The urban heat island itself is amplified during heat waves (Founda and Santamouris, 2017), but the extent to which varies regionally and by time of day (Ward et al., 2016a; Zhao et al., 2018b; Eunice Lo et al., 2020). When combined with warming induced by urban growth, extreme heat risks are expected to affect half of the future urban population, with a particular impact in the tropical Global South and in coastal cities and settlements ((Huang et al., 2019); CCP2.2.2; Table CCP2.A.1).

Heat risk is associated with a range of health issues for urban residents, with the consequences of higher urban temperatures being unevenly distributed across urban populations (*high confidence*). Clear evidence exists of increased health risks to elderly populations in settlements, especially higher levels of mortality in elderly populations from urban heat island during heat wave events (Fernandez Milan and Creutzig, 2015; Taylor et al., 2015; Ward et al., 2016a; Heaviside, Macintyre and Vardoulakis, 2017; Gough et al., 2019; Xu et al., 2020a), while health and fitness variables are also major determinants of the effects of heat stress (Schuster et al., 2017) (see also Table 7.2). Heat stress and dehydration are also related to behavioural and learning concerns, with dehydration impairing concentration and cognition for both adults and children (Merhej, 2019). Literature on pediatric heat exposure is associated with increases in emergency department visits for heat-related illnesses, electrolyte imbalances, fever, renal disease, and respiratory disease in young children (Winquist et al., 2016), with less severe outcomes such as lethargy, headaches, rashes, cramps, and exhaustion negatively affecting children in school and play environments (Vanos, 2015; Hyndman, 2017). Young children in cities are particularly sensitive to heatwaves, and may have little experience or capacity to cope with heat extremes (Norwegian Red Cross, 2019). Such vulnerability of young children to heat is compounded with projected urbanization rates and poor infrastructure, particularly in South Asian and in African cities (Smith, 2019). There is evidence that socioeconomically disadvantaged populations are more likely to live in hotter parts of cities associated with higher-density residential land-use in dwellings with less effective insulation built with poorer or older construction materials (Inostroza, Palme and de la Barrera, 2016; Tomlinson et al., 2011). Specific emerging risks for occupational and related heat illnesses are found in urban tropical or subtropical low-income and middle-income countries (Andrews et al., 2018; Green et al., 2019).

There is an emerging risk of diminished indoor thermal comfort due to climate change, evidenced by research into negatively affected thermal comfort indices and/or increased number of overheating hours under future emissions scenarios (*medium confidence)* (e.g. Liu and Coley, 2015; van Hooff et al., 2014; Vardoulakis et al., 2015; Dodoo and Gustavsson, 2016; Invidiata and Ghisi, 2016; Makantasi and Mavrogianni, 2016; Mulville and Stravoravdis, 2016; Taylor et al., 2016; Hamdy et al., 2017; Pérez-Andreu et al., 2018; Salthammer et al., 2018; Dino and Meral Akgül, 2019; Osman and Sevinc, 2019; Roshan, Oji and Attia, 2019). Decreases in thermal comfort and increases in overheating risks depends on building characteristics, such as thermal resistance, presence of solar shading, thermal mass, ventilation, orientation and geographical location (e.g. Liu and Coley, 2015; van Hooff et al., 2014; Vardoulakis et al., 2015; Dodoo and Gustavsson, 2016; Invidiata and Ghisi, 2016; Makantasi and Mavrogianni, 2016; Mulville and Stravoravdis, 2016; Taylor et al., 2016; Hamdy et al., 2017; Pérez-Andreu et al., 2018; Salthammer et al., 2018; Dino and Meral Akgül, 2019; Osman and Sevinc, 2019; Roshan, Oji and Attia, 2019; Alves, Gonçalves and Duarte, 2021). Most of these studies employed numerical simulations in which different climate scenarios were used to construct future climate data. In hot climates, energy-efficient buildings with high insulation values and high airtightness, which have insufficient protection from solar heat gains and/or limited ventilation capabilities, are generally more vulnerable to overheating than older buildings with lower insulation levels ((e.g. van Hooff et al., 2014; Vardoulakis et al., 2015; Makantasi and Mavrogianni, 2016; Mulville and Stravoravdis, 2016; Salthammer et al., 2018; Fisk, 2015; Hamdy et al., 2017; Fosas et al., 2018; Ozarisoy and Elsharkawy, 2019); see also WGIII 9.7 for building heat mitigation/adaptation links).

Higher urban temperatures result in lower labour productivity levels and economic outputs (*medium confidence*) ((Graff Zivin and Neidell, 2014; Yi and Chan, 2017; Houser et al., 2015; Stevens, 2017); see Section 8.2.1). Globally, urban heat stress is projected to reduce labour capacity by 20% in hot months by 2050 compared to a current 10% reduction (Dunne, Stouffer and John, 2013). Burke et al. (2015) demonstrate a non-linear relationship between temperature and global economic productivity, with potential global losses of 23% by 2100 due to climate change alone. In specific cases, Zander et al. (2015) estimate heat-related reductions in urban labour productivity in Australia to cost USD 3.6 to USD 5.1 billion per year, based on self-reported performance reduction and absenteeism amongst 1,726 workers in 2013–14[2]; while the high-temperature subsidies given in China at outdoor air temperatures above 35°C are projected to

[2] Paper provides figures in Australian dollars: $5.2–7.3 billion Australian dollars. Exchange rate correct July 2020.

increase to USD 35.7 billion per year after 2030 (compared to 5.5 billion USD per year for 1979–2005) (Zhao et al., 2016) [3].

Higher urban temperatures place unequal economic stresses on residents and households through higher utilities demand during warm periods, e.g. electricity in regions where air conditioning is predicted to become more prevalent, and due to medical costs associated with care for heat illnesses and related health effects, missed work, and other related impacts (*medium confidence*) (Jovanović et al., 2015; Liu et al., 2019; Schmeltz, Petkova and Gamble, 2016; Soebarto and Bennetts, 2014; Zander and Mathew, 2019; Zander et al., 2015). Such stresses are projected to increase in many regions associated with continuing global-scale climate change and urbanization (e.g. Véliz et al., 2017; Ang, Wang and Ma, 2017; Bezerra et al., 2021), although some of these effects in cold-climate cities are offset by reduced stresses in winter associated with urban heat island or rising temperatures more generally (see Section 6.2.2.4).

Thermal inequity can also be seen as a distributive justice risk (Mitchell and Chakraborty, 2018). There are often disproportionate increases of risk for individuals of lower socioeconomic status, especially migrants, from exposure to urban heat. These arise from inadequate housing, less access to air-conditioning, and occupations, such as manual labour and waste-picking, that exacerbate heat exposure (Chu and Michael, 2018; Santha et al., 2016). Research from South Africa has shown that housing occupied by poor communities regularly experience indoor temperature fluctuations that are between 4 and 5 °C warmer compared to outdoor temperatures (Naicker et al., 2017); while evidence from the United States indicates that historical housing policies – particularly the 'redlining' of neighbourhoods based on racially motivated perceptions – are associated with areas that are exposed to elevated land surface temperatures (Hoffman, Shandas and Pendleton, 2020).

Social surveys from temperate and tropical cities highlight the risk of reduced quality of life during heat events, including increased incidence of personal discomfort in indoor and outdoor settings, elevated anxiety, depression, and other indicators of adverse psychological health, and reductions in physical activity, social interactions, work attendance, tourism, and recreation (*high confidence*) (Chow et al., 2016; Elnabawi, Hamza and Dudek, 2016; Obradovich and Fowler, 2017; Wang et al., 2017; Wong et al., 2017; Lam, Loughnan and Tapper, 2018; Alves, Duarte and Gonçalves, 2016). Extreme heat may also have a cultural impact, for example affecting major sporting events, with negative impacts on the athletic performance (Brocherie, Girard and Millet, 2015; Casa et al., 2015) and the experience and health of spectators (Hosokawa, Grundstein and Casa, 2018; Kosaka et al., 2018; Matzarakis et al., 2018; Vanos et al., 2019).

6.2.2.2 Urban Flooding

Flood risks in settlements arise from hydrometeorological events interacting with the urban system, which exposes settlements to river (fluvial) floods, flash floods, pluvial (precipitation-driven) floods, sewer floods, coastal floods, and glacial lake outburst floods (Field et al., 2012). Sea level increase and increases in tropical cyclone storm surge and rainfall intensity will increase the probability of coastal city flooding (*high confidence*) (WG1 Box TS14). Globally, the increase in frequencies and intensities of extreme precipitation from global warming will *likely*[4] expand the global land area affected by flood hazards (*medium confidence)* ((Alfieri et al., 2018; Alfieri et al., 2017; Hoegh-Guldberg et al., 2018); Chapter 4.2.4.2). Mishra et al. (2015) noted that out of 241 urban areas, only 17% of cities experienced statistically significant increases in frequencies of extreme precipitation events from 1973-2012. In the future, there is some evidence that changes in high intensity short duration (sub-daily) rainfall in urban areas will increase *(limited evidence, medium agreement)* (Kendon et al., 2014; Ban, Schmidli and Schär, 2015; Abiodun et al., 2017).

[3] Paper provides figures in yuan: 250 billion yuan per year after 2030 (compared to 38.6 billion yuan per year for 1979–2005). Exchange rate correct July 2020.

[4] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

Flooding associated with sea level rise is addressed in more detail in CCP2, with detailed regional examples from Africa discussed in chapter 9.3. Coastal flooding associated with sea-level rise is exacerbated due to the significant number of people living in subsiding areas. As a result of this, the average coastal resident is experiencing (over the last two decades) rates of relative sea-level rise three to four times higher than typical estimates due to climate-induced changes (Nicholls et al., 2021). This process can also result in release of coastal waste into urban areas (Beaven et al., 2020).

Urban flooding risks are also increased by urban expansion, and land use and land cover change, which enlarges impermeable surface areas through soil sealing, impacting drainage of floodwaters with consequent sewer overflows (*high confidence*) (Arnbjerg-Nielsen et al., 2013; Ziervogel et al., 2016; Aroua, 2016; Kundzewicz et al., 2014). These risks are also driven by increasing societal complexity, urban developmental policy on flood control, and long-term economic growth (Berndtsson et al., 2019), including in mega-cities (Januriyadi et al., 2018). The increase in flood risk from urban development can be considerable; based on modelling of two RCP (4.5 and 8.5) scenarios, Kaspersen et al. (2017) noted flooding in four European cities could increase by up to 10% for every 1% increase in impervious surface area. Risks are also compounded by the location of settlements, with greater risks within cities located in low elevation coastal zones subject to sea level rise, potential land subsidence, and exposure to tropical cyclones (((Koop and van Leeuwen, 2017; Hoegh-Guldberg et al., 2018); see also CCP 2.2) and within informal settlements, where generally little investment in drainage solutions exists and flooding regularly disrupts livelihoods and disproportionately undermines local food safety and security for the urban poor ((Dodman, Colenbrander and Archer, 2017; Dodman et al., 2017; Kundzewicz et al., 2014); Chapter 5.4 and 5.8).

Future risks of urban flooding is increasing in conjunction with continued increases in global surface temperature (*high confidence*) (Pörtner et al., 2019; Winsemius et al., 2015; Kulp and Strauss, 2019; Hoegh-Guldberg et al., 2018). In particular, Asian cities are highly exposed to future flood risks arising from urbanization processes. Between 2000 and 2030, rapid urbanization in Indonesia will elevate flood risks by 76-120% for river and coastal floods, while sea level rise will further increase the exposure by 19-37% (Muis et al., 2015). In Can Tho, Vietnam, current urban development patterns put new assets and infrastructure at risk due to sea level rise and river flooding in the Mekong Delta (Chinh et al., 2017; Chinh et al., 2016). Flooding in urban areas is exacerbated both by encroachment of urban areas into areas that retain water, and by the lack of infrastructure such as embankments and flood walls, as is the case for large areas of Dhaka East (Haque, Bithell and Richards, 2020). Zhou et al. (2019) have also shown that for the city of Hohhot, China, the increase in impervious surfaces contributes between 2-4 times more to modelled annual flood risk compared to risk induced by climate change.

Global trends in surface water flooding are increasing, which poses risks to vulnerable urban systems depending on current adaptation measures to manage flooding impacts e.g. stormwater management, green infrastructure, and sustainable urban drainage systems (Molenaar et al., 2015). The economic risks associated with future surface water flooding in towns and cities are considerable. For example in the UK, expected annual damages from surface water flooding may increase by £60-200 million for projected 2-4°C warming scenarios; enhanced adaptation actions could manage flooding up to a 2°C scenario but will be insufficient beyond that (Sayers et al., 2015). Analyses conducted in South Korea suggests that future flood levels could exceed current flood protection design standards by as much as 70% by 2100, considerably increasing urban flood risk (Kang et al., 2016). Modelling of urban flood damage to in the Kelani River Basin in Sri Lanka showed increased frequency of flooding by 2030 could increase potential urban property damage by up to 10.2%" (Komolafe Akinola, Herath and Avtar, 2018). Urban flood impacts may also exacerbate health burdens (including disease outbreaks of malaria, typhoid and cholera), which are compounded by damage to medical facilities (e.g. damage to hospitals, and disruption of medicinal supply chains), as observed in urban areas of Ghana (Gough et al., 2019). In addition emerging research shows the cascading consequences of hazard events – in this case urban flooding - on other risks to wellbeing in ways that are particularly severe for the urban poor, including mental ill-health, incidents of domestic violence impacting children and women, chronic diseases, and salinity of drinking water ((Matsuyama, Khan and Khalequzzaman, 2020); Chapter 4.2.4.5; Chapter 6.2.4.2; Box 7.2; Chapter 8.4.5.2).

6.2.2.3 Urban water scarcity and security

Urban water scarcity occurs when gaps exist between supply and demand of available freshwater resources (Zhang et al., 2019). Urban water security requires a sustainable quantity and quality of water to meet community and ecosystem needs in a changing climate (Romero-Lankao and Gnatz, 2019; Allan, Kenway and Head, 2018; Huang, Xu and Yin, 2015; Chen and Shi, 2016). Risks arising from urban water scarcity worldwide are *very likely* increasing due to climate drivers (e.g. warmer temperatures and droughts) and urbanization processes (e.g. land use changes, migration to cities, and changing patterns of water use including over extraction of surface and groundwater resources) affecting supply and demand (*high confidence*) ((Allan, Kenway and Head, 2018; Crausbay et al., 2020; Haddeland et al., 2014; Pickard et al., 2017; De Stefano et al., 2015; Sun et al., 2019; Van Loon et al., 2016; Zhang et al., 2019); Chapter 4.2.4.4; See Box 8.6 for case study on 2018 Cape Town drought). Flörke et al. (2018) estimates that nearly a third of all major cities worldwide may exhaust their current water resources by 2050. Globally, projections suggest that 350 million (± 158.8 million) more people living in urban areas will be exposed to water scarcity from severe droughts at 1.5°C warming, and 410.7 million (± 213.5) at 2°C warming (Liu et al., 2018).

Decreased regional precipitation and associated changes in runoff and storage from droughts is exacerbating urban scarcity by impairing the quality of water available for its resource management in cities (*high confidence*). For example, less runoff to freshwater rivers can increase salinity, concentrate pathogens and pollutants that increases risks of urban water scarcity (Hellwig, Stahl and Lange, 2017; Jones and van Vliet, 2018; Leddin and Macrae, 2020; Lorenzo and Kinzig, 2020; Ma et al., 2020; Mosley, 2015; Zhang et al., 2019; van Vliet, Flörke and Wada, 2017) ; See also Box 6.2). Drought also changes the dynamics of groundwater pollution leading to increased environmental health risks when those sources are used for urban water supplies (Kubicz et al., 2021; Moreira et al., 2020; Pincetl et al., 2019). Changes in the nature of droughts e.g. hotter droughts (Herrera and Ault, 2017), snow droughts (Cooper, Nolin and Safeeq, 2016; Mote et al., 2016), or 'flash' droughts (Otkin et al., 2016; Otkin et al., 2018; Pendergrass et al., 2020) can exacerbate urban water scarcity exposing the limitations of engineered water infrastructure, designed to accommodate historical patterns of supply and demand (Gober et al., 2016; Ulibarri and Scott, 2019; Zhao et al., 2018a).

Risks of urban water scarcity and security are compounded by vulnerabilities such as service availability and quality of infrastructure to supply water for increased urban demand from in-migration to cities (*medium confidence*) (Ahmadalipour et al., 2019; Dong et al., 2020; Reynolds et al., 2019; Thomas et al., 2017; Mullin, 2020). Risks to local water security in cities are also exacerbated by drivers such as dependence on imported water resources from distant locales that may be exposed to additional drought risks (*high confidence)* (Ahams et al., 2017; Li et al., 2019b; Marston et al., 2015; Zhao et al., 2020; Zhang et al., 2020); from considerable projected urban expansion in drought-stressed areas e.g. across drylands of Western Asia and North Africa (Güneralp et al., (2015b); and by export of virtual water (i.e. export of water embedded in food and energy) from local sources to distant trading partners (Djehdian et al., 2019; D'Odorico et al., 2018; Fulton and Cooley, 2015; Rushforth and Ruddell, 2016; Verdon-Kidd et al., 2017; Vora et al., 2017).

Droughts interact and manifest in complex ways in interconnected urban areas that *likely* increase risks of urban water scarcity (Tapia et al., 2017; Rushforth and Ruddell, 2015). Urban interdependencies mean droughts in one region can limit water resources availability in another (e.g., Macao and Zhuhai, Hong Kong, Shenzhen in China, Singapore and Johor, and in cities in Pakistan and India, in the west and southwest USA) (Chuah, Ho and Chow, 2018; Gober et al., 2016; Srinivasan, Konar and Sivapalan, 2017; Zhang et al., 2019; Zhao et al., 2020). Likewise, physical and social teleconnections mean decisions made about water resources in one region or location may impact another in unexpected ways (Moser and Hart, 2015; Liu et al., 2015).

Urban water security risks are confounded by inequities in economic opportunity, risk exposure, and human well-being (*medium evidence*)((Sena et al., 2017; Stanke et al., 2013); Chapter 4.2.4.5). Water scarcity is felt more acutely among low-income compared to high-income populations (Nerkar et al., 2016), and scarcity on top of inequities and political instability can lead to security issues e.g. conflict between different water users (Cosic et al., 2019; von Uexkull et al., 2016; Ahmadalipour et al., 2019; Döring, 2020; Ide et al., 2021), particularly when road infrastructures and access to water are limited (Detges, 2016; Sena et al., 2017). Scarcity risks may also be exacerbated by human and ecosystem needs in water short years (Srinivasan, Konar and Sivapalan, 2017). Finally, growing populations along with migration into water scarce regions can exacerbate water security issues (Akhtar and Shah, 2020; Singh and Sharma, 2019).

6.2.2.4 Other dynamic interactions

A range of other dynamic climate interactions are relevant for cities, settlements, and infrastructure: cold spells, landslides, wind, fire, and air pollution.

Cold spells. Although frequencies and intensities of cold spells/cold waves are *virtually certain* to have decreased globally, and are projected to consistently decrease for most warming levels (*high confidence*); WGI Table 11.2), cold weather events can periodically occur and impact urban areas and their connected infrastructures. For cities in eastern Canada, the intra-annual distribution of freezing rain events may become more frequent from December-February, and less frequent in other months by 2100 (Cheng, Li and Auld, 2011). Freezing rain is also a risk to urban populations and infrastructure. In general, higher population mortality rates *likely* occur during the winter season, while more temperature-attributable deaths are caused by cold than by heat in cities located in temperate climates (Gasparrini et al., 2015; Chen et al., 2017; Ryti, Guo and Jaakkola, 2016). Winter mortality is unlikely to significantly decrease due to warming trends, partly because a range of other medical factors (e.g. influenza seasons, and elevations in cardiac risk factors) also drive this winter-excess mortality (Kinney et al., 2015). However, the evidence is unclear whether mortality related to cold waves will decrease in coming decades in European (Smid et al., 2019), or United States cities (Wang et al., 2016). While projected global cold extremes are expected to decrease in frequency and intensity, the higher regional variability of future climates means that cold waves may remain locally important threats, including in milder regions where there are larger temperature differences between 'normal' winter days and extreme cold events, and where there is less capacity to adapt (Ma, Chen and Kan, 2014; Ho et al., 2019). This will be accentuated in many cities, particularly in Europe, by anticipated demographic changes that result in a more elderly population susceptible to cold wave health risks (Smid et al., 2019).

The effects of cold waves on the energy sector include breakdowns in power plants and reduced oil and gas production (Jendritzky, 1999), and failures in overhead power lines and towers leading to outages in Moscow and Bucharest (Panteli and Mancarella, 2015; Andrei et al., 2019). Six major power outages associated with cold shocks and ice storms have been recorded since 2010, the majority recorded from large cities the US (Añel et al., 2017). Cold waves can also significantly increase energy demand. A cold wave that affected the Iberian Peninsula in January 2017 caused electricity prices to peak at a mean price of 112.8 €/MWh, the highest ever recorded in Spain (AEMET, 2017).

Landslides. While geomorphological events (e.g. land subsidence from permafrost thaw at high latitudes or from groundwater extraction), and factors associated with the built environment (e.g. settlement location adjacent to steep slopes, and zonation laws for building construction) are major factors determining urban landslide risk, these can also be influenced by a range of climatic variables, namely precipitation (frequency, intensity and duration), snow melt and temperature change. Some 48 million people are exposed to landslide risk in Europe alone, with the majority in smaller urban centres (Mateos et al., 2020). Travassos et al. (2020) also documented all landslide deaths in the São Paulo Macro Metropolis Region from 2016-2019 occurred from extreme rainfall events in vulnerable areas prone to landslides. An increase in the number of people exposed to urban landslide risks is projected for landslide-prone settlements lying within regions projected to experience corresponding increase in extreme rainfall (Gariano and Guzzetti, 2016). In addition, human factors such as expansion of towns onto unstable land and land use changes within settlements (e.g., road building, deforestation) are increasing human exposure to landslides, and the likelihood of landslides occurring (Kirschbaum, Stanley and Zhou, 2015). Rainfall triggered landslides kill at least 5000 people per year, and at least 11.7% of these landslides occurred on road networks (Froude and Petley, 2018). Although the spatial footprint of an individual landslide might be small (i.e., <1km^2), the 'vulnerability shadow' cast over an area in terms of regional transport network disruptions can be a significant proportion of a region, and cascade to other infrastructures (Winter et al., 2016).

Landslides tend to occur on moderate to steep slopes, and are thus particularly prevalent in mountainous regions which are also characterised by low infrastructure redundancy (i.e., few alternative routes) and increased impacts from climate change (Schlögl et al., 2019). More robust forecasts of landslides driven by climate risk requires (a) more complete long-term records of previous landslides and (b) baseline studies of the Global South which are currently missing from the literature (Gariano et al., 2017).

Wind. Urban morphology alters wind conditions at multiple spatial scales; generally, increased surface roughness in settlements have resulted in declining trends in both measured wind speed and frequency of extremely windy days ((Mishra et al., 2015; Peng et al., 2018; Ahmed and Bharat, 2014); WGI Box 10.3). Urban wind risks can also be affected by city location adjacent to mountains, lakes, or coasts with localised wind systems (WGI 10.3.3.4.2; WGI 10.3.3.4.3). In large cities with significant urban heat island, an urban-driven thermal circulation can enhance pollution dispersion under calm conditions (Fan, Li and Yin, 2018) or advect heat to areas downwind of the city (Bassett et al., 2016). Microscale wind conditions within urban canyons also strongly affect ventilation of air pollution dispersion and thermal comfort at pedestrian level, especially in cities located in warm climates (Rajagopalan, Lim and Jamei, 2014; Middel et al., 2014; Lin and Ho, 2016).

In cities, wind risks from climate change hazards can arise from increased exposure from the expanding built environment. Very high wind speeds associated with severe weather systems e.g. tropical cyclones or derechos can cause significant structural damage to buildings and key infrastructure with insufficient wind load, as well as causing human injury through flying debris (Burgess et al., 2014). In particular, there is evidence from North American cities that tornado damage are *likely* fundamentally driven by growing built-environment exposure (*medium confidence*) (Ashley et al., 2014; Rosencrants and Ashley, 2015; Ashley and Strader, 2016).

Extreme winds in urban areas can have particularly damaging effects on poorly constructed buildings, including low-income houses in African cities (Okunola, 2019), as well as on urban trees that may be uprooted by strong wind gusts from downbursts (Ordóñez and Duinker, 2015; Pita and de Schwarzkopf, 2016; Brandt et al., 2016), and on disrupting transportation along urban road and railway networks (Koks et al., 2019; Pregnolato et al., 2016).

Fire. Hotter and drier climates in several regions e.g. Australia, the Western United States, the Mediterranean, and Russia (Masson-Delmotte and Waterfield, 2018), *likely* enable weather conditions driving fire events impacting cities within these regions (Chapter 2.4.4.2, 2.5.5.2). These include wildfires along the margins where cities are adjacent to wildlands i.e. the wildland-urban interface (WUI) (Bento-Gonçalves and Vieira, 2020; Radeloff et al., 2018), or fires in cities with a high degree of informal settlements having greater vulnerability to fire hazards ((Kahanji, Walls and Cicione, 2019; Walls and Zweig, 2017); Chapter 8.3.3.2). This vulnerability is considerable; over 95% of urban fire related deaths and injuries occur within informal settlements in in low- and middle-income countries (Rush et al., 2020).

For wildfires at the WUI, anthropogenic climate change, natural weather variability, expansion of human settlement and a legacy of fire suppression are key factors in determining fire risk (Abatzoglou and Williams, 2016; Knorr, Arneth and Jiang, 2016; van Oldenborgh et al., 2020). Recent wildfires in Australia and in California both occurred under hot and dry weather conditions exacerbated by climate change, and resulted in substantial property damage along the WUI, ecosystem destruction, and lives lost (Brown et al., 2020; Lewis et al., 2020; Yu et al., 2020). Future climate risk of fires at the WUI are *likely* (*medium confidence*), and are compounded by projected urban development along WUI within several regions, such as in the Western United States (Syphard et al., 2019), Australia (Dowdy et al., 2019) and the Bolivian Chiquitania (Devisscher et al., 2016).

Air Pollution. Despite recent observed improvements in air quality arising from COVID-19 restrictions (Krecl et al., 2020); WGI Cross-Chapter Box 6.1), significant risks to human health in cities leading to premature mortality *very likely* arise from exposure to decreased outdoor air quality from a combination of biogenic (e.g. wildfires at the WUI that advect into the urban atmosphere; (Reddington et al., 2014); WGI Chapter 12 Box 12.1), and anthropogenic sources that are influenced by climate change (e.g. fine particulate matter such as $PM_{2.5}$, tropospheric ozone, oxides of nitrogen, and volatile organic compounds)((Burnett et al., 2018; Knight et al., 2016; Turner et al., 2016; West et al., 2016; Chang et al., 2019b; Li et al., 2019a; Alexader, Luisa and Molina, 2016); WGI Chapter 6.7.1.1, 6.7.1.2). Risks of premature mortality from indoor air pollution in cities, arising from biomass burning for heating in winter or cooking, indoor pesticide use, or exposure to volatile organic compounds from poor thermal insulation in buildings, are also *likely* to occur ((Leung, 2015; Peduzzi et al., 2020); Cross-Chapter Box HEALTH in Chapter 7).

The mortality risk for several pollutants, e.g. $PM_{2.5}$, is considerable (*high confidence*). Current estimates indicate that 95% of global population live in areas where ambient $PM_{2.5}$ exceeds the WHO guideline of annual average exposure of 10 µg m^{-3} (Shaddick et al., 2018a; Shaddick et al., 2018b; Chang et al., 2019b). Among the 250 most populous urban areas, estimated $PM_{2.5}$ concentrations are generally highest in cities in Africa, South Asia, the Middle East, and East Asia; $PM_{2.5}$ in many cities in North Africa and the Middle East is *likely* due mainly to windblown dust, whereas that in South Asia and East Asia are mainly anthropogenic in origin (Anenberg et al., 2019). However, data on $PM_{2.5}$ concentrations are unavailable in many cities in low- and middle-income countries due to a lack of measurements (Martin et al., 2019).

For some air pollutants e.g. concentrations of $PM_{2.5}$ in several United States, Western European, and Chinese cities have recently decreased as a result of clean air regulations that have controlled emissions from sources such as motor vehicles, fossil fuel power plants, and major industries (Zheng et al., 2018a; Fleming et al., 2018). These decreases have brought substantial improvements in public health in settlements within these regions (Ciarelli et al., 2019; Zhang et al., 2018). In South Asia, Southeast Asia, and Africa, however, concentrations of other air pollutants e.g. tropospheric ozone, oxides of nitrogen, and volatile organic compounds are *likely* to continue to grow and peak by mid-century before they subside due global urbanization assumptions embedded in the SSPs (WGI Chapter 6.2.1; 6.7.1). Broadly, future air pollutant emissions are projected to decline globally by 2050 as societies become wealthier and more willing to invest in air pollution controls, but the trajectories vary among pollutants, world regions, and scenarios (Silva et al., 2016b; Rao et al., 2017; Silva et al., 2016c). Whereas cities in East Asia and South Asia currently have large exposure to anthropogenic air pollution, African cities may emerge by 2050 as the most polluted because of growing populations and demand for energy, increased urbanization, and relatively weak regulations to control emissions (Liousse et al., 2014).

Studies modelling climate change impacts on air quality find that the spatiotemporal patterns of concentration changes vary strongly at urban scales, and that often those patterns differ among the different years modelled due to internal variability (Saari et al., 2019), and different models used (Weaver et al., 2009). Changes in $PM_{2.5}$ due to climate change are less clear than for ozone, and may be relatively smaller (Westervelt et al., 2019), as climate change can affect $PM_{2.5}$ species differently (Fiore, Naik and Leibensperger, 2015). For Beijing, climate change is expected to cause a 50% increase in the frequency of meteorological conditions conducive to high $PM_{2.5}$ concentrations (Cai et al., 2017). The impacts of future climate change on air quality and consequent risks on human health have been studied at urban (Knowlton et al., 2004; Physick, Cope and Lee, 2014) and national scales (Fann et al., 2015; Orru et al., 2013; Doherty, Heal and O'Connor, 2017); globally, these studies have found a *likely* net increased risk of climate change on air pollution-related health (*low confidence*). They have focused mainly on the US and Europe with few studies elsewhere (Orru, Ebi and Forsberg, 2017), although the relationship between climate and air quality in megacities is particularly complex (Baklanov, Luisa and Molina, 2016). Silva et al. (2017) found that global premature mortality attributable to climate change (and not from urbanisation) from ozone and $PM_{2.5}$ will increase by about 260,000 deaths per year in 2100 under RCP8.5 , but substantial variance in results exists between individual models.

6.2.3 Differentiated Human Vulnerability

Evidence from urban and rural settlements is unambiguous; climate impacts are felt unevenly, with differentiated human vulnerability leading to uneven social, spatial and temporal loss, risk and experiences of resilience - including capacity for transformation (high confidence) (Woroniecki et al., 2019; Tan, Xuchun and Graeme, 2015; Simon and Leck, 2015; Long and Rice, 2019; Chu, Anguelovski and Roberts, 2017; Borie et al., 2019). The evidence is also clear that for those with fewest resources and already constrained life chances, losses from climate change associated events reduce wellbeing and exacerbate vulnerability (high confidence) (van den Berg and Keenan, 2019; Kashem, Wilson and Van Zandt, 2016; Michael, Deshpande and Ziervogel, 2018). Human vulnerability is influenced by the adaptive capacity of physical (built) structures, social processes (economic, wellbeing and health) and institutional structures (organisations, laws, cultural and political systems/norms) (see 6.4). This section should be read in conjunction with Chapter 8 (Poverty, livelihoods and sustainable development) and will emphasise urban processes that lead to the creation of differential vulnerability, risks and impacts.

6.2.3.1 Urban Poverty and Vulnerability

In both developed and less-developed regions, poverty in urban areas is frequently associated with higher levels of vulnerability (Huq et al., 2020b). This is evident in both rural and urban settlements in a wide range of contexts, including the Philippines (Porio et al., 2019; Valenzuela, Esteban and Onuki, 2020), Bangladesh (Matsuyama, Khan and Khalequzzaman, 2020), Brazil (Lemos et al., 2016), Santiago, Chile (Inostroza, Palme and de la Barrera, 2016) and New York City (Madrigano et al., 2015).

For individuals in urban communities, new literature highlights how differences in vulnerability established by social and economic processes are further differentiated by household and individual variability and intersectionality (Kaijser and Kronsell, 2014; Kuran et al., 2020).This includes differences in wealth and capacity (Romero-Lankao, Gnatz and Sperling, 2016); gender and non-binary gender (Michael and Vakulabharanam, 2016; Sauer and Stieß, 2021; Mersha and van Laerhoven, 2018); education, health, political power and social capital (Lemos et al., 2016); age, including young and elderly, low physical fitness, pre-existing disability, length of residence and social and ethnic marginalization (Inostroza, Palme and de la Barrera, 2016; Schuster et al., 2017; Malakar and Mishra, 2017). An increasing proportion of refugees and displaced people now live in urban centres, and their characteristics also make them vulnerable to a range of shocks and stresses (Earle, 2016). While some individuals, including children may be able to exercise agency to reduce their risk (Treichel, 2020) and some indicators are culturally specific, overall, poor, marginalized, socially isolated and informal urban households are particularly at risk (*high confidence*) (Brown and McGranahan, 2016; Kim et al., 2020b; Huq et al., 2020a; Huq et al., 2020b).

6.2.3.2 Informality, planning, and vulnerability

Particularly in Low- and Middle-Income Countries, much urban building occurs outside formal parameters and entails a high degree of urban informality. According to the United Nations statistics, the proportion of urban populations living in slums and informal settlements increased from 23% in 2014 to 23.5% in 2018 (United Nations, 2018). Informality is one pathway through which urbanization generates differentiated vulnerability tending to increase exposure and susceptibility of physical structures and their occupants to climate-related risks (Dodman et al., 2017; Dobson, 2017) in contexts including Guadalajara, Mexico (Gran Castro and Ramos De Robles, 2019), Kampala, Uganda (Richmond, Myers and Namuli, 2018), Bengaluru, India (Kumar, Geneletti and Nagendra, 2016), and Dar es Salaam, Tanzania (Yahia et al., 2018). In addition to facing emerging water- and heat-related risks, such areas are also more vulnerable to the health impacts of climate change (Scovronick, Lloyd and Kovats, 2015).

Even where formal planning is the norm, this has often remained oriented toward enabling value adding construction or the protection of existing high value physical assets, e.g., infrastructure and built cultural heritage; private residential) rather than enabling disaster risk reduction for all (Long and Rice, 2019). This tendency has been widely documented, including from cases in Australia, Thailand and Indonesia (King et al., 2016), Canada (Stevens and Senbel, 2017), Amman, Moscow, and Delhi (Jabareen, 2015), and South Africa (Arfvidsson et al., 2017). Such inconsistencies between the delivery of land-use planning and the aims of the Sustainable Development Goals combine with other social structures, economic pathways, and governance systems to shape city risk profiles (Dodman et al., 2017).

6.2.3.3 Migration and differentiated vulnerability

Migration, displacement, and resettlement each play a foundational role in differentiated vulnerability (see Cross-Chapter Box MIGRATE in Chapter 7). The relationship between migration and vulnerability is complex (*robust evidence, high agreement*), and is the first of the three components discussed within this section. Climate change, as a push factor, is only one among multiple drivers (political, economic, and social) related to environmental migration (Heslin et al., 2019; Plänitz, 2019; Luetz and Merson, 2019). There is consensus that it is difficult to pin climate change as the sole driver of internal (within national boundaries) rural to urban migration decisions due to, among other factors, the disconnect between national and international policies (Wilkinson et al., 2016), the lack of unifying theoretical frameworks, and the complex interactions between climatic and other drivers (social, demographic, economic, and political) at multiple scales (Cattaneo et al., 2019; Borderon et al., 2019). Environmental migration – including rural to urban migration – triggered by climate change may ensue from either slow or rapid onset climatic events and could be either temporary, cyclical, or permanent movement that occurs within or beyond national boundaries (Heslin et al., 2019; Silja, 2017).

A range of specific studies highlight specific elements of vulnerability and migration, including the ways in which slow-onset events affect precarious, resource dependent livelihoods (such as farming and fisheries) (Cai et al., 2016). In small town Pakistan and in small town Colombia, heat stress increases long-term migration of men, driven by a negative effect on farm income (Mueller, Gray and Kosec, 2014; Tovar-Restrepo and Irazábal, 2013). A study from Mexico reveals that an increase in drought months led to increased rural to urban migration, while increased heat (temperature) led to a "non-linear" pattern of rural to urban migration that occurred only after extended periods of heat (nearly 34 months) (Nawrotzki et al., 2017). This aligns with other findings that a consistent increase in temperature between 2-4ºC in some parts of the world render involuntary, forced migration inevitable (Otto et al., 2017).

The complexity of migration drivers (as push or as pull factors) explains why there is little agreement around quantitative estimates on migration (especially international) triggered by climate change (Silja, 2017; Otto et al., 2017), and why estimates of future displacement attributed to climate change and other environmental causes vary between 25 million and 1 billion in 2050 (Heslin et al., 2019). Many authors are critical of existing perspectives on climate-related migration, and argue for more nuanced research on the topic (Boas et al., 2019; Kaczan and Orgill-Meyer, 2020; Silja, 2017; Sakdapolrak et al., 2016; Singh and Basu, 2020; Luetz and Havea, 2018).

Climate-induced migration is not necessarily higher among poorer households whose mobility is more likely to be limited due to the poverty trap (i.e., lack of financial resources) (*high confidence*) (Cattaneo et al., 2019; Kaczan and Orgill-Meyer, 2020; Silja, 2017). For example, in Bangladesh, vulnerability of rural populations is increasing, so many of the poorest employ migration as a strategy of last resort (Paprocki, 2018; Penning-Rowsell, Sultana and Thompson, 2013; Adri and Simon, 2018) that occurs as soil salinity (as opposed to inundation alone) increases and is paralleled by economic diversification (i.e., aquaculture) (Chen and Mueller, 2018). There is robust evidence and high agreement that rapid-onset climatic events trigger involuntary migration and short-term, short-distance mobilities (Cattaneo et al., 2019). There is also robust evidence and high agreement that slow-onset climatic events (such as droughts and sea-level rise) lead to long-distance internal displacement more so than local or international migration (Kaczan and Orgill-Meyer, 2020; Silja, 2017); while sea level rise is expected to lead to the displacement of communities along coastal zones, such as in Florida in the USA (Hauer, 2017; Butler, Deyle and Mutnansky, 2016).

Migration, including rural-urban migration, is also recognized as an adaptation strategy in some circumstances, whether this is voluntary or planned (Jamero et al., 2019; Esteban et al., 2020a; Bettini, 2014). Voluntary migration can be an element of household strategies to diversify risk, depending on the nature of the climatic stress and interacts with household composition, individual characteristics, social networks, and historical, political, and economic contexts (Hunter, Luna and Norton, 2015; Carmin et al., 2015; Hayward et al., 2020). For example, in Colombia, rural to urban migration is differentiated across gender depending on the climatic stress whereby men migrate due to droughts, while women migrate due to excessive rain triggers (Tovar-Restrepo and Irazábal, 2013). Especially in Pacific small island developing states, migration can be a strategy for urban settlements or tribal communities to relocate in customary areas, as in the case of Vunidogoloa in Fiji (McMichael, Katonivualiku and Powell, 2019; Hayward et al., 2020); it can be a livelihood strategy as shown in the Cataret Islands in Papua New Guinea (Connell, 2016); or it can be used to enhance education and international networks (i.e., voluntary "migration with dignity") as is the case in Kiribati (Heslin et al., 2019; Voigt-Graf and Kagan, 2017).

The second component, displacement, also plays a crucial role in differentiated vulnerability. The lack of resources and capacities to support mobility limits the effectiveness of migration as an adaptation strategy, therefore leading to both displacement and trapped populations in the future (Adger et al., 2015; Faist, 2018). For example, studies from Colombia (Tovar-Restrepo and Irazábal, 2013), India (Singh and Basu, 2020), Mekong Delta in Vietnam (Miller, 2019), and Pakistan (Islam and Khan, 2018) showed that migration as an adaptation strategy can be constrained due to resource barriers and low mobility potential, and also, to high-levels of place attachment such as, in the Peruvian Highlands (Adams, 2016), Vanuatu (Perumal, 2018), and the Tulun and Nissan Atolls of Bougainville, Papua New Guinea (Luetz and Havea, 2018). Migration can also be maladaptive for the receiving contexts whether due to the pressure on and/or conflict over land

and/or the urban resources (*high confidence*) (Faist, 2018; Singh and Basu, 2020; Luetz and Havea, 2018). Other views maintain that migration as adaptation overlooks the agency of people and their resilience –i.e., the nuances of 'translocal social resilience' (Kelman, 2018; Silja, 2017; Sakdapolrak et al., 2016). For example, the ni-Vanuatu prioritize in-situ adaptation measures and leave migration as a last resort (Perumal, 2018).

Regardless of the reasons and the initiators for migration, community control over resettlement both at the original and destination leads to more positive outcomes for both the communities being resettled and the receiving communities (*high confidence*) (Perumal, 2018; Ferris, 2015; Price, 2019; Mortreux and Adams, 2015; Tadgell, Doberstein and Mortsch, 2018; Luetz and Havea, 2018). The protection of livelihoods contributes to ensuring the wellbeing (physical and mental) and the protection of the rights of communities *(high confidence*) (Ferris, 2015; Price, 2019). There is *limited evidence but high agreement* that the outcomes of resettlement initiatives are complex and multi-faceted (Ferris, 2015). For example, in Shangnan County, northwest China, the Massive Southern Shaanxi Migration Program, based on voluntary participation, reduced risk exposure and improved the quality of life in general, but also disproportionately increased the vulnerability of disadvantaged groups (the poor, migrants, and those left behind) (Lei et al., 2017). Similarly, vulnerability increased due to the loss of connection to place and community bonds in Mekong Delta, Vietnam (Miller, 2019) and due to unsafe construction, poor infrastructure, institutional incapacity, and general neglect in resettlement initiatives in Malawi, sub-Saharan Africa (Kita, 2017).

6.2.4 Risks to Key Infrastructures

Projected climatic changes – such as changing precipitation patterns, temperatures, and sea levels – contribute to pressures on human wellbeing and the functioning of infrastructure systems (high confidence). Furthermore, risks evolve due to macro-scale drivers of change such as urbanization, economic development, land use changes and other emergent factors (Adger, Brown and Surminski, 2018). Infrastructure networks are rapidly growing around the world (see Table 6.3). Since the quality and accessibility of infrastructure services are varied, it is important to understand how climate change poses different kinds of risk on them. Infrastructure can be broadly understood to include social infrastructure (housing, health, education, livelihoods and social safety nets, security, cultural heritage/institutions, disaster risk management and urban planning), ecological infrastructure (clean air, flood protection, urban agriculture, temperature, green corridors, watercourses and riverways) and physical infrastructure (energy, transport, communications (including digital), built form, water and sanitation and solid waste management) (Thacker et al., 2019). This section focuses especially on physical infrastructure where the literature provides discrete risk and impact assessments. Physical infrastructure systems are often immobile, indivisible, involve high fixed costs, and have longer lifecycles. Social and ecological infrastructure elements are rarely assessed alone and instead tend to be included in wider assessments of event impacts.

Table 6.3 Selected indicators of global proliferation of infrastructure networks and their annual usage.

Infrastructure	Scale	Usage on annual basis	Coverage / Equity of access	References
Electricity networks	>20M km power lines in Europe and USA.	25,721 TWh (2017)	Global: 3130kWh/person Haiti: 39kWh/person Iceland: 53,832kWh/person	(IEA, 2019) (World Bank, 2019) (ETSAP, 2014)
Gas and LPG pipelines	Worldwide: >2.5M km w	40,531 TWh (2017)	Global 4.96 MWh/person (2015) South Africa 0.96 MWh/person (2015) Saudi Arabia: 34.65 MWh/person (2015)	(CIA, 2015) (OWID, 2020)

Railways	2.69M km	3,835 billion passenger km (2019) 9,279.81 billion tonne km (2019)	Switzerland: 0.7m/person; 141m/km^2 Canada: 2.2m/person; 8.6m/km^2 India: 0.06m/person; 23m/km^2	(Koks et al., 2019) (Statista, 2020)
Roads	63.46M km	12,148 billion passenger km private vehicles (2015) 5,713 billion passenger km public vehicles e.g. buses (2015) 302.5 billion passenger km active modes e.g. walking and bicycles (2015)	Belgium: 15m/person; 5km/km^2 Malawi: 1m/person; 164m/km^2 Canada: 31m/person; 115m/km^2	(Koks et al., 2019) (WorldByMap, 2017) (ITF, 2019)
Information and Communication Technology	Worldwide: 91M mobile phones in 1995; 8.2BN in 2018 worldwide	Worldwide: 43,000 PB in 2014 242,000 PB in 2018 (*1PB = 1 million GB)	Europe: 85% population are unique mobile subscribers Asia Pacific: 66% SSA: 45%	(ITU, 2019) (Vodafone, 2019) (GSMA, 2019)
Water	3.3M km^2 land equipped for irrigation The Global Reservoir and Dam Database (conservatively records) at least 7100 dams	This irrigated land accounts for about 70% of total water withdrawals These dams can retain over 7,800km^3 water.	Sub-Saharan Africa: 24% coverage of safely managed drinking water services, 28% safely managed sanitation services Europe & North America: 94%, 78%	(Grigg, 2019) (Lehner et al., 2011) (Lehner et al., 2019) (UN Water, 2018)

Current climate variability is already causing impacts on infrastructure systems around the world (*high confidence*). For global physical infrastructure with a present value of US$143 trillion The Economist Intelligence Unit (2015) estimates present value losses of $4.2 trillion by 2100 under a 2oC scenario. This estimation rises to $13.8 trillion under a 6oC scenario. Extreme events are associated with disruption or complete loss of these infrastructure services, whilst gradual changes in mean conditions are altering physical infrastructure performance. Physical infrastructure is usually costly to repair and also have significant impacts on people's health and wellbeing.

This section synthesises and assesses the emerging literature on climate change risks to key physical infrastructure domains as listed in Table 6.3: energy/electricity infrastructure, transportation infrastructure, and information and communication technology (ICT) (water infrastructure is discussed in Section 6.2.2). It draws on evidence from around the world, but the specific risks to infrastructure in different contexts are explained in more detail in the regional chapters (especially 9.8.4.1 for Africa, 10.4.6.3.8 for Asia, and 13.6.1 for Europe). For cities and settlements such risks are of particular concern due to a lack of adaptive capacity across many economically important sectors and low levels of resource and capacity support to enhance adaptive capacity. Recent literature also illustrates the interconnected and interdependent nature of infrastructure systems (see Box 6.2), which lead to uncertainties over how risks in one sector lead to cascading, compounding, or knock-on effects across other sectors (Zscheischler and Seneviratne, 2017) (see Section 6.2.6 for elaboration). Therefore, adaptation options should address climate risks to infrastructure in an integrated and co-beneficial manner (*medium evidence, high confidence*) (see Section 6.3 and Section 6.4).

[START BOX 6.2 HERE]

Box 6.2: Infrastructure Interdependencies

Infrastructure networks are increasingly dependent on each other —for power, control (via ICT) and access for deliveries or servicing (see Figure 6.2). Moreover, a range of other mechanisms can create interdependencies that impact upon climate risks by creating pathways for cascading failure (Undorf et al., 2020; Barabási, 2013). In the UK, for example, all infrastructures utilities identify failure of components in another utility as a risk to their systems (Dawson et al., 2018).

Key interdependencies include:

i. The use of ICT for data transfer, remote control of other systems, and clock synchronization. Pant et al. (2016) show that ICT is crucial for the successful operation of the UK's rail infrastructure. The study shows that flooding of the ICT assets in the 1-in-200-year floodplain would disrupt 46% of passenger journeys across the whole network.
ii. Water to generate hydroelectricity and for cooling thermal power stations. Reductions in usable capacity for 61–74% of the hydropower plants and 81–86% of the thermoelectric power plants worldwide for 2040–2069 (Van Vliet et al., 2016), with some power generation technologies, including carbon capture and storage, requiring far higher volumes of water for cooling (Byers et al., 2016);
iii. Energy to power other infrastructure systems. Failure of urban energy supply disrupts other infrastructure services, with disproportionate impacts on the urban poor (Silver, 2015);
iv. Transport systems that ensure access for resources such as fuel, personnel and emergency response. Pregnolato et al. (2017) show disruption across the city from a 1-in-10 year storm event could increase by 43% by the 2080s.
v. Green infrastructure can provide multiple services, creating interdependencies between multiple physical infrastructure systems. For example, green space can support sustainable urban drainage, in-situ wastewater treatment, and urban cooling (Demuzere et al., 2014).
vi. Geographical proximity of assets leads to multiple infrastructures being simultaneously exposed to the same climate hazard. Disruption is disproportionately larger for interconnected networks (Fu et al., 2014).

There is usually limited information on the risks between infrastructure sectors. Without frameworks for collaboration and coupled with commercial and security sensitivities this remains a barrier to routine sharing and cooperation between operators. Despite this, methods to tackle interdependence in climate risk analysis are emerging (Dawson, 2015). For example, Thacker et al. (2017) analysed the criticality of the UK's infrastructure networks by integrating data on infrastructure location, connectivity, interdependence, and usage. The analysis showed that criticality hotspots are typically located around the periphery of urban areas where there are large facilities upon which many users depend or where several critical infrastructures are concentrated in one location. As infrastructure systems become increasingly interconnected, associated risks from climate change will increase and require a cross-sectoral approach to adaptation (Dawson et al., 2018).

[END BOX 6.2 HERE]

6.2.4.1 Energy infrastructure

Energy infrastructure underpins modern economies and quality of life. Disruption to power or fuel supplies impacts upon all other infrastructure sectors, and affects businesses, industry, healthcare, and other critical services both within an across jurisdictional boundaries (Groundstroem and Juhola, 2019). The economic impacts of climate change risks are significant, for example in the EU the expected annual damages to energy infrastructure, currently €0.5 billion per year, are projected to increase 1612% by the 2080s (Forzieri et al., 2018). In China, 33.9% of the population are vulnerable to electricity supply disruptions from a flood or drought (Hu et al., 2016), whilst in the USA, higher temperatures are projected to increase power system costs by about $50 billion by the year 2050 (Jaglom et al., 2014). In a study of 11 Central and Eastern Europe countries, researchers found that energy poverty is exacerbated by existing infrastructure deficits, an energy efficient building stock, as well as income inequality, which can lead to reduced economic productivity (Karpinska and Śmiech, 2020). Climate change is expected to alter energy demand (Viguié et al., 2021), for example heatwaves increase spot market prices (Pechan and Eisenack, 2014) with a disproportionate impact on the poorest and most vulnerable populations. Energy infrastructure are susceptible to a range of climate risks (Cronin, Anandarajah and Dessens, 2018), whilst issues pertaining to energy demand are considered by Working Group III.

Climate change can, for example, influence energy consumption patterns by changing how household and industrial consumers respond to short-term weather shocks as well as how they adapt to long-term changes (Auffhammer and Mansur, 2014). Recent studies from Stockholm, Sweden, show that future heating demand will decrease while cooling demand will increase (Nik and Sasic Kalagasidis, 2013). A study from the USA showed that climate change will impacts buildings by affecting peak and annual building energy consumption (Fri and Savitz, 2014). From an infrastructure standpoint, the vulnerability of current hydropower and thermo-electric power generation systems may change due to changes in climate and water systems and projected reduction of usable capacities (Van Vliet et al., 2016; Byers et al., 2016). These examples show how energy infrastructure planning under climate change must take into account a greater number of scenarios and investigate impacts on particular energy segments (Sharifi and Yamagata, 2016).

Electricity generation. Electricity generation infrastructure can be directly damaged by floods, storm and other severe weather events. Furthermore, the performance of renewables (solar, hydro-electric, wind) is affected by changes in climate.

Most thermoelectric plants require water for cooling, many are therefore situated near rivers and coasts and therefore vulnerable to flooding. Increases in water temperature or restrictions on cooling water availability affect hydro-electric and thermoelectric plants. A 1°C increase in the temperature of water used as coolant yields a decrease of 0.12-0.7% in power output (Mima and Criqui, 2015; Ibrahim, Ibrahim and Attia, 2014). Excess biological growth, accelerated by warmer water, increases risk of clogging water intakes (Cruz and Krausmann, 2013). While some regions are expected to experience increased capacity under climate change (namely India and Russia), global annual thermal power plant capacity is likely to be reduced by between 7% in a mid-century RCP2.6 scenario and 12% in a mid-century RCP8.5 scenario (Van Vliet et al., 2016). Worldwide, hydro-electric capacity reductions are projected 0.4-6.1% (Van Vliet et al., 2016). Analysis of the UK's water for energy generation abstractions showed that an energy mix of high nuclear or carbon capture technologies could require as much as six times the current cooling water demands (Byers, Hall and Amezaga, 2014; Byers et al., 2016).

Increasing temperatures improve the efficiency of solar heating, but decrease the efficiency of photovoltaic panels, and deposition and abrasive effects of wind-blown sand and dust on solar energy plants can further reduce power output, and the need for cleaning (Patt, Pfenninger and Lilliestam, 2013). Projected changes in wind and solar potential are uncertain, the trends vary by region and season (Burnett, Barbour and Harrison, 2014; Cradden et al., 2015; Fant, Schlosser and Strzepek, 2016). In an RCP8.5 scenario, Wild et al. (2015) conservatively calculate a global reduction of 1% per decade between 2005-2049 for future solar power production changes due to changing solar resources as a result of global warming and decreasing all-sky radiation over the coming decades. However, positive trends are projected in large parts of Europe, South-East of North America and the South-East of China.

Electricity transmission and distribution. Electricity transmission and distribution networks span large distances, with overhead power lines often traversing exposed areas. Power lines and other assets, such as substations, are often located near population centres, including those in floodplains. Structural damage to overhead distribution lines will increase in areas projected to see more ice or freezing rain (e.g. most of Canada), snowfall (e.g. Japan) or wildfires (e.g. California, USA) (Bompard et al., 2013; Mitchell, 2013; Sathaye et al., 2013; Jeong et al., 2018; Ohba and Sugimoto, 2020). Electricity outages maybe last for prolonged periods of time and across vast areas, in addition to potentially disproportionately affecting poorer or more vulnerable communities. Increases in windstorm frequency and intensity increase the risk of direct damage to overhead lines and pylons, in many locations this is limited but Tyusov et al. (2017) calculate an increase as high as 30% in parts of Russia. Where the mode of failure is recorded, transmission pylons are seen to be more susceptible to wind damage, whilst distribution pylons are more likely to be affected by treefall and debris (Karagiannis et al., 2019). Increased temperatures can lead to the de-rating (lower performance) of power lines whose resistance increases with temperature with efficiency reductions of 2-14% being projected by 2100 (Cradden and Harrison, 2013; Bartos et al., 2016).

Fuels extraction and distribution. Non-electric energy infrastructure is susceptible to many of the same impacts as the electric infrastructure. Extreme weather events impact extraction (onshore and offshore) and refining operations of petroleum, oil, coal, gas and biofuels. Disruption of road, rail and shipping routes (see Section 6.2.5.2) interrupts fuel supply chains. However, there are a number of risks that are specific to these sectors. Heat can lead to expansion in oil and gas pipes, increasing the risk of rupture (Sieber, 2013). Whilst heatwaves and droughts can reduce the availability of biofuel (Moiseyev et al., 2011; Schaeffer et al., 2012). Subsidence and shrinkage of soils damages underground assets such as pipes intakes (Cruz and Krausmann, 2013), while additional human activity such as extractive drilling may induce earthquakes, as observed in the northern Dutch province of Groningen (Van der Voort and Vanclay, 2015). In Alaska, USA, the thaw of permafrost and subsequent ground instability is estimated to lead to $33M damages to fuel pipelines in an end-of-century RCP8.5 scenario (Melvin et al., 2017), with low lying coastal deltas particularly vulnerable (Schmidt, 2015).

6.2.4.2 Transport

Since AR5, research has highlighted the implications for disruption to global supply chains (Becker et al., 2018; Shughrue and Seto, 2018; Pató, 2015), and has made advancements in quantifying costs of climate risks to transportation infrastructure. Climate risks to transport infrastructure (from heat- and cold waves, droughts, wildfires, river and coastal floods and windstorms) in Europe could rise from €0.5 billion to over €10 billion by 2080s (Forzieri et al., 2018). Across the Arctic, nearly four million people and 70% of all current infrastructure, including resource extraction and transportation routes, will be at risk by 2050 (Hjort et al., 2018), although the design of specific infrastructure may also affect the degree of infrastructure damage depending local geological and ecological conditions. Globally, Koks et al. (2019) calculated that approximately 7.5% of road and railway assets are exposed to a 1/100 year flood event, and total global expected annual damages (EAD) of US$3.1-22 billion (mean $14.6 billion) due to direct damage from cyclone winds, surface and river flooding, and coastal flooding. The majority of this is caused by surface water and fluvial flooding (mean $10.7 billion). Although twice as much infrastructure is exposed to cyclone winds compared to flooding, a mean EAD of $0.5 billion is significantly less that for coastal flooding ($2.3 billion) as cyclone damages are largely limited to bridge damage and the cost of removing trees fallen on road carriageways and railway tracks. This is small relative to global GDP (~0.02%). However, in some countries EAD equates to 0.5-1% of GDP, which is the same order of magnitude as typical national transport infrastructure budgets, but especially significant for countries like Fiji that already spend 30% of their government budget on transport (World Bank Group, 2017). Koks et al. (2019) did not assess future climate change impacts, but comparable studies calculating changes in EAD from flooding based upon land use show increases of 170%--1370% depending on global greenhouse gas emissions levels (Alfieri et al., 2017; Winsemius et al., 2015). Moreover, Schweikert et al., (2014) report that climate risks to transport infrastructure could cost as much as 5% of annual road infrastructure budgets by 2100, with disproportionate impacts in some low and lower middle-income countries.

Changes in rainfall and temperature patterns are expected to increase geotechnical failures of embankments and earthworks (Briggs, Loveridge and Glendinning, 2017; Tang et al., 2018; Powrie and Smethurst, 2018) from landslides, subsidence, sinkholes, desiccation and freeze-thaw action. For instance, Pk et al. (2018) show this could lead to a 30% reduction in the engineering factor of safety of earth embankments in Southern Ontario (Canada). Increased river flows in many catchments will also increase failures from bridge scours (Forzieri et al., 2018). HR Wallingford (2014) calculate that the projected 8% increase in scouring from high river flows in the UK will lead to 1 in 20 bridges being at high risk of failure by the 2080s, whilst in the USA the 129,000 bridges currently deficient could increase by 100,000 (Wright et al., 2012). With respect to temperature, analysis by Forzieri et al. (2018) concludes that heatwaves will be the most significant risk to EU transport infrastructure in the 2080s as a result of buckling of roads and railways due to thermal expansion, melting of road asphalt and softening of pavement material. In the USA, over 50% more roads will require rehabilitation (Mallick et al., 2018), whilst $596m will be required through 2050 to maintain and repair roads in Malawi, Mozambique, and Zambia (Chinowsky, Price and Neumann, 2013).

In addition to direct damages from flooding and heatwaves, disruption caused by road blockages will be increased by more frequent flood events. For example in the city of Newcastle upon Tyne (UK), road travel disruption across the city from a 1-in-50 year surface water flood event could increase by 66% by the 2080s

(Pregnolato et al., 2017) whilst heatwaves could treble railway speed restrictions in parts of the UK (Palin et al., 2013). Knott et al. (2017) highlighted risks to coastal infrastructure where ~30cm sea level rise sea level rise would also push up groundwater and reduce design life by 5-17% in New Hampshire (USA). Heavy rain and flooding can also inundate underground transport systems (Forero-Ortiz, Martínez-Gomariz and Canas Porcuna, 2020).

Many airports, and by their nature ports, are in the low elevation coastal zone making them especially vulnerable to flooding and sea level rise. Under a 2ºC scenario the number of airports at risk of storm surge flooding increases from 269 to 338 or as many as 572 in an RCP8.5 scenario; these airports are disproportionately busy and account for up to 20% of the world's passenger routes (Yesudian and Dawson, 2021). Airport and port operations could be disrupted by icing of aircraft wings, vessels, decks, riggings, and docks (Doll, Klug and Enei, 2014; Chhetri et al., 2015). Warming will increase microbiological corrosion of steel marine structures (Chaves et al., 2016). Fog, high winds and waves can disrupt port and airport activity but changes are uncertain and with regional variation (Mosvold Larsen, 2015; Izaguirre et al., 2021; Becker, 2020; León-Mateos et al., 2021; Taszarek, Kendzierski and Pilguj, 2020; Danielson, Zhang and Perrie, 2020; Kawai et al., 2016).

Waterways are still important transport routes for goods in many parts of the world, although they are mostly expected to benefit from reduced closure from ice (Jonkeren et al., 2014; Schweighofer, 2014), low flows will likely lead to reduced navigability and increased closures, van Slobbe et al. (2016) estimate the Rhine may reach a turning point for waterway transportation between 2070-2095. Obstruction due to debris and fallen vegetation of roads and rails and to inland and marine shipping from high winds are expected to increase (Koks et al., 2019; Kawai et al., 2018; Karagiannis et al., 2019)..

6.2.4.3 Information and Communication Technology

Information and Communication Technology (ICT) comprises the integrated networks, systems and components enabling the transmission, receipt, capture, storage and manipulation of information by users on and across electronic devices (Fu, Horrocks and Winne, 2016). ICT infrastructure faces a number of climate risks. Increased frequency of coastal, fluvial or pluvial flooding will damage key ICT assets such as cables, masts, pylons, data centres, telephone exchanges, base stations or switching centres (Fu, Horrocks and Winne, 2016). This leads to loss of voice communications, inability to process financial transactions and interruption to control and clock synchronization signals. Insufficient information about the location and nature of many ICT assets limits detailed quantitative assessment of climate change risks.

Fixed line ICT networks that sprawl over large areas are especially susceptible to increases in the frequency or intensity of storms would increase the risk of wind, ice and snow damage to overhead cables and damage from wind-blown debris. More intense or longer droughts and heatwaves can cause ground shrinkage and damage underground ICT infrastructure (Fu, Horrocks and Winne, 2016). In mountain and northern permafrost regions, communications and other infrastructure networks are subject to subsidence because of warming of ice-rich permafrost (Shiklomanov et al., 2017; Li et al., 2016; Melvin et al., 2017).

6.2.4.4 Housing

For the urban housing sector, climate impacts such as flooding, heat, fire, and wind assessed in Section 6.2.3 will *likely* have detrimental effects on housing stock (including physical damage and loss of property value) as well as on residents exposed to climate risks (robust evidence*, high agreement*)

In the USA, for example, 15.4 million housing units fall within a 1-in-100-year floodplain (Wing et al., 2018). Assessment of the Miami-Dade area in Florida noted that coastal inundation caused by tidal flooding (and to a lesser extent sea level rise) resulted in over $465 million in lost real-estate market value between 2005 and 2016 (McAlpine and Porter, 2018), although property values have increased from high-end housing construction and climate adaptation measures (Kim, 2020). Emergent risk reflecting novel research include aggravated moisture problems in buildings from wind driven rain (Nik et al., 2015). Future risks from future sea level rise are elaborated in CCP2.2.1. Housing infrastructure are also susceptible to extreme heat and wind events (Stewart et al., 2018). These risks are further elaborated on in Section 6.2.3, although it is important to note that heat risks, in particular, tend to be concentrated within communities with higher proportion of social housing (Mavrogianni et al., 2015; Sameni et al., 2015) or low-cost government-built houses and informal settlements.

6.2.4.5 Water and Sanitation

Apart from land subsidence from urbanization (e.g. Case Study 6.2), substantial climate risks to urban sanitation arise from droughts, flooding and storm surges. Low flows from drought can lead to sedimentation, increase pollutant concentration and block sewer infrastructure networks (Campos and Darch, 2015). Flooding poses a greater risk for urban sanitation in low and middle income settings (Burgin et al., 2019) where onsite systems are more common. Floodwater may wash out pits and tanks, mobilising faecal sludges and other hazardous materials leading to both direct and indirect exposure via food and contaminated objects and surfaces and pollute streams and waterbodies (Howard et al., 2016; Braks and de Roda Husman, 2013; Bornemann et al., 2019). Floods also damage infrastructure; toilets, pits, tanks and treatment systems are all vulnerable (Sherpa et al., 2014; UNICEF and WHO 2019).

Sanitation systems coupled with floodwater management are at risk of damage and capacity exceedance from high rainfall (Thakali, Kalra and Ahmad, 2016; Kirshen et al., 2015; Dong, Guo and Zeng, 2017). In England, the number of water and wastewater treatment plants at risk of flooding is projected to increase by 33% under a 4°C scenario (Sayers et al., 2015), but risks are generally increasing for both formal and informal urban sanitation systems (Howard et al., 2016).

6.2.4.6 Natural and Ecological Infrastructure

Urban ecological infrastructure includes green (i.e., vegetated), blue (i.e., water-based), and grey (i.e., non-living) components of urban ecosystems (Li et al., 2017). While land cover change from urbanization directly reduces the extent of natural and ecological infrastructure (e.g. Lin, Meyers and Barnett, 2015), notable risks arise from climate drivers. Recent research particularly highlights future climate impacts on coastal natural infrastructure – including beaches, wetlands, and mangroves – which cause significant economic losses from property damage, decreasing tourism income, as well as loss of natural capital and ecosystem services. Research on climate risks to urban trees and forests is comparatively limited. Instead, urban vegetation and green infrastructure are most often cast as adaptation strategies to reduce urban heat, mitigate drought, and provide other ecosystem benefits (see 6.3.2).

Coastal natural infrastructure is exposed to sea level rise, wave action, and inundation from increasing storm events (See also CCP 2.2.1). Beaches, in particular, are highly exposed to climate-induced coastal erosion ((Toimil et al., 2018); CCP2). Research from settlements across coastal Southern California, USA, show that 67% of all beaches may completely erode by 2100 (Vitousek, Barnard and Limber, 2017). Coastal zones across Cancún, Mexico, are exposed to a combination of sea level rise and tropical hurricanes, further exacerbated by urban development patterns blocking natural sediment replenishment to beaches (Escudero-Castillo et al., 2018). In another case, beach erosion along the heavily urbanized Valparaíso Bay, Chile, is heightened by El Niño Southern Oscillation (ENSO) events, which in the past have caused an additional 15-20cm in mean sea level rise (Martínez et al., 2018).

Wetlands, mangroves, and estuaries – which tend to be heavily urbanized areas – are highly at risk from sea level rise and changing precipitation (Green et al., 2017; Feller et al., 2017; Alongi, 2015; Osland et al., 2017; Chow, 2018; Godoy and Lacerda, 2015). Sea level rise is a concern for wetlands and mangroves across coastal urban Asia, the Mississippi Delta (USA), and low lying small island states (Ward et al., 2016b). Research on the highly urbanized Yangtze River estuary in China shows that soil submersion and erosion from sea level rise, compounded by land conversation to agriculture and urban development, will cause all tidal flats to disappear by 2100 (Wu, Zhou and Tian, 2017). In another example, sea level rise and high rates of tidal inundation have increased overall salinity in the San Francisco Bay-Delta estuary, threatening the ecosystem's ability to support biodiversity (Parker and Boyer, 2019).

Research on climate risks to urban trees and forests highlight direct impacts from extreme temperatures, precipitation, wind events, and sea level rise, as well as exposure to other hazards such as air pollution, fires, invasive species, and disease (Ordóñez and Duinker, 2014). Since the 1960s, climate change has enabled growth of urban trees, supported by longer growing seasons, higher atmospheric CO2 concentrations, reduced diurnal temperature range (Pretzsch et al., 2017), as well as increased fertilization through urban-enhanced nitrogen deposition (Decina, Hutyra and Templer, 2020). However, these trends may change in the future as further warming and decreasing water supply may depress tree fitness, thus enabling more pests (Dale and Frank, 2017).

Climate risks to urban natural and ecosystem infrastructure entail significant economic costs. For example, in 2012, Hurricane Sandy led to total losses of up to US$6.5 million to the New York City region's low-lying salt marshes and beaches (Meixler, 2017). Research from coastal settlements across Catalonia, Spain, shows significant levels of tourism loss (which contribute to 11.1% of the region's GDP), infrastructure damage, and natural capital loss attributed to inundation and erosion of beaches, which are projected to retreat by -0.7 meters per year given current sea level rise projections of 0.53 to 1.75 meters by 2100 (Jiménez et al., 2017).

6.2.4.7 Health systems infrastructure

Healthcare facilities (hospitals, clinics, residential homes) will suffer increasing shocks and stresses related to climate variability and change (Corvalan et al., 2020). Some may be sudden shocks from extreme weather events, which both threaten the facility, staff and patients and increase the number of people seeking health care. There are extensive reports of health facilities being damaged after major floods and windstorms (e.g. 2010 floods in Pakistan, Hurricane Sandy in the US) which can be further exacerbated by power and water supply failures (Powell, Hanfling and Gostin, 2012). Disruption to services may persist for many months due to damage to buildings, loss of drugs and equipment, and damaged transport infrastructure significantly increasing travel time for patients (Hierink et al., 2020). The impacts of climate change on the health of residents of 'slum' settlements will also compound the existing health burdens faced by these individuals, including infectious disease and other environmental public health concerns (Lilford et al., 2016; Mberu et al., 2016).

6.2.5 Compound and Cascading Risks in Urban Areas

Compound events can be initiated via hazards such as single extreme events, or multiple coincident events overlapping and interacting with exposed urban systems or sectors as compound climate risks (Leonard et al., 2014; Pörtner et al., 2019; Piontek et al., 2014). Hydrometeorological hazards - such as extreme precipitation from tropical cyclones, fronts, and thunderstorms - often combine with storm surges and freshwater discharge leading to high compound risks at exposed settlements (Zheng, Westra and Sisson, 2013; Chen and Liu, 2014; Ourbak and Magnan, 2018; Dowdy and Catto, 2017). The compounding effect between these hydrometeorological hazards suggest that the combined impact of these events are greater than each of these variables on its own, and can amplify risks in affected settlements (Kew et al., 2013; Vitousek et al., 2017). These risks are concentrated in coastal cities exposed to sea level rise and severe storms (van den Hurk et al., 2015; Wahl et al., 2015; Paprotny et al., 2018b; Lagmay et al., 2015), or in settlements located in valleys prone to slope failure, such as the 2013 Uttarakhand floods and landslides arising from extreme precipitation and glacial lake outbursts along the Mandakini river in India (Ziegler et al., 2016; Barata et al., 2018).

Cascading climate events occur when an extreme event triggers a sequence of secondary events within natural and human systems that causes additional physical, natural, social or economic disruption. The resulting impact can be significantly larger than the initial hazard (Pörtner et al., 2019). Each step in a risk cascade can generate direct (immediate impacts) and secondary (consequential impacts) losses. Risks from these cascading impacts are complex and multidimensional (Hao, Singh and Hao, 2018; Zscheischler and Seneviratne, 2017). For instance, combined droughts and heat waves increases risks of urban water scarcity (Miralles et al., 2019; Gillner, Bräuning and Roloff, 2014; Gill et al., 2013), as well as increasing wildfire extent and lowering snowpack conditions that affected peri-urban settlements adjacent to forested areas as observed in California during the 2014 drought (AghaKouchak et al., 2014). Similarly, heat waves can increase the risk of mortality associated with air pollution (see 7.2.2.5).

Urban areas and their infrastructure are susceptible to both compounding and cascading risks arising from interactions between severe weather from climate change and increasing urbanization (*medium evidence, high agreement*) (Moretti and Loprencipe, 2018; Markolf et al., 2019). Risks are complex and multidimensional, and can significantly amplify the impact of single events across space, scale, and time.

Impacts are determined by the magnitude of urban vulnerability and/or the interdependence of urban critical infrastructure (Pescaroli and Alexander, 2018; Zuccaro, De Gregorio and Leone, 2018). Poorer and wealthier settlements and cities are then both at risk from compound and cascading risks though potentially through contrasting mechanisms. For richer and poorer cities, managing climate risk as part of compound and cascading risks that can also include technological, biological, and political risks places renewed emphasis on investment in generic capabilities that reduce vulnerability and on risk monitoring capability to track and respond to impacts across infrastructures and places (*low evidence, high agreement*). Considering climate risk and managing such risk as part of complex, compounding and/or cascading risks is in its infancy but rapidly being accepted as necessary especially when considering the wider poverty and justice implications of climate change arising from differentiated vulnerability in cities.

Compound risks to key infrastructure in cities have increased from extreme weather (*medium evidence, high agreement*), such as from urban flooding from extreme precipitation and storm surges disrupting transport infrastructure and networks, e.g. (Mehrotra et al., 2018); See also San Juan case study in this chapter), ICT networks e.g. underground cables or transmission towers (Schwarze et al., 2018), and energy generation from power plants (Marcotullio et al., 2018).

The increased risk arises not just from greater exposure from climate events impacting cities, but is also magnified by low adaptive capacity that can arise from intra-urban variations in infrastructure quality. For instance, infrastructure within expanding informal settlements are associated with deficiency in materials, structural safety, and a lack of accessibility. These areas are often located in the most risk-prone urban areas in developing nations that are vulnerable to compound hazards (Dawson et al., 2018). Further these risks can be exacerbated from complications arising from local vs. national governance and/or regulations related to hazard management (Garschagen, 2016; Castán Broto, 2017).

Projected global compound risks will increase in the future, with significant risks across energy, food, and water sectors that likely overlap spatially and temporally while affecting increasing numbers of people and regions particularly in Africa and Asia (*high confidence*) (Hoegh-Guldberg et al., 2018). In cities, the prevalence of compounding risks therefore necessitates methodologies accounting for nonstationary risk factors.

Secondary impacts occurring sequentially after an extreme hazard can severely affect disaster management especially in complex urban systems (*robust evidence, high agreement*). Over time, relatively small perturbations can cascade outward from a primary failure, triggering further failures in other dependent parts of the network some distance away from the primary failure (Penny et al., 2018). In some cities, such as those prone to compound flood hazards, these dependent network parts can be dams, levees, or other critical flood protection infrastructure that are essential for managing these cascading risks (Serre and Heinzlef, 2018; Fekete, 2019). Failure of these infrastructure systems can result in sequential failures in urban transport (Zaidi, 2018), energy networks (Sharifi and Yamagata, 2016), urban biodiversity (Solecki and Marcotullio, 2013) and so-called na-tech disasters - when natural hazards trigger technological disasters (Girgin, Necci and Krausmann, 2019). This risk cascade can propagate more widely by stopping flows of people, goods, and services, with economic consequences beyond urban areas (Wilbanks and Fernandez, 2014).

Compound and cascading climate risks require a different way of accounting for cumulative hazard impacts in urban areas (*medium evidence, high agreement*). There is emerging literature calling for analysis on interactions between individual and interrelated climate extremes with complex urban systems, so as to ascertain how urban and key infrastructural vulnerabilities can be identified and managed in a warming world (Butler, Deyle and Mutnansky, 2016; Gallina et al., 2016; Moftakhari et al., 2017; Zscheischler et al., 2018; Baldwin et al., 2019; Pescaroli and Alexander, 2018; Yin et al., 2017; AghaKouchak et al., 2020), as well as in managing adaptation for present and future pandemics e.g. COVID-19 (Pelling et al., 2021; Phillips et al., 2020b).

In term of policy, case studies from London's resilience planning process stressed the need for intermodal coordination, hazard risk and infrastructure mapping, clarifying tipping points and acceptable levels of risk, training citizens, strengthening emergency preparedness, identifying relevant data sources, and developing scenarios and contingency plans (Pescaroli, 2018). Others also note the utility of a systems approach to analyzing risks and benefits, including considerations of potential cascading ecological effects, full life cycle environmental impacts, and unintended consequences, as well as possible co-benefits of responses (Ingwersen et al., 2014). Lowering these risks requires urban stakeholders to reduce urban vulnerability by going beyond linear approaches to risk management (*medium evidence, high agreement*).

6.2.6 Impacts and Risks of Urban Adaptation Actions

Planning and implementing climate adaptation in cities and settlements can be hampered by incomplete scientific knowledge, a lack of awareness of cascading impacts (and residual risks), mismanagement of actions, human capacity and financing deficits, as well as opportunities for eroding long-term sustainable development priorities (Juhola et al., 2016). These tensions can become acute in fragile and conflict affected states (see Box 6.3). It is important to differentiate between the climatic drivers of risk and social drivers that may compound risk exposures and experiences (Brown, 2014; Nightingale et al., 2020), especially since technically- and scientifically-informed adaptation actions can be redirected depending on socioeconomic, political, or cultural conditions on the ground (Eriksen, Nightingale and Eakin, 2015). The implementation of adaptation – whether by government, private sector, or civil society actors – can therefore lead to unanticipated and unintended amplification of political, economic and ecological risks (Swatuk et al., 2020). Many cities are still in the phase of piloting or testing out appropriate adaptation actions, although there is emerging consensus that adaptation plans and projects should acknowledge trade-offs, intentionally avoid past development mistakes, not lock-in detrimental impacts or further risks arising from implementation, and explicitly anticipate the risks of maladaptation in decision-making (Magnan et al., 2016; Gajjar, Singh and Deshpande, 2019). Maladaptation describes actions that lead to increased vulnerability or risk to climate impacts or diminish welfare. Urban examples include green gentrification which offers nature based solutions to the few, social safety nets that promote risk inducing subsidies. Whether an action is maladapted can depend on context, e.g. air conditioning can reduce risk for the individual but is maladaptive at a societal level (see 6.3.4.2). It is informed by process – corruption can distort processes and generate maladaptation (see 6.4.5.2). Climate Resilient Development raises the ambition for adaptation actions so that it is also possible to describe actions that do not also enhance climate mitigation and sustainable development outcomes as maladaptive (see 6.4.3.1). This section assesses three broad categories of risk arising from downstream adaptation actions, including interventions that transfer vulnerability across space and time, plans that yield socioeconomically exclusionary outcomes, and actions that undermine long-term sustainable and resilient development priorities.

[START BOX 6.3 HERE]

Box 6.3: Climate Change Adaptation for Cities in Fragile and Conflict Affected States

Larger cities may be the most stable administrative entities in states affected by conflict. Even here ability to plan and deliver adaptation can be hampered. Extending into urban areas within stable states, alienation and loss of trust between local populations and the state can be exacerbated by top-down adaptation planning and delivery; socially and spatially uneven adaptation investment., and in the economic and administrative limits of government that can lead to some places being excluded from formal planned investment (*high confidence*) (see 6.3 and 6.4). These pathways for exclusion can combine amongst already marginalized and low-income populations where trust in government agencies may already be low (Rodrigues, 2021).

Climate change can be a threat multiplier in cities and urban regions, exacerbating existing human security tension (*limited evidence, medium agreement*) (Froese and Schilling, 2019; Flörke, Schneider and McDonald, 2018; Rajsekhar and Gorelick, 2017). Where conflict or administrative tensions extend beyond cities, adapting regional infrastructure systems that underpin urban life is challenging for example where elements of networked infrastructure are under the control of conflicting political interests. This has been noted for the water sector (Tänzler, Maas and Carius, 2010). Coordinating political processes is a major challenge even for industrialized countries with adequate administrative capacity. In post-conflict societies , the difficulties of coordination for urban planning are disproportionately greater (Sovacool, Tan-Mullins and Abrahamse, 2018).

In planning adaptation measures in cities, conflict-sensitive approaches to ensure participatory methods (Bobylev et al., 2021) can avoid adaptation being a polarising activity (Tänzler, Maas and Carius, 2010; Tänzler, 2017). Adaptation can provide a common goal reaching across political differences and be a part of building political trust and local cooperation between alienated communities (Tänzler, Maas and Carius, 2010). Peacebuilding programmes led by government or civil society are typically concerned with the short-term and framed by socioeconomic policy, integrating the longer-term view and engineering-technical expertise for adaptation is a challenge (*limited evidence, medium agreement*) (Ishiwatari, 2021).

[END BOX 6.3 HERE]

Downstream impacts occur because adaptive capacity is often unequally distributed across sectors and communities (Matin, Forrester and Ensor, 2018; Makondo and Thomas, 2018). In cities and settlements, adaptation interventions can displace ecological impacts to more vulnerable areas or directly lead to socioeconomically exclusionary outcomes (Anguelovski et al., 2016), particularly when adaptation plans and actions are primarily assessed through the prism of economic and/or financial viability (Shi et al., 2016; Klein, Juhola and Landauer, 2017). As a result, adaptation actions make only minimal contributions to the reduction of vulnerability – as the increased vulnerability of excluded communities more than offsets the decreased vulnerability of more well-off communities. Numerous examples ranging from the mega coastal planning in Jakarta, Indonesia (Salim, Bettinger and Fisher, 2019; Goh, 2019), fragmentation of urban infrastructure intended to promote climate resilience in Manila, Philippines (Meerow, 2017), exclusionary modes of flood control in São Paulo, Brazil (Henrique and Tschakert, 2019), strategies to reduce risks in the event of mudslides in Sarno, Italy (D'Alisa and Kallis, 2016), involuntary community relocations in Vietnam (Lindegaard, 2019) and Mozambique (Arnall, 2019) all point to how an economic logic to adaptation can lead to exclusion of lower income, informal, or minority communities in adaptation.

A specific form of maladaptation is so called green gentrification, this privileges wealthy urban residents in urban greening projects (Rice et al., 2020; Shokry, Connolly and Anguelovski, 2020; Anguelovski, Irazábal-Zurita and Connolly, 2019; Blok, 2020). For example, in Miami-Dade County, Florida, United States, researchers found that adaptation functionality had a positive effect on property values (Keenan, Hill and Gumber, 2018). In New York City and Atlanta, Georgia, United States, research has shown that adaptation investments can increase property values and lead to neighborhood change (Immergluck and Balan, 2018; Gould and Lewis, 2018). In Gold Coast and Sunshine Coast, South East Queensland, Australia, where local communities have a strong preference for waterfront living, local governments are pressured by property developers to protect these coastal zones (Torabi, Dedekorkut-Howes and Howes, 2018). In Lagos, Nigeria, efforts to achieve climate resilience and sustainability through future city practices risk perpetuating the enclosure and commodification of land (Ajibade, 2017). The exclusionary outcomes of some adaptation interventions can therefore further heighten the risk to communities that are socioeconomically more vulnerable. See Section 6.3 for further discussion of equity and justice considerations in local climate adaptation.

Human behaviour can exacerbate climate impacts – for example in the emergence of 'last chance tourism'(Lemieux et al., 2018) focused on built cultural heritage at risk from climate change associated events including from decay or even total loss generated by increased flooding and sea-level rise (Camuffo, Bertolin and Schenal, 2017) and water infiltration from post-flood standing water (Camuffo, 2019). Last chance tourism can lead to increased touristic interest over a short time horizon and to precarious economic conditions, which can lead to further accelerated degradation cultural heritage sites already at-risk from climate change.

Finally, some adaptation policies or actions can erode the preconditions for sustainable and resilient development by indirectly increasing society's vulnerability (Neset et al., 2019; Juhola et al., 2016). Mandates to mainstream adaptation into existing development logics and structures perpetuates development-as-usual, reinforcing technocratic forms of local governance and locking-in structural causes of marginalization and differential vulnerability (Scoville-Simonds, Jamali and Hufty, 2020). Adaptation policy examples include: Australia's adaptation policy focus on financial strategies, preference for business-as-usual scenarios and incremental change will not contribute to transformative change (Granberg and Glover, 2014); Surat, India, where a focus on adapting industries and economically important assets in the city can divert policy attention away from general social equity and urban sustainability priorities (Chu, 2016; Blok, 2020); Cambodia where conflict between adaptation practitioners and local communities and non-compliance with regulatory safeguards led to conflict and potential for maladaptation (Work et al., 2018). Finally, although insurance has the potential to incentivize practices to reduce risks – including through measures to reduce premiums (see Section 6.4.5 for additional details) – researchers of insurance-led adaptation actions have argued that since insurance regimes privilege normality, they tend to structurally embed risky behavior and inhibit change (O'Hare, White and Connelly, 2016). All of these examples illustrate how incremental strategies that rely on business-as-usual actions can further entrench unequal and unsustainable development patterns in the long-term. There are also significant limits to urban adaptation (see Section 6.4) with consequential impacts on human wellbeing.

Table 6.4 lists a selection of key risks (broadly defined as have severe outcomes common to a majority of cities) identified in our assessment of urban impacts and risks in this section. It provides a description of the consequences of the risk that would constitute a severe outcome, as well as the hazard, exposure and vulnerability conditions contributing to its severity. It also provides adaptation options identified and elaborated on in Section 6.3 as having the highest potential for reducing the risk, and an assessment of the confidence in the judgement that this risk could become severe. This table is also reflected in Chapter 16.5.1, and the methodology is described in Table SM16.5.1.

Table 6.4 Key Risks to Cities, Settlements and Infrastructure

Synthesis of key risks for cities, settlements, and key infrastructure								
Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter & section
Risk to population from increased heat	Global but higher risk in temperate and tropical cities (6.2.3.1)	Increased heat stress, mortality and morbidity events from urbanization and climate change. Increased health risks and mortality in elderly population; vulnerability of the young to heat, (6.2.3.1)	Substantial increase in frequency and duration of extreme heat events, exacerbated by urban heat island effects. (6.2.3.1) Concentration of a mixture of extreme heat and humidity (6.2.3.1)	Large increases in exposure, particularly in urban areas, (6.2.3) driven by population growth, changing demographics, and projected urbanization patterns. Urbanization increases annual mean surface air temperature by more than 1°C Correlation between rising temperatures and	Changing demographics from aging populations, potential for persistent poverty, slow penetration and increasing cost of air conditioning, and inadequate improvements in public health systems. (6.2.3.1) Inadequate housing and occupations with	Nature-based solutions e.g. urban greenery at multiple spatial scales; vegetation; shading; lower energy costs; green roofs; community gardens (6.3.3.1) enhanced space conditioning in buildings; broader access to public health systems for most vulnerable populations.	High confidence, high evidence & agreement	6.2, 6.3

				increased heat capacity of urban structures, anthropogenic heat release and reduced urban evaporation (6.2.3.1)	exposure to heat (6.2.3.1)	Less economic stress on residents through utilities, especially electricity (6.2.3.1) Tree planting in communities that lack urban greening (6.3.3.1)		
Urban infrastructure at risk of damage from flooding and severe storms	Global, but higher risk in coastal cities	Damage to key urban infrastructure (e.g. buildings, transport networks, and power plants) and services from flood events, particularly high risk within coastal cities, especially those located in low elevation coastal zones (6.2.3.2)	Substantial increase in frequency and intensity of extreme precipitation (6.2.3.2) from severe weather events and tropical cyclones contributing to pluvial and fluvial floods, which are exacerbated by long-term sea level rise and potential land subsidence (6.2.3.2)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, and projected urbanization patterns with a geographical focus in coastal regions. Flooding is exacerbated both by encroachment of urban areas into areas that retain water, and lack of infrastructure such as embankments and flood walls (6.2.3.2)	Costly maintenance of protective infrastructure, downstream levee effects, and increased concentrations of coastal urban population. Little investment in drainage solutions (6.2.3.2)	Early warning systems, Adaptive Social Protection (ASP) to reduce vulnerable populations, nature-based solutions e.g. in sponge cities to enhance flood protection and regulate storm- and floodwaters- this can be improved through reduced risk unto vulnerable urban systems such as stormwater management, sustainable urban drainage system, etc. (6.2.3.2) Green infrastructure can be more flexible and cost effective for providing flood risk	High confidence, high evidence & agreement	6.2, 6.3, CCP2

						reduction (6.3.3)		
Population at risk from exposure to urban droughts	Cities located in regions with high drought exposure, (e.g., Europe, South Africa, Australia,)	Water shortages in urban areas, and restricted access to water resources to vulnerable populations and low-income settlements. People living in urban areas will be exposed to water scarcity from severe droughts (6.2.3.3). Increased environmental health risks when using polluted groundwater (6.2.3.3)	Projections of more frequent and prolonged drought events potentially compounded with heat wave hazards, and land subsidence from coastal cities that extract groundwater. Climate drivers (warmer temperatures and droughts) along with urbanization processes (land use changes, migration to cities, and changing patterns of water use) contribute to additional risks (6.2.3.3)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, and projected urbanization patterns. Limitations of engineered water infrastructure is also exposed by flash droughts (6.2.3.3). Settlements are increasingly dependent on imported water resources by locales that may also be exposed to drought risk (6.2.3.3)	Greater water demand from urban populations from in-migration and key economic sectors, and inefficient or ineffective water resource management. (6.2.3.3)	Demand and supply side management strategies that include incorporation of indigenous/local knowledge and practices, equitable access to water. Better water resource management will increase quality of water available. More beneficial physical and social teleconnections to bring mutual benefit of water resources between regions (6.2.3.3)	High confidence, high evidence & agreement	6.2, 6.3
Health risks from air pollution exposure in cities	Global, in cities located in Africa, South Asia, the Middle East and East Asia	Increased mortality and morbidity events from respiratory-related illnesses and co-morbidities towards vulnerable urban populations, arising from	Increased emissions of pollutants from anthropogenic (e.g. transportation, electric power generation, large industries, indoor burning of fuel, and commercial	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, projected urbanization patterns, and demand for energy combined	High proportion of young or aging populations vulnerable to respiratory illness, potential for persistent poverty, advection of pollutants	Enhanced monitoring of air quality in rapidly developing cities, investment in air pollution controls e.g. stricter emissions regulations, and increased GHG emissions	High confidence, medium evidence & agreement	6.2, 6.3

		PM2.5 and tropospheric ozone exposure	and residential sources) and biogenic (e.g. forests, windblown dust, and biomass burning) emissions Potential for severe compound risks arising from droughts and wildfire. Projections for frequency of meteorological conditions are expected to severe PM2.5 concentrations (6.2.3.4)	with weak regulations for emissions control (6.2.3.4)	from upwind, ex-urban areas, and stay in shelter policies from COVID-19 (Box 6.4; 6.2.5)	controls resulting in co-benefits with air quality improvements. Increase in trees or vegetated barriers with low VOC emissions, low allergen emissions, and high pollutant deposition potential to reduce particulate matter and maximize adaptation benefits (6.3.3.2)		
Health risks from water pollution exposure and sanitation in cities	Cities located in regions with high drought exposure resulting in polluted water	Increased environmental health risks when using polluted groundwater (6.2.3.3) Vulnerability of users such as women; children; the elderly; ill or disabled (6.3.4.6)	Decreased regional precipitation and changes in runoff and storage from droughts impairs the quality of water available. Less runoff to freshwater rivers can increase salinity, concentrate pathogens, and pollutants (6.2.3.3)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, and projected urbanization patterns. Low flows from drought can lead to sedimentation, increase pollutant concentration and	Costly maintenance of protective infrastructure. Sanitation systems coupled with flood water management are at risk of damage and capacity exceedance from high rainfall (6.2.5.8)	Investment in well-regulated water sections; wastewater treatment plants; pumping stations. Reducing impacts of floods on sanitation infrastructure through active management such as reducing blockage in sewer infrastructure (6.3.4.6)	High confidence, medium evidence & agreement	6.2, 6.3

				blocking of sewer infrastructure networks (6.2.5.8).		Adaptive planning; integration of measures of climate resilience; improved accounting and management of water resources (6.3.4.6)		

Table Notes:
Following Chapter 16, the severity of a risk or impact is a subjective judgment based on a number of criteria. Key Risks are 'potentially' severe because, while some could already be severe now, more typically they may become so over time due to changes in the nature of the climate-related hazards and/or of the exposure and/or vulnerability of societies or ecosystems to those hazards. They also may become severe due to the adverse consequences of adaptation or mitigation responses to the risk.

6.3 Adaptation Pathways

6.3.1 Introduction

Adaptation pathways are composed of sequences of adaptation actions connected through collaborative learning with the possibility of enabling transformations in urban and infrastructure systems (Werners et al., 2021). Individual adaptation actions co-evolve with risks (see Section 6.2) and development processes (Section 6.4) to compose more or less planned adaptation pathways, that can include a range of unanticipated outcomes. This section engages with this complexity by approaching adaptation through the notion of infrastructure. The adaptation options for individual infrastructure systems are reviewed, and in Section 6.4 brought together through assessment of cross-cutting enabling conditions. Interpreted broadly, infrastructure includes the social systems, ecological systems and grey/physical systems that underpin safe, satisfying and productive life in the city and beyond (Grimm et al., 2016). Social infrastructure includes housing, health, education, livelihoods and social safety nets, cultural heritage/institutions, disaster risk management and security and urban planning. Ecological infrastructure includes nature-based services: temperature regulation, flood protection and urban agriculture. Grey, or physical infrastructure includes energy, transport, water and sanitation, communications (digital), built form and solid waste management. Framing infrastructure in this way enables an assessment of adaptation that is not constrained to the administrative boundaries of urban settlements, but also includes the flows of material, people and money between urban, peri-urban and more rural places and can include adaptation actions deployed by government, individuals and the private sector. Recognising the complexity of adaptation and the research literature that reaches beyond individual infrastructural domains, the section also reviews urban adaptation through the cross-cutting lenses of equity and mitigation. Section 6.4 assesses the enabling environment (political will, governance, knowledge, finance and social context) that shapes specific adaptation contexts and futures.

6.3.2 The Adaptation Gap in Cities and Settlements

The adaptation gap is difference between the ability to manage risk and loss and experienced risk and loss (Chen et al., 2016; UNEP, 2021). It describes both levels of capacity and residual risk. Figure 6.4 presents an analysis by IPCC World Region for urban populations and current levels for risk and loss. The analysis seeks to draw out equity considerations by comparing the poorest and wealthiest quintiles for each region and for adaptation to the direct impacts of flooding and heatwave but also impacts felt in cities that include climate change impacts on supply chains – water and food security. Figure 6.4 should not be used to compare regions but can be used to contrast adaptation gaps by hazard type within regions.

The key finding from Figure 6.4 is that for all urban populations both *currently deployed* and *currently planned* adaptations are not able to meet current levels of risk associated with climate change. Even if *all conceivabl*e adaptation was to be deployed the majority of risks faced by the urban rich and poor today would not be fully resolved. This emphasizes clearly the fundamental importance of climate change mitigation to avoid urban risk and loss.

The urban adaptation gap is also found to be unequal. The poorest quintile has a larger adaptation gap than the richest quintile. Reported inequality in the application of urban adaptation is greatest in North, East and Southeast Asia reflecting rapid urbanization in this region. Reported inequality is lowest in Europe and Australasia. Observed inequalities indicate that the markets, government actions and civil society investments available to reduce vulnerability and risk amongst the poor have not been observed to offset inequalities based on individual and household capacities.

There is some catch-up as analysis moves through *actually deployed* to *planned* and *all conceivable* deployment – particularly for water and food security - but even here inequality in risk is not fully resolved. Africa and South and Central Asia in particular show considerable disparity in adaptation to urban food security even with *all conceivable adaptation*. This means that even if all available adaptation was to be deployed inequality in ability to adapt to climate change would remain. This highlights the significance of addressing underlying inequalities in development that shape differential vulnerability (see 6.2.3.1, 6.2.3.3, 6.3.5.1, 6.4) as part of vision and action on reducing risk to climate change so that no one is left behind.

Some hazard types and regions show strong capacity to close the adaptation gap if *all planned* adaptation was to be deployed: for example, Europe for heatwave and Europe and Central and South America for riverine and coastal flooding (particularly for wealthier populations). This reveals capacity within the current approaches to climate risk management, but also highlights the importance of resolving challenges that prevent planned adaptation from being deployed and deployed equitably.

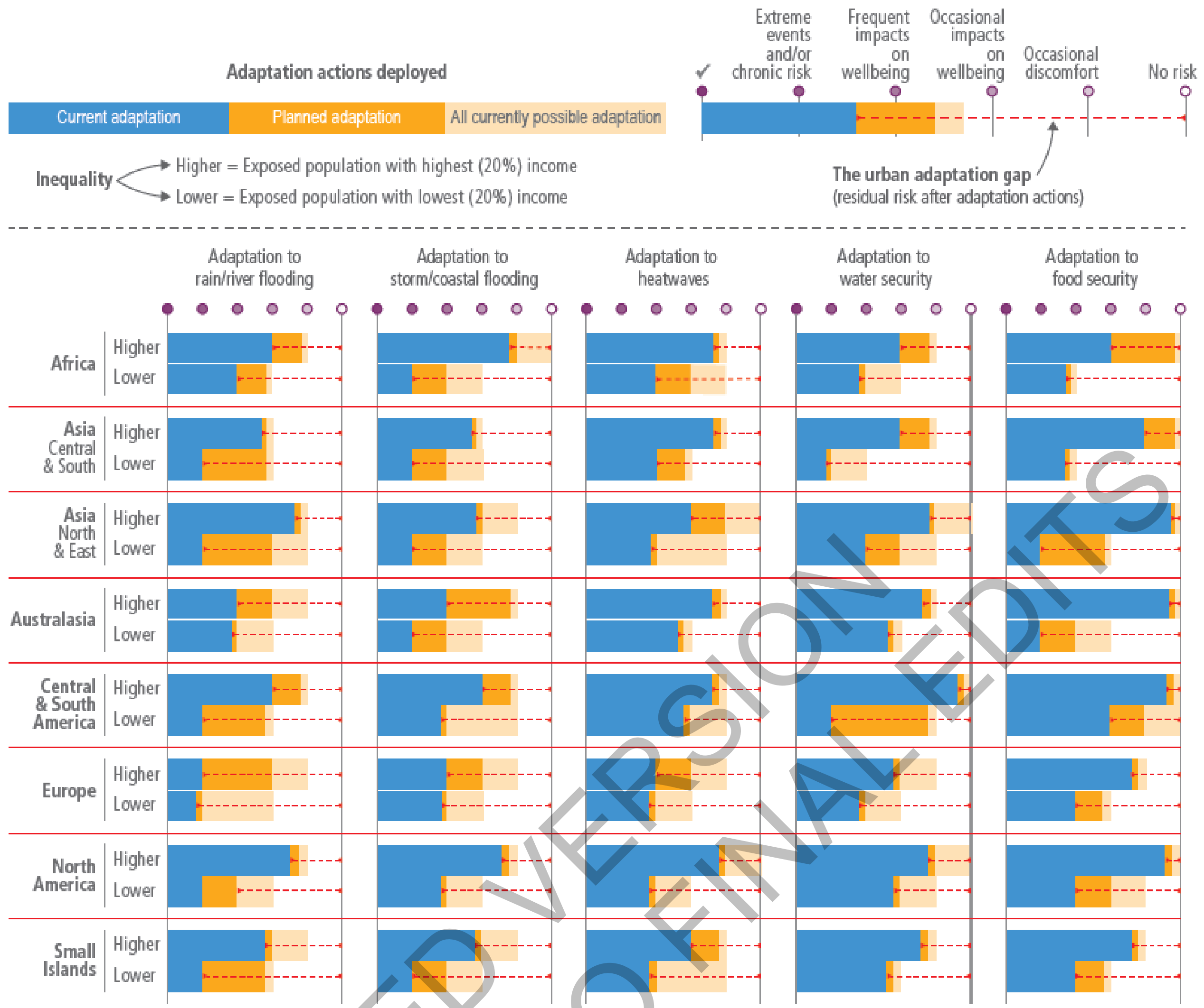


Figure 6.4: The Urban Adaptation Gap. Notes: This is a qualitative assessment presenting individual, non-comparative data for world regions from 25 AR6 CLAs and LAs, the majority from regional chapters. Respondents were asked to make expert summary statements based on the data included within their chapters and across the AR6 report augmented by their expert knowledge. Multiple iterations allowed opportunity for individual and group judgement. Urban populations and risks are very diverse within regions making the presented results indicative only. Variability in data coverage leads to the overall analysis having *medium agreement – medium evidence*. Major trends identified in 6.3.1 at least meet this level of confidence. Analysis is presented for current observed climate change associated hazards and for three adaptation scenarios: (1) current adaptation (based on current levels of risk management and climate adaptation), (2) planned adaptation (assessing the level of adaptation that could be realised if all national, city and neighbourhood plans and policies were fully enacted), (3) transformative adaptation (if all possible adaptation measures were to be enacted). Assessments were made for the lowest and highest quintile by income. Residual risk levels achieved for each income class under each adaptation scenario are indicated by five adaptation levels: no risk, occasional discomfort, occasional impacts on wellbeing, frequent impacts on wellbeing, extreme events and/or chronic risk. The urban adaptation gap is revealed when levels of achieved adaptation fall short of delivering 'no risk'. The graphic uses IPCC Regions, and has split Asia into two regions: North and East Asia, and Central and South Asia. Technical support is acknowledged from Greg Dodds and Sophie Wang

6.3.3 *Adaptation Through Social Infrastructure*

Social infrastructure refers to social, cultural and financial activities and institutions as well as associated property, buildings and artefacts that can be deployed to reduce risk and recover from loss. This section examines land use planning, livelihoods and social protection, emergency and disaster risk management, health systems, education and communication, and cultural heritage.

6.3.3.1 Land Use Planning

Land use planning plays a major role in the siting of settlements and infrastructure. In relation to climate change, it affects whether development takes place in locations that are exposed to hazards; similarly, it shapes the potential effects that the built environment can have on natural systems. Despite this, generally speaking, there is limited implementation of zoning and land use measures for climate adaptation from cities across diverse contexts (*robust evidence, high agreement*), see for example Maputo (Castán Broto, 2014), sub-Saharan cities (Dodman et al., 2017) and Amman, Moscow and Delhi (Jabareen, 2015). Certain countries, such as South Korea, have, however, recently begun to address disaster risk reduction within their land use planning systems (Han et al., 2019).

Conventional zoning regulations (in which only one kind of use is permitted in a given area) and land use planning range in scale from the regional to the local and can be deployed to minimize risks through protection, accommodation, or retreat. Protection entails, in addition to allocating zones for protective urban infrastructure (like seawalls, levees and dykes, and slope revetments), avoidance measures that restrict or prevent urban development (e.g., through growth containment and/or no-build zones). Accommodation involves land use modifications and/or conversions while retreat requires either compulsory or voluntary relocations and may entail buy outs (Butler, Deyle and Mutnansky, 2016; León and March, 2016; Lyles, Berke and Overstreet, 2018). Risk eliminating retreat measures are less widely adopted than other risk reducing zoning and land use measures (Anguelovski et al., 2016; Butler, Deyle and Mutnansky, 2016; Lyles, Berke and Overstreet, 2018). This is attributed to the controversies of relocation and to the complexities of buyouts (Butler, Deyle and Mutnansky, 2016; King et al., 2016).

Evidence from both richer countries and the Global South reveals that conventional zoning is more effective when governance systems facilitate the implementation of land use policies for climate adaptation that preclude negative human-nature interactions and that curb spatial inequity – both of which can trigger climate gentrification and increase the vulnerability of economically disadvantaged groups to climate-related risk (*high confidence*) (Marks, 2015; Liotta et al., 2020; Keenan, Hill and Gumber, 2018).. Cascading benefits of zoning and land use planning for climate adaptation are associated with the use of soft land cover, green infrastructure and improvement of livability through better conditions for walkability and cycling. This decreases auto-dependency and contributes to health and economic development (by attracting businesses and retail that stimulate economic prosperity and increase property values) (Larsen, 2015; Carter et al., 2015). Such increases in property values have also been observed in zones and areas protected from risks (such as flooding), where it may trigger spatial inequity leading to climate gentrification (Marks, 2015; Votsis, 2017; Votsis and Perrels, 2016; Keenan, Hill and Gumber, 2018).

Adaptation actions through zoning and land use are more effective when combined with other planning measures (*high confidence*), for example with ecosystem-based adaptations (e.g., for flood management and curbing the urban heat island effect) (Larsen, 2015; Nalau and Becken, 2018; Perera and Emmanuel, 2018; Anguelovski et al., 2016; Carter et al., 2015; Tsuda and Duarte, 2018; Nolon, 2016); with community-based adaptations (trade-offs and valuations, i.e., which land uses are valued more) (Larsen, 2015; Nalau and Becken, 2018; Perera and Emmanuel, 2018; Anguelovski et al., 2016; Carter et al., 2015; McPhearson et al., 2018; Nolon, 2016); and with built form regulations and codes (León and March, 2016; Yiannakou and Salata, 2017; Perera and Emmanuel, 2018; Straka and Sodoudi, 2019; Larsen, 2015; Nolon, 2016). The imposition of planning-based tools such as scenario planning, flexible zoning, and development incentivisation (among others) has the capacity to influence and encourage these adaptations (United States Environmental Protection Agency, 2017). Local risk-reduction inputs can inform land use adaptation policies (accommodation and/or avoidance, specifically growth containment and no-build zones) that are better integrated within larger urban plans (Lyles, Berke and Overstreet, 2018; Nalau and Becken, 2018; Tsuda and Duarte, 2018) (*limited evidence, high agreement*).

Implementation of zoning and land use measures for climate adaptation from cities across diverse contexts remains limited (*high agreement, robust evidence*) due to a range of challenges. A range of evidence from multiple locations indicates the challenges of mainstreaming land use planning for climate adaptation, including in Bangkok, Thailand (Marks, 2015), Legazpi City and Camalig Municipality in the Philippines (Cuevas et al., 2016; Cuevas, 2016), the United States (Cuevas et al., 2016; Cuevas, 2016), British Columbia, Canada (Stevens and Senbel, 2017), and Australia (Serrao-Neumann et al., 2017). Mainstreaming is hindered by a lack of clarity of implementation strategies for climate adaptation, insufficient funding, competing priorities (especially, among professional planners and politicians), institutional challenges (see

Jabareen's (2015) study of 20 cities globally) and the need to fill data gaps and continuously update weather statistics (Oberlack and Eisenack, 2018) (*medium evidence, high agreement*). At the same time, however, limited evidence from cities around the world such as: the urban Regions of Stuttgart and Berlin in Germany (Larsen, 2015), Greater Manchester in the UK (Carter et al., 2015), and Colombo in Sri Lanka (Perera and Emmanuel, 2018) reveals that risk reduction through zoning and land use can effectively protect and expand green infrastructure and soft land cover to alleviate pluvial flooding and decrease the urban heat island effect. This evidence points that one of the primary roles of land-use planning is to guide the development of the urban form. As such, it underpins and establishes the basis for other infrastructure systems such as physical infrastructure and nature-based solutions (Morrissey, Moloney and Moore, 2018).

6.3.3.2 Livelihoods and Social Protection

Understanding how livelihoods, particularly of the urban poor, are both impacted by climate risk and how they might be strengthened is central to understanding climate adaptation in cities and settlements (Dobson et al. 2015). Rapid urbanization and expanding physical infrastructure do not have a clear relationship with improved outcomes for urban livelihoods of low-income residents (Soltesova et al., 2014). Municipal and national efforts need to be closely aligned with building adaptive capacity of residents themselves, often through community-based adaptation (Soltesova et al., 2014; Dobson, Nyamweru and Dodman, 2015). Social safety nets protect individuals or households from falling below a defined standard of living by providing cash, in kind and other social transfers to fight vulnerabilities (Islam and Hasan, 2019) including those associated with climate change impacts including food shocks. Strengthening the financial and social infrastructure of poor households is a critical component of adaptive and transformative capacity (Haque, Dodman and Hossain, 2014; Ziervogel, Cowen and Ziniades, 2016). Social safety nets are one mechanism for strengthening this capacity.

Social protection, or social security, is defined as the set of policies and programmes designed to reduce and prevent poverty and vulnerability throughout the life cycle (ILO, 2017). Safety nets are intended to protect vulnerable households from impacts of economic shocks, natural hazards and disasters, and other crises. The UN policy frameworks for sustainable development, including the Sendai Framework for Disaster Risk Reduction 2015-2030, the new Strategic Framework 2018-2030 of the United Nations Convention to Combat Desertification (UNCCD) and UNFCCC, highlight the essential role of social protection in promoting comprehensive risk management (Aleksandrova, 2019). Since the term Adaptive Social Protection was introduced by the World Bank (2015) and the IPCC (2014), Adaptive Social Protection has been an emerging strategic tool to integrate poverty reduction, disaster risk reduction and humanitarian-development into adaptation to climate change (Béné, Cornelius and Howland, 2018; Aleksandrova, 2019; Watson et al., 2016).

Adaptive Social Protection (ASP) is defined as a resilience-building approach by combining elements of social protection, disaster risk reduction and climate change adaptation, so as to break the cycle of poverty and vulnerability of household by investing in their capacity to prepare for, cope with, and adapt to all types of shocks especially under climate change and other global challenges (Bowen et al., 2020; Ivaschenko et al., 2018). Adaptive Social Protection has been justified as an effective instrument to build household and community resilience to climate extremes and slow-onset climate events like sea level rise and environmental degradation (Schwan and Yu, 2018; Aleksandrova, 2019). In contexts of extreme poverty or climatic extremes, international development organizations, national provisions and market charities are complementary where family and kinship networks are weak and inadequate. To deal with short-term vulnerability to climate shocks, Adaptive Social Protection can act as a crucial complement to risk management tools provided by communities and markets, tools which tend to be insufficient in the face of large or systemic shocks, by providing predictable transfers, developing human capital and diversifying livelihoods (Hallegatte et al., 2016). Adaptive Social Protection can also facilitate long-term change and adaptation by improving education and health levels, as well as providing a proactive approach to managing climate-induced migration in both rural and urban areas (Schwan and Yu, 2018; Adger et al., 2014).

Many national Adaptive Social Protection programmes are established to cover both rural and urban areas, however, only a small number of researchers pay attention to urban cases (Aleksandrova, 2019). Adaptive Social Protection instruments can be classified into four major types as shown in Table 6.5 (Ivaschenko et al., 2018; ILO, 2017). Adaptive Social Protection can contribute to both incremental and transformative interventions both at the system level (short-term and long-term coping strategies from communities) and at the beneficiaries' level (vulnerable populations) (Béné, Cornelius and Howland, 2018; World Bank, 2015; Aleksandrova, 2019; Ivaschenko et al., 2018).

Table 6.5 Four categories and examples of adaptive social protection.

Category	Example	Urban cases	Function
Social safety nets (or social assistance)	Conditional and unconditional cash transfers, including non-contributory pensions and disability, birth and death allowances; Food stamps, rations, emergency food distribution, school feeding and subsidies; Cash or food for work programmes; Free or subsidized health services; Housing and utility subsidies; Scholarships and fee waivers, etc.	-A targeted asset transfer project for urban extreme poor in Dhaka city (Hossain and Rahman, 2018) - Emergency food stockpiling in Japan; safety net food stocks in India, Indonesia and Malaysia (Lassa et al., 2019) - Household cash transfer programme in contingency planning in Mexico (Ivaschenko et al., 2018) - Governmental transfer to hurricane affected households in United States (Bowen et al., 2020) - Non-contributory disability cash benefits (ILO, 2017)	Incremental adaptation; protective measures
Social insurance	Old age, survivor, and disability contributory pensions; Occupational injury benefit, sick or maternity leave; Health insurance, etc.	Old-age social pensions (Ivaschenko et al., 2018)	Incremental adaptation and ex-ante prevention
Labour market policies	Unemployment, severance, and early retirement compensation; Training, job sharing, and labor market services; Wage subsidizes and other employment incentives, including for disabled people, etc.	Public works and employment protection in Africa, Asia cases (World Bank, 2015; ILO, 2017; Ivaschenko et al., 2018)	Ex-post protection and ex-ante prevention measures, Incremental adaptation
Livelihood development measures	Income diversification, employment support, weather-index insurance, housing subsidies, post disaster construction, relocation planning, livelihood shift strategies, etc.	Multiple programs for differing household needs in Philippines (Bowen et al., 2020) Weather-index insurance in Chinese coastal cities (Rao and Li, 2019); Early warning forecast system and public meteorological service information in Beijing (Song, Zheng and Lin, 2021)	Promotive and anticipatory measures; transformational adaptation

Adaptive Social Protection (ASP) may be very good at reducing extreme poverty by helping to meet individual or household needs but not collective needs to mitigate long-term climate shocks. For example, few programmes consider risk assessment and climate-proof infrastructures as anticipatory measures to foster early action and preparedness (Aleksandrova, 2019; Costella et al., 2017). They therefore need to enable the adoption of forward-looking strategies for long-lasting adaptation (Tenzing, 2020). Some examples from China show social protection can improve adaptive capacity of urban communities with social medical insurance, housing subsidies, weather-index insurance, post disaster construction, relocation planning, livelihood shift strategies, and so on (Pan et al., 2015; Zheng et al., 2018b; Rao and Li, 2019; Song, Zheng and Lin, 2021). However, social protection may lead to maladaptation in urban policy when social security, or similar tools (for example insurance) compensate for exposure deincentivise risk reduction (Grove, 2021). In many developing countries, high concentration of poor and vulnerable groups living in disaster-prone zones of urban centres, new urban dwellers and informal residents are often excluded from community-based networks and social services (Aleksandrova, 2019). Risk transfer tools (like insurance) and risk retention measures (like social safety nets) can avoid and minimise the burden of loss and damage and limit secondary and indirect effects (Aleksandrova, 2019; Roberts and Pelling, 2018).

Inclusive, targeted, responsive and equitable social protection can support long-term transition toward more sustainable, adaptive and resilient societies (Hallegatte et al., 2016; Shi et al., 2018; Béné, Cornelius and Howland, 2018; Carter and Janzen, 2018; Adger et al., 2014). Adaptive Social Protection systems can be cost-effective and equitable when targeting accuracy, timely risk sharing (disaster assistance) and improved policy coherence. Carter & Janzen (2018) find that the long-term level and depth of poverty can be improved by incorporating vulnerability-targeted social protection into a conventional social protection system. Countries at all income levels can set up Adaptive Social Protection systems that increase resilience to natural hazards, but the systems need to identify cost-benefits, be scalable and flexible to adjust to future, increasing climate risk. Bastagli (2014) suggested a new design for effective social protection including: (i) increasing the amount or value of transfer; (ii) extending the coverage of beneficiaries; and (iii) introducing payments or new program of social protections. For social protection programmes to contribute more effectively to adaptation, they need to be better coordinated across a range of agencies; better integrated with climate data to anticipate times of need for vulnerable groups; and better aligned with other risk management instruments such as insurance (Agrawal et al., 2019).

6.3.3.3 Emergency and Disaster Risk Management

There is growing evidence of the benefits of early warning systems for urban preparedness decision-making and action for climate and weather-related hazards such as cyclones, hurricanes and floods (*medium evidence; high agreement*) (Lumbroso, Brown and Ranger, 2016; Zia and Wagner, 2015; Marchezini et al., 2017). Climate forecasting is constantly evolving and becoming increasingly accurate. Global organizations such as the World Meteorological Organizations are increasingly focusing on new and emerging technologies such as crowdsourced data collection to support integrated city services and early warning systems (Baklanov et al., 2018). However, while climate forecasting is an increasingly central tool for risk management agencies, a focus on urban areas or key infrastructure is still considerably rare (Lourenço et al., 2015; Nissan et al., 2019; Harvey et al., 2019). The significant rise in urban risks poses significant challenges to humanitarian agencies. Humanitarian responses and local emergency management are vital for disaster risk reduction yet are compromised in urban contexts where it is difficult to confirm property ownership and where renters and informal dwellers are often excluded from decision making and planning (Parker and Maynard, 2015; Maynard et al., 2017). Disaster survivors and growing urban refugee populations are often displaced across the city thereby complicating efforts to track and provide support (Maynard et al., 2017).

Existing early warning systems remain insufficient and the complexity of urban landforms makes accurate and detailed early warning difficult (*medium evidence; high agreement*) (Jones et al., 2015)This is particularly the case in low- and middle-income countries (LMICs) where urban centres are often characterized by rapid expansion of interlinked formal and informal human settlements and land use zones. In such contexts, early warning services vary in effectiveness within the same urban centre (Allen et al., 2020c; Rangwala et al., 2018). Often, forecast-based action follows linear structures where forecast information is applied mainly for responding to negative impacts rather than anticipatory decision making and preparation to avoid such impacts (Marchezini et al., 2017). Early warning systems are effective for warning of threshold breaching events including cyclonic activity and riverine flooding but less able to provide localised warning, though capability is rapidly increasing. Probabilistic risk forecasting and forecast based early action are only beginning to be applied to urban contexts and often those that are most vulnerable do not receive warnings regarding hazardous events (Nissan et al., 2019). There is less capacity for early warning systems in LMICs with key challenges linked to a lack of well-established risk baseline information; accessibility, communication and understanding of forecast information, as well as political and institutional barriers and limited resources and capacities to act on such information (Jones et al., 2015; Mustafa et al., 2015; Zia and Wagner, 2015; Marchezini et al., 2017; Gotgelf, Roggero and Eisenack, 2020). Political and institutional barriers to the incorporation of climate information to decision making are not limited to LMICs (Harvey et al., 2019). For example, comprehensive studies on sectoral use of climate information in Europe revealed that despite climate services becoming increasingly accessible and well resourced, there is limited organizational uptake of seasonal climate forecasts across key sectors (e.g. energy, transport, water and infrastructure) in informing their decision-making processes (Soares and Dessai, 2016; Soares, Alexander and Dessai, 2018). This is due both to technical and non-technical barriers such as lack of awareness and knowledge of climate information and forecasting (Soares and Dessai, 2016; Soares, Alexander and Dessai, 2018).

Globally, a considerable diversity of tools and frameworks for urban resilience assessments being developed at multiple scales (Arup and Rockefeller, 2015; Elias-Trostmann et al., 2018). These include hybrids such as Ecosystem based Disaster Risk Reduction (Eco-DRR) (Begum et al., 2014).While important advances have been made in assessing urban resilience, much debate remains around such tools and assessment approaches regarding issues such as validation, dynamics in exposure and vulnerability and appropriateness of generic methods in high density urban settlements (Leitner et al., 2018; Cardoso et al., 2020; Rufat et al., 2019). Disaster impact and recovery time are strongly influenced by the behaviour and actions of individuals, communities, businesses, and government organizations (Meriläinen, 2020; Räsänen et al., 2020). For example, Aaerts et al's (2018) review shows how the limitations of existing flood risk assessment methods (which tend to account for human behaviour in limited terms) can be addressed through innovative flood-risk assessments that integrate behavioural adaptation dynamics. Moghadas et al's (2019) study highlights the importance of hybrid multi-criteria approaches for assessing urban flood resilience in Tehran, Iran. A growing literature shows how multidisciplinary and inclusive approaches that include local knowledges can achieve greater accuracy in risk characterization and support lasting impact of investments into more robust climate services (Aerts et al., 2018; Lourenço et al., 2015; Sword-Daniels et al., 2018; Singh et al., 2018; Nissan et al., 2019; Harvey et al., 2019; Simon and Palmer, 2020). This literature highlights the need for innovative approaches in urban contexts that transcend traditional approaches of local knowledge inclusion widely applied in rural contexts, such as participatory rural appraisal.

The inclusion of local knowledge and Indigenous knowledge in urban vulnerability and risk assessments can strongly enhance local resilience but its effectiveness is constrained by wider decision-making and policy contexts dominated by top-down approaches (*medium evidence; high agreement*) (Jones et al., 2015; Sword-Daniels et al., 2018; Nissan et al., 2019). Established non-state actors such as Shack and Slum Dwellers International are particularly effective at implementing inclusive approaches for local knowledge incorporation into urban decision making. Climate change and disaster risk exacerbate existing problems of economic development, yet macro-economic planning seldom incorporates adaptation. Recent evidence also confirms the role of Indigenous knowledge and local knowledge in management practices to reduce climate risks through early warning preparedness and response (see also section 6.3.2.3). These practices are particularly important where alternative early warning methods are absent. For instance, Kasei et al (2019) show that Indigenous knowledge gathered through observations on changes in natural indicators (such as links between rainfall patterns, certain flora and fauna, and temperature changes) could be applied to develop early warning of climate hazards (floods and droughts) in informal urban settlements in African countries like Ghana. Similarly, Hiwaski et al (2015) show that observations of changes in the environment and celestial bodies are used to predict climate-related hazards in Indonesia, the Philippines and Timor-Leste where communities in turn use local materials and methods, and customary practices to respond to the impacts of climate change.

Insurance is a risk transfer mechanism for middle and high-income countries, yet is less widely available in LMICs (Surminski and Thieken, 2017). Additionally, where insurance options do exist in LMICs, these are not usually available to large populations living or operating in the informal sector. Flood insurance is widely available in many Organisation for Economic Co-operation and Development (OECD) countries but the demand and uptake differ significantly across countries (Hanger et al., 2018). This financial tool is subject to increasing pressure under the changing climate with growing concerns around affordability and availability. More integrative approaches are required, such as where changes in the insurance industry are closely linked to adaptation strategies, building standards and land-use planning and their application (Cremades et al., 2018). This is particularly important in LMICs and of central concern for all insurance schemes is ensuring access, fairness and affordability for the most poor and vulnerable. However, there are some notable examples of low-income communities setting up their own disaster insurance mechanisms. For example, the Community Development Funds for the Baan Mankong upgrading programme in Thailand include disaster funds as insurance against housing damage (Archer, 2012). Such approaches also need to be more closely linked to existing urban risk management planning approaches where urban livelihoods are seldom integrated and informed by more dynamic risk reduction frameworks that consider adaptive cycles and how resilience changes over time (Beringer and Kaewsuk, 2018; Cremades et al., 2018).

Disaster risk management systems face increasing challenges in adapting to evolving risk profiles, shaped by expanding urban areas and changing environmental conditions associated with climate change. In addition to flooding, risk monitoring and management systems have recently shown considerable shortfalls in planning for and responding to increased fire risk such as the devastating Californian wildfires in October 2019 (Morley, 2020) and Australia's unprecedented and catastrophic 2019-2020 wildfire season. Risk management has also been challenged by new risk experiences including wild/bush fires encroaching on expanding urban areas and fire outbreaks in densely populated informal settlements pose increasing threats to livelihoods, human health and habitats globally (see also Sections 2.4.4.2 and 2.5.5.2).

6.3.3.4 Climate Resilient Health Systems

Climate resilient health systems are a vital part of adaptation to protect the most vulnerable from climate change (WHO, 2020). Cardiovascular fitness for example is a root cause of morbidity and mortality form heat stress (Schuster et al., 2017). The World Health Organization has developed a framework of climate-resilient health systems that addresses both mitigation and adaptation goals (WHO, 2015). Universal Health Coverage (UHC) is an essential component of climate resilient health systems. In most countries, access to health services is better in urban than in rural areas. However, there remain large urban populations with insufficient coverage of health services (WHO and WB, 2015) and UHC tracking needs to take better account of inequalities in coverage, including differences in access within cities and further disaggregation of urban populations by income. Thus, health sector investment is an important tool in adaptive action and capacity. Analyses of health survey data shows that, globally, access to health care is increasing towards UHC targets (Lozano et al., 2020). Financing for global health has increased steadily in the last two decades and modelling shows this trend is likely to continue to 2050, but at a slower pace of growth and the current disparities in per-capita health spending persist between high and low/middle income countries, leading to insufficient health service coverage for the poorest populations (Chang et al., 2019a). Out-of-pocket spending is projected to remain substantial in LMIC and will remain the only means to access health care for many poor urban populations.

The WHO Operational Framework highlights the components that can be strengthened to adapt to extreme weather (e.g., health care workforce, information systems etc.). The evidence is greatest for impacts on larger health facilities (such as hospitals) and there is less evidence regarding impacts on health service delivery outside these settings (smaller health facilities, pharmacies, first responders, public health inspectors etc.). Improved building design and spatial urban planning (where facilities are located) are essential to increase resilience for higher temperature and flood risk (*medium evidence; high agreement*) (WHO, 2021; Codjoe et al., 2020; Korah and Cobbinah, 2017). Public health systems rely on information systems (including disease and vector surveillance and monitoring) to identify new and emergent public health risks. Improvements to health surveillance will increase resilience, particularly for populations in informal settlements that are absent from health and vital registration systems.

City-level and local government adaptation planning is facilitated by information on health impacts (Reckien et al., 2015), highlighting the need for monitoring and surveillance and the need for local evidence based risk assessments. Adaptation in the health sector can be limited by lack of collaboration between health and other sectors, although this is often easier to facilitate at the local level (Woodhall, Landeg and Kovats, 2021).

6.3.3.5 Education and Communication

Since AR5 there has been significant growth in research about climate education and activism (Simpson, Napawan and Snyder, 2019; O'Brien, Selboe and Hayward, 2018; Hayward, 2021). Access to knowledge is an important determinant of wellbeing, inclusivity and livelihood mobility and of driving human behaviour. Knowledge systems include formal educational provision (capital assets, syllabus and human capital), informal learning based in social interaction and customary institutions (including through social media) and public communication (news media, government and other information systems including commercial messaging). There is a growing body of literature addressing the role of information and communication technology in shaping behaviour in disaster response and recovery and climate action with particular focus on social media use and serious gaming (Houston et al., 2015; Carson et al., 2018) (see Section 6.3.4.3)

Given the amount of time that children spend in school settings, adapting educational infrastructure and programs to climate change is highly important. This includes not only making physical structures safe but also providing students with the knowledge and confidence to support individual and family-based adaptation. Several UN agencies (e.g. UNICEF and UNDRR) and international non-governmental agencies (e.g. Plan International) have prioritised safer schools and child centred risk management that often focus on schools as places that should be prioritised for retrofitting and safe construction but also as focal points for knowledge dissemination and community organising where impacts can extend beyond the school to reduce risk amongst students' families. Universities, think tanks, as well as the third and private sector are key support mechanisms, particularly at the local level and when working in collaboration with local government and communities. They can support the development of critical educational resources and innovative communication methods, as well as facilitate the design and implementation of climate policies and related action plans.

Youth, adult communities, the social media and commercial media can have a significant impact on advancing climate awareness and the legitimacy of adaptive action, particularly in large urban areas (*medium evidence; high agreement*). Climate change education has increasingly focused in urban settlements on enhancing children and young people's political agency in schools, universities, and in formal and informal media settings (Cutter-Mackenzie and Rousell, 2019). However, an ambiguous framing of climate impacts and adaptation, for example around the science of urban heat islands by media can also exacerbate local community confusion and uncertainty (Iping et al., 2019) and further training and capacity building opportunities such as for vocational qualifications is still required across diverse settings (Simmons, 2021). Communication strategies deployed in formal education and social media can be highly influential in exchanging information and establishing narratives and viewpoints that frame what adaptive action is legitimate, especially in large cities (Simpson, Napawan and Snyder, 2019). However, the effectiveness of communication strategies for change for example from Mayoral offices, can also be influenced by wider political and structural drivers including community literacy or political partisanship (Boussalis, Coan and Holman, 2019). Recent research (e.g. Macintyre et al., 2018) highlights the need for new, learning approaches to climate education from school age to adult education. Emphasis is on inclusivity in learning and recognising diverse perspectives across multiple levels and settings, from formal and informal education to wider social learning. Informal learning that takes place outside of school settings such as in libraries and botanical gardens in everyday life is increasingly recognised as a key arena for climate education, life-long learning and nurturing environmental citizenship and activism (Paraskeva-Hadjichambi et al., 2020).

6.3.3.6 Cultural heritage/institutions

The integration of culture into urban policy and planning is increasingly recognised as critical to developing sustainable and resilient cities and features in international agreements such as the SDGs (*limited evidence; high agreement*) (Sitas, 2020). However, urban cultural policies are still limited, for example, Cape Town is the only African city to have developed a city level cultural policy (Sitas, 2020). Cultural heritage refers to both tangible (e.g. historic buildings and sites) and intangible (e.g. oral traditions and social practices) resources inherited from the past (Fatorić and Egberts, 2020; Jackson, Dugmore and Riede, 2018). Learning about past societal and environment changes through heritage offers opportunity for reflection, transfer of knowledge and skills. This takes place in multiple contexts such as museums and cultural landscapes, and in everyday life (Fatorić and Egberts, 2020; Jackson, Dugmore and Riede, 2018). Cultural heritage is primarily associated with identity and is closely intertwined with the complexities of history, politics, economics and memory. Climate change adds another layer of complexity to cultural heritage and resource management (Fatorić and Seekamp, 2017). Changing climatic conditions are already negatively impacting World Heritage Sites such as the Cordilleras' Rice Terraces of the Philippines and earthen architecture sites - for example the Djenné mosque in Mali are particularly vulnerable to changes in temperature and water interactions (UNESCO, 2021). Climate change impacts intangible cultural heritage across diverse settings such as in the Caribbean and Pacific SIDS where traditional ways of life and related aspects such as oral traditions and performing arts are under threat from extreme weather events (UNESCO, 2021).

The climate change adaptation options for built cultural heritage fall into seven categories (Rockman et al., 2016; Fatorić and Seekamp, 2017). Financial constraints are the primary barriers that underpin the first four adaptation options: no action at all, merely monitoring and/or documenting, or annual maintenance (Xiao et al., 2019; Sesana et al., 2019; Fatoric and Seekamp, 2017; Fatorić and Seekamp, 2017; Fatorić and Seekamp, 2018). Core and shell preservation, the fifth and sixth categories, are cost effective when they improve the condition of built cultural heritage (BCH) (Bertolin and Loli, 2018; Loli and Bertolin, 2018a; Loli and Bertolin, 2018b), while elevation and/or relocation, the final adaptation options, are extremely costly and might jeopardize the historic value (Xiao et al., 2019). To date, however, evidence indicates that adaptation actions prioritize archaeological sites (Carmichael et al., 2017; Fatorić and Seekamp, 2018; Pollard et al., 2014; Dawson, 2013). The efficacy of adaptation of historic buildings can be increased through increased and stable funding, incentives, stakeholder engagement, and legal and political frameworks (Dutra et al., 2017; Fatorić and Seekamp, 2018; Fatorić and Seekamp, 2017; Fatoric and Seekamp, 2017; Leijonhufvud, 2016; Phillips, 2015; Sesana et al., 2019; Sesana et al., 2018; Sitas, 2020).

Other barriers to implementation include harnessing expert and local knowledge (of individuals and organizations) to identify both quantitative and qualitative methods and indicators that connect cultural significance and local values vis-à-vis climatic change over time and that move beyond the prevalent high risk- or high vulnerability-centred approaches (Carmichael et al., 2017; Fatorić and Seekamp, 2018; Haugen et al., 2018; Leijonhufvud, 2016; Pollard et al., 2014; Puente-Rodríguez et al., 2016; Richards et al., 2018; Dawson, 2013; Filipe, Renedo and Marston, 2017; Kotova et al., 2019). This is particularly important given that the significance of cultural heritage is often intangible, and its value cannot be determined solely through quantitative indicators. Accessing local resources (craftsmanship and materials compatible with the originals) can also improve built cultural heritage's adaptation capacity (Phillips, 2015).

Effective decision making and practice for adapting built and intangible cultural heritage requires open dialogue and exchange of cultural, historical and technical information between diverse stakeholders and decision-makers (Fatorić and Seekamp, 2017; Benson, Lorenzoni and Cook, 2016). As noted in Section 6.2.6, human behaviour can be a driving force for adaptation impacts on built cultural heritage at risk. Despite challenges associated with intangibility, socio-cultural heritage such as Indigenous knowledge (e.g. food security and water management practices) presents important opportunities for climate adaptation and resilience building. More research is needed across diverse contexts to understand feasible climate adaptation measures and barriers and opportunities for building the resilience of both built and intangible cultural heritage, as well as to increase awareness of cultural heritage benefits among climate change policymakers (Fatorić and Egberts, 2020).

6.3.4 Adaptation Through Nature-Based Solutions

Well-functioning ecosystems can play a significant role in buffering cities, settlements and infrastructure from climate hazards at multiple scales *(robust evidence, high agreement)*. Nature-based solutions (NBS) are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). Widely recognized as low-regret measures for disaster risk reduction and climate change adaptation, green and blue infrastructure investments and natural area conservation in cities can provide NBS at across scales to reduce temperature shocks and provide natural flood defences among other adaptation and resilience benefits (McPhearson et al., 2018; Andersson et al., 2019; Frantzeskaki et al., 2019). Blue infrastructure for example provides ecological and hydrological functions (e.g. evaporation, transpiration, drainage, infiltration, detention) critical to sustainable urban water management (Iojă et al., 2021). Public parks, urban forests, street trees and green roofs as well as lakes, ponds and streams are widely documented for providing local cooling, grass and riparian buffers and forested watersheds can enhance flood and drought protection for cities and settlements, and mangrove stands and wetlands in coastal areas can reduce storm surges. Despite increasing knowledge about NBS (here encompassing literature on ecosystem services for climate change adaptation and resilience, ecosystem-based adaptation, and benefits of green and blue infrastructure for adaptation), recent studies indicate that nature-based approaches to adaptation and resilience are still under-recognised and under-invested in urban planning and development (Matthews, Lo and Byrne, 2015; Geneletti and Zardo, 2016; Frantzeskaki et al., 2019), despite the potential scale of benefits – for example, a recent study covering 70 cities in Latin America calculated that 96 million people would benefit from improving main watersheds with green infrastructure (Tellman et al., 2018).

Grey infrastructure often damages or eliminates biophysical processes (e.g. through soil sealing, stream burial, or altered hydrology) necessary to sustain ecosystems and habitats, and livelihoods, where urban ecological infrastructure (Childers et al., 2019) can be more flexible and cost effective for providing flood risk reduction and other benefits (Palmer et al., 2015). Hybrid approaches are emerging that integrate ecological and grey (engineered) infrastructure in adaptation planning and hazard protection (Grimm et al., 2016; Depietri and McPhearson, 2017). Explicit policy uptake by city authorities is increasing (Hansen et al., 2015; Hölscher et al., 2019) such as in New York where in 2010 the city committed to a hybrid infrastructure plan for storm water management, investing US$ 5.3 billion over 20 years, of which US$2.4 billion was targeted for green infrastructure investments (NYC, 2010). A subset of services from urban ecosystems are being increasingly invested in as NBS for climate adaptation pathways (Keeler et al., 2019; Kabisch et al., 2016) and included as regulatory drivers through flood management, hazard mitigation, and air pollution regulations that encourage or enforce the implementation of green infrastructure practices (Davis et al., 2020).

Development and climate mitigation co-benefits of NBS is an additional reason that NBS are being increasingly taken up by cities including for improving health and livelihoods, particularly for poor, marginalized groups (Poulsen et al., 2015; Poulsen, Neff and Winch, 2017; Maughan, Laycock Pedersen and Pitt, 2018; Simon-Rojo, 2019; Cederlöf, 2016). Co-benefits include a wide range of social and environmental benefits (Brink et al., 2016; Alves et al., 2019) for human physical and mental health (Kabisch, van den Bosch and Lafortezza, 2017; Sarkar, Webster and Gallacher, 2018; Engemann et al., 2019; Rojas-Rueda et al., 2019), climate mitigation (De la Sota et al., 2019) and as habitat for local biodiversity (Ziter, 2016; Knapp, Schmauck and Zehnsdorf, 2019). At the same time concerns about the unintended consequences of investing in green infrastructure for NBS such as how it may contribute to gentrification (Turkelboom et al., 2018; Anguelovski et al., 2018; Haase et al., 2017b), create more public use, increase water demand (Nouri, Borujeni and Hoekstra, 2019), or contribute to criminal activity (Cilliers and Cilliers, 2015) underlines the challenges of investing in adaptation in complex urban systems (See Section 6.2.6). Additionally, more place-based analysis of the efficacy of nature-based solutions for reducing climate impacts across varying urban contexts and future climate scenarios is needed to better understand the cost effectiveness of investing in NBS to provide disaster risk reduction and deliver critical co-benefits for human well-being. Cooperation between scientists, decision makers and indigenous knowledge-holders can supplement current efforts as well as to ensure that investments in nature-based solutions do not negatively impact indigenous communities (Ban et al., 2018; Seddon et al., 2021; Townsend, Moola and Craig, 2020).

6.3.4.1 Temperature Regulation

Nature-based strategies – including street trees, green roofs, green walls, and other urban vegetation – can reduce heat and extreme heat by cooling private and public spaces (*robust evidence, high agreement*). Shading and evapotranspiration are the primary mechanisms for vegetation induced urban cooling (Coutts et al., 2016). Shading reduces mean radiant temperature, which is the dominant influence on outdoor human thermal comfort under warm, sunny conditions (Thorsson et al., 2014; Viguié et al., 2020). Outdoor green space and parks may also slightly reduce indoor heat hazard (Viguié et al., 2020). Apart from lowering temperature, nature-based solutions may also contribute to lower energy costs by reducing extra demand for conventional sources of cooling (e.g. air conditioning) (Viguié et al., 2020; Foustalieraki et al., 2017), especially during peak demand periods. Homes with shade trees that are located in cities where air conditioning systems are common can save over 30% of residential peak cooling demand (Zardo et al., 2017; Wang et al., 2015). Green roofs have been shown to significantly lower surface temperatures on buildings (Bevilacqua et al., 2017) and modelling suggests that green roofs, if employed widely throughout urban areas, have the potential to impact the regional heat profile of cities (Bevilacqua et al., 2017; Rosenzweig, Gaffin and Parshall, 2006). Community or allotment gardens, backyard greening, and other types of low vegetation, as well as lakes, ponds, rivers, and streams, can also provide local cooling benefits to nearby residents (Gunawardena, Wells and Kershaw, 2017; Larondelle et al., 2014; Santamouris, 2020).

Urban climate models show that increased vegetation cover results in reducing both mean air temperatures and extreme temperatures during heat waves (Heaviside, Cai and Vardoulakis, 2015; Ferreira and Duarte, 2019; Schubert and Grossman-Clarke, 2013). Greater density and more canopy coverage relative to other built and paved surfaces increases shade provision and evapotranspiration (Hamstead et al., 2016; Grilo et al., 2020; Herath, Halwatura and Jayasinghe, 2018; Knight et al., 2021). However, local cooling by vegetation depends on regional climate context, geographic setting of the city, urban form, the density and placement of the trees, in addition to a variety of other ecological, technical, and social factors, such as local stewardship (Salmond et al., 2016). Green spaces less than 0.5-2.0 ha may have negligible cooling effects at regional scales, but impacts of shading can have microscale cooling benefits (Gunawardena, Wells and Kershaw, 2017; Zardo et al., 2017). Vegetation impacts on day versus night-time cooling varies (Imran et al., 2019) as does cooling potential in temperate versus tropical climates. The supply of cooler air from surrounding peri-urban and rural areas can impact cooling in the urban core suggesting that regional adaptation planning for NBS is important to maintain or extend ventilation paths from the urban fringe into the city centre (Schau-Noppel, Kossmann and Buchholz, 2020).

To maximize the adaptation benefits of NBS for regulating urban heat, it can be helpful to prioritize tree planting and other urban greening investments in areas where heat vulnerability and risk are the highest, especially communities that lack urban tree canopy or accessibility to parks to cool off during hot days or heat waves (Ziter et al., 2019). Planting trees closely together or in partly permeable vegetated barriers along streets can improve local cooling benefits. Additionally, choosing tree species with leaves that have the greatest leaf area index or the largest leaves can improve cooling performance, as those trees have the greatest shading and evapotranspiration benefits that, in turn, provide the greatest cooling effects (Keeler et al., 2019). Drought resistant trees, often native trees, are ideal to avoid high watering costs, though dry or water scarce areas may limit adoption of urban vegetation as an NBS strategy (Coutts et al., 2013). Native trees and permaculture can provide additional benefits for local biodiversity as shown in study in Melbourne, Australia which found that increasing vegetation from 10 to 30 percent increased occupancy of bats, birds, bees, beetles and bugs by up to 130% (Threlfall et al., 2017), with particularly high impact on native species.. Additionally, planting fruit or nut trees can provide co-benefits for local food production, and yet choice of species and placement is important to consider with respect to local cultural needs and norms (Adegun, 2018; Adegun, 2017).

6.3.4.2 Air Quality Regulation

Nature-based solutions in cities can help regulate air quality by absorbing air pollutants (*medium evidence, medium agreement*). For example, planting trees or vegetated barriers along streets or in urban forests can reduce particulate matter, the ambient air pollutant with the largest global health burden (Janhäll, 2015; Tiwary, Reff and Colls, 2008; Matos et al., 2019; McDonald et al., 2016). However, findings show that trees can also positively affect ground-level ozone (Calfapietra et al., 2013; Kroeger et al., 2014), airborne pollen concentrations (Willis and Petrokofsky, 2017), and indirectly affect air quality through reduced emissions from energy production offset by shade provision (Keeler et al., 2019). Certain tree species however can also be detrimental to urban ozone formation by emitting significant amounts of reactive biogenic volatile organic compounds (VOCs). Decreasing urban emissions of VOCs is an increasingly important ozone mitigation strategy in urban areas (Fitzky et al., 2019).

Trees can also have negative effects by increasing pedestrian exposure to pollution if trees are introduced in heavily travelled street canyons where air pollutants can be trapped (Vos et al., 2013; Gromke and Blocken, 2015). To maximize the adaptation benefits of NBS for improving air quality planners and managers can target tree selection for species with low VOC emissions, low allergen emissions, and high pollutant deposition potential (Keeler et al., 2019) and combine with low pollution transportation policies. Studies suggest sensitive planting of roadside tree canopies can have positive effects on air pollutants (Beckett, Freer Smith and Taylor, 2000; Yang, Chang and Yan, 2015). For example, Xue et al (2021) found that the PM2.5 reduction between 2013 and 2017 in China was associated with a saving of approximately USD 111 billion per year nationally. Tree planting near schools, nursing homes, and hospitals can ensure that benefits provided by trees are delivered to the local populations that stand to benefit the most from improved air quality, but species need to be adapted to regional climate to provide benefits over time (Donovan, 2017; Nowak et al., 2018).

6.3.4.3 Stormwater Regulation and Sanitation

Urban parks and open spaces, forests, wetlands, green roofs and engineered stormwater treatment devices help manage stormwater and wastewater by reducing the volume of stormwater runoff, reducing surface flooding, and reducing contamination of runoff by pollutants (*robust evidence, high agreement*). Engineered devices include bioswales, rain gardens, and detention and retention ponds, and are becoming common and standard approaches to mitigate the negative effects of impervious surfaces on stormwater quality and surface flooding in cities (Zhou, 2014; McPhillips et al., 2020). Allotment gardens, street trees, green roofs and urban forests may also help reduce runoff and provide a stormwater retention service (Pennino, McDonald and Jaffe, 2016; Berland et al., 2017; Gittleman et al., 2017). Modelling and empirical studies show that nature-based solutions at small spatial scales lead to improvements in water quality and reduction of peak flows (Moore et al., 2016; Keeler et al., 2019; Webber et al., 2020). Peak flow reductions are greatest for small rain events. For example, D-Ville et al. (2018) observed 30-70% reduction in peak flow for the 1 in 30 year storm, but performance reduces for more intense rainfall or if saturated (Garofalo et al., 2016). Employing NBS to reduce flooding on roads can be an important adaptation mechanism for reducing the impact of flooding events on traffic flows (Pregnolato et al., 2016).

During periods with intense precipitation, low-lying urban parks and open space, engineered devices, and wetlands can play an important role in reducing stormwater runoff volumes, by providing places for water to be stored and infiltrate during heavy storms (Moore et al., 2016). However, the magnitude of the runoff reduction service will depend on the total area of green infrastructure, vegetation type, and its position on the landscape. There is less evidence of the effectiveness of nature-based solutions at larger temporal and spatial scales (Pregnolato et al., 2017; Jefferson et al., 2017). The performance of NBS depends on the degree to which their extent and spatial configuration in the city are optimized to capture runoff (Fry and Maxwell, 2017). Investing in a diversity of NBS types may be important to maximize stormwater management and flood regulation as different types of engineered NBS have different strengths and weaknesses.

Overall, NBS are attractive adaptation options for stormwater management and to reduce impacts of pluvial and fluvial flooding in cities (Rosenzweig et al., 2018a) compared to, and in combination with, grey infrastructure. Cities with combined sewer infrastructure are likely to see benefits from NBS due to reductions in stormwater quantity and reduced sewage overflows. Cities where a large proportion of residents lack access to piped infrastructure and drink surface water may see large benefits, especially to human health, from NBS investments (Keeler et al., 2019). Where future large-scale upgrades or installation of grey infrastructure will be necessary, new and growing cities may have more opportunity to realize large net benefits from investments in NBS. Older cities, and new, rapidly urbanizing areas that lack large scale water infrastructure may see the greatest benefits from enhanced NBS, relative to cities where heavy investments infrastructure upgrades have already been made. Cities facing climate changes that including more frequent or extreme precipitation may also see large water quality benefits from investment in NBS (Keeler et al., 2019). Overall, there is increasing evidence that NBS for addressing stormwater is cost-effective (Bixler et al., 2020; Kozak et al., 2020; Mguni, Herslund and Jensen, 2016), especially in cities facing a need to update current infrastructures.

6.3.4.4 Coastal Flood Protection

Coastal ecosystems including coral and oyster reefs, coastal forests including mangroves and other tree species, salt marshes and other types of wetland habitat, seagrass, dunes, and barrier islands can reduce impacts of coastal flooding and storms (*robust evidence, high agreement*) (Zhao, Roberts and Ludy, 2014; Boutwell and Westra, 2016; Narayan et al., 2017; Yang, Kerger and Nepf, 2015; Bridges et al., 2015; World Bank, 2016) (see also CCP2 Cities and Settlements by the Sea). Recent literature highlights the value of nature-based approaches for coastal protection in terms of avoided damages and human well- being (Narayan et al., 2017; Silva et al., 2016a). Nature-based solutions (NBS) can protect coasts from flooding through reducing the wave energy by drag friction, reducing wave overtopping by eliminating vertical barriers, and absorbing floodwaters in soil (Arkema, Scyphers and Shepard, 2017; Dasgupta et al., 2019; Zhu et al., 2020). For example, coastal and marine vegetation and reefs can dissipate wave energy, attenuate wave heights and nearshore currents, decrease the extent of wave runup on beaches, and trap sediments (Ferrario et al., 2014; Bridges et al., 2015). These effects result in lower water levels and reduce shoreline erosion, which in turn has potential to save lives and prevent expensive property damages (Narayan et al., 2017).

Researchers, practitioners, and policy-makers are increasingly calling for the use of nature-based approaches to protect urban shorelines from coastal hazards (Cunniff and Schwartz, 2015; Bilkovic et al., 2017). The expectation is that coastal ecosystems can help stabilize shorelines, protect communities against storm surge, and from tidal influenced flooding while providing other co-benefits for people and ecosystems. However, vegetation along protected coastlines, with higher frequency, lower intensity coastal hazards (National Research Council, 2014) may be more effective for stabilizing shorelines and reducing risk to coastal communities and properties and benefits will depend on local hydrology of the coastal region. Narayan et al. (2017) estimate that coastal wetlands alone reduced direct flood damages by US$625 million during Hurricane Sandy in the United States in 2012. Similarly, researchers found that villages with wider mangroves between them and the coast experienced significantly fewer deaths than villages with narrow or no mangroves during a 1999 cyclone in India (World Bank, 2016). Recently, Arkema et al. (2017) noted that the number of people, poor families, elderly and total value of residential property most exposed to hazards along the entire coast of the USA can be reduced by half if existing coastal habitats remain fully intact.

Coastal habitats also have limitations in their ability to protect coasts from extreme events. Some studies suggest reduced effectiveness of vegetation and reefs for coastal protection from large storm waves and surge (Möller et al., 2014; Guannel et al., 2016) and there is active debate in the literature about the ability of ecosystems to mitigate the impact of tsunamis (Gillis et al., 2017). Further research is needed to understand and quantify coastal protection services provided by these hybrid green-grey solutions, especially in urban areas (Bilkovic et al., 2017). Additionally, in some coastlines water may be too deep or waves too high for some species such as mangroves to grow, thrive and provided needed NBS.

Maximizing the adaptation benefits of NBS for improving coastal flood protection research requires that cities seek to restore and conserve the vegetation and reef types that are appropriate for the exposure setting and in sufficient abundance to be effective. In particular planners and managers can use vegetation in protected bays as alternatives to hard infrastructure for shoreline stabilization. However, the influence of ecosystems on flooding and erosion is variable and depends on a suite of social, ecological, and infrastructural factors that vary within and among urban areas (Narayan et al., 2017; Ruckelshaus et al., 2016; Bridges et al., 2015). Additionally, long-term planning to restore or ensure resilience of individual species and ecosystems that may themselves be damaged or destroyed during extreme events is needed in order for urban green and blue infrastructure to continue providing NBS over the longer term.

6.3.4.5 Riverine Flood Impact Reduction

Nature-based solutions reduce both the volume of floodwater and the impact of floods (*medium evidence, medium agreement*). NBS reduce the volume of runoff by increasing infiltration and water storage (Shuster et al., 2005; Salvadore, Bronders and Batelaan, 2015), and affect the production and impact of flood waters through reducing river energy and flow speed through physical blockage, stabilizing riverbanks during flood events, creating space for floodwaters to expand, and combating land subsidence (Palmer, Filoso and Fanelli, 2014; Ahilan et al., 2018). Installing nature-based solutions to increase infiltration on low slopes and high-permeability soils can reduce the impacts of potential increases in urban flooding driven by climate change, especially for small to medium-scale flood events (lower than 20% mean annual flood) (Moftakhari et al., 2018).

Source reduction strategies include creating permeable areas such as parks and open spaces as well as engineered devices like raingardens, bioswales, and retention ponds that help retain stormwater runoff from impervious areas. River restoration can reduce flood peak flow and provide space for floodwaters to expand. Planting and maintaining vegetation along riverbanks, often in the form of parks or river restoration, maintains structural integrity during flood events. Wetland construction and improved connectivity to floodplains also reduces flood peaks. Efforts to restore floodplains are important to create space for floodwaters and reduce exposure by moving people out of the hazard zone. Floodplain restoration also provides access to the river that has multiple benefits including recreation, access to water for domestic use, and other cultural ecosystem services. A key adaptation strategy is to reduce streambank erosion (a result of high peak flow) using riparian vegetation to stabilize riverbanks during flood events.

Cities manage flood risk using different types of adaptation and regulatory mechanisms (Naturally Resilient Communities, 2017). Built flood-control infrastructure, such as levees and stream channelization, reduces the demand for nature-based flood impact reduction. Cities facing flood risk that do not currently have extensive grey flood-mitigation infrastructure may find nature-based solutions to be an appealing, lower cost solution (Keeler et al., 2019). In cities where flood-control grey infrastructure already exists there is less demand for nature-based solutions of flood protection, but nature-based solutions may provide important back-up, especially in a changing climate that may increase flood hazards (City of Los Angeles, 2017; Elmqvist et al., 2019). Overall, city and basin wide NBS for riverine flood impact reduction can reduce the generation of new hazards by making space for water which can reduce the potential for a false sense of security provided by traditional flood management approaches (Ruangpan et al., 2020; Turkelboom et al., 2021).

6.3.4.6 Water Provisioning and Management

The role of nature-based solutions has been increasingly recognized for improving urban water management emphasizing it contribution for climate adapted development and sustainable urbanization (*robust evidence, high agreement)* (Wong and Brown, 2009). Nature-based solutions that protect or restore the natural infiltration capacity of a watershed can increase the water supply service to various extents, improving drought protection, and provide resilient water supply (Drosou et al., 2019; Krauze and Wagner, 2019), although different forms of NBS (e.g. street trees, parks and open space, community gardens, and engineered devices such as rain gardens, bioswales or retention ponds) contribute in different ways to increasing stormwater infiltration. Additional sources of water may be available to replace the water supplied by nature-based solutions, such as rainwater harvesting, inter-basin transfers, or desalination plants. Reliance on naturally sourced, locally available surface water and groundwater is more energy-efficient and economical than desalination or water reuse for potable use (Boelee et al., 2017), while rainwater harvesting is even more economical. Increasing the amount of green space in urban areas can secure and regulate water supplies, improving water security (Liu and Jensen, 2018; Bichai and Cabrera Flamini, 2018). However, Bhaskar et al (2016) reviewed the effect of urbanization and nature-based solutions on baseflow and suggest that the confounded effects of infiltration and evapotranspiration losses, combined with the subsurface infrastructure (sewer systems) and geology, makes it difficult to predict the magnitude of baseflow enhancement resulting from the implementation of nature-based solutions in cities.

To maximize the adaptation benefits of NBS for urban water supply research suggests that managers and planners consider nature-based solutions as alternatives to traditional stormwater management techniques, where possible, since these solutions can promote groundwater recharge. As green infrastructure is increasingly being used for stormwater absorption in cities (McPhillips et al., 2020), rain gardens, wetlands, or engineered infiltration ponds and bioswales are the nature-based solutions most likely to promote recharge, reduce evapotranspiration, and contribute to water provisioning.

6.3.4.7 Food Production and Security

Urban agriculture can serve as a NBS for food security (*medium evidence, medium agreement*) across a range of urban contexts (Lwasa and Dubbeling, 2015; Nogeire-McRae et al., 2018; Pourias, Aubry and Duchemin, 2016) by contributing to food provisioning as well as providing co-benefits including for recreation, place-making, and mental health (Petrovic et al., 2019; Soga, Gaston and Yamaura, 2017; Goldstein et al., 2016b).

Urban agriculture among poorer communities in lower income areas is already an important source of food supply for those communities contributing to food security and health (Orsini et al., 2013). However, potential for expanding open air urban food production may be practically constrained by land availability (Badami and Ramankutty, 2015; Martellozzo et al., 2014). This is particularly true in some lower-income countries where rapid urbanization is occurring, which compounds existing food insecurity (Satterthwaite, McGranahan and Tacoli, 2010; Vermeiren et al., 2013). Land availability and suitability for gardens can be further constrained by land-use history, including past industrial uses that can contaminate soils with pollutants such as lead.

At the same time, investments in vertical agriculture continue to expand, such as in Singapore where private investment in food production is occurring in high rise buildings (Wong, Wood and Paturi, 2020). Not all cities can benefit similarly from vertical agriculture since higher heating costs to produce vegetables indoors during northern winters consumes considerable amounts of energy and may generate fossil fuel emissions depending on the energy source (Goldstein et al., 2016a; Mohareb et al., 2017). Some regions can benefit from more traditional outdoor urban farming such as in South and Southeast Asia which can support multiple growing cycles per year for some crops, particularly in tropical areas where irrigation is available. Light availability, soil health, and water available will impact food production in urban areas. For example, a study conducted in Vancouver, Canada, demonstrated that light attenuation from buildings and trees can both reduce crop yield and reduce water demand for crop growth (Johnson et al., 2015).

Climate change may have important impacts on urban food production and food security. While urban agriculture may provide benefits in terms of stability of food access in low-income households in some regions of the Global South where the climate is warmer, the shorter growing seasons in colder climates will reduce the role of outdoor urban agriculture in year-round food supply and diets. Though urban agriculture constitutes a small fraction of total food consumption in some urban areas, several studies have attempted to estimate the extent to which urban agriculture could theoretically meet urban total food or vegetable demand (Badami and Ramankutty, 2015; McClintock, 2014; Hara et al., 2018). Maximizing the adaptation and resilience benefits of NBS for food production and security suggests the need to embrace the multi-functionality of urban agriculture rather than viewing it as solely concerning food production (Barthel, Parker and Ernstson, 2015).

6.3.5 Adaptation Through Grey/Physical Infrastructure

Globally it is estimated that as much as US$94tn of investment is required between 2016 and 2040 to replace, upgrade and extend the world's physical infrastructure (Oxford Economics, 2017), much of which is ageing and will require replacement. Given the typical lifespan of infrastructure this is both an opportunity and an imperative to ensure this investment is low carbon and resilient to climate change risks (Grafakos et al., 2020). 'Grey' or physical infrastructure is a priority for adaptation because its performance is sensitive to climate (particularly extreme events) and decisions on design and renovation have long-lasting implications and are hard to reverse (Ürge-Vorsatz et al., 2018). Avoiding longer-term impacts on society, the economy, and environment, will require future investment, and retrofit of existing infrastructure, to be undertaken in the context of the risks of climate change (Dawson et al., 2018; Rosenzweig et al., 2018b). However, evidence from Africa shows that the benefits of pro-active adaptation measures and policies for infrastructure can result in net savings depending on the country context (Section 9.8.5).

Engineered measures for hazard mitigation such as seawalls, slope revetments, river levees, as well as air conditioning are increasingly implemented in urban centres but many engineering interventions are less affordable and accessible in low and middle-income countries due to high construction and maintenance costs. These adaptive measures can also counter mitigation objectives due to reliance on climate polluting energy sources. Despite this, engineering measures such as seawalls for tsunami protection and cooling areas in cities provide critical hazard reduction functions in urban contexts (Depietri and McPhearson, 2017). As Pelling et al (2018a) highlight, sustainable risk reduction can be better achieved where these engineering measures include the at-risk poor majority and inclusive planning to support pro-poor risk reduction. Inclusive design and management of physical infrastructure can enhance contributions to Climate Resilient Development (Table 6.6 and Supplementary Material). This section covers urban morphology and built form, building design, information and communication technology, energy, transport, water and sanitation, and coastal management. All these domains of physical infrastructure will require adaptation to cope with a changing climate, many of them can also contribute to broader adaptation for cities and settlements.

6.3.5.1 Urban Morphology and Built Form

Urban morphology describes the overall status of cities as physical, environmental and cultural entities. Cities interact with surrounding environmental processes – for example as documented in Section 6.2 by influencing urban temperature, but also precipitation and through coastal and riverine development fluvial and coastal sedimentary regimes of erosion and deposition that impact on flood risk. Rapid, increased urbanization has contributed to observed flood risks in recent decades (see Chapter 5 4.2.4 (Tramblay et al., 2019)). The design process for physical infrastructure projects and significant construction (e.g. residential or industrial estates and large industrial development) typically includes risk assessments and social and environmental impact assessments that consider neighbouring land uses and connected infrastructure. Land use planning can consider diverse land-uses and their interactions at the neighbourhood level (Section 6.3.2.1). Resilience planning aims to bring together integrated, systemic views and enable joined-up planning at the city level (as well as lower scales) (Section 6.3.2.1). There is however a lack of long-term studies that assess the climate change impacts on urban form, including informal settlements (Bai et al., 2018; Ramyar, Zarghami and Bryant, 2019), leading to impact assessments that often overlook urban form (Ramyar, Zarghami and Bryant, 2019). Additionally, context-specific spatial tools and community-based approaches lack a precise connection to urban morphology. For example, there is a need for further studies that connect solar radiation, urban morphology (e.g., aspect and plot ratio), and the urban heat island spatio-temporal variability (Giridharan and Emmanuel, 2018; Li et al., 2019c).

Several tools and models have emerged in response to recommendations from AR5, including models that assess the impacts of urban heat island (Ramyar, Zarghami and Bryant, 2019), climatic uncertainty (Dhar and Khirfan, 2017), flood vulnerability (Abebe, Kabir and Tesfamariam, 2018), and inundation (Barau et al., 2015; Ford et al., 2019). For example, findings from Kano, Nigeria reveal that a lack of distribution of certain urban morphological features, including open spaces and streets (both pervious and impervious), roof and building materials (e.g., concrete and metallic), and urban ecological features (e.g., urban ponds and ecological basin) exacerbates inundations and their associated impacts (Barau et al., 2015). Also, findings about the urban forms of coastal settlements, particularly in small islands, reveal that they often experience severe beach erosion due to wave action, sea-level rise and storm surge that leads to landward retreat of coastline which threatens their social and economic activities (Dhar and Khirfan, 2016; Lane et al., 2015; Khirfan and El-Shayeb, 2019). Despite these examples very limited research is available to offer assessments of different urban scale morphologies and urban scale adaptation planning, including planning adaptation across supply chains and networked relationships with distant urban and rural places connected through trade and resource (financial, human and material) or waste flows.

Interventions in the morphology and built form of cities can contribute to the reduction of the urban heat island effect and reduce the consequences of urban heat waves. These can include installing air conditioning, establishing public cooling centers (i.e., for use during heat waves), pavement-watering (Parison et al., 2020a), and increasing surface albedo through "cool roofs" (i.e., with high-reflectance materials) and walls. Air conditioning can significantly increase the local urban heat island (Salamanca et al., 2014; Wang et al., 2019a) and the choice of refrigerant has a significant impact on global warming potential (McLinden et al., 2017). The relative efficiency of cool roofs compared to green roofs is variable, because while white roofs have similar potential to reduce the urban heat island (Li, Bou-Zeid and Oppenheimer, 2014), they can quickly turn grey due to dust and air pollution, losing their effectiveness (Gunawardena, Wells and Kershaw, 2017) although these effects are now well studied and newer performance standards should account for ageing and soiling effects on reflectivity (Paolini et al., 2014). Ageing of "cool pavements" is more complex which makes their long term performance less reliable to predict (Lontorfos, Efthymiou and Santamouris, 2018). The cooling performance of green roofs is highly variable and depends on the actual water content of the green roof substrate, with dry vegetation performing poorly in terms of cooling (Parison et al., 2020b). This holds true for regular vegetation and Nature-Based Solutions in general (Daniel, Lemonsu and Viguie, 2018). For all built environment adaptations, changes are locked-in for a long time and are likely to be expensive so that care is needed to avoid potential negative impacts on social equity (Cabrera and Najarian, 2015; Romero-Lankao et al., 2018; Fried et al., 2020; Rode et al., 2017) and carbon-intensive construction (Bai et al., 2018; Seto et al., 2016).

6.3.5.2 Building Design and Construction

Architectural and urban design regulations at the single building scale (building codes and guidelines) facilitate climate responsive buildings that adapt to a changing climate and have the potential to collectively change user behaviour during extreme weather events (Osman and Sevinc, 2019). They include buildings that are adaptive to ensure user comfort during extremes of hot and cold, and to floods (e.g., building on stilts and amphibian architecture). Changes to design standards can scale quickly and widely, but retrofit of existing buildings is expensive so care must be taken to avoid potential negative impacts on social equity (Schünemann et al., 2020; Matopoulos, Kovács and Hayes, 2014; Ajibade and McBean, 2014; Bastidas-Arteaga and Stewart, 2019). Buildings can be adapted to the negative consequences of climate change by altering their characteristics, for example increasing the insulation values (e.g. van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Fisk, 2015; Fosas et al., 2018; Barbosa, Vicente and Santos, 2015; Invidiata and Ghisi, 2016; Pérez-Andreu et al., 2018; Taylor et al., 2018; Triana, Lamberts and Sassi, 2018), adding solar shading (e.g. van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Barbosa, Vicente and Santos, 2015; Invidiata and Ghisi, 2016; Pérez-Andreu et al., 2018; Taylor et al., 2018; Triana, Lamberts and Sassi, 2018; Dodoo and Gustavsson, 2016; Osman and Sevinc, 2019), increasing natural ventilation, preferably during the night (e.g. van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Pérez-Andreu et al., 2018; Triana, Lamberts and Sassi, 2018; Dodoo and Gustavsson, 2016; Osman and Sevinc, 2019; Mulville and Stravoravdis, 2016; Cellura et al., 2017; Fosas et al., 2018; Dino and Meral Akgül, 2019), solar orientation of bedroom windows (Schuster et al., 2017), applying high-albedo materials for the building envelope (van Hooff et al., 2014; Invidiata and Ghisi, 2016; Baniassadi et al., 2018; Triana, Lamberts and Sassi, 2018), altering the thermal mass (van Hooff et al., 2014; Mulville and Stravoravdis, 2016; Din and Brotas, 2017), adding green roofs/facades to poorly insulated buildings (Geneletti and Zardo, 2016;

Skelhorn, Lindley and Levermore, 2014; van Hooff et al., 2014; de Munck et al., 2018; Feitosa and Wilkinson, 2018) and for water harvesting (Sepehri et al., 2018).

In general, the most promising adaptation measures are a combination of solar shading with increased levels of insulation and ample possibilities to apply natural ventilation to cool down a building (e.g. van Hooff et al., 2014; Makantasi and Mavrogianni, 2016; Fosas et al., 2018; Barbosa, Vicente and Santos, 2015; Taylor et al., 2018; Triana, Lamberts and Sassi, 2018; Dodoo and Gustavsson, 2016). However, it must be noted that the cooling potential of natural ventilation will decrease in the future due to increasing outdoor air temperatures (Gilani and O'Brien, 2020). Increased insulation (including through green solutions) without shading and ventilation can also lead to adverse impacts through the lowering of night-time cooling (Reder et al., 2018). Similarly, air conditioning performance also decreases with increasing outdoor temperatures, in addition to being maladaptive where use increases anthropogenic heat emissions into the urban area, and global greenhouse gas emissions if powered by carbon intensive energy systems (Wang et al., 2018c).

Passive cooling is a design-based, widely used strategy to create naturally ventilated buildings, making it an important alternative to address the urban heat island for residential and commercial buildings (Al-Obaidi, Ismail and Rahman, 2014). Generally, passive cooling is achieved by controlling the interactions between the building envelope and the natural elements. Façade fixes such as overhangs, louvres, and insulated walls are effective at shading buildings from solar radiation while complex ones such as texture walls, diode roofs, and roof ponds are effective at minimizing heat gains from solar radiation and ambient heat (Oropeza-Perez and Østergaard, 2018). Passive cooling is inspired also by traditional design forms, for example from Mediterranean, Islamic and Mughal architecture in the Indian sub-continent (Di Turi and Ruggiero, 2017; Izadpanahi, Farahani and Nikpey, 2021).

In addition, wind towers, solar chimneys, and air vents are features that facilitate cool air circulation within buildings while dissipating heat (Bhamare, Rathod and Banerjee, 2019). These features may be arranged to address hotspots or highly frequented spaces within buildings. Similar to nature-based solutions, the effectiveness of passive cooling to ameliorate the urban heat island varies widely depending on the location of the sun, wind direction, and the type of strategy used. For instance, natural ventilation strategies (e.g. wind towers, solar chimneys, etc.) have shown temperature reductions of up to 14°C (Bhamare, Rathod and Banerjee, 2019; Calautit and Hughes, 2016; Rabani et al., 2014). Shading strategies alone can reduce indoor temperatures by 3°C, while heat sinks (in which heat is directed at a medium such as water) may result in indoor temperatures up to 6 °C lower than the outdoor temperature (Oropeza-Perez and Østergaard, 2018). More systemic interventions, such as altering urban form through urban planning can mitigate the urban heat island across suburbs and cities (Lee and Levermore, 2019; Takkanon and Chantarangul, 2019; Yin et al., 2018; Liang and Keener, 2015; Emmanuel and Steemers, 2018). Experience in Kano (Nigeria) has shown that incorporating Indigenous knowledge into building design and urban planning can increase resilience to heat and flood risks (Barau et al., 2015). A review by Lemi (2019) suggests that traditional ecological knowledge can provide wider climate change adaptation benefits.

Limits on housing and building adaptation include failure of regulatory systems so that formal design standards are not followed even when legally required (Arku et al., 2016; Durst and Wegmann, 2017; Pan and Garmston, 2012; Awuah and Hammond, 2014). This can be a result of pressures from clients for cheaper structures, developers illegally cutting costs or regulators lacking capacity for enforcement. Technological innovation can also be slow to embed itself in building norms and standards. Innovation also lies outside the formal sector and can include artisanal building techniques that may have adaptive value. Examples from Latin America demonstrate how initiatives in informal settlement improvement associated with housing policy, guaranteeing access to land and decent housing, show the opportunity for overarching policies encompassing development, poverty reduction, disaster-risk reduction, climate-change adaptation, and climate-change mitigation (See 12.5.5).

6.3.5.3 Information and Communication Technology

Information and Communication Technologies (ICTs) are deeply intertwined with the functioning of urban and infrastructure systems, and are at the core of the 'smart city' concept (Angelidou, 2015). ICT is more flexible than other physical infrastructure, although as other sectors are increasingly reliant on ICT it is creating new climate-related failure mechanisms (Norman, 2018; Maki et al., 2019). ICT assets and networks in urban, national and international communications systems will need to be strengthened to enable ICT infrastructure to better cope with climate change, and to enable ICT infrastructure to support the resilience of cities, settlements, and other infrastructure. The increased pervasiveness of ICT, in smart cities, smart infrastructure and day to day living, will evidently have long term implications for exposure to climate change risks and how cities manage those risks (Norman, 2018; Maki et al., 2019). For example, even if the ICT network is resilient to heatwaves, it is dependent on the electricity network to power it. Conversely, other networks are dependent upon ICT for control systems, e.g., Smart Grids for energy. There is limited information on how these interdependencies, and associated risks, will evolve.

Although networked like many other infrastructure systems, ICT components have some distinctive properties. They are relatively cheap, and the advent of wireless communications has enabled ICT to have the widest reach of all infrastructures. Components can be rapidly deployed or repaired, and generally ICT networks are therefore built with inherent redundancy and flexibility (Sakano et al., 2016). Components have a wide range of expected lifetimes which leads to faster cycles of innovation. There is therefore greater potential to accelerate uptake of climate resilience in this infrastructure sector, but conversely this can increase waste and (energy intensive) resource consumption. For example, mobile phones and computers may last as little as a year, cables and switching units may be moved and upgraded to improve bandwidth every few years, poles and masts are typically designed to last several decades, whilst exchanges and other critical nodes can be in use for over half a century.

ICTs are playing an increasing role in resilience building and enabling climate change adaptation. They are enabling access to information needed for decision-making, facilitating learning and coordination among stakeholders and building social capital, as well as helping to monitor, visualize and disseminate current and future climate impacts (Eakin et al., 2015; Heeks and Ospina, 2019; Haworth et al., 2018; Imam, Hossain and Saha, 2017). Advocacy and awareness raising through ICTs such social media applications can influence behaviours and attitudes in support of adaptive pathways (Laspidou, 2014).

ICTs play a role in adaptive responses to both short-term shocks and long-term trends associated with climate change. Timely access to information (e.g. early warning, temperature and rainfall, agricultural advice) through ICTs (e.g. mobile devices, SMS, radio, social media) can be crucial to respond and mitigate the impact of emergencies such as floods and drought, for identifying pest and disease prevalence, and for informing livelihood options, key in adaptation pathways of vulnerable (Devkota and Phuyal, 2018; Panda et al., 2019).

In addition to contributing to the robustness and stability of the critical infrastructure in the event of disasters, ICTs can strengthen other attributes of resilient urban systems by enabling learning and community self-organization, cross-scale networks and flexibility, helping vulnerable stakeholders, in particular, to adjust to change and uncertainty (Heeks and Ospina, 2015; Heeks and Ospina, 2019). Big data is being used to inform responses to humanitarian emergencies (Pham et al., 2014; Ali et al., 2016), as well as to generate new forms of citizen engagement and reporting (e.g. community-based maps of flood-prone areas) that can help to inform coping and adaptive responses (Ogie et al., 2019).

The selection and use of ICTs for adaptation needs to be fairly grounded in the broader socio-cultural, economic, political and institutional context, to ensure that these tools effectively help address existing, emerging and future adaptive needs. Typically, ICT is inadequate on its own to make a significant difference (Toya and Skidmore, 2015). The role of ICTs in adaptive pathways is influenced by; the availability of locally relevant information (e.g. weather-based advisory messages, local market prices), the accessibility of information by all members of the community (e.g. using various text, audio and visual content, local languages, addressing gender-related exclusion, cost and digital competencies), and the applicability of information at the appropriate scale (local, regional or national), including data quality and verification (Namukombo, 2016; Haworth et al., 2018).

Information privacy and security, as well as the unintended impacts of ICTs on inequality, spread of misinformation, and on widening existing gaps (e.g. due to poverty, gender and power differentials), can also constrain the contribution of ICTs to urban adaptation (Haworth et al., 2018; Coletta and Kitchin, 2017; Leszczynski, 2016) and are among the key challenges that need to be addressed in order to fully realize their potential.

6.3.5.4 Energy

A number of measures are available to adapt existing energy infrastructure to climate change. These typically involve changing engineering design codes and upgrading facilities to cope with new climatic conditions, building redundancy and robustness into systems, and preparation to ensure continued operation following extreme events. Adapting low carbon energy infrastructure improves its climate resilience whilst simultaneously delivering mitigation goals (Kemp, 2017; Feldpausch-Parker et al., 2018), benefitting all other sectors (Dawson et al., 2018; Pescaroli and Alexander, 2018; Kong, Simonovic and Zhang, 2019).

Hall et al. (2019) identified 4223GW of global power generation at risk of flooding. If these assets were protected by 0.5m flood protection, ~700GW would be at risk from the 1 in 100-year flood. Many assets can be strengthened, relocated, or replaced with new equipment built to higher standards. An example of this is in the UK where a total of £172 million is being invested in between 2011-2023 to raise flood protection of substations to be resilient to the 1 in 1000 year flood (ENA, 2015). Electricity cables can be upgraded in anticipation of reduced efficiency in a warmer climate, although in many locations this may be achieved autonomously to meet growth in electricity demand (Fu et al., 2017).

Fuels, including oil, natural gas, hydrogen, biomass, and CO_2 prior to sequestration are delivered and distributed by pipeline or transportation by road, rail and shipping. In addition to engineering improvements, adaptation measures also include planning and preparation for service disruption by changing transport patterns, increasing local storage capacities, and identifying and prioritising protection of critical transport nodes (Wang et al., 2019b; Panahi, Ng and Pang, 2020).

Several options are available to reduce the impacts of reduced cooling water for thermoelectric power generation, increases in water temperature, and lower flows for hydropower generation. These include (i) switching from freshwater to seawater (if available) or air cooling; (ii) replacing once through cooling systems with recirculation systems; (iii) replacing fuel sources for thermoelectric power generation; (iv) increasing the efficiency of hydro and thermoelectric power plants; (v) relaxing discharge temperature rules to allow warmer water to enter rivers; (vi) installation of screens to stop algae or jellyfish blooms clogging intakes (vii) reducing power production and managing demand; and, (viii) changing reservoir operation rules (where available). Shreshta et al. (2021) show that changing reservoir operation rules can offset reduced water availability under RCP8.5 until 2050, but is insufficient by the 2080s. Van Vliet et al., (2016) showed that a 10% increase in hydroelectric generation efficiency can compensate for reduced water availability in most regions. Higher efficiency thermoelectric plans offset impacts under lower climate change scenarios but are shown to be inadequate under RCP8.5 by the 2080s; whereas a switch to seawater and dry (air) cooling provides a net increase under this scenario. However, these technologies can increase costs. Increasing the temperature of water discharged from the power station can have negative environmental impacts (Thome et al., 2016; Yang et al., 2015).

Longer term systemic strategies could include a combination of increased network redundancy and decentralization of generation locations (Fu et al., 2017), or the use of 'defensive islanding' which involves splitting the network into stable islands in order to isolate components susceptible to failure and subsequently trigger a cascading event (Panteli et al., 2016). Smart grids are being increasingly deployed within municipalities to provide more efficient management of supply and demand and mitigate greenhouse gas emissions, however, there is limited understanding of their performance and reliability during floods and other extreme weather events (Vasenev, Montoya and Ceccarelli, 2016; Feldpausch-Parker et al., 2018).

Adaptation and preparedness at the household level can minimize impacts during power outages, but neighbourhood level assistance may be more appropriate to ensure support for vulnerable households, and coordination of action and information (Ghanem, Mander and Gough, 2016). More generally, it is important for responder organisations integrate energy needs in disaster preparedness and response plans. Whilst over the longer term, reducing household and industrial demand for energy supply will reduce the need for capital investments and upgrades (Fu et al., 2017).

Providing a reliable and resilient power supply is crucial to economic and social development (Fankhauser and Stern, 2016). Furthermore, there are co-benefits from the use of low carbon energy systems (Chapter 8, WGIII AR6). For example, solar-charged street lamps and household lighting provides reliable nighttime lighting providing safety, security and resilience to disruption of network power supplies (Burgess et al., 2017). At larger scales, deploying solar power on building roofs, reduces energy demand for cooling by 12% and lowers the urban heat island and thereby has health benefits (Masson et al., 2014a). In the USA, construction of solar panels over 200millin parking spaces would generate a quarter of the country's electricity supply (Erickson and Jennings, 2017).

As shown in Table 6.3 access to energy supply varies considerably. In particular, many African countries require substantial energy infrastructure to support their economic development. The combination of smart technologies with solar and other renewable generation provides a huge opportunity (Anderson et al., 2017; Kolokotsa, 2017). However, care must be taken in rapidly developing cities as failure to ensure energy access during urbanization can reduce resilience (Ürge-Vorsatz et al., 2018).

6.3.5.5 Transport

A wide range of adaptation options are available for transport infrastructure and most provide a good benefit cost ratio (Doll, Klug and Enei, 2014; Forzieri et al., 2018). Options include upgrading infrastructure (which can often be achieved autonomously as part of standard repair and replacement schedules), strengthening, or relocating (critical) assets. Adaptation of road and rail networks in Australasia includes re-routing, coastal protection, improved drainage, and upgrading of rails (Table 11.7. In areas with substantial infrastructure deficits, such as much of Africa, investments in public transport and transit-oriented development are highlighted as desired mitigation-adaptation interventions within cities of South Africa, Ethiopia, and Burkina Faso (Section 9.8.5.3). Adapting low carbon transport infrastructure will be crucial to ensure resilience to climate change impacts whilst simultaneously delivering mitigation goals (Shaheen, Martin and Hoffman-Stapleton, 2019; Costa et al., 2018).

Wright et al. (2012) calculated that strengthening bridges in the USA would cost \$140-\$250bn by 2090 (or several billion dollars a year), but costs are reduced by 30% if interventions are made proactively. Koks et al. (2019) calculate a benefit cost ratio of greater than one for over 60% of the world's roads exposed to flooding. The greatest benefits from adaptation of the global road network are in low- and middle-income countries where reductions in flood risk are typically between 40-80%. Pregnolato et al. (2017) showed that in the city of Newcastle upon Tyne (UK) two carefully targeted interventions at key locations to manage surface water flooding reduced the impacts of the 1 in 50-year event in 2050 by 32%. In permafrost regions geo-reinforcement, foundation and piles can be strengthened (Trofimenko, Evgenev and Shashina, 2017), whilst passive cooling methods, including high-albedo surfacing, sun-sheds, and heat drains can cool infrastructure (Doré, Niu and Brooks, 2016).

Hanson and Nicholls (2020) calculate the total global investment costs for port adaptation to sea-level rise and provision of new areas US\$223-768bn by 2050. However, adaptation of existing ports is only 6% of this. Yesudian and Dawson (2021) estimate the cost of maintaining present levels of flood risk in 2100 for the global air network will cost up to \$57bn (Monioudi et al., 2018; Esteban et al., 2020b).

New technologies and design innovations can improve the resilience of cars, trains, boats and other vehicles to cope with more extreme weather. Mobility transitions have the potential to improve mobility and accessibility, to influence urban form and to reduce vehicular use (and thereby infrastructure degradation), vehicle miles travelled and vehicle-based emissions (Sperling, Pike and Chase, 2018). For example, use of electric vehicles, hydrogen vehicles, and greater uptake of public transport and other vehicles that reduce exhaust head emissions reduces the urban heat island (Kolbe, 2019) Carsharing can reduce carbon emissions by over 50% (Shaheen, Martin and Hoffman-Stapleton, 2019). Ride-hailing - matching nonprofessional drivers of private vehicles with paying passengers - positively impacts low-income, low car ownership households in Los Angeles (Brown, 2018), and fills market gaps in cities where public transit infrastructure is inadequate, unreliable or unsafe (Suatmadi, Creutzig and Otto, 2019; Vanderschuren and Baufeldt, 2018), but can also create a precarious and insecure job market that impacts wellbeing (Fleming, 2017). Whether the resulting impacts are positive or negative, largely depends on local, national and international policy and practices.

Safe and convenient walking and cycling (and public transport) infrastructure in cities reduces carbon emissions and urban heat island intensity, but also improve cardiovascular capacity which reduces heat stress (Schuster et al., 2017). In some regions warmer weather may bring opportunities for increased uptake of cycling and walking, though precipitation or thermal discomfort caused by high temperature and humidity can reduce the use of active travel modes for commuting and recreation (Chapman, 2015). Shaded pavements and lanes, and measures to mitigate the urban heat island can reduce risks to disruption of active travel thereby also enhancing mitigation (Wong et al., 2017).

Full system re-design may enable the greatest resilience but it does not usually have a good benefit cost ratio (Doll, Klug and Enei, 2014). Moreover, Caparros-Midwood et al. (2019) show that transport infrastructure planners will not always be able to resolve trade-offs between managing climate risks and mitigating greenhouse gases without tackling other sectors. However, infrastructure planners should continually seek opportunities for positive infrastructure lock-in where available (Ürge-Vorsatz et al., 2018).

6.3.5.6 Water and Sanitation

Adaptation to water scarcity can be through measures to increase supply (e.g. water storage, rainwater harvesting, desalination, river basin transfers, increased abstraction, reduce pollution of water sources), or manage demand (e.g. reduce leakage lower consumption, use of water efficiency devices, greywater reuse, behaviour change). A combination of these measures is usually required (e.g. Ives, Simpson and Hall, 2018; Dirwai et al., 2021; Wang et al., 2018a). Reliable, well adapted, water and sanitation services support economic growth, public health, reduced marginalisation and poverty, can lower energy use and improve water quality (Campos and Darch, 2015; Miller and Hutchins, 2017; Jeppesen et al., 2015; Hamiche, Stambouli and Flazi, 2016).

Globally, water sector adaptation costs are estimated to be $20 billion per year by 2050 (Fletcher, Lickley and Strzepek, 2019). Globally, the budget required by 2030 for water infrastructure (new and refurbishment) is more than half of the budget required for all infrastructure (Koop and van Leeuwen, 2017). For OECD countries water adaptation increases costs by 2%, but this proportion is far higher for developing nations (Olmstead, 2014).

A number of adaptation actions are available to reduce the impacts of floods on water and sanitation infrastructure. Active management reduces blockages in water infrastructure, and protect related services such as roads and culverts which are essential to ensure the operation of onsite sanitation infrastructure (Capone et al., 2020). The impact of floods for onsite or sewerage systems can be lowered by reducing or eliminating excreta from the environment through regular maintenance, cleaning, and clearing of blockages (O'Donnell and Thorne, 2020; Borges Pedro et al., 2020).

Infrastructure to protect key assets such as water and wastewater treatment plants or pumping stations has a high cost but benefits all connected households and reduces pollution from flood events. In well-regulated water sectors, there has been an increasing focus on such investments (Campos and Darch, 2015). Whereas more diffused cheaper interventions can reduce flood water ingress to domestic toilets (Irwin et al., 2018). Luh et al. (2017) found that protected dug wells were one of the least resilient technologies, whereas piped, treated, utility managed surface water systems had higher resilience.

Protecting water sources from pollution is even more important in a warmer climate that increases the frequency of algal blooms. Individual assets such as water intake pipes can be protected using screens (Kim et al., 2020a), whereas basin scale land management is required to reduce nutrient load from runoff (Me et al., 2018), whilst injecting water or installing barriers can protect coastal aquifers from salinization (Siegel, 2020).

More radical structural interventions may be needed in the longer term, but would need to be planned and delivered in coordination with investments in other sectors, particularly housing (Lüthi, Willetts and Hoffmann, 2020). As an interim measure, sanitation services with a lower reliance on fixed infrastructure, or container based sanitation could be appropriate in many urban areas that are badly affected by flooding (Mills et al., 2020).

Other actions include use of adaptive planning (Evans, Rowell and Semazzi, 2020), integration of measures of climate resilience into water safety plans (Prats et al., 2017), as well as improved accounting and management of water resources (Lasage et al., 2015). Policy prescriptions on technologies for service delivery, and changes in management models offer potential to reduce risks, particularly in low-income settings (Howard et al., 2016). Where formal sewerage provision is lacking, community based adaptation that incorporates both the function of the sanitation system as well as the vulnerability of users (e.g., women, children, elderly, ill or disabled) into the design is essential (Duncker, 2019).

6.3.5.7 Flood management

Cities are deploying a broad range of strategies to adapt infrastructure to flooding, with hard engineering approaches (e.g. dikes and seawalls) increasingly complementing soft approaches, including planning and use of nature based solutions, that emphasize natural and social capital (Jongman, 2018; Sovacool, 2011). The infrastructure can alter downstream risks and lead to increased residual risk by encouraging more floodplain construction (Miller, Gabe and Sklarz, 2019; Ludy and Kondolf, 2012). Physical infrastructure is highly cost effective for large settlements, but not always for small settlements (Tiggeloven et al., 2020) and can be inaccessible to poorer communities (Sayers, Penning-Rowsell and Horritt, 2018; Van Bavel, Curtis and Soens, 2018). It is often inflexible once installed but new designs and adaptive pathways are emerging (Anvarifar et al., 2016; Kapetas and Fenner, 2020).

As urban areas have expanded, so too have the number of vulnerable assets, and efforts may now emphasize reducing construction in high risk regions (Paprotny et al., 2018a). The National Flood and Coastal Erosion Risk Management Strategy for England, for example, calls for reductions in inappropriate developments in floodplains (Kuklicke and Demeritt, 2016; UK Environment Agency, 2020). Because climate change increases the flood risk profile of certain regions, reconsideration of design criteria has become more common (Ayyub, 2018). New York City now requires the sewer system currently designed for hydraulic capacity in 5-year design life should be designed for 50-year design life taking into account climate changes over that period (NYC, 2019).

Adaptation strategies are diverse and often involve hybrid physical and nature-based solutions, and increasingly integrated management plans that consider both flood prevention and designing infrastructure and supporting people to cope with floods when they occur. Adaptation typically focuses on (i) increasing the standard of protection to compensate for the increased magnitude of extreme events; (ii) increased maintenance to cope with increased frequency of extremes and changes in ambient conditions; (iii) changed maintenance regimes from narrower maintenance windows e.g. as assets are used more frequently (Sayers, Walsh and Dawson, 2015); (iv) land use planning and management to reduce exposure and manage hydrological flows, and (v) raising awareness, preparedness, and incident management. In high population areas, hard interventions such as dikes and levees are generally cost effective (Jongman, 2018; Ward et al., 2017).

Prevention or attenuation solutions include: rooftop detention, reservoirs, bioretention, permeable paving, infiltration techniques, open drainage, floating structures, wet-proofing, raised structures, coastal defences, barriers, and levees, and have been deployed in diverse configurations, and environments, around the world (Matos Silva and Costa, 2016). Barcelona (Spain) by the 1980s reached 90% impermeable surface cover, and has recently begun implementing artificial detention, underground reservoir, and permeable pavement technologies (Favaro and Chelleri, 2018; Matos Silva and Costa, 2016). Florida Power and Light (USA) which provides service to approximately 10 million people, is investing $3b in flood protection and the hardening of assets (for example, upgrading wooden polls to steel and concrete) (Brody, Rogers and Siccardo, 2019). The City of Seattle recommends increasing preventative maintenance activities, the regular review of appropriate pavement technologies, and modifications to subgrades and drainage facilities for high risk areas (City of Seattle, 2017), whilst also providing benefits to transport disruption (Arrighi et al., 2019). Adaptation in African cities is often dominated by informal responses (Owusu-Daaku and Diko, 2018). In the absence of centralized responses, low-income residents in Nairobi (Kenya) dig trenches and construct temporary dikes to protect homes, and in Accra (Ghana) the community has developed a range of social responses including communal drains and local evacuation teams, to help protect people and critical valuables, although these innovations require connection to city-wide infrastructure to effectively reduce widespread risk (Amoako, 2018).

More recent developments include sensor arrays to catalogue a river's reach and how changing hydraulics interact with roadways (Forbes et al., 2019). Kuala Lumpur's (Malaysia) Stormwater Management and Road Tunnel (SMART) during extreme rain events transitions the motorway to a stormwater conduit, an example of multifunctionality enabling agility (Isah, 2016; Markolf et al., 2019). Smart stormwater control systems are starting to use real time control to dynamically manage the retention and movement of water during storms, though uptake at large scales which provide the greatest improvements in performance have been limited (Xu et al., 2020b).

In contrast to a "fail-safe" approach to design which emphasises strengthening infrastructure against more intense environmental conditions, "safe-to-fail" flood strategies allow infrastructure to fail in its ability to carry out its primary function but control the consequences of the failure. Examples include the use of a bioretention basin in Scottsdale (Arizona, USA) to accommodate excess runoff and help drain the city; a subsidy for affected farmers for lost crop production as part of the Netherlands' Room for the River program; targeted destruction of a levee to control flooding in the Mississippi River Valley in 2011 (Kim et al., 2019). Water Sensitive Urban Design, Low Impact Development, Sponge Cities, Sustainable Urban Drainage, and Natural Flood Management, involve deployment of systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater to protect water quality and associated aquatic habitat. These are being designed and implemented at increasingly ambitious scales. For example, China's Sponge City initiative sets a goal of 80% or urban land able to absorb or reuse 70% of stormwater through underground storage tanks and tunnels, and use of pervious pavements, in addition to nature-based solutions (Chan et al., 2018; Muggah, 2019). Similarly, several thousand Water Sensitive Urban Design interventions have been implemented across the city of Melbourne (Kuller et al., 2018).

6.3.5.8 Coastal Management

Physical coastal management infrastructure has significant benefits in reducing flood and erosion losses and damage from storms. Physical infrastructure includes seawalls, dikes, breakwaters, revetments, groynes, or tidal barriers. Adapted infrastructure can alter risks in morphologically connected areas, and lead to increased residual risk by encouraging more construction in the coastal zone (Miller, Gabe and Sklarz, 2019; Ludy and Kondolf, 2012). The infrastructure is highly cost effective for large settlements, but not always for small settlements (Tiggeloven et al., 2020) and can be inaccessible to poorer communities (Fletcher et al., 2016; Pelling and Garschagen, 2019).

Anticipated costs for this vary widely. For example, Hinkel et al. (2014) calculate that adaptation costs to maintain current global levels of coastal flood protection would be 1.2–9.3% of Gross World Product but protect assets in human settlements of $US21-210bn; Tiggeloven et al. (2020) calculate the cost of adaptation to be US$176bn (although this would provide a Benefit to Cost Ratio of 106 under RCP8.5); while Nicholls et al (2019) estimate that global coastal protection would cost substantially more, up to $18.3 trillion between 2015 to 2100 for RCP8.5 (this includes ranges of unit costs and maintenance costs which have often been ignored).

Coastal protection infrastructure such as dikes and sluice gates can inhibit salinity intrusion through careful management of water levels, this can provide co-benefits for flood risk reduction and agricultural productivity but can also have negative impact on ecosystems (Renaud et al., 2015). Managed aquifer recharge can be effective if the objective is to secure freshwater drinking supply (Hossain, Ludwig and Leemans, 2018).

Physical infrastructure can provide substantial benefits, can be constructed quickly, and has enabled coastal cities and settlements around the world to flourish and grow. Multifunctional physical infrastructure can also provide economic and social co-benefits. These include integration of transport, recreation, agriculture e.g. cattle pasture, founding for wind turbines, housing, office or industry into the coastal management infrastructure (Anvarifar et al., 2017; Kothuis and Kok, 2017). However, physical infrastructures can also disrupt natural processes, often leading to undesirable impacts such as pollution, degradation of ecosystems, and displacement of erosion and flood risk to other locations (Wang et al., 2018b; Dawson, 2015; Nicholls, Dawson and Day, 2015). Coastal management strategies that take a hybrid approach, integrating physical and natural infrastructure, provide the best opportunities for managing risk and achieving wider socio-economic and environmental benefits (Depietri and McPhearson, 2017; Morris et al., 2018; Schoonees et al., 2019; Powell et al., 2019).

6.3.6 Cross-Cutting Themes

This section builds on 6.3.4 to offer two entry points for assessing urban adaptation that extend beyond individual infrastructure types and that demonstrate the interdependent and dynamic natures of urban systems.

6.3.6.1 Equity and Justice

Questions of equity and justice influence adaptation pathways for cities, settlements and infrastructure (see also Chapter 8). Although infrastructure, ranging from social to ecological and physical to digital, can help to reduce the impacts of climate change (Stewart and Deng, 2014; Baró Porras et al., 2021), there is limited evidence of how infrastructures, implemented to reduce climate risk also reduce inequality. Rather, there is more evidence to suggest that both adaptation plans and associated infrastructure implementation pathways are increasing inequality in cities and settlements (Chu, Anguelovski and Carmin, 2016; Anguelovski et al., 2016; Romero-Lankao and Gnatz, 2019). Social, economic and cultural structures that marginalize people by race, class, ethnicity and gender all contribute in complex ways to climate injustices and need to be urgently surfaced in order for adaptation options to shift to benefit those most vulnerable rather than mainly benefitting the already privileged and maintaining the status quo (Thomas et al., 2019; Porter et al., 2020; Ranganathan and Bratman, 2019). Innovation and imagination are needed in adaptation responses to ensure that cities and settlements shift from perpetuating structural domination and inequality to fairer cities (Porter et al., 2020; Henrique and Tschakert, 2019; Parnell, 2016b). To support these possibilities, this section explores adaptation through the lens of distributive and procedural justice. Although not expanded on here, spatial and recognition injustices are equally important (Fisher, 2015; Chu and Michael, 2018; Campello Torres et al., 2020). Recognition can be supported through a capabilities approach that helps to bring attention to past cultural domination and enable citizens to develop the functioning life they choose (Schlosberg, Collins and Niemeyer, 2017). This brings a focus on local action emphasizing the relevance to vulnerability reduction and resilience building of individual and local/community capacities and supporting structures. This blurs the distinction between climate change adaptation and community development with the former firmly embedded in the latter. Struggles for recognition are deeply political and central to adaptation responses, which requires increased focus on power to support more equitable and just adaptation (Nightingale, 2017). Justice question are not static, Box 6.4 overviews the implications of COVID-19 for urban justice and vulnerability.

[START BOX 6.4 HERE]

Box 6.4: Adapting to Concurrent Risk: COVID-19 and Urban Climate Change

COVID-19 impacts have highlighted the depth and unevenness of systemic social vulnerability and the compounding characteristics of contemporary development models with direct relevance to climate change risk accumulation and its reduction (Patel et al., 2020b; Manzanedo and Manning, 2020; Bahadur and Dodman, 2020). This is plain at the global level: of the estimated 119 to 124 additional people induced into poverty by COVID-19 in 2020, South Asia and sub-Saharan Africa each contribute two-fifths (Lakner et al., 2021). These are rapidly urbanizing and highly climate hazard exposed world regions indicating COVID-19 impacts may further concentrate risk in these regions. Within cities, COVID-19 and climate change risk and loss is concurrent by gender, race and income or livelihood. For example, when vulnerable elderly populations are simultaneously exposed to COVID-19 and heatwave risk. Globally, in 2020, about 431.7 million vulnerable people were exposed to extreme heat during the COVID-19 pandemic, including about 75.5 million during a July and August 2020 European heatwave with an excess mortality of over 9,000 people arising from heat exposure (Walton and van Aalst, 2020).

The pandemic has demonstrated the multiple, often reinforcing ways in which specific drivers of vulnerability interact both in generating urban risk and shaping who is more or less able to recover (Phillips et al., 2020b; Honey-Rosés et al., 2020) (see Section 6.2). Again, this is not a new lesson for urban climate change adaptation, but it is a lesson that has not yet been seen to enter into routine practice for urban adaptation. Two key challenges for climate change adaptation are the associations between COVID-19 risk and urban connectivity and overcrowding. Connectivity has been presented in urban adaptation policy as a virtue, a means to share risk and diversity inputs (Ge et al., 2019; Kim and Bostwick, 2020), COVID-19 has surfaced the unevenness with which people and places are connected and also the need to balance connectivity against risk transfer – through the failure of food supply chains or remittance flows as well as by the direct transfer of disease (Challinor et al., 2018). High density living has advantages for urban resource efficiency including benefiting climate change mitigation. When high density living is not supported by adequate access to critical infrastructure (sufficient internal living space, access to potable water and sanitation, access to open green space) this exacerbates overcrowding and generates vulnerability to multiple risks – including climate change hazards and communicable disease (Bamweyana et al., 2020; Hamidi, Sabouri and Ewing, 2020; Peters, 2020; Satterthwaite et al., 2020). Where overcrowding coincides with precarious livelihoods, for example in informal settlements, risk is further elevated (Wilkinson, 2020). Neighbourhood associations (a benefit of high density living) have been an important source of resilience through providing trusted information, access to food and water for washing during the pandemic, serving populations unable to access government or market provision (Pelling et al., 2021). Here local organising has not only met gaps in service provision but opened dialogue to vision and organise for alternative development futures. These distinctly urban challenges should be read as a sub-set of wider cross-cutting lessons for recovery from COVID-19 (see Cross-Chapter Box COVID in Chapter 7).

Where responses to COVID-19 include addressing inequities in social infrastructure this opens a considerable and potentially society-wide opportunity to reduce social vulnerability to climate change risks. (see Cross-Chapter Box COVID in Chapter 7).

[END BOX 6.4 HERE]

Distributive justice calls attention to unequal access to urban services, land, capital and technology. Related to this, exposure to health, flooding and drought risks of people living in low-income and informal settlements is a growing concern, as is disaster preparedness and the ability to support the needs of vulnerable groups such as the elderly, children and disabled, where data is often lacking (Lilford et al., 2016; Castro et al., 2017). There are also differences in who benefits from infrastructures, as they are inherently political, embedded in social contexts, politics and cultural norms (McFarlane and Silver, 2017) and often tend to benefit those already privileged (Henrique and Tschakert, 2019). As an example, fixing water leaks can depend as much on the politics of who is involved and whose knowledge is prioritised, as on the technical aspects (Anand, 2015).

The quality and maintenance of infrastructure is often unequal across cities benefiting some and increasing vulnerability of others. Some property is seen as dangerous and of lower value if highly exposed to risk (Wamsley et al., 2015). Similarly, areas suffering from disinvestment in infrastructure, might have a high risk of flooding (Haddock and Edwards, 2013). Zoning and land use trade-offs have been seen to be unequally skewed in favour of prime real estate and economically valuable assets (e.g., protecting factories and refineries from flooding) (Anguelovski et al., 2016; Carter et al., 2015). Urban planning reforms are therefore central to building a fairer urban adaptation response (Parnell, 2016b).

Infrastructure is often not adequately implemented in low-income urban areas and not equally accessible to all (Meller et al., 2017). For example, low-income neighbourhoods often have less green space and therefore less associated cooling benefits. Even in high-income areas, there is often unequal access to services. For example, an assessment of sustainable urban mobility plans in Portugal showed that some areas have considered equity in their plans and increased access for disadvantaged users including the elderly and disabled, but in other cities this is lacking (Arsenio, Martens and Di Ciommo, 2016). Understanding who has access to what infrastructure can help to redress the drivers of social vulnerability, that are central to just urban adaptation (Michael, Deshpande and Ziervogel, 2018; Shi et al., 2016).

Changing land use and increasing green spaces to reduce climate risks and attract investments and job opportunities has increased real estate values, triggered climate gentrification in some areas (Keenan, Hill and Gumber, 2018) and decreased access to affordable housing in other areas (Larsen, 2015; Carter et al., 2015). Displacement through evictions and relocations linked to land use conversion and resettlement in the name of adaptation has also increased people's vulnerability (Anguelovski et al., 2016; Henrique and Tschakert, 2019).

Understanding social and economic elites and their investment in infrastructure has implications for distributive justice, particularly when there is secession from public infrastructure services that has financial implications for viability (Romero-Lankao, Gnatz and Sperling, 2016). In the case of the 2015-17 Cape Town drought, wealthy households secured their water needs through off-grid technologies such as rainwater tanks and boreholes. Although this resulted in more water being available in the dams, it also led to less revenue being collected for municipal water and less ability to cross-subsidize water for poor households (Ziervogel, 2019b; Simpson, 2019; Bigger and Millington, 2019). More attention needs to be paid to how shifts in infrastructure are serving the interests of urban elites, often driving by the state, and failing to adequately consider the needs of the disadvantaged (Bulkeley, Castán Broto and Edwards, 2014; Ajibade, 2017; Shi et al., 2016). Equally, more risk-reducing infrastructure is needed across all urban areas (Reckien et al., 2018a).

Procedural justice, which focuses on the institutional processes by which adaptation decisions are made, brings attention to the lack of opportunity for engaging in political decision-making and limited representation of diverse voices in cities and settlements, and in relation to investment in infrastructure (Coates and Nygren, 2020; Henrique and Tschakert, 2019). Even when inclusive adaptation processes are run, they seldom produce procedurally just outcome (Malloy and Ashcraft, 2020). Understanding who is excluded and included is important (Sara, Pfeffer and Baud, 2017). One example, are the increasing numbers of migrants who are confronted with lack of access to citizenship rights and housing tenure (Romero-Lankao and Norton, 2018). Often, migrants are not allowed to formally claim public provisions in health, finance, and shelter (Chu and Michael, 2018). Further, migrants and their settlements are likely unrecognized in spatial or infrastructure development plans. In this context, social infrastructure, zoning and land use planning for climate adaptation has triggered inequity through omission, as some planning process have been racialized and excluded groups such as migrants and ethnic minorities (Anguelovski et al., 2016). Urban adaptation policy-making processes that explicitly integrate multiple stakeholder interests can help to balance top-down solutions (Reckien et al., 2018a).

Identifying who is least able to adapt to climate risks sufficiently is important (Thomas et al., 2019). Some people may have few opportunities to relocate away from flooded areas in the long-term or to evacuate in the short term. It is also harder for many from low-income areas to rebuild after an extreme event. Lack of housing tenure and sub-standard housing has been shown to limit the ability of residents to improve and manage their landscapes and therefore it is hard for them to enhance energy efficiency (Dempsey et al., 2011). Access to information is critical for adapting to climate risk and reducing vulnerability to hazards, yet access to this information is often not equally available (Ma et al., 2014). For example, low literacy can hamper ability to respond to early warning information (Dugan et al., 2011). In other instances, racial violence has surfaced during disasters, with black victims' lives being seen as less important than others (Anderson et al., 2020).

When looking at justice issues in urban adaptation it is important to recognise that the adaptation of one individual or household may lead to maladaptation and negative impacts elsewhere (Holland, 2017; Limthongsakul, Nitivattananon and Arifwidodo, 2017; Atteridge and Remling, 2018). For example, the case of an area of peri-urban Bangkok experiencing localized flooding due to unregulated private sector development saw households take both individual action (building flood walls around homes, digging temporary drainage swales in the carriageway) and collective action (petitioning authorities, pumping water into vacant land). These actions, to a certain extent, merely displaced the flood water to other areas, or created new problems by damaging the carriageway, creating negative impacts on other households and the wider community. However, ultimately it was the actions of improperly-regulated private sector developers driving the need for this autonomous adaptation (Limthongsakul, Nitivattananon and Arifwidodo, 2017).

One of the tensions that emerge when addressing injustice is that the global provision of modern infrastructure is increasingly seen as unfeasible. It is unfeasible, both in terms of the current high emissions associated with infrastructure (World Bank, 2017) as well as the centralized, high standard ideal (Lawhon, Nilsson and Silver, 2018; Coutard and Rutherford, 2015). Decentralisation is increasingly needed, which the urban poor already engage in through their use of 'informal' infrastructure technologies, given their limited access to infrastructure networks. Transformative adaptation pathways that reduce climate risk whilst reducing inequity require an approach that sees infrastructure as inherently social and political.

6.3.6.2 Mitigation and Adaptation

As analytical concepts, mitigation and adaptation have helped, over the years, to structure thinking and action around climate change. However, since AR5 there has been a growing debate about the adequacy of a neat separation between adaptation and mitigation (Castán Broto, 2017).

The delivery of climate change action has revealed numerous co-benefits between adaptation and mitigation, around diverse areas such as implementing nature-based solutions and delivering health and development benefits (Ürge-Vorsatz et al., 2014; Suckall, Stringer and Tompkins, 2015; Puppim de Oliveira and Doll, 2016; Spencer et al., 2017). There has been a strong interest in delivering development benefits alongside climate mitigation, thus benefiting the overall infrastructure base (Suckall, Stringer and Tompkins, 2015). Some of these co-benefits have also emerged in experiences of urban planning, pointing towards the dilemma of separating adaptation and mitigation in a context in which integration, rather than an analytical differentiation, was seen as being required to transcend work in silos (Aylett, 2015). Because urban planning needs to carefully consider long timescales, the neat separation between mitigation and adaptation runs counter to integrated forms of planning that can consider scales (time and space) carefully and that are aimed to deliver the sustainable city as a whole (Solecki et al., 2015; Grafakos et al., 2020).

For example, the ideas of climate resilient development and climate compatible development help planners to consider the simultaneous wins that emerge between adaptation, mitigation, and development, requiring institutional building and partnerships to deliver triple win solutions (Stringer et al., 2014; Seo, Jaber and Srinivasan, 2017; Mitchell and Maxwell, 2010). While the evidence base for the actual possibility of achieving such triple wins remains scarce (Tompkins et al., 2013; Sharifi, 2020), emerging examples show important developments. For example, establishing safe and convenient walking and cycling infrastructure can lead to improvements in population health, thereby highlighting the close interaction between urban land-use, infrastructure and population health (Schuster et al., 2017); while clean cooking has the potential to deliver positive health outcomes alongside improvements in air quality and emissions reductions and through reducing pressure on woodland as a fuel source for expanding urban populations (Msoffe, 2017). Furthermore, active transport infrastructure reduces air pollution and related health risk, and helps to mitigate further climate change (Schuster et al., 2017). These are supported by city networks such as the C40 Clean Air Cities Declaration and the Clean Air Coalition that complements WHO guidelines and standards for example through the Breathe Life Campaign. In conclusion, in both urban environments and infrastructural sectors, triple wins are only realizable through broader perspectives that link climate compatible development to institutional change or the achievements of wider welfare objectives such as those enshrined in the United Nations 2030 Agenda of Development (Castán Broto et al., 2015; England et al., 2018) (*medium evidence, high agreement*).

The aspiration to deliver climate change action within a broader agenda of transformative change, introduced in the SREX report, received renewed attention after the publication of IPCC Special Report on Global Warming of 1.5°C, which argues for a focus on urban transformations and highlighted that informal settlements were vital for understanding the delivery of these transformations. Deep decarbonization has emerged as a new idea that regards the development of low or zero carbon pathways as a condition for good adaptation in the long term. Decarbonization becomes urgent in the face of growing impacts attributable to climate change (Ribera et al., 2015; Bataille et al., 2016; Wesseling et al., 2017). Urbanization opens opportunities for deep mitigation in low impact developments, and hence, it is imperative to understand the implications of those opportunities for climate action (Mulugetta and Broto, 2018). These gains are not limited to urban areas. The reliance on connected urban-rural systems for water, food and fuel has led to city government and urban based businesses supporting landscape adaptations in rural hinterlands with strong potential for mitigation and rural development cobenefits. Water Funds bring downstream urban public and private finance to support upstream, rural residents to make land-use and agricultural management decisins to avoid damaging run-off, soil erosion and downstream sedimentation with reduction in water quality and increased flood risk. There are more than 30 Water Funds in Latin America and sub-Saharan Africa. These operate at landscape scale, the Upper Tana-Nairobi Water Fund, Kenya (Vogl et al., 2017) planned for a US$10 million investment in water fund-led conservation interventions with a projected return of US$21.5 million in economic benefits over a 30-year timeframe (Apse and Bryant, 2015). However, these investments do not occur where communities lack funding or the institutions to direct funding from downstream beneficiaries to upstream residents (Brauman et al., 2019).

6.3.7 Climate Resilient Development Pathways

Table 6.6 represents the contribution of 21 adaptation measures identified in this chapter to 17 components of Climate Resilient Development (CRD). Climate Resilient Development brings together the aims of climate adaptation, climate mitigation, sustainable development and social justice (Singh and Chudasama, 2021). This provides a first assessment of the viability of adaptation to cities, settlements and key infrastructure as a part of global transition to sustainability (see also Cross-Chapter Box FEASIB in Chapter 18).

Two overarching messages and one key consequence for planning arise from Figure 6.4. First, urban adaptation measures can offer a considerable contribution to Climate Resilient Development. Second, this potential is realised by adaptations that extend predominant physical infrastructure approaches to also deploy nature based solutions and social interventions. The consequence for planning is support for comprehensive monitoring and joined-up evaluation across the multiple components of Climate Resilient Development as well as between the sectors that contribute to adaptation.

Table 6.6 shows adapting key grey/physical infrastructure (built form and design, ICT, energy, transport, water and sanitation) is fundamental to Climate Resilient Development. This provides resilience to a range of hazards, with benefits to livelihoods, social capital and health and provides benefits for the adaptation of other, connected infrastructure systems. Challenges to the contributions of grey/physical infrastructure, where adaptation through nature based solutions and social policy offer alternatives are: a lack of flexibility post-deployment constraining ability to flex as climate and vulnerability change; risk transferred to other people/places, not resolved; negative ecological consequences; and, limited evidence of targeting marginality and inequality.

The significance of a Climate Resilient Development lens for the evaluation of adaptation strategy can be seen in approaches to riverine and coastal flooding. This viewpoint brings physical (e.g. embankments and defenses), nature based (e.g. mangrove stands) and social policy (livelihood and social protection) options together. The benefits of physical infrastructure interventions for strengthening existing livelihoods and protecting health, for being deployable at scale and supporting other infrastructures to adapt are recognised and set these against challenges including hazard generation and risk transfer, limited flexibility, ecological harm, carbon costs and an undermining of social inclusion and accountability. Final evaluations will be determined by individual contexts raising the importance of comprehensive monitoring of existing urban systems adaptation interventions and their association with ongoing development processes and outcomes (see Section 6.4).

The most consistent limit for all urban systems infrastructure types is in risk transfer. Current adaptation approaches in cities, settlements and key infrastructure have a tendency to move risk form one sector or place to others. With the exception of social infrastructure the observed contribution of adaptation to social transformation is also limited. There are consequences for equity and sustainability as the impacts of climate change increase, and implications for evaluation and planning to work across adaptation interventions and connect with social and environmental policy and practice.

Table 6.6 Urban Climate Resilient Development

Inf. Systems	Adaptation Measure	Risk coverage				Benefits to Human			Benefits to ecosystem services	Potential effectiveness				Contribution to GHG emission reduction	Equity benefits		Transformation towards sustainable development (human systems fundamental change + impact on wider system)	
		Multi-climate Hazard	Systemic vulnerability reduction	Reduces new hazard exposure generated	Transfer risk or impact to other people or places	Social capital	Livelihood	Health	Ecological	Flexibility post deployment	Deploy at scale	Benefit to other inf. systems adaptation	Economic feasibility	Mitigation cobenefit	Targets poverty and marginality	Inclusive and locally accountable	Social transformation	Ecological transformation
Social Inf.	Land-use planning 6.3.2.1	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-RE	HA-ME	MA-ME	HA-RE	HA-RE	MA-LE	HA-ME	HA-ME	HA-ME
	Livelihoods and social protection 6.3.2.2	HA-ME	HA-RE	HA-ME	HA-LE	HA-LE	HA-ME	HA-LE	LA-LE	MA-ME	HA-ME	HA-LE	MA-ME	LA-LE	HA-ME	MA-RE	MA-ME	LA-LE
	Emergency management and security 6.3.2.3	HA-ME	MA-ME	MA-ME	HA-ME	HA-ME	HA-ME	MA-ME	HA-ME	MA-ME	MA-ME	HA-ME	HA-ME	HA-ME	MA-ME	MA-ME	MA-ME	MA-ME
	Health 6.3.2.4	HA-RE	HA-RE	HA-ME	HA-ME	HA-ME	HA-ME	HA-RE	MA-ME	MA-ME	HA-RE	MA-ME	MA-ME	MA-ME	HA-RE	MA-ME	LA-LE	LA-LE
	Education & Comms. 6.3.2.5	HA-ME	MA-ME	MA-ME	MA-ME	HA-RE	HA-ME	HA-ME	HA-LE	HA-ME	MA-LE	LA-LE	LA-LE	HA-ME	MA-ME	MA-ME	HA-ME	MA-RE
	Cultural heritage & institutions 6.3.2.6	HA-ME	MA-ME	MA-LE	HA-ME	MA-ME	MA-RE	HA-ME	MA-LE	MA-ME	LA-LE	MA-LE	HA-ME	MA-LE	MA-LE	HA-ME	HA-RE	HA-RE
Nature based Solutions	Temp. regulation 6.3.3.1	HA-RE	LA-ME	LA-LE	LA-LE	HA-ME	HA-ME	HA-ME	HA-ME	MA-LE	HA-ME	MA-ME	HA-ME	HA-RE	MA-LE	MA-LE	LA-LE	HA-ME
	Air quality regulation 6.3.3.2	HA-ME	MA-LE	MA-LE	LA-LE	HA-ME	MA-ME	HA-ME	MA-ME	HA-ME	MA-ME	MA-LE	MA-ME	HA-ME	LA-LE	MA-LE	LA-LE	MA-LE
	Stormwater and sanitation 6.3.3.3	HA-ME	MA-ME	MA-LE	HA-ME	MA-ME	MA-LE	HA-LE	HA-ME	MA-ME	MA-LE	HA-ME	HA-ME	HA-ME	MA-LE	MA-LE	LA-LE	MA-ME
	Coastal flood protection 6.3.3.4	HA-ME	MA-ME	HA-LE	LA-LE	MA-LE	HA-RE	HA-LE	HA-ME	HA-LE	MA-LE	HA-ME	HA-ME	MA-ME	MA-LE	LA-LE	MA-LE	MA-ME
	Riverine flood impact reduction 6.3.3.5	HA-RE	MA-ME	MA-ME	HA-ME	HA-ME	LA-ME	HA-ME	HA-RE	MA-LE	MA-ME	MA-ME	LA-ME	HA-RE	LA-ME	MA-LE	LA-LE	MA-ME
	Water provisioning and management 6.3.3.6	HA-RE	MA-LE	MA-LE	MA-LE	MA-LE	MA-ME	HA-ME	HA-RE	MA-ME	HA-ME	MA-ME	HA-RE	HA-ME	LA-LE	MA-LE	MA-LE	HA-ME
	Food production and security 6.3.3.7	HA-ME	HA-ME	MA-LE	LA-LE	MA-ME	MA-ME	MA-ME	HA-ME	MA-ME	HA-ME	MA-ME	HA-ME	MA-ME	MA-ME	MA-LE	HA-ME	MA-ME
Grey/ Physical Inf.	Built form 6.3.4.1	HA-RE	HA-RE	HA-RE	MA-LE	LA-LE	MA-ME	HA-RE	MA-ME	HA-RE	HA-RE	LA-LE	LA-LE	MA-ME	LA-LE	LA-LE	LA-LE	MA-ME
	Housing and building design 6.3.4.2	HA-RE	HA-RE	HA-RE	MA-ME	LA-LE	MA-ME	HA-RE	LA-LE	HA-RE	HA-RE	MA-LE	MA-ME	MA-ME	MA-ME	MA-ME	MA-ME	MA-ME
	ICT 6.3.4.3	HA-RE	HA-ME	LA-LE	LA-LE	HA-RE	HA-ME	LA-LE	LA-LE	HA-RE	HA-ME	HA-RE	HA-ME	MA-ME	LA-ME	LA-ME	MA-ME	LA-LE
	Energy Inf. 6.3.4.4	HA-RE	HA-ME	LA-LE	LA-LE	HA-LE	HA-RE	LA-LE	LA-LE	HA-ME	MA-ME	HA-RE	MA-ME	HA-RE	MA-ME	MA-ME	LA-LE	LA-LE
	Transport 6.3.4.5	HA-RE	HA-ME	LA-LE	LA-LE	HA-LE	HA-RE	LA-LE	LA-LE	HA-ME	MA-ME	MA-ME	MA-ME	MA-LE	MA-ME	MA-ME	LA-LE	LA-LE
	Water and Sanitation 6.3.4.6	HA-RE	HA-LE	MA-ME	LA-ME	HA-LE	HA-RE	HA-RE	HA-RE	HA-ME	MA-ME	HA-RE	MA-ME	HA-ME	MA-RE	MA-ME	LA-LE	HA-RE
	Flood management 6.3.4.7	HA-RE	HA-ME	HA-ME	HA-RE	MA-ME	HA-RE	HA-RE	MA-ME	HA-ME	HA-RE	HA-RE	HA-RE	HA-LE	MA-ME	LA-ME	LA-LE	MA-LE
	Coastal management 6.3.4.8	HA-RE	HA-ME	HA-ME	HA-RE	MA-ME	HA-RE	HA-RE	MA-ME	HA-ME	HA-RE	HA-RE	HA-RE	HA-LE	MA-ME	LA-ME	LA-LE	MA-LE

Key:

Climate Resilient Development Contribution

Negative High	Negative Moderate	Negative Small	Negligible negative	Nil	Positive Negligible	Positive Small	Positive Moderate	Positive High	No data	

Confidence

HA-LE	High agreement – limited evidence	HA-ME	High agreement – medium evidence	HA-RE	High agreement – robust evidence	MA-LE	Medium agreement – limited evidence	MA-ME	Medium agreement – medium evidence	MA-RE	Medium agreement – robust evidence	LA-LE	Low agreement – limited evidence	LA-ME	Low agreement – medium evidence	LA-RE	Low agreement – robust evidence

Table Notes:

Overall confidence: *Medium agreement - medium evidence.* Supplementary Material provides a detailed analysis including definitions for each component of Climate Resilient Development and for each of the 357 entries an underlying explanatory statement linked to key evidence. Analysis was by Chapter 6 Lead and Contributing Authors.

6.4 Enabling Conditions for Adaptation Action in Urban Areas, Settlements, and Infrastructure

This section assesses the effectiveness of efforts to create enabling conditions for adaptation. New policy innovations like National Urban Policies are emerging to address the multi-level governance demands of climate change (UN-Habitat, 2020; Kinyanjui, 2020). There is no one-size-fits-all approach to deliver adaptation that will fit every case because the local conditions of implementation bear a strong influence on adaptation's feasibility and impacts (Archer et al., 2014). Ways to foster adequate enabling conditions for adaptation are well-documented (Masson-Delmotte and Waterfield, 2018 Ch.4). These often include integrated planning, multi-agency working and multi-scale and sector action. Existing techniques can be shared as well as new innovations taken-up (Maxwell et al., 2018).

Adaptation in urban areas and settlements can be *incremental* (when it addresses the causes of problems but without fundamentally changing the social and political structures that drive it, for example through planning or new regulations), *reformist* (when it changes the features that cause problems but without fundamentally changing the structures), or *transformative* (when it addresses fundamental systems attributes and outcomes such as reducing inequality, in political and socio-economic structures or enhancing wellbeing (Mendizabal et al., 2018; Rosenzweig and Solecki, 2018) which change the situation completely) (Heikkinen, Ylä-Anttila and Juhola, 2019; Roberts and Pelling, 2020; O'Brien, Selboe and Hayward, 2018). In the context of the Sustainable Development Goals mission to leave-no-one behind, transformative adaptation addresses fundamental systems' functions to enable enhanced social justice and socio-ecological wellbeing. Incremental adaptation actions seeks to maintain the essence and integrity of a system or process at a given scale (see glossary). Adaptation that seeks only to defend existing development status will not contribute to enhanced wellbeing and is not transformative, even if fundamental infrastructure engineering or legislative systems are changed to maintain the status quo in the face of increasing risk (Mendizabal et al., 2018).

City populations, and non-state actors together with local and regional governments can play an essential role in creating enabling conditions for action, including for example civil society mobilizing concerns of marginalized voices and future generations- as indicated in the worldwide student mobilizations against climate change (Wood, 2019; Maor, Tosun and Jordan, 2017; Cloutier, Papin and Bizier, 2018; Prendergast et al., 2021), which may then be prioritised by local and regional governments. National governments also play a crucial role for example in facilitating resources and finance for urban adaptation actions, alongside financial organizations and the business sector (see 6.4.5). The section starts assessing adaptation experiences in cities, settlements, and infrastructures since the AR5, before reviewing evidence of how to foster enabling conditions for adaptation through institutionalization, governance capacity, finance, evaluation, and social learning.

6.4.1 Adaptation Experiences in Cities, Settlements and Infrastructures

Since AR5, there is increasing evidence that successful adaptation to climate change is context-specific and responsive to the particular needs of urban locations. This section assesses the contributions of key urban actors – local government, civil society and the local private sector – in enabling adaptation. Wider influences from national government cross-cut this and discussed on international agencies, including through finance is assessed in Section 6.4.5.

The literature on the governance of adaptation has grown since the AR5, though with few cases from cities and settlements in the Middle East, North Africa, Central Asia, and former USSR countries. Potential reasons for the continued lack of studies in these areas include the centralized character of decision-making systems in countries in these regions and the early stage of adaptation planning in these urban areas (Clar, 2019; Mitchell and Laycock, 2019; Olazabal et al., 2019a).

Flexible institutions that allow for both top-down and bottom-up action can bring capacities together from across levels of government and actors within a settlement (Sharifi and Yamagata, 2017). Predominant planning and capacity-building strategies, however, lack the flexibility to address the needs of a rapidly changing environment (Carter et al., 2015; Dhar and Khirfan, 2017b; Juhola, 2016). Efforts to adapt to new challenges may have to speed up. This is especially in urban areas and settlements with lower levels of development and experiencing rapid urbanization, growing inequality and exposure to multiple hazards (Dulal, 2019; Grafakos et al., 2019; Solecki et al., 2018). Even within cities that share similar characteristics there are considerable differences in the level of investment in adaptation (Georgeson et al., 2016). There is also a danger that uncoordinated actions for climate change mitigation and adaptation may constrain future adaptation opportunities or create maladaptation (Juhola et al., 2016). The evidence emerging since the AR5 suggests that institutional change can be accelerated by closer collaboration between the diverse actors and deployment of the diverse approaches that can deliver adaptation.

6.4.1.1 Experiences of adaptation action in sub-national governments

The assessment of cases of local adaptation demonstrates that most urban adaptation is led by local governments (although the local government is also a heterogeneous category and local governance arrangements may vary across administrative and political contexts) (*high confidence*) (Amundsen et al., 2018; Lesnikowski et al., 2021). Local government reform at different levels can improve local adaptation, whether this is by strengthening specific teams or building cross-departmental linkages (*high confidence*) (Paterson et al., 2017; Shi, 2019; Wamsler and Raggers, 2018). Adaptation success often depends on having political champions driving the adaptation agenda alongside measures such as access to a knowledge base, resources at hand, political stability, and the presence of dense social networks that can be supported through local government reform (Pasquini et al., 2015). Aligning adaptation objectives with other potential benefits of sustainable development also supports adaptation. Specifically, policies and plans that link adaptation to the objectives of Agenda 2030 supports action at the local level (UN-Habitat, 2016b). Showing the economic benefits of adaptation is a strategy for local institutions to gain support for adaptation action. For example, local governments in Surat, Indore, and Bhubaneswar in India linked adaptation to local development needs in experiments that facilitated accessing human and finance resources, at the local, national and international levels (Chu, 2016b). However, linking adaptation to co-benefits may also divide efforts and reduce the effectiveness of adaptation actions. For example, urban land use planning and management in Ambo town, Ethiopia resulted in the implementation of urban greening projects, but these projects did not directly address the climate-related disaster risks affecting the settlement, including urban flooding, water stress, and water shortages, increased urban heat, wind and dust storms (Ogato et al., 2017).

Multi-level governance measures that support local governments can foster robust adaptation approaches and address risks and vulnerabilities across scales (*high confidence*) (Westman, Broto and Huang, 2019; Hardoy et al., 2014; Romero-Lankao and Hardoy, 2015). Effective action by local government requires national government's support (*medium confidence*). For example, Araos et al (2017) documents the case of Dhaka, Bangladesh where a national plan prioritizes measures for protecting coasts and agricultural production. In this context, the local government has minimal access to human and financial resources. Without national support, the local government struggles to coordinate action amongst different stakeholders. National urban adaptation directives can influence municipal governments' action and planning but evidence suggests that national policy alone is not sufficient to deliver action on the ground without understanding local conditions (*high confidence)* (Archer et al., 2014; Lehmann et al., 2015).

There are barriers for municipal adaptation plans to deliver effective adaptation outcomes and implemented actions often diverge from plans (see 6.4.6). For example, a comparison of adaptation plans and budget expenditures of six metropolitan cities in South Korea between 2012–2016 showed that the implementation of adaptation programs diverged substantially from the original plans, both in terms of total spending and sector-specific spending (Lee and Kim, 2018). Often, a focus on institutional change and reform limits attention to more practical aspects of adaptation that improve communities' resilience (Castán Broto and Westman, 2020). Adaptation actions, even where financed effectively, do not always deliver positive outcomes (*high confidence*) (Reckien et al., 2015; Woodruff and Stults, 2016; Uittenbroek, 2016; Aguiar et al., 2018; Reckien et al., 2018a; Olazabal et al., 2019b; Campello Torres et al., 2021) (see also 6.4.7).

6.4.1.2 The role of non-state actors in local adaptation

There are multiple actors, other than local governments that can deliver adaptation action including businesses, not for profit organizations and trade unions (*high confidence)* (Giordano et al., 2020; Eakin et al., 2021). Empirical evidence since the AR5 highlights the role of communities, universities, the private sector, and transnational networks in adaptation (Hunter et al., 2020; Bäckstrand et al., 2017). Non-state actors are particularly important in enabling adaptation by linking government agencies with low-income and marginalised communities including those living in informal settlements (Kuyper, Linnér and Schroeder, 2018; Khosla and Bhardwaj, 2019).

Since AR5 civil society and private actors have emerged as core knowledge holders and drivers of experimentation, even succeeding in changing public policy in the process (Klein, Juhola and Landauer, 2017; McKnight and Linnenluecke, 2016; Mees, 2017). Previous IPCC Assessment Reports noted that civil society actors enable local risk awareness, sensitization, adaptive capacity and generate locally-based innovation (e.g., through community-based adaptation programs).

Community-based adaptation includes a range of initiatives that put communities at the centre of planning for adaptation, often led by communities themselves (Reid, 2016). Community-based adaptation is a comprehensive and effective strategy to deliver resilience at a human scale (Trogal et al., 2018; Greenwalt et al., 2020). Many community-based responses to climate impacts represent coping strategies developed within households with a small effect on adaptation capacities beyond incremental improvements. Residents adopt private coping strategies to reduce exposure to and the impacts of heat, floods, flash floods, landslides, storms, and diseases on their lives (Hambati and Yengoh, 2018). These coping strategies include the construction of physical protection against flooding, through reforestation, the construction of terraces, flood diversion measures, and interventions to protect houses (such as raised doorsteps or use of sandbags and adoption of building techniques for making homes resilient to storms and landslides), ventilation of houses, urban agriculture, and redefinition of daily practices and livelihoods (Navarro et al., 2020; Malabayabas and Baconguis, 2017; Apreda, 2016; de Andrade and Szlafsztein, 2020; Sahay, 2018; Bausch, Eakin and Lerner, 2018).

Individual coping strategies are generally ineffective in reducing extreme risks and they rarely address the underlying structural causes of vulnerability (*high confidence*) (Sahay, 2018; Rözer et al., 2016; Jay et al., 2021). Expending resources on private coping strategies in some cases may divert resources and capacity for wider community adaptation efforts (de Andrade and Szlafsztein, 2020). However, individual coping strategies can provide foundations for the implementation of collaborative action in communities building on people's experiences, in ways which may have a longer-term, durable impact on developing resilience (*high confidence*) (McEwen et al., 2018). Community-based adaptation can be effective at different scales, whether this is to manage transboundary issues (Limthongsakul, Nitivattananon and Arifwidodo, 2017), support the replication of local solutions (Danière et al., 2016), increase the uptake of adaptation measures (Liang et al., 2017), or inform the design of more effective policies for resilience (Berquist, Daniere and Drummond, 2015; Odemerho, 2015). Community action may be mediated by NGOs or third sector organizations who play a coordinating or enabling role, particularly where other local government mechanisms are absent.

6.4.1.3 The role of the private sector in local adaptation

There is weak evidence of private sector involvement in urban adaptation (Pauw, 2015; Heurkens, 2016). The absence of private sector investment in adaptation is particularly visible in rapidly urbanizing countries (Nagendra et al., 2018). Business continuity describing private sector preparedness notes firms underestimate the impacts of climate risks on their business models (Goldstein et al., 2019; Forino and von Meding, 2021; Korber and McNaughton, 2017; Crick et al., 2018b). There is little research on how businesses can play a leading role in urban adaptation (Klein et al., 2018). A global assessment of the private sector's role in urban adaptation using data from 402 cities shows that most adaptation projects focus on the public sector and do not address private sector concerns or local people's participation (Klein et al., 2018). Recorded private sector action is recognized through partnerships and participation (Peterson and Hughes, 2017; Hughes and Peterson, 2018). There are a few examples of studies of private sector-led adaptation action which adopts a national focus (Crick et al., 2018a; Crick et al., 2018b). This lack of evidence contrasts with a well-developed body of literature on private sector-led mitigation (Averchenkova et al., 2016).

Businesses have an essential role in urban adaptation actions, through the collective formulation of adaptation strategies, through the provision of critical adaptive interventions, and through collaboration in partnerships. Businesses in the property sector, such as real estate developers, are on the frontline of climate change impacts but display differing attitudes towards climate adaptation. A study of property businesses in cities in Australia (Taylor et al., 2012) showed that speeding up planning approval processes facilitated adaptation actions, and joint private-public decision making was the preferred mode of governance for responding to climate concerns. Property businesses in cities in Sweden had a limited and reactive engagement in climate issues and resisted regulation (Storbjörk et al, 2018). Corporate, private sector interventions in urban risk reduction more broadly remain limited with a mix of public and private responsibility for planning, implementing, and maintaining adaptations in the built environment and yet, limited engagement of private sector actors in providing healthcare measures for heat prevention (medium confidence) (Mees, 2017).

There is little published literature documenting the heterogeneity of business and the private sector's responses to climate impacts (Linnenluecke, Birt and Griffiths, 2015; Doh, Tashman and Benischke, 2019). Firms have varying abilities to introduce climate adaptation measures related to staff availability, levels of awareness, perceptions of responsibility, and duration of contracts (short-term projects implies less interest in adaptation outcomes) (Shearer et al., 2016). The impact of COVID-19 has serious but uncertain implications for both access to finances for sustainable development by low and middle income countries and sub-national governments, and the possibility of stimulating mal-adaptive infrastructure and policy responses (OECD, 2020; Sovacool, Del Rio and Griffiths, 2020). The response of businesses to disasters influences the resilience in the communities in which they operate (McKnight and Linnenluecke, 2016; Linnenluecke and McKnight, 2017). However, at the same time there is a growing literature that warns against the conflict interests that businesses may have in their adaptation strategies. For example, real estate responses to flooding have led to processes of climate gentrification, whereby lower income populations are displaced towards higher risk areas which stablishes racialized and class-based patterns of inequality of exposure to risk, with hard evidence rapidly growing specially in US cities (Keenan, Hill and Gumber, 2018a; Shokry, Connolly and Anguelovski, 2020; De Koning and Filatova, 2020; Aune, Gesch and Smith, 2020). Private-sector participation in adaptation solutions depend on having mechanisms to enable transparency and open reporting on the nature of support and the solutions proposed. For example, businesses adopting 'community-centric' disaster management strategies can assist local recovery efforts by protecting employment, provision of emergency supplies, and participation in reparations (McKnight and Linnenluecke, 2016). Private sector actors engaged in community climate responses can play a role in funding and managing programs that address public health and education concerns. The potential of ecopreneurship, social enterprises, cooperatives and other sustainability-oriented business models (Schaltegger, Hansen and Lüdeke-Freund, 2016; Lopes et al., 2020; Battaglia, Gragnani and Annesi, 2020) for urban adaptation remains under-explored in the literature on urban climate governance.

The private sector also constitutes a key stakeholder group involved in collaborative processes to develop adaptation strategies. The inclusion of private sector actors in deliberative policy-making processes in urban adaptation can lead to higher procedural legitimacy levels, as witnessed in Rotterdam's case (Mees, Driessen and Runhaar, 2014). Rotterdam has created an institutional environment that favours eco-innovation (Huang-Lachmann and Lovett, 2016). The municipal government works directly with the private sector to enhance protection against flooding constructing a marketing strategy around a 'floating city' concept. A 'floating housing' market has expanded, with benefits for the local real estate and construction industries and knowledge-exporting businesses that provide consultation expertise, delta technologies, and architectural models. Nevertheless, these new trends raise new governance challenges to deliver adaptation.

There are obstacles associated with reconciling private sector interests with public priorities and justice agendas in local climate programs. The involvement of the private sector in adaptation actions may lead to the appropriation of land and natural resources, and to the exclusion of vulnerable populations (Anguelovski et al., 2016; Rumbach, 2017; Scoppetta, 2016) (see also section 6.4.4.2). Navigating the inclusion of businesses in urban planning processes requires local authorities to engage in ongoing negotiations, to reflect on constantly shifting power balances, and to move delicately between the role of regulator and facilitator in the process of defining and maintaining long-term objectives (Storbjörk, Hjerpe and Glaas, 2019b; Storbjörk, Hjerpe and Glaas, 2019a).

6.4.1.4 Partnerships for adaptation

Multi-level governance remains an influential paradigm that recognizes government institutions' influence at different scales and the diversification of actors intervening in public issues from the private sector and civil society (robust evidence, high agreement). Establishing linkages between multiple organizations can help deliver coordinated action. Multi-level governance includes mechanisms for multiple actors to engage in local adaptation strategies through collaborative processes of planning, learning, experimentation, capacity building, construction of coalitions, and communication channel (Barton, 2013; Jaglin, 2013; Reed et al., 2015; Restemeyer, van den Brink and Woltjer, 2017; Melica et al., 2018). Many of these studies directly focus on institutional arrangements that facilitate interaction between communities and civil society, experts, government representatives, firms, and international organizations. Box 6.5 demonstrates the decisive role that community activists can play in building resilience over long periods.

Institutional fragmentation reduces the capacity to deliver adaptation (Den Uyl and Russel, 2018) Multi-level governance shows a commitment to tackling fragmented and complex policy issues through collaboration between national governments and non-state actors, as explained in the 2030 Development Agenda, especially SDG17 ("Revitalize the global partnership for sustainable development"). Multi-level governance is particularly important to deliver adaptation at the metropolitan scale, that require coordinating actions across different institutions in inter-municipal institutions (Lundqvist, 2016). Gaps in knowledge remain regarding the effectiveness of multi-level governance actions in different contexts and the extent to which multi-level governance strategies transfer the brunt of responsibility for adaptation action to less-resourced local governments (Hale et al., 2021).

Public-private partnerships are increasingly relevant for collaborative development of urban adaptation (Klein et al., 2018). Partnerships can deliver infrastructure, coordinate policy, and support learning. The main limitation of partnerships is scale, as partnership action is usually limited to discrete projects or objectives. Partnerships tend to be linked to reactive (rather than proactive) adaptation projects and the deviation of objectives away from adaptation concerns (Harman, Taylor and Lane, 2015). Partnerships can support capacity building in public and private organizations and facilitate networking efforts that extend beyond the private sector to communities and NGOs (Bauer and Steurer, 2014; Castán Broto et al., 2015b). Public actors can benefit from the private sector's innovation and implementation capacity, and businesses can de-risk investments. Still, partnerships can also strengthen the ideologies of growth and managerialism within the operations of the local government (Taylor et al., 2012). Reconciling divergent norms and routines within public and private organizations remains one of the challenges to establishing successful public-private partnerships for adaptation (Lund, 2018). Administrative and political culture influences the nature of interactions between public and private sector actors in urban adaptation agendas (Bauer and Steurer, 2014) with negative consequences such as the imposition of vertical chains of commands on horizontal collaborations, and the need to formalize contractual relations (Klein and Juhola, 2018).

Local authorities are an important enabling actor that can guide the private sector and communities to take responsibility for creating policy and regulatory environments that encourage private sector participation aligned with the Sustainable Development Goals' equity and ecological sustainability principles (*high confidence*). For example Frantzeskaki et al (2014) report a port relocation project in the Netherlands where sustainability principles drove private sector participation. Klein et al (2017) cite examples from two cities - Helsinki and Copenhagen - where local authorities have shifted adaptation responsibilities to private actors through regulation and public problem ownership. In Mombasa, private companies provide green infrastructure to match local government requirements, in what has frequently been cited as an example of nature-based solutions (Kithiia and Dowling, 2010; Kitha and Lyth, 2011).

[START BOX 6.5 HERE]

Box 6.5: Building Water Resilience in Urban Areas through Community Action and Activism

In Bengaluru, India, communities have traditionally managed a network of water tanks of immense ecological importance. However, in the last half-century, urban development has increasingly threatened this blue network (Unnikrishnan and Nagendra, 2015). Today's Bengaluru depends on long-distance water transfers that create political conflict and a dense network of private boreholes that are depleting the city's water resources. The restoration of the existing community-managed water tanks network offers a more sustainable and socially just alternative for managing water resources.

Unnikrishnan et al (2018) have documented how the colonial and postcolonial history of water management in Bengaluru shapes the water infrastructure and provision systems today. Water access inequalities can be traced to the patterns of spatial development developed by colonial policies. Records from the 6th century onwards show how city rulers invested in an interconnected, community-managed network of tanks and open wells, regularly recharged through harvested rainwater. The water system was changed at the end of the 18th century, as first the colonial state, then the post-independence government of Karnataka took responsibility for water management. Ideas of modernist planning influenced the development of new water infrastructure and piped networks, including the first piped infrastructure, bringing water from sources 30km away, including the Hesaraghatta and then the TG Halli reservoirs. The old network of tanks gradually deteriorated as tanks became disused, polluted, or built over. More prolonged and costly water transfers took place in the post-colonial period, delivering water from the Cauvery river in a massive engineering project with a high energetic cost and enmeshed in inter-state conflicts over water use (Castán Broto and Sudhira, 2019). Scarcity is still a problem in Bengaluru. The citizen response has been an activist movement to reclaim the city's tanks, accompanied by a plea to reconsider current water uses within the city, including actions to protect and rejuvenate water wells (Nagendra, 2016). Unnikrishnan et al (2018) document different actions led by citizen-led collectives, including projects for lake rejuvenation, filtering technologies to treat sewage, recovering the value of lakes through a share of photos and art projects, and involvement of local knowledge in-tank restoration. Those efforts suggest an untapped potential to deliver adaptive green spaces through the recovery of Bengaluru's tanks.

[END BOX 6.5 HERE].

6.4.1.5 Trans-national municipal networks

Since the late 1990s, transnational municipal networks (TMNs) have increased awareness of climate change and served as a bridge for cities to access critical financial resources from private and philanthropic sources (Rashidi and Patt, 2018; Fünfgeld, 2015). Recently, transnational municipal networks have taken on more programmatic functions, working with cities to strategize, plan, and incrementally improve their organization functions in the face of climate change. For example, the Rockefeller Foundation's 100 Resilient Cities program (2014-2019) provided a two-year salary for a Chief Resilience Officer (CRO) to be situated in a municipal authority to bridge silos, incentivize change, and develop development strategies for resilience (Bellinson and Chu, 2019; Spaans and Waterhout, 2017). In these cases, external actors have enabled broad organization change, resource mobilization pathways, and alternative forms of agenda-setting in cities (Chu, 2018a; Hakelberg, 2014) (see also case study 6.2, Semarang).

A range of transnational municipal networks (TMNs) also support and encourage cities and settlements to plan and implement adaptation actions. ICLEI-Local Governments for Sustainability has developed protocols and implemented projects for member cities. The C40 Climate Leadership Group has facilitated the coordination of both local governments and business actors at a global scale (Gordon, 2020). Policy coordination has been central to the signatories of the Covenant of Mayors (Domorenok et al., 2020). Such networks can encourage: the sharing of information about appropriate practices between urban areas; contribute to goal-setting; support experimentation and development of new policy instruments; enhance stakeholder engagement; institutionalize climate agendas; and encourage policy integration across governance levels and sectors (Bellinson and Chu, 2019; Busch, Bendlin and Fenton, 2018; Fünfgeld, 2015; Busch, 2015; Papin, 2019; Rashidi and Patt, 2018). However, participation in TMNs is biased towards cities in the global North (Bansard, Pattberg and Widerberg, 2017; Haupt and Coppola, 2019). A recent comparative study of 337 cities found out that cities that participation in TNMs are more likely to take adaptation action and that being part of multiple networks leads to higher levels of adaptation planning (Heikkinen et al., 2020).

6.4.2 Institutional change to Deliver Adaptation in Cities, Settlements, and Infrastructure

The main barriers to urban climate adaptation, and strategies to address them, relate to institutional change (*high confidence*) (see Table 6.7). Institutions include legislative and policy frameworks and guidelines intended to direct the action of government, civil society and private sector organisations and extend into informal and customary practices that shape individual behaviour. Many of the barriers that inhibit institutions acting in ways that can support action for inclusive and sustainable adaptation have historical roots, grounded in complex political and social relations and can be reinforcing (Table 6.7). Overcoming these barriers requires coordinating the activities of multiple actors who can facilitate institutional and political change (Eisenack et al., 2014).

Table 6.7 Barriers to climate adaptation

Examples of barriers to climate adaptation	Institutional changes to overcome those barriers	Examples	Evidence
Lack of financial resources	Strategic combination of municipal, regional and national level funds Access to multiple financing mechanisms	In European countries, large cities tend to fund their own adaptation, while smaller settlements depend on regional or national funding	(Aguiar et al., 2018) (Moser et al., 2019)
Lack of human resources and capacities	Development of formal and informal partnerships, cooperative agreements and inter-agency arrangements	International cooperation programmes for adaptation in urban areas in the Global South are most likely to succeed if they can align their objectives with local priorities and capacities	(UN-Habitat, 2016b)
Political commitment and willingness to act	Use of policy windows and extreme events to generate interest and create lasting responses	In Germany, responses to flooding were strongly shaped by public perceptions of safety during the electoral cycle, leading to inadequate responses	(Gawel et al., 2018; Di Giulio et al., 2018)
Uncertainty about future impacts and dynamic interactions	Develop institutional arrangements that acknowledge and reduce uncertainty Facilitate the development of bottom-up initiatives that relate directly to the context of action	Power plant operators and the federal state of Baden-Württemberg negotiated the minimum power plant concept (“Mindestkraftwerkskonzept”, MPP), a contract to establish more predictable and workable procedures for curtailment in the event of severe heat waves	(Eisenack, 2016) (Thaler et al., 2019)
Institutional fragmentation and unclear responsibilities	Evaluation of existing institutions to diagnose miscoordination Creation of policy networks that address emerging interdependences	In settlements in Languedoc, France, decentralisation adds complexity to the ongoing challenges of population growth and climate change	(Therville et al., 2019)
Legal issues and regulations	Address the legal hurdles to create frameworks that allow for experimental action	Policy makers in the San Francisco Bay Area, US reported that minor changes could have a definitive influence in delivering regulatory changes to support adaptation action In The Netherlands, a lack of climate change adaptation policy for cultural heritage hamper adaptation of cultural heritage to current and projected climate risks	(Ekstrom and Moser, 2014) (Fatorić and Biesbroek, 2020)
Competition of adaptation with other policy agendas and polarisation	Prioritization and development of synergies across sectors Mainstreaming adaptation into other sectors	In European cities, for example, urban planning is strongly correlated with water management strategies	(Aguiar et al., 2018) (Sieber, Biesbroek and de Block, 2018)
Lack of data, knowledge generation capacity, and knowledge exchange	Mobilise multiple strategies for the use of climate information in local decision-making	In Scotland, Hungary and Portugal local decision makers use HECC scenarios, but most often as background data	(Lourenço et al., 2019) (Herrmann and Guenther, 2017)

	Involve a wide range of stakeholders- with different values and knowledge- in decision making	Sharing knowledge alongside the supply chain favours adaptation for both multinationals and SMEs	(Gotgelf, Roggero and Eisenack, 2020) (Wamsler, 2017)

Institutional change, is needed to open new options for inclusive and sustainable adaptation and to integrate adaptation and mitigation (*robust evidence, high agreement*) (see also Section 6.3.5).

Institutional change refers to processes that aim to shift existing norms and practices within organizations to deliver more effective action for adaptation. Institutional change at the local level can be achieved with diverse strategies (Patterson, de Voogt and Sapiains, 2019). Table 6.7 illustrates various instruments that enable the institutionalisation of climate adaptation concerns into policy and planning. As Table 6.7 shows, institutional change is often used as synonymous with mainstreaming. Both terms refer to the integration of climate adaptation concerns into other areas of work and as part of practical routines and arguments (Chu, Anguelovski and Carmin, 2016; Storbjörk and Uggla, 2015; Runhaar et al., 2018; Uittenbroek et al., 2014). Early assessments understood mainstreaming as activities that integrate climate adaptation into long-range and sectoral plans (Anguelovski and Carmin, 2011; Aylett, 2015). Since then, efforts to mainstream climate adaptation have grown into agendas around the community and economic development (Ayers et al., 2014), climate mitigation (Göpfert, Wamsler and Lang, 2019), spatial and infrastructure planning (Anguelovski, Chu and Carmin, 2014), urban finance (Musah-Surugu et al., 2018; Keenan, Chu and Peterson, 2019), public health (Araos et al., 2015), environmental management (Wamsler, 2015; Kabisch et al., 2016), and multi-level decision-making (Ojea, 2015; Visseren-Hamakers, 2015). Such efforts require various degrees of regulatory or programmatic action to integrate adaptation with other concerns (Wamsler and Pauleit, 2016). However, institutional change has a broader remit than mainstreaming adaptation, as it may include, for example, changing the organizations already dealing with climate adaptation and make them more effective including changes in inputs, procedures, and options (Patterson, de Voogt and Sapiains, 2019).

6.4.2.1 Input-driven institutional change

Input-driven institutional change creates incentives to deliver adaptation action. An input view focuses on the intrinsic capacities of a given organization. Input indicators are often referred to as political capital (Rosenzweig and Solecki, 2018; Diederichs and Roberts, 2016), existing or endogenous resources (Moloney and Fünfgeld, 2015; Wamsler and Brink, 2014), or local drivers for adaptation (Dilling et al., 2017). Research conducted across two municipalities in Western Cape, South Africa, showed the importance of a dedicated environmental champion, access to a knowledge base, the availability of resources, political stability, and the presence of dense social networks (Pasquini et al., 2015). Research from In São Paulo, Brazil, showed how intrinsic political capacities and contextual factors – such as the political ideology of elected officials –shaped opportunities for embedding adaptation into ongoing urban agendas (Di Giulio et al., 2018).

Networks, interactions, and actor coalitions shape options for institutional change. Aylett (2015) noted the importance of internal networks between municipal departments, including informal communication channels, cultivating personal contacts and trust between the person or team responsible for climate planning and staff within other local government agencies. Internal networks can facilitate the commitment of local elected officials (Hughes, 2015), support higher municipal expenditures per capita, and foster perceptions that climate adaptation is needed (Shi, Chu and Debats, 2015). Collective decision making can integrate multiple types of information with moral concerns and provide key rationales that enable adaptation action (Carlson and McCormick, 2015). In urban areas in Africa, research on internal networks has also investigated how informal arrangements shape action possibilities (Satterthwaite et al., 2020). For example, in Zimbabwe, informal, traditional, and civil society institutions are core arenas for issue discussion due to lower public sector capacities (Mubaya and Mafongoya, 2017). In Durban, South Africa, local governments rely considerably on shadow systems and informal spaces of information and knowledge exchange across their operations to introduce and sustain new ideas (Leck and Roberts, 2015). In the Metropolitan Area of Styria, Austria, informal cooperation has supported the development of rural-urban partnerships for the formulation of common goals (Oedl-Wieser et al., 2020). In Arkansas, US, informal governance structures support planning to manage wildfires (Miller, Vos and Lindquist, 2017).

Cities can leverage input driven institutional change even without national support for climate change adaptation or mitigation. For example, where cities have defined policy making and budget raising powers, city level political leadership can support adaptation action going beyond national policy (Hamin, Gurran and Emlinger, 2014; Shi, Chu and Debats, 2015; Carlson and McCormick, 2015). Examples include the Surat Climate Change Trust in Surat, India (Chu, 2016a) and Initiative for Urban Climate Change and Environment in Semarang, Indonesia (Taylor and Lassa, 2015). In Saint Louis, Senegal, support from national and state-level actors enabled local institutional change (Vedeld et al., 2016). Processual levers may be also mobilized in situations of political instability (which disrupts patterns in champions and networks), clientelism (which can cause environmental projects to be discontinued) (Pasquini et al., 2015), or in contexts where there are high political and socioeconomic inequalities (Harris, Chu and Ziervogel, 2018; Chu, Anguelovski and Carmin, 2016).

6.4.2.2 Output-driven institutional change

Output-driven institutional change is shaped by organisational products such as strategies, plans, policies, and evaluative metrics (Patterson and Huitema, 2019; Bellinson and Chu, 2019) (See table 6.8). There are numerous examples of institutional change through planning outcomes. For example, Manizales, Colombia has included climate adaptation into long-established environmental policy (Biomanizales) and a local environmental action plan (Bioplan), which follows on from a long coherent trajectory of climate change policy (Hardoy and Velásquez Barrero, 2014). A significant number of North American cities have integrated adaptation into long-range plans, while fewer cities integrate adaptation in sustainable development plans or sectoral plans (Aylett, 2015). Canadian cities are more likely to have a plan specifically focused on adaptation than having adaptation integrated into municipal long-range planning (Aylett, 2015). In the European Union, adaptation plans depended on national climate legislation or, in fewer cases, the influence of an international climate network (Reckien et al., 2018b). A comparative report from the Covenant of Mayors, however, suggests that the adaptation pillar needs development to demonstrate the effectiveness of adaptation responses and their integration with mitigation goals (Bertoldi et al., 2020). Municipalities in Sweden have been called ‘pre-reactive’ because adequate strategic guidelines are in place to frame the accessibility, aesthetics, and adaptability of waterfront developments (Storbjörk and Uggla, 2015). Some Asian cities also report high output effectiveness, where they are more likely to indicate senior local government officials' performance management contracts, the budgeting procedures of local government agencies, and the procedures that local government agencies use for budgeting infrastructure spending (Aylett, 2015). Despite this evidence, there is a gap in understanding the general trends of planning and institutional change in Africa, Asia, East Europe and the Middle East.

Table 6.8 Examples of institutional and policy instruments to enable adaptation

Objective	Type of instrument	Description	Examples	Assessment
Policy	Information Instruments	A diverse range of activities such as training, research and development, awareness campaigns to produce and share information	Urban-LEDS II Capacity Building Workshop for cities in Laos arranged for local government by ICLEI Southeast Asia Secretariat and UN-Habitat (UN-Habitat, 2019)	Information instruments tend to be low-cost and low-risk options, but their impact is unpredictable and the effects may be uneven (Henstra, 2016). In the example of the workshops in Laos (UN-Habitat, 2019), the result was to map vulnerable sectors and build capacity for mainstreaming
	Voluntary Instruments	Practices such as codes, labeling, management standards or audits, voluntarily, that can	PUB, Singapore's National Water Agency's Voluntary Water Efficiency Labelling Scheme (Voluntary WELS)	A problem with voluntary instruments is that implementation varies. Uptake is likely to be more common among organizations self-identifying as ‘champions’ and less effective among other actors to

		provide incentives for adaptation	(Tortajada and Joshi, 2013)	bring about far-reaching change (Haug et al., 2010)
	Economic Instruments	Taxes or subsidies can be used to promote adaptive activities	US Office for Coastal Management NOAA Coastal Resilience Grants Program (NOAA, 2019)	Economic incentives can be effective as they "engage local stakeholders and provide price signals that stimulate individual adaptation" (Filatova, 2014). However, uptake of incentives may be low (Sadink, 2013; Henstra, 2016) and resource intensiveness and potential regressive effects (equity impacts) must be considered (Henstra, 2016).
	Regulatory Instruments	These include a range of mandatory requirements through controls, bans, quotas, licensing, standards often applied when a specific outcome is required	Building codes to enhance structural stability for storm resilience in Moore, Oklahoma (US) (Ramseyer, Holliday and Floyd, 2016)	Regulatory instruments can be effective in changing and institutionalizing adaptation behaviours (Nilsson, Gerger Swartling and Eckerberg, 2012; Henstra, 2016), but outcomes depend on the strength of implementation (e.g. monitoring, transparency, mechanisms for accountability)
Process	Visioning	Events that bring together different stakeholders to produce a city vision	Rotterdam Resilient City participatory processes to create resilience strategies (Resilient Rotterdam, 2016)	There may be challenges in translating complex climate science into understandable and meaningful forms (Sheppard et al., 2011) and creating inclusive processes that allow for co-creation of visions, for example, by involving new digital platforms (Baibarac and Petrescu, 2019)
	Baseline studies	Focus on understanding the current conditions in a neighbourhood or city from an interdisciplinary perspective	*Flood Risks, Climate Change Impacts and Adaptation Benefits in Mumbai,* an OECD assessment study (Hallegatte, Ranger and Bhattacharya, 2010)	Baseline studies can be mobilized to track the progress of adaptation actions in multiple sectors over time. In the example of the study in Mumbai (Hallegatte, Ranger and Bhattacharya, 2010), the analysis includes different climate scenarios and quantification of how adaptation could reduce economic loss
	Development priorities	Specific methods to ensure an open definition of multiple priorities and contrasting values that will inform the planning process	Participatory housing upgrading through the Baan Mankong Program in Bangkok (Thailand) (Berquist, Daniere and Drummond, 2015)	Participatory planning can help navigate which action to take to build resilience and, at the same time address prioritized social concerns (Cloutier et al., 2015). As with all participatory processes, issues of recognition, access/inclusion, and potential capture of the process by actors in power must be considered
Planning	Profiles	Develop a common understanding of how different sectors interact with adaptation and the governance capacity	New York City Panel on Climate Change 2019 Report (Nycpcc, 2019)	As with baseline studies, the development of profiles can inform plans for adaptation action, which considers social priorities and synergies across various sectors. Multiple forms of knowledge should be considered in the development of profiles (Codjoe, Owusu and Burkett, 2014)

	Risk assessment	This includes a range of instruments to evaluate the impact of risk	Climate risk assessment for Buenos Aires, conducted by the World Bank (Mehrota et al., 2009)	Risk assessments can be a useful starting point for adaptation. However, assessments do not directly prescribe adaptation options but must be seen as the basis for debate (Yuen, Jovicich and Preston, 2013). A common challenge is a lack of data at the city level (Maragno, Dalla Fontana and Musco, 2020; Cloutier et al., 2015)
	Impact assessment tools	Tools such as Strategic Impact Assessment or Sustainability Assessment provide a means to assess the impact of specific policies and programmes concerning adaptive capacity	Economic Impact Assessment of Climate Change in Key Sectors in Nepal (Government of Nepal, 2014)	Embedding climate risks into impact assessment tools (either mandatory or voluntary) builds resilience by integrating climate objectives into plans and specific projects (Richardson and Otero, 2012), and they are seen as a legitimate tool in many contexts (Runhaar, 2016)
	Monitoring systems and indicators	Systems to take measurements at regular intervals to specify progress against objectives and revise the planning process	Climate Change Adaptation Indicators for London (London climate change partnership, 2018)	Monitoring systems are essential to make sure that formal objectives are met. However, many urban climate adaptations do not have monitoring and evaluation components (Woodruff and Stults, 2016) and there is no standard set of indicators to monitor adaptation or resilience (Brown, Shaker and Das, 2018; Ford and Berrang-Ford, 2016)
Management	Budgets and audits	Methods for the periodic revision of adaptation plans and policies	Helsinki Metropolitan area climate change adaptation monitoring strategy (HSY, 2018)	As with monitoring, budgets and audits can be incorporated into the adaptation planning process to ensure reflexivity and accountability. Low levels of implementation and monitoring of adaptation plans suggest that the uptake may be low (although the evidence is limited)

Institutional change processes are complex, contested, and sporadic (Patterson, de Voogt and Sapiains, 2019). Such processes are often inhibited by unclear planning mandates, conflicting development priorities, lack of leadership, and resource and capacity shortfalls (Anguelovski et al 2014). There is no one size fits all approach to institutional change, which works in situ, and benefits from clearly defined plans and an incremental approach to revising new elements and addressing gaps or failures (Beunen et al, 2017). A longitudinal view of institutional change allows for assessing actors and dynamics involved in integrating adaptation into the sectoral agendas or governance arrangements mentioned above. (Patterson and Huitema, 2019).

6.4.3 Solution spaces to address the 'policy action gap'

A policy action gap arises when administrative, communication, financial and other organisational blockages and inertia interrupt implementation of policy, the intent of political leadership and delivery of adaptation interventions on the ground (Ampaire et al., 2017; Bell, 2018; Shi, 2019). Political and policy confidence are key enabling conditions for adaptation decision-making. As the AR5 already acknowledged, political inaction can arise where there is low confidence that adaptation actions can deliver a safer future for all (Chan et al., 2015a). For example, in some administrative jurisdictions (most of them local governments), calls by social movements for the adoption of Climate Emergency Declarations were addressed, however, practical outcomes in terms of adaptation have been limited, and may have foreclosed other future local actions (Nissen et al., 2020; Ruiz Campillo, Castan Broto and Westman, 2020), and raised concerns about maladaptation (Long and Rice, 2019). Political inaction for climate justice is particularly visible in contexts of informality (Ziervogel, 2020). Studies of city and local authority decision making in South America (Di Giulio et al., 2019), Asia (Araos et al., 2017) and Europe (Lesnikowski et al., 2021) indicate where there is insufficient political will (that is lack of prioritization of the issue, and inadequate allocation of resources including staffing and finance) and lack of inclusive, coordinated leadership, it can be difficult to overcome inaction, generating a policy action gap.

Multiple actors contribute to deliver climate change adaptation (Chan et al., 2015a; Bäckstrand et al., 2017). There are also multiple scales of action, from the provision of local services to large infrastructures of national or even international significance. Figure 6.5 provides an insight into the challenges that shape the policy action gap and a range of strategies that can help bridge policy action gaps. Effective adaptation governance will depend on the compound impact of the actions of multiple agents operating at different scales (*medium confidence, medium agreement*) (Di Giulio et al., 2019; Hale et al., 2021; Zwierzchowska et al., 2019).

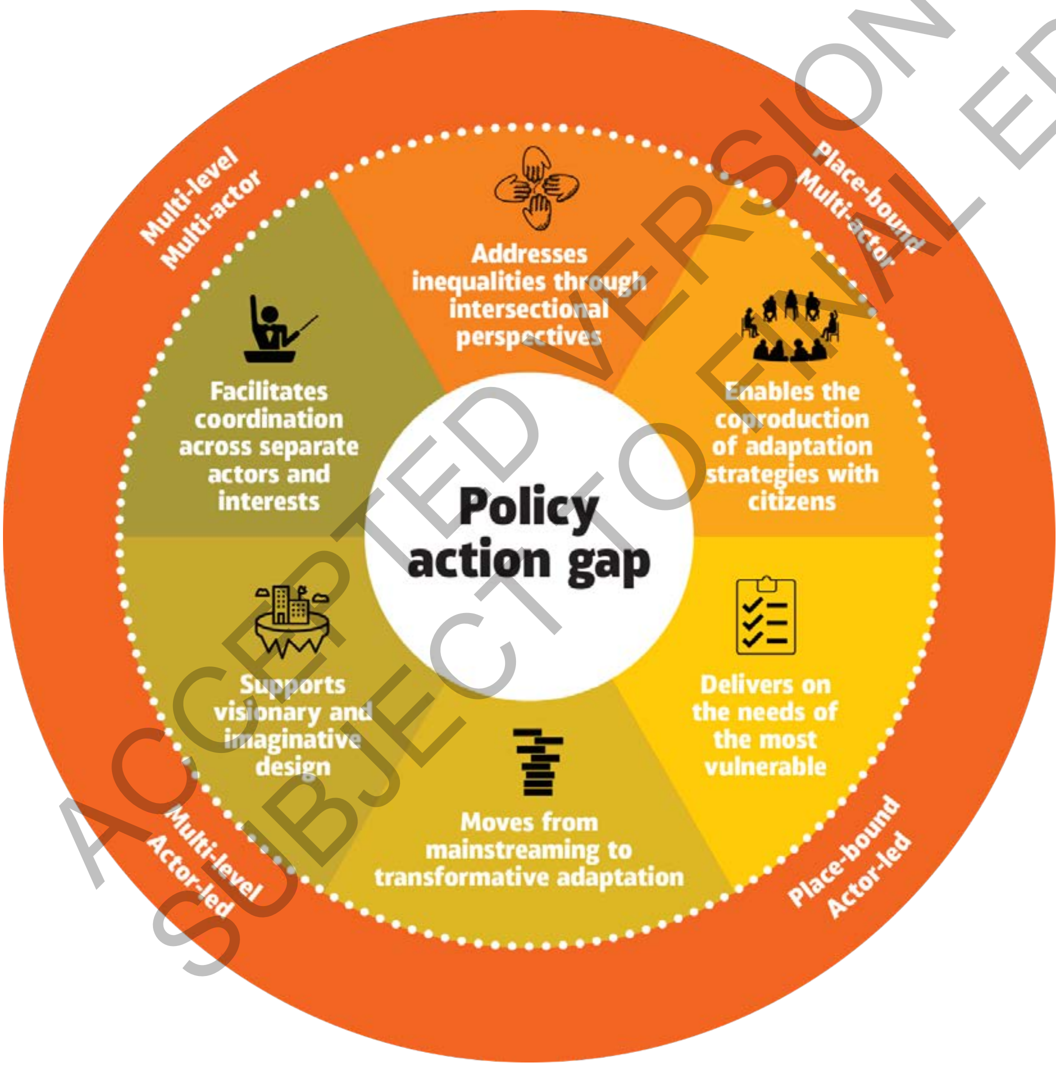


Figure 6.5 Solution spaces for the policy action gap. The categories in the outer circle represent the tension that shape the policy action gap. On the one hand, there is a tension between the need to deliver action at scale (Multi-level) and the need to mobilise the capacities in a given place (Place-bound). On the other hand, there is a tension between the need to facilitate collaborations among multiple actors (Multi-actor) and the fundamental impact that leadership can have in actor-led initiatives (Actor-led). These two tensions interact creating different possibilities for transformative adaptation. The inner ring represents different areas of intervention that configure the solution space to tackle the policy action gap, and that bridge these two tensions.

6.4.3.1 Delivers on the needs of the most vulnerable

Success in urban adaptation is most often understood as requiring measurable outcomes and evaluation (see also section 6.4.6). However, many adaptation outcomes are not measurable (*medium evidence , medium agreement*) (Béné et al., 2018). Adaptation action solely focused on action tends to ignore areas of action in the city for which there is no existing data even though they may play an essential role in shaping resilience and its limits. Informal settlements and informal economies which are integral in managing urban resources for effective climate adaptation are not routinely included in formal urban and national monitoring, including through tax receipts —are (Guibrunet and Castán Broto, 2016). The resulting understanding and monitoring of city needs, capacities and actions that feed into policy is incomplete. The innovation as well as particular concerns and capacities of the informal sector, which is often highly gendered are not always measured (Brown and McGranahan, 2016). An emphasis on measurable adaptation outcomes may lead to prioritizing techno-economic measures to adaptation at the local level. Technocratic approaches to environmental policy continue to shape local sustainability politics (Bulkeley, 2015a). The deployment of such technocratic approaches at the local scale is detrimental for democratic and collaborative practices (Metzger and Lindblad, 2020). For example, China has received praise in terms of delivering urban policies that put climate change at its core, thus suggesting its role providing leadership in climate change debates (Liu et al., 2014; Wang and He, 2015; Fu and Zhang, 2017). However, a detailed analysis of case studies of sustainable development in China's cities demonstrates that processes of planning only take into account certain groups and interests (Westman and Broto, 2018). Urban sustainability policy may, as a result, fail to deliver collaborative social and environmental objectives, and this is maladaptive in the terms of Climate Resilient Development.

6.4.3.2 Moves from mainstreaming to transformative adaptation

Two forms of mainstreaming are usually found in urban policy: incorporating climate adaptation into different sectors or incorporating climate adaptation in holistic sustainability or resilience plans, linking climate adaptation objectives with other social and development objectives (Reckien et al., 2019; Fainstein, 2018). The integration of climate adaptation in local policies in cities and settlements has often been seen as maintaining business-as-usual and not always aligned with transformative efforts to address structural drivers of vulnerability (*high confidence*). For example, mainstream actions that seek to advance other development objectives, as explained above, may reduce adaptation to 'low-hanging fruits,' which may maintain business-as-usual practices without any fundamental transformation of the social, institutional and economic systems that drive vulnerabilities (Aylett, 2014). However, as explained above, mainstreaming can also generate wider processes of institutional change (section 6.4.2). Mainstream strategies may help to demonstrate how policy and frameworks can produce practical outcomes on the ground (Biesbroek and Delaney, 2020). However, previous experiences in other sectors, such as gender mainstreaming, have shown the limitations of the mainstreaming approach, particularly in terms of addressing the structural drivers of inequality and vulnerability, and in achieving justice for those who suffer most (Moser, 2017). Local governments, in particular, can link mainstreaming efforts with specific strategies that support justice in adaptation, including redistribution efforts to address vulnerabilities (see section 6.3.2), representation in local institution and deliberative processes, and recognition of the conditions for self-realization, including personal and collective safety (Agyeman et al., 2016; Castán Broto and Westman, 2017; Castán Broto and Westman, 2019; Hess and McKane, 2021).

6.4.3.3 Facilitates coordination across separate actors and interests

Coordination of adaptation policy goals cuts across cities to integrate cities into international processes of climate policy formulation; coordination in cities produces effective collective outcomes, cementation of common standards and methodologies for climate action (e.g., emission inventories) (*high agreement, medium evidence*) (Gordon and Johnson, 2017; Hsu and Rauber, 2021). A collective global response has become a significant concern in international climate policy (Chan et al., 2015a). The UNFCCC has adopted a role as an orchestrator including providing framework for city governments (Bäckstrand and Kuyper, 2017). Within cities, coordination can arise from active programming; for example, in Rotterdam and New York City local authorities adopted long-term objectives and conditions for action, bringing together a multiplicity of actors across sectors to orient contributions, share knowledge, and coordinate actions (Hölscher et al., 2019). Where national politics is supportive, coordination between city and national government is an asset (Chan and Amling, 2019; Inch, 2019). The use of social media and digital mechanisms for coordination with public interest is ambiguous: in China, Weibo has facilitated an expansion of public engagement, although it remains top down and dominated by a few individuals (Yang and Stoddart, 2021). The pilot project #OurChangingClimate is one example of engaging youth with an understanding of their communities and their resilience or vulnerability to climate change (Napawan, Simpson and Snyder, 2017).

6.4.3.4 Enables the coproduction of adaptation strategies with citizens

Co-production can advance urban sustainability and social justice in cities and settlements to provide infrastructure adapted to the human scale, and advancing SDGs (*medium confidence*) (McGranahan, 2015; McGranahan and Mitlin, 2016; Chowdhury, Jahan and Rahman, 2017; Moretto and Ranzato, 2017; Nastiti et al., 2017). Co-production involves the active involvement of citizens and citizens' organization in iterative public service planning and delivery and has become increasingly central in climate change responses alongside other bottom-up, community-led strategies (Bremer et al., 2019; Vasconcelos, Santos and Pacheco, 2013).

Coproduction builds on public participation that brings together diverse sets of citizen interests, values, and ideas to inform change and solve problems relating to a collective adaptation challenge (Archer et al., 2014; Bisaro, Roggero and Villamayor-Tomas, 2018; Sarzynski, 2015) and is increasingly important in environmental policy more widely (McGranahan, 2015; Moretto and Ranzato, 2017). For example, in three cities across the Czech Republic, stakeholder participation exercises were used to prioritize climate change risks, provide impetus and opportunity for knowledge co-production, and support adaptation planning (Krkoška Lorencová et al., 2018). In municipalities in Malaysia, stakeholders and citizens are active in the adaptation policy cycle (Palermo and Hernandez, 2020). In Quebec, Canada, citizens collaborated with the municipal authority to bring together climate science and 'ordinary' urban management and design solutions (Cloutier et al., 2015). Service coproduction enables integrating multiple actors in the management and delivery of public services (Pestoff and Brandsen, 2013; Pestoff, Brandsen and Verschuere, 2013). Civil society-driven, co-productive approaches can pioneer new forms of institutional relations and practices filling gaps where the public sector is absent or retreating (Frantzeskaki et al., 2016).

A coproduction approach to climate change governance addresses the increasing public interest on climate change (Davies, Broto and Hügel, 2021). Youth movements such as Forum for Future have joined forces with other environmental and Indigenous organisations to lobby governments and institutions to action (Kenis, 2021; Fisher and Nasrin, 2021; Davies and Hügel, 2021; Hayward, 2021). These movements have built momentum moving local governments and other institutions to declare a climate emergency and have supported the creation of new forums where climate change can be addressed collectively, such as citizens' assemblies. In the UK, for example, initial scepticism has led to the proliferation of citizen-centric Climate Assemblies at the local level (Sandover, Moseley and Devine-Wright, 2021).

Cooperative governance models provide insights for designing forms of participatory and collaborative planning through which communities and state actors can identify concrete actions and resources to improve services and mitigate structural vulnerabilities to disasters (Castán Broto et al., 2015b). Experiences of co-production of sanitation services show how co-production may improve outcomes while at the same time opening up avenues for grassroots organizations to claim political influence (McGranahan and Mitlin, 2016). Coproduction may change institutions in response to external interventions (Das, 2016). Although there are drawbacks in terms of the extent to which coproduction can be used to legitimize unfair interventions within a given context, coproduction may also be a tool for improving the accountability of dominant groups to vulnerable sectors of the population (Nastiti et al., 2017). There are limitations to coproduction. The city of Barcelona, Spain used coproduction methodologies to develop the Barcelona Climate Plan. However, policy makers and civil servants were reluctant to use lay knowledge from participants and political deadlines constrained the time dedicated to deliberation (Satorras et al., 2020).

6.4.3.5 Addresses inequalities through intersectional perspectives

Inclusive and sustainable adaptation can address the causes of systemic vulnerability (medium evidence, high agreement). This points to the fundamental requirements of adaptation action in line with the Universal

Declaration of Human Rights. Climate justice theories draw on the environmental justice movement experiences at the local level (Bickerstaff, 2012; Bickerstaff, Walker and Bulkeley, 2013; Perez et al., 2015; Hall, Hards and Bulkeley, 2013). Slogans such as 'leave no one behind' embedded in international policy for cities and settlements recognize the connection between systems of oppression and exclusion that reproduce and perpetuate urban inequality and the delivery of urban services and security (Kabeer, 2016; Stuart and Woodroffe, 2016).

Intersectional strategies of action seek to consider the multiple forms of structural oppression experienced at the local level (Grunenfelder and Schurr, 2015) and, in the context of adaptation, explain how they produce or exacerbate vulnerabilities. For example, intersectionality ties with the idea of how multiple deprivations shape access to services (from sanitation to health and education) and the exposition to environmental risks (Sicotte, 2014; Lau and Scales, 2016; Van Aelst and Holvoet, 2016; Lievanos and Horne, 2017; Raza, 2017; Yon and Nadimpalli, 2017; European Environment Agency, 2020) (see Box 6.6 on the participation of women in local decision making bodies). For example, fisherwomen in the western coast of India rely on a complex arrangement of relationships around categories of class, caste, and gender that shapes their possibilities to draw political resources to maintain their livelihoods, and hence, influence the dynamics of transformation (Thara, 2016). Intersectionality is central to build resilience across communities, rather than in particular areas (Khosla and Masaud, 2010; Reckien et al., 2017). Including intersectionality deliberately in partnerships with communities can empower socially excluded groups and highlight justice issues while aligning agendas with local development priorities (Castán Broto et al., 2015a). Despite the high confidence on the growing importance of intersectionality concerns in the delivery of just environmental policies, there is limited evidence of its explicit inclusion in adaptation policies.

[START BOX 6.6 HERE]

Box 6.6: Invisible Women: Lack of Women's Participation in Urban Authorities

Women are under-represented internationally in governance structures (Prihatini, 2019; Gonzalez-Eiras and Sanz, 2018; Rashkova and Zankina, 2017; Koyuncu and Sumbas). This situation is reflected in urban authorities where participation by those who identify as women is low (Williams, Devika and Aandahl, 2015; Kivoi, 2014). Das (2014) reports deep-rooted economic inequalities are barriers for women's participation in Indore, India, and that women's collective empowerment could increase their bargaining power within households as well as in the community and state. Kivoi (2014) draws a similar conclusion presenting experience from Kenya. The big question is how to make women more visible in the urban governance process?

What are the barriers women face and how do we increase their participation so that urban governance become more inclusive? Escalante and Valdivia (2015) show the participatory tools that can be used at different stages of planning for women's empowerment using bottom up planning models. Using these tools makes planning process more inclusive. Araujo & Tejedo-Romero (2016) show from Spanish local councils that women's political representation in municipalities has a positive influence on the level of transparency, increasing information transparency and reducing information asymmetry. In Myanmar (Minoletti, 2014) increased levels of women's participation in urban authorities helped to improve the quality of governance such as reducing corruption and conflicts and improving service delivery.

[END BOX 6.6 HERE]

People traditionally excluded from climate change governance, such as children, are also more likely to have their needs and priorities considered in urban planning for adaptation where there are national advocacy bodies, for example, Commissions for Future, or Children's commissions (Nordström and Wales, 2019; Watts et al., 2019; Hayward, 2021). An emphasis on procedural justice in decision making has potential to produce transformational outcomes where these are defined as significantly reducing inequality (Holland, 2017). In this light emerging evidence suggests transformative adaptation is more likely to occur if people have the agency to influence decisions and enact change (Archer and Dodman, 2015). Cities are also more likely to build and develop infrastructure that serves the needs of disadvantaged groups, when urban climate governance encourages wider community participation and inclusion (Ziervogel, 2019a; Hölscher et al., 2019; Anguelovski et al., 2016). This can help to stimulate innovation, shift power relations and address diverse needs (Martel and Sutherland, 2019; Chu, Schenk and Patterson, 2018). Experiments in including marginalized groups in adaptation planning are starting to emerge in places such as Quito (Ecuador), Lima (Peru), Manizales (Colombia) and Surat (India), where disadvantaged youth, informal settlers, and other vulnerable communities are included in discussions of short-/long-term adaptation needs and fair distribution of adaptation resources (Chu, Anguelovski and Carmin, 2016; Sara, Pfeffer and Baud, 2017; Hardoy and Velásquez Barrero, 2014). These processes can also support citizens to manage risks as they encounter them in their everyday life (Ziervogel et al., 2017).

In order to respond to urban injustices, attention needs to be paid to both the local level and to broader system-wide governance issues (that are unpacked further in section 6.4). At the local level it is important to understand who is most vulnerable to climate risk, which is likely to be related to class, race, gender, ability and age (Wilby and Keenan, 2012; Ranganathan and Bratman, 2019; Thomas, Cretney and Hayward, 2019). Factors such as age and levels of ability, as well as those pursuing outdoor livelihoods, have a direct link to higher vulnerability to heat stress (Conry et al., 2015). In least developed countries, less than 60% of the urban population have access to piped water which impacts on health and well-being, and emphasizes the importance of alternative resources for these households (World Health Organization, Nations and Fund, 2017).

6.4.3.6 Supports visionary and imaginative design

The failure to deliver inclusive and sustainable adaptation contributes to a collective inability to mobilize the power of creative community vision (*medium evidence, high agreement*). Urban design plays a central role to support creative adaptation strategies (Box 6.7). Much adaptation action repeats previous experiences. However, the potential for building resilience to deliver adaptation- especially transformative adaptation- requires an articulation of collective visions of the future and the imagination of new or alternative urban futures (Glaas et al., 2018) including through design and deliberate engagement with cultural artefacts, technologies, and performances (Jordan, 2020). Social movements can be powerful sources of such alternative visions of the future, as exemplified by recent Youth Climate Strikes and Extinction Rebellion (limited evidence, medium agreement). Community protest including Youth Climate Strikes have influenced urban climate policy agendas including the declaration of climate emergency in municipalities worldwide, fostering a new debate on climate change, although their impact on local policy is ambiguous (Davidson et al., 2020; Thomas, Cretney and Hayward, 2019; Prendergast et al., 2021; Ruiz Campillo, Castan Broto and Westman, 2020). Social movements on climate mitigation, such as the Transition Movement and Transition Towns (Feola and Nunes, 2014), and School strikes may serve as an example for mobilizations more specifically about climate adaptation and the way new, networked, grassroots citizen activism and community organizations can encourage urban institutional change (Gunningham, 2019; Jordan et al., 2018; Wahlström et al., 2019). Other strategies such as cultural production and exhibitions may also have an impact (Stripple, Nikoleris and Hildingsson, 2021).

[START BOX 6.7 HERE]

Box 6.7: The Role of Urban Design in Local Adaptation

Since AR5 there has been a growing literature about the role of urban design, creating new opportunities for both incremental and transformative adaptive responses to climate change (*medium evidence, high agreement*). For example some of these creative design approaches compliment and extend regulatory and land use planning approaches such as form-based codes and established certifications like LEED-ND (Leadership in Energy and Environmental Design – Neighbourhood Design) (Garde, 2018; Garde and Hoff, 2017) and the USA's Sustainable Sites Initiative (SITES) (Valente, 2014). Emphasis on sufficiency has also influenced urban design, for example, with the mobilization of 'doughnut' economics that emphasize both a social foundation and an environmental ceiling, for example Amsterdam (Raworth, 2017). However, such cases are rare, substantial public investment is often required (high confidence, high agreement) (see also section 6.4.7 on finance and insurance). Other approaches underscore innovation and creativity, at the essence of which are context-specific interventions that draw on a compendium of urban design principles such as: indeterminacy (to accommodate climate uncertainty), polyvalency and diversity, and harmony with nature (Dhar and Khirfan, 2017a). Creative interventions include the daylighting of buried streams to create climate adaptive public realms (Khirfan et al., 2020; Khirfan, Mohtat and Peck, 2020). For example, the demolition of a major expressway and the restoration of the Cheonggyecheon stream reorganised downtown Seoul, South Korea and significantly contributed to climate change adaptation through stormwater management and reducing the urban heat island effect (Kim and Jung, 2019). Biomimicry and ecological infrastructure are design features that governance bodies can use to reshape space and contribute to place making (Santos Nouri and Costa, 2017; Prior et al., 2018). For example, urban metabolism and local ecological knowledge has constituted the essence of urban design interventions in the Island of Tobago in ways that capitalize on the contiguous relationship between ecosystems (e.g., the mangrove forest) and human actions (rainwater harvesting and grey water management) (Khirfan and Zhang, 2016). While lack of funding, or design capacity, restrictive planning regulations, inequality and competing urban agendas can create barriers for the implementation of creative design solutions, transition architecture movements are also driving local urban adaptation experiments and exploring ways local learning can be scaled up (Tubridy, 2020; Irwin, 2019).

[END BOX 6.7 HERE]

6.4.4 Limits of Adaptation Capacity at the Institutional Level

In delivering adaptation in cities, settlements, and infrastructure, however, there is a need to understand and measure the adaptive capacity and limits to manage future risks in communities, institutions, and organizations (Filho et al., 2019). However efforts to track urban adaptation lack consistent methods, metrics and data gathering (Olazabal et al., 2019b). The scale of complex, cascading challenges, limited finance and governance capacity combined with the impacts of growing social inequality and sustainable development priorities can result in both soft and hard limits on cities government's capacity to adapt to climate change (Chanza, 2018; Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018; Lehmann et al., 2015; Di Giulio et al., 2018). Hard limits to adaptation are identified when it is unfeasible to avoid severe risks while soft limits exist when technological and socioeconomic options are not immediately deployable (Pachauri, Meyer and Barros, 2014). In urban contexts soft limits may become hard limits when large numbers of people are unable to avoid severe climate related risks of loss and damage (Mechler et al., 2020). Climate change-related loss and damage that are intangible also require more caution in assessment processes (Roberts and Pelling, 2018; Andrei et al., 2015; Barnett et al., 2016; Thomas and Benjamin, 2018). Incorporating Indigenous knowledge can identify people-oriented and place-specific scenarios leading to developing urban adaptation policies that foster identity, dignity, self-determination, and better collective decision-making/capacity to act (McShane, 2017; Preston, 2017) and are sensitive to the local context and limits of community adaptation (Makondo and Thomas, 2018).

Urban transformations represent forms of adaptation that challenge the principles in which a society is established (Pelling, O'Brien and Matyas, 2015) and can be deployed to go beyond the existing limits of development justice and climate change adaptation capacity. While not all adaptation will be transformative, transformative capacities support both ongoing adaptation efforts and the broader systemic change processes that align adaptation efforts with decarbonization requirements and the SDGs' delivery. 'Urban transformative capacity' focuses on understanding what elements of a system to respond to external changing conditions in a manner that transforms the system towards a more sustainable state (Ziervogel, Cowen and Ziniades, 2016). The capacities required to deliver adaptation action in cities and settlements are 'transformative capacities,' because they move away from thinking of adaptation as an adjustment to a changing external environment to think instead of adaptation as a reconfiguration of infrastructures and institutions to build resilience in the surrounding environment (Pelling, 2010; Matyas and Pelling, 2015). Reflective and iterative learning is integral to fostering transformative capacity (c.f. Luederitz et al., 2017). Transformative capacity extends across multiple agency levels or geographical locations, as well as various domains (Wilson et al., 2013; Olsson, Bodin and Folke, 2010; Keeler et al., 2019b). The components of transformative capacity in cities and settlements can be grouped into three categories (see Table 6.9): (1) agency and forms of interaction, (2) development processes, and (3) relational dimensions (Wolfram, 2016). Alongside different forms of technical expertise, there is a need to broaden the interventions of disadvantaged populations in urban sustainability (Wolfram, Borgström and Farrelly, 2019).

Table 6.9 presents a defined framework of ideas that local institutions- mostly local governments- can put into practice to improve their adaptive capacity. Enabling transformative capacity requires novel governance arrangements based on broad participation, a diversity of actor-networks, socially embedded leadership, and empowerment of communities, alongside an understanding of the system dynamics, which refers to system awareness, collective visions, practical experimentation, reflexivity, capacity building, and institutional mainstreaming, and the multiple levels of agency or scales (Ziervogel, Cowen and Ziniades, 2016; Ziervogel, 2019a; Wolfram, 2019; Hölscher and Frantzeskaki, 2020; Castán Broto et al., 2018). Many of the transformative capacity components are already visible in local adaptation actions, but many efforts emphasize one element at others' expense, without delivering a systemic perspective. In particular, measures to facilitate the empowerment of communities, reflexivity, and social learning are rare but often point towards heightened capacities for transformative, alongside incremental, adaptation (Castán Broto et al., 2018). Transformative capacity frameworks may foster inclusive governance to deliver risk management that works for the poor in countries such as South Africa (Ziervogel, 2019a).

Table 6.9 Components of urban transformative capacity with broader relevance for multiple forms of adaptation (Wolfram, 2016).

Component		Manifests in…
Agency and interaction	**Inclusive, multiform urban governance (C1)** Participation / inclusiveness (C1.1)	Citizens and/or civil society organizations participating directly in planning and/or decision-making processes.
	Diverse governance modes / Networks (C1.2)	Different and various stakeholders working together and building connections between sectors in different manners.
	Sustained intermediaries and hybridization (C1.3)	An intermediary positioned between the stakeholders of a project.
	Transformative leadership (C2)	Leadership acting as a collaborative driving force in an initiative.
	Empowered communities (C3) **Social needs (C3.1)**	Either analysing or addressing social needs.
	Autonomous communities (C3.2)	Integrating into the design of the project different aspects of community empowerment.
Development processes	**System awareness (C4)** Baseline analysis and system(s) awareness (C4.1)	Agendas aiming to tackle sustainability challenges after deliberate analysis of urban systems.
	Recognition of path dependencies (C4.2)	Explicitly tackling systemic barriers to change.
	Foresight (C5) Co-production of knowledge (C5.1)	Involvement of various and multiple stakeholders in knowledge production processes.
	A collective vision for change (C5.2)	An explicit future vision shared among stakeholders as a means for motivating partners and fostering commitments.
	Alternative scenarios, future pathways (C5.3)	Comparative scenarios that evaluate the mutual shaping of social, ecological, economic and technological dimensions.
	Experimentation with disruptive solutions (C6)	The deliberate use of experiments or ideas that seek to challenge the existing landscape of established policies, technologies or social practices.
	Innovation embedding (C7) Resources for capacity development (C7.1)	Project stakeholders sharing resources for capacity development outside the project to disseminate and multiply results.
	Mainstreaming transformative action (C7.2)	Attempts to generalise the project operation or results beyond the initial context of an application.
	Regulatory frameworks (C7.3)	A new regulation was established as a result of the project or as part of the project activities.

Relational dimensions	**Reflexivity and social learning (C8)**	Stakeholders reflecting on learning and capacity building processes.
	Working across human agency levels (C9)	Project activities contributing to capacity development across human agency levels.
	Working across levels and scales (C10)	Project activities contributing to building capacity across geographical or political-administrative levels.

6.4.5 Financing Adaptation in Cities, Settlements and Infrastructures

The amount invested in urban adaptation is limited. The Cities Climate Finance Leadership Alliance tracked USD 3.7 billion of investments in adaptation projects in 2017-2018, of which only 3-5% had an urban component (Richmond et al., 2021). Cities and settlements frequently face barriers of inadequate financing for climate adaptation and mitigation (Cook and Chu, 2018).Finance barriers interact with economic barriers and socio-economic conflicts and need to be considered within an integrated perspective (Hinkel et al., 2018).

Many early leaders in climate adaptation are, therefore, perhaps unsurprisingly, political capitals or financial centers in the global North with much larger resource envelopes and well-developed fiscal and financing capacities (Westerhoff, Keskitalo and Juhola, 2011; Shi, Chu and Debats, 2015).

The funding required to deliver climate change adaptation will depend on choices made about climate mitigation (Masson-Delmotte and Waterfield, 2018). Still, the cost of adapting to a global temperature increase of 1.5°C will be a fraction of the cost of adapting to a global temperature increase exceeding 3°C (Pörtner et al., 2019; Shukla et al., 2019; Hoegh-Guldberg et al., 2018). It will also depend on selected adaptation options, as they have different capital requirements, operating costs, and returns on investment (See 6.3). Finally, costs depend on financing sources and mechanisms selected.

Broadly, there are two options for adaptation investment: funding – direct expenditure in preparation for or response to climate change impacts – and financing – the deployment of market-based instruments to attract third-party resources to an adaptation action (Keenan, 2018; Banhalmi-Zakar et al., 2016). Using funding can be a lower-cost strategy, as there is no third party expecting a return on investment. However, using financing can expand the total resources available for adaptation (White and Wahba, 2019).

The choice of funding and financing mechanism is often based on implicit economic world views (Keenan, Chu and Peterson, 2019) or on the technical support available to subnational governments, such as preparing municipal bonds or contracting for public-private partnerships (Bisaro and Hinkel, 2018). The urban finance literature has long called for critical interrogation of these choices, as adaptation finance has profound justice implications (Khan et al., 2020). However, the literature on adaptation investments is limited (Harman, Taylor and Lane, 2015; Keenan, Chu and Peterson, 2019). The use of municipal debt such as green bonds, for example, intensify the financial and environmental risks borne primarily by the poor, the working class, or people discriminate against because of race, sexual orientation, or ability (Bigger and Millington, 2019).

The climate imperative has not yet fundamentally changed urban infrastructure investment (White and Wahba, 2019). Mobilizing adaptation investment in urban areas continues to depend on strengthening public finance capacities (particularly evaluating and integrating climate risk into economic decisions) and meeting private investors and lenders' expectations. Climate change creates new investment risks and physical risks (Martimort and Straub, 2016), and highlights the limitations of current models to account for risk and uncertainty when pricing investments (Keenan, 2018). Private investors and lenders do not seem ready to provide adaptation finance on significantly easier or cheaper terms than conventional finance (White and Wahba, 2019). However, a variety of means for financing climate change adaptation in urban areas exist (Table 6.10).

Table 6.10 Finance instruments to deliver adaptation in urban areas (source: adapted from (Richmond et al., 2021) and (UN-Habitat, 2016b)).

Type of finance	Finance source	Instruments	Examples of specific instruments in urban settings
Public	Municipal government	Local revenue generation	Utility fees Open space funds/land value capture General obligation bonds Local property, income, and sales taxes
	State/Provincial government National government	Grants, incentives, technical assistance funds	Insurance Tax advantages Low-cost project debt Infrastructure investment funds Shared taxes Intergovernmental funding transfers/revenue sharing
Public finance	National DFIs Bilateral DFIs Multilateral DFIs	Grants, project debt (low-cost market rate), technical assistance, risk instruments	Risk mitigation support of PPP Project level debt Project preparation facilities and other technical advisory Insurance
	Climate funds	Grants, debt, equity, guarantees	Dedicated climate fund
Private	Commercial FIs	Project debt and equity (market-rate), guarantees	Internal climate risk mitigation PPP Financing Climate loans
	PE/Infrastructure funds	Project equity (market rate)	Direct urban infrastructure investments Corporate equity investment
	Institutional investors	Project debt and equity (market-rate)	Direct urban infrastructure investment Corporate debt and equity investments
	Private insurance	Insurance	Public and private risk mitigation Catastrophe bonds Parametric insurance
	Corporate actors	Balance sheet financing and project equity (market rate)	Internal risk mitigation Leasing PPP
	Household	Balance sheet financing	Internal climate risk mitigation
	Non-profits, philanthropies and foundations	Grants, technical assistance, donations	Microfinance Impact investment
	Communities	Grants and collective support	Risk sharing Upgrading funds Community development funds Crowdfunding

6.4.5.1 Urban adaptation financing gap

Cities and settlements in higher-income countries typically have access to funding that could be used to enhance resilience and build adaptive capacity; this includes both the private resources of individual households and firms (which varies significantly within and among cities) and public budgets of different government tiers (see Table 6.10).

Depending on fiscal devolution levels within a country, public revenues may be collected and managed primarily at the national, state, metropolitan, or local level. In federal countries, subnational governments collect an average of 49.4% of public revenues compared to only 20.7% in unitary countries (OECD/UCLG, 2019). For example, subnational revenues represent over a quarter of total public revenues in Belgium, Canada, and Denmark, but less than 5% in Greece, Ireland, and New Zealand (OECD/UCLG, 2019). The share of the national revenue transferred to subnational governments also varies significantly among countries: grants and subsidies account for over three-quarters of subnational government revenue in Malta, but less than a quarter of subnational revenue in Iceland (OECD/UCLG, 2019). A local government's capacity to collect revenues is further mediated by incomes within a city (which dictates the prospective tax base) and the capacity of civil servants to administer taxes, fees, and charges. The result is that metropolitan and local governments' budgets vary dramatically, across and within countries. For example, per capita municipal budgets vary from $1,114 in Saskatoon and $2,682 in Peterborough (Canada), $2,635 in Leipzig and $3,638 in Freiburg (Germany), to $4,907 in Bristol and $5,612 in Aberdeen (the United Kingdom) (Löffler, 2016).

Revenue streams are often insufficient relative to the scale of adaptation requirements. For example, Kano, Nigeria, is a large urban area that urgently needs investment in human development and climate resilience, but where a fragmented local government has little capacity to finance their climate plans (Mohammed, Hassan and Badamasi, 2019). Many local governments are unable to mobilise funds for adaptation as they face competing priorities, meaning that resources for resilience must be allocated by higher levels of government (Hughes, 2015) – which also perceive opportunity costs to adaptation investments. Funding from non-state actors is, therefore, proving important. For example, in the U.S., private foundations and non-profit organizations account for 17% and 16% of adaptation support in urban areas (Carmin, Nadkarni and Rhie, 2012). However, tapping into these funding sources raises complex questions about accountability and ownership of urban adaptation (Chu, 2018a). Land reclamation may foster real estate markets and mobilize finance for adaptation, as shown in Germany, the Netherlands, and the Maldives (Bisaro et al., 2019).

City governments need to anticipate climate shocks and stresses and design their operating models and investment plans accordingly to ensure financial resilience (Clarvis et al, 2015). Climate risks threaten fiscal models, for example, a drought may disrupt water revenues by reducing total water consumption and incentivizing households and firms to invest in independent water storage or supply infrastructure (Simpson et al., 2019). Storm surges and sea-level rise may threaten sunk investments in revenue-generating infrastructures, such as toll roads or electricity generation and transmission systems. .

6.4.5.2 Barriers to adaptation investments

Common sources of adaptation finance might include donor agencies including the Green Climate Fund; sovereign funds (e.g. the Bangladesh Climate Change Resilience Fund) and private finance from commercial banks, investment companies, pension funds and insurance companies (Floater et al., 2017). These capital sources have different risk-return expectations and investment horizons, so they will suit different types and stages of projects. Many subnational governments in the global North have access to well-developed domestic, if not global, capital markets to raise and steer finance for urban investment (Banhalmi-Zakar et al., 2016).

However, investments in ex-ante urban climate adaptation may prove less attractive to these financiers than other opportunities because of their long maturities and high risk (Keenan, Chu and Peterson, 2019) (see also Table 6.11). Many generate economic returns primarily through avoided losses from climate impacts, which are difficult to measure and are, in any case, more attractive to funders than financiers (Kaufman, 2014). Ex post, insurance already plays a critical role in protecting urban households, firms, and other stakeholders from the full economic costs of high-severity, low-frequency events by sharing risk over time and space. Insurance can also be designed to incentivize risk-reducing behaviours and investments (Banhalmi-Zakar et al., 2016; Paddam and Wong, 2017). Some researchers suggest that, in urban environments, insurance practices are helping to establish adaptation and risk as a new area of public health and public protection. For example, local governments are using new risk transfer instruments, such as reinsurance and catastrophe bonds, to fund investments in resilience projects and disaster recovery (Collier and Cox, 2021). However, private-sector insurance's commercial feasibility depends on more robust estimates of current and future risks, and premiums commensurate with the ability and willingness of consumers to pay. Therefore, ex-ante investments must complement insurance schemes to improve climate modeling and reduce climate risk (Surminski, Bouwer and Linnerooth-Bayer, 2016). The private sector also faces practical barriers to invest in adaptation.

Table 6.11 Barriers to finance adaptation in urban areas (Richmond et al., 2021)

Barrier Application to urban adaptation Barriers to adaptation finance	

Poor policy Environment	Municipal policy environment lacks conditions supportive to private adaptation investment (e.g., lack of requirements that private sector organizations operating in cities implement climate risk mitigation strategies or invest in systemic resilience).
Poor institutional environment	Legal and regulatory infrastructure in the city lacks clarity of purpose towards addressing urban climate risks (e.g., no limitations on development in high climate risk areas).
Poor market environment	Market environment is unsupportive towards adaptation investment (e.g., lack of creditworthy partner municipalities for private sector engagement).
High cost of projects and unknown value add	The value or benefit of the technology is uncertain; private sector actors do not sufficiently consider climate risk in decisions; upfront costs of technology are high.
Lack of technical capacity	Prospective users of technology do not have technical capacity to implement (e.g., limited or siloed expertise in implementing resilient urban infrastructure solutions).
Limitations of private insurance	Insurance has to date largely not been engaged in cities to efficiently transfer risk or incentivize adaptive action and the private insurance industry is facing considerable risk associated with the accelerating impacts of climate change in

National governments typically determine the fiscal transfers that subnational governments receive and the taxes, fees, and charges they permit to collect (see for example (CBO, 2016)). Local governments may strengthen their own-source revenue collection and management capacities to exploit these funding streams better and improve their balance sheets, but their total budget will be limited to these funding sources (Ahmad et al., 2019). The amount of local public funding available for urban adaptation depends on the relationships across different government levels.

Similarly, mobilizing private finance for urban adaptation projects demands robust institutional, fiscal, and regulatory frameworks, which are typically national authorities' responsibility. For local governments to access private finance for adaptation may require national (or in federal countries, state) governments to reform policies and rules governing municipal borrowing, public-private partnerships, land value capture instruments, and other financing mechanisms (Ware and Banhalmi-Zakar, 2017). Such fiscal reforms tap into fundamental political and policy issues, such as local governments' autonomy or the tariff-setting powers of national ministries (Gorelick, 2018; White and Wahba, 2019).

Access to private finance can support infrastructure development through private provisioning, public-private Partnerships (PPP), and public debt arrangements (*high confidence*) (see also 6.4.1.2). Private provisioning attracts coastal adaptation investment when returns are high (e.g., when there is a real estate market associated with it) (Bisaro and Hinkel, 2018). Public-private partnerships attract investments from dredging and construction companies that involve a large share of operational costs (Bisaro and Hinkel, 2018). Public debt instruments appear less successful in supporting investment in adaptation infrastructure. Real estate firms focus on adaptation actions if they perceive climate change impacts such as flooding may impact their activity, mostly focusing on adaptation action as a means to gain competitive advantage (Teicher, 2018).

There have been numerous attempts to innovate in climate finance, for example, mobilising community and cooperative forms of finance, or crowdfunding which have already proven effective in the context of mitigation (De Broeck, 2018). A well-studied instrument in urban environments is land-value capture. Land-value capture refers to communities' ability to capture the benefit of increased land values that result from public investment or other government actions (Germán and Bernstein, 2020). There is considerable potential to mobilize land-value capture for adaptation (*limited evidence, medium agreement*), but its potential remains unexplored (Dunning and Lord, 2020). While there are numerous examples of the mobilization of land-value capture to finance sustainable development action (Li and Love, 2019; Wang, Samsura and van der Krabben, 2019), there is limited evidence of its use in climate adaptation (see case study 6.2). These innovations are particularly important in contexts were resources are very constrained, such as in the financing of adaptation in African cities (See box 6.7).

Corruption in urban adaptation and disaster risk management finance is a considerable but little researched challenge observed from all world regions (Sanderson et al., 2021). Corruption generates maladaptation increasing risk, for example where infrastructure is constructed with faulty design, substandard materials and inadequate maintenance (Kabir et al., 2021). More widely, corruption increases vulnerability and reduces capacity by damaging the body politic, distorting markets and reducing economic growth (Alexander, 2017). The construction and infrastructure industries are repeatedly identified as sources of corruption (GIACC, 2020; Chan and Owusu, 2017; Sanderson et al., 2021). Corruption and misuse of climate finance is exacerbated by limited public access to information, political considerations in finance decision-making and lack of accountability for decisions and actions (Kabir et al., 2021). In construction Owusu et al (2019) found causes included too-close relationships, poor professional ethical standards, negative industrial and working conditions, negative role models and inadequate sanctions throughout the phases of construction. Post-disaster response and reconstruction, and periods of surge funding following international or national policy priorities are especially vulnerable to corruption with increased funding and pressure to lower norms of financial management (Imperiale and Vanclay, 2021). Mixed delivery mechanisms have been shown to reduce corruption, for example where civil society organizations are involved in project approval stages. Though there is also a risk that civil society organisations will themselves become entangled in corruption. International donors have a role to play in working with government and civil society to promote wider scrutiny and transparency of financing processes and project delivery through promoting media and press freedom and legislation for access to information to reduce corruption by enhancing transparency and accountability (Kabir et al., 2021).

Expanding the resource envelope available for adaptation investment is often beyond the authority or competency of city governments. Sovereign and state governments have critical roles to play in providing funding or securing finance for adaptation investments. Such role is particularly important where the impacts of climate change are distributed inequitably across a country so that the costs borne by a city may exceed local budgets.

[START BOX 6.7 HERE]

Box 6.8: Challenges to Investment in Adaptation in African Cities

In Africa, new investment in institutions and other enabling conditions for climate-resilient urban development (Robins, 2018) While several studies reveal the net economic benefit of climate-resilient, low-carbon African cities (Global Commission on Economy and Climate, 2017), structural impediments remain to the mobilization of investment for the types of public good infrastructure that would unlock this benefit (Dodman et al., 2017).

Since the 1960s, Gross Capital Formation (sometimes called Gross Domestic Investment) has been less than 22% in Africa, whilst in East Asian countries, it has risen to 42% (OECD, 2016). Africa faces an estimated 40% infrastructure financing gap, but this gap is almost certainly higher in the continent's rapidly growing cities (Baker & McKenzie, 2015). Relative poverty, weak or absent local fiscal systems, and contested tenure that prevents land being used as collateral, have restricted investment in African cities (Berrisford, Cirolia and Palmer, 2018; Dodman et al., 2017). Sub-Saharan African countries are reaching the 40%-urban threshold at national per capita incomes of around $1,000 per annum, significantly poorer than South-East Asian and Latin American cities at the same level of urbanization (Freire, Lall and Leipziger, 2014). Absolute poverty, in conjunction with weak revenue collection and low levels of investment, render conventional infrastructure finance difficult (Smolka, 2013; Global Commission on Economy and Climate, 2017; Berrisford, Cirolia and Palmer, 2018; Cirolia and Mizes, 2019). Sprawled urban development in Africa might make the provision of public services, both more energy-intensive and three times more expensive than high-density developments (Collier and Venables, 2016).

Data on private finance in African cities are inadequate (OECD, 2017), but all of Africa secured just 3.5% ($46 billion) of global FDI, despite a 10.9% increase in 2018 (UNCTAD, 2019). Mining and the extraction and processing of fossil fuels accounted for almost a third of greenfield FDI in Africa in 2018 (UNCTAD, 2019). The FDI secured by cities has tended to serve an urban elite and has been used to build shopping malls, housing settlements, and airlines (Watson, 2015). It is also unevenly distributed across the continent and within cities. Five countries, Egypt, South Africa, Congo, Morocco, and Ethiopia accounted for more than half the total FDI in 2018 (UNCTAD, 2019), leaving large parts of Africa's growing cities described by financiers as "high risk" and their citizens deemed "unbankable" (UCLG, 2016).

Private financiers have begun entering public-private partnerships with African cities, often supported by bilateral agreements between the respective countries, including the growing number of Asian and Middle-Eastern countries contributing to infrastructure in African cities (Cirolia and Rode, 2019). In the absence of enforceable spatial plans and strong urban governance, the risk remains that individual investment projects that are completed will aggregate to create urban systems that are at risk from climate change through the locking-in of inequality, urban sprawl, flooding and greenhouse gas emissions (Dodman et al., 2017; Wachsmuth, Cohen and Angelo, 2016). These risks will constitute a future burden for asset owners, financiers, and insurers and cause a progressive hemorrhaging of economic opportunities in Africa's urban centres (UCLG, 2016).

Securing climate finance for urban development is contingent upon robust multi-level governance arrangements (Tait and Euston-Brown, 2017; OECD/UN-Habitat, 2018). Such investments are needed for cities that do not yet have the balance sheets or rate-paying citizens required to enter financial markets on favourable terms. Similarly, Central Banks have a crucial role in managing the transition risks within cities and limiting the systemic impact of stranded urban assets due to technology shifts or sea-level rise (Safarzyńska and van den Bergh, 2017).

New energy, water, and sanitation technologies alter the public good nature of urban services and offer novel opportunities for private sector financiers and blended finance. Still, financial sector innovation remains necessary if technological innovation is to be scaled (Cities Climate Finance Leadership Alliance, 2015; European Environment Agency, 2020). UNEP has cited anecdotal evidence of a "quiet revolution" towards a more developmental and sustainable global finance sector, in part due to global Environmental, Social, and Governance requirements, and industry initiatives within the financial and insurance sectors (UNEP, 2015). Scope remains to strengthen Development Finance Institutions programmes such as the World Bank's City Creditworthiness Programme and the activities of China's ExIm Bank with a bespoke urban climate dimension.

[END BOX 6.7 HERE]

6.4.6 Monitoring and Evaluation Frameworks for Adaptation used in Cities, Settlements and Infrastructures

Urban adaptation plans can focus attention on the needs of marginalised or vulnerable communities including the elderly, children and the disabled (Dahiya and Das, 2020; Yang, Lee and Juhola, 2021). However, monitoring and evaluation (M&E) frameworks for adaptation are far from being fully developed and operationalized both in theory and in practice for cities, settlements, and infrastructures. See also Section 17.5 for an assessment of monitoring and evaluation in climate adaptation. Despite significant experience on the application in other sectors (e.g., health, water, industry, or business) or with other climate change objectives (e.g., emissions reduction), the assessment of adaptation efforts has been to date under-theorized in current urban adaptation literature (Berrang-Ford et al., 2019; Leiter et al., 2019; Olazabal et al., 2019b). There is also limited evaluation of new social innovations of the last two decades, including participatory budgeting, social financing, crowdfunding, and low-cost urban infrastructure that can be enabling conditions for transformative urban adaptation (Dahiya and Das, 2020; Caprotti et al., 2017).

The challenges related to the evaluation of adaptation progress (lack of methods, agreed metrics, data, and definitions, including the ambiguity of the concept of "adaptation") have been widely recognised after the Paris agreement by multiple organisations, including the OECD, the World Bank, the European Environment Agency, the Global Environment Facility (Ford et al., 2015; Magnan, 2016; Bours, McGinn and Pringle, 2014). Monitoring and evaluation systems in urban areas will necessarily be incremental and additive, and will have to build on existing indicator systems (Solecki and Rosenzweig, 2020). There is a need to develop practical and efficient frameworks to assess adaptation progress across all levels of public and private decision-making. This should include the assessment and consideration of top-down adaptations alongside informal, bottom-up, community actions, or corporate-led programs developed to reduce vulnerabilities and climatic risks and increase resilience (high confidence, high agreement).

On the one hand, there is a need to guarantee that planned adaptation actions are efficient, just and equitable (Olazabal et al., 2019b), including being able to disaggregate for example by gendered impacts. On the other hand, there is a need to observe if and how environmental, social and economic vulnerability and climatic risk conditions evolve with time. Surveillance, monitoring and evaluation facilitate adaptation decision-making by linking three aspects (Berrang-Ford et al., 2019): (1) changing vulnerabilities and risks, (2) established adaptation goals and targets, and (3) adaptation efforts put in place. The process will help evaluate whether current adaptation efforts are sufficient or adequate, thus, enabling the learning process that adaptation action requires (Haasnoot, van't Klooster and Van Alphen, 2018; Klostermann et al., 2018).

Monitoring and evaluation of Government led urban adaptation in major cities around the globe is largely missing (Araos et al., 2016; Olazabal et al., 2019a). This reveals: (1) a lack of awareness by local adaptation managers about the critical importance of monitoring and evaluation systems in adaptation decision-making, (2) inadequacy, irrelevancy, or underuse of available monitoring and evaluation resources, or (3) a lack of knowledge, capacity, and resources to make monitoring and evaluation work in practice at city scale.

Olazabal et al (2019b) argue that six components are at least required to make monitoring and evaluation operational for urban adaptation planning: (1) the definition of a context-specific tailored system adapted to existing local institutions, (2) the definition of a responsible party (public authority, department, group or organization) that will be in charge of monitoring and evaluation system management, (3) the definition and assignation of the appropriate budget over time, (4) the identification of monitoring objectives and indicators, (5) the definition of a method and process to evaluate outcomes of the monitoring process and eventually, (6) the reporting process (how and who the outputs will be reported to). Klostermann et al. (2018) emphasize the importance of learning through iterative cycles of selection of monitoring objectives, procedures, data collection and evaluation, and inputs to adaptation policy and planning processes (see also discussion of evaluation and learning in section 17.5.1.7). Yet, practical exemplary approaches are still missing.

The IPCC's Fifth Assessment Report acknowledged the lack of standard metrics to measure and monitor success in urban adaptation and suggested a list of indicators that could be developed, while also taking note of the localized nature of adaptation (see also (Rufat et al., 2015)). However, predominant approaches are typically not conducted at the appropriate scale to inform adaptation decision making (Ford et al., 2018). While some scholars advocate the use of a unifying indicator of social vulnerability (Spielman et al., 2020), other scholars propose to develop flexible sets of comparable indicators that can be adjusted to different contexts (Leiter et al., 2019). Risk-based approaches are seen as an alternative in a context where the monitoring of decision-relevant variables in urban climate adaptation planning is essential to link climatic risk assessment and action (Hallegatte and Engle, 2019; Kingsborough, Borgomeo and Hall, 2016; McDermott and Surminski, 2018). Because of the need to define normative frameworks for risk evaluation - what is acceptable, for what purpose and for how long (Galarraga et al., 2018) - these approaches may offer an opportunity for the generation of a shared understanding on goals and limitations of adaptation (McDermott and Surminski, 2018). However, risk-based indicators may also create a bias towards quantifiable variables that tend to be based on climatic modelling outputs, engineering, or financial assessments. Based on this and various examples of urban development projects, Hallegatte and Engle (2019) claim it is important to consider output-based indicators and process-based indicators that talk about government, voice, and empowerment. Overall, dozens of indicator-based approaches to assess climate adaptation have been proposed across the scientific and policy literature, especially in the broader framework of (community) resilience assessment tools (Sharifi, 2016; Feldmeyer et al., 2019), and in different sectors, e.g., the climate benefits of nature-based solutions (Kabisch et al., 2016; Donatti et al., 2020). Although these efforts may help to mainstream the evaluation of adaptation in current city evaluation initiatives, the development of comprehensive monitoring and evaluation systems is lacking.

There is little evidence on how best to make monitoring and evaluation approaches practical at the local scale. Cities worldwide face important social, environmental, and economic conflicts related to resource inequality, poverty, environmental pollution, and social tensions that coexist with climatic risks. It makes sense to integrate climate change adaptation assessment goals and needs into existing frameworks for the sake of efficiency. This will benefit small urban areas and cities in developing regions that often face data scarcity and may also find available indicators irrelevant to their realities and, thus, be required to adjust them (Simon et al., 2016). Efforts to coordinate frameworks for the assessment of sustainability (e.g., Local Agenda, sustainability appraisals), resilience (e.g., 100 Resilient Cities, new standards for urban resilience), GHG emissions reporting (e.g., Global Covenant of Mayors for Energy & Climate) can be deployed to learn about contexts. However, they need to be applied with caution as enforcing external requirements may lead to local tensions during their application (see for example (Roberts et al., 2020)). In a context where adaptation efforts need to be aggregated and evaluated across nations (Magnan, 2016) and their implications on wider objectives such as sustainable development and social justice need to be assessed (Long and Rice, 2019), urban adaptation monitoring and evaluation can inform national and international processes that enable a global stocktake of adaptation.

6.4.7 Enabling Transformations

Growing awareness of the interlocking of drivers of urban change and vulnerability has motivated an interest in transformational approaches to adaptation action in cities, settlements, and infrastructure. While the idea of transformation has been adopted across the field, there is no consensus about what an urban transformation that addresses adaptation means. There is no one single transformative solution or approach relevant in every case (Chu, Schenk and Patterson, 2018; Shi, 2019; Goh, 2019). What constitutes 'urgent' and 'far-reaching' transformation depends on the local community's expectations and ideas (Choko et al., 2019).

Transformation is often approached as a process of institutional transformation, akin to the process described in section 6.4.2 (see, for example (Duijn and van Buuren, 2017)). Transformation engages with critiques of adaptation or risk reduction as an individual responsibility (Sou, 2018). The idea is to use transformation to focus on coordinating collective efforts (Haque et al, 2014). The coordination of multiple actors is a condition to enable transformative institutions (Torabi et al, 2018) and link adaptation action to development efforts (Chu et al, 2017; Roberts and O'Donoghue, 2013). The role of communities and citizens in such an approach to transformation is ambiguous. Sometimes communities and citizens are presented as critical agents of transformation (Limthongsakul et al, 2017). Other times, however, they are simply situated within strong and durable networks that provide the institutional setting to build resilience (Danière et al., 2016). Despite the political nature of transformative approaches and the evidence that transformative approaches rely on protest and political activism, few authors recognise this strategy (but see (Bahadur and Tanner, 2014; Chu, Anguelovski and Roberts, 2017; Dierwechter and Wessells, 2013)).

Transformation is also more than a single instance of institutional change. Historical perspectives on transformation enable an understanding of the chain of institutional changes that ultimately lead to significant or far reaching reconfiguration of infrastructure and service provision (Rojas et al, 2015).. Paradigm changes, such as new engagements with nature and green infrastructure, will improve adaptation outcomes (Roberts et al., 2012). Changes of paradigms, however, are not inherently positive and may clash with existing interests or involve trade-offs with other priorities. When care is taken to ensure greater inclusion in urban decision making, disadvantaged, vulnerable communities are less likely to be disadvantaged. For example, indigenous traditions of nature management provide entry points for the sustainable management of resources, such as seed banks, urban agriculture, and the local management of watersheds and floods, may be at odds with conventional structures of expert knowledge (Cid-Aguayo, 2016; Chandra and Gaganis, 2016). These traditions are vital both because of the solution space that they open in the local context and how they serve to create resilience through collective and intergenerational learning (Chandra and Gaganis, 2016).

While aspects of transformative capacity identified in the literature may facilitate far-reaching change, there is limited evidence of actual transformations as an outcome of adaptation. While community-led resilience agendas may tackle poverty-related issues, they struggle to tackle city-wide structural forms of inequality (Chu, 2018b). Processes of shared learning and co-production of knowledge can reinforce existing power dynamics and be limited by technical framings of vulnerability that marginalize political issues (Orleans Reed et al., 2013). These issues are especially acute in relation to land-use decisions where short-term fiscal and commercial interests conflict with long-term vulnerability reduction objectives (Brown, Dayal and Rumbaitis Del Rio, 2012). It can be difficult for adaptation actions to target cities' underlying political-economic structure, such as entrenched political-economic interests, elite influence over decision-making, or neoliberal planning logics that maintain and reproduce inequality (Chu, Anguelovski and Roberts, 2017). Urban resilience plans may be formulated in disconnection from broader development strategies, which leads to a limited ability to tackle underlying structures of political power and urban development practices (Weinstein et al, 2019). Evidence from Kolkata demonstrates the limitations of resilience plans to address underlying conditions of vulnerability, including the commodification of hazardous land, under-provision of informal settlements, and spatial segregation of the urban poor (Rumbach, 2017).

Planning for transformative adaptation is more likely where communities can learn collectively (*medium evidence, medium agreement*) (Restemeyer, van den Brink and Woltjer, 2017; Kabisch et al., 2017; Fraser et al., 2017; Putri, Dalimunthe and Prasojo). Greater citizen engagement facilitates implementing specific measures for radical policymaking or the mainstreaming of environmental knowledge into adaptation practices (Reed et al, 2015). DIY planning, in which stakeholders focus on creating and improving specific urban spaces they inhabit, has led to urban greening experiments led by civil society that change paradigms of urban and environmental management (Cloutier, Papin and Bizier, 2018). Social learning may occur through combinations of activism and collaboration with and between informal settlement dwellers, as shown in adaptation experiences in informal settlements in Hanoi and Bangkok (Danière et al., 2016).. The adaptation process can benefit from the inclusion of multiple sources of knowledge for social learning, including universities but also communities and citizens (Chu, 2018b). Citizens assemblies are increasingly recognized as spaces for transformative adaptation (Muradova, Walker and Colli, 2020), although their potential influence at different government levels is still not fully understood.

The integration of multiple forms of knowledge leads to social learning (*medium evidence, high agreement*). Indigenous knowledge and local knowledge can provide essential insights into community needs and experiences of housing and urban infrastructure to inform climate adaptation, including improper waste disposal, inadequate drainage, and poor sanitation, but there is significant variation in community knowledge networks (Roy et al., 2018b; Douglas et al, 2018; Waters and Adger, 2017). It is important to identify and address barriers to the incorporation of Indigenous knowledge and local knowledge, such as the dominance of scientific knowledge, oppression and/or racism and fragmentation of knowledge including gender and generational divides (see Burke and Heynen, 2014; Whyte, 2017; Victor, 2015; Lövbrand et al., 2015; Kelly, 2019).The incorporation of Indigenous knowledge in urban decision making requires a constructive dialogue with scientists and urban planners.

Indigenous knowledge and local knowledge have an important role to play in urban planning and management. They can support impact detection and evaluation in urban areas (Codjoe et al, 2014), weather forecasting in urban areas (Magee et al., 2016; Ebhuoma and Simatele, 2019), climate change adaptation in urban agriculture (Wahab and Popoola, 2018; Solomon et al., 2016), urban food security (Simatele and Simatele, 2015), planning and managing urban solid waste (Kosoe et al, 2019), urban flood management (Thorn et al, 2015; Jameson and Baud, 2016; Hooli, 2016), drought perception and coping strategies (Saboohi et al., 2019), and ecological restoration and urban commons management (Nagendra, 2016; Nagendra and Mundoli, 2019). They can help define baselines for past climate and ecological change providing an historical perspective on changes in urban commons such as lakes and trees (Nagendra, 2016) as well as past climatic changes or climate baselines (Ajayi and Mafongoya, 2017) and Shifting Baseline Syndrome (Fernández-Llamazares et al., 2015; Soga and Gaston, 2018) (see Businger et al., 2018 for a review of Hurricane history in Hawaiian newspapers; also Wickman, 2018). Incorporating Indigenous knowledge and local knowledge can help generate more people-oriented and place-specific approaches leading to adaptation policies that foster identity, dignity, self-determination, and better collective decision-making and capacity to act (Preston, 2017; McShane, 2017) (see also 6.1).

Envisioning development alternatives through adaptation as a first step towards transformative adaptation can leverage social learning. Experiences of migration, length of residence, and the density of local social-networks impact social learning opportunities and underscore why context-specific social education is vital (Waters and Adger, 2017; Karunarathne and Lee, 2020). Learning across and between communities can be enhanced when care is taken to understand local challenges. Given power relationships, cultural needs, and community aspirations, a top-down approach to information sharing is generally less effective than community partnerships and co-created knowledge at surfacing visions and strategies for getting past baked-in, unequal and unsustainable development assumptions and practices (*medium evidence, high agreement*)

(Clemens et al., 2016; Thi Hong Phuong, Biesbroek and Wals, 2017; Fitzgerald and Lenhart, 2016; Fisher and Dodman, 2019). Social learning in formal and informal urban contexts is also enhanced when care is taken to ensure multiple stakeholders have opportunities to understand a variety of viewpoints, values, resources, and ideals, and that these view-points are clearly identified in decision making (Thi Hong Phuong, Biesbroek and Wals, 2017). However much social learning still happens only after a crisis, for example in urban water adaptation and new knowledge is often frustrated by the lock in of powerful local institutions and groups (Johannessen et al., 2019). Social learning is, however, only one component of the development of climate-resilient pathways. System perspectives theorize the possibility of tipping points, leverage points, or disruptive technologies to challenge the stable regime to create a broader reconfiguration (Chapter 17; O'Neill et al., 2018).

Case Studies

Case Study 6.1: Urbanization and Climate Change in the Himalayas – Increased Water Insecurity for the Poor

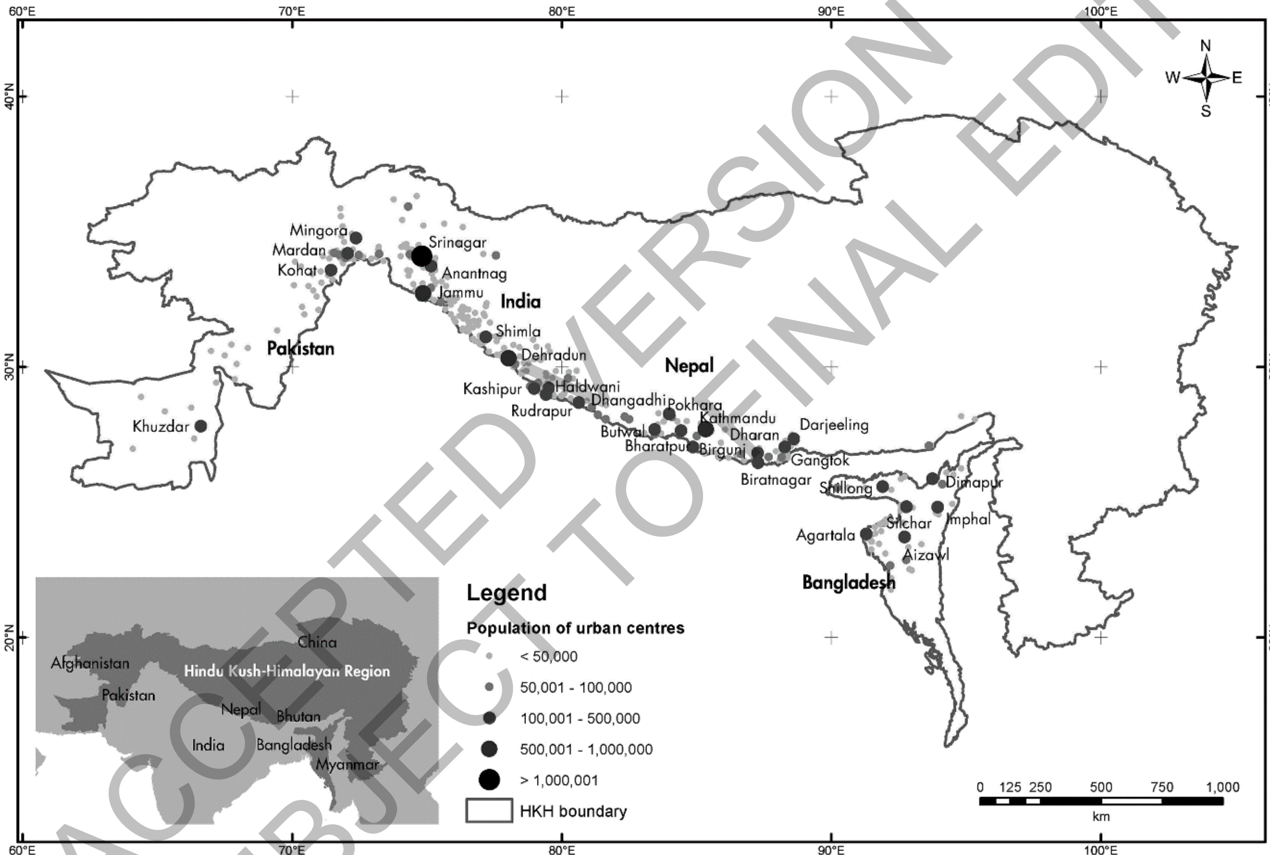


Figure 6.6 Urbanisation in Hindu-Kush Himalayan Region Figure based on (Singh et al., 2019b)

The Hindu Kush Himalayan region extends roughly over 3,500 km covering eight countries - Afghanistan, Pakistan, Nepal, China, India, Bhutan, Bangladesh, and Myanmar. Projections show that by 2050, more than 50% of the population in Hindu Kush countries will live in cities (UNDESA, 2014). The region is home to 10 major river basins that feed south and south-east Asia. In 2017, the total population in the ten major river basins with their headwaters in the region was around 1.9 billion, including 240 million in the mountain and hills of the Hindu Kush (Wester et al., 2019). The region is characterized by unique mountain topography, climate, hydrology, and hydrogeology. Each one of these factors plays an important role in determining the availability of water for people living in the Himalayas (Nepal, Flügel and Shrestha, 2014; Scott et al., 2019; Prakash and Molden, 2020). The total landmass that can support physical infrastructure for towns to develop is much less in the Hindu Kush Himalayan region as compared to the plains. Due to this physical constraint, the process of urbanization is slow in the region. Only 3 per cent of the total population in the region live in larger cities and 8 per cent in smaller towns (Singh et al., 2019b). However, there has been an increase in urbanization largely due to regional imbalances in providing economic opportunities for the poor. People from rural areas are flocking to the nearest urban centres in search of employment and other economic opportunities (Singh and Pandey, 2019). As a result, the share of urban population is increasing in the region, while that of the rural population is declining.

One of the major challenges of urbanization in the Himalayas is sprawling small towns with populations of under 100,000 (see Figure 6.6). These towns are expected to become major urban centres with a decade due to high growth rate. A recent study by Maharjan et al. (2018) on migration documented that 39% of rural communities have at least one migrant, of whom 80% are internal and the remaining 20% are international. Around 10 per cent of the migration is reported as environmental displacement. Most of the migration is of male which forms an important aspect of gendered vulnerability (Sugden et al., 2014; Goodrich, Prakash and Udas, 2019). The ever-expanding urban population in the Himalayas generates many challenges especially in the context of climate change adaptation. First, unplanned urbanization is causing significant changes in land use and land cover with recharge areas of springs being reduced. Most of the towns in Hindu Kush Himalayan region meet their water needs using supplies from springs, ponds, and lakes which largely interlinked systems, Water insecurity in hill towns are becoming an order of the day (Virk et al., 2019; Bharti et al., 2019; Singh et al., 2019a; Sharma et al., 2019). Second, climate-induced changes in the physical environment include increased rainfall variability. Due to this, heavy rains are becoming frequent and are leading to more landslides. Third, global warming has increased the average temperature in the Himalayas which has caused glacier melt and subsequent change in hydrological regimes of the region. One of the contributing factors of glacial decline is also the deposition of black carbon (Gautam et al., 2020; Gul et al., 2021) which is contributed by burning of crop residue in Punjab (Kant et al., 2020). These critical stressors – climatic and non-climatic, are adversely affecting the socio-ecology of urban conglomerations in the region (Pervin et al., 2019). Encroachment or degradation of natural water bodies and the disappearance of traditional water systems such as springs are evident (Shah and Badiger, 2018; Sharma et al., 2019). While water availability in these towns has been adversely affected by the climatic and socio-economic changes, demand for water has increased greatly (Molden, Khanal and Pradhan, 2018). Some of the towns are major tourist attractions that create a floating population in peak tourist seasons challenging the carrying capacities of the towns. The residents must cope with water scarcity as the demand for water increases in peak seasons and water distribution through the public water supply systems becomes highly inequitable (Raina, Gurung and Suwal, 2018). The usual challenges of utilities being inefficient applies in these areas too though it becomes much more critical as the sources of water are limited and the local geology limits the ability to access groundwater. All these processes are resulting in increased water insecurity for the poor and marginalised in urban towns of Hindu Kush (Prakash and Molden, 2020). To cope with the scarcity situation, people are adapting through various means such as rationing of intra-household water access, groundwater extraction to access water supply (Virk et al., 2019; Bharti et al., 2019; Sharma et al., 2019). This is due to lack of long-term strategies and options provided by utilities.

Case Study 6.2: Semarang, Indonesia

The City of Semarang, on the northern coast of Central Java in Indonesia, has a population of nearly 1.8 million (CBS, 2019). The city has experienced rapid urbanization over last three decades, with the population almost doubling and density reaching 4,650 people per square kilometre (Handayani and Rudiarto, 2014; Handayani et al., 2020b). Semarang is vulnerable to sea level rise, tidal flooding, and inundation (Suhelmi and Triwibowo, 2018; Yuniartanti, Handayani and Waskitaningsih, 2016), risks which are worsened by land subsidence along the coast (Abidin et al., 2013). Globally, land subsidence is a notable compounder of climate change-induced sea level rise and coastal flooding (Bagheri et al., 2021). In Semarang, the land subsidence rate is projected to be up to 60 millimetres per year (Abidin et al., 2013; Bott et al., 2021). Approximately 20% of the city's coastline is characterized as extremely vulnerable due to sea level rise and enhanced land subsidence (Husnayen et al., 2018), with the north-eastern portions of the city experiencing larger subsidence than the rest (Yastika, Shimizu and Abidin, 2019). Associated public health and sanitation risks are also evident, including increasing outbreaks of dengue fever and diarrhoea (Pratama et al., 2017; Indonesia Ministry of Health, 2020).

The City of Semarang first engaged with climate change in 2009, when the Rockefeller Foundation launched the Asian Cities Climate Change Resilience Network (ACCCRN), an initiative to develop resilience capacity across secondary and rapidly growing cities in South and Southeast Asia (Reed et al., 2015). Semarang was a pilot city for ACCCRN from 2009 to 2016, when it introduced a participatory approach to planning and decision-making that challenged the government-dominated tradition in the city, and in turn played a key role in Semarang's climate adaptation and resilience planning process (Orleans Reed et al., 2013; Moench, 2014; Kernaghan and Da Silva, 2014). A City Team was formed in 2010 consisting of City Environmental Agency (BLH – *Badan Lingkungan Hidup*), Regional Disaster Management Agency (BPBD - *Badan Penanggulangan Bencana Daerah*), Water Resources Management Office (PSDA - *Kantor Dinas Pengelolaan Sumber Daya Air*), Regional Planning and Development Agency (BAPPEDA - *Badan Perencanaan Pembangunan Daerah*), local universities, and NGOs such as the Bintari Foundation, with technical support from Mercy Corps Indonesia (Nugraha and Lassa, 2018).

The City Team was first established within the City Environment Agency (BLH) but was then transferred to the Development and Planning Agency (BAPPEDA) (Lassa, 2019). This corresponded to a shift in framing of climate change from an environmental priority to encompassing broader development issues such as economic development, housing, and infrastructure delivery. By asserting that climate change affects the operations of every critical sector across the city, the number of municipal agencies involved in climate change programming increased significantly (Setiadi, 2015). Most notably, this approach helped the municipal health agency to recognize the relationship between climate change and health (Setiadi, 2015),and helped to shift the emphasis of dengue fever management towards a more proactive community-based health early warning system (Pratama et al., 2017). In 2017, these measures helped to reduced dengue fever infection rates by 56% compared to 2011-2016 levels (Indonesia Ministry of Health, 2020). ACCCRN also supported policy experimentation through implementing rainwater harvesting facilities and a community-based flood early warning system (Archer and Dodman, 2015; Yuniartanti, Handayani and Waskitaningsih, 2016; Sari and Prayoga, 2018). These projects were designed in conjunction with national government investments in flood management infrastructure, which led to a reduction in the city's inundated area by 24% or approximately 1% of the total urban area (Semarang City Government, 2016).

Building on Semarang's ACCCRN experience, the city then became a member of the Rockefeller Foundation's 100 Resilient Cities (100RC) program between 2016 and 2018. As in ACCCRN, this new process emphasized stakeholder involvement, with the previous City Team recast as a team of City Resilience Officers (CRO), which was in turn led by the City Mayor and received strategic advisory support from the City Secretary. Semarang synthesized its experiences in climate adaptation planning through the *Resilient Semarang Strategy* published in May 2016 (Semarang City Government, 2016). The *Resilient Semarang Strategy* (2016) acknowledged that urban resilience must be pursued in a comprehensive and inclusive manner and highlighted 18 strategies across 6 themes –water and new energy, new economy, disaster and disease, integrated mobility, transparency of public information, and competitive human resource – to be mainstreamed into the revision of the Mid-Term Regional Development Plan (RPJMD - *Rencana Pembangunan Jangka Menengah Daerah*) of 2016-2021. City Resilience Officers were formally appointed to serve on the RPJMD team, thereby formalizing climate resilience as a critical item on the RPJMD program list.

100RC engagement allowed Semarang's resilience programs to appear on 100RC's "marketplace" of municipal projects, allowing them to be connected with bi-/multi-lateral donor resources, while continuing to align projects with goals articulated within the Mid-Term Regional Development Plan. The 100RC marketplace is a *resilience platform* that showcases particular initiatives of 100RC network cities to potential *resilience partners*, thereby attracting investment and donor support to Semarang's resilience programs. Examples include the Water as Leverage (WaL) project that has been working to conserve urban water resources in the face of climate change since 2018 (Handayani et al., 2020a; Laeni et al., 2021) and the Transboundary Flood Risk Management Through Governance and Innovative Information Technology Program (TRANSFORM) that has been helping Semarang tackle flood risks beyond city boundaries through reforestation, development of dry wells and swales in upstream areas, as well as promoting cross-region dialogue (Global Resilience Partnership, 2018). Other collaborations focused on developing resilience indicators (ARUP, 2018; Rangwala et al., 2018). For example, the Zurich Flood Resilience Program implemented resilience measurement tools in 16 sub-districts along the West Flood Canal. Results of the assessment were then used to develop local disaster contingency plans.

The conclusion of the Rockefeller Foundation's formal engagement in Semarang in 2018 has brought forth questions about continued financial and institutional support for climate adaptation action in the city.

Increasing land subsidence will also likely overwhelm current efforts to incrementally adapt to sea level rise and coastal flooding (Abidin et al., 2013). Still, the Semarang case study does highlight several key lessons for urban climate governance in secondary rapidly urbanizing cities in the Global South. First, transnational institutions and partnerships are critical enablers (Aisya, 2019; Setiadi, 2015; Chu, Hughes and Mason, 2018; Handayani et al., 2020a). Institutions such as the Rockefeller Foundation foster programmes and investment in the city, leverage access to adaptation funding, accelerate climate mainstreaming into wider urban sectors, and promote better knowledge management (Setiadi, 2016). However, such opportunities are also supported by the city's ability to further mobilize its own resources in the long-term and remove its dependency on the national government and transnational supporters (Handayani et al., 2020a). Second, scaling up of programmes and replication of adaptation actions are increasingly important to close the gap between planning and implementation (Setiadi, 2016). It is evident that increased community empowerment and participation can help fill this gap (Hadi, 2018; Miladan, 2016) but this must also be evidence-based to ensure its applicability and effectiveness (Suarma et al., 2018). Questions remain around how to determine and assess evidence-based participatory adaptation at the local level. Third, sustainable financing (from both external and internal sources) to support proposed adaptation strategies is essential as it allows for more capacity building, technology transfer, and program implementation in the long run (Handayani et al., 2020a; Laeni et al., 2021; Hadi, 2017). An example is the development of a water retention on the eastern coast of Semarang using a collaborative financing model, which helped further adaptation by protecting water resources for local industries as well as promote the idea of land value capture for community residents.

Case study 6.3: Institutional Innovation to Improve Urban Resilience: Xi'xian New Area in China

Located in Northwest China and the Silk Road Economic Belt, Xi'Xian covers a total of 882 square kilometres of the border zone of two cities of Xi'an and Xianyang, Shaanxi province. Xi"xian accommodates a registered population of 1.06 million with a planned area of 272 square kilometers reserved for urban development. As a new engine for promoting the West Development Strategy and people-centred urbanization in the northwest China, Xi'xian has paved the way for China's ecological city agenda since January 2014.

Xi'xian aims to build a 'modern garden city' when it was selected as national demonstration sites for Sponge City (SC) during 2015-2018 and Climate Resilient City (CRC) during 2017-2020. Under the changing climate, the old cities of Xi'xian suffers urban heat island, drying and water scarcity, heavy rains and waterlogging, thunderstorm and so on, which bring adverse effects to transportation, construction, cultural relics tourism resources, and other industries (Ma, Yan and Zeyu, 2021). Sponge City status requires innovation to reduce flood risk through design to absorb, store, and purify rainfall and storm water in an ecologically friendly way that reduces dangerous and polluted runoff. When required, the stored water is released and added to the urban water supply (MoHURD, 2014). As Climate Resilient City the aim is to adapt to climate risk and environmental change, by integrating climate resilience into urban renewal and revitalization.

In practice, building ecological cities in China has focused more on hard measures than institutional innovation (Li et al., 2020). Among one of nineteen national-level New Areas in China, Xi'xian enjoys special preferential policies in the fields of fiscal autonomy, investment and tax policy and permission in land utility for industrial development purpose. These policy freedoms allow Xi'Xian to explore adaptation options. This has opened engagement with business through an urban construction investment group sponsored and invested in jointly by Xi'Xian Management Committee (administrative authority) and local enterprises (Wei and Zhao, 2018). Second, the municipal government has simplified administrative systems to reduce the project waiting period from evaluation to approval to 50 days. Third, a green financial mechanism creates a leverage effect for national funding, including the first provincial Green Sponge Development Fund (1.2 billion RMB) and in Shaanxi, special funding from the Urbanization Development Fund (2.64 billion RMB). Furthermore, a public-private partnership model with a whole-lifecycle-management approach has been introduced, raising funding of 1.24 billion RMB with a packaged project including public pipelines and sewage water treatment facilities.

Such institutional and financial support have allowed Xi'xian to implement a Pilot Construction Plan and Three-year Action Plan for Adapting to Climate Change. In 2020, Xixian formed an urban ecology system including 21 square meters of green space per capita. The old cities' underground drainage pipe network has been replaced by sponge designs such as green corridors, grass ditches, water storage gardens, and recessed green spaces. The 10 waterlogging prone points in Xi'xian New Area have been eliminated and the green area has alleviated urban heat, with average temperature about 1 degree lower than the neighboring densely populated mega-cities of Xi'an and Xianyang. Groundwater in the New Area has also risen by 3.43 meters compared with 2015.

At the end of 2020, Xi'xian New Area has built 2.4 million square meters of modern garden cities, more than 50 kilometers of sponge roads, 1.4 million square meters of resilient park green space and established a green coverage of more than 50% of the urban space. The target of becoming a green city in which everyone can "see green in 100 meters, step into garden every 300 meter" has been realized (Ma et al., 2021). The urban parks and green spaces play a role in regulating local microclimate and also improve the urban environmental amenities for residents. In a comprehensive performance assessment for the Climate Resilient Cities facilitated by the Climate Change Department of the Ministry of Ecology and Environment (MEE), the Xi'xian ranked the No.9 among all of the twenty eight pilot cities.

Case Study 6.4: San Juan: Multi-Hazard Risk and Resilience in Puerto Rico and its Urban Areas

This case study illustrates multi-hazard risk and reviews the formation of a multi-stakeholder adaptation governance regime as one response to this.

In two weeks in 2017 Puerto Rico experienced two powerful hurricanes, Irma (category 5) and María (category 4). The compound effects decimated the island's power, water, communications, and transportation infrastructure and an estimated 2,975 people lost their lives (Irvin-Barnwell et al., 2020; Santos-Burgoa et al., 2018). Soon after, while many homes still had no electricity or roofs and the tree canopy was still bare, Puerto Ricans were faced with cascading effects including environmental health impacts from air pollution, extreme heat and mosquitoes (Ortiz et al., 2020). In 2020, while still recovering Puerto Ricans experienced earthquakes, extreme African dust events, intense coastal and urban floods, and the COVID-19 pandemic (Keck, 2020; NASA Explore Earth, 2020; NASA/JPL-Caltech, 2020). These events continue to unveil unresolved conditions of social vulnerability and its root causes in economic poverty, social inequities, aged and deteriorating infrastructure, and population loss (Bonilla and LeBrón, 2019). Combined with limited past investment in climate change adaptation and underlying governance challenges including corruption, bankruptcy, and political crisis (Holladay et al., 2019) this has constrained a more climate resilient development for Puerto Rico.

It is in this context that government, academic institutions and local civil society have taken important steps and often joint action towards mitigation and adaptation. Federal funding included US$20 billion of disaster recovery funding with US$8 billion allocated for adaptation and resilience projects, such as flood risk mitigation. During the year 2020, the Federal Emergency Management Agency (FEMA) approved US$13 billion to rebuild the power grid and education system (Delgado, 2020). These programs allow communities and local governments to plan and implement strategies and build new infrastructure that reduces risks and builds long-term adaptive capacities. The Government of Puerto Rico also approved two key climate adaptation policies in 2019. The Puerto Rico Mitigation, Adaptation and Resilience to Climate Change Law (Law 33, Senate Bill PS 773) established, for the first time in the island's history, a legal framework that acknowledges that the climate is changing and threatens the quality of life. The law recognizes important scientific projections for the island, including an increase of 0.5 to 1 meter in sea levels by 2015 and maximum temperatures of up 2.5 C and precipitation decrease of up to 50% by 2100 (Gould et al., 2018). The law generated the formation of an Expert and Advisory Committee on Climate Change to develop the plan with specific recommendations and present it to the Legislature within a year of the passing of the law in 2020. Along with strategies to specifically protect and build the resilience of urban and rural communities to future climate disasters, the law establishes sustainable development goals, including water and food security, urban planning and densification, and transition to renewable and alternative forms of energy. The energy target is reinforced by another key state policy approved in 2019 in response to the failed energy infrastructure during Hurricane María, the Puerto Rico Energy Public Policy Act (Senate Bill PS 1121). This law calls for a transition to 100% renewable and alternative energy by 2050.

Puerto Rico has a strong science base that produced extensive knowledge on climate change and sustainability long before Hurricane María. The Puerto Rico Climate Change Council has collected and synthesized scientific information for Puerto Rico since before its formation in 2009. Many Puerto Rican scientists were also editors and authors on Chapter 20: US Caribbean Region for 4th US National Climate Assessment (Gould et al., 2018). The National Institute of Island Energy and Sustainability (INESI in Spanish) recently published a catalog with more than 60 scientists and experts working on energy and sustainability innovations in the University of Puerto Rico (UPR) system. The scientific community became very active after the hurricane in efforts to empower local groups and communities to build more sustainable and resilient futures. UPR Environmental Health scientists worked with communities to design and implement risk reduction action plans, including nature-based solutions, through the Community Climate Actions Plans and the Puerto Rico Community Resiliency Initiative sponsored by Fundación Comunitaria de Puerto Rico and Education Development Center-Regional Education Laboratories, Northeast and Islands. A successful example of these alliances is the development of the First Solar Power Community in Toro Negro, Puerto Rico. These initiatives were inspired by principles of human-centered design, a problem-solving approach that starts with the people impacted the most by the problem to be solved. In San Juan, the capital and major urban centre of the island, scientists from UPR and the US Forest Service International Institute of Tropical Forestry worked with local stakeholders and communities to develop sustainable and transformative urban futures with the support of the Urban Resilience to Extreme Events Sustainability Research Network (UREx SRN). The UREx SRN is a knowledge network of ten cities in the US and Latin America and twenty other institutions building scientific knowledge, models, and participatory tools to build resilience and transformative capacities for cities.

Perhaps the greatest source of adaptive capacity that emerged after the hurricane came from the civic sector and community-based organizations and local residents. Hundreds of non-profit and grassroots organizations became active in disaster recovery and are now catalyzing actions to advance social transformation and sustainable development. In the energy sector, numerous communities and NGOs developed new action plans to promote transitions to renewable energy and community-based micro grids, such as the Queremos Sol initiative (https://www.queremossolpr.com/), and the establishment of solar panels in community centers and residences by the Puerto Rico Community Foundation and Resilient Power Puerto Rico. The San Juan Bay Estuary Program, an NGO in the San Juan metropolitan area, launched alongside the Clinton Global Initiative the development of a Watershed-Based Mitigation Plan, the first watershed-based plan for the metro region. The organization has established resilience hubs to support the community with critical resources, communications, and energy supply during an emergency. In many of the most isolated areas across the island where government aid did not reach them for months, the communities that self-organized during recovery are also leading examples of community social-ecological resilience. In Utuado, one of the hardest hit areas by the hurricane, their main community organization known as COSSAO (Corporación de Servicios de Salud y Desarrollo Socioeconómico, El Otoao) emerged from the hurricane with a strong and holistic sustainable development vision - the Tetuan Reborn initiative - to improve the socio-economic status and health of community members while building capacity for disaster resilience through various initiatives. The long-term outcome of this initiative is to support efforts toward self-empowerment within neighbourhoods by identifying and designing viable solutions to hurricane- related and economic development challenges specific to the local context including constructing a primary health care clinic, a public health promoter programme, pursuing farms rehabilitation, promoting agritourism, agro-therapy and education (Holladay et al., 2019).

Adaptation efforts, however, continue to face many governance hurdles. Up to 2020, only 2-3% of the US$20 million Federal Government recovery funds had been spent with hundreds of families that lost their homes or roofs in 2017 yet to receive the help they need (Colón Almenas, 2020). Lack of administrative capacities, coordination across sectors and efforts, transparency and accountability are some of the governance barriers that keep recovery and transformation efforts from materializing (Lamba Nieves and Marxuach, 2020). Puerto Ricans are now contending with the reality that the disaster they are experiencing is not an outcome of a singular event but of multiple hazards converging with pre-existing vulnerabilities and low adaptive capacities creating severe multi-hazard risk to the island (Eakin, Muñoz-Erickson and Lemos, 2018; Gould et al., 2018). Many Puerto Ricans now question when the disaster began and when it ended because they have been living in a state of chronic crisis (Bonilla and LeBrón, 2019).

Case Study 6.5: Climate-resilient Pathways in Informal Settlements in Cities in Sub-Saharan Africa

Informal settlements account for over three-quarters of residential areas in sub-Saharan Africa and have grown rapidly over the last three decades (Visagie and Turok, 2020). Informal settlements will remain home to a significant proportion of the urban population of this region which is projected to grow by 2.5 times between 2020 and 2050 (UNDESA, 2018), driven by a complex set of underlying factors including socio-economic conditions, inadequate planning systems, local and foreign investment patterns, and rural to urban migration (De Longueville et al., 2020). Yet residents of informal settlements are often excluded from macro-level visions and policies that seek to make cities safer and improve resilience (Adenle et al., 2017; Pelling et al., 2018b). This case study compares the experience of collective action to manage risk in the informal settlements of Freetown, Sierra Leone with other cases in Sub-Saharan Africa. These examples show how local knowledge and capacity, engagement of policy makers in meaningful ways with residents of informal communities, and institutional change, can combine to deliver adaptation outcomes at a city scale (Kareem et al., 2020).

Despite their diversity and differences across the continent (Kovacic et al., 2019), informal settlements are frequently located in hazard-prone areas, with residents living in precarious housing conditions on marginal lands (Badmos et al., 2020; Kironde, 2016), lacking essential services and risk reducing infrastructure, and often developing outside the legal systems intended to record land tenure and ownership (Satterthwaite et al., 2020; Adelekan et al., 2015). Consequently, they are particularly vulnerable to climate change, and the urban poor residents suffer disproportionate burdens and losses from natural hazards, which undermines urban resilience (Williams et al., 2019). Recent impacts from flooding have brought wide-spread devastation to urban poor residents in major coastal urban centres including Accra, Lagos, Freetown, Maputo, and Dar es Salaam, resulting in injury and death, displacement of people, loss of assets, destruction of public infrastructure, and disruption to livelihoods and economies (Douglas et al., 2008; Adelekan, 2010; Yankson et al., 2017; Allen et al., 2017). Flooding and long-term inundation also lead the spread of diseases and health risks (Sverdlik, 2011; Zerbo, Delgado and González, 2020). Climate change will also bring stresses such as city-wide reductions in freshwater availability, and heat waves that have particularly severe consequences for residents of poorly built homes in informal settlements (Pasquini et al., 2020; Kayaga et al., 2021; Wilby et al., 2021).

In response to these risks, a wide range of adaptation efforts have been implemented in cities across sub-Saharan Africa (Hunter et al., 2020). In Freetown, informal settlement residents have led data generation efforts that capture the value of local knowledge in understanding climate risk. Through partnerships with NGOs and research institutions, informal settlement residents have mapped climate hazard hotspots using geo-referenced tools, producing both digital and hardcopy outputs that serve as a blueprint for climate-informed community development discourses (Allen et al., 2020b; Visman et al., 2020). Similarly, residents of informal settlements in Dar es Salaam, Tanzania, have profiled community climate and health risks by using an adaptation of the 'Action at the Frontline' methodology developed by the Global Network of Civil Society Organisations for Disaster Reduction (GNDR). Locally-informed risk profiles support the development of community action plans based on prioritization and ranking of scaled-down interventions that communities can collectively do on their own (Osuteye et al., 2020). This process highlights the lived experiences of climate change, and allows communities to develop deliberation spaces, communal solidarity and cohesion, and share adaptation strategies (Sakijege et al., 2014). Such sharing and peer-to-peer learning is particularly useful because adaptive capacities are unevenly distributed among exposed populations (Ajibade and McBean, 2014). The community-generated assessments and data consider the range of environmental, socio-economic, and political factors that contribute to a better understanding of how climate change affects the vulnerability of low-income urban residents, and how this changes over time.

Data that is generated and owned by residents of informal settlements provides a basis for making the risks facing these neighbourhoods more visible to city planners, and for enabling collaboration between a range of urban stakeholders (Dobson, 2017). In Freetown, this process has been led by the Federation of the Urban and Rural Poor (FEDURP) and the Centre for Dialogue on Human Settlement and Poverty Alleviation (CODOHSAPA). The FEDURP belongs to the global Slum Dwellers International network, committed to empowering poor residents in urban spaces and has a presence in several other African cities (Macarthy et al., 2017). With the support of CODOHSAPA, FEDURP coordinates Community Development Committees (CDC) and Community Disaster Management Committees (CDMC) in nearly all the informal settlements in the city. Both CODOHSAPA and FEDURP work closely with the local research institution, the Sierra Leone Urban Research Centre (SLURC). SLURC has played an essential role in curating spaces for continuous learning and relationship-building between FEDURP and community residents, including the formation of "Community Learning Platforms" (CLP) for mixed groups of community actors (City Learning Platform, 2019) to build their capacities to address climate risk collectively. This is done by drawing on the data, agency and mobilisation potential of community organizations in informal settlements. In the coastal settlement of Cockle Bay at the western end of the city, uncontrolled traditional land reclamation ("banking") along the shores progressively exposed residents to perennial floods from tidal surges, and the settlement received regular threats of evictions from city authorities. However, residents have drawn on their climate risk knowledge and hazard profiling to self-manage a process of action planning resulting in a decision to prohibit further land reclamation. It also identified and demarcated an exterior boundary of the settlement and planned and constructed new drainage channels to carry away run-off water within the community (Allen et al., 2017). The community organizations have subsequently successfully negotiated with the Ministry of Environment to formalise this new exterior boundary, which has led to the authorities dropping their threats of evictions.

The approach taken in Freetown demonstrates a pathway to adaptation that is based on a more people-centred approach to urban planning that understands the aspirations of urban residents, addresses climate risk, and advances sustainable development (Woodcraft et al., 2020; Fraser et al., 2017). It further provides an example of the ways in which different sources and scales of data can be co-produced (Kovacic et al., 2019) and targeted interventions can be co-designed with community residents (Musango et al., 2020). The community-generated data on climate and health risks and the subsequent strategic action plans developed through local community organizations' work have been recognized and incorporated into a new city-wide initiative led by the Office of the Mayor, dubbed Transform Freetown (Allen et al., 2020a). The action has expanded the political space for the urban poor's collectives to strategically engage in urban resilience planning, highlighting the value and potential of participatory processes and community-generated data.

[START CROSS-WORKING GROUP BOX URBAN HERE]

Cross-Working-Group Box URBAN: Cities and Climate Change

Authors: Xuemei Bai (Australia), Vanesa Castan Broto (United Kingdom/Spain), Winston Chow (Singapore), Felix Creutzig (Germany), David Dodman (Jamaica/United Kingdom), Rafiq Hamdi (Belgium), Bronwyn Hayward (New Zealand), Şiir Kılkış (Turkey), Shuaib Lwasa (Uganda), Timon McPhearson (USA), Minal Pathak (India), Mark Pelling (United Kingdom), Diana Reckien (Germany), Karen Seto (USA), Ayyoob Sharifi (Japan/Iran), Diána Ürge-Vorsatz (Hungary)

Introduction

This Cross-Working Group Box on Cities and Climate Change responds to the critical role of urbanisation as a megatrend impacting climate adaptation and mitigation. Issues associated with cities and urbanization are covered in substantial depth within all three Working Groups (including WGI Box TS.14, WGII Chapter 6 'Cities, settlements and key infrastructure'; WGII regional chapters; WGII Cross-Chapter Paper 'Cities and settlements by the sea'; WGIII Chapter 8 'Urban systems and other settlements'). This Box highlights key findings from Working Groups II and III and substantial gaps in literature where more research is urgently needed relating to policy action in cities. It describes methods of addressing mitigation and adaptation in an integrated way across sectors and cities to advance sustainable development and equity outcomes; and assesses the governance and finance solutions required to support climate resilient responses.

Urbanisation: A Megatrend Driving Global Climate Risk and Potential For Low-Carbon and Resilient Futures

Severe weather events, exacerbated by anthropogenic emissions are already having devastating impacts on people who live in urban areas, on the infrastructure that supports these communities and those of many other distant places (*high confidence*) (Cai et al., 2019; Folke et al., 2021). Between 2000 and 2015, the global population in locations that were affected by floods grew by 58-86 million (Tellman et al., 2021). The direct economic costs of all extreme events reached 210-268 billion USD in 2020 (Aon, 2021) or about $0.7 billion per day – this figure does not include knock-on costs in supply chains or days off work lost so that the actual economic costs could be far higher. Depending on RCP, between half (RCP2.6) and three-quarters (RCP8.5) of the global population could be exposed to periods of life-threatening climatic conditions arising from coupled impacts of extreme heat and humidity by 2100 (see WGII 6.2.2.1; WGII Figure 6.3; (Mora et al., 2017a; Zhao et al., 2021; Huang et al., 2019)).

The interdependencies between infrastructure, services and networks driven by urban production and consumption mean that urban systems are now global – remittance flows and investments reach into rural places shaping natural resource use far from the city and bring risk to the city when these places are impacted by climate change. This urbanization megatrend (Kourtit, Nijkamp and Scholten, 2015) amplifies as well as shapes the potential impacts of climate events. It provides the economic and institutional framework for integrating the aims and approaches that can deliver mitigation, adaptation and sustainable development (*medium evidence, high agreement*) (Zscheischler et al., 2018; Dawson et al., 2018; Tsavdaroglou et al., 2018). For cities facing flood damage wide-ranging impacts have been recorded on other urban areas (Simpson et al., 2021; Carter et al., 2021) as production and trade is disrupted (Shughrue et al., 2020). In the absence of integrated mitigation and adaptation across and between infrastructure systems and local places, impacts that bring urban economies to a standstill can extend into supply chains or across energy networks causing power outages.

Urban settlements are drivers of climate change, generating about 70 percent of global CO2eq emissions (*high confidence*) (WGI Box TS.14; WGIII 8 ES; WGII 6.1, WGII 6.2). This global impact feeds back to cities through the exposure of infrastructure, people and business to the impacts of climate related hazards. In especially the larger cities this climate feedback is exacerbated by local choices in urban design, land-use, building design, and human behaviour (Viguié et al., 2020) that shape local environmental conditions. Local and global conditions influence the nature of hazards in urban centres: urban form can add up to two degrees to warming, concretisation of open space can increase run-off, and building height and orientation influences wind direction and strength (WGII 6.3).

Building today for resilience and lower emissions is far easier than retrofitting tomorrow. As urbanisation unfolds its legacy continues to be the locking in of emissions and vulnerabilities (*high confidence*) (Ürge-Vorsatz et al., 2018; Seto et al., 2016). Retrofitting, disaster reconstruction and urban regeneration programmes offer scope for strategic direction changes to low-carbon and high resilience urban form and function if they are inclusive in design and implementation. Rapid urban growth means new investment, new buildings and infrastructure, new demands for energy and transport and new questions about what a healthy and fulfilling urban life can be. The US$90 trillion expected to be invested in new urban development by 2030 (NCE, 2018), is a global opportunity to place adaptation and mitigation directly into urban infrastructure and planning, social policy including education and health care and environmental management (Ürge-Vorsatz et al., 2018). If this opportunity is missed, if business as usual urbanisation persists, then social and physical vulnerability will be not be so easily confronted.

The benefits of actions taken to reduce GHG emissions and climate stressors diminish with delayed action, indicating the necessity for rapid responses. Delaying the same actions for increasing the resilience of infrastructure from 2020 to 2030 is estimated to have a median cost of at least US$1 trillion (Hallegatte et al., 2019) while also missing the carbon emissions reductions required in the narrowing window of opportunity to limit global warming to 1.5°C (WGI). In contrast, taking integrated actions towards mitigation, adaptation and sustainable development will provide multiple benefits for the health and wellbeing of urban inhabitants and avoid stranded assets (WGII 6.3, WGII 17; WGIII 5; WGIII 8.2; Cross-Chapter Box FEASIB in Chapter 18).

The Policy-Action Gap: Urban Low-Carbon and Climate Resilient Development

Cities are critical places to realize actions on both adaptation and mitigation simultaneously with potential co-benefits that extend far beyond cities (*medium evidence high agreement*) (Grafakos et al., 2020; Göpfert, Wamsler and Lang, 2019). Given rapid changes in the built environment, transforming the use of materials and the land intensiveness of urban development including in many parts of the Global South in the next decades will be critical, as well as mainstreaming low-carbon development principles in new urban development in all regions. Much of this development will be self-built and 'informal' - and new modes of governance and planning will be required to engage with this. Integrating mitigation and adaptation now rather than later, through reshaping patterns of urban development and associated decision-making processes, is a prerequisite for attaining resilient and zero carbon cities.

While more cities have developed plans for climate adaptation and mitigation since AR5, many remain to be implemented (*limited evidence, high agreement*) (Araos et al., 2017; Olazabal and De Gopegui, 2021; Aguiar et al., 2018). A review of local climate mitigation and adaptation plans across 885 urban areas of the European Union suggests mitigation plans are more common than adaptation plans, and that city size, national legislation, and international networks can influence the development of local climate plans with an estimated 80% of cities with above 500,000 inhabitants having a mitigation and/or an adaptation plan (Reckien et al., 2018b).

Integrated approaches to tackle common drivers of emissions and cascading risks provide the basis for strengthening synergies across mitigation and adaptation and managing possible trade-offs with sustainable development (*limited evidence, medium agreement*) (Grafakos et al., 2019; Landauer, Juhola and Klein, 2019). Analysis of 315 local authority emission reduction plans across the European Union reveals that the most common policies cover municipal assets and structures (Palermo et al 2020). Estimates of emission reductions by non-state and sub-state actors in ten high-emitting economies projected GHG emissions in 2030 would be 1.2–2.0 GtCO2e/year or 3.8%–5.5% lower compared to scenario projections for current national policies (31.6–36.8 GtCO2e/year) if the policies are fully implemented and do not change the pace of action elsewhere (Kuramochi et al 2020). The value of integrating mitigation and adaptation is underscored in the opportunities for decarbonizing existing urban areas, and investing in social, ecological, and technological infrastructure resilience (WGII 6.4). Integrating mitigation and adaption is challenging (Landauer, Juhola and Klein, 2019) but can provide multiple benefits for the health and wellbeing of urban inhabitants (Sharifi, 2020).

Effective climate strategies combine mitigation and adaptation responses, including through linking adaptive urban land use with GHG emission reductions (*medium evidence, high agreement*) (Xu et al., 2019; Patterson et al., 2021). For example, urban green and blue infrastructure can provide co-benefits for mitigation and adaptation (Ürge-Vorsatz et al., 2018) and is an important entry point for integrating adaptation and mitigation at the urban level (Frantzeskaki et al., 2019). Grey and physical infrastructure such as sea defences can immediately reduce risk, but can also transfer risk and limit future options. Social policy interventions including social safety nets provide financial security for the most at risk and can manage vulnerability both determined by specific hazards or independently. Hazard independent mechanisms for vulnerability reduction – such as population wide social security - provide resilience in the face of unanticipated cascading impacts or surprise and novel climate related hazard exposure. Social interventions can also support, or be led by ambitions to reach the Sustainable Development Goals (Archer, 2016). Climate resilient development invites planners to plan interventions and monitor the effectiveness of outcomes beyond individual projects and across wider remits that reach into sustainable development. Curbing the emission impacts of urban activities to reach net zero in the next decades while improving the resilience of urban areas necessitates an integrated response now.

Key gaps in knowledge include urban enabling environments; how smaller settlements, low-income communities living in slums and informal settlements – but also those in rental housing spread across the city; and actions to reduce supply chain risk can be supported to accelerate equitable and sustainable adaptation in the face of financial and governance constraints (Birkmann et al., 2016; Shi et al., 2016; Dulal, 2019; Rosenzweig et al., 2018b).

Enabling Action

Innovative governance and finance solutions are required to manage complex and interconnected risks across essential key infrastructures, networks and services and meet basic human needs in urban areas (*medium confidence*) (Moser et al., 2019; Colenbrander, Dodman and Mitlin, 2018). There are many examples of ‘ready-to-use’ policy tools, technologies and practical interventions for policy makers seeking to act on adaptation and mitigation (Keenan, Chu and Peterson, 2019; Bisaro and Hinkel, 2018; Chirambo, 2021). Tax and fiscal incentives for business and individuals can help support city-wide change behaviour towards low carbon and risk reducing choices. Change can start where governments have most control – in public sector institutions and investment but the challenge ahead requires partnership with private sector and community actors acting at scale and with accountability. Urban climate governance and finance needs to address urban inequalities at the forefront if the urban opportunity is to realise the ambition of the Sustainable Development Goals.

Increasing investment at pace will put pressure on governance capability and transparency and accountability of decision making (*medium confidence*) (WG II 6.6.4.5). Urban climate action that actively includes local actors and is built on an evidence base open to independent scrutiny is more likely to avoid unintended, negative maladaptive impacts and mobilise a wide range of local capacities. In the long-run this is also more likely to carry public support, even if some experiments and investments do not deliver the intended social benefits. Legislation, technical capacity and governance capability is required to be able to absorb additional finance. About US$ 384 billion of climate finance has been invested in urban areas per year in recent years. This remains at about 10% of the annual climate finance that would be necessary for low-carbon and resilient urban development (Negreiros et al., 2021). Rapid deployment of funds to stimulate economies in recovery from COVID-19 have highlighted the pitfalls of funding expansion ahead of policy innovation and capacity building. The result can be an intensification of existing urban forms – exactly the kinds of choices and preferences that have contribute to risk creation and its concentration amongst those with little public voice or economic power.

Iterative and experimental approaches to climate adaptation and mitigation decision-making co-generated in partnership with communities, can advance climate resilient decarbonisation (*medium evidence, high agreement*) (Caldarice, Tollin and Pizzorni, 2021; Culwick et al., 2019; van der Heijden and Hong, 2021). Conditions of complexity, uncertainty and constrained resources require innovative solutions which are both adaptive and anticipatory. Complex interactions among multiple agents in times of uncertainty makes decision making about social, economic, governance, and infrastructure choices challenges and can lead decision-makers to postpone action. This is the case for those balancing household budgets, residential investment portfolios and city-wide policy responsibilities. Living with climate change requires changes to business-as-usual design making. Codesign and collaboration with communities through iterative policy experimentation can point the way towards climate resilient development pathways (Ataöv and Peker, 2021). Key to successful learning is transparency in policy making, inclusive policy processes and robust local modelling, monitoring and evaluation which are not yet widely undertaken (Ford et al., 2019; Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018).

The diversity of cities' experiences of climate mitigation and adaptation strategies brings an advantage for those city government and other actors willing to 'learn together' (*limited evidence, high agreement*) (Bellinson and Chu, 2019; Haupt and Coppola, 2019). While contexts are varied, policy options are often similar enough for the sharing of experiments and policy champions. Sharing expertise can build on existing regional and global networks, many of which have already placed knowledge, learning and capacity building at the centre of their agendas. Learning from innovative forms of governance and financial investment, and strengthening coproduction of policy through inclusive access to knowledge and resources, can help address mismatches in local capacities, strengthen wider Sustainable Development Goals and COVID-19 Recovery agendas (limited evidence, medium agreement). Perceptions of risk can greatly influence the reallocation of capital and shift financial resources (Battiston et al., 2021). Coupling mitigation and adaptation in an integrated approach offers opportunities to enhance efficiency, increases the coherence of urban climate action, generates cost savings and provides opportunities to reinvest the savings into new climate action projects to make all urban areas and regions more resilient.

Local governments play an important role in driving climate action across mitigation and adaptation as managers of assets, regulators, mobilizers and catalysts of action, but few cities are undertaking transformative climate adaptation or mitigation actions (*limited evidence, medium agreement)* (Heikkinen, Ylä-Anttila and Juhola, 2019). Local actors are providers of infrastructure and services, regulators of zoning, and can be conveners and champions of an integrated approach for mitigation and adaptation at multiple levels 9Limited evidence high confidence). New opportunities in governance and finance can enable cities to pool resources together and aggregate interventions to innovate ways of mobilizing urban climate finance at scale (White and Wahbah, 2019; Simpson et al, 2019; Colenbrander et al, 2019). However, research increasingly points towards the difficulties faced during the implementation of climate financing in situ, such as for example, the fragmentation of structures of governance capable of managing large investments effectively (Mohammed et al, 2019).

Scaling up transformative place-based action for both adaptation and mitigation requires enabling conditions including land-based financing, intermediaries and local partnerships (*medium evidence, high agreement*) (Chaudhuri et. al, 2021, Tirumala and Tiwari, 2021(Chu et al., 2019). Governance structures that combine actors working at different levels with different mix of tools are effective in addressing challenges related to implementation of integrated action while cross-sectoral coordination is necessary (Singh et al., 2020). Joint institutionalization of mitigation and adaptation in local governance structures can also enable integrated action (Göpfert et al., 2020; Hurlimann et al., 2021). However, the proportion of international finance that reaches local recipients remains low, despite the repeated focus of climate policy on place-based adaptation and mitigation (Manuamorn, 2019). Green financing instruments that enable local climate action without exacerbating current forms of inequality can jointly address mitigation, adaptation and sustainable development. Climate finance that also reaches beyond non-state enterprises, including SMEs, communities and NGOs, and is responsive to the needs of urban inhabitants, including disabled individuals and different races or ethnicities is essential for inclusive and resilient urban development (Colenbrander et al, 2019; Gabaldon-Estevan et al, 2019; Frenova, 2020). Developing networks that can exert climate action at scale is another priority for climate finance.

The urbanisation megatrend is an opportunity to transition global society. Enabling urban governance to avert cascading risk and achieve low-carbon, resilient development will involve coproduction of policy and planning, rapid implementation and greater cross sector coordination, monitoring and evaluation (*limited evidence, medium agreement)* (Grafakos et al., 2019; Di Giulio et al., 2018). New constellations of responsible actors are required to manage hybrid local-city or cross-city risk management and decarbonisation initiatives (*limited evidence, medium agreement*). These may increasingly benefit from linkages across more urban and more rural space as recognition of cascading and systemic risk brings recognition of supply chains, remittance flows and migration trends as vectors of risk and resilience. Urban governance will be better prepared in planning, prioritizing and financing the kind of measures that can reduce GHG emissions and improve resilience at scale and pace when considering a view of cascading risks and carbon lock-ins globally, while acting locally to address local limitations and capacities, including the needs and priorities of urban citizens (Udelsman Rodrigues, 2019; Colenbrander et al, 2018).

[END CROSS-WORKING GROUP BOX URBAN HERE]

[START FAQ6.1 HERE]

FAQ6.1: Why and how are cities, settlements, and different types of infrastructure especially vulnerable to the impacts of climate change?

Cities, settlements and infrastructure become vulnerable when investment decisions fail to take the risks of climate change fully into account. Such failures can result from a lack of understanding, competing priorities, a lack of finance or access to appropriate technology. Around the world, smaller cities and poorer populations are often most vulnerable and suffer the most over time, while large cities can register the greatest losses to individual events.

The world is urban. Billions of people live in towns and cities. Hardly anyone, even in remote rural locations, is separated from the flows of trade that connect the world and are held together by networks of transport and communication infrastructure systems. Connected networks once broken can cascade out, multiplying impacts across urban and rural areas. When major manufacturing centres or regionally important ports are impacted, global trade suffers. For example, flooding in Bangkok in 2011 led to a global shortage in semiconductors and a slowdown in the global computer manufacturing.

Despite cities generating wealth, additional vulnerability to climate change is being created in urban areas every day. Demographic change, social and economic pressures and governance failures that drive inequality and marginality mean that increasing numbers of people who live in towns and cities are exposed to flooding, temperature extremes and water or food insecurity. This leads to an adaptation gap, where rich neighbourhoods can afford strategies to reduce vulnerability while poorer communities are unable to do the same. Although this would be so even without a changing climate, climate change increases the variability and extremes of weather, exposing more people, businesses and buildings to floods and other events. The combination of rising vulnerability and increasing exposure translates to a growth in the number of people and properties at risk from climate change in cities worldwide.

Around the world, vulnerability is rising but differs considerably between and within urban areas. Settlements of up to 1 million people are the most rapidly expanding and also amongst the most vulnerable. These settlements often have limited community level organisation and might not have a dedicated local government. Coping with rapid population growth under conditions of climate change and constrained capacity is a major challenge. For large cities, multiple local governments and well organised community-based organisations interact with large businesses and national political parties in a complicated cocktail of interests that can interfere with planning and action to reduce vulnerability.

For the poorest living in urban slums, informal settlements or renting across the city, lack of secure tenure and inadequate access to basic services compound vulnerability. But even the wealthy in large cities are not fully protected from climate change related shocks. Just like breaks in infrastructure between towns and rural settlements, big city infrastructure can be broken by even local landslides, floods or temperature events with consequences cascading across the city. Electricity blackouts are the most common and can affect water pumping, traffic regulation, streetlights as well as hospitals, schools and homes. Still, it is the urban poor and marginalised who experience the greatest exposure, most vulnerability and least capacity to cope.

Rounds of exposure and impact can reduce the capacity of survivors to cope with future events. As a result, the already vulnerable and exposed become more vulnerable over time, increasing urban inequalities. But this need not be the case. Focussing on vulnerability reduction is not easy, it requires joined up action across social and economic development sectors together with critical infrastructure planning. It often also means partnering local government with informal and community-based actors. But there is considerable experience globally on what works and how to deliver reduced vulnerability for the urban poor and for cities as a whole. The challenge is to scale up this experience and accelerate its application to keep pace with climate change and address the adaptation gap.

[END FAQ6.1 HERE]

[START FAQ6.2 HERE]

FAQ6.2: What are the key climate risks faced by cities, settlements, and vulnerable populations today, and how will these risks change in a mid-century (2050) 2°C warmer world?

Climate change will interact with the changing physical environment in cities and settlements to create or exacerbate a range of risks. Rising temperatures and heat waves will cause human illness, morbidity as well as infrastructure degradation and failures, while heavy rainfall and sea-level rise will worsen flooding. Low-income groups and other vulnerable populations will be affected most severely because of where they live and their limited ability to cope with these stresses.

Cities and settlements are constantly changing. Their populations grow and shrink, economic activities expand or decline, and political priorities shift. The risks that cities and their residents face are influenced by both urban change and climate change. The seriousness of these risks into the 21st Century will be shaped by the interactions between drivers of change including population growth, economic development and land use change.

In a warming world, increasing air temperature makes the Urban Heat Island effect in cities worse. One key risk is heat waves in cities that are likely to affect half of the future global urban population with negative impacts on human health and economic productivity. Heat and built infrastructure such as streets and houses interact with each other and magnify risks in cities. For instance, higher urban temperatures can cause infrastructure to overheat and fail, as well as increase the concentration of harmful air pollutants such as ozone.

The density of roads and buildings in urban areas increases the area of impermeable surfaces, which interact with more frequent heavy precipitation events to increase the risk of urban flooding. This risk of flooding is greater for coastal settlements due to sea level rise and storm surges from tropical cyclones. Coastal inundation in the Miami-Dade region in Florida, USA, is estimated to have caused over USD465 million in lost real estate value between 2005 and 2016, and it is likely that coastal flood risks in the region beyond 2050 will increase without adaptation to climate change.

Within cities, different groups of people can face different risks. Many low-income residents live in informal settlements alongside coasts or rivers, which greatly heightens exposure and vulnerability to climate-driven hazards. In urban areas in Ghana, for example, risks from urban flooding can compound health risks, and have resulted in outbreaks of malaria, typhoid and cholera. Those outbreaks have been shown to disproportionately affect poorer communities.

Severe risks in cities and settlements also arise from reduced water availability. As urban areas grow, the amount of water required to meet basic needs of people and industries increases. When increased demand is combined with water scarcity from lower rainfall due to climate change, water resource management becomes a critical issue. Low-income groups already face major challenges in accessing water, and the situation is likely to worsen due to growing conflicts over scarce resources, increasing water prices, and diminishing infrastructure provisions in ever-expanding informal settlements.

These key risks already differ greatly between cities, and between different groups of people in the same city. By 2050 these discrepancies are likely to be even more apparent. Cities with limited financial resources, regulatory authority and technical capacities are less equipped to respond to climate change. People who already have fewer resources and constrained opportunities face higher levels of risk because of their vulnerability. As a result of this, key risks vary not only over time as climate change is felt more strongly. They also vary over space – between cities exposed to different hazards and with different abilities to adapt – and between social groups, meaning between people who are more or less affected and able to cope.

[END FAQ6.2 HERE]

[START FAQ6.3 HERE]

FAQ6.3: What adaptation actions in human settlements can contribute to reducing climate risks and building resilience across building, neighbourhood, city, and global scales?

Settlements bring together many activities, so climate action will be most effective if it is integrated and collaborative. This requires (i) embedding information on climate change risks into decisions; (ii) building capacity of communities and institutions; (iii) using both nature-based and traditional engineering approaches; (iv) working in partnership with diverse local planning and community organisations; and, (v) sharing best practice with other settlements.

Settlements bring together people, buildings, economic activities and infrastructure services, and thus integrated, cross-sector, adaptation actions offer the best way to build resilience to climate change impacts. For example, actions to manage flood risk include installing flood proofing measures within and outside properties, improving capacity of urban drainage along roads, incorporating nature-based solutions within the urban areas, constructing flood defences, and managing land upstream of settlements to reduce runoff.

Adaptation actions will be more effective if they are implemented in partnership with local communities, national governments, research institutions, and the private and third sector. Climate action should not be considered as an additional or side action to other activities. Rather, climate action should be mainstreamed into existing processes, including those that contribute to the UN Sustainable Development Goals (2015) and New Urban Agenda adopted at the UN Conference on Housing and Sustainable Urban Development (Habitat III) in 2016. Cities are already coming together through international networks to share good practice about adaptation actions, speeding up the dissemination of knowledge.

This integrated approach to adaptation in human settlements needs to be supported by various other actions, including potential co-benefits with carbon emissions reductions, public health, and ecosystem conservation goals. First, information on climate risks needs to be embedded into the architectural design, delivery and retrofitting of housing, transportation, spatial planning and infrastructure across neighbourhood and city scales. This includes making information on climate impacts widely available, updating design standards, and strengthening regulation to avoid development in high-risk locations. Second, the capacity of communities needs to be strengthened, especially amongst those in informal settlements, the poorest and other vulnerable groups including minorities, migrants, women, children, elderly, disabled, and people with serious health conditions such as obesity. This involves raising awareness, incorporating communities into adaptation processes, and strengthening regulation, policies and provision of infrastructure services. Third, nature-based solutions should be integrated to work alongside traditional ‘grey’ or engineered infrastructure. Vegetation corridors, greenspace, wetlands and other green infrastructure can be woven into the built environment to reduce heat and flood risks, whilst providing other benefits such as health and biodiversity.

Although even the largest city covers only a small area of the planet, all settlements are part of larger catchments from which people, water, food, energy, materials, and other resources support them. Actions within cities should be mindful of wider impacts and avoid displacing issues elsewhere.

[END FAQ6.3 HERE]

[START FAQ6.4 HERE]

FAQ6.4: How can actions that reduce climate risks in cities and settlements also help to reduce urban poverty, enhance economic performance, and contribute to climate mitigation?

If carefully planned, adaptation actions can reduce exposure to climate risk as well as reduce urban poverty, advance sustainable development and mitigate greenhouse gas emissions. When adaptation responses are equitable, and if a range of voices are heard in the planning process, the needs of the disadvantaged are more likely to be addressed and wider societal benefits can be maximized.

Urbanization is a global trend which is interacting with climate change to create complex risks in cities and settlements, especially for those that already have high levels of poverty, unemployment, housing informality, and backlogs of services. Many cities and settlements are seeing increasing action to manage climate risks. On top of reducing communities’ exposure to climate risk, adaptation actions can have benefits for reducing urban poverty and enhancing economic performance in ways that reduce inequality and advance sustainability goals. Adaptation actions, however, can also have unintended consequences. That is why care needs to be taken to ensure climate adaptation planning and development of new infrastructure does not exacerbate inequality or negatively impact other sustainable development priorities. Climate adaptation planning is most effective when it is sensitive to the diverse ways that low-income and minority communities are more likely to experience climate risk, including women, children, migrants, refugees, internally displaced peoples, racial/ethnic minority groups, among others.

Adapting to climate change can have benefits for reducing greenhouse gas emissions and urban inequalities. In cities where growing numbers of people live in informal settlements, introducing risk-reducing physical infrastructure such as piped water, sanitation, drainage systems can enhance the quality of life of the community. At the same time, those measures can increase health outcomes and reduce urban inequalities by reducing exposure to flooding or heat impacts. In less developed countries, less than 60% of the urban population have access to piped water which, in turn, impacts their health and well-being. Increasingly, housing is being built better to manage heat risk through insulation, changing building orientation or to flood risk by raising structures, which then contributes to wellbeing and ability to work. Improvements to early warning systems can help people evacuate rapidly in case of storm surges or flooding. Although the most vulnerable often do not get these warnings in time.

Carefully planned nature-based solutions, such as public green space, improved urban drainage systems and storm water management, can deliver both health and development benefits. When these adaptation actions succeed, water, waste and sanitation can be improved to better manage climate risk and provide households and cities with better services. Many nature-based solutions entail bringing back plants and trees into cities which also helps to reduce the concentration of heat-trapping greenhouse gases in the atmosphere.

When care is taken to ensure that adaptation responses are equitable, and that a range of voices are heard in planning, the needs of the disadvantaged are more likely to be addressed. For example, a study that looked at transport plans across 40 cities in Portugal saw that some urban communities have prioritised the needs of disadvantaged users such as the elderly and disabled, while at the same time reducing urban transport emissions while enhancing public wellbeing and equity of transport. On the other hand, in some cities, there is evidence of emerging trade-offs associated with climate adaptation actions where sea walls and temporary flood barriers were erected in economically valuable areas and not is less well-off areas. Going forward, it is important to ensure that vulnerable groups' needs are carefully considered both in terms of climate and other risks as this has not been sufficiently done in the past.

[END FAQ6.4 HERE]

[START FAQ6.5 HERE]

FAQ6.5: What policy tools, governance strategies, and financing arrangements can enable more inclusive and effective climate adaptation in cities and settlements?

Inclusive and effective climate adaptation requires efforts are all levels of governance, including the public sector, the private sector, the third sector, communities and intermediaries such as universities or think tanks. Inclusive and effective adaptation requires action fit for the diverse conditions in which it is needed. Collaborative dialogues can help to map both adaptation opportunities and potential negative impacts.

There is no one-size-fits-all approach to ensure that climate adaptation efforts have positive results and include the concerns of everyone affected. Cities and local communities are diverse, and thus they have diverse perspectives on what responses to prioritize. Moreover, adaptation efforts may impact people's lives in very different ways. Policy tools, strategies and financial arrangements for adaptation can include all society sectors and address socio-economic inequalities. Planning and decision-making must respond to marginalized voices and future generations (including children and youth).

Efforts to adapt to climate change can be incremental, reformist, or transformational, depending on the scale of the change required. Incremental action may address specific climate impacts in a given place, but do not challenge the social and political institutions that prevent people from bouncing back better. Reformist action may address some of the social and institutional drivers of exposure and vulnerability, but without addressing the underlying socio-economic structures that drive differential forms of exposure. For example, social protection measures may improve people's capacity to cope with climate impacts, but that improved capacity will depend on maintaining such protection measures. Transformative action involves fundamental changes in political and socio-economic systems, oriented towards addressing vulnerability drivers (e.g., socio-economic inequalities, consumption cultures). All forms of adaptation are relevant to deliver resilient futures because of the variability of conditions in which adaptation action is needed.

Local and regional governments play an essential role in delivering planning and institutional action suited to local conditions in cities and settlements. Potential strategies can span multiple sectors and scales, ranging from land use management, building codes, critical infrastructure designs and community development actions, to different legal, financial, participatory decision-making and robust monitoring and evaluation arrangements. NGOs or third sector organisations can also play a coordinating role by building dialogues across governments, the private sectors, and communities through effective communication and social learning. Local action tends to falter without the support of national governments as they are often facilitators of resources and finance. They can create institutional frameworks that facilitate (rather than impede) local action. National governments also play a crucial role in the development of large-scale infrastructures.

Private actors can also drive adaptation action. The evaluation of private-led infrastructure and housing projects suggests that the prioritization of profit, however, may have a detrimental impact on the overall resilience of a place. New institutional models such as public-private partnerships respond to the shortcomings of both the public and private sectors. Still, the evidence of them facilitating the inclusion of multiple actors is mixed.

The private sector can mobilize finance. However, the forms of finance available for adaptation are limited and directed to huge projects that do not always address local adaptation needs. Private actors tend to join adaptation projects when there is an expectation of large profits, such as in interventions that increase real estate value. Private-led adaptation can lead to ‘gentrification’ whereby low-income populations are relocated from urban centres and safer settlements. Models that enable the collaboration between public, private and civil society sectors have greater potential to mobilise adaptation finance in inclusive ways.

Forms of collaborative planning and decision-making can create dialogues for a sustainable future in cities, settlements and infrastructure systems. Adaptation action needs multiple approaches. For example, adaptation needs both actions that depend on dialogues between multiple actors (e.g., urban planning and zoning) and action that follows strong determination and leadership (e.g., declarations of emergency and target commitments). There are adaptation actions that depend on place-based conditions (e.g., flood defences) and those that require considering interactions across scales (e.g., regulatory frameworks). The growth of adaptation capacities, fostering dialogues, empowered communities, multi-scalar assessments, and foresight within current institutions can support effective and inclusive adaptation action that is also sustained in the long term.

[START FAQ6.5 HERE]

References

Abatzoglou, J. T. and Williams, A. P. (2016) 'Impact of anthropogenic climate change on wildfire across western US forests', *Proceedings of the National Academy of Sciences,* 113(42), pp. 11770-11775.

Abebe, Y., Kabir, G. and Tesfamariam, S. (2018) 'Assessing Urban Areas Vulnerability to Pluvial Flooding Using GIS Applications and Bayesian Belief Network model', *Journal of cleaner production,* 174, pp. 1629-1641.

Abidin, H. Z., Andreas, H., Gumilar, I., Sidiq, T. P. and Fukuda, Y. (2013) 'Land subsidence in coastal city of Semarang (Indonesia): characteristics, impacts and causes', *Geomatics, Natural Hazards and Risk,* 4(3), pp. 226-240.

Abiodun, B. J., Adegoke, J., Abatan, A. A., Ibe, C. A., Egbebiyi, T. S., Engelbrecht, F. and Pinto, I. (2017) 'Potential impacts of climate change on extreme precipitation over four African coastal cities', *Climatic Change,* 143(3), pp. 399-413.

Abudu Kasei, R., Dalitso Kalanda-Joshua, M. and Tutu Benefor, D. (2019) 'Rapid urbanisation and implications for indigenous knowledge in early warning on flood risk in African cities', *Journal of the British Academy,* 7(2), pp. 183-214.

Acuto, M. (2016) 'Give cities a seat at the top table', *Nature News,* 537(7622), pp. 611.

Adams, H. (2016) 'Why populations persist: mobility, place attachment and climate change', *Population and Environment,* 37(4), pp. 429-448.

Adegun, O. B. (2017) 'Green infrastructure in relation to informal urban settlements', *Journal of Architecture and Urbanism,* 41(1), pp. 22-33.

Adegun, O. B. (2018) 'When green is grievous: downsides in human-nature interactions in informal urban settlements', *Journal of Urbanism: International Research on Placemaking and Urban Sustainability,* 11(3), pp. 347-361.

Adelekan, I., Johnson, C., Manda, M., Matyas, D., Mberu, B., Parnell, S., Pelling, M., Satterthwaite, D. and Vivekananda, J. (2015) 'Disaster risk and its reduction: An agenda for urban Africa', *International Development Planning Review,* 37(1), pp. 33-43.

Adelekan, I. O. (2010) 'Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria', *Environment and urbanization,* 22(2), pp. 433-450.

Adenle, A. A., Ford, J. D., Morton, J., Twomlow, S., Alverson, K., Cattaneo, A., Cervigni, R., Kurukulasuriya, P., Huq, S. and Helfgott, A. (2017) 'Managing climate change risks in Africa-A global perspective', *Ecological Economics,* 141, pp. 190-201.

Adetokunbo, I. and Emeka, M. (2015) 'Urbanization, housing, homelessness and climate change', *Journal of Design and Built Environment,* 15(2).

Adger, W. N., Arnell, N. W., Black, R., Dercon, S., Geddes, A. and Thomas, D. S. G. (2015) 'Focus on environmental risks and migration: causes and consequences', *Environmental Research Letters,* 10(6), pp. 060201.

Adger, W. N., Brown, I. and Surminski, S. (2018) 'Advances in risk assessment for climate change adaptation policy', *The Royal Society Publishing,* 376(2121).

Adger, W. N., Pulhin, J. M., Barnett, J., Dabelko, G. D., Hovelsrud, G. K., Levy, M., Oswald, S. and Vogel, C. H. (2014) 'Human Security', in Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Cambridge: IPCC, pp. 755–791.

Adri, N. and Simon, D. (2018) 'A tale of two groups: focusing on the differential vulnerability of "climate-induced" and "non-climate-induced" migrants in Dhaka City', *Climate and development,* 10(4), pp. 321-336.

AEMET 2017. Informe Mensual Climatológico. Madrid, Spain: Agencia Estatal de Meteorología.

Aerts, J. C. J. H., Botzen, W. J., Clarke, K. C., Cutter, S. L., Hall, J. W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S. and Kunreuther, H. (2018) 'Integrating human behaviour dynamics into flood disaster risk assessment', *Nature Climate Change,* 8(3), pp. 193-199.

AghaKouchak, A., Cheng, L., Mazdiyasni, O. and Farahmand, A. (2014) 'Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought', *Geophysical Research Letters,* 41(24), pp. 8847-8852.

AghaKouchak, A., Chiang, F., Huning, L. S., Love, C. A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S. M., Ragno, E. and Sadegh, M. (2020) 'Climate Extremes and Compound Hazards in a Warming World', *Annual Review of Earth and Planetary Sciences,* 48, pp. 519-548.

Agrawal, A., Costella, C., Kaur, N., Tenzing, J., Shakya, C. and Norton, A. (2019) *Climate resilience through social protection*, Rotterdam and Washington, DC: *Global Commission on Adaptation*. Available at: https://cdn.gca.org/assets/2019-09/ClimateResiliencethroughSocialProtection.pdf.

Aguiar, F. C., Bentz, J., Silva, J. M. N., Fonseca, A. L., Swart, R., Santos, F. D. and Penha-Lopes, G. (2018) 'Adaptation to climate change at local level in Europe: An overview', *Environmental Science & Policy,* 86, pp. 38-63.

Agyeman, J., Schlosberg, D., Craven, L. and Matthews, C. (2016) 'Trends and Directions in Environmental Justice: From Inequity to Everyday Life, Community, and Just Sustainabilities', *Annual Review of Environment and Resources,* 41(1), pp. 321-340.

Ahams, I. C., Paterson, W., Garcia, S., Rushforth, R., Ruddell, B. L. and Mejia, A. (2017) 'Water Footprint of 65 Mid-to Large-Sized US Cities and Their Metropolitan Areas', *JAWRA Journal of the American Water Resources Association,* 53(5), pp. 1147-1163.
Ahilan, S., Guan, M., Sleigh, A., Wright, N. and Chang, H. (2018) 'The influence of floodplain restoration on flow and sediment dynamics in an urban river', *Journal of Flood Risk Management,* 11, pp. S986-S1001.
Ahmadalipour, A., Moradkhani, H., Castelletti, A. and Magliocca, N. (2019) 'Future drought risk in Africa: Integrating vulnerability, climate change, and population growth', *Science of The Total Environment,* 662, pp. 672-686.
Ahmed, A. S. and Bharat, A. (2014) 'Designing the City According to the Wind: Using WAsP to Minimize the Impacts of High Rise Building Complex on Human Comfort', *International Journal of Innovative Research in Advanced Engineering (IJIRAE),* 1(5).
Aisya, N. S. (2019) 'Politik Adaptasi Perubahan Iklim dalam Pendekatan Multilevel Governance di Kota Semarang', *Jurnal Hubungan Internasional,* 8(1), pp. 35-47.
Ajibade, I. (2017) 'Can a future city enhance urban resilience and sustainability? A political ecology analysis of Eko Atlantic city, Nigeria', *International Journal of Disaster Risk Reduction,* 26, pp. 85-92.
Ajibade, I. and McBean, G. (2014) 'Climate extremes and housing rights: A political ecology of impacts, early warning and adaptation constraints in Lagos slum communities', *Geoforum,* 55, pp. 76-86.
Akbulut, B., Demaria, F., Gerber, J.-F. and Martínez-Alier, J. (2019) 'Who promotes sustainability? Five theses on the relationships between the degrowth and the environmental justice movements', *Ecological Economics,* 165, pp. 106418.
Akhtar, F. and Shah, U. (2020) 'Emerging Water Scarcity Issues and Challenges in Afghanistan', in Ranjan, A. (ed.) *Water Issues in Himalayan South Asia*. Singapore: Springer, pp. 1-28.
Al-Obaidi, K. M., Ismail, M. and Rahman, A. M. A. (2014) 'Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review', *Frontiers of Architectural Research,* 3(3), pp. 283-297.
Aleksandrova, M. (2019) 'Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries', *Climate and Development*, pp. 1-10.
Alessa, L., Kliskey, A., Gamble, J., Fidel, M., Beaujean, G. and Gosz, J. (2016) 'The role of Indigenous science and local knowledge in integrated observing systems: moving toward adaptive capacity indices and early warning systems', *Sustainability Science,* 11(1), pp. 91-102.
Alexader, B., Luisa, T. and Molina, M. (2016) 'Megacities, air quality and climate', *Atmospheric Environment,* 126, pp. 235-249.
Alexander, D. (2017) 'Corruption and the governance of natural disaster risk', in Gerber, B. (ed.) *The Oxford Encyclopedia of Natural Hazards Governance*. USA: Oxford University Press.
Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., Wyser, K. and Feyen, L. (2017) 'Global projections of river flood risk in a warmer world', *Earth's Future,* 5(2), pp. 171-182.
Alfieri, L., Dottori, F., Betts, R., Salamon, P. and Feyen, L. (2018) 'Multi-Model Projections of River Flood Risk in Europe under Global Warming', *Climate,* 6(1).
Ali, A., Qadir, J., ur Rasool, R., Sathiaseelan, A., Zwitter, A. and Crowcroft, J. (2016) 'Big data for development: applications and techniques', *Big Data Analytics,* 1(1), pp. 2.
Allan, J. V., Kenway, S. J. and Head, B. W. (2018) 'Urban water security-what does it mean?', *Urban Water Journal,* 15(9), pp. 899-910.
Allen, A., Koroma, B., Manda, M., Osuteye, E. and Lambert, R. (2020a) 'Urban risk readdressed: Bridging resilience-seeking practices in African cities', in Burayidi, M.A., Allen, A., Twigg, J. and Wamsler, C. (eds.) *A Handbook on Urban Resilience*. London: Routledge.
Allen, A., Koroma, B., Osuteye, E. and Rigon, A. (2017) *Urban risk in Freetown's informal settlements: making the invisible visible*: Urban Africa Risk Knowledge BriefingJanuary 2017). Available at: https://www.preventionweb.net/publications/view/54044.
Allen, A., Osuteye, E., Koroma, B. and Lambert, R. (2020b) 'Unlocking urban risk trajectories: Participatory approaches to uncover risk accumulation in Freetown's informal settlements', in Pelling, M. (ed.) *Breaking cycles of Risk Accumulation in African Cities*: UN-Habitat.
Allen, M., Gillespie-Marthaler, L., Abkowitz, M. and Camp, J. (2020c) 'Evaluating flood resilience in rural communities: a case-based assessment of Dyer County, Tennessee', *Natural Hazards,* 101(1), pp. 173-194.
Alongi, D. M. (2015) 'The impact of climate change on mangrove forests', *Current Climate Change Reports,* 1(1), pp. 30-39.
Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z. and Sanchez, A. (2019) 'Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management', *Journal of environmental management,* 239, pp. 244-254.
Alves, C. A., Duarte, D. H. S. and Gonçalves, F. L. T. (2016) 'Residential buildings' thermal performance and comfort for the elderly under climate changes context in the city of São Paulo, Brazil', *Energy and Buildings,* 114, pp. 62-71.
Alves, C. A., Gonçalves, F. L. T. and Duarte, D. H. S. (2021) 'The recent residential apartment buildings' thermal performance under the combined effect of the global and the local warming', *Energy and Buildings,* 238, pp. 110828.

Alves, F. M., Campos, I. and Penha-Lopes, G. (2019) *Multi-actor perspectives for climate resilient cities: a pilot case*, Lisbon: Center for Ecology, Evolution and Environmental changes Faculty of Sciences of the University of Lisbon.
Amoako, C. (2018) 'Emerging grassroots resilience and flood responses in informal settlements in Accra, Ghana', *GeoJournal,* 83(5), pp. 949-965.
Ampaire, E. L., Jassogne, L., Providence, H., Acosta, M., Twyman, J., Winowiecki, L. and Van Asten, P. (2017) 'Institutional challenges to climate change adaptation: A case study on policy action gaps in Uganda', *Environmental Science & Policy,* 75, pp. 81-90.
Amundsen, H., Hovelsrud, G. K., Aall, C., Karlsson, M. and Westskog, H. (2018) 'Local governments as drivers for societal transformation: Towards the 1.5 C ambition', *Current Opinion in Environmental Sustainability,* 31, pp. 23-29.
Anand, N. (2015) 'Leaky States: Water Audits, Ignorance, and the Politics of Infrastructure', *Public Culture,* 27(2 (76)), pp. 305-330.
Anarfi, K., Hill, R. A. and Shiel, C. (2020) 'Highlighting the sustainability implications of urbanisation: A comparative analysis of two urban areas in Ghana', *Land,* 9(9), pp. 300.
Anderson, A., Loomba, P., Orajaka, I., Numfor, J., Saha, S., Janko, S., Johnson, N., Podmore, R. and Larsen, R. (2017) 'Empowering smart communities: electrification, education, and sustainable entrepreneurship in IEEE Smart Village Initiatives', *IEEE Electrification Magazine,* 5(2), pp. 6-16.
Anderson, B., Grove, K., Rickards, L. and Kearnes, M. (2020) 'Slow emergencies: Temporality and the racialized biopolitics of emergency governance', *Progress in Human Geography,* 44(4), pp. 621-639.
Andersson, E., Langemeyer, J., Borgström, S., McPhearson, T., Haase, D., Kronenberg, J., Barton, D. N., Davis, M., Naumann, S., Röschel, L. and Baró, F. (2019) 'Enabling Green and Blue Infrastructure to Improve Contributions to Human Well-Being and Equity in Urban Systems', *BioScience,* 69(7), pp. 566-574.
Andonova, L. B., Hale, T. N. and Roger, C. B. (2017) 'National policy and transnational governance of climate change: Substitutes or complements?', *International Studies Quarterly,* 61(2), pp. 253-268.
Andrei, S., Antonescu, B., Boldeanu, M., Mărmureanu, L., Marin, C. A., Vasilescu, J. and Ene, D. (2019) 'An exceptional case of freezing rain in Bucharest (Romania)', *Atmosphere,* 10(11), pp. 673.
Andrews, O., Le Quéré, C., Kjellstrom, T., Lemke, B. and Haines, A. (2018) 'Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study', *The Lancet Planetary Health,* 2(12), pp. e540-e547.
Anenberg, S. C., Achakulwisut, P., Brauer, M., Moran, D., Apte, J. S. and Henze, D. K. (2019) 'Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide', *Scientific reports,* 9(1), pp. 1-6.
Ang, B. W., Wang, H. and Ma, X. (2017) 'Climatic influence on electricity consumption: The case of Singapore and Hong Kong', *Energy,* 127, pp. 534-543.
Angel, S., Blei, A. M., Parent, J., Lamson-Hall, P., Galarza-Sanchez, N., Civco, D. L. and Thom, K. (2016) *Atlas of urban expansion—2016 edition*, Cambridge, MA: NYU Urban Expansion Program at New York University, UN-Habitat, and the Lincoln Institute of Land Policy.
Angelidou, M. (2015) 'Smart cities: A conjuncture of four forces', *Cities,* 47, pp. 95-106.
Anguelovski, I., Connolly, J. J. T., Masip, L. and Pearsall, H. (2018) 'Assessing green gentrification in historically disenfranchised neighborhoods: a longitudinal and spatial analysis of Barcelona', *Urban Geography,* 39(3), pp. 458-491.
Anguelovski, I., Irazábal-Zurita, C. and Connolly, J. J. T. (2019) 'Grabbed Urban Landscapes: Socio-spatial Tensions in Green Infrastructure Planning in Medellín', *International journal of urban and regional research,* 43(1), pp. 133-156.
Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K. and Teicher, H. (2016) 'Equity Impacts of Urban Land Use Planning for Climate Adaptation: Critical Perspectives from the Global North and South', *Journal of Planning Education and Research,* 36(3), pp. 333-348.
Anvarifar, F., Voorendt, M. Z., Zevenbergen, C. and Thissen, W. (2017) 'An application of the Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood defences in the Netherlands', *Reliability Engineering & System Safety,* 158, pp. 130-141.
Anvarifar, F., Zevenbergen, C., Thissen, W. and Islam, T. (2016) 'Understanding flexibility for multifunctional flood defences: a conceptual framework', *Journal of Water and Climate Change,* 7(3), pp. 467-484.
Apse, C. and Bryant, B. (2015) *The Upper Tana-Nairobi Water Fund: A business case*. Online: The Nature Conservancy. Available at: https://naturalcapitalproject.stanford.edu/sites/g/files/sbiybj9321/f/publications/nairobi-water-fund-business-case_final.pdf.
Araos, M., Ford, J., Berrang-Ford, L., Biesbroek, R. and Moser, S. (2017) 'Climate change adaptation planning for Global South megacities: the case of Dhaka', *Journal of Environmental Policy & Planning,* 19(6), pp. 682-696.
Arboleda, M. (2016a) 'In the Nature of the Non-City: Expanded Infrastructural Networks and the Political Ecology of Planetary Urbanisation', *Antipode,* 48(2), pp. 233-251.
Arboleda, M. (2016b) 'Spaces of extraction, metropolitan explosions: planetary urbanization and the commodity boom in Latin America', *International Journal of Urban and Regional Research,* 40(1), pp. 96-112.

Archer, D. (2012) 'Finance as the key to unlocking community potential: savings, funds and the ACCA programme', *Environment and Urbanization,* 24(2), pp. 423-440.
Archer, D. (2016) 'Building urban climate resilience through community-driven approaches to development: Experiences from Asia', *International Journal of Climate Change Strategies and Management,* 8, pp. 654-669.
Archer, D., Almansi, F., DiGregorio, M., Roberts, D., Sharma, D. and Syam, D. (2014) 'Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale', *Climate and Development,* 6(4), pp. 345-356.
Archer, D. and Dodman, D. (2015) 'Making capacity building critical: Power and justice in building urban climate resilience in Indonesia and Thailand', *Urban Climate,* 14, pp. 68-78.
Arfvidsson, H., Simon, D., Oloko, M. and Moodley, N. (2017) 'Engaging with and measuring informality in the proposed Urban Sustainable Development Goal', *African geographical review,* 36(1), pp. 100-114.
Arkema, K. and Ruckelshaus, M. (2017) 'Transdisciplinary research for conservation and sustainable development planning in the Caribbean', in Levin, P.S. and Poe, M.R. (eds.) *Conservation in the Anthropocene Ocean: Interdisciplinary Science in Support of Nature and People*. London: Elsevier, pp. 333–357
Arkema, K. K., Scyphers, S. B. and Shepard, C. (2017) 'Living shorelines for people and nature', *Living shorelines*: CRC Press, pp. 11-30.
Arku, G., Mensah, K. O., Allotey, N. K. and Addo Frempong, E. (2016) 'Non-compliance with building permit regulations in Accra-Tema city-region, Ghana: exploring the reasons from the perspective of multiple stakeholders', *Planning Theory & Practice,* 17(3), pp. 361-384.
Arnall, A. (2019) 'Resettlement as climate change adaptation: what can be learned from state-led relocation in rural Africa and Asia?', *Climate and Development,* 11(3), pp. 253-263.
Arnbjerg-Nielsen, K., Willems, P., Olsson, J., Beecham, S., Pathirana, A., Bülow Gregersen, I., Madsen, H. and Nguyen, V. T. V. (2013) 'Impacts of climate change on rainfall extremes and urban drainage systems: a review', *Water Science and Technology,* 68(1), pp. 16-28.
Arnell, N. W. and Gosling, S. N. (2016) 'The impacts of climate change on river flood risk at the global scale', *Climatic Change,* 134(3), pp. 387-401.
Aroua, N. (2016) 'Urban vulnerability and resiliency over water-related risks: a case study from Algiers', *Water Science and Technology,* 73(5), pp. 1145-1154.
Arrighi, C., Pregnolato, M., Dawson, R. J. and Castelli, F. (2019) 'Preparedness against mobility disruption by floods', *Science of the Total Environment,* 654, pp. 1010-1022.
Arsenio, E., Martens, K. and Di Ciommo, F. (2016) 'Sustainable urban mobility plans: Bridging climate change and equity targets?', *Research in Transportation Economics,* 55, pp. 30-39.
ARUP (2018) *Cities Resilience Index: Understanding and Measuring City Resilience*.
Arup and Rockefeller (2015) *City Resilience Index: Understanding and Measuring City Resilience*: Arup.
Ashley, W. S., Strader, S., Rosencrants, T. and Krmenec, A. J. (2014) 'Spatiotemporal Changes in Tornado Hazard Exposure: The Case of the Expanding Bull's-Eye Effect in Chicago, Illinois', *Weather, Climate, and Society,* 6(2), pp. 175-193.
Ashley, W. S. and Strader, S. M. (2016) 'Recipe for Disaster: How the Dynamic Ingredients of Risk and Exposure Are Changing the Tornado Disaster Landscape', *Bulletin of the American Meteorological Society,* 97(5), pp. 767-786.
Ataöv, A. and Peker, E. (2021) 'Co-designing local climate action: A methodological framework from a democratic perspective', in Peker, E. and Ataöv, A. (eds.) *Governance of Climate Responsive Cities*. Cham: Springer, pp. 147-164.
Atteridge, A. and Remling, E. (2018) 'Is adaptation reducing vulnerability or redistributing it?', *Wiley Interdisciplinary Reviews: Climate Change,* 9(1), pp. e500.
Auffhammer, M. and Mansur, E. T. (2014) 'Measuring climatic impacts on energy consumption: A review of the empirical literature', *Energy Economics,* 46, pp. 522-530.
Aune, K. T., Gesch, D. and Smith, G. S. (2020) 'A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina', *Environmental research,* 185, pp. 109384.
Awuah, K. G. B. and Hammond, F. N. (2014) 'Determinants of low land use planning regulation compliance rate in Ghana', *Habitat International,* 41, pp. 17-23.
Aylett, A. (2015) 'Institutionalizing the urban governance of climate change adaptation: Results of an international survey', *Urban Climate,* 14, pp. 4-16.
Ayyub, B. M. (2018) *Climate-Resilient Infrastructure: Adaptive Design and Risk Management.* Reston, Virginia: American Society of Civil Engineers.
Añel, J. A., Fernández-González, M., Labandeira, X., López-Otero, X. and De la Torre, L. (2017) 'Impact of cold waves and heat waves on the energy production sector', *Atmosphere,* 8(11), pp. 209.
Badami, M. G. and Ramankutty, N. (2015) 'Urban agriculture and food security: A critique based on an assessment of urban land constraints', *Global Food Security,* 4, pp. 8-15.
Badmos, O. S., Callo-Concha, D., Agbola, B., Rienow, A., Badmos, B., Greve, K. and Jürgens, C. (2020) 'Determinants of residential location choices by slum dwellers in Lagos megacity', *Cities,* 98, pp. 102589.
Bagheri, M., Hosseini, S. M., Ataie-Ashtiani, B., Sohani, Y., Ebrahimian, H., Morovat, F. and Ashrafi, S. (2021) 'Land subsidence: A global challenge', *Science of The Total Environment,* 778, pp. 146193.

Bahadur, A. and Tanner, T. (2014) 'Transformational resilience thinking: putting people, power and politics at the heart of urban climate resilience', *Environment and Urbanization,* 26(1), pp. 200-214.
Bahadur, A. V. and Dodman, D. 2020. Disruptive resilience: an agenda for the new normal in cities of the global South. *IIED Brief.* Online: IIED.
Bai, X., Dawson, R. J., Ürge-Vorsatz, D., Delgado, G. C., Salisu Barau, A., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D. C. and Schultz, S. (2018) 'Six research priorities for cities and climate change', *Nature,* 555, pp. 23-25.
Baklanov, A., Grimmond, C. S. B., Carlson, D., Terblanche, D., Tang, X., Bouchet, V., Lee, B., Langendijk, G., Kolli, R. K. and Hovsepyan, A. (2018) 'From urban meteorology, climate and environment research to integrated city services', *Urban Climate,* 23, pp. 330-341.
Baklanov, A., Luisa, T. and Molina, M. (2016) 'Megacities, air quality and climate', *Atmospheric Environment,* 126, pp. 235-249.
Baldwin, J. W., Dessy, J. B., Vecchi, G. A. and Oppenheimer, M. (2019) 'Temporally compound heat wave events and global warming: An emerging hazard', *Earth's Future,* 7(4), pp. 411-427.
Bamweyana, I., Okello, D. A., Ssengendo, R., Mazimwe, A., Ojirot, P., Mubiru, F., Ndungo, L., Kiyingi, C. N., Ndyabakira, A. and Bamweyana, S. (2020) 'Socio-Economic Vulnerability to COVID-19: The Spatial Case of Greater Kampala Metropolitan Area (GKMA)', *Journal of Geographic Information System,* 12(04), pp. 302.
Ban, N., Schmidli, J. and Schär, C. (2015) 'Heavy precipitation in a changing climate: Does short-term summer precipitation increase faster?', *Geophysical Research Letters,* 42(4), pp. 1165-1172.
Ban, N. C., Frid, A., Reid, M., Edgar, B., Shaw, D. and Siwallace, P. (2018) 'Incorporate Indigenous perspectives for impactful research and effective management', *Nature Ecology & Evolution,* 2(11), pp. 1680-1683.
Baniassadi, A., Sailor, D. J., Crank, P. J. and Ban-Weiss, G. A. (2018) 'Direct and indirect effects of high-albedo roofs on energy consumption and thermal comfort of residential buildings', *Energy and Buildings,* 178, pp. 71-83.
Banks, N., Lombard, M. and Mitlin, D. (2020) 'Urban informality as a site of critical analysis', *The Journal of Development Studies,* 56(2), pp. 223-238.
Barabási, A.-L. (2013) 'Network science', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 371(1987), pp. 20120375.
Barata, M. M. L., Kinney, P. L., Dear, K., Ligeti, E., Ebi, K. L., Hess, J., Dickinson, T., Quinn, A. K., Obermaier, M., Silva Sousa, D. and Jack, D. (2018) 'Urban Health', in Rosenzweig, C., Solecki, W., Romero-Lankao, P., Mehrotra, S., Dhakal, S. and Ali Ibrahim, S. (eds.) *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. New York: Cambridge University Press, pp. 363–398.
Barau, A. S., Maconachie, R., Ludin, A. N. M. and Abdulhamid, A. (2015) 'Urban Morphology Dynamics and Environmental Change in Kano, Nigeria', *Land Use Policy,* 42, pp. 307-317.
Barbosa, R., Vicente, R. and Santos, R. (2015) 'Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon', *Building and Environment,* 92, pp. 440-451.
Barnett, C. and Parnell, S. (2016) 'Ideas, implementation and indicators: epistemologies of the post-2015 urban agenda', *Environment and Urbanization,* 28(1), pp. 87-98.
Barthel, S., Parker, J. and Ernstson, H. (2015) 'Food and green space in cities: A resilience lens on gardens and urban environmental movements', *Urban studies,* 52(7), pp. 1321-1338.
Bartos, M., Chester, M., Johnson, N., Gorman, B., Eisenberg, D., Linkov, I. and Bates, M. (2016) 'Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States', *Environmental Research Letters,* 11(11), pp. 114008.
Baró Porras, F., Langemeyer, J., Łaszkiewicz, E. and Kabisch, N. (2021) 'Editorial to the special issue" Advancing urban ecosystem service implementation and assessment considering different dimensions of environmental justice"', *Environmental Science and Policy,* 102, pp. 54-64.
Bassett, R., Cai, X., Chapman, L., Heaviside, C., Thornes, J. E., Muller, C. L., Young, D. T. and Warren, E. L. (2016) 'Observations of urban heat island advection from a high-density monitoring network', *Quarterly Journal of the Royal Meteorological Society,* 142(699), pp. 2434-2441.
Bassolas, A., Barbosa-Filho, H., Dickinson, B., Dotiwalla, X., Eastham, P., Gallotti, R., Ghoshal, G., Gipson, B., Hazarie, S. A. and Kautz, H. (2019) 'Hierarchical organization of urban mobility and its connection with city livability', *Nature communications,* 10(1), pp. 1-10.
Bastagli, F. (2014) *Responding to a Crisis: The Design and Delivery of Social Protection*, London: Overseas Development Institute. Available at: https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/8919.pdf.
Bastidas-Arteaga, E. and Stewart, M. G. (2019) *Climate adaptation engineering: risks and economics for infrastructure decision-making.* Oxon: Butterworth-Heinemann.
Bataille, C., Waisman, H., Colombier, M., Segafredo, L. and Williams, J. (2016) 'The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues', *Climate Policy,* 16(sup1), pp. S1-S6.
Battaglia, M., Gragnani, P. and Annesi, N. (2020) 'Moving Businesses toward Sustainable Development Goals (SDGs): Evidence from an Italian "Benefit-For-Nature" Corporation', *Entrepreneurship Research Journal,* 10(4).
Beaven, R., Stringfellow, A., Nicholls, R., Haigh, I., Kebede, A. S. and Watts, J. (2020) 'Future challenges of coastal landfills exacerbated by sea level rise', *Waste Management,* 105, pp. 92-101.

Becker, A. (2020) 'Climate change impacts to ports and maritime supply chains', *Maritime Policy & Management,* 47(7), pp. 849-852.
Becker, A., Ng, A. K. Y., McEvoy, D. and Mullett, J. (2018) 'Implications of climate change for shipping: Ports and supply chains', *Wiley Interdisciplinary Reviews: Climate Change,* 9(2), pp. e508.
Beckett, K. P., Freer Smith, P. H. and Taylor, G. (2000) 'Effective tree species for local air quality management', *Arboricultural Journal,* 26(1), pp. 12-19.
Begum, R. A., Sarkar, M. S. K., Jaafar, A. H. and Pereira, J. J. (2014) 'Toward conceptual frameworks for linking disaster risk reduction and climate change adaptation', *International Journal of Disaster Risk Reduction,* 10, pp. 362-373.
Bell, L. (2018) 'Bridging the Gap Between Policy and Action in Residential Graywater Recycling', in Leal, Filho, W., Marans, R. and Callewaert, J. (eds.) *Handbook of Sustainability and Social Science Research*. Cham: Springer, pp. 163-180.
Bellinson, R. and Chu, E. (2019) 'Learning pathways and the governance of innovations in urban climate change resilience and adaptation', *Journal of Environmental Policy & Planning,* 21(1), pp. 76-89.
Benson, D., Lorenzoni, I. and Cook, H. (2016) 'Evaluating social learning in England flood risk management: an 'individual-community interaction'perspective', *Environmental Science & Policy,* 55, pp. 326-334.
Bento-Gonçalves, A. and Vieira, A. (2020) 'Wildfires in the wildland-urban interface: Key concepts and evaluation methodologies', *Science of the total environment,* 707, pp. 135592.
Beringer, A. and Kaewsuk, J. (2018) 'Emerging Livelihood Vulnerabilities in an Urbanizing and Climate Uncertain Environment for the Case of a Secondary City in Thailand', *Sustainability,* 10(5), pp. 1452.
Berland, A., Shiflett, S. A., Shuster, W. D., Garmestani, A. S., Goddard, H. C., Herrmann, D. L. and Hopton, M. E. (2017) 'The role of trees in urban stormwater management', *Landscape and Urban Planning,* 162, pp. 167-177.
Berndtsson, R., Becker, P., Persson, A., Aspegren, H., Haghighatafshar, S., Jönsson, K., Larsson, R., Mobini, S., Mottaghi, M., Nilsson, J., Nordström, J., Pilesjö, P., Scholz, M., Sternudd, C., Sörensen, J. and Tussupova, K. (2019) 'Drivers of changing urban flood risk: A framework for action', *Journal of Environmental Management,* 240, pp. 47-56.
Berrang-Ford, L., Biesbroek, R., Ford, J. D., Lesnikowski, A., Tanabe, A., Wang, F. M., Chen, C., Hsu, A., Hellmann, J. J. and Pringle, P. (2019) 'Tracking global climate change adaptation among governments', *Nature Climate Change,* 9(6), pp. 440.
Bertolin, C. and Loli, A. (2018) 'Sustainable interventions in historic buildings: A developing decision making tool', *Journal of Cultural Heritage,* 34, pp. 291-302.
Bettini, G. (2014) 'Climate migration as an adaptation strategy: de-securitizing climate-induced migration or making the unruly governable?', *Critical Studies on Security,* 2(2), pp. 180-195.
Bevilacqua, P., Mazzeo, D., Bruno, R. and Arcuri, N. (2017) 'Surface temperature analysis of an extensive green roof for the mitigation of urban heat island in southern mediterranean climate', *Energy and Buildings,* 150, pp. 318-327.
Bezerra, P., da Silva, F., Cruz, T., Mistry, M., Vasquez-Arroyo, E., Magalar, L., De Cian, E., Lucena, A. F. and Schaeffer, R. (2021) 'Impacts of a warmer world on space cooling demand in Brazilian households', *Energy and Buildings,* 234, pp. 110696.
Bhamare, D. K., Rathod, M. K. and Banerjee, J. (2019) 'Passive cooling techniques for building and their applicability in different climatic zones—The state of art', *Energy and Buildings,* 198, pp. 467-490.
Bharti, N., Khandekar, N., Sengupta, P., Bhadwal, S. and Kochhar, I. (2019) 'Dynamics of urban water supply management of two Himalayan towns in India', *Water Policy,* 22(S1), pp. 65-89.
Bhaskar, A. S., Beesley, L., Burns, M. J., Fletcher, T. D., Hamel, P., Oldham, C. E. and Roy, A. H. (2016) 'Will it rise or will it fall? Managing the complex effects of urbanization on base flow', *Freshwater Science,* 35(1), pp. 293-310.
Bhide, A. (2020) 'Informal settlements, the emerging response to COVID and the imperative of transforming the narrative', *Journal of Social and Economic Development*, pp. 1-10.
Bichai, F. and Cabrera Flamini, A. (2018) 'The Water-Sensitive City: Implications of an urban water management paradigm and its globalization', *Wiley Interdisciplinary Reviews: Water,* 5(3), pp. e1276.
Bigger, P. and Millington, N. (2019) 'Getting soaked? Climate crisis, adaptation finance, and racialized austerity', *Environment and Planning E: Nature and Space,* 3(3), pp. 601-623.
Bilkovic, D. M., Mitchell, M. M., La Peyre, M., K. and Toft, J. D. (2017) *Living shorelines: The science and management of nature-based coastal protection.* Boca Raton: CRS Press.
Birkmann, J., Welle, T., Solecki, W., Lwasa, S. and Garschagen, M. (2016) 'Boost resilience of small and mid-sized cities', *Nature News,* 537(7622), pp. 605.
Bisaro, A. and Hinkel, J. (2018) 'Mobilizing private finance for coastal adaptation: A literature review', *Wiley Interdisciplinary Reviews: Climate Change,* 9(3), pp. e514.
Bixler, T. S., Houle, J., Ballestero, T. P. and Mo, W. (2020) 'A spatial life cycle cost assessment of stormwater management systems', *Science of The Total Environment,* 728, pp. 138787.
Blay-Palmer, A., Santini, G., Dubbeling, M., Renting, H., Taguchi, M. and Giordano, T. (2018) 'Validating the city region food system approach: Enacting inclusive, transformational city region food systems', *Sustainability,* 10(5), pp. 1680.

Blok, A. (2020) 'Urban green gentrification in an unequal world of climate change', *Urban Studies,* 57(14), pp. 2803–2816.
Boas, I., Farbotko, C., Adams, H., Sterly, H., Bush, S., van der Geest, K., Wiegel, H., Ashraf, H., Baldwin, A. and Bettini, G. (2019) 'Climate migration myths', *Nature Climate Change,* 9(12), pp. 901-903.
Bobylev, N., Gadal, S., Konyshev, V., Lagutina, M. and Sergunin, A. (2021) 'Building Urban Climate Change Adaptation Strategies: The Case of Russian Arctic Cities', *Weather, Climate, and Society,* 13(4), pp. 875-884.
Boelee, E., Janse, J., Le Gal, A., Kok, M., Alkemade, R. and Ligtvoet, W. (2017) 'Overcoming water challenges through nature-based solutions', *Water Policy,* 19(5), pp. 820-836.
Bompard, E., Huang, T., Wu, Y. and Cremenescu, M. (2013) 'Classification and trend analysis of threats origins to the security of power systems', *International Journal of Electrical Power & Energy Systems,* 50, pp. 50-64.
Bonilla, Y. and LeBrón, M. (2019) 'Introduction: Aftershocks of Disaster', in Bonilla, Y. and LeBrón, M. (eds.) *Aftershocks of Disaster: Puerto Rico Before and After the Storm*. Chicago, IL: Haymarket Books.
Borderon, M., Sakdapolrak, P., Muttarak, R., Kebede, E., Pagogna, R. and Sporer, E. (2019) 'Migration influenced by environmental change in Africa: A systematic review of empirical evidence', *Demographic research,* 41, pp. 491-544.
Borges Pedro, J. P., Oliveira, C. A. d. S., de Lima, S. C. R. B. and von Sperling, M. (2020) 'A review of sanitation technologies for flood-prone areas', *Journal of Water, Sanitation and Hygiene for Development,* 10(3), pp. 397-412.
Borie, M., Pelling, M., Ziervogel, G. and Hyams, K. (2019) 'Mapping narratives of urban resilience in the global south', *Global Environmental Change,* 54, pp. 203-213.
Bornemann, F. J., Rowell, D. P., Evans, B., Lapworth, D. J., Lwiza, K., Macdonald, D. M. J., Marsham, J. H., Tesfaye, K., Ascott, M. J. and Way, C. (2019) 'Future changes and uncertainty in decision-relevant measures of East African climate', *Climatic Change,* 156(3), pp. 365-384.
Bott, L.-M., Schöne, T., Illigner, J., Haghighi, M. H., Gisevius, K. and Braun, B. (2021) 'Land subsidence in Jakarta and Semarang Bay–The relationship between physical processes, risk perception, and household adaptation', *Ocean & Coastal Management,* 211, pp. 105775.
Boussalis, C., Coan, T. G. and Holman, M. R. (2019) 'Communicating Climate Mitigation and Adaptation Efforts in American Cities', *Climate,* 7(3), pp. 45.
Boutwell, J. L. and Westra, J. V. (2016) 'The Role of Wetlands for Mitigating Economic Damage from Hurricanes', *JAWRA Journal of the American Water Resources Association,* 52(6), pp. 1472-1481.
Bowen, T., Del Ninno, C., Andrews, C., Coll-Black, S., Johnson, K., Kawasoe, Y., Kryeziu, A., Maher, B. and Williams, A. (2020) *Adaptive Social Protection: Building Resilience to Shocks.* Washington DC: World Bank Publications.
Braks, M. A. H. and de Roda Husman, A. M. (2013) 'Dimensions of effects of climate change on water-transmitted infectious diseases', *Air Water Borne Dis,* 2(109), pp. 2.
Brandt, L., Lewis, A. D., Fahey, R., Scott, L., Darling, L. and Swanston, C. (2016) 'A framework for adapting urban forests to climate change', *Environmental Science & Policy,* 66, pp. 393-402.
Brandtner, C. and Suárez, D. (2021) 'The structure of city action: Institutional embeddedness and sustainability practices in US cities', *The American Review of Public Administration,* 51(2), pp. 121-138.
Brauman, K. A., Benner, R., Benitez, S., Bremer, L. and Vigerstøl, K. (2019) 'Water funds', in Mandle, L., Ouyang, Z., Salzman, J.E. and Daily, G. (eds.) *Green Growth That Works*. Washington, DC.: Island Press, pp. 118-140.
Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R. and van der Sluijs, J. (2019) 'Toward a multi-faceted conception of co-production of climate services', *Climate Services,* 13, pp. 42-50.
Brenner, N. (2014a) *Implosions/explosions.* Berlin: Jovis.
Brenner, N. (2014b) 'Introduction', in Brenner, N. (ed.) *Implosions/explosions*. Berlin: Jovis.
Brenner, N. and Schmid, C. (2017) 'Planetary urbanization', in Ren, X. and Keil, R. (eds.) *The Globalizing Cities Reader*. London: Routledge, pp. 479-482.
Bridges, T. S., Wagner, P. W., Burks-Copes, K. A., Bates, M. E., Collier, Z. A., Fischenich, C. J., Gailani, J. Z., Leuck, L. D., Piercy, C. D., Rosati, J. D., Russo, E. J., Shafer, D. J., Suedel, B. C., Vuxton, E. A. and Wamsley, T. V. (2015) *Use of Natural and Nature-Based Features (NNBF) for coastal resilience*: US Army Corps of Engineers - Engineer Research and Development Center. Available at: https://apps.dtic.mil/dtic/tr/fulltext/u2/a613224.pdf.
Briggs, K. M., Loveridge, F. A. and Glendinning, S. (2017) 'Failures in transport infrastructure embankments', *Engineering Geology,* 219, pp. 107-117.
Brink, E., Aalders, T., Ádám, D., Feller, R., Henselek, Y., Hoffmann, A., Ibe, K., Matthey-Doret, A., Meyer, M. and Negrut, N. L. (2016) 'Cascades of green: a review of ecosystem-based adaptation in urban areas', *Global environmental change,* 36, pp. 111-123.
Brocherie, F., Girard, O. and Millet, P. G. (2015) 'Emerging Environmental and Weather Challenges in Outdoor Sports', *Climate,* 3(3).
Brody, S., Rogers, M. and Siccardo, G. (2019) 'Why, and How, Utilities Should Start to Manage Climate-Change Risk'. Available at: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/why-and-how-utilities-should-start-to-manage-climate-change-risk.

Brondizio, E. S., Settele, J., Díaz, S. and Ngo, H. T. (2019) *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, Bonn: IPBES Secretariat.

Brown, A. E. (2018) *Ridehail revolution: Ridehail travel and equity in Los Angeles.* UCLA, Los Angeles [Online] Available at: https://escholarship.org/uc/item/4r22m57k (Accessed.

Brown, D. and McGranahan, G. (2016) 'The urban informal economy, local inclusion and achieving a global green transformation', *Habitat International,* 53, pp. 97-105.

Brown, K. (2014) 'Global environmental change I: A social turn for resilience?', *Progress in human geography,* 38(1), pp. 107-117.

Brown, T., Leach, S., Wachter, B. and Gardunio, B. (2020) 'The Extreme 2018 Northern California Fire Season', *Bulletin of the American Meteorological Society,* 101(1), pp. S1-S4.

Buchori, I., Rahmayana, L., Pangi, P., Pramitasari, A., Sejati, A. W., Basuki, Y. and Bramiana, C. N. (2021) 'In situ urbanization-driven industrial activities: the Pringapus enclave on the rural-urban fringe of Semarang Metropolitan Region, Indonesia', *International Journal of Urban Sciences*, pp. 1-24.

Bulkeley, H. (2015) 'Can cities realise their climate potential? Reflections on COP21 Paris and beyond', *Local Environment,* 20(11), pp. 1405-1409.

Bulkeley, H. A., Castán Broto, V. and Edwards, G. A. (2014) *An urban politics of climate change: experimentation and the governing of socio-technical transitions.* Oxon: Routledge.

Burgess, D., Ortega, K., Stumpf, G., Garfield, G., Karstens, C., Meyer, T., Smith, B., Speheger, D., Ladue, J. and Smith, R. (2014) '20 May 2013 Moore, Oklahoma, tornado: Damage survey and analysis', *Weather and Forecasting,* 29(5), pp. 1229-1237.

Burgess, P., Shahidehpour, M., Ganji, M. and Connors, D. (2017) 'Remote power units for off-grid lighting and urban resilience', *The Electricity Journal,* 30(4), pp. 16-26.

Burgin, L., Way, C., Evans, B., Rowell, D., Marsham, J., Semazzi, F., Sabiiti, G., Araujo, J., Ascott, M., Lapworth, D., Macdonald, D. and Wainwright, C. (2019) 'FCFA HyCRISTAL Climate Narrative Urban Infographic and Brief', *Zendo*.

Burke, M., Hsiang, S. M. and Miguel, E. (2015) 'Global non-linear effect of temperature on economic production', *Nature,* 527, pp. 235.

Burnett, D., Barbour, E. and Harrison, G. P. (2014) 'The UK solar energy resource and the impact of climate change', *Renewable Energy,* 71, pp. 333-343.

Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C. A., Apte, J. S., Brauer, M., Cohen, A. and Weichenthal, S. (2018) 'Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter', *Proceedings of the National Academy of Sciences,* 115(38), pp. 9592-9597.

Butler, W. H., Deyle, R. E. and Mutnansky, C. (2016) 'Low-regrets incrementalism: Land use planning adaptation to accelerating sea level rise in Florida's Coastal Communities', *Journal of Planning Education and Research,* 36(3), pp. 319-332.

Byers, E. A., Hall, J. W. and Amezaga, J. M. (2014) 'Electricity generation and cooling water use: UK pathways to 2050', *Global Environmental Change,* 25, pp. 16-30.

Byers, E. A., Hall, J. W., Amezaga, J. M., O'Donnell, G. M. and Leathard, A. (2016) 'Water and climate risks to power generation with carbon capture and storage', *Environmental Research Letters,* 11(2), pp. 024011.

Bäckstrand, K. and Kuyper, J. W. (2017) 'The democratic legitimacy of orchestration: the UNFCCC, non-state actors, and transnational climate governance', *Environmental Politics,* 26(4), pp. 1-25.

Bäckstrand, K., Kuyper, J. W., Linnér, B.-O. and Lövbrand, E. (2017) 'Non-state actors in global climate governance: from Copenhagen to Paris and beyond', *Environmental Politics,* 24(6).

Béné, C., Cornelius, A. and Howland, F. (2018) 'Bridging Humanitarian Responses and Long-Term Development through Transformative Changes—Some Initial Reflections from the World Bank's Adaptive Social Protection Program in the Sahel', *Sustainability,* 10(6), pp. 1697.

C40 (2019) *Principles of the Global Green New Deal*. Online: C40. Available at: https://www.c40.org/global-green-new-deal (Accessed: 06.17 2021).

Cabrera, J. F. and Najarian, J. C. (2015) 'How the built environment shapes spatial bridging ties and social capital', *Environment and Behavior,* 47(3), pp. 239-267.

Cai, B., Cui, C., Zhang, D., Cao, L., Wu, P., Pang, L., Zhang, J. and Dai, C. (2019) 'China city-level greenhouse gas emissions inventory in 2015 and uncertainty analysis', *Applied energy,* 253, pp. 113579.

Cai, R., Feng, S., Oppenheimer, M. and Pytlikova, M. (2016) 'Climate variability and international migration: The importance of the agricultural linkage', *Journal of Environmental Economics and Management,* 79, pp. 135-151.

Cai, S., Wang, Y., Zhao, B., Wang, S., Chang, X. and Hao, J. (2017) 'The impact of the "Air Pollution Prevention and Control Action Plan" on PM2.5 concentrations in Jing-Jin-Ji region during 2012–2020', *Science of The Total Environment,* 580, pp. 197-209.

Calautit, J. K. and Hughes, B. R. (2016) 'A passive cooling wind catcher with heat pipe technology: CFD, wind tunnel and field-test analysis', *Applied Energy,* 162, pp. 460-471.

Caldarice, O., Tollin, N. and Pizzorni, M. (2021) 'The relevance of science-policy-practice dialogue. Exploring the urban climate resilience governance in Italy', *City, Territory and Architecture,* 8(1), pp. 1-11.

Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G. and Loreto, F. (2013) 'Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review', *Environmental pollution,* 183, pp. 71-80.

Calvet, M. S. and Castán Broto, V. (2016) 'Green enclaves, neoliberalism and the constitution of the experimental city in Santiago de Chile', in James Evans, A.K., Rob Raven (ed.) *The Experimental City*. London: Routledge, pp. 107-121.

Campello Torres, P. H., Gonçalves, D. A., Mendes de Almeida Collaço, F., Lopes dos Santos, K., Canil, K., Cabral de Sousa Júnior, W. and Jacobi, P. R. (2021) 'Vulnerability of the São Paulo Macro Metropolis to Droughts and Natural Disasters: Local to Regional Climate Risk Assessments and Policy Responses', *Sustainability,* 13(1), pp. 114.

Campello Torres, P. H., Leonel, A. L., de Araujo, G. P. and Jacobi, P. R. (2020) 'Is the Brazilian National Climate Change Adaptation Plan Addressing Inequality? Climate and Environmental Justice in a Global South Perspective', *Environmental Justice,* 13(2).

Campos, I. S., Alves, F. M., Dinis, J., Truninger, M., Vizinho, A. and Penha-Lopes, G. (2016) 'Climate adaptation, transitions, and socially innovative action-research approaches', *Ecology and Society,* 21(1).

Campos, L. C. and Darch, G. (2015) 'Adaptation of UK wastewater infrastructure to climate change', *Infrastructure Asset Management,* 2(3), pp. 97-106.

Camuffo, D. (2019) *Microclimate for Cultural Heritage: Measurement, Risk Assessment, Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments.* Amsterdam: Elsevier, p. 582.

Camuffo, D., Bertolin, C. and Schenal, P. (2017) 'A novel Proxy and the Sea Level Rise in Venice, Italy, from 1350 to 2014', *Climatic Change,* 143(1), pp. 73-86.

Caparros-Midwood, D., Dawson, R. and Barr, S. (2019) 'Low Carbon, Low Risk, Low Density: Resolving choices about sustainable development in cities', *Cities,* 89, pp. 252-267.

Capon, A. (2017) 'Harnessing urbanisation for human wellbeing and planetary health', *The Lancet Planetary Health,* 1(1), pp. e6-e7.

Capone, D., Buxton, H., Cumming, O., Dreibelbis, R., Knee, J., Nalá, R., Ross, I. and Brown, J. (2020) 'Impact of an intervention to improve pit latrine emptying practices in low income urban neighborhoods of Maputo, Mozambique', *International Journal of Hygiene and Environmental Health,* 226, pp. 113480.

Caprotti, F., Cowley, R., Datta, A., Broto, V. C., Gao, E., Georgeson, L., Herrick, C., Odendaal, N. and Joss, S. (2017) 'The New Urban Agenda: key opportunities and challenges for policy and practice', *Urban research & practice,* 10(3), pp. 367-378.

Cardoso, M. A., Brito, R. S., Pereira, C., Gonzalez, A., Stevens, J. and Telhado, M. J. (2020) 'RAF Resilience Assessment Framework—A Tool to Support Cities' Action Planning', *Sustainability,* 12(6), pp. 2349.

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Brockwell, S., Webb, B., Hunter, F. and Bird, D. (2017) 'Local and indigenous management of climate change risks to archaeological sites', *Mitigation and Adaptation Strategies for Global Change,* 23, pp. 231-255.

Carmin, J., Tierney, K., Chu, E., Hunter, L. M., Roberts, J. T. and Shi, L. (2015) 'Adaptation to Climate Change', in Dunlap, R.E. and Brulle, R.J. (eds.). Oxford and New York: Oxford University Press, pp. 164-198.

Carson, A., Windsor, M., Hill, H., Haigh, T., Wall, N., Smith, J., Olsen, R., Bathke, D., Demir, I. and Muste, M. (2018) 'Serious gaming for participatory planning of multi-hazard mitigation', *International journal of river basin management,* 16(3), pp. 379-391.

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J. and Kazmierczak, A. (2015) 'Climate change and the city: Building capacity for urban adaptation', *Progress in Planning,* 95(Complete), pp. 1-66.

Carter, J. G., Handley, J., Butlin, T. and Gill, S. (2018) 'Adapting cities to climate change–exploring the flood risk management role of green infrastructure landscapes', *Journal of Environmental Planning and Management,* 61(9), pp. 1535-1552.

Carter, L. (2019) *Indigenous Pacific Approaches to Climate Change.* Aotearoa/New Zealand: Palgrave.

Carter, M. R. and Janzen, S. A. (2018) 'Social protection in the face of climate change: targeting principles and financing mechanisms', *Environment and Development Economics,* 23(3), pp. 369-389.

Casa, D. J., DeMartini, J. K., Bergeron, M. F., Csillan, D., Eichner, E. R., Lopez, R. M., Ferrara, M. S., Miller, K. C., O'Connor, F., Sawka, M. N. and Yeargin, S. W. (2015) 'National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses', *Journal of Athletic Training,* 50(9), pp. 986-1000.

Castro, C.-P., Sarmiento, J.-P., Edwards, R., Hoberman, G. and Wyndham, K. (2017) 'Disaster risk perception in urban contexts and for people with disabilities: case study on the city of Iquique (Chile)', *Natural hazards,* 86(1), pp. 411-436.

Castán Broto, V. (2014) 'Planning for climate change in the African city', *International Development Planning Review,* 36(3), pp. 257-264.

Castán Broto, V. (2017) 'Urban governance and the politics of climate change', *World development,* 93, pp. 1-15.

Castán Broto, V., Macucule, D. A., Boyd, E., Ensor, J. and Allen, C. (2015) 'Building collaborative partnerships for climate change action in Maputo, Mozambique', *Environment and Planning A,* 47(3), pp. 571-587.

Castán Broto, V., Trencher, G., Iwaszuk, E. and Westman, L. (2018) 'Transformative capacity and local action for urban sustainability', *Ambio,* 48, pp. 449- 462.

Castán Broto, V. and Westman, L. (2017) 'Just sustainabilities and local action: Evidence from 400 flagship initiatives', *Local Environment,* 22(5), pp. 635-650.
Castán Broto, V. and Westman, L. (2019) *Urban sustainability and justice: Just sustainabilities and environmental planning.* London: Zed Books Ltd.
Cattaneo, C., Beine, M., Fröhlich, C. J., Kniveton, D., Martinez-Zarzoso, I., Mastrorillo, M., Millock, K., Piguet, E. and Schraven, B. (2019) 'Human Migration in the Era of Climate Change', *Review of environmental economics and policy,* 13(2), pp. 189-206.
CBS (2019) *Semarang City in Figures*, Semarang: City Bureau of Statistic.
Cederlöf, G. (2016) 'Low-carbon food supply: the ecological geography of Cuban urban agriculture and agroecological theory', *Agriculture and Human Values,* 33(4), pp. 771-784.
Cellura, M., Guarino, F., Longo, S., Mistretta, M. and Tumminia, G. 'Effect of Climate Change on Building Performance: the Role of Ventilative Cooling'. *International Building Performance Simulation Association*, San Francisco, CA, USA.
Challinor, A., Adger, W. N., Benton, T. G. and Conway, D. (2018) 'Transmission of climate risks across sectors and borders A', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 376, pp. 20170301.
Chambers, J. (2020) 'Global and cross-country analysis of exposure of vulnerable populations to heatwaves from 1980 to 2018', *Climatic Change,* 163(1), pp. 539-558.
Chan, A. P. and Owusu, E. K. (2017) 'Corruption forms in the construction industry: Literature review', *Journal of Construction Engineering and Management,* 143(8), pp. 04017057.
Chan, F. K. S., Griffiths, J. A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.-T., Xu, Y. and Thorne, C. R. (2018) '"Sponge City" in China—A breakthrough of planning and flood risk management in the urban context', *Land Use Policy,* 76, pp. 772-778.
Chan, S. and Amling, W. (2019) 'Does orchestration in the Global Climate Action Agenda effectively prioritize and mobilize transnational climate adaptation action?', *International Environmental Agreements: Politics, Law and Economics,* 19(4-5), pp. 429-446.
Chan, S., Falkner, R., van Asselt, H. and Goldberg, M. (2015a) *Strengthening non-state climate action: a progress assessment of commitments launched at the 2014 UN Climate Summit*, London, UK: Centre for Climate Change Economics and Policy and Grantham Research Institute on Climate Change and the Environment. Available at: http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2015/11/Working-Paper-216-Chan-et-al.pdf.
Chan, S., van Asselt, H., Hale, T., Abbott, K. W., Beisheim, M., Hoffmann, M., Guy, B., Höhne, N., Hsu, A. and Pattberg, P. (2015b) 'Reinvigorating international climate policy: a comprehensive framework for effective nonstate action', *Global Policy,* 6(4), pp. 466-473.
Chang, A. Y., Cowling, K., Micah, A. E., Chapin, A., Chen, C. S., Ikilezi, G., Sadat, N., Tsakalos, G., Wu, J. and Younker, T. (2019a) 'Past, present, and future of global health financing: a review of development assistance, government, out-of-pocket, and other private spending on health for 195 countries, 1995–2050', *The Lancet,* 393(10187), pp. 2233-2260.
Chang, K.-L., Cooper, O., West, J. J., Serre, M., Schultz, M., Lin, M., Marécal, V., Josse, B., Deushi, M. and Sudo, K. (2019b) 'A new method (M 3 Fusion v1) for combining observations and multiple model output for an improved estimate of the global surface ozone distribution', *Geosci. Model Dev,* 12, pp. 955–978.
Chanza, N. (2018) 'Limits to climate change adaptation in Zimbabwe: Insights, experiences and lessons', in Leal, Filho, W. and Nalau, J. (eds.) *Limits to Climate Change Adaptation*. Cham: Springer, pp. 109-127.
Chapman, L. (2015) 'Weather and climate risks to road transport', *Infrastructure Asset Management,* 2(2), pp. 58-68.
Chaves, I. A., Melchers, R. E., Peng, L. and Stewart, M. G. (2016) 'Probabilistic remaining life estimation for deteriorating steel marine infrastructure under global warming and nutrient pollution', *Ocean Engineering,* 126, pp. 129-137.
Chen, C., Doherty, M., Coffee, J., Wong, T. and Hellmann, J. (2016) 'Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas', *Environmental Science & Policy,* 66, pp. 403-419.
Chen, J. and Mueller, V. (2018) 'Coastal climate change, soil salinity and human migration in Bangladesh', *Nature climate change,* 8(11), pp. 981-985.
Chen, L. and Shi, J. (2016) 'Analysis and predication of urban water security: a case study of Chengdu City, China', *IOP Conference Series: Earth and Environmental Science,* 39, pp. 1755-1315.
Chen, M. (2014) 'Informal employment and development: Patterns of inclusion and exclusion', *The European Journal of Development Research,* 26(4), pp. 397-418.
Chen, M., Roever, S. and Skinner, C. 2016. Urban livelihoods: Reframing theory and policy. Sage Publications Sage UK: London, England.
Chen, T.-H., Li, X., Zhao, J. and Zhang, K. (2017) 'Impacts of cold weather on all-cause and cause-specific mortality in Texas, 1990–2011', *Environmental Pollution,* 225, pp. 244-251.
Chen, W.-B. and Liu, W.-C. (2014) 'Modeling flood inundation induced by river flow and storm surges over a river basin', *Water,* 6(10), pp. 3182-3199.
Cheng, C. S., Li, G. and Auld, H. (2011) 'Possible impacts of climate change on freezing rain using downscaled future climate scenarios: updated for eastern Canada', *Atmosphere-Ocean,* 49(1), pp. 8-21.

Chhetri, P., Corcoran, J., Gekara, V., Maddox, C. and McEvoy, D. (2015) 'Seaport resilience to climate change: mapping vulnerability to sea-level rise', *Journal of Spatial Science,* 60(1), pp. 65-78.
Childers, D. L., Bois, P., Hartnett, H. E., McPhearson, T., Metson, G. S., Sanchez, C. A., Zak, D. R. and Hellmann, J. J. (2019) 'Urban Ecological Infrastructure: An inclusive concept for the non-built urban environment', *Elementa: Science of the Anthropocene,* 7.
Chinh, D. T., Dung, N. V., Gain, A. K. and Kreibich, H. (2017) 'Flood Loss Models and Risk Analysis for Private Households in Can Tho City, Vietnam', *Water,* 9(5).
Chinh, D. T., Gain, A. K., Dung, N. V., Haase, D. and Kreibich, H. (2016) 'Multi-Variate Analyses of Flood Loss in Can Tho City, Mekong Delta', *Water,* 8(1).
Chinowsky, P. S., Price, J. C. and Neumann, J. E. (2013) 'Assessment of climate change adaptation costs for the US road network', *Global Environmental Change,* 23(4), pp. 764-773.
Chirambo, D. (2021) 'Leveraging Private Finance for Climate Change Adaptation in Africa: Policy Insights from the One-Planet Network', in W., L.F., J., L. and D., A. (eds.) *Handbook of Climate Change Management*. Cham: Springer.
Choudhury, M. U. I., Haque, C., Nishat, A. and Byrne, S. (2021) 'Social learning for building community resilience to cyclones: role of indigenous and local knowledge, power and institutions in coastal Bangladesh', *Ecology and Society,* 26(1).
Chow, J. (2018) 'Mangrove management for climate change adaptation and sustainable development in coastal zones', *Journal of Sustainable Forestry,* 37(2), pp. 139-156.
Chow, T. E., Choi, Y., Yang, M., Mills, D. and Yue, R. (2021) 'Geographic pattern of human mobility and COVID-19 before and after Hubei lockdown', *Annals of GIS*, pp. 1-12.
Chow, W. T. L., Akbar, S. N. A. B. A., Heng, S. L. and Roth, M. (2016) 'Assessment of measured and perceived microclimates within a tropical urban forest', *Urban Forestry & Urban Greening,* 16, pp. 62-75.
Chow, W. T. L., Salamanca, F., Georgescu, M., Mahalov, A., Milne, J. M. and Ruddell, B. L. (2014) 'A multi-method and multi-scale approach for estimating city-wide anthropogenic heat fluxes', *Atmospheric Environment,* 99, pp. 64-76.
Chowdhury, M. R., Jahan, F. and Rahman, R. (2017) 'Developing urban space: the changing role of NGOs in Bangladesh', *Development in Practice,* 27(2), pp. 260-271.
Chu, E. (2016) 'The political economy of urban climate adaptation and development planning in Surat, India', *Environment and Planning C: Government and Policy,* 34(2), pp. 281-298.
Chu, E., Anguelovski, I. and Carmin, J. (2016) 'Inclusive approaches to urban climate adaptation planning and implementation in the Global South', *Climate Policy,* 16(3), pp. 372-392.
Chu, E., Anguelovski, I. and Roberts, D. (2017) 'Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities', *Cities,* 60, pp. 378-387.
Chu, E., Brown, A., Michael, K., Du, J., Lwasa, S. and Mahendra, A. (2019) *Unlocking the potential for transformative climate adaptation in cities*, Washington, DC and Rotterdam: World Resources Institute. Available at: https://gca.org/wp-content/uploads/2020/12/UnlockingThePotentialForTransformativeAdaptationInCities.pdf.
Chu, E., Hughes, S. and Mason, S. (2018) 'Conclusion: Multilevel Governance and Climate Change Innovations in Cities', in Hughes, S., Chu, E. and Mason, S. (eds.) *Climate Change in Cities Innovations in Multi-Level Governance*. Cham: Springer, pp. 361-378.
Chu, E. and Michael, K. (2018) 'Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities', *Environment and Urbanization,* 31(1), pp. 139-156.
Chu, E., Schenk, T. and Patterson, J. (2018) 'The dilemmas of citizen inclusion in urban planning and governance to enable a 1.5 C climate change scenario', *Urban Planning,* 3(2), pp. 128–140.
Chuah, C. J., Ho, B. H. and Chow, W. T. L. (2018) 'Trans-boundary variations of urban drought vulnerability and its impact on water resource management in Singapore and Johor, Malaysia', *Environmental Research Letters,* 13(7), pp. 074011.
CIA (2015) *The World Factbook*: Central Intelligence Agency.
Ciarelli, G., Colette, A., Schucht, S., Beekmann, M., Andersson, C., Manders-Groot, A., Mircea, M., Tsyro, S., Fagerli, H. and Ortiz, A. G. (2019) 'Long-term health impact assessment of total PM2. 5 in Europe during the 1990–2015 period', *Atmospheric Environment: X,* 3, pp. 100032.
Cilliers, J. and Cilliers, S. (2015) 'From green to gold: A South African example of valuing urban green spaces in some residential areas in Potchefstroom', *Town and regional planning,* 67, pp. 1-12.
City Learning Platform (2019) *Principles of Engagement for the City Learning Platform - Practitioner Brief #1*, Freetown: Sierra Leone Urban Research Centre. Available at: https://www.slurc.org/policy-briefs.html%0D%0A.
City of Los Angeles (2017) 'Los Angeles River Revitalization'. DOI: lariver.org (Accessed 1st January 2017).
City of Seattle (2017) *Preparing for Climate Change*. Seattle, WA: Seattle Office of Sustainability and Environment. Available at: http://www.seattle.gov/documents/Departments/Environment/ClimateChange/SEAClimatePreparedness_August2017.pdf.
Clar, C. (2019) 'Coordinating climate change adaptation across levels of government: the gap between theory and practice of integrated adaptation strategy processes', *Journal of Environmental Planning and Management,* 62(12), pp. 2166-2185.

Cloutier, G., Papin, M. and Bizier, C. (2018) 'Do-it-yourself (DIY) adaptation: Civic initiatives as drivers to address climate change at the urban scale', *Cities,* 74, pp. 284-291.
Coates, R. and Nygren, A. (2020) 'Urban floods, clientelism, and the political ecology of the state in Latin America', *Annals of the American Association of Geographers,* 110(5), pp. 1301-1317.
Codjoe, S. N., Gough, K. V., Wilby, R. L., Kasei, R., Yankson, P. W., Amankwaa, E. F., Abarike, M. A., Atiglo, D. Y., Kayaga, S. and Mensah, P. (2020) 'Impact of extreme weather conditions on healthcare provision in urban Ghana', *Social Science & Medicine,* 258, pp. 113072.
Cohen, D. A. (2018) *Climate Justice and the Right to the City*, Philadelphia: University of Pennsylvania.
Cohen, J. E. (2019) 'Cities and Climate Change: A Review Essay', *Population and Development Review,* 45(2), pp. 425-435.
Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S. (2016) 'Nature-based solutions to address global societal challenges', *IUCN: Gland, Switzerland,* 97.
Colenbrander, S., Dodman, D. and Mitlin, D. (2018) 'Using climate finance to advance climate justice: the politics and practice of channelling resources to the local level', *Climate policy,* 18(7), pp. 902-915.
Coletta, C. and Kitchin, R. (2017) 'Algorhythmic governance: Regulating the 'heartbeat'of a city using the Internet of Things', *Big Data & Society,* 4(2), pp. 2053951717742418.
Colsaet, A., Laurans, Y. and Levrel, H. (2018) 'What drives land take and urban land expansion? A systematic review', *Land Use Policy,* 79, pp. 339-349.
Colón Almenas, V. (2020) 'El uso de un 2% del dinero disponible refleja la lentitud del Gobierno de Puerto Rico en el gasto de fondos CDBG-DR', September 3. Available at: http://www.periodismoinvestigativo.com.
Connell, J. (2016) 'Last days in the Carteret Islands? Climate change, livelihoods and migration on coral atolls', *Asia Pacific Viewpoint,* 57(1), pp. 3-15.
Connelly, A., Carter, J., Handley, J. and Hincks, S. (2018) 'Enhancing the practical utility of risk assessments in climate change adaptation', *Sustainability,* 10(5), pp. 1399.
Cooper, M. G., Nolin, A. W. and Safeeq, M. (2016) 'Testing the recent snow drought as an analog for climate warming sensitivity of Cascades snowpacks', *Environmental Research Letters,* 11(8), pp. 084009.
Corvalan, C., Villalobos Prats, E., Sena, A., Campbell-Lendrum, D., Karliner, J., Risso, A., Wilburn, S., Slotterback, S., Rathi, M. and Stringer, R. (2020) 'Towards Climate Resilient and Environmentally Sustainable Health Care Facilities', *International Journal of Environmental Research and Public Health,* 17(23), pp. 8849.
Cosic, D., Popovic, L., Popov, S. and Zivkovic, S. (2019) 'Hydrological conflicts risk estimation in vojvodina, serbia', *Fresenius Environmental Bulletin,* 28(9), pp. 6580-6588.
Costa, E., Paiva, A., Seixas, J., Costa, G., Baptista, P. and Gallachóir, B. Ó. (2018) 'Spatial Planning of Electric Vehicle Infrastructure for Belo Horizonte, Brazil', *Journal of Advanced Transportation,* 2018.
Costella, C., Jaime, C., Arrighi, J., Coughlan de Perez, E., Suarez, P. and van Aalst, M. (2017) 'Scalable and sustainable: how to build anticipatory capacity into social protection systems', *Institute of Development Studies Bulletin,* 48(4).
Coutard, O. and Rutherford, J. (2015) *Beyond the Networked City: Infrastructure Reconfigurations and Urban Change in the North and South.* London: Routledge.
Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M. and Demuzere, M. (2013) 'Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context', *Progress in Physical Geography,* 37(1), pp. 2-28.
Coutts, A. M., White, E. C., Tapper, N. J., Beringer, J. and Livesley, S. J. (2016) 'Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments', *Theoretical and applied climatology,* 124(1-2), pp. 55-68.
Cradden, L., Burnett, D., Agarwal, A. and Harrison, G. (2015) 'Climate change impacts on renewable electricity generation', *Infrastructure Asset Management,* 2(3), pp. 131-142.
Cradden, L. C. and Harrison, G. P. (2013) 'Adapting overhead lines to climate change: Are dynamic ratings the answer?', *Energy Policy,* 63, pp. 197-206.
Crausbay, S. D., Betancourt, J., Bradford, J., Cartwright, J., Dennison, W. C., Dunham, J., Enquist, C. A. F., Frazier, A. G., Hall, K. R. and Littell, J. S. (2020) 'Unfamiliar Territory: Emerging Themes for Ecological Drought Research and Management', *One Earth,* 3(3), pp. 337-353.
Cremades, R., Surminski, S., Costa, M. M., Hudson, P., Shrivastava, P. and Gascoigne, J. (2018) 'Using the adaptive cycle in climate-risk insurance to design resilient futures', *Nature Climate Change,* 8(1), pp. 4.
Crnogorcevic, L. (2019) 'School strike 4 climate: History, challenges and what's next', *Green Left Weekly*, p. 10. Available at: https://www.greenleft.org.au/content/school-strike-4-climate-history-challenges-and-whats-next.
Cronin, J., Anandarajah, G. and Dessens, O. (2018) 'Climate change impacts on the energy system: a review of trends and gaps', *Climatic change,* 151(2), pp. 79-93.
Cruz, A. M. and Krausmann, E. (2013) 'Vulnerability of the oil and gas sector to climate change and extreme weather events', *Climatic change,* 121(1), pp. 41-53.
Cuevas, S. (2016) 'The interconnected nature of the challenges in mainstreaming climate change adaptation: evidence from local land use planning', *Climatic Change,* 136(3-4), pp. 661-676.

Cuevas, S., Peterson, A., Robinson, C. and Morrison, T. (2016) 'Institutional capacity for long-term climate change adaptation: evidence from land use planning in Albay, Philippines', *Regional Environmental Change,* 16(7), pp. 2045-2058.

Culwick, C., Washbourne, C.-L., Anderson, P. M., Cartwright, A., Patel, Z. and Smit, W. (2019) 'CityLab reflections and evolutions: nurturing knowledge and learning for urban sustainability through co-production experimentation', *Current opinion in environmental sustainability,* 39, pp. 9-16.

Cunniff, S. and Schwartz, A. (2015) *Performance of natural infrastructure and nature-based measures as coastal risk reduction features*, New York: Environmental Defense Fund.

Cutter-Mackenzie, A. and Rousell, D. (2019) 'Education for what? Shaping the field of climate change education with children and young people as co-researchers', *Children's Geographies,* 17(1), pp. 90-104.

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G. K., Seekell, D. A. and Suweis, S. (2018) 'The global food-energy-water nexus', *Reviews of Geophysics,* 56(3), pp. 456-531.

Dahiya, B. and Das, A. (2020) 'New urban agenda in Asia-Pacific: governance for sustainable and inclusive cities', in Dahiya, B. and Das, A. (eds.) *New Urban Agenda in Asia-Pacific*. Singapore: Springer, pp. 3-36.

Dale, A. G. and Frank, S. D. (2017) 'Warming and drought combine to increase pest insect fitness on urban trees', *PloS one,* 12(3), pp. e0173844.

Daniel, M., Lemonsu, A. and Viguie, V. (2018) 'Role of watering practices in large-scale urban planning strategies to face the heat-wave risk in future climate', *Urban Climate,* 23, pp. 287-308.

Danielson, R. E., Zhang, M. and Perrie, W. A. (2020) 'Possible impacts of climate change on fog in the Arctic and subpolar North Atlantic', *Advances in Statistical Climatology, Meteorology and Oceanography,* 6(1), pp. 31-43.

Darmanto, N. S., Varquez, A. C. G., Kawano, N. and Kanda, M. (2019) 'Future urban climate projection in a tropical megacity based on global climate change and local urbanization scenarios', *Urban Climate,* 29, pp. 100482.

Dasgupta, S., Islam, M. S., Huq, M., Huque Khan, Z. and Hasib, M. R. (2019) 'Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh', *PloS one,* 14(3), pp. e0214079.

Data Driven Yale New Climate Institute PBL (2018) *Global climate action of regions, states and businesses*: Data Driven Yale New Climate Institute PBL.

Davidson, K., Briggs, J., Nolan, E., Bush, J., Håkansson, I. and Moloney, S. (2020) 'The making of a climate emergency response: Examining the attributes of climate emergency plans', *Urban Climate,* 33, pp. 100666.

Davidson, K., Coenen, L., Acuto, M. and Gleeson, B. (2019) 'Reconfiguring urban governance in an age of rising city networks: A research agenda', *Urban Studies,* 56(16), pp. 3540–3555.

Davies, A. R. and Hügel, S. (2021) 'Just adapt: Engaging disadvantaged young people in planning for climate adaptation', *Politics and Governance,* 9(2), pp. 100-111.

Davis, M., Abhold, K., Mederake, L. and Knoblauch, D. (2020) *Nature-based solutions in European and national policy frameworks. Deliverable 1.5. NATURVATION*: European Commission.

Dawson, R. (2015) 'Handling interdependencies in climate change risk assessment', *Climate,* 3(4), pp. 1079-1096.

Dawson, R. J., Thompson, D., Johns, D., Wood, R., Darch, G., Chapman, L., Hughes, P. N., Watson, G. V. R., Paulson, K. and Bell, S. (2018) 'A systems framework for national assessment of climate risks to infrastructure', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 376(2121), pp. 20170298.

Dawson, T. 'Erosion and Coastal Archaeology: Evaluating the Treat and Prioritising Action'. *HOMER Conference Proceedings*, Oxford: Oxford University Archeopress.

De Koning, K. and Filatova, T. (2020) 'Repetitive floods intensify outmigration and climate gentrification in coastal cities', *Environmental Research Letters,* 15(3), pp. 034008.

De la Sota, C., Ruffato-Ferreira, V., Ruiz-García, L. and Alvarez, S. (2019) 'Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain', *Urban Forestry & Urban Greening,* 40, pp. 145-151.

De Longueville, F., Hountondji, Y.-C., Assogba, L., Henry, S. and Ozer, P. (2020) 'Perceptions of and responses to coastal erosion risks: The case of Cotonou in Benin', *International Journal of Disaster Risk Reduction,* 51, pp. 101882.

de Munck, C., Lemonsu, A., Masson, V., Le Bras, J. and Bonhomme, M. (2018) 'Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change', *Urban Climate,* 23, pp. 260-286.

De Stefano, L., González Tánago, I., Ballesteros, M., Urquijo, J., Blauhut, V., Stagge, J. H. and Y Stahl, K. (2015) 'Methodological approach considering different factors influencing vulnerability-pan-European scale', *Drought-R&SPI Technical Report,* (26).

De-Ville, S., Menon, M. and Stovin, V. (2018) 'Temporal variations in the potential hydrological performance of extensive green roof systems', *Journal of Hydrology,* 558, pp. 564-578.

Dean, B., Dulac, J., Petrichenko, K. and Graham, P. (2016) *Towards zero-emission efficient and resilient buildings.: Global status report*, Online: Global Alliance for Buildings and Construction (GABC). Available at: https://orbit.dtu.dk/en/publications/towards-zero-emission-efficient-and-resilient-buildings-global-st.

Decina, S. M., Hutyra, L. R. and Templer, P. H. (2020) 'Hotspots of nitrogen deposition in the world's urban areas: a global data synthesis', *Frontiers in Ecology and the Environment,* 18(2), pp. 92-100.

Delgado, J. A. (2020) 'FEMA aprueba cerca de $13,000 millones para reconstruir la red eléctrica y el sistema educativo', *El Nuevo Día*. Available at: http://www.endi.com.

Dempsey, N., Bramley, G., Power, S. and Brown, C. (2011) 'The social dimension of sustainable development: Defining urban social sustainability', *Sustainable development,* 19(5), pp. 289-300.
Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A., Mittal, N., Feliú, E. and Faehnle, M. (2014) 'Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure', *Journal of environmental management,* 146, pp. 107-115.
Depietri, Y. and McPhearson, T. (2017) 'Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction', in Kabisch, N., Korn, H., Stadler, J., Bonn and A. (eds.) *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice*. Cham: Springer International Publishing, pp. 91–109
Detges, A. (2016) 'Local conditions of drought-related violence in sub-Saharan Africa: The role of road and water infrastructures', *Journal of Peace Research,* 53(5), pp. 696-710.
Devisscher, T., Anderson, L. O., Aragão, L. E. O. C., Galván, L. and Malhi, Y. (2016) 'Increased Wildfire Risk Driven by Climate and Development Interactions in the Bolivian Chiquitania, Southern Amazonia', *PLOS ONE,* 11(9), pp. e0161323.
Devkota, N. and Phuyal, R. K. (2018) 'Adoption Practice of Climate Change Adaptation Options among Nepalese Rice Farmers: Role of Information and Communication Technologies (ICTs)', *American Journal of Climate Change,* 7(02), pp. 135.
Dhar, T. and Khirfan, L. (2016) 'Community-based Adaptation through Ecological Design: Lessons from Negril, Jamaica', *Journal of Urban Design,* 21(2), pp. 234-255.
Dhar, T. and Khirfan, L. (2017) 'A Multi-scale and Multi-dimensional Framework for Enhancing the Resilience of Urban Form to Climate Change', *Urban Climate,* 17, pp. 72-91.
Di Giulio, G. M., Bedran-Martins, A. M. B., Vasconcellos, M. d. P., Ribeiro, W. C. and Lemos, M. C. (2018) 'Mainstreaming climate adaptation in the megacity of São Paulo, Brazil', *Cities,* 72, pp. 237-244.
Di Giulio, G. M., Torres, R. R., Lapola, D. M., Bedran-Martins, A. M., da Penha Vasconcellos, M., Braga, D. R., Fuck, M. P., Juk, Y., Nogueira, V. and Penna, A. C. (2019) 'Bridging the gap between will and action on climate change adaptation in large cities in Brazil', *Regional environmental change,* 19(8), pp. 2491-2502.
Di Turi, S. and Ruggiero, F. (2017) 'Re-interpretation of an ancient passive cooling strategy: A new system of wooden lattice openings', *Energy Procedia,* 126, pp. 289-296.
Dierwechter, Y. and Wessells, A. T. (2013) 'The uneven localisation of climate action in metropolitan Seattle', *Urban Studies,* 50(7), pp. 1368-1385.
Dijst, M., Worrell, E., Böcker, L., Brunner, P., Davoudi, S., Geertman, S., Harmsen, R., Helbich, M., Holtslag, A. A. and Kwan, M.-P. (2018) 'Exploring urban metabolism—Towards an interdisciplinary perspective', *Resources, Conservation and Recycling,* 132, pp. 190-203.
Din, A. and Brotas, L. (2017) 'Assessment of climate change on UK dwelling indoor comfort', *Energy Procedia,* 122, pp. 21-26.
Diniz, F. R., Gonçalves, F. L. T. and Sheridan, S. (2020) 'Heat Wave and Elderly Mortality: Historical Analysis and Future Projection for Metropolitan Region of São Paulo, Brazil', *Atmosphere,* 11(9), pp. 933.
Dino, I. G. and Meral Akgül, C. (2019) 'Impact of climate change on the existing residential building stock in Turkey: An analysis on energy use, greenhouse gas emissions and occupant comfort', *Renewable Energy,* 141, pp. 828-846.
Dirwai, T. L., Kanda, E. K., Senzanje, A. and Busari, T. I. (2021) 'Water resource management: IWRM strategies for improved water management. A systematic review of case studies of East, West and Southern Africa', *PloS one,* 16(5), pp. e0236903.
Djehdian, L. A., Chini, C. M., Marston, L., Konar, M. and Stillwell, A. S. (2019) 'Exposure of urban food–energy–water (FEW) systems to water scarcity', *Sustainable Cities and Society,* 50, pp. 101621.
Dobson, S. (2017) 'Community-driven pathways for implementation of global urban resilience goals in Africa', *International journal of disaster risk reduction,* 26, pp. 78-84.
Dobson, S., Nyamweru, H. and Dodman, D. (2015) 'Local and participatory approaches to building resilience in informal settlements in Uganda', *Environment and Urbanization,* 27(2), pp. 605-620.
Dodman, D., Colenbrander, S. and Archer, D. (2017) 'Conclusion', in Archer, D., Colenbrander, S. and Dodman, D. (eds.) *Responding to climate change in Asian cities: Governance for a more resilient urban future*. Abingdon: Routledge Earthscan.
Dodman, D., Leck, H., Rusca, M. and Colenbrander, S. (2017) 'African Urbanisation and Urbanism: Implications for risk accumulation and reduction', *International journal of disaster risk reduction,* 26, pp. 7-15.
Dodoo, A. and Gustavsson, L. (2016) 'Energy use and overheating risk of Swedish multi-storey residential buildings under different climate scenarios', *Energy,* 97, pp. 534-548.
Doherty, R. M., Heal, M. R. and O'Connor, F. M. (2017) 'Climate change impacts on human health over Europe through its effect on air quality', *Environmental Health,* 16(1), pp. 118.
Doll, C., Klug, S. and Enei, R. (2014) 'Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years', *Natural hazards,* 72(1), pp. 211-239.
Dong, X., Guo, H. and Zeng, S. (2017) 'Enhancing future resilience in urban drainage system: Green versus grey infrastructure', *Water Research,* 124, pp. 280-289.

Dong, X., Jiang, L., Zeng, S., Guo, R. and Zeng, Y. (2020) 'Vulnerability of urban water infrastructures to climate change at city level', *Resources, Conservation and Recycling,* 161, pp. 104918.
Donovan, G. H. (2017) 'Including public-health benefits of trees in urban-forestry decision making', *Urban forestry & urban greening,* 22, pp. 120-123.
Doré, G., Niu, F. and Brooks, H. (2016) 'Adaptation methods for transportation infrastructure built on degrading permafrost', *Permafrost and Periglacial Processes,* 27(4), pp. 352-364.
Douglas, I., Alam, K., Maghenda, M., McDonnell, Y., McLean, L. and Campbell, J. (2008) 'Unjust waters: climate change, flooding and the urban poor in Africa', *Environment and urbanization,* 20(1), pp. 187-205.
Dowdy, A. J. and Catto, J. L. (2017) 'Extreme weather caused by concurrent cyclone, front and thunderstorm occurrences', *Scientific reports,* 7, pp. 40359.
Dowdy, A. J., Ye, H., Pepler, A., Thatcher, M., Osbrough, S. L., Evans, J. P., Di Virgilio, G. and McCarthy, N. (2019) 'Future changes in extreme weather and pyroconvection risk factors for Australian wildfires', *Scientific reports,* 9(1), pp. 1-11.
Drosou, N., Soetanto, R., Hermawan, F., Chmutina, K., Bosher, L. and Hatmoko, J. U. D. (2019) 'Key factors influencing wider adoption of blue–green infrastructure in developing cities', *Water,* 11(6), pp. 1234.
Dugan, J. E., Airoldi, L., Chapman, M. G., Walker, S. J., Schlacher, T., Wolanski, E. and McLusky, D. (2011) '8.02-Estuarine and coastal structures: environmental effects, a focus on shore and nearshore structures', *Treatise on estuarine and coastal science,* 8, pp. 17-41.
Dulal, H. B. (2019) 'Cities in Asia: how are they adapting to climate change?', *Journal of Environmental Studies and Sciences,* 9(1), pp. 13-24.
Duncker, L. G. (2019) 'Sanitation and climate change adaptation', in Woolley, T., Kimmins, S., Harrison, R. and Harrison, P. (eds.) *Green Building Handbook Volume 12*. New York: Routledge, pp. 88-99.
Dunne, J. P., Stouffer, R. J. and John, J. G. (2013) 'Reductions in labour capacity from heat stress under climate warming', *Nature Climate Change,* 3, pp. 563.
Durst, N. J. and Wegmann, J. (2017) 'Informal housing in the United States', *International Journal of Urban and Regional Research,* 41(2), pp. 282-297.
Dutra, L. X. C., Bayliss, P., McGregor, S., Christophersen, P., Scheepers, K., Woodward, E., Ligtermoet, E. and Melo, L. i. F. C. (2017) 'Understanding climate-change adaptation on Kakadu National Park, using a combined diagnostic and modelling framework: a case study at Yellow Water wetland', *Marine and Freshwater Research,* 69(7), pp. 1146-1158.
Döring, S. (2020) 'Come rain, or come wells: How access to groundwater affects communal violence', *Political geography,* 76, pp. 102073.
D'Alisa, G. and Kallis, G. (2016) 'A political ecology of maladaptation: Insights from a Gramscian theory of the State', *Global environmental change,* 38, pp. 230-242.
Eakin, H., Muñoz-Erickson, T. A. and Lemos, M. C. (2018) 'Critical Lines of Action for Vulnerability and Resilience Research and Practice: Lessons from the 2017 Hurricane Season', *Journal of Extreme Events,* 5(02n03), pp. 1850015.
Eakin, H., Parajuli, J., Yogya, Y., Hernández, B. and Manheim, M. (2021) 'Entry points for addressing justice and politics in urban flood adaptation decision making', *Current Opinion in Environmental Sustainability,* 51, pp. 1-6.
Eakin, H., Wightman, P. M., Hsu, D., Gil Ramón, V. R., Fuentes-Contreras, E., Cox, M. P., Hyman, T.-A. N., Pacas, C., Borraz, F. and González-Brambila, C. (2015) 'Information and communication technologies and climate change adaptation in Latin America and the Caribbean: a framework for action', *Climate and Development,* 7(3), pp. 208-222.
Earle, L. (2016) 'Urban crises and the new urban agenda', *Environment and Urbanization,* 28(1), pp. 77-86.
Ebi, K. L., Hallegatte, S., Kram, T., Arnell, N. W., Carter, T. R., Edmonds, J., Kriegler, E., Mathur, R., O'Neill, B. C. and Riahi, K. (2014) 'A new scenario framework for climate change research: background, process, and future directions', *Climatic Change,* 122(3), pp. 363-372.
Economist Intelligence Unit (2015) 'The cost of inaction: Recognising the value at risk from climate change', *The Economist*. DOI: https://eiuperspectives.economist.com/sites/default/files/The%20cost%20of%20inaction_0.pdf.
Elias-Trostmann, K., Cassel, D., Burke, L. and Rangwala, L. (2018) *Stronger Than The Storm: Applying the Urban Community Resilience Assessment to Extreme Climate Events*, Washington, DC: World Resources Institute. Available at: http://www.wri.org/publication/stronger-.
Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K. and Folke, C. (2019) 'Sustainability and resilience for transformation in the urban century', *Nature Sustainability,* 2(4), pp. 267-273.
Elnabawi, M. H., Hamza, N. and Dudek, S. (2016) 'Thermal perception of outdoor urban spaces in the hot arid region of Cairo, Egypt', *Sustainable Cities and Society,* 22, pp. 136-145.
Emmanuel, R. and Steemers, K. (2018) 'Connecting the realms of urban form, density and microclimate', *Building Research & Information,* 46(8).
ENA (2015) *Climate Change Adaptation Reporting Power Second Round*, London: Energy Networks Association. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/479267/clim-adrep-ena-2015.pdf.

Engemann, K., Pedersen, C. B., Arge, L., Tsirogiannis, C., Mortensen, P. B. and Svenning, J.-C. (2019) 'Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood', *Proceedings of the national academy of sciences,* 116(11), pp. 5188-5193.

England, M. I., Stringer, L. C., Dougill, A. J. and Afionis, S. (2018) 'How do sectoral policies support climate compatible development? An empirical analysis focusing on southern Africa', *Environmental Science & Policy,* 79, pp. 9-15.

Erickson, L. E. and Jennings, M. (2017) 'Energy, transportation, air quality, climate change, health nexus: Sustainable energy is good for our health', *AIMS public health,* 4(1), pp. 47.

Eriksen, C., Simon, G. L., Roth, F., Lakhina, S. J., Wisner, B., Adler, C., Thomalla, F., Scolobig, A., Brady, K. and Bründl, M. (2020) 'Rethinking the interplay between affluence and vulnerability to aid climate change adaptive capacity', *Climatic Change,* 162(1), pp. 25-39.

Eriksen, S. H., Nightingale, A. J. and Eakin, H. (2015) 'Reframing adaptation: The political nature of climate change adaptation', *Global Environmental Change,* 35, pp. 523-533.

Escobedo, F. J., Clerici, N., Staudhammer, C. L. and Corzo, G. T. (2015) 'Socio-ecological dynamics and inequality in Bogotá, Colombia's public urban forests and their ecosystem services', *Urban Forestry & Urban Greening,* 14(4), pp. 1040-1053.

Escudero-Castillo, M., Felix-Delgado, A., Silva, R., Mariño-Tapia, I. and Mendoza, E. (2018) 'Beach erosion and loss of protection environmental services in Cancun, Mexico', *Ocean & Coastal Management,* 156, pp. 183-197.

Esteban, M., Takagi, H., Jamero, L., Chadwick, C., Avelino, J. E., Mikami, T., Fatma, D., Yamamoto, L., Thao, N. D., Onuki, M., Woodbury, J., Valenzuela, V. P. B. and Crichton, R. N. (2020a) 'Adaptation to sea level rise: Learning from present examples of land subsidence', *Ocean & coastal management,* 189, pp. 104852.

Esteban, M., Takagi, H., Nicholls, R. J., Fatma, D., Pratama, M. B., Kurobe, S., Yi, X., Ikeda, I., Mikami, T. and Valenzuela, P. (2020b) 'Adapting ports to sea-level rise: empirical lessons based on land subsidence in Indonesia and Japan', *Maritime Policy & Management,* 47(7), pp. 937-952.

ETSAP (2014) *IEA Energy Technology Systems Analysis Programme - Technology Brief E12*: IEA-ETSAP. Available at: https://iea-etsap.org/ (Accessed: 28 September 2019).

Eunice Lo, Y. T., Mitchell, D. M., Bohnenstengel, S. I., Collins, M., Hawkins, E., Hegerl, G. C., Joshi, M. and Stott, P. A. (2020) 'U.K. Climate Projections: Summer Daytime and Nighttime Urban Heat Island Changes in England's Major Cities', *Journal of Climate,* 33(20), pp. 9015-9030.

Evans, B. E., Rowell, D. P. and Semazzi, F. H. M. (2020) 'The Future-Climate, Current-Policy Framework: towards an approach linking climate science to sector policy development', *Environmental Research Letters*.

Faist, T. (2018) 'The Socio-Natural Question: How Climate Change Adds to Social Inequalities', *Journal of intercultural studies,* 39(2), pp. 195-206.

Fan, Y., Li, Y. and Yin, S. (2018) 'Interaction of multiple urban heat island circulations under idealised settings', *Building and Environment,* 134, pp. 10-20.

Fankhauser, S. and Stern, N. (2016) *Climate change, development, poverty and economics. The State of Economics, the State of the World* Cambridge, MA: MIT Press.

Fann, N., Nolte, C. G., Dolwick, P., Spero, T. L., Brown, A. C., Phillips, S. and Anenberg, S. (2015) 'The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030', *Journal of the Air & Waste Management Association,* 65(5), pp. 570-580.

Fant, C., Schlosser, C. A. and Strzepek, K. (2016) 'The impact of climate change on wind and solar resources in southern Africa', *Applied Energy,* 161, pp. 556-564.

Farzaneh, H. and Wang, X. (2020) *Environmental and economic impact assessment of the Low Emission Development Strategies (LEDS) in Shanghai, China*. APN Science Bulletin: APN Science. Available at: https://www.apn-gcr.org/bulletin/article/environmental-and-economic-impact-assessment-of-the-low-emission-development-strategies-leds-in-shanghai-china/ (Accessed: September 9 2021).

Fatoric, S. and Seekamp, E. (2017) 'Evaluating a decision analytic approach to climate change adaptation of cultural resources along the Atlantic Coast of the United States', *Land Use Policy,* 68, pp. 254-263.

Fatorić, S. and Egberts, L. (2020) 'Realising the potential of cultural heritage to achieve climate change actions in the Netherlands', *Journal of Environmental Management,* 274, pp. 111107.

Fatorić, S. and Seekamp, E. (2017) 'Are cultural heritage and resources threatened by climate change? A systematic literature review', *Climate Change,* 142(1-2), pp. 227–254.

Fatorić, S. and Seekamp, E. (2018) 'A measurement framework to increase transparency in historic preservation decision-making under changing climate conditions', *Journal of Cultural Heritage,* 30(3), pp. 168-179.

Favaro, A. and Chelleri, L. (2018) 'The Evolution of Flooding Resilience: The Case of Barcelona', in Galderisi, A. and Colucci, A. (eds.) *Smart, Resilient and Transition Cities: Emerging Approaches and Tools for A Climate-Sensitive Urban Development*. Amsterdam: Elsevier, pp. 115-123.

Feitosa, R. C. and Wilkinson, S. J. (2018) 'Attenuating heat stress through green roof and green wall retrofit', *Building and Environment,* 140, pp. 11-22.

Fekete, A. (2019) 'Critical infrastructure and flood resilience: Cascading effects beyond water', *Wiley Interdisciplinary Reviews: Water,* 6(5), pp. e1370.

Feldpausch-Parker, A. M., Peterson, T. R., Stephens, J. C. and Wilson, E. J. (2018) 'Smart grid electricity system planning and climate disruptions: A review of climate and energy discourse post-Superstorm Sandy', *Renewable and Sustainable Energy Reviews,* 82, pp. 1961-1968.
Feller, I. C., Friess, D. A., Krauss, K. W. and Lewis, R. R. (2017) 'The state of the world's mangroves in the 21st century under climate change', *Hydrobiologia,* 803(1), pp. 1-12.
Fernandez Milan, B. and Creutzig, F. (2015) 'Reducing urban heat wave risk in the 21st century', *Current Opinion in Environmental Sustainability,* 14, pp. 221-231.
Fernández-Llamazares, Á., Díaz-Reviriego, I., Luz, A. C., Cabeza, M., Pyhälä, A. and Reyes-García, V. (2015) 'Rapid ecosystem change challenges the adaptive capacity of local environmental knowledge', *Global Environmental Change,* 31, pp. 272-284.
Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C. and Airoldi, L. (2014) 'The effectiveness of coral reefs for coastal hazard risk reduction and adaptation', *Nature communications,* 5, pp. 3794.
Ferreira, L. S. and Duarte, D. H. S. (2019) 'Exploring the relationship between urban form, land surface temperature and vegetation indices in a subtropical megacity', *Urban Climate,* 27, pp. 105-123.
Ferris, E. G. (2015) 'Climate-Induced Resettlement: Environmental Change and the Planned Relocation of Communities', *The SAIS review of international affairs,* 35(1), pp. 109-117.
Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, K.-G., Allen, S. K., Tignor, M. and Midgley, P. M. (2012) *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC).* Cambridge: IPCC.
Filipe, A., Renedo, A. and Marston, C. (2017) 'The co-production of what? Knowledge, values, and social relations in health care', *PLoS Biology,* 15(5).
Fiore, A. M., Naik, V. and Leibensperger, E. M. (2015) 'Air Quality and Climate Connections', *Journal of the Air & Waste Management Association,* 65(6), pp. 645-685.
Fisher, D. R. and Nasrin, S. (2021) 'Shifting coalitions within the youth climate movement in the US', *Politics and Governance,* 9(2), pp. 112-123.
Fisher, S. (2015) 'The emerging geographies of climate justice', *The Geographical Journal,* 181(1), pp. 73-82.
Fisk, W. J. (2015) 'Review of some effects of climate change on indoor environmental quality and health and associated no-regrets mitigation measures', *Building and Environment,* 86, pp. 70-80.
Fitzky, A. C., Sandén, H., Karl, T., Fares, S., Calfapietra, C., Grote, R., Saunier, A. and Rewald, B. (2019) 'The interplay between ozone and urban vegetation—BVOC emissions, ozone deposition, and tree ecophysiology', *Frontiers in Forests and Global Change,* 2, pp. 50.
Fleming, P. (2017) 'The human capital hoax: Work, debt and insecurity in the era of Uberization', *Organization Studies,* 38(5), pp. 691-709.
Fleming, Z. L., Doherty, R. M., Von Schneidemesser, E., Malley, C., Cooper, O. R., Pinto, J. P., Colette, A., Xu, X., Simpson, D. and Schultz, M. G. (2018) 'Tropospheric Ozone Assessment Report: Present-day ozone distribution and trends relevant to human health', *Elementa: Science of the Anthropocene,* 6(1).
Fletcher, C. S., Rambaldi, A. N., Lipkin, F. and McAllister, R. R. (2016) 'Economic, equitable, and affordable adaptations to protect coastal settlements against storm surge inundation', *Regional Environmental Change,* 16(4), pp. 1023-1034.
Fletcher, S., Lickley, M. and Strzepek, K. (2019) 'Learning about climate change uncertainty enables flexible water infrastructure planning', *Nature communications,* 10(1), pp. 1-11.
Flörke, M., Schneider, C. and McDonald, R. I. (2018) 'Water competition between cities and agriculture driven by climate change and urban growth', *Nature Sustainability,* 1(1), pp. 51-58.
Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R. and Chapin, F. S. (2021) 'Our future in the Anthropocene biosphere', *Ambio,* 50, pp. 1-36.
Foran, J. (2019) 'System Change, Not Climate Change: Radical Social Transformation in the Twenty-First Century', in Berberoglu and B. (eds.) *The Palgrave Handbook of Social Movements, Revolution, and Social Transformation*. Cham: Palgrave McMillan, pp. 399-425.
Forbes, B. T., Bunch, C. E., DeBenedetto, G., Shaw, C. J. and Gungle, B. (2019) *Reach-scale monitoring and modeling of rivers—Expanding hydraulic data collection beyond the cross section*, Reston, VA: US Geological Survey.
Ford, A., Barr, S., Dawson, R., Virgo, J., Batty, M. and Hall, J. (2019) 'A Multi-Scale Urban Integrated Assessment Framework for Climate Change Studies: A Flooding application', *Computers, Environment and Urban Systems,* 75, pp. 229-243.
Forero-Ortiz, E., Martínez-Gomariz, E. and Canas Porcuna, M. (2020) 'A review of flood impact assessment approaches for underground infrastructures in urban areas: a focus on transport systems', *Hydrological Sciences Journal,* 65(11), pp. 1943-1955.
Forzieri, G., Bianchi, A., e Silva, F. B., Herrera, M. A. M., Leblois, A., Lavalle, C., Aerts, J. C. J. H. and Feyen, L. (2018) 'Escalating impacts of climate extremes on critical infrastructures in Europe', *Global environmental change,* 48, pp. 97-107.
Fosas, D., Coley, D., Natarajan, S., Herrera, M., de Pando, M. and Ramallo-Gonzalez, A. (2018) 'Mitigation versus adaptation: Does insulating dwellings increase overheating risk?', *Building and Environment,* 143, pp. 740- 759.

Founda, D. and Santamouris, M. (2017) 'Synergies between Urban Heat Island and Heat Waves in Athens (Greece), during an extremely hot summer (2012)', *Scientific reports,* 7(1), pp. 10973.
Foustalieraki, M., Assimakopoulos, M., Santamouris, M. and Pangalou, H. (2017) 'Energy performance of a medium scale green roof system installed on a commercial building using numerical and experimental data recorded during the cold period of the year', *Energy and Buildings,* 135, pp. 33-38.
Frank, B., Delano, D. and Caniglia, B. S. (2017) 'Urban systems: A socio-ecological system perspective', *Sociol. Int. J,* 1(1), pp. 1-8.
Frantzeskaki, N., Dumitru, A., Anguelovski, I., Avelino, F., Bach, M., Best, B., Binder, C., Barnes, J., Carrus, G., Egermann, M., Haxeltine, A., Moore, M.-L., Mira, R. G., Loorbach, D., Uzzell, D., Omann, I., Olsson, P., Silvestri, G., Stedman, R., Wittmayer, J., Durrant, R. and Rauschmayer, F. (2016) 'Elucidating the changing roles of civil society in urban sustainability transitions', *Current Opinion in Environmental Sustainability,* 22, pp. 41-50.
Frantzeskaki, N., McPhearson, T., Collier, M. J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., van Wyk, E., Ordóñez, C., Oke, C. and Pintér, L. (2019) 'Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making', *BioScience,* 69(6), pp. 455-466.
Fraser, A., Leck, H., Parnell, S. and Pelling, M. (2017) 'Africa's urban risk and resilience', *International Journal of Disaster Risk Reduction,* 26, pp. 1-6.
Fraser, A., Pelling, M., Scolobig, A. and Mavrogenis, S. (2020) 'Relating root causes to local risk conditions: A comparative study of the institutional pathways to small-scale disasters in three urban flood contexts', *Global Environmental Change,* 63, pp. 102102.
Fri, R. W. and Savitz, M. L. (2014) 'Rethinking energy innovation and social science', *Energy Research & Social Science,* 1, pp. 183-187.
Fried, T., Tun, T. H., Klopp, J. M. and Welle, B. (2020) 'Measuring the Sustainable Development Goal (SDG) transport target and accessibility of Nairobi's matatus', *Transportation Research Record,* 2674(5), pp. 196-207.
Friend, R. and Thinphanga, P. (2018) 'Urban Transformations Across Borders: The Interwoven Influence of Regionalisation, Urbanisation and Climate Change in the Mekong Region', in Miller, M., M., D. and M., G. (eds.) *Crossing Borders*. Singapore: Springer.
Froese, R. and Schilling, J. (2019) 'The nexus of climate change, land use, and conflicts', *Current climate change reports,* 5(1), pp. 24-35.
Frolova, E. V., Vinichenko, M. V., Kirillov, A. V., Rogach, O. V. and Kabanova, E. E. (2016) 'Development of social infrastructure in the management practices of local authorities: trends and factors', *International Journal of Environmental and Science Education,* 11(15), pp. 7421-7430.
Froude, M. J. and Petley, D. N. (2018) 'Global fatal landslide occurrence from 2004 to 2016', *Natural Hazards and Earth System Sciences,* 18(8), pp. 2161-2181.
Fry, T. J. and Maxwell, R. M. (2017) 'Evaluation of distributed BMP s in an urban watershed—High resolution modeling for stormwater management', *Hydrological processes,* 31(15), pp. 2700-2712.
Fu, G., Dawson, R., Khoury, M. and Bullock, S. (2014) 'Interdependent networks: vulnerability analysis and strategies to limit cascading failure', *The European Physical Journal B,* 87(7), pp. 148.
Fu, G., Horrocks, L. and Winne, S. (2016) 'Exploring impacts of climate change on UK's ICT infrastructure', *Infrastructure Asset Management,* 3(1), pp. 42-52.
Fu, G., Wilkinson, S., Dawson, R. J., Fowler, H. J., Kilsby, C., Panteli, M. and Mancarella, P. (2017) 'Integrated approach to assess the resilience of future electricity infrastructure networks to climate hazards', *IEEE Systems Journal,* 12(4), pp. 3169-3180.
Fulton, J. and Cooley, H. (2015) 'The Water Footprint of California's Energy System, 1990–2012', *Environmental Science & Technology,* 49(6), pp. 3314-3321.
Fünfgeld, H. (2015) 'Facilitating local climate change adaptation through transnational municipal networks', *Current Opinion in Environmental Sustainability,* 12, pp. 67-73.
Gajjar, S. P., Singh, C. and Deshpande, T. (2019) 'Tracing back to move ahead: a review of development pathways that constrain adaptation futures', *Climate and Development,* 11(3), pp. 223-237.
Gallina, V., Torresan, S., Critto, A., Sperotto, A., Glade, T. and Marcomini, A. (2016) 'A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment', *Journal of environmental management,* 168, pp. 123-132.
Gao, J. and O'Neill, B. C. (2019) 'Data-driven spatial modeling of global long-term urban land development: The SELECT model', *Environmental Modelling & Software,* 119, pp. 458-471.
Gao, J. and O'Neill, B. C. (2020) 'Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways', *Nature communications,* 11(1), pp. 1-12.
Gariano, S. L. and Guzzetti, F. (2016) 'Landslides in a changing climate', *Earth-Science Reviews,* 162, pp. 227-252.
Gariano, S. L., Rianna, G., Petrucci, O. and Guzzetti, F. (2017) 'Assessing future changes in the occurrence of rainfall-induced landslides at a regional scale', *Science of the total environment,* 596, pp. 417-426.
Garofalo, G., Palermo, S., Principato, F., Theodosiou, T. and Piro, P. (2016) 'The influence of hydrologic parameters on the hydraulic efficiency of an extensive green roof in mediterranean area', *Water,* 8(2), pp. 44.

Garschagen, M. (2016) 'Decentralizing urban disaster risk management in a centralized system? Agendas, actors and contentions in Vietnam', *Habitat International,* 52, pp. 43-49.
Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J. and Forsberg, B. (2015) 'Mortality risk attributable to high and low ambient temperature: a multicountry observational study', *The Lancet,* 386(9991), pp. 369-375.
Gautam, S., Yan, F., Kang, S., Han, X., Neupane, B., Chen, P., Hu, Z., Sillanpää, M. and Li, C. (2020) 'Black carbon in surface soil of the Himalayas and Tibetan Plateau and its contribution to total black carbon deposition at glacial region', *Environmental Science and Pollution Research,* 27(3), pp. 2670-2676.
Gawel, E., Lehmann, P., Strunz, S. and Heuson, C. (2018) 'Public Choice barriers to efficient climate adaptation–theoretical insights and lessons learned from German flood disasters', *Journal of Institutional Economics,* 14(3), pp. 473-499.
Ge, Y., Yang, G., Chen, Y. and Dou, W. (2019) 'Examining social vulnerability and inequality: a joint analysis through a connectivity lens in the urban agglomerations of China', *Sustainability,* 11(4), pp. 1042.
Gebre, T. and Gebremedhin, B. (2019) 'The mutual benefits of promoting rural-urban interdependence through linked ecosystem services', *Global ecology and conservation,* 20, pp. e00707.
Geneletti, D. and Zardo, L. (2016) 'Ecosystem-based adaptation in cities: An analysis of European urban climate adaptation plans', *Land use policy,* 50, pp. 38-47.
Ghanem, D. A., Mander, S. and Gough, C. (2016) '"I think we need to get a better generator": Household resilience to disruption to power supply during storm events', *Energy Policy,* 92, pp. 171-180.
GIACC (2020) *What is Corruption.* Chesham, UK: Global Infrastructure Anti-Corruption Centre.
Gilani, S. and O'Brien, W. (2020) 'Natural ventilation usability under climate change in Canada and the United States', *Building Research & Information,* 49(4), pp. 1-20.
Gill, S. E., Rahman, M. A., Handley, J. F. and Ennos, A. R. (2013) 'Modelling water stress to urban amenity grass in Manchester UK under climate change and its potential impacts in reducing urban cooling', *Urban forestry & urban greening,* 12(3), pp. 350-358.
Gillis, L. G., Jones, C. G., Ziegler, A. D., van der Wal, D., Breckwoldt, A. and Bouma, T. J. (2017) 'Opportunities for protecting and restoring tropical coastal ecosystems by utilizing a physical connectivity approach', *Frontiers in Marine Science,* 4, pp. 374.
Gillner, S., Bräuning, A. and Roloff, A. (2014) 'Dendrochronological analysis of urban trees: climatic response and impact of drought on frequently used tree species', *Trees,* 28(4), pp. 1079-1093.
Giordano, R., Pilli-Sihvola, K., Pluchinotta, I., Matarrese, R. and Perrels, A. (2020) 'Urban adaptation to climate change: Climate services for supporting collaborative planning', *Climate Services,* 17, pp. 100100.
Girgin, S., Necci, A. and Krausmann, E. (2019) 'Dealing with cascading multi-hazard risks in national risk assessment: the case of Natech accidents', *International journal of disaster risk reduction,* 35, pp. 101072.
Giridharan, R. and Emmanuel, R. (2018) 'The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review', *Sustainable Cities and Society,* 40(Complete), pp. 677-687.
Gittleman, M., Farmer, C. J. Q., Kremer, P. and McPhearson, T. (2017) 'Estimating stormwater runoff for community gardens in New York City', *Urban ecosystems,* 20(1), pp. 129-139.
Global Resilience Partnership (2018) *Good Governance and Transboundary Collaboration for Climate Change Resilience*, Portland: Global Resilience Partnership.
Gober, P., Sampson, D. A., Quay, R., White, D. D. and Chow, W. T. L. (2016) 'Urban adaptation to mega-drought: Anticipatory water modeling, policy, and planning for the urban Southwest', *Sustainable Cities and Society,* 27, pp. 497-504.
Godoy, M. D. P. and Lacerda, L. D. d. (2015) 'Mangroves response to climate change: a review of recent findings on mangrove extension and distribution', *Anais da Academia Brasileira de Ciências,* 87(2), pp. 651-667.
Goh, K. (2019) 'Flows in formation: The global-urban networks of climate change adaptation', *Urban Studies,* 57(11), pp. 2222–2240.
Goldstein, B., Hauschild, M., Fernandez, J. and Birkved, M. (2016a) 'Testing the environmental performance of urban agriculture as a food supply in northern climates', *Journal of Cleaner Production,* 135, pp. 984-994.
Goldstein, B., Hauschild, M., Fernández, J. and Birkved, M. (2016b) 'Urban versus conventional agriculture, taxonomy of resource profiles: a review', *Agronomy for Sustainable Development,* 36(1), pp. 9.
Gomes, S. L. and Hermans, L. M. (2018) 'Institutional function and urbanization in Bangladesh: How peri-urban communities respond to changing environments', *Land Use Policy,* 79, pp. 932-941.
Gomes, S. L., Hermans, L. M. and Thissen, W. A. H. (2018) 'Extending community operational research to address institutional aspects of societal problems: Experiences from peri-urban Bangladesh', *European Journal of Operational Research,* 268(3), pp. 904-917.
Goodrich, C. G., Prakash, A. and Udas, P. B. (2019) 'Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights', *Environmental Development,* 31, pp. 1-8.
Gordon, D. J. and Johnson, C. A. (2017) 'The orchestration of global urban climate governance: conducting power in the post-Paris climate regime', *Environmental Politics,* 26(4), pp. 694-714.
Gotgelf, A., Roggero, M. and Eisenack, K. (2020) 'Archetypical opportunities for water governance adaptation to climate change', *Ecology and Society,* 25(4).

Gough, K., Yankson, P., Wilby, R., Amankwaa, E., Abarike, M., Codjoe, S., Griffiths, P., Kasei, R., Kayaga, S. and Nabilse, C. (2019) 'Vulnerability to extreme weather events in cities: implications for infrastructure and livelihoods', *Journal of the British Academy,* 7(2s).
Gould, K. A. and Lewis, T. L. 2018. From green gentrification to resilience gentrification: An example from Brooklyn. SAGE Publications Sage CA: Los Angeles, CA.
Gould, W. A., Díaz, E. L., Álvarez-Berríos, N. L., Aponte-González, F., Archibald, W., Bowden, J. H., Carrubba, L., Crespo, W., Fain, S. J., González, G., Goulbourne, A., Harmsen, E., Holupchinski, E., Khalyani, A. H., Kossin, J., Leinberger, A. J., Marrero-Santiago, V. I., Martínez- Sánchez, O., McGinley, K., Méndez-Lázaro, P., Morell, J., Oyola, M. M., Parés-Ramos, I. K., Pulwarty, R., Sweet, W. V., Terando, A. and Torres-González, S. (2018) *U.S. Caribbean*, Washington: US Climate Change Research Program. Available at: https://nca2018.globalchange.gov/chapter/20/.
Grafakos, S., Trigg, K., Landauer, M., Chelleri, L. and Dhakal, S. (2019) 'Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities', *Climatic Change,* 154(1), pp. 87-106.
Grafakos, S., Viero, G., Reckien, D., Trigg, K., Viguie, V., Sudmant, A., Graves, C., Foley, A., Heidrich, O. and Mirailles, J. M. (2020) 'Integration of mitigation and adaptation in urban climate change action plans in Europe: A systematic assessment', *Renewable and Sustainable Energy Reviews,* 121, pp. 109623.
Graff Zivin, J. and Neidell, M. (2014) 'Temperature and the Allocation of Time: Implications for Climate Change', *Journal of Labor Economics,* 32(1), pp. 1-26.
Gran Castro, J. A. and Ramos De Robles, S. L. (2019) 'Climate change and flood risk: vulnerability assessment in an urban poor community in Mexico', *Environment and Urbanization,* 31(1), pp. 75-92.
Granberg, M. and Glover, L. (2014) 'Adaptation and Maladaptation in Australian National Climate Change Policy', *Journal of Environmental Policy & Planning,* 16(2), pp. 147-159.
Green, A. J., Alcorlo, P., Peeters, E. T. H. M., Morris, E. P., Espinar, J. L., Bravo-Utrera, M. A., Bustamante, J., Díaz-Delgado, R., Koelmans, A. A. and Mateo, R. (2017) 'Creating a safe operating space for wetlands in a changing climate', *Frontiers in Ecology and the Environment,* 15(2), pp. 99-107.
Green, H., Bailey, J., Schwarz, L., Vanos, J., Ebi, K. and Benmarhnia, T. (2019) 'Impact of heat on mortality and morbidity in low and middle income countries: A review of the epidemiological evidence and considerations for future research', *Environmental research,* 171, pp. 80-91.
Greenwalt, J., Raasakka, N. and Alverson, K. (2018) 'Building Urban Resilience to Address Urbanization and Climate Change', in Zommers, Z., Z. and Corps, Z.a.M. (eds.) *Resilience: The Science of Adaptation to Climate Change*. Amsterdam, pp. 151-164.
Grigg, N. S. (2019) 'Global water infrastructure: state of the art review', *International journal of water resources development,* 35(2), pp. 181-205.
Grilo, F., Pinho, P., Aleixo, C., Catita, C., Silva, P., Lopes, N., Freitas, C., Santos-Reis, M., McPhearson, T. and Branquinho, C. (2020) 'Using green to cool the grey: Modelling the cooling effect of green spaces with a high spatial resolution', *Science of The Total Environment*, pp. 138182.
Grimm, N. B., Cook, E. M., Hale, R. L. and Iwaniec, D. M. (2016) 'A broader framing of ecosystem services in cities: benefits and challenges of built, natural or hybrid system function', in Seto, K.C., Solecki, W. and Griffith, C.A. (eds.) *Routledge Handbook of Urbanization and Global Environmental Change* pp. 202–212
Gromke, C. and Blocken, B. (2015) 'Influence of avenue-trees on air quality at the urban neighborhood scale. Part II: Traffic pollutant concentrations at pedestrian level', *Environmental Pollution,* 196, pp. 176-184.
Groundstroem, F. and Juhola, S. (2019) 'A framework for identifying cross-border impacts of climate change on the energy sector', *Environment Systems and Decisions,* 39(1), pp. 3-15.
Grove, K. (2021) 'Insurantialization and the moral economy of ex ante risk management in the Caribbean', *Economy and Society,* 50(2), pp. 224-247.
GSMA (2019) *Unique mobile subscribers penetration rate as share of population worldwide from 2016 to 2025, by region*: Statista. Available at: https://www.statista.com/statistics/740612/worldwide-unique-mobile-subscribers-penetration-by-region/ (Accessed: April 2 2019).
Guannel, G., Arkema, K., Ruggiero, P. and Verutes, G. (2016) 'The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience', *PloS one,* 11(7), pp. e0158094.
Guerreiro, S. B., Dawson, R. J., Kilsby, C., Lewis, E. and Ford, A. (2018) 'Future heat-waves, droughts and floods in 571 European cities', *Environmental Research Letters,* 13(3), pp. 034009.
Gul, C., Mahapatra, P. S., Kang, S., Singh, P. K., Wu, X., He, C., Kumar, R., Rai, M., Xu, Y. and Puppala, S. P. (2021) 'Black carbon concentration in the central Himalayas: Impact on glacier melt and potential source contribution', *Environmental Pollution,* 275, pp. 116544.
Gunawardena, K. R., Wells, M. J. and Kershaw, T. (2017) 'Utilising green and bluespace to mitigate urban heat island intensity', *Science of the Total Environment,* 584, pp. 1040-1055.
Göpfert, C., Wamsler, C. and Lang, W. (2019) 'A framework for the joint institutionalization of climate change mitigation and adaptation in city administrations', *Mitigation and Adaptation Strategies for Global Change,* 24(1), pp. 1-21.
Göpfert, C., Wamsler, C. and Lang, W. (2020) 'Enhancing structures for joint climate change mitigation and adaptation action in city administrations – Empirical insights and practical implications', City and Environment Interactions, 8, Available at: https://doi.org/10.1016/j.cacint.2020.100052

Güneralp, B., Güneralp, n. and Liu, Y. (2015a) 'Changing global patterns of urban exposure to flood and drought hazards', *Global environmental change,* 31, pp. 217-225.
Güneralp, B., Güneralp, İ. and Liu, Y. (2015b) 'Changing global patterns of urban exposure to flood and drought hazards', *Global environmental change,* 31, pp. 217-225.
Haase, D., Kabisch, S., Haase, A., Andersson, E., Banzhaf, E., Baró, F., Brenck, M., Fischer, L. K., Frantzeskaki, N. and Kabisch, N. (2017a) 'Greening cities–To be socially inclusive? About the alleged paradox of society and ecology in cities', *Habitat International,* 64, pp. 41-48.
Haase, D., Kabisch, S., Haase, A., Andersson, E., Banzhaf, E., Baró, F., Brenck, M., Fischer, L. K., Frantzeskaki, N., Kabisch, N., Krellenberg, K., Kremer, P., Kronenberg, J., Larondelle, N., Mathey, J., Pauleit, S., Ring, I., Rink, D., Schwarz, N. and Wolff, M. (2017b) 'Greening cities – To be socially inclusive? About the alleged paradox of society and ecology in cities', *Habitat International,* 64, pp. 41-48.
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y. and Schewe, J. (2014) 'Global water resources affected by human interventions and climate change', *Proceedings of the National Academy of Sciences,* 111(9), pp. 3251-3256.
Haddock, D. and Edwards, C. (2013) *Urban Waters Federal Partnership: Proctor Creek Watershed, Atlanta, GA - Overall assessment of partnership since beginning*. Available at: https://www.epa.gov/sites/production/files/2017-08/documents/proctor_creek_chapter_final.pdf.
Hadi, S. P. 'In search for sustainable coastal management: A case study of Semarang, Indonesia'. *IOP Conf. Ser.: Earth Environ. Sci.*, 2017: IOP Publishing, 012054.
Hadi, S. P. 'Integrated Community Based Coastal Management: Lesson From The Field'. *IOP Conference Series: Earth and Environmental Science*, 2018: IOP Publishing, 012064.
Hale, T. (2016) '"All Hands on Deck": The Paris Agreement and Nonstate Climate Action', *Global Environmental Politics,* 16(3), pp. 12-22.
Hale, T. N., Chan, S., Hsu, A., Clapper, A., Elliott, C., Faria, P., Kuramochi, T., McDaniel, S., Morgado, M. and Roelfsema, M. (2021) 'Sub-and non-state climate action: A framework to assess progress, implementation and impact', *Climate Policy,* 21(3), pp. 406-420.
Hall, J. W., Aerts, J. C. J. H., Hallegatte, S., Harvey, M., Hu, X., Koks, E. E., Lee, C., Liao, X., Mullan, M., Pant, R., Paszkowski, A., Rozenberg, J., Sheng, F., Stenek, V., Thacker, S., Väänänen, E., Vallejo, L., Veldkamp, T. I. E., van Vliet, M., Wada, Y., Ward, P., Watkins, G. and Zorn, C. (2019) *Adaptation of Infrastructure Systems: Background Paper for the Global Commission on Adaptation*, Oxford: University of Oxford Environmental Change Institute. Available at: https://cdn.gca.org/assets/2019-09/GCA-Infrastructure-background-paperV10-refs.pdf.
Hallegatte, S., Bangalore, M., Bonzanigo, L., Fay, M., Kane, T., Narloch, U., Rozenberg, J., Treguer, D. and Vogt-Schilb, A. (2016) *Shock Waves: Managing the Impacts of Climate Change on Poverty. Climate Change and Development*, Washington DC: World Bank.
Hamdy, M., Carlucci, S., Hoes, P.-J. and Hensen, J. L. M. (2017) 'The impact of climate change on the overheating risk in dwellings—A Dutch case study', *Building and Environment,* 122, pp. 307-323.
Hamiche, A. M., Stambouli, A. B. and Flazi, S. (2016) 'A review of the water-energy nexus', *Renewable and Sustainable Energy Reviews,* 65, pp. 319-331.
Hamidi, S., Sabouri, S. and Ewing, R. (2020) 'Does density aggravate the COVID-19 pandemic? Early findings and lessons for planners', *Journal of the American Planning Association,* 86(4), pp. 495-509.
Hamstead, Z. A., Kremer, P., Larondelle, N., McPhearson, T. and Haase, D. (2016) 'Classification of the heterogeneous structure of urban landscapes (STURLA) as an indicator of landscape function applied to surface temperature in New York City', *Ecological indicators,* 70, pp. 574-585.
Han, W., Lee, B. J., Jo, M. and Jeong, Y. (2019) *Research on Natech Disaster Management Coped with Calamity: Focusing on disaster management mapping and application*: KRIHS. Available at: https://library.krihs.re.kr/dl_image2/IMG/07/000000030226/SERVICE/000000030226_01.PDF.
Hanakata, N. C. and Gasco, A. (2018) 'The Grand Projet politics of an urban age: urban megaprojects in Asia and Europe', *Palgrave Communications,* 4(1), pp. 1-10.
Handayani, W., Chigbu, U. E., Rudiarto, I. and Putri, I. H. S. (2020a) 'Urbanization and Increasing Flood Risk in the Northern Coast of Central Java—Indonesia: An Assessment towards Better Land Use Policy and Flood Management', *Land,* 9/10(343).
Handayani, W. and Rudiarto, I. (2014) 'Dynamics of urban growth in Semarang Metropolitan-Central Java: An examination based on built-up area and population change', *Journal of Geography and Geology,* 6(4), pp. 80.
Handayani, W., Setiadi, R., Septiarani, B. and Lewis, L. (2020b) *Clustering and connecting locally championed metropolitan solutions' in Greater than Parts*, Washington: World Bank.
Hanger, S., Linnerooth-Bayer, J., Surminski, S., Nenciu-Posner, C., Lorant, A., Ionescu, R. and Patt, A. (2018) 'Insurance, public assistance, and household flood risk reduction: A comparative study of Austria, England, and Romania', *Risk Analysis,* 38(4), pp. 680-693.
Hansen, R., Frantzeskaki, N., McPhearson, T., Rall, E., Kabisch, N., Kaczorowska, A., Kain, J.-H., Artmann, M. and Pauleit, S. (2015) 'The uptake of the ecosystem services concept in planning discourses of European and American cities', *Ecosystem Services,* 12, pp. 228-246.

Hanson, S. E. and Nicholls, R. J. (2020) 'Demand for ports to 2050: Climate policy, growing trade and the impacts of sea-level rise', *Earth's Future,* 8(8), pp. e2020EF001543.
Hao, Z., Singh, P. V. and Hao, F. (2018) 'Compound Extremes in Hydroclimatology: A Review', *Water,* 10(6).
Haque, A. N., Bithell, M. and Richards, K. S. (2020) 'Adaptation to flooding in low-income urban settlements in the least developed countries: A systems approach', *The Geographical Journal,* 186(3).
Haque, A. N., Dodman, D. and Hossain, M. M. (2014) 'Individual, communal and institutional responses to climate change by low-income households in Khulna, Bangladesh', *Environment and Urbanization,* 26(1), pp. 112-129.
Hara, Y., McPhearson, T., Sampei, Y. and McGrath, B. (2018) 'Assessing urban agriculture potential: A comparative study of Osaka, Japan and New York city, United States', *Sustainability Science,* 13(4), pp. 937-952.
Hardoy, J., Hernández, I., Pacheco, J. A. and Sierra, G. (2014) 'Institutionalizing climate change adaptation at municipal and state level in Chetumal and Quintana Roo, Mexico', *Environment and urbanization,* 26(1), pp. 69-85.
Hardoy, J. and Velásquez Barrero, L. S. (2014) 'Re-thinking "Biomanizales": addressing climate change adaptation in Manizales, Colombia', *Environment and Urbanization,* 26(1), pp. 53-68.
Harris, L. M., Chu, E. K. and Ziervogel, G. (2018) 'Negotiated resilience', *Resilience,* 6(3), pp. 196-214.
Harvey, B., Jones, L., Cochrane, L. and Singh, R. (2019) 'The evolving landscape of climate services in sub-Saharan Africa: What roles have NGOs played', *Climatic Change,* 157(1).
Hauer, M. E. (2017) 'Migration induced by sea-level rise could reshape the US population landscape', *Nature Climate Change,* 7(5), pp. 321.
Haugen, A., Bertolin, C., Leijonhufvud, G., Olstad, T. and Broström, T. (2018) 'A methodology for long-term monitoring of climate change impacts on historic buildings', *Geosciences,* 8(10), pp. 370-387.
Haupt, W. and Coppola, A. (2019) 'Climate governance in transnational municipal networks: advancing a potential agenda for analysis and typology', *International Journal of Urban Sustainable Development,* 11(2), pp. 123-140.
Haworth, B., Biggs, E., Duncan, J., Wales, N., Boruff, B. and Bruce, E. (2018) 'Geographic information and communication technologies for supporting smallholder agriculture and climate resilience', *Climate,* 6(4), pp. 97.
Hayward, B. (2021) *Children, Citizenship and Environment:#SchoolStrike Edition.* London: Routledge.
Hayward, B., Hinge, S. D., Tupuana', L. and Tualamali'i', L. (2020) 'It's not "too late": Learning from Pacific Small Island Developing States in a warming world', *Wires Climate Change,* 11(1), pp. e612.
Heaviside, C., Cai, X. M. and Vardoulakis, S. (2015) 'The effects of horizontal advection on the urban heat island in Birmingham and the West Midlands, United Kingdom during a heatwave', *Quarterly Journal of the Royal Meteorological Society,* 141(689), pp. 1429-1441.
Heaviside, C., Macintyre, H. and Vardoulakis, S. (2017) 'The urban heat island: implications for health in a changing environment', *Current environmental health reports,* 4(3), pp. 296-305.
Heeks, R. and Ospina, A. V. (2015) 'Analysing urban community informatics from a resilience perspective', *The Journal of Community Informatics,* 11(1).
Heeks, R. and Ospina, A. V. (2019) 'Conceptualising the link between information systems and resilience: A developing country field study', *Information Systems Journal,* 29(1), pp. 70-96.
Heidrich, O., Reckien, D., Olazabal, M., Foley, A., Salvia, M., de Gregorio Hurtado, S., Orru, H., Flacke, J., Geneletti, D. and Pietrapertosa, F. (2016) 'National climate policies across Europe and their impacts on cities strategies', *Journal of environmental management,* 168, pp. 36-45.
Heikkinen, M., Ylä-Anttila, T. and Juhola, S. (2019) 'Incremental, reformistic or transformational: what kind of change do C40 cities advocate to deal with climate change?', *Journal of Environmental Policy & Planning,* 21(1), pp. 90-103.
Hellwig, J., Stahl, K. and Lange, J. (2017) 'Patterns in the linkage of water quantity and quality during low-flows', *Hydrological Processes,* 31(23), pp. 4195-4205.
Henderson, J. V., Storeygard, A. and Deichmann, U. (2017) 'Has climate change driven urbanization in Africa?', *Journal of Development Economics,* 124(WPS6925), pp. 60-82.
Henrique, K. P. and Tschakert, P. (2019) 'Contested grounds: Adaptation to flooding and the politics of (in) visibility in São Paulo's eastern periphery', *Geoforum,* 104, pp. 181-192.
Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J. and Zenghelis, D. (2020) 'Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change?', *Oxford Review of Economic Policy,* 36(Supplement_1), pp. S359–S381.
Herath, H., Halwatura, R. and Jayasinghe, G. (2018) 'Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy', *Urban Forestry & Urban Greening,* 29, pp. 212-222.
Herrera, D. and Ault, T. (2017) 'Insights from a New High-Resolution Drought Atlas for the Caribbean Spanning 1950–2016', *Journal of Climate,* 30(19), pp. 7801-7825.
Heslin, A., Deckard, N. D., Oakes, R. and Montero-Colbert, A. (2019) 'Displacement and Resettlement: Understanding the Role of Climate Change in Contemporary Migration', in Mechler, R., Bouwer, L.M., Schinko, T., Surminski, S. and Linnerooth-Bayer, J. (eds.) *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*. Cham: Springer International Publishing, pp. 237-258.
Hess, D. J. and McKane, R. G. (2021) 'Making sustainability plans more equitable: an analysis of 50 US Cities', *Local Environment,* 26(4), pp. 461-476.

Hierink, F., Rodrigues, N., Muñiz, M., Panciera, R. and Ray, N. (2020) 'Modelling geographical accessibility to support disaster response and rehabilitation of a healthcare system: an impact analysis of Cyclones Idai and Kenneth in Mozambique', *BMJ open,* 10(11), pp. e039138.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C. and Levermann, A. (2014) 'Coastal flood damage and adaptation costs under 21st century sea-level rise', *Proceedings of the National Academy of Sciences,* 111(9), pp. 3292-3297.

Hiwasaki, L., Luna, E. and Marçal, J. A. (2015) 'Local and indigenous knowledge on climate-related hazards of coastal and small island communities in Southeast Asia', *Climatic Change,* 128(1-2), pp. 35-56.

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., Etzelmüller, B. and Luoto, M. (2018) 'Degrading permafrost puts Arctic infrastructure at risk by mid-century', *Nature communications,* 9(1), pp. 5147.

Ho, H. C., Abbas, S., Yang, J., Zhu, R. and Wong, M. S. (2019) 'Spatiotemporal Prediction of Increasing Winter Perceived Temperature across a Sub-Tropical City for Sustainable Planning and Climate Change Mitigation', *International journal of environmental research and public health,* 16(3), pp. 497.

Hodson, M. (2010) *World cities and climate change: Producing urban ecological security.* McGraw-Hill Education (UK).

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R. and Zhou, G. (2018) *Impacts of 1.5ºC Global Warming on Natural and Human Systems*: IPCC.

Hoffman, J. S., Shandas, V. and Pendleton, N. (2020) 'The effects of historical housing policies on resident exposure to intra-urban heat: a study of 108 US urban areas', *Climate,* 8(1), pp. 12.

Holladay, P. J., Mendez-Lazaro, P., Centeno, H. M., Rivera-Gutierrez, R., Adams, K. and Brundiers, K. (2019) 'Utuado, Puerto Rico and Community Resilience Post-Hurricane Maria: The Case of Tetuan Reborn', *Recreation, Parks, and Tourism in Public Health,* 3, pp. 5-16.

Holland, B. (2017) 'Procedural justice in local climate adaptation: political capabilities and transformational change', *Environmental Politics,* 26(3), pp. 391-412.

Honey-Rosés, J., Anguelovski, I., Chireh, V. K., Daher, C., Konijnendijk van den Bosch, C., Litt, J. S., Mawani, V., McCall, M. K., Orellana, A. and Oscilowicz, E. (2020) 'The impact of COVID-19 on public space: an early review of the emerging questions–design, perceptions and inequities', *Cities & Health*, pp. 1-17.

Hoornweg, D. and Pope, K. (2017) 'Population predictions for the world's largest cities in the 21st century', *Environment and Urbanization,* 29(1), pp. 195-216.

Horn, P. (2018) 'Indigenous peoples, the city and inclusive urban development policies in Latin America: Lessons from Bolivia and Ecuador', *Development Policy Review,* 36(4), pp. 483-501.

Hosen, N., Nakamura, H. and Hamzah, A. (2020) 'Adaptation to climate change: Does traditional ecological knowledge hold the key?', *Sustainability,* 12(2), pp. 676.

Hosokawa, Y., Grundstein, A. J. and Casa, D. J. (2018) 'Extreme Heat Considerations in International Football Venues: The Utility of Climatologic Data in Decision Making', *Journal of Athletic Training,* 53(9), pp. 860-865.

Hossain, M. Z. and Rahman, M. A. U. (2018) 'Adaptation to climate change as resilience for urban extreme poor: lessons learned from targeted asset transfers programmes in Dhaka city of Bangladesh', *Environment, development and sustainability,* 20(1), pp. 407-432.

Hossain, P. R., Ludwig, F. and Leemans, R. (2018) 'Adaptation pathways to cope with salinization in south-west coastal region of Bangladesh', *Ecology and Society,* 23(3).

Houser, T., Hsiang, S., Kopp, R., Larsen, K., Delgado, M., Jina, A., Mastrandrea, M., Mohan, S., Muir-Wood, R., Rasmussen, D. J. and Rising, J. (2015) *Economic risks of climate change: an American prospectus.* New York: Columbia University Press.

Houston, J. B., Hawthorne, J., Perreault, M. F., Park, E. H., Goldstein Hode, M., Halliwell, M. R., Turner McGowen, S. E., Davis, R., Vaid, S. and McElderry, J. A. (2015) 'Social media and disasters: a functional framework for social media use in disaster planning, response, and research', *Disasters,* 39(1), pp. 1-22.

Howard, G., Calow, R., Macdonald, A. and Bartram, J. (2016) 'Climate change and water and sanitation: likely impacts and emerging trends for action', *Annual review of environment and resources,* 41, pp. 253-276.

HR Wallingford (2014) *Indicators to Assess the Exposure of Critical Infrastructure in England to Current and Projected Climate Hazards. Final report for the Adaptation Sub-Committee*, Wallingford: HR Wallingford for the Committee on Climate Change. Available at: https://www.theccc.org.uk/publication/indicators-assess-exposure-critical-infrastructure-england-current-projected-climate-hazards/.

Hsu, A., Brandt, J., Widerberg, O., Chan, S. and Weinfurter, A. (2020) 'Exploring links between national climate strategies and non-state and subnational climate action in nationally determined contributions (NDCs)', *Climate Policy,* 20(4), pp. 443-457.

Hsu, A. and Rauber, R. (2021) 'Diverse climate actors show limited coordination in a large-scale text analysis of strategy documents', *Communications Earth & Environment,* 2(1), pp. 1-12.

Hsu, A., Weinfurter, A. J. and Xu, K. (2017) 'Aligning subnational climate actions for the new post-Paris climate regime', *Climatic Change,* 142(3), pp. 419-432.

Hu, X., Hall, J. W., Shi, P. and Lim, W. H. (2016) 'The spatial exposure of the Chinese infrastructure system to flooding and drought hazards', *Natural Hazards,* 80(2), pp. 1083-1118.

Huang, K., Li, X., Liu, X. and Seto, K. C. (2019) 'Projecting global urban land expansion and heat island intensification through 2050', *Environmental Research Letters,* 14(11), pp. 114037.
Huang, Y., Xu, L. and Yin, H. (2015) 'Dual-level material and psychological assessment of urban water security in a water-stressed coastal city', *Sustainability,* 7(4), pp. 3900-3918.
Hughes, S. (2015) 'A meta-analysis of urban climate change adaptation planning in the U.S', *Urban Climate,* 14, pp. 17-29.
Hunter, L. M., Luna, J. K. and Norton, R. M. (2015) 'Environmental Dimensions of Migration', *Annual Review of Sociology,* 41(1), pp. 377-397.
Hunter, N. B., North, M. A., Roberts, D. C. and Slotow, R. (2020) 'A systematic map of responses to climate impacts in urban Africa', *Environmental Research Letters,* 15(10).
Huq, E., Cheng, Q., Altan, O., Shoeb, A., Hossain, M. A., Sarker, M., Islam, N., Saleem, N., Javed, A. and Longg, X. (2020a) 'Assessing vulnerability for inhabitants of Dhaka City considering flood-hazard exposure', *Geofizika,* 37(2), pp. 97-130.
Huq, E., Shoeb, A., Hossain, M. A., Fahad, S., Kamruzzaman, M., Javed, A., Saleem, N., Adnan, K. M., Sarker, S. A. and Ali, M. Y. (2020b) 'Measuring Vulnerability to Environmental Hazards: Qualitative to Quantitative', in Fahad, S., Hasanuzzaman, M., Alam, M., H., U., Saeed, M., Khan, I.A. and Adnan, M. (eds.) *Environment, Climate, Plant and Vegetation Growth*: Springer, pp. 421-452.
Hurligmann, A., Moosavi, S. and Browne, G. R. (2021) 'Urban planning policy must do more to integrate climate change adaptation and mitigation actions', *Land Use Policy,* 101. Available at: https://doi.org/10.1016/j.landusepol.2020.105188.
Husnayen, A., Rimba, A. B., Osawa, T., Parwata, I. N. S., As-syakur, A. R., Kasim, F. and Astarini, I. A. (2018) 'Physical assessment of coastal vulnerability under enhanced land subsidence in Semarang, Indonesia, using multi-sensor satellite data', *Advances in Space Research,* 61(8), pp. 2159-2179.
Hyndman, B. (2017) 'Heat-Smart'schools during physical education (PE) activities: Developing a policy to protect students from extreme heat', *Learning Communities Journal,* 21, pp. 56-72.
Hölscher, K. and Frantzeskaki, N. (2020) *Transformative Climate Governance.* Cham: Palgrave Mcmillan.
Hölscher, K., Frantzeskaki, N., McPhearson, T. and Loorbach, D. (2019) 'Tales of transforming cities: Transformative climate governance capacities in New York City, US and Rotterdam, Netherlands', *Journal of environmental management,* 231, pp. 843-857.
Ibrahim, S., Ibrahim, M. and Attia, S. (2014) 'The impact of climate changes on the thermal performance of a proposed pressurized water reactor: nuclear-power plant', *International Journal of Nuclear Energy,* 2014.
Ide, T., Lopez, M. R., Fröhlich, C. and Scheffran, J. (2021) 'Pathways to water conflict during drought in the MENA region', *Journal of Peace Research,* 58(3), pp. 568-582.
IEA (2019) *Electricity Information 2019*: IEA. Available at: https://www.iea.org/statistics/electricity/ (Accessed: 28 September 2019).
IISD (N.D.) *What is grey infrastructure?*: International Institute for Sustainable Development. Available at: https://www.iisd.org/savi/faq/what-is-grey-infrastructure/ (Accessed: September 9 2021).
ILO 2017. World social protection report 2017–19: Universal social protection to achieve the Sustainable Development Goals. Geneva: International Labour Office.
Imam, N., Hossain, M. K. and Saha, T. R. (2017) 'Potentials and challenges of using ICT for climate change adaptation: a study of vulnerable community in riverine islands of bangladesh', in Kaur, H., Lechman, E. and Marszk, A. (eds.) *Catalyzing Development through ICT Adoption*. Cham: Springer, pp. 89-110.
Immergluck, D. and Balan, T. (2018) 'Sustainable for whom? Green urban development, environmental gentrification, and the Atlanta Beltline', *Urban Geography,* 39(4), pp. 546-562.
Imperiale, A. J. and Vanclay, F. (2021) 'Conceptualizing community resilience and the social dimensions of risk to overcome barriers to disaster risk reduction and sustainable development', *Sustainable Development*.
Imran, H. M., Kala, J., Ng, A. and Muthukumaran, S. (2019) 'Effectiveness of vegetated patches as Green Infrastructure in mitigating Urban Heat Island effects during a heatwave event in the city of Melbourne', *Weather and Climate Extremes,* 25, pp. 100217.
Inch, A. (2019) 'Signs of Hope in the Dark?', *Planning Theory & Practice,* 20(3), pp. 317-319.
Indonesia Ministry of Health (2020) *Indonesian Health Profile 2019*, Jakarta: Indonesia Ministry of Health. Available at: https://pusdatin.kemkes.go.id/resources/download/pusdatin/profil-kesehatan-indonesia/Profil-Kesehatan-indonesia-2019.pdf.
Ingwersen, W. W., Garmestani, A. S., Gonzalez, M. A. and Templeton, J. J. (2014) 'A systems perspective on responses to climate change', *Clean Technologies and Environmental Policy,* 16(4), pp. 719-730.
Inostroza, L., Palme, M. and de la Barrera, F. (2016) 'A Heat Vulnerability Index: Spatial Patterns of Exposure, Sensitivity and Adaptive Capacity for Santiago de Chile', *PLOS ONE,* 11(9), pp. e0162464.
International Council for Science (2017) *A Guide to SDG Interactions: from Science to Implementation*, Paris: International Council for Science. Available at: https://council.science/cms/2017/05/SDGs-Guide-to-Interactions.pdf.
Invidiata, A. and Ghisi, E. (2016) 'Impact of climate change on heating and cooling energy demand in houses in Brazil', *Energy and Buildings,* 130, pp. 20-32.

Iojă, C. I., Badiu, D. L., Haase, D., Hossu, A. C. and Niță, M. R. (2021) 'How about water? Urban blue infrastructure management in Romania', *Cities,* 110, pp. 103084.
Iping, A., Kidston-Lattari, J., Simpson-Young, A., Duncan, E. and McManus, P. (2019) '(Re) presenting urban heat islands in Australian cities: A study of media reporting and implications for urban heat and climate change debates', *Urban Climate,* 27, pp. 420-429.
Ireland, P. and Clausen, D. (2019) 'Local action that changes the world: Fresh perspectives on climate change mitigation and adaptation from Australia', in Letcher, T. (ed.) *Managing Global Warming*. London: Elsevier, pp. 769-782.
Irvin-Barnwell, E. A., Cruz, M., Maniglier-Poulet, C., Cabrera, J., Diaz, J. R., Perez, R. D. L. C., Forrester, C., Shumate, A., Mutter, J. and Graziano, L. (2020) 'Evaluating disaster damages and operational status of health-care facilities during the emergency response phase of Hurricane Maria in Puerto Rico', *Disaster medicine and public health preparedness,* 14(1), pp. 80-88.
Irwin, S., Howlett, C., Binns, A. D. and Sandink, D. (2018) 'Mitigation of Basement Flooding due to Sewer Backup: Overview and Experimental Investigation of Backwater Valve Performance', *Natural Hazards Review,* 19(4), pp. 04018020.
Isah, N. (2016) *Flood occurrence, smart tunnel operating system and traffic flow: a case of Kuala Lumpur smart tunnel Malaysia*, Parit Raja, Malaysia: Universiti Tun Hussein Onn Malaysia.
Ishiwatari, M. (2021) 'Regional Policies and Initiatives on Climate Change and Disaster Risks: How Can Peacebuilding Assistance and Climate Change Adaptation Be Integrated?', in Pulhin, J.M., Inoue, M. and Shaw, R. (eds.) *Climate Change, Disaster Risks, and Human Security: Asian Experience and Perspectives*. Singapore: Springer, pp. 333-343.
Islam, M. R. and Khan, N. A. (2018) 'Threats, vulnerability, resilience and displacement among the climate change and natural disaster-affected people in South-East Asia: an overview', *Journal of the Asia Pacific Economy,* 23(2), pp. 297-323.
Islam, M. S. and Hasan, A. R. (2019) 'Social safety net program in strengthening adaptive capacity to disaster and climate change in South Asia: problems and prospects', *Social Science Review,* 36(1), pp. 63-76.
ITF (2019) *ITF Transport Outlook 2019*: International Transport Forum. Available at: https://doi.org/10.1787/25202367.
ITU (2019) *Number of mobile (cellular) subscriptions worldwide from 1993 to 2018 (in millions)*: Statista. Available at: https://www.statista.com/statistics/262950/global-mobile-subscriptions-since-1993/.
Ivaschenko, O., Rodriguez Alas, C. P., Novikova, M., Romero Robayo, C., Bowen, T. V. and Zhu, L. (2018) *The state of social safety nets 2018.* Washington: The World Bank.
Ives, M. C., Simpson, M. and Hall, J. W. (2018) 'Navigating the water trilemma: a strategic assessment of long-term national water resource management options for Great Britain', *Water and environment journal,* 32(4), pp. 546-555.
Izadpanahi, P., Farahani, L. M. and Nikpey, R. (2021) 'Lessons from Sustainable and Vernacular Passive Cooling Strategies Used in Traditional Iranian Houses', *Journal of Sustainability Research,* 3(3).
Izaguirre, C., Losada, I., Camus, P., Vigh, J. and Stenek, V. (2021) 'Climate change risk to global port operations', *Nature Climate Change,* 11(1), pp. 14-20.
Jaakkola, J. J. K., Juntunen, S. and Näkkäläjärvi, K. (2018) 'The holistic effects of climate change on the culture, well-being, and health of the Saami, the only indigenous people in the European Union', *Current environmental health reports,* 5(4), pp. 401-417.
Jabareen, Y. (2015) 'City planning deficiencies & climate change – The situation in developed and developing cities', *Geoforum,* 63, pp. 40-43.
Jackson, R. C., Dugmore, A. J. and Riede, F. (2018) 'Rediscovering lessons of adaptation from the past', *Global Environmental Change,* 52, pp. 58-65.
Jackson, T. (2021) *Post Growth: Life After Capitalism.* London: Polity Press.
Jaglom, W. S., McFarland, J. R., Colley, M. F., Mack, C. B., Venkatesh, B., Miller, R. L., Haydel, J., Schultz, P. A., Perkins, B. and Casola, J. H. (2014) 'Assessment of projected temperature impacts from climate change on the US electric power sector using the Integrated Planning Model®', *Energy Policy,* 73, pp. 524-539.
Jamero, M. L., Onuki, M., Esteban, M., Chadwick, C., Tan, N., Valenzuela, V. P., Crichton, R. and Avelino, J. E. (2019) 'In-situ adaptation against climate change can enable relocation of impoverished small islands', *Marine policy,* 108, pp. 103614.
Janhäll, S. (2015) 'Review on urban vegetation and particle air pollution – Deposition and dispersion', *Atmospheric Environment,* 105, pp. 130-137.
Januriyadi, N. F., Kazama, S., Moe, I. R. and Kure, S. (2018) 'Evaluation of future flood risk in Asian megacities: a case study of Jakarta', *Hydrological Research Letters,* 12(3), pp. 14-22.
Jay, O., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R. S., Ma, W. and Malik, A. (2021) 'Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities', *The Lancet,* 398(10301), pp. 709-724.
Jefferson, A. J., Bhaskar, A. S., Hopkins, K. G., Fanelli, R., Avellaneda, P. M. and McMillan, S. K. (2017) 'Stormwater management network effectiveness and implications for urban watershed function: A critical review', *Hydrological Processes,* 31(23), pp. 4056-4080.

Jendritzky, G. (1999) *Impacts of extreme and persistent temperatures—cold waves and heat waves*, Geneva: *World Meteorological Organization*.
Jeong, D. I., Sushama, L., Vieira, M. J. F. and Koenig, K. A. (2018) 'Projected changes to extreme ice loads for overhead transmission lines across Canada', *Sustainable Cities and Society,* 39, pp. 639-649.
Jeppesen, E., Brucet, S., Naselli-Flores, L., Papastergiadou, E., Stefanidis, K., Noges, T., Noges, P., Attayde, J. L., Zohary, T. and Coppens, J. (2015) 'Ecological impacts of global warming and water abstraction on lakes and reservoirs due to changes in water level and related changes in salinity', *Hydrobiologia,* 750(1), pp. 201-227.
Jiang, L. and O'Neill, B. C. (2017) 'Global urbanization projections for the Shared Socioeconomic Pathways', *Global Environmental Change,* 42, pp. 193-199.
Jiménez, J. A., Valdemoro, H. I., Bosom, E., Sánchez-Arcilla, A. and Nicholls, R. J. (2017) 'Impacts of sea-level rise-induced erosion on the Catalan coast', *Regional environmental change,* 17(2), pp. 593-603.
Johnson, C. (2018) *The Power of Cities in Global Climate Politics: Saviours, Supplicants or Agents of Change?* London: Palgrave Macmillan.
Johnson, M. S., Lathuillière, M. J., Tooke, T. R. and Coops, N. C. (2015) 'Attenuation of urban agricultural production potential and crop water footprint due to shading from buildings and trees', *Environmental Research Letters,* 10(6), pp. 064007.
Jones, E. and van Vliet, M. T. H. (2018) 'Drought impacts on river salinity in the southern US: Implications for water scarcity', *Science of The Total Environment,* 644, pp. 844-853.
Jones, L., Dougill, A., Jones, R. G., Steynor, A., Watkiss, P., Kane, C., Koelle, B., Moufouma-Okia, W., Padgham, J., Ranger, N., Roux, J.-P., Suarez, P., Tanner, T. and Vincent, K. (2015) 'Ensuring climate information guides long-term development', *Nature Climate Change,* 5, pp. 812.
Jongman, B. (2018) 'Effective adaptation to rising flood risk', *Nature communications,* 9(1), pp. 1-3.
Jonkeren, O., Rietveld, P., van Ommeren, J. and Te Linde, A. (2014) 'Climate change and economic consequences for inland waterway transport in Europe', *Regional environmental change,* 14(3), pp. 953-965.
Jordan, A. J., Huitema, D., Hildén, M., van Asselt, H., Rayner, T. J., Schoenefeld, J. J., Tosun, J., Forster, J. and Boasson, E. L. (2015) 'Emergence of polycentric climate governance and its future prospects', *Nature Climate Change,* 5, pp. 977.
Jordan, J. C. (2020) 'Theatre making and storytelling on the margins: the lived experience of climate change in Dhaka', *Research in Drama Education: The Journal of Applied Theatre and Performance,* 25(4), pp. 569-575.
Jovanović, S., Savić, S., Bojić, M., Djordjević, Z. and Nikolić, D. (2015) 'The impact of the mean daily air temperature change on electricity consumption', *Energy,* 88, pp. 604-609.
Juhola, S., Glaas, E., Linnér, B.-O. and Neset, T.-S. (2016) 'Redefining maladaptation', *Environmental Science & Policy,* 55, pp. 135-140.
Kabir, M. R., Khan, S., Chowdhury, S., Jahan, S., Islam, K. A. and Zayed, N. M. (2021) 'Corruption Possibilities in the Climate Financing Sector and Role of the Civil Societies in Bangladesh', *Journal of Southwest Jiaotong University,* 56(2).
Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K. and Bonn, A. (2016) 'Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action', *Ecology and Society,* 21(2).
Kabisch, N., van den Bosch, M. and Lafortezza, R. (2017) 'The health benefits of nature-based solutions to urbanization challenges for children and the elderly–A systematic review', *Environmental research,* 159, pp. 362-373.
Kaczan, D. J. and Orgill-Meyer, J. (2020) 'The impact of climate change on migration: a synthesis of recent empirical insights', *Climatic Change,* 158(3), pp. 281-300.
Kahanji, C., Walls, R. S. and Cicione, A. (2019) 'Fire spread analysis for the 2017 Imizamo Yethu informal settlement conflagration in South Africa', *International journal of disaster risk reduction,* 39, pp. 101146.
Kaijser, A. and Kronsell, A. (2014) 'Climate change through the lens of intersectionality', *Environmental politics,* 23(3), pp. 417-433.
Kaika, M. (2017) ''Don't call me resilient again!': the New Urban Agenda as immunology… or… what happens when communities refuse to be vaccinated with 'smart cities' and indicators', *Environment and Urbanization,* 29(1), pp. 89-102.
Kamalipour, H. and Dovey, K. (2020) 'Incremental production of urban space: A typology of informal design', *Habitat International,* 98, pp. 102133.
Kamei, M., Hanaki, K. and Kurisu, K. (2016) 'Tokyo's long-term Socioeconomic Pathways: Towards a sustainable future', *Sustainable Cities and Society,* 27, pp. 73-82.
Kang, N., Kim, S., Kim, Y., Noh, H., Hong, S. and Kim, H. (2016) 'Urban drainage system improvement for climate change adaptation', *Water,* 8(7), pp. 268.
Kant, Y., Shaik, D. S., Mitra, D., Chandola, H., Babu, S. S. and Chauhan, P. (2020) 'Black carbon aerosol quantification over north-west Himalayas: Seasonal heterogeneity, source apportionment and radiative forcing', *Environmental Pollution,* 257, pp. 113446.
Kapetas, L. and Fenner, R. (2020) 'Integrating blue-green and grey infrastructure through an adaptation pathways approach to surface water flooding', *Philosophical Transactions of the Royal Society A,* 378(2168), pp. 20190204.

Karagiannis, G. M., Cardarilli, M., Turksezer, Z. I., Spinoni, J., Mentaschi, L., Feyen, L. and Krausmann, E. (2019) *Climate change and critical infrastructure – storms*, Luxembourg: Publications Office of the European Union. Available at: https://core.ac.uk/download/pdf/186491046.pdf.

Kareem, B., Lwasa, S., Tugume, D., Mukwaya, P., Walubwa, J., Owuor, S., Kasaija, P., Sseviiri, H., Nsangi, G. and Byarugaba, D. (2020) 'Pathways for resilience to climate change in African cities', *Environmental Research Letters,* 15(7), pp. 073002.

Karpinska, L. and Śmiech, S. (2020) 'Invisible energy poverty? Analysing housing costs in Central and Eastern Europe', *Energy Research & Social Science,* 70, pp. 101670.

Kashem, S. B., Wilson, B. and Van Zandt, S. (2016) 'Planning for Climate Adaptation: Evaluating the Changing Patterns of Social Vulnerability and Adaptation Challenges in Three Coastal Cities', *Journal of Planning Education and Research,* 36(3), pp. 304-318.

Kawai, H., Koshiro, T., Endo, H. and Arakawa, O. (2018) 'Changes in Marine Fog Over the North Pacific Under Different Climates in CMIP5 Multimodel Simulations', *Journal of Geophysical Research: Atmospheres,* 123(19), pp. 10,911-10,924.

Kawai, H., Koshiro, T., Endo, H., Arakawa, O. and Hagihara, Y. (2016) 'Changes in marine fog in a warmer climate', *Atmospheric Science Letters,* 17(10), pp. 548-555.

Kayaga, S. M., Amankwaa, E. F., Gough, K. V., Wilby, R. L., Abarike, M. A., Codjoe, S. N., Kasei, R., Nabilse, C. K., Yankson, P. W. and Mensah, P. (2021) 'Cities and extreme weather events: impacts of flooding and extreme heat on water and electricity services in Ghana', *Environment and Urbanization,* 33(1), pp. 131-150.

Keck, A. (2020) *NASA Helps Puerto Rico Prepare for Saharan Dust Impacts*: NASA. Available at: https://www.nasa.gov/feature/nasa-helps-puerto-rico-prepare-for-saharan-dust-impacts.

Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Meza Prado, K. A., Arkema, K. K., Bratman, G. N., Brauman, K. A., Finlay, J. C., Guerry, A. D., Hobbie, S. E., Johnson, J. A., MacDonald, G. K., McDonald, R. I., Neverisky, N. and Wood, S. A. (2019) 'Social-ecological and technological factors moderate the value of urban nature', *Nature Sustainability,* 2(1), pp. 29-38.

Keenan, J. M., Chu, E. and Peterson, J. (2019) 'From funding to financing: perspectives shaping a research agenda for investment in urban climate adaptation', *International Journal of Urban Sustainable Development*, pp. 1-12.

Keenan, J. M., Hill, T. and Gumber, A. (2018) 'Climate gentrification: from theory to empiricism in Miami-Dade County, Florida', *Environmental Research Letters,* 13(5), pp. 054001.

Keil, R. and Macdonald, S. (2016) 'Rethinking urban political ecology from the outside in: greenbelts and boundaries in the post-suburban city', *Local environment,* 21(12), pp. 1516-1533.

Kelman, I. (2018) 'Islandness within climate change narratives of small island developing states (SIDS)', *Island studies journal,* 13(1), pp. 149-166.

Kemp, R. (2017) 'Electrical system resilience: a forensic analysis of the blackout in Lancaster, UK', *Proceedings of the Institution of Civil Engineers-Forensic Engineering,* 170(2), pp. 100-109.

Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C. and Senior, C. A. (2014) 'Heavier summer downpours with climate change revealed by weather forecast resolution model', *Nature Climate Change,* 4(7), pp. 570.

Kenis, A. (2021) 'Clashing tactics, clashing generations: The politics of the school strikes for climate in Belgium', *Politics and Governance,* 9(2), pp. 135-145.

Kern, K. (2019) 'Cities as leaders in EU multilevel climate governance: embedded upscaling of local experiments in Europe', *Environmental Politics,* 28(1), pp. 125-145.

Kernaghan, S. and Da Silva, J. (2014) 'Initiating and sustaining action: Experiences building resilience to climate change in Asian cities', *Urban Climate,* 7, pp. 47-63.

Kew, S. F., Selten, F. M., Lenderink, G. and Hazeleger, W. (2013) 'The simultaneous occurrence of surge and discharge extremes for the Rhine delta', *Natural hazards and earth system sciences,* 13(8), pp. 2017-2029.

Khirfan, L. and El-Shayeb, H. (2019) 'Urban climate resilience through socio-ecological planning: a case study in Charlottetown, Prince Edward Island', *Journal of Urbanism: International Research on Placemaking and Urban Sustainability,* 13(2).

Khosla, R. and Bhardwaj, A. (2019) 'Urbanization in the time of climate change: Examining the response of Indian cities', *Wiley Interdisciplinary Reviews: Climate Change,* 10(1), pp. e560.

Kim, S. J. and Bostwick, W. (2020) 'Social Vulnerability and Racial Inequality in COVID-19 Deaths in Chicago', *Health education & behavior,* 47(4), pp. 509-513.

Kim, S. K. (2020) 'The economic effects of climate change adaptation measures: Evidence from Miami-Dade County and New York City', *Sustainability,* 12(3), pp. 1097.

Kim, Y., Chester, M. V., Eisenberg, D. A. and Redman, C. L. (2019) 'The infrastructure trolley problem: Positioning safe-to-fail infrastructure for climate change adaptation', *Earth's Future,* 7(7), pp. 704-717.

Kim, Y.-H., Gwon, E.-M., Kim, H.-K., Cho, I.-H., Lee, H. and Kim, B.-H. (2020a) 'Control of Nuisance Cyanobacteria in Drinking Water Resources Using Alternative Algae-Blocking Mats', *Water,* 12(6), pp. 1576.

Kim, Y.-o., Lee, W., Kim, H. and Cho, Y. (2020b) 'Social isolation and vulnerability to heatwave-related mortality in the urban elderly population: A time-series multi-community study in Korea', *Environment International,* 142, pp. 105868.

Kinay, P., Morse, A. P., Villanueva, E. V., Morrissey, K. and Staddon, P. L. (2019) 'Direct and indirect health impacts of climate change on the vulnerable elderly population in East China', *Environmental reviews,* 27(3), pp. 295-303.
King, D., Gurtner, Y., Firdaus, A., Harwood, S. and Cottrell, A. (2016) 'Land use planning for disaster risk reduction and climate change adaptation: Operationalizing policy and legislation at local levels', *International Journal of Disaster Resilience in the Built Environment,* 7(2), pp. 158-172.
Kinney, P. L., Schwartz, J., Pascal, M., Petkova, E., Le Tertre, A., Medina, S. and Vautard, R. (2015) 'Winter season mortality: will climate warming bring benefits?', *Environmental Research Letters,* 10(6), pp. 064016.
Kinyanjui, M. (2020) 'National Urban Policy: Tool for Development', in Kundu, D., Sietchiping, R. and Kinyanjui, M. (eds.) *Developing National Urban Policies*. Singapore: Springer, pp. 51-85.
Kironde, J. M. L. (2016) 'Governance deficits in dealing with the plight of dwellers of hazardous land: the case of the Msimbazi River Valley in Dar es Salaam, Tanzania', *Current Urban Studies,* 4(03), pp. 303.
Kirschbaum, D., Stanley, T. and Zhou, Y. (2015) 'Spatial and temporal analysis of a global landslide catalog', *Geomorphology,* 249, pp. 4-15.
Kirshen, P., Caputo, L., Vogel, R. M., Mathisen, P., Rosner, A. and Renaud, T. (2015) 'Adapting urban infrastructure to climate change: A drainage case study', *Journal of Water Resources Planning and Management,* 141(4), pp. 04014064.
Kita, S. M. (2017) 'Urban vulnerability, disaster risk reduction and resettlement in Mzuzu city, Malawi', *International journal of disaster risk reduction,* 22, pp. 158-166.
Kleibert, J. M. (2018) 'Exclusive development (s): Special economic zones and enclave urbanism in the Philippines', *Critical Sociology,* 44(3), pp. 471-485.
Klein, J., Juhola, S. and Landauer, M. (2017) 'Local authorities and the engagement of private actors in climate change adaptation', *Environment and Planning C: Politics and Space,* 35(6), pp. 1055-1074.
Klein, T. and Anderegg, W. R. (2021) 'Global warming and urban population growth in already warm regions drive a vast increase in heat exposure in the 21st century', *Sustainable Cities and Society*, pp. 103098.
Klenk, N., Fiume, A., Meehan, K. and Gibbes, C. (2017) 'Local knowledge in climate adaptation research: Moving knowledge frameworks from extraction to co-production', *Wiley Interdisciplinary Reviews: Climate Change,* 8(5), pp. e475.
Klopp, J. M. and Petretta, D. L. (2017) 'The urban sustainable development goal: Indicators, complexity and the politics of measuring cities', *Cities,* 63, pp. 92-97.
Knapp, S., Schmauck, S. and Zehnsdorf, A. (2019) 'Biodiversity impact of green roofs and constructed wetlands as progressive eco-technologies in urban areas', *Sustainability,* 11(20), pp. 5846.
Knieling, J. (2016) *Climate Adaptation Governance in Cities and Regions: Theoretical Fundamentals and Practical Evidence.* Chichester: Wiley Blackwell.
Knight, T., Price, S., Bowler, D., Hookway, A., King, S., Konno, K. and Richter, R. L. (2021) 'How effective is 'greening'of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure and the 'urban heat island effect'? An updated systematic review', *Environmental Evidence,* 10(1), pp. 1-38.
Knight, T., Price, S., Bowler, D. and King, S. (2016) 'How effective is 'greening'of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure and the 'urban heat island effect'? A protocol to update a systematic review', *Environmental Evidence,* 5(1), pp. 3.
Knorr, W., Arneth, A. and Jiang, L. (2016) 'Demographic controls of future global fire risk', *Nature Climate Change,* 6(8), pp. 781-785.
Knott, J. F., Elshaer, M., Daniel, J. S., Jacobs, J. M. and Kirshen, P. (2017) 'Assessing the effects of rising groundwater from sea level rise on the service life of pavements in coastal road infrastructure', *Transportation Research Record,* 2639(1), pp. 1-10.
Knowlton, K., Rosenthal Joyce, E., Hogrefe, C., Lynn, B., Gaffin, S., Goldberg, R., Rosenzweig, C., Civerolo, K., Ku, J.-Y. and Kinney Patrick, L. (2004) 'Assessing Ozone-Related Health Impacts under a Changing Climate', *Environmental Health Perspectives,* 112(15), pp. 1557-1563.
Koks, E. E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S. A., Hall, J. W. and Hallegatte, S. (2019) 'A global multi-hazard risk analysis of road and railway infrastructure assets', *Nature communications,* 10(1), pp. 2677.
Kolbe, K. (2019) 'Mitigating urban heat island effect and carbon dioxide emissions through different mobility concepts: Comparison of conventional vehicles with electric vehicles, hydrogen vehicles and public transportation', *Transport Policy,* 80, pp. 1-11.
Kolokotsa, D. (2017) 'Smart cooling systems for the urban environment. Using renewable technologies to face the urban climate change', *Solar Energy,* 154, pp. 101-111.
Komolafe Akinola, A., Herath, S. and Avtar, R. (2018) 'Methodology to Assess Potential Flood Damages in Urban Areas under the Influence of Climate Change', *Natural Hazards Review,* 19(2), pp. 05018001.
Kong, J., Simonovic, S. P. and Zhang, C. (2019) 'Sequential hazards resilience of interdependent infrastructure system: A case study of Greater Toronto Area energy infrastructure system', *Risk Analysis,* 39(5), pp. 1141-1168.
Koop, S. H. A. and van Leeuwen, C. J. (2017) 'The challenges of water, waste and climate change in cities', *Environment, development and sustainability,* 19(2), pp. 385-418.
Korah, P. I. and Cobbinah, P. B. (2017) 'Juggling through Ghanaian urbanisation: flood hazard mapping of Kumasi', *GeoJournal,* 82(6), pp. 1195-1212.

Kosaka, E., Iida, A., Vanos, J., Middel, A., Yokohari, M. and Brown, R. (2018) 'Microclimate Variation and Estimated Heat Stress of Runners in the 2020 Tokyo Olympic Marathon', *Atmosphere,* 9(5).
Kothuis, B. and Kok, M. (2017) *Integral design of multifunctional flood defenses: multidisciplinary approaches & examples.* Delft: Delft University Publishers.
Kotova, L., Jacob, D., Leissner, J., Mathis, M. and Mikolajewicz, U. (2019) 'Climate Information for the Preservation of Cultural Heritage: Needs and Challenges', in Moropoulou, A., Korres, M., Georgopoulos, A., Spyrakos, C. and Mouzakis, C. (eds.) *Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultual Heritage*. Cham: Springer, pp. 353-359.
Kourtit, K., Nijkamp, P. and Scholten, H. (2015) 'Urban Futures', *Applied Spatial Analysis and Policy,* 8(3), pp. 177-179.
Kovacic, Z., Musango, J. K., Ambole, L. A., Buyana, K., Smit, S., Anditi, C., Mwau, B., Ogot, M., Lwasa, S. and Brent, A. C. (2019) 'Interrogating differences: A comparative analysis of Africa's informal settlements', *World Development,* 122, pp. 614-627.
Kozak, D., Henderson, H., de Castro Mazarro, A., Rotbart, D. and Aradas, R. (2020) 'Blue-green infrastructure (BGI) in dense urban watersheds. The case of the Medrano stream basin (MSB) in Buenos Aires', *Sustainability,* 12(6), pp. 2163.
Krauze, K. and Wagner, I. (2019) 'From classical water-ecosystem theories to nature-based solutions—Contextualizing nature-based solutions for sustainable city', *Science of the total environment,* 655, pp. 697-706.
Krecl, P., Targino, A. C., Oukawa, G. Y. and Junior, R. P. C. (2020) 'Drop in urban air pollution from COVID-19 pandemic: Policy implications for the megacity of São Paulo', *Environmental Pollution,* 265, pp. 114883.
Kroeger, T., Escobedo, F. J., Hernandez, J. L., Varela, S., Delphin, S., Fisher, J. R. B. and Waldron, J. (2014) 'Reforestation as a novel abatement and compliance measure for ground-level ozone', *Proceedings of the National Academy of Sciences,* 111(40), pp. E4204-E4213.
Kubicz, J., Lochyński, P., Pawełczyk, A. and Karczewski, M. (2021) 'Effects of drought on environmental health risk posed by groundwater contamination', *Chemosphere,* 263, pp. 128145.
Kuklicke, C. and Demeritt, D. (2016) 'Adaptive and risk-based approaches to climate change and the management of uncertainty and institutional risk: The case of future flooding in England', *Global Environmental Change,* 37, pp. 56-68.
Kuller, M., Bach, P. M., Ramirez-Lovering, D. and Deletic, A. (2018) 'What drives the location choice for water sensitive infrastructure in Melbourne, Australia?', *Landscape and Urban Planning,* 175, pp. 92-101.
Kulp, S. A. and Strauss, B. H. (2019) 'New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding', *Nature communications,* 10(1), pp. 1-12.
Kumar, P., Geneletti, D. and Nagendra, H. (2016) 'Spatial assessment of climate change vulnerability at city scale: A study in Bangalore, India', *Land Use Policy,* 58, pp. 514-532.
Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N. and Mach, K. (2014) 'Flood risk and climate change: global and regional perspectives', *Hydrological Sciences Journal,* 59(1), pp. 1-28.
Kuran, C. H. A., Morsut, C., Kruke, B. I., Krüger, M., Segnestam, L., Orru, K., Nævestad, T. O., Airola, M., Keränen, J., Gabel, F., Hansson, S. and Torpan, S. (2020) 'Vulnerability and vulnerable groups from an intersectionality perspective', *International journal of disaster risk reduction,* 50.
Kusaka, H., Suzuki-Parker, A., Aoyagi, T., Adachi, S. A. and Yamagata, Y. (2016) 'Assessment of RCM and urban scenarios uncertainties in the climate projections for August in the 2050s in Tokyo', *Climatic Change,* 137(3-4), pp. 427-438.
Kuyper, J. W., Linnér, B. O. and Schroeder, H. (2018) 'Non-state actors in hybrid global climate governance: justice, legitimacy, and effectiveness in a post-Paris era', *Wiley Interdisciplinary Reviews: Climate Change,* 9(1), pp. e497.
Laeni, N., Ovink, H., Busscher, T., Handayani, W. and van den Brink, M. (2021) 'A transformative process for urban climate resilience: The case of Water as Leverage Resilient Cities Asia in Semarang, Indonesia', in de and Graaf-van Dinther, R. (eds.) *Climate Resilient Urban Areas*. Cham: Palgrave Macmillan, pp. 155-173.
Lagmay, A. M. F., Agaton, R. P., Bahala, M. A. C., Briones, J. B. L. T., Cacabaca, K. M. C., Caro, C. V. C., Dasallas, L. L., Gonzalo, L. A. L., Ladiero, C. N. and Lapidez, J. P. (2015) 'Devastating storm surges of Typhoon Haiyan', *International journal of disaster risk reduction,* 11, pp. 1-12.
Lakner, C., Yonzan, N., Mahler, D. G., Aguilar, R. A. C. and Wu, H. (2021) 'Updated estimates of the impact of COVID-19 on global poverty: Looking back at 2020 and the outlook for 2021', *World Bank Data Blog*, Available: World Bank.
Lam, C. K. C., Loughnan, M. and Tapper, N. (2018) 'Visitors' perception of thermal comfort during extreme heat events at the Royal Botanic Garden Melbourne', *International Journal of Biometeorology,* 62(1), pp. 97-112.
Lamb, W. F., Creutzig, F., Callaghan, M. W. and Minx, J. C. (2019) 'Learning about urban climate solutions from case studies', *Nature Climate Change,* 9(4), pp. 279-287.
Lamba Nieves, D. and Marxuach, S. M. (2020) *Can We Rebuild Puerto Rico's State Capacity?* : Center for the New Economy. Available at: http://www.grupocne.org.
Landauer, M., Juhola, S. and Klein, J. (2019) 'The role of scale in integrating climate change adaptation and mitigation in cities', *Journal of Environmental Planning and Management,* 62(5), pp. 741-765.

Lane, D. E., Clarke, C. M., Clarke, J. D., Mycoo, M. and Gobin, J. (2015) 'Managing Adaptation to Changing Climate in Coastal Zones', in Baztan, P., Chouinard, O., Jorgensen, B., Tett, P. and Vasseur, L. (eds.) *Coastal Zones: Solutions for the 21st Century*. Amsterdam: Elsevier, pp. 141-160.
Larcom, S., She, P.-W. and van Gevelt, T. (2019) 'The UK summer heatwave of 2018 and public concern over energy security', *Nature Climate Change,* 9(5), pp. 370.
Larondelle, N., Hamstead, Z. A., Kremer, P., Haase, D. and McPhearson, T. (2014) 'Applying a novel urban structure classification to compare the relationships of urban structure and surface temperature in Berlin and New York City', *Applied Geography,* 53, pp. 427-437.
Larsen, L. (2015) 'Urban climate and adaptation strategies', *Frontiers in Ecology and the Environment,* 13(9), pp. 486-492.
Lasage, R., Aerts, J. C. J. H., Verburg, P. H. and Sileshi, A. S. (2015) 'The role of small scale sand dams in securing water supply under climate change in Ethiopia', *Mitigation and Adaptation Strategies for Global Change,* 20(2), pp. 317-339.
Laspidou, C. (2014) 'ICT and stakeholder participation for improved urban water management in the cities of the future', *Water Util. J,* 8, pp. 79-85.
Lassa, J. A. (2019) 'Negotiating institutional pathways for sustaining climate change resilience and risk governance in Indonesia', *Climate,* 7(8), pp. 95.
Lassa, J. A., Teng, P., Caballero-Anthony, M. and Shrestha, M. (2019) 'Revisiting Emergency Food Reserve Policy and Practice under Disaster and Extreme Climate Events', *International Journal of Disaster Risk Science,* 10(1), pp. 1-13.
Latham, A. and Layton, J. (2019) 'Social infrastructure and the public life of cities: Studying urban sociality and public spaces', *Geography Compass,* 13(7), pp. e12444.
Lauermann, J. (2018) 'Geographies of mega-urbanization', *Geography Compass,* 12(8), pp. e12396.
Lawhon, M., Nilsson, D. and Silver, J. (2018) 'Thinking through heterogeneous infrastructure configurations', *Urban Studies,* 55(February 2017), pp. 720-732.
Leal Filho, W., Wolf, F., Castro-Díaz, R., Li, C., Ojeh, V. N., Gutiérrez, N., Nagy, G. J., Savić, S., Natenzon, C. E. and Quasem Al-Amin, A. (2021) 'Addressing the urban heat islands effect: A cross-country assessment of the role of green infrastructure', *Sustainability,* 13(2), pp. 753.
Leddin, D. and Macrae, F. (2020) 'Climate Change: Implications for Gastrointestinal Health and Disease', *Journal of Clinical Gastroenterology,* 54(5), pp. 393-397.
Lee, K. and Levermore, G. J. (2019) 'Sky view factor and sunshine factor of urban geometry for urban heat island and renewable energy', *Architectural Science Review,* 62(1), pp. 26-34.
Lee, T. M., Markowitz, E. M., Howe, P. D., Ko, C.-Y. and Leiserowitz, A. A. (2015) 'Predictors of public climate change awareness and risk perception around the world', *Nature climate change,* 5(11), pp. 1014.
Lehmann, P., Brenck, M., Gebhardt, O., Schaller, S. and Süßbauer, E. (2015) 'Barriers and opportunities for urban adaptation planning: analytical framework and evidence from cities in Latin America and Germany', *Mitigation and adaptation strategies for global change,* 20(1), pp. 75-97.
Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K. and Magome, J. (2011) 'High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management', *Frontiers in Ecology and the Environment,* 9(9), pp. 494-502.
Lehner, B. C., Reidy Liermann, C., Revenga, C., Vorosmarty, C., Fekete, B., Crouzet, P., Doll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rodel, R., Sindorf, N. and Wisse, D. (2019) 'Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. Palisades'. Available at: https://doi.org/10.7927/H4N877QK (Accessed: 28 Sept 2019).
Lei, Y., Finlayson, C., Thwaites, R., Shi, G. and Cui, L. (2017) 'Using Government Resettlement Projects as a Sustainable Adaptation Strategy for Climate Change', *Sustainability (Basel, Switzerland),* 9(8), pp. 1373.
Leijonhufvud, G. (2016) 'Making sense of climate risk information: The case of future indoor climate risks in Swedish churches', *Climate Risk Management,* 13(C), pp. 76-87.
Leiter, T., Olhoff, A., Al Aza, R., Barmby, V., Bours, D., Clemen, V. W. C., Dale, T. W., Davies, C. and Jacobs, H. (2019) *Adaptation Metrics. Current Landscape and Evolving Practices*, Online: Department of Technology, Management and Economics UNEP DTU Partnership. Available at: https://orbit.dtu.dk/en/publications/adaptation-metrics-current-landscape-and-evolving-practices.
Leitner, H., Sheppard, E., Webber, S. and Colven, E. (2018) 'Globalizing urban resilience', *Urban Geography,* 39(8), pp. 1276-1284.
Lemi, T. (2019) 'The Role of Traditional Ecological Knowledge (TEK) for Climate Change Adaptation', *International Journal of Environmental Sciences & Natural Resources,* 18(1), pp. 28-31.
Lemieux, C. J., Groulx, M., Halpenny, E., Stager, H., Dawson, J., Stewart, E. J. and Hvenegaard, G. T. (2018) '"The End of the Ice Age?": Disappearing World Heritage and the Climate Change Communication Imperative', *Environmental Communication,* 12(5), pp. 653-671.
Lemos, M. C., Lo, Y.-J., Nelson, D. R., Eakin, H. and Bedran-Martins, A. M. (2016) 'Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil', *Global environmental change,* 39, pp. 170-179.

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D. and Stafford-Smith, M. (2014) 'A compound event framework for understanding extreme impacts', *Wiley Interdisciplinary Reviews: Climate Change,* 5(1), pp. 113-128.
Lesnikowski, A., Biesbroek, R., Ford, J. D. and Berrang-Ford, L. (2021) 'Policy implementation styles and local governments: the case of climate change adaptation', *Environmental Politics,* 30(5), pp. 753-790.
Leszczynski, A. (2016) 'Speculative futures: Cities, data, and governance beyond smart urbanism', *Environment and Planning A: Economy and Space,* 48(9), pp. 1691-1708.
Leung, D. Y. (2015) 'Outdoor-indoor air pollution in urban environment: challenges and opportunity', *Frontiers in Environmental Science,* 2, pp. 69.
Levermann, A. (2014) 'Climate economics: Make supply chains climate-smart', *Nature News,* 506(7486), pp. 27.
Lewis, S. C., Blake, S. A. P., Trewin, B., Black, M. T., Dowdy, A. J., Perkins-Kirkpatrick, S. E., King, A. D. and Sharples, J. J. (2020) 'Deconstructing factors contributing to the 2018 fire weather in Queensland, Australia', *Bulletin of the American Meteorological Society,* 101(1), pp. S115-S122.
León, J. and March, A. (2016) 'An urban form response to disaster vulnerability: Improving tsunami evacuation in Iquique, Chile', *Environment and Planning B: Planning and Design,* 43(5), pp. 826-847.
León-Mateos, F., Sartal, A., López-Manuel, L. and Quintás, M. A. (2021) 'Adapting our sea ports to the challenges of climate change: Development and validation of a Port Resilience Index', *Marine Policy,* 130, pp. 104573.
Li, D., Bou-Zeid, E. and Oppenheimer, M. (2014) 'The effectiveness of cool and green roofs as urban heat island mitigation strategies', *Environmental Research Letters,* 9(5), pp. 055002.
Li, F., Liu, X., Zhang, X., Zhao, D., Liu, H., Zhou, C. and Wang, R. (2017) 'Urban ecological infrastructure: an integrated network for ecosystem services and sustainable urban systems', *Journal of Cleaner Production,* 163, pp. S12-S18.
Li, G., Yu, Q., Ma, W., Chen, Z., Mu, Y., Guo, L. and Wang, F. (2016) 'Freeze–thaw properties and long-term thermal stability of the unprotected tower foundation soils in permafrost regions along the Qinghai–Tibet Power Transmission Line', *Cold Regions Science and Technology,* 121, pp. 258-274.
Li, H., Qiu, P., Zhang, X., Wang, Y. and Zhao, C. (2020) 'Summarizing the planning elements of climate adaptive cities and assessing the plans of 28 pilots in China', *Environmental Protection,* 48(3), pp. 17-24.
Li, K., Jacob, D. J., Liao, H., Shen, L., Zhang, Q. and Bates, K. H. (2019a) 'Anthropogenic drivers of 2013–2017 trends in summer surface ozone in China', *Proceedings of the National Academy of Sciences,* 116(2), pp. 422-427.
Li, X., Yang, L., Zheng, H., Shan, Y., Zhang, Z., Song, M., Cai, B. and Guan, D. (2019b) 'City-level water-energy nexus in Beijing-Tianjin-Hebei region', *Applied Energy,* 235, pp. 827-834.
Li, X., Zhou, Y., Yu, S., Jia, G., Li, H. and Li, W. (2019c) 'Urban Heat Island Impacts on Building Energy Consumption: A Review of Approaches and Findings', *Energy,* 174, pp. 407-419.
Liang, M. S. and Keener, T. C. (2015) 'Atmospheric feedback of urban boundary layer with implications for climate adaptation', *Environmental science & technology,* 49(17), pp. 10598-10606.
Lichter, D. T. and Ziliak, J. P. (2017) 'The rural-urban interface: New patterns of spatial interdependence and inequality in America', *The ANNALS of the American Academy of Political and Social Science,* 672(1), pp. 6-25.
Lilford, R. J., Oyebode, O., Satterthwaite, D., Chen, Y.-f., Mberu, B., Watson, S. I. and Sartori, J. (2016) 'The health of people who live in slums 2 Improving the health and welfare of people who live in slums', *The Lancet,* 6736(16), pp. 1-11.
Limthongsakul, S., Nitivattananon, V. and Arifwidodo, S. D. (2017) 'Localized flooding and autonomous adaptation in peri-urban Bangkok', *Environment and Urbanization,* 29(1), pp. 51-68.
Lin, B., Meyers, J. and Barnett, G. (2015) 'Understanding the potential loss and inequities of green space distribution with urban densification', *Urban forestry & urban greening,* 14(4), pp. 952-958.
Lin, Y. and Ho, C. S. (2016) 'Solar radiation and urban wind effect on urban canyon in hot, humid regions', *Environment-Behaviour Proceedings Journal,* 1(4), pp. 220-229.
Lindegaard, L. S. (2019) 'Lessons from climate-related planned relocations: the case of Vietnam', *Climate and Development*, pp. 1-10.
Liotta, C., Kervinio, Y., Levrel, H. and Tardieu, L. (2020) 'Planning for environmental justice - reducing well-being inequalities through urban greening', *Environmental science & policy,* 112, pp. 47-60.
Liousse, C., Assamoi, E., Criqui, P., Granier, C. and Rosset, R. (2014) 'Explosive growth in African combustion emissions from 2005 to 2030', *Environmental Research Letters,* 9(3), pp. 035003.
Liu, C. and Coley, D. (2015) 'Overheating Risk of UK Dwellings Under a Changing Climate', *Energy Procedia,* 78, pp. 2796-2801.
Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P. and Kremen, C. (2015) 'Systems integration for global sustainability', *Science,* 347(6225).
Liu, L. and Jensen, M. B. (2018) 'Green infrastructure for sustainable urban water management: Practices of five forerunner cities', *Cities,* 74, pp. 126-133.
Liu, W., Sun, F., Lim, W. H., Zhang, J., Wang, H., Shiogama, H. and Zhang, Y. (2018) 'Global drought and severe drought-affected populations in 1.5 and 2° C warmer worlds', *Earth System Dynamics,* 9(1), pp. 267-283.
Liu, Y., Saha, S., Hoppe, B. O. and Convertino, M. (2019) 'Degrees and dollars – Health costs associated with suboptimal ambient temperature exposure', *Science of The Total Environment,* 678, pp. 702-711.

Loli, A. and Bertolin, C. (2018a) 'Indoor multi-risk scenarios of climate change effects on building materials in Scandinavian countries', *Geosciences,* 8(9).
Loli, A. and Bertolin, C. (2018b) 'Towards zero-emission refurbishment of historic buildings: a literature review', *Buildings,* 8(2), pp. 22-38.
Long, J. and Rice, J. L. (2019) 'From sustainable urbanism to climate urbanism', *Urban Studies,* 56(5), pp. 992-1008.
Lontorfos, V., Efthymiou, C. and Santamouris, M. (2018) 'On the time varying mitigation performance of reflective geoengineering technologies in cities', *Renewable Energy,* 115, pp. 926-930.
Lopes, J., Reis, R. M., Gaivizzo, L. H. B., Litre, G., Rodrigues Filho, S. and Saito, C. H. (2020) 'The contribution of community-based recycling cooperatives to a cluster of SDGs in semi-arid Brazilian peri-urban settlements', in Nhamo , G., Odularu , G.O.A. and Mjimba , V. (eds.) *Scaling up SDGs Implementation*. Cham: Springer, pp. 141-154.
Lorenzo, T. E. and Kinzig, A. P. (2020) 'Double Exposures: Future Water Security across Urban Southeast Asia', *Water,* 12(1), pp. 116.
Lourenço, T. C., Swart, R., Goosen, H. and Street, R. (2015) 'The rise of demand-driven climate services', *Nature Climate Change,* 6, pp. 13.
Lozano, R., Fullman, N., Mumford, J. E., Knight, M., Barthelemy, C. M., Abbafati, C., Abbastabar, H., Abd-Allah, F., Abdollahi, M. and Abedi, A. (2020) 'Measuring universal health coverage based on an index of effective coverage of health services in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019', *The Lancet,* 396(10258), pp. 1250-1284.
Ludy, J. and Kondolf, G. M. (2012) 'Flood risk perception in lands "protected" by 100-year levees', *Natural hazards,* 61(2), pp. 829-842.
Luetz, J. and Havea, P. H. (2018) '"We're not Refugees, We'll Stay Here Until We Die!"—Climate Change Adaptation and Migration Experiences Gathered from the Tulun and Nissan Atolls of Bougainville, Papua New Guinea', in Filho, L.W. (ed.) *Climate change impacts and adaptation strategies for coastal communities*. Cham: Springer, pp. 3-29.
Luetz, J. M. and Merson, J. (2019) 'Climate Change and Human Migration as Adaptation: Conceptual and Practical Challenges and Opportunities', in Leal Filho, W., Azul, A.M., Brandli, L., Özuyar, P.G. and Wall, T. (eds.) *Climate Action*. Cham: Springer International Publishing, pp. 1-13.
Luh, J., Royster, S., Sebastian, D., Ojomo, E. and Bartram, J. (2017) 'Expert assessment of the resilience of drinking water and sanitation systems to climate-related hazards', *Science of the Total Environment,* 592, pp. 334-344.
Lumbroso, D., Brown, E. and Ranger, N. (2016) 'Stakeholders' perceptions of the overall effectiveness of early warning systems and risk assessments for weather-related hazards in Africa, the Caribbean and South Asia', *Natural Hazards,* 84(3), pp. 2121-2144.
Lundqvist, L. J. (2016) 'Planning for climate change adaptation in a multi-level context: The Gothenburg metropolitan area', *European Planning Studies,* 24(1), pp. 1-20.
Lwasa, S. and Dubbeling, M. (2015) 'Urban agriculture and climate change', in de Zeeuw, H., and Dreschel, P. (ed.) *Cities and Agriculture: Developing Resilient Urban Food Systems*. Oxon: Earthscan-Routledge.
Lwasa, S., Mugagga, F., Wahab, B., Simon, D., Connors, J. and Griffith, C. (2014) 'Urban and peri-urban agriculture and forestry: Transcending poverty alleviation to climate change mitigation and adaptation', *Urban Climate,* 7, pp. 92-106.
Lyles, W., Berke, P. and Overstreet, K. H. (2018) 'Where to begin municipal climate adaptation planning? Evaluating two local choices', *Journal of Environmental Planning and Management,* 61(11), pp. 1994-2014.
Lüthi, C., Willetts, J. and Hoffmann, S. (2020) 'City-Wide Sanitation: The Urban Sustainability Challenge', *Frontiers in Environmental Science,* 8(185).
Ma, J., Yan, Z. and Zeyu, Z. (2021) 'Adapting Cities to Climate Change: Xixian New Area Pilot City Case Study', in Gándara, P., ZHENG, Y. and JIN, J. (eds.) *EU-China Climate Adaptation in Cities: Policy and Practice*. Beijing, China: Social Sciences Academic Press.
Ma, T., Sun, S., Fu, G., Hall, J. W., Ni, Y., He, L., Yi, J., Zhao, N., Du, Y. and Pei, T. (2020) 'Pollution exacerbates China's water scarcity and its regional inequality', *Nature Communications,* 11.
Ma, W., Chen, R. and Kan, H. (2014) 'Temperature-related mortality in 17 large Chinese cities: how heat and cold affect mortality in China', *Environmental research,* 134, pp. 127-133.
Ma, Z., Melville, D. S., Liu, J., Chen, Y., Yang, H., Ren, W., Zhang, Z., Piersma, T. and Li, B. (2014) 'Rethinking China's new great wall', *Science,* 346(6212), pp. 912-914.
Macarthy, J. M., Frediani, A. A., Kamara, S. F. and Morgado, M. (2017) *Exploring the role of empowerment in urban humanitarian responses in Freetown.* London: International Institute for Environment and Development.
Macintyre, T., Lotz-Sisitka, H., Wals, A., Vogel, C. and Tassone, V. (2018) 'Towards transformative social learning on the path to 1.5 degrees', *Current Opinion in Environmental Sustainability,* 31, pp. 80-87.
Madrigano, J., Ito, K., Johnson, S., Kinney Patrick, L. and Matte, T. (2015) 'A Case-Only Study of Vulnerability to Heat Wave–Related Mortality in New York City (2000–2011)', *Environmental Health Perspectives,* 123(7), pp. 672-678.
Maes, M. J., Jones, K. E., Toledano, M. B. and Milligan, B. (2019) 'Mapping synergies and trade-offs between urban ecosystems and the sustainable development goals', *Environmental science & policy,* 93, pp. 181-188.

Magnan, A. K., Schipper, E. L. F., Burkett, M., Bharwani, S., Burton, I., Eriksen, S., Gemenne, F., Schaar, J. and Ziervogel, G. (2016) 'Addressing the risk of maladaptation to climate change', *Wiley Interdisciplinary Reviews: Climate Change,* 7(5), pp. 646-665.
Magoni, M. and Colucci, A. (2017) 'Protection of Peri-Urban Open Spaces and Food-System Strategies. The Case of Parco delle Risaie in Milan', *Planning Practice & Research,* 32(1), pp. 40-54.
Maharjan, A., Hussain, A., Bhadwal, S., Ishaq, S., Saeed, B. A., Sachdeva, I., Ahmad, B., Hassan, S. M. T., Tuladhar, S. and Ferdous, J. (2018) *Migration in the lives of environmentally vulnerable populations in four river basins of the HinduKush Himalayan Region.*, Kathmandu: HI-AWARE. Available at: http://hi-aware.org/wp-content/uploads/2018/10/working-paper-20.pdf.
Major, D. C., Lehmann, M. and Fitton, J. (2018) 'Linking the management of climate change adaptation in small coastal towns and cities to the Sustainable Development Goals', *Ocean & coastal management,* 163, pp. 205-208.
Makantasi, A.-M. and Mavrogianni, A. (2016) 'Adaptation of London's social housing to climate change through retrofit: a holistic evaluation approach', *Advances in Building Energy Research (ABER),* 10(1), pp. 99-124.
Maki, S., Chandran, R., Fujii, M., Fujita, T., Shiraishi, Y., Ashina, S. and Yabe, N. (2019) 'Innovative information and communication technology (ICT) system for energy management of public utilities in a post-disaster region: Case study of a wastewater treatment plant in Fukushima', *Journal of cleaner production,* 233, pp. 1425-1436.
Makondo, C. C. and Thomas, D. S. G. (2018) 'Climate change adaptation: Linking indigenous knowledge with western science for effective adaptation', *Environmental science & policy,* 88, pp. 83-91.
Malakar, K. and Mishra, T. (2017) 'Assessing socio-economic vulnerability to climate change: A city-level index-based approach', *Climate and Development,* 9(4), pp. 348-363.
Maldonado, J., Bennett, T. M. B., Chief, K., Cochran, P., Cozzetto, K., Gough, B., Redsteer, M. H., Lynn, K., Maynard, N. and Voggesser, G. (2016) 'Engagement with indigenous peoples and honoring traditional knowledge systems', *Climatic Change,* 135, pp. 111-126.
Mallick, R. B., Jacobs, J. M., Miller, B. J., Daniel, J. S. and Kirshen, P. (2018) 'Understanding the impact of climate change on pavements with CMIP5, system dynamics and simulation', *International Journal of Pavement Engineering,* 19(8), pp. 697-705.
Malloy, J. T. and Ashcraft, C. M. (2020) 'A framework for implementing socially just climate adaptation', *Climatic Change,* 160(1), pp. 1-14.
Manzanedo, R. D. and Manning, P. (2020) 'COVID-19: Lessons for the climate change emergency', *Science of the Total Environment,* 742, pp. 140563.
Maor, M., Tosun, J. and Jordan, A. (2017) 'Proportionate and disproportionate policy responses to climate change: Core concepts and empirical applications', *Journal of Environmental Policy & Planning,* 19(6), pp. 599-611.
Maragno, D., Pozzer, G. and Musco, F. (2021) 'Multi-Risk Climate Mapping for the Adaptation of the Venice Metropolitan Area', *Sustainability,* 13(3), pp. 1334.
Marchezini, V., Trajber, R., Olivato, D., Muñoz, V. A., de Oliveira Pereira, F. and Oliveira Luz, A. E. (2017) 'Participatory Early Warning Systems: Youth, Citizen Science, and Intergenerational Dialogues on Disaster Risk Reduction in Brazil', *International Journal of Disaster Risk Science,* 8(4), pp. 390-401.
Marcotullio, P. J., Bruhwiler, L., Davis, S., Engel-Cox, J., Field, J., Gately, C. and Torrie, R. (2018) 'Chapter 3: Energy systems', in Cavallaro, N., Shrestha, G., Birdsey, R., Mayes, M.A., Najjar, R.G., Reed, S.C., Romero-Lankao, P. and Zhu, Z. (eds.) *Second state of the carbon cycle report (SOCCR2): A sustained assessment report*. Washington, DC: US Global Change Research Program, pp. 110-188.
Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., Miller, T. R., Ruddell, B. L. and Chang, H. (2018) 'Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience', *Earth's Future,* 6(12), pp. 1638-1659.
Markolf, S. A., Hoehne, C., Fraser, A., Chester, M. V. and Underwood, B. S. (2019) 'Transportation resilience to climate change and extreme weather events–Beyond risk and robustness', *Transport policy,* 74, pp. 174-186.
Marks, D. (2015) 'The urban political ecology of the 2011 floods in Bangkok: the creation of uneven vulnerabilities', *Pacific Affairs,* 88, pp. 623.
Marston, L., Konar, M., Cai, X. and Troy, T. J. (2015) 'Virtual groundwater transfers from overexploited aquifers in the United States', *Proceedings of the National Academy of Sciences,* 112(28), pp. 8561-8566.
Martellozzo, F., Landry, J. S., Plouffe, D., Seufert, V., Rowhani, P. and Ramankutty, N. (2014) 'Urban agriculture: a global analysis of the space constraint to meet urban vegetable demand', *Environmental Research Letters,* 9(6), pp. 064025.
Martin, R. V., Brauer, M., van Donkelaar, A., Shaddick, G., Narain, U. and Dey, S. (2019) 'No one knows which city has the highest concentration of fine particulate matter', *Atmospheric Environment: X,* 3, pp. 100040.
Martínez, C., Contreras-López, M., Winckler, P., Hidalgo, H., Godoy, E. and Agredano, R. (2018) 'Coastal erosion in central Chile: A new hazard?', *Ocean & Coastal Management,* 156, pp. 141-155.
Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X. and Lemonsu, A. (2014a) 'Solar panels reduce both global warming and urban heat island', *Frontiers in Environmental Science,* 2, pp. 14.
Masson, V., Marchadier, C., Adolphe, L., Aguejdad, R., Avner, P., Bonhomme, M., Bretagne, G., Briottet, X., Bueno, B. and De Munck, C. (2014b) 'Adapting cities to climate change: A systemic modelling approach', *Urban Climate,* 10, pp. 407-429.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* In Press: IPCC.
Masson-Delmotte, V. Z., P. Pörtner, H.-O. Roberts, D. Skea, J. Shukla, P.R. Pirani, A. Moufouma-Okia, W. Péan, C. Pidcock, R. Connors, S. Matthews, J .B.R. Chen, Y. Zhou, X. Gomis, M.I. Lonnoy, E. Maycock, T. Tignor, M. and Waterfield, T. (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* In Press: IPCC.
Mateos, R. M., López-Vinielles, J., Poyiadji, E., Tsagkas, D., Sheehy, M., Hadjicharalambous, K., Liscák, P., Podolski, L., Laskowicz, I. and Iadanza, C. (2020) 'Integration of landslide hazard into urban planning across Europe', *Landscape and urban planning,* 196, pp. 103740.
Matin, N., Forrester, J. and Ensor, J. (2018) 'What is equitable resilience?', *World Development,* 109, pp. 197-205.
Matopoulos, A., Kovács, G. and Hayes, O. (2014) 'Local resources and procurement practices in humanitarian supply chains: An empirical examination of large-scale house reconstruction projects', *Decision Sciences,* 45(4), pp. 621-646.
Matos, P., Vieira, J., Rocha, B., Branquinho, C. and Pinho, P. (2019) 'Modeling the provision of air-quality regulation ecosystem service provided by urban green spaces using lichens as ecological indicators', *Science of the Total Environment,* 665, pp. 521-530.
Matos Silva, M. and Costa, J. P. (2016) 'Flood adaptation measures applicable in the design of urban public spaces: Proposal for a conceptual framework', *Water,* 8(7), pp. 284.
Matsuyama, A., Khan, F. A. and Khalequzzaman, M. (2020) 'Bangladesh Public Health Issues and Implications to Flood Risk Reduction', in Chan, E. and Shaw, R. (eds.) *Public Health and Disasters. Disaster Risk Reduction (Methods, Approaches and Practices)*. Singapore: Springer.
Matthews, T., Lo, A. Y. and Byrne, J. A. (2015) 'Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners', *Landscape and Urban Planning,* 138, pp. 155-163.
Matzarakis, A., Fröhlich, D., Bermon, S. and Adami, E. P. (2018) 'Quantifying Thermal Stress for Sport Events—The Case of the Olympic Games 2020 in Tokyo', *Atmosphere,* 9(12).
Maughan, C., Laycock Pedersen, R. and Pitt, H. (2018) 'The problems, promise and pragmatism of community food growing', *Renewable Agriculture and Food Systems,* 33(6), pp. 497-502.
Mavrogianni, A., Taylor, J., Davies, M., Thoua, C. and Kolm-Murray, J. (2015) 'Urban social housing resilience to excess summer heat', *Building Research & Information,* 43(3), pp. 316-333.
Maxwell, K., Grambsch, A., Kosmal, A., Larson, L. and Sonti, N. (2018) 'Built environment, urban systems, and cities', in Reidmiller, D., Avery, C., Easterling, D., Kunkel, K., Lewis, K., Maycock, T. and Stewart, B. (eds.) *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Washington, DC: US Global Change Research Program, pp. 438-478.
Maynard, V., Parker, E., Yoseph-Paulus, R. and Garcia, D. (2017) 'Urban planning following humanitarian crises: supporting urban communities and local governments to take the lead', *Environment and Urbanization,* 30(1), pp. 265-282.
Mberu, B. U., Haregu, T. N., Kyobutungi, C. and Ezeh, A. C. (2016) 'Health and health-related indicators in slum, rural, and urban communities: a comparative analysis', *Global health action,* 9(1), pp. 33163.
McAlpine, S. A. and Porter, J. R. (2018) 'Estimating Recent Local Impacts of Sea-Level Rise on Current Real-Estate Losses: A Housing Market Case Study in Miami-Dade, Florida', *Population Research and Policy Review,* 37(6), pp. 871-895.
McClintock, N. (2014) 'Radical, reformist, and garden-variety neoliberal: coming to terms with urban agriculture's contradictions', *Local Environment,* 19(2), pp. 147-171.
McDonald, R., Kroeger, T., Boucher, T., Wang, L. and Salem, R. (2016) *Planting healthy air: A global analysis of the role of urban tress in addressing particulate matter pollution and extreme heat*, Online: The Nature Conservancy. Available at: https://thought-leadership-production.s3.amazonaws.com/2016/10/28/17/17/50/0615788b-8eaf-4b4f-a02a-8819c68278ef/20160825_PHA_Report_FINAL.pdf.
McEvoy, D., Barth, B., Trundle, A. and Mitchell, D. (2020) 'Reflecting on a journey from climate change vulnerability assessments to the implementation of climate resilience actions: Honiara, Solomon Islands', in Sanderson, D. and Bruce, L. (eds.) *Urbanisation at Risk in the Pacific and Asia*. New
York: Routledge, pp. 53-73.
McFarlane, C. and Silver, J. (2017) 'The Poolitical City : " Seeing Sanitation " and Making the Urban Political in Cape Town', *Antipode,* 49(1), pp. 125-148.
McGranahan, G. (2015) 'Realizing the right to sanitation in deprived urban communities: meeting the challenges of collective action, coproduction, affordability, and housing tenure', *World Development,* 68, pp. 242-253.
McGranahan, G. and Mitlin, D. (2016) 'Learning from Sustained Success: How Community-Driven Initiatives to Improve Urban Sanitation Can Meet the Challenges', *World Development,* 87, pp. 307-317.

McIntyre-Mills, J. and Wirawan, R. (2018) 'Cascading Risks of Climate Change Political and Policy Dynamics of Water Crisis: ‘Consequences of Modernity’ and Implications for Transformative Praxis', in McIntyre-Mills, J., Romm, N. and Corcoran-Nantes, Y. (eds.) *Democracy and Governance for Resourcing the Commons. Contemporary Systems Thinking*. Cham: Springer.
McKnight, B. and Linnenluecke, M. K. (2016) 'How firm responses to natural disasters strengthen community resilience: A stakeholder-based perspective', *Organization & Environment,* 29(3), pp. 290-307.
McLinden, M. O., Brown, J. S., Brignoli, R., Kazakov, A. F. and Domanski, P. A. (2017) 'Limited options for low-global-warming-potential refrigerants', *Nature Communications,* 8(1), pp. 1-9.
McMichael, C., Katonivualiku, M. and Powell, T. (2019) 'Planned relocation and everyday agency in low-lying coastal villages in Fiji', *The Geographical Journal,* 185(3), pp. 325-337.
McPhearson, T., Karki, M., Herzog, C., Fink, H. S., Abbadie, L., Kremer, P., Clark, C. M., Palmer, M. I. and Perini, K. (2018) 'Urban Ecosystems and Biodiversity', in Rosenzweig, C., Solecki, W., Romero-Lankao, P., Mehrotra, S., Dhakal, S. and Ibrahim, A.S. (eds.) *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge: Cambridge University Press, pp. 257-318.
McPhillips, L. E., Matsler, M., Rosenzweig, B. R. and Kim, Y. (2020) 'What is the role of green stormwater infrastructure in managing extreme precipitation events?', *Sustainable and Resilient Infrastructure,* 6(3-4), pp. 1-10.
Me, W., Hamilton, D. P., McBride, C. G., Abell, J. M. and Hicks, B. J. (2018) 'Modelling hydrology and water quality in a mixed land use catchment and eutrophic lake: Effects of nutrient load reductions and climate change', *Environmental Modelling & Software,* 109, pp. 114-133.
Meerow, S. (2017) 'Double exposure, infrastructure planning, and urban climate resilience in coastal megacities: A case study of Manila', *Environment and Planning A: Economy and Space,* 49(11), pp. 2649-2672.
Mees, H. (2017) 'Local governments in the driving seat? A comparative analysis of public and private responsibilities for adaptation to climate change in European and North-American cities', *Journal of Environmental Policy & Planning,* 19(4), pp. 374-390.
Megahed, N. A. and Ghoneim, E. M. (2020) 'Antivirus-built environment: lessons learned from covid-19 pandemic', *Sustainable Cities and Society*, pp. 102350.
Mehrotra, S., Zusman, E., Bajpai, J. N., Fedirko, L., Jacob, K., Replogle, M., Woundy, M. and Yoon, S. (2018) 'Urban transportation', in Rosenzweig, C., Solecki, W., Romero-Lankao, P., Mehrotra, S., Dhakal, S. and Ali Ibrahim, S. (eds.) *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. New York: Cambridge University Press, pp. 491–518.
Meixler, M. S. (2017) 'Assessment of Hurricane Sandy damage and resulting loss in ecosystem services in a coastal-urban setting', *Ecosystem Services,* 24, pp. 28-46.
Meller, H., Müller, S.-U., Ramirez, M. C., Serebrisky, T., Watkins, G. and Georgoulias, A. 'Urban Infrastructure and Social Conflict in Latin America'. *International Conference on Sustainable Infrastructure*, 2017, 377-388.
Melore, T. W. and Nel, V. (2020) 'Resilience of informal settlements to climate change in the mountainous areas of Konso, Ethiopia and QwaQwa, South Africa', *Jàmbá: Journal of Disaster Risk Studies,* 12(1), pp. 1-9.
Melvin, A. M., Larsen, P., Boehlert, B., Neumann, J. E., Chinowsky, P., Espinet, X., Martinich, J., Baumann, M. S., Rennels, L. and Bothner, A. (2017) 'Climate change damages to Alaska public infrastructure and the economics of proactive adaptation', *Proceedings of the National Academy of Sciences,* 114(2), pp. E122-E131.
Mendizabal, M., Heidrich, O., Feliu, E., García-Blanco, G. and Mendizabal, A. (2018) 'Stimulating urban transition and transformation to achieve sustainable and resilient cities', *Renewable and Sustainable Energy Reviews,* 94, pp. 410-418.
Merhej, R. (2019) 'Dehydration and cognition: an understated relation', *International Journal of Health Governance,* 24(1), pp. 19-30.
Meriläinen, E. (2020) 'The dual discourse of urban resilience: robust city and self-organised neighbourhoods', *Disasters,* 44(1), pp. 125-151.
Mersha, A. A. and van Laerhoven, F. (2018) 'Gender and climate policy: a discursive institutional analysis of Ethiopia’s climate resilient strategy', *Regional Environmental Change,* 19(2), pp. 429–440.
Mguni, P., Herslund, L. and Jensen, M. B. (2016) 'Sustainable urban drainage systems: examining the potential for green infrastructure-based stormwater management for Sub-Saharan cities', *Natural Hazards,* 82(2), pp. 241-257.
Michael, K., Deshpande, T. and Ziervogel, G. (2018) 'Examining vulnerability in a dynamic urban setting : the case of Bangalore ’ s interstate migrant waste pickers migrant waste pickers', *Climate and Development,* 0(0), pp. 1-12.
Michael, K. and Vakulabharanam, V. (2016) 'Class and climate change in post-reform India', *Climate and Development,* 8(3), pp. 224-233.
Middel, A., Häb, K., Brazel, A. J., Martin, C. A. and Guhathakurta, S. (2014) 'Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones', *Landscape and Urban Planning,* 122, pp. 16-28.
Mika, J., Forgo, P., Lakatos, L., Olah, A. B., Rapi, S. and Utasi, Z. (2018) 'Impact of 1.5 K global warming on urban air pollution and heat island with outlook on human health effects', *Current opinion in environmental sustainability,* 30, pp. 151-159.
Miladan, N. (2016) *Communities’ contributions to urban resilience process: a case study of Semarang city (Indonesia) toward coastal hydrological risk.* Universite Paris-Est, France [Online] Available at: https://tel.archives-ouvertes.fr/tel-01398359/file/TH2016PESC1010_diffusion.pdf (Accessed.

Miller, F. (2019) 'Exploring the consequences of climate-related displacement for just resilience in Vietnam', *Urban studies (Edinburgh, Scotland),* 57(7), pp. 004209801983023-1587.
Miller, J. D. and Hutchins, M. (2017) 'The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom', *Journal of Hydrology: Regional Studies,* 12, pp. 345-362.
Miller, N. G., Gabe, J. and Sklarz, M. (2019) 'The impact of water front location on residential home values considering flood risks', *Journal of Sustainable Real Estate,* 11(1), pp. 84-107.
Miller, S. R., Vos, J. and Lindquist, E. (2017) 'Informal governance structures and disaster planning: The case of wildfire', *UALR L. Rev.,* 40, pp. 633.
Mills, F., Willetts, J., Evans, B. E., Carrard, N. and Kohlitz, J. (2020) 'Costs, climate and contamination: Three drivers for city-wide sanitation investment decisions', *Frontiers in Environmental Science,* 8, pp. 130.
Mima, S. and Criqui, P. (2015) 'The costs of climate change for the European energy system, an assessment with the POLES model', *Environmental Modeling & Assessment,* 20(4), pp. 303-319.
MINURVI (2016) *Latin America and the Caribbean Challenges, dilemmas and commitments of a common urban agenda United Nations*, Santiago: Forum of Ministers and High Authorities of Housing and Urban Development of Latin America and the Caribbean,. Available at: https://repositorio.cepal.org/bitstream/handle/11362/40657/4/S1600985_en.pdf.
Miralles, D. G., Gentine, P., Seneviratne, S. I. and Teuling, A. J. (2019) 'Land-atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges', *Annals of the New York Academy of Sciences,* 1436(1), pp. 19-35.
Mishra, V., Ganguly, A. R., Nijssen, B. and Lettenmaier, D. P. (2015) 'Changes in observed climate extremes in global urban areas', *Environmental Research Letters,* 10(2), pp. 024005.
Mitchell, B. and Chakraborty, J. (2018) 'Thermal Inequity: The Relationship between Urban Structure and Social Disparities in an Era of Climate Change', in Jafry, T. (ed.) *The Routledge Handbook of Climate Justice*. Oxon: Routledge, pp. 330-346.
Mitchell, C. L. and Laycock, K. E. (2019) 'Planning for adaptation to climate change: exploring the climate science-to-practice disconnect', *Climate and Development,* 11(1), pp. 60-68.
Mitchell, D., Enemark, S. and Van der Molen, P. (2015) 'Climate resilient urban development: Why responsible land governance is important', *Land Use Policy,* 48, pp. 190-198.
Mitchell, J. W. (2013) 'Power line failures and catastrophic wildfires under extreme weather conditions', *Engineering Failure Analysis,* 35, pp. 726-735.
Mitchell, T. and Maxwell, S. (2010) *Defining climate compatible development*: Climate and Development Knowledge Network. Available at: https://cdkn.org/wp-content/uploads/2012/10/CDKN-CCD-Planning_english.pdf.
Moench, M. (2014) 'Experiences applying the climate resilience framework: linking theory with practice', *Development in Practice,* 24(4), pp. 447-464.
Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M. and Matthew, R. A. (2018) 'What is nuisance flooding? Defining and monitoring an emerging challenge', *Water Resources Research,* 54(7), pp. 4218-4227.
Moftakhari, H. R., AghaKouchak, A., Sanders, B. F. and Matthew, R. A. (2017) 'Cumulative hazard: The case of nuisance flooding', *Earth's Future,* 5(2), pp. 214-223.
Moghadas, M., Asadzadeh, A., Vafeidis, A., Fekete, A. and Kötter, T. (2019) 'A multi-criteria approach for assessing urban flood resilience in Tehran, Iran', *International journal of disaster risk reduction,* 35, pp. 101069.
Mohammad, M. U., Hassan, N. I. and Badamasi, M. M. (2019). 'In search of missing links: urbanisation and climate change in Kano Metropolis, Nigeria', *International Journal of Urban Sustainable Development,* 11(3), pp. 309-318
Mohareb, E., Heller, M., Novak, P., Goldstein, B., Fonoll, X. and Raskin, L. (2017) 'Considerations for reducing food system energy demand while scaling up urban agriculture', *Environmental Research Letters,* 12(12), pp. 125004.
MoHURD (2014) *Technical Guideline for Sponge City Construction: Low Impact Development Rainwater System (Pilot Edition)*, Beijing: China Ministry of Hosing and Urban-Rural Development. Available at: https://www.chinapp.cn/upload/201605/04/201605041230521650.pdf.
Moiseyev, A., Solberg, B., Kallio, A. M. I. and Lindner, M. (2011) 'An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries', *Journal of Forest Economics,* 17(2), pp. 197-213.
Molden, O. C., Khanal, A. and Pradhan, N. (2018) 'The pain of water: a household perspective of water insecurity and inequity in the Kathmandu Valley', *Water Policy,* 22(S1), pp. 130-145.
Molenaar, A., Aerts, J., Dircke, P. and Ikert, M. (2015) *Connecting Delta Cities: Resilient cities and climate adaptation strategies.* Rotterdam: Connecting Delta Cities.
Monioudi, I. N., Asariotis, R., Becker, A., Bhat, C., Dowding-Gooden, D., Esteban, M., Feyen, L., Mentaschi, L., Nikolaou, A. and Nurse, L. (2018) 'Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia', *Regional Environmental Change,* 18(8), pp. 2211-2225.
Moore, T. L., Gulliver, J. S., Stack, L. and Simpson, M. H. (2016) 'Stormwater management and climate change: vulnerability and capacity for adaptation in urban and suburban contexts', *Climatic change,* 138(3-4), pp. 491-504.

Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., Counsell, C. W. W., Dietrich, B. S., Johnston, E. T. and Louis, L. V. (2017a) 'Global risk of deadly heat', *Nature Climate Change,* 7(7), pp. 501.
Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, Coral R., Counsell, C. W. W., Dietrich, B. S., Johnston, E. T., Louis, L. V., Lucas, M. P., McKenzie, M. M., Shea, A. G., Tseng, H., Giambelluca, T. W., Leon, L. R., Hawkins, E. and Trauernicht, C. (2017b) 'Global risk of deadly heat', *Nature Climate Change,* 7, pp. 501.
Moraci, F., Errigo, M. F., Fazia, C., Campisi, T. and Castelli, F. (2020) 'Cities under pressure: Strategies and tools to face climate change and pandemic', *Sustainability,* 12(18), pp. 7743.
Moreira, R. P., Costa, A. C., Gomes, T. F. and de Oliveira Ferreira, G. (2020) 'Climate and climate-sensitive diseases in semi-arid regions: a systematic review', *International Journal of Public Health*, pp. 1-13.
Moretti, L. and Loprencipe, G. (2018) 'Climate change and transport infrastructures: State of the art', *Sustainability,* 10(11), pp. 4098.
Moretto, L. and Ranzato, M. (2017) 'A socio-natural standpoint to understand coproduction of water, energy and waste services', *Urban Research & Practice,* 10(1), pp. 1-21.
Morley, K. M. (2020) 'Wildfires Reveal Challenges', *Journal-American Water Works Association,* 112(12), pp. 5-5.
Morris, R. L., Konlechner, T. M., Ghisalberti, M. and Swearer, Stephen E. (2018) 'From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence', *Global Change Biology,* 24(5), pp. 1827-1842.
Morrissey, J. E., Moloney, S. and Moore, T. (2018) 'Strategic Spatial Planning and Urban Transition: Revaluing Planning and Locating Sustainability Trajectories', in Moore, T., de Haan, F., Horne, R. and Gleeson, B.J. (eds.) *Urban Sustainability Transitions : Australian Cases- International Perspectives*. Singapore: Springer Singapore, pp. 53-72.
Mortreux, C. and Adams, H. (2015) 'Setting the scene: climate change and resettlement in context'.
Moser, C. O. (2017) 'Gender transformation in a new global urban agenda: challenges for Habitat III and beyond', *Environment and Urbanization,* 29(1), pp. 221-236.
Moser, S., Ekstrom, J., Kim, J. and Heitsch, S. (2019) 'Adaptation finance archetypes: local governments' persistent challenges of funding adaptation to climate change and ways to overcome them', *Ecology and Society,* 24(2).
Moser, S. C. and Hart, J. A. F. (2015) 'The long arm of climate change: societal teleconnections and the future of climate change impacts studies', *Climatic Change,* 129(1-2), pp. 13-26.
Mosley, L. M. (2015) 'Drought impacts on the water quality of freshwater systems; review and integration', *Earth-Science Reviews,* 140, pp. 203-214.
Mosvold Larsen, O. (2015) 'Climate change is here to stay: Reviewing the impact of climate change on airport infrastructure', *Journal of Airport Management,* 9(3), pp. 264-269.
Mote, P. W., Allen, M. R., Jones, R. G., Li, S., Mera, R., Rupp, D. E., Salahuddin, A. and Vickers, D. (2016) 'Superensemble Regional Climate Modeling for the Western United States', *Bulletin of the American Meteorological Society,* 97(2), pp. 203-215.
Msoffe, R. M. (2017) 'Increase in deforestation: A key challenge to household charcoal supply–A case of Tanga urban, Tanzania', *European Journal of Social Sciences Studies,* 2(2).
Mueller, V., Gray, C. and Kosec, K. (2014) 'Heat stress increases long-term human migration in rural Pakistan', *Nature Climate Change,* 4(3), pp. 182-185.
Muggah, R. (2019) 'How China's Sponge Cities Are Preparing for Sea-Level Rise'. Available at: https://www.weforum.org/agenda/2019/06/how-china-s-sponge-cities-are-preparing-for-sea-level-rise/.
Muis, S., Güneralp, B., Jongman, B., Aerts, J. C. J. H. and Ward, P. J. (2015) 'Flood risk and adaptation strategies under climate change and urban expansion: A probabilistic analysis using global data', *Science of the Total Environment,* 538, pp. 445-457.
Mullin, M. (2020) 'The effects of drinking water service fragmentation on drought-related water security', *Science,* 368(6488), pp. 274-277.
Mulugetta, Y. and Broto, V. C. (2018) 'Harnessing deep mitigation opportunities of urbanisation patterns in LDCs', *Current opinion in environmental sustainability,* 30, pp. 82-88.
Mulville, M. and Stravoravdis, S. (2016) 'The impact of regulations on overheating risk in dwellings', *Building Research and Information,* 44(5-6), pp. 520-534.
Murali, R., Suryawanshi, K., Redpath, S., Nagendra, H. and Mishra, C. (2019) 'Changing use of ecosystem services along a rural-urban continuum in the Indian Trans-Himalayas', *Ecosystem Services,* 40, pp. 101030.
Musango, J. K., Currie, P., Smit, S. and Kovacic, Z. (2020) 'Urban metabolism of the informal city: Probing and measuring the 'unmeasurable'to monitor Sustainable Development Goal 11 indicators', *Ecological Indicators,* 119, pp. 106746.
Mustafa, D., Gioli, G., Qazi, S., Waraich, R., Rehman, A. and Zahoor, R. (2015) 'Gendering flood early warning systems: the case of Pakistan', *Environmental Hazards,* 14(4), pp. 312-328.
Myers, G. (2021) 'Urbanisation in the Global South', in Shackleton, C.M., Cilliers, S.S., du Toit, M.J. and Davoren, E. (eds.) *Urban ecology in the Global South*. Cham: Springer, pp. 1-26.
Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B. K., Wolters, G., Jensen, K., Bouma, T. J. and Miranda-Lange, M. (2014) 'Wave attenuation over coastal salt marshes under storm surge conditions', *Nature Geoscience,* 7(10), pp. 727.

Nagendra, H., Bai, X., Brondizio, E. S. and Lwasa, S. (2018) 'The urban south and the predicament of global sustainability', *Nature Sustainability,* 1(7), pp. 341-349.
Naicker, N., Teare, J., Balakrishna, Y., Wright, C. Y. and Mathee, A. (2017) 'Indoor temperatures in low cost housing in Johannesburg, South Africa', *International journal of environmental research and public health,* 14(11), pp. 1410.
Nakashima, D., Krupnik, I. and Rubis, J. T. (2018) *Indigenous Knowledge for climate assessment and adaptation.* Cambridge: Cambridge University Press and UNESCO.
Nalau, J. and Becken, S. (2018) *Ecosystem-based Adaptation to Climate Change: Review of Concepts*, Queensland, Australia: Griffith Institute for Tourism, Research Griffith University.
Nalau, J., Becken, S., Schliephack, J., Parsons, M., Brown, C. and Mackey, B. (2018) 'The role of indigenous and traditional knowledge in ecosystem-based adaptation: a review of the literature and case studies from the Pacific Islands', *Weather, Climate, and Society,* 10(4), pp. 851-865.
Namukombo, J. (2016) 'Information and communication technologies and gender in climate change and green economy: Situating women's opportunities and challenges in Zambian policies and strategies', *Jàmbá: Journal of Disaster Risk Studies,* 8(3).
Narain, V., Ranjan, P., Vij, S. and Dewan, A. (2017) 'Taking the road less taken: reorienting the state for periurban water security', *Action Research,* 18(4), pp. 528-545.
Narayan, S., Beck, M. W., Wilson, P., Thomas, C. J., Guerrero, A., Shepard, C. C., Reguero, B. G., Franco, G., Ingram, J. C. and Trespalacios, D. (2017) 'The value of coastal wetlands for flood damage reduction in the northeastern USA', *Scientific reports,* 7(1), pp. 9463.
NASA Explore Earth (2020) *Puerto Rican Health and Weather Experts Now Have an Early Warning System for When Saharan Dust Affects Air Quality*. Explore Earth: NASA. Available at: https://www.nasa.gov/SpaceforUS/?story=4042 November 2020).
NASA/JPL-Caltech (2020) *Maps Ground Changes From Puerto Rico Quake.* NASA Earth Science Disasters Program: NASA/JPL-Caltech, ESA, USGS. Available at: https://disasters.nasa.gov/puerto-rico-earthquake-2020/nasa-maps-ground-changes-puerto-rico-quake (Accessed: November 2020).
Nastiti, A., Meijerink, S. V., Oelmann, M., Smits, A. J. M., Muntalif, B. S., Sudradjat, A. and Roosmini, D. (2017) 'Cultivating Innovation and Equity in Co-Production of Commercialized Spring Water in Peri-Urban Bandung, Indonesia', *Water Alternatives-an Interdisciplinary Journal on Water Politics and Development,* 10(1), pp. 160-180.
National Research Council (2014) *Reducing coastal risk on the east and gulf coasts.* Washington: The National Academies Press.
Naturally Resilient Communities (2017) 'Riverfront Park, Nashville, Tennessee', Available: Naturally Resilient Communities. DOI: http://nrcsolutions.org/nashville-tennessee/ (Accessed 1st January 2017).
Nawrotzki, R. J., DeWaard, J., Bakhtsiyarava, M. and Ha, J. T. (2017) 'Climate shocks and rural-urban migration in Mexico: exploring nonlinearities and thresholds', *Climatic Change,* 140(2), pp. 243-258.
Nepal, S., Flügel, W.-A. and Shrestha, A. B. (2014) 'Upstream-downstream linkages of hydrological processes in the Himalayan region', *Ecological Processes,* 3(1), pp. 19.
Nerini, F. F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., Tavoni, M., Tomei, J., Zerriffi, H. and Milligan, B. (2019) 'Connecting climate action with other Sustainable Development Goals', *Nature Sustainability,* 2(8), pp. 674-680.
Nerkar, S. S., Tamhankar, A. J., Johansson, E. and Lundborg, C. S. (2016) 'Impact of integrated watershed management on complex interlinked factors influencing health: Perceptions of professional stakeholders in a hilly tribal area of India', *International journal of environmental research and public health,* 13(3), pp. 285.
Neset, T.-S., Wiréhn, L., Klein, N., Käyhkö, J. and Juhola, S. (2019) 'Maladaptation in Nordic agriculture', *Climate Risk Management,* 23(December 2018), pp. 78-87.
Nicholls, R. J., Dawson, R. J. and Day, S. A. (2015) *Broad Scale Coastal Simulation.* Netherlands, Dordrecht: Springer.
Nicholls, R. J., Hinkel, J., Lincke, D. and van der Pol, T. (2019) *Global investment costs for coastal defense through the 21st century,* Washington DC: World Bank8745).
Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., Hanson, S. E., Merkens, J.-L. and Fang, J. (2021) 'A global analysis of subsidence, relative sea-level change and coastal flood exposure', *Nature Climate Change,* 11(4), pp. 338-342.
Nightingale, A. J. (2017) 'Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability', *Geoforum,* 84, pp. 11-20.
Nightingale, A. J., Eriksen, S., Taylor, M., Forsyth, T., Pelling, M., Newsham, A., Boyd, E., Brown, K., Harvey, B. and Jones, L. (2020) 'Beyond Technical Fixes: climate solutions and the great derangement', *Climate and Development,* 12(4), pp. 343-352.
Nik, V. M., Mundt-Petersen, S. O., Kalagasidis, A. S. and De Wilde, P. (2015) 'Future moisture loads for building facades in Sweden: Climate change and wind-driven rain', *Building and Environment,* 93, pp. 362-375.
Nik, V. M. and Sasic Kalagasidis, A. (2013) 'Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties', *Building and Environment,* 60, pp. 291-304.

Nissan, H., Goddard, L., de Perez, E. C., Furlow, J., Baethgen, W., Thomson, M. C. and Mason, S. J. (2019) 'On the use and misuse of climate change projections in international development', *Wiley Interdisciplinary Reviews: Climate Change,* 10(3), pp. e579.
Nissen, S., Prendergast, K., Aoyagi, M., Burningham, K., Hasan, M., Hayward, B., Jackson, T., Jha, V., Mattar, H., Schudel, I., Venn, S. and Yoshida, A. (2020) 'Young people and environmental affordances in urban sustainable development: insights into transport and green and public space in seven cities', *Sustainable Earth,* 3(17).
Nogeire-McRae, T., Ryan, E. P., Jablonski, B. B., Carolan, M., Arathi, H., Brown, C. S., Saki, H. H., McKeen, S., Lapansky, E. and Schipanski, M. E. (2018) 'The role of urban agriculture in a secure, healthy, and sustainable food system', *BioScience,* 68(10), pp. 748-759.
Nolon, J. R. (2016) 'Enhancing the Urban Environment Through Green Infrastructure', *Environmental Law Reporter,* 46(1).
Norman, B. (2018) 'Are autonomous cities our urban future?', *Nature communications,* 9(1), pp. 1-3.
North, P., Nurse, A. and Barker, T. (2017) 'The neoliberalisation of climate? Progressing climate policy under austerity urbanism', *Environment and Planning A: Economy and Space,* 49(8), pp. 1797-1815.
Norwegian Red Cross (2019) *Overlapping vulnerabilities: the impacts of climate change on humanitarian needs*, Oslo: Norwegian Red Cross. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/rk_overlapping-vulnerabilities_digital_singles.pdf.
Nouri, H., Borujeni, S. C. and Hoekstra, A. Y. (2019) 'The blue water footprint of urban green spaces: An example for Adelaide, Australia', *Landscape and urban planning,* 190, pp. 103613.
Nowak, D. J., Hirabayashi, S., Doyle, M., McGovern, M. and Pasher, J. (2018) 'Air pollution removal by urban forests in Canada and its effect on air quality and human health', *Urban Forestry & Urban Greening,* 29, pp. 40-48.
Nugraha, E. and Lassa, J. A. (2018) 'Towards endogenous disasters and climate adaptation policy making in Indonesia', *Disaster Prevention and Management: An International Journal,* 27(2), pp. 228-242.
NYC (2010) *NYC green infrastructure plan: A sustainable strategy for clean waterways*, New York City: NYC Environmental Protection. Available at: https://smartnet.niua.org/sites/default/files/resources/NYCGreenInfrastructurePlan_LowRes.pdf.
NYC (2019) *Climate Resiliency Design Guidelines*, New York: NYC Mayor's Office of Recovery and Resiliency.
O'Brien, K., Selboe, E. and Hayward, B. M. (2018) 'Exploring youth activism on climate change: dutiful, disruptive, and dangerous dissent', *Ecology and Society,* 23(3).
O'Donnell, E. C. and Thorne, C. R. (2020) 'Drivers of future urban flood risk', *Philosophical Transactions of the Royal Society A,* 378(2168), pp. 20190216.
O'Hare, P., White, I. and Connelly, A. (2016) 'Insurance as maladaptation: Resilience and the 'business as usual' paradox', *Environment and Planning C: Government and Policy,* 34(6), pp. 1175-1193.
Oberlack, C. and Eisenack, K. (2018) 'Archetypical barriers to adapting water governance in river basins to climate change', *Journal of institutional economics,* 14(3), pp. 527-555.
Obradovich, N. and Fowler, J. H. (2017) 'Climate change may alter human physical activity patterns', *Nature Human Behaviour,* 1(5), pp. 0097.
OECD and European Commission (2020) *A new perspective on urbanisation*, Paris: OECD Publishing.
OECD/UCLG (2019) *Report of the World Observatory on Subnational Government Finance and Investment – Key Findings*, Paris and Barcelona: Organisation for Economic Co-operation and Development and United Cities and Local Governments. Available at: http://www.sng-wofi.org/publications/2019_SNG-WOFI_REPORT_Key_Findings.pdf.
Oedl-Wieser, T., Hausegger-Nestelberger, K., Dax, T. and Bauchinger, L. (2020) 'Formal and informal governance arrangements to boost sustainable and inclusive rural-urban synergies: An analysis of the metropolitan area of styria', *Sustainability,* 12(24), pp. 10637.
Ogie, R. I., Clarke, R. J., Forehead, H. and Perez, P. (2019) 'Crowdsourced social media data for disaster management: Lessons from the PetaJakarta. org project', *Computers, Environment and Urban Systems,* 73, pp. 108-117.
Ohba, M. and Sugimoto, S. (2020) 'Impacts of climate change on heavy wet snowfall in Japan', *Climate Dynamics,* 54(5), pp. 3151-3164.
Oke, T. R., Mills, G., Christen, A. and Voogt, J. A. (2017) *Urban Climates.* Cambridge: Cambridge University Press.
Okunola, O. H. (2019) 'Spatial analysis of disaster statistics in selected cities of Nigeria', *International journal of emergency management,* 15(4), pp. 299-315.
Olazabal, M. and De Gopegui, M. R. (2021) 'Adaptation planning in large cities is unlikely to be effective', *Landscape and Urban Planning,* 206, pp. 103974.
Olazabal, M., de Gopegui, M. R., Tompkins, E. L., Venner, K. and Smith, R. (2019a) 'A cross-scale worldwide analysis of coastal adaptation planning', *Environmental Research Letters,* 14(12), pp. 124056.
Olazabal, M., Galarraga, I., Ford, J., Sainz De Murieta, E. and Lesnikowski, A. (2019b) 'Are local climate adaptation policies credible? A conceptual and operational assessment framework', *International Journal of Urban Sustainable Development*, pp. 1-20.
Olmstead, S. M. (2014) 'Climate change adaptation and water resource management: A review of the literature', *Energy Economics,* 46, pp. 500-509.
Ordóñez, C. and Duinker, P. N. (2014) 'Assessing the vulnerability of urban forests to climate change', *Environmental Reviews,* 22(3), pp. 311-321.

Ordóñez, C. and Duinker, P. N. (2015) 'Climate change vulnerability assessment of the urban forest in three Canadian cities', *Climatic change,* 131(4), pp. 531-543.

Orleans Reed, S., Friend, R., Toan, V. C., Thinphanga, P., Sutarto, R. and Singh, D. (2013) '"Shared learning" for building urban climate resilience – experiences from Asian cities', *Environment and Urbanization,* 25(2), pp. 393-412.

Orlove, B., Lazrus, H., Hovelsrud, G. and Giannini, A. (2014) 'Recognitions and responsibilities: on the origins and consequences of the uneven attention to climate change around the world', *Current Anthropology,* 55(3).

Oropeza-Perez, I. and Østergaard, P. A. (2018) 'Active and passive cooling methods for dwellings: A review', *Renewable and Sustainable Energy Reviews,* 82, pp. 531-544.

Orru, H., Andersson, C., Ebi, K. L., Langner, J., Åström, C. and Forsberg, B. (2013) 'Impact of climate change on ozone-related mortality and morbidity in Europe', *European Respiratory Journal,* 41(2), pp. 285.

Orru, H., Ebi, K. L. and Forsberg, B. (2017) 'The Interplay of Climate Change and Air Pollution on Health', *Current Environmental Health Reports,* 4(4), pp. 504-513.

Manuamorn, O. P., Biesbroek, R., Cebotari, V. (2020)' What makes internationally-financed climate change adaptation projects focus on local communities? A configurational analysis of 30 Adaptation Fund projects', *Global Environmental Change,* 61. Available at: https://doi.org/10.1016/j.gloenvcha.2020.102035.

Orsini, F., Kahane, R., Nono-Womdim, R. and Gianquinto, G. (2013) 'Urban agriculture in the developing world: a review', *Agronomy for sustainable development,* 33(4), pp. 695-720.

Ortiz, A. P., Calo, W. A., Mendez-Lazaro, P., García-Camacho, S., Mercado-Casillas, A., Cabrera-Márquez, J. and Tortolero-Luna, G. (2020) 'Strengthening Resilience and Adaptive Capacity to Disasters in Cancer Control Plans: Lessons Learned from Puerto Rico', *Cancer Epidemiology and Prevention Biomarkers,* 29(7).

Osland, M. J., Day, R. H., Hall, C. T., Brumfield, M. D., Dugas, J. L. and Jones, W. R. (2017) 'Mangrove expansion and contraction at a poleward range limit: climate extremes and land-ocean temperature gradients', *Ecology,* 98(1), pp. 125-137.

Osman, M. M. and Sevinc, H. (2019) 'Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan', *Sustainable Cities and Society,* 47, pp. 101429.

Osuteye, E., Leck, H., Johnson, C., Ndezi, T., Makoba, F. and Pelling, M. (2020) 'Communicating risk from the frontline: projecting community voices into disaster risk management policies across scales', in Pelling, M. (ed.) *Breaking cycles of Risk Accumulation in African Cities*: UN-Habitat.

Oswin, N. (2018) 'Planetary urbanization: A view from outside', *Environment and Planning D: Society and Space,* 36(3), pp. 540-546.

Otkin, J. A., Anderson, M. C., Hain, C., Svoboda, M., Johnson, D., Mueller, R., Tadesse, T., Wardlow, B. and Brown, J. (2016) 'Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought', *Agricultural and forest meteorology,* 218, pp. 230-242.

Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C. and Basara, J. B. (2018) 'Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States', *Bulletin of the American Meteorological Society,* 99(5), pp. 911-919.

Otto, I. M., Reckien, D., Reyer, C. P. O., Marcus, R., Le Masson, V., Jones, L., Norton, A. and Serdeczny, O. (2017) 'Social vulnerability to climate change: a review of concepts and evidence', *Regional Environmental Change,* 17(6), pp. 1651-1662.

Ourbak, T. and Magnan, A. K. (2018) 'The Paris Agreement and climate change negotiations: Small Islands, big players', *Regional Environmental Change,* 18(8), pp. 2201-2207.

OWID (2020) *Our World In Data: Gas Consumption Per Capita*. Available at: https://ourworldindata.org/grapher/gas-consumption-per-capita (Accessed: 23rd October 2020).

Owusu, E. K., Chan, A. P. and Shan, M. (2019) 'Causal factors of corruption in construction project management: An overview', *Science and engineering ethics,* 25(1), pp. 1-31.

Owusu-Daaku, K. N. and Diko, S. K. (2018) 'Climate Change Mitigation and Adaptation Initiatives in Africa: The Case of the Climate and Development Knowledge Network "Working With Informality to Build Resilience in African Cities" Project', in Galderisi, A. and Colucci, A. (eds.) *Smart, Resilient and Transition Cities: Emerging Approaches and Tools for A Climate-Sensitive Urban Development*. Amsterdam: Elsevier, pp. 53-59.

Oxford Economics (2017) *Global Infrastructure Outlook*, Oxford: Oxford Economics Global Infrastructure Hub.

Ozarisoy, B. and Elsharkawy, H. (2019) 'Assessing overheating risk and thermal comfort in state-of-the-art prototype houses that combat exacerbated climate change in UK', *Energy and Buildings,* 187, pp. 201-217.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. and Solecki, W. (2015) 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change,* 42, pp. 169-180.

Pachauri, R. P., Meyer, L. A. and Barros, V. C. (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva: IPCC.

Pachauri, R. P., Meyer, L. A., Barros, V. C. and al., e. (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva: IPCC.

Palermo, V., Bertoldi, P., Apostolou, M., Kona, A. and Rivas, S. (2020) 'Assessment of climate change mitigation policies in 315 cities in the Covenant of Mayors initiative', *Sustainable Cities and Society,* 60, pp. 102258.
Palin, E. J., Thornton, H. E., Mathison, C. T., McCarthy, R. E., Clark, R. T. and Dora, J. (2013) 'Future projections of temperature-related climate change impacts on the railway network of Great Britain', *Climatic Change,* 120(1-2), pp. 71-93.
Palmer, M. A., Filoso, S. and Fanelli, R. M. (2014) 'From ecosystems to ecosystem services: Stream restoration as ecological engineering', *Ecological Engineering,* 65, pp. 62-70.
Palmer, M. A., Liu, J., Matthews, J. H., Mumba, M. and Odorico, P. (2015) 'Manage water in a green way', *Science,* 349(6248), pp. 584.
Pan, J., Zheng, Y., Wang, J. and Xie, X. (2015) 'Climate capacity: the measurement for adaptation to climate change', *Chinese Journal of Population Resources and Environment,* 13(2), pp. 99-108.
Pan, W. and Garmston, H. (2012) 'Building regulations in energy efficiency: Compliance in England and Wales', *Energy Policy,* 45, pp. 594-605.
Panahi, R., Ng, A. K. and Pang, J. (2020) 'Climate change adaptation in the port industry: A complex of lingering research gaps and uncertainties', *Transport Policy,* 95, pp. 10-29.
Panda, S., Modak, S., Devi, Y. L., Das, L., Pal, P. K. and Nain, M. S. (2019) 'Access and Usage of Information and Communication Technology (ICT) to Accelerate Farmers' Income', *Journal of Community Mobilization and Sustainable Development.,* 14(1), pp. 200-205.
Pant, R., Hall, J. W. and Blainey, S. P. (2016) 'Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network', *European Journal of Transport and Infrastructure Research,* 16(1).
Panteli, M. and Mancarella, P. (2015) 'Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies', *Electric Power Systems Research,* 127, pp. 259-270.
Panteli, M., Trakas, D. N., Mancarella, P. and Hatziargyriou, N. D. (2016) 'Boosting the power grid resilience to extreme weather events using defensive islanding', *IEEE Transactions on Smart Grid,* 7(6), pp. 2913-2922.
Paolini, R., Zinzi, M., Poli, T., Carnielo, E. and Mainini, A. G. (2014) 'Effect of ageing on solar spectral reflectance of roofing membranes: Natural exposure in Roma and Milano and the impact on the energy needs of commercial buildings', *Energy and Buildings,* 84, pp. 333-343.
Paprocki, K. (2018) 'Threatening dystopias: Development and adaptation regimes in Bangladesh', *Annals of the American Association of Geographers,* 108(4), pp. 955-973.
Paprotny, D., Sebastian, A., Morales-Nápoles, O. and Jonkman, S. N. (2018a) 'Trends in flood losses in Europe over the past 150 years', *Nature communications,* 9(1), pp. 1985.
Paprotny, D., Vousdoukas, M. I., Morales-Nápoles, O., Jonkman, S. N. and Feyen, L. (2018b) 'Compound flood potential in Europe', *Hydrol. Earth Syst. Sci. Discuss,* 2018, pp. 1-34.
Paraskeva-Hadjichambi, D., Goldman, D., Hadjichambis, A., Parra, G., Lapin, K., Knippels, M.-C. and Van Dam, F. (2020) 'Educating for Environmental Citizenship in Non-formal Frameworks for Secondary Level Youth', in Hadjichambis, A.C., Reis, P., Paraskeva-Hadjichambi, D., Činčera, J., Boeve-de Pauw, J., Gericke, N. and Knippels, M.C. (eds.) *Conceptualizing Environmental Citizenship for 21st Century Education*. Cham: Springer.
Parison, S., Hendel, M., Grados, A., Jurski, K. and Royon, L. (2020a) 'A lab experiment for optimizing the cooling efficiency and the watering rate of pavement-watering', *Urban Climate,* 31, pp. 100543.
Parison, S., Hendel, M., Grados, A. and Royon, L. (2020b) 'A Study of Pavement-Watering Applied to Different Existing and Innovative Paving Materials', *Energy & Buildings,* 228(110455).
Parker, E. and Maynard, V. (2015) *Humanitarian response to urban crises: a review of area-based approaches*, London: IIED. Available at: http://pubs.iied.org/10742IIED.
Parker, V. T. and Boyer, K. E. (2019) 'Sea-Level Rise and Climate Change Impacts on an Urbanized Pacific Coast Estuary', *Wetlands,* 39(6), pp. 1219-1232.
Parnell, S. (2016a) 'Defining a Global Urban Development Agenda', *World Development,* 78, pp. 529-540.
Parnell, S. (2016b) 'Fair cities: Imperatives in meeting global sustainable developmental aspirations', in Simon, D. (ed.) *Rethinking Sustainable Cities: Accessible, Green and Fair*. Bristol and Chicago: Policy Press, pp. 107-144.
Parsons, M., Fisher, K. and Nalau, J. (2016) 'Alternative approaches to co-design: insights from indigenous/academic research collaborations', *Current Opinion in Environmental Sustainability,* 20, pp. 99-105.
Parsons, M., Nalau, J., Fisher, K. and Brown, C. (2019) 'Disrupting path dependency: Making room for Indigenous knowledge in river management', *Global Environmental Change,* 56, pp. 95-113.
Pasquini, L., van Aardenne, L., Godsmark, C. N., Lee, J. and Jack, C. (2020) 'Emerging climate change-related public health challenges in Africa: A case study of the heat-health vulnerability of informal settlement residents in Dar es Salaam, Tanzania', *Science of The Total Environment,* 747, pp. 141355.
Patel, A., Lotia, H., Malik, A. A., Mundt, M. D., Lee, H. and Rafiq, M. A. (2020a) 'Gendered Impacts of Environmental Degradation in Informal Settlements: A Comparative Analysis and Policy Implications for India, Bangladesh, and Pakistan', *Journal of Comparative Policy Analysis: Research and Practice,* 23(4), pp. 1-17.
Patel, J., Nielsen, F., Badiani, A., Assi, S., Unadkat, V., Patel, B., Ravindrane, R. and Wardle, H. (2020b) 'Poverty, inequality and COVID-19: the forgotten vulnerable', *Public health,* 183, pp. 110.

Paterson, S. K., Pelling, M., Nunes, L. H., de Araújo Moreira, F., Guida, K. and Marengo, J. A. (2017) 'Size does matter: City scale and the asymmetries of climate change adaptation in three coastal towns', *Geoforum,* 81, pp. 109-119.
Patt, A., Pfenninger, S. and Lilliestam, J. (2013) 'Vulnerability of solar energy infrastructure and output to climate change', *Climatic change,* 121(1), pp. 93-102.
Patti, D. (2017) 'Metropolitan governance in the peri-urban landscape: The tower of Babel? The case of the Vienna–Bratislava metropolitan region', *Planning Practice & Research,* 32(1), pp. 29-39.
Pató, B. S. G. (2015) 'The Effect of Climate Change on Distribution Logistics', *International Journal of Business Insights & Transformation,* 8(2).
Pearce, T., Ford, J., Willox, A. C. and Smit, B. (2015) 'Inuit traditional ecological knowledge (TEK), subsistence hunting and adaptation to climate change in the Canadian Arctic', *Arctic,* 68(2), pp. 233-245.
Pechan, A. and Eisenack, K. (2014) 'The impact of heat waves on electricity spot markets', *Energy Economics,* 43, pp. 63-71.
Peduzzi, E., Baldi, M. G., Pisoni, E., Kona, A., Bertoldi, P. and Monforti-Ferrario, F. (2020) 'Impacts of a climate change initiative on air pollutant emissions: Insights from the Covenant of Mayors', *Environment international,* 145, pp. 106029.
Pelling, M., Chow, W., Chu, E., Dawson, R., Dodman, D., Fraser, A., Hayward, B., Khirfan, L., McPhearson, T., Prakash, A. and Ziervogel, G. 2021. A Resilience Renewal: COVID-19, Climate Vulnerability, Systemic Risks and Root Causes in Cities. *Climate and Development*
Pelling, M. and Garschagen, M. (2019) 'Put equity first in climate adaptation', *Nature,* 569, pp. 327-329.
Pelling, M., Leck, H., Pasquini, L., Ajibade, I., Osuteye, E., Parnell, S., Lwasa, S., Johnson, C., Fraser, A. and Barcena, A. (2018a) 'Africa's urban adaptation transition under a 1.5 climate', *Current Opinion in Environmental Sustainability,* 31, pp. 10-15.
Pelling, M., Leck, H., Pasquini, L., Ajibade, I., Osuteye, E., Parnell, S., Lwasa, S., Johnson, C., Fraser, A., Barcena, A. and Boubacar, S. (2018b) 'Africa's urban adaptation transition under a 1.5° climate', *Current Opinion in Environmental Sustainability,* 31, pp. 10-15.
Pendergrass, A. G., Meehl, G. A., Pulwarty, R., Hobbins, M., Hoell, A., AghaKouchak, A., Bonfils, C. J. W., Gallant, A. J. E., Hoerling, M. and Hoffmann, D. (2020) 'Flash droughts present a new challenge for subseasonal-to-seasonal prediction', *Nature Climate Change,* 10(3), pp. 191-199.
Peng, L., Liu, J.-P., Wang, Y., Chan, P.-w., Lee, T.-c., Peng, F., Wong, M.-s. and Li, Y. (2018) 'Wind weakening in a dense high-rise city due to over nearly five decades of urbanization', *Building and Environment,* 138, pp. 207-220.
Penning-Rowsell, E. C., Sultana, P. and Thompson, P. M. (2013) 'The 'last resort'? Population movement in response to climate-related hazards in Bangladesh', *Environmental Science & Policy,* 27, pp. S44-S59.
Pennino, M. J., McDonald, R. I. and Jaffe, P. R. (2016) 'Watershed-scale impacts of stormwater green infrastructure on hydrology, nutrient fluxes, and combined sewer overflows in the mid-Atlantic region', *Science of the Total Environment,* 565, pp. 1044-1053.
Penny, D., Zachreson, C., Fletcher, R., Lau, D., Lizier, J. T., Fischer, N., Evans, D., Pottier, C. and Prokopenko, M. (2018) 'The demise of Angkor: Systemic vulnerability of urban infrastructure to climatic variations', *Science advances,* 4(10), pp. eaau4029.
Perera, N. G. R. and Emmanuel, R. (2018) 'A "Local Climate Zone" based approach to urban planning in Colombo, Sri Lanka', *Urban climate,* 23, pp. 188-203.
Perumal, N. (2018) '" The place where I live is where I belong": community perspectives on climate change and climate-related migration in the Pacific island nation of Vanuatu', *Island studies journal,* 13(1).
Pervin, I. A., Rahman, S. M. M., Nepal, M., Haque, A. K. E., Karim, H. and Dhakal, G. (2019) 'Adapting to urban flooding: a case of two cities in South Asia', *Water Policy,* 22(S1), pp. 162-188.
Pescaroli, G. (2018) 'Perceptions of cascading risk and interconnected failures in emergency planning: Implications for operational resilience and policy making', *International Journal of Disaster Risk Reduction,* 30(January), pp. 269-280.
Pescaroli, G. and Alexander, D. (2018) 'Understanding compound, interconnected, interacting, and cascading risks: a holistic framework', *Risk analysis,* 38(11), pp. 2245-2257.
Peters, D. J. (2020) 'Rural America is more vulnerable to COVID-19 than cities are, and it's starting to show', *The Conversation*.
Petrovic, N., Simpson, T., Orlove, B. and Dowd-Uribe, B. (2019) 'Environmental and social dimensions of community gardens in East Harlem', *Landscape and Urban Planning,* 183, pp. 36-49.
Pham, T.-T.-H., Apparicio, P., Gomez, C., Weber, C. and Mathon, D. (2014) 'Towards a rapid automatic detection of building damage using remote sensing for disaster management: The 2010 Haiti earthquake', *Disaster prevention and management,* 23(1), pp. 53-66.
Phelps, N. A., Miao, J. T. and Zhang, X. (2020) 'Polycentric urbanization as enclave urbanization: a research agenda with illustrations from the Yangtze River Delta Region (YRDR), China', *Territory, Politics, Governance*, pp. 1-20.
Phillips, C. A., Caldas, A., Cleetus, R., Dahl, K. A., Declet-Barreto, J., Licker, R., Merner, L. D., Ortiz-Partida, J. P., Phelan, A. L. and Spanger-Siegfried, E. (2020a) 'Compound climate risks in the COVID-19 pandemic', *Nature Climate Change*, pp. 1-3.

Phillips, C. A., Caldas, A., Cleetus, R., Dahl, K. A., Declet-Barreto, J., Licker, R., Merner, L. D., Ortiz-Partida, J. P., Phelan, A. L. and Spanger-Siegfried, E. (2020b) 'Compound climate risks in the COVID-19 pandemic', *Nature Climate Change,* 10(7), pp. 586-588.

Phillips, H. (2015) 'The capacity to adapt to climate change at heritage sites – The development of a conceptual framework', *Environmental Science and Policy,* 47, pp. 118-125.

Physick, W., Cope, M. and Lee, S. (2014) 'The impact of climate change on ozone-related mortality in Sydney', *International journal of environmental research and public health,* 11(1), pp. 1034-1048.

Pickard, B. R., Nash, M., Baynes, J. and Mehaffey, M. (2017) 'Planning for community resilience to future United States domestic water demand', *Landscape and Urban Planning,* 158, pp. 75-86.

Pieretti, G. (2014) 'Suburbanization', in Michalos, A.C. (ed.) *Encyclopedia of Quality of Life and Well-Being Research*. Dordrecht: Springer.

Pincetl, S., Porse, E., Mika, K. B., Litvak, E., Manago, K. F., Hogue, T. S., Gillespie, T., Pataki, D. E. and Gold, M. (2019) 'Adapting Urban Water Systems to Manage Scarcity in the 21st Century: The Case of Los Angeles', *Environmental Management,* 63(3), pp. 293-308.

Pinchoff, J., Austrian, K., Rajshekhar, N., Abuya, T., Kangwana, B., Ochako, R., Tidwell, J. B., Mwanga, D., Muluve, E. and Mbushi, F. (2021) 'Gendered economic, social and health effects of the COVID-19 pandemic and mitigation policies in Kenya: evidence from a prospective cohort survey in Nairobi informal settlements', *BMJ open,* 11(3), pp. e042749.

Piontek, F., Müller, C., Pugh, T. A. M., Clark, D. B., Deryng, D., Elliott, J., González, F. d. J. C., Flörke, M., Folberth, C. and Franssen, W. (2014) 'Multisectoral climate impact hotspots in a warming world', *Proceedings of the National Academy of Sciences,* 111(9), pp. 3233-3238.

Pita, G. L. and de Schwarzkopf, M. L. A. (2016) 'Urban downburst vulnerability and damage assessment from a case study in Argentina', *Natural Hazards,* 83(1), pp. 445-463.

Pk, S., Bashir, R. and Beddoe, R. (2018) 'Effect of climate change on earthen embankments in Southern Ontario, Canada', *Environmental Geotechnics*, pp. 1-22.

Plastrik, P., Cleveland, J., Coffee, J., Ashmore, J., Barnhart, A., Cleveland, C. J., Fox-Penner, P. and Lusk, K. (2020) *More urgency, not less: The COVID-19 pandemic's lessons for local climate leadership*, Boston: Boston University Institute for Sustainable Energy. Available at: http://www.bu.edu/ise/files/2020/07/covid19-pandemics-lessons-for-local-climate-leadership-june2020-updated.pdf.

Plänitz, E. (2019) 'Neglecting the urban? Exploring rural-urban disparities in the climate change–conflict literature on Sub-Sahara Africa', *Urban Climate,* 30, pp. 100533.

Pollard, B., Storey, M., Robinson, C. and Bell, T. 'The CARRA project: Developing tools to help heritage managers identify and respond to coastal hazard impacts on archaeological resources'. *2014 Oceans - St. John's*, Newfoundland and Labrador: IEEE, 1-4.

Porio, E., Dator-Bercilla, J., Narisma, G., Cruz, F. and Yulo-Loyzaga, A. (2019) 'Drought and Urbanization: The Case of the Philippines', in Ray, B. and Shaw, R. (eds.) *Urban Drought: Emerging Water Challenges in Asia*. Singapore: Springer Singapore, pp. 183-208.

Porter, L., Rickards, L., Verlie, B., Bosomworth, K., Moloney, S., Lay, B., Latham, B., Anguelovski, I. and Pellow, D. (2020) 'Climate justice in a climate changed world', *Planning Theory & Practice,* 21(2), pp. 293-321.

Poulsen, M. N., McNab, P. R., Clayton, M. L. and Neff, R. A. (2015) 'A systematic review of urban agriculture and food security impacts in low-income countries', *Food Policy,* 55, pp. 131-146.

Poulsen, M. N., Neff, R. A. and Winch, P. J. (2017) 'The multifunctionality of urban farming: perceived benefits for neighbourhood improvement', *Local Environment,* 22(11), pp. 1411-1427.

Pourias, J., Aubry, C. and Duchemin, E. (2016) 'Is food a motivation for urban gardeners? Multifunctionality and the relative importance of the food function in urban collective gardens of Paris and Montreal', *Agriculture and Human Values,* 33(2), pp. 257-273.

Powell, E. J., Tyrrell, M. C., Milliken, A., Tirpak, J. M. and Staudinger, M. D. (2019) 'A review of coastal management approaches to support the integration of ecological and human community planning for climate change', *Journal of Coastal Conservation,* 23(1), pp. 1-18.

Powell, T., Hanfling, D. and Gostin, L. O. (2012) 'Emergency preparedness and public health: the lessons of Hurricane Sandy', *Jama,* 308(24), pp. 2569-2570.

Powrie, W. and Smethurst, J. (2018) 'Climate and vegetation impacts on infrastructure cuttings and embankments', in Zhan, L., Chen, Y. and Bouazza, A. (eds.) *The International Congress on Environmental Geotechnics*. Singapore: Springer, pp. 128-144.

Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N. M. (2019) *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*: In Press.

Prakash, A. and Molden, D. (2020) 'Editorial Mapping challenges for adaptive water management in Himalayan towns', *Water Policy,* 22(S1), pp. 1-8.

Pratama, I. P., Handayani, W., Setyono, J. S. and Prayoga, N. (2017) 'Community Capacity Building through an Alternative Approach Based on Participation in Handling Dengue Hemorrhagic Fever (DHF) in Semarang', *Journal of Regional and City Planning,* 28(1), pp. 52-69.

Prats, E. V., Rinehold, A., De France, J. and Campbell-Lendrum, D. (2017) *Climate-resilient water safety plans: Managing health risks associated with climate variability and change*, Geneva: World Health Organisation. Available at: https://apps.who.int/iris/bitstream/handle/10665/258722/9789241512794-eng.pdf.

Pregnolato, M., Ford, A., Glenis, V., Wilkinson, S. and Dawson, R. (2017) 'Impact of climate change on disruption to urban transport networks from pluvial flooding', *Journal of Infrastructure Systems,* 23(4), pp. 04017015.

Pregnolato, M., Ford, A., Robson, C., Glenis, V., Barr, S. and Dawson, R. (2016) 'Assessing urban strategies for reducing the impacts of extreme weather on infrastructure networks', *Royal Society Open Science,* 3(5), pp. 160023.

Prendergast, K., Hayward, B., Aoyagi, M., Burningham, K., Hasan, M., Jackson, T., Jha, V., Kuroki, L., Loukianov, A., Mattar, H., Schudel, I., Venn, S. and Yoshida, A. (2021) 'Youth Attitudes and Participation in Climate Protest: An international cities comparison', *Frontiers in Political Science*.

Pretzsch, H., Biber, P., Uhl, E., Dahlhausen, J., Schütze, G., Perkins, D., Rötzer, T., Caldentey, J., Koike, T., Con, T. v., Chavanne, A., Toit, B. d., Foster, K. and Lefer, B. (2017) 'Climate change accelerates growth of urban trees in metropolises worldwide', *Scientific Reports,* 7(1), pp. 15403.

Price, S. (2019) 'Looking back on development and disaster-related displacement and resettlement, anticipating climate-related displacement in the Asia Pacific region', *Asia Pacific viewpoint,* 60(2), pp. 191-204.

Prieur-Richard, A., Walsh, B. and Craig, M. (2019) *Global Research and Action Agenda on Cities and Climate*, Montreal: Future Earth. Available at: https://citiesipcc.org/wp-content/uploads/2018/09/Research-Agenda-Aug-10_Final_Long-version.pdf.

Princeti, S. (2016) 'Post carbon cities: Distributed and decentralized and demodernized?', in Evans, J., Karvnonen, A. and Raven, R. (eds.) *The Experimental City*. London: Routledge, pp. 236-250.

Puente-Rodríguez, D., Van Slobbe, E., Al, I. A. C. and Lindenbergh, D. E. (2016) 'Knowledge co-production in practice: Enabling environmental management systems for ports through participatory research in the Dutch Wadden Sea', *Environmental Science and Policy,* 55, pp. 456-466.

Puppim de Oliveira, J. A. and Doll, C. N. H. (2016) 'Governance and networks for health co-benefits of climate change mitigation: Lessons from two Indian cities', *Environment International,* 97, pp. 146-154.

Pyhälä, A., Fernández-Llamazares, Á., Lehvävirta, H., Byg, A., Ruiz-Mallén, I., Salpeteur, M. and Thornton, T. F. (2016) 'Global environmental change: local perceptions, understandings, and explanations', *Ecology and society: a journal of integrative science for resilience and sustainability,* 21(3).

Pérez-Andreu, V., Aparicio-Fernández, C., Martínez-Ibernón, A. and Vivancos, J.-L. (2018) 'Impact of climate change on heating and cooling energy demand in a residential building in a Mediterranean climate', *Energy,* 165, pp. 63-74.

Quintana-Talvac, C., Corvacho-Ganahin, O., Smith, P., Sarricolea, P., Prieto, M. and Meseguer-Ruiz, O. (2021) 'Urban Heat Islands and Vulnerable Populations in a Mid-Size Coastal City in an Arid Environment', *Atmosphere,* 12(7), pp. 917.

Rabani, R., Faghih, A. K., Rabani, M. and Rabani, M. (2014) 'Numerical simulation of an innovated building cooling system with combination of solar chimney and water spraying system', *Heat and Mass Transfer,* 50(11), pp. 1609-1625.

Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., Butsic, V., Hawbaker, T. J., Martinuzzi, S. and Syphard, A. D. (2018) 'Rapid growth of the US wildland-urban interface raises wildfire risk', *Proceedings of the National Academy of Sciences,* 115(13), pp. 3314-3319.

Raina, A., Gurung, Y. and Suwal, B. (2018) 'Equity impacts of informal private water markets: case of Kathmandu Valley', *Water Policy,* 22(S1), pp. 189-204.

Rajagopalan, P., Lim, K. C. and Jamei, E. (2014) 'Urban heat island and wind flow characteristics of a tropical city', *Solar Energy,* 107, pp. 159-170.

Rajan, S. I., Sivakumar, P. and Srinivasan, A. (2020) 'The COVID-19 pandemic and internal labour migration in India: A 'crisis of mobility'', *The Indian Journal of Labour Economics,* 63(4), pp. 1021-1039.

Rajsekhar, D. and Gorelick, S. M. (2017) 'Increasing drought in Jordan: Climate change and cascading Syrian land-use impacts on reducing transboundary flow', *Science Advances,* 3(8), pp. e1700581.

Ramyar, R., Zarghami, E. and Bryant, M. (2019) 'Spatio-Temporal Planning of Urban Neighborhoods in the Context of Global Climate Change: Lessons for Urban Form Design in Tehran, Iran', *Sustainable Cities and Society,* 51.

Ranganathan, M. and Bratman, E. (2019) 'From urban resilience to abolitionist climate justice in Washington, DC', *Antipode,* 53(1).

Rangwala, L., Burke, L., Wihanesta , R. and Elias-Trostmann, K. (2018) *Prepared Communities: Implementing the Urban Community Resilience Assessment in Vulnerable Neighborhoods of Three Cities*, Washington: World Resource Institute.

Rao, S., Klimont, Z., Smith, S. J., Van Dingenen, R., Dentener, F., Bouwman, L., Riahi, K., Amann, M., Bodirsky, B. L. and van Vuuren, D. P. (2017) 'Future air pollution in the Shared Socio-economic Pathways', *Global Environmental Change,* 42, pp. 346-358.

Rao, S. L. and Li, X. H. (2019) *Pilot practices for Chinse climate insurance and suggestions for development (in Chinese)*, Beijing: Social Sciences Academic Press.

Raworth, K. (2017) *Doughnut economics: seven ways to think like a 21st-century economist.* White River Junction, Vermont: Chelsea Green Publishing.

Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., Mcevoy, D. and Satterthwaite, D. (2017) 'Climate change, equity and the Sustainable Development Goals: an urban perspective', *Environment and urbanization,* 29(1), pp. 159-182.

Reckien, D., Flacke, J., Olazabal, M. and Heidrich, O. (2015) 'The influence of drivers and barriers on urban adaptation and mitigation plans—an empirical analysis of European cities', *PloS one,* 10(8), pp. e0135597.

Reckien, D., Lwasa, S., Satterthwaite, D., McEvoy, D., Creutzig, F., Montgomery, M., Schensul, D., Balk, D., Alam Khan, I. and Fernandez, B. (2018a) 'Equity, environmental justice, and urban climate change'.

Reckien, D., Salvia, M., Heidrich, O., Church, J. M., Pietrapertosa, F., De Gregorio-Hurtado, S., D'Alonzo, V., Foley, A., Simoes, S. G., Krkoška Lorencová, E., Orru, H., Orru, K., Wejs, A., Flacke, J., Olazabal, M., Geneletti, D., Feliu, E., Vasilie, S., Nador, C., Krook-Riekkola, A., Matosović, M., Fokaides, P. A., Ioannou, B. I., Flamos, A., Spyridaki, N.-A., Balzan, M. V., Fülöp, O., Paspaldzhiev, I., Grafakos, S. and Dawson, R. (2018b) 'How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28', *Journal of Cleaner Production,* 191, pp. 207-219.

Reddington, C., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y., Arnold, S. and Spracklen, D. (2014) 'Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia', *Environmental Research Letters,* 9(9), pp. 094006.

Reder, A., Rianna, G., Mercogliano, P. and Castellari, S. (2018) 'Parametric investigation of Urban Heat Island dynamics through TEB 1D model for a case study: Assessment of adaptation measures', *Sustainable cities and society,* 39, pp. 662-673.

Reed, S. O., Friend, R., Jarvie, J., Henceroth, J., Thinphanga, P., Singh, D., Tran, P. and Sutarto, R. (2015) 'Resilience projects as experiments: implementing climate change resilience in Asian cities', *Climate and Development,* 7(5), pp. 469-480.

Renaud, F. G., Le, T. T. H., Lindener, C., Guong, V. T. and Sebesvari, Z. (2015) 'Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta', *Climatic Change,* 133(1), pp. 69-84.

Revi, A., Satterthwaite, D., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., Roberts, D., Solecki, W., Gajjar, S. P. and Sverdlik, A. (2014) 'Towards transformative adaptation in cities: the IPCC's Fifth Assessment', *Environment and Urbanization,* 26(1), pp. 11-28.

Reynolds, H. L., Brandt, L., Fischer, B. C., Hardiman, B. S., Moxley, D. J., Sandweiss, E., Speer, J. H. and Fei, S. (2019) 'Implications of climate change for managing urban green infrastructure: an Indiana, US case study', *Climatic Change*, pp. 1-18.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R. and Fricko, O. (2017) 'The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview', *Global Environmental Change,* 42, pp. 153-168.

Ribera, T., Sachs, J., Colombier, M., Schmidt-Traub, G., Waisman, H., Williams, J., Segafredo, L. and Pierfederici, R. (2015) *Pathways to deep decarbonization*, New York: SDSN/IDDRI.

Rice, J. L., Cohen, D. A., Long, J. and Jurjevich, J. R. (2020) 'Contradictions of the climate-friendly city: new perspectives on eco-gentrification and housing justice', *International Journal of Urban and Regional Research,* 44(1), pp. 145-165.

Richards, J., Wang, Y., Orr, S. A. and Viles, H. (2018) 'Finding common ground between United Kingdom based and Chinese approaches to earthen heritage conservation', *Sustainability,* 10(9).

Richmond, A., Myers, I. and Namuli, H. (2018) 'Urban informality and vulnerability: A case study in Kampala, Uganda', *Urban Science,* 2(1), pp. 22.

Roberts, E. and Pelling, M. (2018) 'Climate change-related loss and damage: translating the global policy agenda for national policy processes', *Climate and Development,* 10(1), pp. 4-17.

Roberts, E. and Pelling, M. (2020) 'Loss and damage: an opportunity for transformation?', *Climate Policy,* 20(6), pp. 758-771.

Rockman, Marcy, Morgan, M., Ziaja, S., Hambrecht, G. and Meadow, A. (2016) *Cultural Resources Climate Change Strategy*: National Park Service.

Rode, P., Floater, G., Thomopoulos, N., Docherty, J., Schwinger, P., Mahendra, A. and Fang, W. (2017) 'Accessibility in cities: transport and urban form', in Meyer, G. and Shaheen, S. (eds.) *Disrupting mobility*. Cham: Springer, pp. 239-273.

Rodrigues, C. U. 'Where is the State Missing? Addressing Urban Climate Change at the Margins in Luanda and Maputo'. *Urban Forum*: Springer, 1-15.

Rojas-Rueda, D., Nieuwenhuijsen, M. J., Gascon, M., Perez-Leon, D. and Mudu, P. (2019) 'Green spaces and mortality: a systematic review and meta-analysis of cohort studies', *The Lancet Planetary Health,* 3(11), pp. e469-e477.

Romero-Lankao, P., Bulkeley, H., Pelling, M., Burch, S., Gordon, D. J., Gupta, J., Johnson, C., Kurian, P., Lecavalier, E. and Simon, D. (2018) 'Urban transformative potential in a changing climate', *Nature Climate Change,* 8(9), pp. 754-756.

Romero-Lankao, P., Gnatz, D. M. and Sperling, J. B. (2016) 'Examining urban inequality and vulnerability to enhance resilience: insights from Mumbai, India', *Climatic change,* 139(3-4), pp. 351-365.

Romero-Lankao, P. and Hardoy, J. (2015) 'Multilevel governance and institutional capacity for climate change responses in Latin American cities', in Johnson, C., Toly, N. and Schroeder, H. (eds.) *The Urban Climate Challenge*. New York: Routledge, pp. 191-214.
Romero-Lankao, P. A. and Gnatz, D. M. (2019) 'Inequality in risk to people and food-energy-water (FEW) systems in 43 urban adaptation plans', *Frontiers in Sociology,* 4, pp. 31.
Romero-Lankao, P. and Norton, R. (2018) 'Interdependencies and risk to people and critical food, energy, and water systems: 2013 flood, Boulder, Colorado, USA', *Earth's Future,* 6(11), pp. 1616-1629.
Rosencrants, T. D. and Ashley, W. S. (2015) 'Spatiotemporal analysis of tornado exposure in five US metropolitan areas', *Natural Hazards,* 78(1), pp. 121-140.
Rosenzweig, B. R., McPhillips, L., Chang, H., Cheng, C., Welty, C., Matsler, M., Iwaniec, D. and Davidson, C. I. (2018a) 'Pluvial flood risk and opportunities for resilience', *Wiley Interdisciplinary Reviews: Water,* 5(6), pp. e1302.
Rosenzweig, C., Gaffin, S. and Parshall, L. (2006) *Green roofs in the New York metropolitan region*, New York: Columbia University Center for Climate Systems Research. Available at: https://pubs.giss.nasa.gov/abs/ro05800e.html.
Rosenzweig, C. and Solecki, W. (2018) 'Action pathways for transforming cities', *Nature Climate Change,* 8(9), pp. 756.
Rosenzweig, C., Solecki, W. D., Romero-Lankao, P., Mehrotra, S., Dhakal, S. and Ibrahim, S. A. 2018b. Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network. New York: Cambridge University Press.
Roshan, G., Oji, R. and Attia, S. (2019) 'Projecting the impact of climate change on design recommendations for residential buildings in Iran', *Building and Environment,* 155, pp. 283-297.
Roy, J., Tschakert, P., Waisman, H., Abdul Halim, S., Antwi-Agyei, P., Dasgupta, P., Hayward, B., Kanninen, M., Liverman, D., Okereke, C., Pinho, P. F., Riahi, K. and Suarez Rodriguez, A. G. (2018) 'Sustainable Development, Poverty Eradication and Reducing Inequalities', in Masson-Delmotte, Valerie, Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*: IPCC.
Ruangpan, L., Vojinovic, Z., Sabatino, S. D., Leo, L. S., Capobianco, V., Oen, A. M., McClain, M. E. and Lopez-Gunn, E. (2020) 'Nature-based solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area', *Natural Hazards and Earth System Sciences,* 20(1), pp. 243-270.
Ruckelshaus, M. H., Guannel, G., Arkema, K., Verutes, G., Griffin, R., Guerry, A., Silver, J., Faries, J., Brenner, J. and Rosenthal, A. (2016) 'Evaluating the benefits of green infrastructure for coastal areas: location, location, location', *Coastal Management,* 44(5), pp. 504-516.
Ruddick, S., Peake, L., Tanyildiz, G. S. and Patrick, D. (2018) 'Planetary urbanization: An urban theory for our time?', *Environment and Planning D: Society and Space,* 36(3), pp. 387-404.
Rufat, S., Tate, E., Burton, C. G. and Maroof, A. S. (2015) 'Social vulnerability to floods: Review of case studies and implications for measurement', *International journal of disaster risk reduction,* 14, pp. 470-486.
Rufat, S., Tate, E., Emrich, C. T. and Antolini, F. (2019) 'How valid are social vulnerability models?', *Annals of the American Association of Geographers,* 109(4), pp. 1131-1153.
Ruiz Campillo, X., Castan Broto, V. and Westman, L. (2020) 'Motivations and intended outcomes in local governments' declarations of climate emergency', *Politics and Governance,* 9(2).
Rukmana, D. (2020) *The Routledge Handbook of Planning Megacities in the Global South.* New York: Routledge.
Rush, D., Bankoff, G., Cooper-Knock, S.-J., Gibson, L., Hirst, L., Jordan, S., Spinardi, G., Twigg, J. and Walls, R. S. (2020) 'Fire risk reduction on the margins of an urbanizing world', *Disaster Prevention and Management: An International Journal,* 29(5).
Rushforth, R. R. and Ruddell, B. L. (2015) 'The hydro-economic interdependency of cities: Virtual water connections of the Phoenix, Arizona Metropolitan Area', *Sustainability,* 7(7), pp. 8522-8547.
Rushforth, R. R. and Ruddell, B. L. (2016) 'The vulnerability and resilience of a city's water footprint: The case of Flagstaff, Arizona, USA', *Water Resources Research,* 52(4), pp. 2698-2714.
Ryti, N. R. I., Guo, Y. and Jaakkola, J. J. K. (2016) 'Global association of cold spells and adverse health effects: a systematic review and meta-analysis', *Environmental health perspectives,* 124(1), pp. 12-22.
Räsänen, A., Lein, H., Bird, D. and Setten, G. (2020) 'Conceptualizing community in disaster risk management', *International journal of disaster risk reduction,* 45, pp. 101485.
Rözer, V., Müller, M., Bubeck, P., Kienzler, S., Thieken, A., Pech, I., Schröter, K., Buchholz, O. and Kreibich, H. (2016) 'Coping with Pluvial Floods by Private Households', *Water,* 8(7).
Saari, R. K., Mei, Y., Monier, E. and Garcia-Menendez, F. (2019) 'Effect of Health-Related Uncertainty and Natural Variability on Health Impacts and Cobenefits of Climate Policy', *Environmental Science & Technology,* 53(3), pp. 1098-1108.

Saboohi, R., Barani, H., Khodagholi, M., Sarvestani, A. A. and Tahmasebi, A. (2019) 'Nomads' indigenous knowledge and their adaptation to climate changes in Semirom City in Central Iran', *Theoretical and Applied Climatology,* 137(1-2), pp. 1377-1384.
Sabrin, S., Karimi, M., Fahad, M. G. R. and Nazari, R. (2020) 'Quantifying environmental and social vulnerability: Role of urban Heat Island and air quality, a case study of Camden, NJ', *Urban Climate,* 34, pp. 100699.
Sahay, S. (2018) 'Urban adaptation to climate sensitive health effect: Evaluation of coping strategies for dengue in Delhi, India', *Sustainable Cities and Society,* 37, pp. 178-188.
Sakano, T., Kotabe, S., Komukai, T., Kumagai, T., Shimizu, Y., Takahara, A., Ngo, T., Fadlullah, Z. M., Nishiyama, H. and Kato, N. (2016) 'Bringing movable and deployable networks to disaster areas: development and field test of MDRU', *IEEE Network,* 30(1), pp. 86-91.
Sakdapolrak, P., Naruchaikusol, S., Ober, K., Peth, S., Porst, L., Rockenbauch, T. and Tolo, V. (2016) 'Migration in a changing climate. Towards a translocal social resilience approach', *Erde,* 147(2), pp. 81-94.
Sakijege, T., Sartohadi, J., Marfai, M. A., Kassenga, G. and Kasala, S. (2014) 'Government and community involvement in environmental protection and flood risk management: lessons from Keko Machungwa, Dar es Salaam, Tanzania', *Journal of Environmental Protection,* 5(09), pp. 760.
Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M. and Wang, M. (2014) 'Anthropogenic heating of the urban environment due to air conditioning', *Journal of Geophysical Research: Atmospheres,* 119(10), pp. 5949-5965.
Salim, W., Bettinger, K. and Fisher, M. (2019) 'Maladaptation on the Waterfront: Jakarta's Growth Coalition and the Great Garuda', *Environment and Urbanization ASIA,* 10(1), pp. 63-80.
Salmond, J. A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., Dirks, K. N., Heaviside, C., Lim, S., Macintyre, H., McInnes, R. N. and Wheeler, B. W. (2016) 'Health and climate related ecosystem services provided by street trees in the urban environment', *Environmental Health,* 15(S1), pp. S36-S36.
Salthammer, T., Schieweck, A., Gu, J., Ameri, S. and Uhde, E. (2018) 'Future trends in ambient air pollution and climate in Germany – Implications for the indoor environment', *Building and Environment,* 143, pp. 661-670.
Salvadore, E., Bronders, J. and Batelaan, O. (2015) 'Hydrological modelling of urbanized catchments: A review and future directions', *Journal of Hydrology,* 529, pp. 62-81.
Sameni, S. M. T., Gaterell, M., Montazami, A. and Ahmed, A. (2015) 'Overheating investigation in UK social housing flats built to the Passivhaus standard', *Building and Environment,* 92, pp. 222-235.
Sanchez Rodriguez, R., Ürge-Vorsatz, D. and Barau, A. S. (2018) 'Sustainable Development Goals and climate change adaptation in cities', *Nature Climate Change,* 8(3), pp. 181-183.
Sanderson, D., Patel, S. S., Loosemore, M., Sharma, A., Greenwald, K. and Patel, R. (2021) 'A review of peer-reviewed published research on corruption and disasters in the built environment', *Disasters*.
Santamouris, M. (2020) 'Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change', *Energy and Buildings,* 207, pp. 109482.
Santha, S. D., Jaswal, S., Sasidevan, D., Khan, A., Datta, K. and Kuruvilla, A. (2016) 'Climate variability, livelihoods and social inequities: The vulnerability of migrant workers in Indian cities', *International Area Studies Review,* 19(1), pp. 76-89.
Santos, J. R. (2017) 'Discrete landscapes in metropolitan Lisbon: open space as a planning resource in times of latency', *Planning Practice & Research,* 32(1), pp. 4-28.
Santos-Burgoa, C., Sandberg, J., Suárez, E., Goldman-Hawes, A., Zeger, S., Garcia-Meza, A., Pérez, C. M., Estrada-Merly, N., Colón-Ramos, U. and Nazario, C. M. (2018) 'Differential and persistent risk of excess mortality from Hurricane Maria in Puerto Rico: a time-series analysis', *The Lancet Planetary Health,* 2(11), pp. e478-e488.
Sara, L. M., Pfeffer, K. and Baud, I. S. A. (2017) 'Unfolding urban geographies of water-related vulnerability and inequalities: Recognising risks in knowledge building in Lima, Peru', in Bell, S., Allen, A., Hofmann, P. and Teh, T.H. (eds.) *Urban water trajectories*. Cham: Springer, pp. 81-98.
Sari, A. D. and Prayoga, N. (2018) 'Enhancing Citizen Engagement in the Face of Climate Change Risks: A Case Study of the Flood Early Warning System and Health Information System in Semarang City, Indonesia.', in Hughes, S., Chu, E.K. and Mason, S.G. (eds.) *Climate Change in Cities: Innovations in Multi-Level Governance*. Cham: Springer, pp. 121-137.
Sarkar, C., Webster, C. and Gallacher, J. (2018) 'Residential greenness and prevalence of major depressive disorders: a cross-sectional, observational, associational study of 94 879 adult UK Biobank participants', *The Lancet Planetary Health,* 2(4), pp. e162-e173.
Sarkis, J., Cohen, M. J., Dewick, P. and Schröder, P. (2020) 'A brave new world: lessons from the COVID-19 pandemic for transitioning to sustainable supply and production', *Resources, Conservation, and Recycling,* 159, pp. 104894.
Sathaye, J. A., Dale, L. L., Larsen, P. H., Fitts, G. A., Koy, K., Lewis, S. M. and de Lucena, A. F. P. (2013) 'Rising temps, tides, and wildfires: Assessing the risk to California's energy infrastructure from projected climate change', *IEEE Power and Energy Magazine,* 11(3), pp. 32-45.
Satterthwaite, D., Archer, D., Colenbrander, S., Dodman, D., Hardoy, J., Mitlin, D. and Patel, S. (2020) 'Building Resilience to Climate Change in Informal Settlements', *One Earth,* 2(2), pp. 143-156.
Satterthwaite, D. and Bartlett, S. (2017) 'Editorial: The full spectrum of risk in urban centres: changing perceptions, changing priorities', *Environment and urbanization,* 29(1), pp. 3-14.

Satterthwaite, D., McGranahan, G. and Tacoli, C. (2010) 'Urbanization and its implications for food and farming', *Philosophical transactions of the royal society B: biological sciences,* 365(1554), pp. 2809-2820.
Sauer, A. and Stieß, I. (2021) 'Accounting for gender in climate policy advice: adapting a gender impact assessment tool to issues of climate change', *Impact Assessment and Project Appraisal,* 39(3), pp. 262-273.
Sayers, P., Penning-Rowsell, E. C. and Horritt, M. (2018) 'Flood vulnerability, risk, and social disadvantage: current and future patterns in the UK', *Regional environmental change,* 18(2), pp. 339-352.
Sayers, P. B., Horritt, M., Penning-Rowsell, E. and McKenzie, A. (2015) *Climate Change Risk Assessment 2017: Projections of future flood risk in the UK*, London: Committee on Climate Change, UK. Available at: https://www.theccc.org.uk/publication/sayers-for-the-asc-projections-of-future-flood-risk-in-the-uk/.
Sayers, P. B., Walsh, C. and Dawson, R. (2015) 'Climate impacts on flood and coastal erosion infrastructure', *Infrastructure Asset Management,* 2(2), pp. 69-83.
Schaeffer, R., Szklo, A. S., de Lucena, A. F. P., Borba, B. S. M. C., Nogueira, L. P. P., Fleming, F. P., Troccoli, A., Harrison, M. and Boulahya, M. S. (2012) 'Energy sector vulnerability to climate change: a review', *Energy,* 38(1), pp. 1-12.
Schaltegger, S., Hansen, E. G. and Lüdeke-Freund, F. (2016) 'Business models for sustainability: Origins, present research, and future avenues', *Organization & Environment,* 29(1), pp. 3-10.
Schau-Noppel, H., Kossmann, M. and Buchholz, S. (2020) 'Meteorological information for climate-proof urban planning-The example of KLIMPRAX', *Urban Climate,* 32, pp. 100614.
Schipper, E. L. F., Eriksen, S. E., Fernandez Carril, L. R., Glavovic, B. C. and Shawoo, Z. (2020) 'Turbulent transformation: abrupt societal disruption and climate resilient development', *Climate and Development,* 13(6), pp. 1-8.
Schlosberg, D., Collins, L. B. and Niemeyer, S. (2017) 'Adaptation policy and community discourse: risk, vulnerability, and just transformation', *Environmental Politics,* 26(3), pp. 413-437.
Schlögl, M., Richter, G., Avian, M., Thaler, T., Heiss, G., Lenz, G. and Fuchs, S. (2019) 'On the nexus between landslide susceptibility and transport infrastructure–an agent-based approach', *Natural Hazards & Earth System Sciences,* 19(1).
Schmeltz, M. T., Petkova, E. P. and Gamble, J. L. (2016) 'Economic Burden of Hospitalizations for Heat-Related Illnesses in the United States, 2001-2010', *International journal of environmental research and public health,* 13(9), pp. 894.
Schmid, C. (2018) 'Journeys through planetary urbanization: Decentering perspectives on the urban', *Environment and Planning D: Society and Space,* 36(3), pp. 591-610.
Schmidt, C. W. (2015) 'Delta subsidence: an imminent threat to coastal populations', *Environ Health Perspectives,* 123(8), pp. A204–A209.
Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T. J., Silva, R., Schlurmann, T. and Schüttrumpf, H. (2019) 'Hard Structures for Coastal Protection, Towards Greener Designs', *Estuaries and Coasts,* 42(7), pp. 1709-1729.
Schubert, S. and Grossman-Clarke, S. (2013) 'The influence of green areas and roof albedos on air temperatures during extreme heat events in Berlin, Germany', *Meteorologische Zeitschrift,* 22(2), pp. 131-143.
Schuster, C., Honold, J., Lauf, S. and Lakes, T. (2017) 'Urban heat stress: Novel survey suggests health and fitness as future avenue for research and adaptation strategies', *Environmental Research Letters,* 12(4), pp. 044021.
Schwan, S. and Yu, X. (2018) 'Social protection as a strategy to address climate-induced migration', *International Journal of Climate Change Strategies and Management,* 10(1), pp. 43-64.
Schwarze, R., Meyer, P. B., Markandya, A., Kedia, S., Maleki, D., Román de Lara, M. V., Sudo, T. and Surminski, S. (2018) 'Economics, Finance, and the private sector', in Rosenzweig, C., Solecki, W., Romero-Lankao, P., Mehrotra, S., Dhakal, S. and Ali Ibrahim, S. (eds.) *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. New York: Cambridge University Press, pp. 225–254.
Schweighofer, J. (2014) 'The impact of extreme weather and climate change on inland waterway transport', *Natural hazards,* 72(1), pp. 23-40.
Schweikert, A., Chinowsky, P., Espinet, X. and Tarbert, M. (2014) 'Climate change and infrastructure impacts: comparing the impact on roads in ten countries through 2100', *Procedia Engineering,* 78, pp. 306-316.
Schünemann, C., Olfert, A., Schiela, D., Gruhler, K. and Ortlepp, R. (2020) 'Mitigation and adaptation in multifamily housing: overheating and climate justice', *Buildings and Cities,* 1(1).
Scott, A. A., Misiani, H., Okoth, J., Jordan, A., Gohlke, J., Ouma, G., Arrighi, J., Zaitchik, B. F., Jjemba, E. and Verjee, S. (2017) 'Temperature and heat in informal settlements in Nairobi', *PloS one,* 12(11), pp. e0187300.
Scott, C. A., Zhang, F., Mukherji, A., Immerzeel, W., Mustafa, D. and Bharati, L. (2019) 'Water in the Hindu Kush Himalaya', in Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. (eds.) *The Hindu Kush Himalaya Assessment*. Cham: Springer.
Scoville-Simonds, M., Jamali, H. and Hufty, M. (2020) 'The Hazards of Mainstreaming: Climate change adaptation politics in three dimensions', *World Development,* 125, pp. 104683.
Scovronick, N., Lloyd, S. J. and Kovats, R. S. (2015) 'Climate and health in informal urban settlements', *Environment and urbanization,* 27(2), pp. 657-678.
Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S. and Turner, B. (2021) 'Getting the message right on nature-based solutions to climate change', *Global change biology,* 27(8), pp. 1518-1546.

Semarang City Government (2016) *Resilient Semarang: Moving Together towards a Resilient Semarang* Semarang: Semarang City Government. Available at: https://www.acccrn.net/sites/default/files/publication/attach/semarang_resilience_strategy_-_english.pdf.
Sena, A., Ebi, K. L., Freitas, C., Corvalan, C. and Barcellos, C. (2017) 'Indicators to measure risk of disaster associated with drought: Implications for the health sector', *PloS one,* 12(7), pp. e0181394.
Seo, M., Jaber, F. and Srinivasan, R. (2017) 'Evaluating various low-impact development scenarios for optimal design criteria development', *Water,* 9(4), pp. 270.
Sepehri, M., Malekinezhad, H., Ilderomi, A. R., Talebi, A. and Hosseini, S. Z. (2018) 'Studying the effect of rain water harvesting from roof surfaces on runoff and household consumption reduction', *Sustainable cities and society,* 43, pp. 317-324.
Serrao-Neumann, S., Renouf, M., Kenway, S. J. and Low Choy, D. (2017) 'Connecting land-use and water planning: Prospects for an urban water metabolism approach', *Cities,* 60(Part A), pp. 13-27.
Serre, D. and Heinzlef, C. (2018) 'Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks', *International Journal of Disaster Risk Reduction,* 30, pp. 235-243.
Sesana, E., Bertolin, C., Gagnon, A. S. and Hughes, J. J. (2019) 'Mitigating Climate Change in the Cultural Built Heritage Sector', *Climate,* 7(7), pp. 90-113.
Sesana, E., Gagnon, A. S., Bertolin, C. and Hughes, J. J. (2018) 'Adapting cultural heritage to climate change risks: perspectives of cultural heritage experts in Europe', *Geosciences,* 8(8), pp. 305-328.
Setiadi, R. (2015) *The Emergence of Local Climate Change Adaptation Policy: An Advocacy Coalition in Indonesian Cities 1993-2013.* Griffith University, Gold Coast.
Setiadi, R. (2016) 'The governance of climate change in Semarang: past, present and future (in Indonesian: Tata kelola perubahan iklim di Kota Semarang: dulu, sekarang, dan kedepan)', *RIPTEK,* 10(1), pp. 33-42.
Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G. and Ürge-Vorsatz, D. (2016) 'Carbon lock-in: types, causes, and policy implications', *Annual Review of Environment and Resources,* 41, pp. 425-452.
Shaddick, G., Thomas, M. L., Amini, H., Broday, D., Cohen, A., Frostad, J., Green, A., Gumy, S., Liu, Y. and Martin, R. V. (2018a) 'Data integration for the assessment of population exposure to ambient air pollution for global burden of disease assessment', *Environmental science & technology,* 52(16), pp. 9069-9078.
Shaddick, G., Thomas, M. L., Green, A., Brauer, M., van Donkelaar, A., Burnett, R., Chang, H. H., Cohen, A., Van Dingenen, R. and Dora, C. (2018b) 'Data integration model for air quality: a hierarchical approach to the global estimation of exposures to ambient air pollution', *Journal of the Royal Statistical Society: Series C (Applied Statistics),* 67(1), pp. 231-253.
Shah, R. and Badiger, S. (2018) 'Conundrum or paradox: deconstructing the spurious case of water scarcity in the Himalayan Region through an institutional economics narrative', *Water Policy,* 22(S1), pp. 146-161.
Shaheen, S., Martin, E. and Hoffman-Stapleton, M. (2019) 'Shared mobility and urban form impacts: a case study of peer-to-peer (P2P) carsharing in the US', *Journal of Urban Design*, pp. 1-18.
Sharifi, A. (2020) 'Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review', *Science of The Total Environment*, pp. 141642.
Sharifi, A. and Yamagata, Y. (2016) 'Principles and criteria for assessing urban energy resilience: A literature review', *Renewable and Sustainable Energy Reviews,* 60, pp. 1654-1677.
Sharma, G., Namchu, C., Nyima, K., Luitel, M., Singh, S. and Goodrich, C. G. (2019) 'Water management systems of two towns in the Eastern Himalaya: case studies of Singtam in Sikkim and Kalimpong in West Bengal states of India', *Water Policy,* 22(S1), pp. 107-129.
Shaw, K. (2015) 'Planetary urbanisation: what does it matter for politics or practice?', *Planning Theory & Practice,* 16(4), pp. 588-593.
Sheller, M. and Urry, J. (2016) 'Mobilizing the new mobilities paradigm', *Applied Mobilities,* 1(1), pp. 10-25.
Sherpa, A. M., Koottatep, T., Zurbruegg, C. and Cissé, G. (2014) 'Vulnerability and adaptability of sanitation systems to climate change', *Journal of water and climate change,* 5(4), pp. 487-495.
Shi, L. (2019) 'Promise and paradox of metropolitan regional climate adaptation', *Environmental Science & Policy,* 92, pp. 262-274.
Shi, L., Chu, E., Anguelovski, I., Aylett, A., Debats, J., Goh, K., Schenk, T., Seto, K. C., Dodman, D., Roberts, D., Roberts, J. T. and VanDeveer, S. D. (2016) 'Roadmap towards justice in urban climate adaptation research', *Nature Climate Change,* 6(2), pp. 131-137.
Shi, Z., Watanabe, S., Ogawa, K. and Kubo, H. (2018) *Structural Resilience in Sewer Reconstruction: From Theory to Practice.* Kidlington: Elsevier.
Shiklomanov, N. I., Streletskiy, D. A., Swales, T. B. and Kokorev, V. A. (2017) 'Climate change and stability of urban infrastructure in Russian permafrost regions: prognostic assessment based on GCM climate projections', *Geographical review,* 107(1), pp. 125-142.
Shokry, G., Connolly, J. J. T. and Anguelovski, I. (2020) 'Understanding climate gentrification and shifting landscapes of protection and vulnerability in green resilient Philadelphia', *Urban Climate,* 31, pp. 100539.
Shrestha, A., Shrestha, S., Tingsanchali, T., Budhathoki, A. and Ninsawat, S. 'Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal', *Journal of Cleaner Production,* 279, pp. 123483.

Shrestha, A., Shrestha, S., Tingsanchali, T., Budhathoki, A. and Ninsawat, S. (2021) 'Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal', *Journal of Cleaner Production,* 279, pp. 123483.

Shughrue, C. and Seto, K. C. (2018) 'Systemic vulnerabilities of the global urban-industrial network to hazards', *Climatic Change,* 151(2), pp. 173-187.

Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (2019) *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*: In Press.

Shuster, W. D., Bonta, J., Thurston, H., Warnemuende, E. and Smith, D. R. (2005) 'Impacts of impervious surface on watershed hydrology: A review', *Urban Water Journal,* 2(4), pp. 263-275.

Sieber, J. (2013) 'Impacts of, and adaptation options to, extreme weather events and climate change concerning thermal power plants', *Climatic change,* 121(1), pp. 55-66.

Siegel, F. R. (2020) 'Arresting/controlling saltwater contamination of coastal aquifers', in Siegel, F.R. (ed.) *Adaptations of coastal cities to global warming, sea level rise, climate change and endemic hazards*. Cham: Springer, pp. 5-9.

Silja, K. 2017. Climate Change and Migration. Oxford University Press.

Silva, R., Martínez, M. L., Odériz, I., Mendoza, E. and Feagin, R. A. (2016a) 'Response of vegetated dune–beach systems to storm conditions', *Coastal Engineering,* 109, pp. 53-62.

Silva, R. A., Adelman, Z., Fry, M. M. and West, J. J. (2016b) 'The Impact of Individual Anthropogenic Emissions Sectors on the Global Burden of Human Mortality due to Ambient Air Pollution', *Environmental Health Perspectives,* 124(11), pp. 1776-1784.

Silva, R. A., West, J. J., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L. W. and Nagashima, T. (2016c) 'The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble', *Atmospheric chemistry and physics,* 16(15), pp. 9847.

Silva, R. A., West, J. J., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Faluvegi, G., Folberth, G. A., Horowitz, L. W., Nagashima, T. and Naik, V. (2017) 'Future global mortality from changes in air pollution attributable to climate change', *Nature climate change,* 7(9), pp. 647-651.

Silver, J. (2015) 'Disrupted infrastructures: An urban political ecology of interrupted electricity in Accra', *International Journal of Urban and Regional Research,* 39(5), pp. 984-1003.

Simmons, A. (2021) *Impact of climate change on young people in small island communities. Sustainable Development Goals Series* Switzerland: Springer.

Simon, D. (2016) *Rethinking sustainable cities: Accessible, green and fair.* Bristol and Chicago: Policy Press.

Simon, D. and Leck, H. (2015) 'Understanding climate adaptation and transformation challenges in African cities', *Current Opinion in Environmental Sustainability,* 13, pp. 109-116.

Simon, D. and Palmer, H. (2020) *Comparative Urban Research from Theory to Practice; Co-production for sustainability.* Bristol: Policy Press.

Simon-Rojo, M. (2019) 'Agroecology to fight food poverty in Madrid's deprived neighbourhoods', *URBAN DESIGN International,* 24(2), pp. 94-107.

Simpson, N. P. (2019) 'Accommodating landscape-scale shocks: Lessons on transition from Cape Town and Puerto Rico', *Geoforum,* 102, pp. 226-229.

Simpson, S.-A., Napawan, N. C. and Snyder, B. (2019) '# OurChangingClimate: Building Networks of Community Resilience Through Social Media and Design', *GeoHumanities*, pp. 1-17.

Singh, C. and Basu, R. (2020) 'Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural–urban continuum in India', *The Geographical Journal,* 186(1), pp. 87-102.

Singh, C., Daron, J., Bazaz, A., Ziervogel, G., Spear, D., Krishnaswamy, J., Zaroug, M. and Kituyi, E. (2018) 'The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India', *Climate and Development,* 10(5), pp. 389-405.

Singh, C., Ford, J., Ley, D. et al. (2020) 'Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice.' *Climatic Change,* 162, 255–277 (2020). https://doi.org/10.1007/s10584-020-02762-x

Singh, P. K. and Chudasama, H. (2021) 'Pathways for climate resilient development: Human well-being within a safe and just space in the 21st century', *Global Environmental Change,* 68, pp. 102277.

Singh, S. and Sharma, V. K. (2019) 'Urban Droughts in India: Case Study of Delhi', in RayB. and Shaw, R. (eds.) *Urban Drought*. Cham: Springer, pp. 155-167.

Singh, S., Shrestha, K., Hamal, M. and Prakash, A. (2019a) 'Perform or wither: role of water users' associations in municipalities of Nepal', *Water Policy,* 22(S1), pp. 90-106.

Singh, S., Tanvir Hassan, S. M., Hassan, M. and Bharti, N. (2019b) 'Urbanisation and water insecurity in the Hindu Kush Himalaya: insights from Bangladesh, India, Nepal and Pakistan', *Water Policy,* 22(S1), pp. 9-32.

Singh, V. and Pandey, A. (2019) 'Urban water resilience in Hindu Kush Himalaya: issues, challenges and way forward', *Water Policy,* 22(S1), pp. 33-45.

Sitas, R. (2020) 'Cultural policy and just cities in Africa', *City,* 24(3-4), pp. 473-492.

Skelhorn, C., Lindley, S. and Levermore, G. (2014) 'The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK', *Landscape and Urban Planning,* 121, pp. 129-140.
Skougaard Kaspersen, P., Høegh Ravn, N., Arnbjerg-Nielsen, K., Madsen, H. and Drews, M. (2017) 'Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding', *Hydrol. Earth Syst. Sci.,* 21(8), pp. 4131-4147.
Smid, M. and Costa, A. C. (2018) 'Climate projections and downscaling techniques: a discussion for impact studies in urban systems', *International Journal of Urban Sciences,* 22(3), pp. 277-307.
Smid, M., Russo, S., Costa, A. C., Granell, C. and Pebesma, E. (2019) 'Ranking European capitals by exposure to heat waves and cold waves', *Urban Climate,* 27, pp. 388-402.
Smith, C. J. (2019) 'Pediatric Thermoregulation: Considerations in the Face of Global Climate Change', *Nutrients,* 11(9), pp. 2010.
Smith, J. and Patterson, J. (2018) 'Global Climate Justice Activism: "The New Protagonists" and Their Projects for a Just Transition', in Frey, S.R., Gellert, P.K. and Dahms, H.F. (eds.) *Ecologically Unequal Exchange: Environmental Injustice in Comparative and Historical Perspective*. New York: Palgrave Macmillan, pp. 245-272.
Soares, M. B., Alexander, M. and Dessai, S. (2018) 'Sectoral use of climate information in Europe: A synoptic overview', *Climate Services,* 9, pp. 5-20.
Soares, M. B. and Dessai, S. (2016) 'Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe', *Climatic Change,* 137(1-2), pp. 89-103.
Soebarto, V. and Bennetts, H. (2014) 'Thermal comfort and occupant responses during summer in a low to middle income housing development in South Australia', *Building and Environment,* 75, pp. 19-29.
Soga, M., Gaston, K. J. and Yamaura, Y. (2017) 'Gardening is beneficial for health: A meta-analysis', *Preventive Medicine Reports,* 5, pp. 92-99.
Solecki, W. and Marcotullio, P. J. (2013) 'Climate change and urban biodiversity vulnerability', in Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C. and Wilkinson, C. (eds.) *Urbanization, biodiversity and ecosystem services: Challenges and opportunities*. Dordrecht: Springer, pp. 485-504.
Solecki, W., Rosenzweig, C., Dhakal, S., Roberts, D., Barau, A. S., Schultz, S. and Ürge-Vorsatz, D. (2018) 'City transformations in a 1.5 C warmer world', *Nature Climate Change,* 8(3), pp. 177.
Solecki, W., Seto, K. C., Balk, D., Bigio, A., Boone, C. G., Creutzig, F., Fragkias, M., Lwasa, S., Marcotullio, P. and Romero-Lankao, P. (2015) 'A conceptual framework for an urban areas typology to integrate climate change mitigation and adaptation', *Urban Climate,* 14, pp. 116-137.
Soltesova, K., Brown, A., Dayal, A., Dodman and D. (2014) 'Community participation in urban adaptation to climate change', in Schipper, E.L.F., Ayers, J., Reid, H., Huq, R. and Rahman, A. (eds.) *Community-Based Adaptation to Climate Change*: Earthscan Routledge, pp. 214-225.
Song, Q. Y., Zheng, Y. and Lin, C. Z. (2021) 'Improving urban resilience to extraordinary rainstorm: A comparative study in Beijing', *Chinese Journal of Urban and Environmental Studies,* 20.
Sovacool, B. K. (2011) 'Hard and soft paths for climate change adaptation', *Climate policy,* 11(4), pp. 1177-1183.
Sovacool, B. K., Tan-Mullins, M. and Abrahamse, W. (2018) 'Bloated bodies and broken bricks: Power, ecology, and inequality in the political economy of natural disaster recovery', *World Development,* 110, pp. 243-255.
Speckhard, D. (2016) 'World Humanitarian Summit: Laudable, but short on hard political commitments', *Future Development*, Available: Brookings Institute.
Spencer, B., Lawler, J., Lowe, C., Thompson, L., Hinckley, T., Kim, S.-H., Bolton, S., Meschke, S., Olden, J. D. and Voss, J. (2017) 'Case studies in co-benefits approaches to climate change mitigation and adaptation', *Journal of environmental planning and management,* 60(4), pp. 647-667.
Sperling, D., Pike, S. and Chase, R. (2018) 'Will the transportation revolutions improve our lives – or make them worse?', in Sperling, D. (ed.) *Three Revolutions: Steering Automated, Shared, and Electric Vehicles to a Better Future*. Washington D.C.: Island Press, pp. 1-20.
Srinivasan, V., Konar, M. and Sivapalan, M. (2017) 'A dynamic framework for water security', *Water Security,* 1, pp. 12-20.
Srivastava, R. K. (2020) *Urban Agglomerates Under Climate Change Induced Risk. Managing Urbanization, Climate Change and Disasters in South Asia. Disaster Studies and Management* Singapore: Springer.
Stanke, C., Kerac, M., Prudhomme, C., Medlock, J. and Murray, V. (2013) 'Health effects of drought: a systematic review of the evidence', *PLoS currents,* 5.
Statista (2020) *Rail industry worldwide*: Statista. Available at: https://www.statista.com/study/11761/rail-industry--statista-dossier/ (Accessed: 23rd October 2020).
Steele, W. and Legacy, C. (2017) 'Critical urban infrastructure', *Urban Policy and Research,* 35(1), pp. 1-6.
Stevens, A. 2017. *Temperature, wages, and agricultural labor productivity*. Berkeley.
Stevens, M. R. and Senbel, M. (2017) 'Are municipal land use plans keeping pace with global climate change?', *Land Use Policy,* 68(Complete), pp. 1-14.
Stewart, M. G. and Deng, X. (2014) 'Climate impact risks and climate adaptation engineering for built infrastructure', *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering,* 1(1), pp. 04014001.

Stewart, M. G., Ginger, J. D., Henderson, D. J. and Ryan, P. C. (2018) 'Fragility and climate impact assessment of contemporary housing roof sheeting failure due to extreme wind', *Engineering Structures,* 171, pp. 464-475.
Straka, M. and Sodoudi, S. (2019) 'Evaluating climate change adaptation strategies and scenarios of enhanced vertical and horizontal compactness at urban scale (a case study for Berlin)', *Landscape and Urban Planning,* 183(Complete), pp. 68-78.
Stringer, L. C., Dougill, A. J., Dyer, J. C., Vincent, K., Fritzsche, F., Leventon, J., Falcao, M. P., Manyakaidze, P., Syampungani, S. and Powell, P. (2014) 'Advancing climate compatible development: lessons from southern Africa', *Regional Environmental Change,* 14(2), pp. 713-725.
Suarma, U., Hizbaron, D. R., Sudibyakto, S. and Nurjani, E. (2018) 'Participatory implementation within climate change related policies in urbanized area of Indonesia', *Indonesian Journal of Geography,* 50(2), pp. 121-132.
Suatmadi, A. Y., Creutzig, F. and Otto, I. M. (2019) 'On-demand motorcycle taxis improve mobility, not sustainability', *Case Studies on Transport Policy,* 7(2), pp. 218-229.
Suckall, N., Stringer, L. C. and Tompkins, E. L. (2015) 'Presenting triple-wins? assessing projects that deliver adaptation, mitigation and development co-benefits in rural Sub-Saharan Africa', *Ambio,* 44(1), pp. 34-41.
Sugden, F., Maskey, N., Clement, F., Ramesh, V., Philip, A. and Rai, A. (2014) 'Agrarian stress and climate change in the Eastern Gangetic Plains: Gendered vulnerability in a stratified social formation', *Global Environmental Change,* 29, pp. 258-269.
Suhelmi, I. R. and Triwibowo, H. (2018) 'Coastal Inundation Adaptive Strategy in Semarang Coastal Area', *Forum Geografi,* 32(2).
Sun, S., Fu, G., Bao, C. and Fang, C. (2019) 'Identifying hydro-climatic and socioeconomic forces of water scarcity through structural decomposition analysis: A case study of Beijing city', *Science of The Total Environment,* 687, pp. 590-600.
Surminski, S. and Thieken, A. H. (2017) 'Promoting flood risk reduction: The role of insurance in Germany and England', *Earth's Future,* 5(10), pp. 979-1001.
Susca, T. and Pomponi, F. (2020) 'Heat island effects in urban life cycle assessment: Novel insights to include the effects of the urban heat island and UHI-mitigation measures in LCA for effective policy making', *Journal of Industrial Ecology,* 24(2), pp. 410-423.
Sverdlik, A. (2011) 'Ill-health and poverty: a literature review on health in informal settlements', *Environment and Urbanization,* 23(1), pp. 123-155.
Swatuk, L. A., Thomas, B. K., Wirkus, L., Krampe, F. and Batista da Silva, L. P. (2020) 'The ‘boomerang effect’: insights for improved climate action', *Climate and Development,* 13, pp. 1-7.
Sword-Daniels, V., Eriksen, C., Hudson-Doyle, E. E., Alaniz, R., Adler, C., Schenk, T. and Vallance, S. (2018) 'Embodied uncertainty: living with complexity and natural hazards', *Journal of Risk Research,* 21(3), pp. 290-307.
Syphard, A. D., Rustigian-Romsos, H., Mann, M., Conlisk, E., Moritz, M. A. and Ackerly, D. (2019) 'The relative influence of climate and housing development on current and projected future fire patterns and structure loss across three California landscapes', *Global Environmental Change,* 56, pp. 41-55.
Tadgell, A., Doberstein, B. and Mortsch, L. (2018) 'Principles for climate-related resettlement of informal settlements in less developed nations: a review of resettlement literature and institutional guidelines', *Climate and Development,* 10(2), pp. 102-115.
Tagliacozzo, S., Pisacane, L. and Kilkey, M. (2021) 'The interplay between structural and systemic vulnerability during the COVID-19 pandemic: migrant agricultural workers in informal settlements in Southern Italy', *Journal of Ethnic and Migration Studies,* 47(9), pp. 1903-1921.
Takkanon, P. and Chantarangul, P. (2019) 'Effects of urban geometry and green area on thermal condition of urban street canyons in Bangkok', *Architectural Science Review,* 62(1), pp. 35-46.
Tan, Y., Xuchun, L. and Graeme, H. (2015) 'Exploring relationship between social inequality and adaptations to climate change: evidence from urban household surveys in the Yangtze River delta, China', *Population and environment,* 36(4), pp. 400-428.
Tang, A. M., Hughes, P. N., Dijkstra, T. A., Askarinejad, A., Brenčič, M., Cui, Y. J., Diez, J. J., Firgi, T., Gajewska, B. and Gentile, F. (2018) 'Atmosphere–vegetation–soil interactions in a climate change context; impact of changing conditions on engineered transport infrastructure slopes in Europe', *Quarterly Journal of Engineering Geology and Hydrogeology,* 51(2), pp. 156-168.
Tapia, C., Abajo, B., Feliu, E., Mendizabal, M., Martinez, J. A., Fernández, J. G., Laburu, T. and Lejarazu, A. (2017) 'Profiling urban vulnerabilities to climate change: An indicator-based vulnerability assessment for European cities', *Ecological Indicators,* 78, pp. 142-155.
Taszarek, M., Kendzierski, S. and Pilguj, N. (2020) 'Hazardous weather affecting European airports: Climatological estimates of situations with limited visibility, thunderstorm, low-level wind shear and snowfall from ERA5', *Weather and Climate Extremes,* 28, pp. 100243.
Taylor, A., Jack, C., McClure, A., Bharwani, S., Ilunga, R. and Kavonic, J. (2021) 'Understanding and supporting climate-sensitive decision processes in southern African cities', *Current Opinion in Environmental Sustainability,* 51, pp. 77-84.
Taylor, E., Butt, A. and Amati, M. (2017) 'Making the blood broil: Conflicts over imagined rurality in peri-urban Australia', *Planning Practice & Research,* 32(1), pp. 85-102.

Taylor, J., Davies, M., Mavrogianni, A., Shrubsole, C., Hamilton, I., Das, P., Jones, B., Oikonomou, E. and Biddulph, P. (2016) 'Mapping indoor overheating and air pollution risk modification across Great Britain: A modelling study', *Building and Environment,* 99, pp. 1-12.
Taylor, J., Wilkinson, P., Davies, M., Armstrong, B., Chalabi, Z., Mavrogianni, A., Symonds, P., Oikonomou, E. and Bohnenstengel, S. I. (2015) 'Mapping the effects of urban heat island, housing, and age on excess heat-related mortality in London', *Urban Climate,* 14, pp. 517-528.
Taylor, J., Wilkinson, P., Picetti, R., Symonds, P., Heaviside, C., Macintyre, H. L., Davies, M., Mavrogianni, A. and Hutchinson, E. (2018) 'Comparison of built environment adaptations to heat exposure and mortality during hot weather, West Midlands region, UK', *Environmental International,* 111, pp. 287-294.
Tellman, B., McDonald, R. I., Goldstein, J. H., Vogl, A. L., Flörke, M., Shemie, D., Dudley, R., Dryden, R., Petry, P. and Karres, N. (2018) 'Opportunities for natural infrastructure to improve urban water security in Latin America', *Plos one,* 13(12), pp. e0209470.
Tengö, M., Brondizio, E. S., Elmqvist, T., Malmer, P. and Spierenburg, M. (2014) 'Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach', *Ambio,* 43(5), pp. 579-591.
Tenzing, J. D. (2020) 'Integrating social protection and climate change adaptation: A review', *Wiley Interdisciplinary Reviews: Climate Change,* 11(2), pp. e626.
Tessler, Z. D., Vorosmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M. and Foufoula-Georgiou, E. (2015) 'Profiling risk and sustainability in coastal deltas of the world', *Science,* 349(6248), pp. 638-643.
Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G. and Hall, J. W. (2019) 'Infrastructure for sustainable development', *Nature Sustainability,* 2(4), pp. 324-331.
Thacker, S., Barr, S., Pant, R., Hall, J. W. and Alderson, D. (2017) 'Geographic hotspots of critical national infrastructure', *Risk Analysis,* 37(12), pp. 2490-2505.
Thakali, R., Kalra, A. and Ahmad, S. (2016) 'Understanding the effects of climate change on urban stormwater infrastructures in the Las Vegas Valley', *Hydrology,* 3(4), pp. 34.
Thomas, A., Cretney, R. and Hayward, B. (2019) 'Student Strike 4 Climate: Justice, emergency and citizenship', *New Zealand Geographer,* 75(2), pp. 96-100.
Thomas, B. F., Famiglietti, J. S., Landerer, F. W., Wiese, D. N., Molotch, N. P. and Argus, D. F. (2017) 'GRACE Groundwater Drought Index: Evaluation of California Central Valley groundwater drought', *Remote Sensing of Environment,* 198, pp. 384-392.
Thomas, K., Hardy, R. D., Lazrus, H., Mendez, M., Orlove, B., Rivera-Collazo, I., Roberts, J. T., Rockman, M., Warner, B. P. and Winthrop, R. (2019) 'Explaining differential vulnerability to climate change: A social science review', *Wiley Interdisciplinary Reviews: Climate Change,* 10(2), pp. e565.
Thome, C., Mitz, C., Somers, C. M., Manzon, R. G., Boreham, D. R. and Wilson, J. Y. (2016) 'Incubation of lake whitefish (Coregonus clupeaformis) embryos in cooling water discharge and the impacts of fluctuating thermal regimes on development', *Canadian Journal of Fisheries and Aquatic Sciences,* 73(8), pp. 1213-1221.
Thorn, J., Thornton, T. F. and Helfgott, A. (2015) 'Autonomous adaptation to global environmental change in peri-urban settlements: Evidence of a growing culture of innovation and revitalisation in Mathare Valley Slums, Nairobi', *Global Environmental Change,* 31, pp. 121-131.
Thorsson, S., Rocklöv, J., Konarska, J., Lindberg, F., Holmer, B., Dousset, B. and Rayner, D. (2014) 'Mean radiant temperature–A predictor of heat related mortality', *Urban Climate,* 10, pp. 332-345.
Threlfall, C. G., Mata, L., Mackie, J. A., Hahs, A. K., Stork, N. E., Williams, N. S. and Livesley, S. J. (2017) 'Increasing biodiversity in urban green spaces through simple vegetation interventions', *Journal of applied ecology,* 54(6), pp. 1874-1883.
Tiggeloven, T., Moel, H. d., Winsemius, H. C., Eilander, D., Erkens, G., Gebremedhin, E., Diaz Loaiza, A., Kuzma, S., Luo, T. and Iceland, C. (2020) 'Global-scale benefit–cost analysis of coastal flood adaptation to different flood risk drivers using structural measures', *Natural Hazards and Earth System Sciences,* 20(4), pp. 1025-1044.
Tirumala, R.D. and Tiwari, P. (2021) 'Land-Based Financing Elements in Infrastructure Policy Formulation: A Case of India', *Land*, 10(2), p.133.
Tiwary, A., Reff, A. and Colls, J. J. (2008) 'Collection of ambient particulate matter by porous vegetation barriers: Sampling and characterization methods', *Journal of Aerosol Science,* 39(1), pp. 40-47.
Toimil, A., Diaz-Simal, P., Losada, I. J. and Camus, P. (2018) 'Estimating the risk of loss of beach recreation value under climate change', *Tourism Management,* 68, pp. 387-400.
Tomlinson, C. J., Chapman, L., Thornes, J. E. and Baker, C. J. (2011) 'Including the urban heat island in spatial heat health risk assessment strategies: a case study for Birmingham, UK', *International Journal of Health Geographics,* 10(1), pp. 42.
Tompkins, E. L., Mensah, A., King, L., Long, K., Lawson, E. T., Hutton, C., Anh, V., Gordon, C., Fish, M., Dyer, J. and Bood, N. (2013) 'An investigation of the evidence of benefits from climate compatible development', *Centre for Climate Change Economics and Policy,* (124), pp. 1-31.
Tonmoy, F. N., Cooke, S. M., Armstrong, F. and Rissik, D. (2020) 'From science to policy: Development of a climate change adaptation plan for the health and wellbeing sector in Queensland, Australia', *Environmental Science & Policy,* 108, pp. 1-13.
Torabi, E., Dedekorkut-Howes, A. and Howes, M. (2018) 'Adapting or maladapting: building resilience to climate-related disasters in coastal cities', *Cities,* 72, pp. 295-309.

Tovar-Restrepo, M. and Irazábal, C. (2013) 'Indigenous Women and Violence in Colombia: Agency, Autonomy, and Territoriality', *Latin American Perspectives,* 41(1), pp. 39-58.
Townsend, J., Moola, F. and Craig, M.-K. (2020) 'Indigenous Peoples are critical to the success of nature-based solutions to climate change', *FACETS,* 5(1).
Toya, H. and Skidmore, M. (2015) 'Information/communication technology and natural disaster vulnerability', *Economics Letters,* 137, pp. 143-145.
Tramblay, Y., Mimeau, L., Neppel, L., Vinet, F. and Sauquet, E. (2019) 'Detection and attribution of flood trends in Mediterranean basins', *Hydrology and Earth System Sciences,* 23(11), pp. 4419-4431.
Travassos, L., Torres, P. H. C., Di Giulio, G., Jacobi, P. R., Dias De Freitas, E., Siqueira, I. C. and Ambrizzi, T. (2020) 'Why do extreme events still kill in the São Paulo Macro Metropolis Region? Chronicle of a death foretold in the global south', *International Journal of Urban Sustainable Development*, pp. 1-16.
Treichel, P. (2020) 'Why focus on children: A literature review of child-centred climate change adaptation approaches', *Australian Journal of Emergency Management,* 35(2), pp. 26.
Triana, M. A., Lamberts, R. and Sassi, P. (2018) 'Should we consider climate change for Brazilian social housing? Assessment of energy efficiency adaptation measures', *Energy and Buildings,* 158, pp. 1379-1392.
Trofimenko, Y. V., Evgenev, G. and Shashina, E. (2017) 'Functional loss risks of highways in permafrost areas due to climate change', *Procedia engineering,* 189, pp. 258-264.
Trundle, A. (2020) 'Resilient cities in a Sea of Islands: Informality and climate change in the South Pacific', *Cities,* 97, pp. 102496.
Tsavdaroglou, M., Al-Jibouri, S. H., Bles, T. and Halman, J. I. (2018) 'Proposed methodology for risk analysis of interdependent critical infrastructures to extreme weather events', *International journal of critical infrastructure protection,* 21, pp. 57-71.
Tsuda, F. P. and Duarte, D. 'The Conflicts between the Simplification of Building Regulations and the Challenge of Building Cities for a Changing Climate: The case of Sao Paulo city'. *Passive and Low Energy Architecture*, Hong Kong: PLEA.
Turkelboom, F., Demeyer, R., Vranken, L., De Becker, P., Raymaekers, F. and De Smet, L. (2021) 'How does a nature-based solution for flood control compare to a technical solution? Case study evidence from Belgium', *Ambio,* 50, pp. 1-15.
Turkelboom, F., Leone, M., Jacobs, S., Kelemen, E., García-Llorente, M., Baró, F., Termansen, M., Barton, D. N., Berry, P., Stange, E., Thoonen, M., Kalóczkai, Á., Vadineanu, A., Castro, A. J., Czúcz, B., Röckmann, C., Wurbs, D., Odee, D., Preda, E., Gómez-Baggethun, E., Rusch, G. M., Pastur, G. M., Palomo, I., Dick, J., Casaer, J., van Dijk, J., Priess, J. A., Langemeyer, J., Mustajoki, J., Kopperoinen, L., Baptist, M. J., Peri, P. L., Mukhopadhyay, R., Aszalós, R., Roy, S. B., Luque, S. and Rusch, V. (2018) 'When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning', *Ecosystem Services,* 29, pp. 566-578.
Turner, M. C., Jerrett, M., Pope Iii, C. A., Krewski, D., Gapstur, S. M., Diver, W. R., Beckerman, B. S., Marshall, J. D., Su, J. and Crouse, D. L. (2016) 'Long-term ozone exposure and mortality in a large prospective study', *American journal of respiratory and critical care medicine,* 193(10), pp. 1134-1142.
Twinomuhangi, R., Sseviiri, H., Mulinde, C., Mukwaya, P. I., Nimusiima, A. and Kato, A. M. (2021) 'Perceptions and vulnerability to climate change among the urban poor in Kampala City, Uganda', *Regional Environmental Change,* 21(2), pp. 1-13.
Tyusov, G. A., Akentyeva, E. M., Pavlova, T. V. and Shkolnik, I. M. (2017) 'Projected climate change impacts on the operation of power engineering facilities in Russia', *Russian Meteorology and Hydrology,* 42(12), pp. 775-782.
Tänzler, D. (2017) 'Adaptation to Climate Change: Conflict Prevention through Expanded Vulnerability Assessments', in Dadwal, S. and Sinha, U. (eds.) *Non-Traditional Security Challenges in Asia*. New Delhi, London, New York: Routledge, pp. 61-92.
Tänzler, D., Maas, A. and Carius, A. (2010) 'Climate change adaptation and peace', *Wiley Interdisciplinary Reviews: Climate Change,* 1(5), pp. 741-750.
Uittenbroek, C. J. (2016) 'From policy document to implementation: organizational routines as possible barriers to mainstreaming climate adaptation', *Journal of Environmental Policy & Planning,* 18(2), pp. 161-176.
UK Environment Agency (2020) *National Flood and Coastal Erosion Risk Management Strategy for England.* UK: UK Environment Agency.
Ulibarri, N. and Scott, T. A. (2019) 'Environmental hazards, rigid institutions, and transformative change: How drought affects the consideration of water and climate impacts in infrastructure management', *Global Environmental Change,* 59, pp. 102005.
Ulloa, A. (2017) 'Perspectives of environmental justice from Indigenous peoples of Latin America: A relational Indigenous environmental justice', *Environmental Justice,* 10(6), pp. 175-180.
UN Environment (2019) *Global Environment Outlook (GEO-6): Healthy Planet, Healthy People*, Cambridge: Cambridge University Press.
UN Water (2018) *Sustainable Development Goal 6 Synthesis Report on Water and Sanitation*, New York: UN Water. Available at: https://sustainabledevelopment.un.org/content/documents/19901SDG6_SR2018_web_3.pdf.
UN-Habitat (2016a) *World Cities Report*, Nairobi: UN-Habitat.
UN-Habitat (2016b) *World Cities Report 2016 Urbanization and development emerging futures*, Nairobi: UN-Habitat.
UN-Habitat (2017) *Sustainable Urbanization in the Paris Agreement* Nairobi: UNHABITAT.

UN-Habitat (2020) *World Cities Report: the Value of Sustainable Urbanization*, Nairobi: UN-Habitat.
UNDESA (2014) *World's Population Increasingly Urban with More Than Half Living in Urban Areas.*: United Nations Department of Economic and Social Affairs. . Available at: http://www.un.org/en/development/desa/news/population/world- urbanization-prospects-2014.html.
UNDESA (2018) *Revision of World Urbanization Prospects produced by the Population Division of the UN Department of Economic and Social Affairs*, UNDESA Website: UNDESA. Available at: https://population.un.org/wup/.
UNDESA (2020) *World social report 2020: inequality in a rapidly changing world*, Online: UNDESA. Available at: https://www.un.org/development/desa/dspd/world-social-report/2020-2.html.
Undorf, S., Tett, S. F., Hagg, J., Metzger, M. J., Wilson, C., Edmond, G., Jacques-Turner, M., Forrest, S. and Shoote, M. (2020) 'Understanding interdependent climate change risks using a serious game', *Bulletin of the American Meteorological Society,* 101(8), pp. E1279-E1300.
UNDP (2021) *The Peoples' Climate Vote*, Online: University of Oxford and UNDP. Available at: https://www.undp.org/publications/peoples-climate-vote.
UNDRR (2019) *Global Assessment Report on Disaster Risk Reduction*, Geneva: United Nations Office for Disaster Risk Reduction.
UNEP (2021) *Adaptation Gap Report 2020*, Nairobi: United Nations Environment Programme. Available at: https://www.unep.org/resources/adaptation-gap-report-2020.
UNESCO (2021) *Cutting Edge | Culture: the ultimate renewable resource to tackle climate change*: UNESCO. Available at: https://en.unesco.org/news/cutting-edge-culture-ultimate-renewable-resource-tackle-climate-change (Accessed: 16 May 2021).
UNHABITAT (2016) *HABITAT III ISSUE PAPERS. 22 – INFORMAL SETTLEMENTS* Quito: UNHABITAT. Available at: https://unhabitat.org/habitat-iii-issue-papers-22-informal-settlements.
UNICEF and WHO (2019) *Progress on household drinking water, sanitation and hygiene 2000- 2017, Special focus on inequalities*, New York: UNICEF/WHO. Available at: https://www.who.int/water_sanitation_health/publications/jmp-report-2019/en/.
UNISDR (2015) *Sendai Framework for Disaster Risk Reduction 2015-2030*. Available at: https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf.
United Nations (2015a) *Addis Ababa Action Agenda of the Third International Conference on Financing for Development*, Addis Ababa: United Nations. Available at: https://www.un.org/esa/ffd/wp-content/uploads/2015/08/AAAA_Outcome.pdf.
United Nations (2015b) *The Paris Agreement: Agreement of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015*, Paris: United Nations. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
United Nations (2015c) *Transforming our World: the 2030 Agenda for Sustainable Development.* New York: United Nations.
United Nations (2015d) *UN Charter on Sustainable Housing*, Geneva: United Nations. Available at: https://unece.org/DAM/hlm/charter/Language_versions/ENG_Geneva_UN_Charter.pdf.
United Nations (2016a) *New Urban Agenda : Quito Declaration on Sustainable Cities and Human Settlements for All (Habitat III)* Quito. Available at: http://habitat3.org/wp-content/uploads/New-Urban-Agenda-GA-Adopted-68th-Plenary-N1646655-E.pdf.
United Nations (2016b) *New Urban Agenda: Quito Declaration on Sustainable Cities and Human Settlements for All (Habitat III)*, Quito: United Nations. Available at: http://habitat3.org/wp-content/uploads/New-Urban-Agenda-GA-Adopted-68th-Plenary-N1646655-E.pdf.
United Nations (2018) *Make cities and human settlements inclusive, safe, resilient and sustainable: Rapid urbanization and population growth are outpacing the construction of adequate and affordable housing*. Available at: https://unstats.un.org/https://unstats.un.org/sdgs/report/2019/goal-11/.
United States Environmental Protection Agency (2017) *SMART GROWTH FIXES FOR CLIMATE ADAPTATION AND RESILIENCE*, Online: United States Environmental Protection Agency.
Valencia, S. C., Simon, D., Croese, S., Nordqvist, J., Oloko, M., Sharma, T., Taylor Buck, N. and Versace, I. (2019) 'Adapting the Sustainable Development Goals and the New Urban Agenda to the city level: Initial reflections from a comparative research project', *International Journal of Urban Sustainable Development,* 11(1), pp. 4-23.
Valenzuela, V. P. B., Esteban, M. and Onuki, M. (2020) 'Perception of Disasters and Land Reclamation in an Informal Settlement on Reclaimed Land: Case of the BASECO Compound, Manila, the Philippines', *International Journal of Disaster Risk Science,* 11(5), pp. 640-654.
Van Bavel, B., Curtis, D. R. and Soens, T. (2018) 'Economic inequality and institutional adaptation in response to flood hazards', *Ecology and Society,* 23(4).
van den Berg, H. J. and Keenan, J. M. (2019) 'Dynamic vulnerability in the pursuit of just adaptation processes: A Boston case study', *Environmental Science & Policy,* 94, pp. 90-100.
van den Berg , R., Otto, B. and Fikresilassie , A. (2021) *As Cities Grow Across Africa, They Must Plan for Water Security*: World Resource Institute. Available at: https://www.wri.org/insights/cities-grow-across-africa-they-must-plan-water-security (Accessed: 06.17 2021).

van den Hurk, B., van Meijgaard, E., de Valk, P., van Heeringen, K.-J. and Gooijer, J. (2015) 'Analysis of a compounding surge and precipitation event in the Netherlands', *Environmental Research Letters,* 10(3), pp. 035001.
van der Heijden, J. and Hong, S.-H. (2021) 'Urban Climate Governance Experimentation in Seoul: Science, Politics, or a Little of Both?', *Urban Affairs Review,* 57(4), pp. 1115-1148.
van der Heijden, J., Patterson, J., Juhola, S. and Wolfram, M. (2018) 'Special section: advancing the role of cities in climate governance – promise, limits, politics', *Journal of Environmental Planning and Management*, pp. 1-9.
Van der Voort, N. and Vanclay, F. (2015) 'Social impacts of earthquakes caused by gas extraction in the Province of Groningen, The Netherlands', *Environmental Impact Assessment Review,* 50, pp. 1-15.
van Hooff, T., Blocken, B., Hensen, J. L. M. and Timmermans, H. J. P. (2014) 'On the predicted effectiveness of climate adaptation measures for residential buildings', *Building and Environment,* 82, pp. 300-316.
Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M. and Uijlenhoet, R. (2016) 'Drought in the Anthropocene', *Nature Geoscience,* 9(2), pp. 89.
van Oldenborgh, G. J., Krikken, F., Lewis, S., Leach, N. J., Lehner, F., Saunders, K. R., van Weele, M., Haustein, K., Li, S. and Wallom, D. (2020) 'Attribution of the Australian bushfire risk to anthropogenic climate change', *Natural Hazards and Earth System Sciences Discussions,* 21(3), pp. 1-46.
van Slobbe, E., Werners, S. E., Riquelme-Solar, M., Bölscher, T. and van Vliet, M. T. H. (2016) 'The future of the Rhine: stranded ships and no more salmon?', *Regional Environmental Change,* 16(1), pp. 31-41.
van Vliet, M. T. H., Flörke, M. and Wada, Y. (2017) 'Quality matters for water scarcity', *Nature Geoscience,* 10(11), pp. 800-802.
Van Vliet, M. T. H., Wiberg, D., Leduc, S. and Riahi, K. (2016) 'Power-generation system vulnerability and adaptation to changes in climate and water resources', *Nature Climate Change,* 6(4), pp. 375.
van Vuuren, D. P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., Kc, S., Kriegler, E. and O'Neill, B. (2017a) 'The Shared Socio-economic Pathways: Trajectories for human development and global environmental change', *Global Environmental Change,* 42, pp. 148-152.
van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Doelman, J. C., Van den Berg, M., Harmsen, M., de Boer, H. S., Bouwman, L. F., Daioglou, V. and Edelenbosch, O. Y. (2017b) 'Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm', *Global Environmental Change,* 42, pp. 237-250.
van Wesenbeeck, C. F. A., Sonneveld, B. G. J. S. and Voortman, R. L. (2016) 'Localization and characterization of populations vulnerable to climate change: Two case studies in Sub-Saharan Africa', *Applied geography (Sevenoaks),* 66, pp. 81-91.
Vandepitte, E., Vandermoere, F. and Hustinx, L. (2019) 'Civil Anarchizing for the Common Good: Culturally Patterned Politics of Legitimacy in the Climate Justice Movement', *VOLUNTAS: International Journal of Voluntary and Nonprofit Organizations,* 30(2), pp. 327-341.
Vanderschuren, M. and Baufeldt, J. (2018) 'Ride-sharing: A potential means to increase the quality and availability of motorised trips while discouraging private motor ownership in developing cities?', *Research in Transportation Economics,* 69, pp. 607-614.
Vanos, J. K. (2015) 'Children's health and vulnerability in outdoor microclimates: A comprehensive review', *Environment International,* 76, pp. 1-15.
Vanos, J. K., Kosaka, E., Iida, A., Yokohari, M., Middel, A., Scott-Fleming, I. and Brown, R. D. (2019) 'Planning for spectator thermal comfort and health in the face of extreme heat: The Tokyo 2020 Olympic marathons', *Science of The Total Environment,* 657, pp. 904-917.
Vardoulakis, S., Dimitroulopoulou, C., Thornes, J., Lai, K.-M., Taylor, J., Myers, I., Heaviside, C., Mavrogianni, A., Shrubsole, C., Chalabi, Z., Davies, M. and Wilkinson, P. (2015) 'Impact of climate change on the domestic indoor environment and associated health risks in the UK', *Environmental International,* 85, pp. 299-313.
Vasconcelos, V. V., Santos, F. C. and Pacheco, J. M. (2013) 'A bottom-up institutional approach to cooperative governance of risky commons', *Nature Climate Change,* 3(9), pp. 797.
Vasenev, A., Montoya, L. and Ceccarelli, A. 'A Hazus-based method for assessing robustness of electricity supply to critical smart grid consumers during flood events'. *11th International Conference on Availability, Reliability and Security (ARES)*, 2016: IEEE, 223-228.
Vegliò, S. (2021) 'POSTCOLONIZING PLANETARY URBANIZATION: Aníbal Quijano and an Alternative Genealogy of the Urban', *International Journal of Urban and Regional Research,* 45(4), pp. 663-678.
Verdon-Kidd, D. C., Scanlon, B. R., Ren, T. and Fernando, D. N. (2017) 'A comparative study of historical droughts over Texas, USA and Murray-Darling Basin, Australia: Factors influencing initialization and cessation', *Global and Planetary Change,* 149, pp. 123-138.
Vermeiren, K., Adiyia, B., Loopmans, M., Tumwine, F. R. and Van Rompaey, A. (2013) 'Will urban farming survive the growth of African cities: A case-study in Kampala (Uganda)?', *Land Use Policy,* 35, pp. 40-49.
Viguié, V., Juhel, S., Ben-Ari, T., Colombert, M., Ford, J., Giraudet, L. and Reckien, D. (2021) 'When adaptation increases energy demand: A systematic map of the literature', *Environmental research letters,* 16(3), pp. 033004.
Viguié, V., Lemonsu, A., Hallegatte, S., Beaulant, A.-L., Marchadier, C., Masson, V., Pigeon, G. and Salagnac, J.-L. (2020) 'Early adaptation to heat waves and future reduction of air-conditioning energy use in Paris', *Environmental Research Letters,* 15(7), pp. 075006.

Virk, Z. T., Khalid, B., Hussain, A., Ahmad, B., Dogar, S. S., Raza, N. and Iqbal, B. (2019) 'Water availability, consumption and sufficiency in Himalayan towns: a case of Murree and Havellian towns from Indus River Basin, Pakistan', *Water Policy,* 22(S1), pp. 46-64.
Visagie, J. and Turok, I. (2020) 'Getting urban density to work in informal settlements in Africa', *Environment and Urbanization,* 32(2), pp. 0956247820907808.
Visman, E., Audia, C., Crowley, F., Ilboudo, J., Sanou, P., Henley, E., Victor, M., Ritchie, A., Fox, G., Traoré, M. B., Tazen, F., Diarra, A., Warnaars, T., Klein, C., Fitzpatrick, R., Pelling, M. and McOmber, C. (2020) *Developing decision-relevant climate information and supporting its appropriate application*. BRACED Learning Paper 6: King's College. Available at: file:///C:/Users/fs1lkw/Downloads/BRACED+Learning+Paper+6+-+Developing+decision-relevant+climate+information.pdf October 2020).
Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L. and Storlazzi, C. D. (2017) 'Doubling of coastal flooding frequency within decades due to sea-level rise', *Scientific reports,* 7(1), pp. 1399.
Vitousek, S., Barnard, P. L. and Limber, P. (2017) 'Can beaches survive climate change?', *Journal of Geophysical Research: Earth Surface,* 122(4), pp. 1060-1067.
Vodafone (2019) *Annual mobile data usage worldwide from 2015 to 2021 (in thousand petabytes)*. Available at: https://www.statista.com/statistics/630107/annual-mobile-data-usage-vodafone-worldwide/.
Vogl, A. L., Bryant, B. P., Hunink, J. E., Wolny, S., Apse, C. and Droogers, P. (2017) 'Valuing investments in sustainable land management in the Upper Tana River basin, Kenya', *Journal of Environmental Management,* 195, pp. 78-91.
Voigt-Graf, C. and Kagan, S. (2017) *Migration and labour mobility from Kiribati*: SSRN56). Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2937416.
von Uexkull, N., Croicu, M., Fjelde, H. and Buhaug, H. (2016) 'Civil conflict sensitivity to growing-season drought', *Proceedings of the National Academy of Sciences,* 113(44), pp. 12391-12396.
Vora, N., Shah, A., Bilec, M. M. and Khanna, V. (2017) 'Food–Energy–Water Nexus: Quantifying Embodied Energy and GHG Emissions from Irrigation through Virtual Water Transfers in Food Trade', *ACS Sustainable Chemistry & Engineering,* 5(3), pp. 2119-2128.
Vos, P. E., Maiheu, B., Vankerkom, J. and Janssen, S. (2013) 'Improving local air quality in cities: to tree or not to tree?', *Environmental pollution,* 183, pp. 113-122.
Votsis, A. (2017) 'Utilizing a cellular automaton model to explore the influence of coastal flood adaptation strategies on Helsinki's urbanization patterns', *Computers, environment and urban systems,* 64, pp. 344-355.
Votsis, A. and Perrels, A. (2016) 'Housing Prices and the Public Disclosure of Flood Risk: A Difference-in-Differences Analysis in Finland', *The journal of real estate finance and economics,* 53(4), pp. 450-471.
Véliz, K. D., Kaufmann, R. K., Cleveland, C. J. and Stoner, A. M. K. (2017) 'The effect of climate change on electricity expenditures in Massachusetts', *Energy Policy,* 106, pp. 1-11.
Wachsmuth, D., Cohen, D. A. and Angelo, H. (2016) 'Expand the frontiers of urban sustainability', *Nature News,* 536(7617), pp. 391.
Wahl, T., Jain, S., Bender, J., Meyers, S. D. and Luther, M. E. (2015) 'Increasing risk of compound flooding from storm surge and rainfall for major US cities', *Nature Climate Change,* 5(12), pp. 1093.
Walls, R. and Zweig, P. (2017) 'Towards sustainable slums: understanding fire engineering in informal settlements', in Bahei-El-Din, Y. and Hassan, M. (eds.) *Advanced technologies for sustainable systems*. Cham: Springer, pp. 93-98.
Walton, D. and van Aalst, M. (2020) *Climate-related extreme weather events and COVID-19.* Geneva: IFRC, p. 21.
Wamsler, C. and Raggers, S. (2018) 'Principles for supporting city–citizen commoning for climate adaptation: From adaptation governance to sustainable transformation', *Environmental Science & Policy,* 85, pp. 81-89.
Wamsley, T. V., Collier, Z. A., Brodie, K., Dunkin, L. M., Raff, D. and Rosati, J. D. (2015) 'Guidance for developing coastal vulnerability metrics', *Journal of Coastal Research,* 31(6), pp. 1521-1530.
Wandl, A. and Magoni, M. (2017) 'Sustainable planning of peri-urban areas: introduction to the special issue', *Planning Practice & Research* 32(1).
Wang, H., Mei, C., Liu, J. and Shao, W. (2018a) 'A new strategy for integrated urban water management in China: Sponge city', *Science China Technological Sciences,* 61(3), pp. 317-329.
Wang, K., Aktas, Y. D., Stocker, J., Carruthers, D., Hunt, J. and Malki-Epshtein, L. (2019a) 'Urban heat island modelling of a tropical city: case of Kuala Lumpur', *Geoscience Letters,* 6(1), pp. 1-11.
Wang, R. Q., Stacey, M. T., Herdman, L. M. M., Barnard, P. L. and Erikson, L. (2018b) 'The influence of sea level rise on the regional interdependence of coastal infrastructure', *Earth's Future,* 6(5), pp. 677-688.
Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G. and Bowden, D. (2019b) 'How can the UK road system be adapted to the impacts posed by climate change? By creating a climate adaptation framework', *Transportation Research Part D: Transport and Environment,* 77, pp. 403-424.
Wang, Y., Bakker, F., de Groot, R., Wortche, H. and Leemans, R. (2015) 'Effects of urban trees on local outdoor microclimate: synthesizing field measurements by numerical modelling', *Urban Ecosystems,* 18(4), pp. 1305-1331.
Wang, Y., de Groot, R., Bakker, F., Wörtche, H. and Leemans, R. (2017) 'Thermal comfort in urban green spaces: a survey on a Dutch university campus', *International Journal of Biometeorology,* 61(1), pp. 87-101.

Wang, Y., Li, Y., Di Sabatino, S., Martilli, A. and Chan, P. (2018c) 'Effects of anthropogenic heat due to air-conditioning systems on an extreme high temperature event in Hong Kong', *Environmental Research Letters,* 13(3), pp. 034015.
Wang, Y., Shi, L., Zanobetti, A. and Schwartz, J. D. (2016) 'Estimating and projecting the effect of cold waves on mortality in 209 US cities', *Environment international,* 94, pp. 141-149.
Ward, C. D. and Shackleton, C. M. (2016) 'Natural resource use, incomes, and poverty along the rural–urban continuum of two medium-sized, South African towns', *World Development,* 78, pp. 80-93.
Ward, K., Lauf, S., Kleinschmit, B. and Endlicher, W. (2016a) 'Heat waves and urban heat islands in Europe: A review of relevant drivers', *Science of the Total Environment,* 569, pp. 527-539.
Ward, P. J., Jongman, B., Aerts, J. C. J. H., Bates, P. D., Botzen, W. J. W., Loaiza, A. D., Hallegatte, S., Kind, J. M., Kwadijk, J. and Scussolini, P. (2017) 'A global framework for future costs and benefits of river-flood protection in urban areas', *Nature climate change,* 7(9), pp. 642-646.
Ward, R. D., Friess, D. A., Day, R. H. and MacKenzie, R. A. (2016b) 'Impacts of climate change on mangrove ecosystems: a region by region overview', *Ecosystem Health and Sustainability,* 2(4), pp. e01211.
Watson, C., Lone, T., Qazi, U., Smith, G. and Rashid, F. (2016) *Shock-Responsive Social Protection Systems Research*, Oxford: Oxford Policy Management. Available at: https://assets.publishing.service.gov.uk/media/59e0d4f7ed915d6aadcdaf04/OPM-Case-Study-2017-SRSP-Pakistan.pdf.
Weaver, C. P., Liang, X. Z., Zhu, J., Adams, P. J., Amar, P., Avise, J., Caughey, M., Chen, J., Cohen, R. C. and Cooter, E. (2009) 'A preliminary synthesis of modeled climate change impacts on US regional ozone concentrations', *Bulletin of the American Meteorological Society,* 90(12), pp. 1843-1864.
Webber, J., Fletcher, T., Cunningham, L., Fu, G., Butler, D. and Burns, M. (2020) 'Is green infrastructure a viable strategy for managing urban surface water flooding?', *Urban Water Journal,* 17(7), pp. 598-608.
Wei, C. and Zhao, Y. 2018. *Sponge City: From Concept to Implementation*. Nanjing: Jiangsu Phenix Science and Technology Press.
Werners, S. E., Wise, R. M., Butler, J. R., Totin, E. and Vincent, K. (2021) 'Adaptation pathways: a review of approaches and a learning framework', *Environmental Science & Policy,* 116, pp. 266-275.
Wesseling, J. H., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E. and Coenen, L. (2017) 'The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research', *Renewable and Sustainable Energy Reviews,* 79, pp. 1303-1313.
West, J. J., Cohen, A., Dentener, F., Brunekreef, B., Zhu, T., Armstrong, B., Bell, M. L., Brauer, M., Carmichael, G. and Costa, D. L. (2016) 'What we breathe impacts our health: improving understanding of the link between air pollution and health', *Environ. Sci. Technol.,* 50(10), pp. 4895–4904.
Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B. (2019) *The Hindu Kush Himalaya Assessment—Mountains, Climate Change, Sustainability and People* Cham: Springer Nature.
Westervelt, D. M., Ma, C. T., He, M. Z., Fiore, A. M., Kinney, P. L., Kioumourtzoglou, M. A., Wang, S., Xing, J., Ding, D. and Correa, G. (2019) 'Mid-21st century ozone air quality and health burden in China under emissions scenarios and climate change', *Environmental Research Letters,* 14(7), pp. 074030.
Westman, L. K., Broto, V. C. and Huang, P. (2019) 'Revisiting multi-level governance theory: Politics and innovation in the urban climate transition in Rizhao, China', *Political Geography,* 70, pp. 14-23.
WHO (2015) *Operational framework for building climate resilient health systems.* Geneva: World Health Organization, p. 56.
WHO (2020) *WHO Global Strategy on Health, Environment and Climate Change. The transformation needed to improve lives and wellbeing sustainably through healthy environments*, Geneva: WHO.
WHO (2021) *Heat and health evidence update*, Online: WHO. Available at: https://www.euro.who.int/en/publications/abstracts/heat-and-health-in-the-who-european-region-updated-evidence-for-effective-prevention-2021.
WHO and WB (2015) *Tracking Universal Health Coverage*, France: WHO/WB. Available at: https://apps.who.int/iris/bitstream/handle/10665/174536/9789241564977_eng.pdf.
Wilbanks, T. J. and Fernandez, S. (2014) *Climate change and infrastructure, urban systems, and vulnerabilities: Technical report for the US Department of Energy in support of the national climate assessment.* Washington, Covelo and London: Island Press.
Wilby, R. L., Kasei, R., Gough, K., Amankwaa, E., Abarike, M., Anderson, N., Codjoe, S., Griffiths, P., Kaba, C. and Abdullah, K. (2021) 'Monitoring and moderating extreme indoor temperatures in low-income urban communities', *Environmental Research Letters,* 16(2), pp. 024033.
Wilby, R. L. and Keenan, R. (2012) 'Adapting to flood risk under climate change', *Progress in physical geography,* 36(3), pp. 348-378.
Wild, M., Folini, D., Henschel, F., Fischer, N. and Müller, B. (2015) 'Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems', *Solar Energy,* 116, pp. 12-24.
Wilkinson, A. (2020) 'Local response in health emergencies: key considerations for addressing the COVID-19 pandemic in informal urban settlements', *Environment and Urbanization,* 32(2), pp. 503-522.

Wilkinson, E., Kirbyshire, A., Mayhew, L., Batra, P. and Milan, A. (2016) 'Climate-induced migration and displacement: closing the policy gap', *Overseas Development Institute (ODI), London, UK.*
Williams, D. S., Máñez Costa, M., Sutherland, C., Celliers, L. and Scheffran, J. (2019) 'Vulnerability of informal settlements in the context of rapid urbanization and climate change', *Environment and Urbanization,* 31(1), pp. 157-176.
Willis, K. J. and Petrokofsky, G. (2017) 'The natural capital of city trees', *Science,* 356(6336), pp. 374-376.
Wilson, J. (2018) 'Amazon Unbound: Utopian Dialectics of Planetary Urbanization', in Knierbein, S. and Viderman, T. (eds.) *Public Space Unbound*. New York: Routledge, pp. 23-37.
Wing, O. E. J., Bates, P. D., Smith, A. M., Sampson, C. C., Johnson, K. A., Fargione, J. and Morefield, P. (2018) 'Estimates of present and future flood risk in the conterminous United States', *Environmental Research Letters,* 13(3), pp. 034023.
Winquist, A., Grundstein, A., Chang, H. H., Hess, J. and Sarnat, S. E. (2016) 'Warm season temperatures and emergency department visits in Atlanta, Georgia', *Environmental Research,* 147, pp. 314-323.
Winsemius, H. C., Aerts, Jeroen C. J. H., van Beek, Ludovicus P. H., Bierkens, Marc F. P., Bouwman, A., Jongman, B., Kwadijk, Jaap C. J., Ligtvoet, W., Lucas, Paul L., van Vuuren, Detlef P. and Ward, Philip J. (2015) 'Global drivers of future river flood risk', *Nature Climate Change,* 6, pp. 381.
Winter, M. G., Shearer, B., Palmer, D., Peeling, D., Harmer, C. and Sharpe, J. (2016) 'The economic impact of landslides and floods on the road network', *Procedia Engineering,* 143, pp. 1425-1434.
Wolfram, M. (2019) 'Assessing transformative capacity for sustainable urban regeneration: A comparative study of three South Korean cities', *Ambio,* 48(5), pp. 478-493.
Wong, C., Wood, J. and Paturi, S. (2020) 'Vertical farming: an assessment of Singapore City', *Etropic: electronic journal of studies in the tropics,* 19, pp. 228-248.
Wong, L. P., Alias, H., Aghamohammadi, N., Aghazadeh, S. and Nik Sulaiman, N. M. (2017) 'Urban heat island experience, control measures and health impact: A survey among working community in the city of Kuala Lumpur', *Sustainable Cities and Society,* 35, pp. 660-668.
Wong, T. H. F. and Brown, R. R. (2009) 'The water sensitive city: principles for practice', *Water science and technology,* 60(3), pp. 673-682.
Wood, B. (2019) 'Teaching an active citizenship curriculum', *Ethos,* 27(1), pp. 8-10.
Woodcraft, S., Osuteye, E., Ndezi, T. and Makoba, F. D. (2020) 'Pathways to the 'good life': Co-producing prosperity research in informal settlements in Tanzania', *Urban Planning,* 5(3), pp. 288-302.
Woodhall, S. C., Landeg, O. and Kovats, S. (2021) 'Public health and climate change: How are local authorities preparing for the health impacts of our changing climate?', *Journal of Public Health,* 43(2), pp. 425-432.
Woodruff, S. C. and Stults, M. (2016) 'Numerous strategies but limited implementation guidance in US local adaptation plans', *Nature Climate Change,* 6, pp. 796.
Woodworth, M. D. and Wallace, J. L. (2017) 'Seeing ghosts: Parsing China's "ghost city" controversy', *Urban Geography,* 38(8), pp. 1270-1281.
Work, C., Rong, V., Song, D. and Scheidel, A. (2018) 'Maladaptation and development as usual? Investigating climate change mitigation and adaptation projects in Cambodia', *Climate Policy,* 3062, pp. 1-16.
World Bank (2015) *Global Monitoring Report 2014/2015: Ending Poverty and Sharing Prosperity*, Washington DC: World Bank.
World Bank (2016) *Managing coasts with natural solutions: guidelines for measuring and valuing the coastal protection services of mangroves and coral reefs*, Washington DC: World Bank. Available at: http://documents.worldbank.org/curated/en/995341467995379786/pdf/103340-WP-Technical-Rept-WAVES-Coastal-2-11-16-web-PUBLIC.pdf.
World Bank (2017) *Low-Carbon Infrastructure Private Participation in Infrastructure (PPI) 2002 TO H1 2017*, Washington DC: World Bank. Available at: http://documents.worldbank.org/curated/en/197351524565842344/pdf/WP-2017-Low-Carbon-Infrastructure-PPI-PUBLIC.pdf.
World Bank (2019) *World Bank Data Indicator EG.USE.ELEC.KH.PC*: World Bank. Available at: https://data.worldbank.org/indicator/.
World Bank Group (2017) *Climate vulnerability assessment: Making Fiji climate resilient* Washington: World Bank Group120756). Available at: http://documents.worldbank.org/curated/en/163081509454340771/Climate-vulnerability-assessment-making-Fiji-climate-resilient.
WorldByMap (2017) *World By Map version 2017-01-24*: WorldByMap. Available at: http://world.bymap.org/Roadways.html (Accessed: September 28 2019).
Woroniecki, S., Krüger, R., Rau, A. L., Preuss, M. S., Baumgartner, N., Raggers, S., Niessen, L., Holländer, L., Beyers, F., Rathgens, J., Wagner, K. C., Habigt, L., Krause, T., Wamsler, C., von Wehrden, H. and Abson, D. (2019) 'The framing of power in climate change adaptation research', *Wiley interdisciplinary reviews. Climate change,* 10(6), pp. n/a.
Wouters, H., De Ridder, K., Poelmans, L., Willems, P., Brouwers, J., Hosseinzadehtalaei, P., Tabari, H., Vanden Broucke, S., van Lipzig, N. P. M. and Demuzere, M. (2017) 'Heat stress increase under climate change twice as large in cities as in rural areas: A study for a densely populated midlatitude maritime region', *Geophysical Research Letters,* 44(17), pp. 8997-9007.

Wright, L., Chinowsky, P., Strzepek, K., Jones, R., Streeter, R., Smith, J. B., Mayotte, J.-M., Powell, A., Jantarasami, L. and Perkins, W. (2012) 'Estimated effects of climate change on flood vulnerability of US bridges', *Mitigation and Adaptation Strategies for Global Change,* 17(8), pp. 939-955.
Wu, F. and Keil, R. (2020) 'Changing the geographies of sub/urban theory: Asian perspectives', *Urban Geography,* 41(7), pp. 947-953.
Wu, W.-t., Zhou, Y.-x. and Tian, B. (2017) 'Coastal wetlands facing climate change and anthropogenic activities: A remote sensing analysis and modelling application', *Ocean & Coastal Management,* 138, pp. 1-10.
Xiao, X., Seekamp, E., van Der Burg, M. P., Eaton, M., Fatorić, S. and McCreary, A. (2019) 'Optimizing historic preservation under climate change: Decision support for cultural resource adaptation planning in national parks', *Land Use Policy,* 83, pp. 379-389.
Xu, R., Zhao, Q., Coelho, M. S., Saldiva, P. H., Abramson, M. J., Li, S. and Guo, Y. (2020a) 'Socioeconomic level and associations between heat exposure and all-cause and cause-specific hospitalization in 1,814 Brazilian cities: A nationwide case-crossover study', *PLoS medicine,* 17(10), pp. e1003369.
Xu, W. D., Burns, M. J., Cherqui, F. and Fletcher, T. D. (2020b) 'Enhancing stormwater control measures using real-time control technology: a review', *Urban Water Journal,* 18(2), pp. 1-14.
Xue, T., Zhu, T., Peng, W., Guan, T., Zhang, S., Zheng, Y., Geng, G. and Zhang, Q. (2021) 'Clean air actions in China, PM2. 5 exposure, and household medical expenditures: A quasi-experimental study', *PLoS medicine,* 18(1), pp. e1003480.
Yahia, M. W., Johansson, E., Thorsson, S., Lindberg, F. and Rasmussen, M. I. (2018) 'Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania', *International journal of biometeorology,* 62(3), pp. 373-385.
Yang, H., Lee, T. and Juhola, S. (2021) 'The old and the climate adaptation: Climate justice, risks, and urban adaptation plan', *Sustainable Cities and Society,* 67, pp. 102755.
Yang, J., Chang, Y. and Yan, P. (2015) 'Ranking the suitability of common urban tree species for controlling PM2. 5 pollution', *Atmospheric Pollution Research,* 6(2), pp. 267-277.
Yang, J. Q., Kerger, F. and Nepf, H. M. (2015) 'Estimation of the bed shear stress in vegetated and bare channels with smooth beds', *Water Resources Research,* 51(5), pp. 3647-3663.
Yang, S., Xu, K., Milliman, J., Yang, H. and Wu, C. (2015) 'Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes', *Scientific reports,* 5(1), pp. 1-14.
Yankson, P. W. K., Owusu, A. B., Owusu, G., Boakye-Danquah, J. and Tetteh, J. D. (2017) 'Assessment of coastal communities' vulnerability to floods using indicator-based approach: a case study of Greater Accra Metropolitan Area, Ghana', *Natural hazards,* 89(2), pp. 661-689.
Yastika, P., Shimizu, N. and Abidin, H. (2019) 'Monitoring of long-term land subsidence from 2003 to 2017 in coastal area of Semarang, Indonesia by SBAS DInSAR analyses using Envisat-ASAR, ALOS-PALSAR, and Sentinel-1A SAR data', *Advances in Space Research,* 63(5), pp. 1719-1736.
Yesudian, A. and Dawson, R. J. (2021) 'Global analysis of sea level rise risk to airports', *Climate Risk Management,* 31(100266).
Yi, W. and Chan, A. (2017) 'Effects of heat stress on construction labor productivity in Hong Kong: a case study of rebar workers', *International journal of environmental research and public health,* 14(9), pp. 1055.
Yiannakou, A. and Salata, K.-D. (2017) 'Adaptation to climate change through spatial planning in compact urban areas: a case study in the city of Thessaloniki', *Sustainability,* 9(2), pp. 271.
Yin, C., Yuan, M., Lu, Y., Huang, Y. and Liu, Y. (2018) 'Effects of urban form on the urban heat island effect based on spatial regression model', *Science of the Total Environment,* 634, pp. 696-704.
Yin, J., Yu, D., Lin, N. and Wilby, R. L. (2017) 'Evaluating the cascading impacts of sea level rise and coastal flooding on emergency response spatial accessibility in Lower Manhattan, New York City', *Journal of Hydrology,* 555, pp. 648-658.
Yu, P., Xu, R., Abramson, M. J., Li, S. and Guo, Y. (2020) 'Bushfires in Australia: a serious health emergency under climate change', *The Lancet Planetary Health,* 4(1), pp. e7-e8.
Yu, R., Jiang, Z. and Zhai, P. (2016) 'Impact of urban land-use change in eastern China on the East Asian subtropical monsoon: A numerical study', *Journal of Meteorological Research,* 30(2), pp. 203-216.
Yuniartanti, R. K., Handayani, W. and Waskitaningsih, N. (2016) 'Monitoring and evaluation effectiveness in flood early warning system project in Semarang City', *International Journal of Society Systems Science,* 8(1), pp. 49-77.
Zaidi, R. Z. (2018) 'Beyond the Sendai indicators: application of a cascading risk lens for the improvement of loss data indicators for slow-onset hazards and small-scale disasters', *International Journal of Disaster Risk Reduction,* 30, pp. 306-314.
Zander, K. K., Botzen, W. J. W., Oppermann, E., Kjellstrom, T. and Garnett, S. T. (2015) 'Heat stress causes substantial labour productivity loss in Australia', *Nature Climate Change,* 5, pp. 647.
Zander, K. K. and Mathew, S. (2019) 'Estimating economic losses from perceived heat stress in urban Malaysia', *Ecological Economics,* 159, pp. 84-90.
Zardo, L., Geneletti, D., Pérez-Soba, M. and Van Eupen, M. (2017) 'Estimating the cooling capacity of green infrastructures to support urban planning', *Ecosystem Services,* 26, pp. 225-235.
Zerbo, A., Delgado, R. C. and González, P. A. (2020) 'Vulnerability and everyday health risks of urban informal settlements in Sub-Saharan Africa', *Global Health Journal,* 42(2), pp. 46-50.

Zhang, X., Chen, N., Sheng, H., Ip, C., Yang, L., Chen, Y., Sang, Z., Tadesse, T., Lim, T. P. Y. and Rajabifard, A. (2019) 'Urban drought challenge to 2030 sustainable development goals', *Science of the Total Environment,* 693, pp. 133536.

Zhang, X., Zhao, X., Li, R., Mao, G., Tillotson, M. R., Liao, X., Zhang, C. and Yi, Y. (2020) 'Evaluating the vulnerability of physical and virtual water resource networks in China's megacities', *Resources, Conservation and Recycling,* 161, pp. 104972.

Zhang, Y., West, J. J., Mathur, R., Xing, J., Hogrefe, C., Roselle, S. J., Bash, J. O., Pleim, J. E., Gan, C.-M. and Wong, D. C. (2018) 'Long-term trends in the ambient PM 2.5-and O 3-related mortality burdens in the United States under emission reductions from 1990 to 2010', *Atmospheric chemistry and physics,* 18(20), pp. 15003-15016.

Zhao, G., Gao, H., Kao, S.-C., Voisin, N. and Naz, B. S. (2018a) 'A modeling framework for evaluating the drought resilience of a surface water supply system under non-stationarity', *Journal of Hydrology,* 563, pp. 22-32.

Zhao, H., Qu, S., Liu, Y., Guo, S., Zhao, H., Chiu, A. C. F., Liang, S., Zou, J.-P. and Xu, M. (2020) 'Virtual water scarcity risk in China', *Resources, Conservation and Recycling,* 160, pp. 104886.

Zhao, H., Roberts, H. and Ludy, J. (2014) *Coastal green infrastructure research plan for New York City*. Available at: https://www.dec.ny.gov/docs/remediation_hudson_pdf/cginyc.pdf.

Zhao, L., Oleson, K., Bou-Zeid, E., Krayenhoff, E. S., Bray, A., Zhu, Q., Zheng, Z., Chen, C. and Oppenheimer, M. (2021) 'Global multi-model projections of local urban climates', *Nature Climate Change,* 11(2), pp. 152-157.

Zhao, L., Oppenheimer, M., Zhu, Q., Baldwin, J. W., Ebi, K. L., Bou-Zeid, E., Guan, K. and Liu, X. (2018b) 'Interactions between urban heat islands and heat waves', *Environmental research letters,* 13(3), pp. 034003.

Zhao, Y., Sultan, B., Vautard, R., Braconnot, P., Wang, H. J. and Ducharne, A. (2016) 'Potential escalation of heat-related working costs with climate and socioeconomic changes in China', *Proceedings of the National Academy of Sciences,* 113(17), pp. 4640.

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., Li, H., Li, X., Peng, L. and Qi, J. (2018a) 'Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions', *Atmospheric Chemistry and Physics,* 18(19), pp. 14095-14111.

Zheng, F., Westra, S. and Sisson, S. A. (2013) 'Quantifying the dependence between extreme rainfall and storm surge in the coastal zone', *Journal of Hydrology,* 505, pp. 172-187.

Zheng, Y., Xin-Lu, X. I. E., Chen-Zhen, L. I. N., Mou, W. and Xiao-Jia, H. E. (2018b) 'Development as adaptation: Framing and measuring urban resilience in Beijing', *Advances in Climate Change Research,* 9(4), pp. 234-242.

Zhou, Q. (2014) 'A review of sustainable urban drainage systems considering the climate change and urbanization impacts', *Water,* 6(4), pp. 976-992.

Zhou, Q., Leng, G., Su, J. and Ren, Y. (2019) 'Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation', *Science of The Total Environment,* 658, pp. 24-33.

Zhu, L., Huguenard, K., Zou, Q.-P., Fredriksson, D. W. and Xie, D. (2020) 'Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies', *Coastal Engineering,* 160, pp. 103737.

Zia, A. and Wagner, C. H. (2015) 'Mainstreaming Early Warning Systems in Development and Planning Processes: Multilevel Implementation of Sendai Framework in Indus and Sahel', *International Journal of Disaster Risk Science,* 6(2), pp. 189-199.

Ziegler, A. D., Cantarero, S. I., Wasson, R. J., Srivastava, P., Spalzin, S., Chow, W. T. L. and Gillen, J. (2016) 'A clear and present danger: Ladakh's increasing vulnerability to flash floods and debris flows', *Hydrological Processes,* 30(22), pp. 4214-4223.

Ziervogel, G. (2019a) 'Building transformative capacity for adaptation planning and implementation that works for the urban poor: Insights from South Africa', *Ambio,* 48, pp. 494–506.

Ziervogel, G. (2019b) *Unpacking the Cape Town Drought: Lessons Learnt*: African Centre for Cities. Available at: https://www.africancentreforcities.net/wp-content/uploads/2019/02/Ziervogel-2019-Lessons-from-Cape-Town-Drought_A.pdf.

Ziervogel, G. (2020) 'Climate urbanism through the lens of informal settlements', *Urban Geography*, pp. 1-5.

Ziervogel, G., Cowen, A. and Ziniades, J. (2016) 'Moving from Adaptive to Transformative Capacity: Building Foundations for Inclusive, Thriving, and Regenerative Urban Settlements', *Sustainability,* 8(9).

Ziervogel, G., Pelling, M., Cartwright, A., Chu, E., Deshpande, T., Harris, L., Hyams, K., Kaunda, J., Klaus, B., Michael, K., Pasquini, L., Pharoah, R., Rodina, L., Scott, D. and Zweig, P. (2017) 'Inserting rights and justice into urban resilience: a focus on everyday risk', *Environment and Urbanization,* 29(1), pp. 123-138.

Ziervogel, G., Waddell, J., Smit, W. and Taylor, A. (2016) 'Flooding in Cape Town's informal settlements: barriers to collaborative urban risk governance', *South African Geographical Journal,* 98(1), pp. 1-20.

Ziter, C. (2016) 'The biodiversity–ecosystem service relationship in urban areas: a quantitative review', *Oikos,* 125(6), pp. 761-768.

Ziter, C. D., Pedersen, E. J., Kucharik, C. J. and Turner, M. G. (2019) 'Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer', *Proceedings of the National Academy of Sciences,* 116(15), pp. 7575-7580.

Zittis, G., Hadjinicolaou, P., Almazroui, M., Bucchignani, E., Driouech, F., El Rhaz, K., Kurnaz, L., Nikulin, G., Ntoumos, A. and Ozturk, T. (2021) 'Business-as-usual will lead to super and ultra-extreme heatwaves in the Middle East and North Africa', *npj Climate and Atmospheric Science,* 4(1), pp. 1-9.
Zscheischler, J. and Seneviratne, S. I. (2017) 'Dependence of drivers affects risks associated with compound events', *Science Advances,* 3(6), pp. e1700263.
Zscheischler, J., Westra, S., Van Den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M. and Wahl, T. (2018) 'Future climate risk from compound events', *Nature Climate Change,* 8(6), pp. 469.
Zuccaro, G., De Gregorio, D. and Leone, M. F. (2018) 'Theoretical model for cascading effects analyses', *International journal of disaster risk reduction,* 30, pp. 199-215.
Zwierzchowska, I., Fagiewicz, K., Poniży, L., Lupa, P. and Mizgajski, A. (2019) 'Introducing nature-based solutions into urban policy–facts and gaps. Case study of Poznań', *Land Use Policy,* 85, pp. 161-175.
Ürge-Vorsatz, D., Herrero, S. T., Dubash, N. K. and Lecocq, F. (2014) 'Measuring the co-benefits of climate change mitigation', *Annual Review of Environment and Resources,* 39, pp. 549-582.
Ürge-Vorsatz, D., Rosenzweig, C., Dawson, R. J., Sanchez Rodriguez, R., Bai, X., Barau, A. S., Seto, K. C. and Dhakal, S. (2018) 'Locking in positive climate responses in cities', *Nature Climate Change,* 8(3), pp. 174-177.

Chapter 7: Health, Wellbeing, and the Changing Structure of Communities

Coordinating Lead Authors: Guéladio Cissé (Mauritania/Switzerland/France), Robert McLeman (Canada)

Lead Authors: Helen Adams (United Kingdom), Paulina Aldunce (Chile), Kathryn Bowen (Australia), Diarmid Campbell-Lendrum (United Kingdom), Susan Clayton (USA), Kristie L. Ebi (USA), Jeremy Hess (USA), Cunrui Huang (China), Qiyong Liu (China), Glenn McGregor (United Kingdom/New Zealand), Jan Semenza (Italy), Maria Cristina Tirado (USA/Spain)

Contributing Authors: Nicola Banwell (Australia), Rachel Bezner Kerr (Canada/USA,), Katrin Burkart (USA), Marlies Craig (South Africa), Ashlee Cunsolo (Canada), Michael Davies (United Kingdom), Susan Elliott (Canada), Elisabeth Gilmore (USA/Canada), Sherilee Harper (Canada), John Ji (China), Rhys Griffith Jones (New Zealand), Saori Kitabatake (Japan), Krishna Krishnamurthy (Mexico), Ronald Law (Philippines), Wei Ma (China), Angelo Maggiore (Italy), Amina Maharjan (Nepal), Gerardo Sanchez Martinez (Spain), Júlia Alves Menezes (Brazil), Naho Mirumachi (Japan), Virginia Murray (United Kingdom), Jacques Andre Ndione (Senegal), Hannah Neufeld (Canada), Lena Maria Nilsson (Sweden), Nick Obradovich (Germany), Jennifer J Otten (USA), Revati Phalkey (India), Joacim Rocklöv (Sweden), Andrea Rother (South Africa), Sonia Salas (Chile), Amiera Sawas (United Kingdom), Daniel Schensul (USA), Sam Sellers (USA), Yona Sipos (USA/Canada), Marco Springmann (Germany), Jeff Stanaway (USA), Janet Swim (USA), J.L. Vivero-Pol (Italy), Nick Watts (Australia)

Review Editors: Bettina Menne (Italy/Germany), Sergey Semenov (Russian Federation), Jean-François Toussaint (France)

Chapter Scientists: Christopher Boyer (USA), Nikhil Ranadive (USA)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Climate-related illnesses, premature deaths, malnutrition in all its forms, and threats to mental health and wellbeing are increasing *(very high confidence[1])*. Climate hazards are a growing driver of involuntary migration and displacement (*high confidence*) and are a contributing factor to violent conflict *(high confidence)*. These impacts are often interconnected, are unevenly distributed across and within societies, and will continue to be experienced inequitably (*very high confidence*). Cascading and compounding risks affecting health due to extreme weather events have been observed in all inhabited regions, and risks are expected to increase with further warming (*very high confidence*). [7.1.3, 7.1.4, Cross-Chapter Box COVID in Chapter 7, 7.2.1, 7.2.2, 7.2.3, 7.2.4, 7.3.1, 7.3.2, 7.3.3, 7.4.1, 7.4.4, Cross-Chapter Box HEALTH in Chapter 7, Cross-Capter Box ILLNESS in Chapter 2]

Since AR5, new evidence and awareness of current impacts and projected risk of climate change on health, wellbeing, migration, and conflict emerged, including greater evidence of the detrimental impacts of climate change on mental health (*very high confidence*). New international agreements were reached on climate change (Paris Agreement), disaster risk reduction (Sendai Agreement), sustainable development (the SDGs), urbanisation (The New Urban Agenda), migration (Global Compact for Safe, Orderly and Regular Migration), and refugees (Global Compact on Refugees) that, if achieved, would reduce the impacts of climate change on health, wellbeing, migration, and conflict (*very high confidence*). However, the challenges with implementing these agreements are highlighted by the COVID-19 pandemic, which exposed systemic weaknesses, at community, national, and international levels in the ability of societies to anticipate and respond to global risks *(high confidence)*. Incremental changes in policies and strategies have proven insufficient to reduce climate-related risks to health, wellbeing, migration, and conflict, highlighting the value of more integrated approaches and frameworks for solutions across systems and sectors that are embodied in these new international agreements *(high confidence)* [7.1.3, 7.2.1, 7.4.1, 7.4.2, 7.4.3, 7.4.6, Cross-Chapter Box COVID in Chapter 7]

With proactive, timely, and effective adaptation, many risks for human health and wellbeing could be reduced and some potentially avoided (*very high confidence*). A significant adaptation gap exists for human health and well-being and for responses to disaster risks (*very high confidence*). Most Nationally Determined Contributions to the Paris Agreement from low- and middle-income countries identify health as a priority concern. National planning on health and climate change is advancing, but the comprehensiveness of strategies and plans need to be strengthened and implementing action on key health and climate change priorities remains challenging *(high confidence)*. Multisectoral collaboration on health and climate change policy is evident, with uneven progress, and financial support for health adaptation is only 0.5% of dispersed multilateral climate finance projects *(high confidence)*. This level of investment is insufficient to protect population health and health systems from most climate-sensitive health risks (*very high confidence*) [7.4.1, 7.4.2, 7.4.3].

Climate resilient development has a strong potential to generate substantial co-benefits for health and wellbeing, and to reduce risks of involuntary displacement and conflict (*very high confidence*). Sustainable and climate-resilient development that decreases exposure, vulnerability, and societal inequity, and that increases timely and effective adaptation and mitigation more broadly, has the potential to reduce but not necessarily eliminate climate change impacts on health, wellbeing, involuntary migration, and conflict *(high confidence)*. This development includes, but is not limited to, greenhouse gas emissions reductions through: clean energy and transport; climate resilient urban planning; sustainable food systems that lead to healthier diets; universal access to health care and social protection systems; wide-scale, proactive adaptive capacity building for climate change; and, achievement of the Sustainable Development Goals *(very high confidence)*. Meeting the objectives of the Global Compact for Safe, Orderly, and Regular Migration, and building inclusive and integrative approaches to climate resilient peace would help prevent health risks related to migration and conflict (*high agreement, medium evidence*)**.** The net global financial gains from these co-benefits to health and well-being, including avoided hospitalizations, morbidity, and

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

premature deaths, exceed the financial costs of mitigation (*high confidence*) As an example of co-benefits, the financial value of health benefits from improved air quality alone is projected to be greater than the costs of meeting the goals of the Paris Agreement *(high confidence)*. All pathways to climate resilient development, including those for the health and healthcare systems, involve balancing complex synergies and trade-offs between development pathways and the options that underpin climate mitigation and adaptation pathways (*very high confidence*). [7.4.6, Cross-Capter Box HEALTH in Chapter 7, Cross-Chapter Box MIGRATE in Chapter 7].

Key transformations are needed to facilitate climate resilient development pathways for health, well-being, migration and conflict avoidance *(high confidence)*. The transformational changes will be more effective if they are responsive to regional, local, and Indigenous Knowledge, and consider the many dimensions of vulnerability, including those that are gender- and age-specific *(high confidence)*. A key pathway toward climate resilience in the health sector is universal access to primary health care, including mental health care (*high confidence*). Investments in other sectors and systems that improve upon the social determinants of health have the potential to reduce vulnerability to climate-related health risks (*high confidence*). Links between climate risks, adaptation, migration, and labour markets highlight the value of providing better mobility options as part of transformative change *(medium confidence)*. Strong governance and gender-sensitive approaches to natural resource management reduce the risk of intergroup conflict in climate-disrupted areas *(medium confidence).* [7.4.6, Cross-Chapter Box COVID in Chapter 7, Cross-Chapter Box HEALTH in Chapter 7, Cross-Chapter Box GENDER in Chapter 18, Cross-Chapter Box INDIG in Chapter 18, Cross-Capter Box MIGRATE in Chapter 7]

Observed Impacts

Climate hazards are increasingly contributing to a growing number of adverse health outcomes (including communicable and non-communicable diseases) in multiple geographical areas *(very high confidence)*. The net impacts are largely negative at all scales *(very high confidence),* and there are very few examples of beneficial outcomes from climate change at any scale *(high confidence)*. While malaria incidence has declined globally due to non-climatic socio-economic factors and health system responses, a shift to higher altitudes has been observed as the climate warms *(very high confidence)*. Climate variability and change (including temperature, relative humidity, and rainfall) and population mobility are significantly and positively associated with observed increases in dengue globally, chikungunya virus in Asia, Latin America, North America, and Europe *(high confidence)*, Lyme disease vector *Ixodes scapularis* in North America *(high confidence)*, and Lyme disease and Tick-Borne Encephalitis vector *Ixodes ricinus* in Europe *(medium confidence)*. Higher temperatures (*very high confidence*), heavy rainfall events *(high confidence),* and flooding *(medium confidence)* are associated with an increase of diarrheal diseases in affected regions, including cholera *(very high confidence)*, other gastro-intestinal infections *(high confidence)*, and foodborne diseases due to Salmonella and Campylobacter *(medium confidence).* Floods have led to increases in vector-borne and water-borne diseases and to disturbances of public health services *(high confidence)*. Climate extremes increase the risks of several types of respiratory tract infections *(high confidence)*. Climate-related extreme events such as wildfires, storms, and floods are followed by increased rates of mental illness in exposed populations (*very high confidence*). [7.2.1, 7.2.2, 7.2.3, 7.2.4, 7.2.5]

Several chronic, non-communicable respiratory diseases are climate-sensitive based on their exposure pathways (e.g., heat, cold, dust, small particulates, ozone, fire smoke, and allergens) *(high confidence),* although climate change is not the dominant driver in all cases. Worldwide, rates of adverse health impacts associated with small particulate matter exposure have decreased steadily due to decreasing primary emissions *(very high confidence)*, while rates of adverse health impacts from ozone air pollution exposure have increased *(very high confidence)***.** Exposure to wildland fires and associated smoke has increased in several regions (*very high confidence*). Spring pollen season start dates in northern mid-latitudes are occurring earlier due to climate change, increasing the risks of allergic respiratory diseases *(high confidence)*. [7.2.3.2.]

Heat is a growing health risk due to burgeoning urbanization, an increase in high temperature extremes, and demographic changes in countries with aging populations *(very high confidence)*. Potential hours of work lost due to heat has increased significantly over the past two decades (*high confidence*). Some regions are already experiencing heat stress conditions at or approaching the upper limits of labour productivity *(high confidence).* A significant proportion of warm season heat-related mortality in temperate regions is linked to observed anthropogenic climate change, (*medium confidence*) but greater evidence is required for tropical regions. For some heatwave events over the last two decades, associated health impacts can be at least partially attributed to observed climate change (*high confidence*). Extreme heat has negative impacts on mental health, wellbeing, life satisfaction, happiness, cognitive performance, and aggression (*medium confidence*). [7.2.4.1, 7.2.4.5]

Climate variability and change contribute to food insecurity, which can lead to malnutrition, including undernutrition, overweight, obesity; and to disease susceptibility in low- and middle-income countries (*high confidence*). Populations exposed to extreme weather and climate events may consume inadequate or insufficient food, leading to malnutrition and increasing the risk of disease (*high confidence*). Children and pregnant women experience disproportionately greater adverse nutrition and health impacts *(high confidence)*. Climatic influences on nutrition are strongly mediated by socio-economic factors (*very high confidence*). [7.2.4.4, 7.3.1]

Extreme climate events act as both direct drivers (e.g., destruction of homes by tropical cyclones) and as indirect drivers (e.g., rural income losses during prolonged droughts) of involuntary migration and displacement *(very high confidence).* Most documented examples of climate-related displacement occur within national boundaries, with international movements occurring primarily within regions, particularly between countries with contiguous borders *(high confidence)*. Global statistics collected since 2008 by the Internal Displacement Monitoring Centre show an annual average of over 20 million people internally displaced by weather-related extreme events, with storms and floods the most common drivers *(high confidence).* The largest absolute number of people displaced by extreme weather each year occurs in Asia (South, Southeast and East), followed by sub-Saharan Africa, but small island states in the Caribbean and South Pacific are disproportionately affected relative to their small population size (*high confidence*). Immobility in the context of climate risks can reflect vulnerability and lack of agency but can also be a deliberate choice of people to maintain livelihoods, economic considerations and social and cultural attachments to place (*high confidence*). [7.2.6, Cross-Chapter Box MIGRATE in Chapter 7].

Climate hazards have affected armed conflict within countries (medium confidence), but the influence of climate is small compared to socio-economic, political, and cultural factors *(high confidence).* Climate increases conflict risk by undermining food and water security, income and livelihoods, in situations where there are large populations, weather-sensitive economic activities, weak institutions and high levels of poverty and inequality *(high confidence).* In urban areas, food and water insecurity and inequitable access to services has been associated with civil unrest where there are weak institutions *(medium confidence)*. Climate hazards are associated with increased violence against women, girls and vulnerable groups and the experience of armed conflict is gendered *(medium confidence)*. Adaptation and mitigation projects implemented without consideration of local social dynamics have exacerbated non-violent conflict *(medium confidence)*. [7.2.7]

Projected Risks and Vulnerabilities

A significant increase in ill health and premature deaths from climate-sensitive diseases and conditions is projected due to climate change *(high confidence)*. An excess of 250,000 deaths per year by 2050 attributable to climate change are projected just due to heat, undernutrition, malaria, and diarrheal disease, with more than half of this excess mortality projected for Africa (compared to a 1961-1991 baseline period, for a mid-range emissions scenario) *(high confidence)*. Risks for heat-related morbidity and mortality, ozone-related mortality, malaria, diseases carried by Aedes sp. mosquitoes, Lyme disease, and West Nile fever, with the temperature at which risk transitions occur, from moderate to high to very high, contingent on future development pathways *(high confidence)*. [7.3.1]

Climate change is projected to significantly increase population exposure to heat waves (*very high confidence*). Models suggest exposure increases 16 times under RCP4.5/SSP3 and 36 times under RCP8.5/SSP3, with the impact of warming amplified under development pathways that do not foster sustainable development. Globally, the impact of projected climate change on temperature-related mortality is expected to be a net increase under RCP4.5 to RCP8.5, even with adaptation (*high confidence).* Strong geographical differences in heat-related mortality are projected to emerge later this century, mainly driven by growth in regions with tropical and subtropical climates *(very high confidence).* [7.3.1]

The burdens of several climate-sensitive food-borne, water-borne, and vector-borne diseases are projected to increase under climate change, assuming no additional adaptation *(very high confidence)*. The distribution and intensity of transmission of malaria is expected to decrease in some areas and increase in others, with increases projected mainly along the current edges of its geographic distribution in endemic areas of Sub-Saharan Africa, Asia, and South America *(high confidence)*. Dengue risk will increase, with a larger spatio-temporal distribution in Asia, Europe, and sub-Saharan Africa under RCPs 6.0 and 8.5, potentially putting another 2.25 billion people at risk *(high confidence).* Higher incidence rates are projected for Lyme disease in the northern hemisphere *(high confidence)* and for transmission of *Schistosoma mansoni* in eastern Africa *(high confidence)*. [7.3.1, Cross-Chapter Box ILLNESS in Chapter 2]

Increasing atmospheric concentrations of carbon dioxide and climate change are projected to increase diet-related risk factors and related non-communicable diseases globally, and increase undernutrition, stunting, and related childhood mortality particularly in Africa and Asia, with outcomes depending on the extent of mitigation and adaptation *(high confidence)*. These projected changes are expected to slow progress towards eradication of child undernutrition and malnutrition *(high confidence)*. Higher atmospheric concentrations of carbon dioxide reduce the nutritional quality of wheat, rice, and other major crops, potentially affecting millions of people at a doubling of carbon dioxide *(very high confidence)* [7.3.1].

Climate change is expected to have adverse impacts on wellbeing and to further threaten mental health (*very high confidence*). Children and adolescents, particularly girls, as well as people with existing mental, physical, and medical challenges and elderly people, are particularly at risk. Mental health impacts are expected to arise from exposure to high temperatures, extreme weather events, displacement, malnutrition, conflict, climate-related economic and social losses, and anxiety and distress associated with worry about climate change (*very high confidence*) [7.3.1.11]

Future climate-related migration is expected to vary by region and over time, according to future climatic drivers, patterns of population growth, adaptive capacity of exposed populations, and international development and migration policies (*high confidence*). The wide range of potential outcomes is reflected in model projections of population displacements by 2050 in Latin America, Sub-Saharan Africa and South Asia due to climate change, which vary from 31 million to 143 million people, depending on assumptions made about future emissions and socio-economic development trajectories *(high confidence)*. With every additional one degree Celsius of warming, the global risks of involuntary displacement due to flood events have been projected to rise by approximately 50% *(high confidence)*. High emissions/low development scenarios raise the potential for higher levels of migration and involuntary displacement *(high confidence)* and increase the need for planned relocations and support for people exposed to climate extremes but lacking the means to move (*high confidence*) [7.3.2, Cross-Chapter Box MIGRATE in Chapter 7].

Climate change may increase susceptibility to violent conflict, primarily intrastate conflicts, by strengthening climate-sensitive drivers of conflict *(medium confidence)*. Future violent conflict risk is highly mediated by socio-economic development trajectories (high confidence) and so trajectories that prioritise economic growth, political rights and sustainability are associated with lower conflict risk *(medium confidence)*. Future climate change may exceed adaptation limits and generate new causal pathways not observed under current climate variability *(medium confidence).* Economic shocks are currently not included in the models used and some projections do not incorporate known socio-economic predictors of conflict *(medium confidence)*. As such, future increases in conflict-related deaths with climate change have been estimated, but results are inconclusive *(medium confidence)*.

Solutions

Since AR5, the value of cross-sectoral collaboration to advance sustainable development has been more widely recognized, but despite acknowledgement of the importance of health adaptation as a key component, action has been slow *(high confidence)*. Building climate resilient health systems will require multi-sectoral and multisystem and collaborative efforts at all governance scales (*very high confidence*)

[7.4.1, 7.4.2]. Globally, health systems are poorly resourced in general, and their capacity to respond to climate change is weak, with mental health support being particularly inadequate (*very high confidence*). The health sectors of some countries have focused on implementing incremental changes to policies and measures to fill the adaptation gap (*very high confidence*). As the likelihood of dangerous risks to human health continue to increase, there is greater need for transformational changes to health and other systems (*very high confidence*). This highlights an urgent and immediate need to address the wider interactions between environmental change, socioeconomic development, and human health and wellbeing *(high confidence)*. [7.4.1, 7.4.2, 7.4.3]

Targeted investments in health and other systems, including multi-sectoral, integrated approaches, to protect against key health risks can effectively increase resilience (*high confidence*). Increased investment in strengthening general health systems, along with targeted investments to enhance protection against specific climate-sensitive exposures (e.g., hazard early warning and response systems, and integrated vector control programs for vector-borne diseases) will increase resilience, if implemented to at least keep pace with climate change *(high confidence).*

- The future effects of climate change on vector borne diseases can be significantly offset through enhanced commitment to and implementation of integrated vector control management approaches, disease surveillance, early warning systems, and vaccine development *(very high confidence).* [7.4.1, 7.4.2]
- Adaptation options for future climate risks associated with water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved (including expanded) early warning systems *(very high confidence).* [7.4.1, 7.4.2]
- Adaptation options for future extreme heat risks include heat action plans that incorporate early warning and response systems for urban and non-urban settings; tried, tested, and iteratively updated response strategies targeting both the general population and vulnerable groups such as older adults or outside workers; and effective stakeholder communication plans (*high confidence*). These short-term responses can be complemented by longer term urban planning and design, including Nature-based Solutions that mitigate urban heat island effects *(high confidence)* [7.4.1, 7.4.2, 7.4.3]
- Adaptation options to reduce the future risks of malnutrition include access to healthy, affordable diverse diets from sustainable food systems *(high confidence)*; health services including maternal, child and reproductive health (*high confidence*); nutrition services, nutrition and shock sensitive social protection, water and sanitation and early warning systems *(high confidence)*; and risk reduction schemes such as insurance *(medium confidence)*. [7.4.2.1.3]

The COVID-19 pandemic has demonstrated the value of coordinated and multi-sectoral planning, social protection systems, safety nets, and other capacities in societies to cope with a range of shocks and stresses *(high confidence)*. The pandemic posed a severe shock to many socio-economic systems, resulting in substantial changes in vulnerability and exposure of people to climate risks (*high confidence*). The pandemic underscores the interconnected and compound nature of risks, vulnerabilities, and responses to emergencies that are simultaneously local and global *(high confidence).* Pathways to climate resilient development can be pursued simultaneously with recovering from the COVID-19 pandemic *(high confidence).* The COVID-19 pandemic has aggravated climate risks, demonstrated the global and local vulnerability to cascading shocks, and illustrated the importance of integrated solutions that tackle ecosystem degradation and structural vulnerabilities in human societies *(high confidence)*. [Cross-Chapter Box COVID in Chapter 7]

Transitioning toward equitable, low-carbon societies has multiple benefits for health and wellbeing *(very high confidence)*. Benefits for health and wellbeing can be gained from wide-spread, equitable access to affordable renewable energy (*high confidence*); active transport (e.g., walking and cycling) (*high confidence*); green buildings and nature-based solutions, such as green and blue urban infrastructure (*high confidence*), and by transitioning to a low-carbon, wellbeing-oriented and equity-oriented economy consistent with the aims of the Sustainable Development Goals *(high confidence)*. Plant-rich diets consistent with international recommendations for healthy diets, could contribute to lower greenhouse gas emissions while also generating health co-benefits, such as reducing ill health related to over-consumption of animal-based products *(high confidence)* [7.4.2*,* Cross-Chapter Box HEALTH in Chapter 7, 7.4.4]

Reducing future risks of involuntary migration and displacement due to climate change is possible through cooperative international efforts to enhance institutional adaptive capacity and sustainable development *(high confidence).* Institutional and cross-sectoral efforts to build adaptive capacity, coupled with policies aimed at ensuring safe and orderly movements of people within and between states, can form part of climate-resilient development pathways that reduce future risks of climate-related involuntary migration, displacement, and immobility *(medium confidence)*. In locations where permanent, government-assisted relocation becomes unavoidable, active involvement of local populations in planning and decision-making increases the likelihood of successful outcomes *(medium confidence)*. People who live on small island states do not view relocation as an appropriate or desirable means of adapting to the impacts of climate change *(high confidence)* [7.4.3, Cross-Chapter Box MIGRATE in Chapter 7]

Adaptation and development build peace in conflict-prone regions by addressing both the drivers of grievances that lead to conflict and vulnerability to climate change *(high confidence).* Environmental peacebuilding through natural resource sharing, conflict-sensitive adaptation, and climate-resilient peacebuilding offer promising avenues to addressing conflict risk but their efficacy is still to be demonstrated through effective monitoring and evaluation *(high confidence)*. However, formal institutional arrangements for natural resource management have been shown to contribute to wider cooperation and peacebuilding *(high confidence)* and gender-based approaches provide underutilised pathways to achieving sustainable peace *(medium confidence)*. Inclusion, cross-issue and cross-sectoral integration in policy and programming, and approaches that incorporate different geographical scales and work across national boundaries, can support climate resilient peace *(high confidence)* [7.4.5; 7.4.6].

7.1 Introduction

This chapter assesses peer-reviewed and selected grey literature published since the IPCC's Fifth Assessment Report (AR5) on the impacts and projected future risks of climate change for health, wellbeing, migration and conflict, taking into consideration determinants of vulnerability and the dynamic structure of human populations and communities. Particular attention is given to potential adaptation challenges and actions, as well as the potential of co-benefits for health associated with mitigation actions. AR5 presented strong evidence-based statements regarding the *likely*[2] impacts of climate change on health, migration, and conflict in two separate chapters on Human Health (Chapter 11) and Human Security (Chapter 12). The present chapter covers all topics found in AR5 Chapter 11 and sections 12.4 (Migration and Mobility Dimensions of Human Security), 12.5 (Climate Change and Armed Conflict), and 12.6 (State Integrity and Geopolitical Rivalry), and provides additional, expanded assessment of mental health impacts, gender dimensions of climate risks, and solution pathways.

7.1.1 Major Health-related Statements in AR5

AR5 stated with very high confidence that the health of human populations is sensitive to climate change (Smith et al., 2014). Specific observations of current impacts included the expansion of the geographical ranges of some diseases into previously unaffected areas and changes in the distributions of some food-, water- and vector-borne diseases *(high confidence)*. Increasing future health risks were projected from injury, disease, and death due to more intense heat waves and fires *(very high confidence)*, undernutrition in poor regions *(high confidence)*, food- and water-borne diseases *(very high confidence),* and vector-borne diseases *(medium confidence)*. AR5 found that climate change is a multiplier of existing health vulnerabilities, including insufficient access to safe water and improved sanitation, food insecurity, and limited access to health care and education, and that the most effective measures to reduce vulnerability in the near term are programmes that implement and improve basic public health *(very high confidence)*. Opportunities for co-benefits from mitigation actions were identified, through such actions as reducing local emission of short-lived climate pollutants from energy systems *(very high confidence)* and transport systems that promote active travel *(high confidence)*. The significant growth in peer-reviewed publications on links between climate change and human health and wellbeing since AR5 allowed for a more detailed and wider reaching assessment in the present chapter and stronger confidence statements for many climate-sensitive health outcomes.

7.1.2 Major Statements About Migration and Conflict in AR5

Key statements made in AR5 Chapter 12 (Human Security) about the impacts of climate change on migration were that climate change will have significant impacts on forms of migration that compromise human security, and that mobility is a widely used strategy to maintain livelihoods in response to social and environmental changes (*high agreement, medium evidence*). Research on the influence of climate change and climate extremes on multiple forms of migration (including voluntary migration, involuntary displacement, and immobility) has expanded significantly since AR5, which has allowed for a more robust assessment in this chapter, with migration also featuring in most other sectoral and regional chapters of this report as well. With respect to violent conflict, AR5 Chapter 12 found that people living in places affected by violent conflict are particularly vulnerable to climate change (*medium evidence, high agreement*), that some of the factors that increase the risk of violent conflict within states are sensitive to climate change (*medium evidence, medium agreement*). and that climate change will lead to new challenges to states and will increasingly shape both conditions of security and national security policies (*medium evidence, medium agreement*). As with other subjects assessed in this chapter, there has been significant growth in the number of assessable studies, but there remain shortcomings with respect to the availability of evidence regarding the specific nature of causal linkages and the attributability of particular outcomes to climate events or conditions.

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

7.1.3 Important Developments Since AR5

7.1.3.1 International Agreements

Since AR5, several new international agreements came into effect that have implications for international responses to climate risks assessed in this chapter. The 2015 Paris Agreement, which explicitly mentions health in three separate sections, set new goals for adaptation, and established a working group to study the effects of climate change on population displacement. The seventeen United Nations (UN) Sustainable Development Goals (SDGs) for 2030, adopted in 2015, are all important for building adaptive capacity in general, with goals 13 ("Climate Action") and 3 ("Good Health and Wellbeing") being directly relevant for this chapter. Other SDG goals contain specific targets that are also relevant for this chapter, including Target 10.7 ("Well-managed migration policies"), Target 8.3 ("Decent work for all") and Target 5.4 ("Promotion of peaceful and inclusive societies") (Piper, 2017). The 2015 Sendai Framework for Disaster Risk Reduction, puts an emphasis on health and wellbeing (Aitsi-Selmi and Murray, 2016) In 2018, UN members states negotiated Global Compacts for Safe, Orderly and Regular Migration and on Refugees that, taken together with the Paris Agreement, provide pathways for coordinated international responses to climate-related migration and displacement (Warner, 2018). Since AR5, the UN system has been reforming its Peace and Security agenda, as part of a larger series of reforms initiated by the Secretary-General in 2017, and under the 2018 Climate Security Mechanism.

7.1.3.2 IPCC Special Reports

All three post-AR5 IPCC Special Reports considered some of the research that is assessed here in greater detail. The 2018 report on 1.5° C (SR1.5) included a review of climate change and health literature published since AR5 and called for further efforts for protecting health and wellbeing of vulnerable people and regions (Ebi et al., 2018b), and highlighted links between climate change hazards, poverty, food security, migration, and conflict. The 2019 Special Report on Climate Change and Land (SRCCL) (SRCCL, 2019) emphasized the impacts of climate change on food security; highlighted links between reduced resilience of dryland populations, land degradation migration, and conflict; and raised concerns about the impacts of climate extremes. The 2019 Special Report on the Ocean and Cryosphere in a Changing Climate (Pörtner et al., 2019) detailed how changes in the cryosphere and ocean systems have impacted people and ecosystem services, particularly food security, water resources, water quality, livelihoods, health and wellbeing, infrastructure, transportation, tourism, and recreation, as well as the culture of human societies, particularly for Indigenous peoples. It also noted the risks of future displacements due to rising sea levels and associated coastal hazards.

7.1.4 Interpretation of "Health and Wellbeing" Used in This Chapter

Assessing the links between human health, wellbeing, and climate change is a new task for AR6, reflecting a broad perspective on health that increasingly acknowledges the importance of wellbeing and its interactions with individual and population health. The World Health Organization (WHO) defines health as "a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity" (Organization, 1946). Although this chapter assesses physical health, mental health, and general wellbeing separately, they are interconnected; any type of health problem can reduce overall wellbeing, and vice versa. For example, a child receiving inadequate nutrition may not be sick, but is experiencing a clear threat to wellbeing that has implications for future physical and mental health.

There is no consensus definition of wellbeing, but it is generally agreed that it includes a predominance of positive emotions and moods (e.g. happiness) compared with extreme negative emotions (e.g. anxiety), satisfaction with life, a sense of meaning, and positive functioning, including the capacity for unimpaired cognitive functioning and economic productivity (Diener and Tay, 2015) (Piekałkiewicz, 2017). A capabilities approach (Sen, 2001) focuses on the opportunity for people to achieve their goals in life (Vik and Carlquist, 2018) or the ability to take part in society in a meaningful way: the result of personal freedoms, human agency, self-efficacy, an ability to self-actualize, dignity and relatedness to others (Markussen et al., 2018). An Indigenous perspective on wellbeing is broad and typically incorporates a healthy relationship with the natural world (Sangha et al., 2018); emotional and mental health have also been linked to a strong cultural identity (Butler et al., 2019);(Dockery, 2020). "Health" itself is sometimes described as including relationships between humans and nature as well as links to community and culture (Donatuto et al., 2020);(Dudgeon et al., 2017)

Subjective wellbeing is consistently associated with personal indicators such as higher income, greater economic productivity, better physical health (Diener and Tay, 2015);(Delhey and Dragolov, 2016);(De Neve et al., 2013), and environmental health; and associated with societal indicators such as social cohesion and equality (Delhey and Dragolov, 2016). In a global sample of over 1 million people obtained between 2004-2008 via the Gallup World Poll, annual income and access to food were strong predictors of subjective wellbeing, and a healthy environment, particularly access to clean water, was also associated even when household income was controlled (Diener and Tay, 2015). Access to green spaces is also associated with wellbeing (high confidence) (Lovell et al., 2018);(Yuan et al., 2018).

7.1.5 Toward Socio-Ecological Perspectives on Health, Wellbeing, and Loss and Damage

Since the AR5, more comprehensive frameworks for framing and studying global health issues, including planetary health, 'one health', and eco-health, have gained traction. These frameworks share an ecological perspective, emphasize the role of complex systems, and highlight the need for interdisciplinary approaches related to human health research and practice (Lerner and Berg, 2015);(Zinsstag et al., 2018);(Whitmee et al., 2015);(Steffen et al., 2015). These frameworks increasingly shape the evidence related to climate change health impacts and response options, highlight the dynamics of complex systems in risk management, and direct risk management efforts in new directions.

Building on these frameworks and perspectives, there is increasing overlap in literature on global health, climate change impacts, and estimates of loss and damage. The Global Burden of Disease study for 2019 now includes non-optimal temperature as a risk factor (Murray et al., 2020). Work by social scientists continues to explore how climate change indirectly affects resource availability, productivity, migration, and conflict (Burke et al., 2015a);(Carleton and Hsiang, 2016);(Hsiang et al., 2017), bringing multiple lines of inquiry together to study the associations between global environmental changes, socio-economic dynamics, and impacts on health and wellbeing. Morbidity associated with migration and displacement, especially in the context of small island states, has been called out as a non-material form of loss and damage (Thomas and Benjamin, 2020);(McNamara et al., 2021). Social costs of carbon estimates have been updated to include excess mortality associated with climate change, increasing estimates substantially (Dressler, 2021).

7.1.6 Developments Relevant to Tracking and Assessing Climate Change Impacts on Health

Since AR5 there has been a steady increase in standardized, globally scoped, data-driven health impact assessments, signified by the ongoing Global Burden of Disease study (James et al., 2018) that now includes scenario-based projections (Foreman et al., 2018) and its linkages with other global priorities, including the SDGs (Fullman et al., 2017). Attention has turned from prioritizing specific diseases like HIV/AIDS, malaria, and tuberculosis, to strengthening health systems and providing universal health coverage (Chang et al., 2019), accompanying an ongoing emphasis on the social determinants of health. Several climate-sensitive health outcomes are now tracked in the annual Lancet Countdown reports (Watts et al., 2015);(Watts et al., 2017);(Watts et al., 2018b);(Watts et al., 2019);(Watts et al., 2021). The Global Burden of Disease study is beginning to examine climate sensitive disease burdens, incorporate temperature as a risk factor(Murray et al., 2020), and project future cause-specific disease burdens in a warming world (Burkart et al., 2021). Although not assessed in this chapter, there are numerous ongoing assessments of climate change impacts on health and wellbeing being undertaken by national and local health authorities that continue to generate insights into climate-related health impacts and suggest response options relevant for decision makers.

While the knowledge base regarding global health has increased, a comprehensive framework is not in place that fully integrates health, wellbeing, and environmental impacts from climate change allowing for the cumulative assessment of their impact. Moreover, significant cracks in the foundation of global health governance that affect preparedness and adaptive capacity for climate change, among other threats, have been laid bare (Phelan et al., 2020); (Defor and Oheneba-Dornyo, 2020); (Ostergard et al., 2020); (A, 2021). While attention to climate change and health has increased (Watts et al., 2019) and there is evidence of increasing adaptation activity in the health sector (Watts et al., 2019), there is also continued evidence of substantial adaptation gaps (UNEP, 2018);(UNEP, 2021) including gaps in humanitarian response capacity for climate-related disasters (Watts et al., 2021), that appear to be widening as adverse climate change impacts on health and wellbeing accrue.

7.1.7 Hazards, Exposure and Vulnerability in the Context of Human Health, Wellbeing and Changing Structure of Communities

7.1.7.1 Possible Climate Futures and Hazards from AR6 WGI

This chapter uses the conceptual framing described in Chapter 1, in which risks emerging from climate change are described in terms of hazard, exposure, and vulnerability, with adaptation and climate-resilient development being responses that have the potential to reduce or modify risk. The observed and projected future risks to health, wellbeing, involuntary population displacements, and conflict identified in this chapter are associated with a range of hazards that are manifested at a variety of geographical and temporal scales. These include observed and projected changes in climate normals, changes in the frequency, duration, and or severity of extreme events, and hazards such as rising sea levels and extreme temperatures where the impacts have only begun to be widely experienced. The 2021 report of IPCC Working Group I provides an assessment of observed and projected changes in these hazards and is the backdrop against which assessments of future risks and adaptation options identified in the present chapter should be considered. The exposure to such hazards of populations, infrastructure, ecosystem capital, socio-economic systems, and cultural assets critical to health and wellbeing varies considerably across and within regions. Exposure is also projected to vary across and within regions over time, depending on future greenhouse gas (GHG) emissions pathways and development trajectories (Figures 7.1 a and b). For this reason, region-specific assessments of climate-related risks for health, displacement and conflict are found in each of the regional chapters of this report in addition to the general assessment that appears in this chapter.

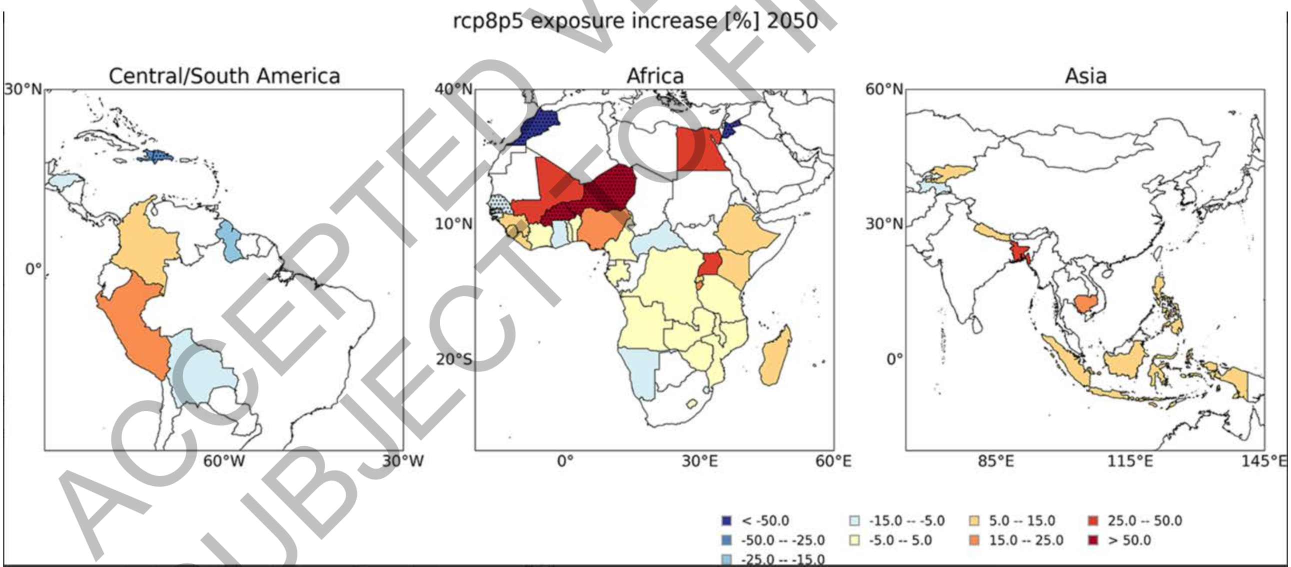


Figure 7.1a: Projected exposure of poor people to floods in selected regions by 2050 under a high emissions scenario (RCP 8.5) (Winsemius et al., 2018)

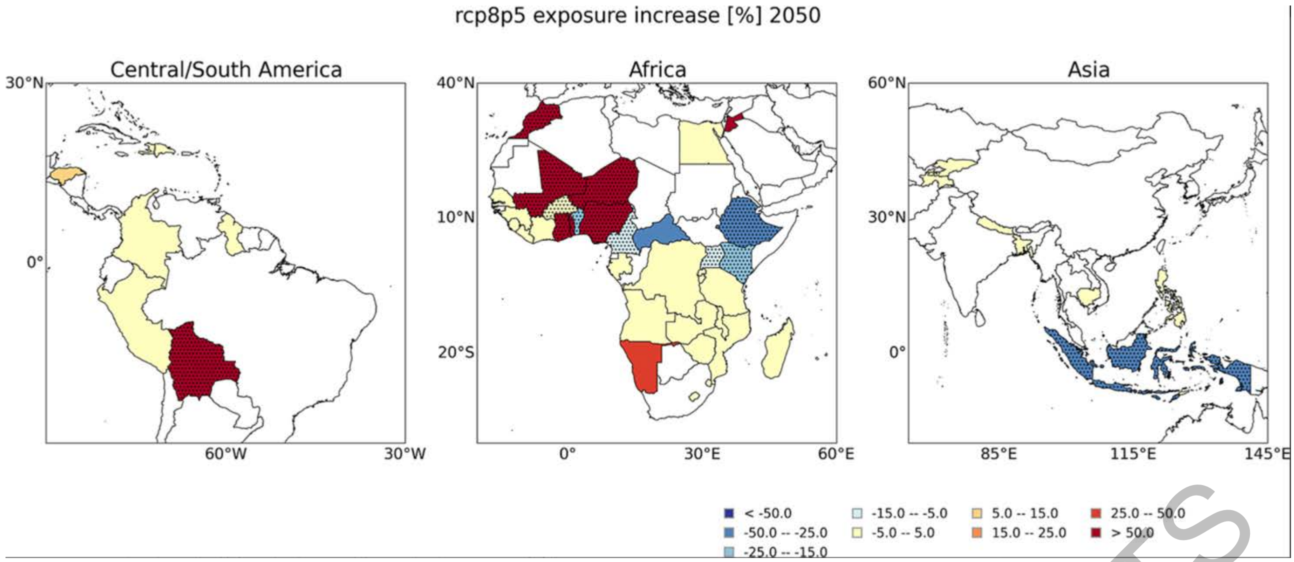


Figure 7.1b: Projected exposure of poor people to droughts in selected regions by 2050 under a high emissions scenario (RCP 8.5) (Winsemius et al., 2018)

7.1.7.2 *Differential Vulnerability and Cascading Effects*

Vulnerability to climate change varies across time and location, across communities, and among individuals within communities, and reflects variations and changes in macro-scale non-climatic factors (such as changes in population, economic development, education, infrastructure, behaviour, technology, and ecosystems) and individual- or household-specific characteristics, such as age, socioeconomic status, access to livelihood assets, pre-existing health conditions and ability, among others (Program, 2016); Chapter 1).

Many direct and indirect effects of climate change pose multiple threats to human health and wellbeing, and can occur simultaneously, resulting in compounding or cascading impacts for vulnerable populations. For example, many of the long-term impacts of climate change on non-communicable diseases and injury described in sections 7.2 and 7.3 are associated with future increases in air temperatures and levels of air pollution; in many regions, and especially in large urban centres in Asia and Africa, these particular hazards are already causing substantial increases in morbidity and mortality due to respiratory illnesses (Tong et al., 2016). Climate change can therefore be expected to magnify such health risks over the long term.

At the same time, urban populations will also be experiencing indirect risks through climate change impacts on food and potable water systems, variations in the distribution and seasonality of infectious diseases, and growing demand for shelter due to increased in-migration. The accumulation of these risks over time can be expected to generate accelerating declines in community resilience and health, with future vulnerability potentially expanding in a non-linear fashion (Dilling et al., 2017);(Liang and Gong, 2017);(El-Zein and Tonmoy, 2017);see also Chapter 6). Further, although each individual risk in isolation may be transitory or temporary for the individuals or groups exposed, taken cumulatively the impacts could create conditions of chronic lack of wellbeing, and early-life experiences with specific illnesses and conditions could have lifelong consequences (Watts et al., 2015);(Otto et al., 2017);(Organization, 2018a). In this context, there is a distinct need for greater longitudinal research on vulnerability to multiple climatic and non-climatic health and wellbeing hazards over time (Fawcett et al., 2017). There is also need for more research to identify critical thresholds in social vulnerability to climate change (Otto et al., 2017); these include rapid, stepwise changes in vulnerability that emerge from changes in exposure (for example, air temperatures above which mortality rates or impacts on pre-natal health accelerate (Arroyo et al., 2016);(Ngo and Horton, 2016);(Abiona, 2017);(Auger et al., 2017); (Molina and Saldarriaga, 2017); (Zhang et al., 2017b)) and thresholds in adaptation processes (such as when rural out-migration rates grow due to climate-related crop failures (McLeman, 2017).

In virtually all of the research identifying particular climate-related risks to health, wellbeing, migration and conflict, specific types of individuals are identified as having higher levels of vulnerability and exposure to climate-related health hazards: people who are impoverished, undernourished, struggle with chronic or repeated illnesses, live in insecure housing in polluted or heavily degraded environments, work in unsafe conditions, are disabled, have limited education, and/or have poor access to health and social infrastructure (Organization, 2018a). Their disproportionate exposure to ongoing climate hazards and their inability to recover from extreme events, increase not only their own vulnerability, but also that of the wider communities in which they live (USGCRP, 2016). Highly vulnerable populations are not evenly distributed across regions (Figure 7.2) nor within countries. Yet even those fortunate enough to live in better neighbourhoods with greater financial means, higher-paying jobs, and good access to resources and services, may experience adverse climate-related outcomes through community-level interactions and linkages (Haines and Ebi, 2019). Increased inequity itself threatens wellbeing, and an effective response to climate change should not only avoid increased inequity but identify ways in which to reduce existing inequity.

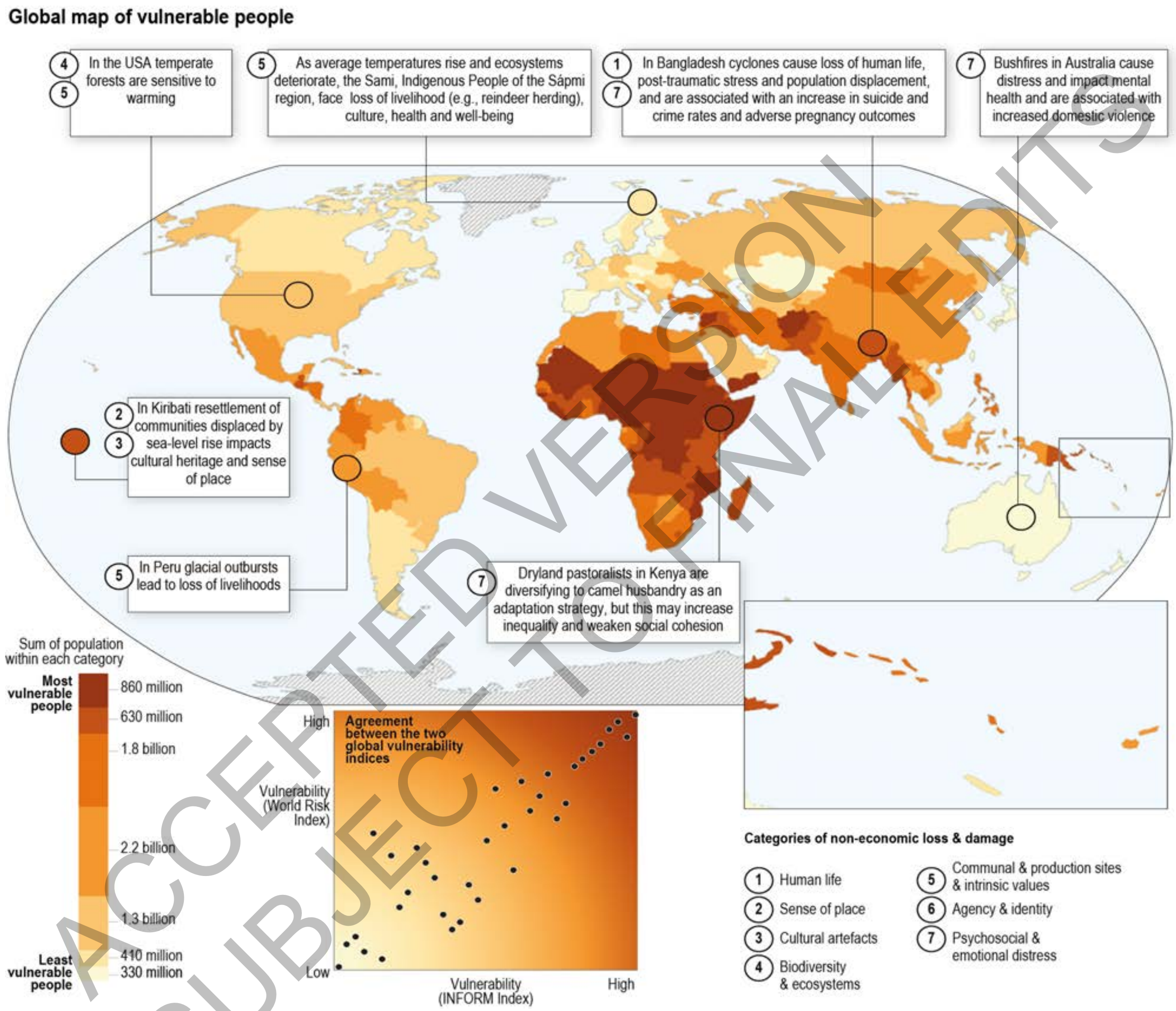


Figure 7.2: Global distribution of vulnerable people from two indices, with examples (from Technical Summary, this report)

7.1.7.3 Heightened Vulnerability to Climate-related Impacts on Health and Wellbeing experienced by specific groups and through specific pathways

7.1.7.3.1 Women and Girls

Climate change poses distinct risks to women’s health. Vulnerability to climate-related impacts on health and wellbeing shows notable differentiations according to gender, beyond implications for pregnant women. In many societies, differential exposure to such risks relate to gendered livelihood practices and mobility options. Pregnancy and maternal status heighten vulnerability to heat, infectious diseases, foodborne infections, and air pollution (Arroyo et al., 2016);(Ngo and Horton, 2016);(Zhang et al., 2017b). Extreme heat events, high ambient temperatures, high concentrations of airborne particulates, water-related illnesses, and natural hazards are associated with higher rates of adverse pregnancy outcomes such as spontaneous abortion, stillbirth, low birth weight, and preterm birth (Arroyo et al., 2016);(Ngo and Horton, 2016);(Abiona, 2017);(Auger et al., 2017);(Molina and Saldarriaga, 2017); (Zhang et al., 2017b). Women and girls are at greater risk of food insecurity (FAO, 2018; (Alston and Akhter, 2016), which is particularly problematic in combination with the nutritional needs associated with pregnancy or breastfeeding. Women and girls are more likely to die in extreme weather events (Garcia and Sheehan, 2016);(Yang et al., 2019). Women are also expected to face a greater mental health burden in a changing climate (Manning and Clayton, 2018). Further, climatic extremes and water scarcity are associated with increases in violence against girls and women (Anwar et al., 2019); (Opondo et al., 2016); (Le Masson et al., 2016);(Udas et al., 2019).

7.1.7.3.2 Children

Children often have unique pathways of exposure and sensitivity to climate hazards, given their immature physiology and metabolism, and high intake of air, food, and water relative to their body weight as compared with adults (USGCRP, 2016). Climate change is expected to increase childhood risks of malnutrition and infectious disease for children in low-income countries through its impacts on household food access, dietary diversity, nutrient quality, water, and changes in maternal and childcare access and breastfeeding (Tirado, 2017);(FAO et al., 2018); (Perera, 2017)). Children living in locations with poor sanitation are especially vulnerable to gastro-intestinal illnesses, with future rates of diarrheal diseases among children expected to rise under many climate change scenarios (Cissé et al., 2018);(WHO, 2014). Outdoor recreational opportunities for children may be reduced by extreme weather events, heat, and poor air quality (Evans, 2019)). Children and adolescents are particularly vulnerable to post-traumatic stress after extreme weather events, and the effects may be long-lasting, with impacts even on their adult functioning (Brown et al., 2017; UNICEF, 2021);(Thiery et al., 2021)

7.1.7.3.3 Elderly

Population age structures and changes over time have a significant influence on vulnerability to the impacts of weather and climate. Older adults (generally defined as persons aged 65 and older) are disproportionately vulnerable to the health impacts associated with climate change and weather extremes, including a greater risk of succumbing to waterborne pathogens, due to less well-functioning thermoregulatory mechanisms, greater sensitivity to dehydration, changes in immune systems, and greater likelihood of having pre-existing chronic illnesses such as diabetes or respiratory, cardiovascular, and pulmonary illnesses (Benmarhnia et al., 2016);(Diaz et al., 2015);(Mayrhuber et al., 2018);(Paavola, 2017). Older adults may be less prompt in seeking medical attention when suffering from gastrointestinal illness, which can lead to dehydration (Haq and Gutman, 2014). Åström et al. (2017) anticipate heat-related mortality among the elderly in Europe to rise in the 2050s under RCP 4.5 and RCP 8.5 in the absence of significant preventative measures. In a study of the combined effects of warming temperatures and an aging population in Korea, Lee & Kim (Lee and Kim, 2016) projected a four- to six-fold increase in heat-related mortality by the 2090s when accounting for temperature and age structure.

7.1.7.3.4 Socio-economically Marginalized Populations and People with Disabilities

People living in poverty are more likely to be exposed to extreme heat and air pollution, and have poorer access to clean water and sanitation, accentuating their exposure to climate change-associated health risks (UNEP, 2021);(FAO et al., 2018). Poverty influences how people perceive the risks to which they are exposed, how they respond to evacuation orders and other emergency warnings, and their ability to evacuate or relocate to a less risk-prone location (USGCRP, 2016). Poorer households, who often live in highly exposed locations, are more likely to be forced into low-agency migration as a means of adapting to climate risks, and at the same time are the most likely to be immobile or trapped in deteriorating circumstances where migration would be a preferred response (Leichenko and Silva, 2014);(Fazey et al., 2016);(Sheller, 2018). Climate emergencies disproportionally affect people with disabilities because of their inherent vulnerabilities, which may impair their ability to take protective action; they are also frequently excluded from adaptation planning (Gaskin et al., 2017)

7.1.7.3.5 Urban vs Rural Populations

Rural and urban populations are often exposed to different types of climate-related health risks. For example, because of the urban heat island and high concentrations of motor vehicle pollution and industrial activity, people who live in urban areas may have higher rates of exposure to extreme heat stress and air-quality-related respiratory illnesses than rural counterparts (Hondula et al., 2014);(Heaviside et al., 2016);(Macintyre et al., 2018);(Schinasi et al., 2018). Conversely, rural populations, especially those dependent on resource-based livelihoods, may have a greater exposure to climate impacts on food production or natural hazard events, which have subsequent effects on household nutrition and food security (Springmann et al., 2016a); see also Chapters 5 & 6 of this report).

7.1.7.3.6 Indigenous People

Indigenous Peoples, especially those that live in geographically isolated, resource-dependent, and/or impoverished communities, are often at greater risk of health impacts of climate change (Ford et al., 2020) (USGCRP, 2016). The close interconnection of land-based livelihoods and cultural identity of many Indigenous groups exposes them to multiple health- and nutrition related hazards (Durkalec et al., 2015);(Sioui, 2019), with potential implications for community social relations and for individuals' mental health (Cunsolo Willox et al., 2013);(Cunsolo Willox et al., 2015). Climate change risk exposures may be complicated by changes in lifestyle, diet, and morbidity driven by socio-economic processes, further increasing health risks for Indigenous peoples (Jaakkola et al., 2018). Environmental consequences of climate change can also affect social ties and spiritual wellbeing, in part because land is often an integral part of their culture and spiritual identity.

[INSERT BOX 7.1 HERE]

Box 7.1: Indigenous Peoples' Health and Wellbeing in a Changing Climate

The Indigenous population worldwide is estimated at 476 million people spread across all geographic regions of the world (CIAT and and, 2021). Indigenous Peoples globally represent a large heterogeneity of people in terms of living conditions and social determinants of health. There is no simple definition of who is Indigenous. In this text, we refer to Indigenous Peoples as people self-identified and organized as Indigenous, according to the principles of the International Work Group for Indigenous Affairs (IWGIA), an International NGO with observer status at the United Nations. In addition, the United Nations describes Indigenous Peoples as "distinct social and cultural groups that share collective ancestral ties to the lands and natural resources where they live, occupy or from which they have been displaced" (Organization, 2021). A common experience among Indigenous Peoples are historical traumas related to overseas and/or settler/industrial colonisation.

Studies on climate change as it affects the health of Indigenous Peoples generally focus on non-displaced Indigenous groups, i.e., Indigenous people maintaining culturally important elements of a land-based traditional lifestyle. Here we use an eco-medicine perspective, in which the impacts of climate change on health are divided into primary, secondary, and tertiary effects; discussed below (Butler and Harley, 2010). Many analyses of Indigenous health in relation to climate change use the One Health concept (Mackenzie and Jeggo, 2019); (see 7.1.5).

Current Impacts of Climate Change on Health and Wellbeing of Indigenous Peoples

Primary health effects of climate change include the immediate physical effects on human health, such as health hazards due to high temperatures, extreme weather events, or accidents from exposure to a climate-related hazards. For example, in arid and semi-arid areas, an increased frequency of severe droughts is associated with immediate health problems related to overheating, and lack of water for drinking, sanitation and livestock (Hall and Crosby, 2020);(Mamo, 2020);(Rankoana, 2021). In many cases, the possibilities for Indigenous people to apply traditional strategies to mitigate droughts by migration are limited by competing land use, environmental protection, and national borders, with many examples across Africa (Mamo, 2020). In the Jordan river valley, the second most water stressed area in the world, water resources are not equally distributed to Indigenous Bedouin people, amplifying their immediate health threat during predictable as well as unpredictable droughts (Mamo, 2020).

In Arctic and sub-Arctic areas, higher temperatures with increased numbers of freeze-thaw cycles during the winter means increased occurrences of transport-related accidents in Indigenous communities due to weaker ice on travel routes that cross lakes, rivers and sea, along with changes in the snow cover and increased risk of avalanches (Durkalec et al., 2015);(Jaakkola et al., 2018). Impeded access to health care during extreme weather conditions is a primary health risk for Indigenous Peoples living in remote areas (Amstislavski et al., 2013);(Hall and Crosby, 2020);(Mamo, 2020).

Pastoralists in many regions may experience changes in livestock behaviour due to climate change, leading to increased mobility-related health hazards (Jaakkola et al., 2018);(Mamo, 2020). Indigenous Peoples living in low lying coastal areas and small island states face long term risk of flooding and the stresses of resettlement (Maldonado et al., 2021);(McMichael and Powell, 2021)).

Extreme rainfall, flooding, storms, heat waves, and wildfires lead to individual health hazards that may include injuries and thermal and respiratory traumas (Mamo, 2020) There are many examples when emergency responses to extreme events have ignored the needs of displaced Indigenous Peoples (Mendez et al., 2020);(Maldonado et al., 2021). Population-based quantitative studies documenting the direct effects of these events on Indigenous Peoples are rare. In Mexico, respiratory diseases are almost twice as common among Indigenous people compared to non-Indigenous (de Leon-Martinez et al., 2020). In Alaska and Northern Canada alarming levels of respiratory stress and disease has been reported among Inuit and First Nation communities in relation to wildfires (Howard et al., 2021), as well as increased mold in houses due to flooding resulting from increased precipitation (Furgal and Seguin, 2006);(Harper et al., 2015);(Norton-Smith et al., 2016). Climate and housing related respiratory stress is also a risk factor for severe COVID-19 infection, which has been highlighted in recent literature from an Indigenous health perspective (de Leon-Martinez et al., 2020).

Secondary effects relate to ecosystem changes, for example, increased risk of the acute spread of airborne, soilborne, vector-borne, food-, and water-borne infectious diseases (Hueffer et al., 2019). Higher proportions of climate-related infectious diseases are reported among Indigenous groups compared to their non-Indigenous neighbours, with examples from Torres Strait, Australia, showing a greater proportion of tuberculosis, dengue, Ross River virus, melioidosis, and nontuberculous mycobacterial infections (Hall et al., 2021) and in the Republic of Sakha, Russia, high levels of zoonoses (Huber et al., 2020a). Increasing levels of livestock and canine diseases are also reported (Mamo, 2020);(Bogdanova et al., 2021);(Hillier et al., 2021). Another secondary health effect is an increase in human-animal conflicts, for example human-elephant conflicts in Namibia due to plant food scarcity (Mamo, 2020), human-bear conflicts in Arctic regions within Canada (Wilder et al., 2017), human-tiger conflicts in Bangladesh (Haque et al., 2015), and increased predatory pressure on Indigenous Peoples' livestock and game worldwide (Haque et al., 2015);(Jaakkola et al., 2018);(Mukeka et al., 2019);(Mamo, 2020);(Terekhina et al., 2021). Undernutrition and metabolic disturbances associated with overnutrition and obesity due to decreased availability or safety of local and traditional foods, and increased dependency on imported substitutes, affect many Indigenous Peoples worldwide (Amstislavski et al., 2013);(Zavaleta et al., 2018);(Houde et al., 2020);(Jones et al., 2020);(Akande et al., 2021);(Bogdanova et al., 2021);(Bryson et al., 2021), especially severe for pregnant women and small children (Mamo, 2020);(Olson and Metz, 2020);(Bryson et al., 2021); these are amplified by the combination of warming and the COVID-19 situation (Zavaleta-Cortijo et al., 2020). Decreased access to wild plants and animals as food sources and medicine due to climate change is another threat to the health and wellness of Indigenous communities (Greenwood and Lindsay, 2019);(Mamo, 2020);(CIAT and and, 2021);(Rankoana, 2021);(Teixidor-Toneu et al., 2021).

Tertiary effects relate to culture-wide changes; for example, all forms of malnutrition due to climate-driven changes in food systems; and anxiety, mental illness, and suicidal thoughts related to cultural and spiritual losses. A wide range of tertiary, culture-related effects of climate change have been documented for Indigenous Peoples. These include anxiety, distress and other mental health impacts due to direct and indirect processes of dispossession of land and culture related to the combination of climate change in and other factors (Richmond and Ross, 2009);(Bowles, 2015);(Norton-Smith et al., 2016);(Jaakkola et al., 2018);(Fuentes et al., 2020);(Mamo, 2020);(Middleton et al., 2020b);(Middleton et al., 2020a);(Olson and Metz, 2020);(Timlin et al., 2021). Increased risks of conflict and abuse, including violence and homicide against females, and/or resulting from environment activism, are other tertiary health threats for Indigenous Peoples (Mamo, 2020). Between 2017 and 2019, close to 500 Indigenous people were killed for activism in 19 different countries (Mamo, 2020). In Uganda, climate change drives Indigenous men to increase their distance and time from home and their families in search of water, food, and water, leading to an increase in sexual violence against Indigenous women and girls in their communities (Mamo, 2020).

Gender inequities amplify the tertiary health effects of climate change (Williams, 2018);(Garnier et al., 2020). In an Inuit community, for instance, women reported a higher level of mental stress related to climate change than men (Harper et al., 2015). Adverse pregnancy outcomes and altered developmental trajectories have also been associated with climate change (Hall et al., 2021). Indigenous Batwa women in Uganda reported experiencing more severe circumstances of food insecurity during pregnancy due to drought and unpredictable seasons negatively impacting agricultural practices (de Leon-Martinez et al., 2020). More studies with a gender perspective on climate change as a determinant of Indigenous Peoples' health are needed, along with the perspectives of Indigenous children and youth, displaced individuals, and communities in urban settings (Kowalczewski and Klein, 2018).

Because cultural continuity is a recognized health factor (Lemelin et al., 2010);(de Leon-Martinez et al., 2020);(Middleton et al., 2020b) displaced Indigenous people may suffer from climate change by worrying about impacts on non-displaced relatives and family, and from traditional food staples turning into expensive commodified products. This is a knowledge gap with lasting implications not only on physical environments (Guo et al., 2018). Social connections and knowledge pathways are disrupted, leading to a decreased ability to share locally harvested and cultivated foods (King and Furgal, 2014);(Neufeld et al., 2020).

Tertiary effects of climate change on Indigenous Peoples' health are primarily described in smaller case studies and not designed in a way allowing for systematic international comparisons, which represents an important and significant gap in our understanding of these often-complex associations and impacts (Middleton et al., 2020b).

Future Risks for Indigenous People's Health and Wellbeing in a Changing Climate

Future risks for Indigenous Peoples' health and wellbeing in a changing climate will result foremost from exacerbations of observed impacts. Primary and secondary health risks are expected to increase as the frequency and/or severity of climate hazards grow in many regions. As one example, melting permafrost in the Siberian Arctic is projected to lead to more outbreaks of anthrax (Bogdanova et al., 2021). Tertiary health threats are expected to persist even with strong global initiatives to mitigate greenhouse gases (Butler and Harley, 2010). Climate change is expected to compound non-climatic processes that lead to social exclusion and land dispossession that underlay health inequalities experienced by Indigenous peoples (Huber et al., 2020a).

Options and Opportunities for Reducing Future Risks and Building Capacity/Resilience for Indigenous Peoples' Health and Wellbeing

Indigenous organizations worldwide stress the importance of applying a rights-based approach in responding to climate change (Mamo, 2020). Although Indigenous Peoples are often identified as being vulnerable to climate change, this framing does not always reflect the diverse responses and adaptations of Indigenous Peoples to these on-going challenges (Nursey-Bray et al., 2020). An emerging body of research is focusing on the strength and resilience of Indigenous communities globally as they adapt to these complex changes (Whyte, 2018);(CIAT and and, 2021).

During droughts and water shortages, for example, Indigenous pastoralists may face additional challenges if water supply assistance provides only for human needs and neglects water requirements of livestock (Mamo, 2020). Indigenous knowledge on how to adapt to drought, through storing and sharing strategies, for example, is valuable (Fatehpanah et al., 2020);(Mamo, 2020).

Indigenous Peoples have been adapting to changes in their environments since time immemorial by developing new practices and techniques (CIAT and and, 2021). Their beliefs, value systems, and principles include core elements and common values such as reciprocity, solidarity, co-responsibility, and community that are expressed in the dynamism of their knowledge systems (Lewis et al., 2020);(Schramm et al., 2020b). The relevance of these knowledge systems, which are holistic and tied to relationships between all living things, cannot be ignored at this critical time (Garnier et al., 2020).

The health and equity impact of climate change for Indigenous Peoples make mitigation efforts critical (Jones et al., 2020), which includes policies and actions consider the effects of colonization. Colonization constrains the design and diversity of potential climate and health responses through its historic and ongoing suppression of Indigenous knowledge systems that are critical in supporting community-led actions to reduce future risks (Billiot et al., 2019; Reid et al., 2019) (Nursey-Bray et al., 2020).

Four Brief Case Studies to Illustrate the Innovativeness of Indigenous Peoples' Adaptation to Climate Risks

Bedouin Pastoralists' Grazing Practices Decrease the Risk of Wildfires in Israel and Increase Food Sovereignty.

Wildfires are a main cause of deforestation in Israel, and in recent years climate stress decreased the forest resilience to fires (Klein et al., 2019). The original landscape, a shrubland or maquis consisting mostly of oak and pistacia, has been used since time immemorial as grazing land for goats, sheep, and camels belonging to Indigenous Bedouin people (Degen and El-Meccawi, 2009). Competing land use has reshaped the landscape with pine monocultures and cattle farming, reducing the availability of land suitable for herding goats the Indigenous way (Perevolotsky and Sheffer, 2011). In addition, since 1950, plant protection legislation has decreased Bedouin forest pastoralism in Israel, by defining Indigenous black goats as an environmental threat (FAOLEX, 2021). In nature reserves where no human interference has been allowed, these areas have regenerated into herbaceous shrublands susceptible to wildfires (Turco et al., 2017). Meanwhile, urbanized Bedouin exist on lower incomes and experience higher level of unemployment compared to other citizens, and some keep non-pastoralized livestock in cities as a strategy for food sovereignty (Degen and El-Meccawi, 2009). In 2019, many severe wildfires occurred in Israel due to extreme heat waves and, in response, plant protection legislation was appealed, allowing Bedouin pastoralists to graze their goats in areas from which they had been excluded. The amount of combustible undergrowth subsequently decreased, reducing the risk for wildfire and their related impacts, while simultaneously facilitating Indigenous food sovereignty among the Bedouin (Mamo, 2020).

Gardening in the Ashes of Wildfires in the Pacific Northwest as a Strategy to Decrease Food Insecurity and Increase Connections With the land

In the central interior of what is now known as British Columbia, 2017 was an especially severe wildfire season, with over 1.3 million hectares of land burned and 65,000 people displaced (Timler and Sandy, 2020). The unceded and ancestral lands of the Tsilhqot'in, Dakelh, and Secwépemc were impacted by two of the largest fires (Verhaeghe et al., 2017). Communities affected by the BC wildfires subsequently started Indigenous gardens closer to home, to protect medicine and food plants and thereby sustaining relationships with these plants, the land, and community (Timler and Sandy, 2020). As there are cultural teachings for fire to cleanse the territory and the land, community members and plants previously isolated became better connected because of the wildfires. The regrowth of plants is part of the healing relationship between people, plants, and other animals (Timler and Sandy, 2020). The wildfires were seen as events to catalyse action and emphasize the importance of relationships to support foodways and gardening as responsibility.

Widening our understanding of gardening, in the face of climate change and colonialism, can support health and healing for Indigenous and non-Indigenous Peoples. Gardening as a means of Indigenous food sovereignty has long been utilized by a variety of Indigenous groups within Canada and elsewhere to address circumstances of chronic food insecurity and support health and wellness (Johnson-Jennings et al., 2020);(Timler and Sandy, 2020). The concept of gardening as both a Euro-Western agricultural practice and Indigenous practice encourages an increased reverence and connection with the land, and wider engagement with the natural world (Whyte, 2018). Much of this is because Indigenous Knowledge and land management practices encompass processes that are known to be synergistic and sustainable (Ottenhoff, 2021). Indigenous worldviews offer a different perspective on social resilience to environmental change, one that is based on moral relationships of responsibility that connect humans to animals, plants, and habitats (Grey and Patel, 2015). These responsible practices not only ensure ecosystems are maintained for future generations. They centre the moral qualities necessary to carry out the responsibilities of consent, reciprocity, and trust.

Moral qualities of responsibility are the foundation for relying on each other when facing environmental challenges (Whyte, 2018);(Miltenburg et al., 2021).

To restore these sustainable relationships, a resurgence is needed of community roles and responsibilities (Cidro et al., 2015), as well as a reconsideration of the concept of food security and the role of gardening within diverse Indigenous contexts. Offering individual or community gardening as a solution to "food insecurity", a Euro-centric measure of health, ignores colonial contexts and sovereignty (Borrows, 2019);(Timler and Sandy, 2020). Indigenous communities have historic, ongoing, and evolving gardening and food gathering practices, including a wide variety of land-based and aquatic foods (Turner and Turner, 2008);(Mt. Pleasant, 2016). Euro-Western science is beginning to recognize these longstanding relationships (Kamal et al., 2015);(Hatfield et al., 2018);(Timler and Sandy, 2020). For many Indigenous communities, reconnecting with ancestral foodways holds the potential not only to address food security, but to provide the community cohesion, self-esteem, and wellness (Gordon et al., 2018).

A New Food Composition Database in Uganda May Guide Local Health Policy Workers in Healthy Eating Based on Indigenous Foods

In sub-Saharan Africa, climate change is an emerging risk factor for undernutrition, particularly in countries that rely on subsistence agriculture (Sorgho et al., 2020). In Uganda, negative health effects associated with climate change are being observed, including increased rates of food insecurity, with the highest rates recorded among the Batwa of Kanungu District, Uganda, where 97% of households are severely food insecure (Patterson et al., 2017). For many Indigenous Peoples, food security in a changing climate is a growing concern (Guyot et al., 2006);(Patterson et al., 2017). Locally harvested Indigenous foods have been adversely impacted by climate change, while connection to land is being disrupted by processes of colonization, discrimination, and lack of representation in decision-making groups, thereby restricting adaptive capacity for Indigenous communities (Bryson et al., 2021). In Uganda, the Indigenous Batwa have experienced significant disparities resulting from the forced eviction from their territory, dispossessing them of their land and ability to provide Indigenous foods to their families (Patterson et al., 2017);(Scarpa et al., 2021).

Nutrient specific knowledge of lndigenous foods is limited among many communities in Africa**.** A new food composition database in Uganda was constructed in dialogue with knowledge keepers from the Batwa and Bakiga Peoples, to assess the nutrient density of these locally harvested foods (Scarpa et al., 2021). As in other lower resource settings, no food composition tables are available for southwestern Uganda. The only existing food database was designed for central and eastern Uganda; it does not include common recipes and local foods consumed by Batwa and Bakiga communities (Scarpa et al., 2021). Using a community-based approach and collaboration with local nutritionists, a list of foods was collected through focus group discussions, an individual dietary survey, and market assessments. Including these locally familiar foods ultimately supports a focus on Indigenous justice and the importance of valuing Indigenous food systems and practices, which in many contexts have been found to have superior nutritional and environmental benefits for communities (Kuhnlein et al., 2013);(Scarpa et al., 2021). This new and unique database including Indigenous foods will not only guide local nutrition and health initiatives, but also contribute towards policies related to Indigenous food sovereignty and resilience to climate change.

Decreased Fragmentation of Winter Grazing Increases Mental and Spiritual Wellbeing in Reindeer Herding Sámi and Decreases their Dependency on Fossil Fuels

Sami are the Indigenous people of Northernmost Scandinavia and the Kola Peninsula of Russia, whose livelihoods have been traditionally sustained by reindeer herding, hunting, fishing and small-scale farming (Nilsson et al., 2011). Climate change is threatening core conditions for reindeer herding, with Sami pastoralists describing the situation as 'facing the limit of resilience' (Furberg et al., 2011). Sami pastoralists stress that an ability to continue reindeer herding is a prerequisite for their mental and spiritual health (Jaakkola et al., 2018).

In a pilot project for climate adaptation of reindeer herding run by the Swedish Sami Parliament, reindeer herding management plans (in Swedish, *renbruksplaner*) were used as a tool to develop strategies for climate adaptation (Walkepää, 2019). Four Sami reindeer herding cooperatives participated in the pilot study. They all agreed that climate change means that grazing patterns need to change. Traditionally, mountain reindeer graze in the Scandinavian mountains close to Norway in summertime, and in the coastal areas close to the Gulf of Bothnia in wintertime, representing a total migration route of up to 400 kilometres one-way. Rising temperatures are causing spring to occur earlier in the coastal winter grazing land, before the calving areas in the summer land are suitable for grazing and free from snow. When the snow cover disappears, the herds are dispersed, so it is important to migrate while snow is still present (Walkepää, 2019). Migration routes are being destabilized by weaker ice cover on water and by hazardous weather events. Competing land use due to infrastructure, extractive industries, tourism, and energy production makes it difficult to find alternative grazing land. Supplementary feeding and increased use of trucks to transport reindeer is one result. Herds that are dispersed due to bad snow conditions have an increased exposure to predators (Walkepää, 2019 (Walkepää, 2019);(Uboni et al., 2020). By working strategically to secure adequate winter grazing and reduce fragmentation of grazing areas more generally represents win-win strategies for achieving decreased mental stress levels while reducing herders' consumption of fossil fuels (Walkepää, 2019).

[END BOX 7.1]

7.1.7.3.7 Vulnerability Experienced through Food Systems

Stresses and shocks associated with climate change are drivers of food and nutrition security, particularly in sub-Saharan Africa, Asia, and Latin America (Betts et al., 2018). The most vulnerable groups include smallholder farmers, pastoralists, agricultural laborers, poorer households, refugees, Indigenous groups, women, children, the elderly, and those who are socio-economically marginalized (FAO et al., 2018);(SRCCL, 2019)*(high confidence)*. Men, women, children, the elderly and chronically ill have different nutritional needs, and these vulnerabilities may be amplified by gendered norms and differential access to resources, information and power (SRCCL, 2019). Extreme climate events have immediate and long-term impacts on food and nutrition insecurity of poor and vulnerable communities, including when women and girls need to undertake additional duties as laborers and caregivers (FAO et al., 2018).

7.1.7.3.8 Health Vulnerability Experienced through Water and Sanitation Systems

Water and sanitation systems are particularly vulnerable to extreme weather events, and damage to such systems can lead to contamination of drinking water and subsequent adverse health impacts (Howard et al., 2016);(Khan et al., 2015);(Sherpa et al., 2014). In areas with only very simple traditional excreta disposal facilities (e.g. latrines) and traditional sources of water (e.g. unprotected wells), the repeated occurrence of floods and other extreme events can negatively affect water quality at household and community levels, and increase the burden of food-borne and water-borne diseases (Cissé et al., 2016);(Khan et al., 2015);(Kostyla et al., 2015).

7.1.8 Visual Guide to this Chapter

Figure 7.3 provides a visual guide to this chapter. Section 7.1 has summarized major global frameworks and highlighted groups that exhibit heightened vulnerability to the climatic risks assessed in this chapter. Section 7.2 assesses observed impacts on health and wellbeing, migration and conflicts that have emerged from interactions of climate and weather-related hazards, exposure to such hazards, and vulnerability of communities and systems, while Section 7.3 assesses projected future risks. Section 7.4 assesses adaptation responses to climate risks, opportunities for transformative change, co-benefits, and how solutions for reducing climate impacts on health, wellbeing, migration, and conflicts may form part of wider climate resilient development pathways.

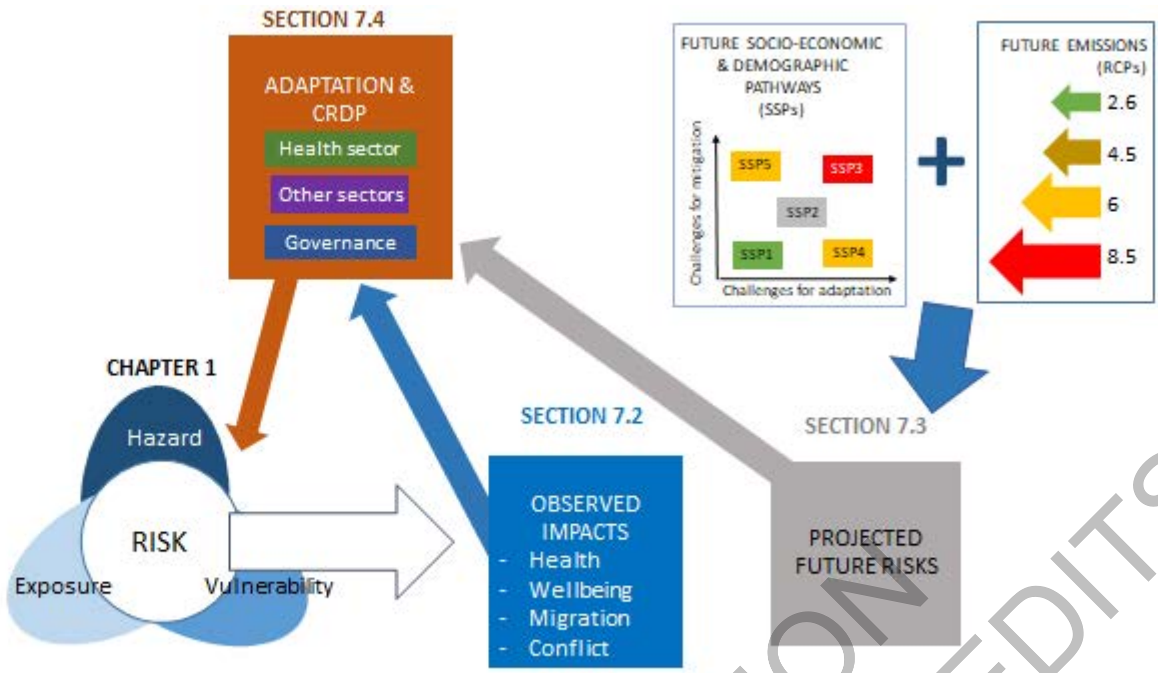


Figure 7.3: Structure of the chapter following a pathway from hazard, exposure and vulnerabilities to observed impacts, projected risks and solution space of adaptation and resilient development

7.2. Observed Impacts of Climate Change on Health, Wellbeing, Migration and Conflict

7.2.1 Observed Impacts on Health and Wellbeing

Eleven categories of diseases and health outcomes have been identified in this assessment as being climate-sensitive through direct pathways (e.g., heat, floods) and indirect pathways mediated through natural and human systems and economic and social disruptions (e.g. disease vectors, allergens, air and water pollution, and food system disruption) (high confidence). A key challenge in quantifying the specific relationship between climate and health outcomes is distinguishing the extent to which observed changes in prevalence of a climate sensitive disease or condition are attributable directly or indirectly to climatic factors as opposed to other, non-climatic, causal factors (Ebi et al., 2020). A subsequent challenge is then determining the extent to which those observed changes in health outcomes associated with climate are attributable to events or conditions associated with natural climate variability versus persistent human induced shifts in the mean and/or the variability characteristics of climate (i.e., anthropogenic climate change). The context within which the impacts of climate change affect health outcomes and health systems is described in this chapter as being a function of risk, which is in turn a product of interactions between hazard, exposure and vulnerability (Chapter 1), with the impacts in turn having the potential to reinforce vulnerability and/or exposure to risk (Figure 7.4).

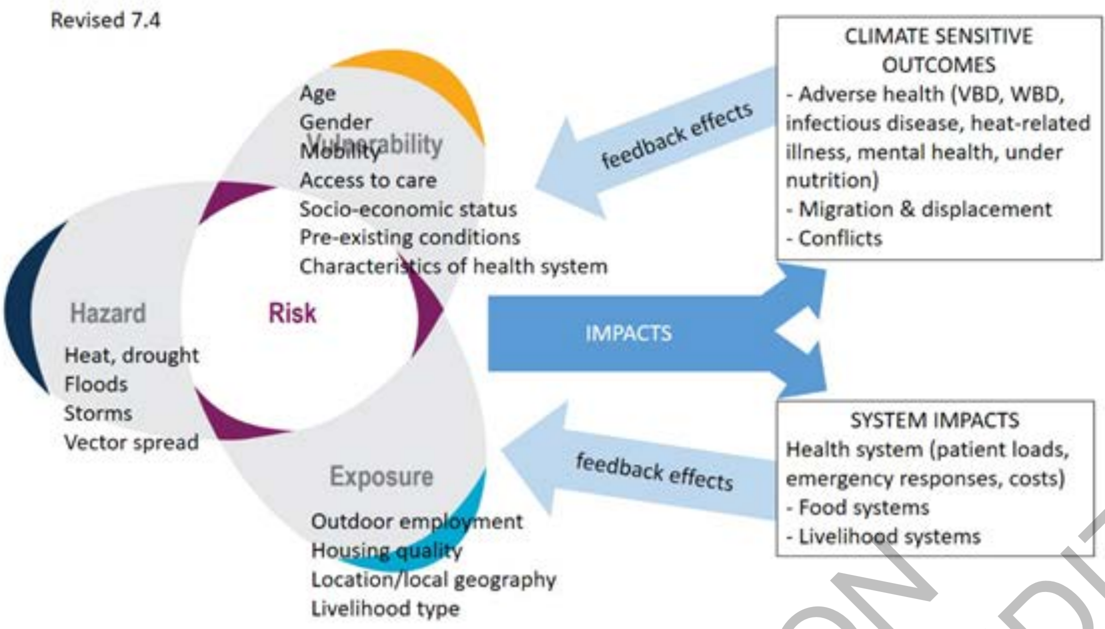


Figure 7.4: Interactions between hazard, exposure and vulnerability that generate impacts on health systems and outcomes, with selected examples.

[START BOX 7.2 HERE]

Box 7.2: The Global Burden of Climate-sensitive Health Outcomes Assessed in this Chapter

Global statistics for death and loss of health are increasingly described in terms of *burden*, which describes gaps between a population's actual health status and what its status would be if its members lived free of disease and disability to their collective life expectancy (Shaffer et al., 2019). Burden for each disease/health outcome is estimated by adding together the number of years of life a person loses because of early death (Years of Life Lost (YLL)) and the number of years a person lives with disability (Years of Life lived with Disability (YLD)) from the considered outcome. The resulting statistic, the Disability Adjusted Life Year (or DALY) represents the loss of one year of life lived in full health. The total global burden of disease (Collaborators and Injuries, 2020), expressed in DALYs, is what the world's health systems must manage, and is reported annually in Global Burden of Disease Study (Collaborators and Injuries, 2020). The estimated current global burden of climate sensitive diseases and conditions described in this chapter, and the geographical regions most affected, are summarized in Table Box 7.2.1. As was observed in the Health chapter of AR5, the "background climate-related disease burden of a population is often the best single indicator of vulnerability to climate change - doubling of risk of disease in a low disease population has much less absolute impact than doubling of the disease when the background rate is high."

The global magnitude of climate-sensitive diseases was estimated in 2019 to be 39,503,684 deaths (69.9 % of total annual deaths) and 1,530,630,442 DALYs (Collaborators and Injuries, 2020). Of these, cardiovascular diseases comprised the largest proportion of climate-sensitive diseases (32.8% of deaths, 15.5% DALYs). The next largest category consists of respiratory diseases – with chronic respiratory disease contributing to 7% of deaths and 4.1% of DALYs and respiratory infection and tuberculosis contributing to 6.5% of deaths and 6% of DALYs. The observed trend of climate-sensitive disease deaths since 1990 is marked by increasing cardiovascular mortality and decreasing mortality from respiratory infections, enteric diseases, and other infectious diseases (Collaborators and Injuries, 2020).

Table Box 7.2.1: Global burden of climate-sensitive health risks assessed in this chapter (in order of assessment) (Collaborators and Injuries, 2020) and synthesis of major observed and projected impacts in most affected regions. Blue represents an increase in positive health impacts, green represents an increase in negative health impacts, and purple represents an increase in both positive and negative impacts, but not necessarily equal. The confidence level refers to the both the attributed observed and projected changes to climate change. No assessment means the evidence is insufficient for assessment.

Legend

Climate Change Impacts		**Confidence**	
Positive health impacts		*Very high*	****
Negative health impacts		*High*	***
Positive and negative impacts		*Medium*	**
No assessment		*Low*	*

	Data from GBD 2019		**Chapter 7 Assessment**		
Health Outcome (Disease/ condition)	**Global annual deaths**	**Regions most affected (deaths)**	**Climate change observed impacts**	**Climate change projected impacts in most affected regions**	**Selected key references of the assessment**
Malaria	643,381.00	Africa (92%)	****	***	(M'Bra et al., 2018); (Caminade et al., 2019); (Gibb et al., 2020); (Tompkins and Caporaso, 2016b); (Ebi et al., 2021a)
Dengue	36,055	Asia (96%)	***	***	(Bhatt et al., 2013); (J. and R., 2020); (Messina et al., 2019); (Monaghan et al., 2018)
Diarrheal diseases	1,534,443	Asia (56%)	***	**	(Cisse, 2019); (Levy et al., 2018); (Lo Iacono et al., 2017);(Carlton et al., 2016)
Salmonella	79,046	Africa (89%)	***	**	(Cisse, 2019); (Smith and Fazil, 2019); (Lake, 2017)
Respiratory tract infections	2,493,200	Asia (47%)	**		(Geier et al., 2018); (Oluwole, 2017)
Non-communicable respiratory illness	3,741,705	Asia (74%)	***	**	(Schweitzer et al., 2018); (Hansel et al., 2016); (Collaco et al., 2018); (D'Amato et al., 2020); (Silva et al., 2017); (Doherty et al., 2017); (Beggs, 2021)
Cardiovascular disease	18,562,510	Asia (58%)	**	***	(Stewart et al., 2017); Phung, 2016; Sun. 2018; Wang, 2016; Tian, 2019; Chen, 2019; Zhang, 2018
Death from malignant neoplasms	10,079,637	Asia (55%)	***		(Ahmed et al., 2014); (Modenese et al., 2018);

					(Prueksapanich et al., 2018)
Diabetes	1,551,170	Asia (56%)	**	**	(Hajat et al., 2017) ; (Xu et al., 2019b) ; (Li et al., 2014);(Yang et al., 2016); (Velez-Valle et al., 2016); (Quast and Feng, 2019)
Environmental heat and cold exposure	47,461	Asia (46%)	***	****	(Zhang et al., 2019b); (Green et al., 2019); (Murray et al., 2020); (Ma and Yuan, 2021); (Jones et al., 2018); (Russo et al., 2019); (Gosling et al., 2017)
Nutritional deficiencies	251,577	Africa (43%)	***	***	(Mbow et al., 2019); (Lloyd, 2018); (Springmann et al., 2016b); (Zhu et al., 2018); (Weyant et al., 2018)
Mental Health*	N/A	N/A	****	****	(Cianconi et al., 2020); (Charlson et al., 2021); (Hayes and Poland, 2018); (Hrabok et al., 2020); (Obradovich et al., 2018)

Table Notes:
*Mental health data were non-available (NA) due to lack of information in GBD 2019 related to annual deaths and most affected regions.

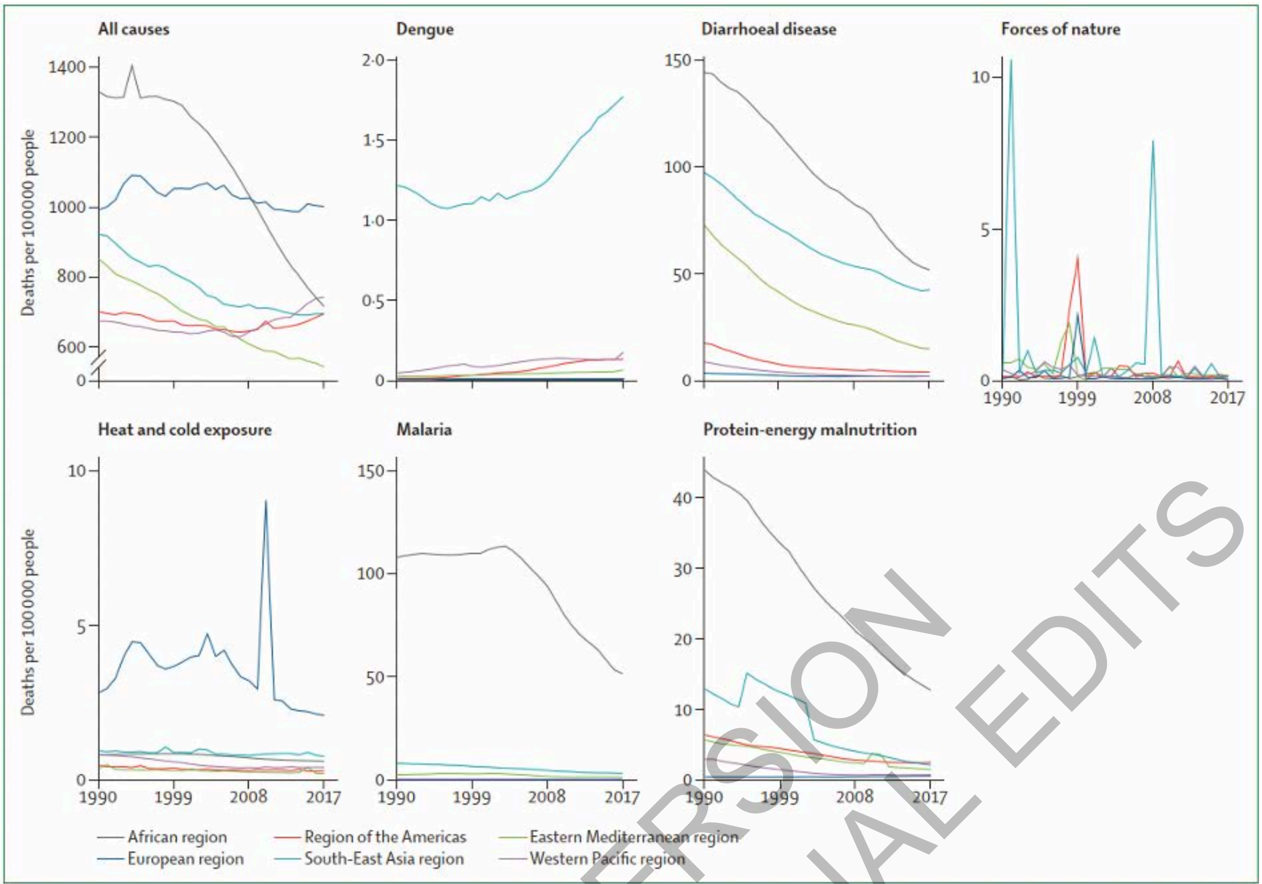


Figure Box 7.2.1: Global trends of selected health outcomes estimated by GBDs. Source: (Collaborators, 2018a)

[END BOX 7.2 HERE]

7.2.2 Observed Impacts on Communicable Diseases

7.2.2.1 Observed Impacts on Vector-borne Diseases

Climate-sensitive vector-borne diseases (VBDs) include mosquito-borne diseases, rodent-borne diseases and tick-borne diseases. Many infectious agents, vectors, non-human reservoir hosts, and pathogen replication rates can be sensitive to ambient climatic conditions. Elevated proliferation and reproduction rates at higher temperatures, longer transmission season, changes in ecology, and climate-related migration of vectors, reservoir hosts, or human populations contribute to this climate sensitivity (J. and R., 2020);(Semenza and Paz, 2021). Age-standardized disability-adjusted life year (DALY) rates for many VBDs have decreased over the last decade due to factors unrelated to climate. Vulnerability to VBD is strongly determined by sociodemographic factors (e.g., children, the elderly and pregnant women are at greater risk) with exposure to vectors being strongly influenced by various factors including socioeconomic status, housing quality, health care access, susceptibility, occupational setting, recreational activity, conflicts and displacement (J. and R., 2020);(Semenza and Paz, 2021). Figure 7.5 illustrates how climatic and non-climatic drivers and responses determine VBD outcomes.

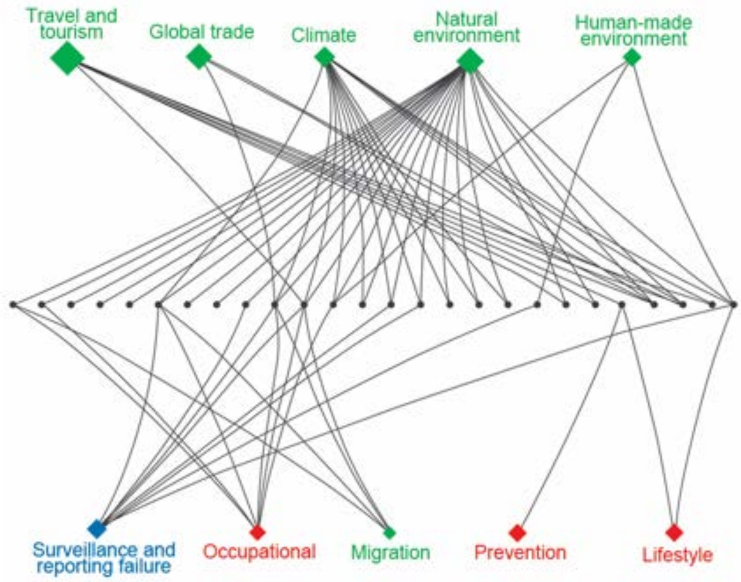


Figure 7.5: Analysis of the underlying drivers of infectious disease threat events (IDTE) detected in Europe during 2008–2013 by epidemic intelligence at the European Centre of Disease Prevention and Control. Seventeen drivers were identified and categorized into 3 groups: globalization and environment (green), sociodemographic (red), and public health system (blue). The drivers are illustrated as diamond shapes and arranged in the top and bottom row, the sizes of which are proportional to the overall frequency of the driver. Here IDTE (epidemics or first autochthonous cases) of VBD are illustrated as a horizontal row of dots in the middle. These empirical data include IDTE of VBD such as West Nile fever, malaria, dengue fever, chikungunya, or Hantavirus infection. Source: (Semenza et al., 2016)

Evidence has increased since AR5 that the vectorial capacity has increased for dengue fever, malaria, and other mosquito borne diseases, and that higher global average temperatures are making wider geographic areas more suitable for transmission (very high confidence). Transmission rates of malaria are directly influenced by climatic and weather variables such as temperature, with non-climatic socio-economic factors and health system responses counteracting the climatic drivers *(very high confidence).* The burden of malaria is greatest in Africa, where more than 90% of all malaria-related deaths occur (M'Bra et al., 2018);(Caminade et al., 2019). Between 2007 and 2017, DALYs for malaria have decreased by 39% globally. Malaria is mainly caused by five distinct species of plasmodium parasite (*Plasmodium falciparum*, *Plasmodium vivax*, *Plasmodium malariae*, *Plasmodium ovale*, *Plasmodium knowlesi*), transmitted by Anopheline mosquitoes. Evidence suggests that in highland areas of Colombia and Ethiopia, malaria has shifted in warmer years toward higher altitudes, indicating that, without intervention, malaria will increase at higher elevations as the climate warms (Siraj et al., 2014);(Midekisa et al., 2015). Each year, local outbreaks of malaria occur due to importation, in areas from which it was once eradicated, such as Europe, but the risk of re-establishment is considered low.

The transmission of dengue fever is linked to climatic and weather variables such as temperature, relative humidity, and rainfall (high confidence). The dengue virus is carried and spread by *Aedes* mosquitoes, primarily *Aedes aegypti*. Dengue has the second highest burden of VBDs, with the majority of deaths occurring in Asia (Bhatt et al., 2013). Since 1950, global dengue burden has grown, attributable to a combination of climate-associated expansion in the geographic range of the vector species and non-climatic factors such as globalized air traffic, urbanization, and ineffective vector abatement measures. Temperature, relative humidity, and rainfall variables are significantly and positively associated with increased dengue case incidence and/or transmission rates globally, including in Vietnam (Phung et al., 2015);(Xuan le et al., 2014), Thailand (Xu et al., 2019a), India (Mutheneni et al., 2017);(Rao et al., 2018);(Mala and Jat, 2019), Indonesia (Kesetyaningsih et al., 2018), the Philipines (Carvajal et al., 2018), the United States (Lopez et al., 2018);(Pena-Garcia et al., 2017);(Duarte et al., 2019);(Rivas et al., 2018);(Silva et al., 2016a), Jordan (Obaidat and Roess, 2018), and Timor-Leste (Wangdi et al., 2018). Variation in winds, sea surface temperatures and rain over the tropical eastern Pacific Ocean (El Nino Southern Oscillation) have been linked to increased dengue incidence in Colombia (Quintero-Herrera et al., 2015);(McGregor and Ebi, 2018);(Pramanik et al., 2020) and its interannual variation successfully forecasted in Ecuador using ENSO indices as predictors (Petrova et al., 2019). The observed lag time between climate exposures and increased dengue incidence is approximately 1–2 months (Chuang et al., 2017);(Lai, 2018);(Chang et al., 2018).

Changing climatic patterns are facilitating the spread of chikungunya virus (CHIKV), Zika, Japanese encephalitis and Rift Valley Fever in Asia, Latin America, North America and Europe (high confidence). Climate change may have facilitated the emergence of CHIKV as a significant public health challenge in some Latin American and Caribbean countries (Yactayo et al., 2016);(Pineda et al., 2016), and contributed to a chikungunya outbreak in Italy in 2017 (Rocklov et al., 2019) and in Europe (Chadsuthi et al., 2016);(Mascarenhas et al., 2018);(Morens and Fauci, 2014). The Zika virus outbreak in South America in 2016 was preceded by 2007 outbreaks on Pacific islands and followed a period of record high temperatures and severe drought conditions in 2015 (Paz and Semenza, 2016);(Tesla et al., 2018). Increased use of household water storage containers during the drought is correlated with a range expansion of *Aedes aegypti* during this period, increasing household exposure to the vector (Paz and Semenza, 2016). Changing climate also appears to be a risk factor for the spread of Japanese encephalitis to higher altitudes in Nepal (Ghimire and Dhakal, 2015) and in southwest China (Zhao et al., 2014). In Eastern Africa, climate change may be a risk factor in the spread of Rift Valley Fever (Taylor et al., 2016a).

Changes in temperature, precipitation, and relative humidity have been implicated as drivers of West Nile fever in southeastern Europe (medium confidence). The average temperature and precipitation prior to the exceptional 2018 West Nile outbreak in Europe was above the 1981–2010 period average, which may have contributed to an early upsurge of the vector population (Marini et al., 2020);(Haussig et al., 2018);(Semenza and Paz, 2021). In 2019 and in 2020, West Nile fever was first detected in birds and subsequently in humans in both Germany and Netherlands, respectively (Ziegler et al., 2020);(Vlaskamp et al., 2020).

Climate change has contributed to the spread of the Lyme disease vector Ixodes scapularis, and a corresponding increase in cases of Lyme disease in North America (high confidence), and of the spread of the Lyme disease and Tick-Borne Encephalitis vector Ixodes ricinus in Europe (medium confidence). In Canada, there has been a geographic range expansion of the black-legged tick *I. scapularis,* the main vector of *Borrelia burgdorferi*, the agent of Lyme disease. Vector surveillance of *I. scapularis* has identified strong correlation between temperatures and the emergence of tick populations, their range and recent geographic spread, with recent climate warming coinciding with a rapid increase in human Lyme disease cases (Clow et al., 2017);(Cheng et al., 2017);(Gasmi et al., 2017);(Ebi et al., 2017). *Ixodes ricinus*, the primary vector in Europe for both Lyme borreliosis and tick-borne encephalitis is sensitive to humidity and temperature (Daniel et al., 2018);(Estrada-Peña and Fernández-Ruiz, 2020) (*high confidence*). There has been an observed range expansion to higher latitudes in Sweden and to higher elevations in Austria and the Czech Republic.

Rodent-borne disease outbreaks have been linked to weather and climate conditions in a small number of studies published since AR5, but more research is needed in this area. In Kenya, a positive association exists between precipitation patterns and *Theileria*-infected rodents, but for *Anaplasma*, *Theileria* and *Hepatozoon*, the association between rainfall and pathogen varies according to rural land-use types (Young et al., 2017). Weather variability plays a significant role in transmission rates of haemorrhagic fever with renal syndrome (HFRS) (Hansen et al., 2015);(Xiang et al., 2018);(Liang et al., 2018);(Fei et al., 2015);(Xiao et al., 2014);(Vratnica et al., 2017);(Roda Gracia et al., 2015);(Monchatre-Leroy et al., 2017);(Bai et al., 2019). In Chongqing, HFRS incidence has been positively associated with rodent density and rainfall (Bai et al., 2015).

7.2.2.2 Observed Impacts on Water-borne Diseases

Important water-borne diseases (WBDs) include diarrhoeal diseases (such as cholera, shigella, cryptosporidium and typhoid), schistosomiasis, leptospirosis, hepatitis A and E and poliomyelitis (Cisse, 2019);(Houéménou et al., 2021);(Hassan et al., 2021);(Archer et al., 2020);(Mbereko et al., 2020);(Fan et al., 2021). The number of cases of water-borne diseases is considerable, and even in high-income countries water-borne illness continues to be a concern (Cissé et al., 2018);(Kirtman et al., 2014);(Levy et al., 2018);(Murphy et al., 2014);(Brubacher et al., 2020);(Lee et al., 2021). Nevertheless, diarrhoea mortality has declined substantially since 1990, although there are variations by country, and the global burden of WBD has decreased in line with vaccination coverage of some WBDs (such as polio and cholera), poverty reduction and improved sanitation and hygiene (Jacob and Kazaura, 2021);(Mutono et al., 2020);(Lee et al., 2019);(Semenza and Paz, 2021);(Jacob and Kazaura, 2021); (Mutono et al., 2020).

Drinking water containing pathogenic microorganisms is the main driver of the burden of WBDs (Murphy et al., 2014);(Lee et al., 2021);(Chen et al., 2021b);(Musacchio et al., 2021). WBDs outbreaks, particularly intestinal diseases, are attributable to a combination of the presence of particular pathogens (bacteria, protozoa, viruses or parasites) and the characteristics of drinking water systems in a given location (Bless et al., 2016);(Ligon and Bartram, 2016);(Mutono et al., 2021);(Ferreira et al., 2021).

[START BOX 7.3 HERE]

Box 7.3: Cascading Risk Pathways Linking Waterborne Disease to Climate Hazards

The causal linkages between climate variability and change and incidence of waterborne diseases follows multiple direct and indirect pathways, often as part of a cascading series of risks (Semenza, 2020). For example, extreme precipitation can result in a cascading hazard or disease event with implications of greater magnitude than the initial hazard, especially if there are pre-existing vulnerabilities in critical infrastructure and human populations (Semenza and Paz, 2021). Intense or prolonged precipitation can flush pathogens in the environment from pastures and fields to groundwater, rivers and lakes, consequently infiltrating water treatment and distribution systems (Howard et al., 2016);(Khan et al., 2015);(Sherpa et al., 2014);(Cissé et al., 2016);(Kostyla et al., 2015); Chapter 4). Table 7.3.1 shows the variety and complexity of pathways between climate hazard and waterborne disease outcomes (Semenza, 2020).

Table Box 7.3.1: Pathways between climate hazard and waterborne disease outcomes (source: (Semenza, 2020)

Cascading risk pathways from heavy rain and flooding
Storm runoff yields water turbidity which compromises water treatment efficiency Storm runoff and floods mobilizes and transports pathogens Overwhelmed or damaged infrastructure compromises water treatment efficiency Floods overwhelm containment system and discharge untreated wastewater Floods damage critical water supply and sanitation infrastructure Floods displace populations towards inadequate sanitation infrastructure
Cascading risk pathways from drought
Low water availability augments travel distance to alternate (contaminated) sources Intensified demand and sharing (e.g. with livestock) of limited water resources decreases water availability and quality Intermittent drinking water supply results in cross-connections with sewer lines and water contamination Uncovered household water containers are a source of vector breeding Poor hygiene due to decreased volume of source water and increased concentration of pathogens Exposure to accumulated human excrements and animal manure
Cascading risk pathways from increasing temperature
Extended transmission season for opportunistic pathogens Permissive temperature for the replication of marine bacteria Enhanced pathogen load in animal reservoirs (e.g., chicken) Pathogen survival and proliferation outside of host Wildfires during heat waves degrade water quality Exposure to contaminated water due to higher water consumption Behaviour change due to extended season; e.g., food spoilage during barbeque
Cascading risk pathways from sea-level rise
Population displacement due to powerful storm surges Disruption of drinking water supply and sanitation infrastructure due to inundation Decline in soil and water quality due to saline intrusion into coastal aquifers

Seawater infiltration into drinking water distribution and sewage lines

Table Notes:
Examples are purposely not exhaustive and should be considered illustrative.

[END BOX 7.3 HERE]

Since AR5 there is a growing body of evidence that increases in temperature (very high confidence), heavy rainfall (high confidence), flooding (medium confidence) and drought (low confidence) are associated with an increase of diarrheal diseases. In the majority of studies there is a significant positive association observed between waterborne diseases and elevated temperatures, especially in areas where water, sanitation and hygiene deficiencies are significant (Levy et al., 2018);(Carlton et al., 2016);(Levy et al., 2018);(Sherpa et al., 2014);(Guzman Herrador et al., 2015);(Levy et al., 2016);(Lo Iacono et al., 2017). In Ethiopia, South Africa and Senegal, increases in temperatures are associated with increases in diarrhoea, while in Ethiopia, Senegal and Mozambique, increases in monthly rainfall are associated with an increase in cases of childhood diarrhea (Azage et al., 2015);(Thiam et al., 2017);(Horn et al., 2018). Similar associations between weather and diarrhoea have been observed in Cambodia, China, Bangladesh, Pacific Island Countries and the Philippines (McIver et al., 2016a);(McIver et al., 2016b);(Liu et al., 2018);(Wu et al., 2014);(Matsushita et al., 2018). Heavy precipitation events have been consistently associated with outbreaks of waterborne diseases in Europe (including Scandinavia), USA, UK and Canada (Guzman Herrador et al., 2015);(Levy et al., 2016);(Lo Iacono et al., 2017);(Curriero et al., 2001);(Guzman Herrador et al., 2016);(Levy et al., 2018);(Semenza and Paz, 2021).

Impacts of floods include outbreaks of waterborne diseases, with such events disproportionately affecting the young, elderly and immunocompromised (Suk et al., 2020);(Guzman Herrador et al., 2015);(Levy et al., 2016);(Lo Iacono et al., 2017);(Zhang et al., 2019a). Water shortage and drought have been found associated with diarrheal disease peaks (Epstein et al., 2020b);(Subiros et al., 2019);(Boithias et al., 2016 while some reviews found insufficient or limited evidence of the effects of drought on diarrhea {Levy, 2016, Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought);(Asmall et al., 2021);(Epstein et al., 2020b);(Subiros et al., 2019);(Boithias et al., 2016) (Ramesh et al., 2016).

Heavy rainfall and higher than normal temperatures are associated with increased cholera risk in affected regions (very high confidence). Cholera is an acute diarrheal disease typically caused by the bacterium *Vibrio cholerae* that can result in severe morbidity and mortality. Maximum and minimum temperatures and precipitation have been negatively associated with cholera cases and cholera outbreaks have occurred in several regions after natural disasters, including cholera incidence increasing three-fold in Africa El Niño-sensitive regions (Mpandeli et al., 2018);(Amegah et al., 2016);(Escobar et al., 2015);(Jutla et al., 2017);(Asadgol et al., 2019);(Moore et al., 2018);(Moore et al., 2017);(Camacho et al., 2018);(Pörtner et al., 2019); Cross-Chapter Box ILLNESS in Chapter 2; Box 3.3).

Heavy rainfall, warmer weather and drought are linked to increased risks for other gastro-intestinal (GI) infections (high confidence). As temperature increases bacterial causes of GI infection appear to increase and this association is variably influenced by humidity and rainfall (Ghazani et al., 2018);(Levy, 2016). In New York it has been found that every 1°C increase in temperature was correlated with a 0.70-0.96% increase in daily hospitalization for GI infections (Lin et al., 2016). In the Philippines, leptospirosis and typhoid fever showed an increase in incidence following heavy rainfall and flooding events (Matsushita et al., 2018).

7.2.2.3 Observed Impacts on Food-borne Diseases

Food-borne diseases (FBDs) refer to any illness resulting from ingesting food that is spoiled or contaminated by pathogenic bacteria, viruses, parasites, toxins, pesticides and/or medicines (WHO, 2015d). FBD risks are present throughout the food chain, from production to consumption, and most often arise due to contamination at source and from improper handling, preparation and/or food storage (Smith and Fazil, 2019);(Semenza and Paz, 2021). As with waterborne disease, FBD outbreaks can follow multiple causal pathways as climatic risk factors interact with food production and distribution systems, urbanization and population growth, resource and energy scarcity, decreasing agricultural productivity, price volatility, modification of diet trends, new technologies and the emergence of antimicrobial resistance (Lake, 2018);(Yeni and Alpas, 2017). The burden of FBDs is also linked to malnutrition as reduced immunity increases susceptibility to various foodborne pathogens and toxins (FAO, 2020).

A strong association exists between increases in food-borne diseases and high air and water temperatures and longer summer seasons (very high confidence). The risks occur through complex transmission pathways throughout the food chain and the wide range of foodborne pathogens (Cisse, 2019);(Hellberg and Chu, 2016);(Lake and Barker, 2018);(Park et al., 2018b);(Smith and Fazil, 2019). Food-borne pathogens of most concern are those having low infective doses, a significant persistence in the environment and high stress tolerance to temperature change (e.g. enteric viruses, *Campylobacter spp*., *E. coli* STEC strains, *Mycobacterium avium,* tuberculosis complexes, parasitic protozoa and *Salmonella*) (Lake, 2018);(Lake, 2017);(Lake and Barker, 2018);(Smith and Fazil, 2019);(Authority) et al., 2020);(Semenza and Paz, 2021). Priority risks include marine biotoxins, mycotoxins, salmonellosis, vibriosis, transfer of contaminants due to extreme precipitation, floods, increased use of chemicals (plant protection products, fertilizers, veterinary drugs) in the food chain, and potential residues in food (Authority) et al., 2020);(Organization, 2018b).

There is a strong association observed between the increase in average ambient temperature and increases in Salmonella infections (high confidence). Most types of *Salmonella* infections lead to salmonellosis, while some other types (*Salmonella* Typhi and *Salmonella* Paratyphi) can lead to typhoid fever or paratyphoid fever. The transmission to humans of the non-typhoidal *Salmonella* infection, one of the most widespread foodborne diseases, occurs usually through eating foods contaminated with animal faeces. Studies conducted in Australia (Milazzo et al., 2016), New Zealand (Lal et al., 2016), the UK (Lake, 2017), South Korea (Park et al., 2018a);(Park et al., 2018c);(Park et al., 2018a), Singapore (Aik et al., 2018) and Hong Kong, SAR of China (Wang et al., 2018a);(Wang et al., 2018b) have shown that *Salmonella* outbreaks are strongly associated with temperature increases.

Significant associations exist between food-borne diseases due to Campylobacter, precipitation and temperature (medium confidence). The timing of heat-associated Campylobacteriosis events varies across countries, whilst infection rates in the UK appear to decline immediately after periods of high rainfall (Djennad et al., 2019);(Lake et al., 2019);(Rosenberg et al., 2018);(Yun et al., 2016);(Weisent et al., 2014). This suggests the association with climate may be indirect and due to weather conditions that encourage outdoor food preparation and recreational activities (Lake, 2017);(Semenza and Paz, 2021).

Outbreaks of human and animal Cryptococcus have been reported as being associated with a combination of climatic factors, and shifts in host and vector populations (Chang and Chen, 2015);(Rickerts, 2019). The prevalence of childhood cryptosporidiosis, which is the second leading cause of moderate-to-severe diarrhoea among infants in the tropics and subtropics, shows associations with population density and rainfall, with contamination due to Cryptosporidium spp. being 2.61 times higher during and after heavy rain (Lal et al., 2019);(Young et al., 2015);(Khalil et al., 2018). Studies from Ghana, Guinea Bissau, Tanzania, Kenya and Zambia show a higher prevalence of Cryptosporidium during high rainfall seasons, with some peaks observed before, at the onset or at the end of the rainy season (Squire and Ryan, 2017).

7.2.2.4 Respiratory Tract Infections

Climatic risk factors for respiratory tract infections (RTIs) due to multiple pathogens (bacteria, viruses, fungi) include temperature and humidity extremes, dust storms, extreme precipitation events, and increased climate variability. Amongst a range of RTIs, pneumonia and influenza represent a significant disease burden (Ferreira-Coimbra et al., 2020);(Lafond et al., 2021);(McAllister et al., 2019);(Wang et al., 2020c). The drivers of pneumonia incidence are complex and include a range of possible non-climate as well as climate factors. For example, chronic diseases (e.g., lung disease, chronic obstructive pulmonary disease, asthma) and other comorbidities, a weak immune system, age, gender, community, passive smoking, air pollution, and childhood immunization may confound the climate pneumonia relationship (Miyayo et al., 2021).

In temperate regions, the incidence of pneumonia is higher in the winter months, but the exact causes of this seasonality remain debated (Mirsaeidi et al., 2016). With regards to temperature, various J-shaped, U-shaped, or V-shaped temperature-pneumonia relationships have been reported in the literature (Huang et al., 2018);(Kim et al., 2016);(Liu et al., 2014);(Qiu et al., 2016);(Sohn et al., 2019) with such relationships dependent of location. Humidity also appears important but like temperature its effect is not consistent across studies - low temperatures and low humidity (Davis et al., 2016), high temperatures and high humidity (Lam et al., 2020) and low temperatures and high humidity (Miyayo et al., 2021) have all been found to be associated with an increased incidence of pneumonia.

Day to day variations in temperature also appear important. For Australia, increases in emergency visits for childhood pneumonia are associated with sharp temperature drops (Xu et al., 2014). Large inter-daily changes in temperature are important for respiratory disease incidence in Guangzhou, China (Lin et al., 2013) and Shanghai (Lei et al., 2021) while rapidly changing and extreme temperatures during pregnancy have been linked to childhood pneumonia (Miao et al., 2017);(Zeng et al., 2017);(Zheng et al., 2021)). In tropical and subtropical areas of Africa and Asia, pneumonia incidence has been reported to be higher during the rainy season, pointing to a positive association between pneumonia patterns and temperature and precipitation (Chowdhury et al., 2018a);(Lim and Siow, 2018);(Paynter et al., 2010).

The degree to which the timing, duration and magnitude of local influenza virus epidemics is dependent on climate factors is poorly understood (Lam et al., 2020). Further, a host of non-climate confounders are likely to influence the incidence of seasonal influenza (Caini et al., 2018). This poses a number of challenges for making reliable climate-based epidemiological forecasts for influenza (Gandon et al., 2016). Although no association between anomalous climate conditions and influenza have been reported in some locations (Lam et al., 2020), generally, low winter temperatures and humidity in temperate regions and periods of high humidity and precipitation in the tropical and subtropical regions have been linked to outbreaks of influenza (Deyle et al., 2016);(Soebiyanto et al., 2015);(Tamerius et al., 2013). However, the climate sensitivity of influenza may be more complex than this with both high and low humidity, the amount and intensity of precipitation and solar activity/sunshine and latitude also important (Axelsen et al., 2014);(Chong et al., 2020b);(Geier et al., 2018);(Park et al., 2019);(Qu, 2016);(Smith et al., 2017);(Wang et al., 2017c);(Zhao et al., 2018a). Moreover, the shape of the climate variable influenza relationship may be conditioned on influenza type (Chong et al., 2020a). Further distinct periods of weather variability characterised by rapid inter-daily changes in temperature may act as precursors to influenza epidemics as has been demonstrated for the marked 2017-18 influenza season and others across the US (Liu et al., 2020a);(Zhao et al., 2018a). For the Eastern Mediterranean, such rapid weather changes are associated with the 'Cyprus Low', with the timing and magnitude of seasonal influenza related to the inter-annual frequency of this particular weather regime (Hochman et al., 2021). Potentially, large-scale modes of climatic variability such as El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole, which strongly moderate the frequency of weather regimes in some parts of the world, could affect influenza pandemic dynamics. However, studies conducted to date report inconsistent results. Some point to an increased (decreased) severity of seasonal influenza during El Nino (La Nina) (Oluwole, 2015),(Oluwole, 2017), while others find influenza to be more severe and frequent when coinciding with La Niña events (Chun et al., 2019);(Flahault et al., 2016);(Shaman and Lipsitch, 2013). This raises the possibly of non-stationary associations between large-scale modes of climatic variability and influenza dynamics (Onozuka and Hagihara, 2015) as found for other diseases (Kreppel et al., 2014), something that might be expected given El Niño's time-varying impact on global precipitation and temperature fields and associated impacts on health outcomes (McGregor and Ebi, 2018).

7.2.2.5 Other Water Shortage and Drought-associated Diseases

Water shortage and drought are associated with skin diseases (Schachtel et al., 2021);(Lundgren, 2018);(Andersen and Davis, 2017);(Kaffenberger et al., 2017);(Andersen and Davis, 2017), trachoma (Ramesh et al., 2016), and violence (Epstein et al., 2020a),

[START CROSS-CHAPTER BOX COVID HERE]

Cross-Chapter Box COVID: COVID-19

Authors: Maarten van Aalst (Netherlands, Chapter 16), Guéladio Cissé (Mauritania/Switzerland/France, Chapter 7), Ayansina Ayanlade (Nigeria, Chapter 9), Lea Berrang-Ford (United Kingdom/Canada, Chapter

16), Rachel Bezner Kerr (Canada/USA, Chapter 5), Robbert Biesbroek (Netherlands, Chapter 13), Kathryn Bowen (Australia, Chapter 7), Martina Angela Caretta (Sweden, Chapter 4), So-Min Cheong (Republic of Korea, Chapter 17), Winston Chow (Singapore, Chapter 6), Mark John Costello (New Zealand/Norway/Ireland, Chapter 11, CCP1), Kristie Ebi (USA, Chapter 7), Elisabeth Gilmore (USA/Canada, Chapter 14), Bruce Glavovic (South Africa/New Zealand, Chapter 18, CCP2), Walter Leal (Germany, Chapter 8), Stefanie Langsdorf (Germany, TSU), Elena Lopez-Gunn (Spain/United Kingdom, Chapter 4), Ruth Morgan (Australia, Chapter 4), Aditi Mukherji (India, Chapter 4), Camille Parmesan (France/ United Kingdom /USA, 2), Mark Pelling (United Kingdom, Chapter 6), Elvira Poloczanska (United Kingdom, TSU), Marie-Fanny Racault (United Kingdom/France, Chapter 3), Diana Reckien (Germany/Netherlands, Chapter 17), Jan C. Semenza (Sweden, Chapter 7), Pramod Kumar Singh (India, Chapter 18), Stavana E. Strutz (USA), Maria Cristina Tirado von der Pahlen (Spain/USA, Chapter 7), Corinne Schuster-Wallace (Canada), Alistair Woodward (New Zealand, Chapter 11), Zinta Zommers (Latvia, Chapter 17)

Introduction

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes Coronavirus Disease 2019 (COVID-19), emerged in late 2019, halfway through the preparation of the IPCC WGII Sixth Assessment Report. This Cross-Chapter Box assesses how the massive shock of the pandemic and its response measures interact with climate-related impacts and risks, as well as its significant implications for risk management and climate resilient development.

COVID-19 and environmental connections

Infectious diseases may emerge and spread through multiple climate-related avenues, including direct effects of climatic conditions on disease reproduction and transmission and various indirect effects, often interlinked with ecosystem degradation (high confidence). Climate change is affecting the risk of emerging infectious diseases by contributing to factors that dive the movements of species, including vectors and reservoirs of diseases, into novel human populations and vice-versa (*high confidence*) {2.4.2.7; 5.2.2.3; Cross-Chapter Box Illness in Chapter 2; SRCCL; IPBES 2020}. The spillover of some emerging infectious diseases from wildlife into humans is associated with live animal-human markets, intensified livestock production and climate-related movements of humans and wild animals into new areas that alter human-animal interactions. {2.4.2.7} {Chapter 3} {5.2.2.3} {7.2} {Cross-Chapter Box ILLNESS in Chapter 2} {Cross-Chapter Box MOVING PLATE in Chapter 5}.

Human to human transmission is the prominent driver in the spread of the COVID-19 pandemic, rather than climatic drivers (high confidence). There is emerging literature on the environmental determinants of COVID-19 transmission, incidence and mortality rates, with initial evidence suggesting that temperature, humidity and air pollution contribute to these patterns (Brunekreef et al., 2021); (Xiong et al., 2020);(Zhang et al., 2020b); IPCC WGI AR6 Cross-Chapter Box). Climate change is altering environmental factors like temperature and seasonality that affect COVID-19 transmission (Choi et al., 2021).

The impact of COVID-19 containment measures resulted in a temporary reduction in greenhouse gas emissions and reduced air pollution *(high confidence)* (IPCC WGI TS and Cross-Chapter Box 6.1}. However, global and regional climate responses to the radiative effect were undetectable above internal climate variability due to the temporary nature of emission reductions. They, therefore, do not result in detectable changes in impacts or risks due to changes in climate hazards (IPCC WGI TS and Cross-Chapter Box 6.1; (Naik et al., 2021).

Cascading and compounding risks and impacts

The COVID-19 pandemic posed a severe shock to many socio-economic systems, resulting in substantial changes in vulnerability and exposure of people to climate risks (*high confidence*). The disease and response measures significantly affected human health, economic activity, food production and availability, health services, poverty, social and gender inequality, education, supply chains, infrastructure maintenance, and the environment. These COVID-19 impacts interact with many risks associated with climate change (IMF, 2020), often through a cascade of impacts across numerous sectors (van den Hurk et al., 2020). Beyond

COVID-19-related mortality and long-term COVID, mortality from other diseases (some of which may also have a climate-related component), as well as maternal and neonatal mortality, increased because of disruption in health services (Barach et al., 2020);(Maringe et al., 2020);(Zadnik et al., 2020); (Goyal et al., 2021). In addition, a rapid rise in poverty has disproportionately affected poorer countries and people (Ferreira et al., 2021), and thus increased their vulnerability. After many years of steady declines, extreme poverty increased by about 100 million people in 2020 (Bank, 2021). The effects of the pandemic increased food insecurity and malnourishment, which increased by 1.5 percentage points to around 9.9 per cent in 2020 after being virtually unchanged for the previous five years (FAO et al., 2021).

During the pandemic, extreme weather and climate events such as droughts, storms, floods, wildfires and heatwaves continued, resulting in disastrous compounding impacts (*high confidence*). Between March and September 2020, 92 extreme weather events coincided with the COVID-19 pandemic, affecting an estimated 51.6 million people; additionally, 431.7 million people were exposed to extreme heat, and 2.3 million people were affected by wildfires (Walton and van Aalst, 2020). The COVID-19 pandemic, in combination with extreme events, affected disaster preparedness, response and safe evacuations, while physical distancing regulations reduced the capacity of temporary shelters (Pacific), 2020); (Tozier de la Poterie et al., 2020);(Network, 2020); (Bose-O'Reilly et al., 2021). Complex humanitarian emergencies were aggravated, with vulnerable populations facing the combined risks of conflict, displacement, COVID-19 and climate impacts (FSIN, 2020). Compounding events are not only found in low-income countries but also in medium- and high-income countries, for instance in the case of COVID-19 and heatwaves (Network, 2020); (Bose-O'Reilly et al., 2021).

Responses and implications for adaptation and climate resilience development

The pandemic underscores the interconnected and compound nature of risks, vulnerabilities, and responses to emergencies that are simultaneously local and global (high confidence). COVID-19 is often considered a more "explosive" risk than the more gradual anthropogenic climate change. However, many climate-related risks do already appear as severe shocks at smaller scales, and infrequent or unprecedented extreme weather related events often warrant similar rapid responses (Dodds et al., 2020); (Gebreslassie, 2020); (Hynes et al., 2020); (Phillips et al., 2020); (Schipper, 2020); (Semenza et al., 2021); illustrated in Figure Cross-Chapter Box COVID in Chapter 7). Individuals, households, sub-national and national entities, and international organizations have generally delayed responses or denied the pandemic's severity before responding at the scale and urgency required; a pattern that resembles international action on climate change required; a pattern that resembles international action on climate change (Polyakova et al., 2020), (Shrestha et al., 2020).

Improved contingency and recovery planning, including disease mitigation measures, were crucial in responding to the pandemic in similar ways to those seen in the aftermath of climate-related disasters (Guo et al., 2020); (Ebrahim et al., 2020); (Baidya et al., 2020); (Shultz et al., 2020); (Mukherjee et al., 2020). The pandemic highlighted the lack of global and country-specific capacity to respond to an unexpected and unplanned-for event and the need to implement more flexible detection and response systems (Ebi et al., 2021b).

It also exposed underlying vulnerabilities, such as the lack of water access and health care in select low- and middle-income countries and among Indigenous and marginalised groups in high-income countries (see section 4.4.3, Box 4.3 and 5.12.1). Increased risks of COVID-19 transmission emerged in crowded areas such as urban settings, refugee camps, detention centres, and some workplaces, including in rural settings(Brauer et al., 2020); (Ramos et al., 2020); (Staddon et al., 2020); (Haddout et al., 2020). Public health responses to the COVID-19 pandemic, such as mandates for social distancing and advice for frequent handwashing, underlined the need for access to water and sanitation facilities and wastewater management. However, they have also interfered with access sometimes, for example, in evacuation and shelter infrastructure during climate-related disasters (Armitage and Nellums, 2020);(Adelodun et al., 2020); (Poch et al., 2020);(Hallema et al., 2020);(Patel et al., 2020); (Espejo et al., 2020).

The experience of COVID-19 demonstrates that many warnings about the risks of the emergence of zoonotic transmission ("delay is costly", "adapt early", and "prevention pays") did not result in sufficient political attention, funding, and pandemic prevention. In some countries, there has been an increased awareness of risks and the real or perceived trade-offs associated with risk management (e.g., economy vs. health; impacts vs. adaptation). Building trust, participatory processes and establishing stronger relationships with communities and other civic institutions may enable a recalibration in how the government responds to crises and society-government relationships more generally (Amat and et al., 2020); (Deslatte, 2020)

The management of the COVID-19 pandemic has highlighted the value of scientific (including medical and epidemiological) expertise and the importance of fast, accurate, and comprehensive data to inform policy decisions and to anticipate and manage risk (high confidence). It underscores the importance of effective communication of scientific knowledge (Semenza et al., 2021), decision-making under uncertainty, and decision frameworks that navigate different values and priorities. Successful policy responses were based on the emerging data, medical advice and collaboration with a wider set of societal stakeholders beyond public health experts. For instance, experience in Aotearoa New Zealand highlights the importance of pandemic responses attuned to the needs of different socio-cultural groups and Indigenous people in particular. Their strengths-based COVID-19 response goes beyond identifying vulnerabilities to unlocking the resources, capabilities and potential that might otherwise be latent in communities (McMeeking and Savage, 2020). As far as the value of information for risk management is concerned, compared to the initial uncertainties regarding COVID-19, data about near- and longer term climate-related hazards is generally very good; however, high-quality and dense meteorological data are often still lacking in lower income countries (Otto et al., 2020). Health data are particularly difficult to obtain in real-time, as is the case for biodiversity data, which has a time lag of years before being made available, and for which there is no coordinated monitoring, hampering effective risk management (Navarro et al., 2017). Therefore, both epidemiological and meteorological forecasts would benefit from more focus on (1) decision support, (2) conveying uncertainty, and (3) capturing vulnerability (Coughlan de Perez et al., 2021).

There is a considerable evidence base of specific actions that have co-benefits for reducing pandemic and climate change risks while enhancing social justice and biodiversity conservation (high confidence). The pandemic highlighted aspects of risk management that have long been recognised but are often not reflected in national and international climate policy: the value of addressing structural vulnerability rather than taking specific measures to control single hazards and drivers of risk, and the importance of decision-making capacities and transparency, the rule of law, accountability, and addressing inequities (or social exclusion) (reviewed by (Pelling et al., 2021), see also Figure Cross-Chapter Box COVID in Chapter 7).

Comprehensive and integrated risk management strategies can enable countries to address both the current pandemic and increase resilience against climate change and other risks (Reckien, 2021); (Semenza et al., 2021); (Ebi et al., 2021b). In particular, given their immense scale, COVID-19 recovery investments may offer an opportunity to contribute to Climate-Resilient Development Pathways through a green, resilient, healthy and inclusive recovery (*high confidence*) (Sovacool et al., 2020);(Rosenbloom and Markard, 2020); (Lambert et al., 2020); (Boyle et al., 2020); (Bouman et al., 2020); (Pacific), 2020);(Brosemer et al., 2020);(Dodds et al., 2020); (Hynes et al., 2020); (Markard and Rosenbloom, 2020); (Phillips et al., 2020); (Schipper, 2020); (Willi et al., 2020); (Semenza et al., 2021);(Pasini and Mazzocchi, 2020);(Meige et al., 2020); (Pelling et al., 2021). However, windows of opportunity to enable such transitions are only open for a limited period and need to be swiftly acted upon to effect change (*high confidence*) (chapter 18, (Weible et al., 2020); (Reckien, 2021). Initial indications suggest that only US$1.8 trillion of the >US$17 trillion COVID-19-related stimulus financing by G20 countries and other major economies that was committed until mid-2021 contributed to climate action and biodiversity objectives, with significant differences between countries and sectors (Economics, 2021). Moreover, responses to previous crises (e.g., the 2008-2011 global financial crisis) demonstrate that despite high ambitions during the response phase, opportunities for reform do not necessarily materialize (Bol et al., 2020), (Boin et al., 2005). In addition, heightened societal and political attention to one crisis often comes at the cost of other policy priorities (*high confidence*) (Maor, 2018); (Tosun et al., 2017), which could affect investments for climate-resilient development (Hepburn et al., 2020); (WHO, 2020a);(Bateman et al., 2020); (Meige et al., 2020); (Semenza et al., 2021).

In summary, the emerging literature suggests that the COVID-19 pandemic has aggravated climate risks, demonstrated the global and local vulnerability to cascading shocks, and illustrated the importance of integrated solutions that tackle ecosystem degradation and structural vulnerabilities in human societies. This highlights the potential and urgency of interventions that reduce pandemic and climate change risks while enhancing compound resilience, social justice and biodiversity conservation (see Figure Cross-Chapter Box COVID.1 in Chapter 7).

Figure Cross-Chapter Box COVID.1: Compound risk and compound resilience to pandemic and climate change. Source: (Pelling et al., 2021)

[END CROSS-CHAPTER BOX COVID HERE]

7.2.3 Observed Impacts on Non-communicable Diseases

Non-communicable diseases (NCDs) are those that are not directly transmitted from one person to another person, and impose the largest disease burden globally. NCDs constitute approximately 80% of the burden of disease in high-income countries; the NCD burden is lower in low- and middle-income countries but expected to rise (Bollyky et al., 2017). NCDs constitute a large group of diseases driven principally by environmental, lifestyle, and other factors; those identified as being climate sensitive include non-infectious respiratory disease, cardiovascular disease, cancer, and endocrine disease including diabetes. There are, additionally, potential interactions between multiple climate-sensitive NCDs and food security, nutrition, and mental health.

The literature on climate change and NCDs continues to develop. More recently, scientists have identified key gaps in the calculation of the global burden of disease due to environmental health factors (Shaffer et al., 2019).

7.2.3.1 Cardiovascular Diseases

Cardiovascular diseases (CVD) are a group of disorders of the heart and blood vessels that include coronary heart disease, cerebrovascular disease, peripheral arterial disease, rheumatic heart disease, congenital heart disease, deep vein thrombosis and pulmonary embolism. CVDs are the leading cause of death globally and over three quarters of the world's CVD deaths now occur in low- and middle-income countries (Roth et al., 2020).

Climate change affects the risk of CVD through high temperatures and extreme heat (assessed in 7.2.4.1) and through other mechanisms (medium confidence), though the degree to which non-temperature risks may increase remains unclear. For example, exposure to air pollutants including particulate matter, ozone (via its precursors), black carbon, oxides of nitrogen, oxides of sulphur, hydrocarbons and metals can invoke pro-inflammatory and prothrombotic states, endothelial dysfunction and hypertensive responses (Giorgini et al., 2017);(Stewart et al., 2017). Winter peaks in CVD events, associated with greater concentrations of air pollutants, have been reported in a range of countries and climates (Claeys et al., 2017);(Stewart et al., 2017); however, the association between air pollution, weather and CVD events is complex and seems to differ in cold *versus* warm months, particularly for gaseous pollutants such as ozone (Shi et al., 2020).

Climate change is projected to increase the number and severity of wildfires (Liu et al., 2015b);(Youssouf et al., 2014) and the evidence for wildfire smoke-related CVD morbidity and mortality is suggestive of increased CVD morbidity and mortality risk (Chen et al., 2021a)including significant increases in certain cardiovascular outcomes (e.g., cardiac arrests) (Dennekamp et al., 2015). CVD risks to highly exposed populations, such as fire firefighters, are clearer (Navarro et al., 2019), and could increase with additional exposure driven by climate change.

Other climate related mechanisms that may increase CVD risk include hot weather-related reduction in physical activity (Obradovich et al., 2017), sleep disturbance (Obradovich et al., 2017), and dehydration (Lim et al., 2015);(Frumkin and Haines, 2019) . There is little literature on how changes in winter weather may affect these risks. Sea level rise-related saline intrusion of groundwater (Taylor et al., 2012) may increase the salt intake of affected populations, a risk factor for hypertension that has been observed to increase blood pressure in exposed populations (Talukder et al., 2017);(MA. et al., 2018).

7.2.3.2 Non-communicable Respiratory Diseases

Lung diseases, including asthma, chronic obstructive pulmonary disease (COPD), and lung cancer, comprise the largest subsets of non-communicable pulmonary disease (Ferkol and Schraufnagel, 2014). Overall, the global burden of non-communicable lung disease including all chronic lung disease and lung cancer is substantial, responsible for 10.6% of deaths and 5.9% of DALYs globally in 2019 (Vos et al., 2020).

Several non-communicable respiratory diseases are climate sensitive based on their exposure pathways (very high confidence). Multiple exposure pathways contribute to non-communicable respiratory disease (Deng et al., 2020), some of which are climate-related, (Rice et al., 2014), including mobilization and transport of dust (Schweitzer et al., 2018 (Schweitzer et al., 2018); changes in concentrations of air pollutants such as small particulates (PM2.5) and ozone formed by photochemical reactions sensitive to temperature (Hansel et al., 2016), increased wildland fires and related smoke exposure (Johnston et al., 2002);(Reid et al., 2016); increased exposure to ambient heat driving reduced lung function and exacerbations of chronic lung disease (Collaco et al., 2018) (Jehn et al., 2013);(McCormack et al., 2016);(Witt et al., 2015); and modification of aeroallergen production and duration of exposure (Ziska et al., 2019).

Burdens of allergic disease, particularly allergic rhinitis and allergic asthma may be changing in response to climate change (medium confidence). (D'Amato et al., 2020);(Eguiluz-Gracia et al., 2020), (Deng et al., 2020), (Demain, 2018). This is supported by evidence showing an increase in the length of the North American pollen season attributable to climate change (Ziska et al., 2019), an association between timing of spring onset and higher asthma hospitalizations presumed to be due to higher pollen exposure (Sapkota et al., 2020), and other evidence linking aeroallergen exposure with a worsening burden of allergic disease (Demain, 2018);(Poole et al., 2019).

7.2.3.3 Cancer

Climate change is likely to increase the risk of several malignancies (high confidence), though the degree to which risks may increase remains unclear. Cancers, also known as malignant neoplasms, include a heterogeneous collection of diseases with various causal pathways, many with environmental influences. Malignant neoplasms impose a substantial burden of disease globally, responsible for slightly over 10 million deaths and 251 million DALYs globally in 2019 (Vos et al., 2020). Climatic hazards affect exposure pathways for several different chemical hazards associated with carcinogenesis (Portier et al., 2010). Most relevant literature has focused on elaborating potential pathways and producing qualitative or quantitative estimates of effect, though there is limited literature on current and projected impacts.

The vast majority of elaborated pathways point to increased risk; for example, there is concern that climate change may alter the fate and transport of carcinogenic polyaromatic hydrocarbons (Domínguez-Morueco et al., 2019) and increase mobilization of carcinogens such as bromide (Regli et al., 2015), persistent organic pollutants including polychlorinated-biphenyls that have accumulated in areas contaminated by industrial runoff (Miner et al., 2018), and radioactive material (Evangeliou et al., 2014). Exposure to these known carcinogens can occur through multiple environmental media and can be increased by climate change, for example through increased flooding related to extreme precipitation events and mobilization of sediment where carcinogens have accumulated (León et al., 2017);(Santiago and Rivas, 2012). In addition, there is concern that changes in ultraviolet light exposure related to shifts in precipitation may increase the incidence of malignant melanoma, particularly for outdoor workers (Modenese et al., 2018). Other harmful pathways include migration of and increased exposure to liver flukes, which cause hepatobiliary cancer (Prueksapanich et al., 2018) and introduction of infectious diseases such as schistosomiasis that increase cancer risk due to climate-related migration (Ahmed et al., 2014). Increased exposure to carcinogenic toxins via multiple pathways is also a concern. Aflatoxin exposure, for example, is expected to increase in Europe (Moretti et al., 2019), India (Shekhar et al., 2018), Africa (Gnonlonfin et al., 2013);(Bandyopadhyay et al., 2016), and North America (Wu et al., 2011). Other carcinogenic toxins originate from cyanobacteria blooms (Lee et al., 2017a), which are projected to increase in frequency and distribution with climate change (Wells et al., 2015);(Paerl et al., 2016);(Chapra et al., 2017).

7.2.3.4 Diabetes

Individuals suffering from diabetes are at higher risk of heat-related illness and death (medium confidence). Extreme weather events and rising temperatures ihave been found ncreasing morbidity and mortality in patients living with diabetes, especially in those with cardiovascular complications (Méndez-Lázaro et al., 2018; Zilbermint, 2020) (Hajat et al., 2017). Evidence suggests that the local heat loss response of skin blood flow (SkBF) is affected by diabetes-related impairments, resulting in lower elevations in SkBF in response to a heat or pharmacological stimulus. Thermoregulatory sweating may also be diminished by type 2 diabetes, impairing the body's ability to transfer heat from its core to the environment (Xu et al., 2019b). Observed higher rates of doctor consultations by patients with type-2 diabetes, and diabetics with cardiovascular comorbidities increased their rates of medical consultation during hot days, but there was no heightened risk with renal failure or neuropathy comorbidities.

People with chronic illness/es are at particular risk during and after extreme weather events due to treatment interruptions and lack of access to medication (medium confidence). The impacts of extreme weather events on the health of chronically ill people are due to a range of factors including disruption of transport, weakened health systems including drug supply chains, loss of power, and evacuations of populations (Ryan et al., 2015a). Evacuations also pose specific health risks to older adults (especially those who are frail, medically incapacitated, or residing in nursing or assisted living facilities) and may be complicated by the need for concurrent transfer of medical records, medications and medical equipment (Becquart et al., 2018);(Quast and Feng, 2019);(USGCRP, 2016). Emergency room visits after Hurricane Sandy rose among individuals with type-2 diabetes (Velez-Valle et al., 2016).

7.2.4 Observed Impacts on Other Climate-sensitive Health Outcomes

7.2.4.1 Heat and Cold Related Mortality and Morbidity

E*xtreme heat events and extreme temperature have well documented, observed impacts on health, mortality (very high confidence) and morbidity (high confidence).* AR5 described the thermoregulatory mechanisms and responses, including acclimatization, linking heat, cold and health, and these have been further confirmed by recent studies and reviews (e.g., (Giorgini et al., 2017);(Ikaheimo, 2018);(McGregor et al., 2015);(Stewart et al., 2017);(Schuster et al., 2017);(Zhang et al., 2018b). The health impacts of heat manifest clearly in periods of extreme heat often codified as heatwaves. For example, heatwaves across Europe (2003), Russia (2010), India (2015) and Japan (2018) resulted in significant death tolls and hospitalizations (McGregor et al., 2017), (Hayashida et al., 2019). Heat continues to pose a significant health risk due to increases in exposure, an outcome of changes in the size and spatial distribution of the human population, mounting vulnerability and an increase in extreme heat events (high confidence) (Harrington et al., 2017; Liu et al., 2017);(Mishra et al., 2017);(Rohat et al., 2019a; Rohat et al., 2019b; Rohat et al., 2019c);(Watts et al., 2019). Furthermore, some regions are already experiencing heat stress conditions approaching the upper limits of labour productivity and human survivability (high confidence). These include the Persian Gulf and adjacent land areas, parts of the Indus River Valley, eastern coastal India, Pakistan, north-western India, the shores of the Red Sea, the Gulf of California, the southern Gulf of Mexico, and coastal Venezuela and Guyana (Krakauer et al., 2020);(Li et al., 2020);(Raymond et al., 2020);(Saeed et al., 2021);(Xu et al., 2020).

Notwithstanding the variety of methods applied, estimates of the world's current population exposed to extreme heat indicate very large numbers and an increase since pre-industrial times. For example, Li et al (2020) estimate that globally and annually, 1.28 billion people experience heatwave conditions similar to that of the lethal Chicago 1995 event compared to 0.99 billion under a preindustrial climate. Further, for the 150 most populated cities of the world, a 500% increase in the exposure to extreme heat events occurred over the period 1980 – 2017 (Li et al., 2021), while for the period 1986–2005, the total exposure to dangerous heat in Africa's 173 largest cities was 4.2 billion person-days per year (Rohat et al., 2019a). Globally the present exposure to heatwave events is estimated to be 14.8 billion person-days per year, with the greatest cumulative exposures measured in person-days occurring across southern Asia (7.19 billion), sub-Saharan Africa (1.43 billion) and North Africa and the Middle East (1.33 billion) (Jones et al., 2018).

The country level percentage of mortality attributable to non-optimum temperature (heat and cold) has been found to range from 3·4% to 11·00% (Gasparrini et al., 2015);(Zhang et al., 2019b). Heat as a health risk factor has largely been overlooked in low and middle-income countries, (Campbell et al., 2018) (Green et al., 2019);(Dimitrova et al., 2021). For 2019, the Global Burden of Disease report estimates the burden of DALYs attributable to low temperature was 2.2 times greater than the burden attributable to high temperature. However, this global figure obscures important regional variations. Countries with a high socio-demographic index - mainly mid-latitude high income temperate to cool climate countries -, were found to have a cold-related burden 15.4 times greater than the heat-related burden, while for warm lower income regions, such as south Asia and sub-Saharan Africa, the heat-related burden was estimated to be 1.7 times and 3.6 times greater respectively (Murray et al., 2020). For countries where data availability permits, there is evidence that extreme heat (and extreme cold) leads to higher rates of premature deaths (Armstrong et al., 2017);(Cheng et al., 2018);(Costa et al., 2017).
Rapid changes and variability in temperatures are observed to increase heat-related health and mortality risks, the outcomes varying across temperate and tropical regions (Guo et al., 2016);(Cheng et al., 2019); (Kim et al., 2019a);(Tian et al., 2019);(Zhang et al., 2018b);(Zhao et al., 2019).

Several lines of evidence point to a possible decrease in population sensitivity to heat, albeit mainly for high-income countries (high confidence), arising from the implementation of heat warning systems, increased *awareness, and improved quality of life.* (Sheridan and Allen, 2018). Evidence manifests as, a general decrease in the impact of heat on daily mortality(Diaz et al., 2018);(Kinney, 2018);(Miron et al., 2015), a decline in the relative risk attributable to heat (Åström et al., 2018);(Barreca et al., 2016);(Petkova et al., 2014), and an increase in the minimum mortality temperature (MMT) (Åström et al., 2018);(Folkerts et al., 2020);(Follos et al., 2021);(Chung et al., 2018);(Todd and Valleron, 2015); (Yin et al., 2019). It is difficult to draw conclusions regarding trends in heat sensitivity for low to middle-income countries and specific vulnerable groups as these are under-represented in the literature (Sheridan and Allen, 2018). Trends in heat sensitivity are likely to be scale and situation dependent as considerable inter-city variability in changes in heat sensitivity as measured by trends in heat-related mortality or MMT (Follos et al., 2021);(Kim et al., 2019a);; (Lee et al., 2021) exist as well as variability amongst different population groups (Lu et al., 2021).

Temperature interacts with heat-sensitive physiological mechanisms via multiple pathways to affect health. In the worst cases these lead to organ failure and death (Mora et al., 2017a; Mora et al., 2017b). Excess deaths during extreme heat events occur predominantly in older individuals and are overwhelmingly cardiovascular in origin *(very high confidence)*. A higher occurrence of CVD mortality in association with prolonged period of low temperatures has been well documented globally (Giorgini et al., 2017);(Stewart et al., 2017); however, there is growing evidence that cardiovascular deaths are more related to heat events than cold spells (Chen et al., 2019);(Liu et al., 2015a);(Bunker et al., 2016). Whilst there is strong association between ambient temperature and cardiovascular events globally, there are complex interactions and modulators of individual response (Wang et al., 2017b). Further, some CVD morbidity sub-groups such as myocardial infarction and stroke hospitalization display temperature sensitivity, while others do not (Bao et al., 2019);(Sun et al., 2018);(Wang et al., 2016). Although older adults have inherent sensitivities to temperature-related health impacts (Bunker et al., 2016);(Phung et al., 2016), children can also be affected by extreme heat (Xu et al., 2014). Cardiovascular capacity/health is also a critical determinant of individual health outcomes (Schuster et al., 2017). Medications to treat CVD diseases, such as diuretics and beta-blockers, may impair resilience to heat stress (Stewart et al., 2017). Other mediating factors in the causal pathway range from alcohol consumption (Cusack et al., 2011);(Epstein and Yanovich, 2019) and obesity (Speakman, 2018) to pre-existing conditions such as diabetes and hyperlipidaemia, and urban characteristics (Chen et al., 2019), (Sera et al., 2019).

Under extreme heat conditions, increases in hospitalizations have been observed for fluid disorders, renal failure, urinary tract infections, septicaemia, general heat stroke as well as unintentional injuries (Borg et al., 2017);(Phung et al., 2017);(Goggins and Chan, 2017);(Hayashida et al., 2019);(Hopp et al., 2018);(Ito et al., 2018);(Kampe et al., 2016);(McTavish et al., 2018);(Ponjoan et al., 2017);(van Loenhout et al., 2018). Hospitalisations and mortality due to respiratory disorders also occur during heat events with the interactive role of air quality important for some locations but not others (Krug et al., 2019);(Pascal et al., 2021);(Patel et al., 2019). Increased levels of heat-related hospitalisation also manifest in elevated levels of emergency services call out (Cheng et al., 2016);(Guo, 2017);(Papadakis et al., 2018);(Williams et al., 2020).

Heat and cold related health outcomes vary by location (Dialesandro et al., 2021);(Hu et al., 2019);(Phung et al., 2016), suggesting outcomes are highly moderated by socio-economic, occupational and other non-climatic determinants of individual health and socio-economic vulnerability (Åström et al., 2020);(McGregor et al., 2017);(McGregor et al., 2017);(Schuster et al., 2017), (Benmarhnia et al., 2015);(Watts et al., 2019) (*high confidence*). For example, access to air conditioning is an important determinant of heat-related health outcomes for some locations (Guirguis et al., 2018);(Ostro et al., 2010). Although there is a paucity of global level studies of the effectiveness of air conditioning for reducing heat-related mortality, a recent assessment indicates increases in air conditioning explains only part of the observed reduction in heat-related excess deaths, amounting to 16.7% in Canada, 20.0% in Japan, 14.3% in Spain and 16.7% in the US (Sera et al., 2020).

Significant effects of heat exposure are evident in sport and work settings with exertional heat illness leading to death and injury (Adams and Jardine, 2020). Although most studies of heat-related sports injuries refer to high-income countries, these point to an increasing number of heat injuries with widening participation in sport and an increasing frequency of extreme heat events. The highest rates of exertional heat illness are reported for endurance type events (running, cycling, adventure races), American football and athletics (Gamage et al., 2020); (Grundstein et al., 2017);(Kerr et al., 2020);(McMahon et al., 2021);(Yeargin et al., 2019). The health, safety and productivity consequences of working in extreme heat are widespread (Ma et al., 2019);(Morabito et al., 2021);(Kjellstrom et al., 2019);(Orlov et al., 2020);(Smith et al., 2021);(Vanos et al., 2019);(Varghese et al., 2020);(Williams et al., 2020). Occupational heat strain in outdoor workers manifests as dehydration, mild reduction in kidney function, fatigue, dizziness, confusion, reduced brain function, loss of concentration and discomfort (Al-Bouwarthan et al., 2020);(Boonruksa et al., 2020);(Habibi et al., 2021);(Levi et al., 2018);(Venugopal et al., 2021);(Xiang et al., 2014). In the case of the armed forces, a global review of the available literature points to a slightly higher incidence of heat stroke in men compared to women but a higher proportion of heat intolerance and greater risk of exertional heat illness amongst women (Alele et al., 2020). There is also some evidence that for healthcare workers, the risk of occupational heat stress heightened during the COVID-19 pandemic due to the need to wear personal protective equipment (Foster et al., 2020);; (Lee et al., 2020);(Messeri et al., 2021). Based on a systematic review of the literature, one study estimates global costs from heat-related lost work time were USD 280 billion in 1995 and USD 311 billion in 2010 with low- and middle-income countries and countries with warmer climates possessing greater losses as a proportion of GDP (Borg et al., 2021). Other global level assessments note an increase in the potential hours of work lost due to heat over the period 2000 –2018; in 2018, 133·6 billion potential work hours were lost amounting to 45 billion hours more than in 2000 (Watts et al., 2019). Further, for China heat-related productivity losses have been estimated at 9·9 billion hours in 2019, equivalent to 0·5% of the total national work hours for that year with Guangdong province, one of the warmest regions in China, accounting for almost a quarter of the losses (Cai et al., 2021).

Wide ranging knowledge regarding the specific detection and attribution of heat and cold-related mortality/morbidity to observed climate change is lacking. Although there has been an observed increase in winter season temperatures for a number of regions, to date there is variable evidence for a consequential reduction in winter mortality and susceptibility to cold over time due to milder winters - some countries demonstrate decreasing trends, other countries stable or even increasing trends in cold-attributable mortality fractions over time (e.g. (Arbuthnott et al., 2020);(Åström et al., 2013);(Diaz et al., 2019);(Hajat, 2017);(Hanigan et al., 2021);(Lee et al., 2018b). While there is a burgeoning literature on the attribution of extreme heat events to climate change (e.g. (Vautard et al., 2020)), the number of studies that assess the extent to which observed changes in heat-related mortality may be attributable to climate change is small (Ebi et al., 2020). During the 2003 European heatwave, anthropogenic climate change increased the risk of heat-related mortality by approximately 70% and 20% for London and Paris respectively (Mitchell et al., 2016). For the severe heat event across Egypt in 2015, the impact on human discomfort was 69% (±17%) more likely due to anthropogenic climate change (Mitchell, 2016) and for Stockholm, Sweden it has been estimated that mortality due to temperature extremes for 1980–2009 was double what would have occurred without climate change (Åström et al., 2013). To date there has only been one multi-country attempt to quantify the heat-related human health impacts that have already occurred due to climate change. Based on an analysis of 732 locations spanning 43 countries, for the period 1991–2018, the study found that on average, 37.0% (inter-quartile range 20.5–76.3%) of warm-season heat-related deaths can be attributed to anthropogenic climate change, equivalent to an average mortality rate of 2.2/100,000 (median: 1.67/100,00; interquartile range: 1.08 - 2.34/100,000) Regions with a high attributed percentage (> 50%) include southern and western Asia (Iran and Kuwait), Southeast Asia (Philippines and Thailand) and several countries in Central and South America. Those with lower values (<35%) include western Europe (Netherlands, Germany, Switzerland), eastern Europe (Moldova, Czech Republic, Romania), southern Europe (Greece, Italy, Portugal, Spain), North America (USA) and eastern Asia (China, Japan, South Korea) (Vicedo-Cabrera et al., 2021). Due to data restrictions some of the poorest and most susceptible regions to climate change and increases in heat exposure, such as West and East Africa (Asefi-Najafabady et al., 2018);(Sylla et al., 2018) and South Asia, could not be included in the analysis (Mitchell, 2021).

7.2.4.2 Injuries Arising from Extreme Weather Events Other than Heat and Cold

Injuries comprise a substantial portion of the global burden of disease. In 2019, injuries comprised 9.82% of total global DALYs and 7.61% of deaths (Vos et al., 2020). The causal pathways for many injuries, particularly those from heat and extreme weather events, flooding, and fires, exhibit clear climate sensitivity (Roberts and Arnold, 2007);(Roberts and Hillman, 2005), as do some injuries occurring in occupational settings (Marinaccio et al., 2019);(Sheng et al., 2018), but a comprehensive assessment of climate sensitivity in injury causal pathways has not been done. Certain groups, including Indigenous Peoples, children, and elders (Ahmed et al., 2020) are at greater risk for a wide range of injuries. Extreme events impose substantial disease burden directly as a result of traumatic injuries, drowning, and burns and large mental health burdens associated with displacement (Fullilove, 1996), depression, and post-traumatic stress disorder, but the overall injury burden associated with extreme weather is not known. It is known that the Asia-Pacific region experienced the highest relative burden of injuries from extreme weather in recent decades (Hashim and Hashim, 2016).

Extreme weather imposes a substantial morbidity and mortality burden that is quite variable by location and hazard. The proportion of this burden related to injuries specifically is not established. From 1998-2017 there were 526,000 deaths from 11,500 extreme weather events, and the average annual attributable all-cause mortality incidence in the ten most affected countries was 3.5 per 100,000 population (Eckstein et al., 2017). Rates can be much higher, however; mortality incidence in Puerto Rico and Dominica from extreme weather were 90.2 and 43.7 per 100,000 population in 2017, respectively (Eckstein et al., 2017). Not all of these deaths are from injuries, and the proportion of mortality and morbidity associated with injuries varies by location and hazard. One review found that one-year post-event prevalence rates for injuries associated with extreme events (floods, droughts, heatwaves, and storms) in developing countries ranged from 1.4% to 37.9% (Rataj et al., 2016). Other literature has documented an increase in risk of motor vehicle accidents in association with extreme precipitation (Liu et al., 2017);(Stevens et al., 2019) and temperature (Leard and Roth, 2019)and in association with sandstorms (Islam et al., 2019), and an increased risk of traumatic occupational injuries associated with temperature extremes, particularly extreme heat, likely from fatigue and decreased psychomotor performance (Varghese et al., 2019).

There is clear evidence of climate sensitivity for multiple injuries from floods, fires, and storms, but limited evidence regarding current injury burden attributable to climate change. It is *as likely as not* that climate change has increased the current burden of disease from injuries related to extreme weather, particularly in low-income settings *(low confidence)*. Approximately 120 million people are exposed to coastal flooding annually (Nicholls et al., 2007), causing an estimated 12,000 deaths (Shultz et al., 2005)and there is significant concern for worsening associated with climate change (Shultz et al., 2018a);(Shultz et al., 2018b);(Woodward and Samet, 2018)but very limited quantification of attributable burden. As for projected exposures, there is sufficient evidence to assess risks related to flooding only, though there is very limited literature highlighting increased morbidity and mortality an increase in fires in sub-zero temperatures that are thought to be highly attributed to climate change (Metallinou and Log, 2017).

7.2.4.3 Observed Impacts on Maternal, Fetal, and Neonatal Health

Maternal and neonatal disorders accounted for 3.67% of total global deaths and 7.83% of global DALYs in 2019 (Vos et al., 2020). Children and pregnant women have potentially higher rates of vulnerability and/or exposure to climatic hazards, extreme weather events, and undernutrition (Garcia and Sheehan, 2016), (Sorensen et al., 2018), (Chersich et al., 2018). Available evidence suggests that heat is associated with higher rates of preterm birth (Wang et al., 2020a) low birthweight, stillbirth, and neonatal stress (Cil and Cameron, 2017);(Kuehn and McCormick, 2017) and with adverse child health (Kuehn and McCormick, 2017). Extreme weather events are associated with reduced access to prenatal care and unattended deliveries (Abdullah et al., 2019) and decreased paediatric health care access (Haque et al., 2019).

7.2.4.4 Observed Impacts on Malnutrition

Climate variability and change contribute to food insecurity that can lead to malnutrition, including undernutrition, overweight, obesity; and to disease susceptibility, particularly in low- and middle-income countries (high confidence). Since AR5, analyses of the links between climate change and food expanded beyond undernutrition to include the impacts of climate change on a wider set of diet and weight-related risk factors and their impacts on NCDs, along with the role of dietary choices for GHG emissions (SRCCL, 2019 including dietary inadequacy (deficiencies, excesses, or imbalances in energy, protein, and micronutrients), infections, and sociocultural factors {Global, 2020, Global Nutrition Report: Action on equity to end malnutrition). Undernutrition exists when a combination of insufficient food intake, health, and care conditions results in one or more of underweight for age, short for age (stunted), thin for height (wasted), or functionally deficient in vitamins and/or minerals (micronutrient malnutrition or "hidden hunger"). Food insecurity and poor access to nutrient dense food contribute not only to undernutrition, but also to obesity and susceptibility to non-communicable diseases in low- and middle-income countries (FAO et al., 2018);(Swinburn et al., 2019).

Globally, more than 690 million people are undernourished, 144 million children are stunted (chronic undernutrition), 47 million children are wasted (acute undernutrition), and more than 2 billion people have micronutrient deficiencies (FAO, 2020). More than 135 million people across 55 countries experienced acute hunger requiring urgent food, nutrition, and livelihoods assistance in 2019 (FSIN/GNAFC, 2020). The COVID-19 pandemic is projected to increase the number of acutely food insecure people to 270 million people (FSIN, 2020) and worsen malnutrition levels (FAO et al., 2020); (Rippin et al., 2020)). The relationships between climate change and obesity vary based on geography, population subgroups, and/or stages of economic growth and population growth. (An et al., 2017). Increasing temperatures could contribute to obesity through reduced physical activity, increased prices of produce, or shifts in eating patterns of populations toward more processed foods. (An et al., 2018). In the largest global study to date exploring the connections between child diet diversity and recent climate, data from 19 countries in six regions (Asia, Central America, North Africa, South America, Southeast Africa, and West Africa) indicated significant reductions in diet diversity associated with higher temperatures and significant increases in diet diversity associated with higher precipitation (Niles et al., 2021).

Climate change can affect the four aspects of food security: food production and availability, stability of food supplies, access to food, and food utilization (SRCCL, 2019). Access to sufficient food does not guarantee nutrition security. Extreme weather and climate events can result in inadequate or insufficient food consumption, increasing susceptibility to infectious diseases (Rodriguez-Llanes et al., 2016);(Gari et al., 2017);(Kumar et al., 2016);(Lazzaroni and Wagner, 2016 but also to being overweight or obese, and susceptibility to non-communicable diseases in LIMICs {FAO, 2018, The State of Food Security and Nutrition in the World 2018);(Swinburn et al., 2019).

Nearly half of all deaths in children under 5 are attributable to undernutrition, putting children at greater risk of dying from common infections (2021). Undernutrition in the first 1,000 days of a child's life can lead to stunted growth, which can result in impaired cognitive ability and reduced future school and work performance and the associated costs of stunting in terms of lost economic growth can be of the order of 10% of GDP per year in Africa (UNICEF/WHO/WBG, 2019).

At the same time, diseases associated with high-calorie, unhealthy diets are increasing globally, with 38.3 million overweight children under five years of age (GNR, 2018), 2.1 billion adults are overweight or obese and the global prevalence of diabetes almost doubled in the past 30 years (Swinburn et al., 2019). Unbalanced diets, such as diets low in fruits and vegetables and high in red and processed meat, are the number one risk factor for mortality globally and in most regions (Collaborators, 2018b);(Collaborators, 2019).

Socio-economic factors that mediate the influence of climate change on nutrition include cultural and societal norms; governance, institutions, policies, and fragility; human capital and potential; social position and access to healthcare, education, and food aid (Rozenberg, 2017); Alkerwi et al. 2015;(Tirado, 2017);(FAO et al., 2018);(Report, 2020). Extreme events may affect access to adequate diets, leading to malnutrition and increasing the risk of disease (Beveridge et al., 2019);(Rodriguez-Llanes et al., 2016);(Gari et al., 2017);(Kumar et al., 2016);(Lazzaroni and Wagner, 2016);(Thiede and Gray, 2020).

7.2.4.5 Observed Impacts on Exposure to Chemical Contaminants

Climate change in northern regions, including Arctic ecosystems, is causing permafrost to thaw, creating the potential for mercury (Hg) to enter the food chain (medium agreement, low evidence), as Methyl mercury (MeHg) is highly neurotoxic and nephrotoxic and bioaccumulates and biomagnifies throughout the food chain via dietary uptake of fish, seafood, and mammals. Mercury methylation processes in aquatic environments have been found exacerbated by ocean warming, coupled with more acidic and anoxic sediments (FAO, 2020). Consumption of mercury-contaminated fish has been found linked to neurological disorders due to methyl mercury poisoning (i.e., Minamata disease) that is associated withlimate change-contaminant interactions that alter the bioaccumulation and biomagnification of toxic and fat-soluble persistent organic pollutants, such as persistent organic pollutants (POPs) and polychlorinated biphenyls (PCBs) (J.J. et al., 2017) in seafood and marine mammals (*medium confidence)*. Indigenous peoples have a higher exposure to such risks because of the accumulation of such toxins in traditional foods (J.J. et al., 2017). Contamination of food with PCBs and dioxins that have a range of adverse health impacts (Lake et al., 2015).

Chapter 5 (5.4.3, 5.5.2.3, 5.8.1, 5.8.2, 5.8.3, 5.9.1, 5.11.1, 5.11.3, 5.12.3) discusses the possible impacts of climate change on food safety, including exposure to toxigenic fungi, PCBs, and other persistent organic pollutants, mercury, and harmful algal blooms.

Climate change may affect animal health management practices, potentially leading to an increased use of pesticides or veterinary drugs (such as preventive antimicrobials) that could result in increased levels of residues in foods (high agreement, medium/low evidence). (Beyene et al., 2015); (FAO and WHO, 2018);(Authority) et al., 2020);(Authority) et al., 2020); (MacFadden et al., 2018)).

7.2.5 Observed Impacts on Mental Health and Wellbeing

7.2.5.1 Observed Impacts on Mental Disorders

A wide range of climatic events and conditions have observed and detrimental impacts on mental health (very high confidence). The pathways through which climatic events affect mental health are varied, complex and interconnected with other non-climatic influences that create vulnerability. The climatic exposure may be direct, such as experiencing an extreme weather event or prolonged high temperatures, or indirect, such as mental health consequences of undernutrition or displacement. Exposure may also be vicarious, with people experiencing decreased mental health associated with observing the impact of climate change on others, or simply with learning about climate change. Non-climatic moderating influences range from an individual's personality and pre-existing conditions, to social support, to structural inequities (Gariepy et al., 2016);(Hrabok et al., 2020);(Nagy et al., 2018);(Silva et al., 2016b). Depending on these background and contextual factors, similar climatic events may result in a range of potential mental health outcomes, including anxiety, depression, acute traumatic stress, post-traumatic stress disorder, suicide, substance abuse, and sleep problems, with conditions ranging from being mild in nature to those that require hospitalization (Berry et al., 2010);(Cianconi et al., 2020);(Clayton et al., 2017);(Ruszkiewicz et al., 2019);(Bromet et al., 2017);{Lowe, 2019, Posttraumatic Stress and Depression in the Aftermath of Environmental Disasters: A Review of Quantitative Studies Published in 2018}. The line between mental health and more general wellbeing is permeable, but in this section we refer to diagnosable mental disorders, conditions that disrupt or impair normal functioning through impacts on mood, thinking, or behaviour.

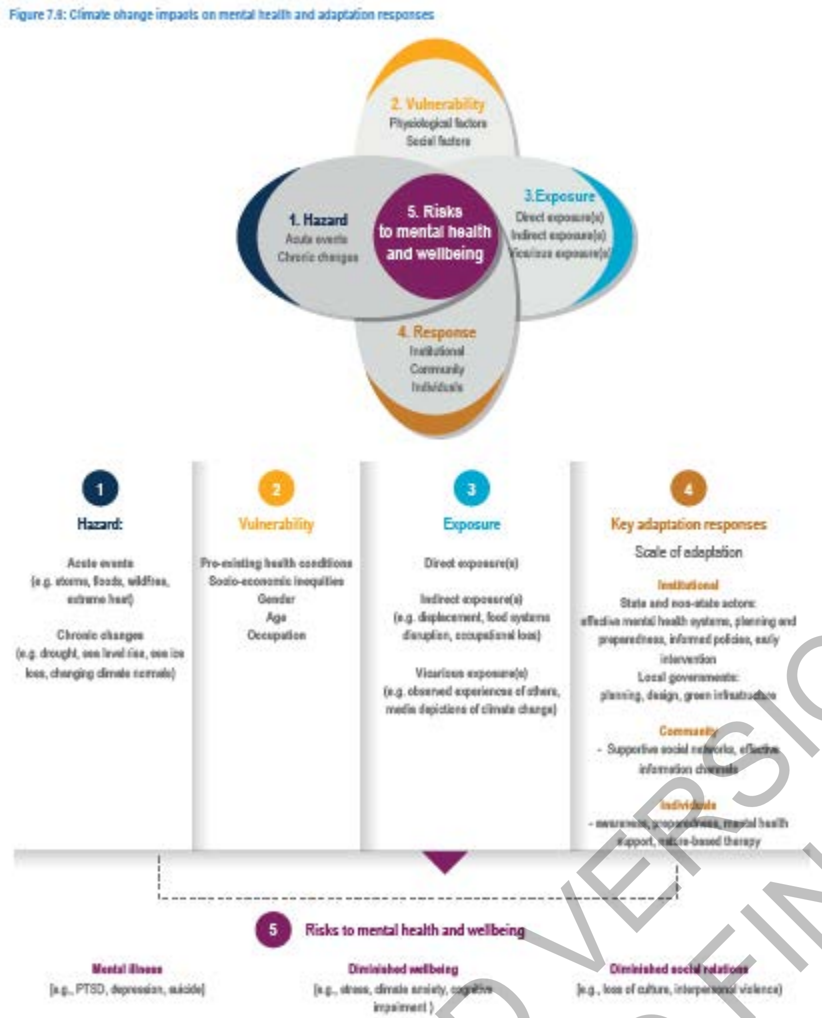


Figure 7.6: Climate change impacts on mental health and key adaptation responses

There is an observable association between high temperatures and mental health decrements (high confidence), with an additional possible influence of increased precipitation (medium agreement, medium evidence). Heat-associated mental health outcomes include suicide (Williams et al., 2015a);(Carleton, 2017);(Burke et al., 2018);(Kim et al., 2019b);(Thompson et al., 2018), (Schneider et al., 2020);(Cheng et al., 2021);(Baylis et al., 2018);(Obradovich et al., 2018); psychiatric hospital admissions and ER visits for mental disorders (Hansen et al., 2008);(Wang et al., 2014);(Chan et al., 2018);(Mullins and White, 2019);(Yoo et al., 2021), experiences of anxiety, depression, and acute stress (Obradovich et al., 2018);(Mullins and White, 2019), and self-reported mental health (Li et al., 2020). In Canada, Wang et al. (2014) found an association between mean heat exposure of 28°C within 0 to 4 days of exposure and greater hospital admissions for mood and behavioural disorders (including schizophrenia, mood, and neurotic disorders). A US study found mental health problems increased by 0.5% when average temperatures exceeded 30°C, compared to averages between 25–30°C; a 1°C warming over 5 years was associated with a 2% increase in mental health problems (Obradovich et al., 2018). Another study found a 1°C rise in monthly average temperatures over several decades was associated with a 2.1% rise in suicide rates in Mexico and a 0.7% rise in suicide rates in the US (Burke et al., 2018). A systematic review of published research using a variety of methodologies from 19 countries (Thompson et al., 2018) found increased risk of suicide associated with a 1°C rise in ambient temperature.

Discrete climate hazards including storms have significant negative consequences for mental health (very high confidence). (Kessler et al., 2008);(Boscarino et al., 2013);(Boscarino et al., 2017);(Obradovich et al., 2018), floods (Baryshnikova and Pham, 2019), heatwaves, wildfires, and drought (Hanigan et al., 2012);(Carleton, 2017);(Zhong et al., 2018) (Charlson et al., 2021).A large body of research identifies impacts of extreme weather events on post-traumatic stress disorder, anxiety, and depression; much of the research has been done in the U.S. and the UK, but a growing number of studies find evidence for similar impacts on mental health in other countries, including Spain (Foudi et al., 2017), Brazil (Alpino et al., 2016), Chile (Navarro et al., 2016), Small Island Developing States (Kelman et al., 2021), and Vietnam (Pollack et al., 2016). Approximately 20–30% of those who live through a hurricane develop depression and/or post-traumatic stress disorder (PTSD) within the first few months following the event (Obradovich et al., 2018);(Schwartz et al., 2015);(Whaley, 2009), with similar rates for people who have experienced flooding (Waite et al., 2017);(Fernandez et al., 2015). Studies conducted in South America and Asia indicate an increase in post-traumatic stress disorders and depressive disorders after extreme weather events (Rataj et al., 2016). Evidence is lacking for African countries (Otto et al., 2017). Children and adolescents are particularly vulnerable to post-traumatic stress after extreme weather events (Brown et al., 2017);(Hellden et al., 2021);(Kousky, 2016), and increased susceptibility to mental health problems may linger into adulthood (Maclean et al., 2016).

Wildfires have observed negative impacts on mental health (high confidence). This is due to the trauma of the immediate experience and/or subsequent displacement and evacuation (Dodd et al., 2018);(Brown et al., 2019);(Psarros et al., 2017);(Silveira et al., 2021b), Subclinical outcomes, such as increases in anxiety, sleeplessness, or substance abuse are reported in response to wildfires and extreme weather events, with impacts being pronounced among those who experience greater losses or are more directly exposed to the event; this may include first responders.

Mental health impacts can emerge as result of climate impacts on economic, social and food systems (high confidence). For example, malnutrition among children has been associated with a variety of mental health problems (Adhvaryu et al., 2019);(Hock et al., 2018);(Yan et al., 2018), as has food insecurity among adults (Lund et al., 2018). The economic impacts of droughts have been associated with increases in suicide, particularly among farmers (Carleton, 2017);(Edwards et al., 2015);(Vins et al., 2015); those whose occupations are likely to be affected by climate change report that it is a source of stress that is linked to substance abuse and suicidal ideation (Kabir, 2018). Studies of Indigenous Peoples often describe food insecurity or reduced access to traditional foods as a link between climate change and reduced mental health (Middleton et al., 2020b). The loss of family members, e.g. due to an extreme weather event, increases the risk of mental illness (Keyes et al., 2014). Individuals in low and middle-income countries may be more severely impacted due to lesser access to mental health services and lower financial resources to help cope with impacts, compared with high-income countries (Abramson et al., 2015).

Anxiety about the potential risks of climate change and awareness of climate change itself can affect mental health even in the absence of direct impacts (low confidence). There is not yet robust evidence about the prevalence or severity of climate change-related anxiety, sometimes called ecoanxiety, but national surveys in the U.S., Europe, and Australia show that people express high levels of concern and perceived harm associated with climate change (Steentjes et al., 2017), (Clayton and Karazsia, 2020);(Cunsolo and Ellis, 2018);(Helm et al., 2018). (Leiserowitz et al., 2017);(Reser et al., 2012);(Steentjes et al., 2017). In a U.S. sample, perceived ecological stress, defined as personal stress associated with environmental problems, predicted depressive symptoms (Helm et al., 2018);in a sample of Filipinos, climate anxiety was correlated with lower mental health (Reyes et al., 2021), and a non-random study in 25 countries showed positive correlations between negative emotions about climate change and self-rated mental health (Ogunbode et al., 2021). However, an earlier study found no correlation between climate change worry and mental health issues (Berry and Peel, 2015). Because the perceived threat of climate change is based on subjective perceptions of risk and coping ability as well as on experiences and knowledge (Bradley et al., 2014), even people who have not been directly affected may be stressed by a perception of looming danger (Clayton and Karazsia, 2020). Not surprisingly, those who have directly experienced some of the effects of climate change may be more likely to show such responses. Indigenous Peoples, whose culture and wellbeing tend to be strongly linked to local environments, may be particularly likely to experience mental health effects associated with changes in environmental risks; studies suggest connections to an increase in depression, substance abuse, or suicide in some Indigenous Peoples (Canu et al., 2017);(Cunsolo Willox et al., 2013);(Middleton et al., 2020b);(Jaakkola et al., 2018).

7.2.5.2 Observed Impacts on Wellbeing

*Overall, research suggests that climate change has already had negative effects on subjective wellbeing (medium confidence). C*limate change can affect wellbeing through a number of pathways, including loss of access to green and blue spaces due to damage from storms, coastal erosion, drought, or wildfires; heat; decreased air quality; and disruptions to one's normal pattern of behaviour, residence, occupation, or social interactions (Hayward and Ayeb-Karlsson, 2021). For example, substantial evidence shows a negative correlation between air pollution and subjective wellbeing or happiness (Apergis, 2018);(Cunado and de Gracia, 2013);(Lu, 2020);(Luechinger, 2010);(Menz and Welsch, 2010);(Orru et al., 2016);(Yuan et al., 2018);(Zhang et al., 2017a); in the reverse direction, there is evidence not only that time in nature but more specifically a feeling of connectedness to nature are both associated with wellbeing (Martin et al., 2020) and healthy ecosystems offer opportunities for health improvements (Pretty and Barton, 2020). Negative emotions such as grief - often termed 'solastalgia'(Albrecht et al., 2007) -- are associated with the degradation of local or valued landscapes (Eisenman et al., 2015);(Ellis and Albrecht, 2017);(Polain et al., 2011);(Tschakert et al., 2017);(Tschakert et al., 2019), which may threaten cultural rituals, especially among Indigenous Peoples (Cunsolo and Ellis, 2018);(Cunsolo et al., 2020). Studies conducted in the Solomon Islands and in Tuvalu found qualitative and quantitative evidence of experiences of climate change and worry about the future, with negative impacts on respondents' wellbeing (Asugeni et al., 2015);(Gibson et al., 2020).

Heat is one of the best-studied aspects of climate change observed to reduce wellbeing (high confidence). Higher summer temperatures are associated with decreased happiness and ratings of wellbeing (Carleton and Hsiang, 2016);(Miles-Novelo and Anderson, 2019). (Connolly, 2013);(Noelke et al., 2016);(Baylis et al., 2018);(Moore et al., 2019);(Wang et al., 2020b). A study of 1.9 million Americans, (Noelke et al., 2016) found that exposure to one day averaging 21–27 °C was associated with reduced wellbeing by 1.6% of a standard deviation, and days above 32°C were associated with reduced wellbeing by 4.4% of a standard deviation relative to a reference interval of 10–16 °C. A similar relationship between heat and mood has been observed in China, where expressed mood began to decrease when the average daily temperature was over 20°C (Wang et al., 2020b). The causal mechanism is unclear, but could be due to impacts on health, economic costs, social interactions (Belkin and Kouchaki, 2017);(Osberghaus and Kühling, 2016), or reduced quality or quantity of sleep (Fujii et al., 2015);(Obradovich et al., 2017);(Obradovich and Migliorini, 2018). Heat has also been associated with interpersonal and intergroup aggression, and increases in violent crime (Heilmann et al., 2021);(Mapou et al., 2017);(Tiihonen et al., 2017). For the most part, studies have measured daily response to average daily temperatures and are unable to predict whether the effect is cumulative in response to a sequence of unusually warm days. However, there is no evidence that adaptation occurs over time to eliminate the negative response to very warm temperatures (Moore et al., 2019). Some research has found a negative effect of extreme cold on wellbeing (Yoo et al., 2021); increasing winter temperatures associated with climate change could serve to compensate for the impact of increased summer temperatures. However, the effect of high temperatures is typically found to be stronger than the effect of low temperatures, and in some cases no detrimental impacts of cold weather are found (Almendra et al., 2019);(Mullins and White, 2019).

Climate change also threatens wellbeing defined in terms of capabilities, or the capacity to fulfil one's potential and fully participate in society. Heat can limit labour capacity, one study estimating that 45 billion hours of labour productivity were lost in 2018 compared to 2000 due to high temperatures (Watts et al., 2019). Both heat and air pollution also impair human capabilities through a negative effect on cognitive performance (Taylor et al., 2016b), and even impair skills acquisition, reducing the ability to learn (Park et al., 2021) and affecting marginalized groups more strongly (Park et al., 2020), although findings are inconsistent and depend in part on the nature of the task *(low confidence).*

Systematic reviews have found an association between higher ambient levels of fine airborne particles and cognitive impairment in the elderly, or behavioural problems (related to impulsivity and attention problems) in children (Power et al., 2016);(Yorifuji et al., 2017);(Younan et al., 2018) (Zhao et al., 2018b) (*medium confidence*). Malnutrition has also been associated with reduced educational achievement and long-term decrements in cognitive function (Acharya et al., 2019);(Asmare et al., 2018);(Na et al., 2020);(Kim et al., 2017);(Talhaoui et al., 2019).

7.2.6 Observed Impacts on Migration

Consistent with peer-reviewed scholarship and with the UNFCCC Cancun Adaptation Framework section 14(f) and the Paris Agreement, this Chapter assesses the impacts of climate change on four types of migration: 1) adaptive migration (i.e where migration is an outcome of individual or household choice); (2) involuntary displacement (i.e. where people have few or no options except to move); (3) organized relocation of populations from sites highly exposed to climatic hazards; and (4) immobility (i.e. an inability or unwillingness to move from areas of high exposure for cultural, economic or social reasons) (see Cross-Chapter Box MIGRATE).

A general theme across studies from all regions is that climate-related migration outcomes are diverse (high confidence) and may be manifest as decreases or increases in migration flows, and lead to changes in the timing or duration of migration, and to changes in migration source locations and destinations. Multi-country studies of climatic impacts on migration patterns in Africa have found that migration exhibits weak, inconsistent associations with variations in temperatures and precipitation, and that migration responses differ significantly between countries, and between rural and urban areas (Gray and Wise, 2016);(Mueller et al., 2020). Multidirectional findings such as these are also common in single-country studies from multiple regions (A.Call et al., 2017);(Nawrotzki et al., 2017);(Cattaneo et al., 2019);(Kaczan and Orgill-Meyer, 2020). The diversity of potential migration and displacement outcomes reflects (1) the variable nature of climate hazards in terms of their rate of onset, intensity, duration, spatial extent, and severity of damage caused to housing, infrastructure, and livelihoods; and (2) the wide range of social, economic, cultural, political and other non-climatic factors that influence exposure, vulnerability, adaptation options and the contexts in which migration decisions are made (Neumann and Hermans, 2015);(McLeman, 2017);(Barnett and McMichael, 2018);(Cattaneo et al., 2019);(Hoffmann et al., 2020) (*high confidence*).

Weather events and climate conditions can act as direct drivers of migration and displacement (e.g. destruction of homes by tropical cyclones) and as indirect drivers (e.g. rural income losses and/or food insecurity due to heat- or drought-related crop failures that in turn generate new population movements) (high confidence). Extreme storms, floods and wildfires are strongly associated with high levels of short- and long-term displacement, while droughts, extreme heat and precipitation anomalies are more likely to stimulate longer term changes in migration patterns (Kaczan and Orgill-Meyer, 2020);(Hoffmann et al., 2020). Longer term environmental changes attributable to anthropogenic climate change - such as higher average temperatures, desertification, land degradation, biodiversity loss and sea level rise - have had observed effects on migration and displacement in a limited number of locations in recent decades but are projected to have wider-scale impacts on future population patterns and migration, and are therefore assessed in section 7.3.2 (Projected Risks).

[START CROSS-CHAPTER BOX MIGRATE HERE]

Cross-Chapter Box MIGRATE: Climate-related Migration

Authors: David Wrathall (Chapter 8), Robert McLeman (Chapter 7), Helen Adams (Chapter 7), Ibidun Adelekan (Chapter 9), Elisabeth Gilmore (Chapter 14), Francois Gemenne (Chapter 8), Nathalie Hilmi (Chapter 18), Ben Orlove (Chapter 17), Ritwika Basu (Chapter 18), Halvard Buhaug (Chapter 16), Edwin Castellanos (Chapter 12), David Dodman (Chapter 6), Felix Kalaba (Chapter 9), Rupa Mukerji (Chapter1 8), Karishma Patel (Chapter 1), Chandni Singh (Chapter 10), Philip Thornton (Chapter 5), Christopher Trisos (Chapter 9), Olivia Warrick (Chapter 15); Vishnu Pandey (Chapter 4),

Key messages on migration in this report

Migration is a universal strategy that individuals and households undertake to improve wellbeing and livelihoods in response to economic uncertainty, political instability and environmental change (*high confidence*). Migration, displacement, and immobility that occur in response to climate hazards are assessed in general in Chapter 7, with specific sectoral and regional dimensions of climate-related migration assessed in sectoral and regional chapters 5 to 15 [Table Cross-Chapter Box MIGRATE.1] and involuntary immobility and displacement being identified as a representative key risk in Chapter 16 [16.2.3.8, 16.5.2.3.8]. Since AR5 there has been a considerable expansion in research on climate-migration linkages, with five key messages from the present assessment report warranting emphasis:

Climatic conditions, events and variability are important drivers of migration and displacement (high confidence) [Table Cross-Chapter Box MIGRATE.1], with migration responses to specific climate hazards being strongly influenced by economic, social, political and demographic processes (high agreement, robust evidence)[7.2.6, 8.2.1.3]. Migration is among a wider set of possible adaptation alternatives, and often emerges when other forms of adaptation are insufficient [5.5.1.1, 5.5.3.5, 7.2.6, 8.2.1.3, 9.7.2]. Involuntary displacement occurs when adaptation alternatives are exhausted or not viable, and reflects non-climatic factors that constrain adaptive capacity and create high levels of exposure and vulnerability (*high confidence*) [Cross-Chapter Box SLR in Chapter 3, 4.3.7, 7.2.6, Box 8.1, 10.3, Box 14.7]. There is strong evidence that climatic disruptions to agricultural and other rural livelihoods can generate migration (*high confidence*) [5.5.4, 8.2.1.3, 9.8.3, Box 9.8].

Specific climate events and conditions may cause migration to increase, decrease, or flow in new directions (high confidence), and the more agency migrants have (i.e. the degree of voluntarity and freedom of movement), the greater the potential benefits for sending and receiving areas (high agreement, medium evidence) [5.5.3.5, 7.2.6, 8.2.1.3, Box 12.2]. Conversely, displacement or low-agency migration is associated with poor outcomes in terms of health, wellbeing and socio-economic security for migrants, and returns fewer benefits to sending or receiving communities (*high agreement, medium evidence*) [4.3.7, 4.5.7, Box 8.1, 9.7.2, 10.3, Box 14.7].

Most climate-related migration and displacement observed currently takes place within countries (high confidence) [4.3.7, 4.5.7, 5.12.2, 7.2.6]. The climate hazards most commonly associated with displacement are tropical cyclones and flooding in most regions, with droughts being an important driver in Sub-Saharan Africa, parts of South Asia and South America (*high confidence*) [7.2.6.1, 9.7.2, 10.4.6.3, 11.4.1, 12.5.8.4, 13.8.1.3, 14.4.7.3]. Currently observed international migration associated with climatic hazards is considerably smaller, relative to internal migration, and is most often observed as flowing between states that are contiguous, have labour-migration agreements, and/or longstanding cultural ties (*high agreement, robust evidence*) [4.3.7, 4.5.7, 5.12.2, 7.2.6].

In many regions, the frequency and/or severity of floods, extreme storms, and droughts is projected to increase in coming decades, especially under high-emissions scenarios [AR6 WGI Ch12], raising future risk of displacement in the most exposed areas (high confidence) [7.3.2.1]. Additional impacts of climate change anticipated to generate future migration and displacement include mean sea level rise that increases flooding and saltwater contamination of soil and/or groundwater in low-lying coastal areas and small islands (*high confidence*) [7.3.2.1, Cross-Chapter Box SLR in Chapter 3], and more frequent extreme heat events that threaten the habitability of urban centres in the tropics and arid/semi-arid regions (*medium agreement, medium evidence*), although the links between heat and migration are less clear [7.3.2.1].

There is growing concern among researchers about the future prospects of immobile populations: groups and individuals that are unable or unwilling to move away from areas highly exposed to climatic hazards (high confidence) [4.6.9, 7.2.6.2, Box 8.1, Box 10.2]. Involuntarily immobile populations may be anticipated to require government interventions to continue living in exposed locations or to relocate elsewhere (*high agreement, medium evidence)* [Box 8.1]. Managed retreat and organized relocations of people from hazardous areas in recent years have proven to be politically and emotionally charged, socially disruptive and costly (*high confidence*) [7.4.5.4].

Climate-migration interactions and outcomes

Figure Cross-Chapter Box MIGRATE.1 presents a simplified framework for understanding how migration and displacement may emerge from the interactions of climatic and non-climatic factors, based on the risk framework introduced in Chapter 1, in which climatic risks are represented as emerging from interactions of hazard, exposure and vulnerability in a characteristic propeller-shaped diagram [1.3]. Voluntary migration can be used by households in particular locations for adapting to climate hazards, while less voluntary forms of migration and involuntary displacement emerge when other forms of adaptation (referred to in Figure Cross-Chapter Box MIGRATE.1 as *in situ* adaptation) are inadequate. The success of migration – expressed in Figure Cross-Chapter Box MIGRATE.1 as changes in future risks to the wellbeing of migrants, sending and destination communities — is heavily influenced by the political, legal, cultural and socio-economic conditions under which it occurs. Groups and individuals that are involuntary immobile may find that their exposure, vulnerability and risk increase over time. Table Cross-Chapter Box MIGRATE.1 summarizes the range of potential migration outcomes that may emerge from this dynamic, and indicates specific sections in sectoral and regional chapters of the report that describe examples of each.

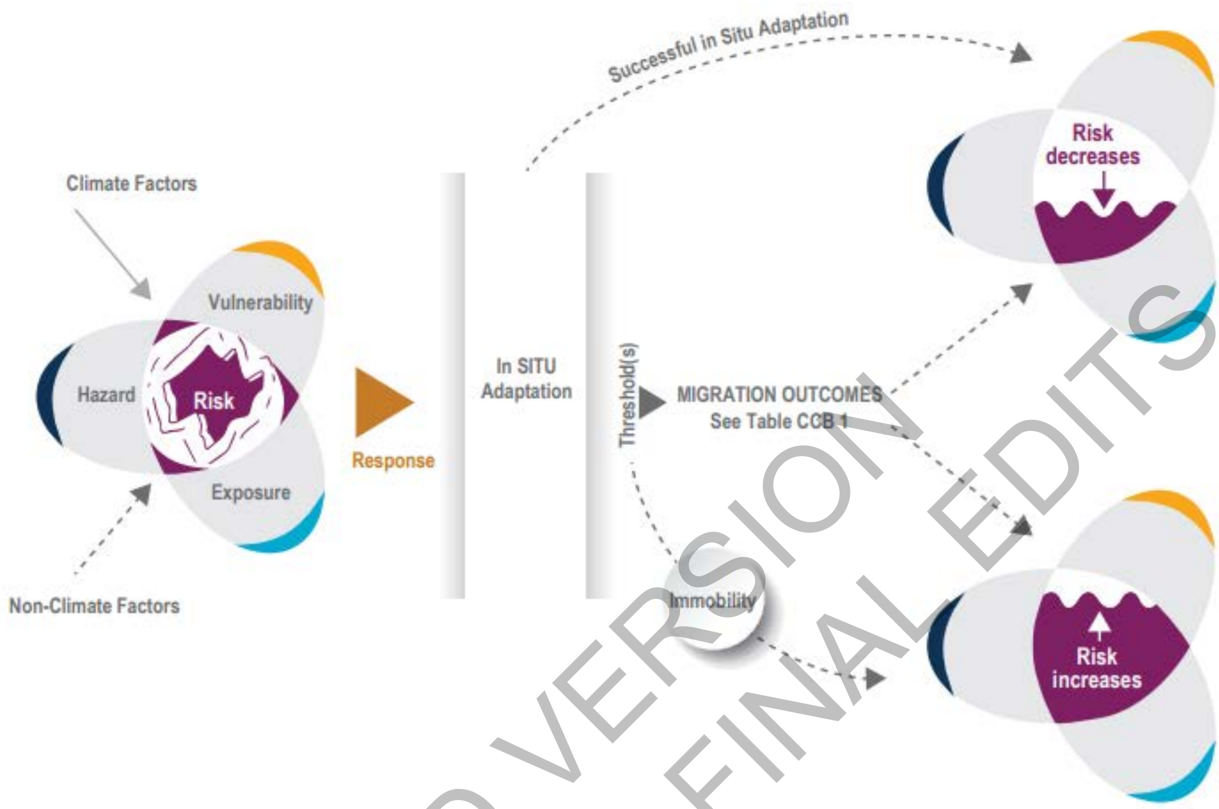


Figure Cross-Chapter Box MIGRATE.1: General interactions between climatic and non-climatic processes, adaptation, potential migration outcomes and implications for future risk. Adapted from (McLeman et al., 2021).

Table Cross-Chapter Box MIGRATE.1: Typology of climate-related migration and examples in sectoral and regional chapters of AR6

Type of climate-related migration	**Characteristics**	**Recent/current examples**	**Examples in literature**	**References in AR6**
Temporary and/or seasonal migration	Frequently used as a risk-reduction strategy by rural households in less-developed regions with highly seasonal precipitation. Includes transhumance	Pastoralists in sub-Saharan Africa; seasonal farm workers in South Asia; rural-urban labour migration in Central America	(Afifi et al., 2016), (Call et al., 2017);(Piguet et al., 2018);(Borderon et al., 2019);(Cattaneo et al., 2019);(Hoffmann et al., 2020);(Lopez-i-Gelats et al., 2015) ; (Lu et al., 2016)(detecting climate networks); (Kaczan and Orgill-Meyer, 2020)	Chapter 5.5.1.1; 5.5.3.5; Chapter 7.2.6; Chapter 8.2.1.3; Chapter 9.8.3; Chapter 13 Box 13.2
Indefinite or permanent migration	Less common than temporary or seasonal migration, particularly when the whole household permanently relocates.	Numerous examples in all regions	See reviews listed in cell above	Chapter 7.2.6; Chapter 8.2.1.3; Chapter 10 Box 10.2

Internal migration	Movements within state borders, most common form of climate-related migration	Numerous examples in all regions	See reviews in cells above	Chapter 4.3.7; Chapter 5.5.4; 5.10.1.1; Chapter 7.2.6; Chapter 9.7.2; 9.11-Box 9.8; Chapter 10.3.3, 10.2 10.4.6.3, Box 10.2; Chapter 11.4.1; Chapter 12.5.8.4; Chapter 13.8.1.3; Chapter 14.4.7.3; Chapter 15.3.4.6
International migration	Less common than internal migration; most often occurs between contiguous countries within the same region; often undertaken for purpose of earning wages to remit home	Cross-border migration within South and Southeast Asia, Sub-Saharan Africa	See reviews in cells above; also (Veronis et al., 2018);(McLeman, 2019);(Cattaneo and G., 2016);(Missirian and Schlenker, 2017);(Schutte et al., 2021)	Chapter 4.3.7; 4.5.7; Chapter 5.12.2; Chapter 7.2.6

Rural-urban or rural-rural	Typically internal, but may also flow between contiguous states; may be for temporary or indefinite periods; migration may be undertaken by an individual household member or the entire household; may be followed by remittances	Drought migration in Mexico, East Africa, South Asia	See reviews in cells above; also (Adger et al., 2015);(Gautier et al., 2016);(Nawrotzki et al., 2017);(Wiederkehr et al., 2018);(Robalino et al., 2015);(Borderon et al., 2019);(Murray-Tortarolo and Martnez, 2021)	Chapter 5.13.4; Chapter 7.2.6; Chapter 6.2.4.3; Chapter 8.2.1.3; Chapter 9.8.1.2; Chapter 12.5.8.4; Chapter 14.4.7.1
Displacement	Households are forced to leave homes for temporary or indefinite period; typically occurs as a result of extreme events and starts with seemingly temporary evacuation; risk is expected to rise in most regions due to sea level rise	Tropical cyclones in Caribbean, Southeast Asia, Bay of Bengal region;	(Islam and Shamsuddoha, 2017);(Desai et al., 2021); see annual reports of Internal Displacement Monitoring Centre for global statistics	Cross-Chapter Box SLR in Chapter 3; Chapter 4.3.7; 4.5.7; Cross-Chapter Box MOVING PLATE in Chapter 5; Chapter 7.2.6.1; Chapter 8 Box 8.1; Chapter 9.7.2; 9.9.2; Chapter 10.3; Chapter 14 Box 14.7; Chapter 15.3.4.6; CCP2.2.2

Planned/organized resettlement	Initiated in areas where settlements become permanently uninhabitable; requires assistance from governments/institutions. Government-sponsored sedentarisation of pastoral populations	Fiji; Carteret Islands, Papua New Guinea; US Gulf of Mexico coast and coastal Alaska	(Marino and Lazrus, 2015);(Hino et al., 2017);(McNamara et al., 2018);(McMichael and Katonivualiku, 2020);(Tadgell et al., 2017);(Arnall, 2014);(Wilmsen and Webber, 2015)	Chapter 4.6.9; Chapter 5.14.1; 5.14.2; Chapter 7.4.4.4; Chapter 10.4.6; Chapter 15.5.3; CCP 2.2.2; CCP 6.3.2;
Immobility	Adverse weather or climatic conditions warrant moving, but households are unable to relocate because of lack of resources, or choose to remain because of strong social, economic or cultural attachments to place	Examples in most regions	(Adams, 2016);(Zickgraf, 2018);(Nawrotzki and DeWaard, 2018);(Farbotko et al., 2020)	Chapter 4.6.9; Chapter 7.2.6.2; Chapter 8. Box 8.1; Chapter 10 Box 10.2

Policy implications

Future migration and displacement patterns in a changing climate will depend not only on the physical impacts of climate change, but also on future policies and planning at all scales of governance (high confidence) [4.6.9, 5.14.1&2, 7.3.2, 7.4.4, 8.2.1.3, Box 8.1, CCP 6.3.2]. Policy interventions can remove barriers to and expand the alternatives for safe, orderly and regular migration that allows vulnerable people to adapt to climate change (*high confidence*) [7.2.6]. With adequate policy support, migration in the context of climate change can result in synergies for both adaptation and development [5.12.2, 7.4.4, 8.2.1.3]. Migration governance at local, national and international levels will influence to a great extent the outcomes of climate-related migration, for the migrants themselves as well as for receiving and origin communities [5.13.4, 7.4.4, 8.2.1.3]. At the international level, a number of relevant policy initiatives and agreements have already been established and merit continued pursuit, including Global Compacts for Safe, Orderly and Regular Migration and for the protection of Refugees; the Warsaw International Mechanism of the UNFCCC; the Sustainable Development Goals; the Sendai Framework for Disaster Risk Reduction; and, the Platform on Disaster Displacement provide potential migration governance pathways [7.44]. Policy and planning decisions at regional, national and local scales that relate to housing, infrastructure, water provisioning, schools and healthcare are relevant for successful integration of migrants into receiving communities [5.5.4, 5.10.1.1, 5.12.2, 9.8.3]. Policies and practices on movements of people across international borders are also relevant to climate-related migration, with restrictions on movement having implications for the adaptive capacity of communities exposed to climate hazards [7.4.4.2, Box 8.1]. Perceptions of migrants and the framing of policy discussions in receiving communities and nations are important determinants of the future success of migration as an adaptive response to climate change [7.4.4.3] (*high agreement, medium evidence*).

Reducing the future risk of large-scale population displacements, including those requiring active humanitarian interventions and organized relocations of people, requires the international community to meet the requirements of the Paris Agreement and take further action to control future warming (high confidence) [Cross-Chapter Box SLR in Chapter 3, 7.3.1, Box 8.1]. Current emissions pathways lead to scenarios for the period between 2050 and 2100 in which hundreds of millions of people will be at risk of displacement due to rising sea levels, floods, tropical cyclones, droughts, extreme heat, wildfires and other hazards, with land degradation exacerbating these risks in many regions [7.3.2, IPCC Special report on Land 2019, Cross-Chapter Box SLR in Chapter 3]. At high levels of warming, tipping points may exist, particularly related to sea level rise, that, if crossed, would further increase the global population potentially at risk of displacement [IPCC 2021 Cross-Chapter Box 12.1]. Populations in low-income countries and small-island states that have historically had low greenhouse gas emissions are at particular risk of involuntary migration and displacement due to climate change, reinforcing the urgency for industrialized countries to continue lowering greenhouse gas emissions, to support adaptive capacity-building initiatives under the UNFCCC, and to meet objectives expressed in the Global Compacts regarding safe, orderly and regular migration, and the support and accommodation of displaced people [4.3.7, 4.5.7, 5.12.2, 7.4.5.5, 8.4.2, Box 8.1, Cross-Chapter Box SLR].

[END CROSS-CHAPTER BOX MIGRATE HERE]

The diversity of potential migration and displacement outcomes reflects the scale and physical impacts of specific climate hazard events and the wide range of social, economic, cultural, political and other non-climatic factors that influence exposure, vulnerability, adaptation options and the contexts in which migration decisions are made (high confidence). The diversity in drivers, contexts and outcomes make it difficult to offer simple generalizations about the relationship between climate change and migration. The characteristics of climatic drivers vary in terms of their rate of onset, intensity, duration, spatial extent, and severity of damage caused to housing, infrastructure, and livelihoods; the potential migration responses to these are further mediated by cultural, demographic, economic, political, social, and other non-climatic factors operating across multiple scales (Neumann and Hermans, 2015);(McLeman, 2017);(Barnett and McMichael, 2018);(Cattaneo et al., 2019);(Hoffmann et al., 2020).

Climate-related migration and displacement outcomes display high variability in terms of migrant success, often reflecting pre-existing socio-economic conditions and household wealth (high confidence). The decision to migrate or remain in place when confronted by climatic hazards is strongly influenced by the range and accessibility of alternative, *in situ* (i.e., non-migration) adaptation options that may be less costly or disruptive (Cattaneo et al., 2019). Migration decisions (whether climate-related or not) are typically made at the individual or household level, and are influenced by a household's perceptions of risk, social networks, wealth, age structure, health, and livelihood choices (Koubi et al., 2016b);(Gemenne and Blocher, 2017). Households with greater financial resources and higher levels of educational attainment have greater capacity to adapt *in situ* (Cattaneo and Massetti, 2019);(Ocello et al., 2015) but are also better able to migrate, and with greater agency once such a decision is made (Kubik and Maurel, 2016), (Koubi et al., 2016b);(Riosmena et al., 2018);(Adams and Kay, 2019). By contrast, poor households with limited physical, social and financial resources have less capacity to adapt *in situ* and are often limited in their migration options (Nawrotzki and DeWaard, 2018), (Suckall et al., 2017), (Zickgraf et al., 2016). Thus, when poorer households do migrate after an extreme climate event, it is often in reaction to lost income or livelihood due to an extreme climate event and occurs with low voluntarity (Mallick et al., 2017), (Bhatta et al., 2015) and may perpetuate or amplify migrants' socio-economic precarity and/or their exposure to environmental hazards (Natarajan et al., 2019); see also Chapter 8 section 8.3.1).

Climate-related migration originates most often in rural areas in low- and middle-income countries, with migrant destinations usually being other rural areas or to urban centres within their home countries (i.e., internal migration) (medium confidence). Rural livelihoods and incomes based on farming, livestock rearing and/or natural resource collection, are inherently sensitive to climate variability and change, creating greater potential for migration as a response (Bohra-Mishra et al., 2017);(Viswanathan and Kumar, 2015). Drought events have been associated with periods of higher rural to urban migration within Mexico (Chort and de la Rupelle, 2016);(Leyk et al., 2017);(Nawrotzki et al., 2017; Murray-Tortarolo and Martnez, 2021)and Senegal (Nawrotzki and Bakhtsiyarava, 2017). Extreme temperatures are associated with higher rates of temporary rural out-migration in South Africa and in Bangladesh (Mastrorillo et al., 2016);(Call et al., 2017). In rural Tanzania, weather-related shocks to crop production have been observed to increase the likelihood of migration, but typically only for households in the middle of community wealth distribution (Kubik and Maurel, 2016)Weather-related losses in rice production have been associated with small-percentage increases in internal migration in India (Viswanathan and Kumar, 2015) and the Philippines (Bohra-Mishra et al., 2017). In East Africa, temporary rural-urban labour migration does not show a strong response to climatic drivers (Mueller et al., 2020). There is a small literature on mobility as adaptation in urban populations, with a focus on resettlement of flood-prone informal settlements within cities (Kita, 2017);(Tadgell et al., 2017).

Most documented examples of international climate-related migration are intra-regional movements of people between countries with shared borders (high agreement, medium evidence). Systematic reviews find few documented examples of long-distance, inter-regional migration driven by climate events (Veronis et al., 2018);(Kaczan and Orgill-Meyer, 2020);(Hoffmann et al., 2020). One macro-economic analysis found a correlation between migrant flows from low- to high-income countries and adverse climatic events in the source country (Coniglio and Pesce, 2015), another found that high heat stimulates higher rates of international migration from middle-income countries but typically not from low-income countries (Cattaneo and G., 2016), while other studies found international climate-related migration originates primarily from the agriculture-dependent countries (Cai et al., 2016);(Nawrotzki and Bakhtsiyarava, 2017). Small-sample studies of migrants to Canada from Bangladesh, Haiti, and sub-Saharan Africa suggest environmental factors in the source country can be a primary or secondary motivation for some migrants within larger flows of economic and family-reunification migrants (Veronis and McLeman, 2014);(Mezdour et al., 2015);(McLeman et al., 2017). Research on links between climate hazards and international movements of refugees and/or asylum seekers shows differing results. One study found that asylum applications in Europe increase during climate fluctuations, due to interactions with conflict (Missirian and Schlenker, 2017), and another found links between heat, drought, conflict and asylum-seeking migration originating in the Middle East between 2011 and 2015 (Abel et al., 2019). Other studies have found that asylum claims in Europe correspond minimally with climatic hazards in source countries (Schutte et al., 2021), with choices in baseline data, timeframes for analysis and methodological approaches likely explaining the inconsistent results across studies (Boas et al., 2019). Media reports and other studies in recent years suggest that climate change has driven large numbers of migrants to the US from Central America and to Europe from the Middle East and Africa, but empirical studies were not identified for this assessment.

7.2.6.1 Relative Importance of Specific Climatic Drivers of Migration and Displacement

Reliable global estimates of voluntary climate-related migration within and between countries are not available due to a general absence of concerted efforts to date to collect data of this specific nature, with existing national and global datasets often lacking information on migration causation or motivation. Better data are available for involuntary displacements within countries for reasons associated with weather-related hazards. Data collected annually since 2008 on internal displacements attributed to extreme weather events by the Internal Displacement Monitoring Centre (IDMC) indicate that extreme storms and floods are the two most significant weather-related drivers of population displacements globally. Because of improvements in collection sources and methods since it first began reporting data in 2008, upward trends since that year in the total reported annual number of people displaced should be treated cautiously; it is reasonable to conclude that the average annual rate currently exceeds 20 million people globally, with considerable interannual variation due to the frequency and severity of extreme events in heavily populated areas. Regional distribution of displacement events has been consistent throughout the period of IDMC data collection (*high confidence*), with displacement events occurring most often in East, Southeast, and South Asia; sub-Saharan Africa; the US; and the Caribbean region (Figure 7.7). Relative to their absolute population size, Small Island states experience a disproportionate risk of climate-related population displacements (Desai et al., 2021) (*high confidence*).

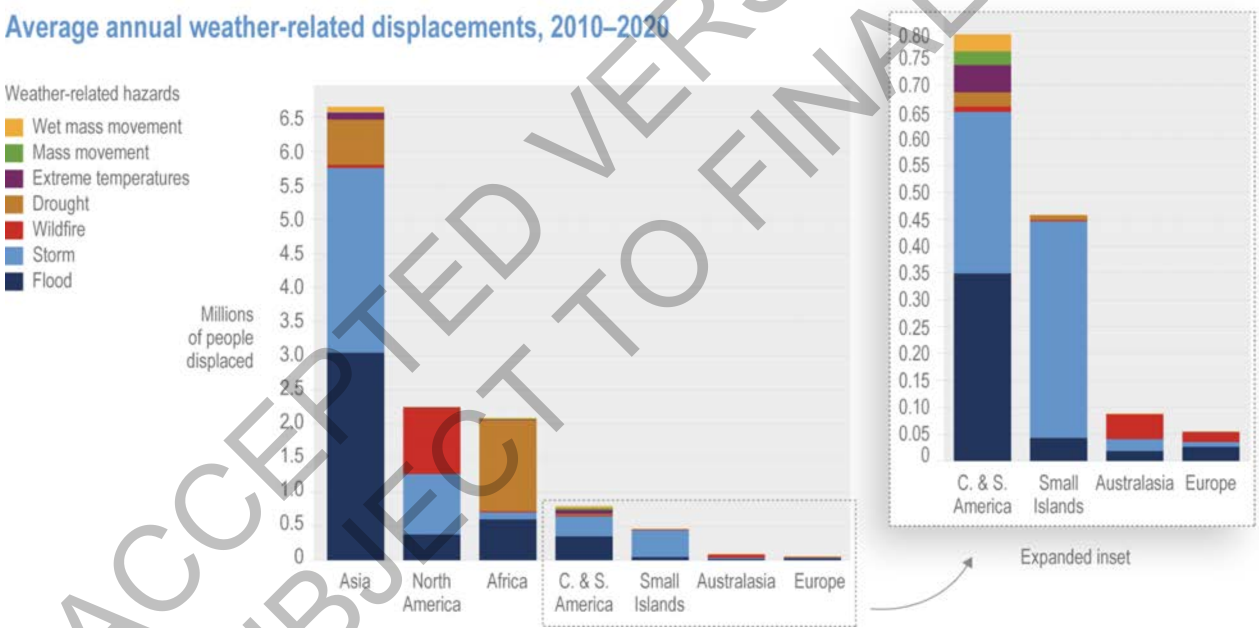


Figure 7.7: Average number of people displaced annually, 2010-2020 by selected weather-related events, by region and category of event. Source statistics provided by Internal Displacement Monitoring Centre.

Tropical cyclones and extreme storms are a particularly significant displacement risk in East and Southeast Asia, the Caribbean region, the Bay of Bengal region, and southeast Africa (IDMC 2020) (high confidence). The scale of immediate displacement from any given storm and potential for post-event migration depend heavily on the extent of damage to housing and livelihood assets, and the responsive capacity of governments and humanitarian relief agencies (Saha, 2016);(Islam et al., 2018);(Mahajan, 2020);(Spencer and Urquhart, 2018). In Bangladesh, the rural poor are most often displaced, with initial increases in short-term, labour-seeking migration followed by more permanent migration by some groups (Saha, 2016);(Islam and Hasan, 2016);(Islam and Shamsuddoha, 2017). Past hurricanes in the Caribbean basin have generated internal and interstate migration within the region, typically along pre-existing social networks, and to the US (Loebach, 2016);(Chort and de la Rupelle, 2016). In 2017, Hurricanes Irma and Maria caused widespread damage to infrastructure and health services, and a slow recovery response by authorities was followed by the migration of tens of thousands of Puerto Ricans to Florida and New York (Zorrilla, 2017);(Echenique and Melgar, 2018). In the US, coastal counties experience increased out-migration after hurricanes that flows along existing social networks (Hauer, 2017), with post-disaster reconstruction employment opportunities potentially attracting new labour migrants to affected areas (Ouattara and Strobl, 2014);(Curtis et al., 2015);(DeWaard et al., 2016);(Fussell et al., 2018).

Flood displacement can lead to increases or decreases in temporary or short-distance migration flows, depending on the local context (medium confidence). (Robalino et al., 2015);(Ocello et al., 2015);(Afifi et al., 2016);(Koubi et al., 2016b)Floods are a particularly important driver of displacement in river valleys and deltas in Asia and Africa, although large flood-related displacements have been recorded by IDMC in all regions. In Africa, populations exposed to low flood risks, as compared with other regions, are observed to have a greater vulnerability to displacement due to limited economic resources and adaptive capacity (Kakinuma et al., 2020). In areas where flooding is especially frequent, *in situ* adaptations may be more common, and out-migration may temporarily decline after a flood (Afifi et al., 2016), (Chen et al., 2017);(Call et al., 2017). Rates of indefinite or permanent migration tend not to change following riverine floods unless damage to homes and livelihood assets is especially severe and widespread, with household perceptions of short- and longer-term risks playing an important role (Koubi et al., 2016a).

Displacements due to droughts, extreme heat, and associated impacts on food and water security are most frequent in East Africa and, to a lesser extent, South Asia, and West and Southern Africa (Centre), 2020). Because droughts unfold progressively and typically do not cause permanent damage to housing or livelihood assets, there is greater opportunity for government and NGO interventions, and greater use of *in situ* adaptation options (Koubi et al., 2016b);(Koubi et al., 2016a);(Cattaneo et al., 2019). Drought-related population movements are most common in dryland rural areas of low-income countries, and occur after a threshold is crossed and *in situ* adaptation options are exhausted (Gautier et al., 2016);(Wiederkehr et al., 2018);(McLeman, 2017)). A time lag may ensue between the onset of drought and any observed population movements; one study of Mexican data found this lag to be up to 36 months after the event (Nawrotzki et al., 2017). The most common response to drought is an increase in short-distance, rural-urban migration (*medium confidence*), with examples being documented in Bangladesh, Ethiopia, Pakistan, sub-Saharan Africa, Latin America and Brazil (Neumann and Hermans, 2015);(Gautier et al., 2016);(Gautier et al., 2016);(Mastrorillo et al., 2016);(Baez et al., 2017);(Call et al., 2017);(Nawrotzki et al., 2017);(Jessoe et al., 2018)*;(Carrico and Donato, 2019)*;(Hermans and Garbe, 2019).

Few assessable studies were identified that examine links between wildfires and migration. Wildfire events are often associated with urgent evacuations and temporary relocations, which place significant stress on receiving communities (Spearing and M., 2020) but research in the US suggests fires have only a modest influence on future migration patterns in exposed areas (Winkler and D., 2021). More research, particularly in other regions, is needed.

7.2.6.2 Immobility and Resettlement in the Context of Climatic Risks

Immobility in the context of climatic risks can reflect vulnerability and lack of agency (i.e., inability to migrate), but can also be a deliberate choice (high confidence). Research since AR5 shows that immobility is best described as a continuum, from people who are financially or physically unable to move away from hazards (i.e. *involuntary immobility*) to people who choose not to move (i.e. voluntary immobility) because of strong attachments to place, culture, and people (Nawrotzki and DeWaard, 2018); (Adams, 2016);(Farbotko and McMichael, 2019);(Zickgraf, 2019);(Neef et al., 2018);(Suckall et al., 2017);(Ayeb-Karlsson et al., 2018);(Zickgraf, 2018);(Mallick and Schanze, 2020). Involuntary immobility is associated with individuals and households with low adaptive capacity and high exposure to hazard and can exacerbate inequality and future vulnerability to climate change (Sheller, 2018), including through impacts on health (Schwerdtle et al., 2018). Voluntary immobility represents an assertion of the importance of culture, livelihood and people to wellbeing, and is of particular relevance for Indigenous Peoples (Suliman et al., 2019).

Planned relocations by governments of settlements and populations exposed to climatic hazards are not presently commonplace, although the need is expected to grow in coming decades. Examples include relocations of coastal settlements exposed to storm and erosion hazards, as well as smaller numbers of cases of flood-prone settlements in river valleys, and these examples suggest that organized relocations are expensive, contentious, create multiple challenges for governments, and generate short- and longer term disruptions for the people involved (high agreement, medium evidence) (Ajibade et al., 2020);(Henrique and Tschakert, 2020);(Desai et al., 2021).

Examples of relocations of small Indigenous communities in coastal Alaska and villages in the Solomon Islands and Fiji suggest that relocated people can experience significant financial and emotional distress as cultural and spiritual bonds to place and livelihoods are disrupted (Albert et al., 2018);(Neef et al., 2018);(McMichael and Katonivualiku, 2020);(McMichael and Katonivualiku, 2020);(McMichael et al., 2021);(Piggott-McKellar et al., 2019);(Bertana, 2020). Voluntary relocation programs offered by US state governments in communities damaged by 2012's Hurricane Sandy have been subject to multiple studies, and these show participants' longer term economic outcomes, social connections and mental wellbeing can compare either favourably or unfavourably with non-participants for a range of reasons unrelated to the impacts of the hazard event itself (Bukvic and Owen, 2017);(Binder et al., 2019);(Koslov and Merdjanoff, 2021),

[START BOX 7.4 HERE]

Box 7.4: Gender Dimensions of Climate-related Migration

Migration decision-making and outcomes – in both general terms and in response to climatic risks – are strongly mediated by gender, social context, power dynamics, and human capital (Bhagat, 2017);(Singh and Basu, 2020);(Rao et al., 2019a);(Ravera et al., 2016). Women tend to suffer disproportionately from the negative impacts of extreme climate events for reasons ranging from caregiving responsibilities to lack of control over household resources to cultural norms for attire (i.e. saris in South Asia) (Belay et al., 2017);(Jost et al., 2016). In many cultures, migrants are most often able-bodied, young men (Call et al., 2017);(Heaney and Winter, 2016). Women wait longer to migrate because of higher social costs and risks (Evertsen and Van Der Geest, 2019) and barriers such as social structures, cultural practices, lack of education, and reproductive roles (Belay et al., 2017);(Afriyie et al., 2018);(Evertsen and Van Der Geest, 2019)).

Research critiques the tendency to portray women as victims of climate hazards, rather than recognizing differences between women and the potential for women to use their agency and informal networks to negotiate their situations (Eriksen et al., 2015);(Ngigi et al., 2017);(Pollard et al., 2015);(Rao et al., 2019b);(Ravera et al., 2016). Migration can change household composition and structure, which in turn affect the adaptive capacity and choices of those who do not move (Rao et al., 2019a);(Rao et al., 2019b);(Singh, 2019). When only male household members move, the remaining members of the now female-headed household must take on greater workloads and their vulnerability may increase (Goodrich et al., 2019);(Rao et al., 2019b);(Rigg and Salamanca, 2015), leading to increased workload and greater vulnerability for those left behind (Arora et al., 2017);(Bhagat, 2017);(Flat ø et al., 2017);(Lawson et al., 2019). It can, however, also increase women's economic freedom and decision-making capacity, enhance their agency (Djoudi et al., 2016);(Rao, 2019) and alter the gendered division of paid work and care and intra-household relations (Rigg et al., 2018);(Singh and Basu, 2020), a process that may reduce household vulnerability to extreme climate events (Banerjee et al., 2019b).

[END BOX 7.4 HERE]

7.2.6.3 Connections Between Climate-related Migration and Health

The number of assessable peer-reviewed studies that make connections between climate-related migration and health and wellbeing is small and merits further encouragement. The health outcomes of migrants generally, and of climate-migrants in particular, vary according to geographical context, country, and the particular circumstances of migration or immobility (Hunter and Simon, 2017; Hunter et al., 2021) (Hunter et al., 2021); (Schwerdtle et al., 2020). Such linkages are best described as "multidirectional", with studies suggesting that healthy individuals may be more likely to migrate internationally in search of economic opportunities than people in poorer health except during adverse climatic conditions, when migration rates may change across all groups; and, that migrants may have different long-term health outcomes than people born in destination areas, potentially displaying a range of positive and negative health outcomes compared to non-migrants (Kennedy et al., 2015);(Dodd et al., 2017); (Hunter and Simon, 2017);(Riosmena et al., 2017). Refugees and other involuntary migrants often experience higher exposure to disease and malnutrition, adverse indirect health effects of changes in diet or activity, and increased rates of mental health concerns attributable to sense of loss or to fear (Schwerdtle et al., 2018);(Torres and Casey, 2017) as well as due to interruption of health care, occupational injuries, sleep deprivation, non-hygienic lodgings and insufficient sanitary facilities, heightened exposure to vector- and water-borne diseases, vulnerability to psychosocial, sexual, and reproductive issues, behavioural disorders, substance abuse and violence (Farhat et al., 2018);(Wickramage et al., 2018). Linkages between climate migration and the spread of infectious disease are bidirectional; migrants may be exposed to diseases at the destination to which they have lower immunity than the host community; in other cases, migrants could introduce diseases to the receiving community (McMichael, 2015). Thus, receiving areas may have to pay greater attention to building migrant sensitive health systems and services (Hunter and Simon, 2017). Further, the risk of migration leading to disease transmission is exacerbated by weak governance and lack of policy to support public health measures and access to medicines (Pottie et al., 2015).

7.2.7 Observed Impacts of Climate on Conflict

7.2.7.1 Introduction

In AR5, conflict was addressed in Chapter 12 on Human Security. The chapter concluded that some of the factors that increase the risk of violent conflict within states are sensitive to climate change (medium evidence, medium agreement), people living in places affected by violent conflict are particularly vulnerable to climate change (medium evidence, high agreement) and that climate change will lead to new challenges to states and will increasingly shape both conditions of security and national security policies (medium evidence, medium agreement). The evidence since AR5 has strengthened the evidence for these findings and allowed statements to be made on direct associations between increased risk of conflict and climate change. AR5 characterised the major debate within the field: authors supporting an association between climate anomalies and conflict that can be extrapolated into the future (e.g. (Hsiang et al., 2013);(Hsiang and Marshall, 2014);(Burke et al., 2015a) and authors that argue that these associations are not so universal, breaking down when contextual, scale and political factors are introduced (e.g. (Buhaug et al., 2014);{Buhaug, 2016, Climate Change and Conflict: Taking Stock.

Consistent with AR5 findings, there continues to be little observed evidence that climatic variability or change cause violent inter-state conflict. In intra-state settings, climate change has been associated both with the onset of conflict, particularly in the form of civil unrest or riots in urban settings (high agreement, medium evidence). {Ide, 2020, Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk} as well as with changes in the duration and severity of existing conflicts (Koubi, 2019) Climate change is conceptualised as one of many factors that interact to raise tensions (Boas and Rothe, 2016) through diverse causal mechanisms (Mach et al., 2019);(Ide et al., 2020) and as part of the peace-vulnerability and development nexus (Barnett 2019)(Abrahams, 2020);(Buhaug and von Uexkull, 2021). New areas of literature assessed in this report include the security implications of responses to climate change, and the gendered dynamics of conflict and exposure to violence under climate change, and civil unrest in urban settings. The impact of violent conflict on vulnerability is not addressed in this chapter, but does arise in other chapters [8.3.2.3; 17.2.2.2]. Other chapters address non-violent conflict over changing availability and distribution of resources, for example, competing land uses and fish stocks shifting to different territories [5.8.2.3; 5.8.3, 5.9.3, 5.13; 9.8.1.1; 9.8.5.1]. A commonly used definition of armed conflict is conflicts involving greater than 25 battle-related deaths in a year; this number represents the Uppsala Conflict Data Program threshold for inclusion in their database, a core resource in this field.

Climatic conditions have affected armed conflict within countries, but their influence has been small compared to socio-economic, political and cultural factors (Mach et al., 2019) (high agreement, medium evidence). Inter-group inequality, and consequent relative deprivation can lead to conflict, and the negative impacts of climate change lower the opportunity cost of involvement in conflict (Buhaug et al., 2020);(Vestby, 2019). Potential pathways linking climate and conflict include direct impacts on physiology from heat, or resource scarcity; indirect impacts of climatic variability on economic output, agricultural incomes, higher food prices, increasing migration flows; and the unintended effects of climate mitigation and adaptation policies (Koubi, 2019);(Busby, 2018);(Sawas et al., 2018).Relative deprivation, political exclusion and ethnic fractionalisation and ethnic grievances (Schleussner et al., 2016);(Theisen, 2017) are other key variables. Research shows that factors such as land tenure and competing land uses interacting with market-driven pressures and existing ethnic divisions produce conflict over land resources, rather than a scarcity of natural resources caused by climate impacts such as drought. (*high agreement, medium evidence*) (Theisen, 2017); (Balestri and Maggioni, 2017);(Kuusaana and Bukari, 2015);[also Box 8.3]

7.2.7.2 Impacts of Climate Change and Violent Conflict

Positive temperature anomalies, and average increases in temperature over time, have been associated with collective violent conflict in certain settings (medium agreement, low evidence). Helman and Zaitchik (2020) find statistical associations between temperature and violent conflict in Africa and the Middle East that are stronger in warmer places and identify seasonal temperature effects on violence. However, they are unable to detect the impact of regional temperature increases on violence. For Africa, Van Weezel (2019) found associations between average increases in temperature and conflict risk. Caruso et al (2016) found an association between rises in minimum temperature and violence; through the impact of temperature on rice yields [also Box 9.4]. However, the associations between temperature and violence are weak compared to those with political and social factors (e.g. (Owain and Maslin, 2018) and research focuses on areas where conflict is already present and, as such, is sensitive to bias (Adams et al., 2018). There is a body of literature that finds statistical associations between temperature anomalies and interpersonal violence, crime and aggression in the Global North, predominantly in the United States (e.g. (Ranson, 2014);(Mares and Moffett, 2019);(Tiihonen et al., 2017);(Parks et al., 2020)[14.4.8]. However, authors have cautioned against extrapolating seasonal associations into long-term trends, and against focusing on individual crimes rather than wider social injustices associated with climate change and its impacts (Lynch et al., 2020).

Variation in availability of water has been associated with international political tension and intra-national collective violence (low agreement, medium evidence). Drought conditions have been associated with violence due to impacts on income from agriculture and water and food security, with studies focusing predominantly on sub-Saharan Africa and the Middle East (Ide and Frohlich, 2015);(De Juan, 2015);(Von Uexkull et al., 2016);(Waha et al., 2017);(Abbott et al., 2017);(D'Odorico et al., 2018). A small set of published studies has argued inconclusively over the role of drought in causing the Syrian civil war (Gleick, 2014);(Kelley et al., 2015);(Selby et al., 2017) [also 16.2.3.9]. In general, research stresses the underlying economic, social and political drivers of conflict. For example, research on conflict in the Lake Chad region has demonstrated that the lake drying was only one of many factors including lack of development and infrastructure (Okpara et al., 2016);(Nagarajan et al., 2018);(Tayimlong, 2020). Fewer studies examine the relationship between flooding (excess water) and violence and often rely on migration as the causal factor (see below). However, some studies have shown an association between flooding and political unrest (Ide et al., 2020). [also 4.3.6, 12.5.3, Box 9.4].

Extreme weather events can be associated with increased conflict risk (low agreement, medium evidence). There is the potential for extreme weather events and disasters to cause political instability and increase the risk of violent conflict, although not conclusively (Brzoska, 2018). Post-disaster settings can be used to intensify state repression (Wood and Wright, 2016) and to alter insurgent groups' behaviour (Walch, 2018). Different stakeholders use disasters to establish new narratives and alter public opinion (Venugopal and Yasir, 2017). However, some research has demonstrated how post-disaster activities have had positive impacts on the social contract between people and the state, reducing the risk of conflict by strengthening relations between government and citizens and strengthened citizenship of marginalized communities (Siddiqi, 2018; (Pelling and Dill, 2010; Siddiqi, 2019). However, post-disaster and disaster-risk related activities in of themselves, have limited capacity to support diplomatic efforts to build peace (Kelman et al., 2018)

7.2.7.3 Causal Pathways Between Climate Change Impacts and Violent Conflict

Increases in food price due to reduced agricultural production and global food price shocks are associated with conflict risk and represent a key pathway linking climate variability and conflict (medium confidence).

Rises in food prices are associated with civil unrest in urban areas among populations unable to afford or produce their own food, and in rural populations due to changes in availability of agricultural employment with shifting commodity prices (Martin-Shields and Stojetz, 2019). Under such conditions, locally specific grievances, hunger, and social inequalities can initiate or exacerbate conflicts. Food price volatility in general is not associated with violence, but sudden food price hikes have been linked to civil unrest in some circumstances (Bellemare, 2015);(McGuirk and Burke, 2020);(Winne and Peersman, 2019). In urban settings in Kenya, Koren et al (2021) found an association between food and water insecurity that is mutually reinforcing and associated with social unrest (although insecurity in either one on its own was not). Analysing global food riots 2007-2008, and 2011, Heslin (2021) stresses the role of local politics and pre-existing grievances in determining whether people mobilise around food insecurity [also Chapter 5].

Climate-related internal migration has been associated with experience of violence by migrants, the prolongation of conflicts in migrant receiving areas and civil unrest in urban areas *(medium agreement, low evidence)*. Research points to the potential for conflict to serve as an intervening factor between climate and migration. However, the nature of the relationship is diverse and context specific. For example, displaced people and migrants may be associated with heightened social tensions in receiving areas through mechanisms such as ecological degradation, reduced access to services, and a disturbed demographic balance in the host area (Rüegger and Bohnet, 2020). Ghimire et al (2015) observed that an influx of flood-displaced people prolonged conflict by causing a lack of access to services for some of the host population and feelings of grievance. Migration from drought-stricken areas to local urban centres has been used to suggest a climate trigger for the Syrian conflict (e.g.(Ash and Obradovich, 2020)). However, this link has been strongly contested by research that contextualizes the drought in wider political economic approaches and existing migration patterns (De Châtel, 2014);(Fröhlich, 2016);(Selby, 2019) [16.2.3.9].

There is some evidence of an association between climate-related rural-to-urban migration and the risk of civil unrest (medium agreement, low evidence). Petrova (2021) found that while migration in general was associated with increased protests in urban receiving areas, the relationship did not hold for hazard-related migration. In other settings, the association of civil unrest with in-migration was found to depend on the political alignment of the host state with the capital (Bhavnani and Lacina, 2015), previous experience of extreme climate hazards (Koubi et al., 2021) and previous experience of violence in migrants (Linke et al., 2018). Climate-related migrants have reported higher levels of perception, and experience, of violence in their destination (Linke et al., 2018);(Koubi et al., 2018). There has been no association established between international migration and conflict. The literature highlights how unjust racial logics generate spurious links between climate migration and security (Fröhlich, 2016);(Telford, 2018).

7.2.7.4 Gendered Dimensions of Climate-related Conflict

Structural inequalities play out at an individual level to create gendered experiences of violence (high agreement, medium evidence). Violent conflict is experienced differently by men and women because of gender norms that already exist in society and shape vulnerabilities. For example, conflict deepens gendered vulnerabilities to climate change related to unequal access to land and livelihood opportunities (Chandra et al., 2017). Motivations for intergroup violence may be influenced by constructions of masculinity, for example the responsibility to secure their family's survival, or pay dowries (Myrttinen et al., 2017), and gendered roles may incentivize young men to protest or to join non-state armed groups during periods of adverse climate (Myrttinen et al., 2015), (Myrttinen et al., 2017);(Anwar et al., 2019);(Hendrix and Haggard, 2015);(Koren and Bagozzi, 2017). Research has found a positive correlation between crop failures and suicides by male farmers who could not adapt their livelihoods to rising temperatures (Bryant & Garnham 2015; (Kennedy and King, 2014); (Carleton, 2017).

Extreme weather and climate impacts are associated with increased violence against women, girls and vulnerable groups (high agreement, medium evidence). During and after extreme weather events, women, girls and LGBTQI people are at increased risk of domestic violence, harassment, sexual violence and trafficking (Le Masson et al., 2019);(Nguyen, 2019);(Myrttinen et al., 2015);(Chindarkar, 2012). For example, early marriage is used as a coping strategy for managing the effects of extreme weather events (Ahmed et al., 2019)and women are exposed to increase risk of harassment and sexual assault as scarcity and gender-based roles cause them to walk longer distances to fetch water and fuel (Le Masson et al., 2019). Within the household, violence may arise from changing gender norms as men migrate to find work in post-disaster settings may lead to violent backlash or heightened tensions (Stork et al., 2015) and men's use of negative coping mechanisms, such as alcoholism, when unable to meet norms of providing for the household (Anwar et al., 2019);(Stork et al., 2015). Rates of intimate partner violence have been found to increase with higher temperatures (Sanz-Barbero et al., 2018).

7.2.7.5 Observed impacts on non-violent conflict and geopolitics

Climate adaptation and mitigation projects implemented without taking local interests and dynamics into account have the potential to cause conflict (high agreement, medium evidence). Reforestation or forest management programs driven by reducing emissions through deforestation, land zoning and managed retreat due to sea level rise have been identified as having the potential to cause friction and conflict within and between groups and communities (de la Vega-Leinert et al., 2018);(Froese and Schilling, 2019). Conflict may arise when there is resistance to a proposed project, where interventions favour one group over another, projects undermine livelihoods or displace populations (e.g. (Nightingale, 2017);(Sovacool et al., 2015);(Sovacool, 2018) Corbera, 2017; Hunsberger 2018) [also 4.6.8, 5.13.4, 14.4.7.3]. In addition to conflict generated by the poor implementation of land-based climate mitigation and adaptation projects, Gilmore and Buhaug (2021) highlight the links between climate policy and conflict through potential effects on economic growth and unequal distribution of economic burdens, and fossil fuel markets. There is a small literature that draws attention to potential security of nuclear proliferation, if nuclear is increasingly employed as a low-carbon energy source (e.g. (Parthemore et al., 2018);(Bunn, 2019).

Economic and social changes due to changes in sea ice extent in the Arctic are anticipated to be managed as part of existing governance structures (high agreement, medium evidence). The opening-up of the Arctic and associated geopolitical manoeuvring for access to shipping routes and sub-sea hydrocarbons is often highlighted as a potential source of climate conflict (e.g. Koivurova, 2009; (Åtland, 2013);(Tamnes and Offerdal, 2014). Research assessed in AR5 focused on the potential for resource wars and Arctic land grabs. However, research since AR5 is less sensationalist in its approach to Arctic security, focusing instead on the practicalities of polycentric Arctic governance under climate change, the economic impacts of climate change, protecting the human security of Arctic populations whose autonomy is at risk (Heininen and Exner-Pirot, 2020), understanding how different regions (e.g. EU) are positioning themselves more prominently in the Arctic space (Raspotnik & Østhagen, 2019), and Arctic Indigenous People's understanding of security (Hossain, 2016) [also Chapter 3, Chapter 14, CCP6. IPCC SROCC]

7.3 Projected Future Risks under Climate Change

7.3.1 Projected Future Risks for Health and Wellbeing

7.3.1.1 Global Impacts

Climate change is expected to significantly increase the health risks resulting from a range of climate-sensitive diseases and conditions, with the scale of impacts depending on emissions and adaptation pathways in coming decades (very high confidence). Sub-sections 7.3.1.2 to 7.3.1.11 assess available studies on future projections for risks associated with specific climate sensitive diseases and conditions previously described in Section 7.2.1. In the case of diabetes, cancer, injuries, mosquito-borne diseases other than dengue and malaria, rodent borne diseases, and most mental illnesses, insufficient literature was found to allow for assessment. Adaptation pathways and options for managing such risks are detailed in Section 7.4.

Even in the absence of further warming beyond current levels, the proportion of the overall global deaths caused by climate sensitive diseases and conditions would increase marginally by mid-century (high confidence). Studies that incorporate climate forcing project an additional 250,000 deaths per year by mid-century due to climate-sensitive diseases and conditions, and under high-emissions scenarios, over 9 million additional deaths per year by 2100 (*high confidence*). Two global projections of climate change health impacts were conducted since AR5. The first focused on cause-specific mortality for eight exposures for 2030 and 2050 for a mid-range emissions scenario (A1b) and three scenarios of economic growth (WHO, 2014). The study estimated that the climate change projected to occur by 2050 (compared to 1961-1990) could result in an excess of approximately 250,000 deaths per year, dominated by increases in deaths due to heat (94,000, mainly Asia and high-income countries), childhood undernutrition (85,000, mainly Africa, also Asia), malaria (33,000, mainly Africa), and diarrheal disease (33,000, mainly Africa and Asia). Overall, more than half of this excess mortality is projected for Africa. Near term projections (2030) are predominantly for childhood undernutrition (95 200 out of 241 000 total excess deaths) (Figure 7.8). The second study focused on all-cause mortality associated with warming under both a high emissions scenario (RCP 8.5) and a low emissions scenario (RCP4.5). Under the high emissions scenario, and accounting for population growth, economic development, and adaptation, an increase of approximately 85 excess deaths per 100,000 population per year by the end of the century was projected, for a total annual excess of 9,250,000 per year based on United Nations Department of Economic and Social Affairs population projections. The authors estimate that removing adaptation and projected economic growth increased the estimate by a factor of 2.6.

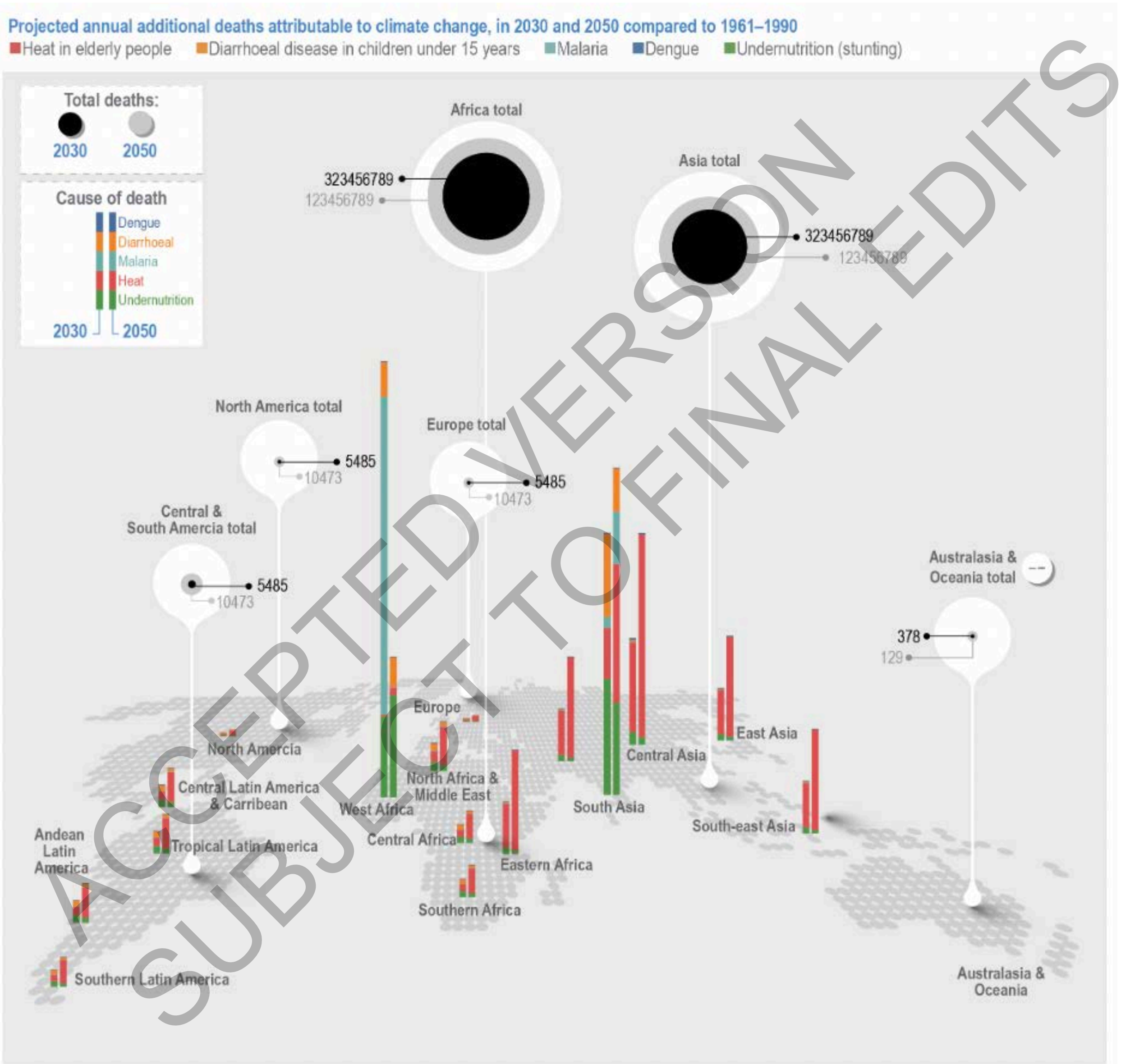


Figure 7.8: Projected additional annual deaths attributable to climate change, in 2030 and 2050 compared to 1961-1990 (WHO, 2014)

Temperature increases are projected to exceed critical risk thresholds for six key climate-sensitive health outcomes, highlighting the criticality of building adaptive capacity in health systems and in other sectors that influence health and well-being (high confidence). Recently reported research illustrates the temperature thresholds at which the following health risks change under three SSP-based adaptation scenarios: heat-related morbidity and mortality; ozone-related mortality; malaria incidence rates; incidence rates of Dengue and other diseases spread by *Aedes sp*. mosquitos; Lyme disease; and West Nile fever (Ebi et al., 2021a). As shown in Figure 7.9, adaptation under SSP1, SSP2, and SSP3 significantly alters the warming thresholds at which risks accelerate, with SSP1, an adaptation scenario that emphasizes international cooperation toward achieving sustainable development, having the greatest potential to avoid significant increases in risks under all but the highest levels of warming. SSP2 describes a world with moderate challenges to adaptation and mitigation. SSP3 describes a world with high challenges to adaptation and mitigation. In the figure, transitions are based on the peer-reviewed literature projecting risks for each of the health outcomes. Projections for time slices were changed to temperature increase above pre-industrial based on the climate models and scenarios used in the projections. The black dots are levels of confidence, from very high (four dots) to low (one dot).

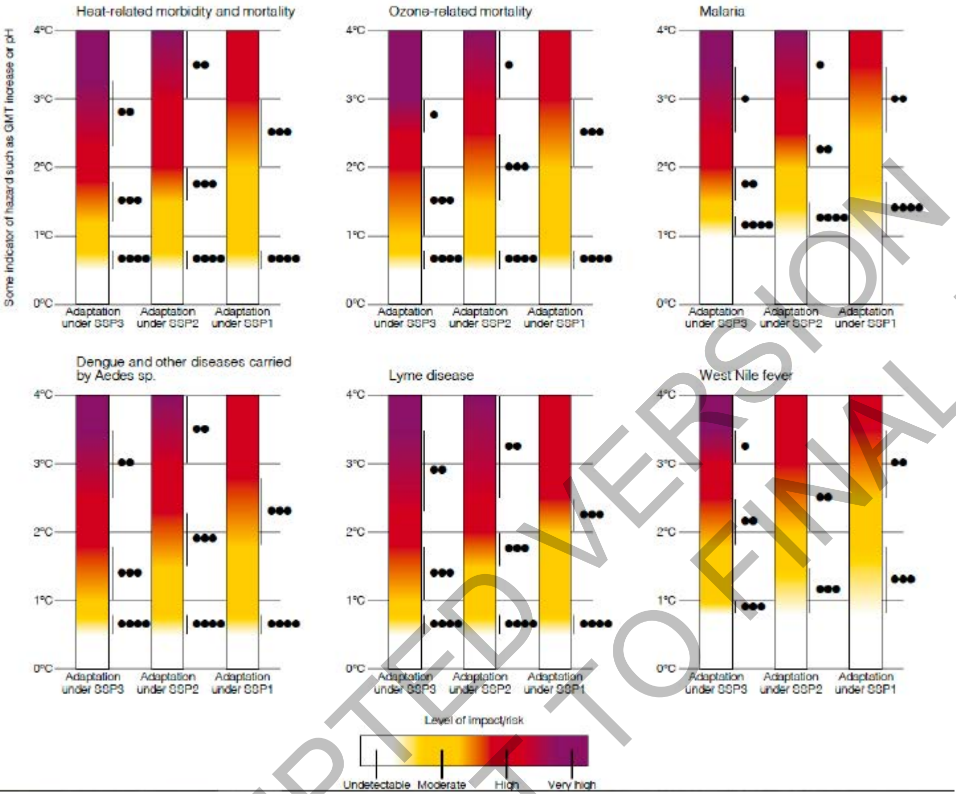


Figure 7.9: Change in risks for six climate-sensitive health outcomes by increases in temperature above pre-industrial levels, under adaptation scenarios (Ebi et al., 2021a)

7.3.1.2 Projected Changes in Heat- and Cold-related Exposure and Related Outcomes

This section considers the broad impacts of projected changes in heat- and cold-related exposure and related outcomes including mortality and work productivity. Several of the most common heat and cold-related specific health outcomes (e.g., cardiovascular disease) are assessed individually in later sections of this chapter.

Population heat exposure will increase under climate change (very high confidence). Since AR5 there has been considerable progress with quantifying the future human exposure to extreme heat (Schwingshackl et al., 2021), especially as determined by different combinations of Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) (Chambers, 2020);(Cheng et al., 2020);(Jones et al., 2018);(Liu et al., 2017);(Ma and Yuan, 2021);(Russo et al., 2019). For example, Table 7.1 shows projections of population exposure to heatwaves, as expressed by the number of person days, for the period 2061- 2080 aggregated by geographical region and SSP/RCP. At the global level, projected future exposure increases from approximately 15-million person-days for the current period to 535 billion person-days for the high population growth under the high greenhouse gas SSP3-RCP8.5 scenario, while for the low population growth/high urbanization and business as usual SSP5-RCP4.5 scenario, the exposure is substantially lower at 170 billion person-days. Spatial variations in future heatwave frequency and population growth play out in the form of significant geographical contrasts in exposure with the largest increases projected for low latitude regions such as India and significant portions of Sub-Saharan Africa where increases in heatwave frequency and population are expected. Over East Asia and especially eastern China, exposures are projected to rise, with the effect of increases in heatwave frequency exceeding the countering effect of projected reductions in population, especially in non-urban areas. Further, for North America and Europe, where rural depopulation is projected, the predominant driver of increases in exposure is urban growth (Jones et al., 2018).

Table 7.1: Projected exposure in millions of person days by region under different RCP/SSP combinations {Supplementary material in: Jones, B., Tebaldi, C., O'Neill, B.C., Olsen K, Gao, J.. (2018) Avoiding population exposure to heat-related extremes: demographic change vs climate change. Climatic Change 146, 423–437 (2018). https://doi.org/10.1007/s10584-017-2133-7

Region	**Exposure in Millions of Person Days**				
	Current	RCP4.5/SSP3	RCP4.5/SSP5	RCP8.5/SSP3	RCP8.5/SSP5
Global	14,811	244,807	168,488	534,848	374,269
USA	375	4,769	8,671	10,802	19,646
North America	376	4,821	8,778	10,990	20,153
Europe	191	2,967	3,775	7,326	9,969
Latin America & Caribbean	803	17,287	10,856	45,612	28,435
North Africa & Middle East					
Subsaharan Africa	1,335	34,721	23,160	65,072	43,648
Russia & Central Asia	1,427	67,442	41,339	158,290	96,054
South Asia	272	3,074	1,951	6,554	4,360
East Asia	7,194	84,044	53,655	146,709	94,288
Southeast Asia	977	12,176	10,855	35,381	31,918
Oceania	711	12, 452	9,146	60,909	47,141
	37	247	492	822	1,158

Comparisons of heatwave exposure for 1.5°C and 2.0°C warming for different SSPs indicate strong geographical contrasts in potential heatwave risk (high confidence). One global level assessment for a 1.5°C warming projects that low-human development index countries will experience exposure levels equal to or greater than the exposure levels for very high-human-development index countries under a 2°C warming {Russo, 2019, Half a degree and rapid socioeconomic development matter for heatwave risk}. The same assessment also finds that holding global warming below 1.5°C, in tandem with achieving sustainable socioeconomic development, (e.g., SSP1 as opposed to SSP4), yields reduced levels of heatwave exposure, especially for low-human development index countries, particularly across sub-Saharan Africa (Russo et al., 2019). Similar findings were apparent in other global level assessments, such that global exposure to extreme heat increases almost 30 times under a RCP8.5/SSP3 combination, with the average exposure for Africa 118 times greater than historical levels, in stark contrast to the four-fold increase projected for Europe. Compared to a RCP8.5/SSP3 scenario, exposure was reduced by 65% and 85% under RCP4.5/SSP2 and RCP2.6/SSP1 scenarios, respectively (Liu et al., 2017).

Regional level assessments of changes in population heat exposure for Africa, Europe, the US, China and India corroborate the general findings at the global level – the impact of warming is amplified under divergent regional development pathways (e.g., SSP4 - inequality) compared to those fostering sustainable development (e.g., SSP1 - sustainability) (high confidence). (Rohat et al., 2019a);(Weber et al., 2020), (Broadbent et al., 2020);(Dahl et al., 2019);(Harrington and Otto, 2018);(Rohat et al., 2019b);(Vahmani et al., 2019);(Huang and et al., 2018);(Zhang et al., 2020a);(Liu et al., 2017). For some regions, such as Europe, changes in exposure are projected to be largely a consequence of climate change, while for others, such as Africa and to a lesser extent Asia, Oceania, North and South America, the interactive effects of demographic and climate change are projected to be important (Jones et al., 2018);(Liu et al., 2017);(Russo et al., 2016);(Ma and Yuan, 2021) (*medium confidence*).

Compared to research that estimates the temperature only impacts of climate change on heat-related mortality (see below), the number of studies that explicitly model mortality responses considering various combinations of Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) is small and mostly restricted to the country or regional level. These studies point to increases in heat-related mortality especially amongst the elderly across a range of SSPs with the greatest increases under SSP5 and RCP8.5 (Rail et al., 2019);(Yang et al., 2021).

Estimates of heat-related mortality based solely on changes in temperature point to elevated levels of global and regional level mortality compared to the present with the magnitude of this increasing from RCP4.5 through to RCP8.5 (high confidence). (Ahmadalipour and Moradkhani, 2018);(Cheng et al., 2019);(Kendrovski et al., 2017);(Lee et al., 2020);(Limaye et al., 2018);(Morefield et al., 2018). Further support comes from the projection that heat-related health impacts for a 2°C increase in global temperatures will be greater than those for a 1.5°C warming (*very high confidence*) (Dosio et al., 2018);(Mitchell et al., 2018);(King and Karoly, 2017);(Vicedo-Cabrera et al., 2018a).

Estimates of future mortality that incorporate adaptation, using a variety of temperature adjustment methods, indicate increases in heat-related mortality under global warming, albeit at lower levels than the case of no adaptation (high confidence). (Anderson et al., 2018);(Gosling et al., 2017);(Guo et al., 2018);(Honda and Onozuka, 2020);(Vicedo-Cabrera et al., 2018b);(Wang et al., 2018b). Whether adaptation is considered or not, the consensus is Central and South America, Southern Europe, Southern and Southeast Asia and Africa will be the most affected by climate change related increases in heat-related mortality (*high confidence*). Similarly, projections of the impacts of future heat on occupational health, worker productivity and workability point to these regions as problematic under climate change (*high confidence*) (Andrews et al., 2018);(de Lima et al., 2021);(Dillender, 2021);(Kjellstrom et al., 2018);(Orlov et al., 2020);(Rao et al., 2020);(Tigchelaar et al., 2020), especially for occupations with high exposure to heat, such as agriculture and construction. This accords with the findings from independent projections of population heat-exposure as outlined above (*high confidence*).

The effect of climate change on productivity is projected to reduce GDP at a range of geographical scales (high confidence). (Borg et al., 2021);(Oppermann et al., 2021);(Orlov et al., 2020); For example, measuring economic costs using occupational health and safety recommendations, it was estimated that RCP8.5 would result in a 2.4% reduction in global GDP, compared to a 0.5% reduction under RCP2.6 (Orlov et al., 2020). For the USA, it was estimated that the total hours of labour supplied declined ~0.11 (±0.004) % per °C increase in global mean surface temperature for low-risk workers and 0.53 (±0.01) % per °C increase for high-risk workers exposed to outdoor temperatures (Hsiang et al., 2017). Further, a systematic review of the literature indicates that extreme heat exacts a substantial economic burden on health systems, which bears implications for future heat-attributable health care costs (Wondmagegn et al., 2019).

Since AR5 there has been an increase in the understanding of the extent to which a warming world is likely to affect cold/winter related health impacts. Future increases in heat-related deaths are expected to outweigh those related to cold (high confidence). (Aboubakri et al., 2020);(Achebak et al., 2020);(Burkart et al., 2021);(Huber et al., 2020b);(Martinez et al., 2018);(Rodrigues et al., 2020);(Vardoulakis et al., 2014);(Weinberger et al., 2017);(Weinberger et al., 2018a);(Weitensfelder and Moshammer, 2020). However, strong regional contrasts in heat- and cold-related mortality trends are *likely* under a RCP8.5 scenario with countries in the global north experiencing minimal to moderate decreases in cold related mortality while warm climate countries in the global south are projected to experience increases in heat-attributable deaths by end of century (Gasparrini et al., 2017);(Burkart et al., 2021)Projections of the magnitude of change in the temperature related burden of disease do however demonstrate great variability, due to the application of a wide range of climate change, adaptation and demographic scenarios (Cheng et al., 2019).

A particular focus since AR5 has been the impact of climate change on cities (see AR6 Chapter 6). Heat risks are expected to be greater in urban areas due to changes in regional heat exacerbated by 'heat island' effects (high confidence). (Doan and Kusaka, 2018);(Heaviside et al., 2016);(Li et al., 2021);(Rohat et al., 2019a);(Rohat et al., 2019c);(Varquez et al., 2020);(Wouters et al., 2017);(Zhao et al., 2021), with intra-urban scale variations in heat exposure attributable to land cover contrasts and urban form and function (Avashia et al., 2021);(Jang et al., 2020);(Macintyre et al., 2018);(Schinasi et al., 2018) . However, further research is required to establish the health implications of increasing chronic slow-onset extreme heat (Oppermann et al., 2021), in addition to the acute health outcomes of urban heat island - heatwave synergies under climate change. The latter is particularly important as studies that address urban heat island – heatwave interactions have mainly focused on changes in urban heat island intensity (e.g. (Ramamurthy and Bou-Zeid, 2017);(Scott et al., 2018). Whether significant urban mortality anomalies arise from the interplay of heatwaves and urban heat islands largely remains an open question although at least one study demonstrated higher urban compared to rural mortality rates during heatwaves (Ruuhela et al., 2021). Yet, the benefits of the winter urban heat island (UHI) effect for cold related mortality remain largely unexplored but one study for Birmingham, UK indicates the winter UHI will continue to have a protective effect in future climate (Macintyre et al., 2021).

7.3.1.3 Projected impacts on vector-borne diseases

The distribution and abundance of disease vectors, and the transmission of the infections that they carry, are influenced both by changes in climate, and by trends such as human population growth and migration, urbanization, land-use change, biodiversity loss, and public health measures. Each of these may increase or decrease risk, interact with climate effects, and may contribute to emergence of infectious disease, although there are few studies assessing future risk of emergence (Gibb et al., 2020). Unless stated otherwise, the assessments below are specifically for the effects of climate change on individual diseases, assuming other determinants remain constant.

There is a high likelihood that climate change will contribute to increased distributional range and vectorial capacity of malaria vectors in parts of Sub-Saharan Africa, Asia, and South America (high confidence) In Nigeria, the range and abundance of *Anopheles* mosquitoes are projected to increase under both lower (RCP2.6) and especially under higher emissions scenarios (RCP8.5) due to increasing and fluctuating temperature, longer tropical rainfall seasons and rapid land use changes (Akpan et al., 2018). Similarly, vegetation acclimation due to elevated atmospheric CO_2 under climate change will likely increase the abundance of *Anopheles* vectors in Kenya (Le et al., 2019). Distribution of *Anopheles* may decrease in parts of India and Southeast Asia, but there is an expected increase in vectorial capacity in China (Khormi and Kumar, 2016). In South America, climate change is projected to expand the distributions of malaria vectors to 35-46% of the continent by 2070, particularly species of the *Albitarsis* Complex (Laporta et al., 2015).

Malaria infections have significant potential to increase in parts of Sub-Saharan Africa and Asia, with risk varying according to the warming scenario (medium confidence). In Africa, where most malaria is due to the more deadly *Plasmodium falciparum* parasite, climate change is likely to increase the overall transmission risk due to the likely expansion of vector distribution and increase in biting rates (Bouma et al., 2016);(M'Bra et al., 2018);(Nkumama et al., 2017);(Ryan et al., 2015b) ; (Tompkins and Caporaso, 2016a). The projected effect of climate change varies markedly by region, with projections for West Africa tending to indicate a shortening of transmission seasons and neutral or small net reductions in overall risk, whereas studies consistently project increases in Southern and Eastern Africa, with potentially an additional 76 million people at risk of endemic exposure (10-12 months per year) by the 2080s (Nkumama et al., 2017);(Ryan et al., 2015b);(Semakula et al., 2017);(Zaitchik, 2019);(Leedale et al., 2016);(Murdock et al., 2016);(Yamana et al., 2016);(Ryan et al., 2020). In Sub-Saharan Africa, malaria case incidence associated with dams in malaria-endemic regions will likely be exacerbated by climate change, with significantly higher rates projected under RCP 8.5 in comparison to lower-emission scenarios (Kibret et al., 2016). Incidence of malaria in Madagascar is projected to increase under RCPs 4.5 through 8.5 (Rakotoarison et al., 2018). Distribution of *P. vivax* and *P. falciparum* malaria in China is likely to increase under RCPs higher than 2.6, especially RCP8.5 (Hundessa et al., 2018). In India, projected scenarios for the 2030s under RCP4.5 indicate changes in the spatial distribution of malaria, with new foci and potential outbreaks in the Himalayan region, southern and eastern states, and an overall increase in months suitable for transmission overall, with some other areas experiencing a reduction in transmission months (Sarkar et al., 2019).

Rising temperatures are likely to cause poleward shifts and overall expansion in the distribution of mosquitoes Aedes aegypti and Ae. albopictus, the principal vectors of dengue, yellow fever, chikungunya and zika (high confidence). Globally, the population exposed to disease transmission by one or other of these vectors is expected to increase significantly due to the combination of climate change and non-climatic processes including urbanization and socio-economic interconnectivity, with exposure rates rising under higher warming scenarios (Kamal et al., 2018);(Kraemer et al., 2019). For example, approximately 50% of the global population is projected to be exposed to these vectors by 2050 under RCP6.0 (Kraemer et al., 2019). The effect of climate change alone is projected to increase the population exposed to *Ae. aegypti* by 8-12% by 2061–2080 (Monaghan et al., 2018), and its abundance is projected to increase by 20% under RCP 2.6 and 30% under RCP 8.5 by the end of the century (Liu-Helmersson et al., 2019) (Figure 7.10) Exposure to transmission by *Ae. albopictus* specifically would be highest at intermediate climate change scenarios and would decrease in the warmest scenarios (Ryan et al., 2019). Under scenarios other than RCP2.6, most of Europe would experience significant increases in exposure to viruses transmitted by both vectors (Liu-Helmersson et al., 2019).

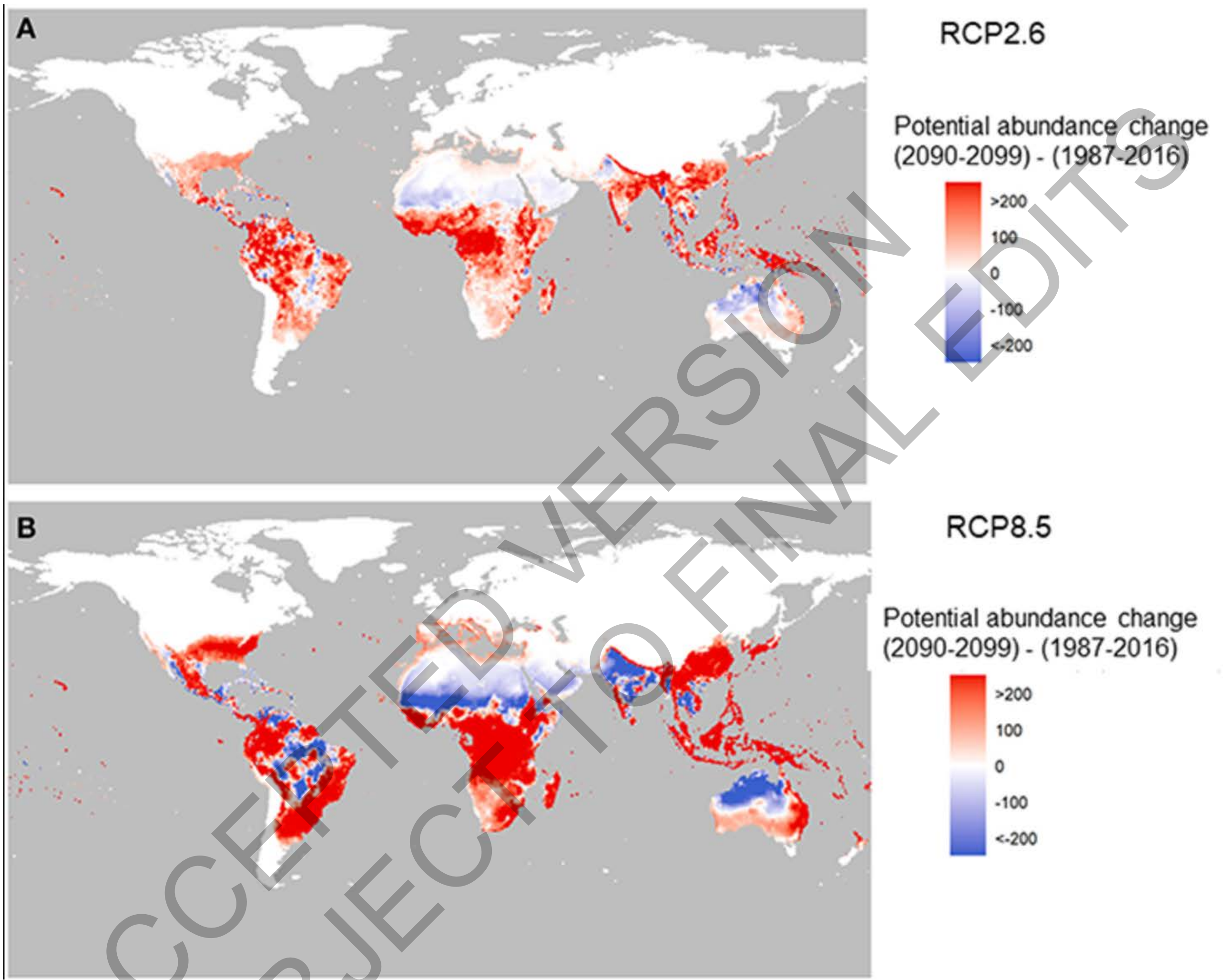


Figure 7.10: Projected change in the potential abundance of *Aedes aegypti* over the twenty-first century (2090-2099 relative to 1987-2016) (Liu-Helmersson et al., 2019)

Climate change is expected to increase dengue risk and facilitate its global spread, with the risk being greatest under high emissions scenarios (high confidence). Future exposure to risk will be influenced by the combined effects of climate change and non-climatic factors such as population density and economic development (Akter et al., 2017). Overall, risk levels are expected to rise on all continents (Akter et al., 2017);(Messina et al., 2015);(Rogers, 2015);(Liu-Helmersson et al., 2016);(Messina et al., 2019). Compared to 2015, an additional 1 billion people are projected to be at risk of dengue exposure by 2080 under an RCP4.5/SSP1 scenario, 2.25 billion under RCP6.0/SSP2, and 5 billion under RCP8.5/SSP3 (Messina et al., 2019). In North America, risk is projected to expand in north-central Mexico, with annual dengue incidence in Mexico increasing by up to 40% by 2080, and to expand from US southern states to mid-western regions, with annual dengue incidence in Mexico increasing by up to 40% by 2080 (Proestos et al., 2015);(Colon-Gonzalez et al., 2013). In China, under RCP8.5, dengue exposure would increase from 168 million people in 142 counties to 490 million people in 456 counties by the late 2100s (Fan and Liu, 2019). In Nepal, dengue fever is expected to expand throughout the 2050s and 2070s under all RCPs (Acharya et al., 2018). In Tanzania, there is a projected shift in distribution towards central and north-eastern areas and risk intensification in nearly all parts of the country by 2050 (Mweya et al., 2016). Dengue vectorial capacity is projected to increase in Korea under higher RCP scenarios (Lee et al., 2018a).

There are insufficient studies for assessment of projected effects of climate change on other arboviral diseases, such as chikungunya and zika. Zika virus transmits under different temperature optimums than does dengue, suggesting environmental suitability for zika transmission could expand with future warming (low confidence).
(Tesla et al., 2018)

Climate change can be expected to continue to contribute to the geographical spread of the Lyme disease vector Ixodes scapularis *(high confidence) and the spread of tick-borne encephalitis and Lyme disease vector* Ixodes ricinus *in Europe (medium confidence).* In Canada, vector surveillance of the black-legged tick *I. scapularis* identified strong temperature effects on the limits of their occurrence, on recent geographic spread, temporal coincidence in emergence of tick populations, and acceleration of the speed of spread (Clow et al., 2017);(Cheng et al., 2017). In Europe, increasing temperatures over the period 1950-2018 significantly accelerated the life cycle of *Ixodes ricinus* and contributed to its spread (Estrada-Peña and Fernández-Ruiz, 2020). Under RCP4.5 and RCP8.5 scenarios, projections indicate a northward and eastward shift of the distribution of *I. persulcatus and I. ricinus,* vectors of Lyme disease and tick-borne encephalitis in Northern Europe and Russia, with an overall large increase in distribution in the second half of the current century (Popov and Yasyukevich, 2014);(Yasjukevich et al., 2018) and increases in intensity of tick-borne encephalitis transmission in central Europe (Nah et al., 2020).

Climate change is projected to increase the incidence of Lyme disease and tick-borne encephalitis in the Northern Hemisphere (high confidence) (see also Figure 7.3). The basic reproduction number (R0) of *I. scapularis* in at least some regions of Canada is projected to increase under all RCP scenarios (McPherson et al., 2017). In the United States, a 2°C warming could increase the number of Lyme disease cases by over 20% over the coming decades, and lead to an earlier onset and longer length of the annual Lyme disease season (Dumic and Severnini, 2018);(Monaghan et al., 2015).

Climate change is projected to change the distribution of schistosomiasis in Africa and Asia (high confidence), with a possible increase in global land area suitable for transmission (medium confidence). A global increase in land area with temperatures suitable for transmission by the three main species of *Schistosoma* (*S. japonicum*, *S. mansoni* and *S. haematobium)* is projected under the RCP4.5 scenario for the periods 2021–2050 and 2071–2100 (Yang and Bergquist, 2018) but regional outcomes are expected to vary. In Africa, shifting temperature regimes associated with climate change are expected to lead to reduced snail populations in areas with already high temperatures, and higher populations in areas with currently low winter temperatures (Kalinda et al., 2017);(McCreesh and Booth, 2014). Infection risk with *Schistosoma mansoni* may increase by up to 20% over most of eastern Africa over the next 20-50 years but decrease by more than 50% in parts of north and east Kenya, southern South Sudan and eastern PDRC (McCreesh et al., 2015), with a possible overall net contraction (Stensgaard et al., 2013). In China, currently endemic areas in Sichuan Province may become unsuitable for snail habitats, but currently non-endemic areas in Sichuan and Hunan/Hubei provinces may see new emergence (Yang and Bergquist, 2018). In addition to the projected effects of temperature described above, distribution and transmission of schistosomiasis will also be affected positively or negatively by changes in the availability of freshwater bodies, which were not included in these models.

7.3.1.4 Projected impacts on water-borne diseases

Climate change will contribute to additional deaths and mortality due to diarrheal diseases in the absence of adaptation (medium confidence) (see Figure 7.3*).* Risk factors for future excess deaths due to diarrheal diseases are highly mediated by future levels of socio-economic development and adaptation. An additional 1°C increase in mean average temperature is expected to result in a 7% (95% CI, 3%-10%) increase in all-cause diarrhoea (Carlton et al., 2016), and an 8% (95% CI, 5%-11%) increase in the incidence of diarrheic *E. coli* (Philipsborn et al., 2016)*,* and a 3% to 11% increase in deaths attributable to diarrhoea (WHO, 2014). WHO Quantitative Risk Assessments for the effects of climate change on selected causes of death for the

2030s and 2050s project that overall deaths from diarrhoea should fall due to socioeconomic development, but that the effect of climate change under higher emission scenarios could cause an additional 48,000 deaths in children aged under 15 years in 2030 and 33,000 deaths for 2050, particularly in Africa and parts of Asia. In Ecuador, projected increases in rainfall variability and heavy rainfall events may increase diarrhoea burden in urban regions (Deshpande et al., 2020). A limit in the assessable literature is a lack of studies in the highest risk areas (Liang and Gong, 2017);(UNEP, 2018).

Climate change is expected to increase future health risks associated with a range of other waterborne diseases and parasites, with effects varying by region (medium confidence). Waterborne diseases attributable to protozoan parasites including *Cryptosporidium* spp and *Giardia duodenalis (intestinalis)* are expected to increase in Africa due to increasing temperatures and drought (Ahmed et al., 2018);(Efstratiou et al., 2017). Recent data suggest a poleward expansion of *Vibrios* to areas with no previous incidence, particularly in mid- to high- latitude regions in areas where rapid warming is taking place (Baker-Austin et al., 2017). The number of *Vibrio*-induced diarrhoea cases per year increased in past decades in the Baltic Sea region, and the projected risk of vibriosis will increase in northern areas, where waters are expected to become warmer, more saline due to reduced precipitation, and have higher chlorophyll concentrations (Escobar et al., 2015);(Semenza et al., 2017).

The risk of Campylobacteriosis and other enteric pathogens could rise in regions where heavy precipitation events or flooding are projected to increase (medium confidence). In Europe, the risk of Campylobacteriosis and diseases caused by other enteric pathogens could also rise in regions where precipitation or extreme flooding are projected to increase (Agency, 2017), although incidence rates may be further mediated by seasonal social activities (Rushton et al., 2019);(Williams et al., 2015b). Accelerated releases of dissolved organic matter to inland and coastal waters through increases in precipitation are expected to reduce the potential for solar UV inactivation of pathogens and increase risks for associated waterborne diseases (Williamson et al., 2017). The combined relative risk for waterborne campylobacteriosis, salmonellosis and diseases due to Verotoxin-producing Escherichia coli was estimated to be 1.1 (i.e. a 10% increase) for every 1°C in mean annual temperature, while by the 2080s, under RCP8.5, annual rates of cryptosporidiosis and giardiasis could rise by approximately 16% due to more severe precipitation events (Brubacher et al., 2020);(Chhetri et al., 2019).

7.3.1.5 Projected impacts on food-borne diseases

The prevalence of Salmonella *infections are expected to rise as higher temperatures enable more rapid replication (medium confidence)*. Research from Canada finds a very strong association of salmonellosis and other food-borne diseases with higher temperatures, suggesting that climate change could increase food safety risks ranging from increased public health burden to emergent risks not currently seen in the food chain (Smith and Fazil, 2019). In Europe, the average annual number of temperature-related cases of salmonellosis under high emissions scenarios could increase by up to 50% more than would be expected on the basis of on population change alone, by 2100 (Lake, 2017);(Agency, 2017). Warming trends in the southern US may lead to increased rates of Salmonella infections (Akil et al., 2014).

7.3.1.6 Projected impacts on pollution and aeroallergens related health outcomes

Global air pollution-related mortality attributable directly to climate change – the human health climate penalty associated with climate-induced changes in air quality - is likely to increase and partially counteract any decreases in air pollution-related mortality achieved through ambitious emission reduction scenarios or stabilisation of global temperature change at 2°C (medium confidence). Demographic trends in aging and more vulnerable population are likely to be important determinants of future air quality – a human health climate penalty *(high confidence)*.

Poor air quality contributes to a range of non-communicable diseases including cardiovascular, respiratory, and neurological, commonly resulting in hospitalisation or death. This section considers the possible risks for health of future climate-related changes in ozone and particulate matter (PM). The climate penalty, the degree to which global warming could affect future air quality, is better understood for ozone than particulate matter (von Schneidemesser et al., 2020). This is because increases in air temperature enhance ozone formation via associated photochemical processes (Archibald et al., 2020);(Fu and Tian, 2019). The association between climate and particulate matter is complex and moderated by a diverse range of PM components as well as formation and removal mechanisms (von Schneidemesser et al., 2020), added to which is uncertainty about future climate related PM sources such as wildfires (Ford et al., 2018) and changes in aridity (Achakulwisut et al., 2019). As noted in Chapter 6 of the WG1 report, future air quality will largely depend on precursor emissions, with climate change projected to have mixed effects. Because of the uncertainty of how natural processes will respond, there is low confidence in the projections of surface ozone and PM under climate change (Szopa et al., 2021 – Chapter 6, IPCC AR6 WGI). This bears implications for the levels of confidence in projections of the health climate penalty associated with climate-induced changes in air quality (Orru et al., 2017), (Orru et al., 2019);(Silva et al., 2017).

There is a rich literature on global and regional level projections of air quality-related health effects arising from changes in emissions. Comparatively few studies assess how changes in air pollution directly attributable to climate change are likely to affect future mortality levels. Projections indicate that emission reduction scenarios consistent with stabilisation of global temperature change at 2°C or below would yield substantial co-benefits for air quality related health outcomes(Chowdhury et al., 2018b); (von Schneidemesser et al., 2020);(Silva et al., 2016c);(Markandya et al., 2018);(Orru et al., 2019);(Shindell et al., 2018) (*high confidence*). For example, by 2030, compared to 2000, it was estimated that globally and annually 289,000 PM2.5 - related premature deaths could have been avoided under RCP 4.5 compared to 17,200 PM2.5 - related excess premature deaths under RCP 8.5(Silva et al., 2016c). Further, and notwithstanding estimated reductions in global PM2.5 levels and an associated increase in the number of avoidable deaths, the benefits of following a low emissions pathway are expected to be apparent by 2100, with avoidable deaths estimated at 2.39 million deaths per year under RCP4.5. This contrasts with the 1.31 million estimated under RCP8.5. A few projections of the health related climate-penalty indicate a possible increase in ozone and PM2.5 - associated mortality under RCP8.5 (Doherty et al., 2017);(Orru et al., 2019);(Silva et al., 2017).

At the global level for PM2.5, annual premature deaths due to climate change were projected to be 55,600 (−34,300 to 164,000) and 215,000 (−76,100 to 595,000) in 2030 and 2100, respectively, countering by 16% the projected decline in PM2.5 -related mortality between 2000 and 2100 without climate change (Silva et al., 2017). Similarly for ozone , the number of annual premature ozone-related deaths due to climate change were projected to be 3,340 in 2030 and 43,600 in 2050, with climate change accounting for 1.2% (14%) of the annual premature deaths in 2030 (2100) (Silva et al., 2017). These global level projections average over considerable geographical variations (Silva et al., 2017). Projections of the climate change effect on ozone mortality in 2100 were greatest for East Asia (41 deaths per year per million people), India (8 deaths per year per million people) and North America (13 deaths per year per million people). For PM2.5, mortality was projected to increase across all regions except Africa (−25,200 deaths per year per million people) by 2100, with estimated increases greatest for India (40 deaths per year per million people), the Middle East (45 deaths per year per million people), East Asia (43 deaths per year per million people) and the Former Soviet Union (57 deaths per year per million people). Overall, higher ozone-related health burdens were projected to occur in highly populated regions and greater PM2.5 health burdens were projected in high PM emission regions (Doherty et al., 2017).

For Central and Southern Europe, climate change alone could result in an 11% increase in ozone-associated mortality by 2050. However, projected declines in ozone precursor emissions could reduce the EU-wide climate change effect on ozone-related mortality by up to 30%; the reduction was projected to be approximately 24% if aging and an increasingly susceptible population were accounted for in projections to 2050 (Orru et al., 2019). For the US in 2069, the impact of climate change alone on annual PM2.5 and ozone-related deaths were estimated to be 13,000 and 3,000 deaths respectively, with heat-driven adaptation of air conditioning accounting for 645 and 315 of the PM2.5 and ozone related annual excess deaths, respectively (Abel et al., 2018). An aging population as a determinant of future air quality related mortality levels. An aging population along with an increase in the number of vulnerable people may work to offset the decrease in deaths associated with a low emission pathway (RCP4.5) and possibly dominate the net increase in deaths under a business as usual pathway (RCP8.5) (Chen et al., 2020) ;(Doherty et al., 2017);(Hong et al., 2019);(Schucht et al., 2015).

Complementing the longer-term changes in air quality arising from climate change are those associated with air pollution sensitive short-term meteorological events, such as heatwaves. Studies of individual heat events

(Garrido-Perez et al., 2019);(Johansson et al., 2020);(Kalisa et al., 2018);(Pu et al., 2017);(Pyrgou et al., 2018);(Schnell and Prather, 2017);(Varotsos et al., 2019) and systematic reviews (Anenberg et al., 2020) provide evidence for synergistic effects of heat and air pollution. However, the health consequences of a possible additive effect of air pollutants during heatwave events were heterogeneous, varying by location and moderated by socio-economic factors at the intra-urban scale (Analitis et al., 2014);(Fenech et al., 2019);(Krug et al., 2020);(Pascal et al., 2021);(Schwarz et al., 2021);(Scortichini et al., 2018). This, combined with the challenges associated with projecting future concentrations of health-relevant pollutants during heatwave events (Jahn and Hertig, 2021);(Meehl et al., 2018) makes it difficult to say with any certainty that synergistic effects of heat and poor air quality will result in a heatwave-air pollution health penalty under climate change.

The burden of disease associated with aeroallergens is anticipated to grow due to climate change (high confidence). The incidence of pollen allergy and associated allergic disease increases with pollen exposure, and the timing of the pollen season and pollen concentrations are expected to change under climate change (Beggs, 2021);(Ziska et al., 2019), (Ziska, 2020). The overall length of the pollen season and total seasonal pollen counts/concentrations for allergenic species such as birch (Betula) and ragweed (Ambrosia) are expected to increase as a result of CO_2 fertilization and warming, leading to greater sensitization (Hamaoui-Laguel et al., 2015);(Lake et al., 2017);(Zhang et al., 2013). Changes in pollen levels for several species of trees and grasses are projected to increase annual emergency department visits in the US by between 8% for RCP4.5 and 14% for RCP8.5 by the year 2090 (Neumann et al., 2019) with the exposure to some pollen types estimated to double beyond present levels in Europe by 2041-2060 (Lake et al., 2017). The prospect of increases in summer thunderstorm events under climate change (Brooks, 2013) may hold implications for changes in the occurrence of epidemic thunderstorm asthma (Bannister et al., 2021);(Emmerson et al., 2021);(Price et al., 2021). Similarly projected alterations in hydroclimate under climate change may bear implications for increased exposure to mould allergens in some climates (D'Amato et al., 2020); (Paudel et al., 2021).

7.3.1.7 Cardiovascular diseases

Climate change is expected to increase heat-related cardiovascular disease (CVD) mortality by the end of the 21st century, particularly under higher emission scenarios (high confidence). Most modelling studies conducted since AR5 project higher rates of heat-related CVD mortality throughout the remainder of this century(Huang and et al., 2018);(Li et al., 2015);(Li et al., 2018);(Limaye et al., 2018);(Zhang et al., 2018a);(Silveira et al., 2021a); (Yang et al., 2021). CVD mortality in Beijing, China could increase by an average of 18.4%, 47.8%, and 69.0% in the 2020s, 2050s, and 2080s, respectively, under RCP 4.5, and by 16.6%, 73.8% and 134%, respectively, under RCP 8.5 relative to a 1980s baseline (Li et al., 2015). Projections of temperature-related mortality from CVD for Beijing in the 2080s varying depending on RCP and population assumptions (Zhang et al., 2018a). Projections for Ningo, China, suggest heat-related years of life lost could increase significantly in the month of August, by between 3 and 11.5 times greater over current baselines by the 2070s, even with adaptation (Huang and et al., 2018). Yang and colleagues project that heat-related excess CVD mortality in China could increase to approximately 6% (from a 2010 baseline of under 2%) by the end of the century under RCP 8.5 and to over 3% under RCP 4.5 (Yang et al., 2021). The future burden of temperature-related myocardial infarctions (MI) in Germany is projected to rise under high emissions scenarios (Chen et al., 2019), while in the eastern US, Limaye et al. (2018) projected an additional 11,562 annual deaths (95% CI: 2,641–20,095) by mid-century due to cardiovascular stress in the population 65 years of age and above. CVD mortality in Brazil is projected to increase up to 8.6% by the end of the century under RCP 8.5, compared with an increase of 0.7% for RCP 4.5 (Silveira et al., 2021a).

It is important to note that the assessed studies typically take an observed epidemiological relationship and apply future temperature projections (often derived from regional climate projections), to these relationships. Because the relationships between temperature and CVD death are influenced by both climatic and non-climatic factors (such as population fitness and aging), future projections are highly sensitive to assumptions about interactions between climate, population characteristics, and adaptation pathways. Changes in air quality because of climate change are an additional important factor. For example, an assessment of future annual and seasonal excess mortality from short-term exposure to higher levels of ambient ozone in Chinese cities under RCP 8.5 projected approximately 1,500 excess annual CVD deaths in 2050 (Chen et al., 2018).

To the extent possible, the relationships reported above reflect changes derived from changes in heat exposure driven by climate change, and not changes in population demographics or air pollution exposure.

Climate change could impact CVD through other pathways, including exposure to fine dust. For example, Achakulwisut and colleagues found that adult mortality attributable to fine dust exposure in the American southwest could increase by 750 deaths per year (a 130% increase over baseline) by the end of the century under RCP 8.5 (Achakulwisut et al., 2018).

7.3.1.8 Maternal, foetal, and neonatal health

Additional research is needed on future impacts of climate change on maternal, foetal and neonatal health. Maternal heat exposure is a risk factor for several adverse maternal, foetal, and neonatal outcomes (Kuehn and McCormick, 2017), including foetal growth (Sun et al., 2019) and congenital anomalies (Haghighi et al., 2021). There is very limited research on this subject, an exception being Zhang et al. 2020 (Zhang et al.) that projected an 34% increase in congenital health disease risk in the US in 2025 and 2035 based on increased maternal extreme heat exposure.

7.3.1.9.1 Malnutrition

Climate change is projected to exacerbate malnutrition (high confidence). Climate change attributable moderate and severe stunting in children less than 5 years of age was projected for 2030 across 44 countries to be an additional 570,000 cases under a prosperity and low climate change scenario (RCP2.6) to one million cases under a poverty and high climate change scenario (RCP8.5), with the highest effects in rural areas.(Lloyd, 2018). Future disability-adjusted life years (DALYs) lost due to protein-energy undernutrition and micronutrient deficiencies without climate change have been projected to increase between 2010 and 2050 by over 30 million. With climate change (RCP8.5), DALYs were projected to increase by nearly 10%, with the largest increases in Africa and Asia (Sulser et al., 2021).

The projected risks of hunger and childhood underweight vary under the five SSPs, with population growth, improvement in the equality of food distribution, and income-related increases in food consumption influencing future risks (Ishida et al., 2014);(Hasegawa et al., 2015). A review of 57 studies projecting global food security to 2050 under the SSPs concluded that global food demand was expected to increase by 35% to 56% between 2010 and 2050, with the population at risk of hunger expected to change by −91% to +8% (van Dijk et al., 2021);(van Dijk et al., 2021). Taking climate change into account changed the ranges slightly but with no statistical differences overall.

7.3.1.9.2 Climate Change, Carbon Dioxide, Diets, and Health

Climate change could further limit equitable access to affordable, culturally acceptable, and healthy diets (high confidence). Climate impacts on agricultural production and regional food availability will affect the composition of diets, which can have major consequences for health. Variable by region and context, healthy diets are an outcome of the four interconnected domains of sustainable food systems, namely ecosystems, society, economics, and health (Drewnowski et al., 2020);(Fanzo et al., 2020). Climate change limits the potential for healthy diets through adverse impacts on natural and human systems that are disproportionately experienced by low-income countries and communities (FAO et al., 2021). Climate-driven droughts, floods, storms, wildfires, and extreme temperatures reduce food production potential by diminishing soil health, water security, and biological and genetic diversity (Macdiarmid and Whybrow, 2019). Models project that climate-related reductions in food availability, specifically fruit and vegetables, could result in an additional 529,000 deaths a year by 2050 (Springmann et al., 2016b).

Diets reliant on marine fisheries and fish also face complex climate-driven challenges (Hollowed et al., 2013). Rapidly warming oceans (Cheng et al., 2020) limit the size of many fish and hamper their ability to relocate or adapt; many commonly consumed fish, like sardines, pilchards, and herring could face extinction due to these pressures (Avaria-Llautureo et al., 2021). Other fisheries models project end of century pollock and Pacific cod fisheries decreasing by >70% and >35% under RCP 8.5 (Holsman et al., 2020). Climate-driven increases in marine mercury concentrations (Booth and Zeller, 2005) and harmful algal blooms (Jardine et al., 2020) could impact dietary quality and human health.

Global crop and economic models project higher cereal prices of up to 29% by 2050 under RCP 6.0, resulting in an additional 183 million people in low-income households at risk of hunger (Hasegawa et al., 2018). Climate impacts on human health disrupt agricultural labour, food supply chain workers, and ultimately regional food availability and affordability. A recent meta-analysis focused on Sub-Saharan Africa and Southeast Asia combined metrics of heat stress and labour to project that a 3°C increase in global mean temperature, without adaptation or mechanization, could reduce agricultural labour capacity by 30-50%, leading to 5% higher crop prices and a global welfare loss of $136 billion (de Lima et al., 2021).

The nutritional density of wheat, rice, barley, and other important food crops, including of protein content, micronutrients, and B-vitamins, is affected negatively by higher CO_2 concentrations (*very high confidence*). (SRCCL, 2019 5.4.3);(Smith and Myers, 2018). Projections indicate negative impacts on human nutrition of rising CO_2 concentrations by mid- to late-century (Medek et al., 2017);(Smith and Myers, 2018);(Weyant et al., 2018);(Zhu et al., 2018);(Beach et al., 2019). Staple crops are projected to have decreased protein and mineral concentrations by 5-15% and B vitamins up to 30% when the concentrations of CO_2 double above pre-industrial (Ebi and Loladze, 2019);(Beach et al., 2019);(Smith and Myers, 2018). Without changes in diets and accounting for nutrient declines in staple crops, a projected additional 175 million people could be zinc deficient and an additional 122 million people could become protein deficient (Smith and Myers, 2018).Weyant et al. (2018) projected that CO_2-related reductions in crop zinc and iron levels could result in 125.8 million DALYs lost globally, with South-East Asian and sub-Saharan African countries most affected. Zhu et al. (2018) estimated 600 million people at risk from reductions in the protein, micronutrient, and B-vitamin content of widely grown rice cultivars in Southeast Asia.

The combined effect of CO_2 and rising temperatures because of climate change could result in a 2.4% to 4.3% penalty on expected gains by mid-century in nutritional content because of technology change, market responses, and the fertilization effects of CO_2 on yield (Beach et al., 2019). These penalties are expected to slow progress in achieving reductions in global nutrient deficiencies, disproportionately affecting countries with high levels of such deficiencies.

7.3.1.10 Projected impacts on harmful algal blooms, mycotoxins, aflatoxins, and chemical contaminants

Harmful algal blooms are projected to increase globally, thus increasing the risk of seafood contamination with marine toxins (high confidence). (Authority) et al., 2020);(Gobler et al., 2017);(Barange et al., 2018);(SRCCL, 2019);(Wells et al., 2020). Climate change impacts on oceans could generate increased risks of ciguatera poisoning in some regions *(medium confidence).* Studies suggest that rising sea surface temperatures could increase rates of ciguatera poisoning in Spain (Botana, 2016), and other parts of Europe {EFSA, 2020, Climate change as a driver of emerging risks for food and feed safety`, plant`, animal health and nutritional quality.

Mycotoxins and aflatoxins may become more prevalent due to climate change (medium agreement, low evidence). Models of aflatoxin occurrence in maize under climate change scenarios of +2 °C and +5 °C in Europe over the next 100 years project that aflatoxin B1 may become a major food safety issue in maize, especially in Eastern Europe, the Balkan Peninsula and the Mediterranean regions (Battilani, 2016). The occurrence of toxin-producing fungal phytopathogens has the potential to increase and expand from tropical and subtropical into regions where such contamination does not currently occur (Battilani, 2016).

Climate change may alter regional and local exposures to anthropogenic chemical contaminants (medium agreement, low evidence). Changes in future occurrences of wildfires could lead to a 14 percent increase in global emissions of mercury by 2050, depending on the scenarios used (Kumar et al., 2018a). Mercury exposure via consumption of fish may be affected by warming waters. Warming trends in the Gulf of Maine could increase the methyl mercury levels in resident tuna by 30 percent between 2015 and 2030 (Schartup et al. (2019). An observed annual 3.5 percent increase in mercury levels was attributed to fish having higher metabolism in warmer waters, leading them to consume more prey. The combined impacts of climate change and the presence of arsenic in paddy fields are projected to potentially double the toxic heavy metal content of rice in some regions, potentially leading to a 39 percent reduction in overall production by 2100 under some models (Muehe et al., 2019).

7.3.1.11 Mental Health and Wellbeing

Climate change is expected to have adverse impacts on wellbeing, some of which will become serious enough to threaten mental health (very high confidence). However, changes (Hayes and Poland, 2018) in extreme events due to climate change, including floods {Baryshnikova, 2019 #3530} , droughts (Carleton, 2017) and hurricanes (Kessler et al., 2008);(Boscarino et al., 2013), (Boscarino et al., 2017) ; (Obradovich et al., 2018), which are projected to increase due to climate change, directly worsen mental health and wellbeing, and increase anxiety (*high confidence)*. Projections suggest that sub-Saharan African children and adolescents, particularly girls, are extremely vulnerable to negative direct and indirect impacts on their mental health and wellbeing (Atkinson and Bruce, 2015);(Owen et al., 2016). The direct risks are greatest for people with existing mental disorders, physical injuries, impacts on respiratory, cardiovascular and reproductive systems, with indirect impacts potentially arising from displacement, migration, famine and malnutrition, degradation or destruction of health and social care systems, conflict, and climate-related economic and social losses (*high to very high confidence*) (Burke et al., 2018);(Curtis et al., 2017);(Hayes et al., 2018); (Serdeczny et al., 2017);(Watts et al., 2019). Demographic factors increasing vulnerability include age, gender, and low socioeconomic status, though the effect of these will vary depending on the specific manifestation of climate change; overall, climate change is predicted to increase inequality in mental health across the globe (Cianconi et al., 2020). Based on evidence assessed in Section 7.2 of this chapter, future direct impacts of increased heat risks and associated illnesses can be expected to have negative implications for mental health and wellbeing, with outcomes being highly mediated by adaptation, but there are no assessable studies that quantify such risks. There may be some benefits to mental health and wellbeing associated with fewer very cold days in the winter; however, research is inconsistent. Any positive effect associated with reduced low-temperature days is projected to be outweighed by the negative effects of increased high temperatures (Cianconi et al., 2020).

Human behaviors and systems will be disrupted by climate change in a myriad of ways, and the potential consequences for mental health and wellbeing are correspondingly large in number and complex in mechanism (high confidence). For example, climate change may alter human physical activity and mobility patterns, in turn producing alterations in the mental health statuses promoted by regular physical activity (Obradovich and Fowler, 2017);(Obradovich and Rahwan, 2019). Climate change may affect labour capacity, because heat can compromise the ability to engage in manual labor as well as cognitive functioning, with impacts on the economic status of individual households as well as societies (Kjellstrom et al., 2016);(Liu, 2020). Migrations and displacement caused by climate change may worsen the wellbeing of those affected (Vins et al., 2015);(Missirian and Schlenker, 2017). Climate change is expected to increase aggression through both direct and indirect mechanisms, with one study predicting a 6% increase in homicides globally for a 1°C temperature increase, although noting significant variability across countries (Mares and Moffett, 2016). Broad societal outcomes such as economic unrest, political conflict, or governmental dysfunction assessed in sections 7.3.5 may undermine mental health of populations in the future (*medium confidence*). Food insecurity presents its own severe risks for mental health and cognitive function (Jones, 2017).

7.3.2 Migration and displacement in a Changing Climate

Future changes in climate-related migration and displacement are expected to vary by region and over time, according to: (1) region-specific changes in climatic drivers, (2) changes in the future adaptive capacity of exposed populations, (3) population growth in areas most exposed to climatic risks, and (4) future changes in mediating factors such as international development and migration policies (high agreement, medium evidence). (Gemenne and Blocher, 2017);(Cattaneo et al., 2019);(McLeman, 2019) Assessed in this section are future risks associated with changes in the frequency and/or severity of storms, floods, droughts, extreme heat, wildfires and other events assessed in section 7.2 that currently affect migration and displacement patterns; as well as the impacts of emerging hazards, including average temperature increases that may affect the habitability of settlements in arid regions and the tropics, and sea level rise and associated hazards that threaten low-lying coastal settlements. Studies assessed here consider projected changes in future exposure to hazards over a variety of geographical and temporal periods, with some considering changes in population numbers in exposed areas. However, the uneven distribution of exposure of age cohorts is typically overlooked in existing research. For example, people younger than age 10 in the year 2020 are projected to experience a nearly fourfold increase in extreme events under 1.5C of global warming, and a fivefold increase under 3C warming; such increases in exposure would not be experienced by a person of the age of 55 in 2020 in their remaining lifetime under any warming scenario (Thiery et al., 2021).

7.3.2.1 Region-specific changes in climatic risks

As outlined in 7.2, the most common drivers of observed climate-related migration and displacement are extreme storms (particularly tropical cyclones), floods, extreme heat, and droughts (high confidence). The future frequency and/or severity of such events due to anthropogenic climate change are expected to vary by region according to future GHG emission pathways [IPCC 2021 Chapter 12; Regional Chapters, this report], with there being an increased potential for compound effects of successive or multiple hazards (e.g., tropical storms accompanied by extreme heat events, (Matthews et al., 2019). Table 7.2 summarizes anticipated changes in future migration and displacement risks due to sudden-onset climate events, by region (and by sub-regions for Africa and Asia, where climatic risks vary within the region).

Table 7.2: Projected changes in sudden-onset climate events associated with migration and displacement, by region

Region	**Main directions of current migration flows (from (Abel and Sander, 2014))**	**Current climatic drivers of migration & displacement [7.2.6.1]**	**Expected changes in drivers (*including confidence statements*) from IPCC 2021 TS 4.3.1-4.3.2**
Asia	East and Southeast Asia: Within countries and between countries within same region. South and Central Asia: Within countries and between countries within same region; from South Asia to Middle East, North America, Europe. West Asia: Within countries and between countries within the same region; to Europe	Floods, extreme storms, extreme heat	Increased risk of flooding in East, North, South & Southeast Asia due to increases in annual mean precipitation (*high confidence*) and extreme precipitation events in East, South, West Central, North & Southeast Asia (*medium confidence*); uncertainty regarding future trends in cyclones (current trend = decreased frequency, increased intensity); higher average temperatures across region (*high confidence*)
Africa	Within countries and between countries within the same region; to Europe and the Middle East	Floods, droughts, extreme heat	Decrease in total annual precipitation in northernmost and southernmost parts of Africa (*high confidence*); west-to-east pattern of decreasing-to-increasing annual precipitation in West Africa and East Africa (medium confidence); increased risk of heavy precipitation events that trigger flooding, across most parts of Africa (*medium confidence*); increased aridity and drought risks in North Africa, southern Africa and western parts of West Africa (*medium-high confidence*)
Europe	Within countries and between countries in same region	Floods	Increased risk of floods across all areas of Europe except Mediterranean areas (high confidence); higher risks of drought, fire weather in Mediterranean areas (high confidence)
North America	Within countries and between countries in same region	Floods; tropical cyclones (US Atlantic & Caribbean coast);	Increased frequency of heavy precipitation events across most areas (high confidence); tropical cyclones to become more severe (medium confidence); increased risk of drought

		tornadoes; wildfires	and fire weather in central and western North America
Central and South America	Within countries and between countries in same region; to North America, Europe	Floods (Central and South America; extreme storms (Central America)	Increases in mean annual precipitation and extreme precipitation events with higher risks of floods in most areas of South America (*medium confidence*); increased risk of droughts in northeastern and southern South America and northern Central America (*medium confidence*); tropical cyclones becoming more extreme (*medium confidence*)
Australasia	Displacement within countries	Wildfires	Increases in fire weather across Australia and New Zealand (*medium confidence*)
Small island states	Within and between countries in same region (e.g., Pacific Islands to Australia & New Zealand; Caribbean islands to USA)	Extreme storms	Potentially fewer but more extreme tropical cyclones (medium confidence)

In low-lying coastal areas of most regions, future increases in mean sea levels will amplify the impacts of coastal hazards on settlements, including erosion, inland penetration of storm surges and groundwater contamination by salt water, and eventually lead to inundation of very low-lying coastal settlements (high confidence). (Diaz, 2016);(Hauer et al., 2016);(Neumann et al., 2015);(Rahman et al., 2019);(Pörtner et al., 2019) Projections of the number of people at risk of future displacement by sea level rise range from tens of millions to hundreds of millions by the end of this century, depending on (1) the sea level rise scenario or RCP selected, (2) projections of future population growth in exposed areas and (3) the criteria used for identifying exposure. These latter measures can include estimates of populations situated within selected elevations above sea level (with 1m, 2m and 10m being common parameters), populations situated in 1-in-100 year floodplains, or populations in areas likely to be entirely inundated under specific RCPs (Neumann et al., 2015);(Hauer et al., 2016);(Merkens et al., 2018);(McMichael et al., 2020);(Hooijer and Vernimmen, 2021). As an illustrative example, an estimated 267 million people (error range = 197-347 million at 68% confidence level) worldwide lived within 2m of sea level in 2020, 59% of whom reside in tropical regions of Asia (Hooijer and Vernimmen, 2021). At a 1m increase in sea level and holding coastal population numbers constant, the number of people worldwide living within 2m of sea level expands to 410 million (error range = 341-473 million). However, it is *unlikely* that coastal population growth rates will remain constant at global or regional scales in future decades. At present, coastal cities in many regions have relatively high rates of population growth due to the combined effects of in-migration from other regions and natural increase, with coastal areas of Africa having the highest projected future population growth rates (Neumann et al., 2015);(Hooijer and Vernimmen, 2021); see also Box 7.5. Further complicating future estimates is that many large coastal cities are situated in deltas with high rates of subsidence, meaning that locally experienced changes in relative sea level may be much greater than sea level rise attributable to climate change, thereby further increasing the number of people exposed (Edmonds et al., 2020);(Nicholls et al., 2021).

Sea level rise is not presently a significant driver of migration in comparison with hazards assessed in 7.2.6, but it has been attributed as a factor necessitating the near-term resettlement of small coastal settlements in Alaska, Louisiana, Fiji, Tuvalu, and the Carteret Islands of Papua New Guinea (Marino and Lazrus, 2015);(Connell, 2016);(Hamilton et al., 2016; Nichols, 2019). In coastal Louisiana, communities tend to resist leaving exposed settlements until approximately 50% of available land has been lost (Hauer et al., 2019). Movements away from highly exposed areas may have longer-term demographic implications for inland settlements (Hauer, 2017), but this requires further study. Based on the limited empirical evidence available, sea level rise does not appear to currently be a primary motivation for international migration originating in small island states in the Indian and Pacific Oceans; economic considerations and family reunification appear to be the dominant current drivers (McCubbin et al., 2015);(Stojanov and Du, 2016);(Heslin, 2019);(Kelman et al., 2019). However, climatic drivers of migration are anticipated to take on a much greater causal role in migration decisions in coming decades (Thomas et al., 2020), and may discourage return migration to small island states (van der Geest et al., 2020). Even under best-case sustainable development scenarios, rising sea levels and associated hazards create risks of involuntary displacement in low-lying coastal areas and should be expected to generate a need for organized relocation of populations where protective infrastructure cannot be constructed (Horton and de Sherbinin, 2021) (Hamilton et al., 2016) . In high emissions scenarios, low-lying island states may face the long-term risk of becoming functionally uninhabitable, creating the potential for a new phenomenon of climate-induced statelessness (Piguet, 2019);(Desai et al., 2021).

[START BOX 7.5]

Box 7.5: Uncertainties in projections of future demographic patterns at global, regional and national scales

Projections of future numbers of people exposed to climate change-related hazards described in this chapter and elsewhere in this report are heavily influenced by assumptions about population change over time at global, regional, and national scales. One challenge concerns global and regional variability of baseline data for current populations, which is typically aggregated from national censuses that vary considerably in terms of frequency, timing, and reliability, especially in low-income countries. A number of gridded mapping dataset initiatives emerged in recent years to support population-environment modelling research at global and regional levels, common ones being the Gridded Population of the World, the Global Rural Urban Mapping Project, and LandScan Global Population dataset (McMichael et al., 2020). For future population projections at national levels, researchers commonly draw upon data generated by the Population Division of the United Nations Department of Economic and Social Affairs, which publishes periodic projections for future fertility, mortality, and international migration rates for over 200 countries, the most recent projections being for the period 2020 to 2100 (Division and Population, 2019). There have been debates among demographers regarding the precision of DESA projections, with some debate over whether these overestimate or underestimate future population growth in some regions (Ezeh et al., 2020). Population growth rates are highly influenced by socio-economic conditions, meaning that future population levels at local, national, and regional scales are likely to respond to relative rates of progress toward meeting the Sustainable Development Goals (Abel et al., 2016). The Shared Socio-economic Pathways used in climate impacts and adaptation research include a variety of assumptions about future mortality, fertility, and migration rates, and provide a range of population growth scenarios that diverge after the year 2030 according to future development trajectories (Samir and Lutz, 2017) and which are then further modified and downscaled by researchers for national-level studies. Understanding of future risks of climate change will benefit from continued efforts by the international community to collect and share data on observed population numbers and trends, and to work toward better projected data for population characteristics that strongly influence vulnerability to climate risks, such as gender, age, and indigeneity.

[END OF BOX 7.5]

Increased frequency of extreme heat events and long-term increases in average temperatures pose future risks to the habitability of settlements in tropical and sub-tropical regions, and may in the long term affect migration patterns in exposed areas, especially under high emissions scenarios (medium agreement, low evidence). Greater research into the specific dynamics between extreme heat and population movements is required in order to make an accurate assessment of this risk. Recent studies suggest that future increases in average temperatures could expose populations across wide areas of the tropics and subtropics to ambient temperatures for extended periods each year that are beyond the threshold for human habitability (Pal and Eltahir, 2016);(Im et al., 2017);(Xu et al., 2020). This effect would be amplified in urban settings where heat-island effects occur and create heightened need for air conditioning and other adaptation measures. In addition to risks associated with average temperature changes, Dosio et al (2018) project that at 1.5°C warming, between 9% and 18% of the global population will be regularly exposed to extreme heat events at least once in 5 years, with the exposure rate nearly tripling with 2°C warming. How these changes in exposure to high temperatures will affect future migration patterns, particularly among vulnerable groups, will depend heavily on future adaptation responses (Horton and de Sherbinin, 2021). Multiple country-level studies assessed in section 7.2 observe existing associations between extreme heat, its impacts on agricultural livelihoods, and changes in rural-to-urban migration flows in parts of South Asia and sub-Saharan Africa. A study conducted in Indonesia, Malaysia, and the Philippines suggests that an increased risk of heat stress would likely influence migration intentions of significant numbers of people (Zander et al., 2019).

7.3.2.2 Interactions with non-climatic determinants and projections of future migration flows

Only a very small number of studies have attempted to make systematic projections of future regional or global migration and displacement numbers under climate change. Key methodological challenges for making such projections include the availability of reliable data on migration within and between countries, definitional ambiguity in distinguishing climate-related migration from migration undertaken for other reasons, and accounting for the future influence of non-climatic factors. The most reliable example of such studies to date is a World Bank report by Rigaud et al (2018) generated projections of future internal population displacements in South Asia, sub-Saharan Africa,, and Latin America by 2050 using multiple climate and development scenarios, resulting in a very large range of possible outcomes (from 31 to 143 million people being displaced, depending on assumptions). An important outcome is the study's emphasis on how the potential for future migration and displacement will be strongly mediated by socio-economic development pathways in low- and middle-income countries. Consistent with this, Hoffmann et al (2020) used metaregression-based analyses to project that future environmental influences on migration are likely to be greatest in low- and middle-income countries in Latin America and the Caribbean, Sub-Saharan Africa, the Middle East and most of continental Asia.

Research reviewed in AR4 and AR5 observed that at higher rates of socio-economic development, the in situ adaptive capacity of households and institutions rises, and climatic influences on migration correspondingly decline. Recent evidence adds further support for such conclusions (high confidence). (Kumar et al., 2018b);(Mallick, 2019);(Gray et al., 2020) (Box 7.5). Population growth rates are currently highest in low-income countries (Division and Population, 2019), many of which have high rates of exposure to climatic hazards associated with population displacement, further emphasizing the importance of socio-economic development and adaptive capacity building. Although country-specific scenarios for socio-economic development and population are embedded in SSPs, research into future migration flows under climate change has not to date made great use of these. One of the few studies to do so found that safe and orderly international migration tends to increase wealth at regional and global scales in all SSP narratives, which in turn reduces income inequality between countries (Benveniste et al., 2021). International barriers to safe and orderly migration may potentially impede progress toward attainment of objectives described in the Sustainable Development Goals and increase exposure to climatic hazards in low- and middle income countries (McLeman, 2019);(Benveniste et al., 2020).

7.3.3 Climate Change and Future Risks of Conflict

Climate change may increase susceptibility to violent conflict, primarily intrastate conflicts, by strengthening climate-sensitive drivers of conflict *(medium confidence).* Section 7.2.7 demonstrated how climate variability and extremes affect violent conflict through food and water insecurity, loss of income, and loss of livelihoods. Risks are amplified by insecure land tenure, competing land uses and weather-sensitive economic activities, when they occur in the context of weak institutions and poor governance, poverty, and inequality (7.2.7). These known, climate-sensitive risk factors allow projections of where conflict is more likely to arise or worsen under climate change impacts (see Chapters 1, 4, 5, 6, 16) (Mach et al., 2020). However, there is also the potential for new causal pathways to emerge as climate changes beyond the variability observed in available datasets and adaptation limits are met (Theisen, 2017);(Mach et al., 2019);(von Uexkull and Buhaug, 2021).

Future violent conflict risk is highly mediated by socio-economic development trajectories (high confidence). Development trajectories that prioritise economic growth, political rights, and sustainability are associated with lower conflict risk (medium confidence, low evidence). Hegre et al (2016) forecast future conflict under the SSPs) and found that SSP1, which prioritises sustainable development is associated with lower risks of conflict. Using data from sub-Saharan Africa, Witmer et al (2017) forecast conflict along the SSPs and find that any increases in conflict that may be associated with climate change could be offset by increases in political rights. Strong predictors of future conflict are a recent history of conflict, large populations, and low levels of socio-economic development (Hegre and Sambanis, 2006) ; (Blattman and Miguel, 2010).

Increases in conflict-related deaths with climate change have been estimated but results are inconclusive (high agreement, medium evidence). Some studies attempted to attribute observed conflict outbreaks to changes in the physical environment and quantify future conflict risk associated with climate change (von Uexkull and Buhaug, 2021);(Theisen, 2017). Burke et al (2015b) concluded that with each one standard deviation increase in temperature, interpersonal conflict increased by 2.4% and intergroup conflict by 11.3%. However, this kind of approach has been criticised for its statistical methods and underrepresenting the known role that socioeconomic conditions and conflict history play in determining the prevalence of violence (Buhaug et al., 2014);(van Weezel, 2019);(Abel et al., 2019). Forecasting armed conflict is used as a heuristic policy tool rather than a representation of the future (Cederman and Weidmann, 2017) and forecasts have limitations. What constitutes, and is experienced as, a hazard will shift over time as societies adapt to climate change (Roche et al., 2020), the drivers of conflict change over time. The SSPs assume economic convergence between countries and do not reflect growth disruptions (e.g. commodity price shocks) that are often a key conflict risk factor (Dellink et al., 2017);(Buhaug and Vestby, 2019);(Hegre et al., 2021).

Asia represents a key region where the peace, vulnerability, and development nexus has been analysed. In Central, South, and South East Asia, there are large numbers of people exposed to the changing climate (Busby et al., 2018);(Vinke et al., 2017);(Reyer et al., 2017). South Asia is one of the least peaceful regions in the world with intra-state communal conflict, international military conflict, and political tension (Wischnath and Buhaug, 2014);(Huda, 2021), and many of the factors that drive conflict risk (large populations and high levels of inequality) are present (Nordqvist and Krampe, 2018). Despite these risks, studies in this region also support the case for environmental peacebuilding and resource sharing, as it relates to transboundary water sharing(Berndtsson and Tussupova, 2020);(Huda and Ali, 2018); Sections 4.3.6; 7.4.5.2).

In Asia, there is little evidence of weather-related impacts on conflict risk or prevalence, but the region is understudied in general (Wischnath and Buhaug, 2014);(Nordqvist and Krampe, 2018). Climate stressors may have contributed, in part, to local level conflicts in Bangladesh and Nepal (Sultana et al., 2019) and intensified water use conflict in peri-urban areas (Roth et al., 2019). There is the potential for climate change to stretch the effectiveness of transboundary water agreements by raising regional geopolitical tensions (Atef et al., 2019);(Scott et al., 2019) or to generate water use conflicts between hydropower and irrigation within countries (Jalilov et al., 2018). Climate change may impact on conflict by affecting food security (Caruso et al., 2016);(Raghavan et al., 2019). There may be greater military involvement in humanitarian response to cyclones, flooding, and to other impacts of climate change that might contribute to increased instability (Pai, 2008) ; (Busby and Krishnan, 2017).

7.4 Adaptation to Key Risks and Climate Resilient Development Pathways

With proactive, timely, and effective adaptation, many observed and projected risks for human health and wellbeing, health systems, and those associated with migration and conflict, can be reduced or potentially avoided (high confidence). Given the key health risks identified in this chapter, adaptation that increases resilience and sustainability will require moving beyond incremental adaptation and to sustained, adaptive management (Ebi, 2011);(Hess et al., 2012) with the goal of transformative change. This includes differentiating adaptation to climate variability from adaptation to climate change (Ebi and Hess, 2020). Health adaptation efforts are increasingly aiming to transition to building climate-resilient and environmentally sustainable health systems (WHO, 2015b);(WHO, 2020a) and healthcare facilities, emphasizing service delivery, including climate-informed health policies and programs, management of the environmental determinants of health; emergency preparedness and management; and health information systems, including health and climate research, integrated risk monitoring and early warning systems, and vulnerability, capacity, and adaptation assessments (Marinucci et al., 2014);(Mousavi et al., 2020);; (Organization, 2015);(CDC, 2019);(WHO, 2020a).

Migration can contribute to or work against adaptation goals and progress, depending on the circumstances under which it occurs. Policies that support safe and orderly movements of people, protect migrant rights, and facilitate flows of financial and other resources between sending and receiving communities are consistent with adaptive capacity building and building sustainability, and are part of climate resilient development pathways.

Adaptation to prevent climate from exacerbating conflict risk involves meeting development objectives encapsulated in the SDGs. Conflict-sensitive adaptation, environmental peacebuilding, and climate-sensitive peace building offer promising avenues to addressing conflict risk, but their efficacy is yet to be demonstrated through effective monitoring and evaluation (Gilmore et al., 2018). Associations between environmental factors and conflict are weak in comparison to socio-economic and political drivers. Therefore, meeting the SDGs, including Goal 16 on Peace, justice, and strong institutions represent unambiguous pathways to reducing conflict risk under climate change (Singh and Chudasama, 2021). Analysing peace rather than taking conflict for granted (Barnett, 2019) improving focus on gender within peacebuilding (Dunn and Matthew, 2015);(UNEP, 2021), and understand how natural resources and their governance interact with peacebuilding (Krampe et al., 2021) present key elements of climate resilient development pathways for sustainable peace.

As documented across this chapter, there is a large adaptation deficit for health and wellbeing, with climate change causing avoidable injuries, illnesses, disabilities, diseases, and deaths (high confidence). Implementation of health adaptation has been incremental because of significant constraints, primarily relating to financial and human resources, and because of limited research funding on adaptation (Berrang-Ford et al., 2021). Current global investments in health adaptation are insufficient to protect the health of populations and communities *(high confidence)* from most climate-sensitive risks, with large variability across and within countries and regions (UNEP, 2018). Climate change adaptation in health is <1% of international climate finance despite health being a priority sector in 54% of NDCs featuring adaptation (UNEP, 2018).

As climate change progresses and the likelihood of dangerous risks to human health continue to increase (Ebi et al., 2021a), there will be greater pressure for more transformational changes to health systems to reduce future vulnerabilities and limit further dangerous climate change. Transformational resilience would need parallel investments in social and health protections, including achieving the SDGs, coupled with investments in mitigation (Ebi and Hess, 2020). Further, investments in mitigating greenhouse gas emissions will not only reduce risks associated with dangerous climate change but will improve population health and wellbeing through several salutary pathways.

This chapter section identifies and assesses specific elements in adapting to risks identified in 7.2 and 7.3 and opportunities for fostering sustainability and pursuing climate resilient development pathways.

7.4.1 Adaptation Solution Space for Health and Wellbeing

The solution space is the space within which opportunities and constraints determine why, how, when, and who adapts to climate change (Chapter 1). *There is increased understanding of exposure and vulnerabilities to climate variability and change, and of the capacities to manage the health risks, of the effectiveness of adaptation (including a growing number of lessons learned and best practices), and of the co-benefits of mitigation policies and technologies (high confidence).*

Effectively preparing for and managing the health risks of climate change requires considering the multiple interacting sectors that affect population health and the effective functioning of health systems (high confidence). Given the wide range of causal pathways through which climate change affects environmental and social systems resulting in health impacts, a systems-based approach can promote identifying, implementing, and evaluating solutions that support population health and health systems in the short and longer-term (high agreement, medium evidence). Such an approach provides insights into policies and programs that promote health and wellbeing via multiple sectors (e.g. water and food safety and security), and can ensure that health policies do not have adverse consequences in other sectors (Organization, 2015);(Ebi and Otmani del Barrio, 2017);(Wright et al., 2021).

Figure 7.11 illustrates the context within which risks to health outcomes and health systems emerge because of climate change. The figure presents the emergence of risk from interactions between specific types of climatic hazards and exposure and vulnerability to those hazards, and the responses taken within the health sector. The figure illustrates also how health risks are situated within larger interactions between the health system and other sectors and systems, with underlying enabling conditions making adaptation and transformation possible. Within this context, response options can decrease the impacts of climate change on human health, wellbeing, and health systems by 1) reducing exposure to climate-related hazards; 2) reducing vulnerability to such hazards; and 3) strengthening health system responses to future risks. Such approaches are described as "Lateral Public Health" and emphasize the importance of involving community members and stakeholders in the planning and coordination of activities (Semenza, 2021);(Semenza, 2011). Lateral public health strives for community engagement (e.g., through access to technology in decision making, such as low-cost air sensors for wildfire smoke) in preparedness and response.

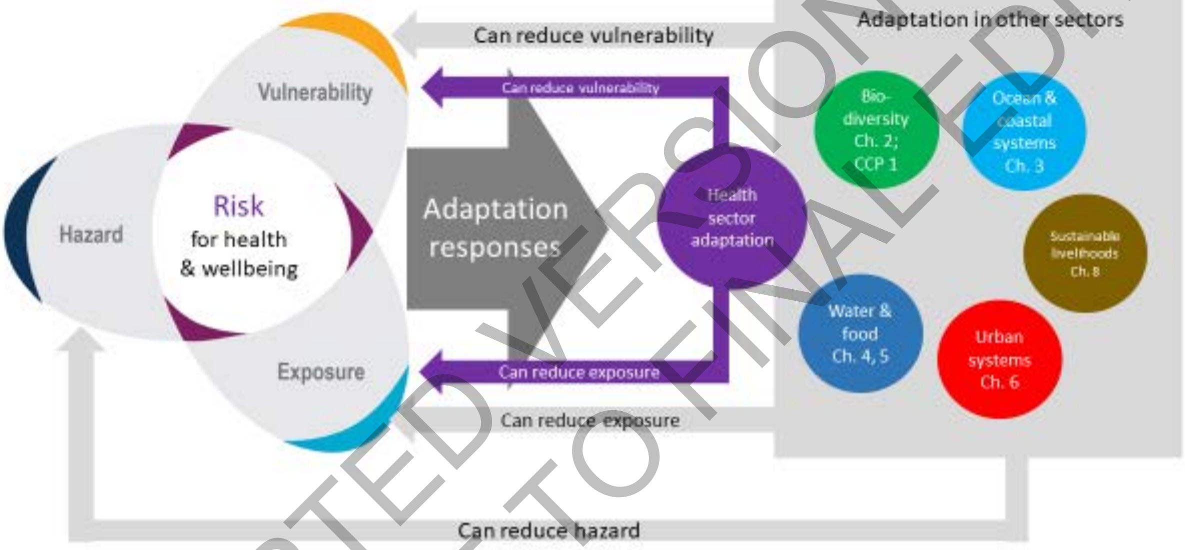


Figure 7.11: Context within which adaptation responses to climatic risks to health are implemented, in the frame of interactions between health and multiple other sectors..

Effective health risk management incorporates the magnitude and pattern of future climate risks as well as potential changes in factors that determine vulnerability and exposure to climate hazards, such as determinants of healthcare access, demographic shifts, urbanization patterns, and changes in ecosystems (very high confidence). Climate change is associated with shocks and stresses that can affect the capacity and resilience of health systems and healthcare facilities (WHO, 2020a). Figure 7.12 illustrates some possible extents to which the capacity of health systems could be reduced when exposed to a stress or shock, and possible pathways forward, from collapse to transformation. The subsequent sections assess adaptation and mitigation options to facilitate building the resilience of health systems and healthcare facilities to recover better than before or to transform.

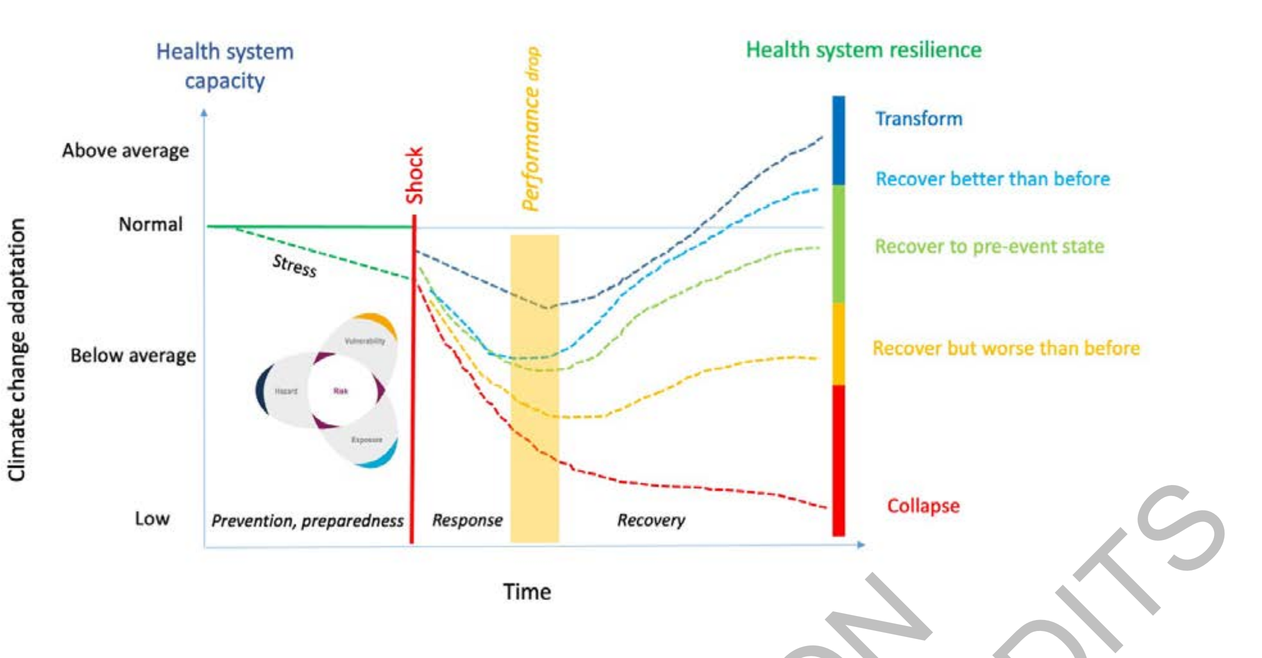


Figure 7.12: Health systems capacity and resilience to climate change-related shocks and stresses (from WHO 2020).

7.4.2 Adaptation Strategies, Policies and Interventions for Health and Wellbeing

7.4.2.1 Current state of health adaptation

Analysis of the Nationally Determined Contributions (NDC) to the Paris Agreement to determine how health was incorporated, including impacts, adaptation, and co-benefits, concluded that most low- and middle-income countries referred to health in their NDC (Dasandi et al., 2021). Figure 7.14 shows the degree of health engagement; this engagement is based on indicators measuring the specificity and detail of health references within the country NDC. Many vulnerable countries had high engagement of the health sector in the country NDC. However, this analysis did not determine whether the ambition expressed was sufficient to address the health adaptation needs.

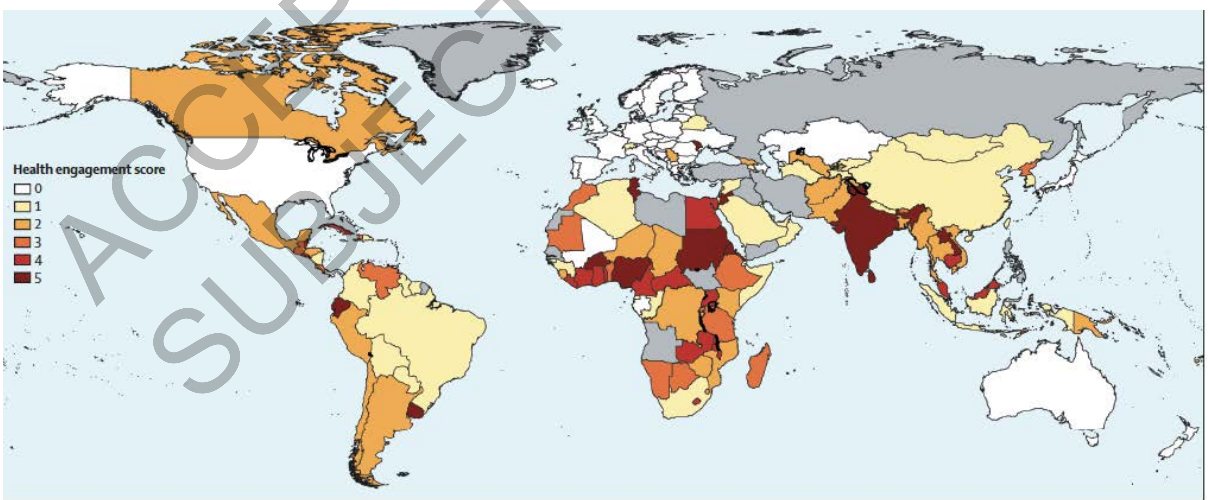


Figure 7.13: Health engagement score in NDCs by country. Source: Dasandi et al. 2021 (Dasandi et al., 2021)

The 2018 WHO Health and Climate Change Survey, a voluntary national survey sent to all 194 WHO member states, to which 101 responded, found that national planning on health and climate change is advancing, but the comprehensiveness of strategies and plans need to be strengthened; implementing action on key health and climate change priorities remains challenging; and multisectoral collaboration on health and climate change policy is evident, with uneven progress (Watts et al., 2021). Approximately 50% of respondent countries had developed national health and climate strategies, over 2/3 within the preceding five years, and 48/101 had conducted a health vulnerability and adaptation assessment (Watts et al., 2019). However, most countries reported only moderate or low levels of implementation, with financing cited as the most common barrier due to a lack of information on opportunities, a lack of connection by health actors to climate change processes and a lack of capacity to prepare country proposals. A review of public health systems in 34 countries found that only slightly more than half considered climate change impacts and adaptation needs (Berry et al., 2018).

Given the key health risks identified in this chapter, adaptation that increases resilience requires sustained, adaptive management (Ebi, 2011);(Hess et al., 2012) with the goal of transformative change. This includes differentiating adaptation to climate variability from adaptation to climate change (Ebi and Hess, 2020). Health adaptation efforts are increasingly aiming to transition to building climate-resilient and environmentally sustainable health systems (WHO, 2015b);(WHO, 2020a) and healthcare facilities, emphasizing service delivery, including climate-informed health policies and programs, management of the environmental determinants of health; emergency preparedness and management; and health information systems, including health and climate research, integrated risk monitoring and early warning systems, and vulnerability, capacity, and adaptation assessments (Marinucci et al., 2014);(Mousavi et al., 2020);(Organization, 2015);(CDC, 2019);(Organization, 2020). Previous and current projects funded by a range of groups, such as bilateral and multilateral development partners, include addressing key enabling conditions (e.g., leadership and governance) and developing the capacity of the health workforce to manage and govern changing risks. Because the health risks of climate change often vary within a country, sub-national assessments and plans are needed to help local authorities protect and promote population health in a changing climate (Aracena et al., 2021);(Basel et al., 2020);(Schramm et al., 2020a).

7.4.2.2 Adaptation in health policies and programs

Health policies were historically not designed or implemented taking into consideration the risks of climate change and as currently structured are likely insufficient to manage the changing health burdens in coming decades (very high confidence). The magnitude and pattern of future health burdens attributable to climate change, at least until mid-century, will be determined primarily by adaptation and development choices. Current and future emissions will play an increasing role in determining attributable burdens after mid-century. Increased investment in strengthening general health systems, along with targeted investments to enhance protection against specific climate-sensitive exposures (e.g., hazard early warning and response systems, and integrated vector control programs for vector-borne diseases) will increase resilience, if implemented to at least keep pace with climate change (*high confidence*). Investments to address the social determinants of health can reduce inequities and increase resilience (*high confidence).* (Thornton et al., 2016) ; (Marmot et al., 2020) (Wallace et al., 2015 measured as health, aging, retirement, are predictors of mortality and disability, with cross-country differences.) (Semenza and Paz, 2021)

Peer-reviewed publications of health adaptation to climate change in low- and middle-income countries have typically focused on flooding, rainfall, drought, and extreme heat, through improving community resilience, disaster risk reduction, and policy, governance, and finance (Berrang-Ford et al., 2021);(Scheelbeek et al., 2021). Health outcomes of successful adaptation have included reductions in infectious disease incidence, improved access to water and sanitation, and improved food security. Figure 7.14 shows a Sankey diagram of climate hazards, adaptation responses, and health outcomes, where CSA is climate-smart agriculture. The figure highlights the range of health adaptation responses that are discussed in more detail earlier in this chapter and demonstrates the potential health benefit of adaptation efforts that affect a broad range of health determinants.

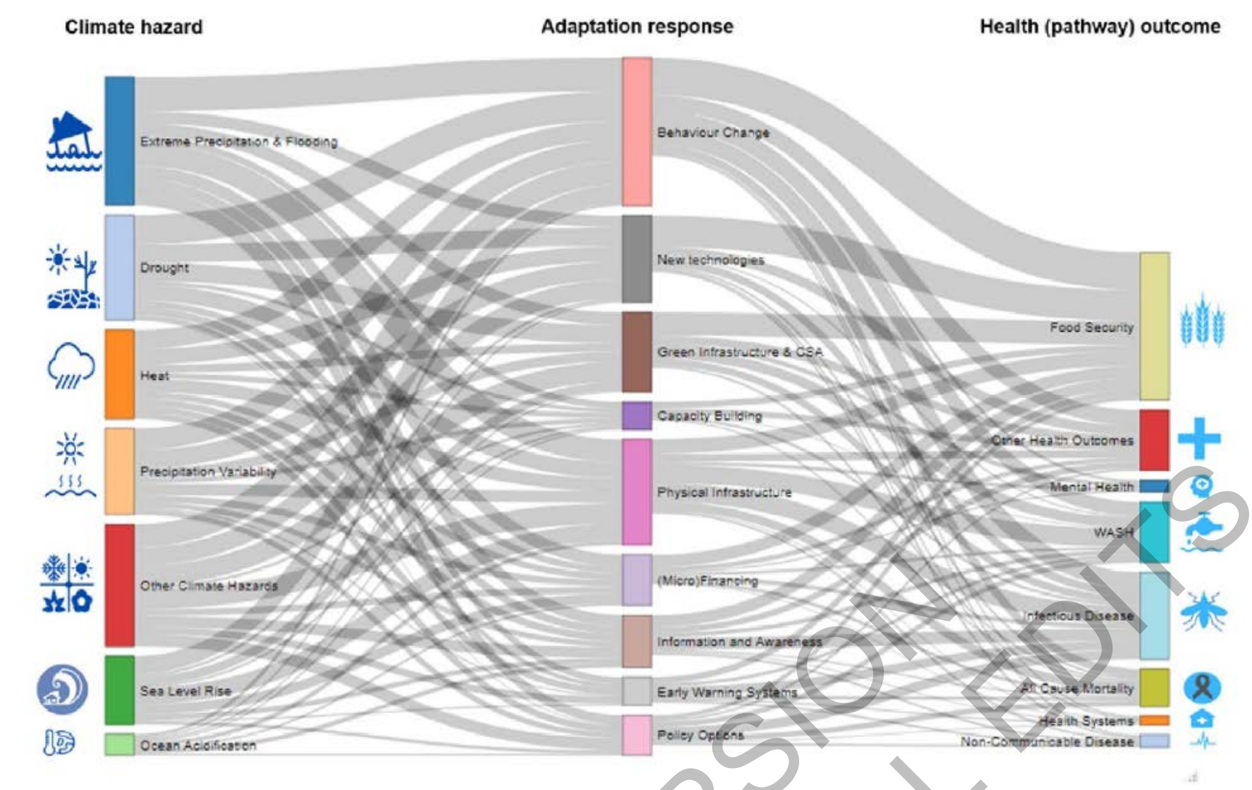


Figure 7.14: Sankey diagram of climate hazards, adaptation responses, and health outcomes. CSA is climate-smart agriculture. Source: Scheelbeek et al. 2021 (Scheelbeek et al., 2021).

Questions of the feasibility and effectiveness of health adaptation options differ from those in other sectors because public health is a societal enterprise that cuts across many different spheres of society. Consequently, there are dependencies that lie outside the jurisdiction of the health sector. All the health risks of a changing climate currently cause adverse outcomes, with policies and programs implemented in at least some health programs in some places. Policies and programs are continuously modified to increase effectiveness; this should accelerate in a changing climate. Improvements are needed as more is understood about disease aetiology, changing socioeconomic and environmental conditions, obstacles to uptake, and other factors.

A feasibility and effectiveness assessment was conducted of six adaptation strategies often used and recommended by the UN to respond to malnutrition risks, combining a literature review and expert judgment assessment of 80 peer-reviewed studies (UNSCN 2010; Tirado et al 2013; methods adapted from de Coninck et al. (2018) and Singh et al (2020). Nineteen indicators of six dimensions of feasibility (economic, technical, social, institutional, environmental, and geophysical) were considered. The lead time to initiate and expected longevity of each option were examined. Feasibility was defined as how significant the reported barriers were to implement a particular adaptation option. Highly feasible options were those where no or very few barriers were reported. Moderately feasible were those where barriers existed but did not have a strong negative effect on the adaptation option (or evidence was mixed). Low feasibility options had multiple barriers reported that could block implementation. Effectiveness ratings were based on expert consultation and reflected the potential of the adaptation option to reduce risk. The final effectiveness and feasibility scores were categorized as high, medium, or low, and reflect the combined results of all studies for a given adaptation option (Table 7.3). The assessed studies and categorizations are included as Supplementary Materials for this chapter.

Table 7.3: Feasibility and effectiveness assessments of multisectoral adaptation for food security and nutrition

Climate change impacts on food security and nutrition	Adaptation option	Evidence	Agreement	Feasibility Dimensions						Effectiveness	Enablers			
				Eco	Tec	Inst	Soc	Env	Geo		Women empowerment	Education	HDP Nexus	Rights-based approach & good governance
KEY RISK: Malnutrition in all its forms linked to decline in food availability and increased cost of healthy food	Climate-resilient, nutrition-sensitive and agroecological food production	Robust	High	M	M	H	L	H	H	Moderate	HR	HR	HR	HR
	Sustainable and healthy diets (local, equitable, diverse)	Robust	High	H	H	H	M	H	L	High	HR	HR	LR	LR
	Access to health, nutrition services and healthy environments (Water and sanitation)	Medium	High	M	M	M	H	M	L	Moderate	HR	HR	MR	HR
	Early warning systems to prevent adverse effects on nutrition	Robust	Medium	H	M	M	H	H	L	High	LR	HR	HR	LR
	Nutrition-sensitive social protection	Robust	High	H	H	L	L	H	H	High	HR	HR	MR	HR
	Nutrition-sensitive risk reduction, risk sharing and insurance	Medium	Low	L	H	L	H	H	NA	Low	MR	MR	LR	MR

Table Notes:
Abbreviations: Ec: Economic; Tec: Technical; Inst: Institutional; Soc: Socio-cultural; Env: Environmental; Geo: Geophysical. HR: high relevance, MR: medium relevance, LR: low relevance. NA = Not applicable/insufficient evidence

Policies and programs for climate-sensitive health outcomes are only beginning to incorporate the challenges and opportunities of climate change, although this is critical for increasing resilience. The fundamentals of many policies and programs in a changing climate will remain the same: implementing infectious disease control programs, preventing heat-related mortality and morbidity, and reducing the burden of other climate-related health endpoints, but activities will need to explicitly account for climate change to continue to protect health. Even with such attention to climate change, regrettably, there are limits to the feasibility and effectiveness of health adaptation options for some of these programs. For example, there are limits to adaptation to extreme heat, controlling emerging infectious diseases, and controlling cascading risk pathways.

As discussed in Chapter 1.4.2 and Chapter 1.5, an adaptation option is feasible when it is capable of being implemented by one or more relevant actors. In the health sector, the World Health Organization, UNICEF, and other organizations provide technical expertise to Ministries of Health, who then provide national to local healthcare and public health services. Generally, the question is less of overall feasibility, given the range of potential adaptation options that have yet to be fully explored and implemented, but more of readiness to buy-in to the adaptation efforts required from health and other sectors. In specific contexts, feasibility also depends on governance capacity, financial capacity, public opinion, and the distribution of political and economic power (Chapter 17). In other words, adaptation to climate change health impacts is broadly feasible with adequate investment and engagement, although this has yet to materialize, and in specific contexts, feasibility is contingent and time-varying and needs to be assessed at national to sub-national scales. For example, a scoping review in the Pacific region noted the following areas where further and significant investment and support are needed to increase feasibility of climate and health action: i) health workforce capacity development; ii) enhanced surveillance and monitoring systems; and iii) research to address priorities and their subsequent translation into practice and policy (Bowen et al., 2021). Vulnerability, adaptation, and capacity assessments include consideration of the feasibility and effectiveness of priority health adaptation options and can help decision makers identify strategies for enhancing adaptation feasibility in specific contexts.

7.4.2.3 Adaptation options for vector-borne, food-borne, and water-borne diseases

Integrated vector control approaches are crucial to effectively manage the geographic spread, distribution, and transmission of vector-borne diseases associated with climate change (high confidence). Some of the projected risks of climate change on VBD can be offset through enhanced commitment to existing approaches to integrated case management and integrated vector control management (Cissé et al., 2018);(Confalonieri et al., 2017);(Semenza and Paz, 2021). Important components include enhanced disease surveillance and early warning and response systems that can identify potential outbreaks at sub-seasonal to decadal time scales (J. and R., 2020);(Semenza and Zeller, 2014)(Table 7.4). In many cases, the exposure dynamics of VBD are strongly influenced by socio-economic dynamics that should be considered when developing and deploying adaptation options (UNEP, 2018). This is especially the case in low-income countries. For example, insufficient access to sanitation and presence of standing water are important determinants of the presence of *Ae. aegypti* populations and pathogens that cause visceral leishmaniasis (*L. donovani* and *L. infantum*) in urban and peri-urban areas; and low housing quality and lack of refuse management are associated with higher rodent infestation. Strategies expected to have important health co-benefits include those that support health systems strengthening; improve access to health coverage; increase awareness and education; and address underlying conditions of uneven development and lack of adequate housing and access to water and sanitation systems in areas endemic to mosquito-borne diseases (Semenza and Paz, 2021); Cross-Chapter Box ILLNESS in Chapter 2).

Adaptation options for climate-related risks for water-borne and food-borne diseases are strongly associated with wider, multi-sectoral initiatives to improve sustainable development in low-income communities (high confidence). Effective measures include improving access to potable water and reducing exposure of water and sanitation systems to flooding and extreme weather events (Brubacher et al., 2020);(Cisse, 2019) (Table 7.4). This requires focusing on farm-level interventions that limit the spread of pathogens into adjacent waterways, preventing the ongoing contamination of water and sanitation systems, and the promotion of food-safe human behaviours (Levy et al., 2018);(Nichols et al., 2018). It is also important to implement well-targeted and integrated WASH interventions, including at schools and ensuring proper disposal of excreta and wastewater. Cities can integrate regional climate projections into their engineering models, to produce lower-risk source waters, to increase the resilience of water and sanitation technologies and management systems under a range of climate scenarios. Technologies can help abstract source waters from depth, introduce or increase secondary booster disinfection, design or modify systems to reduce residence times within pipes, and/or coat exposed pipes (Levy et al., 2018). Other efficient interventions include source water protection, promoting water filtration, testing the presence of waterborne pathogens in shellfish, trade restrictions and improvement of hygiene at all levels (Semenza and Paz, 2021). Needed actions include early warning and response systems, strengthening the resilience of communities and health systems, and promoting water safety plans and sanitation safety plans (Brubacher et al., 2020);(Cisse, 2019);(Ford and Hamner, 2018);(Lake and Barker, 2018);(Levy et al., 2018);(Nichols et al., 2018);(Organization and Association, 2009);(Organization, 2016);(Organization, 2018b);(Semenza, 2021);(Rocklöv et al., 2021).

.

Table 7.4: Summary of adaptation options for key risks associated with climate-sensitive vector-, water- and food-borne diseases

Key risk	Geographic region(s) at higher risk	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with high potential for reducing risk	Selected key references
Vector-borne diseases	Global	Increase in the incidence of some vector-borne diseases such as malaria, dengue, and other mosquito-borne diseases, in endemic areas and in new risk areas (e.g., cities, mountains, northern hemisphere)	Increased climatic suitability for transmission (e.g., enhanced vectorial capacity through a temperature shift)	Large increases in human exposure to vectors driven by growth in human and vector populations, globalization, population mobility, and urbanization	Few effective vaccines, weak health systems, ineffective personal and household protections, susceptibility to disease, poverty, poor hygiene conditions, insecticide resistance, behavioral factors	Improved housing, better sanitation conditions and self-protection awareness. Insecticide treated bednets and indoor spraying of insecticide. Broader access to healthcare for the most vulnerable. Establishment of disease surveillance and early warning systems for vector-borne diseases. Cross-border joint control of outbreaks. Effective vector control. Targeted efforts to develop vaccines.	(Cissé et al., 2018);(Semenza, 2021);(J. and R., 2020)
Water-borne diseases	Mostly low- and middle-income countries (Africa and Asia); small islands; global for *Vibrios*	Increase in the occurrence and intensity of waterborne diseases such as *Vibrios* (particularly *V. cholerae*), diarrheal diseases, other water-borne gastro-intestinal illnesses	Substantial changes in temperature and precipitation patterns, increased frequency and intensity of extreme weather events (e.g., droughts, storms, floods), ocean warming and acidification	Large increases in exposure, particularly in areas with poor sanitation, flood-prone areas, and favourable ecological environments for waterborne disease pathogens	Poor hygiene conditions, lack of clean drinking water and safe food, flood and drought prone areas, vulnerabilities of water and sanitation systems	Improved water, sanitation and hygiene conditions and better surveillance system. Improved personal drinking and eating habits, behaviour change	(Brubacher et al., 2020);(Ford and Hamner, 2018);(Lake, 2018);(Levy et al., 2018);(Nichols et al., 2018);(Rocklöv et al., 2021)
Food-borne diseases	Global	Increase in the occurrence and intensity of foodborne diseases such as *Salmonella* and *Campylobacter,*	Substantial changes in temperature and precipitation patterns, increased frequency and intensity of	Large increases in exposure, particularly in areas with poor sanitation, flood-prone areas and favourable ecological	Poor hygiene conditions; lack of clean drinking water and safe food; flood and drought prone areas. Vulnerabilities in water and sanitation systems, food storage	Improved water, sanitation and hygiene conditions and better surveillance system. Improved personal drinking and eating habits, behaviour change. Improved food storage, food	(Brubacher et al., 2020);(Ford and Hamner, 2018);(Lake, 2018);(Levy et al., 2018);(Nichols et

		including in high-income countries	extreme weather events (e.g., droughts, storms, floods), ocean warming and acidification	environment for foodborne disease pathogens	systems, food processes, food preservation, and cold chain/storage	processing, food preservation, cold chain/storage	al., 2018);(Rocklöv et al., 2021)

7.4.2.4 Adaptation options for heat-related morbidity and mortality

Adaptations options for heat refer to strategies implemented at short time scales such as air conditioning and heat action plans, including heat warning systems and longer-term solutions such as urban design and planning and nature -based solutions (Table 7.5).

To date, air conditioning is the main adaptation approach for mitigating the health effects of high temperatures, especially in relation to cardiorespiratory health (Madureira et al., 2021). However, air conditioning may constitute a maladaptation because of its high demands on energy and associated heat emissions, especially in high-density cities (Eriksen et al., 2021);(Magnan et al., 2016);(Schipper, 2020) and also lead to 'heat inequities' as this is not an affordable or practical option for many (Jay et al., 2021);(Turek-Hankins et al., 2021). Heat action plans (HAP) link weather forecasts with alert and communication systems and response activities, including public cooling centres, enhanced heat-related disease surveillance, and a range of individual actions designed to reduce the health effects of extreme heat events such as seeking shade and altering the pattern of work (McGregor et al., 2015). While well designed and operationalisable HAPs possess the potential to reduce the likelihood of mortality from extreme heat events (*medium confidence*) (Benmarhnia et al., 2016);(Heo et al., 2019b);(Martinez-Solanas and Basagana, 2019);(Martinez et al., 2019);(De'Donato et al., 2018);, full process and outcome based evaluations of HAPs and their constituent components are lacking, (Boeckmann and Rohn, 2014);(Chiabai et al., 2018b);(Boeckmann and Rohn, 2014);(Nitschke et al., 2016; Diaz et al., 2019);(Benmarhnia et al., 2016);(Heo et al., 2019a), (Heo et al., 2019b)); (Ragettli and Roosli, 2019). Evaluations of heatwave early warning systems as a component within HAPs show inconsistent results in terms of their impact on predicting mortality rates (Nitschke et al., 2016);(Benmarhnia et al., 2016);(Heo et al., 2019a), (Heo et al., 2019b)); (Ragettli and Roosli, 2019);(Martinez et al., 2019);(De'Donato et al., 2018);{;(Weinberger et al., 2018b), indicating climate-based heat warning systems, which use a range of heat stress metrics (Schwingshackl et al., 2021), are not sufficient as a stand-alone approach to heat risk management (*high confidence*). To support HAP and heat risk related policy development, identification and mapping of heat vulnerability 'hot spots' within urban areas have been proposed (Chen et al., 2019); (Hatvani-Kovacs et al., 2018)

A multi-sectoral approach, including the engagement of a range of stakeholders will likely benefit the response to longer term heat risks, through implementation of measures such as climate sensitive urban design and planning that mitigates urban heat island effects (high confidence). (Ebi, 2019), (Jay et al., 2021);(Alexander et al., 2016);;(Levy, 2016);(Masson et al., 2018);(McEvoy, 2019);(Pisello et al., 2018). In the shorter-term, potentially localized solutions can include awnings, louvers, directional reflective materials, altering roof albedo), mist sprays, evaporative materials, green roofs and building facades and cooling centres (Jay et al., 2021);(Macintyre and Heaviside, 2019);(Spentzou et al., 2021);(Takebayashi, 2018). Nature-based solutions (NbS) to reduce heat that offer co-benefits for ecological systems include green and blue infrastructure (e.g., urban greening/forestry and the creation of water bodies) (Koc et al., 2018);(Lai et al., 2019);(Shooshtarian et al., 2018);(Ulpiani, 2019);(Zuvela-Aloise et al., 2016), (Hobbie and Grimm, 2020). The implementation of climate-sensitive design and planning can be constrained by governance issues;(Jim et al., 2018) and the benefits are not always evenly distributed among residents. Implementation of climate-sensitive design and NbS does, however, need to be carried out within the context of wider public health planning because water bodies and moist vegetated surfaces provide suitable habitats for a range of disease vectors;(Nasir et al., 2017);(Tian et al., 2016);(Trewin et al., 2020). Solutions recommended for managing exposure to heat in outdoor workers include improved basic protection (including shade, planned rest breaks), heat-appropriate personal protective equipment, work scheduling for cooler times of the day, heat acclimation, improved aerobic fitness, access to sufficient cold drinking water, and on-site cooling facilities and mechanisation of work (Morabito et al., 2021);(Morris et al., 2020);(Varghese et al., 2020);(Williams et al., 2020).

Most adaptation options were developed in high- and middle-income countries, and typically require significant financial resources for their planning and implementation. Studies are needed of the benefits of Indigenous and non-Western approaches to managing and adapting to extreme heat risk. Recently published reviews of approaches to heat adaptation outline the nature and limitations of a range of cooling strategies with optimal solutions for a number of settings recommended (Jay et al., 2021);(Turek-Hankins et al., 2021).

Table 7.5: Summary of adaptation options for key health risks associated with heat.

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with high potential for reducing risk	Selected key references
Heat-related mortality and morbidity and mental illness	Global but especially where temperature extremes beyond physical and mental health and thermal comfort threshold levels are expected to increase	Substantial increase in heat-related mortality and morbidity rates, especially in urban centres (heat island effect) and rural areas (outside workers), outdoors in general (sports and related activities) and for people suffering from obesity, weak cardiovascular capacity /physical fitness. Increased risk of respiratory diseases and cardiovascular diseases (CVD) mortality. Loss of economic productivity. Substantial increase in mental illness compared to base rate.	Substantial increase in frequency and duration of extreme heat events, especially in cities where heat will be exacerbated by urban heat island effects. Unintended increases in urban temperatures from anthropogenic heat (vehicles, air conditioning, urban metabolism) Increased number of days with high temperatures in non-urban settings such as agricultural areas.	Large increases in urban heat and population heat exposure driven by demographic change (e.g., aging) and increasing urbanization. Exposure will increase amongst agricultural and construction workers	Mortality/morbidity: Increases in the number of very young and elderly, and of those with other health conditions such as lack of physical fitness, obesity, diabetes and associated comorbidities, lack of adaptation capacity Mental illness: Lack of air conditioning. Lack of access to health care systems and services	Heat warning systems. Improved building and urban design (including green and blue infrastructure), passive cooling systems acknowledging that not all will have access to air conditioning. Broader understanding of heat hazard and better access to public health systems for the most vulnerable. Application where possible of renewable energy sources. Communication around drinking, availability of clean water, via simple effective water purification systems in low water quality settings, and water spray cooling. Mental health support.	(Benmarhnia et al., 2016);(Chen et al., 2019); (Jay et al., 2021);(Heo et al., 2019b);(Martinez-Solanas and Basagana, 2019);(Morabito et al., 2021);(Schwingshackl et al., 2021)

7.4.2.5 Adaptation options for air pollution

As noted in 7.3.1.6, air pollution projections indicate ambitious emission reduction scenarios or stabilisation of global temperature change at 2ºC or below would yield substantial co-benefits for air quality-related health outcomes. Improvements in air quality could be achieved by the deliberate adoption of a range of adaptation options to complement mitigation measures such as decarbonisation (e.g. renewable energy, fuel switching, energy efficiency gains, carbon capture storage and utilization) and negative emissions technologies (e.g. bioenergy carbon capture and storage, soil carbon sequestration, afforestation and reforestation, wetland construction and restoration).

Adaptation options for air pollution include implementing ozone precursor emission control programmes, developing mass transit/efficient public transport systems in large cities, encouraging car-pooling and cycling and walking (active transport), traffic congestion charges, low emission zones in cities and integrated urban planning, implementing NbS such as the green infrastructure for pollutant interception and removal, managing wildfire risk regionally and across jurisdictional boundaries, developing air quality warning systems, altering activity on high pollution days, effective air pollution risk communication and education, wearing protective equipment such as face masks, avoiding solid fuels for cooking and indoor heating, ventilating and isolating cooking areas, and using portable air cleaners fitted with high-efficiency particulate air filters (Abhijith et al., 2017);(Carlsten et al., 2020);(Cromar et al., 2020);(Ding et al., 2021);(Holman et al., 2015);(Jennings et al., 2021);(Kelly et al., 2021);(Kumar et al., 2019);(Masselot et al., 2019);(Ng et al., 2021);(Riley, 2021);(Voordeckers et al., 2021);(Xu et al., 2017)(Table 7.6). While the range of air pollution adaptation options is potentially extensive, barriers may need to be overcome to achieve successful implementation, including financial, institution, political/inter- and intra-governmental and social barriers (Barnes et al., 2014);(Ekstrom and Bedsworth, 2018);(Fogg-Rogers et al., 2021);(Schumacher and Shandas, 2019).

Table 7.6: Summary of adaptation options for key health risks associated with air pollution.

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with high potential for reducing risk	Selected key references
Air pollution related health	Global but especially in regions with existing poor air quality particularly in relation to particulate matter and ozone. Greatest climate change driven ozone related mortality is expected for East Asia and North America. For particulate matter the highest climate and air quality related mortalities are projected for India, the Middle East, Former Soviet Union and East Asia	Substantial increase in air pollution-related mortality and morbidity rates, especially in urban centres related to both severe pollution episodes and longer-term deterioration of air quality. People particularly vulnerable include those with respiratory tract infections and respiratory and cardiovascular disease. Increase in mental illness (depression) as a result of poor air quality and visibility.	Non-achievement of emission reduction targets. Substantial increase in frequency and duration of meteorological conditions conducive to the build-up of both primary and secondary air pollutants (e.g. greater frequency of calm atmospheric 'blocking' conditions) and no long term improvement in air quality at a range of geographical scales (global to the local). Increase in frequency and intensity of wildfires and dust storms. Increase in the	Large increases in exposure to air pollutants driven by demographic change (e.g., aging) and increasing urbanization. For arid regions increases in exposure to dust storms. Areas adjacent/downwind of major wildfires. For urban populations intensifying urban heat islands and enhanced formation of secondary pollutants	Increases in the number of very young and elderly, and those with respiratory or cardiovascular conditions and lack of adaptation capacity (e.g., reduce reliance on solid fuel for cooking/heating) Mental illness: Lack of access to health care systems and services	Air quality management policies, air quality warning systems, efficient and cheap mass transit systems, integrated urban planning, (including NBS and green infrastructure) Broader understanding of air pollution hazard and better access to public health systems for the most vulnerable. Application where possible of renewable energy sources to reduce emissions.	(Carlsten et al., 2020);(Doherty et al., 2017);(Jennings et al., 2021);(Kumar et al., 2019);(Orru et al., 2017; Orru et al., 2019) (Schumacher and Shandas, 2019);(Silva et al., 2017);(Voordeckers et al., 2021)

			intensity of urban heat islands especially in the summer and the occurrence of ozone episodes due to anomalously high urban temperatures.				

7.4.2.6 Multisectoral Adaptation for Nutrition

Adaptation to reduce the risk of malnutrition requires multi-sectoral, integrated approaches (very high confidence). Adaptation actions include access to healthy, affordable diverse diets from sustainable food systems *(high confidence)*; a combination of access to health -including maternal, child and reproductive health-, nutrition services, water and sanitation (*high confidence*); access to nutrition-sensitive and shock-responsive social protection (*high confidence*); early warning systems (*high agreement*), risk sharing, transfer, and risk reduction schemes such as insurance index-based weather insurance *(medium confidence)*. (Mbow et al., 2019);(Swinburn et al., 2019; UNICEF/WHO/WBG, 2019);(FAO et al., 2021);(Macdiarmid and Whybrow, 2019);(Liverpool-Tasie et al., 2021);(Fakhri, 2021). Common enablers across adaptation actions that enhance the effectiveness and feasibility of the adaptation include: education, women and girls' empowerment (*high confidence*), rights-based governance, and peace-building social cohesion initiatives such as the framework of the Humanitarian Development and Peace Nexus *(medium confidence).*

Nutrition-sensitive and integrated agroecological farming systems offer opportunities to increase dietary diversity at household levels while building local resilience to climate-related food insecurity (high confidence). (Bezner Kerr et al., 2021);(IPES-Food, 2020);(Altieri et al., 2015) especially when gender equity, racial equity, and social justice are integrated (Bezner Kerr et al., 2021). Adaptation responses include a combination of healthy, culturally appropriate, and sustainable food systems and diets, soil and water conservation, social protection schemes and safety nets, access to health services, nutrition-sensitive risk reduction, community-based development, women's empowerment, nutrition-smart investments, increased policy coherence, and institutional and cross-sectoral collaboration *(high agreement, medium evidence)* (FAO et al., 2018);(Mbow et al., 2019);(Pozza and Field, 2020);(FAO et al., 2021) (Table 7.7). Nutrition security can be enhanced through consideration of nutrient flows in food systems (Harder et al., 2021).This 'circular nutrient economy' perspective highlights the potential for adaptations throughout the food supply chain, including sustainable production practices that promote nutrient diversity and density, processing, storage, and distribution that conserves nutrition, equitable access and consumption of available, affordable, appropriate, and healthy foods, and waste management that supports nutrient recovery (Harder et al., 2021);(Boon and Anuga, 2020);(FAO et al., 2021);(Pozza and Field, 2020);(Ritchie et al., 2018). Traditional, Indigenous, and small-scale agroecology and regional food systems provide context-specific adaptations that promote food and nutrition security as well as principles of food sovereignty and food systems resilience (HLPE, 2020);(Bezner Kerr et al., 2021);(IPES-Food, 2020);(IPES-Food, 2018).

Adaptive social protection programs and mechanisms that can support food insecure households and individuals include cash transfers or public work programs, land reforms, and extension of credit and insurance services that reduce food insecurity and malnutrition during times of environmental stress (Carter and Janzen, 2018), (Johnson et al., 2013); (Alderman, 2016). For example, children from families participating in Ethiopia's Productive Safety Net Program experienced improved nutritional outcomes, partly due to better household food consumption patterns and reduced child labor (Porter and Goyal, 2016). School feeding programs improve nutritional outcomes, especially among girls, by promoting education, and by reducing child pregnancy and fertility rates (Bukvic and Owen, 2017). Adaptive social protection is most effective when it combines climate risk assessment with disaster risk reduction and wider socioeconomic development objectives (Davies et al., 2013).

Transformative approaches towards healthier, more sustainable, plant-based diets require integrated strategies, policies, and measures, including economic incentives for the agroecological production and equitable access to and consumption of more fruits, vegetables, and pulses, inclusion of sustainability criteria in dietary guidelines, labelling, public education programs and promoting collaboration, good governance, and policy coherence {Glover, 2019, Principles of innovation to build nutrition-sensitive food systems in South Asia

Table 7.7: Summary of adaptation options for key risks associated with malnutrition

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with high potential for reducing risk	Selected key references
Malnutrition due to decline in food availability and increased cost of healthy food	Global, with greater risks in Africa, South Asia, Southeast Asia, Latin America, Caribbean, Oceania	Substantial number of additional people at risk of hunger, stunting, and diet-related morbidity and mortality, including decreased mental health and cognitive function. Micro- and macronutrient deficiencies. Severe impacts on low-income populations from LIMICs. Risks especially high to groups that suffer greater inequality and marginalization.	Climate changes leading to reductions in crop, livestock, or fisheries yield, including temperature and precipitation changes and extremes, drought, and ocean warming and acidification	Large numbers of people in areas and markets particularly affected by climate impacts on food security and nutrition	High levels of inequality (including gender inequality), substantial numbers of people subject to poverty or violent conflict, in marginalized groups, or with low education levels. Slow economic development. Ineffective social protection systems, nutrition services, and health services.	Multi-sectoral approach to nutrition-sensitive adaptation and disaster risk reduction / management, including food, health, and social protection systems. Inclusive governance involving marginalized groups. Improved education for girls and women. Maternal and child health, water and sanitation, gender equality, climate services, social protection mechanisms.	(Glover and Poole, 2019);(Mbow et al., 2019);; (Swinburn et al., 2019)

7.4.2.7 Adaptation options for risks to mental health

Adaptation options for reducing mental health risks associated with extreme weather include preventive and post-event responses (high confidence). (Brown et al., 2017); {Cohen, 2019 #3534},(James et al., 2020) (Table 7.8). Responses include improving funding and access to mental health care, which is under-resourced (WHO, 2019); surveillance and monitoring of psychosocial impacts of extreme weather events; community-level planning for mental health as part of climate resilience planning (Clayton et al., 2017); and mental health and psychological first aid training for care providers and first responders (Hayes et al., 2018);(O'Donnell et al., 2021);(Hayes et al., 2018; Taylor, 2020);(Morgan et al., 2018);(Sijbrandij et al., 2020). Legislation can ensure access to services as well as establish a regulatory framework (Ayano, 2018). Advanced disaster risk planning reduces post-event mental health challenges. One example is from China, where pre-planning of temporary shelters resulted in significantly lower rates of anxiety, depression, and PTSD in the aftermath of flooding among displaced people who accessed them (Zhong et al., 2020). Key elements of successful initiatives include coordinated planning and action between key regional agencies and governments, with a focus on improving accountability and removing barriers to implementation and subsequent access to programs (Ali et al., 2020). As an example, following the 2019/2020 Australian bushfires, the federal government allocated funds to support mental health through free counselling for those affected, increased access to tele-health, extended hours for mental health services and programs designed specifically for youth (Newnham et al., 2020).

Because mental health is fundamentally intertwined with social and economic wellbeing, adaptation for climate-related mental health risks benefits from wider multi-sectoral initiatives to enhance wellbeing, with the potential for co-benefits to emerge (high confidence). Improvements in education, quality of housing, safety, and social protection support enhance general wellbeing and make individuals more resilient to climate risks (Lund et al., 2018);(Hayes et al., 2019). Among Indigenous Peoples, connections to traditional culture and to place are associated with health and wellbeing (Bourke et al., 2018) as well as with resilience to environmental change (Ford et al., 2020). As an example of the connection between infrastructure improvements and mental health, a study of domestic rainwater harvesting initiatives to promote household water security also improved mental health in participating households (Mercer and Hanrahan, 2017). Adaptive urban design that provides access to healthy natural spaces – an option for reducing risks associated with heat stress – also promotes social cohesion and mitigates mental health challenges *(high confidence)* (Buckley et al., 2019);(Clayton et al., 2017);(Jennings and Bamkole, 2019);(Liu et al., 2020b);(Mygind et al., 2019);(Marselle et al., 2020).

Table 7.8: Summary of adaptation options for key risks associated with mental health

Key Risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with high potential for reducing risk	Selected key references
Mental health impacts in response to floods, storms, and fires	Global; some areas at greater risk for storms, flooding, or wildfires	Substantial increase in mental illness compared to base rate	Increased frequency of major storms, weather-related flooding, or wildfires	Low-lying areas, dry areas, urban areas	Physical infrastructure that is vulnerable to extreme weather, inadequate emergency response and mental health services, social inequality	Improved urban infrastructure, warning systems, and post-disaster social support, improving funding and access to mental health care; improved surveillance and monitoring of mental health impacts of extreme weather events; climate change resilience planning in the mental health system (including at a community level); and mental health first aid training for care providers and first responders	(Ali et al., 2020);(Ayano, 2018);(Buckley et al., 2019);(Clayton et al., 2017);(Hayes et al., 2019);(James et al., 2020);(Sijbrandij et al., 2020)

7.4.2.8 Adaptation options to facilitate non-heat early warning and response systems

Early warning systems are a potentially valuable tool in adapting to climate-related risks associated with infectious diseases when based on forecasts with high skill and when there are effective responses within the time frame of the forecast (high confidence). Through advanced seasonal weather forecasting that draws upon established associations between weather/climate and infection/transmission conditions, conditions conducive to disease outbreaks can be identified months in advance, providing time to implement effective population health responses (Morin et al., 2018). Most current early warning systems are focused on malaria and dengue, but there are examples for other diseases, such as an early warning system developed for *Vibrios* monitoring in the Baltic Sea (Semenza et al., 2017). An early warning system for dengue outbreaks in Colombia based on temperature, precipitation, and humidity successfully detected 75% of all outbreaks between one and five months in advance, detecting 12.5% in the same month (Lee et al., 2017b). Dengue warning systems in Brazil, Malaysia, and Mexico have generated satisfactory results (Hussain-Alkhateeb et al., 2018). An effective early warning system for malaria was implemented in the Amhara region of Ethiopia (Merkord et al., 2017).

Early warning systems are effective at detecting and potentially reducing food security and nutrition risks (high confidence). Examples of proven systems include the USAID Famine Early Warning System, FAO's Global Information and Early Warning System, and WFP's Corporate Alert System. Such systems are fundamental for anticipating when a crisis might occur and setting priorities for interventions (Funk et al., 2019). Financial investments to develop early warning systems are cost-effective and reduce human suffering (Choularton and Krishnamurthy, 2019) (*high confidence*). For instance, during the 2017 drought-induced food crisis in Kenya, 500,000 fewer people required humanitarian assistance than would have been expected based on past experiences; this was largely due to timely and effective interventions triggered by the early warning (Funk et al., 2018).

Early warning systems have been established for other climate-sensitive health outcomes, such as respiratory diseases associated with air pollution (Shih et al., 2019);(Li and Zhu, 2018);(Yang and Wang, 2017). Early warning systems for non-heat extreme weather and climate events, such as storms and floods, are designed to protect human health and wellbeing; disaster risk management organizations and institutions typically communicate these warnings through their networks. Research is ongoing to extend the time period for warnings.

7.4.2.9 Incorporating Disaster Risk Reduction into Adaptation

Integrating health into national disaster risk management plans has wider benefits for resilience and adaptation to climate change risks (high confidence). (UNFCCC, 2017a);(Watts et al., 2019). Disaster risk reduction (DRR), including disaster preparedness, management and response, is widely recognized as important for reducing health consequences of climate-related hazards and extreme weather events (Keim, 2008);(Phalkey and Louis, 2016). A systematic review by Islam et al., (2020) identified multiple, ongoing challenges to integrating climate adaptation and DRR at global and national levels, including a lack of capacity among key actors and institutions, a lack of coordination and collaboration across scales of government, and general lack of funding – challenges that are particularly relevant for the health sector. Global events, including climate-related extreme events and public health emergencies of international concern (for example, Ebola, MERS and COVID-19) have influenced the development of national public health preparedness and response systems and attracted significant investment over the last two decades (Khan et al., 2015);(Murthy et al., 2017);(Watson et al., 2017). The Sendai Framework for Disaster Risk Reduction and the International Health Regulations establish important global and regional goals for increasing health system resilience, and reducing health impacts from biological hazards and extreme climate events (Aitsi-Selmi et al., 2015);(Maini et al., 2017);(UNFCCC, 2017b);(Wright et al., 2020). There are explicit links between the health aspect of the Sendai Framework and UN Sustainable Development Goals 1, 2, 3, 4, 6, 9, 11, 13, 14, 15 and 17 (Wright et al., 2020). More specifically, reducing the number of disaster-related deaths, illnesses and injuries, as well as damage to health facilities are key indicators for achieving the goals set out in the Sendai Framework (UNFCCC, 2017b).

The intersection of health and multisectoral disaster risk reduction and management, generally described as as Health Emergency and Disaster Risk Management (Health-EDRM), encompasses multisectoral approaches from, epidemic preparedness and response including the capacities for implementing the International Health Regulations (IHR, 2005), health systems strengthening and health systems resilience (Lo Iacono et al., 2017);(Organization, 2019);(Wright et al., 2020). Health-EDRM costs to governments are notably lower than the cost of inaction (Peters et al., 2019). Additional per capita costs in low-income countries have been estimated to range from 4.33 USD (capital) and 4.16 USD (annual recurrent costs), and in upper middle-income countries to an additional 1.35 USD in capital costs and 1.41 USD in extra annual recurrent costs (Peters et al., 2019). Adopting a Health-EDRM approach supports the systematic integration of health and multisectoral DRM to ensure a holistic approach to health risks and assists alignment of action in health security, climate change and sustainable development (Chan and Peijun, 2017);(Dar et al., 2014);(Organization, 2019);(Wright et al., 2020).

Climate-informed Health-EDRM is crucial for the climate resilience of health systems (Organization, 2015), particularly to account for additional risks and uncertainties associated with climate change and allow for well-planned, effective and appropriate DRM and adaptation (Watts et al., 2018a);(WHO, 2013);(Organization, 2015). Potential coherent approaches to addressing climate change and disaster risks to health include: strengthening health systems; vulnerability and risk assessments that incorporate disaster and climate change risk; building resilience of health systems and health infrastructure; and climate-informed EWSs (Banwell et al., 2018);(Phalkey and Louis, 2016). However, a review of DRR projects including climate change in South Asia found that the health sector was the least represented with only 2% of 371 projects relating to health (Mall et al., 2019) indicating a need to strengthen the incorporation of climate change in Health-EDRM. Current tracking under the Sendai Framework of Disaster Risk Reduction 2015-2030 shows that most countries (particularly low-income countries and lower-middle income countries) still lack robust systems for integrated risk monitoring and early warning (UNEP, 2018). The incorporation of disaster risk reduction and management strategies into climate adaptation for health and health systems at local scales is particularly important, given that it is at local scales where health services are most often delivered and where knowledge of specific needs and challenges is often greater (Amaratunga et al., 2018) (Schramm et al., 2020a). Indigenous knowledge has been shown to be valuable in disaster risk reduction, with particularly strong evidence existing for drought risk reduction in sub-Saharan Africa (Fummi et al., 2017; Muyambo et al., 2017) (Dube and Munsaka, 2018);(Macnight Ngwese et al., 2018). In the US, disaster risk reduction strategies that draw upon traditional knowledge and local expertise are being incorporated into climate adaptation planning for health in a number of Indigenous communities under the "Climate-ready Tribes Initiative" (Schramm et al., 2020b).

7.4.2.10 Monitoring, Evaluation and Learning

Monitoring, evaluation and learning (MEL) can assess the ability of nations and communities to prepare for and adequately respond to the health risks of climate change over time (high confidence). (Boyer et al., 2020). MEL describes a process that includes baseline assessment, prioritizing actions and activities, identifying key indicators to track, ongoing data collection, and periodically considering new information (Kruk et al 2015). MEL determines whether adaptation options achieved their goals and whether resources were used effectively and efficiently (Boyer et al., 2020). One of the challenges for MEL in the context of adaptation is that climate risks vary as a function of time, location, socio-economic development, demographics, and activities in other sectors (Ebi et al., 2018a). MEL indicators in the health sector need to account for factors related to governance, implementation, and learning as well as for exposures, impacts, and programmatic activities, all of which are context dependent and are often outside the health sector (Boyer et al., 2020);(Ebi et al., 2018a);(Fox et al., 2019).

No universal standardized approach exists for monitoring or evaluating adaptation activities in the health sector (high confidence). Candidate indicators of climate change health impacts and adaptation activity, typically at the national level, are available (Bowen and Ebi, 2017);(Cheng and Berry, 2013);(Kenney et al., 2016);(Navi et al., 2017);(Organization, 2015). Indicators are best grouped by category of activity, i.e., vulnerability, risk, and exposure; impacts; and adaptation and resilience (Ebi et al., 2018a). As health adaptation expands, enhanced monitoring will be needed to ensure that scientific advances are translated into policy and practice. A promising initiative that emerged since the AR5 is the *Lancet Countdown*, which represents a global effort at tracking various indicators of exposures, impacts, adaptation activities, finance, and media activity related to climate change and health (Watts et al., 2018a), although this effort is principally focused on monitoring and does not explicitly focus on evaluation adaptation efforts or learning from adaptation efforts.

Community-based monitoring of adaptation responses to health impacts, especially in Indigenous Peoples, has not been widely undertaken, despite its potential to improve monitoring of, and local adaptation to, environmental change (Kipp et al., 2019). The health sector has been particularly weak at recognizing climate impacts on and adaptation needs of Indigenous peoples and in engaging Indigenous Peoples in monitoring progress (Ford et al., 2018, (David-Chavez and Gavin, 2018); (Ramos-Castillo et al., 2017). Successful adaptation to the health impacts of climate change in Indigenous Peoples requires recognition of their rights to self-determination, focusing on Indigenous conceptualizations of wellbeing, prioritizing Indigenous knowledge, and understanding the broader agenda of decolonization, health, and human rights (*high confidence)* (Ford and King, 2015);(Green and Minchin, 2014);(Hoy et al., 2014);(Jones, 2019);(Jones et al., 2014);(Mugambiwa, 2018);(Nursey-Bray and Palmer, 2018).

Indicators should capture measures of processes that drive adaptation readiness, including leadership, institutional learning, and intersectoral collaboration (Boyer et al., 2020);(Ford and King, 2015), as well as outcome measures such as presence of programming known to reduce risks (Ebi et al., 2018a). Additionally, indicators related to scaling up of effective interventions, relying on implementation science frameworks are important (Damschroder et al., 2009);(Theobald et al., 2018 2020, Using Implementation Science For Health Adaptation: Opportunities For Pacific Island Countries);(Ebi et al., 2018a);(Fox et al., 2019). Measuring impacts attributable to climate change could be addressed with a combination of indicators related to overall health system performance and population vulnerability (Ebi et al., 2017);(Ebi et al., 2018a).

7.4.3 Enabling Conditions and Constraints for Health and Wellbeing Adaptation

7.4.3.1 Governance, Collaboration, and Coordination

Effective governance institutions, arrangements, funding, and mandates are key for adaptation to climate-related health risks (high confidence). Without integration and collaboration across sectors, health adaptation can become siloed, leading to less effective adaptation or even maladaptation (Magnan et al., 2016);(Fox et al., 2019). Integration and collaboration include working laterally across national government departments and agencies, as well as vertically, from national agencies to local governments, and with the private sector, academia, NGOs, and civil society. In this context, top-down policy design and implementation are complemented by bottom-up approaches that engage community actors in program design, and draw upon their local practices, perspectives, opinions, and experiences. Opportunities exist to better integrate public health into climate change discourse and policymaking processes and strengthen public health partnerships and collaborative opportunities (Awuor et al., 2020). Creating networks, integration across organizations and jointly developed policies can facilitate cross-sectoral collaboration (Bowen and Ebi, 2017).

7.4.3.2 Multisectoral Collaborations

Multisectoral collaborations aimed at strengthening the health sector can generate multiple co-benefits in other sectors (high agreement, medium evidence). Solutions for health and wellbeing risks described in 7.2 and 7.3 often have their origins in sectors that include water, sanitation, agriculture, food systems, social protection systems, energy, and key components of urban systems such as housing and employment (Organization, 2015);(Bowen et al., 2014b);(Machalaba et al., 2015);(Confalonieri et al., 2015);(Bowen et al., 2014a);(Semenza, 2021).Climate resilient development pursued in these other sectors, and in cooperation with the health sector, simultaneously increases the potential for adaptation and climate resilience in terms of health and wellbeing *(high confidence)* (Ahmad et al., 2017); (Watts et al., 2018b);(Levy and Patz, 2015);; (Organization, 2018b);(Chiabai et al., 2018a); (Dudley et al., 2015);(Zinsstag et al., 2018);(Sherpa et al., 2014).

7.4.3.3 Financial Constraints

Financial constraints are the most referenced barrier to health adaptation and so scaling up financial investments remains a key international priority (very high confidence). (Wheeler and Watts, 2018) (UNFCCC, 2017a). AR5 estimated the costs of adaptation in developing countries at between US$70 billion and US$100 billion annually in the year 2050, but these are likely to be a significant underestimate, particularly in the years 2030 and beyond (UNEP, 2014). National surveys conducted by the World Health Organization identified financial constraints as a major barrier to the implementation of health adaptation priorities (WHO, 2019);(Watts et al., 2021). Novel research drawing on global financial transaction data suggests that in 2019, global financial transactions with the potential to deliver adaptation in the health and healthcare sector reached US$18.4 billion, driven by transactions in high- and upper-middle income countries, with investment in Africa, South-East Asia, and the Eastern Mediterranean mostly stagnant (Watts et al., 2021).

There has been limited participation of the health sector in international climate financing mechanisms (Martinez and Berry, 2018). Of 149 projects listed in the Adaptation Fund database in October 2020, a large number were broad based initiatives that may have considerable indirect benefits for health systems, such as enhanced disaster preparedness and food security, but none were explicitly aimed at strengthening health systems or directed funds through ministries of health. A review of projects funded by the major multilateral climate funds showed that less than 1.5% of dispersed adaptation funding, and less than 0.5% of overall funding has been allocated to projects aimed at protecting health (WHO, 2015a).A survey of national public health organization representatives from a mix of low-, middle- and high-income countries found that a lack of political commitment, insufficient coordination across sectors, and inadequate funding for public health-specific adaptation initiatives were common barriers to building climate resilience (Marcus and Hanna, 2020). Under-investment in climate-specific initiatives in health systems coincides with persistent under-investment in health care more generally, especially in low- and middle-income countries (Schaferhoff et al., 2019).

Adaptation financing often does not reach places where the climate-sensitivity of the health sector is greatest (Weiler, 2019). Financial constraints in Africa are one of the key reasons for slow implementation of health adaptation measures (Nhamo and Muchuru, 2019). Strengthening health systems in vulnerable countries has the potential to reduce current and future economic costs related to environmental health risks, thus enabling reinvestment in the health system and sustainable development (WHO, 2020b);(Organization, 2015). Robust and comprehensive climate and health financing builds first on core health sector investments (Organization, 2015). Other potential opportunities for resource mobilization include health-specific funding mechanisms, climate change funding streams, and investments from multi-sectoral actions and actions in health-determining sectors (Organization, 2015). Incorporating climate change and health considerations into disaster reduction and management strategies could improve funding opportunities and increase potential funding streams (Aitsi-Selmi et al., 2015). Reinforcing cross-sectoral governance mechanisms maximizes health co-benefits and economic savings, by allowing for multisectoral costs and benefits to be comprehensively considered in decision-making (Belesova et al., 2016); (WHO, 2020b);(Organization, 2015). An additional financial need concerns health research, the existing funding for which does not match what is needed to support the implementation of the combined objectives of the UN 2030 Agenda for Sustainable Development, the Sendai Framework for Disaster Risk Reduction; and the Paris Agreement (Green and Minchin, 2014; Ebi, 2016);(Green et al., 2017)

7.4.3.4 Perceptions of Climate Change Risks and Links to Adaptation

Adaptation decisions and responses to climate change can be influenced by perceptions of risks, which are shaped by individuals' characteristics, knowledge, and experience (medium agreement, medium evidence). Institutional and governmental responses are critical for adapting to climate-related risks in health and other sectors, but individual responses also are relevant, such as choosing to implement adaptation measures. Individual responses are in turn affected not only by capabilities but also by perceptions that climate change is real and requires a response (Ogunbode et al., 2019). Perceptions of climate risks are formed by experiences of changes in local weather and extreme weather events (Sattler et al., 2018), (Sattler et al., 2020);(van der Linden, 2015),observations of environmental changes (Hornsey et al., 2016), experiences of and knowledge about climate change impacts (Ngo et al., 2020);(van der Linden, 2015), and individual characteristics such as values and worldviews (Poortinga et al., 2019) (*high agreement, medium evidence*). Risk perceptions include both logical assessments about the likelihood and severity of climate change impacts, and affective feelings about those impacts. On average, affective measures of risk perception are more strongly associated with disaster preparation than cognitive measures (Bamberg et al., 2017);(van Valkengoed and Steg, 2019).

In addition to perceptions of risk, the likelihood that an individual will implement behavioural adaptations, or support relevant public policy, is affected by subjective assessments of the response options (Bamberg et al., 2017); (van Valkengoed and Steg, 2019);(Akompab et al., 2013), (Carman and Zint, 2020);(Hornsey et al., 2016);(Brenkert-Smith et al., 2015).

Efficacy beliefs, social norms, and subjective resilience also affect adaptation behaviour (medium confidence), which has implications for communication about the need for climate adaptation. Efficacy beliefs represent the belief in one's ability to carry out particular action(s) and the belief that the action(s) will have the desired outcome. Belief that one is personally able to complete a behavior is moderately associated with engaging in disaster preparations (Navarro et al., 2021); (van Valkengoed and Steg, 2019) and with adaptation intentions (Burnham and Ma, 2017). *Collective efficacy*, the belief that a group of people working together can achieve a desired outcome, is important for participating in community adaptation behaviors (Bandura, 1982);(Chen, 2015);(Thaker et al., 2015). Related to this is *response efficacy*, a belief that a behavior will achieve its desired outcome, which is also moderately associated with engaging in disaster preparations (van Valkengoed and Steg, 2019). Collective efficacy can potentially be developed by strengthening communication networks and social ties within a community (Haas et al., 2021);(Jugert et al., 2016). Norms describing the adaptation strategies of others in a community, particularly those with high social status, can either facilitate or inhibit individual adaptation decisions (Neef et al., 2018);(Smith et al., 2021).

Distinct from efficacy beliefs, subjective resilience is a more general optimism or belief about one's ability (Jones, 2019);(Khanian et al., 2019). Subjective resilience (Clare et al., 2017) can influence preferred responses to climate change via assessment of one's ability to engage in specific response options. Identities can influence assessment of subjective resilience. Place attachment, having a strong emotional connection to a particular location, is weakly associated with disaster preparation (Brügger et al., 2015). In some cases, place attachment may inhibit adaptive responses, either by reducing perceptions of risk, or by making people reluctant to leave an area that is threatened (De Dominicis et al., 2015);(van Valkengoed and Steg, 2019). Place attachment can also contribute to enhanced community resilience (Khanian et al., 2019);(Jones, 2019);(Wang et al., 2021).

7.4.4 Migration and Adaptation in the Context of Climate Change

7.4.4.1 Linkages between Migration, Adaptation, Household Resilience

AR5 (Chapter 17 Human Security) concluded that migration is often, though not in all situations, a potential form of adaptation initiated by households. *Subsequent research indicates that the circumstances under which migration occurs, and the degree of agency under which household migration decisions are made, are important determinants of whether migration outcomes are successful in terms of advancing the wellbeing of the household and providing benefits to sending and receiving communities (high confidence).* (Adger et al., 2015);(Cattaneo et al., 2019); Cross-Chapter Box MIGRATE in Chapter 7]. Evidence from refugee studies and general migration research indicates that higher agency migration, in which migrants have mobility options, allows migrants greater opportunities for integrating into labour markets at the destination, makes it easier to remit money home, and generally creates conditions for potential for benefits for migrant households and for sending and receiving communities (Migration, 2019). Bilateral agreements that facilitate labour migration have been identified as being especially urgently needed for Pacific small island states (Weber, 2017).

Adaptive migration and the implied assumption that people can or should simply move out of harm's way is not a substitute for investment in adaptive capacity building (high agreement). (Bettini and Gioli, 2016). Climate-related migration, and especially involuntary displacement, often occurs only after *in situ* adaptation options have been exhausted and/or where government actions are inadequate (Adger et al., 2015);(Ocello et al., 2015); Cross-Chapter Box MIGRATE in Chapter 7). The threshold at which household adaptation transitions from *in situ* measures to migration is highly context specific and reflects the degree of exposure to specific climate risks, mobility options and the socio-economic circumstances of the household and the local community (McLeman, 2017);(Adams and Kay, 2019);(Semenza and Ebi, 2019) [also Cross-Chapter Box MIGRATE in Chapter 7]. A consistent theme in the research literature reviewed for all sections of this chapter is that proactive investments in health, social, and physical infrastructure, including those not aimed specifically at climate risks, build societal adaptive capacity and household resilience. In turn, expanding the range of adaptation options available to households and increases the likelihood that, when migration does occur, it does so under conditions of high agency that lead to greater chances of success. In communities where climate-related migration and/or relocation is occurring or may be likely to occur, policymaking and planning benefits from understanding the cultural, social and economic needs of exposed populations helps in the identification of responses and policies that build resilience (Adams and Kay, 2019).

7.4.4.2 Climate, Migration and linkages to Labour Markets and Social Networks

Adaptive climate-related migration is often closely related to wage-seeking labour migration (medium confidence). Because of the circumstances under which they move, climate-related migrants' destination and labour market choices, and the returns from migration, may be more heavily constrained than are those of other labour migrants (Jessoe et al., 2018);(Wrathall and Suckall, 2016).Within low- and middle-income countries, rural-urban migrant networks are important channels for remittances that may help build socio-economic resilience to climate hazards (Porst and Sakdapolrak, 2020), with higher levels of wage-seeking labour participation observed in climate-sensitive locales in South Asia (Maharjan et al., 2020). Local level research in China and South Asia shows, however, that the potential for remittances to generate improvements in household level adaptive capacity or resilience is highly context specific, has significant gender dimensions, and depends on such factors as the nature of the hazard, the distance migrated, and the length of time over which remittances are received (Banerjee et al., 2019a; Banerjee et al., 2019b). Social networks are a key asset in helping climate migrants overcome financial and structural impediments to their mobility, but these have their limits, particularly with respect to international migration (Semenza and Ebi, 2019). Since AR5, greater restrictions have emerged on movement between many low- and high-income countries (not including those necessitated by public health measures during the COVID-19 pandemic), a trend that, if it continues, would generate additional constraints on destination choices for future climate migrants (McLeman, 2019). Transnational diasporic connections are a potential asset for building resilience in migrant-sending communities highly exposed to climatic risks, with migrants' remittances potentially providing resources for long term resilience building, recovery from extreme events, and reducing income inequality (Bragg et al., 2018);(Mosuela et al., 2015);(Obokata and Veronis, 2018);(Shayegh, 2017);(Semenza and Ebi, 2019). Safe and orderly labour migration is consequently a potentially beneficial component of wider cross sectoral approaches to building adaptive capacity and supporting sustainable development in regions highly exposed to climate risks (McLeman, 2019).

7.4.4.3 Attitudes Toward Climate Migration

The success of climate-related migration as an adaptive response is shaped by how migrants are perceived and how policy discussions are framed (high agreement, medium evidence). The possibility that climate change may enlarge international migrant flows has in some policy discussions been interpreted as a potential threat to the security of destination countries (Sow et al., 2016);(Telford, 2018), but there is little empirical evidence in peer-reviewed literature assessed for this chapter of climate migrants posing significant threats to security at state or international levels. There is also an inconsistency between framing in some policy discussions of undocumented migration (climate-related and other forms) as being "illegal'' and the objectives of the Global Compact on Safe, Orderly and Regular Migration and the Global Compact on Refugees (McLeman, 2019). Although the Global Compact on Refugees explicitly avoids the inclusion of climate-related migrants as refugees, terms such as 'climate refugees' are common in popular media and some policy discussions (Høeg and Tulloch, 2018);(Wiegel et al., 2019). The framing of migration policy discussions is relevant, for example, in discussing climate adaptation options for Pacific Island Countries, where there is considerable disagreement over policy discussions that range from a 'migration-with dignity' approach that would liberalize labour migration in the Pacific region, to those that see migration as a last resort option to be avoided as much as possible (McNamara, 2015);(Farbotko and McMichael, 2019);(Oakes, 2019);(Remling, 2020). A more beneficial policy framing in terms of ensuring that future migration contributes to climate resilience and sustainable development has been established since AR5 within the framework of the Global Compact for Safe, Orderly and Regular Migration (see 7.4.7.7).

Attitudes of residents in migrant-receiving areas with respect to climate-related migration warrant consideration when formulating adaptation policy (medium confidence). Existing research is modest and difficult to generalize with respect to the impacts of climate-related migration and displacement on social dynamics and stability in receiving destinations, with outcomes being tied to attitudes and social acceptance of receiving communities and efforts to integrate migrant arrivals into the community (Koubi and Nguyen, 2020). Research from Kenya and Vietnam shows that residents of receiving communities view environmental drivers as being legitimate reasons for people to move, and are unlikely to stigmatize such migrants (Spilker et al., 2020). In these examples, urban residents viewed environmental motivations as being comparable to economic reasons for migrating, and did not see climate-related migrants as posing any particular risks for receiving communities. However, more research is needed to determine whether such findings are generalizable. Case studies from India suggest that a lack of recognition by local authorities of climatic factors as being legitimate drivers of rural-urban migration may lead to discrimination against migrants in terms of access to housing and other social protections, thereby undermining household resilience (Chu and Michael, 2018).

7.4.4.4 Planned Relocation and Managed Retreats

There is high agreement among existing studies that immobile populations often have high vulnerability and/or high long term exposure to climate hazards, and that non-climatic political, economic and social factors within countries may strongly constrain mobility (Zickgraf, 2019);(Ayeb-Karlsson et al., 2020);(Cundill et al., 2021). Section 7.2.6.2 highlighted the particular vulnerability of immobile populations in the face of growing climatic risks. However, research suggests governments should be slow to label such populations as being 'trapped' or to actively promote relocations in the absence of local agreement that *in situ* adaptation options have been exhausted (Adams, 2016);(Farbotko and McMichael, 2019). In the case of Indigenous settlements, efforts made to incorporate traditional knowledge in decision making and planning increase the potential for longer term success {Manrique, 2018, Climate-related displacements of coastal communities in the Arctic: Engaging traditional knowledge in adaptation strategies and policies}. Considerable health implications can potentially emerge within populations that are relocated as part of planned retreat and represent an important consideration for planners that requires greater research (Dannenberg et al., 2019). Organized relocations are not inherently transformative in their outcomes but, depending on the circumstances under which they occur and on how issues of equity and respect for the rights of those affected, are implemented, relocation could potentially be made transformative in a positive sense (Siders et al., 2021).

Disruptive and expensive relocations of low-lying coastal settlements in many regions would become increasingly necessary in coming decades under high levels of warming (high confidence). Organized relocations require long-term innovation, planning and cooperation on the part of governments, institutions, affected populations, and civil society (Hauer, 2017; Hino et al., 2017);(Haasnoot et al., 2021);(Moss et al., 2021). Recent examples illustrate the substantial financial costs of organized relocations, ranging from US$10,000 per person in examples from Fiji, to US$100,000 per person in coastal Louisiana, USA (Hino et al., 2017). Organized relocations are politically and emotionally charged, will not necessarily be undertaken autonomously by exposed populations, and are most successful when approached proactive and strategically to avoid increasing the socio-economic vulnerability of those who are relocated (Jamero et al., 2017), (Wilmsen and Webber, 2015);(Chapin et al., 2016);(McNamara et al., 2018);(Hauer et al., 2019);(Bertana, 2020). Key considerations for protecting the rights and wellbeing of people who might need to be resettled include proactive communication with and participation of the affected communities, availability of compensation, livelihood protection, and ensuring there is permanence and security of tenure at the relocation destination (Tadgell et al., 2018). Availability of funds for resettlement, how to manage relocation from communally owned lands, how to value privately owned land to be abandoned, and the potential for loss and damage claims are just some of the many potential complications (Marino, 2018);(McNamara et al., 2018). As a proactive option, researchers in Bangladesh have suggested the creation of "migrant-friendly towns" to provide options for autonomous relocation from hazardous areas (Khan and Huq, 2021).

7.4.5 Adaptation Solutions for Reducing Conflict Risks

There has been increased activity within the international community to understand and address climate-conflict linkages since AR5, with high level actions including the UN Climate Security Mechanism, launched in 2018, tasked with providing integrated climate risk assessments to the UN Security Council and other UN bodies, in partnership with UN and external actors (DPPA et al., 2020). G7 governments initiated an integrated agenda for resilience (Rüttinger et al., 2015) and the Berlin Call for Action in 2019 sought foreign policy as a platform to address climate security concerns focusing on risk-informed planning, enhanced capacity for action within the UN and improvements to operational response to climate security risks (Federal Foreign Office 2019). The non-peer-reviewed literature that currently addresses these policy dimensions is generated by a small number of consultancies funded by governments from the Global North and can lack diverse perspectives and priorities.

7.4.5.1 Environmental Cooperation and Peacebuilding

The environment can form the basis for active peacebuilding and a sustainable natural environment is important for ongoing peace (high agreement, medium evidence). Environmental peacebuilding (EP) is a framework increasingly utilised to understand the diverse ways in which the natural environment supports peace and can be utilised in peace building: preserving the natural environment such that degradation does not contribute to violence, protecting natural resources during conflict and using natural resources in post-conflict economic recovery (Kron, 2019). EP frames natural resources as facilitating peace rather than driving conflict (Dresse et al., 2019) with emerging literature analysing what this means in practice(Kovach and Conca, 2016);(Krampe, 2017);(Ide, 2019);(Ide et al., 2021);(Johnson, 2021);(Kalilou, 2021). There is emergent evidence for the success of these pathways. For example, a natural resource sharing agreement on the Kenya-Uganda border was able to reconcile spatial, logistical and conceptual barriers to addressing climate risks in development contexts (Abrahams, 2020). However, the long-term impacts of EP approaches on sustaining peace are yet to be monitored and evaluated (Ide and Tubi, 2020). EP may be successful depending on the context and the element of peace being built (Johnson, 2021) or undermine processes when environmental arguments are co-opted for geopolitical purposes (Barquet, 2015) or depoliticise conflict (Ide, 2020).

Formal institutional arrangements for natural resource management can contribute to transnational cooperation (high confidence) (See also Chapter 4). Evidence from the transboundary water sharing agreements provides evidence for cooperation rather than conflict over resources (Timmerman et al., 2017);(Timmerman, 2020);(Dinar et al., 2015). Transboundary water agreements and river basin organizations help build robust institutions that facilitate trust and relationship building that have benefits in other domains (strong agreement, medium evidence) (Dombrowsky, 2010);(Krampe and Gignoux, 2018) ;(Barquet et al., 2014) (Ide and Detges 2018). However, outcomes can be mixed as combining issues can stall progress and the international and top down nature of these approaches limits transferability to intra-state conflict at the local level (Rigi and Warner, 2020);(Ide et al., 2021);(Krampe et al., 2021).

7.4.5.2 Adaptation in Fragile Settings

Climate-resilient peace building has the potential to limit the impact of future climate change on peace efforts (medium confidence). Practical guidance has been developed, driven by policy concerns on climate-conflict links. The United Nations Environment Programme, the European Union and Adelphi have developed a toolkit for addressing climate fragility risks in peacebuilding, adaptation and livelihoods support (Programme et al., 2019)). Crawford et al (2015) provide recommendations for climate-resilient peacebuilding consistent with the UN Secretary-General's five peacebuilding principles, including integrating ex-combatants through the construction of climate resilient infrastructure, using climate impacts as a platform to engage previously conflicting groups, developing national disaster risk reduction and management strategies, and climate-proofing economic development activities. The United States Agency for International Development, in a report prepared for the Adaptation Thought Leadership and Assessments (ATLAS) program (Adelphi and Inc, 2020) drawing on resilience and peacebuilding programs in the Horn of Africa, recommend two critical conditions to ensure activities address compound climate fragility risks. Firstly, conducting local analyses of the links between climate, conflict, and fragility to identify specific risks to target; and secondly, ensuring long term commitment with a focus on participation and flexibility.

Conflict-sensitive adaptation that focuses on institutional frameworks, conflict management, and governance mechanisms has the potential to address complex interacting risks and emergencies over the long term (medium agreement, limited evidence). (Scheffran et al., 2012);(Matthew, 2018) (Okpara et al., 2018). However, most adaptation activities are planned and implemented under development or climate finance funds without systematic integration of conflict sensitivity, and National Adaptation strategies rarely and only implicitly address conflict and potential changes to power relations (Tänzler et al., 2019). Practitioners and policy researchers have attempted to address this gap by developing guidance and delivering training (e.g. (Tänzler et al., 2019);(Bob and Bronkhorst, 2014). However, there are real challenges relating to discounting indirect impacts on conflict and maladaptation (Asplund and Hjerpe, 2020) and risks of unintended, perverse outcomes (Mirumachi et al., 2020). Crawford and Church (2020) highlight the synergies between adaptation planning under the UNFCCC's National Adaptation Plan process and conflict reduction. Discussing development more broadly, Abrahams (2020) suggests three barriers to development that incorporate conflict-climate risks: geographically disconnected impacts and outcomes, the discourse of climate as a threat multiplier (rather than underlying peace), and teleconnected risks occurring at different scales. Effective approaches rely on understanding local power dynamics and social relations (Sovacool 2018; Roth et al. 2019, Sapiains et al 2021) (*high agreement, medium evidence*).

7.4.5.3 Gender-based Approaches toPpeacebuilding

Gender-based approaches provide novel underutilised pathways to achieving sustainable peace (high confidence, high evidence). Security council resolutions have encouraged the incorporation of gender analysis into peacebuilding, and research has shown that taking into account the gendered nature of networks and dialogues opens new avenues for cooperation and are conflict-sensitive (Dunn and Matthew, 2015), creating potential for women's rights and advocacy groups to be drivers of peace (Céspedes-Báez, 2018). For example, women are working to reduce climate vulnerability security risks in urban settings by entering local politics and joining community based organised and civil society networks (Kellog, 2020). The gendered nature of vulnerability and access to natural resources [see 4.6.4, 4.7.5.3, 5.4.2.3, 5.5.2.6, 5.8.2.2, Cross-Chapter Box GENDER in Chapter 18] will influence the efficacy of interventions to prevent conflict or to build durable peace (Pearse, 2017);(Chandra et al., 2017);(Fröhlich et al., 2018). However, this understanding has not so far resulted in widespread employment of gender-led analyses (Fröhlich and Gioli, 2015). However, this understanding has not so far resulted in widespread employment of gender-led analyses (Fröhlich and Gioli, 2015). This represents a key opportunity for expansion of the solution space for climate-related conflict. Analysis of peace processes (not confined to climate drivers) demonstrates the benefits of women's participation in peace processes for devising strategies for building peace (Paffenholz, 2018);(Cárdenas and Olivius, 2021) and for the durability of that peace (Shair-Rosenfield and Wood, 2017);(Krause et al., 2018).

7.4.6 Climate Resilient Development Pathways

Climate resilient development is a set of trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities, while promoting fair and equitable reductions of GHG emissions. Climate resilient development also serves to steer societies towards low-carbon, prosperous, and ecologically safer futures (WGII, Chapter 1). *All pathways to pursue climate resilient development will involve balancing complex synergies and trade-offs between development pathways and the options that underpin climate mitigation and adaptation (very high confidence; WGII, Chapter 18).* Pathways to climate resilient development can be pursued simultaneously with recovering from the COVID-19 pandemic (WHO Manifesto for a healthy recovery from COVID-19; Cross-Chapter Box COVID in Chapter 7, Ebi et al., 2021).

Meeting commitments against seven existing global priorities would facilitate climate resilient development pathways and transformational futures for health, wellbeing, conflict and migration (*high agreement, medium evidence*):

1. Fully implementing the World Health Organization (WHO) Operational Framework for building climate-resilient health systems (WHO, 2015b)
2. Achieving Universal Health Coverage (UHC) under SDG 3 (good health and wellbeing)
3. Achieving net zero GHG emissions from healthcare systems and services
4. Achieving the Sustainable Development Goals
5. Adopting mitigation policies and technologies that have significant health co-benefits (see Cross-Chapter Box, including energy systems, urban, infrastructure, societal)
6. Meeting the objectives of the Global Compact for Safe, Orderly, and Regular Migration
7. **7.** Inclusive and integrative approaches to climate resilient peace

These transformations map across all of the five system transitions identified in WGII Chapter 18 – energy systems; land, ocean, and ecosystems; urban and infrastructural systems; industrial systems, and societal systems.

7.4.7.1 Fully implementing the WHO Operational Framework

The WHO Operational Framework for building climate-resilient health systems was designed to increase the capacity of health systems and public health programming to protect health in an unstable and changing climate (WHO, 2015b). The guidance defines a climate resilient health system as *one that is capable to anticipate, respond to, cope with, recover from, and adapt to climate-related shocks and stress, so as to bring sustained improvements in population health, despite an unstable climate*. Full implementation of this framework has the potential to achieve transformational adaptation; the fundamental attributes of health system would change to anticipate and effectively manage the population health and healthcare risks of climate change. This includes having the knowledge, capacity, tools, and human and financial resources for health systems to extend beyond soft limits to adaptation.

The framework outlines 10 key components (Figure 7.15) that, when achieved, will:

- guide professionals working in health systems, and in health determining sectors (e.g. water and sanitation, food and agriculture, energy, urban planning) to understand and effectively prepare for the additional health risks posed by climate variability and change;
- identify the main health functions that need to be strengthened to build climate resilience, and to use these to develop comprehensive and practical plans (e.g., the health component of NAP (H-NAP)); and
- support health decision-makers to identify roles and responsibilities to implement this plan, for actors within and outside the formal health sector.

Achieving full implementation of the WHO Operational Framework requires determination and commitment – with associated funding – from the health community specifically, and health-determining sectors more generally. Identifying priority areas is an immediate step required to commence this implementation process, which will be different in different contexts. The active engagement with Communities of Practice to share lessons and experiences would be a useful approach to support national and sub-national efforts – many of these exist already (e.g., Climate Change Community of Practice in Canada, and the 'weADAPT' initiative under the auspices at Stockholm Environment Institute).

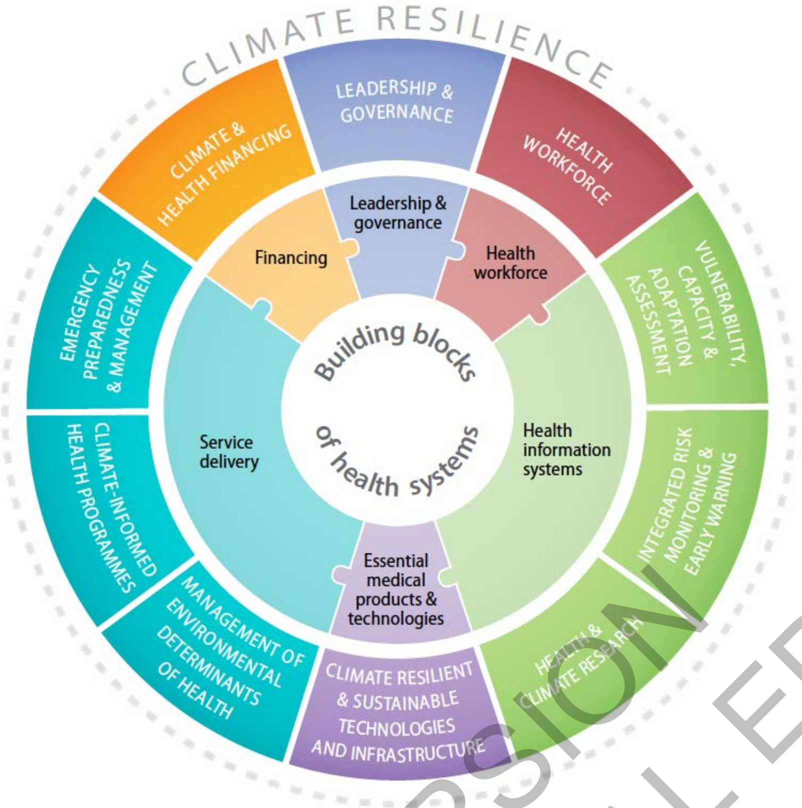


Figure 7.15: Ten components of the WHO operational framework for building climate resilient health systems, with links to the building blocks of health systems. Source (WHO, 2015b)

Table 7.9 summarizes selected characteristics of health systems under SSPs 1 (a world aiming to sustainable development), 2 (a world continuing current trends), and 3 (a world with high challenges to adaptation and mitigation). The table highlights the importance of investments that promote sustainable and resilient development, to decrease vulnerability no matter the magnitude and pattern of climate change. Adapting under SSP3 would be challenging even under pathways of limited additional climate change.

Table 7.9: Characteristics of health systems under SSPs 1, 2, and 3. Modified from Sellers and Ebi (2017) (Sellers and Ebi, 2017)

	SSP3	SSP2	SSP1
Basic characteristics	Reactive; failure to adapt; siloed information channels and national governance; limited partnerships	Incomplete planning; new information incorporated as convenient; occasional partnerships	Proactive; adaptively managed; frequent partnerships; interdisciplinary
Leadership and governance	Little focus at national and international levels on climate change and health; minimal planning conducted	Planning on climate change and health, but not comprehensive and often side-tracked on other issues	Strong climate change and health planning apparatus, including health components of national adaptation plans; regional / international partnerships
Health workforce	Climate change and health not rarely incorporated into training; few provisions for new training programs or funding for increase health worker positions in climate change-relevant specialties; health disparities not addressed	Climate change and health not systematically incorporated into training; new training programs insufficient to fill gaps in demand; limited attention to addressing health disparities	Systematic inclusion of climate change and health in worker training; expansion of funding and training; financing and incentive mechanisms to address health disparities

Health information systems	Assessments of vulnerability and adaptation rarely, if ever conducted; information not useful for planning; minimal risk monitoring or research	Vulnerability and adaptation assessments occasionally conducted, but generally of poor quality; early warnings incomplete; fiscal and political constraints on research	Vulnerability and adaptation assessments regularly conducted and used in planning; robust early warning networks; research agenda focused on vulnerable communities
Climate resilient and sustainable technologies and infrastructure	Facilities sited and constructed without climate consideration incorporated; medical supply chains no modified	Capital cost serves as key factor in siting and construction; increasing vulnerability of facilities to shocks	Health infrastructure designed to be robust to storms/floods, with redundant systems added to ensure continuity of care
Service delivery	Policies to manage environmental health hazards generally not followed; care practices not modified to accommodate climate information; few changes to emergency management procedures; health inequities worsen	Environmental health policies are not robust; marginal improvements in care practices; risk assessments and communication inadequate; no shift in health inequities	Policies to manage environmental health hazards regularly reviewed; practitioners review care practices and adjust as appropriate based on local climate and health conditions; robust communication tools developed; health service improvements reduce health inequities
Climate and health financing	Few funds devoted to climate change and health activities, particularly in low- and middle-income countries; few if any financing partnerships between high- and low- and middle-income countries; very weak regional and international coordinating bodies due to funding constraints	High-income countries generally form robust financing mechanisms; fiscal pressures in low- and middle-income countries constrain their financing abilities; financial partnerships formed across countries, but financing often not robust; regional and international coordinating bodies receive inadequate funds	Robust funding streams for climate change and health; climate change and health activities receive continuing financial support; effective financing partnerships; regional and international coordinating bodies effectively funded

Stress testing is an approach for evaluating the extent to which health systems are prepared for a future different from today (Ebi et al., 2018a). These desk-based exercises identify a desirable future outcome, such as successfully managing an extreme heatwave, flood, or storm with characteristics outside the range of recent experiences. The exercises move beyond identifying likely challenges from hazardous exposures to specifying policies and measures that could be successful under a different climate and development pathway. The exercises consider socioeconomic and political factors that can influence the extent of health system vulnerability and factors that can affect health system demands by impacting population health. Stress testing is designed to identify conditions under which it would be difficult for the health system to maintain its essential functions and to identify interventions that could maintain essential system functions despite climate-related shocks and stresses.

7.4.6.2 Achieving Universal Health Coverage Under SDG 3 (good health and wellbeing)

Universal Health Coverage (UHC) is when all people have access to the health services they need, when and where they need them, without financial hardship (WHO, 2021b). Achieving UHC is one of the targets in the SDGs. However, climate change is threatening to undermine the achievement of UHC through negative health outcomes and healthcare system disruptions (Salas and Jha, 2019);(Phillips et al., 2020);(Kadandale et al., 2020);(Roa et al., 2020). Climate change and UHC progress are closely linked to one another, as they both strive to improve health and achieve health equity (Salas and Jha, 2019). Supporting UHC is key to securing population health under a changing climate, as well as addressing structural inequalities (Roos et al., 2021);(Aleksandrova, 2020);(Phillips et al., 2020). Many regions of the world with the highest levels of vulnerability to the health impacts of climate change also have low levels of UHC; an integrated approach to

UHC planning that incorporates climate change will have great benefits particularly in improving health equity (Salas and Jha, 2019).

The COVID-19 pandemic has shown some countries taking positive steps to achieving UHC. For example, Ireland nationalized healthcare for the duration of the pandemic, and many countries including Australia have enhanced their telehealth services which has enabled specific groups to access health services, particularly those in rural and remote settings, and has allowed continuous care to the community (Monaghesh and Hajizadeh, 2020); see also Cross-Chapter Box COVID in Chapter 7).

7.4.6.3 Achieving Net Zero GHG Emissions from Healthcare Systems and Services

The health care system is a core component of UHC, supporting climate resilient and environmentally sustainable healthcare facilities (Corvalan et al., 2020). Health systems are large carbon polluters and have the potential to look beyond traditional 'green' initiatives towards more fundamental, longer-term redesign of current service models, with health practitioners participating actively in this process (Charlesworth and Jamieson, 2018). In the largest and most comprehensive accounting of national healthcare service emissions, the UK's National Health Service (NHS) quantified its health services' emissions and identified that 62% came from the supply chain, 24% from the direct delivery of case, 10% from staff commute and patient and visitor travel, and 4% from private health and care services commissioned by the NHS (Tennison et al., 2021).

The health sector has considerable opportunity to reduce its own carbon footprint, and by doing so would contribute to mitigation efforts, and help reduce health burdens associated with greenhouse gases emissions (Vidal et al., 2014);(Duane et al., 2019);(Charlesworth and Jamieson, 2019);(Charlesworth et al., 2018);(Guetter et al., 2018);(Bharara et al., 2018);(Frumkin, 2018)(high confidence). The UK's NHS National Health Service has committed to becoming the world's first net zero national healthcare system. Other examples of recent and ongoing initiatives include those undertaken by the Kaiser Permanente and the Gundersen Clinics in the US. Health Care without Harm, particularly across the Asia Pacific region; and the Green Hospital Initiative in New Delhi (Frumkin, 2018; Bharara et al, 2018).

7.4.6.4 Achieving the Sustainable Development Goals Would Increase Resilience in Health-determining Sectors and Contribute to Reducing the Risks of Involuntary Displacement and Conflict.

The Sustainable Development Goals (SDGs) are globally agreed objectives that integrate the economic, environmental, and social aspects of sustainable development, to end poverty, protect nature, and ensure that all people enjoy peace and prosperity. The SDGs were developed under the principle that the goals are integrated and indivisible, such that progress in one goal depends on progress in others (WHO, 2016a). Promoting health and wellbeing is not the sole responsibility of the health sector; it is also partially determined by strategies, policies, and options such as poverty reduction, promoting gender equality, ensuring all people enjoy peace and prosperity, eliminating nutritional insecurity, and ensuring availability and sustainable management of water and sanitation (Morton et al., 2019);(Bennett et al., 2020). Unique themes in the SDGs for health policy and systems research include social protection to protect and promote access to health services; stronger and more effective multisectoral collaborations beyond the health sector to address the upstream drivers of health and wellbeing; and participatory and accountable institutions to strengthen civic engagement and local accountability within health systems (Bennett et al. 2020).

For example, clean water, sanitation, and hygiene (WASH) are essential to human health and wellbeing. Unsafe water and sanitation and lack of hygiene caused an estimate 870,000 associated deaths in 2016 (WHO, 2021c). Only 71% of the global population have access to safely managed drinking water services; only 45% of the global population has access to safely managed sanitation services; and 60% had basic handwashing facilities in their home. About 25% of healthcare facilities lack basic water services, exposing workers and patients to higher infection risks. More than 80% of countries reported in 2018 that they lacked sufficient funding to meet national WASH targets. As detailed in 7.2.2.2, Box 7.3, 7.3.1.4, and 7.4.2.3, the burden of climate-sensitive waterborne diseases would be reduced if WASH targets were met.

The World Health Organization developed a Global Action Plan for Healthy Lives and Wellbeing for All that brings together multilateral health, development, and humanitarian agencies to support countries to accelerate progress towards the health-related SDGs (WHO, 2021c). Themes include sustainable financing to reduce unmet needs for services; community and civil society engagement to generate knowledge to inform policymaking and health responses; addressing the socio-environmental determinants of health; ensuring health and humanitarian services in fragile and vulnerable settings; research and development; and digital health. In 2020, enhanced collaboration through the Global Action Plan provided support for an equitable recovery from the COVID-19 pandemic in, for example, Lao People's Democratic Republic, Pakistan, Tajikistan, Somalia, South Sudan, Malawi, Nepal, and Columbia, highlighting the potential for multisectoral integration of economic, environmental, and social aspects of sustainable development to maintain essential health services and core public health functions during shocks and stresses (WHO, 2021a).

Meeting the SDGs also contributes toward reducing involuntary displacement and conflict, as assessed in sections 7.4.7.7 and 7.4.7.8.

7.4.6.6 Adopting Mitigation Policies and Technologies that have Significant Health Co-benefits)

Substantial benefits from climate action can result from investing in health, infrastructure, water and sanitation, clean energy, affordable healthy diets, low-carbon housing, clean public transport for all, improved air quality from transformative solutions across several economic sectors, and social protection. These benefits are in addition to the avoided health impacts associated with climate change. (see Cross-Chapter Box HEALTH in Chapter 7).

[START CROSS CHAPTER BOX HEALTH]

Cross-Chapter Box HEALTH: Co-benefits of Climate Actions for Human Health, Wellbeing and Equity

Authors: Cristina Tirado (Chapter 7 WGII); Robbert Biesbroek (Chapter 13); Mark Pelling (Chapter 6); Jeremy Hess (Chapter 7); Felix Creutzig (Chapter 5, WGIII); Rachel Bezner Kerr (Chapter 5); Siri Eriksen (Chapter 18); Diarmid Campbell-Lendrum (Chapter 7); Elisabeth Gilmore (Chapter 14); Maria Figueroa (Chapter 2, WGIII); Nathalie Hilmi (Chapter 18); Peter Newman (Chapter 10, WGIII); Sebastian Mirasgedis (Chapter 9, WGIII); Yamina Saheb (Chapter 9, WGIII); Gerardo Sanchez (Chapter 7); Pete Smith (Chapter 12, WGIII); Adrian Leip (Chapter 12, WGIII); Dhar Subash (Chapter 10, WGIII); Chris Tristos (Chapter 9); Mercedes Bustamante (Chapter 7; WGIII); Luisa Cabeza (Chapter 9, WGIII); Diana Urge-Vorsatz, (Chapter 8, WGIII),

Achieving the Paris Agreement and SDGs can result in low-carbon, healthy, resilient, and equitable societies with high-wellbeing for all (very high confidence). (Alfredsson et al., 2018);(O'Neill et al., 2018) {1.5 WGII} {5. WGIII}. Given the overlap in sources of GHGs and co-pollutants in energy systems, strategies that pursue GHG emission reductions and improvements in energy efficiency hold significant potential health co-benefits through air pollution emission reductions (*high confidence*) (Gao et al., 2018). Air quality improvements alone can substantially offset, or most likely exceed, mitigation costs at the societal level (Schucht et al., 2015);(Chang et al., 2017);(Markandya et al., 2018);(Vandyck et al., 2018);(Peng et al., 2017; Woodward et al., 2019; Sampedro et al., 2020);(Xie et al., 2018);{Fig.Ch5 WGIII[KE4] }). Pursuit of a mitigation pathway compatible with warming of +1.5 C, with associated cleaner air, avoided extreme events, and improved food security and nutrition, could result in 152 +/- 43 million fewer premature deaths worldwide between 2020 and 2100 compared with a business-as-usual scenario (Shindell et al., 2018)Reaching the Paris Agreement across nine major economies by 2040 could result in an annual reduction of 1.18 million air pollution-related deaths, 5.86 million diet-related deaths, and 1.15 million deaths due to physical inactivity (Hamilton et al., 2021). In Europe, a mitigation scenario compatible with RCP 2.6 could reduce total pollution costs, mostly from PM2.5, by 84%, with human health benefits equal to more than 1 € trillion over five years (Scasny et al., 2015). In the EU, ambitious climate mitigation policies could reduce years of lost life due to fine particulate matter from over 4.6 million in 2005 to 1 million in 2050, reduce ozone-related premature deaths from 48,000 to 7,000, and generate health benefits of 62 billion €/year in 2050 (Schucht et al., 2015).

However, there may be significant trade-offs between mitigation and other societal goals (Dong et al., 2019);(Gao et al., 2018). In some scenarios, mitigation policies consistent with the NDCs may slow poverty reduction efforts (Campagnolo and Davide, 2019) with implications for health. A framework of "co-impacts" that assumes neither a general beneficial nature of all implications from mitigation policy nor a hierarchy between climate and other types of benefits, may be more appropriate (Ürge-Vorsatz et al., 2014);(Cohen et al., 2017).

Transitioning to affordable clean energy sources for all presents opportunities for substantial wellbeing, health, and equity co-benefits (high confidence). (Gibon et al., 2017);(Lacey et al., 2017) (Peng et al., 2018);(Vandyck et al., 2018); (Williams et al., 2018);{18. WGII} {6.3. WGIII}. Residential solid fuel use affects health and degrades indoor air quality for up to 3.1 billion people in low and middle-income countries (WHO, 2016b); (Wang et al., 2017a). Adherence to planned emission reductions from the Paris Agreement related to renewables could subsequently improve air quality and prevent 71,000-99,000 premature deaths annually by 2030 (Vandyck et al., 2018). This effect increases with a 2°C pathway, with 0.7–1.5 million premature deaths avoided annually by 2050 (Vandyck et al., 2018). Co-benefits are also observed at national and regional levels. For instance, China could expect 55,000–69,000 averted deaths in 2030 if it transitioned to a half-decarbonized power supply for its residential and vehicle sectors (Peng et al., 2018).

Investing in universal basic infrastructure, including sanitation, clean drinking water, drainage, electricity, and land-rights, can transform development opportunities, increase adaptive capacity, and reduce vulnerability to climate-related risks (high agreement, high evidence). {6.1, 6.3 WGII}. Transformative approaches that reduce climate-related risks and deliver enhanced social inclusion and development opportunities for the urban poor are most likely where local governments act in partnership with local communities and other civil society actors (*high confidence*) {6.1, 6.3, 6.4 WGII}.

Rapid urbanization offers a time-limited opportunity to work at scale towards transformational adaptation and climate resilient development (medium evidence, high agreement). Multi-level leadership, institutional capacity, and financial resources to support inclusive adaptation, in the context of multiple pressures and interconnected risks, can help ensure that the additional 2.5 billion people projected to live in urban areas by 2050 are less exposed to climate-related hazards and contribute less to global warming (*high confidence*) {6.1, 6.3, 6.4 WG II}. Integrating low-carbon, inclusive adaptation into infrastructure investment driven by rapid urban population growth and COVID-19 recovery can accelerate co-benefits {Ch6, WGII, Urban X-WG Box}.

Urban planning that combines clean, affordable public transportation, shared clean vehicles, and accessible active modes can improve air quality and contribute to healthy, equitable societies and higher wellbeing for all. Stimulating active mobility (walking and bicycling) can bring physical and mental health benefits (high confidence). {6. WGII} {8.2 WG III} (Rojas-Rueda et al., 2016); (Avila-Palencia et al., 2018); (Gascon et al., 2019); (Hamilton et al., 2021). The health gains from active mobility outweigh traffic-related injuries, from a decreased incidence of chronic diseases(Ahmad et al., 2017);(Maizlish et al., 2017);(Tainio et al., 2017);(Woodcock et al., 2018).

Urban green and blue spaces contribute to climate change adaptation and mitigation and improve physical and mental health and wellbeing (high confidence). (Hansen 2017; EC, 2018; WHO, 2018; Rojas-Rueda et al. 2019). {13.7.3, WGII} {6. WGII} {8.4 WGIII). Urban green infrastructure including urban gardens, can bring benefits to social cohesion, mental health and wellbeing and reduce the health impacts of heatwaves by decreasing temperatures, thus reducing inequities in exposure to heat stress for low income, marginalized groups (Hoffman et al., 2020; Hoffmann et al., 2020){5.12.5;14.4.10.3 WGII} {7.4 WGII} {6. WGII} {13.7}. Trade-offs of increasing urban green and blue spaces include potential public health risks related to increased vectors or hosts for infectious diseases, toxic algal blooms, drowning, and aeroallergens (Choi et al., 2021);(Stewart-Sinclair et al., 2020); {6. WGII}

Climate adaptation and mitigation policies in the building sector offer multiple wellbeing and health co-benefits (high confidence). (Diaz-Mendez et al., 2018);(Macnaughton et al., 2018) {3.6.2, WGII} 9.8 WGIII}. Leadership in Energy and Environmental Design (LEED) certified buildings in the United States, Brazil, China, India, Germany, and Turkey saved $7.5 billion in energy costs and averted 33MT of CO2 from 2000-2016.(Macnaughton et al., 2018) These measures can increase health benefits through better indoor air quality, reduction of the heat island effect, improved social wellbeing through energy poverty alleviation, creation of new jobs, increased productive time and income, increased thermal comfort and lighting indoors, and reduced noise impact. (Smith et al., 2016); (McCollum et al., 2018);(Thema et al., 2017);(Mirasgedis et al., 2014);(Alawneh et al., 2019);(Diaz-Mendez et al., 2018);{9.8 WGIII}. The value of these multiple co-benefits associated with climate actions in buildings is equal or greater than the costs of energy savings (Ürge-Vorsatz et al., 2016);(Payne et al., 2015);{9.8 WGIII){14.4.5.3 WGII}.

Shifting to sustainable food systems that provide affordable diverse plant-rich diets with moderate quantities of GHG-intensive animal protein can bring health co-benefits and substantially reduce GHG emissions, especially in high income countries and where ill health related to overconsumption of animal-based products is prevalent (very high confidence). {5.12.6, WGII} {7.4, 13.5, WGII} {5.WGIII} (7.4 WGIII) (Springmann et al., 2018c);(SRCCL, 2019); (Clark and Tilman, 2017); (Poore and Nemecek, 2018); (Hayek et al., 2021). Transforming the food system by limiting the demand for GHG-intensive animal foods, reducing food over-consumption and transitioning to nutritious, plant-rich diets, can have significant co-benefits to health (*high confidence*) (Hedenus et al., 2014); (Ripple et al., 2014);(Tirado, 2017); (Springmann et al., 2018c); IPCC SR1.5, 2018). (SROC 2019).(SRCCL, 2019); (Nelson et al., 2016); (Willett et al., 2019);(Tilman and Clark, 2014);(Green et al., 2015);(Springmann et al., 2016b);(Springmann et al., 2018b);(Springmann et al., 2018a);(Springmann et al., 2018c); (Milner et al., 2015);(Milner et al., 2017);(Farchi et al., 2017);(Song et al., 2017); (Willett et al., 2019). Reduction of red meat consumption reduces the risk of cardiovascular disease and colorectal cancer; and the consumption of more fruits and vegetables can reduce the risk of cardiovascular disease, type II diabetes, cancer, and all causes of mortality (WHO, 2015c);(Tilman and Clark, 2014);(Sabate and Soret, 2014); (Willett et al., 2019). {7.4 WGIII} {5.12.5 WGII} {6.3 WGIII}. Globally, it is estimated that transitioning to more plant-based diets - in line with WHO recommendations on healthy eating - could reduce global mortality by 6–10% and food-related greenhouse gas emissions by 29–70% by 2050 (Springmann et al., 2016b). There are limitations in accessibility of affordable of healthy and diverse diets for all (Springmann et al., 2020) and trade-offs such as the potential increase of GHG emissions from producing healthy and diverse diets in low- and medium-income countries (Semba et al. 2020). Agroecological approaches have mitigation and adaptation potential, deliver ecosystem services, biodiversity, livelihoods and benefits to nutrition, health, and equity (Rosenstock et al., 2019);(Bezner Kerr et al., 2021);{5.4.4; 5.14.1 WGII} {13.5, 14.4.4 WGII}.

[END CROSS CHAPTER BOX HEALTH HERE]

7.4.6.7 International policy frameworks for migration that contribute to climate-resilient development

Climate-related migration, displacement and immobility in coming decades will coincide with global and regional demographic changes that will produce a widening distinction between high-income countries that have aging, slow-growing (or in some countries, shrinking) population numbers and low-income countries that have rapidly growing, youthful populations. Given this dynamic, coordinated national and international strategies that integrate migration and displacement considerations with wider adaptation and sustainable development policies may contribute to climate-resilient development. Since AR5, the international community has established a number of agreements and initiatives that, with continued pursuit and implementation, would create potential for climate-related migration to be a positive contribution toward adaptive capacity building and sustainable development more broadly (Warner, 2018).

The 2018 Global Compact for Safe, Orderly and Regular Migration provides an important opportunity for planning for and responding to future climate-related migration and displacement (Kälin, 2018). Among its 23 objectives, the Compact explicitly encourages the international community to implement migration policies that facilitate voluntary migration and actively prepare for involuntary displacements due to climate change, especially in low- and middle-income countries. The Compact's objectives include reducing barriers to legal and safe migration, facilitating the freer flow of remittances between sending and receiving communities, and by doing so aim to increase the potential for migration to make positive contributions to sustainable development and to adaptive capacity-building. It also contains specific provisions pertaining to climate- and disaster-related migration and displacement. Objective 2 of the Compact aims at reducing drivers of involuntary or low-agency migration, and recommends that states establish systems for sharing information on environmental migration, develop climate adaptation and resilience strategies harmonized at sub-regional and regional levels; and cooperate on disaster risk prevention and response. Other objectives in the Compact relevant to climate-related migration include Objective 5 (increasing pathways for regular migration) and Objective 19 (facilitating migrants' ability to contribute to sustainable development). Objective 18, which links migration with skills development, is consistent with the 'migration with dignity' approach to displacement risks (McNamara, 2015);(Kupferberg, 2021). The 2018 Global Compact on Refugees observes that climate hazards increasingly interact with the drivers of refugee movements. The guidelines this Compact provides to governments regarding options and actions for addressing the causes of refugee movements and considerations for assisting and supporting refugees are useful for governments seeking guidance for all forms of displacement more generally, including displacement linked to climate change.

Pursuant to the Paris Agreement, a task force was struck by the Warsaw International Mechanism to make recommendations to the Conference of the Parties to the UNFCCC on how to reduce the risks of climate-related displacement. Its 2018 report recommended that parties work toward development of national legislation, cooperate on research, strengthen preparedness, integrate mobility into wider adaptation plans, work toward safe and orderly migration, and provide assistance to people internally displaced for climate-related reasons. Such recommendations dovetail strongly with the objectives of the Compacts on Migration and Refugees, as well as the Sendai Framework for Disaster Risk Reduction and the 2030 Sustainable Development Goals (SDGs). The SDGs, which include multiple goals and targets in which migration plays an explicit role in fostering development (Nurse, 2019), may be seen as completing the international policy arrangements necessary for addressing future climate-related migration and displacement.

7.4.6.8 Inclusive and integrative approaches to climate resilient peace

Climate resilient development pathways to reduce conflict risk rely on a shift in perspective; from framings around resource scarcity and security to sustainable natural resource governance and peace (Brauch et al 2016, Barnett, 2018; Dresse et al 2018). (Day and Caus, 2020) Recognizing that conflict results from underlying vulnerabilities, development that reduces vulnerability offers the best win-win option for building sustainable, climate-resilient peace rather than specific security-focused interventions *(high confidenc*e). To this end, meeting the Sustainable Development Goals represents an unambiguous path to reducing conflict risk in a climate-changed world (Singh and Chudasama, 2021). There is growing acceptance in the development community, despite reservations about the securitization of climate, that instability and conflict exacerbated by climate change has the potential to undermine development gains (Casado-Asensio et al., 2020);(Day and Caus, 2020).

Core to achieving climate resilient peace are new ways of working, that involve cross-issue and cross-sectoral collaboration and integration as a default to policy and programming. The Security Council Resolution 1325 Women and peace and security (S/RES/1325 (2000)) and the Sustaining Peace Agenda (A/RES/70/262 (2016) are notable examples of this. The 2020 UNEP report on gender and security recommends integrating policy frameworks, better financing to strengthen women's roles in peacebuilding, integrated programme design and further research on gender, climate and security linkages. Inclusive approaches recognize that much of the vulnerability that drives conflict risk, is generated by existing inequality and marginalization of large proportions of the population – for example women and youth – and that peace cannot be achieved without their needs being taken into account, and their participation in peace processes (Mosello et al., 2021). Diverse and inclusive partnerships also require ways to better engage local level participation and improving understanding of how to build consensus, through human rights-based approaches that understand non-violent conflict and protest to be potentially positive and constructive elements of transformational approaches to building resilience (Nursey-Bray, 2017);(Ensor et al., 2018);(Schipper et al., 2021). There is an increasing focus on the role of environmental defenders in highlighting violations and gaps in state obligations through non-violent protest (Butt et al., 2019);(Scheidel et al., 2020). Addressing the lack of participation of researchers and experts from countries most at risk of conflict in many climate-related conflict and peacebuilding assessments and initiatives, would also support this objective.

Climate resilient development pathways for sustainable peace also require different ways of gathering intelligence and informing conflict risk. Dynamics that affect such risks exist across scales from the local to the regional and require response in a transboundary manner. There is increasing emphasis on engaging local stakeholders and diverse partnerships to inform context appropriate measures and better policy coordination (Bremberg et al., 2019);(Tshimanga et al., 2021);(Abrahams, 2020). The UN's Climate Security Mechanism, working across three UN departments, takes an integrated approach to analyze and support timely and appropriate responses to conflict risk focusing on risk assessments and early warning systems to aid conflict prevention, climate-informed peace and security activities and conflict-sensitive development, and promoting inter-sectoral cooperation, partnership, and information sharing (DPPA et al., 2020). There is already acknowledgement that adaptation needs to be effectively monitored and to help learning so that maladaptation can be avoided (Eriksen et al., 2021). Here the academic community, which until now has predominantly focused on understanding the causal relationship between conflict and climate, could contribute to advancing monitoring and evaluation of climate resilient peacebuilding initiatives (Mach et al., 2020);(Gilmore et al., 2018)..

[START FAQ7.1 HERE]

FAQ7.1: How will climate change affect physical and mental health and wellbeing?

Climate change will affect human health and wellbeing in a variety of direct and indirect ways, depending on exposure to hazards and vulnerabilities that are heterogeneous and vary within societies, influenced by social, economic and geographical factors as well as individual differences (see Figure FAQ7.1.1). Changes in the magnitude, frequency and intensity of extreme climate events (e.g. storms, floods, wildfires, heatwaves and dust storms) will expose people to increased risks of climate-sensitive illnesses and injuries, and, in worst cases, higher mortality rates. Increased risks for mental health and wellbeing are associated with changes caused by impacts of climate change on climate-sensitive health outcomes and systems (see Figure FAQ7.1.2). Higher temperatures and changing geographical and seasonal precipitation patterns will facilitate the spread of mosquito- and tick-borne diseases, such as Lyme disease and dengue fever, and water- and food-borne diseases. An increase in the frequency of extreme heat events will exacerbate health risks associated with cardiovascular disease, and affect access to fresh water in multiple regions, impairing agricultural productivity, increasing food insecurity, undernutrition, and poverty in low-income areas.

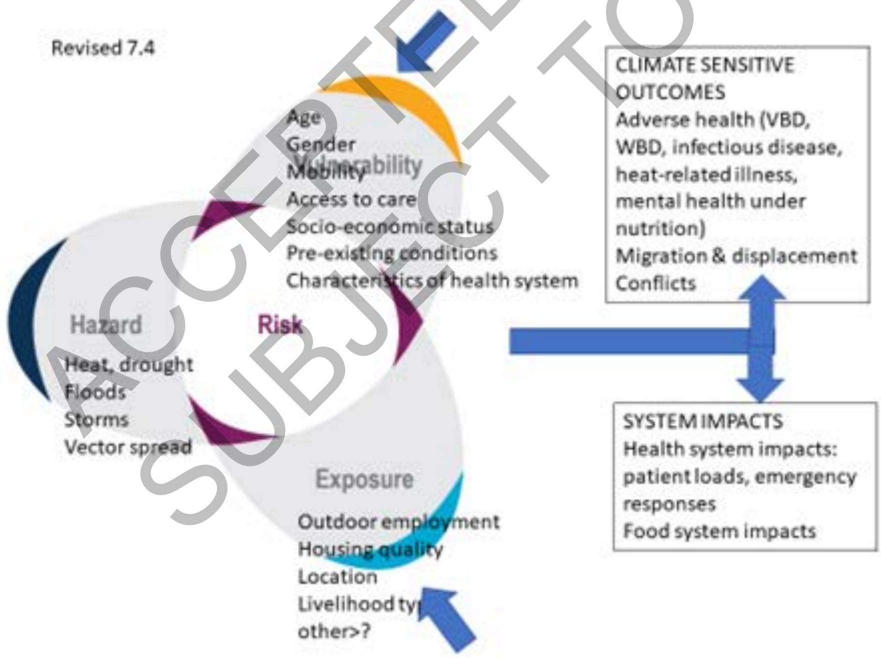


Figure FAQ7.1.1: Pathways from hazards, exposure and vulnerabilities to climate change impacts on health outcomes and health Systems

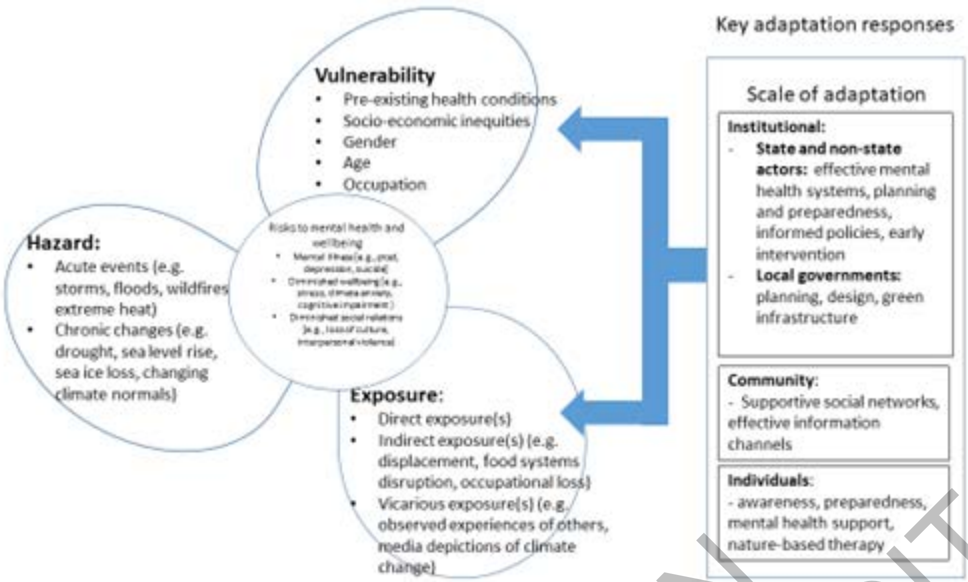


Figure FAQ7.12.: Climate change impacts on mental health and key adaptation responses

[END FAQ7.1 HERE]

[START FAQ7.2 HERE]

FAQ7.2: Will climate change lead to wide-scale forced migration and involuntary displacement?

Climate change will have impacts on future migration patterns that will vary by region and over time, depending on the types of climate risks people are exposed to, their vulnerability to those risks, and their capacity – and the capacity of their governments – to adapt and respond. Depending on the range of adaptation options available, households may use migration as a strategy to adapt to climate risks, often through labour migration. The most common drivers of involuntary climate-related displacement are extreme weather events, floods, and droughts, especially when these events cause severe damage to homes, livelihoods and food systems. Rising sea levels will present a new risk for communities situated in low-lying coastal areas and small island states. The greater the scale of future warming and extreme events, the greater the likely scale of future, involuntary climate-related migration; progress toward the sustainable development goals has the opposite effect.

[END FAQ7.2 HERE]

[START FAQ7.3 HERE]

FAQ7.3: Will climate change increase the potential for violent conflict?

Adverse impacts of climate change threaten to increase poverty and inequality, undermine progress in meetings sustainable development goals, and place strain on civil institutions – all of which are factors that contribute to the emergence or worsening of civil unrest and conflict. Climate change impacts on crop productivity and water availability can function as a 'risk multiplier' for conflict in areas that are already politically and/or socially fragile and depending on circumstances, could increase the length or the nature of an existing conflict. Institutional initiatives within or between states to protect the environment and manage natural resources can serve simultaneously as mechanisms for engaging rival groups and adversaries to cooperate in policymaking and peacebuilding.

[END FAQ7.3 HERE]

[START FAQ7.4 HERE]

FAQ7.4: What solutions can effectively reduce climate change risks to health, wellbeing, forced migration and conflict?

The solution space includes policies, strategies and programmes that consider why, how, when, and who to sustainably adapt to climate change. Effectively preparing for and managing the health risks of climate change requires considering the multiple interacting sectors that affect population health and effective functioning of health systems. Considering the close interconnections between health, migration and conflict, interventions that address climate risks in one area often have synergistic benefits in others. For example, conflicts often result in large numbers of people being involuntarily displaced and facilitate the spread of climate-sensitive diseases; tackling the underlying causes of vulnerability and exposure that generate conflict reduces risks across all areas. A key starting point for health and wellbeing is strengthening public health systems so that they become more climate resilient, which also requires cooperation with other sectors (water, food, sanitation, transportation, etc) to ensure appropriate funding and progress on sustainable development goals. Interventions to enhance protection against specific climate-sensitive health could reduce morbidity and mortality and prevent many losses and damages (Figure FAQ7.4.1). These range from malaria net initiatives, vector control programs, health hazard (syndromic) surveillance and early warning systems, improving access to water, sanitation and hygiene, heat action plans, behavioral changes and integration with disaster risk reduction and response strategies. More importantly, climate-resilient development pathways (CRDP) are essential to improve overall health and wellbeing, reduce underlying causes of vulnerability, and provide a framework for prioritizing mitigation and adaptation options that support sustainable development. Transformative changes in key sectors including water, food, energy, transportation and built environments offer significant co-benefits for health.

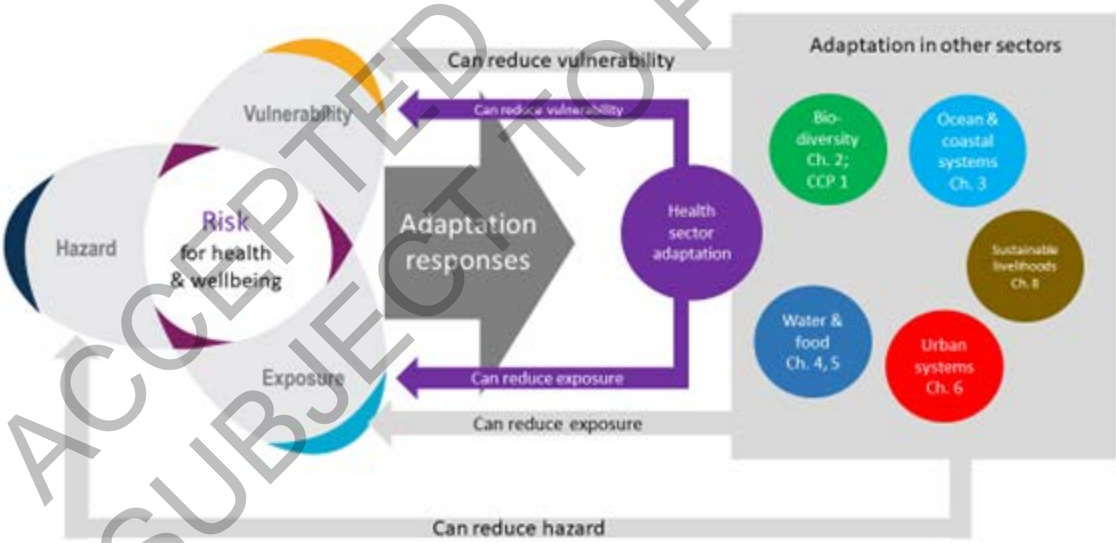


Figure FAQ7.4.1: Solution space for adaptation to climate change in health and other sectors.

[END FAQ7.4 HERE]

[START FAQ7.5 HERE]

FAQ 7.5: What are some specific examples of actions taken in other sectors that reduce climate change risks in the health sector?

Many of the greatest actions to face risks of climate change in other sectors lead to benefits for health and wellbeing. Adaptive urban design that provides greater access to green and natural spaces simultaneously enhances biodiversity, improves air quality, and moderates the hydrological cycle; it also helps reduce health risks associated with heat stress and respiratory illnesses, and mitigates mental health challenges associated with congested urban living. Transitioning away from internal-combustion vehicles and fossil fuel-powered generating stations to renewable energy mitigates GHG emissions, improves air quality and lowers risks of respiratory illnesses. Policies and designs that facilitate active urban transport (walking and bicycling) increase efficiency in that sector, reduce emissions, improve air quality, and generate physical and mental health benefits for residents. Improved building and urban design that foster energy efficiency improve indoor air quality reduce risks of heat stress and respiratory illness. Food systems that emphasize healthy, plant-centered diets reduce emissions in the agricultural sector while helping in the fight against malnutrition.

[END FAQ7.5 HERE]

References

, U. N. C. s. F., W. H. Organization, I. B. f. R. Bank and D. T. World, 2021: Joint child malnutrition estimates — levels and trends – 2021 edition. United Nations Children's Fund, New York.

A, S., 2021: International Institutions and Global Governance on Climate Change. Chapter 20 in Lemery J, Knowlton K, Sorensen C, editors. Global climate change and human health: from science to practice. John Wiley & Sons.

A.Call, M., C. Gray, M. Yunus and M. Emch, 2017: Disruption, not displacement: Environmental variability and temporary migration in Bangladesh. *Global Environmental Change*, **46**, 157-165.

Abbott, M., M. Bazilian, D. Egel and H. H. Willis, 2017: Examining the food–energy–water and conflict nexus. *Current Opinion in Chemical Engineering*, **18**, 55-60.

Abdullah, A. S. M. et al., 2019: Effects of Climate Change and Maternal Morality: Perspective from Case STUDIES in rural Bangladesh.

Abel, D. W. et al., 2018: Air-quality-related health impacts from climate change and from adaptation of cooling demand for buildings in the eastern United States: An interdisciplinary modeling study. *Plos Medicine*, **15**(7), doi:10.1371/journal.pmed.1002599.

Abel, G. and N. Sander, 2014: Quantifying Global International Migration Flows. *Science*, **343**(6178), 1520-1522, doi:10.1126/science.1248676.

Abel, G. J., B. Barakat, K. C. Samir and W. Lutz, 2016: Meeting the Sustainable Development Goals leads to lower world population growth. *Proceedings of the National Academy of Science*, **113**(50), 14294-14299.

Abel, G. J., M. Brottrager, J. C. Cuaresma and R. Muttarak, 2019: Climate, conflict and forced migration. *Global Environmental Change*, **54**, 239-249.

Abhijith, K. V. et al., 2017: Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments - A review. *Atmospheric Environment*, **162**, 71-86, doi:10.1016/j.atmosenv.2017.05.014.

Abiona, O., 2017: Adverse effects of early life extreme precipitation shocks on short-term health and adulthood welfare outcomes. *Review of Development Economics*, **21**(4), 1229-1254.

Aboubakri, O. et al., 2020: Projection of mortality attributed to heat and cold; the impact of climate change in a dry region of Iran, Kerman. *Science of The Total Environment*, **728**, 138700, doi:https://doi.org/10.1016/j.scitotenv.2020.138700.

Abrahams, D., 2020: Conflict in abundance and peacebuilding in scarcity: Challenges and opportunities in addressing climate change and conflict. *World Development*, **132**, 104998.

Abramson, M. et al., 2015: The resilience activation framework: a conceptual model of how access to social resources promotes adaptation and rapid recovery in post-disaster settings. *The Journal of Behavioral Health Services and Research*, **42**(1), 42-57.

Achakulwisut, P. et al., 2019: Effects of Increasing Aridity on Ambient Dust and Public Health in the U.S. Southwest Under Climate Change. *Geohealth*, **3**(5), 127-144, doi:10.1029/2019gh000187.

Achakulwisut, P., L. J. Mickley and S. C. Anenberg, 2018: Drought-sensitivity of fine dust in the US Southwest: Implications for air quality and public health under future climate change. *Environ. Res. Lett.*, **13**(5), 054025, doi:10.1088/1748-9326/aabf20.

Acharya, B. K. et al., 2018: Present and Future of Dengue Fever in Nepal: Mapping Climatic Suitability by Ecological Niche Model. *Int J Environ Res Public Health*, **15**(2), doi:10.3390/ijerph15020187.

Acharya, Y. et al., 2019: Nutritional status, cognitive achievement, and educational attainment of children aged 8-11 in rural South India. *Plos One*, **14**(10), doi:10.1371/journal.pone.0223001.

Achebak, H., D. Devolder, V. Ingole and J. Ballester, 2020: Reversal of the seasonality of temperature-attributable mortality from respiratory diseases in Spain. *Nature Communications*, **11**(1), doi:10.1038/s41467-020-16273-x.

Adams, C., T. Ide, J. Barnett and A. Detges, 2018: Sampling bias in climate-conflict research. *Nature Climate Change*, **8**(3), 200-203, doi:10.1038/s41558-018-0068-2.

Adams, H., 2016: Why populations persist: mobility, place attachment and climate change. *Population and Environment*, **37**(4), 429-448.

Adams, H. and S. Kay, 2019: Migration as a human affair: Integrating individual stress thresholds into quantitative models of climate migration. *Environmental Science & Policy*, **93**, 129-138, doi:10.1016/j.envsci.2018.10.015.

Adams, W. M. and J. F. Jardine, 2020: Overview of Exertional Heat Illness. *Exertional Heat Illness: a Clinical and Evidence-Based Guide*, 1-16, doi:10.1007/978-3-030-27805-2_1.

Adelodun, B. et al., 2020: Snowballing transmission of COVID-19 (SARS-CoV-2) through wastewater: Any sustainable preventive measures to curtail the scourge in low-income countries? *Science of the Total Environment*, **742**, doi:10.1016/j.scitotenv.2020.140680.

Adelphi and C. I. Inc, 2020: *Pathways to peace: addressing conflict and strengthening stability in a changing climate. Lessons learned from resilience and peacebuilding programs in the horn of Africa*. AdaptationThought Leadership and Assessments (ATLAS), United States Agency for International Developement.

Adger, W. et al., 2015: Focus on environmental risks and migration: Causes and consequence. *Environmental Research Letters*, **10**, 60201, doi:10.1088/1748-9326/10/6/060201.

Adhvaryu, A., J. Fenske and A. Nyshadham, 2019: Early life circumstance and adult mental health. *Journal of Political Economy*, **127**(4).

Afifi, T. et al., 2016: Human mobility in response to rainfall variability: Opportunities for migration as a successful adaptation strategy in eight case studies. . *Migration and Development*, **5**, 254-274.
Afriyie, K., J. Ganle and E. Santos, 2018: 'The floods came and we lost everything': Weather extremes and households' asset vulnerability and adaptation in rural Ghana. *Climate and Development*, **10**(3), 259-274, doi:10.1080/17565529.2017.1291403.
Agency, E. E., 2017: *Climate change, impacts and vulnerability in Europe 2016: An indicator-based report*. 419 pp. pp.
Ahmad, S., S. Pachauri and F. Creutzig, 2017: Synergies and trade-offs between energy-efficient urbanization and health. **12**(11)), doi:10.1088/1748-9326/aa9281.
Ahmadalipour, A. and H. Moradkhani, 2018: Escalating heat-stress mortality risk due to global warming in the Middle East and North Africa (MENA). *Environment International*, **117**, 215-225, doi:10.1016/j.envint.2018.05.014.
Ahmed, K. J., S. M. A. Haq and F. Bartiaux, 2019: The nexus between extreme weather events, sexual violence, and early marriage: a study of vulnerable populations in Bangladesh. *Population and Environment*, **40**(3), 303-324.
Ahmed, S. et al., 2020: Effect of extreme weather events on injury, disability, and death in Bangladesh.
Ahmed, S. A., M. Guerrero Flórez and P. Karanis, 2018: The impact of water crises and climate changes on the transmission of protozoan parasites in Africa. *Pathog Glob Health*, **112(6)**, 281-293.
Ahmed, S. A., A. Saad-Hussein, A. El Feel and M. A. Hamed, 2014: Time Series Trend of Bilharzial Bladder Cancer in Egypt and its relation to Climate Change: A study from 1995-2005. *INTERNATIONAL JOURNAL OF PHARMACEUTICAL AND CLINICAL RESEARCH.*, **6**(1), 46-53.
Aik, J. et al., 2018: Climate variability and salmonellosis in Singapore - A time series analysis. *Science of the Total Environment*, **639**, 1261-1267, doi:10.1016/j.scitotenv.2018.05.254.
Aitsi-Selmi, A. and V. Murray, 2016: Protecting the Health and Well-being of Populations from Disasters: Health and Health Care in The Sendai Framework for Disaster Risk Reduction 2015-2030. *Prehosp Disaster Med*, **31**(1), 74-78, doi:10.1017/S1049023X15005531.
Aitsi-Selmi, A. et al., 2015: The Sendai Framework for Disaster Risk Reduction: Renewing the Global Commitment to People's Resilience, Health, and Well-being. *International Journal of Disaster Risk Science*, **6**(2), 164--176, doi:10.1007/s13753-015-0050-9.
Ajibade, I., M. Sullivan and M. Haeffner, 2020: Why climate migration is not managed retreat: Six justifications. *Global Environmental Change*, **65**, 102187.
Akande, V., T. Fawehinmi, R. Ruiter and S. Kremers, 2021: Healthy Dietary Choices and Physical Activity Participation in the Canadian Arctic: Understanding Nunavut Inuit Perspectives on the Barriers and Enablers. *International Journal of Environmental Research and Public Health*, **18**(3), doi:10.3390/ijerph18030940.
Akil, L., H. A. Ahmad and R. S. Reddy, 2014: Effects of climate change on Salmonella infections. *Foodborne Pathog Dis*, **11**(12), 974-980, doi:10.1089/fpd.2014.1802.
Akompab, D. et al., 2013: Heat Waves and Climate Change: Applying the Health Belief Model to Identify Predictors of Risk Perception and Adaptive Behaviours in Adelaide, Australia. *International Journal of Environmental Research and Public Health*, **10**(6), 2164-2184, doi:10.3390/ijerph10062164.
Akpan, G., K. Adepoju, O. Oladosu and S. Adelabu, 2018: Dominant malaria vector species in Nigeria: Modelling potential distribution of Anopheles gambiae sensu lato and its siblings with MaxEnt. *Plos One*, **13**(10), doi:10.1371/journal.pone.0204233.
Akter, R. et al., 2017: Joint effects of climate variability and socioecological factors on dengue transmission: epidemiological evidence. *Trop Med Int Health*, **22**(6), 656-669, doi:10.1111/tmi.12868.
Al-Bouwarthan, M., M. M. Quinn, D. Kriebel and D. H. Wegman, 2020: Risk of Kidney Injury among Construction Workers Exposed to Heat Stress: A Longitudinal Study from Saudi Arabia. *International Journal of Environmental Research and Public Health*, **17**(11), doi:10.3390/ijerph17113775.
Alawneh, R., F. Ghazali, H. Ali and M. Asif, 2019: A new index for assessing the contribution of energy efficiency in LEED 2009 certified green buildings to achieving UN sustainable development goals in Jordan. *International Journal of Green Energy*, **16**(6), 490-499, doi:10.1080/15435075.2019.1584104.
Albert, S. et al., 2018: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, 2261-2272. Available at: https://doi.org/10.1007/s10113-017-1256-8.
Albrecht, G. et al., 2007: Solastalgia: the distress caused by environmental change. *Australasian Psychiatry*, **15**, S95-S98, doi:10.1080/10398560701701288.
Alderman, H., 2016: *Leveraging Social Protection Programs for Improved Nutrition: Summary of Evidence Prepared for the Global Forum on Nutrition-Sensitive Social Protection Programs, 2015*. World Bank, Washington, DC.
Aleksandrova, M., 2020: Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries. *Climate and Development*, **12**(6), 511-520, doi:10.1080/17565529.2019.1642180.
Alele, F., B. Malau-Aduli, A. Malau-Aduli and M. Crowe, 2020: Systematic review of gender differences in the epidemiology and risk factors of exertional heat illness and heat tolerance in the armed forces. *Bmj Open*, **10**(4), doi:10.1136/bmjopen-2019-031825.
Alexander, P. J., R. Fealy and G. M. Mills, 2016: Simulating the impact of urban development pathways on the local climate: A scenario-based analysis in the greater Dublin region, Ireland. *Landscape and Urban Planning*, **152**, 72-89, doi:10.1016/j.landurbplan.2016.02.006.

Alfredsson, E. et al., 2018: Why achieving the Paris Agreement requires reduced overall consumption and production. *Sustainability: Science, Practice and Policy*, **14**(1), 1-5.
Ali, S. et al., 2020: Mental health in the Pacific: Urgency and opportunity. *Asia Pacific Viewpoint*, **n/a**(n/a), doi:10.1111/apv.12286.
Almendra, R. et al., 2019: Short-term impacts of air temperature on hospitalizations for mental disorders in Lisbon. *Science of the Total Environment*, **647**, 127-133, doi:10.1016/j.scitotenv.2018.07.337.
Alpino, T. A., A. R. M. d. Sena and C. M. d. Freitas, 2016: Desastres relacionados à seca e saúde coletiva – uma revisão da literatura científica. *Ciência & Saúde Coletiva*, **21**(3), 809-820, doi:https://dx.doi.org/10.1590/1413-81232015213.21392015.
Alston, M. and B. Akhter, 2016: Gender and food security in Bangladesh: the impact of climate change. *Gender Place and Culture*, **23**(10), 1450-1464, doi:10.1080/0966369x.2016.1204997.
Altieri, M., C. Nicholls, A. Henao and M. Lana, 2015: Agroecology and the design of climate change-resilient farming systems. *Agronomy For Sustainable Development*, **35**(3), 869-890, doi:10.1007/s13593-015-0285-2.
Amaratunga, D. et al., 2018: Sound Practices of Disaster Risk Reduction at Local Level. *Procedia Engineering*, **212**, 1163--1170, doi:https://doi.org/10.1016/j.proeng.2018.01.150.
Amat, F. and et al., 2020: Pandemics meet democracy: Experimental evidence from the COVID-19 crisis in Spain. *SOC ARXiv Papers*, doi:10.31235/osf.io/dkusw.
Amegah, A. K., G. Rezza and J. J. Jaakkola, 2016: Temperature-related morbidity and mortality in Sub-Saharan Africa: A systematic review of the empirical evidence. *Environ Int*, **91**, 133-149, doi:10.1016/j.envint.2016.02.027.
Amstislavski, P. et al., 2013: Effects of increase in temperature and open water on transmigration and access to health care by the Nenets reindeer herders in northern Russia. *International Journal of Circumpolar Health*, **72**, 447-455, doi:10.3402/ijch.v72i0.21183.
An, R., M. Ji and S. Zhang, 2017: Global warming and obesity: a systematic review.
An, R., M. Ji and S. Zhang, 2018: Global warming and obesity: a systematic review. *Obesity Reviews*, **19**(2), 150-163, doi:10.1111/obr.12624.
Analitis, A. et al., 2014: Effects of Heat Waves on Mortality Effect Modification and Confounding by Air Pollutants. *Epidemiology*, **25**(1), 15-22, doi:10.1097/EDE.0b013e31828ac01b.
Andersen, L. K. and M. D. P. Davis, 2017: A wake-up call to dermatologists - climate change affects the skin. *Int J Dermatol*, **56**(10), e198-e199, doi:10.1111/ijd.13617.
Anderson, G. B., K. W. Oleson, B. Jones and R. D. Peng, 2018: Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities. *Climatic Change*, **146**(3-4), 455-470, doi:10.1007/s10584-016-1779-x.
Andrews, O. et al., 2018: Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study. *Lancet Planetary Health*, **2**(12), E540-E547, doi:10.1016/s2542-5196(18)30240-7.
Anenberg, S. C. et al., 2020: Synergistic health effects of air pollution, temperature, and pollen exposure: a systematic review of epidemiological evidence. *Environmental Health*, **19**(1), doi:10.1186/s12940-020-00681-z.
Anwar, N., A. Sawas and D. Mustafa, 2019: 'Without water, there is no life': Negotiating everyday risks and gendered insecurities in Karachi's informal settlements. *Urban Studies*, doi:https://doi.org/10.1177/0042098019834160.
Apergis, N., 2018: The Impact of Greenhouse Gas Emissions on Personal Well-Being: Evidence from a Panel of 58 Countries and Aggregate and Regional Country Samples. *Journal of Happiness Studies*, **19**(1), 69-80, doi:10.1007/s10902-016-9809-y.
Aracena, S. et al., 2021: Health system adaptation to climate change: a Peruvian case study. *Health Policy and Planning*, **36**(1), 45-83, doi:10.1093/heapol/czaa072.
Arbuthnott, K., S. Hajat, C. Heaviside and S. Vardoulakis, 2020: Years of life lost and mortality due to heat and cold in the three largest English cities. *Environment International*, **144**, 105966, doi:https://doi.org/10.1016/j.envint.2020.105966.
Archer, J. et al., 2020: Intestinal Schistosomiasis and Giardiasis Co-Infection in Sub-Saharan Africa: Can a One Health Approach Improve Control of Each Waterborne Parasite Simultaneously? *Trop Med Infect Dis*, **5**(3), doi:10.3390/tropicalmed5030137.
Archibald, A. T. et al., 2020: On the changes in surface ozone over the twenty-first century: sensitivity to changes in surface temperature and chemical mechanisms. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **378**(2183), doi:10.1098/rsta.2019.0329.
Armitage, R. and L. Nellums, 2020: Water, climate change, and COVID-19: prioritising those in water-stressed settings. *Lancet Planetary Health*, **4**(5), E175-E175.
Armstrong, B. et al., 2017: Longer-Term Impact of High and Low Temperature on Mortality: An International Study to Clarify Length of Mortality Displacement. *Environmental Health Perspectives*, **125**(10), doi:10.1289/ehp1756.
Arnall, A., 2014: A climate of control: flooding, displacement and planned resettlement in the Lower Zambezi River valley, Mozambique. *Geographical Journal*, **180**(2), 141-150, doi:10.1111/geoj.12036.
Arora, D. et al., 2017: Gender (Im)balance in Productive and Reproductive Labor Among Livestock Producers in Colombia: Implications for Climate Change Responses. *CGIAR Research Program on Climate Change, Agriculture and Food Security*, doi:https://hdl.handle.net/10568/79940.

Arroyo, V. et al., 2016: Impact of air pollution and temperature on adverse birth outcomes: Madrid, 2001-2009. *Environ Pollut*, **218**, 1154-1161, doi:10.1016/j.envpol.2016.08.069.
Asadgol, Z. et al., 2019: The effect of climate change on cholera disease: The road ahead using artificial neural network. *PLoS One*, **14**(11), e0224813, doi:10.1371/journal.pone.0224813.
Asefi-Najafabady, S. et al., 2018: Climate change, population, and poverty: vulnerability and exposure to heat stress in countries bordering the Great Lakes of Africa. *Climatic Change*, **148**(4), 561-573, doi:10.1007/s10584-018-2211-5.
Ash, K. and N. Obradovich, 2020: Climatic stress, internal migration, and Syrian civil war onset. *Journal of Conflict Resolution*, **64**(1), 3-31.
Asmall, T. et al., 2021: The adverse health effects associated with drought in Africa. *Sci Total Environ*, **793**, 148500, doi:10.1016/j.scitotenv.2021.148500.
Asmare, B., M. Taddele, S. Berihun and F. Wagnew, 2018: Nutritional status and correlation with academic performance among primary school children, northwest Ethiopia. *BMC research notes*, **11**(1), 1-6.
Asplund, T. and M. Hjerpe, 2020: Project coordinators' views on climate adaptation costs and benefits–justice implications. *Local Environment*, **25**(2), 114-129.
Åström, C. et al., 2017: Vulnerability Reduction Needed to Maintain Current Burdens of Heat-Related Mortality in a Changing Climate—Magnitude and Determinants. *International Journal of Environmental Research and Public Health*, **14**(7), 741-741.
Åström, D. O. et al., 2020: Heat wave-related mortality in Sweden: A case-crossover study investigating effect modification by neighbourhood deprivation. *Scandinavian Journal of Public Health*, **48**(4), 428-435, doi:10.1177/1403494818801615.
Åström, D. O., K. L. Ebi, A. M. Vicedo-Cabrera and A. Gasparrini, 2018: Investigating changes in mortality attributable to heat and cold in Stockholm, Sweden. *International Journal of Biometeorology*, **62**(9), 1777-1780, doi:10.1007/s00484-018-1556-9.
Åström, D. O., B. Forsberg, K. L. Ebi and J. Rocklöv, 2013: Attributing mortality from extreme temperatures to climate change in Stockholm, Sweden. *Nature Climate Change*, **3**(12), 1050-1054, doi:10.1038/nclimate2022.
Asugeni, J., D. MacLaren, P. D. Massey and R. Speare, 2015: Mental health issues from rising sea level in a remote coastal region of the Solomon Islands: current and future. *Australasian Psychiatry*, **23**(6), 22-25, doi:10.1177/1039856215609767.
Atef, S. S., F. Sadeqinazhad, F. Farjaad and D. M. Amatya, 2019: Water conflict management and cooperation between Afghanistan and Pakistan. *Journal of hydrology*, **570**, 875-892.
Atkinson, H. and J. Bruce, 2015: Adolescent Girls, Human Rights and the Expanding Climate Emergency. *Annals of Global Health*, **81**(3), 323-330, doi:10.1016/j.aogh.2015.08.003.
Åtland, K., 2013: The security implications of climate change in the Arctic Ocean. In: *Environmental Security in the Arctic Ocean*. Springer, pp. 205-216.
Auger, N. et al., 2017: Elevated outdoor temperatures and risk of stillbirth. *International Journal of Epidemiology*, **46**(1), 200-208.
Authority), E. et al., 2020: Climate change as a driver of emerging risks for food and feed safety, plant, animal health and nutritional quality. *EFSA (European Food Safety Authority)*, 1-146, doi:doi:10.2903/sp.efsa.2020.EN-1881.
Avaria-Llautureo, J. et al., 2021: Historical warming consistently decreased size, dispersal and speciation rate of fish. *Nature Climate Change*, 1-7.
Avashia, V., A. Garg and H. Dholakia, 2021: Understanding temperature related health risk in context of urban land use changes. *Landscape and Urban Planning*, **212**, doi:10.1016/j.lurbplan.2021.104107.
Avila-Palencia, I. et al., 2018: The effects of transport mode use on self-perceived health, mental health, and social contact measures: A cross-sectional and longitudinal study. *Environment International*, **120**, 199-206, doi:10.1016/j.envint.2018.08.002.
Awuor, L., R. Meldrum and E. Liberda, 2020: Institutional Engagement Practices as Barriers to Public Health Capacity in Climate Change Policy Discourse: Lessons from the Canadian Province of Ontario. *International Journal of Environmental Research and Public Health*, **17(17)**, doi:https://doi.org/10.3390/ijerph17176338
Axelsen, J. B., R. Yaari, B. T. Grenfell and L. Stone, 2014: Multiannual forecasting of seasonal influenza dynamics reveals climatic and evolutionary drivers. *Proceedings of the National Academy of Sciences of the United States of America*, **111**(26), 9538-9542, doi:10.1073/pnas.1321656111.
Ayano, G., 2018: Significance of mental health legislation for successful primary care for mental health and community mental health services: A review. *African Journal of Primary Health Care & Family Medicine*, **10**(1), 1-4, doi:10.4102/phcfm.v10i1.1429.
Ayeb-Karlsson, S., D. Kniveton and T. Cannon, 2020: Trapped in the prison of the mind: Notions of climate-induced (im)mobility decision-making and wellbeing from an urban informal settlement in Bangladesh. *Palgrave Communications*, **6**(1), 62, doi:10.1057/s41599-020-0443-2.
Ayeb-Karlsson, S., C. D. Smith and D. Kniveton, 2018: A discursive review of the textual use of 'trapped' in environmental migration studies: The conceptual birth and troubled teenage years of trapped populations. *Ambio*, **47**(5), 557-573, doi:10.1007/s13280-017-1007-6.
Azage, M., A. Kumie, A. Worku and A. Bagtzoglou, 2015: Childhood Diarrhea Exhibits Spatiotemporal Variation in Northwest Ethiopia: A SaTScan Spatial Statistical Analysis. *Plos One*, **10**(12), doi:10.1371/journal.pone.0144690.

Baez, J., G. Caruso, V. Mueller and C. Niu, 2017: Droughts augment youth migration in Northern Latin America and the Caribbean. *Climatic Change*, **140**(3-4), 423-435.
Bai, X. et al., 2019: Distribution of geographical scale, data aggregation unit and period in the correlation analysis between temperature and incidence of HFRS in mainland China: A systematic review of 27 ecological studies. *Plos Neglected Tropical Diseases*, **13**(8), doi:10.1371/journal.pntd.0007688.
Bai, Y. T. et al., 2015: Effects of Climate and Rodent Factors on Hemorrhagic Fever with Renal Syndrome in Chongqing, China, 1997-2008. *Plos One*, **10**(7), doi:10.1371/journal.pone.0133218.
Baidya, D., S. Maitra and S. Bhattacharjee, 2020: Facing Post-Cyclone Disaster in Times of COVID-19 Pandemic in India: Possible Testing Strategy to Reduce Further Spread of Disease. *Asia-Pacific Journal of Public Health*, **32**(6-7), 376-376, doi:10.1177/1010539520944717.
Baker-Austin, C., J. Trinanes, N. Gonzalez-Escalona and J. Martinez-Urtaza, 2017: Non-Cholera Vibrios: The Microbial Barometer of Climate Change. *Trends Microbiol*, **25**(1), 76-84, doi:10.1016/j.tim.2016.09.008.
Balestri, S. and M. A. Maggioni, 2017: Land-Use Change and Communal Confllicts in Sub-Saharan Africa. *Peace Economics Peace Science and Public Policy*, **23**(4), doi:10.1515/peps-2017-0032.
Bamberg, S., T. Masson, K. Brewitt and N. Nemetschek, 2017: Threat, coping and flood prevention - A meta-analysis. *Journal of Environmental Psychology*, **54**, 116-126, doi:10.1016/j.jenvp.2017.08.001.
Bandura, A., 1982: Self-efficacy mechanism in human agency. . *Self-efficacy mechanism in human agency*, **37(2)**, 122–147, doi:https://doi.org/https://doi.org/10.1037/0003-066X.37.2.122
Bandyopadhyay, R. et al., 2016: Biological control of aflatoxins in Africa: current status and potential challenges in the face of climate change. *World Mycotoxin J.*, **9**(5), 771-789, doi:10.3920/wmj2016.2130.
Banerjee, S., R. Black, A. Mishra and D. Kniveton, 2019a: Assessing vulnerability of remittance-recipient and nonrecipient households in rural communities affected by extreme weather events: Case studies from South-West China and North-East India. *Population Space and Place*, **25**(2), doi:10.1002/psp.2157.
Banerjee, S., A. Hussain, S. Tuladhar and A. Mishra, 2019b: Building capacities of women for climate change adaptation: Insights from migrant-sending households in Nepal. *Climatic Change*, **157**(3-4), 587-609, doi:10.1007/s10584-019-02572-w.
Bank, W., 2021: *Global Economic Prospects, June 2021*. Global Economic Prospects, June 2021, World Bank, Washington DC, USA. ISBN 978-1-4648-1665-9.
Bannister, T. et al., 2021: A Pilot Forecasting System for Epidemic Thunderstorm Asthma in Southeastern Australia. *Bulletin of the American Meteorological Society*, **102**(2), E399-E420, doi:10.1175/bams-d-19-0140.1.
Banwell, N., S. Rutherford, B. Mackey and C. Chu, 2018: Towards improved linkage of disaster risk reduction and climate change adaptation in health: a review. *International journal of environmental research and public health*, **15**(4), doi:https://doi.org/10.3390/ijerph15040793.
Bao, J. et al., 2019: Effects of heat on first-ever strokes and the effect modification of atmospheric pressure: A time-series study in Shenzhen, China. *Science of The Total Environment*, **654**, 1372-1378, doi:https://doi.org/10.1016/j.scitotenv.2018.11.101.
Barach, P. et al., 2020: Disruption of healthcare: Will the COVID pandemic worsen non-COVID outcomes and disease outbreaks? *Prog Pediatr Cardiol*, **59**, 101254, doi:10.1016/j.ppedcard.2020.101254.
Barange, M. et al., 2018: Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. *FAO Fisheries and Aquaculture Technical Paper*.
Barnes, J. H., E. T. Hayes, T. J. Chatterton and J. W. S. Longhurst, 2014: Air quality action planning: why do barriers to remediation in local air quality management remain? *Journal of Environmental Planning and Management*, **57**(5), 660-681, doi:10.1080/09640568.2012.762573.
Barnett, J., 2019: Global environmental change I: Climate resilient peace? *Progress in Human Geography*, **43**(5), 927-936, doi:10.1177/0309132518798077.
Barnett, J. and C. McMichael, 2018: The effects of climate change on the geography and timing of human mobility. *Population and Environment*, **39**(4), 339-356, doi:10.1007/s11111-018-0295-5.
Barquet, K., 2015: "Yes to peace"? Environmental peacemaking and transboundary conservation in Central America. *Geoforum*, **63**, 14-24.
Barquet, K., P. Lujala and J. Rod, 2014: Transboundary conservation and militarized interstate disputes. *Political Geography*, **42**, 1-11, doi:10.1016/j.polgeo.2014.05.003.
Barreca, A. et al., 2016: Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century. *Journal of Political Economy*, **124**(1), 105-159, doi:10.1086/684582.
Baryshnikova, N. and N. Pham, 2019: Natural disasters and mental health: A quantile approach *Economics Letters, 180, 62-66. https://doi.org/10.1016/j.econlet.2019.04.016*, **180**, 62-66, doi:https://doi.org/10.1016/j.econlet.2019.04.016.
Basel, B., G. Goby and J. Johnson, 2020: Community-based adaptation to climate change in villages of Western Province, Solomon Islands. *Marine Pollution Bulletin*, **156**, doi:10.1016/j.marpolbul.2020.111266.
Bateman, I. et al., 2020: Editorial: Economics of the Environment in the Shadow of Coronavirus. *Environmental & Resource Economics*, **76**(4), 519-523, doi:10.1007/s10640-020-00496-z.
Battilani, P., Toscano, P., Van der Fels-Klerx, H. J., Moretti, A., Camardo Leggieri, M., Brera, C., … Robinson, T. , 2016: Aflatoxin B1 contamination in maize in Europe increases due to climate change. Scientific reports, 6.
Baylis, P. et al., 2018: Weather impacts expressed sentiment. *Plos One*, **13**(4), doi:10.1371/journal.pone.0195750.

Beach, R. et al., 2019: Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. *Lancet Planetary Health*, **3**(7), E307-E317, doi:10.1016/s2542-5196(19)30094-4.
Becquart, N. A., E. N. Naumova, G. Singh and K. K. H. Chui, 2018: Cardiovascular Disease Hospitalizations in Louisiana Parishes' Elderly before, during and after Hurricane Katrina. *Int J Environ Res Public Health*, **16**(1), doi:10.3390/ijerph16010074.
Beggs, P. J., 2021: Climate change, aeroallergens, and the aeroexposome. *Environmental Research Letters*, **16**(3), doi:10.1088/1748-9326/abda6f.
Belay, A., J. Recha, T. Woldeamanuel and J. Morton, 2017: Smallholder farmers' adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. *Agriculture and Food Security*, **6**, 1-13, doi:https://doi.org/10.1186/s40066-017-0100-1 .
Belesova, K., I. Kelman and R. Boyd, 2016: Governance through Economic Paradigms: Addressing Climate Change by Accounting for Health. *Politics and Governance*, **4**(4), 87-96, doi:10.17645/pag.v4i4.729.
Belkin, L. and M. Kouchaki, 2017: Too hot to help! Exploring the impact of ambient temperature on helping. *European Journal of Social Psychology*, **47**(5), 525-538, doi:10.1002/ejsp.2242.
Bellemare, M. F., 2015: Rising food prices, food price volatility, and social unrest. *american Journal of agricultural economics*, **97**(1), 1-21.
Benmarhnia, T. et al., 2016: A Difference-in-Differences Approach to Assess the Effect of a Heat Action Plan on Heat-Related Mortality, and Differences in Effectiveness According to Sex, Age, and Socioeconomic Status (Montreal, Quebec). *Environ Health Perspect*, **124**(11), 1694-1699, doi:10.1289/ehp203.
Benmarhnia, T., S. Deguen, J. S. Kaufman and A. Smargiassi, 2015: Vulnerability to Heat-related Mortality A Systematic Review, Meta-analysis, and Meta-regression Analysis. *Epidemiology*, **26**(6), 781-793, doi:10.1097/ede.0000000000000375.
Bennett, S. et al., 2020: Understanding the implications of the Sustainable Development Goals for health policy and systems research: results of a research priority setting exercise. *Globalization and Health*, **16**(1), doi:10.1186/s12992-019-0534-2.
Benveniste, H., J. C. Cuaresma, M. Gidden and R. Muttarak, 2021: Tracing international migration in projections of income and inequality across the Shared Socioeconomic Pathways. *Climatic Change*, 166. Available at: https://link.springer.com/article/10.1007/s10584-021-03133-w.
Benveniste, H., O. Michael and F. Marc, 2020: Effect of border policy on exposure and vulnerability to climate change. *Proceedings of the National Academy of Sciences*, **117**(43), doi:10.1073/pnas.2007597117.
Berndtsson, R. and K. Tussupova, 2020: The future of water management in Central Asia. Multidisciplinary Digital Publishing Institute.
Berrang-Ford, L. et al., 2021: Systematic mapping of global research on climate and health: a machine learning review. The Lancet Planetary Health.
Berry, H. L., K. Bowen and T. Kjellstrom, 2010: Climate change and mental health: a causal pathways framework. *International Journal of Public Health*, **55**(2), 123-132, doi:10.1007/s00038-009-0112-0.
Berry, L. and D. Peel, 2015: Worrying about climate change: is it responsible to promote public debate? *BJPsych International*, **12**(2), 31-32.
Berry, P. et al., 2018: Assessing Health Vulnerabilities and Adaptation to Climate Change: A Review of International Progress. *Int J Environ Res Public Health*, **15**(12), doi:10.3390/ijerph15122626.
Bertana, A., 2020: The role of power in community participation: Relocation as climate change adaptation in Fiji. *Environment and Planning C: Politics and Space*, **38**, 239965442090939, doi:10.1177/2399654420909394.
Bettini, G. and G. Gioli, 2016: Waltz with development: insights on the developmentalization of climate-induced migration. *Migration and Development*, **5**(2), 171-189.
Betts, R. et al., 2018: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5 degrees C and 2 degrees C global warming with a higher-resolution global climate model. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **376**(2119), doi:10.1098/rsta.2016.0452.
Beveridge, L. et al., 2019: Experiences and Drivers of Food Insecurity in Guatemala's Dry Corridor: Insights From the Integration of Ethnographic and Household Survey Data. *Frontiers in Sustainable Food Systems*, **3**, doi:10.3389/fsufs.2019.00065.
Beyene, T., D. Endalamaw, Y. Tolossa and A. Feyisa, 2015: Evaluation of rational use of veterinary drugs especially antimicrobials and anthelmintics in Bishoftu, Central Ethiopia. *BMC Research Notes*.
Bezner Kerr, R. et al., 2021: Can agroecology improve food security and nutrition? A review. *Global Food Security-Agriculture Policy Economics and Environment*, **29**, doi:10.1016/j.gfs.2021.100540.
Bhagat, R., 2017: Migration, gender and right to the city. *Economic and Political Weekly*, 35-40.
Bharara, T. et al., 2018: Green Hospital Initiative by a North Delhi Tertiary Care Hospital: Current Scenario and Future Prospects. *Journal of Clinical and Diagnostic Research*, **12**, DC10-DC14, doi:10.7860/jcdr/2018/34360.11758.
Bhatt, S. et al., 2013: The global distribution and burden of dengue. *Nature*, **496**(7446), 504-507, doi:10.1038/nature12060.

Bhatta, G., P. Aggarwal, S. Poudel and D. Belgrave, 2015: Climate-induced migration in South Asia: Migration decisions and the gender dimensions of adverse climatic events. *Journal of Rural and Community Development*, **10**, 1-23.
Bhavnani, R. R. and B. Lacina, 2015: The effects of weather-induced migration on sons of the soil riots in India. *World Pol.*, **67**, 760.
Billiot, S. et al., 2019: Indigenous perspectives for strengthening social responses to global environmental changes: a response to the social work grand challenge on environmental change. *Journal of Community Practice*, **27**(3-4), 296-316, doi:10.1080/10705422.2019.1658677.
Binder, S., J. Barile, C. Baker and B. Kulp, 2019: Home buyouts and household recovery: neighborhood differences three years after Hurricane Sandy. *Environmental Hazards*, **18**(2), 127-145, doi:10.1080/17477891.2018.1511404.
Blattman, C. and E. Miguel, 2010: Civil war. *Journal of Economic literature*, **48**(1), 3-57.
Bless, P. J. et al., 2016: Acute Gastroenteritis and Campylobacteriosis in Swiss Primary Care: The Viewpoint of General Practitioners. *PLoS One*, **11**(9), e0161650, doi:10.1371/journal.pone.0161650.
Boas, I. et al., 2019: Climate migration myths. *Nature Climate Change*, **9**(12), 901-903, doi:10.1038/s41558-019-0633-3.
Boas, I. and D. Rothe, 2016: From conflict to resilience? Explaining recent changes in climate security discourse and practice. *Environmental Politics*, **25**(4), 613-632, doi:10.1080/09644016.2016.1160479.
Bob, U. and S. Bronkhorst, 2014: *Conflict-sensitive adaptation to climate change in Africa* [Carius, A. and D. Tänzler (eds.)]. Climate Diplomacy Series, Berliner Wissenschafts-Verlag.
Boeckmann, M. and I. Rohn, 2014: Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. *Bmc Public Health*, **14**, doi:10.1186/1471-2458-14-1112.
Bogdanova, E. et al., 2021: The Impact of Climate Change on the Food (In)security of the Siberian Indigenous Peoples in the Arctic: Environmental and Health Risks. *Sustainability*, **13**(5), doi:10.3390/su13052561.
Bohra-Mishra, P. et al., 2017: Climate variability and migration in the Philippines. *Population and Environment*, **38**(3), 286-308, doi:10.1007/s11111-016-0263-x.
Boin, A., P. 't Hart, E. Stern and B. Sundelius, 2005: The politics of crisis management: Public leadership under pressure.
Boithias, L. et al., 2016: Hydrological Regime and Water Shortage as Drivers of the Seasonal Incidence of Diarrheal Diseases in a Tropical Montane Environment. *PLoS Negl Trop Dis*, **10**(12), e0005195, doi:10.1371/journal.pntd.0005195.
Bol, D., M. Giani, A. Blais and P. Loewen, 2020: The effect of COVID-19 lockdowns on political support: Some good news for democracy? *European Journal of Political Research*, **60**(2), 497-505, doi:10.1111/1475-6765.12401.
Bollyky, T. J., T. Templin, M. Cohen and J. L. Dieleman, 2017: Lower-income countries that face the most rapid shift in noncommunicable disease burden are also the least prepared. *Health affairs*, **36**(11), 1866-1875.
Boon, E. K. and S. W. Anuga, 2020: Circular Economy and Its Relevance for Improving Food and Nutrition Security in Sub-Saharan Africa: the Case of Ghana. *Materials Circular Economy*, **2**.
Boonruksa, P., T. Maturachon, P. Kongtip and S. Woskie, 2020: Heat Stress, Physiological Response, and Heat-Related Symptoms among Thai Sugarcane Workers. *International Journal of Environmental Research and Public Health*, **17**(17), doi:10.3390/ijerph17176363.
Booth, S. and D. Zeller, 2005: Mercury, food webs, and marine mammals: Implications of diet and climate change for human health. *Environmental Health Perspectives*, **113**(5), 521-526, doi:10.1289/ehp.7603.
Borderon, M. et al., 2019: Migration influenced by environmental change in Africa: A systematic review of empirical evidence. *Demographic Research*, **41**, 491-544, doi:10.4054/DemRes.2019.41.18.
Borg, M. et al., 2017: The impact of daily temperature on renal disease incidence: an ecological study. *Environmental Health*, **16**, doi:10.1186/s12940-017-0331-4.
Borg, M. A. et al., 2021: Occupational heat stress and economic burden: A review of global evidence. *Environmental Research*, **195**, doi:10.1016/j.envres.2021.110781.
Borrows, J., 2019: Earth Bound: Indigenous Resurgence and Environmental Reconciliation. In: *Resurgence and Reconciliation: Indigenous-Settler Relations and Earth Teachings* [Asch, M., J. Borrows and J. Tully (eds.)]. University of Toronto Press, pp. 49-82.
Boscarino, J. A. et al., 2017: Mental Health Outcomes Among Vulnerable Residents After Hurricane Sandy: Implications for Disaster Research and Planning. *American Journal of Disaster Medicine*, **9**(2), 97-106.
Boscarino, J. A. et al., 2013: Mental Health Outcomes at the Jersey Shore After Hurricane Sandy. *International journal of emergency mental health*, **15**(3), 147–158.
Bose-O'Reilly, S. et al., 2021: COVID-19 and heat waves: New challenges for healthcare systems. *Environmental Research*, **198**, 111153, doi:10.1016/j.envres.2021.111153.
Botana, L. M., 2016: Toxicological Perspective on Climate Change: Aquatic Toxins. *Chemical Research in Toxicology*, **29**(4), 619-625, doi:10.1021/acs.chemrestox.6b00020.
Bouma, M., A. Siraj, X. Rodo and M. Pascual, 2016: El Nino-based malaria epidemic warning for Oromia, Ethiopia, from August 2016 to July 2017. *Tropical Medicine & International Health*, **21**(11), 1481-1488, doi:10.1111/tmi.12776.
Bouman, T., L. Steg and T. Dietz, 2020: Insights from early COVID-19 responses about promoting sustainable action. *Nature Sustainability*, doi:https://doi.org/10.1038/s41893-020-00626-x.

Bourke, S. et al., 2018: Evidence Review of Indigenous Culture for Health and Wellbeing. *International Journal of Health, Wellness & Society*, **8**(4).
Bowen, K., D. Alexander, F. Miller and V. Dany, 2014a: Using Social Network Analysis to Evaluate Health-Related Adaptation Decision-Making in Cambodia. *International Journal of Environmental Research and Public Health*, **11**(2), 1605-1625, doi:10.3390/ijerph110201605.
Bowen, K., K. Ebi and S. Friel, 2014b: Climate change adaptation and mitigation: next steps for cross-sectoral action to protect global health. *Mitigation and Adaptation Strategies For Global Change*, **19**(7), 1033-1040, doi:10.1007/s11027-013-9458-y.
Bowen, K. et al., 2021: Human health and climate change in the Pacific: a review of current knowledge. *Global Sustainabilty*.
Bowen, K. J. and K. L. Ebi, 2017: Health risks of climate change in the World Health Organization South-East Asia Region. *WHO South East Asia J Public Health*, **6**(2), 3-8.
Bowles, D. C., 2015: Climate Change and Health Adaptation: Consequences for Indigenous Physical and Mental Health. *Annals of Global Health*, **81**(3), 427-431, doi:https://doi.org/10.1016/j.aogh.2015.06.004.
Boyer, C. et al., 2020: Using Implementation Science For Health Adaptation: Opportunities For Pacific Island Countries. *Health Affairs*, **39**(12), 2160-2167, doi:10.1377/hlthaff.2020.01101.
Boyle, M. et al., 2020: Cities and the climate and ecological emergency: The liverpool city region response. *Journal of Urban Regeneration and Renewal*, **13**, 365–379.
Bradley, G. L., J. P. Reser, A. I. Glendon and M. C. Ellul, 2014: Distress and coping in response to climate change. *Stress and anxiety: Applications to social and environmental threats, psychological well-being, occupational challenges, and developmental psychology climate change*, 33-42.
Bragg, C. et al., 2018: Remittances as aid following major sudden-onset natural disasters. *Disasters*, **42**(1), 3-18, doi:10.1111/disa.12229.
Brauer, M., J. Zhao, F. Bennitt and J. Stanaway, 2020: Global Access to Handwashing: Implications for COVID-19 Control in Low-Income Countries. *Environmental Health Perspectives*, **128**(5), doi:10.1289/ehp7200.
Bremberg, N., H. Sonnsjö and M. Mobjörk, 2019: The EU and climate-related security risks: a community of practice in the making? *Journal of European integration*, **41**(5), 623-639.
Brenkert-Smith, H., R. Meldrum and A. Champ, 2015: Climate change beliefs and hazard mitigation behaviors: homeowners and wildfire risk. *Environmental Hazards*, **14**(4), 341-360.
Broadbent, A. M., E. S. Krayenhoff and M. Georgescu, 2020: The motley drivers of heat and cold exposure in 21st century US cities. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(35), 21108-21117, doi:10.1073/pnas.2005492117.
Bromet, E. et al., 2017: Post-traumatic stress disorder associated with natural and human-made disasters in the World Mental Health Surveys. *Psychological Medicine*, **47**(2), 227-241, doi:10.1017/s0033291716002026.
Brooks, H. E., 2013: Severe thunderstorms and climate change. *Atmospheric Research*, **123**, 129-138, doi:10.1016/j.atmosres.2012.04.002.
Brosemer, K. et al., 2020: The energy crises revealed by COVID: Intersections of Indigeneity, inequity, and health. *Energy Research & Social Science*, **68**, doi:10.1016/j.erss.2020.101661.
Brown, M. R. G. et al., 2019: After the Fort McMurray wildfire there are significant increases in mental health symptoms in grade 7-12 students compared to controls (vol 19, 18, 2019). *BMC Psychiatry*, **19**, doi:10.1186/s12888-019-2074-y.
Brown, R. C. et al., 2017: Psychosocial interventions for children and adolescents after man-made and natural disasters: a meta-analysis and systematic review. *Psychological Medicine*, **47**(11), 1893-1905, doi:10.1017/s0033291717000496.
Brubacher, J. et al., 2020: Associations of five food- and water-borne diseases with ecological zone, land use and aquifer type in a changing climate. *Sci Total Environ*, **728**, 138808, doi:10.1016/j.scitotenv.2020.138808.
Brügger, A. et al., 2015: Psychological responses to the proximity of climate change. *Nature Climate Change*, **5**(12), 1031-1037, doi:10.1038/nclimate2760.
Brunekreef, B. et al., 2021: Airpollution and COVID-19 . Including elements of air pollution in rural areas, indoor air pollution and vulnerability and resilience aspects of our society against respiratory disease, social inequality stemming from air pollution s tudy for the committee on Environment, Public Health and Food Safety, Policy Department for Economic, Scientific and Quality of Life Policies, European Parliament, Luxembourg.
Bryson, J. et al., 2021: Seasonality, climate change, and food security during pregnancy among indigenous and non-indigenous women in rural Uganda: Implications for maternal-infant health. *Plos One*, **16**(3), doi:10.1371/journal.pone.0247198.
Brzoska, M., 2018: Weather extremes, disasters, and collective violence: Conditions, mechanisms, and disaster-related policies in recent research. *Current Climate Change Reports*, **4**(4), 320-329.
Buckley, R. et al., 2019: Economic value of protected areas via visitor mental health. *Nature Communications*, **10**(1), 1-10, doi:10.1038/s41467-019-12631-6.
Buhaug, H., M. Croicu, H. Fjelde and N. v. Uexkull, 2020: A conditional model of local income shock and civil conflict.
Buhaug, H. et al., 2014: One effect to rule them all? A comment on climate and conflict. *Climatic Change*, **127**(3-4), 391-397.

Buhaug, H. and J. Vestby, 2019: On growth projections in the Shared Socioeconomic Pathways. *Global Environmental Politics*, **19**(4), 118-132.
Buhaug, H. and N. von Uexkull, 2021: Vicious circles: Violence, vulnerability, and climate change. *Annual Review of Environment and Resources*, **46**.
Bukvic, A. and G. Owen, 2017: Attitudes towards relocation following Hurricane Sandy: should we stay or should we go? *Disasters*, **41**(1), 101-123, doi:10.1111/disa.12186.
Bunker, A. et al., 2016: Effects of Air Temperature on Climate-Sensitive Mortality and Morbidity Outcomes in the Elderly; a Systematic Review and Meta-analysis of Epidemiological Evidence. *EBioMedicine*, **6**, 258-268, doi:10.1016/j.ebiom.2016.02.034.
Bunn, M., 2019: Nuclear disarmament, nuclear energy, and climate change: Exploring the linkages. *Nuclear Disarmament*, 185-204.
Burkart, K., Gabriele. et al., 2021: Projecting Global Mortality Due to Non-Optimal Temperature From 2020 to 2100: A Global Burden of Disease Forecasting Study.
Burke, M. et al., 2018: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8**(8), 723-+, doi:10.1038/s41558-018-0222-x.
Burke, M., S. M. Hsiang and E. Miguel, 2015a: Global non-linear effect of temperature on economic production. *Nature*, **527**(7577), 235-239, doi:10.1038/nature15725.
Burke, M., H. S. M. and M. Edward, 2015b: Climate and Conflict. *Annual Review of Economics*, **7**(1), 577--617, doi:10.1146/annurev-economics-080614-115430.
Burnham, M. and Z. Ma, 2017: Climate change adaptation: factors influencing Chinese smallholder farmers' perceived self-efficacy and adaptation intent. *Regional Environmental Change*, **17**(1), 171-186.
Busby, J., 2018: Taking stock: the field of climate and security. *Current Climate Change Reports*, **4**(4), 338-346.
Busby, J. and N. Krishnan, 2017: Widening the Scope to Asia: Climate Change and Security. *The Centre for Climate and Security*.
Busby, J. et al., 2018: In harm's way: Climate security vulnerability in Asia. *World Development*, **112**, 88-118.
Butler, C. D. and D. Harley, 2010: Primary, secondary and tertiary effects of eco-climatic change: the medical response. *Postgraduate Medical Journal*, **86**(1014), 230, doi:10.1136/pgmj.2009.082727.
Butler, T. et al., 2019: Aboriginal and Torres Strait Islander people's domains of wellbeing: A comprehensive literature review. *Social Science & Medicine*, **233**, 138-157, doi:10.1016/j.socscimed.2019.06.004.
Butt, N., F. Lambrick, M. Menton and A. Renwick, 2019: The supply chain of violence. *Nature Sustainability*, **2**(8), 742-747.
Cai, R., S. Feng, M. Oppenheimer and M. Pytlikova, 2016: Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management*, **79**, 135-151, doi:https://doi.org/10.1016/j.jeem.2016.06.005.
Cai, W. J. et al., 2021: The 2020 China report of the Lancet Countdown on health and climate change. *Lancet Public Health*, **6**(1), E64-E81, doi:10.1016/s2468-2667(20)30256-5.
Caini, S., F. Schellevis, C. E. Seblain and J. Paget, 2018: Important changes in the timing of influenza epidemics in the WHO European Region over the past 20 years: virological surveillance 1996 to 2016. *Eurosurveillance*, **23**(1), 2-10, doi:10.2807/1560-7917.es.2018.23.1.17-00302.
Call, M., C. Gray, M. Yunus and M. Emch, 2017: Disruption, not displacement: Environmental variability and temporary migration in Bangladesh. *Global Environmental Change*, **46**, 157-165.
Camacho, A. et al., 2018: Cholera epidemic in Yemen, 2016-18: an analysis of surveillance data. *Lancet Glob Health*, **6**(6), e680-e690, doi:10.1016/s2214-109x(18)30230-4.
Caminade, C., K. M. McIntyre and A. E. Jones, 2019: Impact of recent and future climate change on vector-borne diseases. *Ann N Y Acad Sci*, **1436**(1), 157-173, doi:10.1111/nyas.13950.
Campagnolo, L. and M. Davide, 2019: Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality. *World Development*, **122**, 96-109, doi:https://doi.org/https://doi.org/10.1016/j.worlddev.2019.05.015.
Campbell, S., T. A. Remenyi, C. J. White and F. H. Johnston, 2018: Heatwave and health impact research: A global review. *Health & Place*, **53**, 210-218, doi:https://doi.org/10.1016/j.healthplace.2018.08.017.
Canu, W. H., J. P. Jameson, E. H. Steele and M. Denslow, 2017: Mountaintop Removal Coal Mining and Emergent Cases of Psychological Disorder in Kentucky. *Community Ment. Health J.*, **53**(7), 802-810, doi:10.1007/s10597-017-0122-y.
Cárdenas, M. L. and E. Olivius, 2021: Building Peace in the Shadow of War: Women-to-Women Diplomacy as Alternative Peacebuilding Practice in Myanmar. *Journal of Intervention and Statebuilding*, 1-20.
Carleton, T. A., 2017: Crop-damaging temperatures increase suicide rates in India. . *Proceedings of the National Academy of Sciences of the United States of America*, **114(33)**, 8746-8751, doi:https://doi.org/10.1073/pnas.1701354114.
Carleton, T. A. and S. M. Hsiang, 2016: Social and economic impacts of climate. *Science*, **353**(6304).
Carlsten, C., S. Salvi, G. W. K. Wong and K. F. Chung, 2020: Personal strategies to minimise effects of air pollution on respiratory health: advice for providers, patients and the public. *European Respiratory Journal*, **55**(6), doi:10.1183/13993003.02056-2019.

Carlton, E. et al., 2016: A systematic review and meta-analysis of ambient temperature and diarrhoeal diseases. *International Journal of Epidemiology*, **45**(1), 117-130, doi:10.1093/ije/dyv296.
Carman, J. and M. Zint, 2020: Defining and classifying personal and household climate change adaptation behaviors. *Global Environmental Change-Human and Policy Dimensions*, **61**, doi:10.1016/j.gloenvcha.2020.102062.
Carrico, A. R. and K. Donato, 2019: Extreme weather and migration: evidence from Bangladesh. *Population and Environment*, **41**(1), 1-31, doi:10.1007/s11111-019-00322-9.
Carter, M. and S. Janzen, 2018: Social protection in the face of climate change: targeting principles and financing mechanisms. *Environment and Development Economics*, **23**(3), 369-389, doi:10.1017/s1355770x17000407.
Caruso, R., I. Petrarca and R. Ricciuti, 2016: Climate change, rice crops, and violence: Evidence from Indonesia. *Journal of Peace Research*, **53**(1), 66-83, doi:10.1177/0022343315616061.
Carvajal, T. M. et al., 2018: Machine learning methods reveal the temporal pattern of dengue incidence using meteorological factors in metropolitan Manila, Philippines. *BMC Infect Dis*, **18**(1), 183, doi:10.1186/s12879-018-3066-0.
Casado-Asensio, J., T. Kato and J. Sedemund, 2020: Climate-resilient development. In: *Development Co-operation Report 2020: Learning from Crises, Building Resilience* [Oecd (ed.)]. OECD Publishing, Paris.
Cattaneo, C. et al., 2019: Human Migration in the Era of Climate Change. *Review of Environmental Economics and Policy*, **13**(2), 189-206, doi:10.1093/reep/rez008.
Cattaneo, C. and P. G., 2016: The migration response to increasing temperatures. *Journal of Development Economics*, **122**, 127--146.
Cattaneo, C. and E. Massetti, 2019: Does Harmful Climate Increase or Decrease Migration? Evidence from Rural Households in Nigeria. *Climate Change Economics*, **10**(4), doi:10.1142/s2010007819500131.
CDC, U., 2019: CDC's Building Resilience Against Climate Effects (BRACE) Framework. National Centre for Environmental Health.
Cederman, L.-E. and N. B. Weidmann, 2017: Predicting armed conflict: Time to adjust our expectations? *Science*, **355**(6324), 474-476.
Centre), I., 2020: Global Report on Internal Displacement, Geneva, 136p pp.
Céspedes-Báez, L. M. R., F.J., 2018: 'Peace Without Women Does Not Go!' Women's Struggle for Inclusion in Colombia's Peace Process with the FARC, 83-109 pp.
Chadsuthi, S., S. Iamsirithaworn, W. Triampo and D. A. Cummings, 2016: The impact of rainfall and temperature on the spatial progression of cases during the chikungunya re-emergence in Thailand in 2008-2009. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **110**(2), 125-133, doi:10.1093/trstmh/trv114.
Chambers, J., 2020: Global and cross-country analysis of exposure of vulnerable populations to heatwaves from 1980 to 2018. *Climatic Change*, **163**(1), 539-558, doi:10.1007/s10584-020-02884-2.
Chan, E. et al., 2018: Association between ambient temperatures and mental disorder hospitalizations in a subtropical city: A time-series study of Hong Kong special administrative region. *International Journal of Environmental Research and Public Health*, **15**(4), 754.
Chan, E. Y. Y. and S. Peijun, 2017: Health and Risks: Integrating Health into Disaster Risk Reduction, Risk Communication, and Building Resilient Communities. *International Journal of Disaster Risk Science*, **8**(2), 107--108, doi:10.1007/s13753-017-0131-z.
Chandra, A. et al., 2017: Gendered vulnerabilities of smallholder farmers to climate change in conflict-prone areas: A case study from Mindanao, Philippines. *Journal of Rural Studies*, **50**, 45-59, doi:10.1016/j.jrurstud.2016.12.011.
Chang, A. Y. et al., 2019: Past, present, and future of global health financing: a review of development assistance, government, out-of-pocket, and other private spending on health for 195 countries, 1995–2050. *The Lancet*, **393**(10187), 2233-2260.
Chang, C. C. and S. C. Chen, 2015: Colliding Epidemics and the Rise of Cryptococcosis. *J Fungi (Basel)*, **2**(1), doi:10.3390/jof2010001.
Chang, C. J., C. S. Chen, C. J. Tien and M. R. Lu, 2018: Epidemiological, clinical and climatic characteristics of dengue fever in Kaohsiung City, Taiwan with implication for prevention and control. *PLoS One*, **13**(1), e0190637, doi:10.1371/journal.pone.0190637.
Chang, K. M. et al., 2017: Ancillary health effects of climate mitigation scenarios as drivers of policy uptake: a review of air quality, transportation and diet co-benefits modeling studies. *Environ. Res. Lett.*, **12**(11), 113001, doi:10.1088/1748-9326/aa8f7b.
Chapin, F. S., III et al., 2016: Community-empowered adaptation for self-reliance. *Current Opinion in Environmental Sustainability*, **19**, 67-75, doi:10.1016/j.cosust.2015.12.008.
Chapra, S. C. et al., 2017: Climate change impacts on harmful algal blooms in US freshwaters: a screening-level assessment. *Environ. Sci. Technol.*, **51**(16), 8933-8943.
Charlesworth, K. and M. Jamieson, 2019: Healthcare in a carbon-constrained world. *Australian Health Review*, **43**(3), 241-245, doi:10.1071/ah17184.
Charlesworth, K. E. and M. Jamieson, 2018: Healthcare in a carbon-constrained world. *Aust Health Rev*, doi:10.1071/ah17184.
Charlesworth, K. E., G. J. Stewart and P. Sainsbury, 2018: Addressing the carbon footprint of health organisations: eight lessons for implementation. *Public Health Research & Practice*, **28**(4), doi:10.17061/phrp2841830.

Charlson, F. et al., 2021: Climate Change and Mental Health: A Scoping Review. *Int J Environ Res Public Health*, **18**(9), doi:10.3390/ijerph18094486.
Chen, C. C. et al., 2021a: Projection of future temperature extremes, related mortality, and adaptation due to climate and population changes in Taiwan. *Science of the Total Environment*, **760**, doi:10.1016/j.scitotenv.2020.143373.
Chen, J. et al., 2020: Global socioeconomic exposure of heat extremes under climate change,. *Journal of Cleaner Production*, **Volume 277, 2020,123275,**, 123275
doi:https://doi.org/10.1016/j.jclepro.2020.123275.
.
Chen, J. J., V. Mueller, Y. Jia and S. Tseng, 2017: Validating Migration Responses to Flooding Using Satellite and Vital Registration Data. *American Economic Review*, **107**(5), 441-445.
Chen, K. et al., 2019: Temporal variations in the triggering of myocardial infarction by air temperature in Augsburg, Germany, 1987-2014. *European heart journal*, doi:10.1093/eurheartj/ehz116.
Chen, K. et al., 2018: Future ozone-related acute excess mortality under climate and population change scenarios in China: A modeling study. *Plos Medicine*, **15**(7), doi:10.1371/journal.pmed.1002598.
Chen, L. et al., 2021b: The occurrence and control of waterborne viruses in drinking water treatment: A review. *Chemosphere*, **281**, 130728, doi:10.1016/j.chemosphere.2021.130728.
Chen, M., 2015: Self-efficacy or collective efficacy within the cognitive theory of stress model: Which more effectively explains people's self-reported proenvironmental behavior? *Journal of Environmental Psychology*, **42**, 66-75, doi:10.1016/j.jenvp.2015.02.002.
Cheng, A. et al., 2017: Analyzing the Potential Risk of Climate Change on Lyme Disease in Eastern Ontario, Canada Using Time Series Remotely Sensed Temperature Data and Tick Population Modelling. *Remote Sensing*, **9**(6), doi:10.3390/rs9060609.
Cheng, J. and P. Berry, 2013: Development of key indicators to quantify the health impacts of climate change on Canadians. *Int. J. Public Health*, **58**(5), 765-775, doi:10.1007/s00038-013-0499-5.
Cheng, J. et al., 2018: Heatwave and elderly mortality: An evaluation of death burden and health costs considering short-term mortality displacement. *Environment International*, **115**, 334-342, doi:10.1016/j.envint.2018.03.041.
Cheng, J. et al., 2019: Impacts of heat, cold, and temperature variability on mortality in Australia, 2000-2009. *Science of the Total Environment*, **651**, 2558-2565, doi:10.1016/j.scitotenv.2018.10.186.
Cheng, J. et al., 2016: Impacts of temperature change on ambulance dispatches and seasonal effect modification. *International Journal of Biometeorology*, **60**(12), 1863-1871, doi:10.1007/s00484-016-1173-4.
Cheng, L. et al., 2020: Record-Setting Ocean Warmth Continued in 2019. *Advances in Atmospheric Sciences*, **37**(2), 137-142, doi:10.1007/s00376-020-9283-7.
Cheng, S. et al., 2021: The effect of average temperature on suicide rates in five urban California counties 1999–2019: an ecological time series analysis.
Chersich, M. F., F. Scorgie, H. Rees and C. Y. Wright, 2018: How climate change can fuel listeriosis outbreaks in South Africa. *S Afr Med J*, **108**(6), 453-454, doi:10.7196/SAMJ.2018.v108i6.13274.
Chhetri, B. K. et al., 2019: Projected local rain events due to climate change and the impacts on waterborne diseases in Vancouver, British Columbia, Canada. *Environ Health*, **18**(1), 116, doi:10.1186/s12940-019-0550-y.
Chiabai, A. et al., 2018a: The nexus between climate change, ecosystem services and human health: Towards a conceptual framework. *Science of the Total Environment*, **635**, 1191-1204, doi:10.1016/j.scitotenv.2018.03.323.
Chiabai, A., J. V. Spadaro and M. B. Neumann, 2018b: Valuing deaths or years of life lost? Economic benefits of avoided mortality from early heat warning systems. *Mitigation and Adaptation Strategies for Global Change*, **23**(7), 1159-1176, doi:10.1007/s11027-017-9778-4.
Chindarkar, N., 2012: Gender and climate change-induced migration: proposing a framework for analysis. *Environmental Research Letters*, **7**(2), 025601-025601, doi:10.1088/1748-9326/7/2/025601.
Choi, C., P. Berry and A. Smith, 2021: The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. *Journal of Environmental Management*, **291**, doi:10.1016/j.jenvman.2021.112583.
Chong, K. C. et al., 2020a: Association between meteorological variations and activities of influenza A and B across different climate zones: a multi-region modelling analysis across the globe. *Journal of Infection*, **80**(1), 84-98, doi:10.1016/j.jinf.2019.09.013.
Chong, K. C. et al., 2020b: Latitudes mediate the association between influenza activity and meteorological factors: A nationwide modelling analysis in 45 Japanese prefectures from 2000 to 2018. *Science of the Total Environment*, **703**, doi:10.1016/j.scitotenv.2019.134727.
Chort, I. and M. de la Rupelle, 2016: Determinants of Mexico-U.S. Outward and Return Migration Flows: A State-Level Panel Data Analysis. *Demography*, **53**(5), 1453-1476.
Choularton, R. and P. Krishnamurthy, 2019: How accurate is food security early warning? Evaluation of FEWS NET accuracy in Ethiopia. *Food Security*, **11**(2), 333-344, doi:10.1007/s12571-019-00909-y.
Chowdhury, F. R. et al., 2018a: The association between temperature, rainfall and humidity with common climate-sensitive infectious diseases in Bangladesh. *PLoS One*, **13**(6), e0199579, doi:10.1371/journal.pone.0199579.
Chowdhury, S., S. Dey and K. R. Smith, 2018b: Ambient PM2.5 exposure and expected premature mortality to 2100 in India under climate change scenarios. *Nat. Commun.*, **9**(1), 318, doi:10.1038/s41467-017-02755-y.
Chu, E. and K. Michael, 2018: Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. *Environment and Ubanization*, **31**(1), 139-156, doi:10.1177/0956247818814449.

Chuang, T. W., L. F. Chaves and P. J. Chen, 2017: Effects of local and regional climatic fluctuations on dengue outbreaks in southern Taiwan. *PLoS One*, **12**(6), e0178698, doi:10.1371/journal.pone.0178698.
Chun, H. B. C., K., Hwang, H., and S. Sohn, 2019: Effects of the El Niño Southern Oscillation on Influenza Peak Activity Timing. *Online Journal of Public Health Informatics*, 11(1).
Chung, Y. et al., 2018: Changing Susceptibility to Non-Optimum Temperatures in Japan, 1972-2012: The Role of Climate, Demographic, and Socioeconomic Factors. *Environmental health perspectives*, **126**(5), 057002-057002, doi:10.1289/ehp2546.
Cianconi, P., S. Betro and L. Janiri, 2020: The Impact of Climate Change on Mental Health: A Systematic Descriptive Review. *Frontiers in Psychiatry*, **11**, doi:10.3389/fpsyt.2020.00074.
CIAT, F. and A. o. B. I. and, 2021: Indigenous Peoples' food systems: Insights on sustainability and resilience from the front line of climate change, Rome.
Cidro, J., B. Adekunle, E. Peters and T. Martens, 2015: Beyond food security: understanding access to cultural food for urban indigenous people in Winnipeg as indigenous food sovereignty. *Canadian Journal of Urban Research*, **24**, 24+.
Cil, G. and T. A. Cameron, 2017: Potential Climate Change Health Risks from Increases in Heat Waves: Abnormal Birth Outcomes and Adverse Maternal Health Conditions. *Risk Anal.*, **37**(11), 2066-2079, doi:10.1111/risa.12767.
Cisse, G., 2019: Food-borne and water-borne diseases under climate change in low- and middle-income countries: Further efforts needed for reducing environmental health exposure risks. *Acta Trop*, **194**, 181-188, doi:10.1016/j.actatropica.2019.03.012.
Cissé, G., J. A. Menezes and U. Confalonieri, 2018: Climate-sensitive infectious diseases. In: *The Adaptation Gap Report 2018* [Unep (ed.)]. United Nations Environment Programme (UNEP), Nairobi, Kenya, pp. 49-59. ISBN 978-92-807-3728-8.
Cissé, G. et al., 2016: Vulnerabilities of water and sanitation at households and community levels in face of climate variability and change: trends from historical climate time series in a West African medium-sized town. *Int. J. Global Environmental Issues* **Vol. 15, Nos. 1/2**, 81–99.
Claeys, M. J., S. Rajagopalan, T. S. Nawrot and R. D. Brook, 2017: Climate and environmental triggers of acute myocardial infarction. *Eur. Heart J.*, **38**(13), 955-960, doi:10.1093/eurheartj/ehw151.
Clare, A., R. Graber, L. Jones and D. Conway, 2017: Subjective measures of climate resilience: What is the added value for policy and programming? *Global Environmental Change-Human and Policy Dimensions*, **46**, 17-22, doi:10.1016/j.gloenvcha.2017.07.001.
Clark, M. and D. Tilman, 2017: Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, **12**(6), doi:10.1088/1748-9326/aa6cd5.
Clayton, S. and B. Karazsia, 2020: Development and validation of a measure of climate change anxiety. *Journal of Environmental Psychology*, **69**, doi:10.1016/j.jenvp.2020.101434.
Clayton, S., C. M. Manning, K. Krygsman and M. Speiser, 2017: *Mental Health and Our Changing Climate: Impacts, Implications, and Guidance.* American Psychological Association, and ecoAmerica. , Washington, DC, 69 pp.
Clow, K. M. et al., 2017: Northward range expansion of Ixodes scapularis evident over a short timescale in Ontario, Canada. *Plos One*, **12**(12), doi:10.1371/journal.pone.0189393.
Cohen, B., E. Tyler and T. Gunfas, 2017: Lessons from co-impacts assessment under the Mitigation Action Plans and Scenarios (MAPS) Programme. *Climate Policy*, **17**(8), 1065-1075, doi:https://doi.org/10.1080/14693062.2016.1222258.
Collaborators, G. B. o. D. D. and Injuries, 2020: Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *10258*, **396**.
Collaborators, G. B. o. D. M., 2018a: Global, regional, and national age-sex-specific mortality and life expectancy, 1950–2017: a systematic analysis for the Global Burden of Disease Study 2017. **392**(10159), 1684-1735, doi:https://doi.org/10.1016/S0140-6736(18)31891-9.
Collaborators, G. D., 2019: Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, **393**(10184), 1958-1972, doi:https://doi.org/10.1016/S0140-6736(19)30041-8.
Collaborators, G. R. F., 2018b: Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, **392**(10159), 1923-1994, doi:https://doi.org/10.1016/S0140-6736(18)32225-6.
Collaco, J. M., L. J. Appel, J. McGready and G. R. Cutting, 2018: The relationship of lung function with ambient temperature. *PLoS One*, **13**(1), e0191409, doi:10.1371/journal.pone.0191409.
Colon-Gonzalez, F., C. Fezzi, I. Lake and P. Hunter, 2013: The Effects of Weather and Climate Change on Dengue. *Plos Neglected Tropical Diseases*, **7**(11), doi:10.1371/journal.pntd.0002503.
Confalonieri, U., J. A. Menezes and C. Margonari, 2017: Environmental Change and the Emergence of Infectious Diseases: A Regional Perspective from South America. In: *Examining the Role of Environmental Change on Emerging Infectious Diseases and Pandemics:*, pp. 109-137.
Confalonieri, U. E., J. A. Menezes and C. Margonari de Souza, 2015: Climate change and adaptation of the health sector: The case of infectious diseases. *Virulence*, **6**(6), 554-557, doi:10.1080/21505594.2015.1023985.

Coniglio, N. D. and G. Pesce, 2015: Climate variability and international migration: an empirical analysis. *Environment and Development Economics*, **20**(4), 438-468.
Connell, J., 2016: Last days in the Carteret Islands? Climate change, livelihoods and migration on coral atolls. *Asia Pacific Viewpoint*, **57**(1), 3--15.
Connolly, M., 2013: Some Like It Mild and Not Too Wet: The Influence of Weather on Subjective Well-Being. *Journal of Happiness Studies*, **14**(2), 457-473, doi:10.1007/s10902-012-9338-2.
Corvalan, C. et al., 2020: Towards Climate Resilient and Environmentally Sustainable Health Care Facilities. *International Journal of Environmental Research and Public Health*, **17**(23), doi:10.3390/ijerph17238849.
Costa, A. F., G. Hoek, B. Brunekreef and A. de Leon, 2017: Air Pollution and Deaths among Elderly Residents of Sao Paulo, Brazil: An Analysis of Mortality Displacement. *Environmental Health Perspectives*, **125**(3), 349-354, doi:10.1289/ehp98.
Coughlan de Perez, E. et al., 2021: Epidemiological versus meteorological forecasts: best practice for linking models to policy making. *International Journal of Forecasting*, In press.
Crawford, A. and C. Church, 2020: *The NAP Process and Peacebuilding*. NAP Global Network Briefing Note, International Institute for Sustainable Development (IISD).
Crawford, A. et al., 2015: *Promoting climate-resilient peacebuilding in fragile states*. International Institute for Sustainable Development (IISD), Geneva.
Cromar, K. R., M. Ghazipura, L. A. Gladson and L. Perlmutt, 2020: Evaluating the US Air Quality Index as a risk communication tool: Comparing associations of index values with respiratory morbidity among adults in California. *Plos One*, **15**(11), doi:10.1371/journal.pone.0242031.
Cunado, J. and F. P. de Gracia, 2013: Environment and Happiness: New Evidence for Spain. *Social Indicators Research*, **112**(3), 549-567, doi:10.1007/s11205-012-0038-4.
Cundill, G. et al., 2021: Toward a climate mobilities research agenda: Intersectionality, immobility, and policy responses. *Global Environmental Change*, 69. Available at: https://www.sciencedirect.com/science/article/pii/S0959378021000947.
Cunsolo, A. et al., 2020: "You can never replace the caribou": Inuit Experiences of Ecological Grief from Caribou Declines. *American Imago*, **77**(1), 31-59, doi:10.1353/aim.2020.0002.
Cunsolo, A. and N. R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8**(4), 275-281, doi:10.1038/s41558-018-0092-2.
Cunsolo Willox, A. et al., 2013: Climate change and mental health: an exploratory case study from Rigolet, Nunatsiavut, Canada. *Climatic Change*, **121**(2), 255-270.
Cunsolo Willox, A. et al., 2015: Examining relationships between climate change and mental health in the Circumpolar North. *Regional Environmental Change*, **15**(1), 169-182.
Curriero, F. C., J. A. Patz, J. B. Rose and S. Lele, 2001: The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *American Journal of Public Health*, **91**(8), 1194-1199, doi:10.2105/ajph.91.8.1194.
Curtis, K., E. Fussell and J. DeWaard, 2015: Recovery Migration After Hurricanes Katrina and Rita: Spatial Concentration and Intensification in the Migration System. *Demography*, **52**(4), 1269-1293.
Curtis, S. et al., 2017: Impact of extreme weather events and climate change for health and social care systems. *Environmental Health*, **16**, 23-32, doi:10.1186/s12940-017-0324-3.
Cusack, L., C. de Crespigny and P. Athanasos, 2011: Heatwaves and their impact on people with alcohol, drug and mental health conditions: a discussion paper on clinical practice considerations. *Journal of Advanced Nursing*, **67**(4), 915-922, doi:10.1111/j.1365-2648.2010.05551.x.
D'Amato, G. et al., 2020: The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens. *Allergy*, **75**(9), 2219-2228, doi:10.1111/all.14476.
D'Odorico, P. et al., 2018: The global food-energy-water nexus. *Reviews of Geophysics*, **56**(3), 456-531.
Dahl, K., R. Licker, J. T. Abatzoglou and J. Declet-Barreto, 2019: Increased frequency of and population exposure to extreme heat index days in the United States during the 21st century. *Environmental Research Communications*, **1**(7), doi:10.1088/2515-7620/ab27cf.
Damschroder, L. J. et al., 2009: Fostering implementation of health services research findings into practice: a consolidated framework for advancing implementation science. *Implement. Sci.*, **4**(1), 50.
Daniel, M. et al., 2018: Increased Relative Risk of Tick-Borne Encephalitis in Warmer Weather. *Frontiers in Cellular and Infection Microbiology*, **8**, doi:10.3389/fcimb.2018.00090.
Dannenberg, A., H. Frumkin, J. Hess and K. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: public health implications. *Climatic Change*, **153**(1-2), 1-14, doi:10.1007/s10584-019-02382-0.
Dar, O. et al., 2014: Integrating Health Into Disaster Risk Reduction Strategies: Key Considerations for Success. *American Journal of Public Health*, **104**(10), 1811--1816, doi:10.2105/ajph.2014.302134.
Dasandi, N., H. Graham, P. Lampard and S. Mikhaylov, 2021: Engagement with health in national climate change commitments under the Paris Agreement: a global mixed-methods analysis of the nationally determined contributions. *Lancet Planetary Health*, **5**(2), 93-101.
David-Chavez, D. and M. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environmental Research Letters*, **13**(12), doi:10.1088/1748-9326/aaf300.

Davies, M. et al., 2013: Promoting Resilient Livelihoods Through Adaptive Social Protection: Lessons from 124 Programmes in South Asia. *Development Policy Review*, **31**, doi:10.1111/j.1467-7679.2013.00600.x.
Davis, R. E. et al., 2016: Cold, dry air is associated with influenza and pneumonia mortality in Auckland, New Zealand. *Influenza and Other Respiratory Viruses*, **10**(4), 310-313, doi:10.1111/irv.12369.
Day, A. and J. Caus, 2020: *Conflict Prevention in the Era of Climate Change: Adapting the UN to Climate-Security Risks*. United Nations University. ISBN 9280865145.
De'Donato, F. et al., 2018: Temporal variation in the effect of heat and the role of the Italian heat prevention plan. *Public Health*, **161**, 154-162, doi:10.1016/j.puhe.2018.03.030.
De Châtel, F., 2014: The role of drought and climate change in the Syrian uprising: Untangling the triggers of the revolution. *Middle Eastern Studies*, **50**(4), 521-535.
De Dominicis, S. et al., 2015: We are at risk, and so what? Place attachment,environmental risk perceptions and preventive coping behaviours. *Journal of Environmental Psychology*, **43**, 66-78.
De Juan, A., 2015: Long-term environmental change and geographical patterns of violence in Darfur, 2003–2005. *Political Geography*, **45**, 22-33.
de la Vega-Leinert, A. C., S. Stoll-Kleemann and E. Wegener, 2018: Managed Realignment (MR) along the Eastern German Baltic Sea: A Catalyst for Conflict or for a Coastal Zone Management Consensus. *Journal of Coastal Research*, **34**(3), 586-601, doi:10.2112/jcoastres-d-15-00217.1.
de Leon-Martinez, L. et al., 2020: Critical review of social, environmental and health risk factors in the Mexican indigenous population and their capacity to respond to the COVID-19. *Science of the Total Environment*, **733**, doi:10.1016/j.scitotenv.2020.139357.
de Lima, C. et al., 2021: Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters*, **16**(4), doi:10.1088/1748-9326/abeb9f.
De Neve, J.-E., E. Diener, L. Tay and C. Xuereb, 2013: *The Objective Benefits of Subjective Well-Being* [Helliwell, J. L. R. and J. e. Sachs (eds.)]. World Happiness Report 2013, New York: UN Sustainable Development Solutions Network. Available at: https://ssrn.com/abstract=2306651.
Defor, A. and T. V. Oheneba-Dornyo, 2020: IS CLIMATE CHANGE HAMPERING GLOBAL HEALTH SECURITY?: A REVIEW OF THE EVIDENCE.
Degen, A. and S. El-Meccawi, 2009: Livestock production among urban Negev Bedouin. *Outlook on Agriculture*, **38**(4), 327-335, doi:10.5367/000000009790422106.
Delhey, J. and G. Dragolov, 2016: Happier together. Social cohesion and subjective well-being in Europe. *Int. J. Psychol.*, **51**(3), 163-176, doi:10.1002/ijop.12149.
Dellink, R., J. Chateau, E. Lanzi and B. Magné, 2017: Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 200-214.
Demain, J., 2018: Climate Change and the Impact on Respiratory and Allergic Disease: 2018. *Current Allergy and Asthma Reports*, **18**(4), 1-5, doi:10.1007/s11882-018-0777-7.
Deng, S. Z. et al., 2020: Climate change, air pollution, and allergic respiratory diseases: a call to action for health professionals. *Chin Med J (Engl)*, **133**(13), 1552-1560, doi:10.1097/cm9.0000000000000861.
Dennekamp, M. et al., 2015: Forest Fire Smoke Exposures and Out-of-Hospital Cardiac Arrests in Melbourne, Australia: A Case-Crossover Study. *Environ. Health Perspect.*, **123**(10), 959-964, doi:10.1289/ehp.1408436.
Desai, B. et al., 2021: Addressing the human cost in a changing climate. *Science*, 372(6548), 1284 LP - 1287. Available at: http://science.sciencemag.org/content/372/6548/1284.abstract.
Deshpande, A., H. H. Chang and K. Levy, 2020: Heavy Rainfall Events and Diarrheal Diseases: The Role of Urban-Rural Geography. *Am J Trop Med Hyg*, **103**(3), 1043-1049, doi:10.4269/ajtmh.19-0768.
Deslatte, A., 2020: The Erosion of Trust During a Global Pandemic and How Public Administrators Should Counter It. *American Review of Public Administration*, **50**(6-7), 489-496, doi:10.1177/0275074020941676.
DeWaard, J., K. J. Curtis and E. Fussell, 2016: Population recovery in New Orleans after Hurricane Katrina: exploring the potential role of stage migration in migration systems. *Population and Environment*, **37**(4), 449-463, doi:10.1007/s11111-015-0250-7.
Deyle, E. R. et al., 2016: Global environmental drivers of influenza. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(46), 13081-13086, doi:10.1073/pnas.1607747113.
Dialesandro, J., N. Brazil, S. Wheeler and Y. Abunnasr, 2021: Dimensions of Thermal Inequity: Neighborhood Social Demographics and Urban Heat in the Southwestern US. *International Journal of Environmental Research and Public Health*, **18**(3), doi:10.3390/ijerph18030941.
Diaz-Mendez, S. E. et al., 2018: Economic, environmental and health co-benefits of the use of advanced control strategies for lighting in buildings of Mexico. *Energy Policy*, **113**, 401-409, doi:10.1016/j.enpol.2017.11.028.
Diaz, D. B., 2016: Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). *Climatic Change*, **137**(1-2), 143-156.
Diaz, J. et al., 2018: Time trend in the impact of heat waves on daily mortality in Spain for a period of over thirty years (1983-2013). *Environment International*, **116**, 10-17, doi:10.1016/j.envint.2018.04.001.
Diaz, J. et al., 2019: Time trends in the impact attributable to cold days in Spain: Incidence of local factors. *Science of the Total Environment*, **655**, 305-312, doi:10.1016/j.scitotenv.2018.11.254.

Diaz, J. et al., 2015: Comparison of the effects of extreme temperatures on daily mortality in Madrid (Spain), by age group: The need for a cold wave prevention plan. *Environ Res*, **143**(Pt A), 186-191, doi:10.1016/j.envres.2015.10.018.
Diener, E. and L. Tay, 2015: Subjective well-being and human welfare around the world as reflected in the Gallup World Poll. *Int. J. Psychol.*, **50**(2), 135-149, doi:10.1002/ijop.12136.
Dillender, M., 2021: Climate Change and Occupational Health Are There Limits to Our Ability to Adapt? *Journal of Human Resources*, **56**(1), 184-224, doi:10.3368/jhr.56.1.0718-9594R3.
Dilling, L. et al., 2017: Drivers of adaptation: Responses to weather- and climate-related hazards in 60 local governments in the Intermountain Western U.S. *Environment and Planning A: Economy and Space*, **49**(11), 2628-2648, doi:10.1177/0308518x16688686.
Dimitrova, A. et al., 2021: Association between ambient temperature and heat waves with mortality in South Asia: Systematic review and meta-analysis. *Environment International*, **146**, doi:10.1016/j.envint.2020.106170.
Dinar, S., D. Katz, L. De Stefano and B. Blankespoor, 2015: Climate change, conflict, and cooperation: global analysis of the effectiveness of international river treaties in addressing water variability. *Political Geography*, **45**, 55-66.
Ding, H. L., H. J. Li and N. N. Sze, 2021: Effects of the abolishment of London western charging zone on traffic flow and vehicle emissions. *International Journal of Sustainable Transportation*, doi:10.1080/15568318.2021.1914790.
Division, U. N. D. o. E. and S. A. Population, 2019: World Population Prospects 2019.
Djennad, A. et al., 2019: Seasonality and the effects of weather on Campylobacter infections. *BMC Infect Dis*, **19**(1), 255, doi:10.1186/s12879-019-3840-7.
Djoudi, H. et al., 2016: Beyond dichotomies: gender and intersecting inequalities in climate change studies. *Ambio*, **45**(3), S248-S262.
Doan, V. Q. and H. Kusaka, 2018: Projections of urban climate in the 2050s in a fast-growing city in Southeast Asia: The greater Ho Chi Minh City metropolitan area, Vietnam. *International Journal of Climatology*, **38**(11), 4155-4171, doi:10.1002/joc.5559.
Dockery, A., 2020: Inter-generational transmission of Indigenous culture and children's wellbeing: Evidence from Australia. *International Journal of Intercultural Relations*, **74**, 80-93, doi:10.1016/j.ijintrel.2019.11.001.
Dodd, W. et al., 2018: The summer of smoke: ecosocial and health impacts of a record wildfire season in the Northwest Territories, Canada. *Lancet Global Health*, **6**, S30-S30, doi:10.1016/s2214-109x(18)30159-1.
Dodd, W. et al., 2017: Determinants of internal migrant health and the healthy migrant effect in South India: a mixed methods study. *Bmc International Health and Human Rights*, **17**, doi:10.1186/s12914-017-0132-4.
Dodds, K. et al., 2020: The COVID-19 pandemic: territorial, political and governance dimensions of the crisis. *Territory Politics Governance*, **8**(3), 289-298, doi:10.1080/21622671.2020.1771022.
Doherty, R. M., M. R. Heal and F. M. O'Connor, 2017: Climate change impacts on human health over Europe through its effect on air quality. *Environmental Health*, **16**, 33-44, doi:10.1186/s12940-017-0325-2.
Dombrowsky, I., 2010: The role of intra-water sector issue linkage in the resolution of transboundary water conflicts. *Water International*, **35**(2), 132-149.
Domínguez-Morueco, N. et al., 2019: Combining monitoring and modelling approaches for BaP characterization over a petrochemical area. *Sci. Total Environ.*, **658**, 424-438, doi:10.1016/j.scitotenv.2018.12.202.
Donatuto, J., L. Campbell and W. Trousdale, 2020: The "value" of values-driven data in identifying Indigenous health and climate change priorities. *Climatic Change*, **158**(2), 161-180, doi:10.1007/s10584-019-02596-2.
Dong, C. et al., 2019: Wastewater treatment in amine-based carbon capture. *Chemosphere*, **222**, 742-756, doi:https://doi.org/10.1016/j.chemosphere.2019.01.038.
Dosio, A., L. Mentaschi, E. Fischer and K. Wyser, 2018: Extreme heat waves under 1.5 °C and 2 °C global warming. *Environmental Research Letters*, **13**, doi:10.1088/1748-9326/aab827.
DPPA, UNDP and UNEP, 2020: *United Nations Climate Security Mechanism Toolbox briefing note*.
Dresse, A., I. Fischhendler, J. Ø. Nielsen and D. Zikos, 2019: Environmental peacebuilding: Towards a theoretical framework. *Cooperation and Conflict*, **54**(1), 99-119.
Drewnowski, A. et al., 2020: Toward Healthy Diets from Sustainable Food Systems. *Current Developments in Nutrition*, **4**(6), doi:10.1093/cdn/nzaa083.
Duane, B. et al., 2019: Environmentally sustainable dentistry: a brief introduction to sustainable concepts within the dental practice. *British Dental Journal*, **226**, 292-295, doi:10.1038/s41415-019-0010-7.
Duarte, J. L., F. A. Diaz-Quijano, A. C. Batista and L. L. Giatti, 2019: Climatic variables associated with dengue incidence in a city of the Western Brazilian Amazon region. *Revista da Sociedade Brasileira de Medicina Tropical*, **52**, e20180429, doi:10.1590/0037-8682-0429-2018.
Dube, E. and E. Munsaka, 2018: The contribution of indigenous knowledge to disaster risk reduction activities in Zimbabwe: A big call to practitioners. *Jamba-Journal of Disaster Risk Studies*, **10**, doi:10.4102/jamba.v10i1.493.
Dudgeon, P., A. Bray, B. D'Costa and R. Walker, 2017: Decolonising Psychology: Validating Social and Emotional Wellbeing. *Australian Psychologist*, **52**(4), 316-325, doi:10.1111/ap.12294.
Dudley, J. P., E. P. Hoberg, E. J. Jenkins and A. J. Parkinson, 2015: Climate Change in the North American Arctic: A One Health Perspective. *Ecohealth*, **12**(4), 713-725, doi:10.1007/s10393-015-1036-1.

Dumic, I. and E. Severnini, 2018: "Ticking Bomb": The Impact of Climate Change on the Incidence of Lyme Disease. *The Canadian journal of infectious diseases & medical microbiology = Journal canadien des maladies infectieuses et de la microbiologie medicale*, **2018**, 5719081, doi:10.1155/2018/5719081.
Dunn, H. and R. Matthew, 2015: Natural Resources and Gender in Conflict Settings. *Peace Review-a Journal of Social Justice*, **27**(2), 156-164, doi:10.1080/10402659.2015.1037619.
Durkalec, A., C. Furgal, M. Skinner and T. Sheldon, 2015: Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community *Social Science & Medicine*, **136**, 17-26.
Ebi, K., 2011: Climate Change And Health Risks: Assessing And Responding To Them Through 'Adaptive Management'. *Health Affairs*, **30**(5), 924-930, doi:10.1377/hlthaff.2011.0071.
Ebi, K., 2016: Adaptation and resilience. *Public Health Reviews*, **37**, doi:10.1186/s40985-016-0032-5.
Ebi, K. et al., 2020: Using Detection And Attribution To Quantify How Climate Change Is Affecting Health. *Health Affairs*, **39**(12), 2168-2174, doi:10.1377/hlthaff.2020.01004.
Ebi, K. et al., 2018a: Stress Testing the Capacity of Health Systems to Manage Climate Change-Related Shocks and Stresses. *International Journal of Environmental Research and Public Health*, **15**(11), doi:10.3390/ijerph15112370.
Ebi, K. et al., 2021a: Burning embers: synthesis of the health risks of climate change. *Environmental Research Letters*, **16**(4), doi:10.1088/1748-9326/abeadd.
Ebi, K. and J. Hess, 2020: Health Risks Due To Climate Change: Inequity In Causes And Consequences. *Health Affairs*, **39**(12), 2056-2062, doi:10.1377/hlthaff.2020.01125.
Ebi, K. and I. Loladze, 2019: Elevated atmospheric CO2 concentrations and climate change will affect our food's quality and quantity Comment. *Lancet Planetary Health*, **3**(7), E283-E284, doi:10.1016/s2542-5196(19)30108-1.
Ebi, K. L., 2019: Effective heat action plans: research to interventions. *Environmental Research Letters*, **14**(12), doi:10.1088/1748-9326/ab5ab0.
Ebi, K. L. et al., 2021b: Two-way learning from COVID-19 and climate change.
Ebi, K. L. et al., 2018b: Health risks of warming of 1.5 degrees C, 2 degrees C, and higher, above pre-industrial temperatures. *Environmental Research Letters*, **13**(6), doi:ARTN 063007
10.1088/1748-9326/aac4bd.
Ebi, K. L., N. H. Ogden, J. C. Semenza and A. Woodward, 2017: Detecting and Attributing Health Burdens to Climate Change. *Environ. Health Perspect.*, **125**(8), 085004, doi:10.1289/EHP1509.
Ebi, K. L. and M. Otmani del Barrio, 2017: Lessons Learned on Health Adaptation to Climate Variability and Change: Experiences Across Low- and Middle-Income Countries. *Environmental Health Perspectives*, **125**(6), doi:10.1289/EHP405.
Ebrahim, S. et al., 2020: Forward planning for disaster-related mass gatherings amid COVID-19. *Lancet Planetary Health*, **4**(9), E379-E380, doi:10.1016/s2542-5196(20)30175-3.
Echenique, M. and L. Melgar, 2018: Mapping Puerto Rico's Hurricane Migration With Mobile Phone Data.
Eckstein, D., V. Künzel and L. Schäfer, 2017: Global climate risk index 2018. *Germanwatch eV: Bonn, Germany*.
Economics, V., 2021: Greenness of Stimulus Index. An assessment of COVID-19 stimulus by G20 countries and other major economies in relation to climate action and biodiversity goals, London, UK, 93 pp.
Edmonds, D. A., C. R. L., B. E. S. and S. S. M. O., 2020: Coastal flooding will disproportionately impact people on river deltas. *Nature Communications*, **11**(1), 4741, doi:10.1038/s41467-020-18531-4.
Edwards, B., M. Gray and B. Hunter, 2015: The Impact of Drought on Mental Health in Rural and Regional Australia. *Social Indicators Research*, **121**(1), 177-194, doi:10.1007/s11205-014-0638-2.
Efstratiou, A., J. Ongerth and P. Karanis, 2017: Waterborne transmission of protozoan parasites: Review of worldwide outbreaks - An update 2011-2016. *Water Research*, **114**, 14-22, doi:10.1016/j.watres.2017.01.036.
Eguiluz-Gracia, I. et al., 2020: The need for clean air: The way air pollution and climate change affect allergic rhinitis and asthma. *Allergy*, **75**(9), 2170-2184, doi:10.1111/all.14177.
Eisenman, D., S. McCaffrey, I. Donatello and G. Marshal, 2015: An ecosystems and vulnerable populations perspective on solastalgia and psychological distress after a wildfire. *EcoHealth*, **12**(4), 602-610.
Ekstrom, J. A. and L. Bedsworth, 2018: Adapting air quality management for a changing climate: Survey of local districts in California. *Journal of the Air & Waste Management Association*, **68**(9), 931-944, doi:10.1080/10962247.2018.1459325.
El-Zein, A. and F. N. Tonmoy, 2017: Nonlinearity, fuzziness and incommensurability in indicator-based assessments of vulnerability to climate change: A new mathematical framework. *Ecological Indicators*, **82**, 82-93.
Ellis, N. R. and G. A. Albrecht, 2017: Climate change threats to family farmers' sense of place and mental wellbeing: A case study from the Western Australian Wheatbelt. *Social Science & Medicine*, **175**, 161-168, doi:10.1016/j.socscimed.2017.01.009.
Emmerson, K. M. et al., 2021: Atmospheric modelling of grass pollen rupturing mechanisms for thunderstorm asthma prediction. *Plos One*, **16**(4), doi:10.1371/journal.pone.0249488.
Ensor, J., J. Forrester and N. Matin, 2018: Bringing rights into resilience: revealing complexities of climate risks and social conflict. *Disasters*, **42**, S287-S305.
Epstein, A. et al., 2020a: Drought and intimate partner violence towards women in 19 countries in sub-Saharan Africa during 2011-2018: A population-based study. *PLoS Med*, **17**(3), e1003064, doi:10.1371/journal.pmed.1003064.

Epstein, A., T. Benmarhnia and S. D. Weiser, 2020b: Drought and Illness among Young Children in Uganda, 2009-2012. *Am J Trop Med Hyg*, **102**(3), 644-648, doi:10.4269/ajtmh.19-0412.
Epstein, Y. and R. Yanovich, 2019: Heatstroke. *New England Journal of Medicine*, **380**(25), 2449-2459, doi:10.1056/NEJMra1810762.
Eriksen, S., A. Nightingale and H. Eakin, 2015: Reframing adaptation: the political nature of climate change adaptation. *Global Environmental Change*, **35**, 523-533.
Eriksen, S. et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, doi:10.1016/j.worlddev.2020.105383.
Escobar, L. E. et al., 2015: A global map of suitability for coastal Vibrio cholerae under current and future climate conditions. *Acta Tropica*, **149**, 202-211, doi:10.1016/j.actatropica.2015.05.028.
Espejo, W., J. Celis, G. Chiang and P. Bahamonde, 2020: Environment and COVID-19: Pollutants, impacts, dissemination, management and recommendations for facing future epidemic threats. *Science of the Total Environment*, **747**, doi:10.1016/j.scitotenv.2020.141314.
Estrada-Peña, A. and N. Fernández-Ruiz, 2020: A Retrospective Assessment of Temperature Trends in Northern Europe Reveals a Deep Impact on the Life Cycle of Ixodes ricinus (Acari: Ixodidae). *Pathogens*, **9**(5), doi:10.3390/pathogens9050345.
Evangeliou, N. et al., 2014: Wildfires in Chernobyl-contaminated forests and risks to the population and the environment: a new nuclear disaster about to happen? *Environ. Int.*, **73**, 346-358, doi:10.1016/j.envint.2014.08.012.
Evans, G., 2019: Projected Behavioral Impacts of Global Climate Change. *Annual Review of Psychology*, **70**, 449-474, doi:https://doi.org/10.1146/annurev-psych-010418-103023.
Evertsen, K. and K. Van Der Geest, 2019: Gender, environment and migration in Bangladesh. *Climate and Development*, doi:10.1080/17565529.2019.1596059.
Ezeh, A., F. Kissling and P. Singer, 2020: Why sub-Saharan Africa might exceed its projected population size by 2100. *The Lancet*, **396**(10258), 1131-1133, doi:10.1016/s0140-6736(20)31522-1.
Fakhri, M., 2021: UN Food Systems Report on The Right to Food.
Fan, J. and Q. Liu, 2019: Potential impacts of climate change on dengue fever distribution using RCP scenarios in China. *Advances in Climate Change Research*, **10**(1), 1-8, doi:10.1016/j.accre.2019.03.006.
Fan, Y. et al., 2021: Molecular characterization of the waterborne pathogens Cryptosporidium spp., Giardia duodenalis, Enterocytozoon bieneusi, Cyclospora cayetanensis and Eimeria spp. in wastewater and sewage in Guangzhou, China. *Parasit Vectors*, **14**(1), 66, doi:10.1186/s13071-020-04566-5.
Fanzo, J. et al., 2020: Nutrients, Foods, Diets, People: Promoting Healthy Eating. *Current Developments in Nutrition*, **4**(6), doi:10.1093/cdn/nzaa069.
FAO, 2020: *Climate change: Unpacking the burden on food safety*. Food safety and quality series, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome, Italy.
FAO et al., 2018: *The State of Food Security and Nutrition in the World 2018*. Building climate resilience for food security and nutrition, Policy Support and Governance, Fao, Rome. Available at: http://www.fao.org/3/I9553EN/i9553en.pdf.
FAO et al., 2020: *The State of Food Security and Nutrition in the World 2020*. Transforming food systems for affordable healthy diets., Fao, Rome. Available at: http://www.fao.org/3/ca9692en/ca9692en.pdf.
FAO et al., 2021: The State of Food Security and Nutrition in the World 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all. FAO, Rome.
FAO and WHO, 2018: Evaluation of Certain Veterinary Drug Residues in Food: Eighty-Fifth Report of the Joint FAO/WHO Expert Committee on Food Additives. *Evaluation of Certain Veterinary Drug Residues in Food: Eighty-Fifth Report of the Joint Fao/who Expert Committee on Food Additives*, **1008**, 1-150.
FAOLEX, 2021: Plant Protection (Damage by Goats) Law, 1950.
Farbotko, C. et al., 2020: Relocation planning must address voluntary immobility. *Nature Climate Change*, **10**(8), 702-704, doi:10.1038/s41558-020-0829-6.
Farbotko, C. and C. McMichael, 2019: Voluntary immobility and existential security in a changing climate in the Pacific. *Asia Pacific Viewpoint*, **60**, 148-162, doi:10.1111/apv.12231.
Farchi, S. et al., 2017: Meat consumption reduction in Italian regions: Health co-benefits and decreases in GHG emissions. *Plos One*, **12**(8), doi:10.1371/journal.pone.0182960.
Farhat, J. B. et al., 2018: Syrian refugees in Greece: experience with violence, mental health status, and access to information during the journey and while in Greece. BMC medicine, 1-12 pp.
Fatehpanah, A. et al., 2020: Water safety in drought: an indigenous knowledge-based qualitative study. *Journal of Water and Health*, **18**(5), 692-703, doi:10.2166/wh.2020.141.
Fawcett, D., T. Pearce, J. D. Ford and L. Archer, 2017: Operationalizing longitudinal approaches to climate change vulnerability assessment. *Global Environmental Change*, **45**, 79-88.
Fazey, I. et al., 2016: Past and future adaptation pathways. *Climate and Development*, **8**(1), 26-44, doi:10.1080/17565529.2014.989192.
Fei, L. et al., 2015: [Population change of farmland rodent and the influences of climate and cultivation factors in Fengxian District of Shanghai, China]. *Ying yong sheng tai xue bao = The journal of applied ecology*, **26**(2), 579-587.

Fenech, S. et al., 2019: Meteorological drivers and mortality associated with O-3 and PM2.5 air pollution episodes in the UK in 2006. *Atmospheric Environment*, **213**, 699-710, doi:10.1016/j.atmosenv.2019.06.030.
Ferkol, T. and D. Schraufnagel, 2014: The global burden of respiratory disease. *Ann. Am. Thorac. Soc.*, **11**(3), 404-406, doi:10.1513/AnnalsATS.201311-405PS.
Fernandez, A. et al., 2015: Flooding and Mental Health: A Systematic Mapping Review. *Plos One*, **10**(4), doi:10.1371/journal.pone.0119929.
Ferreira-Coimbra, J., C. Sarda and J. Rello, 2020: Burden of Community-Acquired Pneumonia and Unmet Clinical Needs. *Advances in Therapy*, **37**(4), 1302-1318, doi:10.1007/s12325-020-01248-7.
Ferreira, D. C., I. Graziele, R. C. Marques and J. Gonçalves, 2021: Investment in drinking water and sanitation infrastructure and its impact on waterborne diseases dissemination: The Brazilian case. *Sci Total Environ*, **779**, 146279, doi:10.1016/j.scitotenv.2021.146279.
Flahault, A., R. R. de Castaneda and I. Bolon, 2016: Climate change and infectious diseases. *Public Health Reviews*, **37**, doi:10.1186/s40985-016-0035-2.
Flat ø, M., R. Muttarak and A. Pelser, 2017: Women, weather, and woes: The triangular dynamics of female-headed households, economic vulnerability, and climate variability in South Africa. *World Development*, **90**, 41-62.
Fogg-Rogers, L. et al., 2021: Applying Social Learning to Climate Communications-Visualising 'People Like Me' in Air Pollution and Climate Change Data. *Sustainability*, **13**(6), doi:10.3390/su13063406.
Folkerts, M. A. et al., 2020: Long Term Adaptation to Heat Stress: Shifts in the Minimum Mortality Temperature in the Netherlands. *Frontiers in Physiology*, **11**, doi:10.3389/fphys.2020.00225.
Follos, F. et al., 2021: Evolution of the minimum mortality temperature (1983-2018): Is Spain adapting to heat? *Science of the Total Environment*, **784**, doi:10.1016/j.scitotenv.2021.147233.
Ford, J. and D. King, 2015: *A framework for examining adaptation readiness*. vol. 20.
Ford, J. et al., 2020: The Resilience of Indigenous Peoples to Environmental Change. *One Earth*, **2**(6), 532-543, doi:10.1016/j.oneear.2020.05.014.
Ford, J. D. et al., 2018: Preparing for the health impacts of climate change in Indigenous communities: The role of community-based adaptation. *Global Environmental Change*, **49**, 129-139, doi:10.1016/j.gloenvcha.2018.02.006.
Ford, T. E. and S. Hamner, 2018: A Perspective on the Global Pandemic of Waterborne Disease. *Microb Ecol*, **76**(1), 2-8, doi:10.1007/s00248-015-0629-0.
Foreman, K. J. et al., 2018: Forecasting life expectancy, years of life lost, and all-cause and cause-specific mortality for 250 causes of death: reference and alternative scenarios for 2016-40 for 195 countries and territories. *Lancet*, **392**(10159), 2052-2090, doi:10.1016/s0140-6736(18)31694-5.
Foster, J., S. G. Hodder, J. Goodwin and G. Havenith, 2020: Occupational Heat Stress and Practical Cooling Solutions for Healthcare and Industry Workers During the COVID-19 Pandemic. *Annals of Work Exposures and Health*, **64**(9), 915-922, doi:10.1093/annweh/wxaa082.
Foudi, S., N. Osés-Eraso and I. Galarraga, 2017: The effect of flooding on mental health: lessons learned for building resilience. *Water Resource Research*, **53**(7), 5831-5844.
Fox, M. et al., 2019: Integrating Public Health into Climate Change Policy and Planning: State of Practice Update. *Int. J. Environ. Res. Public Health*, **16**(18), doi:10.3390/ijerph16183232.
Froese, R. and J. Schilling, 2019: The nexus of climate change, land use, and conflicts. *Current climate change reports*, **5**(1), 24-35.
Fröhlich, C. and G. Gioli, 2015: Gender, Conflict, and Global Environmental Change. *Peace Review-a Journal of Social Justice*, **27**(2), 137-146, doi:10.1080/10402659.2015.1037609.
Fröhlich, C., G. Gioli, R. Cremades and H. Myrttinen, 2018: *Water security across the gender divide*. Springer. ISBN 3319640461.
Fröhlich, C. J., 2016: Climate migrants as protestors? Dispelling misconceptions about global environmental change in pre-revolutionary Syria. *Contemporary levant*, **1**(1), 38-50.
Frumkin, H., 2018: The US Health Care Sector's Carbon Footprint: Stomping or Treading Lightly? *American Journal of Public Health*, **108**(S2), S56–S57, doi:10.2105/ajph.2017.304160.
Frumkin, H. and A. Haines, 2019: Global Environmental Change and Noncommunicable Disease Risks. *Annual Review of Public Health*, **40**(1), 261-282, doi:10.1146/annurev-publhealth-040218-043706.
FSIN, 2020: Global Report on Food Crises: Joint Analysis for Better Decisions.
FSIN/GNAFC, 2020: *Global Report on Food Crises 2020*. Food Security Information Network and Global Network Against Food Crises, FSIN/GNAFC, Rome.
Fu, T. M. and H. Tian, 2019: Climate Change Penalty to Ozone Air Quality: Review of Current Understandings and Knowledge Gaps. *Current Pollution Reports*, **5**(3), 159-171, doi:10.1007/s40726-019-00115-6.
Fuentes, L., H. Asselin, A. Belisle and O. Labra, 2020: Impacts of Environmental Changes on Well-Being in Indigenous Communities in Eastern Canada. *International Journal of Environmental Research and Public Health*, **17**(2), 11, doi:10.3390/ijerph17020637.
Fujii, H. et al., 2015: Fatigue and sleep under large summer temperature differences. *Environmental Research*, **138**, 17-21, doi:10.1016/j.envres.2015.02.006.
Fullilove, M. T., 1996: Psychiatric implications of displacement: contributions from the psychology of place. *American Journal of Psychiatry*, **153**(1516-1523).

Fullman, N. et al., 2017: Measuring progress and projecting attainment on the basis of past trends of the health-related Sustainable Development Goals in 188 countries: an analysis from the Global Burden of Disease Study 2016. *Lancet*, **390**(10100), 1423-1459, doi:10.1016/s0140-6736(17)32336-x.
Fummi, M., J. Andries and B. Yonas, 2017: The role of indigenous knowledge in drought risk reduction: a case of communal farmers in South Africa. *Journal of Disaster Risk Studies*, **9**, 1-6, doi:10.4102/jamba.v9i1.420.
Funk, C. et al., 2018: *CONTRASTING KENYAN RESILIENCE TO DROUGHT: 2011 AND 2017*. US AID, Special Report ed., Aid, U. S., USA, 20 pp. Available at: https://www.usaid.gov/sites/default/files/documents/1867/Kenya_Report_-_Full_Compliant.PDF.
Funk, C. et al., 2019: Recognizing the Famine Early Warning Systems Network: Over 30 Years of Drought Early Warning Science Advances and Partnerships Promoting Global Food Security. *Bulletin of the American Meteorological Society*, **100**(6), 1011-1027, doi:10.1175/bams-d-17-0233.1.
Furberg, M., B. Evengard and M. Nilsson, 2011: Facing the limit of resilience: perceptions of climate change among reindeer herding Sami in Sweden. *Global Health Action*, **4**, doi:10.3402/gha.v4i0.8417.
Furgal, C. and J. Seguin, 2006: Climate change, health, and vulnerability in Canadian northern Aboriginal communities. *Environmental Health Perspectives*, **114**(12), 1964-1970, doi:10.1289/ehp.8433.
Fussell, E., R. McLeman and F. Gemenne, 2018: Population displacements and migration patterns in response to Hurricane Katrina. *Routledge Handbook of Environmental Displacement and Migration*, 277-288.
Gamage, P. J., L. V. Fortington and C. F. Finch, 2020: Epidemiology of exertional heat illnesses in organised sports: A systematic review. *Journal of Science and Medicine in Sport*, **23**(8), 701-709, doi:10.1016/j.jsams.2020.02.008.
Gandon, S., T. Day, C. J. E. Metcalf and B. T. Grenfell, 2016: Forecasting Epidemiological and Evolutionary Dynamics of Infectious Diseases. *Trends in Ecology & Evolution*, **31**(10), 776-788, doi:10.1016/j.tree.2016.07.010.
Gao, J. et al., 2018: Public health co-benefits of greenhouse gas emissions reduction: A systematic review. *Sci. Total Environ.*, **627**, 388-402, doi:10.1016/j.scitotenv.2018.01.193.
Garcia, D. M. and M. C. Sheehan, 2016: Extreme Weather-driven Disasters and Children's Health. *Int. J. Health Serv.*, **46**(1), 79-105, doi:10.1177/0020731415625254.
Gari, T. et al., 2017: Anaemia among children in a drought affected community in south-central Ethiopia. *PLOS ONE*, **12**(3), e0170898, doi:10.1371/journal.pone.0170898.
Gariepy, G., H. Honkaniemi and A. Quesnel-Vallée, 2016: Social support and protection from depression: systematic review of current findings in Western countries. *The British Journal of Psychiatry*, **209**, doi:10.1192/bjp.bp.115.169094.
Garnier, J. et al., 2020: Helping to heal nature and ourselves through human-rights-based and gender-responsive One Health. *One Health Outlook*, **2**(1), 22, doi:10.1186/s42522-020-00029-0.
Garrido-Perez, J. M., C. Ordonez, R. Garcia-Herrera and J. L. Schnell, 2019: The differing impact of air stagnation on summer ozone across Europe. *Atmospheric Environment*, **219**, doi:10.1016/j.atmosenv.2019.117062.
Gascon, M. et al., 2019: Correlates of Walking for Travel in Seven European Cities: The PASTA Project. *Environmental Health Perspectives*, **127**(9), doi:10.1289/ehp4603.
Gaskin, C. et al., 2017: Factors Associated with the Climate Change Vulnerability and the Adaptive Capacity of People with Disability: A Systematic Review. *Weather Climate and Society*, **9**(4), 801-814, doi:10.1175/wcas-d-16-0126.1.
Gasmi, S. et al., 2017: Surveillance for Lyme disease in Canada: 2009-2015. *Can Commun Dis Rep*, **43**(10), 194-199, doi:10.14745/ccdr.v43i10a01.
Gasparrini, A., Y. Guo and F. Sera, 2017: Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health*, **1**(9), e360-e367.
Gasparrini, A. et al., 2015: Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet*, **386**(9991), 369-375, doi:10.1016/s0140-6736(14)62114-0.
Gautier, D., D. Denis and B. Locatelli, 2016: Impacts of drought and responses of rural populations in West Africa: a systematic review. *WIREs Climate Change*, **7**(5), 666-681.
Gebreslassie, M., 2020: COVID-19 and energy access: An opportunity or a challenge for the African continent? *Energy Research & Social Science*, **68**, doi:10.1016/j.erss.2020.101677.
Geier, D. A., J. K. Kern and M. R. Geier, 2018: A longitudinal ecological study of seasonal influenza deaths in relation to climate conditions in the United States from 1999 through 2011. *Infection Ecology & Epidemiology*, **8**, doi:10.1080/20008686.2018.1474708.
Gemenne, F. and J. Blocher, 2017: How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *The Geographical Journal*, **183**(4), 336-347, doi:10.1111/geoj.12205.
Ghazani, M. et al., 2018: Temperature Variability and Gastrointestinal Infections: A Review of Impacts and Future Perspectives. *International Journal of Environmental Research & Public Health [Electronic Resource]*, **15**(4), 16, doi:https://dx.doi.org/10.3390/ijerph15040766.
Ghimire, R., S. Ferreira and J. H. Dorfman, 2015: Flood-Induced Displacement and Civil Conflict. *World Development*, **66**, 614-628, doi:10.1016/j.worlddev.2014.09.021.
Ghimire, S. and S. Dhakal, 2015: Japanese encephalitis: Challenges and intervention opportunities in Nepal. *Veterinary world*, **8**(1), 61-65, doi:10.14202/vetworld.2015.61-65.
Gibb, R. et al., 2020: Zoonotic host diversity increases in human-dominated ecosystems. *Nature*, **584**(7821), 398-+, doi:10.1038/s41586-020-2562-8.

Gibon, T. et al., 2017: Health benefits, ecological threats of low-carbon electricity. *Environ. Res. Lett.*, **12**(3), 034023, doi:10.1088/1748-9326/aa6047.
Gibson, K., J. Barnett, N. Haslam and I. Kaplan, 2020: The mental health impacts of climate change: Findings from a Pacific Island atoll nation. *Journal of Anxiety Disorders*, **73**, doi:10.1016/j.janxdis.2020.102237.
Gilmore, E. A. and H. Buhaug, 2021: Climate mitigation policies and the potential pathways to conflict: Outlining a research agenda. *Wiley Interdisciplinary Reviews: Climate Change*, e722.
Gilmore, E. A., L. H. Risi, E. Tennant and H. Buhaug, 2018: Bridging research and policy on climate change and conflict. *Current climate change reports*, **4**(4), 313-319.
Giorgini, P. et al., 2017: Climate Changes and Human Health: A Review of the Effect of Environmental Stressors on Cardiovascular Diseases Across Epidemiology and Biological Mechanisms. *Curr Pharm Des*, **23**(22), 3247-3261, doi:10.2174/1381612823666170317143248.
Gleick, P. H., 2014: Water, Drought, Climate Change, and Conflict in Syria. *Weather Climate and Society*, **6**(3), 331-340, doi:10.1175/wcas-d-13-00059.1.
Glover, D. and N. Poole, 2019: Principles of innovation to build nutrition-sensitive food systems in South Asia. *Food Policy*, **82**, 63-73, doi:10.1016/j.foodpol.2018.10.010.
Gnonlonfin, G. J. B. et al., 2013: A review on aflatoxin contamination and its implications in the developing world: a sub-Saharan African perspective. *Crit. Rev. Food Sci. Nutr.*, **53**(4), 349-365, doi:10.1080/10408398.2010.535718.
GNR, 2018: Global Nutrition Report: Shining a light to spur action on nutrition. Bristol, UK: Development Initiatives.
Gobler, C. J. et al., 2017: Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proceedings of the National Academy of Sciences*, **114**(19), 4975, doi:10.1073/pnas.1619575114.
Goggins, W. B. and E. Y. Y. Chan, 2017: A study of the short-term associations between hospital admissions and mortality from heart failure and meteorological variables in Hong Kong: Weather and heart failure in Hong Kong. *International Journal of Cardiology*, **228**, 537-542, doi:https://doi.org/10.1016/j.ijcard.2016.11.106.
Goodrich, C., A. Prakash and P. Udas, 2019: Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. *Environmental Development*, **31**, 1-8, doi:https://doi.org/10.1016/j.envdev.2019.01.001.
Gordon, K., A. L. Xavier and H. T. Neufeld, 2018: Healthy Roots: Building capacity through shared stories rooted in Haudenosaunee knowledge to promote Indigenous foodways and well-being. *Canadian Food Studies / La Revue canadienne des études sur l'alimentation*, **52**(2), 180-195.
Gosling, S. N. et al., 2017: Adaptation to Climate Change: A Comparative Analysis of Modeling Methods for Heat-Related Mortality. *Environmental Health Perspectives*, **125**(8), doi:10.1289/ehp634.
Goyal, M. et al., 2021: The effect of the COVID-19 pandemic on maternal health due to delay in seeking health care: experience from a tertiary center. *International Journal of Gynecology & Obstetrics*, **152**(2), 231-235, doi:10.1002/ijgo.13457.
Gray, C., D. Hopping and V. Mueller, 2020: The changing climate-migration relationship in China, 1989–2011. *Climatic Change*. Available at: https://doi.org/10.1007/s10584-020-02657-x.
Gray, C. and E. Wise, 2016: Country-specific effects of climate variability on human migration. *Climatic Change*, **135**(3-4), 555-568, doi:10.1007/s10584-015-1592-y.
Green, D. and L. Minchin, 2014: Living on climate-changed country: indigenous health, well-being and climate change in remote Australian communities. *Ecohealth*, **11**(2), 263-272, doi:https://dx.doi.org/10.1007/s10393-013-0892-9.
Green, D. et al., 2017: Advancing Australia's role in climate change and health research. *Nature Climate Change*, **7**(2), 103-106, doi:10.1038/nclimate3182.
Green, H. et al., 2019: Impact of heat on mortality and morbidity in low and middle income countries: A review of the epidemiological evidence and considerations for future research. *Environmental Research*, **171**, 80-91, doi:10.1016/j.envres.2019.01.010.
Green, R. et al., 2015: The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. **129**(1), 253-265, doi:10.1007/s10584-015-1329-y.
Greenwood, M. and N. Lindsay, 2019: A commentary on land, health, and Indigenous knowledge(s). *Global Health Promotion*, **26**(3), 82-86, doi:10.1177/1757975919831262.
Grey, S. and R. Patel, 2015: Food sovereignty as decolonization: some contributions from Indigenous movements to food system and development politics. *Agriculture and Human Values*, **32**(3), 431-444, doi:10.1007/s10460-014-9548-9.
Grundstein, A. et al., 2017: American football and fatal exertional heat stroke: a case study of Korey Stringer. *International Journal of Biometeorology*, **61**(8), 1471-1480, doi:10.1007/s00484-017-1324-2.
Guetter, C. R. et al., 2018: Greening the operating room. *The American Journal of Surgery*, **216**(4), 683-688, doi:https://doi.org/10.1016/j.amjsurg.2018.07.021.
Guirguis, K. et al., 2018: Heat, Disparities, and Health Outcomes in San Diego County's Diverse Climate Zones. *GeoHealth*, **2**(7), 212-223, doi:10.1029/2017gh000127.
Guo, Y. et al., 2020: The origin, transmission and clinical therapies on coronavirus disease 2019 (COVID-19) outbreak - an update on the status. *Military Medical Research*, **7**(1), doi:10.1186/s40779-020-00240-0.
Guo, Y. et al., 2016: Temperature Variability and Mortality: A Multi-Country Study. *Environmental Health Perspectives*, **124**(10), 1554-1559, doi:10.1289/ehp149.

Guo, Y. et al., 2018: Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLOS Medicine*, **15**(7), e1002629, doi:10.1371/journal.pmed.1002629.
Guo, Y. M., 2017: Hourly associations between heat and ambulance calls. *Environmental Pollution*, **220**, 1424-1428, doi:10.1016/j.envpol.2016.10.091.
Guyot, M. et al., 2006: Local observations of climate change and impacts on traditional food security in two northern Aboriginal communities. *International Journal of Circumpolar Health*, **65**(5), 403-415, doi:10.3402/ijch.v65i5.18135.
Guzman Herrador, B. et al., 2016: Association between heavy precipitation events and waterborne outbreaks in four Nordic countries, 1992-2012. *J Water Health*, **14**(6), 1019-1027, doi:10.2166/wh.2016.071.
Guzman Herrador, B. R. et al., 2015: Analytical studies assessing the association between extreme precipitation or temperature and drinking water-related waterborne infections: a review. *Environ Health*, **14**, 29, doi:10.1186/s12940-015-0014-y.
Haas, S., A. Gianoli and M. Van Eerd, 2021: The roles of community resilience and risk appraisal in climate change adaptation: the experience of the Kannagi Nagar resettlement in Chennai. *Environment and Urbanization*, doi:10.1177/0956247821993391.
Haasnoot, M., J. Lawrence and A. K. Magnan, 2021: Pathways to coastal retreat. *Science*, 372(6548), 1287 LP - 1290. Available at: http://science.sciencemag.org/content/372/6548/1287.abstract.
Habibi, P. et al., 2021: The impacts of climate change on occupational heat strain in outdoor workers: A systematic review. *Urban Climate*, **36**, doi:10.1016/j.uclim.2021.100770.
Haddout, S., K. L. Priya, A. M. Hoguane and I. Ljubenkov, 2020: Water Scarcity: A Big Challenge to Slums in Africa to Fight against COVID-19. *Science & Technology Libraries*, 1-8.
Haghighi, M. M. et al., 2021: Impacts of High Environmental Temperatures on Congenital Anomalies: A Systematic Review. *Int J Environ Res Public Health*, **18**(9), doi:10.3390/ijerph18094910.
Haines, A. and K. Ebi, 2019: The Imperative for Climate Action to Protect Health. *New England Journal of Medicine*, **380**(3), 263-273, doi:10.1056/NEJMra1807873.
Hajat, S., 2017: Health effects of milder winters: A review of evidence from the United Kingdom. *Environmental Health*, **16**, 109, doi:10.1186/s12940-017-0323-4.
Hajat, S. et al., 2017: The effect of ambient temperature on type-2-diabetes: case-crossover analysis of 4+ million GP consultations across England. *Environ Health*, **16**(1), 73, doi:10.1186/s12940-017-0284-7.
Hall, N. et al., 2021: Climate change and infectious diseases in Australia's Torres Strait Islands. *Australian and New Zealand Journal of Public Health*, **45**(2), 122-128, doi:10.1111/1753-6405.13073.
Hall, N. and L. Crosby, 2020: Climate Change Impacts on Health in Remote Indigenous Communities in Australia. *International Journal of Environmental Health Research*, 16, doi:10.1080/09603123.2020.1777948.
Hallema, D., F. Robinne and S. McNulty, 2020: Pandemic spotlight on urban water quality. *Ecological Processes*, **9**(1), doi:10.1186/s13717-020-00231-y.
Hamaoui-Laguel, L. et al., 2015: Effects of climate change and seed dispersal on airborne ragweed pollen loads in Europe. *Nat. Clim. Chang.*, **5**, 766, doi:10.1038/nclimate2652.
Hamilton, I. et al., 2021: The public health implications of the Paris Agreement: a modelling study. *Lancet Planetary Health*, **5**(2), E74-E83.
Hamilton, L. C., K. Saito and P. A. Loring, 2016: Climigration? Population and climate change in Arctic Alaska, 115-133 pp.
Hanigan, I., C. Butler, P. Kokic and M. Hutchinson, 2012: Suicide and drought in New South Wales, Australia, 1970-2007. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(35), 13950-13955, doi:10.1073/pnas.1112965109.
Hanigan, I. C., K. B. G. Dear and A. Woodward, 2021: Increased ratio of summer to winter deaths due to climate warming in Australia, 1968-2018. *Australian and New Zealand Journal of Public Health*, doi:10.1111/1753-6405.13107.
Hansel, N. N., M. C. McCormack and V. Kim, 2016: The Effects of Air Pollution and Temperature on COPD. *COPD*, **13**(3), 372-379, doi:10.3109/15412555.2015.1089846.
Hansen, A. et al., 2008: The effect of heat waves on mental health in a temperate Australian city. *Environmental Health Perspectives*, **116**(10), 1369-1375, doi:10.1289/ehp.11339.
Hansen, A. et al., 2015: Transmission of haemorrhagic fever with renal syndrome in china and the role of climate factors: a review. *International journal of infectious diseases : IJID : official publication of the International Society for Infectious Diseases*, **33**, 212-218, doi:10.1016/j.ijid.2015.02.010.
Haq, G. and G. Gutman, 2014: Climate gerontology Meeting the challenge of population ageing and climate change. *Zeitschrift Fur Gerontologie Und Geriatrie*, **47**(6), 462-+, doi:10.1007/s00391-014-0677-y.
Haque, M. et al., 2015: Behavioral Change Due to Climate Change Effects Accelerate Tiger Human Conflicts: A Study on Sundarbans Mangrove Forests, Bangladesh. *International Journal of Conservation Science*, **6**(4), 669-684.
Haque, M. R., N. Parr and S. Muhidin, 2019: Parents' healthcare-seeking behavior for their children among the climate-related displaced population of rural Bangladesh. *Soc. Sci. Med.*, **226**, 9-20, doi:10.1016/j.socscimed.2019.02.032.
Harder, R., M. Giampietro and S. Smukler, 2021: Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems. *Resources Conservation and Recycling*, **172**, doi:10.1016/j.resconrec.2021.105693.

Harper, S. et al., 2015: Climate-sensitive health priorities in Nunatsiavut, Canada. *Bmc Public Health*, **15**, doi:10.1186/s12889-015-1874-3.
Harrington, L. and F. Otto, 2018: Changing population dynamics and uneven temperature emergence combine to exacerbate regional exposure to heat extremes under 1.5°C and 2°C of warming. *Environmental Research Letters*, **13**, doi:10.1088/1748-9326/aaaa99.
Harrington, L. J., D. J. Frame, E. Hawkins and M. Joshi, 2017: Seasonal cycles enhance disparities between low- and high-income countries in exposure to monthly temperature emergence with future warming. *Environmental Research Letters*, **12**(11), doi:10.1088/1748-9326/aa95ae.
Hasegawa, T. et al., 2018: Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, **8**(8), 699-703, doi:10.1038/s41558-018-0230-x.
Hasegawa, T., S. Fujimori, K. Takahashi and T. Masui, 2015: Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. *Environmental Research Letters*, **10**(1), doi:10.1088/1748-9326/10/1/014010.
Hashim, J. H. and Z. Hashim, 2016: Climate Change, Extreme Weather Events, and Human Health Implications in the Asia Pacific Region. *Asia. Pac. J. Public Health*, **28**(2 Suppl), 8S-14S, doi:10.1177/1010539515599030.
Hassan, E. M. et al., 2021: A review of Cryptosporidium spp. and their detection in water. *Water Sci Technol*, **83**(1), 1-25, doi:10.2166/wst.2020.515.
Hatfield, S. et al., 2018: Indian time: time, seasonality, and culture in Traditional Ecological Knowledge of climate change. *Ecological Processes*, **7**, doi:10.1186/s13717-018-0136-6.
Hatvani-Kovacs, G., J. Bush, E. Sharifi and J. Boland, 2018: Policy recommendations to increase urban heat stress resilience. . *Urban Climate*, **25**, 51-63. .
Hauer, M. E., 2017: Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change*, **7**(5), 321-+, doi:10.1038/nclimate3271.
Hauer, M. E., J. M. Evans and D. R. Mishra, 2016: Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, **6**, 691-695.
Hauer, M. E., R. D. Hardy, D. R. Mishra and J. S. Pippin, 2019: No landward movement: examining 80 years of population migration and shoreline change in Louisiana. *Population and Environment*.
Haussig, J. M. et al., 2018: Early start of the West Nile fever transmission season 2018 in Europe. *Eurosurveillance*, **23**(32), 7-12, doi:10.2807/1560-7917.es.2018.23.32.1800428.
Hayashida, K., K. Shimizu and H. Yokota, 2019: Severe heatwave in Japan. *Acute Medicine & Surgery*, **6**(2), 206-207, doi:10.1002/ams2.387.
Hayek, M., H. Harwatt, W. Ripple and N. Mueller, 2021: The carbon opportunity cost of animal-sourced food production on land. *Nature Sustainability*, **4**(1), 21-24, doi:10.1038/s41893-020-00603-4.
Hayes, K., P. Berry and K. Ebi, 2019: Factors Influencing the Mental Health Consequences of Climate Change in Canada. *International Journal of Environmental Research and Public Health*, **16**, 1583, doi:10.3390/ijerph16091583.
Hayes, K. et al., 2018: Climate change and mental health: risks, impacts and priority actions. *International Journal of Mental Health Systems*, **12**, 1-12, doi:10.1186/s13033-018-0210-6.
Hayes, K. and B. Poland, 2018: Addressing Mental Health in a Changing Climate: Incorporating Mental Health Indicators into Climate Change and Health Vulnerability and Adaptation Assessments. *International Journal of Environmental Research and Public Health*, **15**(9), doi:10.3390/ijerph15091806.
Hayward, G. and S. Ayeb-Karlsson, 2021: 'Seeing with Empty Eyes': a systems approach to understand climate change and mental health in Bangladesh. *Climatic Change*, **165**(1), 1-30.
Heaney, A. and S. Winter, 2016: Climate-driven migration: An exploratory case study of Maasai health perceptions and help-seeking behaviors. *International Journal of Public Health*, **61**(6), 641-649, doi:10.1007/s00038-015-0759-7.
Heaviside, C., S. Vardoulakis and X. M. Cai, 2016: Attribution of mortality to the urban heat island during heatwaves in the West Midlands, UK. *Environmental Health*, **15**, doi:10.1186/s12940-016-0100-9.
Hedenus, F., S. Wirsenius and D. J. A. J. C. C. Johansson, 2014: The importance of reduced meat and dairy consumption for meeting stringent climate change targets. **124**(1), 79-91, doi:10.1007/s10584-014-1104-5.
Hegre, H. et al., 2016: Forecasting civil conflict along the shared socioeconomic pathways. *Environmental Research Letters*, **11**(5), 054002.
Hegre, H., H. M. Nygård and P. Landsverk, 2021: Can We Predict Armed Conflict? How the First 9 Years of Published Forecasts Stand Up to Reality. *International Studies Quarterly*.
Hegre, H. and N. Sambanis, 2006: Sensitivity analysis of empirical results on civil war onset. *Journal of conflict resolution*, **50**(4), 508-535.
Heilmann, K., M. Kahn and C. Tang, 2021: The urban crime and heat gradient in high and low poverty areas. *Journal of Public Economics*, **197**, doi:10.1016/j.jpubeco.2021.104408.
Heininen, L. and H. Exner-Pirot, 2020: Climate Change and Arctic Security. Springer International Publishing.
Hellberg, R. S. and E. Chu, 2016: Effects of climate change on the persistence and dispersal of foodborne bacterial pathogens in the outdoor environment: A review. *Crit Rev Microbiol*, **42**(4), 548-572, doi:10.3109/1040841x.2014.972335.
Hellden, D. et al., 2021: Climate change and child health: a scoping review and an expanded conceptual framework. *Lancet Planetary Health*, **5**(3), E164-E175.

Helm, S. et al., 2018: Differentiating environmental concern in the context of psychological adaption to climate change. *Global Environmental Change-Human and Policy Dimensions*, **48**, 158-167, doi:10.1016/j.gloenvcha.2017.11.012.
Hendrix, C. and S. Haggard, 2015: Global food prices, regime type, and urban unrest in the developing world. *Journal of Peace Research*, **52**(2), 143-157, doi:10.1177/0022343314561599.
Henrique, K. and P. Tschakert, 2020: Pathways to urban transformation: From dispossession to climate justice. *Progress in Human Geography*, doi:10.1177/0309132520962856.
Heo, S., M. L. Bell and J. T. Lee, 2019a: Comparison of health risks by heat wave definition: Applicability of wet-bulb globe temperature for heat wave criteria. *Environmental Research*, **168**, 158-170, doi:10.1016/j.envres.2018.09.032.
Heo, S. et al., 2019b: The Use of a Quasi-Experimental Study on the Mortality Effect of a Heat Wave Warning System in Korea. *International Journal of Environmental Research and Public Health*, **16**(12), doi:10.3390/ijerph16122245.
Hepburn, C. et al., 2020: Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Review of Economic Policy*, **36**, S359-S381, doi:10.1093/oxrep/graa015.
Hermans, K. and L. Garbe, 2019: Droughts, livelihoods, and human migration in northern Ethiopia. *Regional Environmental Change*, doi:doi.org/10.1007/s10113-019-01473-z.
Heslin, A., 2019: *Climate Migration and Cultural Preservation: The Case of the Marshallese Diaspora. In Loss and Damage from Climate Change: Concepts, Methods and Policy Options*. Loss and Damage from Climate Change: Concepts, Methods and Policy Options, Springer, Cham. ISBN 978-3-319-72026-5.
Heslin, A., 2021: Riots and resources: How food access affects collective violence. *Journal of Peace Research*, **58**(2), 199-214.
Hess, J., J. McDowell and G. Luber, 2012: Integrating Climate Change Adaptation into Public Health Practice: Using Adaptive Management to Increase Adaptive Capacity and Build Resilience. *Environmental Health Perspectives*, **120**(2), 171-179, doi:10.1289/ehp.1103515.
Hillier, S. A., A. Taleb, E. Chaccour and C. Aenishaenslin, 2021: Examining the concept of One Health for indigenous communities: A systematic review. *One Health*, **12**, 100248, doi:10.1016/j.onehlt.2021.100248.
Hino, M., C. B. Field and K. J. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, **7**, 364-370.
HLPE, 2020: Food security and nutrition: building a global narrative towards 2030, Rome.
Hobbie, S. E. and N. B. Grimm, 2020: Nature-based approaches to managing climate change impacts in cities. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **375**(1794), doi:10.1098/rstb.2019.0124.
Hochman, A. et al., 2021: The relationship between cyclonic weather regimes and seasonal influenza over the Eastern Mediterranean. *Science of the Total Environment*, **750**, doi:10.1016/j.scitotenv.2020.141686.
Hock, S. et al., 2018: Childhood malnutrition and maltreatment are linked with personality disorder symptoms in adulthood: Results from a Barbados lifespan cohort. *Psychiatry Research*,(269), 301-308.
Høeg, E. and C. Tulloch, 2018: Sinking Strangers: Media Representations of Climate Refugees on the BBC and Al Jazeera. *Journal of Communication Inquiry*, **43**, 019685991880948, doi:10.1177/0196859918809486.
Hoffman, J., V. Shandas and N. Pendleton, 2020: The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas. *Climate*, **8**(1), doi:10.3390/cli8010012.
Hoffmann, R. et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change*, **10**(10), 904-912, doi:10.1038/s41558-020-0898-6.
Hollowed, A. et al., 2013: Projected impacts of climate change on marine fish and fisheries. *Ices Journal of Marine Science*, **70**(5), 1023-1037, doi:10.1093/icesjms/fst081.
Holman, C., R. M. Harrison and X. Querol, 2015: Review of the efficacy of low emission zones to improve urban air quality in European cities. *Atmospheric Environment*, **111**, 161-169, doi:10.1016/j.atmosenv.2015.04.009.
Holsman, K. et al., 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11**(1), doi:10.1038/s41467-020-18300-3.
Honda, Y. and D. Onozuka, 2020: Heat-Related Mortality/Morbidity in East Asia. *Extreme Weather Events and Human Health: International Case Studies*, 131-144, doi:10.1007/978-3-030-23773-8_10.
Hondula, D. M., M. Georgescu and R. C. Balling, 2014: Challenges associated with projecting urbanization-induced heat-related mortality. *Science of the Total Environment*, **490**, 538-544, doi:10.1016/j.scitotenv.2014.04.130.
Hong, C. P. et al., 2019: Impacts of climate change on future air quality and human health in China. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(35), 17193-17200, doi:10.1073/pnas.1812881116.
Hooijer, A. and R. Vernimmen, 2021: Global LiDAR land elevation data reveal greatest sea-level rise vulnerability in the tropics. *Nature Communications*, 12(1), 3592. Available at: https://doi.org/10.1038/s41467-021-23810-9.
Hopp, S., F. Dominici and J. F. Bobb, 2018: Medical diagnoses of heat wave-related hospital admissions in older adults. *Preventive Medicine*, **110**, 81-85, doi:10.1016/j.ypmed.2018.02.001.
Horn, L. M. et al., 2018: Association between precipitation and diarrheal disease in mozambique. *International Journal of Environmental Research and Public Health*, **15**(4), doi:10.3390/ijerph15040709.
Hornsey, M., E. Harris, P. Bain and K. Fielding, 2016: Meta-analyses of the determinants and outcomes of belief in climate change. *Nature Climate Change*, **6**(6), 622-+, doi:10.1038/nclimate2943.

Horton, R. M. and A. W. de Sherbinin, David.Oppenheimer, Michael., 2021: Assessing human habitability and migration. 372(6548), 1279 LP - 1283. Available at: http://science.sciencemag.org/content/372/6548/1279.abstract.
Hossain, K., 2016: Securitizing the Arctic indigenous peoples: A community security perspective with special reference to the Sámi of the European high north. *Polar Science*, **10**(3), 415-424.
Houde, M. et al., 2020: Mercury in Ringed Seals (Pusa hispida) from the Canadian Arctic in Relation to Time and Climate Parameters. *Environmental Toxicology and Chemistry*, **39**(12), 2462-2474, doi:10.1002/etc.4865.
Houéménou, H. et al., 2021: Pathogenic Leptospira and water quality in African cities: A case study of Cotonou, Benin. *Sci Total Environ*, **774**, 145541, doi:10.1016/j.scitotenv.2021.145541.
Howard, C. et al., 2021: SOS! Summer of Smoke: a retrospective cohort study examining the cardiorespiratory impacts of a severe and prolonged wildfire season in Canada's high subarctic. *Bmj Open*, **11**(2), doi:10.1136/bmjopen-2020-037029.
Howard, G., R. Calow, A. Macdonald and J. Bartram, 2016: Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action. *Annu. Rev. Environ. Resour.*, **2016.41**, 253-276, doi:10.1146/annurev-environ-110615-085856
Hoy, D. et al., 2014: Adapting to the health impacts of climate change in a sustainable manner. *Globalization and Health*, **10**, doi:10.1186/s12992-014-0082-8.
Hrabok, M., A. Delorme and V. I. Agyapong, 2020: Threats to mental health and well-being associated with climate change. *Journal of Anxiety Disorders*, **76**, doi:102295.
Hsiang, S., M. Burke and E. Miguel, 2013: Quantifying the Influence of Climate on Human Conflict. *Science*, **341**(6151), 1212-+, doi:10.1126/science.1235367.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356**(6345), 1362-1369, doi:10.1126/science.aal4369.
Hsiang, S. M. and B. Marshall, 2014: Climate, conflict, and social stability: what does the evidence say? *Climatic Change*, **123**(1), 39--55, doi:10.1007/s10584-013-0868-3.
Hu, L. Q., O. V. Wilhelmi and C. Uejio, 2019: Assessment of heat exposure in cities: Combining the dynamics of temperature and population. *Science of the Total Environment*, **655**, 1-12, doi:10.1016/j.scitotenv.2018.11.028.
Huang, C. et al., 2018: Mortality burden attributable to heatwaves in Thailand: A systematic assessment incorporating evidence-based lag structure. *Environment International*, **121**, 41-50, doi:https://doi.org/10.1016/j.envint.2018.08.058.
Huang, J., . and et al., 2018: Projections for temperature-related years of life lost from cardiovascular diseases in the elderly in a Chinese city with typical subtropical climate. *Environmental Research*, **167**, 614-621.
Huber, R. et al., 2020a: Symposium report: emerging threats for human health - impact of socioeconomic and climate change on zooanthroponosis in the Republic of Sakha (Yakutia), Russia. *International Journal of Circumpolar Health*, **79**(1), doi:10.1080/22423982.2020.1715698.
Huber, V. et al., 2020b: Temperature-related excess mortality in German cities at 2 degrees C and higher degrees of global warming. *Environmental Research*, **186**, doi:10.1016/j.envres.2020.109447.
Huda, M. S., 2021: An ecological response to ethno-nationalistic populism: grassroots environmental peacebuilding in south Asia. *International Affairs*, **97**(1), 119-138.
Huda, M. S. and S. H. Ali, 2018: Environmental peacebuilding in South Asia: Establishing consensus on hydroelectric projects in the Ganges-Brahmaputra-Meghna (GBM) Basin. *Geoforum*, **96**, 160-171.
Hueffer, K., M. Ehrlander, K. Etz and A. Reynolds, 2019: One health in the circumpolar North. *International Journal of Circumpolar Health*, **78**(1), doi:10.1080/22423982.2019.1607502.
Hundessa, S. et al., 2018: Projecting potential spatial and temporal changes in the distribution of Plasmodium vivax and Plasmodium falciparum malaria in China with climate change. *Sci Total Environ*, **627**, 1285-1293, doi:10.1016/j.scitotenv.2018.01.300.
Hunter, L. M. and D. H. Simon, 2017: Might climate change the “healthy migrant” effect? . *Global Environmental Change*, **47**, 133-142.
Hunter, L. M. et al., 2021: Scales and sensitivities in climate vulnerability, displacement, and health. *Population and Environment*, **43**(1), 61--81, doi:10.1007/s11111-021-00377-7.
Hussain-Alkhateeb, L. et al., 2018: Early warning and response system (EWARS) for dengue outbreaks: Recent advancements towards widespread applications in critical settings. *Plos One*, **13**(5), doi:10.1371/journal.pone.0196811.
Hynes, W., T. Benjamin, L. Patrick and L. Igor, 2020: Bouncing forward: a resilience approach to dealing with COVID-19 and future systemic shocks. *Environment Systems and Decisions*, **40**, 174–184.
Ide, T., 2019: The impact of environmental cooperation on peacemaking: definitions, mechanisms, and empirical evidence. *International Studies Review*, **21**(3), 327-346.
Ide, T., 2020: The dark side of environmental peacebuilding. *World Development*, **127**, 104777.
Ide, T. et al., 2021: The past and future (s) of environmental peacebuilding. *International Affairs*, **97**(1), 1-16.
Ide, T., M. Brzoska, J. Donges and C. Schleussner, 2020: Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk. *Global Environmental Change-Human and Policy Dimensions*, **62**, doi:10.1016/j.gloenvcha.2020.102063.

Ide, T. and C. Frohlich, 2015: Socio-environmental cooperation and conflict? A discursive understanding and its application to the case of Israel and Palestine. *Earth System Dynamics*, **6**(2), 659-671, doi:10.5194/esd-6-659-2015.
Ide, T. and A. Tubi, 2020: Education and environmental peacebuilding: insights from three projects in Israel and Palestine. *Annals of the American Association of Geographers*, **110**(1), 1-17.
Ikaheimo, T. M., 2018: Cardiovascular diseases, cold exposure and exercise. *Temperature (Austin, Tex.)*, **5**(2), 123-146, doi:10.1080/23328940.2017.1414014.
Im, E., J. Pal and E. Eltahir, 2017: Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science Advances*, **3**(8), doi:10.1126/sciadv.1603322.
IMF, 2020: World Economic Outlook: A Long and Difficult Ascent. International Monetary Fund, Washington, DC.
IPES-Food, 2018: Breaking away from industrial food and farming systems: Seven case studies of agroecological transition.
IPES-Food, 2020: The added value(s) of agroecology: Unlocking the potential for transition in West Africa.
Ishida, H. et al., 2014: Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research. *Environmental Research Letters*, **9**(6), doi:10.1088/1748-9326/9/6/064014.
Islam, M., M. Alharthi and M. Alam, 2019: The Impacts of Climate Change on Road Traffic Accidents in Saudi Arabia. *Climate*, **7**(9), 103.
Islam, M. R. and M. Hasan, 2016: Climate-induced human displacement: a case study of Cyclone Aila in the south-west coastal region of Bangladesh. *Natural Hazards*, **81**(2), 1051-1071.
Islam, M. R. and M. Shamsuddoha, 2017: Socioeconomic consequences of climate induced human displacement and migration in Bangladesh. *International Sociology*, **32**(3).
Islam, M. Z., O. Kolade and G. Kibreab, 2018: Post-disaster Housing Reconstruction: The Impact of Resourcing in Post-cyclones Sidr and Aila in Bangladesh. *Journal of International Development*, **30**(6), 934-960.
Islam, S., C. Chu, J. Smart and L. Liew, 2020: Integrating disaster risk reduction and climate change adaptation: a systematic literature review. *Climate and Development*, **12**(3), 255-267, doi:10.1080/17565529.2019.1613217.
Ito, Y., M. Akahane and T. Imamura, 2018: Impact of Temperature in Summer on Emergency Transportation for Heat-Related Diseases in Japan. *Chinese medical journal*, **131**, 574-582, doi:10.4103/0366-6999.226061.
J., R. and D. R., 2020: Climate change: an enduring challenge for vector-borne disease prevention and control. *Nature Immunology*, **21**(5), 479-483.
J.J., A., W. W. L. Cheung, P. S. Ross and U. R. Sumaila, 2017: Climate change–contaminant interactions in marine food webs: Toward a conceptual framework. *Glob Change Biol.*, **23**, 3984-4001, doi:https://doi.org/10.1111/gcb.13667.
Jaakkola, J. J. K., S. Juntunen and K. Nakkalajarvi, 2018: The Holistic Effects of Climate Change on the Culture, Well-Being, and Health of the Saami, the Only Indigenous People in the European Union. *Curr Environ Health Rep*, **5**(4), 401-417, doi:10.1007/s40572-018-0211-2.
Jacob, B. and M. Kazaura, 2021: Access to Safe Water, Sanitation, and Hygiene: A Cross-Sectional Study among the Maasai in Tanzania. *Am J Trop Med Hyg*, doi:10.4269/ajtmh.20-0134.
Jahn, S. and E. Hertig, 2021: Modeling and projecting health-relevant combined ozone and temperature events in present and future Central European climate. *Air Quality Atmosphere and Health*, **14**(4), 563-580, doi:10.1007/s11869-020-00961-0.
Jalilov, S. M., S. A. Amer and F. A. Ward, 2018: Managing the water-energy-food nexus: Opportunities in Central Asia. *Journal of Hydrology*, **557**, 407-425.
Jamero, M. et al., 2017: Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change*, **7**(8), 581-586, doi:10.1038/nclimate3344.
James, L. E., C. Welton-Mitchell, J. R. Noel and A. S. James, 2020: Integrating mental health and disaster preparedness in intervention: a randomized controlled trial with earthquake and flood-affected communities in Haiti. *Psychological Medicine*, **50**(2), 342-352, doi:10.1017/s0033291719000163.
James, S. L. et al., 2018: Global, regional, and national incidence, prevalence, and years lived with disability for 354 diseases and injuries for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, **392**(10159), 1789-1858.
Jang, J. et al., 2020: Roles of urban heat anomaly and land-use/land-cover on the heat-related mortality in the national capital region of South Korea: A multi-districts time-series study. *Environment International*, **145**, doi:10.1016/j.envint.2020.106127.
Jardine, S., M. Fisher, S. Moore and J. Samhouri, 2020: Inequality in the Economic Impacts from Climate Shocks in Fisheries: The Case of Harmful Algal Blooms. *Ecological Economics*, **176**, doi:10.1016/j.ecolecon.2020.106691.
Jay, O. et al., 2021: Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *The Lancet*, **398**(10301), 16, doi:https://doi.org/10.1016/S0140-6736(21)01209-5.
Jehn, M. et al., 2013: Tele-monitoring reduces exacerbation of COPD in the context of climate change--a randomized controlled trial. *Environ. Health*, **12**, 99, doi:10.1186/1476-069x-12-99.
Jennings, V. and O. Bamkole, 2019: The Relationship between Social Cohesion and Urban Green Space: An Avenue for Health Promotion. *International Journal of Environmental Research and Public Health*, **16**(3), doi:10.3390/ijerph16030452.

Jennings, V., C. E. Reid and C. H. Fuller, 2021: Green infrastructure can limit but not solve air pollution injustice. *Nature Communications*, **12**(1), doi:10.1038/s41467-021-24892-1.
Jessoe, K., M. D. T. and T. J. E., 2018: Climate Change and Labour Allocation in Rural Mexico: Evidence from Annual Fluctuations in Weather. *The Economic Journal*, **128**(608), 230--261.
Jim, C. Y., C. K. van den Bosch and W. Y. Chen, 2018: Acute Challenges and Solutions for Urban Forestry in Compact and Densifying Cities. *Journal of Urban Planning and Development*, **144**(3), doi:10.1061/(asce)up.1943-5444.0000466.
Johansson, J. M. et al., 2020: The European heat wave of 2018 and its promotion of the ozone climate penalty in southwest Sweden. *Boreal Environment Research*, **25**, 39-50.
Johnson-Jennings, M. et al., 2020: Ode'imin Giizis: Proposing and Piloting Gardening as an Indigenous Childhood Health Intervention. *Journal of Health Care For the Poor and Underserved*, **31**(2), 871-888, doi:10.1353/hpu.2020.0066.
Johnson, C. et al., 2013: Social Protection and Climate Change: Emerging Issues for Research, Policy and Practice. *Development Policy Review*, **31**(s2), o2-o18, doi:https://doi.org/10.1111/dpr.12036.
Johnson, M. F., 2021: Local engagement in environmental peacebuilding: protected area development as a pathway to peace in Afghanistan. *Development in Practice*, 1-13.
Johnston, F. H., A. M. Kavanagh, D. M. Bowman and R. K. Scott, 2002: Exposure to bushfire smoke and asthma: an ecological study. *Med. J. Aust.*, **176**(535-8).
Jones, A., 2017: Food Insecurity and Mental Health Status: A Global Analysis of 149 Countries. *American Journal of Preventive Medicine*, **53**(2), 264-273, doi:10.1016/j.amepre.2017.04.008.
Jones, B. et al., 2018: Avoiding population exposure to heat-related extremes: demographic change vs climate change. *Climatic Change*, **146**(3-4), 423-437, doi:10.1007/s10584-017-2133-7.
Jones, L., 2019: Resilience isn't the same for all: Comparing subjective and objective approaches to resilience measurement. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(1), doi:https://doi.org/10.1002/wcc.552.
Jones, R., H. Bennett, G. Keating and A. Blaiklock, 2014: Climate change and the right to health for Maori in Aotearoa/New Zealand. *Health & Human Rights*, **16**(1), 54-68.
Jones, R., A. Macmillan and P. Reid, 2020: Climate Change Mitigation Policies and Co-Impacts on Indigenous Health: A Scoping Review. *International Journal of Environmental Research and Public Health*, **17**(23), doi:10.3390/ijerph17239063.
Jost, C. et al., 2016: Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, **8**(2), 133-144, doi:10.1080/17565529.2015.1050978.
Jugert, P. et al., 2016: Collective efficacy increases pro-environmental intentions through increasing self-efficacy. *Journal of Environmental Psychology*, **48**, 12-23, doi:10.1016/j.jenvp.2016.08.003.
Jutla, A., R. Khan and R. Colwell, 2017: Natural Disasters and Cholera Outbreaks: Current Understanding and Future Outlook. *Curr Environ Health Rep*, **4**(1), 99-107, doi:10.1007/s40572-017-0132-5.
Kabir, S. M. S., 2018: Psychological health challenges of the hill-tracts region for climate change in Bangladesh. *Asian J Psychiatr*, **34**, 74-77, doi:10.1016/j.ajp.2018.04.001.
Kaczan, D. J. and J. Orgill-Meyer, 2020: The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change*, **158**(3), 281-300, doi:10.1007/s10584-019-02560-0.
Kadandale, S. et al., 2020: Primary health care and the climate crisis. *Bulletin of the World Health Organization*, **98**(11), 818-820, doi:10.2471/blt.20.252882.
Kaffenberger, B. H., D. Shetlar, S. A. Norton and M. Rosenbach, 2017: The effect of climate change on skin disease in North America. *J Am Acad Dermatol*, **76**(1), 140-147, doi:10.1016/j.jaad.2016.08.014.
Kakinuma, K. et al., 2020: Flood-induced population displacements in the world. *Environmental Research Letters*, **15**(12), 124029, doi:10.1088/1748-9326/abc586.
Kalilou, O., 2021: Climate change and conflict in the Sahel: the acacia gum tree as a tool for environmental peacebuilding. *International Affairs*, **97**(1), 201-218.
Kälin, W., 2018: The Global Compact on Migration: A Ray of Hope for Disaster-Displaced Persons. *International Journal of Refugee Law*, **30**(4), 664-667, doi:10.1093/ijrl/eey047.
Kalinda, C., M. Chimbari and S. Mukaratirwa, 2017: Effect of temperature on the Bulinus globosus - Schistosoma haematobium system. *Infectious Diseases of Poverty*, **6**, doi:10.1186/s40249-017-0260-z.
Kalisa, E. et al., 2018: Temperature and air pollution relationship during heatwaves in Birmingham, UK. *Sustainable Cities and Society*, **43**, 111-120, doi:10.1016/j.scs.2018.08.033.
Kamal, A. et al., 2015: A Recipe for Change: Reclamation of Indigenous Food Sovereignty in O-Pipon-Na-Piwin Cree Nation for Decolonization, Resource Sharing, and Cultural Restoration. *Globalizations*, **12**(4), 559-575, doi:10.1080/14747731.2015.1039761.
Kamal, M. et al., 2018: Mapping the global potential distributions of two arboviral vectors Aedes aegypti and Ae. albopictus under changing climate. *Plos One*, **13**(12), doi:10.1371/journal.pone.0210122.
Kampe, E. O. I., S. Kovats and S. Hajat, 2016: Impact of high ambient temperature on unintentional injuries in high-income countries: a narrative systematic literature review. *Bmj Open*, **6**(2), doi:10.1136/bmjopen-2015-010399.
Keim, M., 2008: Building Human Resilience The Role of Public Health Preparedness and Response As an Adaptation to Climate Change. *American Journal of Preventive Medicine*, **35**(5), 508-516, doi:10.1016/j.amepre.2008.08.022.

Kelley, C. P. et al., 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc Natl Acad Sci U S A*, **112**(11), 3241-3246, doi:10.1073/pnas.1421533112.
Kellog, M., 2020: Women Building Resilient Cities in the Context of Climate Change Lessons from Freetown, Sierra Leone. Georgetown Institute for Women, Peace and Security.
Kelly, F. J., I. S. Mudway and J. C. Fussell, 2021: Air Pollution and Asthma: Critical Targets for Effective Action. *Pulmonary Therapy*, **7**(1), 9-24, doi:10.1007/s41030-020-00138-1.
Kelman, I., J. Field, K. Suri and G. M. Bhat, 2018: Disaster diplomacy in Jammu and Kashmir. *International journal of disaster risk reduction*, **31**, 1132-1140.
Kelman, I. et al., 2019: Does climate change influence people's migration decisions in Maldives? *Climatic Change*, **153**(1-2), 285-299, doi:10.1007/s10584-019-02376-y.
Kendrovski, V. et al., 2017: Quantifying Projected Heat Mortality Impacts under 21st-Century Warming Conditions for Selected European Countries. *International Journal of Environmental Research and Public Health*, **14**(7), doi:10.3390/ijerph14070729.
Kennedy, J. and L. King, 2014: The political economy of farmers' suicides in India: indebted cash-crop farmers with marginal landholdings explain state-level variation in suicide rates. *Globalization and Health*, **10**(1), 16-16, doi:10.1186/1744-8603-10-16.
Kennedy, S., M. P. Kidd, J. T. McDonald and N. Biddle, 2015: The Healthy Immigrant Effect: Patterns and Evidence from Four Countries. *Journal of International Migration and Integration*, **16**(2), 317-332, doi:10.1007/s12134-014-0340-x.
Kenney, M. A., A. C. Janetos and G. C. Lough, 2016: Building an integrated U.S. National Climate Indicators System. In: *The US National Climate Assessment: Innovations in Science and Engagement* [Jacobs, K., S. Moser and J. Buizer (eds.)]. Springer International Publishing, Cham, pp. 85-96. ISBN 9783319418025.
Kerr, Z. Y. et al., 2020: The Epidemiology and Management of Exertional Heat Illnesses in High School Sports During the 2012/2013-2016/2017 Academic Years. *Journal of Sport Rehabilitation*, **29**(3), 332-338, doi:10.1123/jsr.2018-0364.
Kesetyaningsih, T. W., S. Andarini, Sudarto and H. Pramoedyo, 2018: Determination of Environmental Factors Affecting Dengue Incidence in Sleman District, Yogyakarta, Indonesia. *African journal of infectious diseases*, **12**(1 Suppl), 13-25, doi:10.2101/Ajid.12v1S.3.
Kessler, R. C. et al., 2008: Trends in Mental Illness and Suicidality After Hurricane Katrina. Nature Publishing Group, 374–384 pp.
Keyes, K. et al., 2014: The Burden of Loss: Unexpected Death of a Loved One and Psychiatric Disorders Across the Life Course in a National Study. *American Journal of Psychiatry*, **171**(8), 864-871, doi:10.1176/appi.ajp.2014.13081132.
Khalil, I. A. et al., 2018: Morbidity, mortality, and long-term consequences associated with diarrhoea from Cryptosporidium infection in children younger than 5 years: a meta-analyses study. *Lancet Glob Health*, **6**(7), e758-e768, doi:10.1016/s2214-109x(18)30283-3.
Khan, M. R. and S. R. Huq, Adeeba N.Alam, Sarder S., 2021: High-density population and displacement in Bangladesh. *Science*, 372(6548). Available at: http://science.sciencemag.org/content/372/6548/1290.abstract.
Khan, S. et al., 2015: Extreme weather events: Should drinking water quality management systems adapt to changing risk profiles? *Water Research*, **85**, 124-136, doi:10.1016/j.watres.2015.08.018.
Khanian, M., B. Serpoush and N. Gheitarani, 2019: Balance between place attachment and migration based on subjective adaptive capacity in response to climate change: the case of Famenin County in Western Iran. *Climate and Development*, **11**(1), 69-82, doi:10.1080/17565529.2017.1374238.
Khormi, H. and L. Kumar, 2016: Future malaria spatial pattern based on the potential global warming impact in South and Southeast Asia. *Geospatial Health*, **11**(3), 290-298, doi:10.4081/gh.2016.416.
Kibret, S. et al., 2016: Malaria and large dams in sub-Saharan Africa: future impacts in a changing climate. *Malaria Journal*, **15**, doi:10.1186/s12936-016-1498-9.
Kim, H. et al., 2019a: Difference in temporal variation of temperature-related mortality risk in seven major South Korean cities spanning 1998–2013. *Science of The Total Environment*, **656**, 986-996, doi:https://doi.org/10.1016/j.scitotenv.2018.11.210.
Kim, J. et al., 2016: Effect of Climate Factors on the Childhood Pneumonia in Papua New Guinea: A Time-Series Analysis. *International Journal of Environmental Research and Public Health*, **13**(2), doi:10.3390/ijerph13020213.
Kim, S., B. Fleisher and Y. Sun, 2017: The Long-term Health Effects of Fetal Malnutrition: Evidence from the 1959–1961 China Great Leap Forward Famine. *Health Economics*, **26**(10), 1264-1277.
Kim, Y. et al., 2019b: Suicide and Ambient Temperature: A Multi-Country Multi-City Study. *Environmental Health Perspectives*, **127**(11), doi:10.1289/ehp4898.
King, A. D. and D. J. Karoly, 2017: Climate extremes in Europe at 1.5 and 2 degrees of global warming. *Environmental Research Letters*, **12**(11), doi:10.1088/1748-9326/aa8e2c.
King, U. and C. Furgal, 2014: Is Hunting Still Healthy? Understanding the Interrelationships between Indigenous Participation in Land-Based Practices and Human-Environmental Health. *International Journal of Environmental Research and Public Health*, **11**(6), 5751-5782, doi:10.3390/ijerph110605751.

Kinney, P., 2018: Temporal Trends in Heat-Related Mortality: Implications for Future Projections. *Atmosphere*, **9**, 409, doi:10.3390/atmos9100409.
Kipp, A. et al., 2019: The need for community-led, integrated and innovative monitoring programmes when responding to the health impacts of climate change. *International Journal of Circumpolar Health*, **78**(2), doi:10.1080/22423982.2018.1517581.
Kirtman, B. et al., 2014: Near- term Climate Change: Projections and Predictability. *Climate Change 2013: The Physical Science Basis*, 953-1028.
Kita, S. M., 2017: Urban vulnerability, disaster risk reduction and resettlement in Mzuzu city, Malawi. *International journal of disaster risk reduction*, **22**, 158-166.
Kjellstrom, T. et al., 2016: Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. *Annual Review of Public Health*, **37**(1), 97-112, doi:10.1146/annurev-publhealth-032315-021740.
Kjellstrom, T. et al., 2018: Estimating population heat exposure and impacts on working people in conjunction with climate change. *International Journal of Biometeorology*, **62**(3), 291-306, doi:10.1007/s00484-017-1407-0.
Kjellstrom, T., B. Lemke and J. Lee, 2019: Workplace Heat: An increasing threat to occupational health and productivity. *American Journal of Industrial Medicine*, **62**(12), 1076-1078, doi:10.1002/ajim.23051.
Klein, T. et al., 2019: A nation-wide analysis of tree mortality under climate change: Forest loss and its causes in Israel 1948-2017. *Forest Ecology and Management*, **432**, 840-849, doi:10.1016/j.foreco.2018.10.020.
Koc, C. B., P. Osmond and A. Peters, 2018: Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. *Solar Energy*, **166**, 486-508, doi:10.1016/j.solener.2018.03.008.
Koren, O., B. Bagozzi and T. Benson, 2021: Food and water insecurity as causes of social unrest: Evidence from geolocated Twitter data. *Journal of Peace Research*, **58**(1), 67-82, doi:10.1177/0022343320975091.
Koren, O. and B. E. Bagozzi, 2017: Living off the land: The connection between cropland, food security, and violence against civilians. *Journal of Peace Research*, **54**(3), 351-364, doi:10.1177/0022343316684543.
Koslov, L. and A. S. Merdjanoff, Elana.Klinenberg, Eric., 2021: When rebuilding no longer means recovery: the stress of staying put after Hurricane Sandy. *Climatic Change*, 165(3), 59. Available at: https://doi.org/10.1007/s10584-021-03069-1.
Kostyla, C., R. Bain, R. Cronk and J. Bartram, 2015: Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review. *Sci Total Environ*, **514**, 333-343, doi:10.1016/j.scitotenv.2015.01.018.
Koubi, V., 2019: Climate Change and Conflict. In: *Annual Review of Political Science, Vol 22* [Levi, M. and N. L. Rosenblum (eds.)]. Annual Reviews, Palo Alto, pp. 343-360.
Koubi, V., T. Bˆhmelt, G. Spilker and L. Schaffer, 2018: The determinants of environmental migrants' conflict perception. *Internation Organisation*, **72**(4), 905-936.
Koubi, V., Q. Nguyen, G. Spilker and T. Bohmelt, 2021: Environmental migrants and social-movement participation. *Journal of Peace Research*, **58**(1), 18-32, doi:10.1177/0022343320972153.
Koubi, V. and Q. S. Nguyen, G.Böhmelt, T., 2020: Environmental migrants and social-movement participation. *Journal of Peace Research*, 58(1), 18-32.
Koubi, V., G. Spilker, L. Schaffer and T. Bernauer, 2016a: Environmental Stressors and Migration: Evidence from Vietnam. *World Development*, **79**, 197-210, doi:10.1016/j.worlddev.2015.11.016.
Koubi, V., G. Spilker, L. Schaffer and T. Böhmelt, 2016b: The role of environmental perceptions in migration decision-making: evidence from both migrants and non-migrants in five developing countries. *Population and Environment*, **38**(2), 134-163, doi:10.1007/s11111-016-0258-7.
Kousky, C., 2016: Impacts of Natural Disasters on Children. *Future of Children*, **26**(1), 73-92, doi:10.1353/foc.2016.0004.
Kovach, T. and K. Conca, 2016: Environmental priorities in post-conflict recovery: Efficacy of the needs-assessment process. *Journal of Peacebuilding & Development*, **11**(2), 4-24.
Kowalczewski, E. and J. Klein, 2018: Sámi youth health, the role of climate change, and unique health-seeking behaviour. *Int J Circumpolar Health*, **77**(1), 1454785, doi:10.1080/22423982.2018.1454785.
Kraemer, M. et al., 2019: Past and future spread of the arbovirus vectors Aedes aegypti and Aedes albopictus. *Nature Microbiology*, **4**(5), 854-863, doi:10.1038/s41564-019-0376-y.
Krakauer, N. Y., B. I. Cook and M. J. Puma, 2020: Effect of irrigation on humid heat extremes. *Environmental Research Letters*, **15**(9), doi:10.1088/1748-9326/ab9ecf.
Krampe, F., 2017: Toward sustainable peace: A new research agenda for post-conflict natural resource management. *Global Environmental Politics*, **17**(4), 1-8.
Krampe, F. and S. Gignoux, 2018: Water service provision and peacebuilding in East Timor: Exploring the socioecological determinants for sustaining peace. *Journal of Intervention and Statebuilding*, **12**(2), 185-207.
Krampe, F., F. Hegazi and S. D. VanDeveer, 2021: Sustaining peace through better resource governance: Three potential mechanisms for environmental peacebuilding. *World Development*, **144**, 105508.
Krause, J., W. Krause and P. Bränfors, 2018: Women's participation in peace negotiations and the durability of peace. *International Interactions*, **44**(6), 985-1016.
Kreppel, K. S. et al., 2014: A Non-Stationary Relationship between Global Climate Phenomena and Human Plague Incidence in Madagascar. *Plos Neglected Tropical Diseases*, **8**(10), doi:10.1371/journal.pntd.0003155.

Kron, A., 2019: Environmental Peacebuilding and the UN Security Council, Vol. 29 ed. [Schrijver, N. J. and N. M. Blokker (eds.)]. Nijhoff Law Specials, Brill, 248-266 pp.
Krug, A., D. Fenner, A. Holtmann and D. Scherer, 2019: Occurrence and Coupling of Heat and Ozone Events and Their Relation to Mortality Rates in Berlin, Germany, between 2000 and 2014. *Atmosphere*, **10**(6), doi:10.3390/atmos10060348.
Krug, A., D. Fenner, H. G. Mucke and D. Scherer, 2020: The contribution of air temperature and ozone to mortality rates during hot weather episodes in eight German cities during the years 2000 and 2017. *Natural Hazards and Earth System Sciences*, **20**(11), 3083-3097, doi:10.5194/nhess-20-3083-2020.
Kubik, Z. and M. Maurel, 2016: Weather Shocks, Agricultural Production and Migration: Evidence from Tanzania *Journal of Development Studies*, **52(5)**, 665-680, doi:https://doi.org/10.1080/00220388.2015.1107049.
Kuehn, L. and S. McCormick, 2017: Heat Exposure and Maternal Health in the Face of Climate Change. *Int. J. Environ. Res. Public Health*, **14**(8), doi:10.3390/ijerph14080853.
Kuhnlein, H., B. Erasmus and D. Spigelski, 2013: Indigenous Peoples' Food Systems & Well-Being. Interventions & Policies for Healthy Communities. Agriculture Organization United Nations, Rome.
Kumar, A. et al., 2018a: Mercury from wildfires: Global emission inventories and sensitivity to 2000-2050 global change. *Atmospheric Environment*, **173**, 6-15, doi:10.1016/j.atmosenv.2017.10.061.
Kumar, J. C., V. Gupta, U. Chattopadhyay and B. A. Sreeraman, 2018b: Migration as adaptation strategy to cope with climate change: A study of farmers' migration in rural India. *International Journal of Climate Change Strategies and Management*, **10**(1), 121--141, doi:10.1108/ijccsm-03-2017-0059.
Kumar, P. et al., 2019: The nexus between air pollution, green infrastructure and human health. *Environment International*, **133**, doi:10.1016/j.envint.2019.105181.
Kumar, S., R. Molitor and S. Vollmer, 2016: Drought and Early Child Health in Rural India. *Population and Development Review*, **42**(1), 53-68.
Kupferberg, J. S., 2021: Migration and dignity – relocation and adaptation in the face of climate change displacement in the Pacific – a human rights perspective. *The International Journal of Human Rights*, 1--26, doi:10.1080/13642987.2021.1889515.
Kuusaana, E. D. and K. N. Bukari, 2015: Land conflicts between smallholders and Fulani pastoralists in Ghana: Evidence from the Asante Akim North District (AAND). *Journal of Rural Studies*, **42**, 52-62.
Lacey, G. et al., 2017: Transient climate and ambient health impacts due to national solid fuel cookstove emissions. *Proceedings of the national Academy of Sciences of the United States of America*, **114**(6), 1269-1274, doi:https://doi.org/10.1073/pnas.1612430114.
Lafond, K. E. et al., 2021: Global burden of influenza-associated lower respiratory tract infections and hospitalizations among adults: A systematic review and meta-analysis. *Plos Medicine*, **18**(3), doi:10.1371/journal.pmed.1003550.
Lai, D. Y. et al., 2019: A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *Science of the Total Environment*, **661**, 337-353, doi:10.1016/j.scitotenv.2019.01.062.
Lai, Y. H., 2018: The climatic factors affecting dengue fever outbreaks in southern Taiwan: an application of symbolic data analysis. *Biomedical engineering online*, **17**(Suppl 2), 148, doi:10.1186/s12938-018-0575-4.
Lake, A. A., 2018: Neighbourhood food environments: food choice, foodscapes and planning for health. *Proceedings of the Nutrition Society*, **77**(3), 239-246, doi:10.1017/s0029665118000022.
Lake, I. R., 2017: Food-borne disease and climate change in the United Kingdom. *Environ Health*, **16**(Suppl 1), 117, doi:10.1186/s12940-017-0327-0.
Lake, I. R. and G. C. Barker, 2018: Climate Change, Foodborne Pathogens and Illness in Higher-Income Countries. *Curr Environ Health Rep*, **5**(1), 187-196, doi:10.1007/s40572-018-0189-9.
Lake, I. R. et al., 2019: Exploring Campylobacter seasonality across Europe using The European Surveillance System(TESSy) 2008 to 2016. *Euro Surveill*, **24**(13), doi:doi:10.2807/1560-7917.es.2019.24.13.180028.
Lake, I. R. et al., 2017: Climate Change and Future Pollen Allergy in Europe. *Environ. Health Perspect.*, **125**(3), 385-391, doi:10.1289/ehp173.
Lake, L. et al., 2015: The effects of flooding on dioxin and PCB levels in food produced on industrial river catchments. *Environment International*, **77**, 106-115, doi:10.1016/j.envint.2015.01.006.
Lal, A., E. Fearnley and E. Wilford, 2019: Local weather, flooding history and childhood diarrhoea caused by the parasite Cryptosporidium spp.: A systematic review and meta-analysis. *Sci Total Environ*, **674**, 300-306, doi:10.1016/j.scitotenv.2019.02.365.
Lal, A. et al., 2016: Spatial and temporal variation in the association between temperature and salmonellosis in NZ. *Aust N Z J Public Health*, **40**(2), 165-169, doi:10.1111/1753-6405.12413.
Lam, E. K. S. et al., 2020: The impact of climate and antigenic evolution on seasonal influenza virus epidemics in Australia. *Nature Communications*, **11**(1), doi:10.1038/s41467-020-16545-6.
Lambert, H. et al., 2020: COVID-19 as a global challenge: towards an inclusive and sustainable future. *Lancet Planetary Health*, **4**(8), E312-E314, doi:10.1016/s2542-5196(20)30168-6.
Laporta, G. et al., 2015: Malaria vectors in South America: current and future scenarios. *Parasites & Vectors*, **8**, doi:10.1186/s13071-015-1038-4.
Lawson, E., R. Alare, A. Salifu and M. Thompson-Hall, 2019: Dealing with climate change in semi-arid Ghana: Understanding intersectional perceptions and adaptation strategies of women farmers. *GeoJournal*, doi:https://doi.org/10.1007/s10708-019-09974-4.

Lazzaroni, S. and N. Wagner, 2016: Misfortunes never come singly: Structural change, multiple shocks and child malnutrition in rural Senegal. *Economics & Human Biology*, **23**, 246-262, doi:10.1016/j.ehb.2016.10.006.
Le Masson, V., C. Benoudji and S. Reyes, 2019: *Everyday violence and its impact on insecurity and resilience in Chad*. UNEP, Nairobi.
Le Masson, V. et al., 2016: Gender Resilience from Theory to Practice. Building Resilience and Adaptation to Climate Extremes and Disasters, 60 pp.
Le, P. et al., 2019: Predicting the direct and indirect impacts of climate change on malaria in coastal Kenya. *Plos One*, **14**(2), doi:10.1371/journal.pone.0211258.
Leard, B. and K. Roth, 2019: Voluntary Exposure Benefits and the Costs of Climate Change. *Journal of the Association of Environmental and Resource Economists*, **6**(1), 151-185, doi:10.1086/700268.
Lee, E. C. et al., 2019: The projected impact of geographic targeting of oral cholera vaccination in sub-Saharan Africa: A modeling study. *PLoS Med*, **16**(12), e1003003, doi:10.1371/journal.pmed.1003003.
Lee, J., S. Lee and X. Jiang, 2017a: Cyanobacterial Toxins in Freshwater and Food: Important Sources of Exposure to Humans. *Annu. Rev. Food Sci. Technol.*, **8**, 281-304, doi:10.1146/annurev-food-030216-030116.
Lee, J. S. et al., 2017b: Early warning signal for dengue outbreaks and identification of high risk areas for dengue fever in Colombia using climate and non-climate datasets. *BMC Infect Dis*, **17**(1), 480, doi:10.1186/s12879-017-2577-4.
Lee, J. Y. and H. Kim, 2016: Projection of future temperature-related mortality due to climate and demographic changes. *Environment International*, **94**, 489-494, doi:10.1016/j.envint.2016.06.007.
Lee, S. et al., 2018a: Mental disease-related emergency admissions attributable to hot temperatures. *Science of the Total Environment*,(616), 688-694.
Lee, S. H. et al., 2021: Trends in recent waterborne and foodborne disease outbreaks in South Korea, 2015-2019. *Osong Public Health Res Perspect*, **12**(2), 73-79, doi:10.24171/j.phrp.2021.12.2.04.
Lee, W. et al., 2018b: Temporal changes in mortality attributed to heat extremes for 57 cities in Northeast Asia. *Science of The Total Environment*, **616-617**, 703-709, doi:https://doi.org/10.1016/j.scitotenv.2017.10.258.
Lee, W. et al., 2020: Projections of excess mortality related to diurnal temperature range under climate change scenarios: a multi-country modelling study. *Lancet Planetary Health*, **4**(11), E512-E521.
Leedale, J. et al., 2016: Projecting malaria hazard from climate change in eastern Africa using large ensembles to estimate uncertainty. *Geospat Health*, **11**(1 Suppl), 393, doi:10.4081/gh.2016.393.
Lei, X. N. et al., 2021: Temperature changes between neighboring days and childhood asthma: a seasonal analysis in Shanghai, China. *International Journal of Biometeorology*, **65**(6), 827-836, doi:10.1007/s00484-020-02057-x.
Leichenko, R. and J. A. Silva, 2014: Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews-Climate Change*, **5**(4), 539-556, doi:10.1002/wcc.287.
Leiserowitz, A. et al., 2017: Climate change in the American mind: October 2017. Yale University and George Mason University., New Haven, CT: Yale Program on Climate Change Communication.
Lemelin, H. et al., 2010: Climate change, wellbeing and resilience in the Weenusk First Nation at Peawanuck: the Moccasin Telegraph goes global. *Rural and Remote Health*, **10**(2).
León, V. M., R. Moreno-González, V. García and J. A. Campillo, 2017: Impact of flash flood events on the distribution of organic pollutants in surface sediments from a Mediterranean coastal lagoon (Mar Menor, SE Spain). *Environ Sci Pollut Res Int*, **24**(5), 4284-4300, doi:10.1007/s11356-015-4628-y.
Lerner, H. and C. Berg, 2015: The concept of health in One Health and some practical implications for research and education: what is One Health? *Infect. Ecol. Epidemiol.*, **5**, 25300, doi:10.3402/iee.v5.25300.
Levi, M., T. Kjellstrom and A. Baldasseroni, 2018: Impact of climate change on occupational health and productivity: a systematic literature review focusing on workplace heat. *La Medicina del lavoro*, **109**, doi:10.23749/mdl.v109i3.6851.
Levy, A., 2016: Climate change, urban heat islands and health effects : urban planning in Paris. *Environnement Risques & Sante*, **15**(4), 351-356, doi:10.1684/ers.2016.0888.
Levy, B. S. and J. A. Patz, 2015: Climate Change, Human Rights, and Social Justice. *Ann Glob Health*, **81**(3), 310-322, doi:10.1016/j.aogh.2015.08.008.
Levy, K., S. M. Smith and E. J. Carlton, 2018: Climate Change Impacts on Waterborne Diseases: Moving Toward Designing Interventions. *Curr Environ Health Rep*, **5**(2), 272-282, doi:10.1007/s40572-018-0199-7.
Levy, K., A. P. Woster, R. S. Goldstein and E. J. Carlton, 2016: Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. *Environ Sci Technol*, **50**(10), 4905-4922, doi:10.1021/acs.est.5b06186.
Lewis, D., L. Williams and R. Jones, 2020: A radical revision of the public health response to environmental crisis in a warming world: contributions of Indigenous knowledges and Indigenous feminist perspectives. *Canadian Journal of Public Health*, **111**(6), 897-900, doi:10.17269/s41997-020-00388-1.
Leyk, S. et al., 2017: Internal and International Mobility as Adaptation to Climatic Variability in Contemporary Mexico: Evidence from the Integration of Census and Satellite Data. *Population, Space and Place*, doi:10.1002/psp.2047.
Li, C. and Z. Zhu, 2018: Research and application of a novel hybrid air quality early-warning system: A case study in China. *Science of the Total Environment*, **626**, 1421-1438, doi:10.1016/j.scitotenv.2018.01.195.
Li, M., S. Ferreira and T. Smith, 2020: Temperature and self-reported mental health in the United States. *Plos One*, **15**(3), doi:10.1371/journal.pone.0230316.

Li, T. et al., 2015: Heat-related mortality projections for cardiovascular and respiratory disease under the changing climate in Beijing, China. *Scientific Reports*, **5**, 11441, doi:10.1038/srep11441 https://www.nature.com/articles/srep11441#supplementary-information.
Li, X. Q., L. C. Stringer and M. Dallimer, 2021: The Spatial and Temporal Characteristics of Urban Heat Island Intensity: Implications for East Africa's Urban Development. *Climate*, **9**(4), doi:10.3390/cli9040051.
Li, Y. et al., 2014: Extremely cold and hot temperatures increase the risk of diabetes mortality in metropolitan areas of two Chinese cities. *Environ Res*, **134**, 91-97, doi:10.1016/j.envres.2014.06.022.
Li, Y. et al., 2018: Projecting future climate change impacts on heat-related mortality in large urban areas in China. *Environmental Research*, **163**, 171-185, doi:10.1016/j.envres.2018.01.047.
Liang, L. and P. Gong, 2017: Climate change and human infectious diseases: A synthesis of research findings from global and spatio-temporal perspectives. *Environment International*, **103**, 99-108.
Liang, W. et al., 2018: Mapping the epidemic changes and risks of hemorrhagic fever with renal syndrome in Shaanxi Province, China, 2005-2016. *Sci Rep*, **8**(1), 749, doi:10.1038/s41598-017-18819-4.
Ligon, G. and J. Bartram, 2016: Literature Review of Associations among Attributes of Reported Drinking Water Disease Outbreaks. *Int J Environ Res Public Health*, **13**(6), doi:10.3390/ijerph13060527.
Lim, T. K. and W. T. Siow, 2018: Pneumonia in the tropics. *Respirology*, **23**(1), 28-35, doi:10.1111/resp.13137.
Lim, Y. et al., 2015: Effects of cold and hot temperature on dehydration: a mechanism of cardiovascular burden. *International Journal of Biometeorology*, **59**(8), 1035-1043, doi:10.1007/s00484-014-0917-2.
Limaye, V. S. et al., 2018: Climate Change and Heat-Related Excess Mortality in the Eastern USA. *Ecohealth*, **15**(3), 485-496, doi:10.1007/s10393-018-1363-0.
Lin, H. L. et al., 2013: Temperature Changes between Neighboring Days and Mortality in Summer: A Distributed Lag Non-Linear Time Series Analysis. *Plos One*, **8**(6), doi:10.1371/journal.pone.0066403.
Lin, S., M. Sun, E. Fitzgerald and S. A. Hwang, 2016: Did summer weather factors affect gastrointestinal infection hospitalizations in New York State? *Sci Total Environ*, **550**, 38-44.
Linke, A. M. et al., 2018: The consequences of relocating in response to drought: human mobility and conflict in contemporary Kenya. *Environmental Research Letters*, **13**(9), 094014.
Liu-Helmersson, J. et al., 2019: Estimating Past, Present, and Future Trends in the Global Distribution and Abundance of the Arbovirus Vector Aedes aegypti Under Climate Change Scenarios. *Frontiers in Public Health*, **7**, doi:10.3389/fpubh.2019.00148.
Liu-Helmersson, J. et al., 2016: Climate Change and Aedes Vectors: 21st Century Projections for Dengue Transmission in Europe. *Ebiomedicine*, **7**, 267-277, doi:10.1016/j.ebiom.2016.03.046.
Liu, C., Z. Yavar and Q. Sun, 2015a: Cardiovascular response to thermoregulatory challenges. *American Journal of Physiology-Heart and Circulatory Physiology*, **309**(11), H1793-H1812, doi:10.1152/ajpheart.00199.2015.
Liu, K. et al., 2015b: A national assessment of the epidemiology of severe fever with thrombocytopenia syndrome, China. *Sci Rep*, **5**, 9679, doi:10.1038/srep09679.
Liu, Q. et al., 2020a: Changing rapid weather variability increases influenza epidemic risk in a warming climate. *Environmental Research Letters*, **15**(4), doi:10.1088/1748-9326/ab70bc.
Liu, X., 2020: Reductions in Labor Capacity from Intensified Heat Stress in China under Future Climate Change. *International Journal of Environmental Research and Public Health*, **17**(4), doi:10.3390/ijerph17041278.
Liu, Y. et al., 2014: Temporal relationship between hospital admissions for pneumonia and weather conditions in Shanghai, China: a time-series analysis. *Bmj Open*, **4**(7), doi:10.1136/bmjopen-2014-004961.
Liu, Y. et al., 2020b: Natural outdoor environment, neighbourhood social cohesion and mental health: Using multilevel structural equation modelling, streetscape and remote-sensing metrics. *Urban Forestry & Urban Greening*, **48**, doi:10.1016/j.ufug.2019.126576.
Liu, Z. et al., 2017: Global and regional changes in exposure to extreme heat and the relative contributions of climate and population change. *Scientific Reports*, **7**, doi:10.1038/srep43909.
Liu, Z. et al., 2018: Association between floods and infectious diarrhea and their effect modifiers in Hunan province, China: A two-stage model. *Science of the Total Environment*, **626**, 630-637, doi:https://dx.doi.org/10.1016/j.scitotenv.2018.01.130.
Liverpool-Tasie, L. S. O., T. Reardon and B. Belton, 2021: "Essential non-essentials": COVID-19 policy missteps in Nigeria rooted in persistent myths about African food supply chains. *Applied Economic Perspectives and Policy*, **43**(1), 205-224, doi:10.1002/aepp.13139.
Lloyd, 2018: A Global-Level Model of the Potential Impacts of Climate Change on Child Stunting via Income and Food Price in 2030. *Environmental Health Perspectives*, **126**(9), 097007, doi:10.1289/ehp2916.
Lo Iacono, G. et al., 2017: Challenges in developing methods for quantifying the effects of weather and climate on water-associated diseases: A systematic review. *Plos Neglected Tropical Diseases*, **11**(6), doi:10.1371/journal.pntd.0005659.
Loebach, P., 2016: Household migration as a livelihood adaptation in response to a natural disaster: Nicaragua and Hurricane Mitch. *Population and Environment*.
Lopez-i-Gelats, F. et al., 2015: Adaptation Strategies of Andean Pastoralist Households to Both Climate and Non-Climate Changes. *Human Ecology*, **43**(2), 267-282, doi:10.1007/s10745-015-9731-7.

Lopez, M. S., G. V. Muller and W. F. Sione, 2018: Analysis of the spatial distribution of scientific publications regarding vector-borne diseases related to climate variability in South America. *Spat Spatiotemporal Epidemiol*, **26**, 35-93, doi:10.1016/j.sste.2018.04.003.

Lovell, R., M. Depledge and S. Maxwell, 2018: Health and the natural environment: A review of evidence, policy, practice and opportunities for the future. Department for Environment, Food and Rural Affairs (DFRA).

Lu, J. G., 2020: Air pollution: A systematic review of its psychological, economic, and social effects. *Curr Opin Psychol*, **32**, 52-65, doi:10.1016/j.copsyc.2019.06.024.

Lu, P. et al., 2021: Temporal trends of the association between ambient temperature and cardiovascular mortality: a 17-year case-crossover study. *Environmental Research Letters*, **16**(4), doi:10.1088/1748-9326/abab33.

Lu, X. et al., 2016: Detecting climate adaptation with mobile network data in Bangladesh: Anomalies in communication, mobility and consumption patterns during Cyclone Mahasen. *Climate Change*, **138**(3-4), 505-519.

Luechinger, S., 2010: Life satisfaction and transboundary air pollution. *Economics Letters*, **107**(1), 4-6, doi:10.1016/j.econlet.2009.07.007.

Lund, C., E. Baron and E. Breuer, 2018: Social determinants of mental disorders and the Sustainable Development Goals: a systematic review of reviews. *The Lancet Psychiatry*, **5**.

Lundgren, A. D., 2018: Climate change and skin disease. *Cutis*, **101**(4), E12-E14.

Lynch, M. J., P. B. Stretesky, M. A. Long and K. L. Barrett, 2020: The climate change-temperature-crime hypothesis: evidence from a sample of 15 large US cities, 2002 to 2015. *International journal of offender therapy and comparative criminology*, 0306624X20969934.

M'Bra, R. K. et al., 2018: Impact of climate variability on the transmission risk of malaria in northern Cote d'Ivoire. *PLoS One*, **13**(6), e0182304, doi:10.1371/journal.pone.0182304.

Ma, F. and X. Yuan, 2021: Impact of climate and population changes on the increasing exposure to summertime compound hot extremes. *Science of the Total Environment*, **772**, doi:10.1016/j.scitotenv.2021.145004.

Ma, R. et al., 2019: Estimation of work-related injury and economic burden attributable to heat stress in Guangzhou, China. *Sci Total Environ*, **666**, 147-154, doi:10.1016/j.scitotenv.2019.02.201.

MA., N. et al., 2018: Drinking water salinity associated health crisis in coastal Bangladesh. *Elementa: Science of the Anthropocene*, **6**.

Macdiarmid, J. and S. Whybrow, 2019: Nutrition from a climate change perspective. *Proceedings of the Nutrition Society*, **78**(3), 380-387, doi:10.1017/s0029665118002896.

MacFadden, D. et al., 2018: Antibiotic resistance increases with local temperature. *Nature Climate Change*, **8**(6), 510-+, doi:10.1038/s41558-018-0161-6.

Mach, K. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-+, doi:10.1038/s41586-019-1300-6.

Mach, K. J. et al., 2020: Directions for Research on Climate and Conflict. *Earth's Future*.

Machalaba, C. et al., 2015: Climate Change and Health: Transcending Silos to Find Solutions. *Ann Glob Health*, **81**(3), 445-458, doi:10.1016/j.aogh.2015.08.002.

Macintyre, H. L. and C. Heaviside, 2019: Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city. *Environment International*, **127**, 430-441, doi:10.1016/j.envint.2019.02.065.

Macintyre, H. L., C. Heaviside, X. Cai and R. Phalkey, 2021: The winter urban heat island: Impacts on cold-related mortality in a highly urbanized European region for present and future climate. *Environment international*, **154**, 106530, doi:10.1016/j.envint.2021.106530.

Macintyre, H. L. et al., 2018: Assessing urban population vulnerability and environmental risks across an urban area during heatwaves - Implications for health protection. *Science of the Total Environment*, **610**, 678-690, doi:10.1016/j.scitotenv.2017.08.062.

Mackenzie, J. and M. Jeggo, 2019: The One Health Approach-Why Is It So Important? *Tropical Medicine and Infectious Disease*, **4**(2), 88, doi:10.3390/tropicalmed4020088.

Maclean, C., I. Popovici and T. French, 2016: Are natural disasters in early childhood associated with mental health and substance use disorders as an adult? *Social Science and Medicine*,(151), 78-91.

Macnaughton, P. et al., 2018: Energy savings, emission reductions, and health co-benefits of the green building movement. *J. Expo. Sci. Environ. Epidemiol.*, **28**(4), 307-318, doi:10.1038/s41370-017-0014-9.

Macnight Ngwese, N. et al., 2018: Traditional and Local Knowledge Practices for Disaster Risk Reduction in Northern Ghana. *Sustainability*, **10**(3), 825.

Madureira, H. et al., 2021: Evidences on adaptive mechanisms for cardiorespiratory diseases regarding extreme temperatures and air pollution: A comparative systematic review. *Geography and Sustainability*, doi:https://doi.org/10.1016/j.geosus.2021.08.001.

Magnan, A. et al., 2016: Addressing the risk of maladaptation to climate change. *Wiley interdisciplinary reviews: Climate Change*, **7**, 646-665, doi:10.1002/wcc.409.

Mahajan, P. Y., Dean., 2020: Taken by storm: Hurricanes, migrant networks and US immigration. *American Economic Journal: Applied Economics*, **12**(2), 250-277, doi:10.1257/app.20180438.

Maharjan, A. et al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, doi:10.1007/s40641-020-00153-z.

Maini, R., C. Lorcan, B. Kevin and M. Virginia, 2017: The Sendai Framework for Disaster Risk Reduction and Its Indicators—Where Does Health Fit in? *International Journal of Disaster Risk Science*, **8**(2), 150--155, doi:10.1007/s13753-017-0120-2.
Maizlish, N., N. J. Linesch and J. Woodcock, 2017: Health and greenhouse gas mitigation benefits of ambitious expansion of cycling, walking, and transit in California. *J Transp Health*, **6**, 490-500, doi:10.1016/j.jth.2017.04.011.
Mala, S. and M. K. Jat, 2019: Implications of meteorological and physiographical parameters on dengue fever occurrences in Delhi. *Sci Total Environ*, **650**(Pt 2), 2267-2283, doi:10.1016/j.scitotenv.2018.09.357.
Maldonado, J. et al., 2021: Addressing the challenges of climate-driven community-led resettlement and site expansion: knowledge sharing, storytelling, healing, and collaborative coalition building. *Journal of Environmental Studies and Sciences*, 1-11, doi:10.1007/s13412-021-00695-0.
Mall, R. K. et al., 2019: Disaster Risk Reduction Including Climate Change Adaptation Over South Asia: Challenges and Ways Forward. *International Journal of Disaster Risk Science*, **10**(1), 14--27, doi:10.1007/s13753-018-0210-9.
Mallick, B., 2019: The Nexus between Socio-Ecological System, Livelihood Resilience, and Migration Decisions: Empirical Evidence from Bangladesh. *Sustainability*, **11**(12), doi:10.3390/su11123332.
Mallick, B., B. Ahmed and J. Vogt, 2017: Living with the risks of cyclone disasters in the South-Western coastal region of Bangladesh. *Environments*, **4**(1), 13.
Mallick, B. and J. Schanze, 2020: Trapped or Voluntary? Non-Migration Despite Climate Risks. *Sustainability*, **12**(11), doi:10.3390/su12114718.
Mamo, D., ed., 2020: The Indigenous World 2020. The International Work Group for Indigenous Affairs (IWGIA), 784 pp.
Manning, C. and S. Clayton, 2018: Threats to mental health and wellbeing associated with climate change. pp. 217-244.
Maor, M., 2018: Rhetoric and doctrines of policy over- and underreactions in times of crisis. *Policy and Politics*, **46**(1), 47-63, doi:10.1332/030557317x14843233064353.
Mapou, A. E. M. et al., 2017: Environmental Factors and Fluctuations in Daily Crime Rates. *J. Environ. Health*, **80**(5), 8-22.
Marcus, H. and L. Hanna, 2020: Understanding national barriers to climate change adaptation for public health: a mixed-methods survey of national public health representatives. *International Journal of Health Governance*, doi:10.1108/ijhg-06-2020-0061.
Mares, D. M. and K. W. Moffett, 2016: Climate change and interpersonal violence: A “global” estimate and regional inequities. *Climatic change*, **135**(2), 297-310.
Mares, D. M. and K. W. Moffett, 2019: Climate change and crime revisited: An exploration of monthly temperature anomalies and UCR crime data. *Environment and Behavior*, **51**(5), 502-529.
Marinaccio, A. et al., 2019: Nationwide epidemiological study for estimating the effect of extreme outdoor temperature on occupational injuries in Italy. *Environment international*, **133**, 105176.
Maringe, C. et al., 2020: The impact of the COVID-19 pandemic on cancer deaths due to delays in diagnosis in England, UK: a national, population-based, modelling study. *The Lancet Oncology*, **21**(8), 1023-1034, doi:10.1016/s1470-2045(20)30388-0.
Marini, G. et al., 2020: A quantitative comparison of West Nile virus incidence from 2013 to 2018 in Emilia-Romagna, Italy. *PLOS Neglected Tropical Diseases*, 14(1).
Marino, E., 2018: Adaptation privilege and Voluntary Buyouts: Perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. *Global Environmental Change-Human and Policy Dimensions*, **49**, 10-13, doi:10.1016/j.gloenvcha.2018.01.002.
Marino, E. and H. Lazrus, 2015: Migration or Forced Displacement?: The Complex Choices of Climate Change and Disaster Migrants in Shishmaref, Alaska and Nanumea, Tuvalu. . *Human Organization*, **74(4)**, 341-350. .
Marinucci, G. D. et al., 2014: Building Resilience Against Climate Effects—a novel framework to facilitate climate readiness in public health agencies. *Int J Environ Res Public Health*, **11**(6), 6433-6458, doi:10.3390/ijerph110606433.
Markandya, A. et al., 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. *Lancet Planet Health*, **2**(3), e126-e133, doi:10.1016/s2542-5196(18)30029-9.
Markard, J. and D. Rosenbloom, 2020: A tale of two crises: COVID-19 and climate. *Sustainability: Science, Practice and Policy*, **16**(1), 53-60, doi:10.1080/15487733.2020.1765679.
Markussen, T., M. Fibæk, F. Tarp and N. D. A. Tuan, 2018: The happy farmer: self-employment and subjective well-being in rural Vietnam. *Journal of Happiness Studies*, **19**(6), 1613- 1636, doi:https://doi.org/10.1007/s10902-017-9858-x.
Marmot, M. et al., 2020: Health equity in England: The Marmot Review 10 years on. Institute of Health Equity, London.
Marselle, M. et al., 2020: Urban street tree biodiversity and antidepressant prescriptions. *Scientific Reports*, **10**(1), doi:10.1038/s41598-020-79924-5.
Martin-Shields, C. P. and W. Stojetz, 2019: Food security and conflict: Empirical challenges and future opportunities for research and policy making on food security and conflict. *World Development*, **119**, 150-164.

Martin, L. et al., 2020: Nature contact, nature connectedness and associations with health, wellbeing and pro-environmental behaviours. *Journal of Environmental Psychology*, **68**, doi:10.1016/j.jenvp.2020.101389.
Martinez-Solanas, E. and X. Basagana, 2019: Temporal changes in temperature-related mortality in Spain and effect of the implementation of a Heat Health Prevention Plan. *Environmental Research*, **169**, 102-113, doi:10.1016/j.envres.2018.11.006.
Martinez, G. S. and P. Berry, 2018: The adaptation health gap: a global overview, Adaptation Gap Report 2018. United Nations Environment Programme (unep), Nairobi, Kenya.
Martinez, G. S. et al., 2018: Cold-related mortality vs heat-related mortality in a changing climate: A case study in Vilnius (Lithuania). *Environmental Research*, **166**, 384-393, doi:https://doi.org/10.1016/j.envres.2018.06.001.
Martinez, G. S. et al., 2019: Heat-health action plans in Europe: Challenges ahead and how to tackle them. *Environmental Research*, **176**, doi:10.1016/j.envres.2019.108548.
Mascarenhas, M. et al., 2018: A scoping review of published literature on chikungunya virus. *PLoS One*, **13**(11), e0207554, doi:10.1371/journal.pone.0207554.
Masselot, P. et al., 2019: Toward an Improved Air Pollution Warning System in Quebec. *International Journal of Environmental Research and Public Health*, **16**(12), doi:10.3390/ijerph16122095.
Masson, V., A. Lemonsu and J. Voogt, 2018: The 9th International Conference on Urban Climate. *Urban Climate*, **23**, 1-7, doi:10.1016/j.uclim.2017.07.007.
Mastrorillo, M. et al., 2016: The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change*, **39**, 155-169.
Matsushita, N. et al., 2018: The non-linear and lagged short-term relationship between rainfall and leptospirosis and the intermediate role of floods in the Philippines. *PLoS Negl Trop Dis*, **12**(4), e0006331, doi:10.1371/journal.pntd.0006331.
Matthew, R. A., 2018: Climate change adaptation and peacebuilding. In: *Routledge Handbook of Environmental Conflict and Peacebuilding*. Routledge, pp. 108-120. ISBN 1315473771.
Matthews, T., R. Wilby and C. Murphy, 2019: An emerging tropical cyclone-deadly heat compound hazard. *Nature Climate Change*, **9**(8), 602-+, doi:10.1038/s41558-019-0525-6.
Mayrhuber, E. A. et al., 2018: Vulnerability to heatwaves and implications for public health interventions - A scoping review. *Environ Res*, **166**, 42-54, doi:10.1016/j.envres.2018.05.021.
Mbereko, A., M. J. Chimbari, T. Manyangadze and S. Mukaratirwa, 2020: Knowledge and perceptions of schistosomiasis, a water-borne disease, in two semi-arid rural areas of South Africa (Ndumo) and Zimbabwe (Ntalale). *Food Waterborne Parasitol*, **21**, e00091, doi:10.1016/j.fawpar.2020.e00091.
Mbow, C. et al., 2019: *Food Security*. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, Intergovernmental Panel on Climate Change, Geneve.
McAllister, D. A. et al., 2019: Global, regional, and national estimates of pneumonia morbidity and mortality in children younger than 5 years between 2000 and 2015: a systematic analysis. *Lancet Global Health*, **7**(1), E47-E57, doi:10.1016/s2214-109x(18)30408-x.
McCollum, D. et al., 2018: Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters*, **13**(3), doi:10.1088/1748-9326/aaafe3.
McCormack, M. C. et al., 2016: Respiratory Effects of Indoor Heat and the Interaction with Air Pollution in Chronic Obstructive Pulmonary Disease. *Ann. Am. Thorac. Soc.*, **13**(12), 2125-2131, doi:10.1513/AnnalsATS.201605-329OC.
McCreesh, N. and M. Booth, 2014: The Effect of Increasing Water Temperatures on Schistosoma mansoni Transmission and Biomphalaria pfeifferi Population Dynamics: An Agent-Based Modelling Study. *Plos One*, **9**(7), doi:10.1371/journal.pone.0101462.
McCreesh, N., G. Nikulin and M. Booth, 2015: Predicting the effects of climate change on Schistosoma mansoni transmission in eastern Africa. *Parasit Vectors*, **8**, 4, doi:10.1186/s13071-014-0617-0.
McCubbin, S., B. Smit and T. Pearce, 2015: Where does climate fit? Vulnerability to climate change in the context of multiple stressors in Funafuti, Tuvalu. *Global Environmental Change*, **30**, 43-55.
McEvoy, D., 2019: Climate Resilient Urban Development. *Sustainability*, **11**(3), doi:10.3390/su11030724.
McGregor, G., K. Ebi, B. Menne and P. Bessmoulin, 2015: *Heatwaves and Health Guidance on Warning System Development*. World Meteorological Organisation, Organisation, W. M., Geneva.
McGregor, G. R., A. Bone and F. Pappenberger, 2017: Meteorological risk: extreme temperatures. In: *Science for disaster risk management 2017: knowing better and losing less* [Poljanšek, K. (ed.)]. European Union, Luxembourg, pp. 257-270.
McGregor, G. R. and K. Ebi, 2018: El Nino Southern Oscillation (ENSO) and Health: An Overview for Climate and Health Researchers. *Atmosphere*, **9**(7), 32, doi:10.3390/atmos9070282.
McGuirk, E. and M. Burke, 2020: The Economic Origins of Conflict in Africa. *Journal of Political Economy*, **128**(10), 3940-3997, doi:10.1086/709993.
McIver, L. et al., 2016a: Health Impacts of Climate Change in Pacific Island Countries: A Regional Assessment of Vulnerabilities and Adaptation Priorities. *Environmental Health Perspectives*, **124**(11), 1707-1714, doi:10.1289/ehp.1509756.

McIver, L. J. et al., 2016b: Review of Climate Change and Water-Related Diseases in Cambodia and Findings From Stakeholder Knowledge Assessments. *Asia Pac J Public Health*, **28**(2 Suppl), 49S-58S, doi:10.1177/1010539514558059.
McLeman, R., 2017: Thresholds in climate migration. *Population and Environment*, doi:10.1007/s11111-017-0290-2.
McLeman, R., 2019: International migration and climate adaptation in an era of hardening borders. *Nature Climate Change*, **9**(12), 911-918, doi:10.1038/s41558-019-0634-2.
McLeman, R., M. Mohammad and A. Nasima, 2017: Environmental influences on skilled worker migration from Bangladesh to Canada. *The Canadian Geographer*, **62**(3), 352--371, doi:10.1111/cag.12430.
McLeman, R. et al., 2021: Conceptual framing to link climate risk assessments and climate-migration scholarship. *Climatic Change*, **165**(24), doi:10.1007/s10584-021-03056-6.
McMahon, S., P. Gamage and L. V. Fortington, 2021: Sports related heat injury in Victoria, Australia: An analysis of 11 years of hospital admission and emergency department data. *Journal of Science and Medicine in Sport*, **24**(3), 224-228, doi:10.1016/j.jsams.2020.08.011.
McMeeking, S. and C. Savage, 2020: Māori Responses to Covid-19. *Policy Quarterly*, **16**(3), 36-41, doi:10.26686/pq.v16i3.6553.
McMichael, C., 2015: Climate change-related migration and infectious disease. *Virulence*, **6**(6), 548-553.
McMichael, C. et al., 2021: Rising seas, immobilities, and translocality in small island states: case studies from Fiji and Tuvalu. *Population and Environment*, **43**(1), 82--107, doi:10.1007/s11111-021-00378-6.
McMichael, C., S. Dasgupta, S. Ayeb-Karlsson and I. Kelman, 2020: A review of estimating population exposure to sea-level rise and the relevance for migration. *Environmental Research Letters*, 15(12), 123005. Available at: http://dx.doi.org/10.1088/1748-9326/abb398.
McMichael, C. and M. Katonivualiku, 2020: Thick temporalities of planned relocation in Fiji. *Geoforum*, **108**, 286-294, doi:https://doi.org/10.1016/j.geoforum.2019.06.012.
McMichael, C. and T. Powell, 2021: Planned Relocation and Health: A Case Study from Fiji. *International Journal of Environmental Research and Public Health*, **18**(8), doi:10.3390/ijerph18084355.
McNamara, K., R. Bronen, N. Fernando and S. Klepp, 2018: The complex decision-making of climate-induced relocation: adaptation and loss and damage. *Climate Policy*, **18**(1), 111-117, doi:10.1080/14693062.2016.1248886.
McNamara, K. E., 2015: Cross-border migration with dignity in Kiribati. *Forced Migration Review*, **49**, 62-62.
McNamara, K. E., R. Westoby and A. Chandra, 2021: Exploring climate-driven non-economic loss and damage in the Pacific Islands. *Current Opinion in Environmental Sustainability*, **50**, 1-11.
McPherson, M. et al., 2017: Expansion of the Lyme Disease Vector Ixodes Scapularis in Canada Inferred from CMIP5 Climate Projections. *Environmental Health Perspectives*, **125**(5), doi:10.1289/ehp57.
McTavish, R. K. et al., 2018: Association Between High Environmental Heat and Risk of Acute Kidney Injury Among Older Adults in a Northern Climate: A Matched Case-Control Study. *American Journal of Kidney Diseases*, **71**(2), 200-208, doi:10.1053/j.ajkd.2017.07.011.
Medek, S., E. Danielle, J. Schwartz and M. S, 2017: Estimated Effects of Future Atmospheric CO2 Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region. *Environmental Health Perspectives*, **125**(8), 087002, doi:10.1289/ehp41.
Meehl, G. A. et al., 2018: Future heat waves and surface ozone. *Environmental Research Letters*, **13**(6), doi:10.1088/1748-9326/aabcdc.
Meige, P., R. Blewitt and M. K. van Aalst, 2020: A humanitarian recipe for a green, resilient and inclusive recovery from COVID-19, Solferino Academy.
Méndez-Lázaro, P. A. et al., 2018: Climate change, heat, and mortality in the tropical urban area of San Juan, Puerto Rico. *Int J Biometeorol*, **62**(5), 699-707, doi:10.1007/s00484-016-1291-z.
Mendez, M., G. Flores-Haro and L. Zucker, 2020: The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and indigenous immigrants. *Geoforum*, **116**, 50-62, doi:10.1016/j.geoforum.2020.07.007.
Menz, T. and H. Welsch, 2010: Population aging and environmental preferences in OECD countries: The case of air pollution. *Ecological Economics*, **69**(12), 2582-2589, doi:10.1016/j.ecolecon.2010.08.002.
Mercer, N. and M. Hanrahan, 2017: "Straight from the heavens into your bucket": domestic rainwater harvesting as a measure to improve water security in a subarctic indigenous community. *International Journal of Circumpolar Health*, **76**(1).
Merkens, J. et al., 2018: Regionalisation of population growth projections in coastal exposure analysis. *Climatic Change*, **151**(3-4), 413-426, doi:10.1007/s10584-018-2334-8.
Merkord, C. L. et al., 2017: Integrating malaria surveillance with climate data for outbreak detection and forecasting: the EPIDEMIA system. *Malaria journal*, **16**(1), 89, doi:10.1186/s12936-017-1735-x.
Messeri, A. et al., 2021: A Web Survey to Evaluate the Thermal Stress Associated with Personal Protective Equipment among Healthcare Workers during the COVID-19 Pandemic in Italy. *International Journal of Environmental Research and Public Health*, **18**(8), doi:10.3390/ijerph18083861.
Messina, J. et al., 2019: The current and future global distribution and population at risk of dengue. *Nature Microbiology*, **4**(9), 1508-1515, doi:10.1038/s41564-019-0476-8.
Messina, J. P. et al., 2015: The many projected futures of dengue. **13**(4), 230-239, doi:10.1038/nrmicro3430.

Metallinou, M.-M. and T. Log, 2017: Health Impacts of Climate Change-Induced Subzero Temperature Fires. *Int. J. Environ. Res. Public Health*, **14**(7), doi:10.3390/ijerph14070814.
Mezdour, A., L. Veronis and R. McLeman, 2015: Environmental Influences on Haitian Migration to Canada and Connections to Social Inequality: Evidence from Ottawa-Gatineau and Montreal. [McLeman, R., J. Schade and T. Faist (eds.)]. Springer, Dordrecht, pp. 103-116.
Miao, Y. F. et al., 2017: Maternal exposure to ambient air temperature during pregnancy and early childhood pneumonia. *Journal of Thermal Biology*, **69**, 288-293, doi:10.1016/j.jtherbio.2017.09.001.
Middleton, J. et al., 2020a: "We're people of the snow:" Weather, climate change, and Inuit mental wellness. *Social Science & Medicine*, **262**, doi:10.1016/j.socscimed.2020.113137.
Middleton, J. et al., 2020b: Indigenous mental health in a changing climate: a systematic scoping review of the global literature. *Environmental Research Letters*, **15**(5), doi:10.1088/1748-9326/ab68a9.
Midekisa, A. et al., 2015: Seasonal associations of climatic drivers and malaria in the highlands of Ethiopia. *Parasites & Vectors*, **8**, doi:10.1186/s13071-015-0954-7.
Migration, I. O. f., 2019: *World Migration Report 2020*. Geneva. Available at: https://www.un.org/sites/un2.un.org/files/wmr_2020.pdf.
Milazzo, A. et al., 2016: Heatwaves differentially affect risk of Salmonella serotypes. *J Infect*, **73**(3), 231-240, doi:10.1016/j.jinf.2016.04.034.
Miles-Novelo, A. and C. Anderson, 2019: Climate Change and Psychology: Effects of Rapid Global Warming on Violence and Aggression. *Current Climate Change Reports*, **5**(1), 36-46, doi:10.1007/s40641-019-00121-2.
Milner, J. et al., 2015: Health effects of adopting low greenhouse gas emission diets in the UK. *Bmj Open*, **5**(4), doi:10.1136/bmjopen-2014-007364.
Milner, J. et al., 2017: Projected health effects of realistic dietary changes to address freshwater constraints in India: a modelling study. *The Lancet Planetary Health*, **1**(1), e26-e32, doi:https://doi.org/10.1016/S2542-5196(17)30001-3.
Miltenburg, E. et al., 2021: Seed Sowing: Indigenous Relationship-Building as Processes of Environmental Action.
Miner, K. R. et al., 2018: Quantitative screening level assessment of human risk from PCBs released in glacial meltwater: Silvretta Glacier, Swiss Alps. *Ecotoxicol. Environ. Saf.*, **166**, 251-258, doi:10.1016/j.ecoenv.2018.09.066.
Mirasgedis, S., C. Tourkolias, E. Pavlakis and D. Diakoulaki, 2014: A methodological framework for assessing the employment effects associated with energy efficiency interventions in buildings. *Energy and Buildings*, **82**, 275-286, doi:10.1016/j.enbuild.2014.07.027.
Miron, I. J. et al., 2015: Changes in cause-specific mortality during heat waves in central Spain, 1975-2008. *International Journal of Biometeorology*, **59**(9), 1213-1222, doi:10.1007/s00484-014-0933-2.
Mirsaeidi, M. et al., 2016: Climate Change and Respiratory Infections. *Annals of the American Thoracic Society*, **13**(8), 1223-1230, doi:10.1513/AnnalsATS.201511-729PS.
Mirumachi, N., A. Sawas and M. Workman, 2020: Unveiling the security concerns of low carbon development: climate security analysis of the undesirable and unintended effects of mitigation and adaptation. *Climate and Development*, **12**(2), 97-109.
Mishra, V., S. Mukherjee, R. Kumar and D. A. Stone, 2017: Heat wave exposure in India in current, 1.5 degrees C, and 2.0 degrees C worlds. *Environmental Research Letters*, **12**(12), doi:10.1088/1748-9326/aa9388.
Missirian, A. and W. Schlenker, 2017: Asylum applications respond to temperature fluctuations. *Science*, **358**(6370), 1610-1614.
Mitchell, D., 2016: Human Influences on Heat-Related Health Indicators During the 2015 Egyptian Heat Wave. *Bulletin of the American Meteorological Society*, **97**, S70-S74, doi:10.1175/bams-d-16-0132.1.
Mitchell, D., 2021: Climate attribution of heat mortality. *Nature Climate Change*, **11**(6), 467-468, doi:10.1038/s41558-021-01049-y.
Mitchell, D. et al., 2018: Extreme heat-related mortality avoided under Paris Agreement goals. *Nature Climate Change*, **8**(7), 551-553, doi:10.1038/s41558-018-0210-1.
Mitchell, D. et al., 2016: Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environmental Research Letters*, **11**, doi:10.1088/1748-9326/11/7/074006.
Miyayo, S. F., P. O. Owili, M. A. Muga and T. H. Lin, 2021: Analysis of Pneumonia Occurrence in Relation to Climate Change in Tanga, Tanzania. *International Journal of Environmental Research and Public Health*, **18**(9), doi:10.3390/ijerph18094731.
Modenese, A., L. Korpinen and F. Gobba, 2018: Solar Radiation Exposure and Outdoor Work: An Underestimated Occupational Risk. *Int J Environ Res Public Health*, **15**(10), doi:10.3390/ijerph15102063.
Molina, O. and V. Saldarriaga, 2017: The perils of climate change: In utero exposure to temperature variability and birth outcomes in the Andean region. *Economics & Human Biology*, **24**, 111-124.
Monaghan, A. et al., 2018: The potential impacts of 21st century climatic and population changes on human exposure to the virus vector mosquito Aedes aegypti. *Climatic Change*, **146**(3-4), 487-500, doi:10.1007/s10584-016-1679-0.
Monaghan, A. J. et al., 2015: Climate change influences on the annual onset of Lyme disease in the United States. *Ticks and tick-borne diseases*, **6**(5), 615-622, doi:10.1016/j.ttbdis.2015.05.005.
Monaghesh, E. and A. Hajizadeh, 2020: The role of telehealth during COVID-19 outbreak: a systematic review based on current evidence. *Bmc Public Health*, **20**(1), doi:10.1186/s12889-020-09301-4.

Monchatre-Leroy, E. et al., 2017: Spatial and Temporal Epidemiology of Nephropathia Epidemica Incidence and Hantavirus Seroprevalence in Rodent Hosts: Identification of the Main Environmental Factors in Europe. *Transboundary and Emerging Diseases*, **64**(4), 1210-1228, doi:10.1111/tbed.12494.
Moore, F. C., N. Obradovich, F. Lehner and P. Baylis, 2019: Rapidly declining remarkability of temperature anomalies may obscure public perception of climate change. *Proceedings of the National Academy of Sciences,*, **116(11)**, 4905-4910. .
Moore, S. et al., 2018: Dynamics of cholera epidemics from Benin to Mauritania. *PLoS Negl Trop Dis*, **12**(4), e0006379, doi:10.1371/journal.pntd.0006379.
Moore, S. M. et al., 2017: El Niño and the shifting geography of cholera in Africa. *Proc Natl Acad Sci U S A*, **114**(17), 4436-4441, doi:10.1073/pnas.1617218114.
Mora, C., W. W. Counsell Chelsie, R. Bielecki Coral and V. Louis Leo, 2017a: Twenty-Seven Ways a Heat Wave Can Kill You. *Circulation: Cardiovascular Quality and Outcomes*, **10**(11), e004233, doi:10.1161/circoutcomes.117.004233.
Mora, C. et al., 2017b: Global risk of deadly heat. *Nature Climate Change*, **7**(7), 501-+, doi:10.1038/nclimate3322.
Morabito, M. et al., 2021: Heat-related productivity loss: benefits derived by working in the shade or work-time shifting. *International Journal of Productivity and Performance Management*, **70**(3), 507-525, doi:10.1108/ijppm-10-2019-0500.
Morefield, P. E. et al., 2018: Heat-Related Health Impacts under Scenarios of Climate and Population Change. *International Journal of Environmental Research and Public Health*, **15**(11), doi:10.3390/ijerph15112438.
Morens, D. M. and A. S. Fauci, 2014: Chikungunya at the door--deja vu all over again? *The New England journal of medicine*, **371**(10), 885-887, doi:10.1056/NEJMp1408509.
Moretti, A., M. Pascale and A. F. Logrieco, 2019: Mycotoxin risks under a climate change scenario in Europe. *Trends Food Sci. Technol.*, **84**, 38-40, doi:10.1016/j.tifs.2018.03.008.
Morgan, A., A. Ross and N. Reavley, 2018: Systematic review and meta-analysis of Mental Health First Aid training: Effects on knowledge, stigma, and helping behaviour. *Plos One*, **13**(5), doi:10.1371/journal.pone.0197102.
Morin, C. et al., 2018: Unexplored Opportunities: Use of Climate- and Weather-Driven Early Warning Systems to Reduce the Burden of Infectious Diseases. *Current Environmental Health Reports*, **5**(4), 430-438, doi:10.1007/s40572-018-0221-0.
Morris, N. B. et al., 2020: Sustainable solutions to mitigate occupational heat strain - an umbrella review of physiological effects and global health perspectives. *Environmental Health*, **19**(1), doi:10.1186/s12940-020-00641-7.
Morton, S., D. Pencheon and G. Bickler, 2019: The sustainable development goals provide an important framework for addressing dangerous climate change and achieving wider public health benefits. *Public Health*, **174**, 65-68, doi:10.1016/j.puhe.2019.05.018.
Mosello, B., C. König, A. Day and C. Nagarajan, 2021: *Addressing Climate-related security Risks: Towards a Programme for Action*. adelphi, Berlin.
Moss, R. H., P. M. Reed, A. Hadjimichael and J. Rozenberg, 2021: Planned relocation: Pluralistic and integrated science and governance. *Science*, 372(6548), 1276 LP - 1279. Available at: http://science.sciencemag.org/content/372/6548/1276.abstract.
Mosuela, C. et al., 2015: The Role of A Priori Cross-Border Migration after Extreme Climate Events: The Case of the Philippines after Typhoon Haiyan. *Environmental Change, Adaptation and Migration: Bringing in the Region*, 98-116.
Mousavi, A. et al., 2020: Climate change and health in Iran: a narrative review. *Journal of Environmental Health Science and Engineering*, **18**(1), 367-378, doi:10.1007/s40201-020-00462-3.
Mpandeli, S. et al., 2018: Climate Change Adaptation through the Water-Energy-Food Nexus in Southern Africa. *Int J Environ Res Public Health*, **15**(10), doi:10.3390/ijerph15102306.
Mt. Pleasant, J., 2016: Food Yields and Nutrient Analyses of the Three Sisters: A Haudenosaunee Cropping System. *Ethnobiology Letters*, **7**(1).
Muehe, E. et al., 2019: Rice production threatened by coupled stresses of climate and soil arsenic. *Nature Communications*, **10**, doi:10.1038/s41467-019-12946-4.
Mueller, V., G. Sheriff, X. Dou and C. Gray, 2020: Temporary migration and climate variation in eastern Africa. *World Development*, 126, 104704. Available at: http://www.sciencedirect.com/science/article/pii/S0305750X19303523.
Mugambiwa, S., 2018: Adaptation measures to sustain indigenous practices and the use of indigenous knowledge systems to adapt to climate change in Mutoko rural district of Zimbabwe. *Jamba-Journal of Disaster Risk Studies*, **10**, doi:10.4102/jamba.v10i1.388.
Mukeka, J., J. Ogutu, E. Kanga and E. Roskaft, 2019: Human-wildlife conflicts and their correlates in Narok County, Kenya. *Global Ecology and Conservation*, **18**, doi:10.1016/j.gecco.2019.e00620.
Mukherjee, A., S. Babu and S. Ghosh, 2020: Thinking about water and air to attain Sustainable Development Goals during times of COVID-19 Pandemic. *Journal of Earth System Science*, **129**(1), doi:10.1007/s12040-020-01475-0.
Mullins, J. and C. White, 2019: Temperature and mental health: Evidence from the spectrum of mental health outcomes. *Journal of Health Economics*, **68**, doi:10.1016/j.jhealeco.2019.102240.

Murdock, C. C., E. D. Sternberg and M. B. Thomas, 2016: Malaria transmission potential could be reduced with current and future climate change. *Sci Rep*, **6**, 27771, doi:10.1038/srep27771.
Murphy, H. M., K. D. Pintar, E. A. McBean and M. K. Thomas, 2014: A systematic review of waterborne disease burden methodologies from developed countries. *J Water Health*, **12**(4), 634-655, doi:10.2166/wh.2014.049.
Murray-Tortarolo, G. N. and S. M. Martnez, 2021: Drought as a driver of Mexico-US migration. *Climatic Change*, **164**(3), 48, doi:10.1007/s10584-021-03030-2.
Murray, C. J. L. et al., 2020: Global burden of 87 risk factors in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet*, **396**(10258), 1223-1249.
Murthy, B. P. et al., 2017: Progress in Public Health Emergency Preparedness—United States, 2001–2016. *American Journal of Public Health*, **107**(S2), S180--S185, doi:10.2105/ajph.2017.304038.
Musacchio, A. et al., 2021: Planning for the health impacts of climate change: Flooding, private groundwater contamination and waterborne infection - A cross-sectional study of risk perception, experience and behaviours in the Republic of Ireland. *Environ Res*, **194**, 110707, doi:10.1016/j.envres.2021.110707.
Mutheneni, S. R., A. P. Morse, C. Caminade and S. M. Upadhyayula, 2017: Dengue burden in India: recent trends and importance of climatic parameters. *Emerg Microbes Infect*, **6**(8), e70, doi:10.1038/emi.2017.57.
Mutono, N. et al., 2020: The nexus between improved water supply and water-borne diseases in urban areas in Africa: a scoping review protocol. *AAS Open Res*, **3**, 12, doi:10.12688/aasopenres.13063.2.
Mutono, N. et al., 2021: The nexus between improved water supply and water-borne diseases in urban areas in Africa: a scoping review. *AAS Open Res*, **4**, 27, doi:10.12688/aasopenres.13225.1.
Muyambo, F., A. Jordaan and Y. Bahta, 2017: Assessing social vulnerability to drought in South Africa: Policy implication for drought risk reduction. *Jamba-Journal of Disaster Risk Studies*, **9**(1), doi:10.4102/jamba.v9i1.326.
Mweya, C. et al., 2016: Climate Change Influences Potential Distribution of Infected Aedes aegypti Co-Occurrence with Dengue Epidemics Risk Areas in Tanzania. *Plos One*, **11**(9), doi:10.1371/journal.pone.0162649.
Mygind, L. et al., 2019: Immersive Nature-Experiences as Health Promotion Interventions for Healthy, Vulnerable, and Sick Populations? A Systematic Review and Appraisal of Controlled Studies. *Front Psychol*, **10**, 943-943, doi:10.3389/fpsyg.2019.00943.
Myrttinen, H., L. Khattab and C. Maydaa, 2017: 'Trust no one, beware of everyone'. Routledge, Abingdon, Oxon ; New York, NY : Routledge, 2017., pp. 61-76.
Myrttinen, H., J. Naujoks and J. Schilling, 2015: Gender, Natural Resources, and Peacebuilding in Kenya and Nepal. *Peace Review*, **27**(2), 181-187, doi:10.1080/10402659.2015.1037623.
Na, M. et al., 2020: Food Insecurity and Cognitive Function in Middle to Older Adulthood: A Systematic Review. *Advances in Nutrition*, **11**(3), 667-676, doi:10.1093/advances/nmz122.
Nagarajan, C. et al., 2018: Climate fragility profile: lake Chad Basilisks.
Nagy, G. J. et al., 2018: An Assessment of the Relationships between Extreme Weather Events, Vulnerability, and the Impacts on Human Wellbeing in Latin America. *International Journal of Environmental Research and Public Health*, **15**, 1802.
Nah, K., A. Bede-Fazekas, A. Trajer and J. Wu, 2020: The potential impact of climate change on the transmission risk of tick-borne encephalitis in Hungary. *Bmc Infectious Diseases*, **20**(1), doi:10.1186/s12879-019-4734-4.
Naik, V., S. et al., 2021: *Short-Lived Climate Forcers* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U.
Nasir, S. et al., 2017: Effect of Climatic Conditions and Water Bodies on Population Dynamics of the Dengue Vector, Aedes aegypti (Diptera: Culicidae). *Journal of Arthropod-Borne Diseases*, **11**(1), 50-59.
Natarajan, N., K. Brickell and L. Parsons, 2019: Climate change adaptation and precarity across the rural–urban divide in Cambodia: Towards a 'climate precarity'approach. *Environment and Planning E: Nature and Space*, **2**(4), 899-921.
Navarro, J. et al., 2016: Children's disaster experiences and psychological symptoms: An international comparison between the Chilean earthquake and tsunami and Hurricane Katrina. *International Social Work*, **59**(4), 545-558.
Navarro, K. et al., 2019: Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. *Environmental Research*, **173**, 462-468, doi:10.1016/j.envres.2019.03.060.
Navarro, L. et al., 2017: Monitoring biodiversity change through effective global coordination. *Current Opinion in Environmental Sustainability*, **29**, 158-169, doi:10.1016/j.cosust.2018.02.005.
Navarro, O. et al., 2021: Coping Strategies Regarding Coastal Flooding Risk in a Context of Climate Change in a French Caribbean Island. *Environment and Behavior*, **53**(6), 636-660, doi:10.1177/0013916520916253.
Navi, M. et al., 2017: Developing Health-Related Indicators of Climate Change: Australian Stakeholder Perspectives. *Int. J. Environ. Res. Public Health*, **14**(5), doi:10.3390/ijerph14050552.
Nawrotzki, R. and J. DeWaard, 2018: Putting trapped populations into place: Climate change and inter-district migration flows in Zambia. *Regional Environmental Change*, **18**(2), 533-546, doi:10.1007/s10113-017-1224-3.
Nawrotzki, R. J. and M. Bakhtsiyarava, 2017: International Climate Migration: Evidence for the Climate Inhibitor Mechanism and the Agricultural Pathway. *Population, Space and Place*, **23**(4), e2033-e2033.

Nawrotzki, R. J., J. DeWaard, M. Bakhtsiyarava and J. T. Ha, 2017: Climate shocks and rural-urban migration in Mexico: exploring nonlinearities and thresholds. *Climatic Change*, **140**(2), 243-258, doi:10.1007/s10584-016-1849-0.
Neef, A. et al., 2018: Climate adaptation strategies in Fiji: The role of social norms and cultural values. *World Development*, **107**, 125-137, doi:https://doi.org/10.1016/j.worlddev.2018.02.029.
Nelson, M. et al., 2016: Alignment of Healthy Dietary Patterns and Environmental Sustainability: A Systematic Review. *Advances in Nutrition*, **7**(6), 1005-1025, doi:10.3945/an.116.012567.
Network, G. H. H. I., 2020: *Technical Brief: Protecting health from hot weather during the COVID-19 pandemic*. Global Heat Health Information Network, Geneva, 8 pp. Available at: https://ghhin.org/wp-content/uploads/technical-brief-COVID-and-Heat-finalv2-1.pdf (accessed 02/09/2021).
Neufeld, H. T., C. Richmond and S. O. A. H. A. Centre, 2020: Exploring First Nation Elder Women's Relationships with Food from Social, Ecological, and Historical Perspectives. *Current Developments in Nutrition*, **4**(3), nzaa011, doi:10.1093/cdn/nzaa011.
Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. *PLoS ONE*, **10**(6), e0131375-e0131375.
Neumann, J. E. et al., 2019: Estimates of Present and Future Asthma Emergency Department Visits Associated With Exposure to Oak, Birch, and Grass Pollen in the United States. *GeoHealth*, **3**(1), 11-27, doi:10.1029/2018gh000153.
Neumann, K. and F. Hermans, 2015: What Drives Human Migration in Sahelian Countries? A Meta-analysis. *Population, Space and Place*, doi:10.1002/psp.1962.
Newnham, E., N. Titov and P. McEvoy, 2020: Preparing mental health systems for climate crisis. *Lancet Planetary Health, 4(3), E89-E90.* , **4(3)**, E89-E90.
Ng, K. Y. Y. et al., 2021: Factors influencing protective behaviours during haze episodes in Singapore: A population-based study. *Annals Academy of Medicine Singapore*, **50**(7), 514-526, doi:10.47102/annals-acadmedsg.2020614.
Ngigi, M., U. Mueller and R. Birner, 2017: Gender differences in climate change adaptation strategies and participation in group-based approaches: An intra-household analysis from rural Kenya. *Ecological Economics*, **138**, 99-108, doi:https://doi.org/10.1016/j.ecolecon.2017.03.019.
Ngo, C., P. Poortvliet and P. Feindt, 2020: Drivers of flood and climate change risk perceptions and intention to adapt: an explorative survey in coastal and delta Vietnam. *Journal of Risk Research*, **23**(4), 424-446, doi:10.1080/13669877.2019.1591484.
Ngo, N. S. and R. M. Horton, 2016: Climate change and fetal health: The impacts of exposure to extreme temperatures in New York City. *Environ Res*, **144**(Pt A), 158-164, doi:10.1016/j.envres.2015.11.016.
Nguyen, H., 2019: Gendered Vulnerabilities in Times of Natural Disasters: Male-to-Female Violence in the Philippines in the Aftermath of Super Typhoon Haiyan. *Violence Against Women*, **25**(4), 421-440, doi:10.1177/1077801218790701.
Nhamo, G. and S. Muchuru, 2019: Climate adaptation in the public health sector in Africa: Evidence from United Nations Framework Convention on Climate Change National Communications. *Jamba-Journal of Disaster Risk Studies*, **11**, doi:10.4102/jamba.v11i1.644.
Nicholls, R. J. et al., 2021: A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, **11**(4), 338--342, doi:10.1038/s41558-021-00993-z.
Nicholls, R. J. et al., 2007: Ranking of the world's cities most exposed to coastal flooding today and in the future. *Organisation for Economic Co-operation and Development (OECD), Paris*.
Nichols, A., 2019: Climate change, natural hazards, and relocation: insights from Nabukadra and Navuniivi villages in Fiji. *Climatic Change*, **156**(1), 255-271, doi:10.1007/s10584-019-02531-5.
Nichols, G., I. Lake and C. Heaviside, 2018: Climate Change and Water-Related Infectious Diseases. *Atmosphere*, **9**(10), doi:10.3390/atmos9100385.
Nightingale, A., 2017: Power and politics in climate change adaptation efforts: struggles over authority and recognition in the context of political instability. *Geoforum*, **84**, 11-20.
Niles, M. et al., 2021: Climate impacts associated with reduced diet diversity in children across nineteen countries. *Environmental Research Letters*, **16**(1), doi:10.1088/1748-9326/abd0ab.
Nilsson, L. et al., 2011: Diet and lifestyle of the Sami of southern Lapland in the 1930s-1950s and today. *International Journal of Circumpolar Health*, **70**(3), 301-318, doi:10.3402/ijch.v70i3.17831.
Nitschke, M. et al., 2016: Evaluation of a heat warning system in Adelaide, South Australia, using case-series analysis. *Bmj Open*, **6**(7), doi:10.1136/bmjopen-2016-012125.
Nkumama, I. N., W. P. O'Meara and F. H. A. Osier, 2017: Changes in Malaria Epidemiology in Africa and New Challenges for Elimination. *Trends Parasitol*, **33**(2), 128-140, doi:10.1016/j.pt.2016.11.006.
Noelke, C. et al., 2016: Increasing ambient temperature reduces emotional well-being. *Environmental Research*, **151**, 124-129, doi:10.1016/j.envres.2016.06.045.
Nordqvist, P. and F. Krampe, 2018: *Climate change and violent conflict: sparse evidence from South Asia and South East Asia*. Stockholm International Peace Research Institute.
Norton-Smith, K. et al., 2016: Climate change and indigenous peoples: a synthesis of current impacts and experiences. US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Nurse, K., 2019: Migration, Diasporas, Remittances and the Sustainable Development Goals in Least Developed Countries. *Journal of Globalization and Development*, **9**(2), 20190006.
Nursey-Bray, M., 2017: Towards socially just adaptive climate governance: the transformative potential of conflict. *Local Environment*, **22**(2), 156-171, doi:10.1080/13549839.2016.1181618.
Nursey-Bray, M. and R. Palmer, 2018: Country, climate change adaptation and colonisation: insights from an Indigenous adaptation planning process, Australia. *Heliyon*, **4**(3), e00565, doi:https://dx.doi.org/10.1016/j.heliyon.2018.e00565.
Nursey-Bray, M. et al., 2020: Scale, colonisation and adapting to climate change: Insights from the Arabana people, South Australia. *Geoforum*, **114**, 138-150, doi:10.1016/j.geoforum.2020.05.021.
O'Neill, D., A. Fanning, W. Lamb and J. Steinberger, 2018: A good life for all within planetary boundaries. *Nature Sustainability*, **1**(2), 88-95, doi:10.1038/s41893-018-0021-4.
O'Donnell, R., M. Savaglio, D. Vicary and H. Skouteris, 2021: Effect of community mental health care programs in Australia: a systematic review. *Australian Journal of Primary Health*, **26**(6), 443-451.
Oakes, R., 2019: Culture, climate change and mobility decisions in Pacific Small Island Developing States. *Population and Environment*, **40**(4), 480-503, doi:10.1007/s11111-019-00321-w.
Obaidat, M. M. and A. A. Roess, 2018: First report on seroprevalence and risk factors of dengue virus in Jordan. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **112**(6), 279-284, doi:10.1093/trstmh/try055.
Obokata, R. and L. Veronis, 2018: Transnational approaches to remittances, risk reduction, and disaster relief: Evidence from post-Typhoon Haiyan experiences of Filipino immigrants in Canada. [McLeman, R. and F. Gemenne (eds.)]. Routledge, London.
Obradovich, N. and J. H. Fowler, 2017: Climate change may alter human physical activity patterns. *Nature Human Behaviour*, **1**, 0097, doi:10.1038/s41562-017-0097 https://www.nature.com/articles/s41562-017-0097#supplementary-information.
Obradovich, N. and R. Migliorini, 2018: Sleep and the human impacts of climate change. *Sleep Medicine Reviews*, **42**, 1-2, doi:10.1016/j.smrv.2018.09.002.
Obradovich, N., R. Migliorini, S. C. Mednick and J. H. Fowler, 2017: Nighttime temperature and human sleep loss in a changing climate. *Science advances*, **3**(5), e1601555-e1601555, doi:10.1126/sciadv.1601555.
Obradovich, N., R. Migliorini, M. P. Paulus and I. Rahwan, 2018: Empirical evidence of mental health risks posed by climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(43), 10953-10958, doi:10.1073/pnas.1801528115.
Obradovich, N. and I. Rahwan, 2019: Risk of a Feedback Loop Between Climatic Warming and Human Mobility. The Royal Society.
Ocello, C., A. Petrucci, M. R. Testa and D. Vignoli, 2015: Environmental aspects of internal migration in Tanzania. *Population and Environment*, 37(1), 99-108.
Ogunbode, C. et al., 2021: Negative emotions about climate change are related to insomnia symptoms and mental health: Cross-sectional evidence from 25 countries. *Current Psychology*, doi:10.1007/s12144-021-01385-4.
Ogunbode, C. A., C. Demski, S. B. Capstick and R. G. Sposato, 2019: Attribution Matters: Revisiting the link between extreme weather experience and climate change mitigation responses. *Global Environmental Change*, **54**, 31-39.
Okpara, U. T., L. C. Stringer and A. J. Dougill, 2016: Perspectives on contextual vulnerability in discourses of climate conflict. *Earth System Dynamics*, **7**(1), 89-102, doi:10.5194/esd-7-89-2016.
Okpara, U. T., L. C. Stringer and A. J. Dougill, 2018: Integrating climate adaptation, water governance and conflict management policies in lake riparian zones: Insights from African drylands. *Environmental Science & Policy*, **79**, 36-44.
Olson, D. M. and G. A. S. Metz, 2020: Climate change is a major stressor causing poor pregnancy outcomes and child development. *F1000Res*, **9**, doi:10.12688/f1000research.27157.1.
Oluwole, O. S. A., 2015: Seasonal Influenza Epidemics and El Ninos. *Frontiers in Public Health*, **3**, doi:10.3389/fpubh.2015.00250.
Oluwole, O. S. A., 2017: Dynamic Regimes of El Nino Southern Oscillation and Influenza Pandemic Timing. *Frontiers in Public Health*, **5**, doi:10.3389/fpubh.2017.00301.
Onozuka, D. and A. Hagihara, 2015: Non-stationary dynamics of climate variability in synchronous influenza epidemics in Japan. *International Journal of Biometeorology*, **59**(9), 1253-1259, doi:10.1007/s00484-014-0936-z.
Opondo, M., U. Abdi and P. Nangiro, 2016: Assessing Gender in Resilience Programming: Uganda, 16 pp.
Oppermann, E. et al., 2021: Establishing intensifying chronic exposure to extreme heat as a slow onset event with implications for health, wellbeing, productivity, society and economy. *Current Opinion in Environmental Sustainability*, **50**, 225-235, doi:https://doi.org/10.1016/j.cosust.2021.04.006.
Organization, W. B., 2021: Indigenous Peoples.
Organization, W. H., 1946: Preamble to the Constitution of WHO as adopted by the International Health Conference, New York, 19 June - 22 July 1946; signed on 22 July 1946 by the representatives of 61 States and entered into force on 7 April 1948. Official Records of WHO, New York, 100 pp.
Organization, W. H., 2015: *Operational framework for building climate resilient health systems*. World Health Organization, Geneva, Switzerland.

Organization, W. H., 2016: *Sanitation safety planning: manual for safe use and disposal of wastewater, greywater and excreta* [Who (ed.)]. Geneva, Switzerland. Available at: https://www.who.int/water_sanitation_health/publications/ssp-manual/en/.
Organization, W. H., 2018a: COP24 Special Report on Health and Climate Change.
Organization, W. H., 2018b: *WASH and Health working together: a 'how-to' guide for neglected tropical disease programmes* [Who (ed.)]. Geneva.
Organization, W. H., 2019: The WHO special initiative for mental health (2019-2023): universal health coverage for mental health. World Health Organization.
Organization, W. H., 2020: Joint child malnutrition estimates.
Organization, W. H. and I. W. Association, 2009: *Water safety plan manual: step-by-step risk management for drinking-water suppliers* [Who (ed.)]. Geneva, Switzerland. Available at: https://apps.who.int/iris/handle/10665/75141.
Orlov, A. et al., 2020: Economic costs of heat-induced reductions in worker productivity due to global warming. *Global Environmental Change-Human and Policy Dimensions*, **63**, doi:10.1016/j.gloenvcha.2020.102087.
Orru, H. et al., 2019: Ozone and heat-related mortality in Europe in 2050 significantly affected by changes in climate, population and greenhouse gas emission. *Environmental Research Letters*, **14**(7), doi:10.1088/1748-9326/ab1cd9.
Orru, H., K. L. Ebi and B. Forsberg, 2017: The Interplay of Climate Change and Air Pollution on Health. *Curr Environ Health Rep*, **4**(4), 504-513, doi:10.1007/s40572-017-0168-6.
Orru, K. et al., 2016: Well-being and environmental quality: Does pollution affect life satisfaction? *Qual. Life Res.*, **25**(3), 699-705, doi:10.1007/s11136-015-1104-6.
Osberghaus, D. and J. Kühling, 2016: Direct and indirect effects of weather experiences on life satisfaction–which role for climate change expectations? *Journal of Environmental Planning and Management*, **59**(12), 2198-2230.
Ostergard, J., R. L. and N. Seltzer, 2020: CLIMATE CHANGE AND GLOBAL HEALTH SECURITY: AN OVERVIEW OF THE SCOPE AND ISSUES. *Global Health Governance*, 5-23.
Ostro, B. et al., 2010: The Effects of Temperature and Use of Air Conditioning on Hospitalizations. *American Journal of Epidemiology*, **172**(9), 1053-1061, doi:10.1093/aje/kwq231.
Ottenhoff, L., 2021: Indigenous conservation can get Canada to climate goals: former MP Ethel Blondin-Andrew to Trudeau.
Otto, F. E. L. et al., 2020: Challenges to understanding extreme weather changes in lower income countries. *Bulletin of the American Meteorological Society*, **101**(10), E1851-E1860, doi:10.1175/bams-d-19-0317.1.
Otto, I. M. et al., 2017: Social vulnerability to climate change: a review of concepts and evidence. *Regional Environmental Change*, **17**(6), 1651-1662.
Ouattara, B. and E. Strobl, 2014: Hurricane strikes and local migration in US coastal counties. *Economics Letters*, **124**(1), 17-20.
Owain, E. L. and M. A. Maslin, 2018: Assessing the relative contribution of economic, political and environmental factors on past conflict and the displacement of people in East Africa. *Palgrave Communications*, **4**, doi:10.1057/s41599-018-0096-6.
Owen, J. P., B. Baig, C. Abbo and Y. Baheretibeb, 2016: Child and adolescent mental health in sub-Saharan Africa: a perspective from clinicians and researchers. *BJPsych International*, **13**, 45–47, doi:https://doi.org/10.1192/s2056474000001136.
Paavola, J., 2017: Health impacts of climate change and health and social inequalities in the UK. *Environ Health*, **16**(Suppl 1), 113, doi:10.1186/s12940-017-0328-z.
Pacific), U., 2020: COVID-19 Brief: Combating the dual challenges of climate-related disasters and COVID-19. United Nations Office for Disaster Risk Reduction, Bangkok, Thailand, 15 pp.
Paerl, H. W. et al., 2016: Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. *Harmful Algae*, **54**, 213-222, doi:10.1016/j.hal.2015.09.009.
Paffenholz, T., 2018: Women in peace negotiations. In: *Gendering diplomacy and international negotiation*. Springer, pp. 169-191.
Pai, N., 2008: *Climate Change and National Security: Preparing India for New Conflict Scenarios*. Indian National Interest Policy Brief, **No.1**, Takshashila Institution.
Pal, J. S. and E. A. B. Eltahir, 2016: Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change*, 6(2), 197-200. Available at: https://doi.org/10.1038/nclimate2833.
Papadakis, G., Z. Chalabi and J. E. Thornes, 2018: Ambulance Service Resource Planning for Extreme Temperatures: Analysis of Ambulance 999 Calls during Episodes of Extreme Temperature in London, UK. *Atmosphere*, **9**(5), doi:10.3390/atmos9050182.
Park, C. et al., 2019: The global effect of extreme weather events on nutrient supply: a superposed epoch analysis. *The Lancet Planetary Health*, **3**, e429-e438, doi:10.1016/s2542-5196(19)30193-7.
Park, J. et al., 2020: Association between short-term air pollution exposure and attention-deficit/hyperactivity disorder-related hospital admissions among adolescents: A nationwide time-series study. *Environ Pollut*, **266**(Pt 1), 115369, doi:10.1016/j.envpol.2020.115369.
Park, M., K. Park and G. Bahk, 2018a: Combined influence of multiple climatic factors on the incidence of bacterial foodborne diseases. *Science of the Total Environment*, **610**, 10-16, doi:10.1016/j.scitotenv.2017.08.045.

Park, M. S., K. H. Park and G. J. Bahk, 2018b: Combined influence of multiple climatic factors on the incidence of bacterial foodborne diseases. *Sci Total Environ*, **610-611**, 10-16, doi:10.1016/j.scitotenv.2017.08.045.

Park, M. S., K. H. Park and G. J. Bahk, 2018c: Interrelationships between Multiple Climatic Factors and Incidence of Foodborne Diseases. *Int J Environ Res Public Health*, **15**(11), doi:10.3390/ijerph15112482.

Park, R. J., A. P. Behrer and J. Goodman, 2021: Learning is inhibited by heat exposure, both internationally and within the United States. *Nat Hum Behav*, **5**(1), 19-27, doi:10.1038/s41562-020-00959-9.

Parks, R. M. et al., 2020: Anomalously warm temperatures are associated with increased injury deaths. *Nature medicine*, **26**(1), 65-70.

Parthemore, C., F. Femia and C. Werrell, 2018: The global responsibility to prepare for intersecting climate and nuclear risks. *Bulletin of the Atomic Scientists*, **74**(6), 374-378, doi:10.1080/00963402.2018.1533186.

Pascal, M. et al., 2021: Extreme heat and acute air pollution episodes: A need for joint public health warnings? *Atmospheric Environment*, **249**, doi:10.1016/j.atmosenv.2021.118249.

Pasini, A. and F. Mazzocchi, 2020: Perception and risk of Covid-19 and climate change: investigating analogies in a common framework. *Global Sustainability*, **3**, e32, doi:10.1017/sus.2020.30.

Patel, D. et al., 2019: Joint effects of heatwaves and air quality on ambulance services for vulnerable populations in Perth, western Australia. *Environmental Pollution*, **252**, 532-542, doi:10.1016/j.envpol.2019.05.125.

Patel, P., S. Mondal and K. Ghosh, 2020: Some respite for India's dirtiest river? Examining the Yamuna's water quality at Delhi during the COVID-19 lockdown period. *Science of the Total Environment*, **744**, doi:10.1016/j.scitotenv.2020.140851.

Patterson, K. et al., 2017: Seasonal variation of food security among the Batwa of Kanungu, Uganda. *Public health nutrition*, **20**(1).

Paudel, B. et al., 2021: Increased duration of pollen and mold exposure are linked to climate change. , , . *Scientific reports*, **11(1)**, 12816-12816, doi:https://doi.org/10.1038/s41598-021-92178-z.

Payne, J., D. Weatherall and F. Downy, 2015: Capturing the "multiple benefits" of energy efficiency in practice: the UK example. *ECEE Summer Study Proc*, 229-238.

Paynter, S. et al., 2010: Childhood pneumonia: a neglected, climate-sensitive disease? *Lancet*, **376**(9755), 1804-1805, doi:10.1016/s0140-6736(10)62141-1.

Paz, S. and J. C. Semenza, 2016: El Niño and climate change--contributing factors in the dispersal of Zika virus in the Americas? *Lancet*, **387**(10020), 745, doi:10.1016/s0140-6736(16)00256-7.

Pearse, R., 2017: Gender and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(2), e451.

Pelling, M. et al., 2021: Synergies Between COVID-19 and Climate Change Impacts and Responses. *Journal of Extreme Events*.

Pelling, M. and K. Dill, 2010: Disaster politics: tipping points for change in the adaptation of sociopolitical regimes. *Progress in human geography*, **34**(1), 21-37.

Pena-Garcia, V. H., O. Triana-Chavez and S. Arboleda-Sanchez, 2017: Estimating Effects of Temperature on Dengue Transmission in Colombian Cities. *Ann Glob Health*, **83**(3-4), 509-518, doi:10.1016/j.aogh.2017.10.011.

Peng, W., J. Yang, X. Lu and D. L. Mauzerall, 2018: Potential co-benefits of electrification for air quality, health, and CO2 mitigation in 2030 China. *Appl. Energy*, **218**, 511-519, doi:10.1016/j.apenergy.2018.02.048.

Peng, W., J. Yang, F. Wagner and L. Mauzerall, 2017: Substantial air quality and climate co-benefits achievable now with sectoral mitigation strategies in China. *Science of the Total Environment*, **598**, 1076-1084, doi:https://doi.org/10.1016/j.scitotenv.2017.03.287.

Perera, F., 2017: Multiple Threats to Child Health from Fossil Fuel Combustion: Impacts of Air Pollution and Climate Change. *Environmental Health Perspectives*, **125**(2), 141-148, doi:10.1289/ehp299.

Perevolotsky, A. and E. Sheffer, 2011: Integrated Management of Heterogenous Landscape - Mediterranean Israel as a Study Case. *Israel Journal of Ecology & Evolution*, **57**(1-2), 111-128.

Peters, D. H. et al., 2019: Financing Common Goods for Health: Core Government Functions in Health Emergency and Disaster Risk Management. *Health Systems & Reform*, **5**(4), 307--321, doi:10.1080/23288604.2019.1660104.

Petkova, E. P., A. Gasparrini and P. L. Kinney, 2014: Heat and Mortality in New York City Since the Beginning of the 20th Century. *Epidemiology*, **25**(4), 554-560, doi:10.1097/ede.0000000000000123.

Petrova, D. et al., 2019: Sensitivity of large dengue epidemics in Ecuador to long-lead predictions of El Nino. *Climate Services*, **15**, doi:10.1016/j.cliser.2019.02.003.

Petrova, K., 2021: Natural hazards, internal migration and protests in Bangladesh. *Journal of Peace Research*, **58**(1), 33-49, doi:10.1177/0022343320973741.

Phalkey, R. and V. Louis, 2016: Two hot to handle: How do we manage the simultaneous impacts of climate change and natural disasters on human health? *European Physical Journal-Special Topics*, **225**(3), 443-457, doi:10.1140/epjst/e2016-60071-y.

Phelan, A. L., R. Katz and L. O. Gostin, 2020: The Novel Coronavirus Originating in Wuhan, China Challenges for Global Health Governance. *Jama-Journal of the American Medical Association*, **323**(8), 709-710, doi:10.1001/jama.2020.1097.

Philipsborn, R., S. M. Ahmed, B. J. Brosi and K. Levy, 2016: Climatic Drivers of Diarrheagenic Escherichia coli Incidence: A Systematic Review and Meta-analysis. *J Infect Dis*, **214**(1), 6-15, doi:10.1093/infdis/jiw081.

Phillips, C. A. et al., 2020: Compound climate risks in the COVID-19 Pandemic. *Nature Climate Change*, **10**, 586–598.

Phung, D. et al., 2017: Heatwave and risk of hospitalization: A multi-province study in Vietnam. *Environmental Pollution*, **220**, 597-607, doi:10.1016/j.envpol.2016.10.008.
Phung, D. et al., 2015: Climate change, water quality, and water-related diseases in the Mekong Delta Basin: a systematic review. *Asia Pac J Public Health*, **27**(3), 265-276, doi:10.1177/1010539514565448.
Phung, D. et al., 2016: Ambient temperature and risk of cardiovascular hospitalization: An updated systematic review and meta-analysis. *Sci Total Environ*, **550**, 1084-1102, doi:10.1016/j.scitotenv.2016.01.154.
Piekałkiewicz, M., 2017: Why do economists study happiness? *The Economics and Labour Relations Review*, ***28***, 361-377, doi:https://doi.org/https://doi.org/10.1177/ 1035304617717130.
Piggott-McKellar, A., K. McNamara, P. Nunn and S. Sekinini, 2019: Moving People in a Changing Climate: Lessons from Two Case Studies in Fiji. *Social Sciences*, **8**, 133, doi:10.3390/socsci8050133.
Piguet, E., 2019: Climatic Statelessness: Risk Assessment and Policy Options. *Population and Development Review*, **45**(4), 865--883, doi:https://doi.org/10.1111/padr.12295.
Piguet, E., R. Kaenzig and J. Guélat, 2018: The uneven geography of research on "environmental migration". *Population and Environment*, 39(4), 357-383. Available at: https://doi.org/10.1007/s11111-018-0296-4.
Pineda, C., R. Munoz-Louis, C. V. Caballero-Uribe and D. Viasus, 2016: Chikungunya in the region of the Americas. A challenge for rheumatologists and health care systems. *Clinical rheumatology*, **35**(10), 2381-2385, doi:10.1007/s10067-016-3390-y.
Piper, N., 2017: Migration and the SDGs. *Global Social Policy*, **17**(2), 231-238.
Pisello, A. L. et al., 2018: Facing the urban overheating: Recent developments. Mitigation potential and sensitivity of the main technologies. *Wiley Interdisciplinary Reviews-Energy and Environment*, **7**(4), doi:10.1002/wene.294.
Poch, M. et al., 2020: When the fourth water and digital revolution encountered COVID-19. *Science of the Total Environment*, **744**, doi:10.1016/j.scitotenv.2020.140980.
Polain, J. D., H. L. Berry and J. O. Hoskin, 2011: Rapid change, climate adversity and the next 'big dry': Older farmers' mental health. *Aust. J. Rural Health*, **19**(5), 239-243, doi:10.1111/j.1440-1584.2011.01219.x.
Pollack, A., B. Weiss and T. Trung, 2016: Mental health, life functioning and risk factors among people exposed to frequent natural disasters and chronic poverty in Vietnam. *BJPsych Open*, **2**(3), 221-232.
Pollard, G., M. Davies and H. Moore, 2015: Women, marketplaces and exchange partners amongst the Marakwet of northwest Kenya. *Journal of Eastern African Studies*, **9**(3), 412-439, doi:https://doi.org/10.1080/17531055.2015.1089699.
Polyakova, M., G. Kocks, V. Udalova and A. Finkelstein, 2020: Initial economic damage from the COVID-19 pandemic in the United States is more widespread across ages and geographies than initial mortality impacts. *Proc Natl Acad Sci U S A*, doi:10.1073/pnas.2014279117.
Ponjoan, A. et al., 2017: Effects of extreme temperatures on cardiovascular emergency hospitalizations in a Mediterranean region: a self-controlled case series study. *Environmental Health*, **16**, doi:10.1186/s12940-017-0238-0.
Poole, J. A. et al., 2019: - Impact of weather and climate change with indoor and outdoor air quality in asthmatic patients.
Poore, J. and T. Nemecek, 2018: Reducing food's environmental impacts through producers and consumers. *Science*, **360**(6392), 987-992, doi:10.1126/science.aag0216.
Poortinga, W. et al., 2019: Climate change perceptions and their individual-level determinants: A cross-European analysis. *Global Environmental Change*, **55**, 25-35.
Popov, I. and V. Yasyukevich, 2014: The taiga tick Ixodes persulcatus: Propagation under climate change conditions in the 21st century. *Russian Meteorology and Hydrology*, **39**(8), 558-563, doi:10.3103/s1068373914080081.
Porst, L. and P. Sakdapolrak, 2020: Gendered translocal connectedness: Rural–urban migration, remittances, and social resilience in Thailand. *Population, Space and Place*, **26**(4), e2314, doi:10.1002/psp.2314.
Porter, C. and R. Goyal, 2016: Social protection for all ages? Impacts of Ethiopia's Productive Safety Net Program on child nutrition. *Social Science & Medicine*, **159**, 92-99, doi:10.1016/j.socscimed.2016.05.001.
Portier, C. et al., 2010: A human health perspective on climate change. Environmental Health Perspectives, National Institute of Environmental Health Sciences, Research Triangle Park, NC.
Pörtner, H. O. et al., 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Intergovernmental Panel on Climate Change, 1170 pp. Available at: https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_FullReport.pdf.
Pottie, K. et al., 2015: Access to healthcare for the most vulnerable migrants: a humanitarian crisis. *Conflict and Health*, **9**, doi:10.1186/s13031-015-0043-8.
Power, M., S. Adar, J. Yanosky and J. Weuve, 2016: Exposure to air pollution as a potential contributor to cognitive function, cognitive decline, brain imaging, and dementia: A systematic review of epidemiologic research. *Neurotoxicology*, **56**, 235-253, doi:10.1016/j.neuro.2016.06.004.
Pozza, L. E. and D. J. Field, 2020: The science of Soil Security and Food Security.
Pramanik, M. et al., 2020: El Nino Southern Oscillation as an early warning tool for dengue outbreak in India. *Bmc Public Health*, **20**(1), doi:10.1186/s12889-020-09609-1.
Pretty, J. and J. Barton, 2020: Nature-Based Interventions and Mind-Body Interventions: Saving Public Health Costs Whilst Increasing Life Satisfaction and Happiness. *International Journal of Environmental Research and Public Health*, **17**(21), doi:10.3390/ijerph17217769.

Price, D., K. M. Hughes, F. Thien and C. Suphioglu, 2021: Epidemic Thunderstorm Asthma: Lessons Learned from the Storm Down-Under. *Journal of Allergy and Clinical Immunology-in Practice*, **9**(4), 1510-1515, doi:10.1016/j.jaip.2020.10.022.
Proestos, Y. et al., 2015: Present and future projections of habitat suitability of the Asian tiger mosquito, a vector of viral pathogens, from global climate simulation (vol 370, 20130554, 2015). *Philosophical Transactions of the Royal Society B-Biological Sciences*, **370**(1678), doi:10.1098/rstb.2015.0246.
Program, U. C. C. S., 2016: The impacts of climate change on human health in the United States : a scientific assessment. Available at: http://purl.fdlp.gov/GPO/gpo68498.
Programme, U. N. E., E. Union and Adelphi, 2019: *Guidance Note and Tools to Address Climate-Fragility Risks*.
Prueksapanich, P. et al., 2018: Liver Fluke-Associated Biliary Tract Cancer. *Gut Liver*, **12**(3), 236-245, doi:10.5009/gnl17102.
Psarros, C. et al., 2017: Insomnia and PTSD one month after wildfires: evidence for an independent role of the "fear of imminent death". *Int. J. Psychiat. Clin.*, **21**(2), 137-141, doi:10.1080/13651501.2016.1276192.
Pu, X. et al., 2017: Enhanced surface ozone during the heat wave of 2013 in Yangtze River Delta region, China. *Science of the Total Environment*, **603**, 807-816, doi:10.1016/j.scitotenv.2017.03.056.
Pyrgou, A., P. Hadjinicolaou and M. Santamouris, 2018: Enhanced near-surface ozone under heatwave conditions in a Mediterranean island. *Scientific Reports*, **8**, doi:10.1038/s41598-018-27590-z.
Qiu, H. et al., 2016: Pneumonia Hospitalization Risk in the Elderly Attributable to Cold and Hot Temperatures in Hong Kong, China. *American Journal of Epidemiology*, **184**(8), 570-578, doi:10.1093/aje/kww041.
Qu, J., 2016: Is sunspot activity a factor in influenza pandemics? *Reviews in Medical Virology*, **26**(5), 309-313, doi:10.1002/rmv.1887.
Quast, T. and L. Feng, 2019: Long-term Effects of Disasters on Health Care Utilization: Hurricane Katrina and Older Individuals with Diabetes. *Disaster medicine and public health preparedness*, 1-8, doi:10.1017/dmp.2018.128.
Quintero-Herrera, L. L. et al., 2015: Potential impact of climatic variability on the epidemiology of dengue in Risaralda, Colombia, 2010-2011. *Journal of infection and public health*, **8**(3), 291-297, doi:10.1016/j.jiph.2014.11.005.
Ragettli, M. S. and M. Roosli, 2019: Heat-health action plans to prevent heat-related deaths-experiences from Switzerland. *Bundesgesundheitsblatt-Gesundheitsforschung-Gesundheitsschutz*, **62**(5), 605-611, doi:10.1007/s00103-019-02928-8.
Raghavan, S. V. et al., 2019: ASEAN Food Security under the 2°C-4°C Global Warming Climate Change Scenarios. In: *Towards a Resilient ASEAN Volume 1: Disasters, Climate Change, and Food Security: Supporting ASEAN Resilience* [Anbum Ozhi, V., M. B. Reiling and V. Reddy (eds.)]. Economic Research Institute for ASEAN and East Asia, Jakarta.
Rahman, S. et al., 2019: Projected changes of inundation of cyclonic storms in the Ganges–Brahmaputra–Meghna delta of Bangladesh due to SLR by 2100. *Journal of Earth System Science*, doi:https://doi.org/10.1007/s12040-019-1184-8.
Rail, M. et al., 2019: Impact of climate and population change on temperature-related mortality burden in Bavaria, Germany. *Environmental Research Letters*, **14**(12), doi:10.1088/1748-9326/ab5ca6.
Rakotoarison, N. et al., 2018: Assessment of Risk, Vulnerability and Adaptation to Climate Change by the Health Sector in Madagascar. *Int J Environ Res Public Health*, **15**(12), doi:10.3390/ijerph15122643.
Ramamurthy, P. and E. Bou-Zeid, 2017: Heatwaves and urban heat islands: A comparative analysis of multiple cities. *Journal of Geophysical Research-Atmospheres*, **122**(1), 168-178, doi:10.1002/2016jd025357.
Ramesh, A. et al., 2016: The impact of climate on the abundance of Musca sorbens, the vector of trachoma. *Parasit Vectors*, **9**, 48, doi:10.1186/s13071-016-1330-y.
Ramos-Castillo, A., E. Castellanos and K. McLean, 2017: Indigenous peoples, local communities and climate change mitigation. *Climatic Change*, **140**(1), 1-4, doi:10.1007/s10584-016-1873-0.
Ramos, A. K. et al., 2020: Invisible No More: The Impact of COVID-19 on Essential Food Production Workers. *Journal of Agromedicine*, **25**, 378-382.
Rankoana, S. A., 2021: Climate change impacts on indigenous health promotion: the case study of Dikgale community in Limpopo Province, South Africa. *Glob Health Promot*, 17579759211015183, doi:10.1177/17579759211015183.
Ranson, M., 2014: Crime, weather, and climate change. *Journal of Environmental Economics and Management*, **67**(3), 274-302, doi:10.1016/j.jeem.2013.11.008.
Rao, K. K. et al., 2020: Projections of heat stress and associated work performance over India in response to global warming. *Scientific Reports*, **10**(1), doi:10.1038/s41598-020-73245-3.
Rao, M. R. K., R. N. Padhy and M. K. Das, 2018: Episodes of the epidemiological factors correlated with prevailing viral infections with dengue virus and molecular characterization of serotype-specific dengue virus circulation in eastern India. *Infection, genetics and evolution : journal of molecular epidemiology and evolutionary genetics in infectious diseases*, **58**, 40-49, doi:10.1016/j.meegid.2017.12.005.
Rao, N., 2019: From abandonment to autonomy: Gendered strategies for coping with climate change, Isiolo County, Kenya. *Geoforum*, **102**, 27-37, doi:https://doi.org/10.1016/j.geoforum.2019.03.017.
Rao, N. et al., 2019a: Gendered vulnerabilities to climate change: insights from the semi-arid regions of Africa and Asia. *Climate and Development*, **11**(1), 14-26.

Rao, N. et al., 2019b: Managing risk, changing aspirations and household dynamics: Implications from wellbeing and adaptation in semi-arid Africa and India. *World Development*, doi:https://doi.org/10.1016/j.worlddev.2019.104667.
Rataj, E., K. Kunzweiler and S. Garthus-Niegel, 2016: Extreme weather events in developing countries and related injuries and mental health disorders - a systematic review. *BMC Public Health*, **16**(1), 1020, doi:10.1186/s12889-016-3692-7.
Ravera, F., B. Martin-Lopez, U. Pascual and A. Drucker, 2016: The diversity of gendered adaptation strategies to climate change of Indian farmers: a feminist intersectional approach. *Ambio*, **45**, 335-351, doi:https://doi.org/10.1007/s13280-016-0833-2.
Raymond, C., T. Matthews and R. M. Horton, 2020: The emergence of heat and humidity too severe for human tolerance. *Science Advances*, **6**(19), doi:10.1126/sciadv.aaw1838.
Reckien, D., 2021: What Can Local Climate Planning Learn from COVID-19? Transform the City - It Saves the Climate and Lowers the Risk of Pandemics. *Planning Theory & Practice*, doi:10.1080/14649357.2021.1951578.
Regli, S. et al., 2015: Estimating Potential Increased Bladder Cancer Risk Due to Increased Bromide Concentrations in Sources of Disinfected Drinking Waters. *Environ. Sci. Technol.*, **49**(22), 13094-13102, doi:10.1021/acs.est.5b03547.
Reid, C. E. et al., 2016: Critical Review of Health Impacts of Wildfire Smoke Exposure. *Environ. Health Perspect.*, **124**(9), 1334-1343, doi:10.1289/ehp.1409277.
Reid, P., D. Cormack and S. J. Paine, 2019: Colonial histories, racism and health-The experience of Māori and Indigenous peoples. *Public Health*, **172**, 119-124, doi:10.1080/10705422.2019.1658677.
Remling, E., 2020: Migration as climate adaptation? Exploring discourses amongst development actors in the Pacific Island region. *Regional Environmental Change*, **20**(1), 3, doi:10.1007/s10113-020-01583-z.
Report, G. N., 2020: Global Nutrition Report: Action on equity to end malnutrition. Development Initiatives, Bristol, UK.
Reser, J. P. et al., 2012: Public risk perceptions, understandings, and responses to climate change and natural disasters in Australia, 2010 and 2011. National Climate Change Adaptation Research Facility, Gold Coast, 245 pp.
Reyer, C. P. et al., 2017: Climate change impacts in Central Asia and their implications for development. *Regional Environmental Change*, **17**(6), 1639-1650.
Reyes, M. E. S. et al., 2021: An investigation into the relationship between climate change anxiety and mental health among Gen Z Filipinos. *Curr Psychol*, 1-9, doi:10.1007/s12144-021-02099-3.
Rice, M. B., G. D. Thurston, J. R. Balmes and K. E. Pinkerton, 2014: Climate change. A global threat to cardiopulmonary health. *Am. J. Respir. Crit. Care Med.*, **189**(5), 512-519, doi:10.1164/rccm.201310-1924PP.
Richmond, C. A. M. and N. A. Ross, 2009: The determinants of First Nation and Inuit health: a critical population health approach. *Health Place*, **15**(2), 403-411, doi:10.1016/j.healthplace.2008.07.004.
Rickerts, V., 2019: [Climate change and systemic fungal infections]. *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz*, **62**(5), 646-651, doi:10.1007/s00103-019-02931-z.
Rigaud, K. K. et al., 2018: *Groundswell : Preparing for Internal Climate Migration*. Washington DC. Available at: https://openknowledge.worldbank.org/handle/10986/29461.
Rigg, J., T. Nguyen, T. Thu and H. Luong, 2018: The texture of livelihoods: Migration and making a living in Hanoi. *The Journal of Development Studies*, **50**, 368-382.
Rigg, J. and A. Salamanca, 2015: The Devil in the Details: Interpreting livelihood turbulence from a 25-year panel study from Thailand. *Area 47*,(3), 296-304.
Rigi, H. and J. F. Warner, 2020: Two-level games on the trans-boundary river Indus: obstacles to cooperation. *Water Policy*, **22**(6), 972-990.
Riley, M., 2021: The New South Wales air quality alert system: a brief history. *Australian Journal of Emergency Management*, **36**(1), 21-24.
Riosmena, F., R. Kuhn and W. C. Jochem, 2017: Explaining the Immigrant Health Advantage: Self-selection and Protection in Health-Related Factors Among Five Major National-Origin Immigrant Groups in the United States. *Demography*, **54**(1), 175-200, doi:10.1007/s13524-016-0542-2.
Riosmena, F., R. Nawrotzki and L. Hunter, 2018: Climate migration at the height and end of the Great Mexican Emigration Era. *Population and Development Review*, **44**(3), 455-488, doi:10.1111/padr.12158.
Rippin, H. et al., 2020: Disrupted food systems in the WHO European region - a threat or opportunity for healthy and sustainable food and nutrition? *Food Security*, **12**(4), 859-864, doi:10.1007/s12571-020-01079-y.
Ripple, W. et al., 2014: COMMENTARY: Ruminants, climate change and climate policy. *Nature Climate Change*, **4**(1), 2-5, doi:10.1038/nclimate2081.
Ritchie, H., D. Reay and P. Higgins, 2018: Beyond Calories: A Holistic Assessment of the Global Food System. *Frontiers in Sustainable Food Systems*, **2**, doi:10.3389/fsufs.2018.00057.
Rivas, A. V. et al., 2018: Building Infestation Index for Aedes aegypti and occurrence of dengue fever in the municipality of Foz do Iguacu, Parana, Brazil, from 2001 to 2016. *Revista da Sociedade Brasileira de Medicina Tropical*, **51**(1), 71-76, doi:10.1590/0037-8682-0228-2017.
Roa, L. et al., 2020: Climate change: challenges and opportunities to scale up surgical, obstetric, and anaesthesia care globally. *Lancet Planetary Health*, **4**(11), E538-E543.

Robalino, J., J. Jiminez and A. Chacón, 2015: The Effect of Hydro-Meteorological Emergencies on Internal Migration. *World Development*, **67**, 438-448.

Roberts, I. and E. Arnold, 2007: Policy at the crossroads: climate change and injury control. *Inj. Prev.*, **13**(4), 222-223.

Roberts, I. and M. Hillman, 2005: Climate change: the implications for policy on injury control and health promotion. *Inj. Prev.*, **11**(6), 326-329.

Roche, K. R. et al., 2020: Climate change and the opportunity cost of conflict. *Proceedings of the National Academy of Sciences*, **117**(4), 1935-1940.

Rocklöv, J., V. Huber, K. Bowen and R. Paul, 2021: Taking globally consistent health impact projections to the next level. The Lancet Planetary Health.

Rocklov, J. et al., 2019: Using Big Data to Monitor the Introduction and Spread of Chikungunya, Europe, 2017. *Emerging Infectious Diseases*, **25**(6), 1041-1049, doi:10.3201/eid2506.180138.

Roda Gracia, J., B. Schumann and A. Seidler, 2015: Climate Variability and the Occurrence of Human Puumala Hantavirus Infections in Europe: A Systematic Review. *Zoonoses Public Health*, **62**(6), 465-478, doi:10.1111/zph.12175.

Rodrigues, M., P. Santana and A. Rocha, 2020: Statistical Modelling of Temperature-Attributable Deaths in Portuguese Metropolitan Areas under Climate Change: Who Is at Risk? *Atmosphere*, **11**(2), doi:10.3390/atmos11020159.

Rodriguez-Llanes, J., S. Ranjan-Dash, A. Mukhopadhyay and D. Guha-Sapir, 2016: Looking upstream: enhancers of child nutritional status in post-flood rural settings. *Peerj*, **4**, doi:10.7717/peerj.1741.

Rogers, D. J., 2015: Dengue: recent past and future threats. *Philos Trans R Soc Lond B Biol Sci*, **370**(1665), doi:10.1098/rstb.2013.0562.

Rohat, G. et al., 2019a: Projections of Human Exposure to Dangerous Heat in African Cities Under Multiple Socioeconomic and Climate Scenarios. *Earths Future*, **7**(5), 528-546, doi:10.1029/2018ef001020.

Rohat, G. et al., 2019b: Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe. *Global and Planetary Change*, **172**, 45-59, doi:10.1016/j.gloplacha.2018.09.013.

Rohat, G. et al., 2019c: Characterizing the role of socioeconomic pathways in shaping future urban heat-related challenges. *Science of the Total Environment*, **695**, doi:10.1016/j.scitotenv.2019.133941.

Rojas-Rueda, D. et al., 2016: Health Impacts of Active Transportation in Europe. *Plos One*, **11**(3), doi:10.1371/journal.pone.0149990.

Roos, N. et al., 2021: Maternal and newborn health risks of climate change: A call for awareness and global action. *Acta Obstetricia Et Gynecologica Scandinavica*, **100**(4), 566-570, doi:10.1111/aogs.14124.

Rosenberg, A. et al., 2018: Ambient temperature and age-related notified Campylobacter infection in Israel: A 12-year time series study. *Environ Res*, **164**, 539-545, doi:10.1016/j.envres.2018.03.017.

Rosenbloom, D. and J. Markard, 2020: A COVID-19 recovery for climate. *Science*, **368**(6490), 447-447, doi:10.1126/science.abc4887.

Rosenstock, T. et al., 2019: A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa. *One Earth*, **1**(3), 330-344, doi:10.1016/j.oneear.2019.10.017.

Roth, D. et al., 2019: Climates of urbanization: local experiences of water security, conflict and cooperation in peri-urban South-Asia. *Climate Policy*, **19**(sup1), S78-S93.

Roth, G. A. et al., 2020: Global Burden of Cardiovascular Diseases and Risk Factors, 1990-2019: Update From the GBD 2019 Study. *J Am Coll Cardiol*, **76**(25), 2982-3021, doi:10.1016/j.jacc.2020.11.010.

Rozenberg, H. a., 2017: Climate change through a poverty lens. Nature Climate Change 7(4):250–256.

Rüegger, S. and H. Bohnet, 2020: The Link between Forced Migration and Conflict. *Environmental Conflicts, Migration and Governance*, 177.

Rushton, S. P. et al., 2019: Climate, human behaviour or environment: individual-based modelling of Campylobacter seasonality and strategies to reduce disease burden. *J Transl Med*, **17**(1), 34, doi:10.1186/s12967-019-1781-y.

Russo, S., A. F. Marchese, J. Sillmann and G. Imme, 2016: When will unusual heat waves become normal in a warming Africa? *Environmental Research Letters*, **11**(5), doi:10.1088/1748-9326/11/5/054016.

Russo, S. et al., 2019: Half a degree and rapid socioeconomic development matter for heatwave risk. *Nature Communications*, **10**, doi:10.1038/s41467-018-08070-4.

Ruszkiewicz, J. et al., 2019: Brain diseases in changing climate. *Environmental Research*, **177**, doi:10.1016/j.envres.2019.108637.

Rüttinger, L. et al., 2015: A new climate for peace: taking action on climate and fragility risks. *Berlin/London/Washington/Paris: Adelphi*.

Ruuhela, R. et al., 2021: Temperature-Related Mortality in Helsinki Compared to Its Surrounding Region Over Two Decades, with Special Emphasis on Intensive Heatwaves. *Atmosphere*, **12**(1), doi:10.3390/atmos12010046.

Ryan, B. et al., 2015a: Identifying and Describing the Impact of Cyclone, Storm and Flood Related Disasters on Treatment Management, Care and Exacerbations of Non-communicable Diseases and the Implications for Public Health. *PLoS currents*, **7**, ecurrents.dis.62e9286d9152de04799644dcca04799647d04799288, doi:10.1371/currents.dis.62e9286d152de04799644dcca47d9288.

Ryan, S., C. Carlson, E. Mordecai and L. Johnson, 2019: Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *Plos Neglected Tropical Diseases*, **13**(3), doi:10.1371/journal.pntd.0007213.

Ryan, S., C. Lippi and F. Zermoglio, 2020: Shifting transmission risk for malaria in Africa with climate change: a framework for planning and intervention. *Malaria Journal*, **19**(1), doi:10.1186/s12936-020-03224-6.
Ryan, S. J. et al., 2015b: Mapping Physiological Suitability Limits for Malaria in Africa Under Climate Change. *Vector Borne Zoonotic Dis*, **15**(12), 718-725, doi:10.1089/vbz.2015.1822.
Sabate, J. and S. Soret, 2014: Sustainability of plant-based diets: back to the future. *The American Journal of Clinical Nutrition*, **100**, 476S-483S.
Saeed, F., C. F. Schleussner and M. Almazroui, 2021: From Paris to Makkah: heat stress risks for Muslim pilgrims at 1.5 degrees C and 2 degrees C. *Environmental Research Letters*, **16**(2), doi:10.1088/1748-9326/abd067.
Saha, S. K., 2016: Cyclone Aila, livelihood stress, and migration: empirical evidence from coastal Bangladesh. *Disasters*, doi:10.1111/disa.12214.
Salas, R. and A. Jha, 2019: Climate change threatens the achievement of effective universal healthcare. *Bmj-British Medical Journal*, **366**, doi:10.1136/bmj.l5302.
Samir, K. and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change-Human and Policy Dimensions*, **42**, 181-192, doi:10.1016/j.gloenvcha.2014.06.004.
Sampedro, J. et al., 2020: Health co-benefits and mitigation costs as per the Paris Agreement under different technological pathways for energy supply. *Environment International*, **136**, 1-12, doi:10.1016/j.envint.2020.105513.
Sangha, K. K. et al., 2018: An ecosystem services framework to evaluate Indigenous and local peoples' connections with nature. *Ecosystem services*, **31**, 111-125.
Santiago, E. C. and F. Rivas, 2012: Polychlorinated biphenyls in selected sites in Pasig River and Laguna Lake in the Philippines before and after a big flood event investigated under the UNU East Asia Regional POPs monitoring project. *Bull Environ Contam Toxicol*, **89**(2), 407-411, doi:10.1007/s00128-012-0677-9.
Sanz-Barbero, B. et al., 2018: Heat wave and the risk of intimate partner violence. *Science of the Total Environment*, **644**, 413-419, doi:10.1016/j.scitotenv.2018.06.368.
Sapkota, A. et al., 2020: - Association Between Changes in Timing of Spring Onset and Asthma Hospitalization in Maryland. **- 3**(- 7).
Sarkar, S., V. Gangare, P. Singh and R. Dhiman, 2019: Shift in Potential Malaria Transmission Areas in India, Using the Fuzzy-Based Climate Suitability Malaria Transmission (FCSMT) Model under Changing Climatic Conditions. *International Journal of Environmental Research and Public Health*, **16**(18), doi:10.3390/ijerph16183474.
Sattler, D. N. et al., 2020: Climate change in Tonga: Risk perception and behavioral adaptation. *Managing Climate Change Adaptation in the Pacific Region*, 273-292.
Sattler, D. N., A. Whippy, J. M. Graham and J. Johnson, 2018: A psychological model of climate change adaptation: Influence of resource loss, posttraumatic growth, norms, and risk perception following Cyclone Winston in Fiji. *Climate change impacts and adaptation strategies for coastal communities*, 427-443.
Sawas, A., M. Workman and N. Mirumachi, 2018: *Climate change, low-carbon transitions and security. Grantham Institute Briefing paper No. 25*. Imperial College, London.
Scarpa, G. et al., 2021: Developing an online food composition database for an Indigenous population in south-western Uganda. *Public Health Nutrition*, **24**(9), 2455-2464, doi:10.1017/s1368980021001397.
Scasny, M., E. Massetti, J. Melichar and S. Carrara, 2015: Quantifying the Ancillary Benefits of the Representative Concentration Pathways on Air Quality in Europe. *Environmental and Resource Economics*, **62**(2), 383-415, doi:https://doi.org/10.1007/s10640-015-9969-y.
Schachtel, A., J. A. Dyer and M. D. Boos, 2021: Climate change and pediatric skin health. *Int J Womens Dermatol*, **7**(1), 85-90, doi:10.1016/j.ijwd.2020.07.006.
Schaferhoff, M. et al., 2019: Trends in global health financing. *Bmj-British Medical Journal*, **365**, doi:10.1136/bmj.l2185.
Scheelbeek, P. et al., 2021: The effects on public health of climate change adaptation responses: a systematic review of evidence from low- and middle-income countries. *Environmental Research Letters*, **16**(7), doi:10.1088/1748-9326/ac092c.
Scheffran, J. et al., 2012: Disentangling the Climate-conflict Nexus: Empirical and Theoretical Assessment of Vulnerabilities and Pathways. *Review of European Studies*, **4**(5), 13.
Scheidel, A. et al., 2020: Environmental conflicts and defenders: A global overview. *Global Environmental Change*, **63**, 102104.
Schinasi, L. H., T. Benmarhnia and A. J. De Roos, 2018: Modification of the association between high ambient temperature and health by urban microclimate indicators: A systematic review and meta-analysis. *Environmental Research*, **161**, 168-180, doi:10.1016/j.envres.2017.11.004.
Schipper, E. et al., 2021: Turbulent transformation: abrupt societal disruption and climate resilient development. *Climate and Development*, **13**(6), 467-474.
Schipper, E. L. F., 2020: Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, **3**(4), 409-414, doi:10.1016/j.oneear.2020.09.014.
Schleussner, C.-F., J. F. Donges, R. V. Donner and H. J. Schellnhuber, 2016: Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proceedings of the National Academy of Sciences*, **113**(33), 9216-9221.

Schneider, A. et al., 2020: Impact of meteorological parameters on suicide mortality rates: A case-crossover analysis in Southern Germany (1990-2006). *Science of the Total Environment*, **707**, doi:10.1016/j.scitotenv.2019.136053.
Schnell, J. L. and M. J. Prather, 2017: Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(11), 2854-2859, doi:10.1073/pnas.1614453114.
Schramm, P. et al., 2020a: Climate Change and Health: Local Solutions to Local Challenges. *Current Environmental Health Reports*, **7**(4), 363-370, doi:10.1007/s40572-020-00294-1.
Schramm, P. et al., 2020b: How Indigenous Communities Are Adapting To Climate Change: Insights From The Climate-Ready Tribes Initiative. *Health Affairs*, **39**(12), 2153-2159, doi:10.1377/hlthaff.2020.00997.
Schucht, S. et al., 2015: Moving towards ambitious climate policies: Monetised health benefits from improved air quality could offset mitigation costs in Europe. *Environmental Science and Policy*, **50**, 252-269, doi:https://doi.org/10.1016/j.envsci.2015.03.001.
Schumacher, K. A. and V. Shandas, 2019: Rescaling Air Quality Management: An Assessment of Local Air Quality Authorities in the United States. *Air Soil and Water Research*, **12**, doi:10.1177/1178622119842125.
Schuster, C., J. Honold, S. Lauf and T. Lakes, 2017: Urban heat stress: Novel survey suggests health and fitness as future avenue for research and adaptation strategies. *Environmental Research Letters*, **12**, doi:10.1088/1748-9326/aa5f35.
Schutte, S., J. Vestby, J. Carling and H. Buhaug, 2021: Climatic conditions are weak predictors of asylum migration. *Nature Communications*, 12(1), 2067. Available at: https://doi.org/10.1038/s41467-021-22255-4.
Schwartz, R. et al., 2015: The impact of Hurricane Sandy on the mental health of New York area residents. *American journal of disaster medicine*, **10**(4), 339-346.
Schwarz, L. et al., 2021: Spatial variation in the joint effect of extreme heat events and ozone on respiratory hospitalizations in California. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(22), doi:10.1073/pnas.2023078118.
Schweitzer, M. D. et al., 2018: Lung health in era of climate change and dust storms. *Environ. Res.*, **163**, 36-42, doi:10.1016/j.envres.2018.02.001.
Schwerdtle, P., K. Bowen and C. McMichael, 2018: The health impacts of climate-related migration. *BMC medicine*, **16**(1), 1-7.
Schwerdtle, P. et al., 2020: Health and migration in the context of a changing climate: a systematic literature assessment. *Environmental Research Letters*, **15**(10), doi:10.1088/1748-9326/ab9ece.
Schwingshackl, C. et al., 2021: Heat Stress Indicators in CMIP6: Estimating Future Trends and Exceedances of Impact-Relevant Thresholds. *Earths Future*, **9**(3), doi:10.1029/2020ef001885.
Scortichini, M. et al., 2018: The inter-annual variability of heat-related mortality in nine European cities (1990–2010). *Environmental Health*, **17**(1), 66, doi:10.1186/s12940-018-0411-0.
Scott, A. A., D. W. Waugh and B. Zaitchik, 2018: Reduced Urban Heat Island intensity under warmer conditions. *Environmental Research Letters*, **13**(6), doi:10.1088/1748-9326/aabd6c.
Scott, C. A. et al., 2019: Water in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment*. Springer, pp. 257-299.
Selby, J., 2019: Climate change and the Syrian civil war, Part II: The Jazira's agrarian crisis. *Geoforum*, **101**, 260-274.
Selby, J., O. S. Dahi, C. Frohlich and M. Hulme, 2017: Climate change and the Syrian civil war revisited. *Political Geography*, **60**, 232-244, doi:10.1016/j.polgeo.2017.05.007.
Sellers, S. and K. L. Ebi, 2017: Climate Change and Health under the Shared Socioeconomic Pathway Framework. *Int J Environ Res Public Health*, **15**(1), doi:10.3390/ijerph15010003.
Semakula, H. et al., 2017: Prediction of future malaria hotspots under climate change in sub-Saharan Africa. *Climatic Change*, **143**(3-4), 415-428, doi:10.1007/s10584-017-1996-y.
Semenza, J., 2020: Cascading risks of waterborne diseases from climate change. *Nature Immunology*, **21**(5), 484-487, doi:10.1038/s41590-020-0631-7.
Semenza, J., 2021: Lateral public health: advancing systemic resilience to climate change. *The Lancet Regional Health*.
Semenza, J. et al., 2021: COVID-19 research priorities for non-pharmaceutical public health and social measures. *Epidemiology and Infection*, **149**, e87, doi:10.1017/s0950268821000716.
Semenza, J. et al., 2016: Determinants and Drivers of Infectious Disease Threat Events in Europe. *Emerging Infectious Diseases*, **22**(4), 581-589, doi:10.3201/eid2204.151073.
Semenza, J. et al., 2017: Environmental Suitability of Vibrio Infections in a Warming Climate: An Early Warning System. *Environmental Health Perspectives*, **125**(10), doi:10.1289/ehp2198.
Semenza, J. and H. Zeller, 2014: Integrated surveillance for prevention and control of emerging vector-borne diseases in Europe. *Eurosurveillance*, **19**(13), 2-5, doi:10.2807/1560-7917.Es2014.19.13.20757.
Semenza, J. C., 2011: Lateral Public Health: A Comprehensive Approach to Adaptation in Urban Environments. In: *Climate Change Adaptation in Developed Nations: From Theory to Practice Advances in Global Research* [Ford, J. D. and L. Berrang-Ford (eds.)]. Springer Science +Business Media, New York, NY., pp. 143-159.
Semenza, J. C. and K. L. Ebi, 2019: Climate change impact on migration, travel, travel destinations and the tourism industry. *Journal of Travel Medicine*, 26(5). Available at: https://doi.org/10.1093/jtm/taz026.
Semenza, J. C. and S. Paz, 2021: Climate Change and Infectious Disease in Europe: Impact, Projection and Adaptation. *The Lancet Regional Health*.

Sen, A., 2001: *Development as Freedom*. Oxford University Press, Oxford.
Sera, F. et al., 2019: How urban characteristics affect vulnerability to heat and cold: a multi-country analysis. *International Journal of Epidemiology*, **48**(4), 1101-1112, doi:10.1093/ije/dyz008.
Sera, F. et al., 2020: Air Conditioning and Heat-related Mortality A Multi-country Longitudinal Study. *Epidemiology*, **31**(6), 779-787, doi:10.1097/ede.0000000000001241.
Serdeczny, O. et al., 2017: Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions *Regional Environmental Change*, **17(6)**, 1585-1600, doi:https://doi.org/10.1007/s10113-015-0910-2.
Shaffer, R. et al., 2019: Improving and Expanding Estimates of the Global Burden of Disease Due to Environmental Health Risk Factors. *Environmental Health Perspectives*, **127**(10), doi:10.1289/ehp5496.
Shair-Rosenfield, S. and R. M. Wood, 2017: Governing well after war: How improving female representation prolongs post-conflict peace. *The Journal of Politics*, **79**(3), 995-1009.
Shaman, J. and M. Lipsitch, 2013: The El Nino-Southern Oscillation (ENSO)-pandemic Influenza connection: Coincident or causal? *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 3689-3691, doi:10.1073/pnas.1107485109.
Shayegh, S., 2017: Outward migration may alter population dynamics and income inequality. *Nature Climate Change*, **7**, 828-828.
Shekhar, M. et al., 2018: Effects of Climate Change on Occurrence of Aflatoxin and its Impacts on Maize in India. *Int. J. Curr. Microbiol. App. Sci*, **7**(6), 109-116.
Sheller, M., 2018: Theorising mobility justice. *Tempo Soc.*, **30**(2), 17-34, doi:10.11606/0103-2070.ts.2018.142763.
Sheng, R. et al., 2018: Does hot weather affect work-related injury? A case-crossover study in Guangzhou, China. *Int J Hyg Environ Health*, **221**(3), 423-428, doi:10.1016/j.ijheh.2018.01.005.
Sheridan, S. and M. Allen, 2018: Temporal trends in human vulnerability to excessive heat. *Environmental Research Letters*, **13**, doi:10.1088/1748-9326/aab214.
Sherpa, A., T. Koottatep, C. Zurbrugg and G. Cisse, 2014: Vulnerability and adaptability of sanitation systems to climate change. *Journal of Water and Climate Change*, **5**(4), 487-495, doi:10.2166/wcc.2014.003.
Shi, J., Z. Y. Chen, S. S. Ding and Y. Q. Lu, 2020: A Hot Blob Eastward of New Zealand in December 2019. *Atmosphere*, **11**(12), doi:10.3390/atmos11121267.
Shih, D. H., T. W. Wu, W. X. Liu and P. Y. Shih, 2019: An Azure ACES Early Warning System for Air Quality Index Deteriorating. *International Journal of Environmental Research and Public Health*, **16**(23), doi:10.3390/ijerph16234679.
Shindell, D., G. Faluvegi, K. Seltzer and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8**(4), 291-+, doi:10.1038/s41558-018-0108-y.
Shooshtarian, S., P. Rajagopalan and A. Sagoo, 2018: A comprehensive review of thermal adaptive strategies in outdoor spaces. *Sustainable Cities and Society*, **41**, 647-665, doi:10.1016/j.scs.2018.06.005.
Shrestha, N. et al., 2020: The impact of COVID-19 on globalization. *One Health*, 100180, doi:10.1016/j.onehlt.2020.100180.
Shultz, J., C. Fugate and S. Galea, 2020: Cascading Risks of COVID-19 Resurgence During an Active 2020 Atlantic Hurricane Season. *Jama-Journal of the American Medical Association*, **324**(10), 935-936, doi:10.1001/jama.2020.15398.
Shultz, J. M. et al., 2018a: Risks, Health Consequences, and Response Challenges for Small-Island-Based Populations: Observations From the 2017 Atlantic Hurricane Season. *Disaster Med. Public Health Prep.*, 1-13, doi:10.1017/dmp.2018.28.
Shultz, J. M., J. Russell and Z. Espinel, 2005: Epidemiology of tropical cyclones: the dynamics of disaster, disease, and development. *Epidemiol. Rev.*, **27**, 21-35, doi:10.1093/epirev/mxi011.
Shultz, J. M. et al., 2018b: Mitigating tropical cyclone risks and health consequences: urgencies and innovations. *Lancet Planet Health*, **2**(3), e103-e104, doi:10.1016/s2542-5196(18)30021-4.
Siddiqi, A., 2019: *In the Wake of Disaster: Islamists, the State and a Social Contract in Pakistan*. Cambridge University Press. ISBN 110859770X.
Siders, A. R., I. Ajibade and D. Casagrande, 2021: Transformative potential of managed retreat as climate adaptation. *Current Opinion in Environmental Sustainability*, 50, 272-280. Available at: https://www.sciencedirect.com/science/article/pii/S1877343521000798.
Sijbrandij, M. et al., 2020: The Effect of Psychological First Aid Training on Knowledge and Understanding about Psychosocial Support Principles: A Cluster-Randomized Controlled Trial. *International Journal of Environmental Research and Public Health*, **17**(2), doi:10.3390/ijerph17020484.
Silva, F. D., A. M. dos Santos, G. Correa Rda and J. Caldas Ade, 2016a: Temporal relationship between rainfall, temperature and occurrence of dengue cases in Sao Luis, Maranhao, Brazil. *Cien Saude Colet*, **21**(2), 641-646, doi:10.1590/1413-81232015212.09592015.
Silva, M., A. Loureiro and G. Cardoso, 2016b: Social determinants of mental health: a review of the evidence. *The European Journal of Psychiatry*, **30**(4), 259-292.
Silva, R. A. et al., 2016c: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmos. Chem. Phys.*, **16**(15), 9847-9862, doi:10.5194/acp-16-9847-2016.

Silva, R. A. et al., 2017: Future global mortality from changes in air pollution attributable to climate change. *Nat. Clim. Chang.*, **7**(9), 647-651, doi:10.1038/nclimate3354.
Silveira, I. H., T. R. Cortes, B. F. A. de Oliveira and W. L. Junger, 2021a: Projections of excess cardiovascular mortality related to temperature under different climate change scenarios and regionalized climate model simulations in Brazilian cities. *Environ Res*, **197**, 110995, doi:10.1016/j.envres.2021.110995.
Silveira, S. et al., 2021b: Chronic Mental Health Sequelae of Climate Change Extremes: A Case Study of the Deadliest Californian Wildfire. *Int J Environ Res Public Health*, **18**(4), doi:10.3390/ijerph18041487.
Singh, C., 2019: Migration as a driver of changing household structures: implications for local livelihoods and adaptation. *Migration and Development*, **8**(3), 301-319, doi:https://doi.org/10.1080/21632324.2019.1589073.
Singh, C. and R. Basu, 2020: Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural-urban continuum in India. *Geographical Journal*, **186**(1), doi:10.1111/geoj.12328.
Singh, P. K. and H. Chudasama, 2021: Pathways for climate resilient development: Human well-being within a safe and just space in the 21st century. *Global Environmental Change*, **68**, 102277.
Sioui, M., 2019: Drought in the Yucatan: Maya Perspectives on Tradition, Change, and Adaptation. In: *Drought Challenges: Policy Options for Developing Countries* [Mapedza, E., D. Tsegai, M. Bruntrup and R. McLeman (eds.)]. Elsevier.
Siraj, A. et al., 2014: Altitudinal Changes in Malaria Incidence in Highlands of Ethiopia and Colombia. *Science*, **343**(6175), 1154-1158, doi:10.1126/science.1244325.
Smith, A. et al., 2016: Health and environmental co-benefits and conflicts of actions to meet UK carbon targets. *Climate Policy*, **16**(3), 253-283, doi:10.1080/14693062.2014.980212.
Smith, B. A. and A. Fazil, 2019: How will climate change impact microbial foodborne disease in Canada? *Can Commun Dis Rep*, **45**(4), 108-113, doi:10.14745/ccdr.v45i04a05.
Smith, C., K. Dupre, A. McEvoy and S. Kenny, 2021: Community Perceptions and Pro-Environmental Behavior: The Mediating Roles of Social Norms and Climate Change Risk. *Canadian Journal of Behavioural Science-Revue Canadienne Des Sciences Du Comportement*, **53**(2), 200-210, doi:10.1037/cbs0000229.
Smith, J. et al., 2017: Malaria early warning tool: linking inter-annual climate and malaria variability in northern Guadalcanal, Solomon Islands. *Malaria journal*, **16**(1), 472, doi:10.1186/s12936-017-2120-5.
Smith, K. et al., 2014: Human Health: Impacts, Adaptation, and Co-Benefits. *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Pt a: Global and Sectoral Aspects*, 709-754.
Smith, M. R. and S. S. Myers, 2018: Impact of anthropogenic CO2 emissions on global human nutrition. *Nature Climate Change*, **8**(9), 834-839, doi:10.1038/s41558-018-0253-3.
Soebiyanto, R. P. et al., 2015: Associations between Meteorological Parameters and Influenza Activity in Berlin (Germany), Ljubljana (Slovenia), Castile and Leon (Spain) and Israeli Districts. *Plos One*, **10**(8), doi:10.1371/journal.pone.0134701.
Sohn, S. et al., 2019: 'Pneumonia Weather': Short-term Effects of Meteorological Factors on Emergency Room Visits Due to Pneumonia in Seoul, Korea. *Journal of preventive medicine and public health = Yebang Uihakhoe chi*, **52**(2), 82-91, doi:10.3961/jpmph.18.232.
Song, G. et al., 2017: Dietary changes to mitigate climate change and benefit public health in China. *Science of the Total Environment*, **577**, 289-298, doi:10.1016/j.scitotenv.2016.10.184.
Sorensen, C. et al., 2018: Climate Change and Women's Health: Impacts and Opportunities in India. *GeoHealth*, **2**(10).
Sorgho, R. et al., 2020: Climate Change Policies in 16 West African Countries: A Systematic Review of Adaptation with a Focus on Agriculture, Food Security, and Nutrition. *International Journal of Environmental Research and Public Health*, **17**(23), doi:10.3390/ijerph17238897.
Sovacool, B., D. Del Rio and S. Griffiths, 2020: Contextualizing the Covid-19 pandemic for a carbon-constrained world: Insights for sustainability transitions, energy justice, and research methodology. *Energy Research & Social Science*, **68**, doi:10.1016/j.erss.2020.101701.
Sovacool, B. K., 2018: Bamboo Beating Bandits: Conflict, Inequality, and Vulnerability in the Political Ecology of Climate Change Adaptation in Bangladesh. *World Development*, **102**, 183-194, doi:10.1016/j.worlddev.2017.10.014.
Sovacool, K., B. LinnEr and M. Goodsite, 2015: The political economy of climate adaptation. *Nature Climate Change*, **5**, 616-618.
Sow, P., E. Marmer and J. Scheffran, 2016: Between the heat and the hardships. Climate change and mixed migration flows in Morocco. *Migration and Development*, **5**(2), 293-313.
Speakman, J. R., 2018: Obesity and thermoregulation. *Thermoregulation: from Basic Neuroscience to Clinical Neurology, Pt I*, **156**, 431-443, doi:10.1016/b978-0-444-63912-7.00026-6.
Spearing, L. A. and F. K. M., 2020: Cascading system impacts of the 2018 Camp Fire in California: The interdependent provision of infrastructure services to displaced populations. *International Journal of Disaster Risk Reduction*, **50**, 101822, doi:https://doi.org/10.1016/j.ijdrr.2020.101822.
Spencer, N. and M. A. Urquhart, 2018: Hurricane Strikes and Migration: Evidence from Storms in Central America and the Caribbean. *Weather Climate and Society*, **10**(3), 569-577, doi:10.1175/wcas-d-17-0057.1.
Spentzou, E., M. J. Cook and S. Emmitt, 2021: Low-energy cooling and ventilation refurbishments for buildings in a Mediterranean climate. *Architectural Engineering and Design Management*, doi:10.1080/17452007.2021.1926898.

Spilker, G., Q. Nguyen, V. Koubi and T. Bohmelt, 2020: Attitudes of urban residents towards environmental migration in Kenya and Vietnam. *Nature Climate Change*, **10**(7), 622-627, doi:10.1038/s41558-020-0805-1.

Springmann, M. et al., 2018a: Options for keeping the food system within environmental limits. *Nature*, **562**(7728), 519-525, doi:10.1038/s41586-018-0594-0.

Springmann, M., H. C. J. Godfray, M. Rayner and P. Scarborough, 2016a: Analysis and valuation of the health and climate change cobenefits of dietary change. **113**(15), 4146-4151, doi:10.1073/pnas.1523119113 %J Proceedings of the National Academy of Sciences.

Springmann, M. et al., 2018b: Health-motivated taxes on red and processed meat: A modelling study on optimal tax levels and associated health impacts. *Plos One*, **13**(11), doi:10.1371/journal.pone.0204139.

Springmann, M. et al., 2016b: Global and regional health effects of future food production under climate change: a modelling study. *Lancet*, **387**(10031), 1937-1946, doi:10.1016/s0140-6736(15)01156-3.

Springmann, M. et al., 2020: The healthiness and sustainability of national and global food based dietary guidelines: modelling study. *Bmj-British Medical Journal*, **370**, doi:10.1136/bmj.m2322.

Springmann, M. et al., 2018c: Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *The Lancet Planetary Health*, **2**(10), e451-e461, doi:10.1016/s2542-5196(18)30206-7.

Squire, S. A. and U. Ryan, 2017: Cryptosporidium and Giardia in Africa: current and future challenges. *Parasit Vectors*, **10**(1), 195, doi:10.1186/s13071-017-2111-y.

SRCCL, I., 2019: Special Report on Climate Change and Land (SRCCL). Chapter 5 Food Security. Draft version.

Staddon, C. et al., 2020: Water insecurity compounds the global coronavirus crisis. *Water International*, **45**(5), 416-422, doi:10.1080/02508060.2020.1769345.

Steentjes, K. et al., 2017: *European Perceptions of Climate Change: Topline findings of a survey conducted in four European countries in 2016*. Cardiff University, Cardiff.

Steffen, W. et al., 2015: Planetary boundaries: Guiding human development on a changing planet. *Science*, **347**(6223), doi:10.1126/science.1259855.

Stensgaard, A. et al., 2013: Large-scale determinants of intestinal schistosomiasis and intermediate host snail distribution across Africa: does climate matter? *Acta Tropica*, **128**(2), 378-390, doi:10.1016/j.actatropica.2011.11.010.

Stevens, S. E. et al., 2019: - Precipitation and fatal motor vehicle crashes: continental analysis with high-resolution radar data.(- 2019).

Stewart-Sinclair, P. et al., 2020: Blue Restoration - Building Confidence and Overcoming Barriers. *Frontiers in Marine Science*, **7**, doi:10.3389/fmars.2020.541700.

Stewart, S., A. K. Keates, A. Redfern and J. J. V. McMurray, 2017: Seasonal variations in cardiovascular disease. *Nat Rev Cardiol*, **14**(11), 654-664, doi:10.1038/nrcardio.2017.76.

Stojanov, R. and Du, 2016: Local perceptions of climate change impacts and migration patterns in Mal \' e , Maldives. *The Geographical Journal*, **183**(4), 370--385.

Stork, A., C. Travis and S. Halle, 2015: Gender-Sensitivity in Natural Resource Management in Côte d'Ivoire and Sudan. *Peace Review*, **27**(2), 147-155, doi:10.1080/10402659.2015.1037617.

Subiros, M. et al., 2019: Health monitoring during water scarcity in Mayotte, France, 2017. *BMC Public Health*, **19**(1), 288, doi:10.1186/s12889-019-6613-8.

Suckall, N., E. Fraser and P. Forster, 2017: Reduced migration under climate change: evidence from Malawi using an aspirations and capabilities framework. *Climate and Development*, **9**(4), 298-312, doi:10.1080/17565529.2016.1149441.

Suk, J. E., E. C. Vaughan, R. G. Cook and J. C. Semenza, 2020: Natural disasters and infectious disease in Europe: a literature review to identify cascading risk pathways. *Eur J Public Health, 30(5), 928-935*, **30(5)**, 928-935, doi:https://doi.org/10.1093/eurpub/ckz111

Suliman, S. et al., 2019: Indigenous (im) mobilities in the Anthropocene. *Mobilities*, **14**(3), 298-318.

Sulser, T. B. et al., 2021: Disability-adjusted life years due to chronic and hidden hunger under food system evolution with climate change and adaptation to 2050. *American Journal of Clinical Nutrition*, **114**(2), 550-563, doi:10.1093/ajcn/nqab101.

Sultana, P. et al., 2019: Transforming local natural resource conflicts to cooperation in a changing climate: Bangladesh and Nepal lessons. *Climate Policy*, **19**(sup1), S94-S106.

Sun, S. et al., 2019: - Ambient temperature and markers of fetal growth: a retrospective observational study of 29 million US singleton births. **- 127**(- 6).

Sun, Z., C. Chen, D. Xu and T. Li, 2018: Effects of ambient temperature on myocardial infarction: A systematic review and meta-analysis. *Environ Pollut*, **241**, 1106-1114, doi:10.1016/j.envpol.2018.06.045.

Swinburn, B. A. et al., 2019: The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report. *The Lancet*, **393**(10173), 791-846, doi:10.1016/s0140-6736(18)32822-8.

Sylla, M. B. et al., 2018: Projected Heat Stress Under 1.5 degrees C and 2 degrees C Global Warming Scenarios Creates Unprecedented Discomfort for Humans in West Africa. *Earths Future*, **6**(7), 1029-1044, doi:10.1029/2018ef000873.

Tadgell, A., B. Doberstein and L. Mortsch, 2018: Principles for climate-related resettlement of informal settlements in less developed nations: a review of resettlement literature and institutional guidelines. *Climate and Development*, **10**(2), 102-115, doi:10.1080/17565529.2017.1291401.
Tadgell, A., M. Linda and D. Brent, 2017: Assessing the feasibility of resettlement as a climate change adaptation strategy for informal settlements in Metro Manila, Philippines. *International Journal of Disaster Risk Reduction*, **22**, 447--457, doi:https://doi.org/10.1016/j.ijdrr.2017.01.005.
Tainio, M. et al., 2017: Mortality, greenhouse gas emissions and consumer cost impacts of combined diet and physical activity scenarios: a health impact assessment study. *BMJ Open*, **7**(2), e014199, doi:10.1136/bmjopen-2016-014199.
Takebayashi, H., 2018: A Simple Method to Evaluate Adaptation Measures for Urban Heat Island. *Environments*, **5**(6), doi:10.3390/environments5060070.
Talhaoui, A. et al., 2019: Association between Malnutrition and Cognitive Impairment among Morocco's Older Adults. *Open Journal of Medical Psychology*, **8**(1), 1-14.
Talukder, M. R. R. et al., 2017: Drinking water salinity and risk of hypertension: A systematic review and meta-analysis. *Archives of Environmental & Occupational Health*, **72**(3), 126-138, doi:10.1080/19338244.2016.1175413.
Tamerius, J. D. et al., 2013: Environmental Predictors of Seasonal Influenza Epidemics across Temperate and Tropical Climates. *Plos Pathogens*, **9**(3), doi:10.1371/journal.ppat.1003194.
Tamnes, R. and K. Offerdal, 2014: *Geopolitics and Security in the Arctic: Regional dynamics in a global world*. Routledge. ISBN 1317801598.
Tänzler, D., N. Scherer and Adelphi, 2019: *Guidelines for conflict-sensitive adaptation to climate change* [Agency, G. E. (ed.)]. Dessau-Roßla.
Tayimlong, R. A., 2020: Fragility and Insurgency as Outcomes of Underdevelopment of Public Infrastructure and Socio-Economic Deprivation: The Case of Boko Haram in the Lake Chad Basin. *Journal of Peacebuilding & Development*, 1542316620950188.
Taylor, D. et al., 2016a: Environmental change and Rift Valley fever in eastern Africa: projecting beyond HEALTHY FUTURES. *Geospat Health*, **11**(1 Suppl), 387, doi:10.4081/gh.2016.387.
Taylor, L. et al., 2016b: The Impact of Different Environmental Conditions on Cognitive Function: A Focused Review. *Frontiers in Physiology*, **6**, doi:10.3389/fphys.2015.00372.
Taylor, R. G. et al., 2012: Ground water and climate change. *Nature Climate Change*, **3**, 322, doi:10.1038/nclimate1744.
Taylor, S., 2020: Anxiety disorders, climate change, and the challenges ahead: Introduction to the special issue. *Journal of Anxiety Disorders*, **76**.
Teixidor-Toneu, I. et al., 2021: Which plants matter? A comparison of academic and community assessments of plant value and conservation status in the Moroccan High Atlas. *Ambio*, doi:10.1007/s13280-021-01584-0.
Telford, A., 2018: A threat to climate-secure European futures? Exploring racial logics and climate-induced migration in US and EU climate security discourses. *Geoforum*, **96**, 268-277.
Tennison, I. et al., 2021: Health care's response to climate change: a carbon footprint assessment of the NHS in England. *Lancet Planetary Health*, **5**(2), E84-E92.
Terekhina, A. et al., 2021: The context of an emerging predation problem: Nenets reindeer herders and Arctic foxes in Yamal. *European Journal of Wildlife Research*, **67**(3), 13, doi:10.1007/s10344-021-01497-z.
Tesla, B. et al., 2018: Temperature drives Zika virus transmission: evidence from empirical and mathematical models. *Proceedings of the Royal Society B-Biological Sciences*, **285**(1884), doi:10.1098/rspb.2018.0795.
Thaker, J. et al., 2015: The Role of Collective Efficacy in Climate Change Adaptation in India. *Weather, Climate, and Society*, **8**(1), 21–34, doi:https://doi.org/10.1175/WCAS-D-14-00037.1.
Theisen, O. M., 2017: Climate change and violence: insights from political science. *Current Climate Change Reports*, **3**(4), 210-221.
Thema, J. et al., 2017: More than energy savings: quantifying the multiple impacts of energy efficiency in Europe, 1727–1736 pp.
Theobald, S. et al., 2018: Implementation research: new imperatives and opportunities in global health. *Lancet*, **392**(10160), 2214-2228, doi:10.1016/S0140-6736(18)32205-0.
Thiam, S. et al., 2017: Association between Childhood Diarrhoeal Incidence and Climatic Factors in Urban and Rural Settings in the Health District of Mbour, Senegal. *Int J Environ Res Public Health*, **14**(9), doi:10.3390/ijerph14091049.
Thiede, B. and C. Gray, 2020: Climate exposures and child undernutrition: Evidence from Indonesia. *Social Science & Medicine*, **265**, doi:10.1016/j.socscimed.2020.113298.
Thiery, W. et al., 2021: Age-dependent extreme event exposure. *Science*, **accepted**.
Thomas, A. et al., 2020: Climate Change and Small Island Developing States. *Annual Review of Environment and Resources*, **45**, 6.1-6.27.
Thomas, A. and L. Benjamin, 2020: Non-economic loss and damage: lessons from displacement in the Caribbean. *Climate Policy*, **20**(6), 715-728, doi:10.1080/14693062.2019.1640105.

Thompson, R., R. Hornigold, L. Page and T. Waite, 2018: Associations between high ambient temperatures and heat waves with mental health outcomes: a systematic review. *Public Health*, **161**, 171-191, doi:10.1016/j.puhe.2018.06.008.
Thornton, R. L. et al., 2016: Evaluating strategies for reducing health disparities by addressing the social determinants of health. *Health Affairs*, **35**(8), 1416-1423.
Tian, H. Y. et al., 2016: Surface water areas significantly impacted 2014 dengue outbreaks in Guangzhou, China. *Environmental Research*, **150**, 299-305, doi:10.1016/j.envres.2016.05.039.
Tian, Y. et al., 2019: Association between temperature variability and daily hospital admissions for cause-specific cardiovascular disease in urban China: A national time-series study. *PLOS Medicine*, **16**, e1002738, doi:10.1371/journal.pmed.1002738.
Tigchelaar, M., D. S. Battisti and J. T. Spector, 2020: Work adaptations insufficient to address growing heat risk for US agricultural workers. *Environmental Research Letters*, **15**(9), doi:10.1088/1748-9326/ab86f4.
Tiihonen, J. et al., 2017: The Association of Ambient Temperature and Violent Crime. *Scientific Reports*, **7**(1), 1-7, doi:10.1038/s41598-017-06720-z.
Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515**(7528), 518-522, doi:10.1038/nature13959 http://www.nature.com/nature/journal/v515/n7528/abs/nature13959.html#supplementary-information.
Timler, K. and D. Sandy, 2020: Gardening in Ashes: The Possibilities and Limitations of Gardening to Support Indigenous Health and Well-Being in the Context of Wildfires and Colonialism. *International Journal of Environmental Research and Public Health*, **17**(9), doi:10.3390/ijerph17093273.
Timlin, U. et al., 2021: Living conditions and mental wellness in a changing climate and environment: focus on community voices and perceived environmental and adaptation factors in Greenland. *Heliyon*, **7**(4), e06862, doi:10.1016/j.heliyon.2021.e06862.
Timmerman, J., 2020: Building resilience through transboundary water resources management. *The Palgrave Handbook of Climate Resilient Societies*, 1-19.
Timmerman, J. et al., 2017: Improving governance in transboundary cooperation in water and climate change adaptation. *Water policy*, **19**(6), 1014-1029.
Tirado, M. C., 2017: Sustainable Diets for Healthy People and a Healthy Planet. United Nations System Standing Committee on Nutrition. Discussion paper. Italy, Rome.
Todd, N. and A. J. Valleron, 2015: Space-Time Covariation of Mortality with Temperature: A Systematic Study of Deaths in France, 1968-2009. *Environmental Health Perspectives*, **123**(7), 659-664, doi:10.1289/ehp.1307771.
Tompkins, A. M. and L. Caporaso, 2016a: Assessment of malaria transmission changes in Africa, due to the climate impact of land use change using Coupled Model Intercomparison Project Phase 5 earth system models. *Geospat Health*, **11**(1 Suppl), 380, doi:10.4081/gh.2016.380.
Tompkins, A. M. and L. Caporaso, 2016b: Assessment of malaria transmission changes in Africa, due to the climate impact of land use change using Coupled Model Intercomparison Project Phase 5 earth system models. *Geospatial Health*, **11**, doi:10.4081/gh.2016.380.
Tong, S. et al., 2016: Climate change, food, water and population health in China. *Bulletin of the World Health Organization*, **94**(10), 759-765, doi:10.2471/blt.15.167031.
Torres, J. M. and J. A. Casey, 2017: The centrality of social ties to climate migration and mental health. *BMC Public Health*, **17**, 600-600, doi:10.1186/s12889-017-4508-0.
Tosun, J., A. Jordan and M. Maor, 2017: Governing climate change: the (dis)proportionality of policy responses. *Journal of Environmental Policy & Planning*, **19**(6), 596-598, doi:10.1080/1523908x.2017.1354451.
Tozier de la Poterie, A. et al., 2020: Managing Multiple Hazards: Lessons from Anticipatory Humanitarian Action for Climate Disasters during COVID-19. *Climate and Development*.
Trewin, B. J. et al., 2020: Urban Landscape Features Influence the Movement and Distribution of the Australian Container-Inhabiting Mosquito Vectors Aedes aegypti (Diptera: Culicidae) and Aedes notoscriptus (Diptera: Culicidae). *Journal of Medical Entomology*, **57**(2), 443-453, doi:10.1093/jme/tjz187.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *WIREs Climate Change*, **8**(5), e476-e476.
Tschakert, P. et al., 2019: One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change-Human and Policy Dimensions*, **55**, 58-72, doi:10.1016/j.gloenvcha.2018.11.006.
Tshimanga, R. M. et al., 2021: An Integrated Information System of Climate-Water-Migrations-Conflicts Nexus in the Congo Basin. *Sustainability*, **13**(16), 9323.
Turco, M., N. Levin, N. Tessler and H. Saaroni, 2017: Recent changes and relations among drought, vegetation and wildfires in the Eastern Mediterranean: The case of Israel. *Global and Planetary Change*, **151**, 28-35.
Turek-Hankins, L. L. et al., 2021: Climate change adaptation to extreme heat: a global systematic review of implemented action. *Oxford Open Climate Change*, **1**(1), 13, doi:https://doi.org/10.1093/oxfclm/kgab005.
Turner, N. and K. Turner, 2008: "Where our women used to get the food": Cumulative effects and loss of ethnobotanical knowledge and practice; case study from coastal British Columbia. *Botany*, **86**.
Uboni, A., B. Ahman and J. Moen, 2020: Can management buffer pasture loss and fragmentation for Sami reindeer herding in Sweden? *Pastoralism-Research Policy and Practice*, **10**(1), doi:10.1186/s13570-020-00177-y.

Udas, B. et al., 2019: Basin level gendered vulnerabilities and adaptation: A case of Gandaki River Basin. *Environmental Development*, **31**, 43-54.
Ulpiani, G., 2019: Water mist spray for outdoor cooling: A systematic review of technologies, methods and impacts. *Applied Energy*, **254**, doi:10.1016/j.apenergy.2019.113647.
UNEP, 2014: *The Adaptation Gap Report 2014.* . United Nations Environment Programme (UNEP).
UNEP, 2018: *The Adaptation Gap Report 2018*. United Nations Environment Programme (UNEP), Nairobi, Kenya. ISBN 978-92-807-3728-8.
UNEP, 2021: *Adaptation Gap Report*. Nairobi. Available at: https://www.unep.org/resources/adaptation-gap-report-2020.
UNFCCC, 2017a: Human health and adaptation: understanding climate impacts on health and opportunities for action synthesis paper by the secretariat. In: *Nairobi work programme on impacts, vulnerability and adaptation to climate change*, March 3, Bonn, Subsidiary Body for Scientific and Technological Advice.
UNFCCC, 2017b: Opportunities and options for integrating climate change adaptation with the Sustainable Development Goals and the Sendai Framework for Disaster Risk Reduction 2015–2030 Technical paper by the secretariat.
UNICEF, 2021: The Climate Crisis is a Child Rights Crisis: Introducing the Children's Climate Risk Index, New York.
UNICEF/WHO/WBG, 2019: United Nations Children's Fund (UNICEF), World Health Organization, International Bank for Reconstruction and Development/The World Bank. Levels and trends in child malnutrition: key findings of the 2019 Edition Joint Child Malnutrition Estimates. Geneva: World Health Organization, Geneva.
Ürge-Vorsatz, D., T. Herrero, K. Dubash and F. Lecocq, 2014: Measuring the Co-Benefits of Climate Change Mitigation. *Annual Review of Environment and Resources*, **39**(6), 549-582, doi:https://doi.org/10.1146/annurev-environ-031312-125456.
Ürge-Vorsatz, D. et al., 2016: Measuring multiple impacts of low-carbon energy options in a green economy context. *Applied Energy*, **179**, 1409-1426, doi:10.1016/j.apenergy.2016.07.027.
USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC. Available at: http://dx.doi.org/10.7930/J0R49NQX.
Vahmani, P., A. D. Jones and C. M. Patricola, 2019: Interacting implications of climate change, population dynamics, and urban heat mitigation for future exposure to heat extremes. *Environmental Research Letters*, **14**(8), doi:10.1088/1748-9326/ab28b0.
van den Hurk, B. et al., 2020: What can COVID-19 teach us about preparing for climate risks in Europe?, 17 pp.
van der Geest, K. et al., 2020: Climate change, ecosystem services and migration in the Marshall Islands: are they related? *Climatic Change*, **16**(1), 109-127.
van der Linden, S., 2015: The social-psychological determinants of climate change risk perceptions: Towards a comprehensive model. *Journal of Environmental Psychology*, **41**, 112-124, doi:10.1016/j.jenvp.2014.11.012.
van Dijk, M., T. Morley, M. L. Rau and Y. Saghai, 2021: A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, **2**(7), 494-501, doi:https://doi.org/10.1038/s43016-021-00322-9.
van Loenhout, J. A. F. et al., 2018: Heat and emergency room admissions in the Netherlands. *BMC Public Health*, **18**(1), 108, doi:10.1186/s12889-017-5021-1.
van Valkengoed, A. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour *Nature Climate Change, 9(2), 158-+. https://doi.org/10.1038/s41558-018-0371-y*, **9(2), 158-+. https://doi.org/10.1038/s41558-018-0371-y**, 158-+, doi:https://doi.org/10.1038/s41558-018-0371-y.
van Weezel, S., 2019: On climate and conflict: Precipitation decline and communal conflict in Ethiopia and Kenya. *Journal of Peace Research*, **56**(4), 514-528.
Vandyck, T. et al., 2018: Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nat. Commun.*, **9**(1), 4939, doi:10.1038/s41467-018-06885-9.
Vanos, J., D. J. Vecellio and T. Kjellstrom, 2019: Workplace heat exposure, health protection, and economic impacts: A case study in Canada. *American Journal of Industrial Medicine*, **62**(12), 1024-1037, doi:10.1002/ajim.22966.
Vardoulakis, S. et al., 2014: Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. *Environmental health perspectives*, **122**(12), 1285-1292, doi:10.1289/ehp.1307524.
Varghese, B. M. et al., 2019: - The effects of ambient temperatures on the risk of work-related injuries and illnesses: Evidence from Adelaide, Australia 2003–2013. **- 170**.
Varghese, B. M. et al., 2020: Heat-related injuries in Australian workplaces: Perspectives from health and safety representatives. *Safety Science*, **126**, doi:10.1016/j.ssci.2020.104651.
Varotsos, K. V., C. Giannakopoulos and M. Tombrou, 2019: Ozone-temperature relationship during the 2003 and 2014 heatwaves in Europe. *Regional Environmental Change*, **19**(6), 1653-1665, doi:10.1007/s10113-019-01498-4.
Varquez, A. C. G. et al., 2020: Future increase in elderly heat-related mortality of a rapidly growing Asian megacity. *Scientific Reports*, **10**(1), doi:10.1038/s41598-020-66288-z.
Vautard, R. et al., 2020: Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe. *Environmental Research Letters*, **15**(9), doi:10.1088/1748-9326/aba3d4.
Velez-Valle, E. M., S. Echeverria and M. Santorelli, 2016: Type II Diabetes Emergency Room Visits Associated With Hurricane Sandy in New Jersey: Implications for Preparedness. *Journal of environmental health*, **79**(2), 30-37.

Venugopal, R. and S. Yasir, 2017: The politics of natural disasters in protracted conflict: the 2014 flood in Kashmir. *Oxford Development Studies*, **45**(4), 424-442.
Venugopal, V. et al., 2021: Epidemiological evidence from south Indian working population-the heat exposures and health linkage. *Journal of Exposure Science and Environmental Epidemiology*, **31**(1), 177-186, doi:10.1038/s41370-020-00261-w.
Verhaeghe, C., E. Feltes and J. Stacey, 2017: Nagmwedizk'an Gwanes Gangu Ch'inidzed Ganexwilagh: The Fires Awakened Us. Tsilhqot'in National Government, Williams Lake, BC, Canada.
Veronis, L., B. Boyd, R. Obokata and B. Main, 2018: Environmental change and international migration: A review. In: *Routledge Handbook of Environmental Displacement and Migration* [McLeman, R. and F. Gemenne (eds.)].
Veronis, L. and R. McLeman, 2014: Environmental influences on African migration to Canada: focus group findings from Ottawa-Gatineau. *Population and Environment*, **36**(2), 234-251, doi:10.1007/s11111-014-0214-3.
Vestby, J., 2019: Climate variability and individual motivations for participating in political violence. *Global Environmental Change*, **56**, 114-123.
Vicedo-Cabrera, A. M. et al., 2018a: Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. *Climatic Change*, **150**(3-4), 391-402, doi:10.1007/s10584-018-2274-3.
Vicedo-Cabrera, A. M. et al., 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11**(6), 492-+, doi:10.1038/s41558-021-01058-x.
Vicedo-Cabrera, A. M. et al., 2018b: A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. *Environment International*, **111**, 239-246, doi:10.1016/j.envint.2017.11.006.
Vidal, R. et al., 2014: Comparison of the carbon footprint of different patient diets in a Spanish hospital. *Journal of health services research & policy*, **20**, doi:10.1177/1355819614553017.
Vik, M. H. and E. Carlquist, 2018: Measuring subjective well-being for policy purposes: The example of well-being indicators in the WHO "Health 2020" framework. *Scandinavian Journal of Public Health*, **46**(2), 279-286, doi:10.1177/1403494817724952.
Vinke, K. et al., 2017: Climatic risks and impacts in South Asia: extremes of water scarcity and excess. *Regional Environmental Change*, **17**(6), 1569-1583.
Vins, H., J. Bell, S. Saha and J. J. Hess, 2015: The Mental Health Outcomes of Drought: A Systematic Review and Causal Process Diagram. *International Journal of Environmental Research and Public Health*, **12**(10), 13251-13275, doi:10.3390/ijerph121013251.
Viswanathan, B. and K. Kumar, 2015: Weather, agriculture and rural migration: evidence from state and district level migration in India. *Environment and Development Economics*, **20**(4), 469-492, doi:10.1017/s1355770x1500008x.
Vlaskamp, D. et al., 2020: First autochthonous human West Nile virus infections in the Netherlands, July to August 2020. *Eurosurveillance*, **25**(46), doi:10.2807/1560-7917.Es.2020.25.46.2001904.
von Schneidemesser, E., C. Driscoll, H. E. Rieder and L. D. Schiferl, 2020: How will air quality effects on human health, crops and ecosystems change in the future? . *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **378(2183), Article 20190330** doi:https://doi.org/10.1098/rsta.2019.0330.
von Uexkull, N. and H. Buhaug, 2021: Security implications of climate change: A decade of scientific progress. *Journal of Peace Research*, **58**(1), 3-17, doi:10.1177/0022343320984210.
Von Uexkull, N., M. Croicu, H. Fjelde and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proceedings of the National Academy of Sciences*, **113**(44), 12391-12396.
Voordeckers, D. et al., 2021: Guidelines for passive control of traffic-related air pollution in street canyons: An overview for urban planning. *Landscape and Urban Planning*, **207**, doi:10.1016/j.landurbplan.2020.103980.
Vos, T. et al., 2020: - Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. **- 396**(- 10258).
Vratnica, Z. et al., 2017: Haemorrhagic fever with renal syndrome in Montenegro, 2004-14. *Eur J Public Health*, **27**(6), 1108-1110, doi:10.1093/eurpub/ckx149.
Waha, K. et al., 2017: Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. *Regional Environmental Change*, **17**(6), 1623-1638.
Waite, T. D. et al., 2017: The English national cohort study of flooding and health: cross-sectional analysis of mental health outcomes at year one. *Bmc Public Health*, **17**, doi:10.1186/s12889-016-4000-2.
Walch, C., 2018: Disaster risk reduction amidst armed conflict: informal institutions, rebel groups, and wartime political orders. *Disasters*, **42**, S239-S264, doi:10.1111/disa.12309.
Walkepää, A., 2019: Syntesrapport - En sammanställning av fyra samebyars pilotprojekt med klimat- och sårbarhetsanalys samt handlingsplan för klimatanpassning. (In English: Synthesis report - A compilation of four Sami villages' pilot projects with climate and vulnerability analysis and an action plan for climate adaptation) Uppdragsnummer 12602183.
Wallace, L. M. et al., 2015: Social vulnerability as a predictor of mortality and disability: cross-country differences in the survey of health, aging, and retirement in Europe (SHARE). *Aging clinical and experimental research*, **27**(3), 365-372.
Walton, D. and M. K. van Aalst, 2020: Climate-related extreme weather events and COVID-19: A first look at the number of people affected by intersecting disasters. IFRC, Geneva, 21 pp.

Wang, H. et al., 2017a: Global, regional, and national under-5 mortality, adult mortality, age-specific mortality, and life expectancy, 1970–2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet*, **390**(10100), 1084-1150, doi:https://doi.org/10.1016/S0140-6736(17)31833-0.
Wang, H. et al., 2020a: Global age-sex-specific fertility, mortality, healthy life expectancy (HALE), and population estimates in 204 countries and territories, 1950–2019: a comprehensive demographic analysis for the Global Burden of Disease Study 2019. **396**(10258), 1160-1203, doi:https://doi.org/10.1016/S0140-6736(20)30977-6.
Wang, J., N. Obradovich and S. Zheng, 2020b: A 43-million person investigation into weather extremes and expressed sentiment under climate change. *One Earth*, **2**(6).
Wang, P., W. B. Goggins and E. Y. Y. Chan, 2018a: Associations of Salmonella hospitalizations with ambient temperature, humidity and rainfall in Hong Kong. *Environ Int*, **120**, 223-230, doi:10.1016/j.envint.2018.08.014.
Wang, Q. et al., 2017b: Environmental ambient temperature and blood pressure in adults: A systematic review and meta-analysis. *Science of The Total Environment*, **575**, 276-286, doi:https://doi.org/10.1016/j.scitotenv.2016.10.019.
Wang, X. et al., 2016: Ambient Temperature and Stroke Occurrence: A Systematic Review and Meta-Analysis. *Int J Environ Res Public Health*, **13**(7), doi:10.3390/ijerph13070698.
Wang, X., E. Lavigne, H. Ouellette-kuntz and B. Chen, 2014: Acute impacts of extreme temperature exposure on emergency room admissions related to mental and behavior disorders in Toronto, Canada. *Journal of Affective Disorders*, **155**, 154-161, doi:10.1016/j.jad.2013.10.042.
Wang, X. et al., 2020c: Global burden of respiratory infections associated with seasonal influenza in children under 5 years in 2018: a systematic review and modelling study. *Lancet Global Health*, **8**(4), E497-E510, doi:10.1016/s2214-109x(19)30545-5.
Wang, X. L. et al., 2017c: Different responses of influenza epidemic to weather factors among Shanghai, Hong Kong, and British Columbia. *International Journal of Biometeorology*, **61**(6), 1043-1053, doi:10.1007/s00484-016-1284-y.
Wang, Y. et al., 2018b: Accounting for adaptation and intensity in projecting heat wave-related mortality. *Environmental Research*, **161**, 464-471, doi:10.1016/j.envres.2017.11.049.
Wang, Z., Z. Han, L. Liu and S. Yu, 2021: Place Attachment and Household Disaster Preparedness: Examining the Mediation Role of Self-Efficacy. *International Journal of Environmental Research and Public Health*, **18**(11), doi:10.3390/ijerph18115565.
Wangdi, K., A. C. A. Clements, T. Du and S. V. Nery, 2018: Spatial and temporal patterns of dengue infections in Timor-Leste, 2005-2013. *Parasit Vectors*, **11**(1), 9, doi:10.1186/s13071-017-2588-4.
Warner, K., 2018: Coordinated approaches to large-scale movements of people: contributions of the Paris Agreement and the Global Compacts for migration and on refugees. *Population and Environment*, **39**(4), 384-401, doi:10.1007/s11111-018-0299-1.
Watson, C. R., W. Matthew and S. T. Kirk, 2017: Public Health Preparedness Funding: Key Programs and Trends From 2001 to 2017. *American Journal of Public Health*, **107**(S2), S165--S167, doi:10.2105/ajph.2017.303963.
Watts, N. et al., 2017: The Lancet Countdown: tracking progress on health and climate change. *Lancet*, **389**(10074), 1151-1164, doi:10.1016/s0140-6736(16)32124-9.
Watts, N. et al., 2015: Health and climate change: policy responses to protect public health. *Lancet*, **386**(10006), 1861-1914, doi:10.1016/s0140-6736(15)60854-6.
Watts, N. et al., 2021: The 2020 report of the Lancet Countdown on health and climate change: responding to converging crises. *Lancet*, **397**(10269), 129-170, doi:10.1016/s0140-6736(20)32290-x.
Watts, N. et al., 2018a: The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come. *The Lancet*, **392**(10163), 2479-2514.
Watts, N. et al., 2019: The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *Lancet*, **394**(10211), 1836-1878, doi:10.1016/s0140-6736(19)32596-6.
Watts, N. et al., 2018b: The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health (vol 391, pg 581, 2017). *Lancet*, **391**(10120), 540-540.
Weber, E., 2017: Trade agreements, labour mobility and climate change in the Pacific Islands. *Regional Environmental Change*, **17**, 1089--1101.
Weber, T. et al., 2020: Analysis of Compound Climate Extremes and Exposed Population in Africa Under Two Different Emission Scenarios. *Earths Future*, **8**(9), doi:10.1029/2019ef001473.
Weible, C. et al., 2020: COVID-19 and the policy sciences: initial reactions and perspectives. *Policy Sciences*, **53**(2), 225-241, doi:10.1007/s11077-020-09381-4.
Weiler, F., 2019: Adaptation and Health: Are Countries with More Climate-Sensitive Health Sectors More Likely to Receive Adaptation Aid? *International Journal of Environmental Research and Public Health*, **16**(8), doi:10.3390/ijerph16081353.
Weinberger, K. R. et al., 2017: Projected temperature-related deaths in ten large U.S. metropolitan areas under different climate change scenarios. *Environment International*, **107**, 196-204, doi:https://doi.org/10.1016/j.envint.2017.07.006.
Weinberger, K. R. et al., 2018a: Projected Changes in Temperature-related Morbidity and Mortality in Southern New England. *Epidemiology*, **29**(4), 473-481, doi:10.1097/ede.0000000000000825.

Weinberger, K. R., A. Zanobetti, J. Schwartz and G. A. Wellenius, 2018b: Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities. *Environment International*, **116**, 30-38, doi:10.1016/j.envint.2018.03.028.
Weisent, J., W. Seaver, A. Odoi and B. Rohrbach, 2014: The importance of climatic factors and outliers in predicting regional monthly campylobacteriosis risk in Georgia, USA. *Int J Biometeorol*, **58**(9), 1865-1878, doi:10.1007/s00484-014-0788-6.
Weitensfelder, L. and H. Moshammer, 2020: Evidence of Adaptation to Increasing Temperatures. *International Journal of Environmental Research and Public Health*, **17**(1), doi:10.3390/ijerph17010097.
Wells, M. L. et al., 2020: Future HAB science: Directions and challenges in a changing climate. *Harmful Algae*, **91**, 101632, doi:https://doi.org/10.1016/j.hal.2019.101632.
Wells, M. L. et al., 2015: Harmful algal blooms and climate change: Learning from the past and present to forecast the future. *Harmful Algae*, **49**, 68-93, doi:10.1016/j.hal.2015.07.009.
Weyant, C. et al., 2018: Anticipated burden and mitigation of carbon-dioxide-induced nutritional deficiencies and related diseases: A simulation modeling study. *PLoS Med.*, **15**(7), e1002586, doi:10.1371/journal.pmed.1002586.
Whaley, A. L., 2009: Trauma Among Survivors of Hurricane Katrina: Considerations and Recommendations for Mental Health Care. *J. Loss Trauma*, **14**(6), 459-476, doi:10.1080/15325020902925480.
Wheeler, N. and N. Watts, 2018: Climate Change: From Science to Practice. *Curr Environ Health Rep*, **5**(1), 170-178, doi:10.1007/s40572-018-0187-y.
Whitmee, S. et al., 2015: Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation-Lancet Commission on planetary health. *Lancet*, **386**(10007), 1973-2028, doi:10.1016/s0140-6736(15)60901-1.
WHO, 2013: Protecting health from climate change: vulnerability and adaptation assessment.
WHO, 2014: Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. WHO. Geneva.
WHO, 2015a: CLIMATE AND HEALTH COUNTRY PROFILES - 2015 A GLOBAL OVERVIEW, Geneva, Switzerland, 24 pp.
WHO, 2015b: *Operational framework for building climate resilient health systems*. World Health Organization, Geneva, Switzerland.
WHO, 2015c: Reducing global health risks through mitigation of short lived climate pollutants, 1-121 pp.
WHO, 2018: WHO estimates of the global burden of foodborne diseases, World Health Organization. Available at: http://www.who.int/foodsafety/publications/foodborne_disease/fergreport/en/.
WHO, 2016a: Chapter 6 Sustainable Development Goals Health and Health Related Targets.
WHO, WHO household energy database. Available at: https://www.who.int/airpollution/data/household-energy-database/en/.
WHO, 2019: WHO Health and Climate Change Survey Report: Tracking Global Progess. World Health Organization, Geneva.
WHO, 2020a: WHO guidance for climate resilient and environmentally sustainable health care facilities. World Health Organization, Geneva.
WHO, 2020b: *WHO Manifesto for a Healthy Recovery from COVID-19: Prescriptions and Actionables for a Healthy and Green Recovery* [Who (ed.)]. 26 pp. Available at: https://www.who.int/publications/i/item/who-manifesto-healthy-recovery-covid19.
WHO, 2021a: Stronger collaboration for an equitable and resilient recovery towards the health-related sustainable development goals: 2021 progress report on the global action plan for healthy lives and well-being for all, Geneva.
WHO, 2021b: Universal health coverage (UHC).
WHO, 2021c: World health statistics 2021: monitoring health for the SDGs, sustainable development goals, Geneva.
Whyte, K., 2018: Critical Investigations of Resilience: A Brief Introduction to Indigenous Environmental Studies & Sciences. *Daedalus*, **147**(2), 136-147, doi:10.1162/DAED_a_00497.
Wickramage, K. et al., 2018: Migration and health: a global public health research priority. *Bmc Public Health*, **18**, doi:10.1186/s12889-018-5932-5.
Wiederkehr, C., M. Beckmann and K. Hermans, 2018: Environmental change, adaptation strategies and the relevance of migration in Sub-Saharan drylands. *Environmental Research Letters*, **13**(11).
Wiegel, H., I. Boas and J. Warner, 2019: A mobilities perspective on migration in the context of environmental change. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(6), e610.
Wilder, J. et al., 2017: Polar Bear Attacks on Humans: Implications of a Changing Climate. *Wildlife Society Bulletin*, **41**(3), 537-547, doi:10.1002/wsb.783.
Willett, W. et al., 2019: Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet*, **393**(10170), 447-492, doi:10.1016/s0140-6736(18)31788-4.
Willi, Y., G. Nischik, D. Braunschweiger and M. Putz, 2020: Responding to the COVID-19 Crisis: Transformative Governance in Switzerland. *Tijdschrift Voor Economische En Sociale Geografie*, **111**(3), 302-317, doi:10.1111/tesg.12439.
Williams, L., 2018: Climate change, colonialism, and women's well-being in Canada: what is to be done? *Canadian Journal of Public Health-Revue Canadienne De Sante Publique*, **109**(2), 268-271, doi:10.17269/s41997-018-0031-z.

Williams, M. L. et al., 2018: The Lancet Countdown on health benefits from the UK Climate Change Act: a modelling study for Great Britain. *Lancet Planet Health*, **2**(5), e202-e213, doi:10.1016/s2542-5196(18)30067-6.
Williams, M. N., S. R. Hill and J. Spicer, 2015a: Will Climate Change Increase or Decrease Suicide Rates? The Differing Effects of Geographical, Seasonal, and Irregular Variation in Temperature on Suicide Incidence. Springer, Netherlands, 1–10 pp.
Williams, M. S. et al., 2015b: Temporal patterns of Campylobacter contamination on chicken and their relationship to campylobacteriosis cases in the United States. *Int J Food Microbiol*, **208**, 114-121, doi:10.1016/j.ijfoodmicro.2015.05.018.
Williams, S. et al., 2020: Workers' health and safety in the heat: current practice in Australian workplaces. *Policy and Practice in Health and Safety*, **18**(2), 67-79, doi:10.1080/14773996.2020.1765610.
Williamson, C. et al., 2017: Climate change-induced increases in precipitation are reducing the potential for solar ultraviolet radiation to inactivate pathogens in surface waters. *Scientific Reports*, **7**, doi:10.1038/s41598-017-13392-2.
Wilmsen, B. and M. Webber, 2015: What can we learn from the practice of development-forced displacement and resettlement for organised resettlements in response to climate change? *Geoforum*, **58**, 76-85.
Winkler, R. L. and R. M. D., 2021: Amenities or disamenities? Estimating the impacts of extreme heat and wildfire on domestic US migration. *Population and Environment*, **42**(4), 622--648, doi:10.1007/s11111-020-00364-4.
Winne, J. D. and G. Peersman, 2019: The impact of food prices on conflict revisited. *Journal of Business & Economic Statistics*, 1-14.
Winsemius, H. et al., 2018: Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, **23**(3), 328-348, doi:10.1017/s1355770x17000444.
Wischnath, G. and H. Buhaug, 2014: Rice or riots: On food production and conflict severity across India. *Political Geography*, **43**, 6-15, doi:10.1016/j.polgeo.2014.07.004.
Witmer, F. D. et al., 2017: Subnational violent conflict forecasts for sub-Saharan Africa, 2015–65, using climate-sensitive models. *Journal of Peace Research*, **54**(2), 175-192.
Witt, C. et al., 2015: The Effects of Climate Change on Patients With Chronic Lung Disease. *Deutsches Aerzteblatt Online*, doi:10.3238/arztebl.2015.0878.
Wondmagegn, B. et al., 2019: What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. *Science of the Total Environment*, **657**, 608-618, doi:10.1016/j.scitotenv.2018.11.479.
Wood, R. M. and T. M. Wright, 2016: Responding to catastrophe: Repression dynamics following rapid-onset natural disasters. *Journal of Conflict Resolution*, **60**(8), 1446-1472.
Woodcock, J. et al., 2018: Development of the Impacts of Cycling Tool (ICT): A modelling study and web tool for evaluating health and environmental impacts of cycling uptake. *PLoS Med.*, **15**(7), e1002622, doi:10.1371/journal.pmed.1002622.
Woodward, A. et al., 2019: Population health impacts of China's climate change policies. *Environmental Research*, **175**, 178-185, doi:https://doi.org/10.1016/j.envres.2019.05.020.
Woodward, A. J. and J. M. Samet, 2018: Climate Change, Hurricanes, and Health. *American Journal of Public Health*, **108**(1), 33-35, doi:10.2105/ajph.2017.304197.
Wouters, H. et al., 2017: Heat stress increase under climate change twice as large in cities as in rural areas: A study for a densely populated midlatitude maritime region. *Geophysical Research Letters*, **44**(17), 8997-9007, doi:10.1002/2017gl074889.
Wrathall, D. and N. Suckall, 2016: Labour migration amidst ecological change. *Migration and Development*, **5**(2), 314-329.
Wright, C. et al., 2021: A Transdisciplinary Approach to Address Climate Change Adaptation for Human Health and Well-Being in Africa. *International Journal of Environmental Research and Public Health*, **18**(8), doi:10.3390/ijerph18084258.
Wright, N. et al., 2020: Health Emergency and Disaster Risk Management: Five Years into Implementation of the Sendai Framework. *International Journal of Disaster Risk Science*, **11**(2), 206--217, doi:10.1007/s13753-020-00274-x.
Wu, F. et al., 2011: Climate change impacts on mycotoxin risks in US maize. *World Mycotoxin J.*, **4**(1), 79-93, doi:10.3920/wmj2010.1246.
Wu, J., M. Yunus, P. K. Streatfield and M. Emch, 2014: Association of climate variability and childhood diarrhoeal disease in rural Bangladesh, 2000-2006. *Epidemiol Infect*, **142**(9), 1859-1868, doi:10.1017/s095026881300277x.
Xiang, J. et al., 2018: Impact of meteorological factors on hemorrhagic fever with renal syndrome in 19 cities in China, 2005-2014. *Sci Total Environ*, **636**, 1249-1256, doi:10.1016/j.scitotenv.2018.04.407.
Xiang, J. J., P. Bi, D. Pisaniello and A. Hansen, 2014: Health Impacts of Workplace Heat Exposure: An Epidemiological Review. *Industrial Health*, **52**(2), 91-101, doi:10.2486/indhealth.2012-0145.
Xiao, H. et al., 2014: Animal reservoir, natural and socioeconomic variations and the transmission of hemorrhagic fever with renal syndrome in Chenzhou, China, 2006-2010. *PLoS Negl Trop Dis*, **8**(1), e2615, doi:10.1371/journal.pntd.0002615.
Xie, Y. et al., 2018: Co-benefits of climate mitigation on air quality and human health in Asian countries. *Environment International*, **119**, 309-318, doi:https://doi.org/10.1016/j.envint.2018.07.008.

Xiong, J. et al., 2020: Impact of COVID-19 pandemic on mental health in the general population: A systematic review. *Journal of Affective Disorders*, **277**, 55-64, doi:10.1016/j.jad.2020.08.001.
Xu, C. et al., 2020: Future of the human climate niche. *Proceedings of the National Academy of Sciences*, **117**, 201910114, doi:10.1073/pnas.1910114117.
Xu, Y. Z., W. D. Yang and J. Z. Wang, 2017: Air quality early-warning system for cities in China. *Atmospheric Environment*, **148**, 239-257, doi:10.1016/j.atmosenv.2016.10.046.
Xu, Z. et al., 2019a: Spatiotemporal patterns and climatic drivers of severe dengue in Thailand. *Sci Total Environ*, **656**, 889-901, doi:10.1016/j.scitotenv.2018.11.395.
Xu, Z. et al., 2014: The impact of heat waves on children's health: a systematic review. *Int. J. Biometeorol.*, **58**(2), 239-247, doi:10.1007/s00484-013-0655-x.
Xu, Z. et al., 2019b: Heatwaves and diabetes in Brisbane, Australia: a population-based retrospective cohort study. *International Journal of Epidemiology*, 48(4), 1091-1100.
Xuan le, T. T., P. Van Hau, T. Thu do and T. T. Toan do, 2014: Estimates of meteorological variability in association with dengue cases in a coastal city in northern Vietnam: an ecological study. *Glob Health Action*, **7**, 23119, doi:10.3402/gha.v7.23119.
Yactayo, S. et al., 2016: Epidemiology of Chikungunya in the Americas. *J Infect Dis*, **214**(suppl 5), S441-S445, doi:10.1093/infdis/jiw390.
Yamana, T. K., A. Bomblies and E. A. B. Eltahir, 2016: Climate change unlikely to increase malaria burden in West Africa. *Nature Climate Change*, **6**, 1009-1013.
Yan, X. et al., 2018: Effects of early-life malnutrition on neurodevelopment and neuropsychiatric disorders and the potential mechanisms. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, **83**, 64-75.
Yang, G. and R. Bergquist, 2018: Potential Impact of Climate Change on Schistosomiasis: A Global Assessment Attempt. *Tropical Medicine and Infectious Disease*, **3**(4), doi:10.3390/tropicalmed3040117.
Yang, J. et al., 2019: Heatwave and mortality in 31 major Chinese cities: Definition, vulnerability and implications. *Sci Total Environ*, **649**, 695-702, doi:10.1016/j.scitotenv.2018.08.332.
Yang, J. et al., 2016: The effect of ambient temperature on diabetes mortality in China: A multi-city time series study. *Sci Total Environ*, **543**(Pt A), 75-82, doi:10.1016/j.scitotenv.2015.11.014.
Yang, J. et al., 2021: Projecting heat-related excess mortality under climate change scenarios in China. *Nature Communications*, **12**(1), doi:10.1038/s41467-021-21305-1.
Yang, Z. and J. Wang, 2017: A new air quality monitoring and early warning system: Air quality assessment and air pollutant concentration prediction. *Environmental Research*, **158**, 105-117, doi:10.1016/j.envres.2017.06.002.
Yasjukevich, V. V., I. O. Popov, S. N. Titkina and N. V. Yasjukevich, 2018: The vulnerability of Subjects of the Russian Federation in Relation to the Distribution of the Main Vectors of Ixodes Tick-Borne Borelliosis and Tick-Borne Encephalitis in the Expected Climate Change. *Problems of Ecological Monitoring and Ecosystem Modelling*, **xix**(4), 8-28.
Yeargin, S. W. et al., 2019: Epidemiology of Exertional Heat Illnesses in National Collegiate Athletic Association Athletes During the 2009-2010 Through 2014-2015 Academic Years. *Journal of Athletic Training*, **54**(1), 55-63, doi:10.4085/1062-6050-504-17.
Yeni, F. and H. Alpas, 2017: Vulnerability of global food production to extreme climatic events. *Food Res Int*, **96**, 27-39, doi:10.1016/j.foodres.2017.03.020.
Yin, Q. et al., 2019: Mapping the increased minimum mortality temperatures in the context of global climate change. *Nature Communications*, **10**, doi:10.1038/s41467-019-12663-y.
Yoo, E. H. et al., 2021: Association between extreme temperatures and emergency room visits related to mental disorders: A multi-region time-series study in New York, USA. *Science of The Total Environment*.
Yorifuji, T. et al., 2017: Prenatal exposure to outdoor air pollution and child behavioral problems at school age in Japan. *Environment International*, **99**, 192-198, doi:10.1016/j.envint.2016.11.016.
Younan, D. et al., 2018: Longitudinal analysis of particulate air pollutants and adolescent delinquent behavior in Southern California. *Journal of Abnormal Child Psychology*, **46**(6), 1283-1293.
Young, H. S. et al., 2017: Interacting effects of land use and climate on rodent-borne pathogens in central Kenya. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **372**(1722), doi:10.1098/rstb.2016.0116.
Young, I., B. A. Smith and A. Fazil, 2015: A systematic review and meta-analysis of the effects of extreme weather events and other weather-related variables on Cryptosporidium and Giardia in fresh surface waters. *J Water Health*, **13**(1), 1-17, doi:10.2166/wh.2014.079.
Youssouf, H. et al., 2014: Non-accidental health impacts of wildfire smoke. *Int J Environ Res Public Health*, **11**(11), 11772-11804, doi:10.3390/ijerph111111772.
Yuan, L., K. Shin and S. Managi, 2018: Subjective Well-being and Environmental Quality: The Impact of Air Pollution and Green Coverage in China. *Ecological Economics*, **153**, 124-138, doi:10.1016/j.ecolecon.2018.04.033.
Yun, J. et al., 2016: Association between the ambient temperature and the occurrence of human Salmonella and Campylobacter infections. *Sci Rep*, **6**, 28442, doi:10.1038/srep28442.
Zadnik, V. et al., 2020: Impact of COVID-19 on cancer diagnosis and management in Slovenia - preliminary results. *Radiology and Oncology*, **54**(3), 329-334, doi:10.2478/raon-2020-0048.
Zaitchik, B. F., 2019: Climate and Health across Africa. *OXFORD RESEARCH ENCYCLOPEDIA, CLIMATE SCIENCE* doi:10.1093/acrefore/9780190228620.013.555.

Zander, K., C. Richerzhagen and S. Garnett, 2019: Human mobility intentions in response to heat in urban South East Asia. *Global Environmental Change-Human and Policy Dimensions*, **56**, 18-28, doi:10.1016/j.gloenvcha.2019.03.004.

Zavaleta-Cortijo, C. et al., 2020: Climate change and COVID-19: reinforcing Indigenous food systems. *Lancet Planetary Health*, **4**(9), E381-E382, doi:10.1016/s2542-5196(20)30173-x.

Zavaleta, C. et al., 2018: Multiple non-climatic drivers of food insecurity reinforce climate change maladaptation trajectories among Peruvian Indigenous Shawi in the Amazon. *Plos One*, **13**(10), doi:10.1371/journal.pone.0205714.

Zeng, J., C. Lu and Q. H. Deng, 2017: Prenatal exposure to diurnal temperature variation and early childhood pneumonia. *Journal of Thermal Biology*, **65**, 105-112, doi:10.1016/j.jtherbio.2017.02.012.

Zhang, B., G. Li, Y. Ma and X. Pan, 2018a: Projection of temperature-related mortality due to cardiovascular disease in beijing under different climate change, population, and adaptation scenarios. *Environmental Research*, **162**, 152-159, doi:https://doi.org/10.1016/j.envres.2017.12.027.

Zhang, J. et al., 2020a: The effects of elevated carbon dioxide concentration and mental workload on task performance in an enclosed environmental chamber. *Building and Environment*, **178**, 106938, doi:https://doi.org/10.1016/j.buildenv.2020.106938.

Zhang, N. et al., 2019a: The impact of the 2016 flood event in Anhui Province, China on infectious diarrhea disease: An interrupted time-series study. *Environ Int*, **127**, 801-809, doi:10.1016/j.envint.2019.03.063.

Zhang, Y., S. Isukapalli, L. Bielory and P. Georgopoulos, 2013: Bayesian Analysis of Climate Change Effects on Observed and Projected Airborne Levels of Birch Pollen. *Atmos. Environ.*, **68**, 64-73, doi:10.1016/j.atmosenv.2012.11.028.

Zhang, Y. et al., 2017a: Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050. *Environmental Research Letters*, **12**(11), doi:https://doi.org/10.1088/1748-9326/aa8f76.

Zhang, Y., C. Yu and L. Wang, 2017b: Temperature exposure during pregnancy and birth outcomes: An updated systematic review of epidemiological evidence. *Environ Pollut*, **225**, 700-712, doi:10.1016/j.envpol.2017.02.066.

Zhang, Y. Q., M. J. Peng, L. Wang and C. H. Yu, 2018b: Association of diurnal temperature range with daily mortality in England and Wales: A nationwide time-series study. *Science of the Total Environment*, **619**, 291-300, doi:10.1016/j.scitotenv.2017.11.056.

Zhang, Y. Q. et al., 2019b: Socio-geographic disparity in cardiorespiratory mortality burden attributable to ambient temperature in the United States. *Environmental Science and Pollution Research*, **26**(1), 694-705, doi:10.1007/s11356-018-3653-z.

Zhang, Z., T. Xue and X. Jin, 2020b: Effects of meteorological conditions and air pollution on COVID-19 transmission: Evidence from 219 Chinese cities. *Sci Total Environ*, **741**, 140244, doi:10.1016/j.scitotenv.2020.140244.

Zhao, L. et al., 2021: Global multi-model projections of local urban climates. *Nature Climate Change*, **11**(2), doi:10.1038/s41558-020-00958-8.

Zhao, N., G. Cao, J. K. Vanos and D. J. Vecellio, 2018a: The effects of synoptic weather on influenza infection incidences: a retrospective study utilizing digital disease surveillance. *International Journal of Biometeorology*, **62**(1), 69-84, doi:10.1007/s00484-017-1306-4.

Zhao, Q. et al., 2019: Temperature variability and hospitalization for ischaemic heart disease in Brazil: A nationwide case-crossover study during 2000–2015. *Science of The Total Environment*, **664**, 707-712, doi:https://doi.org/10.1016/j.scitotenv.2019.02.066.

Zhao, T. et al., 2018b: Ambient ozone exposure and mental health: A systematic review of epidemiological studies. *Environmental Research*, **165**, 459-472, doi:10.1016/j.envres.2018.04.015.

Zhao, X. et al., 2014: Japanese encephalitis risk and contextual risk factors in southwest China: a Bayesian hierarchical spatial and spatiotemporal analysis. *Int J Environ Res Public Health*, **11**(4), 4201-4217, doi:10.3390/ijerph110404201.

Zheng, X. R. et al., 2021: Preconceptional and prenatal exposure to diurnal temperature variation increases the risk of childhood pneumonia. *Bmc Pediatrics*, **21**(1), doi:10.1186/s12887-021-02643-x.

Zhong, S. et al., 2020: Assessing the effectiveness and pathways of planned shelters in protecting mental health of flood victims in China. *Environmental Research Letters*.

Zhong, S. et al., 2018: The long-term physical and psychological health impacts of flooding: A systematic mapping. *Sci Total Environ*, **626**, 165-194, doi:10.1016/j.scitotenv.2018.01.041.

Zhu, C. et al., 2018: Carbon dioxide (CO₂) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. **4**(5), eaaq1012, doi:10.1126/sciadv.aaq1012 %J Science Advances.

Zickgraf, 2019: Keeping People in Place: Political Factors of (Im)mobility and Climate Change. *Social Sciences*, **8**, 228, doi:10.3390/socsci8080228.

Zickgraf, C., 2018: Immobility. [McLeman, R. and F. Gemenne (eds.)]. Routledge, London.

Zickgraf, C. et al., 2016: The impact of vulnerability and resilience to environmental changes on mobility patterns in West Africa. World Bank, Washington, DC.

Ziegler, U. et al., 2020: West Nile Virus Epidemic in Germany Triggered by Epizootic Emergence, 2019. *Viruses-Basel*, **12**(4), doi:10.3390/v12040448.

Zilbermint, M., 2020: Diabetes and climate change. *J Community Hosp Intern Med Perspect*, **10**(5), 409-412, doi:10.1080/20009666.2020.1791027.
Zinsstag, J. et al., 2018: Climate change and One Health. *Fems Microbiology Letters*, **365**(11), doi:10.1093/femsle/fny085.
Ziska, L. H., 2020: - An Overview of Rising CO2 and Climatic Change on Aeroallergens and Allergic Diseases. **- 12**(-5).
Ziska, L. H. et al., 2019: Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis. *Lancet Planet Health*, **3**(3), e124-e131, doi:10.1016/s2542-5196(19)30015-4.
Zorrilla, C. D., 2017: The View from Puerto Rico — Hurricane Maria and Its Aftermath. *New England Journal of Medicine*, 377(19), 1801-1803. Available at: https://doi.org/10.1056/NEJMp1713196.
Zuvela-Aloise, M., R. Koch, S. Buchholz and B. Fruh, 2016: Modelling the potential of green and blue infrastructure to reduce urban heat load in the city of Vienna. *Climatic Change*, **135**(3-4), 425-438, doi:10.1007/s10584-016-1596-2.

Chapter 8: Poverty, Livelihoods and Sustainable Development

Coordinating Lead Authors: Joern Birkmann (Germany), Emma Liwenga (Tanzania), Rajiv Pandey (India)

Lead Authors: Emily Boyd (Sweden), Riyanti Djalante (Indonesia), François Gemenne (Belgium), Walter Leal Filho (Germany), Patricia Fernanda Pinho (Brazil), Lindsay Stringer (United Kingdom), David Wrathall (USA)

Contributing Authors: Stavros Afionis (Greece), Liana Anderson (Brazil), Desalegn Ayal (Ethiopia), Connor Joseph Cavanagh (Norway), Jon Ensor (United Kingdom), Harald Heubaum (United Kingdom), Monirul Islam (Bangladesh), Rachel James (United Kingdom), Emma li Johansson (Sweden), Murukesan Krishnapillai (The Federated States of Micronesia), Joanna M. McMillan (Germany/Australia); Nicholas P. Simpson (South Africa), Jamon Van Den Hoek (USA), Emmanuel Raju (Denmark)

Review Editors: Taikan Oki (Japan), Marta G. Rivera-Ferre (Spain), Taha Zatari (Saudi Arabia)

Chapter Scientists: Ali Jamshed (Germany/Pakistan), Joanna M. McMillan (Germany/Australia), Mohammad Ravankhah (Germany/Iran)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Adverse impacts of climate change, development deficits and inequality exacerbate each other. Existing vulnerabilities and inequalities intensify with adverse impacts of climate change (high confidence[1]). These impacts disproportionately affect marginalised groups, amplifying inequalities and undermining sustainable development across all regions (*high confidence*). Due to their socio-economic conditions and the broader development context, many poor communities, especially in regions with high levels of vulnerability and inequality, are less resilient to diverse climate impacts (*high confidence*) {8.2.1, 8.2.2, 8.3.2, 8.3.3}

Under all emissions scenarios, climate change reduces capacities for adaptive responses and limits choices and opportunities for sustainable development. Higher levels of global warming lead to greater constraints on societies. Climate change increases the threat of chronic and sudden onset development challenges, such as poverty traps and food insecurity (high confidence). Adaptation interventions and transformative solutions that prioritize inclusive and wide-ranging climate resilient development and the reduction of poverty and inequality are increasingly seen as necessary to minimize loss and damage from climate change (*high confidence*) {8.2.1, 8.2.2, 8.3.1, 8.3.2, 8.3.3}.

Observed societal impacts of climate change, such as mortality due to floods, droughts and storms, are much greater for regions with high vulnerability compared to regions with low vulnerability, which reveals the different starting points that regions have in their move towards climate resilient development (high confidence). Observed average mortality from floods, drought and storms is 15 times higher for countries ranked as very high vulnerable, such as Mozambique, Somalia, Nigeria, Afghanistan and Haiti compared to very low vulnerable countries, such as UK, Australia, Canada and Sweden in the last decade (*high confidence*). Over 3.3 billion people are living in countries classified as very highly or highly vulnerable, while 1.8 billion people live in countries with low or very low vulnerability. The population in most vulnerable countries is projected to increase significantly by 2050 and 2100, while the population in countries with low vulnerability is projected to decrease or grow only slightly. Vulnerability is a result of many interlinked issues concerning poverty, migration, inequality, access to basic services, education, institutions and governance capacities often made more complex by past developments, such as histories of colonialism (*high confidence*) {8.3.2, 8.3.3}.

A growing range of economic and non-economic losses have been detected and attributed to climate extremes and slow onset events under observed increases in global temperatures (medium evidence, high agreement). If future climate change under high emissions scenarios continues and increases risks, without strong adaptation measures, losses and damages will *likely*[2] be concentrated among the poorest vulnerable populations (*high confidence*). The intersection of inequality and poverty presents significant adaptation limits, resulting in residual risks for people/groups in vulnerable situations, including women, youth, elderly, ethnic and religious minorities, Indigenous People and refugees. Climate change is *likely* to force economic transitions among the poorest groups, accelerating the switch from agriculture to other forms of wage labour, with implications for labour migration and urbanization (medium evidence, high agreement). Under an inequality scenario (SSP4) the projected number of people living in extreme poverty may increase by 122 million by 2030 (*medium confidence*) {8.2, 8.3.4, 8.4.1, 8.4.5, Map 8.8, Box 8.5, 16.5.2.3.4}

Both climate change and vulnerability threaten the achievement of the UN Sustainable Development Goals (SDGs) (medium confidence). This undermines progress toward various goals such as no poverty

---

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

(SDG1), zero hunger (SDG2), gender equality (SDG5) and reducing inequality (SDG10), among others (*medium evidence, high agreement*). Gender inequality and discrimination are among the barriers to adaptation (*high confidence*) {8.2.1¸8.4.5}. Also maladaptation can lead to additional complex and compounding future risks and threaten sustainable development (*high confidence*) {8.4.5.5, 8.2.1.7}

Under higher emissions scenarios and increasing climate hazards, the potential for social tipping points increases (medium confidence). Even with moderate climate change[3] people in vulnerable regions will experience a further erosion of livelihood security that can interact with humanitarian crises, such as displacement and forced migration (*high confidence*) and violent conflict, and lead to social tipping points (*medium confidence*). Social tipping points can also be coupled with environmental tipping points {8.3, 8.4.4}.

Vulnerable population groups in most vulnerable regions have the most urgent need for adaptation (high confidence). The most vulnerable regions are particularly located in East, Central and West Africa, South Asia, Micronesia and Melanesia and in Central America (high confidence). These regions are characterized by compound challenges of high levels of poverty, a significant number of people without access to basic services, such as water and sanitation and wealth and gender inequalities as well as governance challenges. Areas of high human vulnerability are characterized by larger transboundary regional clusters (*high confidence*). Additional support and structures are needed to reduce the existing gaps between future adaptation needs and current capacities, and to support transitions from vulnerable livelihood with adequate integration of the Indigenous Knowledge and Local Knowledge systems. Greater investments are required under higher levels of global warming and of inequality (RCP 4.5; RCP8.5 and SSP4) (*high confidence*) {8.3, 8.4, Box 8.6}.

The direct and indirect consequences of the COVID-19 pandemic have worsened inequalities within societies, thereby increasing existing vulnerabilities to climate change and further limiting the ability of marginalized communities to adapt (medium confidence). The COVID-19 pandemic is expected to increase the adverse consequences of climate change since the financial consequences have led to a shift in priorities and constrain vulnerability reduction (*medium confidence*). Moreover, the COVID-19 pandemic is also influencing the capacities of governmental institutions in developing nations to support planned adaptation and poverty reduction of most vulnerable people/groups, since the crisis also means significant reductions in tax revenues (*high confidence*) {8.3, 8.4¸8.4.5.5}.

Those with climate-sensitive livelihoods and precarious livelihood conditions are often least able to adapt, afforded limited adaptation opportunities and have little influence on decision making (high confidence). Enabling environments that support sustainable development are essential for adaptation and climate resilient development (high confidence). Enabling and supportive environments for adaptation share common governance characteristics, including multiple actors and assets, and multiple centres of power at different levels and an effective vertical and horizontal integration between levels (*high confidence*). Enabling conditions can support livelihood strategies that do not undermine human wellbeing (*medium confidence*) {8.5.1, 8.5.2, 8.6.3, 5.13}.

Mitigation and adaptation responses to climate change influence inequalities, poverty and livelihood security and thereby aspects of climate justice (medium confidence). Improving coherence between adaptations of different social groups and sectors at different scales can reduce maladaptation, enable mitigation and advance progress towards climate resilience (medium confidence). The poor typically have low carbon footprints but are disproportionately affected by adverse consequences of climate change and also lack access to adaptation options. In many cases, the poor and most vulnerable people/groups are most adversely affected by maladaptation (*medium evidence, high agreement*). Climate justice and right based approaches are increasingly recognized as a key principle within mitigation and adaptation strategies and projects (*medium confidence*). Narrowing gender gaps can play a transformative role in pursuing climate justice (*medium confidence*). Climate resilient development is therefore closely coupled with issues of climate justice. Synergies between adaptation and mitigation exist and these can have benefits for the poor (*medium confidence*) {8.4, 8.4.5.5, 8.6}.

---

[3] meaning low or moderate emission scenarios

There is increasing evidence that nature-based solutions (e.g., urban green infrastructure, ecosystem-based management) can provide important livelihood options and reduce poverty while also supporting mitigation and adaptation (medium confidence). However, the trade-offs over time between nature-based solutions and their dynamics are insufficiently understood. Appropriate governance, including mainstreaming and policy coherence, supported by adaptation finance that targets the poor and marginalised, is essential for adaptation and climate compatible development (*medium confidence*) {8.5.2, 8.6.3, 5.14}.

8.1 Introduction

The impacts of climate change have already significantly affected the livelihoods and living conditions, especially of the poorest and most vulnerable, and will continue to undermine development during the coming century. This chapter assesses the societal consequences of climate change and related hazards in terms of adverse and irreversible consequences for the most vulnerable. To understand societal consequences of climate change we assess impacts through the perspective of vulnerability, poverty and livelihoods of people and identify why climate events trigger sudden and slow-onset disasters, and how the most severe, acute and chronic impacts cause and deepen human suffering. We also examine issues of climate justice. Understanding and engaging with climate justice requires a plural focus on the historical social and institutional relations and inequalities which produce climate change, cause people to be vulnerable to climate hazards, and shape responses to them (Newell et al., 2021). An assessment of observed impacts on the poorest and their strategies for adaptation carries important lessons for inclusive, broad-based solutions to climate change.

As a starting point, this chapter examines linkages between climate change, specific climate-related hazards and impacts on multidimensional poverty, vulnerability and livelihoods. Past assessments have identified the linkages between climate change, poverty, livelihoods and human vulnerability, and shown how climate change leads to differential consequences for different communities and populations. The IPCC Fifth Assessment Report (AR5) identified socially and geographically disadvantaged people exposed to persistent inequalities at the intersection of various dimensions of discrimination based on gender, age, ethnicity, class and caste (IPCC, 2014a). AR5 also showed evidence climate change is a universal driver and multiplier of risk that shapes dynamic interactions between these factors. Climate change is one stressor that shapes dynamic and differential livelihood trajectories. Also, the IPCC Special 1.5°C report underscored with very *high confidence* that global mean temperature, harm and human wellbeing losses are increasing substantially (Hoegh-Guldberg et al., 2018; Roy et al., 2018).

This chapter builds on this, examining equitable development, robust institutions and poverty reduction as essential inputs to societies' capacity for adaptation (i.e., closes the adaptation gap) in order to avoid losses and damages from climate change. It assesses quantitative spatio-temporal information on human vulnerability at a global scale and for specific sub-regions, livelihood groups and communities at the local level. The chapter assesses the newest literature on how multidimensional poverty and human vulnerability to climate change is measured and also examined the agreement of different index systems in terms of global hotspots of human vulnerability.

In addition, the chapter explores how climate change affects different livelihoods and livelihood assets and also examines factors that characterize vulnerability to climate change, focusing on different dimensions of human vulnerability and its sub-systems (e.g., access to infrastructure services). In this context the chapter also assesses quantitative data to map human vulnerability as well as economic and non-economic losses that are highly relevant for understanding adverse impacts of climate change.

The chapter assesses the newest scientific knowledge on how the most vulnerable and marginalized people are experiencing different climate influenced hazards and changes, how these groups prepare for and adapt to these changes. Hence, it examines how climate change intersects with broader processes of development. It also considers the various impacts of climate change on the livelihoods of the poorest, the capabilities, assets and activities required for a means of living. It examines the institutional conditions that promote livelihood resilience in the face of climate change. Quantitative analysis and qualitative data on observed adverse climate change impacts and future projections and trends in vulnerability show that societal impacts of climate change cannot solely be explained by looking at temperature changes or climatic hazards alone.

The chapter provides due consideration as how societal impacts of climate change are emerging as a result of climatic changes, development and vulnerability. In this regard, it also explores how past and present conditions of poverty, inequality and vulnerability determine observed and future societal impacts of climate change, including future adaptive capacities of societies exposed to climate change. It highlights new entry points to address climate risks and adaptation needs through the targeted reduction of poverty, inequity and vulnerability, linking particularly global quantitative information with local livelihood-oriented qualitative information.

The chapter also outlines new approaches for identifying social tipping points, meaning moments of rapid, destabilizing change across scales that can complement the discussion about physical tipping points in the climate system. It also addresses new perspectives on the baselines for assessing future vulnerabilities, and potential for irreversible losses, emphasizing not only economic but also non-economic losses, which are linked to past and present development trajectories. There is mounting evidence on non-economic losses, including the loss of land, livelihoods, social networks, cultural values and the irreversible degradation of ecosystem functions, as observed, for example, in parts of the Amazon. Non-economic losses are intertwined with economic losses to influence human health, nutrition, wellbeing and social stability, and therefore also influence present and future vulnerabilities and adaptive capacities. Non-economic losses from climate change disproportionately affect the poor. People in vulnerable situations are often disproportionally affected as they are less resilient and have less access to institutional support (including protection mechanisms) and coping strategies. This knowledge is key for informing integrated strategies for sustainable livelihood transitions and adaptation.

The chapter assesses newer literature about the synergies and trade-offs for the poorest and most vulnerable people/groups between adaptation mitigation, and sustainable development strategies, which societies must negotiate in order to pursue Climate Resilient Development. It explores synergies and mismatches in key development sectors that the poorest rely on, including agriculture, forestry and energy. It identifies the development strategies, elements of institutional design and financial mechanisms likely able to support risk reduction and adaptation. Our assessment reveals that successful adaptation is not solely a question of levels of funding, but depends on broader institutional design that determine societal development and enabling conditions for adaptation to and mitigation of climate change. An assessment of enabling conditions for adaptation supports the finding that more convergent, integrated and comprehensive approaches to adaptation are needed. The chapter concludes that climate justice requires consideration of the legal, institutional and governance frameworks that significantly determine whether adaptation is successful in addressing the needs of the poor.

Thus, intersections between climate hazards and socioeconomic development are assessed from the point of view of vulnerability, poverty, livelihoods and inequality (see Figure 8.1). Chapter 8 adopts this wider perspective to examine the differential nature of observed and future disproportionate vulnerabilities (i.e., who is most susceptible to climate hazards and events, where, at the core to understanding of what scale and why?) as well as the inequalities inherent in adaptation and mitigation solutions as part of a wider climate justice perspective adopted in Chapter 8, and challenges for climate resilient development.

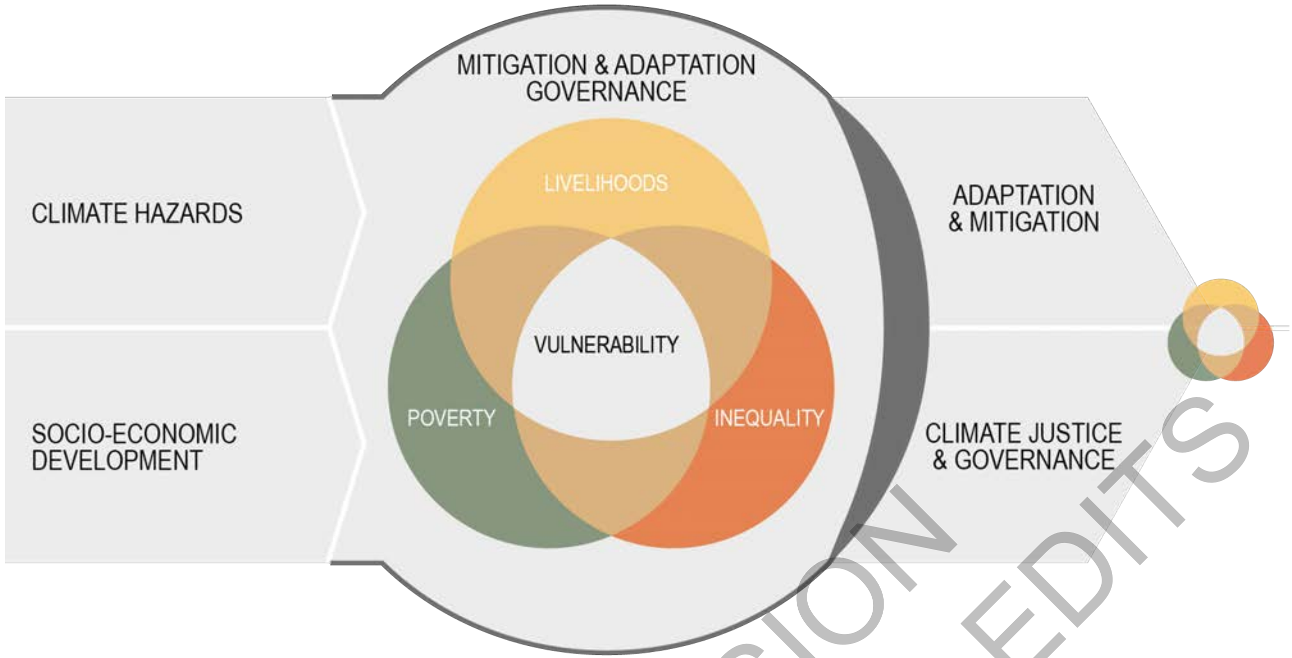


Figure 8.1: The lens of chapter 8 to better understand the human dimension of climate change at the nexus of climate change, climate hazards and socio-economic development.

Finally, our assessment points towards the fact that human vulnerability to climate change is a complex and multifaceted phenomenon that is often influenced by historic development processes, such as structures that originated with colonization. Also, recent global shocks not directly related to climate change, such as the COVID-19 pandemic and its socio-economic consequences, impact climate vulnerability and inequitable impacts occurring between countries and within countries. Recent studies show that COVID-19, and other social, economic and political crises, have worsened the circumstances of the poor and further marginalized them.

Overall, the chapter is a key in terms of understanding societal impacts of climate change and factors that determine the various differential adverse consequences of climate change on societies. The information presented and assessed in the chapter is fundamental for informing adaptation and risk reduction strategies, since climatic information alone cannot explain sufficiently why some regions, societies or groups are suffering significantly more under climate change compared to others. Concepts such as vulnerability, intersectionality and climate justice provide important insights on how societal impacts of climate change are influenced and determined by broader societal development contexts.

8.2 Detection and Attribution of Observed Impacts and Responses

8.2.1 Observed impacts of climate change with implications for poverty, livelihoods and sustainable development

This section reports on new evidence on the observed impacts of climate change to livelihoods and the poor since the previous assessment (IPCC, 2014a). New evidence provides additional insight into the interlinkages between climate change, poverty and livelihoods, and affords this assessment with greater confidence. New evidence has been evaluated according to climate change hazard categories developed for the AR6 (IPCC, 2021), and summarized in Figure 8.2.

8.2.1.1 Interactions between climate hazards and non-climatic stressors affecting livelihoods

New evidence highlights the potential for multi-hazard risks to push the poor into persistent traps of extreme poverty (Räsänen et al., 2016). Risk of extreme impoverishment increases for low-income people experiencing repeated and successive climatic events, whereby before they have recovered from one disaster, they face another impact (Forzieri et al., 2016). Cascading and compounding risks arise from multiple climate hazards producing 'overlaying impacts,' for example, in mountainous regions, where the combination of glacier recession and extreme rainfall result in landslides (Martha et al., 2015). There is *robust evidence* that this effect has been observed around slow- and rapid-onset climate events related to drought, i.e., rising temperatures, heatwaves, and rainfall scarcity, with devastating consequences for agriculture(Vogt et al., 2018; Bouwer, 2019). Particularly the urban and rural landless poor face difficulties rebuilding assets following one-off disasters or a series of shocks (Garcia-Aristizabal et al., 2015).

Climate change is one driver among many that challenges livelihoods of the rural poor, including economic transitions associated with industrialization and urbanization, and also governance failures such as unclear property rights and civil conflict (e.g., Nyantakyi-Frimpong and Bezner-Kerr, 2015). Recent research adds evidence about the ways that climate hazards impact non-climatic stressors with implications for poverty reduction (Nelson et al., 2016). The risk that climate hazards may push the poor into persistent extreme poverty intensify with stagnant wages, rising costs of living, mobility traps, and ethnic or religious discrimination (Cramer et al., 2014; Carter et al., 2016). Likewise in both urban and rural environments, non-climatic factors related to governance exacerbate the impacts of climate events among the poorest, including poor service provisioning (e.g., waste collection), poor urban planning (e.g., waste water drainage), and water management failures (Di Baldassarre et al., 2010; Leal Filho et al., 2018) as well as poor rangeland management, intensification of farming land uses (i.e. overgrazing, deforestation), degradation of wetlands, shortage of water and soil erosion in rural areas (Olsson et al., 2019).

A key risk for the poor is shocks to specific livelihood assets that may force low-income groups into persistent poverty traps (Figure 8.4; Chambers and Conway, 1992; Cinner et al., 2018) but evidence also suggests that climate change impacts are also driving transient forms of poverty, i.e. a modality of poverty which is recurring (Angelsen et al., 2014). Recurrent poverty is, for instance, seen in relation to crop losses and decreasing agricultural production when income losses worsen living conditions (Ward, 2016; Kihara et al., 2020). Recent research shows that climate change impacts may exacerbate poverty indirectly through increasing cost of food, housing and healthcare, among other rising costs borne by the poor (Islam et al., 2014; Ebi et al., 2017; Hallegatte et al., 2018) (*high confidence*). Severe adverse impacts of climate change at present and future risks may result from permanent, sudden, destabilizing changes accompanying climate events such as decreases in food security, large-scale migration, changes in labour capacity or conflict (Bentley et al., 2014). Overall, there is more evidence that even under medium warming pathways, climate change risks to poverty would become severe if vulnerability is high and adaptation is low (*limited evidence, high agreement*) (see Section 16.5.2.3.4)

Reliable and precise estimates of the impacts of climate change on persistent poverty are difficult to generate, e.g., due to data scarcity and data gaps (Hallegatte et al., 2015; Hallegatte et al., 2018; Kugler et al., 2019). However, progress has been made towards detection and attribution of climate change impacts on the poorest by linking standard climate observations in low-income countries with new non-traditional forms of data (including Indigenous Knowledge, historical archival data, satellite imagery, and data from digital devices) (Kuffer et al., 2016; Lu et al., 2016; Bennett and Smith, 2017; Steele et al., 2017).

8.2.1.2. Links between climate-related hazards, observed losses, poverty and inequality globally

There is *high confidence* that climate-related hazards, including both slow-onset shifts and extreme events, directly affect the poor through adverse impacts on livelihoods (see Figure 8.2), including reductions and losses of agricultural yields, impacts on human health and food security, destruction of homes, and loss of income (Hallegatte et al., 2015; Connolly-Boutin and Smit, 2016). One of the key factors that drives disproportionate impacts among poor households globally is lost agricultural income (*high confidence*) (Hallegatte et al., 2015; Islam and Winkel, 2017). Also of concern are the impacts of climate hazards to human health, which is a primary resource that the poor rely on (Figure 8.2). There are only few robust global estimates of observed income losses to the poor that comprehensively account for all climate hazards;

nevertheless, (Hallegatte and Rozenberg, 2017), estimating average impacts of climate change on incomes of the poor, found that across 92 developing countries, the poorest 40% of the population experienced losses that were 70% greater than the losses of people with average wealth.

a)

	Heat			Cold		Wet				Dry			Wind/Storm		Snow/Ice				Coastal				Other		
Livelihood Resource	Heatwave	Permafrost thawing	Warming trend	Cold spell	Frost	Landslides	Pluvial flood	River flood	Wet trend	Drought	Dry trend	Wildfire	Hail	Severe storms	Heavy snow	Lake/sea ice reduction	Snow avalanche	Snow reduction	Coastal erosion	Coastal flood	Salinity	Sea level rise	Ocean/lake acidification	Average Confidence (1-3)	Total risk from all hazards:
Crop Yield	MC	LC	HC	MC	HC	MC	HC	HC	LC	HC	HC	LC	HC	HC	LC	LC	MC	MC	LC	MC	HC	MC	LC	2.1	MC
Farmland/Arable Cropland	LC	LC	MC	LC	LC	MC	MC	MC	LC	MC	MC	LC	LC	MC	LC	LC	LC	LC	MC	MC	MC	HC	LC	1.5	MC
Fisheries and Aquaculture	MC	LC	HC	LC	LC	LC	MC	LC	LC	HC	MC	LC	LC	HC	LC	LC	LC	LC	LC	MC	HC	HC	HC	1.7	MC
Forest Products	LC	LC	MC	LC	MC	LC	LC	LC	LC	HC	MC	MC	LC	LC	LC	LC	LC	MC	LC	MC	LC	MC	LC	1.4	LC
Housing Stock	LC	MC	LC	LC	LC	MC	HC	HC	LC	LC	LC	MC	LC	HC	LC	LC	MC	LC	MC	MC	LC	HC	LC	1.6	MC
Income/Financial Assets	MC	LC	HC	LC	LC	MC	HC	MC	LC	HC	MC	LC	LC	HC	LC	LC	LC	MC	MC	MC	MC	MC	MC	1.8	MC
Life/Bodily Health/Food Security	HC	MC	HC	LC	LC	MC	HC	HC	LC	HC	HC	HC	LC	HC	LC	LC	MC	MC	LC	HC	HC	HC	MC	2.2	MC
Pasture/Rangeland/Livestock	HC	LC	HC	LC	MC	LC	HC	MC	MC	HC	HC	LC	MC	MC	MC	LC	LC	HC	LC	LC	MC	LC	LC	1.8	MC
Crop Variety	LC	LC	HC	LC	LC	LC	MC	LC	MC	MC	HC	LC	LC	LC	LC	LC	LC	LC	LC	MC	MC	MC	LC	1.4	LC
Average Confidence (1-3)	1.8	1.2	2.6	1.1	1.4	1.6	2.4	2.0	1.2	2.6	2.3	1.4	1.3	2.3	1.1	1.0	1.3	1.7	1.3	2.0	2.1	2.3	1.4		
Total risk to livelihoods:	MC	LC	HC	LC	LC	MC	MC	MC	LC	HC	MC	LC	LC	MC	LC	LC	LC	MC	LC	MC	MC	MC	LC		

b)

	Climate Hazards							
Livelihood Resources	Warming trend	Pluvial flood	River flood	Drought	Severe storms	Sea level rise	Average Confidence (1-3)	Total risk from all hazards:
Crop yield	HC	HC	HC	HC	HC	MC	2.8	HC
Fisheries and Aquaculture	HC	MC	LC	HC	HC	HC	2.5	HC
Income/Financial Assets	HC	HC	MC	HC	HC	MC	2.7	HC
Life/Bodily Health/Food Security	HC	HC	HC	HC	HC	HC	3.0	HC
Pasture/Rangeland/Livestock	HC	HC	MC	HC	MC	LC	2.3	MC
Average Confidence (1-3)	3.0	2.8	2.2	3.0	2.8	2.2		
Total risk to livelihoods:	HC	HC	MC	HC	HC	MC		

c)

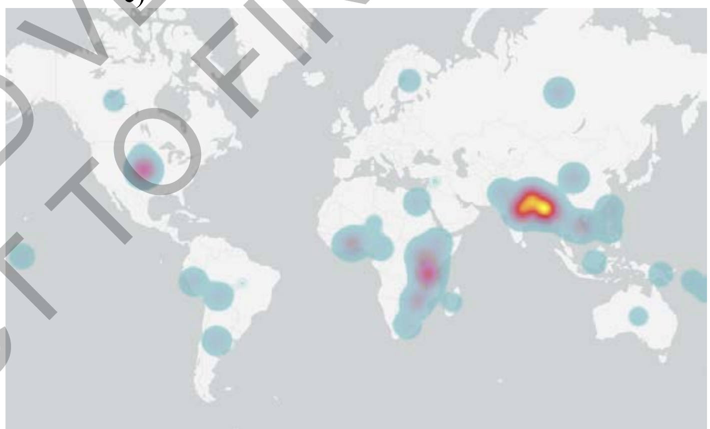


Figure 8.2: Summary of confidence on the observed impacts of 23 climate hazards on 9 key livelihood resources on which the poor depend most. Panel A displays 207 confidence statements on the total set of livelihood impacts. Based on a standardized assessment of available literature since the AR5 (2014), each impact category was assigned a confidence statement based on weight of evidence; *high confidence* is represented with HC, *medium confidence* with MC and *low confidence* with LC. An average numerical confidence score is assigned for impacts from each climate hazard, and for each livelihood resource category, representing total risk. Panel B depicts the "high risk" cluster of livelihood impacts, where confidence is highest. Panel C represents the spatial distribution of relative confidence. Hotspots represent highest confidence of observed livelihood impacts; however the absence of spatial information reflects not an absence of observed livelihood risk, but the relative weight of evidence sampled in this assessment exercise.

Overall, our assessment shows (see Figure 8.2) *high confidence* that two categories of climate hazards pose high risk to a broad range of livelihood resources that the poor rely on: warming trends and droughts (Figure 8.2b). Two key livelihood resource categories –life, bodily health and food security, and crop yield (representing agricultural productivity) are most at risk to a broad range of climate hazards (*high confidence,* Figure 8.2b). In addition to warming and drought, both pluvial and fluvial flooding, severe storms, and sea level rise represent a high-risk cluster for livelihood impacts (*high confidence,* Figure 8.2b).

Figure 8.2 reflects the fundamental threat that climate hazards pose to the survival of plants, livestock, fish as well as the human bodies on which livelihoods depend (*high confidence*) (see Horton et al., 2021). The dependence of livelihoods on biological, ecological and human survival depicted in Figure 8.2 is also treated in Chapter 5. Likewise, impacts to livelihood resources can be compared to impacts to other key assets (see AR6 WGI Chapter 12, Section 12.3 and Table 12.2).

It is revealed that warming trends and droughts pose greatest risks to the widest array of livelihood resources, and are particularly detrimental to crops and human health, a long-term requirement for livelihoods and wellbeing (*high confidence*) (see Figure 8.2b; Section 8.4.5.3; Section 16.5.2.3.4; Campbell et al., 2018). A wide range of hazards also threaten the survival of fish and livestock that livelihoods depend on (*high confidence,* Figure 8.2b), as well as other sources of income for the poor. Salinity is a secondary hazard related to droughts, coastal flooding and sea level rise, and poses a fundamental risk to agriculture (*high confidence*). There is also *robust evidence* for rainfall variability driving short-term impacts to agricultural productivity as well as permanent loss of agriculture (*high confidence*).

While severe storms, pluvial and riverine floods, and coastal floods primarily impact private livelihood resources, such as homes and income (*high confidence,* Figure 8.2b), warming and droughts also affect common pool resources, such as rangeland, fisheries and forests (*high confidence,* Figure 8.2b). Multiple hazards undermine ecosystems that Indigenous Peoples and poor communities depend on for food security and income and have sustainably managed over the long-term, such as forests, grazing land, and marine fisheries (Barange et al., 2014; Leichenko and Silva, 2014; Béné et al., 2016; Jantarasami et al., 2018).

Highest confidence for observed livelihood impacts is spatially concentrated in South Asia, Africa, North America, and to a lesser extent Small Island States (SIDS) (Figure 8.2c). The hazards most prevalent in all regions include warming trends, droughts and sea level rise (Figure 8.2c), and undermine crop productivity, crop varieties, and cropland in most regions (high confidence). Along coastlines, climate hazards threaten livelihoods particularly exposed to extreme weather, flooding, and sea level rise, and where poor populations are heavily dependent on agriculture and fisheries (*high confidence*). One third of total sampled evidence on livelihood impacts was observed in just three countries—Nepal, India and Bangladesh—indicating accumulating experience with livelihood impacts in South Asia (Figure 8.2c). However, this spatial representation of confidence does not mean that observed livelihood impacts are not occurring in other regions as well. Relative to South Asia, in Central Asia and the Caribbean, for example, the weight of evidence of livelihood impacts though lighter is still robust. Among industrialized nations, there is highest confidence that climate change has impacted livelihood resources in the United States.

8.2.1.3. Observed differential vulnerability to climate change, and loss and damage

The negative impacts of climate change on groups of vulnerable and/or marginalized communities generate so-called 'residual impacts' and residual risks that can remain a challenge in their lives (Warner and Van der Geest, 2013; James et al., 2014; Klein et al., 2014; Boyd et al., 2017). Such 'unacceptable' losses and damages include the loss of income sources, food insecurity, malnutrition, permanent impacts to health and labour productivity, loss of life, loss of homelands, among others (McNamara and Jackson, 2019; Schwerdtle et al., 2020). The literature on loss and damage provides evidence not only on economic dimensions of global losses and damages, but also experiences of non-economic losses from the impacts of climate change, (see detail in Section 8.3; Barnett et al., 2016; Roy et al., 2018; McNamara and Jackson, 2019). The extreme events that have occurred in recent years highlight the potential for loss and damage, including 2019's Cyclone Kenneth, the strongest in the recorded history of the African continent, which made landfall in northern Mozambique causing 45 deaths and destroying approximately 40,000 houses, leaving hundreds of thousands at risk of acquiring waterborne diseases such as cholera during a prolonged recovery period (Cambaza et al., 2019).

In parallel to evidence on loss and damage, the science of climate event attribution has evolved from a theoretical possibility into a subfield of climate science. As attribution science strengthens, with it the evidence base linking greenhouse gas emissions to extreme heat events, heavy rainfall and wind storms grows and becomes more robust (Otto et al., 2016; Stott et al., 2016; Otto et al., 2018a; Otto, 2020; Clarke et al., 2021; van Oldenborgh et al., 2021a; van Oldenborgh et al., 2021b; Verschuur et al., 2021).

Climate justice questions arise about the observed differential losses and damages due to climatic hazards to affected populations in close connection with their vulnerability (Wrathall et al., 2015). Individual extreme weather events attributable to climate change result in losses and damages in communities and societies, which allow a quantification of the differential impacts of such events on different groups (Hoegh-Guldberg et al., 2019a). Considering the disproportionate adverse impacts of climatic hazard on most vulnerable groups and regions and their relatively minor contribution to anthropogenic climate change (Mora et al., 2018; Robinson and Shine, 2018), it is evident that vulnerability reduction and adaptation to climate change have also to be seen as an issue of climate justice and climate just development (Byers et al., 2018).

Probabilistic attribution allows an assessment of people's future climate risks and estimates about the costs of successfully adapting to them (James et al., 2014; James et al., 2019). To answer questions about impacts on people, the vulnerable and poor in particular, requires attribution, vulnerability and adaptation science to move far beyond understanding physical events and incorporate information (including Indigenous Knowledge and Local Knowledge) on people's vulnerability and capacities, and exposure and losses resulting from discrete events (Bellprat et al., 2019). Attribution science is therefore highly compatible with risk management tools (i.e., risk reduction, risk transfer, insurance, risk pooling, recovery, rehabilitation, and compensation) suggested in policy (James et al., 2019).

New observations provide greater evidence on the role of extreme poverty and global inequality, most of the detrimental direct impacts of climate change (e.g., rising food insecurity) disproportionately affecting the Global South (Hasegawa et al., 2018; Mbow et al., 2019; Khan and Zhang, 2021) compared with the Global North. Poor populations in many countries are also disproportionately facing extreme losses and damage from heatwaves, flooding and tropical weather extremes (Gamble et al., 2016). New case studies, such as the European heatwave of 2018, illustrate significant negative impacts across crop production in the Global North (Beillouin et al., 2020), livestock value chain (FAO, 2018; Godde et al., 2021), and fishing (Plagányi, 2019). Heatwave-induced intense fires can cause property damage, physical injury and death, as well as health and psychological harm of the victims. Heatwaves also create ideal conditions for the prevalence of certain pathogens, increase the risk of temperature related health problems, and exacerbate many pre-existing diseases (Rossiello and Szema, 2019).

A focus in the chapter is on the intersections between climate hazards and differential vulnerability resulting in actual and potential economic and non-economic losses (Section 8.3, 8.4; Thomas et al., 2019). Increasingly intersections of age, gender, socio-economic class, ethnicity and race are recognised as important to the climate risks and differential impacts and losses experienced by vulnerable, marginal and poor in societies (*high confidence*).(Section 8.2,2.3; Cross-Chapter Box GENDER in Chapter 18; Nyantakyi-Frimpong and Bezner-Kerr, 2015). For example, linkages between wildfires and gendered norms and values are real-world examples (Walker et al., 2021). A broader climate agenda which considers social structures and power relations intersecting with climate change extremes is important (Versey, 2021), in order to understand disproportionate impacts of climate hazards, observed and future losses and vulnerability (see Figure 8.3).

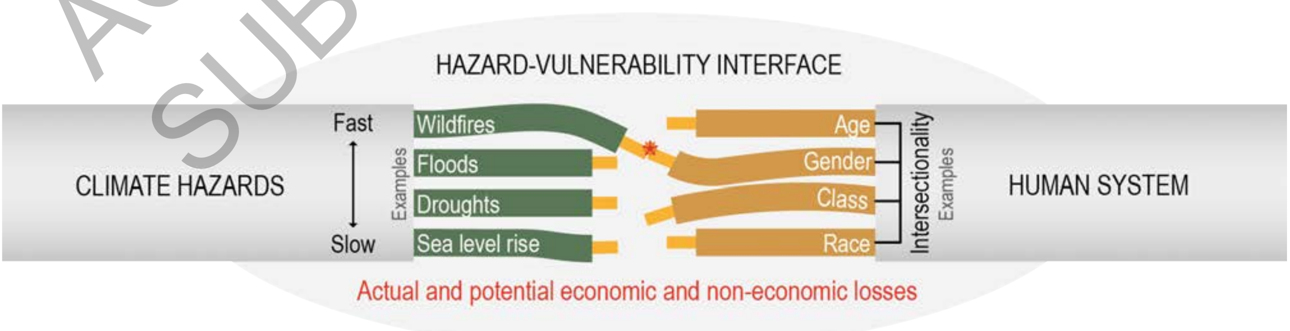


Figure 8.3: This is a schematic figure to illustrate the relationship between risk and impacts from climate change (including economic and non-economic losses and damages) and human systems lead to systemic vulnerability. We need to understand who is vulnerable, where, at what scale and why. We cannot just look at the climate hazard (e.g., wild fires, floods, droughts, sea-level rise, etc.) but must also look at who is being affected by these hazards and factors that make people/groups vulnerable (e.g., poverty, uneven power structures, disadvantage and discrimination due to, for

example, social location and the intersectionality or the overlapping and compounding risks from ethnicity or racial discrimination, gender, age, or disability, etc.) (see also Cross-Chapter Box GENDER in Chapter 18 and Section 5.12).

Extreme events (e.g., heatwaves, cold periods, icy conditions) occurring in the Global North illustrate that such events cause disproportionate impacts among aging populations, due to their immobility, isolation, infrastructure deficiencies and poor health assistance (Carter et al., 2016; Reckien et al., 2018). A well-known example is the heatwave in 2003 that killed thousands of elderly citizens across Europe (Poumadere et al., 2005; García-Herrera et al., 2010; Laaidi et al., 2011). More recently, in the Nordic region, elderly populations are experiencing distress associated with heatwaves and extreme cold events, with significant increases in morbidity and mortality due to cardiovascular and respiratory failure, showing that both age and underlying health issues intersect with climate change impacts (Carter et al., 2016; Li et al., 2016). The elderly also experience severe impacts from extreme winter seasons, such as in Finland, where of the from 3 000 deaths associated with extreme winter weather and 50 000 injuries associated with slippery from pavement conditions, the majority were people over 65 years old (Carter et al., 2016). Adaptation to extreme events including heatwaves, cold periods and icy conditions in the Global South and North will increase energy demand and the individuals' carbon footprint across all income levels (van Ruijven et al., 2019).

The 2018 US National Climate Assessment has identified the fact that south-eastern United States is already experiencing more frequent and longer summer heatwaves, and by 2050, rising global temperatures are expected to mean that cities in the south-eastern part of the United States of America may experience extreme heat (USGCRP, 2018). This includes disadvantaged African American communities who are more exposed and hence disproportionately experiencing the impacts of climate change (Shepherd and KC, 2015; Marsha et al., 2018). The historically discriminated Sami as an example of Indigenous People in Northern Sweden, and Maasai in Africa are examples of Indigenous People who also face climate risks and have limited resources, capacity or power to respond (Leal Filho et al., 2017; Persson et al., 2017)

8.2.1.4 Climate-related hazards, livelihood transitions and migration

Agricultural livelihoods of the rural poor, especially in Africa, Asia and Latin America, are already in transition due to the forces of industrialization, urbanization and economic globalization (De Brauw et al., 2014; Tacoli et al., 2015), and scientific evidence shows that climate change is accelerating livelihood transitions from rural agricultural production to urban wages (Cai et al., 2016; Cattaneo and Peri, 2016; Kaczan and Orgill-Meyer, 2020).

There is now *robust evidence* from virtually every region on earth showing that the livelihood impacts from a multitude of climate hazards are driving people to diversify rural income sources (Figure 8.2; Cross-Chapter Box MIGRATE in Chapter 7). Rural households frequently accomplish the goal of livelihood diversification with an increasing reliance on migration, urban wage labour and remittances (Marchiori et al., 2012; Bohra-Mishra et al., 2014; Gray and Wise, 2016; Nawrotzki and DeWaard, 2016; Banerjee et al., 2019a). What is different about rural-to-urban livelihood transitions under climate change impacts is that they accelerate both rural and urban stratification of wealth (Barrett and Santos, 2014; Thiede et al., 2016). On the one hand, climate change impacts on rural livelihoods increase the necessity of migration as in income strategy, accelerating migration (Cai et al., 2016) even while households that cannot select individuals for migration become more impoverished (Suckall et al., 2017; Nawrotzki and DeWaard, 2018).

On the other hand, climate change impacts widen the range of households willing or needing to engage in migration to include those less able to bear the costs of urban migration (Afifi et al., 2016; Hunter and Simon, 2017). The effect is also greater urban poverty, and a higher social burden of migrants seeking urban wages (Singh, 2019). Evidence suggests that poor households often move in desperation to make ends meet. In the context of climate hazards such as coastal inundation and salinity, economic necessity often drives working-age adults in poor households to seek outside earnings(Dasgupta et al., 2016). Labour migration in the context of climate change is also gendered, and as more men seek employment opportunities away from home, women are required to acquire new capacities to manage new challenges, including increasing vulnerability to climate change (Banerjee et al., 2019b).

Migration and displacement are directly induced by the impacts of climate change (*high confidence*, Cross-Chapter Box MIGRATE in Chapter 7), however, migration responses to climate change are differentiated across the spectrum of households' wealth. In well-off households, migration can be used as a way to support income diversification through remittances (Gemenne and Blocher, 2017). High levels of poverty mean that a large part of African populations do not have sufficient resources to be mobile (Borderon et al., 2019; Leal Filho et al., 2020b). The poorest households, conversely, will typically lack the resources that would allow them to migrate in ways that maintain an acceptable standard of living, and may find themselves unable or unwilling to move in the face of climate change impacts (Sam et al., 2021).

There is *high agreement* and *robust evidence* that climate change impacts also have a major influence on key enabling conditions for migration, such as sociodemographic, economic and political factors (Abel et al., 2019; Borderon et al., 2019), and that climate change impacts to development and governance may affect how people migrate (Wrathall et al., 2019; Cross-Chapter Box MIGRATE in Chapter 7). Mobility, which was considered as most viable climate change adaptation strategy to poor pastoralists, is restricted due to the political marginalization of pastoral groups, land privatization, governments' decentralisation policies, and plantation investment (Blench, 2001; Randall, 2015; Leal Filho et al., 2020b). While migration can be an adaptation response to climate change impacts (Black et al., 2011; Gemenne and Blocher, 2017), climate change impacts can also act as a direct driver of forced displacement (Marchiori et al., 2012). Societal groups that are forced to involuntarily migrate in response to climate change impacts may lack resources to invest in planned relocation mainly due to lack of good governance systems (Reckien et al., 2018). For people displaced by climate change impacts, policy interventions have a determining influence on migration outcomes, such as the numbers of migrants, the timing of migration and destinations (Gemenne and Blocher, 2017; Wrathall et al., 2019).The process of displacement and forced migration leaves people more exposed to climate change related extreme weather events, particularly in low income countries which often host the highest number of displaced people (Adger et al., 2018).

Climate change may be accelerating livelihood transitions and migration in ways that accelerate urbanization (Adger et al., 2020). Although a range of climate hazards are noted for accelerating rural-to-urban livelihood transitions (see Cross-Chapter Box MIGRATE in Chapter 7), a key theme to emerge across many case studies is the impact of rising temperatures on agricultural productivity (Mueller et al., 2014; Cattaneo and Peri, 2016; Call et al., 2017; Wrathall et al., 2018). In other words, when people cannot farm due to rising temperatures (and related stressors), they migrate. In this context, migration as a livelihood diversification strategy may evolve and take multiple forms over time (Bell et al., 2019), such as temporary migration (Mueller et al., 2020), seasonal migration (Gautam, 2017), or permanent migration (Nawrotzki et al., 2017), but generally conforms to existing patterns of migration (Curtis et al., 2015).

A key concern for the poor are climate change impacts that undermine livelihood diversification and resilience, narrowing the set of available livelihood alternatives (Tanner et al., 2015; Bailey and Buck, 2016; Perfecto et al., 2019).

8.2.1.5 The long-lasting effects of climate change on poverty and inequality

New studies document the long-term effects of climate change impacts on people's livelihoods that persist long after a hazard event. For example, in Mali, 30 years after 1982-1984, the period of most intense drought during the protracted late 20th century drying of the Sahel, the impact of drought on livelihoods and food security is still recognizable. The most food secure households associated with persistent drought induced famine were those that diversified livelihoods away from subsistence agriculture during and after the famine (Giannini et al., 2017). Meanwhile, a larger fraction of households with fewer livelihood activities, lower food security with higher reliance on detrimental nutrition-based coping strategies (such as reducing the quantity or quality of meals) were those unable to diversify livelihoods 30 years previously. Sufficient time has passed to consider the long-term outcomes for the poor in extreme cases featured in previous IPCC assessments, including Hurricane Katrina (2005) (e.g., Fussell, 2015; Raker et al., 2019) and Hurricane Mitch (1998) (e.g., Alaniz, 2017), forewarning that recovery is complex and requires significant sustained long-term investment in 'soft' aspects of development, including community organization and mental health (O'Neill et al., 2020; Fraser et al., 2021).

The IPCC Special Report on 1.5°C concluded that climate change has already increased the probability and intensity of individual extreme weather events occurring(Roy et al., 2018), and our new baseline consideration should be that serious climate change impacts are already being experienced by the most vulnerable, with long-term implications for development (Box 8.1; Roy et al., 2018). In both developing and developed countries the disproportionate impacts of the compounding effects of climate change on development are felt by the most disadvantaged. For example, the residual impacts of storms like Hurricane Maria (see Section 8.2.1.1) illustrate how rising temperatures, extreme weather events, coral bleaching, and sea level rise come together and create compounding hazard-cascades to leave long-lasting effects on the lives of the poor, as well as their food and water security, health, livelihoods and prospects for sustainable development—not only in developing countries (Adger et al., 2014; Olsson et al., 2014; Hoegh-Guldberg et al., 2018; Roy et al., 2018), but also in highly inequitable industrialized countries within the same region (Gamble et al., 2016). According to the US National Climate Assessment (USGCRP, 2018). damages caused to communities by Hurricanes Irma and Maria in 2017 sparked unprecedented humanitarian crises. Hurricane Maria, a category 5 hurricane, passed through Dominica, St Croix, and Puerto Rico and is considered the worst climate disaster in recorded history to affect those islands (Rodríguez-Díaz, 2018). Approximately 200,000 people migrated from Puerto Rico to the mainland US in the weeks following the storm (Alexander et al., 2019). Estimates for direct and indirect casualties in Puerto Rico point out a total of 4645 excess deaths, equivalent to a 62% increase in the mortality rate (Kishore et al., 2018). The example of Hurricane Maria and Puerto Rico illustrates that vulnerability is part of a long history of discrimination and colonial governance which led to greater impacts on the island (Moleti et al., 2020). In Puerto Rico, the economic costs of the collapse of the island's energy, water, transport, and communication infrastructures are estimated to range from $25 to $43 billion (USD in 2017), further indebting the island, and putting its long-term development at risk. Meanwhile the economic impacts of Hurricanes Irma and Maria on the Caribbean region are estimated between $27 and $48 billion, and have long-term implications for state budgets, infrastructure supporting development of the poorest.

New evidence provides little expectation of net positive impacts of climate change for the poor (Hallegatte et al., 2015). Nevertheless, some benefits of climate change adaptation include improved disaster preparedness, the accumulation of social assets, economic benefits of agricultural diversification, and benefits associated with migration, as well as the political benefits of collective action (Pelling et al., 2018). In contrast, wealthier tiers of society facing climate change impacts are more able to liquidate assets to avoid losses from climate change, to be formally compensated for losses (Fang et al., 2019), and employ social positions to leverage gains from adaptation (Nadiruzzaman and Wrathall, 2015).

The poor frequently suffer the direct and indirect impacts of climate change, including the cost of adopting adaptive measures (Atteridge and Remling, 2018; Bro et al., 2020). Costs to the poor may also include the secondary impacts of first order adaptation activities, including the livelihood consequences to people migrating due to climate change impacts. The poor frequently bear indirect impacts of adaptation interventions, such as flood protection barriers, which may displace flood waters away from high-income populations toward poorer communities (Mustafa and Wrathall, 2011). Adaptation programming may also indirectly affect the poor as public resources are drawn into risk reduction interventions, and away from spending on social welfare and safety nets (Eriksen et al., 2015). Measures to enhance social welfare and safety nets themselves help enhance the poor's resilience to climate impacts because they focus on non-climatic stressors affecting livelihoods, which interact with climate hazards. Therefore, diverting attention away from safety nets may in fact undermine adaptation efforts (Leichenko and O'Brien, 2019; Tenzing, 2020).

[START BOX 8.1 HERE]

Box 8.1: Climate Traps: A Focus on Refugees and Internally Displaced People

A population of concern, extremely vulnerable to climate change impacts with limited capacity to adapt, are those displaced and resettled in the course of conflict or disaster, either internally or across borders (Burrows and Kinney, 2016). The risk for refugees and internally displaced people (IDPs) is two-fold: on the one hand, refugee and IDP settlements are disproportionately concentrated in regions (e.g., Central Africa and the Near East) that are exposed to higher-than-average warming levels and specific climate hazards, including temperature extremes and drought. On the other, these populations frequently inhabit settlements and legal circumstances that are intended to be temporary but are protracted across generations, and at the same time, face legal and economic barriers on their ability to migrate away from climate impacts. (Adams, 2016; Devictor and Do, 2016). Large concentrations of these settlements are located in the Sahel, the Near East and Central Asia, where temperatures will rise higher than the global average, and extreme temperatures will exceed thresholds for safe habitation (Figure Box8.1.1). Already largely dependent on state and humanitarian intervention, these immobile populations will require interventions to safely maintain residence in areas exposed to climate hazards. Adaptation planning should prioritize immobile populations living in an already destabilized development context, on improving their capacities to deal with the further consequences of climate change.

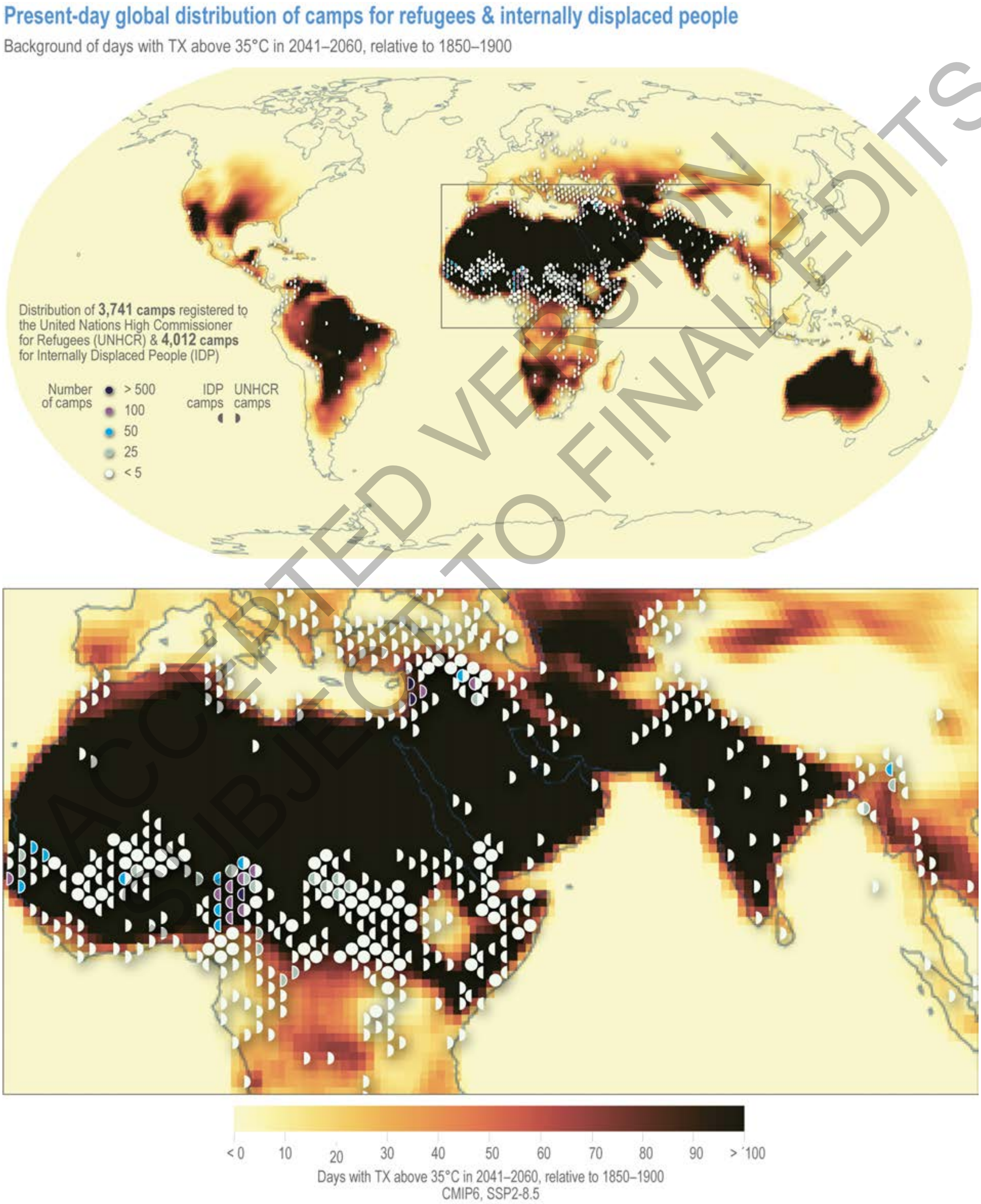


Figure Box 8.1.1: The global distribution of the United Nations High Commissioner for Refugees (UNHCR) refugee and internally displaced people (IDP) settlements (as of 2018) overlaid with annual mean near surface air temperature (°C) in 2040-2059 under RCP8.5.

Refugees and IDPs fit into a global category of extremely structurally vulnerable people that are missing from standard poverty assessments, officially uncounted or uncountable using traditional census and survey methods (Carr-Hill, 2013). These include highly mobile populations, internally displaced by war and environmental hazards (UNHCR, 2020; IDMC, 2021); itinerant labourers; urban poor in informal settlements (Lucci et al., 2018); unauthorized migrants living in countries where they do not hold citizenship (Passel, 2006); guest workers (Reichel and Morales, 2017); the homeless and institutionalized (Caton et al., 2007); rural nomadic, pastoralist or landless populations (Randall, 2015); Indigenous Peoples and forest dwelling communities (Galappaththi et al., 2020); among others. Frequently living without social safety nets, such as health care and formal education, these uncounted or 'missing millions' are vulnerable to problems associated with acute and chronic poverty, such as the spread of infectious disease and malnutrition (Ezeh et al., 2017). Because these 'missing' populations are not counted, they are frequently not a part of planning (Carr-Hill, 2013), including adaptation planning. In any particular national context, these missing populations may represent a small fraction of the population (about 5% in South Asian countries), however cumulatively hundreds of millions of people may be missing from official estimates (Carr-Hill, 2013). Over the last decade, techniques for estimating the locations, numbers and socioeconomic status of missing populations have moved beyond census and nationally representative household surveys, leveraging advances in satellite imagery (Kuffer et al., 2016; Bennett and Smith, 2017) and data from mobile digital devices (Jean et al., 2016; Xie et al., 2016; Steele et al., 2017).

[END BOX 8.1 HERE]

8.2.1.6 Interactions between climate hazards and social-ecological thresholds

Climate change threatens to rapidly transform unique and threatened ecosystems (RFC1), such as tropical rain forests, coral reefs, arctic and high-mountain ecosystems, as well as the Indigenous and forest-dwelling people whose livelihoods, cultures and identities are dependent on these ecosystems. In recent years, the case of Amazonia illustrates how such systems are transforming, with detrimental consequences for Indigenous Peoples, and the vital role that Indigenous Peoples serve in protecting vulnerable ecosystems (Ricketts et al., 2010; Box 8.6). Globally, Indigenous territories cover the greatest area of remaining tropical forest in comparison to other protected areas, and encompass the bulk of Earth's biodiversity, and are the locus for a number of key ecosystem services across spatial and temporal scales(Walker et al., 2020). Specifically, in 2014 Indigenous territories and other protected areas represented the equivalent of 58.5% of all the carbon stored in the Brazilian Amazon biome and had the lowest deforestation rate (2.1%) and fire incidences, evidencing the effectiveness in safeguarding important ecosystems services and wellbeing (Nogueira et al., 2018). It is estimated that Indigenous territories in the Brazilian Amazon contribute at least US$5 billion each year to the global economy through food and energy production, greenhouse emissions offsets, and climate regulation and stability (Siqueira-Gay et al., 2020). Given the high incidence of poverty of the Amazonian countries and high proportion of traditional and Indigenous Peoples, remoteness and neglected governance place these unique ecosystems and Indigenous populations as highly vulnerable to climate change impacts (Pinho et al., 2014; Brondízio et al., 2016; Mansur et al., 2016; Kasecker et al., 2018). Despite their importance, the survival of Indigenous Peoples in the Amazon is on the brink in the wake of increasing deforestation, land conflicts and invasions, cattle ranching, mining, fire incidence, health problems, and human rights violation (Ferrante and Fearnside, 2019). There is increasing evidence that both economic and non-economic losses and damages are currently and will be unevenly experienced by populations in vulnerable conditions, such as children, women, Indigenous Peoples and traditional communities (Pinho, 2016; Lapola et al., 2018; Roy et al., 2018; Eloy et al., 2019; Machado-Silva et al., 2020). Increasing wildfires inside protected areas, in particular, territories of Indigenous Peoples and traditional communities, is worrisome and presents challenges for the future of unique and threatened socio-ecological systems, and the ecosystem services they provide. The Amazonian Indigenous territories and protected areas can deliver protection of biodiversity and important ecosystem services if appropriate governance mechanisms are in place and their land tenure rights and livelihoods are secured (Steege et al., 2015). The role of enabling environments is discussed in Section 8.5.

8.2.1.7 Linkages between climate change impacts and sustainable development goals (SDGs)

Many of the observed outcomes of climate change, for example migration, are also outcomes of multidimensional poverty in low income countries (Burrows and Kinney, 2016). Future impacts may be better understood if the vulnerability and the capacity for adaptation is understood to be rooted in a sustainable development context (see Box 8.2). The UN Sustainable Development Goals (SDGs), which aim to reduce poverty and inequality, and identify options for achieving development progress, also provide insight on reducing climate vulnerability (United Nations, 2015). Firstly, climate change impacts may undermine progress toward various SDGs (medium confidence), primarily poverty reduction (SDG1), zero hunger (SDG2), gender equality (SDG5) and reducing inequality (SDG10), among others (*medium evidence, high agreement*). In both developing and high-income countries, climate change hazards in connection with other non-climatic drivers already accelerate trends of wealth inequality (SDG 1) (Leal-Filho et al., 2020). Climate impacts on SDGs illustrate the complex interrelations between development. For example, in regions encountering obstacles to SDGs, characterized by high levels of inequality and poverty, such as in Africa, Central Asia and Central America, climate change is likely to exacerbate water insecurity (SDG 6), which may then also drive food insecurity (SDG 2), impacting the poor directly (i.e. via crop failure), or indirectly (e.g. via rising food prices) (Conway et al., 2015; Hertel, 2015; Cheeseman, 2016; Rasul and Sharma, 2016). There is a pressing need to address poverty issues, since these may negatively influence the implementation of all SDGs (Leal Filho et al., 2021a).

At the same time, there is increasing evidence that successful adaptation depends on equitable development and climate justice; for example, gender inequality (SDG 5) and discrimination (SDG 16) are among the barriers to effective adaptation (*high confidence*) (Bryan et al., 2018; Onwutuebe, 2019; Garcia et al., 2020). Likewise, both climatic and non-climatic threats to development, such as conflict (SDG 16), may seriously undermine capacity to formulate and implement adaptation policies, and design planning pathways (Hinkel et al., 2018). The risk of conflict associated with climate change has great potential to undermine other development goals (Box 8.4). Where sustainable development lags and human vulnerability is high, there is also often also a severe adaptation gap (Figure 8.12; Birkmann et al., 2021a). The SDGs may provide important cues on how to close the adaptation gap: climate action needs to be prioritized where past and future climate change impacts threaten SDGs, and where investment in SDGs improve capacity for adaptation (see Section 8.6).

[START BOX 8.2 HERE]

Box 8.2: Livelihood Strategies of Internally Displaced Atoll Communities in Yap

On Yap Island in the Federated States of Micronesia, displaced atoll communities have been under considerable pressure due to climate change. This is because of the island's vulnerability, as a result of its weak economic status, and the little access it has to technologies that may support adaptation efforts. This trend is seen in many Small Island Developing States (SIDS) (see also Chapter 15). On small islands and remote atolls where resources are often limited, recognizing the starting point for action is critical to maximizing benefits from adaptation. They do not have uniform climate risk profiles, and not all adaptations are equally appropriate in all contexts (Nurse et al., 2014) (*high confidence)*.

The recurrences of natural hazards (e.g., El Nino driven tropical storms, associated coastal erosion and saltwater or seasonal droughts leading to water scarcity) and crises threaten food and nutrition security through impacts on traditional agriculture, leading to income losses and causing the forced migration of coastal communities to highlands in search of better living conditions. As many of the projected climate change impacts are unavoidable, implementing some degree of adaptation becomes crucial for enhancing food and nutrition security, strengthening livelihoods, preventing poverty traps, and increasing the resilience of coastal communities to future climate risks (Krishnapillai, 2018).

With support from the US Department of Agriculture and USAID, the Cooperative Research and Extension wing of the College of Micronesia- Federated States of Micronesia Yap Campus has been providing outreach, technical assistance and extension education to regain food and nutrition security and stability by improving the soil and cultivating community vegetable gardens as well as indigenous trees and traditional crops. This program implemented a three-pronged adaptation model to boost household and community resilience under harsh conditions on a degraded landscape, hence addressing poverty risks and promoting more sustainable livelihoods (Meyer and Jose, 2017).

The following three strategies- a) gender-focused capacity development on soil health management, b) good practices in Sustainable Land Management and c) income generation activities were employed to mitigate crop production losses and increase resilience to climate influenced hazard events within the 258 hectares of degraded lands in Gargey Village.

The project first focused on increasing the capacity development for 1,100 residents of Gargey Village, including women and youth, in order to create a base of community knowledge for soil health management. Training on soil health management including the following: use of cover crops and improved fallow, legumes, composting and agroforestry systems, mulching, minimum tillage, and contour farming, as well as altering production practices (planting time, spacing, pest and disease, harvesting time), alternative crop production methods (container gardening, raised bed gardening, small plot intensive farming), hands-on training on compost preparation, and seed germination.

Dissemination and use of good practices in Sustainable Land Management (SLM)

Following capacity building, the project trained villagers on the use of SLM practices to further soil resilience during ongoing and acute precipitation events. The SLM practices focused on volcanic soil management and compost preparation and use, along with the planting of native trees and crops. The protective soil cover was improved through cover crops, crop residues or mulch, and crop diversification through rotations. Local salt-tolerant crop varieties were introduced. Seed packets and seedlings were distributed to ensure a continuous supply of resilient traditional plants and to provide for sustainable post-disaster recovery.

Income generation activities

The project also included training to increase the incomes of households by training household members in the cultivation of vegetables using various alternative crop production methods. Households were then able to sell their vegetables in the local markets.

Less hunger and more cash from leafy vegetables is a concept adopted at the household level to not only reduce poverty, but also to empower displaced communities to address the dilemma of malnutrition. Practices include growing a variety of nutritious vegetables as part of a large crop portfolio and using alternative crop production methods, such as small-plot intensive farming using container gardening or raised-bed gardening (Krishnapillai and Gavenda, 2014). In addition, focusing efforts on increasing the sustainable production of staple crops confers significant nutritional benefits.

More households in the settlements are consuming vegetables since home gardeners started harvesting regularly and sharing their produce with extended families or selling them for income generation. The location-specific, community-based adaptation model improved food and nutrition security and livelihoods (Krishnapillai, 2017). People can access more nutritious and reliable food sources, and they are growing their own food and selling their surplus, creating new optimism about their future.

The climate-smart agriculture package increased land cover by more than 50% within Gargey village. This includes the planting of 42 varieties of native trees and crops. Current major crops that are being successfully grown at this location include coconut, breadfruit, mango, noni, chestnut, pineapple, sugarcane, land taro, tapioca, and sweet potato, among others. There have been additional benefits in terms of improvement in water availability. These activities directly benefited the resilience and food security of more than 1,000 residents in Gargey Village, and lessons learned from this project have helped to scale up similar projects at 3 locations in Yap that have experienced equivalent climate-damaging processes.

Overall, this case study illustrates the benefits of promoting resilient crop production in Gargey Village, as an example of displaced atoll communities. Innovative and sustainable CSA strategies offered broader insights and lessons for enhancing adaptive capacity and resilience, on a degraded landscape. The coherent strategies and methods employed strengthened livelihood opportunities by improving access to services, knowledge, and resources. By its concurrent focus on enhancing food security through traditional crops, coupled with nutrient-rich vegetables, promoting rainwater-harvesting systems and water conservation, and promoting resilient household livelihood opportunities, atoll communities brought together crucial elements needed to reduce vulnerabilities, and to better cope with disasters and climate extremes while embracing the traditional culture. The location-specific yet knowledge-intensive CSA methods deployed, offered opportunities for atoll communities to revitalize themselves, overcoming barriers while adjusting to new landscapes.

[END BOX 8.2 HERE]

8.2.2 Poverty-environment traps and observed responses to climate change with implications for poverty, livelihoods and sustainable development

Across all geographical regions, there is evidence that anthropogenic climate change is hindering poverty alleviation and thereby constraining responses to climate change in five main ways:

a) by worsening living conditions (Hallegatte et al., 2017; Hsiang et al., 2017),
b) by threatening food and nutrition security due to undernutrition and reduced opportunities for income generation (Burke et al., 2015),
c) by disrupting access to basic ecosystems services such as rainwater, soil moisture (reducing the productivity of agricultural land) or via the depletion of habitats (e.g., mangroves, fishing grounds) that particularly vulnerable and poor people are depending on (Malhi et al., 2020),
d) by creating favourable conditions for the spread of vector-transmitted diseases (Liang and Gong, 2017).
e) and by threatening underlying gender inequalities exacerbated by climate impacts such as access and control to productive inputs and reinforcing social-cultural norms that discriminate against gender, age groups, social classes and race (Singh et al., 2019b).

Responses to observed impacts such as glacier melt, sea level rise and increases in the frequency of extreme weather events such as droughts, hurricanes and floods need to take into account how they influence other policy issues and sectors, including poverty alleviation, human health and well-being (Orimoloye et al., 2019), water/energy and the built environment (Andrić et al., 2018), transportation and mobility (Markolf et al., 2019), agriculture (Hertel and Lobell, 2014) and biodiversity/ecosystems (Nogués-Bravo et al., 2019), only to mention a few. Recent literature provides evidence that impacts of climate change together with non-climatic drivers can create poverty-environment traps that may increase the probability of long-term and chronic poverty (Figure 8.4; Hallegatte et al., 2015; Djalante et al., 2020; Malhi et al., 2020; McCloskey et al., 2020) (*high confidence*) (see Figure 8.4).

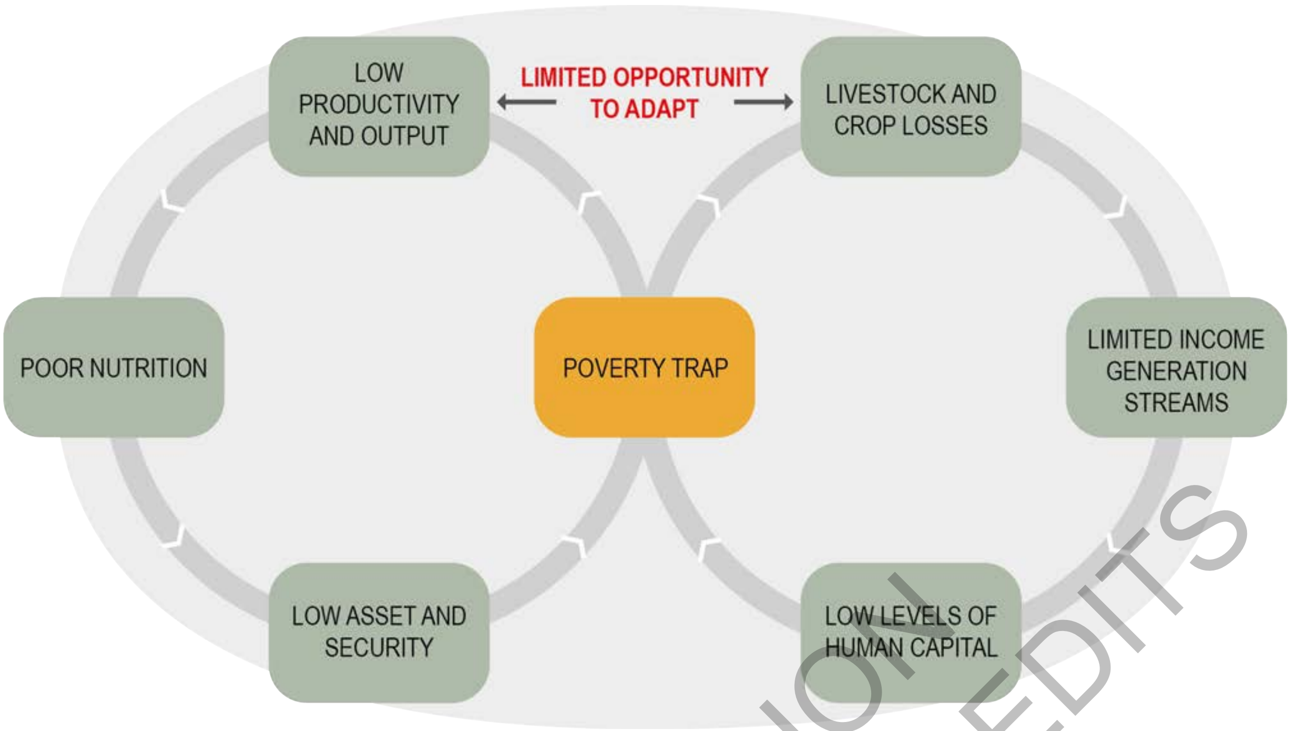


Figure 8.4: Schematic representation of a poverty-environment traps that can increase chronic poverty.

In addition, observed climate change responses, including autonomous and planned adaptation, can exacerbate poverty and vulnerability (Eriksen et al., 2021). There is *robust evidence* that planned responses to climate change, such as large scale adaptation projects, in some context can also increase vulnerability due to the reinforcement of inequalities and the effects of further marginalization (Fritzell et al., 2015; Eriksen et al., 2021). There is increasing *evidence* that also the responses to indirect impacts of climate change, such as to shifts in marine or terrestrial ecosystems due to climate change (Seddon et al., 2016) affect different groups differently and impact poverty and livelihood security. Apart from influences on agriculture trends (Reichstein et al., 2014) and changes in yields (Reyes-Fox et al., 2014; Craparo et al., 2015), climate change has significant (direct and indirect) impacts on livelihood assets and resources such as forests, livestock production and fisheries, which may undermine the livelihoods security in the medium- and long-run.

[START BOX 8.3 HERE]

Box 8.3: COVID-19 Pandemic

During the COVID-19 pandemic, countries such as India were affected by with hydro-meteorological hazards (Raju, 2020) making it extremely difficult to handle a public health crisis in the context of compounding risks and cascading hazards (Phillips et al., 2020). The COVID-19 pandemic can increase the adverse consequences of climate change, since it has the potential to delay some key adaptation actions. On the other hand, the pandemic also highlights the importance of better preparedness to the impacts of climate change (Djalante et al., 2020). Overall, the COVID-19 pandemic has worsened the economic situation within many countries and local communities particularly for already marginalized groups (Gupta et al., 2021). The accumulation of crises, such as the COVID-19 pandemic alongside climate change impacts, underscore the fact that stressors do not occur in isolation, but are interlinked, with clear implications for structural vulnerability and adaptation options available to the poorest (Sultana, 2021). Responses to COVID-19 has led to significant economic and social distress within and across societies and local communities, especially in poorer countries. The direct health and economic impacts of the lockdowns have further limited the ability of many people across the developing world to pursue income-generating activities, and sustain livelihoods that are already affected by climate hazards. In addition, poor or most vulnerable groups face further marginalization due to misinformation that these groups transmit the virus to other wealthier groups and areas. The pandemic has intensified inequalities in both developing countries (FAO, 2020) and in industrialised nations (Anderson et al., 2020; McCloskey et al., 2020) whereby vulnerable groups are especially affected (Raju et al., 2021). Whereas different models and scenarios contain different data and figures, an agreement exists that it is likely that socio-economic impacts are particularly severe within selected global regions and areas that are already characterized by a rather high level of human vulnerability (see also Section 8.3). This also implies that the capacity of people to prepare for present and future climate change impacts will further decrease within these countries and population groups under the direct and indirect consequences of the COVID-19 pandemic.

Moreover, the COVID-19 pandemic has not only influenced climate change research (Leal Filho et al., 2021b) but is also influencing the capacities of governmental institutions and nations to support planned adaptation and poverty reduction favouring the most vulnerable groups, since the crisis also means among other issues a significant reductions in tax revenues (Clemens and Veuger, 2020). COVID-19 may also force people to seek alternative sources of income that can lead to the further erosion of long term adaptive capacities. In many settings, the pandemic has had significant impact on businesses and SMEs (Schmid et al., 2021). The important role of governmental support for buffering crises and periods of income loss of individual households (e.g., unemployment) and private businesses (e.g., SMEs) has also been demonstrated during the COVID-19 pandemic in OECD countries (OECD, 2020b).

Livelihood disruptions and an increasing probability of higher levels of poverty and of structural vulnerability in various countries have already been observed (Laborde et al., 2020b). These vulnerabilities and the new layers created by the pandemic must be seen with an intersectional lens (Raju, 2019; Sultana, 2021).

In addition, the COVID-19 pandemic has also revealed the unequal access to vaccine and the importance of national state institutions to buffer negative impacts, for example of the lock downs or in terms of unemployment. The COVID-19 pandemic recovery also sets some basis for a stronger narrative towards a green recovery approach (Djalante et al., 2020; Forster et al., 2020).

[END OF BOX 8.3]

8.2.2.1 Characteristics of responses

Many of the observed responses to climate change aim to reduce exposure of people to climate-related hazards, such as flood defences, sea walls and embankments (Gralepois et al., 2016), rather than aimed at specifically addressing structural vulnerability to climate change, which means the root causes of vulnerability (e.g., Mikulewicz, 2020; McNamara et al., 2021a). Evidence emerges that responses to impacts of climate change should consider next to the physical climate event, also historical, institutional root causes that make people or systems vulnerable. However, addressing structural vulnerability must be balanced with the political context and the range of options available to people, communities or countries (see Section 8.3). Political frameworks need to consider both types of responses, to revive democratic debate and citizenship (Pepermans et al., 2016). In addition to reducing poverty and vulnerability, planned climate change responses must also be intersectoral, in order to increase their effectiveness. This requires higher levels of vertical and horizontal coordination and integration (GIZ, 2019). Horizontal coordination encompasses for example the integrated coordination of responses to climate change across different sectors, which requires suitable governance structures and processes that allow for such a coordination (Di Gregorio et al., 2017; Burch et al., 2019). Vertical integration is needed in order to ensure that effective responses also include different levels of governance and benefit from knowledge at different scales. The inclusion of local knowledge within national or provincial adaptation strategies requires such linkages and vertical coordination. Overall, there is an increasing body of literature that highlights the importance of improved integration and coordination also in order to promote a higher effectiveness of strategies and an improved consideration of social justice and climate justice when designing and implementing responses (Levy and Patz, 2015).

However, evaluating the effectiveness, social impacts and social justice of climate change responses is not uniform across locations, nations and regions for three principal reasons:

a) temporal dimensions of responses: effective and appropriate climate change responses require that strategies and responses are tested in a specific context and that ongoing learning and adaptive management is a necessary to avoid maladaptation or other unintended consequences (Eriksen et al., 2021),

b) goal of responses: responses may have distinct and locally specific goals, such as reducing vulnerability(Sarker et al., 2019), which is distinct from increasing resilience (Alam et al., 2018). Vulnerability reduction and the increase of resilience (i.e., raising the ability to cope) are two different goals and often involve different processes, and
c) level of responses: there is a need to ascertain the relevant level at which the responses are needed or expected (e.g., the individual level, community level, regional level). This analysis, however, also needs to consider the differential capacities of people, for example, the limited capacities of poor people or constrained capacities of most vulnerable countries (see also Section 8.3).

Effective responses to climate change impacts for one group could impose higher costs and negative consequences for other groups, in terms of shifts in exposure and vulnerability. This category of response is known as maladaptation. Maladaptation actions defined in the IPCC SR1.5°C (IPCC, 2018b) and in the Land Report (IPCC, 2019a) are the ones that usually have unintended consequence, and can lead to increased negative risk to poor population mostly in the global south to climate hazards by either increasing greenhouse gas (GHG) emissions and or by increasing the vulnerabilities to climate change with diminished welfare, now and in the near future (Roy et al., 2018). For example, migration to urban centres can represent a significant adaptation opportunity for the migrants themselves, but can also increase the vulnerability of their community of origin or destination (for example, through a depletion of the workforce or an addition pressure on environmental resources and infrastructure respectively) (Gemenne and Blocher, 2017). Some types of observed responses to climate change may not yield long-term benefits. For example, food imports during droughts or adverse climate conditions are not a fully adequate response, since they may alleviate a problem on the one hand (i.e., an imminent food shortage due to crop failure), but on the other, lead to no long-lasting improvements in physical conditions and create new dependencies that can increase vulnerability in the long-run (Zimmermann et al., 2018).

In the AR5, the maladaptation outcomes emerge when impacts of climate change impacts and risks are disproportionately born by the poorest populations (Olsson et al., 2014). Since then, most maladaptation evidence emerges as a consequence of failure to address root causes of vulnerabilities that emerge under high and multiple forms of inequalities. In fact, the literature shows that adaptation practices can indeed redistribute vulnerabilities and increase risks to already poor and marginalized people with risk to maladaptation outcomes mainly in the Global South countries (Atteridge and Remling, 2018).

The maladaptation outcomes also emerge when responses are not equitable at the policy level, and exacerbate the precarity of vulnerable populations by excluding them from benefits and support, while attending to the needs of people of the most enfranchised segments of society (Thomas and Warner, 2019); Asplund and Hjerpe 2020). In Tanzania, the political marginalization of pastoralist access to critical riparian wetlands and increasing expansion of agriculture may result in adaptation pathways that heighten risk for these groups while reducing risk for others (Smucker et al., 2015). Salim et al. (2019) found that adaptation to flooding in Jakarta privileges political economic elites, while poor infrastructure in poorest neighbourhoods exacerbates loss of assets, housing and displacements (Salim et al., 2019). In Bangladesh, intense and consecutive flooding led to that national and regional-level adaptation plans, that resulted in maladaptive trajectories as local poverty context and precarities of properties are not carefully considered and disconnected from local autonomous practice (Rahman and Hickey, 2019).

Overall, the assessment shows that understanding impacts of climate change should not be limited to the analysis of direct impacts or physical changes under different climatic conditions, but needs also account for the distributional effects that responses to climate change may imply. For example, responses implemented in order to benefit one sector or social group (e.g., farmers), should not undermine the wellbeing of others (e.g., pastoralists). Documented cases of maladaptation (see Eriksen et al., 2021), hint towards the fact that responses to climate change can exacerbate in some cases existing inequality and may discourage other types of responses (see also Section 8.5 and 8.6). Furthermore, responses to similar climate change impacts and hazards may be extremely differentiated according to various social contexts (see Section 8.3). In some cases responses to climate change (e.g., relocation programmes) can even trigger social tipping points when climate change responses lead to major social transformations, such as forced displacement (see Section 8.4).

Also the influence of new global phenomena, such as urbanization, issues of urban health (Schmid and Raju, 2020) and the consequences of the COVID-19 pandemic need to be considered when assessing actual and potential consequences of different responses to climate change. For example, inequalities, vulnerabilities and poverty pockets are expected to change and increase, particularly in urban areas in countries with rapid urbanization processes and high levels of poverty (Djalante et al., 2020), hence urban and urbanization trends need more attention. Urbanization processes add another level of complexity (Raju et al., 2021). This is particularly the case in rapidly growing medium-sized cities in Africa that at present do not have sufficient the resources to cope and adapt and to implement climate sensitive land-use planning (Birkmann et al., 2016).

[START BOX 8.4 HERE]

Box 8.4: Conflict and Governance

Climate change impacts carry the risk of amplifying or aggravating existing tensions within and between communities or countries (Sakaguchi et al., 2017). There is however little evidence for a universal direct causal linkage between climate change and violent conflicts (Mach et al., 2019). The triggering of conflicts related to climate impacts is strongly determined by contextual factors, such as the type of government or the level of development (Mach et al., 2019). A study of 156 countries (Abel et al., 2019) showed that an increase in periods of drought exacerbate the risk of conflict, especially in democratic countries. This influence was particularly marked during the period 2010-2012 in countries of Western Asia and Northern Africa which were undergoing political transformations such as the Arab Spring. Conflict can then represent people's discontent in governments' inefficient responses to climate impacts (Abel et al., 2019). Research has noted conditions under which climate change can increase risk of armed conflict, which include ethnic exclusion, agricultural dependence, large populations, insufficient infrastructure, dysfunctional local institutions, and low levels of development (von Uexkull et al., 2016; Ide et al., 2020).

Since the AR5, there is *robust evidence* of the socially-destabilizing measures and high-risk income alternatives that the world's poorest commonly take to cope with the impacts of climate change on livelihoods (Blattman and Annan, 2016). To avoid impoverishment, households often pursue risky livelihood alternatives, with high potential for return on investment (Sovacool et al., 2018), but which in some cases undermine environmental quality (Bolognesi et al., 2015), violate laws (Ahmed et al., 2019), contradict social norms (Hagerman and Satterfield, 2014), erode institutions (Sovacool et al., 2018), or affect intra- and inter-community cooperation (Nadiruzzaman and Wrathall, 2015). At the same time, a narrowing of livelihood options carries a strong potential for participation and association with violent non-state organizations and movements, either criminal or ideological (Nett and Rüttinger, 2016). In order to reduce the risk of instability and violence associated with climate change, a broadening of livelihood options among the most vulnerable people appears as an effective policy approach (Miguel et al., 2004).

The determinants of violence in the context of climate shocks are primarily poor institutional planning and response to impacts, such as the capacity of a government to respond to and manage environmental risk (Selby et al., 2017). In Latin America, for example, evidence on social conflicts related to disputes over access water use in the context of drought and decreasing water availability point to institutional failures, such as poor, inequitable or corrupt water governance (Poupeau et al., 2017). Such observation is not confined to low income countries. In industrialised countries, failure of governments to address climate change is *likely* to fuel discontent, a condition in which violent outcomes are possible (Ide et al., 2020).

In this regard, specific attention ought to be paid to how responses to climate change exacerbates inequalities within societies and create tensions between different groups—typically between those who are able to protect themselves from climate change impacts and those who do not have sufficient resources and/or are not prioritised in the responses to climate change. Frequently the possibility of migration from climate change is conflated with conflict outcomes from climate change; however there is *limited evidence* and *low agreement* that climate change and migration will result in increased conflict (Okpara et al., 2016b), while there is *robust evidence* and *medium agreement* that climate change can exacerbate existing tensions, which can in turn result in political violence and an increase in asylum-seeking (Marchiori et al., 2012). In the future, conflict in the context of climate change impacts may increase the number of migrants seeking asylum, although at present there is scant empirical evidence for this (Schutte et al., 2021). Recent evidence also provides support for social conflict around inequitable climate mitigation policy as well (e.g., fossil fuel subsidies and emissions reductions targets) (Rentschler, 2016).

In recent years, research on the climate-security nexus has developed considerably, and has highlighted risks pertaining to conflicts, geo-political rivalries, critical infrastructure, terrorism or human security (Gemenne et al., 2014). While different studies have identified have identified strong past correlations between climatic variations (of temperature and rainfall in particular) and the occurrence of violent conflicts (Hsiang et al., 2013), while others have stressed the need for stronger explanatory models or the risk of a selection bias (Benjaminsen et al., 2012; Solow, 2013; Buhaug et al., 2014).

While climate change may increase armed conflict risks in certain contexts (Mach et al., 2019), responses to climate change will be crucial to mitigate these risks. Poor institutional responses can directly drive violence, and there is *robust evidence* that inequitable responses further exacerbate marginalisation, exclusion or disenfranchisement of some populations, which are commonly recognized drivers of violent conflict.

As a ray of hope, *robust evidence* suggests environmental problems (related to climate change) can be dealt with cooperatively, hence leading to more positive and peaceful relations between groups (Wolf et al., 2003; Ide, 2019). To avert violent outcomes induced by climate change, stronger local and national climate adaptation institutions within vulnerable societies, and stronger cooperative resource governance mechanisms between vulnerable countries (such as transboundary water governance agreements) are needed.

[END BOX 8.4 HERE]

Table 8.1 and Table 8.2 present a summary of a set of common climate change responses observed, classified according to their main approach. All these responses demand a certain level of commitment, the support of adequate policies, and enough budget for their implementation (Archie et al., 2018). The observed climate change adaptation responses—differentiated along urban and rural settings—underscore the very different nature of various responses and the need for cross-sectoral approaches.

Table 8.1: Selected observed climate change adaptation responses in urban and rural areas commonly associated with positive implications for poverty, livelihoods and sustainable development

Modality of response	Impacts to urban communities	Impacts to rural communities (e.g., farmers, pastoralists)
Integrated natural resource management (e.g., van Noordwijk, 2019)	Better conservation of green areas and reduced exposure to floods	Conservation of natural resources e.g., water, soil, pasture, forest, wildlife, biodiversity, aquatic life.
Disaster Risk Management (e.g., Mall et al., 2019)	Pre-disaster risk management and post-disaster risk management measures reduce loss of life and damage to property	Disaster risk management may play an important role to avoid or limit the impacts of floods, droughts and other extreme events
Structural/physical improvements (e.g., Vallejo and Mullan, 2017)	Improving physical/structural measures to prevent property damages and foster ecosystems integrity	Flood defences may help to prevent property losses, planting of trees may stabilize slopes, reduce soil erosion and siltation, rainwater harvesting increases water availability, protection of biotopes supports biodiversity
Relocation of vulnerable communities (e.g., McNamara and Des Combes, 2015)	Moving vulnerable communities before and during climate-induced hazards may reduce loss of life	Reduces the exposure of vulnerable communities to climate change and extremes hazards e.g., floods and droughts, lessen their vulnerability, improve access to better resources and build their capacity to adjust to a new context

Education and Communication (e.g., Monroe et al., 2017)	Public education and awareness, improved communication may reduce the damages and losses from adverse impacts of climate change and from extreme events	Fosters awareness creation, reducing the degree of vulnerability to certain climate induced hazards and help build the capacity to adapt

While Table 8.1 shows selected adaptation responses, Table 8.2 shows selected mitigation responses that highlight that some mitigation responses (e.g., increasing energy efficiency) have a potential benefit also for the poor or more vulnerable groups for example through the reduction of costs for electricity. Both tables underscore that climate change mitigation and adaptation responses are strongly interlinked with broader development issues (industrial production, land-use planning, education, etc.) at different scales.

Table 8.2: Selected climate change mitigation responses

Modality of response	Impacts to urban communities	Impacts to rural communities (e.g., farmers pastoralists)
Land use planning (e.g., Frose and Schiling, 2019)	Helps to reduce greenhouse gas (GHG) emissions and support environmental conservation, preventing urban heat islands	Helps to reduce pressure on the natural resources (deforestation, land filling, damaging wetland) and promotes carbon sequestration
Improving industrial processes (e.g., van Vuuren et al., 2018)	Unlocks many opportunities for improvement, including the optimised use of energy, reuse of waste in the production, reducing GHG emissions, use of biomass and more efficient equipment	In rural settings, industrialization and technological innovation may directly assist vulnerable communities through provision of inputs e.g., water storage, drip irrigation, forecast information, or reuse of biowaste in agriculture or energy production, hence reducing costs and pollution levels
Renewable Energy (e.g., Cronin et al., 2018)	Reduction of GHG emissions and reduction of the cost of electricity	Some options (e.g., solar, wind) may help to reduce deforestation, reduce GHG emissions and promote healthier air within households
Energy efficiency (e.g., Abrahamse and Shwom, 2018)	Efficient end-user's energy utilization reduces energy wastage, reduces costs and lowers carbon emissions	Efficient end-user's energy utilization leads to natural resource conservation and a reduction of GHG emissions
Local/individual actions (e.g., Shaffril et al., 2018; Tvinnereim et al., 2018)	Can contribute to reduce carbon footprints	Fosters personal and community motivation to manage individually and communally owned resources. Helps to reduce GHG emission and foster resources conservation

8.2.2.2 Observed impacts and implications for structural inequalities, gender and access to resources

This section examines the mutual reinforcement of climate change impacts and structural inequalities. There is robust evidence that negative impacts and harm posed by climate change are also a result of social and political processes and existing structural inequalities (Sealey-Huggins, 2018). Climate change encompasses unevenly distributed impacts on women, youth, elderly, Indigenous Peoples, communities of colour, urban poor and socially excluded groups, exacerbated by unequal distribution of resources and poor access for some (Rufat et al., 2015; McNeeley, 2017; Sealey-Huggins, 2018). Structurally disadvantaged people, who are subject to social, economic and political inequalities resulting historically from discrimination, marginality or disenfranchisement because of gender, age, ethnicity, class, language, ability and/or sexual orientation, are disproportionately vulnerable to the negative impacts of climate change hazards (Kaijser and Kronsell, 2014; Otto et al., 2016). High levels of vulnerability at national scale (see Section 8.3) are often linked to complex histories, including long-term economic dependencies established and reinforced in the context of colonization.

Links between climate change, structural racism and development are less well established as an element of disproportionate impacts of climate change is relatively new (Sealey-Huggins, 2018). Discrimination is not restricted to structural racism and includes discrimination of all kinds including that of gender and caste because of which a considerable population is directly bound to suffer the harsh impacts of the climate change. The climate change and gender literature has come a long way demonstrating concrete examples of how structural inequalities operate. The political and micro-political aspects and how they interact with structural inequalities are also important to understand vulnerability. Henrique and Tschakert (2020) shows how the many adaptation efforts benefit powerful actors while further entrenching the poor and disadvantaged in cycles of dispossession. This critical analysis recommends acknowledging injustices, embracing deliberation, and nurturing responsibility for human and more-than-human others. Garcia et al. (2020) describes the socio-political drivers of gendered inequalities that produce discriminatory opportunities for adaptation. It utilises an intersectional subjectivities lens to examine how entrenched power dynamics and social norms related to gender create barriers to adaptation, such as lack of resources and agency. The analysis shows a pronounced dichotomy as women experience the brunt of these barriers and a persistent power imbalance that positions them as 'less able' to adapt than men.

Historical marginality and exclusion are context-specific conditions that shape vulnerability (Leichenko and Silva, 2014). There also exists *robust evidence* that on gender inequalities contribute to climate vulnerability, and that attention to gender is a key approach to climate justice (see Cross-Chapter Box GENDER in Chapter 18) and includes *robust evidence* on the differentiated impacts of climate change and climate-oriented policies on women (McOmber, 2020). For example, Friedman et al. (2019) show in Ghana that homogeneous representations of women farmers and technical focus of climate-orientated policy interventions may threaten to further marginalize the most vulnerable and exacerbate existing inequalities. Climate change impacts can also heighten existing gender inequalities (Jost et al., 2016; Glazebrook et al., 2020). On the one hand, climate change impacts can be gendered as a result of customary roles in society, such as triple workloads for women (i.e., economic labour, household and family labour as well as duties of community participation), and occupational hazards from gendered work indoors and outdoors (Murray et al., 2016). On the other, climate change hazards interact with changing gender roles in society, such as urban migration of both men and women in ways that break with tradition (Bhatta et al., 2016).

Gender influences the way that people also experience loss and process psychological and emotional distress of losses, such as mortality of children and other relatives in climate-related disasters (Chandra et al., 2017).Women's capacities are often constrained due to their roles in their household and society, institutional barriers and social norms. These constraints result in low adaptive capacity of women, which make them more vulnerable to hazards. As more men seek employment opportunities away from home, women are required to acquire new capacities to manage new challenges, including risks from climate change. Banerjee et al. (2019b) finds that capacity-building interventions for women staying behind, which aimed to strengthen autonomous adaptation measures (e.g. precautionary savings and flood preparedness), also positively influenced women to approach formal institutions. Besides, the intervention households were more likely to invest a part of the precautionary savings in flood preparedness measures than control households.

Next to the direct differential impacts of climate change on different social groups, the impacts of climate change can also exacerbate inequality due to the lower access and limited ability to benefit from services provided by ecosystems. The marginalised poor people often significantly depend on the access to surrounding environments, natural resources and ecosystem services for their livelihoods, for leisure or cultural practices. Thus shifts in such resources, for example, due to the bleaching of coral reefs or shifts in fish stock also cause severe challenges and risks to these communities (Leal Filho, 2018; Le, 2019), see also (UNTTSDCC, 2014).

Overall, the assessed literature highlights that climate change impacts are not emerging in isolation from development context and development pathways. Economic and social ramifications mean that they may exacerbate poverty and marginalization (Finkbeiner et al., 2018; Dogru et al., 2019). Choudhary et al. (2019) and Orimoloye et al. (2019) highlight how the effects of climate change can be even more prejudicial to poor countries, who in most cases already suffer from weak governance, high prevalence of informal settlements and lack of resources. Health, livelihood assets and economy are examples of aspects that will worsen as a result of the negative impacts of climate change and failure to provide opportunities for sustainable adaptation (United Nations, 2015). These facts highlight the importance of mitigation and adaptation measures especially in these regions characterized by high levels of vulnerability (see also Section 8.3).

8.2.3 Observed impacts and responses and their relevance for decision-making

Many countries base their adaptation strategies on National Adaptation Programmes of Action (NAPs), which often correlate different levels of decision-making and governance (Golrokhian et al., 2016). Whereas the involvement of national governments is needed for designing appropriate responses to climate change, recent studies underscore the need to also consider Local Knowledge and Indigenous Knowledge within adaptation and risk reduction strategies, thus fostering stronger linkages with local communities, leading to an improved vertical integration between different strategies, programs and different actors (Ford et al., 2016; Vij et al., 2017; Singh et al., 2020). The relevance of addressing the issue of vulnerability and poverty to reduce the climate change risks has been demonstrated within the assessed literature on the impact of climate change (Hallegatte et al., 2017). In this regard, it is noticeable that not many National Adaptation Programmes of Actions explicitly aim to reduce poverty, even though poverty reduction is associated with vulnerability reduction to climate change (Demski et al., 2017).

Next to issues of observed impacts and responses to climate change, it is important to assess observed barriers in implementing climate change responses. The discussion of barriers is complemented later in the chapter with an assessment of the enabling environments for adaptation (see Section 8.5.1). Some of the most common barriers outlined in the scientific literature are summarised in Table 8.3.

Table 8.3: Some common barriers in implementing climate change responses and their implications

Dimensions	Barriers in implementing effective climate change responses	Implications
Governance	Unfavourable political frameworks (Gupta, 2016).	Governance structures can undermine autonomous adaptation (Section 8.4 Table 8.6); Inability to include gender differentiated vulnerabilities in governance schemes (Bryan et al., 2017).
Social	Attitudes to risks and cultural values may hamper responses (Billi et al., 2019).	Social norms of reciprocity and cohesion may erode as a consequence of climate change responses (Volpato and King, 2019); Socio-cultural conditions as key barriers to gender differentiated support to impact reduction (Bryan et al., 2017).
Institutional	Limited availability coordination and prioritisation processes (Patterson and Huitema, 2019).	Lack of anticipatory risks undermining local's effort to cope with hazards (Singh et al., 2019a).
Behavioural	Psychological distress may cause insecurity and behaviour of some groups may increase vulnerability (Van Lange et al., 2018).	The psychological distress associated to loss of attachment to a place has also been observed among vulnerable communities in regions such as South Asia (Maharjan et al., 2020)
Financial	Limited financial resources to support adaptation projects (Khan et al., 2019).	The lack of financial resources and assets among urban poor increase their exposure and vulnerabilities to the increasing climate hazards (Salim et al., 2019)
Structural	Unsuitable infrastructure may increase exposure (Chinowsky et al., 2015; Vallejo and Mullan, 2017).	Structural Marginalization of Indigenous people and their local knowledge can exacerbate risks of maladaptation among SIDs countries (McNamara

		(McNamara and Prasad, 2014; Aipira et al., 2017; Granderson, 2017). Infrastructure projects to adapt to climate change impacts may increase the vulnerability of poor slum people
Technical	Lack of access to technologies which may support adaptation (e.g., climate services) (Bel and Joseph, 2018).	The highest level of illiteracy among women prevent their engagement to access technology and risk reductions in vulnerable communities (Balehey et al., 2018)

There are various characteristics of responses to climate change, which aim to protect livelihoods and prevent poverty expansion (i.e., an enlargement of the group of people already affected by poverty). Some of them are:

a) Timely: meaning that responses need to take place within a matter of weeks or months and not over years (Wise et al., 2014)
b) Targeted: with a focus on the affected communities and groups, to help alleviate the pressures they are under; (e.g., Aleksandrova, 2020)
c) Sustainable: with long-lasting results leading to self-sufficiency of the affected communities and their resource base, as opposed to short-term ones relying on external support (e.g., Caetano et al., 2020)
d) Integrated: the impact of climate change is multifaceted and far reaching and requires the engagement of various actors e.g., the vulnerable community, government agencies, local and international nongovernmental organisations, civil societies, media (Ayal et al., 2020)

Finally, responses as those outlined in Table 8.1 and Table 8.2, need to ensure the active participation of local stakeholders taking into account their diverse interests, so that they are grounded in reality. In addition, responses need to be complemented with operational procedures and timeframes so that they can be more systematically pursued and implemented (Alves et al., 2020).

8.3 Human Vulnerability, Spatial Hotspots, Observed Loss and Damage and Livelihood Challenges

This section assesses the literature on vulnerability—the assessment of vulnerability at global and national scales—and explores economic and non-economic losses of people and livelihoods exposed to and impacted by climate change. The section examines how climate change threatens livelihoods and juxtaposes global and local level assessments of vulnerability based on empirical data at different scales. The analysis of recent literature underscores that climate change impacts and adaptation needs cannot be understood by looking at climate change only. Vulnerability and livelihood security are seen as an important component to understand the human dimension of climate change (Rhiney et al., 2016; Cardona, 2017; Byers et al., 2018; Eriksen et al., 2020; Wisner, 2020; Birkmann et al., 2021a; Cole et al., 2021).

Linkages between global and individual vulnerability and livelihood security, including aspects of intersectionality are also assessed. Overall, the sub-chapter reveals that different countries, societies and specific groups within a society have very different starting points on their move towards climate resilience.

8.3.1 Assessments of risk and vulnerability

Conventional assessments of risks and the benefits of adaptation and risk reduction measures in the context of climate change primarily focus on the financial value of the avoided losses (in US Dollars) and the assets that are going to be protected from adverse consequences of climate change or extreme events due to specific measures (e.g., dyke construction). Even though these assessments fall short of measuring the real costs of addressing climate change impacts (see DeFries et al., 2019), they often support the definition of priorities in terms of protecting economic values and assets. However, these assessments do not sufficiently account for how climate change impacts and imposes risks on poor people, nor does it capture issues of climate justice and more complex societal impacts and future risks. For example, various observed losses in the context of climate change can not sufficiently be expressed in terms of an economic value (see Section 8.3.5), but these items or assets are highly relevant for various people with limited economic resources (Hallegatte et al., 2017). Consequently, the assessment of risks from climate change facing particularly poor people requires comprehensive assessments of human vulnerability, resilience and the impacts of climate change on human wellbeing going beyond a simple temperature societal-impact understanding. Knowledge about methods and approaches to assess human or human-environmental vulnerability and livelihood security, including aspects of intersectionality, is important in order to explore whether or not adaptation and development programmes are able to reduce vulnerability. The body of literature on these issues has grown significantly since the AR5 publication (IPCC, 2014a; Moser, 2014).

Literature since AR5 underscores that approaches to assess resilience, vulnerability, human wellbeing include global assessments that can inform strategies and priority settings for adaptation and risk reduction in the context of climate change (*high confidence*) (WHO, 2014b; Young et al., 2015; Feldmeyer et al., 2017; GIZ and BMZ, 2017; Hallegatte et al., 2017; Birkmann et al., 2021a; Garschagen et al., 2021; Toolkit, 2021).

These quantitative global assessments that emerged within the last decades have not sufficiently been assessed in former IPCC reports, for example in terms of the agreement on spatial hotspots or in terms of regional clusters of vulnerability and the linkages between past societal impacts and levels of vulnerability. The assessed literature show that conditions and phenomena that characterize systemic vulnerability (hazard independent vulnerability), such as high levels of poverty and gender inequality, limited access to basic infrastructure services or state fragility are highly relevant for understanding societal impacts of climatic hazards and future risks of climate change (e.g., Cutter et al., 2003; ADB, 2005; Cutter and Finch, 2008; World Bank, 2008; UNISDR, 2009; Crawford et al., 2015; Rufat et al., 2015; Carrao et al., 2016; Gupta, 2016; Rahman, 2018; Andrijevic et al., 2020; Jamshed et al., 2020a; Feldmeyer et al., 2021; Garschagen et al., 2021). These factors and context conditions also influence individual vulnerability at households or community level. Access to basic services, such as water and sanitation are linked to human rights and that if not granted increase the likelihood that people disproportionately suffer from climate induced hazards, due to their pre-existing lack of access to such services. In addition, increasing climate hazards further constrain the access to such services (United Nations, 2018; Kohlitz et al., 2019; Gupta et al., 2020).

There is an increasing evidence base that successful adaptation and risk reduction strategies need to acknowledge not only climate change and/or specific climate hazards (sea-level rise, flooding, droughts, etc.), but also human vulnerability and existing adaptation gaps and thereby the different starting points that societies or different groups have towards climate resilience (see UNEP, 2016; Birkmann et al., 2021a). Recent reports underscore that development and capacity indicators are useful to assess the broader adaptation challenges and adaptive capacities at global scale independent of a specific climatic hazard. Examples include the percentage of population with access to improved water sources and improved sanitation, the number of physicians per 1000 people or the dependency ratio (UNEP, 2018). These indicators are also part of more comprehensive vulnerability assessments, such as those assessed within this section namely the vulnerability components of the INFORM risk index (e.g., INFORM, 2019) and of the WorldRiskIndex (e.g., Birkmann and Welle, 2016; Birkmann et al., 2021a; Feldmeyer et al., 2021). Recent literature underscores that measuring vulnerability is seen as key for assessing factors that significantly determine actual and future adverse consequences of climate change and complex risks (Cutter and Finch, 2008; Cardona et al., 2012; de Sherbinin et al., 2019; Peters et al., 2019; Jamshed et al., 2020c; Visser et al., 2020; Feldmeyer et al., 2021). However, there is also important critique on indicator based assessments of vulnerability (see de Sherbinin et al., 2019; Rufat et al., 2019; Visser et al., 2020), particularly with regard to issues of validation and its use in decision-making processes. Nevertheless, we observe an emerging agreement in the literature that resilience building and adaptation to climate change has to be informed by climate and multidimensional assessment of the vulnerability of people, different groups and coupled human-environmental systems, including both quantitative and qualitative assessment approaches (IPCC, 2014b; UNEP, 2018; Singleton et al., 2021; Birkmann et al., 2022). Since, interdependencies between regional (supranational/sub-continental), national, community and individual vulnerability have often been overlooked, the chapter assesses both global and regional vulnerability as well as local livelihood vulnerabilities.

While past research regarding the nexus between climate change and poverty focused often on vulnerable groups in rural areas of low income countries (de Sherbinin, 2014; IPCC, 2014a; Barbier and Hochard, 2018), new global mega-trends, such as urbanization, underscore the need to assess both rural and urban communities and their vulnerability. In many rapidly growing cities in the global south, access to land and to housing is a challenge particularly for the poor and marginalized, contributing to a further increase in informal settlements that often emerge in highly hazard-exposed areas (Jeschonnek et al., 2014; Rana et al., 2021). In addition, migration from rural areas to urban centres, also due to increasing adverse impacts of climate change on rural livelihoods, can add another level of complexity (Flavell et al., 2020). Moreover, the context in which such urbanization processes take place is key. For example, rapidly growing medium-sized cities, for example in West-Africa, often do not have sufficient financial, technical and institutional resources to adapt urban structures to climate change (Birkmann and Welle, 2016; Birkmann et al., 2016; de Sherbinin et al., 2017). Hence, vulnerability in urban contexts is an emerging issue for international, national and local adaptation programmes. Rather than focusing on mega-cities and their exposure as primary hotspots, more attention has to be given to rapidly growing small- and medium-sized cities and their adaptation needs from the perspective of vulnerability reduction and poverty.

8.3.2 Global hotspots of human vulnerability to climate change

8.3.2.1 Hotspots and spatial patterns of multi-dimensional vulnerability

The assessment of literature published since the AR5 suggests that alongside already deteriorated specific conditions that determine individual vulnerability and livelihood security to climate change (see Section 8.2), high levels of poverty, lack of access to basic services (human rights to water and sanitation), poor governance, and conflicts are important factors that characterise vulnerability and systemic human vulnerability in particular (EC-DRMKC, 2020; Wisner, 2020; Feldmeyer et al., 2021; Garschagen et al., 2021; GIZ, 2021). These context conditions within a country or region limit the access to effective adaptation options particularly for the poor and marginalized groups.

Recent studies underscore that human vulnerability—thus the predisposition to be adversely affected—is largely determined by past and present development processes, rather than by the occurrence of individual events (Wisner, 2016; Cutter, 2018; Birkmann et al., 2020). Also the consequences of the COVID-19 pandemic will create newly poor particularly in countries that are already characterized by high levels of vulnerability (see Box 8.3; Laborde et al., 2020b; Lakner et al., 2020).

Quantitative studies and assessments published since AR5 provide additional insights about human vulnerability to climate change and resilience of societies at different scales using different indicator sets and approaches (Feldmeyer et al., 2017; Hallegatte et al., 2017; EC-DRMKC, 2020; Birkmann et al., 2021a; Feldmeyer et al., 2021; Garschagen et al., 2021).

While quantitative measures of vulnerability are widely used at different scales (Cutter et al., 2016; Garschagen et al., 2021), there are also studies that caution the use of such indices in policy making or risk reduction efforts (Rufat et al., 2019; Spielman et al., 2020). Such assessments of vulnerability have to be internally and externally validated and handled with care when applied in decision-making processes also in terms of their options and limits. At the same time, these assessments capture important conditions and structures that make people more susceptible to various climate hazards and climate change impacts and the relevance of these conditions is confirmed by quantitative impact assessments as well as many case study specific assessments (Welle and Birkmann, 2015; Feldmeyer et al., 2021; Birkmann et al., 2022). For example, the access to basic services (e.g., water and sanitation) (Bollin and Hidajat, 2013; Pandey et al., 2017b; UNEP, 2018; United Nations, 2018; Gupta et al., 2020; Jamshed et al., 2020a), and broader modes of engagement in governance and governance fragility (Crawford et al., 2015; Rahman, 2018; Andrijevic et al., 2020) significantly influence how climatic hazards translate into severe or non-severe losses and harm (see Section 8.5.2).

The lack of such support structures and resources can severely constrain opportunities of people to cope with and adapt to climate change, since it is not only the climate hazard, but also exposure and particularly the vulnerability of a society, a specific community or an individual household that determine adverse societal consequences of climatic hazards. International vulnerability and resilience assessments show that vulnerability varies across countries of similar wealth or income because multi-dimensional vulnerability, wellbeing and resilience depend on a larger set of factors (Birkmann and Welle, 2016; Hallegatte et al., 2017; INFORM, 2019). In this regard, vulnerability assessment is significantly different from climate exposure mapping.

The findings of these global assessments suggest, among other issues, that options to reduce vulnerability and enhance resilience do exist in various countries at different levels, in part irrespective of their income level (Feldmeyer et al., 2017; Hallegatte et al., 2017). Vulnerabilities at national and regional level influence community and individual vulnerability, particularly through structures that determine entitlements, the access to resources and processes of marginalization (Watts and Bohle, 1993; Thomas and Warner, 2019).

While different assessments use different sets of indicators, most of the global assessments with national scale resolution (Birkmann and Welle, 2016; Kreft et al., 2016; Feldmeyer et al., 2017; Hallegatte et al., 2017; Eckstein et al., 2019; INFORM, 2019; ND-GAIN, 2019; Garschagen et al., 2021), contain indicators that cover different aspects of economic poverty, inequality, access to basic infrastructure services, education and human capital (e.g., adult literacy rate) and some also include issues of gender inequality, specific vulnerable groups or insurance against extreme events. The assessments also differ, for example, in terms of their consideration of aspects of governance, such as corruption and conflict, or the consideration of social safety nets, such as insurance coverage, or the number of people affected by hazards(Feldmeyer et al., 2017; INFORM, 2019), as well as in terms of the consideration of losses experienced in the past or issues such as biodiversity as an aspect of adaptive capacity (Hallegatte et al., 2017; Birkmann et al., 2022). Moreover, the assessments differ in terms of the consideration of specific indicators and the inclusion or non-inclusion of specific hazard exposure (Welle and Birkmann, 2015; Hallegatte et al., 2017; INFORM, 2019; ND-GAIN, 2019; Birkmann et al., 2022).

Recent comparative studies of global assessments of vulnerability show *high agreement* on the spatial clusters that have very high or very low vulnerability to climate change, compared to larger differences in terms of exposure and risk (Birkmann and Welle, 2016; Hallegatte et al., 2017; INFORM, 2019; Feldmeyer et al., 2021; Garschagen et al., 2021; Schleussner et al., 2021). The comparison of the averaged ranking results at the scale of ’climate regions’ using the vulnerability components of the INFORM and the WorldRiskIndex—as two comprehensive global assessment approaches of systemic vulnerability (hazard independent vulnerability) (see Figure 8.5 and Figure 8.6)—also finds a *high agreement* in terms of most vulnerable regions and regions with low vulnerability (Figure 8.5; Feldmeyer et al., 2021). The assessment at this scale reveals that global hotspots of human vulnerability can be found in climate regions in East Africa, Central Africa and West-Africa. Followed by high vulnerability in Central America and South Asia and South East Asia, for example. Garschagen et al. (2021) in a comparison of further risk indices also found that there is high agreement on global assessments of vulnerability compared to exposure or overall risk.

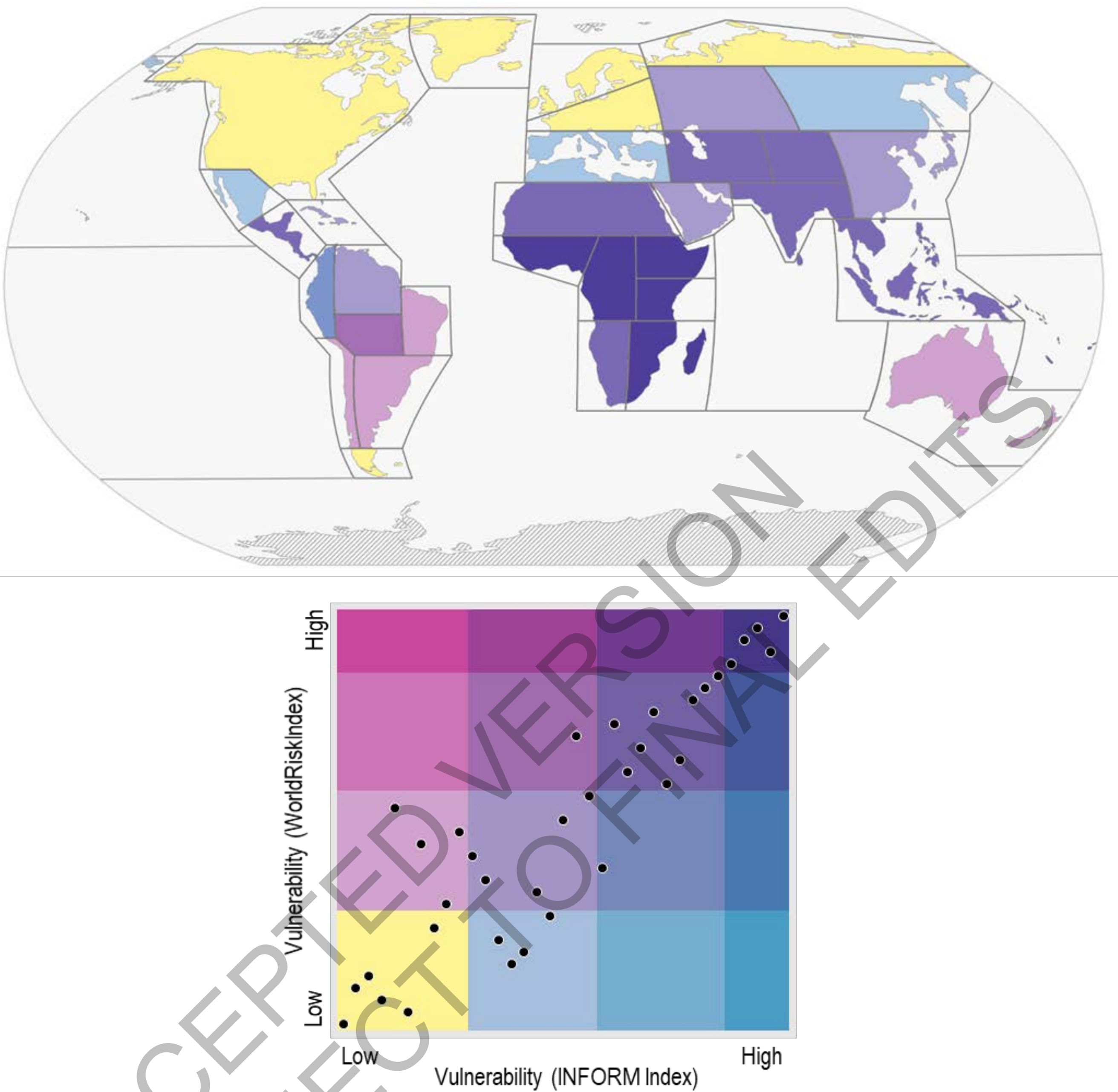


Figure 8.5: Aggregated vulnerability map at the scale of climate regions based on the averaged ranking of the INFORM Index's vulnerability component and the averaged ranking of the vulnerability component of the WorldRiskIndex. Based on the rankings of the INFORM index (INFORM, 2019) and the WorldRiskIndex (Birkmann and Welle, 2016; Feldmeyer et al., 2017). The map and diagram show the agreement between the two global vulnerability indices when ranking climate regions according to their vulnerability—darker colours show regions of higher vulnerability. The diagram shows how the 35 climate regions are ranked by each index and also serves as a legend for the map above.

The analysis of vulnerability assessment results of the INFORM Risk Index and WorldRiskIndex at the level of countries also coupled with population data confirms a *high agreement* on most vulnerable countries and it shows that global hotspots of human vulnerability are not just single countries, but often emerge within regional clusters, particularly in Africa, but also in Asia and Central America (see Figure 8.6 and Birkmann et al., 2021a). These regional clusters (Figure 8.6) are characterized by high levels of vulnerability in terms of socio-economic, demographic, environmental and governance conditions that make people more likely to face adverse consequences once a climate hazard occurs. The internal and external validation of these index systems shows its statistical validity and robustness (Welle and Birkmann, 2015; Marin-Ferrer et al., 2017; Birkmann et al., 2022). It also confirms a quantitative relationship between most vulnerable regions and fatalities and severely affected people due to climate influenced hazards (Birkmann et al., 2022). The vulnerability map in Figure 8.5 shows the vulnerability level (systemic societal vulnerability) linked to national scale and provides additional information about the population density within these countries. The background map does not show specific vulnerable populations within countries. Selected examples of sub-national human vulnerabilities have been added as additional information in terms of case studies based on information of other chapters within this report (see for example, Box 8.7, Chapter 14 Section 14.4.7, Chapter 13 Section 13.8.1, Chapter 10 Sections 10.3.3 and 10.5.1, Cross-Chapter Paper 6, Section 6.2.7, Chapter 5 Section 5.12 and Chapter 15 Section 15.3.4).

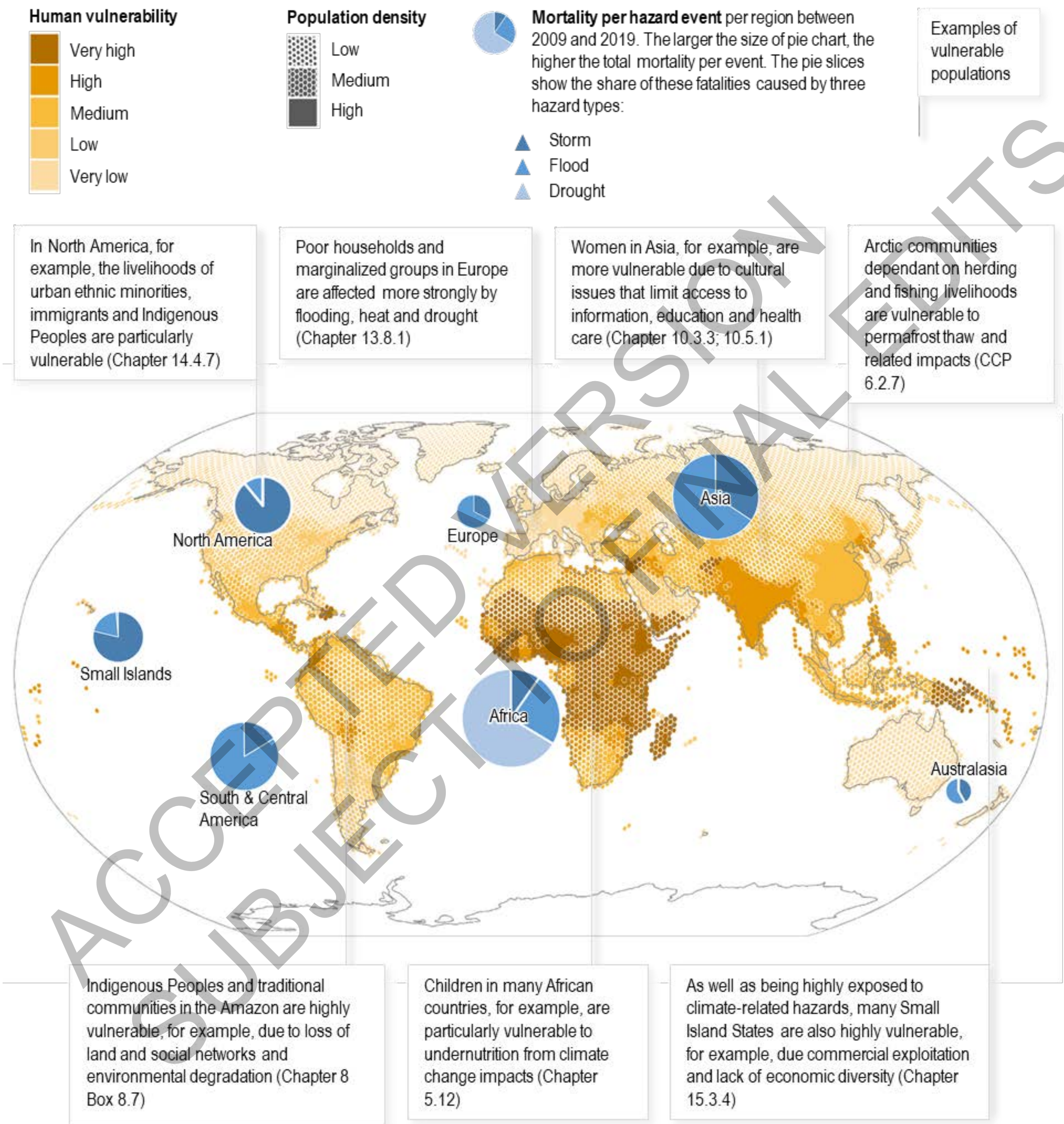


Figure 8.6: Global map of vulnerability. This map shows the relative level of average vulnerability as calculated by global indices (INFORM and WRI see details in 8.3.2). Areas shaded light yellow are on average the least vulnerable and those shaded darker brown are the most vulnerable. The map combines information about the level of vulnerability (independent of the population size) with the population density (see legend) to show where both high vulnerability and high population density coincide. The map reveals that there are densely populated areas of the world that are highly vulnerable, but also highly vulnerable populations in more sparsely populated areas. There are also highly vulnerable communities and populations in countries with overall low vulnerability as shown with sub-national case studies alongside the map. The map shows in the pie charts the number of deaths (mortality) per hazard (storm, flood, drought) event per continental region based on EM-DAT Data (CRED, 2020). This reveals that significantly more fatalities per

hazard (droughts, floods, storms) did occur in the past decade in more vulnerable regions. Over 3.3 billion people are living in countries classified as very highly and highly vulnerable, while approximately 2 billion people live in countries with low and very low vulnerability (Birkmann et al., 2022). These vulnerability values are based on the average of the vulnerability components of the INFORM Index (INFORM, 2019) and WorldRiskIndex (Birkmann and Welle, 2016; Feldmeyer et al., 2017) with updated data from 2019 classified into 5 classes using the quantile method. Other studies applied more vulnerability classes within their assessment and therefore provide slightly different numbers (Birkmann et al., 2021a). However, despite different calculation methods, the fact remains that there are significantly more people residing in countries with very high and highly vulnerability compared to those living in countries classified as having low or very low vulnerability.

Figure 8.7: Selected aspects of vulnerability. The diagram presents normalized indicator scores for a selection of aspects of human vulnerability aggregated to average values for each region. These indicator scores are based on the vulnerability indices mapped in Figure 8.6 (i.e., the INFORM Risk Index and WorldRiskIndex). This figure provides a more differentiated picture about the various dimensions of vulnerability that different regions and countries face and the severity of such challenges in each region. Such vulnerability challenges increase the risk of severe adverse impacts of climate change and related hazards (Birkmann et al., 2022).

Figure 8.7 provides an aggregated regional overview of selected indicators used within the vulnerability index mapped in Figure 8.6. The overview (Figure 8.7) shows that the many compounded challenges faced by African countries are starkly pronounced, but also on the other regions, especially Asia, Central and South America, and amongst the Small Island States there are several challenges such as inequality, governance issues and displacement which all increase the vulnerability and constrain adaptive capacities of these regions to climate change.

However, it is also important to note that vulnerability assessments do have their limitations (Heesen et al., 2014; Rufat et al., 2019). For example, also in high income countries specific groups can be highly vulnerable to climate change due to marginalization and discrimination due to ethnicity or gender. Gender inequality for example is also high in some countries classified in the literature as having low vulnerability (see Birkmann et al., 2021a; Birkmann et al., 2022). Nevertheless, these countries have in theory sufficient financial resources and governance capacities to deal with these challenges, while this is different for many country clusters classified as highly vulnerable.

Countries and regional clusters with low vulnerability (see Figure 8.5 and Figure 8.6), such as Australia and New Zealand or Iceland and North Europe, encompass population groups that are exposed and vulnerable to climate hazards, such as sea-level rise or droughts, but within these regions context conditions exist that allow the negative impacts and losses to be buffered (also for most vulnerable groups). These regions have higher financial and institutional capacities to support people at risk and planned adaptation at a different magnitude within their region, for example, as seen in compensation payments for drought exposed farmers (Hochrainer-Stigler and Hanger-Kopp, 2017; Australian-Government, 2021) or flood affected households in Germany in 2021. Also, the percentage of insured households against climate influenced hazards, such as floods or storms, is significantly higher in these regions (North America, Western Europe) compared to regions such as Western Africa or Micronesia (Welle and Birkmann, 2015; Feldmeyer et al., 2021; Birkmann et al., 2022).

While climate change differentially impacts people in vulnerable situations within countries including the poor, children, women, marginalized Indigenous or other ethnic minority people (Rhiney et al., 2016; Méndez et al., 2020), the global assessment results underscore that in most vulnerable regions and countries very limited resources and structures exist to support these groups when droughts, floods or storms occur and place an additional burden to these groups.

The assessments of human vulnerability also point towards important adaptation options that are not visible if one focuses on climatic hazards or temperature changes alone (Figure 8.9; Dückers et al., 2015; Cutter et al., 2016; Birkmann et al., 2021a). It is increasingly recognized as fundamental for vulnerability reduction and adaptation are social insurances and infrastructure programmes as well as legislation that improves the access of poor and marginalized groups towards basic infrastructure services and basic security. For example, the "free basic service programme" of the national government of South Africa (GovSA, 2021) is one example where a national government (Government of South Africa) has committed itself to provide a basic amount of free water, electricity and sanitation to low income households, particularly indigent people such as those living in informal settlements or remote rural areas. Coupled with incentives, for example in terms of a higher use of renewable energy e.g., solar home systems in rural areas (see GovSA, 2021) these investments can support vulnerability reduction and mitigation of greenhouse gas emissions. However, there is also critique of the programme design and implementation (see Nel and Rogerson, 2005; Muller, 2008) as is witnessed by ongoing service delivery protests (Mutyambizi et al., 2020). However, the example shows that current national programmes can—even if they are not classified as adaptation measures—provide important entry point to also reduce human vulnerability to climate change.

The relevance of human vulnerability has also been confirmed by recent assessments. Studies found that the average mortality[4] from floods, storms and droughts is 15 times higher in countries and regions ranked as very highly vulnerable (e.g., Mozambique, Somalia, Nigeria, Haiti, Afghanistan) compared to countries with very low vulnerability (e.g., UK, Sweden, Italy, Canada) (Birkmann et al., 2022). Even if one takes solely "high vulnerable countries" such as India, Pakistan and the Philippines (and not "very high" vulnerable countries), mortality is still nine times higher compared to very low vulnerable countries. Similarly, studies further revealed that average number of adversely affected people per hazard event (e.g., loss of the house) are 11 times higher in countries categorized as very high vulnerable compared to very low vulnerable (Birkmann et al., 2022). In addition to floods, droughts and storms, published EM-DAT data for wildfires and heat stress, confirmed higher suffering (higher average mortality) in more vulnerable regions compared to low vulnerable regions, particularly when excluding extreme outliers (CRED, 2020). These findings point towards the fact that in regions identified as highly vulnerable in the assessments even moderate future climate change and future climate hazards are likely to push people further into poverty and lead to significant destabilization processes in terms of livelihoods security (Wallemacq and House, 2018; Birkmann et al., 2022).

8.3.2.1.1 Historic roots of vulnerability in regions classified as highly vulnerable

While increasing attention is given to issues of human vulnerability, less attention has been given to the historical conditions that foster systemic vulnerability of societies. It is important to acknowledge that drivers and root causes of systemic human vulnerabilities and development challenges are not always new, and sometimes—for example in various countries in the Caribbean, Africa and Asia—can be linked to histories of imperialism, colonial structures (Grasham et al., 2019), and subsequent development and governance contexts (Southard, 2017; Zhukova, 2020). Thus, root causes of present structures of human and human-environmental vulnerability have in many cases historic dimensions, for example chronic poverty and structural inequality in Africa (Grasham et al., 2019) or the Caribbean are still influenced by the colonial power-relations outside of these countries making solutions for vulnerability reduction more difficult (see e.g., Douglass and Cooper, 2020). Also national borders, such as in many regions in Africa, sometimes cut through ethnic groups and therewith ignore important interrelations between communities on both sides of the border.

8.3.2.1.2 People residing in most vulnerable versus least vulnerable regions

[4] measured as death per hazard event and calculated by averaging the country values of mortality per event falling in different vulnerability categories

While global assessments often allow for country rankings, it is similarly important to better understand how many people are living in these different levels of vulnerability. The quantitative assessments underscore that a significantly higher amount of people is living in countries with very high and high vulnerability compared to the population living in countries classified as having low and very low vulnerability. An analysis that measured the vulnerability of countries according to the INFORM Risk Index and the WorldRiskIndex vulnerability-index components, differentiating vulnerability values into 7 vulnerability classes found that nearly twice as many people are living in most vulnerable countries compared to the number living in less vulnerable countries (Birkmann et al., 2021a). Another study that uses the same data and differentiates vulnerability into 5 classes (also considering the lack of coping capacity within the INFORM index, see (Marin-Ferrer et al., 2017)) concludes that about 3.3 billion people are living in countries classified as highly vulnerable, while approximately 2 billion people live in countries with low vulnerability (Birkmann et al., 2022). While these numbers are different, both results underscore that the absolute and relative number of people living in most vulnerable contexts is significantly higher compared to those that live in a country with a low vulnerability status (Birkmann et al., 2021a; Birkmann et al., 2022). These differences have also been observed in former years (Welle and Birkmann, 2015; Feldmeyer et al., 2017).

That means, even moderate changes in the global mean temperature, as identified in the recent IPCC report SR1.5°C (IPCC, 2018c) and in scientific literature (Hoegh-Guldberg et al., 2019a), can mean substantial increases in risks for more than 3 billion people due to high levels of vulnerability.

Overall, there is *robust evidence and high agreement* in the recent literature that countries and regions classified as highly vulnerable face multiple development challenges at once, in which high levels of poverty interact with limited access to water and sanitation or with high levels of forced migration and in some cases with state fragility making solutions difficult (Hallegatte et al., 2017; Marin-Ferrer et al., 2017; Feldmeyer et al., 2021; Garschagen et al., 2021; Birkmann et al., 2022). High levels of vulnerability within these regional clusters are the product of current development challenges, but are often caused by long and complex histories, including issues of colonization and marginalization, for example, in hotspots in Africa (Birkmann et al., 2021a).

8.3.2.2 Transboundary vulnerability and adaptation

Next to the identification of the level of agreement between different vulnerability assessments (Garschagen et al., 2021) and the spatial hotspots, global assessments of vulnerability and adaptation readiness also point towards the need of a transboundary perspective and the need for transboundary cooperation in terms of vulnerability reduction and adaptation (Tilleard and Ford, 2016; Birkmann et al., 2021a). Newer research points towards the fact that various phenomena of vulnerability particularly in highly vulnerable regions spill over national borders and emerge in rather regional clusters, such as forced migration and poverty in West and Central Africa as well as conflicts in the Near East or Asia (IDMC, 2020). That mean regional and transboundary challenges contribute to the formation of systemic human vulnerability, for example, forced migration that is occurring within countries, but also across international borders that is also influenced by climate change (Kaczan and Orgill-Meyer, 2020). In summary, these findings point towards the need for more transboundary approaches in vulnerability and risk reduction, adaptation and development. Recent literature and data presented in Figure 8.6 and (Birkmann and Welle, 2016; Feldmeyer et al., 2017; Hallegatte et al., 2017; INFORM, 2019; Birkmann et al., 2021a) demonstrate the need to strengthen approaches to monitor the regional dimensions of vulnerability and to develop strategies and programmes that allow for transboundary vulnerability and risk reduction and cooperation at different scales, for example, cooperation between national level institutions, but also transboundary networks of cities or communities (Tilleard and Ford, 2016; Benzie and Persson, 2019; Birkmann et al., 2021a). The transnational nature of climate change impacts means that addressing them requires concerted efforts among nations (IPCC, 2014b; Dzebo, 2019).

In addition, national response strategies for specific transboundary climate influenced hazards, such as river flooding, droughts or coastal flooding can also significantly influence neighbouring countries and can affect exposure and vulnerability of the respective country (Nadin and Roberts, 2018; Booth et al., 2020). Likewise, climate change may affect transboundary resources (e.g., underground water reserves) and transboundary ecosystems (e.g., in terms of the migration of species) (Vij et al., 2017) and thereby further reduces the capacity of vulnerable groups to cope and adapt. In addition, recent research indicates that social inequities are coupled with access to and quality of environmental resources, also in urban environments—meaning social and environmental justices are interconnected (see Schell et al., 2020).

Individual adaptation projects to specific climate hazards in regions classified as highly vulnerable are needed, however, recent studies underscore that deeper development challenges need to be addressed in order to make progress towards adaptation and vulnerability reduction and to avoid maladaptation (Eriksen et al., 2021). Adaptation and development projects, such as the construction of a dam as a response to water shortages in one country can significantly influence the exposure to water shortages and the response capacities of another country downstream. Often, transboundary challenges are a result of policy and resource management choices or uncertainty and addressing them requires a greater engagement between governing bodies, which may guide more suitable responses also in the context of climate change adaptation and vulnerability reduction (Earle et al., 2015; Tilleard and Ford, 2016; McLeman, 2018; Birkmann et al., 2021a).

Most of those countries and regional clusters identified as highly vulnerable have contributed little to the overall amount of greenhouse gas emissions and therefore support for (transboundary) adaptation from the international community is required in these places and for those living under these conditions also in order to support and achieve climate justice.

8.3.2.3 The effect of higher levels of global warming for most vulnerable regions and specific livelihoods

Evidence exists that threats to land-based livelihoods and risks of undernutrition increase significantly with higher levels of global warming (Hoegh-Guldberg et al., 2019a). With global warming of 1.5°C or less, impacts of climate change on livelihoods are still significant, for example, for West Africa and Sahel due to a reduction of area suitable for maize production of about 40%, however, the consequences of global warming of up to 3°C would mean a high risk of undernutrition for entire regions (see Hoegh-Guldberg et al., 2019a) that are already classified as most vulnerable (see Figure 8.6). That means the consequences of significant warming are a particular challenge for the regional hotspots of vulnerability, since already observed small changes in crop productivity due to increasing droughts or floods or changes in rainfall patterns could lead to severe health risks and undernutrition due to already existing precarious living conditions and due to the limited capacities that people and institutions have to build and enhance coping and adaptive capacities at the level of individual households, communities and even at the level of state institutions (see UNEP, 2018; Birkmann et al., 2021a). The risk of loss of life, displacement and adverse health consequences due to climate change in these most vulnerable regions (such as West Africa, Micronesia, South Asia—see Figure 8.5 and Figure 8.6) is higher compared to regions classified as having medium or low vulnerability (Birkmann et al., 2022). Nevertheless, also other regions and countries classified as less vulnerable, for example in Asia, are experiencing disasters and have a relative high share of the global fatalities or losses observed when considering also non-climatic natural hazards (CRED and UNDRR, 2020). In addition, changing climatic hazard and exposure patterns have to be considered, however, the agreement of major global index systems on exposure is significantly lower as compared to vulnerability (Garschagen et al., 2021).

Moreover, the assessment reveals that in most vulnerable regions a double burden of existing destabilized livelihood conditions and additional climatic hazards is already visible and largely influences societal impacts of climate change. For example, flooding along the White Nile in Uganda and South Sudan hit vulnerable communities that were displaced before because of conflicts and were thus up-rooted again by flooding (IDMC, 2020). Societal impacts and future risks of climate change to societies need to incorporate information about vulnerability and exposure—including capacities of people to cope and adapt (Wisner, 2016; Cardona et al., 2020). There is increasing evidence that individual and societal capacities to cope and adapt also depend on how governmental and national institutions can support people at risk (see Section 8.6). For example, climate information services depend on a functioning weather service, likewise, social safety nets as an adaptation strategy require financial resources, which are often absent for most people in highly vulnerable regions. In addition, examples of national programmes that target most vulnerable groups such as the free basic service programme in South Africa show that next to the adaptation to individual hazards, strategies exist that aim to reduce systemic human vulnerability (see GovSA, 2021).

At the same time, scientific evidence exists that more intense and frequent climate influenced hazards (e.g., storms, flooding, droughts, heat stress) can undermine decade-long poverty reduction efforts, particularly in most vulnerable regions (Mysiak et al., 2016; Formetta and Feyen, 2019; Laborde et al., 2020b; Lakner et al., 2020). There is agreement that with global warming of about 3°C such undermining of poverty reduction efforts will intensify and more regions will face development setbacks due to the spatial and temporal expansion of climate hazards, including the further erosion of capitals that enable people to develop adaptive capacities (*high confidence*) (see Section 8.5). Such trends can further exacerbate poverty traps (see Section 8.2.2). According to a World Bank report, between 32 and 132 million people could fall into extreme poverty in 2030 due to the impacts of climate change (Jafino et al., 2020). Models estimate that at 3°C warming and under an SSP1 there would be an additional 245 million people exposed to poverty. Under an SSP2 this number would increase to 904 million additional people exposed to poverty (SSP2) and under an SSP3 (with significant challenges for equity) about 1718 million additional people could be exposed to poverty (SSP3) in the year 2050 (Byers et al., 2018).

Overall, the assessments above underscores that adaptation and risk reduction require not only information about changing climatic conditions, but also assessments that capture the development contexts and structural inequality that determine and influence human vulnerability. Strategies that reduce poverty and inequality and that improve the access of people to basic services need to become a higher priority in adaptation and development planning in order to avoid that more than 3 billion people currently and even more in the future are exposed to severe adverse consequences of climate change. Reducing vulnerability to climate change is therefore indispensable for climate justice and just transitions (*high confidence*).

8.3.2.4 Compound challenges: vulnerability and state fragility

Literature in the area of climate change risk management and adaptation highlights the importance of overall governance systems and their functioning and inclusiveness in terms of vulnerability and risk reduction (Burch et al., 2019). Empirical evidence and scientific studies show linkages between issues of governance, conflicts and high levels of state fragility and systemic human vulnerability (see Figure 8.8; Section 8.5.2; Eklöw and Krampe, 2019; Peters et al., 2019; Mawejje and Finn, 2020)

The comparison of state fragility and vulnerability at the level of regions (UNSD regions) based on the vulnerability information of the INFORM and WRI index systems and information of the Failed State Index indicates clear linkages (see Figure 8.8), meaning that societal development and governance challenges often interact and in many cases are influenced by complex histories (see FFP, 2020; Birkmann et al., 2021a; Feldmeyer et al., 2021). Strategies to reduce systemic vulnerability and multi-dimensional poverty have to account for these broader governance challenges that hamper resilience building and the development of adaptive capacities to climate change at various levels.

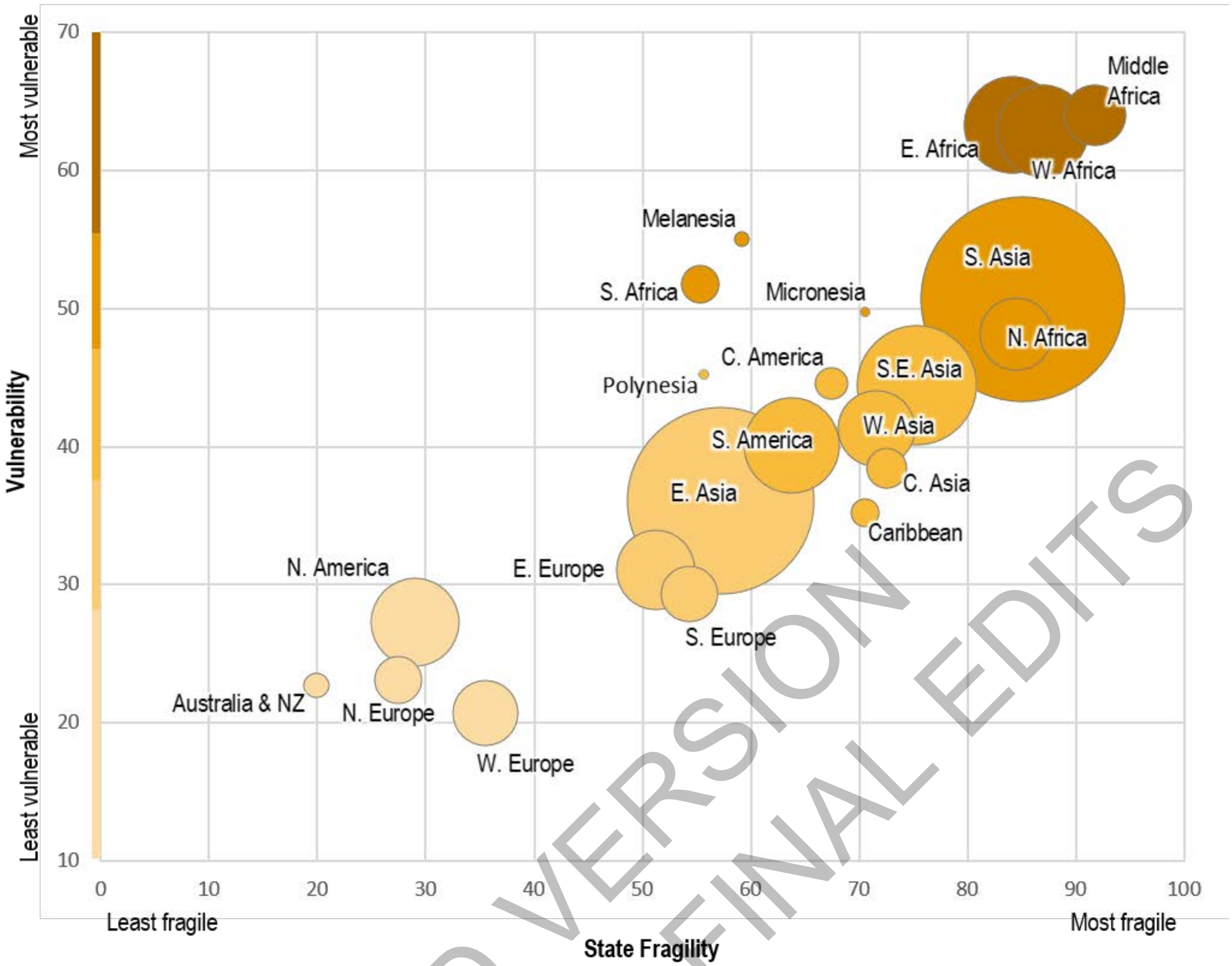


Figure 8.8: Comparison of the vulnerability and state fragility of global regions. The vulnerability values are the average of the vulnerability component of the WorldRiskIndex 2019 (Birkmann et al., 2021a; Feldmeyer et al., 2021) and the vulnerability and lack of coping capacity components of the INFORM Risk Index 2019 (Marin-Ferrer et al., 2017) classified into 5 classes using the equal count method(Birkmann et al., 2022). The state fragility values are based on the Fragile States Index 2019 (FFP, 2020), and regions are based on the intermediate and sub-regions of the United Nations Statistical Division. The size of each circle is proportional to the population (World Bank, 2019b) in the respective region.

Strategies to strengthen adaptation to climate change have therefore to acknowledge these interdependencies between climate change, vulnerability, development and governance (see Section 8.6.5). The results of different global vulnerability assessments and the role of governance conditions underscore that next to individual adaptation projects in specific sectors, integrated strategies and programmes are needed that reduce systemic vulnerability and support enabling conditions for adaptation for most vulnerable groups (see Section 8.6.5).

8.3.2.5 Trends in vulnerability and poverty in light of climate change and the COVID-19 pandemic

Literature that assesses trends of poverty and vulnerability as well as exposure to climate change reveals that geographic patterns of poverty and vulnerability are uneven and changing over time (Feldmeyer et al., 2017). However, a robust finding of different studies is that the population growth in most vulnerable country groups and regions “is” and very likely “will be” significantly higher in the future compared to population growth in countries classified as low vulnerable (see Section 8.4.5.2). In summary, a significant increase of population is expected in highly vulnerable countries in the future. In addition, global studies show that by 2030 it is expected that almost 50% of the world’s poor will be living in countries affected by state fragility, conflict and violence (UNISDR, 2009; Hallegatte et al., 2017).

Another important phenomena that modifies trends in vulnerability to climate change and poverty is the COVID-19 pandemic (see Box 8.3). It is *likely* that the COVID-19 pandemic with its global repercussions will continue to modify and, in many cases, intensify poverty and human vulnerability (Laborde et al., 2020a; Sumner et al., 2020). Recent studies that estimate the impact of COVID-19 on global poverty agree that a significant increase of poverty due to COVID-19 and the respective lockdown of countries is already observed or expected in the near future (Laborde et al., 2020b; Sumner et al., 2020). These studies underscore that 80% of those newly living in extreme poverty (living on under 1.9 USD per day) due to COVID-19 would be located in mainly two global regions: Sub-Saharan Africa and South Asia (Sumner et al., 2020). Consequently, the COVID-19 pandemic is likely to further increase inequality at different scales and increase the burden within regions already characterized by a significant adaptation gap in terms of high vulnerability (see also Figure 8.6). This implies that the capacity of people to prepare for present and future climate change impacts will further decrease within these countries and for specific vulnerable people/groups in these regions.

Recent scientific studies in the context of climate influenced hazards and disasters also underscore that various regions and countries classified as highly vulnerable are characterized by a high persistence of human vulnerability and chronic poverty (Feldmeyer et al., 2017; UN-DESA, 2020; World Bank, 2020). For example, various highly vulnerable regions in Central, West and East Africa, such as countries like Haiti, Afghanistan, Democratic Republic of Congo, but also Small Island Developing States (SIDS) in Melanesia and Micronesia have been characterized by high levels of poverty for decades (World Bank, 2020). Several of these highly vulnerable regions are also likely to experience a further increase in climate hazards such as sea-level rise in Melanesia and Micronesia and in coastal zones of West- and more severe droughts in Africa (IPCC, 2021).

There is evidence that in many world regions the exposure to climatic hazards is increasing with additional global warming (Chin-Yee, 2019; Hoegh-Guldberg et al., 2019a; IPCC, 2021). In addition, development patterns and practices such as urbanization and migration to exposed areas, for example, to coastal zones in West-Africa or South Asia is increasing exposure. While the spatial and temporal exposure to impacts from climate change and extreme events increases with higher levels of global warming (Hoegh-Guldberg et al., 2019a), in all global regions and various climate zones (IPCC, 2021), the burden is greater for the most vulnerable regions where people have limited support and capacities to build adaptive capacities for future impacts of climate change.

In this regard, vulnerability assessment results provide an important additional layer of information for decision making in terms of defining adaptation and risk reduction needs and priorities, as shown in Figure 8.9. The figure shows the published climatic information regarding observed changes in agricultural and ecological droughts (IPCC, 2021) combined with a background map of vulnerability. For example, the combined information reveals that even if the agreement on the type of changes in observed changes in droughts is low for North and South-East Africa, it is the high vulnerability in this region that requires urgent attention (see Figure 8.9).

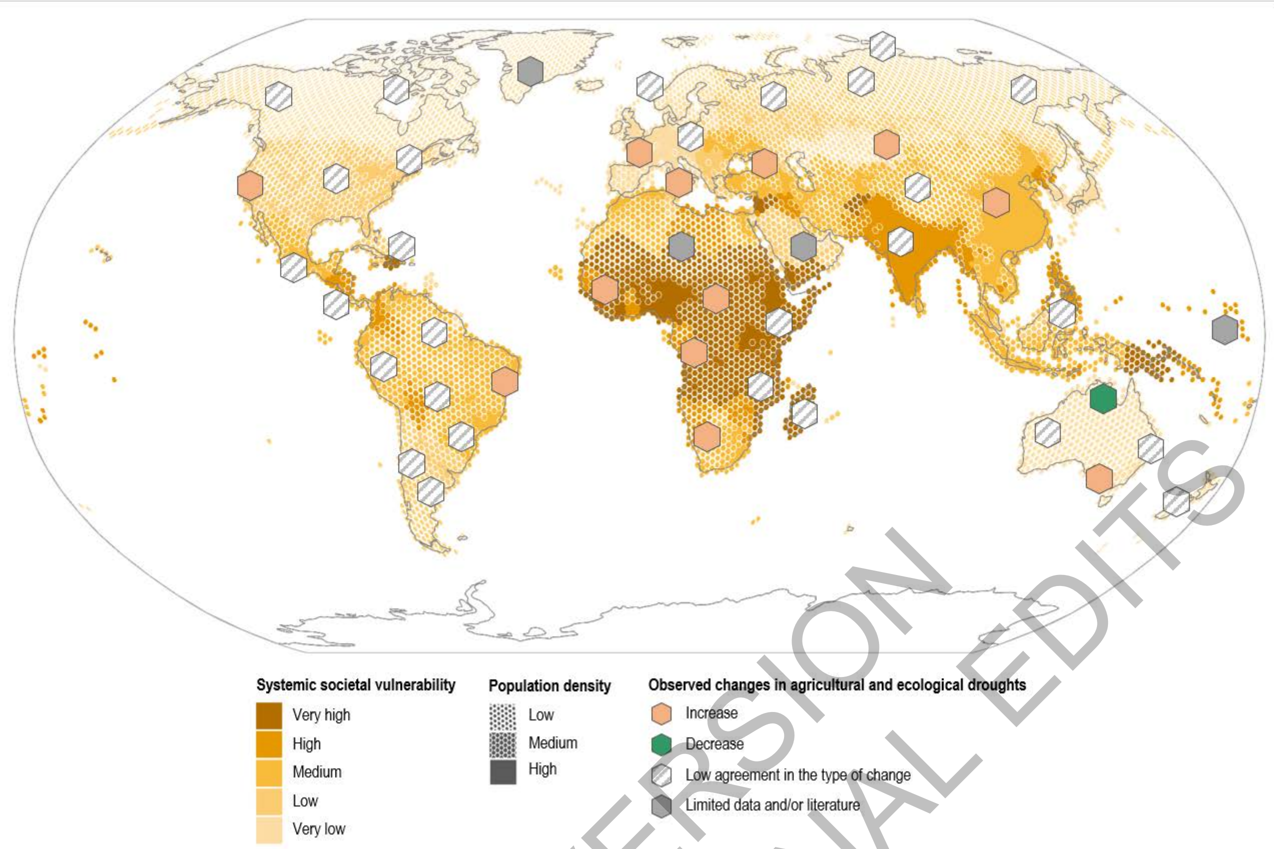


Figure 8.9: Map with observed changes in agricultural and ecological droughts (IPCC, 2021) overlaid over human vulnerability (see Figure 8.6) provides a more comprehensive overview for defining adaptation priorities.

Recent reports on extreme poverty and human rights (Alston, 2019) show that already millions face malnutrition due to devastating drought. In addition, the linkages between ecosystem vulnerability and human vulnerability and human well-being are important aspects that need more attention, since for example the degradation of marine ecosystems that support food systems for hundreds of millions of people will threaten food security (see for details Cross-Chapter Box Moving Plate chapter 5).

While the findings of the Alston report underscore the urgency to act in order to protect people's livelihoods, particularly in low income countries, it also shows that extreme poverty (Alston, 2019) and different dimensions of poverty are found in middle and high income countries.

A study of the World Bank (Hallegatte et al., 2017) estimates that losses in terms of wellbeing are significantly higher compared to actual asset losses experienced (Hallegatte et al., 2017). A higher proportion of the global absolute economic losses occurred in high income countries. About 56% of all disasters reported occurred in high-income countries, while the low-income countries account for 44% of the recorded disasters. However, low income countries account for about 68% of the total deaths reported, high income countries for about 32% (CRED, 2015; see also Section 8.3.2.1). In contrast, average absolute economic losses[5] were significantly lower in most vulnerable countries compared to low vulnerable countries (Birkmann et al., 2022). Economic loss trends from EMDAT database (CRED, 2020) must be interpreted with caution. Economic loss data is often incomplete and needs to be improved. However, these differences in terms of economic losses can also be explained in part with significant wealth differences and the monetary value of assets exposed. Consequently, there is a need to critically reflect the measures used to assess loss and damage from climate change. Interestingly, the number of people affected by droughts, floods and storms as a percentage of the total population and per hazard event again points to the disproportional suffering of most vulnerable countries (Birkmann et al., 2022).

[5] calculated by averaging the country values of economic losses per event falling in different vulnerability categories

Overall, there is *robust evidence* that at the global scale poor and most vulnerable people particularly in regions classified as highly vulnerable are disproportionately affected by wellbeing losses and loss of life in the context of climate change and climate influenced natural hazards (CRED, 2015; Hallegatte et al., 2017; Birkmann et al., 2022) (*high agreement*). In this context, also non-economic losses need to receive a higher attention (see Section 8.3.3.2). While there is an emerging understanding that inequality and multidimensional poverty are important determinants of systemic vulnerability to climate change (Dennig et al., 2015; Hallegatte and Rozenberg, 2017; Islam and Winkel, 2017) that affects more than 3 billion people today, only very few countries explicitly aim to reduce poverty and income inequality as an adaptation measure (see e.g., Brazil Ministry of Environment, 2016) *(high agreement)*. Reducing vulnerability is a prerequisite for climate justice and just transitions.

8.3.3 Livelihood impacts, shifting livelihoods and the challenges for equity and sustainability in the context of climate change

This section complements the global and regional assessment of vulnerability in the previous section with a more precise assessment of observed local conditions and livelihood impacts and shifts. Firstly, the section reviews linkages between vulnerability and livelihood impacts of climate change broadly. Secondly, it examines the range of observed disproportionate impacts according to economic (e.g., income) and non-economic (e.g., cultural) impacts of climate change. Thirdly, it examines current risks of adaptation limits and compounding effects across social groups and associated livelihood shifts.

8.3.3.1 The implications of vulnerability for past and present livelihood impacts of climate change

Climate change impacts add to livelihood challenges and can further increase inequality and poverty (see Section 8.2.1), whose root causes are social, institutional and governance-related. Various regional clusters of high vulnerability (see Figure 8.6) are also influenced by historical processes, such as colonialism and power-relations that made people and countries vulnerable (Schell et al., 2020). Thus, vulnerability to climate change is not primarily linked to the degree of exposure to climate change impacts, but determined by societal structures and development processes that shape context and individual vulnerability (see the above Section 8.3.2), and values and lived experiences of climate hazards (Djoudi et al., 2016; Walker et al., 2021). Intersectionality approaches are central to grasping differential vulnerability (Thomas et al., 2019) for past and present livelihood impacts of climate change (see Figure 8.3 and Section 8.2.2.2). Assessing observed local conditions and livelihood impacts and shifts requires us to consider reinforcing social phenomena such as age, gender, class, race and ethnicity which shape social inequalities and experiences of the world and also intersect with climate hazards and vulnerability (Walker et al., 2021).

This understanding helps to clarify how social structures, institutions and governance mechanisms matter to address social causes in addition to climate magnifiers while holding them accountable (see Section 8.5). For example, low-elevation coastal zones concentrate high levels of poverty in some specific areas: 90% of the world's rural poor are concentrated in the low-elevation coastal zones of just 15 countries, and this population keeps growing (Barbier, 2015). Yet studies on the economic impacts of climate change and also Integrated Assessment Models typically overlook the distributional effects of these impacts according to vulnerability and exposure and do not sufficiently account for agent and societal heterogeneity (Balint et al., 2017; Sovacool et al., 2021).

Since the AR5, *high confidence* is attributed to the fact that the, mostly detrimental, climate change impacts and risks are experienced mainly by the poorest people around the world (Olsson et al., 2014; Roy et al., 2018). There is *high confidence* that climate change impacts will put a disproportionate burden on low-income households and thus increase poverty levels (IPCC, 2014a; Hallegatte and Rozenberg, 2017).

There is *robust evidence* that economic development based on the exploitation of natural resources can significantly increase the vulnerability of communities at the local level. For example, there is a correlation between political arrangements and environmental degradation that brings about both disasters and an increase in disaster risk (Cannon and Müller-Mahn, 2010; Pereira et al., 2020) and while development is recognised by some as a key element for adaptation (Cannon and Müller-Mahn, 2010).

Maladaptation is an important thread given its relevance to assess ways that well intentioned development can exacerbate past and existing vulnerabilities and undermine livelihoods (see Section 8.2.2.1). Evidence shows that some local development projects can undermine resilience and increase the vulnerability of neighbouring communities, leading to maladaptation (Magnan et al., 2016; Schipper, 2020; Eriksen et al., 2021). Development projects can also negatively affect the vulnerability and create new ones of the very community where they are implemented (Burby, 2006; Magnan et al., 2016; Atteridge and Remling, 2018; Thomas and Warner, 2019; Work et al., 2019). Maladaptation has also received growing attention since AR5 as projected future climate risk for vulnerable social groups (see Section 8.4.5.5) and in the context of adaptation constraints and trade-offs in climate resilient development (see Section 8.5.1 and 8.6.1), Despite maladaptation, there is however *robust evidence* that inclusive and sustainable development at the local level, can reduce vulnerability (Cannon and Müller-Mahn, 2010; Patnaik et al., 2019).

8.3.3.2 Economic and non-economic losses and their relevance for poverty and livelihoods

Economic losses include income and physical assets and non-economic losses include mortality, mobility, mental wellbeing losses from climate change (see Section 8.3.4). The IPCC WGII AR5 primarily associated losses and damages with extreme weather events and economic impacts, and treated it primarily as a future risk. New evidence provides insights into present-day losses and damages from slow-onset impacts (e.g., sea level rise) (Adamo et al., 2021) and non-economic losses (e.g., cultural impacts, emotional and psychological distress) (McNamara et al., 2021b) which previously received much less attention. AR5 had more focus on losses and damages in high-income regions than in regions most at risk, such as Small Island Developing states and Least Developed Countries (LDCs) (van der Geest and Warner, 2020).

Impacts of climate change are affecting the economic and non-economic dimensions of people's lives, including subsistence practices of communities that are experiencing decreases in agriculture productivity and quality, water stress, increases in pests and diseases, disruption to culture, and emotional and psychological distress, just to cite a few (Savo et al., 2016). For example, the cumulative effects of slow-onset events threaten food security especially among the poor in Latin America and the Caribbean—regions which face the largest gender gap in terms of food security globally (Zuñiga et al., 2021). In general for Global South countries, the global average temperature warming (including the Paris target of 1.5°C) means substantially higher warming and including higher frequency and magnitude of extreme events, that will result in significant impacts on societal vulnerability (Aitsi-Selmi and Murray, 2016; Djalante, 2019).

Measuring losses from climate change impacts in terms of poverty and inequality can be difficult, and part of the lack of assessments of non-economic loss and damage can be attributed to the limited observational climate data on poor countries and population impacted, which are mostly concentrated in the Southern hemisphere (Roy et al., 2018).This is also due to the challenges posed by limited data available for assessing attribution (Cramer et al., 2014; Harrington and Otto, 2020; Otto et al., 2020a) and no comprehensive set of adaptation metrics (Otto et al., 2020b). Economic losses and damages from climate change are often assessed and reported after disasters or within crises, however, non-economic losses from climate change are often overlooked as is their relevance for poverty and livelihoods. For those who experience both economic and non-economic losses the impacts of climate change are very real and profound (Tschakert et al., 2017; Roy et al., 2018) Particularly in low-income and most vulnerable regions, it is not the absolute economic loss, but the combination of economic and especially non-economic losses that need to receive higher attention and need to inform adaptation strategies.

8.3.4 Observed disproportionate impacts according to economic and non-economic losses and damages due to climate change

Since AR5 a new discourse on Loss and Damage (L&D) has emerged with new typology and elaboration of a definition. L&D has a long and contentious history and is enshrined in the Paris Agreement (see Cross-Chapter Box LOSS in Chapter 17). Despite ambiguity about what constitutes L&D (Boyd et al., 2017), it focuses on how to avert, minimize, and address the negative impacts of climate change, including those that cannot be avoided through adaptation. It can also be thought of as the observed residual risk (and potentially irreversible losses) from climate change when adaptation limits are encountered and mitigation has failed (Boda et al., 2020). L&D is considered a policy mechanism (see Cross-Chapter Box LOSS in Chapter 17). It is also a burgeoning science for loss and damage (Mechler et al., 2019b) which advances the breakdown on compounding vulnerabilities and highlights the disproportionate effects of climate change on the vulnerable and marginal (see Box 8.5 for illustration of distributional effect of both the drought and responses in the Cape region in South Africa). New evidence provides additional insight into loss and damage from slow onset events related to climate change (sea level rise, drought) (see Anjum and Fraser, 2021; Lund, 2021) For example, (Singh et al., 2021) found growing evidence of urban droughts leading to economic losses (e.g., groundwater over-extraction, financial impacts) and non-economic losses (e.g., conflict, increased drudgery).

The literature is assessed according to this new L&D typology, which includes both extreme and slow onset events and has a strong emphasis on climate justice and disproportionate impacts of climate hazards (see Figure 8.3) with a new focus non-economic loss and damage.

8.3.4.1 Economic (e.g., income, assets) impacts of climate change and vulnerability

While extreme events are not new, the intensity and frequency of extreme events are stacking, leading to additional increase in poverty or vulnerability in some regions, exacerbated by Covid-19, and up against existing development pathways leading to significant impact on economic losses globally (*high confidence*). There is *robust evidence* that many African countries experience climate-related losses in terms of loss of crop yields, destroyed homes, food insecurity through increased food prices, and displacement (Box 8.5; Olsson et al., 2014). Attention has been focussed on low income groups, women and children, poor rural communities, and Indigenous Peoples such as the example of the Dupong, an Indigenous Peoples in Ghana using indigenous strategies to limit adverse impacts of climate change-induced water shortages (Opare, 2018). In Kenya economic loss and damage during droughts between 2009−11 drought incurred costs including trucking emergency water and food supplies as well as loss of livestock and livelihoods, particularly in areas cross-sectoral economic effects were estimated to reduce GDP by 2.8% per year (King-Okumu et al., 2021a). Past studies have similarly shown that in context of extreme events such as floods or droughts the most commonly sold assets are livestock and land. The sale of property particularly reduces the asset base and creates long-term vulnerabilities to future events and can trigger chronic poverty *(high confidence*). People may face food shortages in the future from lack of crop production (Opondo, 2013).The sale of cattle affects the household asset base, as well as the important access to animal traction power for farming.

In South Asia, there is *robust evidence* of economic impacts of climate change (Cao et al., 2021), for example in the Sundarbans (a transboundary ecosystem with components in both India and Bangladesh, with the problem of unproductive livelihoods being common across residents of both countries) observations show local livelihoods are rapidly becoming unproductive (loss of fish, and increasing salination making agriculture increasingly difficult) (Ghosh, 2018); conditions that are exacerbated by climate change impacts (*high confidence*). Cyclone and storm surges induced by climate change force saline water into agricultural lands along the coast, which damages crops not only in the year the cyclone hits, but for several years afterwards (Rabbani et al., 2013). They showed in Shyamnagar Upazilla in Satkhira district the proportion of salinity-free farmland has gone down over the past 20 years, from more than 60% to nil (Rabbani et al., 2013). Vietnam has also experienced effects of flooding and salinization in the Mekong delta coupled with rapid social development. Intensified floods and droughts have dramatically resulted in loss of livelihoods in agriculture and fisheries in some areas of the basin (Evers and Pathirana, 2018). In Vietnam the expected salinization increases livelihood shifts into areas that are more risky, such as shrimp farming. Furthermore, the Vietnamese Mekong Delta is characterized by strong migration processes towards cities, particularly Ho Chi Min, meaning that abrupt livelihood shifts are already happening. There are emerging examples of Indigenous Peoples affected by climate change in indigenous farming mountain communities of the Nepal Himalaya. (Sujakhu et al., 2019). The Philippines has experienced extreme events, such as typhoon Haiyan in 2013, which left more than 7353 reported people dead or missing, and damaged or swept away more than 1.1million houses and injured more than 27,000 people (McPherson et al., 2015). More than 4 million were displaced. The cost of damages has been estimated at US$864 million with US$435 million for infrastructure and US$440 million for agriculture in affected regions (McPherson et al., 2015).

Sea-level rise, coastal flooding and surge inundation is an increasingly pressing problem across the urban Pacific, including the urban and coastal population of Vanuatu (McDonnell, 2021). Pacific region islands such as Vanuatu (Handmer and Nalau, 2019) are particularly vulnerable to climate change. Kiribati and

Tuvalu are impacted by exceptionally high tides that affect the urban atolls of South Tarawa and Funafuti, and cyclonic activity causing extensive economic damage in Tuvalu (Curtain and Dornan, 2019). Limited migration opportunities for low-income households can result in forced immobility, and high tides, sea-level rise and cyclonic damages could result in relocation of significant groups of the population.

A pertinent example of economic losses is the example of the Torres Strait in Australia. This example shows evidence of communities living on remote islands Boigu, a low-lying mud island inundated by the sea during high tides and storm surges, and those most exposed and vulnerable to climate change have limited livelihood assets and face challenges to secure external support with government and others. Place-based values evoke a reluctance to relocate or retreat with economic losses such as community infrastructure, housing, and cultural sites (McNamara et al., 2017). In the Great Barrier Reef, Australia sea level rise and sea level global temperature warming affects fisheries productivity and tourism (Evans et al., 2016). Unprecedented burn area of wild forest fires in Australia between September 2019 and January 2020 (Boer et al., 2020) burnt almost 19 million hectares, destroyed over 3,000 houses, and killed 33 people (Filkov et al., 2020).

The 2018 European heatwave in Northern and Eastern Europe experienced multiple and simultaneous crop failures—among the highest observed in recent decades (*high agreement*). These yield losses were associated with extremely low rainfalls in combination with high temperatures between March and August 2018 (Beillouin et al., 2020). Across Europe, in 2018 people experienced one of the worst harvests in a generation. Northern and Eastern Europe experienced multiple and simultaneous crop failures—among the highest observed in recent decades. These yield losses were associated with extremely low rainfalls in combination with high temperatures between March and August 2018. This compounding of extreme conditions in 2018 led to one of the highest negative relative yield anomalies at the scale of Eastern and Northern Europe, across a large array of crop species(Beillouin et al., 2020).

Extreme climate events are disproportionately impacting economies of the most vulnerable everywhere (*medium evidence, high agreement*). In the United States, Central America and Caribbean, Hurricanes Katrina, Harvey, Irma, Maria and Michael are examples of extreme climate events that have displaced households, destroyed homes, and led to loss of income among the poor and marginalized (Klinenberg et al., 2020). Puerto Rico was devastated by Maria but received less support from the Federal Emergency Management Agency (FEMA) (García, 2021). Evidence is emerging on unequal governance response in the US versus Puerto Rico (Joseph et al., 2020). Floods, storms and heatwaves have impacted the poorer communities, and even wildfires in California, impact many wealthy groups, also impacted infrastructure used by all, for example, with lengthy electrical power blackouts, but particularly impacted vulnerable to disasters such as undocumented Latino/a and Indigenous immigrants in the case of the Thomas Fire in California's Ventura and Santa Barbara counties(Méndez et al., 2020) Hurricane Irma in 2017 hit Ragged Island in the Bahamas as a category 5 storm leaving the island in ruins and deemed 'unlivable' by its authorities, with most infrastructure left as rubble, no essential utilities remained, schools and health clinics were in ruins and the stench of dead animals was overwhelming. This storm resulted in significant economic loss and damage by the community through loss of their homes, churches, schools, agricultural land, and infrastructure (Thomas and Benjamin, 2020).

Across South America, groups of farmers, children, elderly, Indigenous Peoples and traditional communities are increasingly exposed to floods, droughts, wild forest fires, losses in crop yields, resulting in significant economic costs (*medium evidence, high agreement*) (see Box 8.6). Urban communities, in particular those living in informal settlements, are exposed to heatwaves. In Peru, analysis of water risks posed by climate change in the Vilcanota-Urubamba basin, Southern Peru, seasonal water scarcity and 'Glacial Lake Outburst Floods' (GLOF), pose a serious threat for highly exposed and vulnerable people. It showed that very high risk potentials of 134 current and another six out of 20 future glacier lakes as potentially highly susceptible to outburst floods. A total of eight existing and one possible future lakes indicate future river discharge could be reduced by some 2-11% (7-14%) until 2050 (2100). Farmers, in particular smallholders risk losses to growing irrigated agriculture and hydropower capacity with effects on water scarcity and food security (Drenkhan et al., 2019).

There are additional dimensions of economic losses that are of a more diffuse nature. In particular, climate change is also expected to negatively affect labour supply, particularly in temperature exposed industries (agriculture, mining, manufacturing, construction), due to increases in the number of extreme hot days (Graff Zivin and Neidell, 2014; Garg et al., 2020). Low-income countries have on average a large share of workers in such industries and will thus be especially hard hit. Aside from labour supply, a number of studies also document negative impacts to manufacturing productivity (Acharya et al., 2018; Pogacar et al., 2018; Somanathan et al., 2021). These findings provide a channel to explain macroeconomic consequences of climate change (Burke et al., 2015). However, there are also noneconomic costs in that extreme heat will cause increased discomfort to workers, such as psychological stress, disease and in extreme cases, death among the workforce in developing economies as well as tropical and sub-tropical countries (Ansah et al., 2021).

8.3.4.2 Non-economic (e.g., mobility, wellbeing)

Climate change loss and damage presents an existential threat to some (Boyd et al., 2017). For example the Pacific Island Countries have contributed least to total greenhouse gas emissions, the nations of the South Pacific are highly vulnerable to rising sea-levels, tropical cyclones and other climate-related risks (Nand and Bardsley, 2020). For example across Oceania there is significant risk that sea-level rise will lead to forced relocation. Pacific leaders underscore importance of losses including deep connections between their world views and their land, and that leaving their islands can only be considered an option of 'last resort' (McDonnell, 2021).

Non-economic loss and damage (NELD) is values based (subjective and intangible) and relates to norms, social values and highlights intersectional experiences and perspectives on climate risk. The discourse on loss and damage includes a framing of NELD as loss of human and non-human life and mental and physical health and are experienced widely across the world in vastly different ways associated with social values (Tschakert et al., 2019). There are respectable arguments for the case that all life has intrinsic value (Vetlesen, 2019). The NELD framing of climate impacts highlights that not all risks are measurable. While difficult to measure, there are a growing number of cases of non-economic loss and damage globally (*medium evidence, high agreement*). Illustrative examples of non-economic loss and damage from climate change include the Pacific (McNamara et al., 2021b) and Small Island Developing States (SIDS) in the Caribbean. (Martyr-Koller et al., 2021). For example, the hurricane season in 2017 was particularly extreme resulting in climate-induced displacement with direct implications for non-economic loss and damage, including threats to health and wellbeing and loss of culture and agency (Thomas and Benjamin, 2020).

In the context of the Pacific Islands NELDs are thought of as interconnected and span human mobility and territory, cultural heritage and Indigenous Knowledge, life and health, biodiversity and ecosystem services, and sense of place and social cohesion (Carmona et al., 2017; Ojwang et al., 2017; McNamara et al., 2021b). There are gaps in our understanding of NELD, much of the evidence is from the Global South and at smaller scales (*high agreement*), NELD is not explicitly linked to attribution science yet and evidence often lacks coverage on certain groups (Boyd et al., 2017; Carmona et al., 2017; Ojwang et al., 2017). Non-economic losses are often associated with displacements and migration in terms of climate change and human vulnerability (Section 8.2.1.4), studies show that the impacts of extreme flooding, droughts and/or hurricanes and cyclones that can lead to a sense of lost identity and place, and emotional distress, that are hardly assessed dimensions of impacts and risks (Adger et al., 2014; Barnett et al., 2016; Tschakert et al., 2017; Serdeczny et al., 2018). Non-economic losses are particularly relevant for understanding adverse consequences of climate change on the poor and most vulnerable population groups (*high confidence*). These NELD categories are still overlooked vulnerability assessments and adaptation planning. A novel way to consider NELD in assessments is to interconnect to a sustainable development perspective (Boyd et al., 2017; Boda et al., 2020).

In order to categorise the different types of non-economic loss and damage that exist (Serdeczny et al., 2016), based on their literature review, the authors come up with a set of systematic categories that capture what is usually thought about as having intrinsic value and according this framing of non-economic loss and damage this includes: human life, sense of place and mobility, cultural artefacts, biodiversity and ecosystems, communal and production sites and agency and identity (Serdeczny et al., 2016; Serdeczny, 2019). For example, there is emerging evidence on linkages between slow onset events and mobility decisions, trajectories and outcomes (Zickgraf, 2021). In addition, categories include psychosocial and emotional distress (van Der Geest and Schindler, 2016). For example, research shows potential increased risk of Intimate Partner Violence (IPV) following disasters, noting that societies that are vulnerable to climate change may need to prepare for the social disasters that can accompany disasters revealed by natural hazards (Malik and Stolove, 2017; Rai et al., 2021).

Geographical focus on non-economic losses in the literature is mainly on the Global South with studies mainly smaller in scale (*high agreement*). Many events studied include severe storms, floods and landslides. Key groups affected include low income groups, agropastoralists, women and girls, children and youth, Indigenous Peoples, ethnic and religious minorities. In Europe, the Samis who as a group face significant challenges to health as ecosystems deteriorate (Jaakkola et al., 2018). In Africa, In Zimbabwe storm Idai affected 270,000 people and subsequent flooding and landslides left 340 people dead and many others missing (Chanza et al., 2020). There is evidence of loss of cultural heritage sites where effects of sea-level rise and coastal erosion, the other considering climate change and variability (Brooks et al., 2020). Haile et al. (2013) show flood casualties in Ethiopia include children drowned while playing outside during the 2007 flood period although official data is hard to come by (p. 489). Moreover, loss of place was experienced when many of local houses in Itang built from wood, grasses and mud walls, which are easy to reconstruct building economics are not strong enough to withstand an extreme flood and 38% of the surveyed houses were severely damaged by the 2007 flood. These houses were constructed as an adaptation strategy but could not withstand the floods. In Kenya, Opondo (2013) shows loss of human life was the most severe impact of floods. For example, in the focus group discussion with men, 'it was reported that a boat capsized on River Nzoia at Siginga and ten people died'. (p. 457). In Mozambique, Brida et al. (2013) show loss of sense of place occurred after flooding in the central districts of Caia and Mopeia, flooding had a devastating impact on homes and livestock (Brida et al., 2013). Health impacts of the forest fire impacts in Amazon basin countries have disproportionately affected vulnerable people/social groups (see Box 8.6).

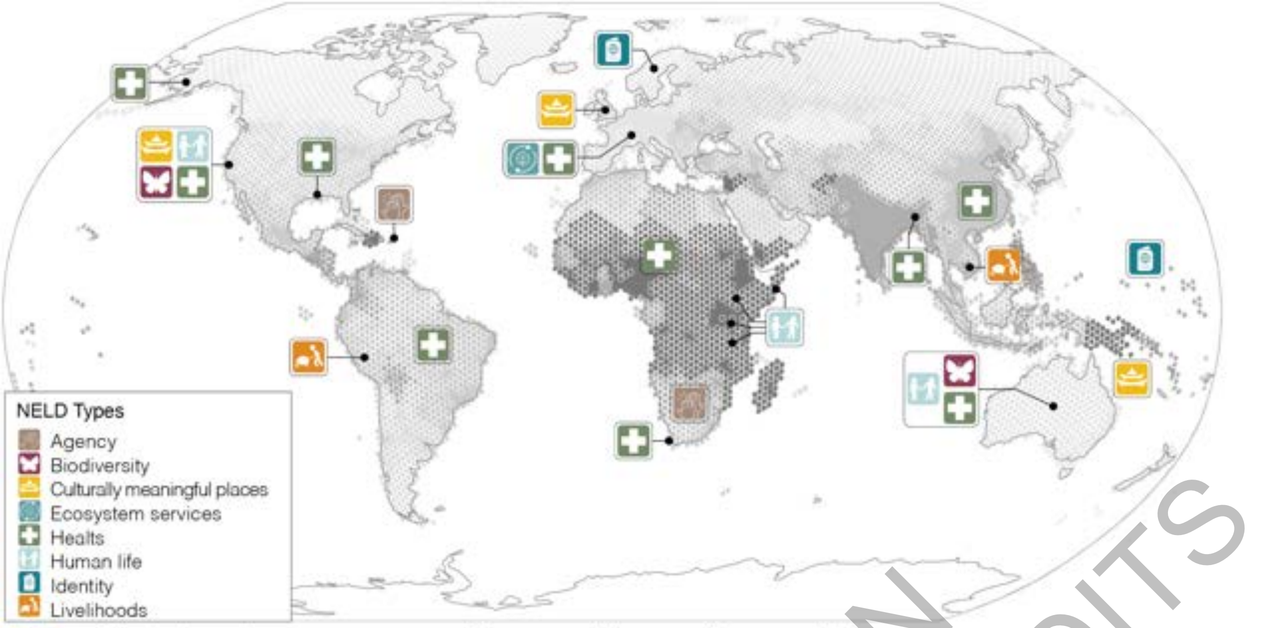
In the literature on non-economic loss and damage there are many examples of loss of life (*high agreement*), one such is in Nepal related to one of the deadliest deadliest landslides in Nepal history resulting in the death-toll of 156 people (van der Geest, 2018). Evidence from landslide Jure and consecutive rainfall in Sindhupalchok in Nepal also indicated that experience with impacts led to harmful mental stress such as fear of new landslides in about 68.4% of people interviewed (van Der Geest and Schindler, 2016). One study in Nepal has shown that almost a quarter (23%) of the households interviewed had sold property including homes, livestock, and heirloom possessions in response to flooding (Bauer, 2013). Human deaths are increasingly associated with losses and damages from tropical cyclones/typhoons Bangladesh, such as the Southern coastal districts of Bangladesh, in particular Khulna and Satkhira (Chiba et al., 2017). Chandra et al. (2017) A case study from Mindanao`, Philippines also reports physical injuries and loss of life in the Philippines from the most powerful typhoon for over a century until 2012, affecting more than six million people, killing at least 1000 people (Eugenio et al., 2016). Beckman and Nguyen (2016) identify the floods 2004 pulled away 24 houses in the commune, loss of families when their houses were flushed away.

An illustrative example is climate-induced loss of wellbeing and (im)mobility in Bhola Slum, an informal settlement in Dhaka, Bangladesh. Research revealed that Internally Displaced People from the southern coast experienced loss of belonging, identity, quality of life and social value produced in people a nostalgia and desire to return home (Ayeb-Karlsson et al., 2020). Another example is of urban climate change justice through the lens of migrants in the Indian cities of Bengaluru and Surat, where experiences of environmental marginality can be attributed to a lack of recognition of citizenship rights and informal livelihood strategies driven by broken social networks and a lack of political voice, as well as heightened exposure to emerging climate risks and economic precariousness. In this case migrants experience extreme forms of climate injustice in their invisibility to formal government and even are actively erased from cities through force or discriminatory development policies (Chu and Michael, 2019). Non-economic loss and damage also includes the loss of social networks that has lasting implications for psychological health as well as for coping with crises following disasters or challenges posed by adverse climate change impacts. For example, many households from Cyclone Aila-affected villages of Dacope and Koyra upazilas of Khulna District in Bangladesh migrated to other places permanently after the cyclone as these affected villages were subject to long-term flooding (e.g., two or three years) following the cyclone. They migrated as they were unable to restore their livelihoods and thus, were unable to secure necessary income for survival (Saha, 2017).

The examples show the multifaceted nature also of intangible and non-economic losses that people experience in the context of climate change and daily risks they are exposed to. Conventional vulnerability assessments cover some aspects that are linked to the likelihood to experience non-economic losses, such as aspects of health, governance, education and in some cases also forced migration and the role of social networks. Overall, both elements of this assessment here underscore that it is not just the climatic stressor, but rather the underlying context conditions that decide whether an extreme event translates into a disaster.

8.3.5 Economic and non-economic losses and damages due to climate change and their implications for livelihoods and livelihood shifts

This section examines the intersections between losses and damages and livelihood shifts. This requires an examination of the differentiated aspects of livelihoods. Understanding economic (e.g., loss of food crops, infrastructure, assets etc.) and non-economic losses (e.g., health, wellbeing, loss of place, agency) and their consequences for livelihoods is important that the intangible aspects clearly become visible and to receive greater attention in loss assessments and in designing adaptation strategies and programmes. Figure 8.10 provides a summary of examples of observed impacts of climate hazards on economic and non-economic capitals and the section assesses livelihood implications across regions. It shows examples of climate hazards attributed to climate change in studies since AR5, across a range of geographical sites for heatwaves, drought, hurricanes, and floods and non-economic losses and damages. The figure 8.10 reveals examples of climate hazards attributed to climate change in studies since AR5 across a range of geographical sites for extreme and slow onset events, such as heatwaves, drought, hurricanes and sea level rise. These are associated with non-economic losses and damages. These figure underscores that non-economic losses and damages lead to significant livelihood threats and livelihood changes. Also limits of adaptation become evident (Chapter 16).



NELD	Climate hazard	Non-economic Loss and Damage	References
Health	Western Cape region in South Africa drought "Day Zero"	Loss of quality of life	Pascale et al., 2020; see also AR6 WGI Chapter 10, Section 10.6.2; M. Fanadzo 2021
Human life	East Africa drought 2017 (Tanzania, Ethopia, Keny and Somalia)	Loss of lives	Funk, C. et al. 2018; Haile et al., 2020
Culturally meaningful places, Human life, Biodiversity, Health	The 2011–2017 California drought	Loss of life, loss of quality of life, loss of culturally meaningful places and biodiversity	Seager et al 2015; Murray et al. 2021; Greene 2021, Greene, 2018; Barreau et al., 2017. Hung et al, 2021; Garwood et al. (n.d.)
Health	2015 Amazon forest fire in Brazil	Loss of quality of life	AR5 WGII Chapter 8, Box 8.6; Li et al., 2021
Identity	Wildfires Sweden 2018	Loss of cultural way of life	Krikken et al. 2021; Jaakkola et al., 2018
Human life, Biodiversity, Health	Australia bushfires, 2019-20	Loss of life, loss of quality of life, loss of biodiversity	van Oldenborgh et al. 2020; Celermajer et al., 2021; Nguyen et al., 2021; Godfree et al., 2021
Agency	Hurricane Maria "extreme rainfall" over Puerto Rico, 2017	Loss of safety networks and displacement	Patricola et al., 2018; Keellings and Hernández Ayala, 2019; Moleti et al., 2020; Salas-Wright et al., 2021
Livelihoods	Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat	Loss of livelihoods	Stuart-Smith et al., 2021; Bergmann et al., 2020; Drenkhan, 2019
Identity	Pacific sea level rise	Loss of Indigenous and local knowledge	Herring et al., 2014; Herring et al., 2015; Herring et al., 2015; McNamara et al., 2021
Culturally meaningful places	Great Barrier Reef mass bleaching, 2016	Loss of culturally meaningful places	Lewis and Mallela, 2018; Curnock et al., 2019
Health	East China's hottest spring, 2018	Loss of quality of life	Lu et al., 2021; Kinay et al. 2019
Health	Sahel drought	Loss of quality of life	AR6 WGII Chapter 8; Semde et al. 2021
Health	Alaska wildfires, July 2019	Loss of quality of life	Yu et al., 2021; Hahn et al., 2021
Health	Urban drought Dhaka, Bangladesh	Loss of quality of life	Singh et al., 2021; Ray and Shaw, 2019; Amjad 2019
Culturally meaningful places	Storm Desmond, 2018 UK	Loss of cultural heritage	Howard et al., 2017; Otto et al., 2017
Ecosystem services	Unprecedented Europe heat, June-July 2019	Loss of ecosystem services and loss of quality of life	Ma et al., 2020; Kandic, 2020; Schuldt et al., 2020
Health	Lousiana floods, August 2016	Loss of quality of life	Wang et al., 2016; Zhang et al., 2021; Boullion et al., 2020; Keegan et al., 2018
Agency	Severe drought and poor harvests over southern Africa, 2016	Loss of agency	Funk, C. et al., 2018; Feeny and Chagutah, 2016; King-Okumu et al., 2021
Livelihoods	Flooding on the Lancang-Mekong River Basin, 2008–16	Loss of livelihoods	Yun, X. et al. 2020; Evers and Pathirana, 2018

Figure 8.10: Examples of non-economic loss and damage associated with climate hazards attributed to climate change with background on the global vulnerability and symbols with corresponding detail in the table showing examples where non-economic losses have been documented. It is important to note the following. 1. The figure is not exhaustive in terms of examples of extreme or slow onset events or losses. 2. It does not capture undocumented cases in the scientific literature. 3. It is an illustration of the relationship between unequivocal human induced climate change and intangible losses (Adapted from Boyd et al., 2021).

8.3.5.1 Livelihood shifts resulting from loss and damage from climate change

While there are limited studies that directly link economic and non-economic loss and damage from climate change to global-scale in livelihood transformations there is *robust evidence* on the granular linkages, at community, national and regional levels, between losses, coping strategies and livelihood shifts. Across Africa climate change is impacting crop yields, destroying homes and resulting in loss of infrastructure, and leading to non-economic losses associated with involuntary migration and displacement (Olsson et al., 2014), and loss of livestock and assets (see IPCC SR 1.5°C Chapter 3 (Hoegh-Guldberg et al., 2018)), resulting in long-term reduction in the capacity for agriculture and land management. For example, in March 2019 tropical cyclone Idai in Mozambique, Zimbabwe and Malawi led to substantial losses of agriculture, loss of infrastructure, and lack of access for aid and support, all of which contributed to significant displacement in each country (Fischel de Andrade and de Lima Madureira, 2021). Examples of livelihood impacts include livelihood shifts among Kenyan pastoralists to camel husbandry, resulting from household inequalities in assets and changes in relation to weakening of social norms of reciprocity and social cohesion (Volpato and King, 2019).

Extreme climatic events pose serious disruptions to local livelihoods and asset bases and requires them to reconstruct, transform and diversify livelihoods (Uddin et al., 2021). Examples of livelihoods shifts across Asia and Southeast Asia (e.g., India, Bangladesh, Vietnam, Philippines) include rural communities in coastal areas, urban settlements that are experiencing economic losses (high confidence) from for example crop failure and reduced access to fish, which contribute to non-economic losses associated with involuntary migration (Ghosh, 2018) and the malnutrition of children (Siddiqi et al., 2011). Chiba et al. (2017) shows in Bangladesh the connection between mental stress and impacts to the fundamental capacity to sustain livelihoods, such as food and a place to live, due to severe damage to houses, homesteads, properties, livestock and crops, loss of family members and relatives, and anxiousness about securing employment and income in the future. In Bangladesh coastal communities experienced losses in livelihood assets due to Cyclones Sidr and Aila (Uddin et al., 2021) and a significant number of cyclone victims were displaced from their homes by severe cyclones. People have had to change their occupations – both intra- and intersectorally – and confronted increased consumption and social costs. The study uncovered differences in impacts between occupations such as farming and fishing, and the latter was likely to change occupation post-disaster. They also show evidence that local people are learning to live with change and uncertainty by nurturing and combining various types of knowledge and social memory, generating diversified livelihood options, and self-organizing to enhance their resilience to future extreme weather events. In Bangladesh Ahmed et al. (2019) found cyclones, riverbank erosion, salinity intrusion, and floods negatively impacted people's lives by reducing their livelihood options. Their study found when there are limits to adaptation strategies many people turn to 'illegal livelihoods' included using fine mesh nets to collect shrimp fry in the rivers as well as logging in the Sundarbans. These people include the poorest and vulnerable, and law enforcement only exacerbate their vulnerability. Escarcha et al. (2020), studied impacts of typhoons, floods, and droughts on crop production and effects on livelihoods of cash crop focused rural villages in the Philippines. Their preliminary observations show a shift from crop to livestock production as a buffer activity to recover from crop losses. Farmers changed their farming activities as a multi-adaptive response driven by past experiences of climatic changes, farmers' social relations, household capacity, and resources available.

In Central Asia, the Sahel and South Asia, three global poverty hotspots, change impacts were shown to undermine traditional knowledge about livelihoods in ways that jeopardise future culture cohesion and sense of place (Tucker et al., 2015). Acosta et al. (2016) identified loss to productive sites in the Philippines with landslides destroying agriculture leaving many farmers without livelihoods. Similarly, Beckman and Nguyen (2016) in Vietnam identified an example where communal dams had been destroyed in floods leading to lack of irrigation for communal sites and local loss of farmland for farming communities. Chandra et al. (2017) identified the vicious cycle between declining agricultural production and conditions of soil erosion due to floods and droughts resulting in decreased crop fertility to productive sites with implications for decline in crop yields, loss of crops and of livelihood assets. Climate change related extreme weather events such as typhoons, floods, and droughts can have detrimental impacts on crop production (*high confidence*) and in the Philippines and Pakistan have significantly affected the livelihoods of cash crop focused rural villages (Escarcha et al., 2020; Jamshed et al., 2020b). There is an emerging shift from crop to livestock production as a buffer activity to recover from crop losses (Section 5.10.4; Jamshed et al., 2017; Escarcha et al., 2020). As with many examples of livelihood shifts, the viability of the shifts long-term under climate change have yet to be assessed further.

In Africa, many communities do already experience drought and flood-related disasters (high confidence) such as those that negatively impact livelihoods and assets the Muzarabani district of Zimbabwe (Mavhura, 2017). The Muzarabani community has revived and developed new livelihood strategies to manage risks, including local informal safety nets, local farming practices and the traditional flood-proofing structures. Food security and agriculture productivity are examples of livelihood resources most at risk to climate hazards (see Figure 8.2) (*high confidence*). An illustration of such risks to cocoa farmers in Ghana includes increased incidences of crop pests and diseases, wilting of cocoa leaves, high mortality of cocoa seedlings which affected expansion and farm rehabilitation, and wilting of cherelles resulting in losses of crop yield. An illustration of livelihood shifts resulting from losses is of farmers shifting to cereals due to the unpredictable climatic patterns and the shortened duration of rainfall. Yet, insecurity with storage, supply chains and low returns from cereal production, coupled with land scarcity in the Western Region, have resulted in a return to cocoa production (Asante et al., 2017).

Research from Australia shows complex linkages between the impacts of drought on livelihood income, health and cultural heritage, increasing risk of heat stroke, and possibly a link to suicide among male farmers (Alston, 2012; Hanigan et al., 2012; Marshall et al., 2019). The link between agricultural losses and suicides has also been noted in South Asia, including India (Carleton, 2017). Livelihoods are shifting with impacts to wellbeing, as noted by (Evans et al., 2016) showing connections between loss of fishery productivity and impact on tourism sector livelihoods in the Great Barrier Reef region. In Europe, losses to Indigenous Peoples are associated with loss of wellbeing of Sami communities and has forced livelihood shifts from reindeer herding due to loss of ecosystems to support the animals (Persson et al., 2017; Jaakkola et al., 2018). Traditional pastoralist systems are also greatly impacted by cumulative dual challenges of encroachments of other land users and by climate change. Traditional Sami reindeer herding strategies are still practiced, but that rapidly changing environmental circumstances are forcing herders into uncharted territories where traditional strategies and the transmission of knowledge between generations may be of limited use. For example, rotational grazing is no longer possible as all pastures are being used, and changes in climate result in unpredictable weather patterns unknown to earlier generations (Axelsson-Linkowski et al., 2020). These examples show that there are complex factors underpinning the linking loss and damage and shifting livelihoods. Moreover, there are significant challenges to undertake a shift and secure alternative livelihoods.

Linkages between losses, coping strategies and livelihood shifts in Small Islands (e.g., in the Pacific region Kiribati and Tuvalu, and in the Caribbean the Bahamas) shed light on impacted low-income households. For example, farmers have experienced extensive damage to homes and loss of infrastructure, and experience lack of migration opportunities (Curtain and Dornan, 2019). Evidence is growing that there is also significant loss of cultural heritage in resettlement (Barnett and O'neill, 2012), evidence from Small Islands displaced communities suggests that resettlement can have impacts on sense of place, identity and social fabric, a theme highly relevant to loss, coping and adapting livelihoods, and not only restricted to Small Islands (McNamara et al., 2021b). Roberts (2015) identified loss of communal sites in Kiribati and it is predicted that by 2050 up to 80% of the land on the island of Buariki and 50% of the land on Bikenibeu may be completely inundated and these effects will result in significant loss of livelihoods and displacement. Throughout the Caribbean evidence indicates that there will be an overall reduction in the area of land suitable for crop cultivation, as the region’s climate gets progressively warmer and as rainfall becomes more variable (Rhiney et al., 2016).

The multiple shocks of extreme events reduce crop yields, destroy homes, and lead to loss of infrastructure and displacement (high confidence) and are experienced in South and North America. For example in Peru glacial outbursts have led to loss of livelihoods (Drenkhan et al., 2019). People use a range of coping and adaptation strategies to deal with hazards where they live, such as shifting livelihood activities, inputs or production areas. However, traditional techniques are increasingly failing due to changing weather patterns. Across Peru, findings demonstrate that people use temporary and permanent migration among their many coping and adaptation strategies. Hazards related to water excess have been the key force in destroying homes and driving displacement in Peru. On the flipside, studies demonstrate that water scarcity also threatens livelihoods and thereby influences migration in Peru. While non-climatic reasons for moving dominate migrants’ motivations in many areas of Peru, water-related climatic drivers of migration are becoming increasingly relevant (Wrathall et al., 2014). Peru’s smallholder farmers and urban poor are not responsible for the climate crisis, yet their lives and cultural heritage are being increasingly jeopardized by its effects, making improvements in governance an imperative for Peru (Bergmann et al., 2021). Another area of significance is coffee production in Brazil where the majority of Brazilian coffee farms are operated by smallholders, producers with relatively small properties and mostly reliant on family labour (Koh et al., 2020). In the United States (e.g., New Orleans and Puerto Rico) people have lost livelihoods due to displaced households, destroyed homes, and led to loss of income as well as loss of social networks and family networks and loss of cultural heritage. For example, impacts of Hurricane Katrina have led to people being displaced from their employment, many evacuees had to relocate to new areas, which disrupted their social networks and placed them in unfamiliar labour markets, resulting in mental health challenges (Palinkas, 2020). There has also been a 'climate gentrification' in parts of New Orleans (Aune et al., 2020). Many of those who returned to their pre-Katrina areas had to deal with extensive damage to their homes and to public infrastructure.

In summary, across regions there are an increasing number of examples of observed economic and non-economic loss and damage from climate change. Adaptation measures need to better incorporate actions to tackle the burgeoning negative social, psychological and wellbeing impacts of climate change (Barnett et al., 2016; Box 8.5). At present, losses from climate change are potentially growing faster than adaptation measures across the globe. It is still uncertain how economic and non-economic losses trigger successful or viable new climate-related livelihood transitions for the poor and people/groups in vulnerable situations in the future (see Section 8.4.4, 8.4.5). In all likelihood, economic losses from climate hazards (e.g., drought) will be compounded by many factors including COVID-19 and other vulnerability drivers. For instance, globally small-scale coffee producers have been destabilised by COVID-19, but also because of history of recurrent (climate) shocks and structural inequalities, and may have to shift into alternative livelihoods (Guido et al., 2020). Coastal communities in Vanuatu have been impacted in the immediate period after COVID-19 showing changes in village populations, loss of cash income, difficulties in accessing food and experiencing shifting pressures on particular resources and habitats (Steenbergen et al., 2020). This trend poses real challenges to equity and sustainability.

[START BOX 8.5 HERE]

Box 8.5: Western Cape Region in South Africa: Drought Challenges to Equity and Sustainability

Nature of the drought

Between 2015 and 2017, the Western Cape region experienced an unprecedented three consecutive years of below average rainfall—leading to acute water shortages, most prominently in the city of Cape Town (Sousa et al., 2018). Anthropogenic climate change made the drought five to six times more likely (Pascale et al., 2020; see also AR6 WGI Chapter 10, Section 10.6.2). The severity of the drought presented new challenges to the existing management and governance capacity to ensure equitable and sustainable water service delivery. The city's water supply infrastructure and demand management practice were unprepared for the 'rare and severe' event of three consecutive years of below average rainfall (Wolski, 2018; Muller, 2019). Despite a potential total storage volume of about 900,000 ML of water (enough water for around a year and a half of normal usage, after taking evaporation into account), Cape Town's reservoirs fell from 97% in 2014 to less than 20% in May 2018 (Ouweneel et al., 2020; Cole et al., 2021). The drought saw residents queue for water as restrictions were imposed together with threats of closure of water provision to households (Sorensen, 2017; Scheba and Millington, 2018). Poor communication in the early stages of the drought (Hellberg, 2020), and a lack of trust in the administration, contributed to a near-panic situation at the threat of 'Day Zero' as dams almost ran dry in the first half of 2018 (Enqvist and Ziervogel, 2019; Simpson et al., 2020c). 'Day Zero' was avoided largely through public response, water demand management and the 2018 winter rains (Sorensen, 2017; Booysen et al., 2019a; Muller, 2019; Rodina, 2019b; Matikinca et al., 2020). At a household-level, responses to the drought saw everyday residents can display unprecedented degrees of resilience (Sorensen, 2017), including behavioural and attitudinal shifts and technological innovation across the full socio-economic spectrum (Ouweneel et al., 2020). But the private nature of some of these responses extended existing inequality in water access through privileged forms of 'gated adaptation' by elites which conventional water governance arrangements were unprepared for (Simpson et al., 2019b; Simpson et al., 2020a).

These 'climate gating' actions, such as drilling boreholes, secured water access for high-income households and companies, but excluded a large proportion of Cape Town's population who could not afford such private technologies (Simpson et al., 2019a; Simpson et al., 2020b). These responses were unanticipated by the city administration and compounded fiscal challenges faced by the municipality which could no longer use revenues from high-consumption households to cross-subsidise water for low-income households (Simpson et al., 2020a). This shift threatened to undermine the sustainability of the municipal fiscus and general water access (Box 9.8; Simpson et al., 2019a; Simpson et al., 2020a). In order to recover losses, municipal water tariffs for consumers were raised by 26% in 2018 (Muller, 2018; Simpson et al., 2019a). In addition to decline in tourism, median estimations of the overall economic impact of the drought indicate loss of 27.6 billion South African Rand (US$1.7 billion) translating into 64,810 job losses in the Western Cape, with Cape Town accounting for approximately half of those job losses (DEDAT, 2018). This had a disproportionate impact on unskilled and semi-skilled workers, particularly for those from low- and middle-income households (DEDAT, 2018). The drought also exacerbated the potential for sanitation health risks of the urban poor where tens of thousands of people lack access to safely managed sanitation facilities (Enqvist and Ziervogel, 2019).

The Day Zero Disaster Plan included prioritising and protecting the poor and most vulnerable communities where critical infrastructure and facilities and vulnerable and informal residential areas would remain connected while higher income residential areas would be cut off (Cole et al., 2021). Yet it is important to recognise that pre-existing deficiencies in service delivery meant water access for the urban poor did not change as significantly during the drought, particularly those in informal settlements who collect water from standpipes (Enqvist and Ziervogel, 2019; Matikinca et al., 2020). For these communities, the negative economic impact of the drought was compounded by the unintended consequences of demand management regulation emanating from the drought response. South Africa ostensibly ensures a constitutional right to water, regardless of ability to pay (Rodina, 2016), 58). Since 2018 however, as a consequence of new water tariffs instituted during the drought, Cape Town residents now have had to 'prove their poverty' in order to register as indigent households and access their water right (Scheba and Millington, 2018). Further, since 2007 and with increasing effect during the drought, the municipality has installed approximately 250,000 water management devices as a credit control and, during the drought, also a consumption control measure. As these have been largely installed in low-income homes, this control measure disproportionately affected poor households (Scheba and Millington, 2018; Enqvist and Ziervogel, 2019).

Lessons from the drought

The effect of communication at different stages in the drought highlights how critical information needs to be provided in a format and language that empowers people to act appropriately and collaboratively (Muller, 2019; Rodina, 2019b; Rodina, 2019a). Getting political decisions made in a timely fashion and with public support is a long-standing challenge for managers of urban water supplies (Muller, 2017; Muller, 2019). In Cape Town this was further challenged by dependence on a malfunctioning national department for water supply planning, poor coordination between the spheres of government—city, provincial and national governments—and poor collaboration between political representatives, technical experts, and strategic managers (Madonsela et al., 2019; Nhamo and Agyepong, 2019; Rodina, 2019a; Ziervogel, 2019b). This highlights the need to strengthen partnerships and collaboration across sectors and scales of governance (Ziervogel, 2019a) including the adoption of a 'whole-of-society' approach that recognises the contributions of non-state actors as adopted in the Cape Town Resilience Strategy (CoCT, 2019; Simpson et al., 2020a). Experienced yet inflexible water management initially operated at a distance from politicians and their citizens here was limited knowledge and capacity in how various municipal departments thought about risk, exposure and vulnerability of Cape Town's highly-differentiated population(Mukheibir and Ziervogel, 2007; Pasquini et al., 2015; Madonsela et al., 2019). In the later stages of the drought, Cape Town's water management department was able to work collaboratively across different departments and with politicians to implement responses.

The Cape Town case highlights how disaster planning for slow-onset city-wide shocks will be become increasingly important to safeguard equity and sustainability across African cities (Cole et al., 2021). It demonstrates the importance of integrating state and non-state responses to climate change in municipal adaptation and disaster planning (Booysen et al., 2019a; Booysen et al., 2019b; Simpson et al., 2020a), particularly for responses with unintended consequences. Further, water tariff models need to be flexible enough and have built-in redundancies in order to prioritize the needs of the urban poor and ensure climate responses do not disproportionately affect low-income groups and deepen existing inequalities (Scheba and Millington, 2018; Enqvist and Ziervogel, 2019; Simpson et al., 2019b). Systems and relationships of mutual accountability can also build more effective water management between spheres of government and enhance horizontal collaboration between municipal departments and non-state entities (Ziervogel, 2019b; Ziervogel, 2019a).

[END BOX 8.5 HERE]

In summary, this section has moved beyond the IPCC WGII AR5 in laying out structural elements of vulnerability and climate related vulnerability hotspots globally such as poverty, lack of access to basic services, gender inequality and undernourishment. The assessment provides new quantitative evidence about the global spatial distribution of systemic human vulnerability and therewith underscores that various hotspots of countries classified as very high or high vulnerable emerge in regional clusters. In addition, the number of people living in very high and high vulnerable country contexts is significantly higher in some assessments even twice as many as the number of people living in countries classified as low and very low vulnerable. The evidence suggest that statistically relevant differences in fatalities per hazard events are not just a produce of the hazard event, but strongly linked also with the level of vulnerability of a region or community exposed. The assessment of non-economic losses has also received only little attention in past IPCC Assessment Reports, therefore this sub-chapter provides new insights on how (next to measurable economic losses) non-economic losses and intangible losses emerge. These non-economic losses represent an important dimension of societal impacts of climate change that has not sufficiently captured so far within standard damage or post disaster assessments. Finally, the section provides evidence about the existing adaptation gap in terms of differential vulnerabilities and various non-economic losses already experienced.

8.4 Future Vulnerabilities, Risks and Livelihood Challenges and Consequences for Equity and Sustainability

Future climate vulnerability and risks to livelihood security are significantly influenced by present and past development trends, equity and sustainability. Consequently, observed impacts covered in previous sections provide essential insight for enhancing future adaptation and risk reduction. Since the AR5, new research approaches incorporate past lessons to project and assess climate change vulnerability and socio-economic conditions into the future. Scenario tools and methods are a powerful approach for integrated assessments of emissions pathways, associated warming and development contexts, helpful in guiding analysis of adaptation policy and planning (Berkhout et al., 2014; Birkmann et al., 2021a). Both quantitative and qualitative scenario approaches that assess future vulnerability and risks as well as livelihood challenges at global, national and local scales allow experts, planners, decision-makers and affected people to articulate and visualize development futures. These approaches can complement emissions pathway scenarios.

8.4.1 Future exposure, climate change vulnerability and poverty at the global scale

The Shared Socioeconomic Pathways (SSPs) scenarios orient climate models around possible development pathways that produce future exposure patterns, risk probabilities and vulnerability for future populations (O'Neill et al., 2014; O'Neill et al., 2017a). While the likelihood of any given scenario actually occurring is highly uncertain, they have the advantage of pairing with computational models to generate robust projections about risk profiles in possible futures, and therefore assess the relative influence of different drivers of change. In this way, scenario tools generate pictures of future vulnerability and adaptation pathways, and often have both an analytic and normative function. The decision-making context will determine which specific scenario approach is most appropriate (Rozenberg et al., 2014). Scenarios are limited by stakeholders' imaginations, and as such, new emergent challenges, such as the COVID-19 pandemic, are difficult to anticipate in scenario planning. Nevertheless, recent studies and forecasts of the impact of COVID-19 on poverty conclude that in the near and medium-term future major portions of the newly poor will emerge in Sub-Saharan Africa and South Asia (Laborde et al., 2020b; Sumner et al., 2020). Since these countries are already characterized by high levels of absolute poverty and vulnerability to climate change, it is likely that these regions will face more severe challenges in overcoming vulnerability and will be confronted with a growing adaptation gap. Thus, the implication for scenario planning is that single crises or events, such as the COVID-19 pandemic, might not significantly alter existing vulnerabilities, but rather reinforce them.

8.4.1.1 Exposure and vulnerability under different scenarios and alternative development pathways

At the international and national level, the Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2017a) have been developed to outline various development pathways, associated emissions and levels of warming, but also different possible development profiles (i.e., levels of economic growth, poverty, inequality, demographic change, etc.) that are highly relevant for adaptation.

Studies using the SSPs to understand multidimensional poverty are few but growing, and underscore the impacts of climate change on poverty are extremely sensitive to different levels of warming (Byers et al., 2018). Multi-sector risks approximately double between 1.5ºC and 2ºC GMT change, and double again in a +3°C world. Comparing a +1.5°C world pursuing sustainable development (SSP1) to a high-poverty and high-inequality +3°C world (SSP3), Byers et al. (2018) project substantial increases in populations exposed to drought, water stress, heat stress and habitat degradation (see in detail Byers et al., 2018). While in a +1.5°C world exposed populations increase by 7-17%, the increase within a +3°C plus world is 27-51% (Byers et al., 2018; Frame et al., 2018). Populations in Asia and Africa account for more than 80% of the global population exposed to these phenomena, and within South Asia and the Sahel, up to 90% of populations are exposed. Scenario tools help us to understand the burden of increasing multidimensional poverty, and potential for poverty traps, if mitigation and adaptation measures are not taken rapidly and effectively implemented.

At the national and sub-national levels, studies on development and risk scenarios capture specific challenges, for example, urban growth, demographic change, human health and aging (e.g., Dong et al., 2015; Chapman et al., 2019). In this regard, local scenarios of human vulnerability can inform future strategies for adapting to hazards such as heatwaves in cities under different socio-economic development strategies. These scenario approaches allow to focus on changes in climatic and societal conditions as well as urban transformations. This provides a more comprehensive basis for defining adaptation goals (see Fekete, 2019; Birkmann et al., 2021b). Also costs and benefits of different adaptation measures can be assessed against different future scenarios of climatic and societal change.

Contrasting with 'top-down' SSP scenarios, (Berkhout et al., 2014) outline how mesoscale and 'bottom-up' scenarios have been developed to inform spatial planning, for example, in the Netherlands. Increasing computational power has opened possibilities for large-scale 'bottom-up' simulations of people's livelihoods in the context of evolving climate change impacts, such as the migration decisions of farmers facing drought in Mexico over the coming century (Bell et al., 2019) and livelihood decisions of people facing coastal flooding in Bangladesh to the year 2100 (Bell et al., 2021). Such 'bottom-up' scenarios can generate projections about future outcomes, inform mapping and assess future vulnerability, with special emphasis on livelihoods of the poor. Researchers conclude that results of respective scenarios that aim to inform adaptation and risk reduction policies in the context of climate change have to match the frames of the stakeholder (Berkhout et al., 2014; Conway et al., 2019). Scenarios that assess potential future vulnerabilities and future capacities for adaptation require more attention, since many approaches for projecting future climate risk still largely overlook non-climatic drivers that determine future vulnerability and exposure (Windfeld et al., 2019).

8.4.2 The influence of future climate change impacts on future response capacities

The influence of climate change also impacts the future response capacities of people and nations to deal with future climate change and climate hazards. Recent studies (Mysiak et al., 2016) conclude that climate change can increase the severity and intensity of crises or even trigger disasters, particularly floods, storms, forest and wildfires, and droughts, have undermined decade-long poverty reduction efforts, particularly in low income and at-risk countries (Djalante, 2019). Climate influenced (disaster) risks are getting more complex and systemic (UNDRR, 2019). The magnitude of global annual average economic losses from natural and climate induced hazards to the built environment alone are estimated in the United Nations Office for Disaster Risk Reduction (UNDRR) Global Assessment Report (2019) comparable with the gross domestic product (GDP) of the 36th largest economy in the world - the Philippines at that time (in 2015) (UNISDR, 2015; Mysiak et al., 2016). In addition, a World Bank study concludes that losses of human-wellbeing are higher than the overserved economic losses from natural hazards (Hallegatte et al., 2017). In this regard, it is *likely* that future impacts of climate change, particularly under increasing levels of global warming (above 1.5°C) will also increase non-economic losses (see Section 8.3.2.3) and losses of human-wellbeing that are particularly relevant to most vulnerable groups and the poor.

Furthermore, the expected future increase in the number of exposed people to climate hazards, such as sea-level rise and coastal flooding is not only determined by changing hazard patterns, but also by regional processes of migration and urbanization for example in Asia and Africa, including an increasing number of urban poor living in low-elevation coastal zones (United Nations, 2018). This can increase again the probability that more people require assistance and support for buffering these effects of climate related hazards, for example in coastal zones. Historical urbanization processes, in coastal cities in Asia (e.g., in China, Vietnam, etc.) and Africa (e.g., in Nigeria) have increased the exposure of people to climate hazards, such as sea-level rise, which by 2100 under RCP8.5 will globally threaten 630 million people, largely in coastal cities (Kulp and Strauss, 2019).

In addition, Smirnov et al. (2016) conclude that worldwide the number of people exposed to extreme droughts will increase under both the RCP4.5 and the RCP8.5 particularly at the end of the century. The authors assess that under RCP4.5 the average monthly global population exposed to drought will increase between the periods 2008-2017 and 2081-2100 from the mean of 80 million to 212 million, and under RCP8.5 from about 90 million to approximately 472 million people. The research findings underscore that there is a high probability that exposure increases to extreme droughts particularly in regions and countries classified already today as high vulnerable (e.g., Sudan, Nigeria, etc.) (Smirnov et al., 2016). Extreme droughts are expected to further erode coping and adaptive capacities of those already characterized by high levels of vulnerability (see Section 8.3.1). Building adaptive capacities for most vulnerable groups in the future in these areas will be a challenge, since high levels of livelihood insecurity are coupled with high levels of structural vulnerability at national and regional scale (poverty, state fragility, etc.) making planned adaptation support very complex and difficult. Therefore, increasing adaptation gaps at different scales are anticipated in the future.

Increasing population exposure (e.g., due to urbanization of coastal zones, etc.), coupled with higher frequencies and intensities of specific climate hazards are *likely* in connection with the existing adaptation gap (e.g., high levels of vulnerability) to compromise development and human security. Recent studies, such as by Harrington (2018), conclude that the actual exposure and the physical individual recognition of some climate hazards, will be higher in low-income countries. The study of Harrington (2018) underscores that changes in extreme heat, for example, will be felt by the average citizen of a low-income country after 1.5ºC of global warming and will not be felt by about 40% of people living in high-income nations until well after double the amount of global warming is reached (3°C increase). In this context, it is important to note that even if a city or place is exposed to heat stress, people experience it quite differently due to different levels of vulnerability and adaptive capacities, such as the ability to afford air conditioning (Barreca et al., 2016). That means well-off populations are better insulated from effects of global warming than poorer or more vulnerable groups, even if they are geographically living in the same exposure zone. These findings underscore that issues of climate justice need to be considered within the problem definition and not solely at the end when designing adaptation strategies. Impacts of future climate hazards (heat stress, flooding, etc.) differ not only due to changes in frequency and intensity of the hazard itself, but also significantly in terms of the opportunities people have to respond and prepare for these hazards and climatic changes at present and in the future. However, it is also important to note the extreme heat stress has also caused significant fatalities in countries classified as low vulnerable, such as seen within the heat wave in Europe in 2003.

8.4.3 The influence of climate change responses on projected development pathways

Responses to climate change can have dual effects on development pathways. On the one hand, mitigation and adaptation processes can create significant development opportunities. The potential of mitigation policies for jobs creation, in particular, has been highlighted (Healy and Barry, 2017). However, responses to climate change can also have detrimental effects on future development: mitigation policies such as the building of hydro-electrical dams or the culture of biofuels can lead to communities' dislocation and populations' resettlement, particularly of disadvantaged groups within a society (de Sherbinin et al., 2011; Eriksen et al., 2021). Adaptation policies can also hinder some development processes: for example, the promotion of migration as an adaptation strategy can lead to communities being deprived of their workforce, and resenting the departure of some of their members (Gemenne and Blocher, 2017), even though they may offer new livelihood opportunities. However, the migration consequences in the context of climate change are often more nuanced and different trade-offs and benefits occur (see Porst and Sakdapolrak, 2020). For example, remittances support family members, at the same time in some cases these can also create imbalances in local markets (Melde et al., 2017). Evidence exists that some climate responses such as small-scale agricultural livelihood adaptation strategies have improved the ability of people to sustain their livelihood and to reduce poverty (Osbahr et al., 2010).

8.4.4 Social tipping points in the context of future climate change

Climate change has the potential to trigger major, sudden social transformations, yet there are no clear linear relationships between the magnitude of climate change impacts and the social changes they induce(Steffen et al., 2018). Evidence shows that major destabilizing social transformations (e.g., forced migration) can occur in response to limited climate change impacts, even while major climate change impacts can be mitigated through the resilience of social, political and economic systems and thus yield only minor social impacts.

In the context of climate change, 'tipping points' have been identified as critical thresholds at which a tiny perturbation can qualitatively alter the state or development of a system (Lenton et al., 2008; Lenton et al., 2019). The concept of tipping points is usually associated with large-scale components of the climate system that could be pushed past an irretrievable threshold as a result of human-induced climate change (Lenton et al., 2008), such as the deterioration of Antarctic ice sheets (Pattyn and Morlighem, 2020). Social tipping points refer to similar mechanisms of destabilization resulting from impacts of climate change on human societies at multiple scales and the societal context conditions in which these impacts occur. They are reached when climate change impacts force destabilizing social transformations from one state to another (Lenton et al., 2019): from sporadic losses due to climate change to chronic losses and impoverishment, from peace to violence, from a democracy to an authoritarian regime, from adequate food provisioning to famine, or into forced migration. For example, small variations in the rainfall or temperature can jeopardise livelihoods that are dependent upon subsistence agriculture, which can lead to migration and/or tensions around resources (see Figure 8.11). Social tipping points can also occur when intangible elements that ensure the survival of individuals and communities are eroded or removed. This is the case, for example, when the social fabric of a community falls apart. The Millennium drought in Australia led to higher rates of male suicide, especially among farmers, and droughts in Ghana led to similar outcome when people were forced to drink from the same water source as their animals, which they perceived as robbing them off their human dignity (Bryant and Garnham, 2015; Tschakert et al., 2019).

In socio-ecological systems, tipping points occur when a (small quantitative) change inevitably triggers a non-linear change in the corresponding social component of the socio-ecological systems, driven by a self-reinforcing positive feedback mechanisms, that inevitably and often irreversibly lead to a qualitatively different state of the social system' (Milkoreit et al., 2018).

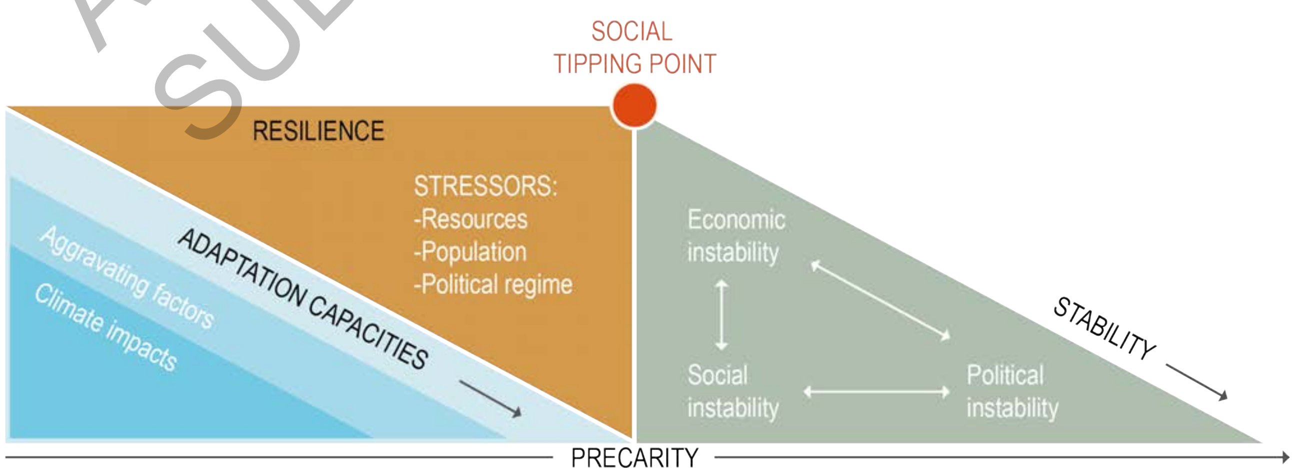


Figure 8.11: A social tipping point is reached when climate impacts push a society towards a state of instability. Those climate impacts are typically aggravated by economic, social and political stressors that reduce adaptive capacity and overwhelm its resilience. Once a social tipping point is reached, a society may experience mutually reinforcing states of economic, social and political instability, leading to cascading disruptions such as livelihoods insecurity, migration and displacement, food insecurity, impoverishment, civil and political conflict, and change of political regimes.

In recent years, significant research efforts have been made to identify early warning signals for social tipping points (Barrett and Dannenberg, 2014; Bentley et al., 2014; Lenton et al., 2019). While some identify early warning signals through time series (Scheffer et al., 2012), others see them in interaction networks and individual thresholds (Barrett and Dannenberg, 2014; McLeman, 2018). Empirical research conducted in a transboundary contentious region—the Jordan river valley—showed that there were significant local and regional differences in the identification of social tipping points (Rodriguez Lopez et al., 2019).

Empirical evidence shows that social tipping points can be triggered long before climate tipping points are reached. For example, recent research in West Africa shows that migration decisions are often based on the perceptions of environmental changes by local populations rather than on the actual observed changes (De Longueville et al., 2020). The migration of some members of a community can also trigger the migration of the whole group, as the migration of some members can have a strong impact on the community (Gemenne and Blocher, 2017). In other contexts, the expectation of a climate impact can trigger social or political shifts: for example, the expectation of lower snow cover levers can reduce or stop investments in ski resorts. Some planned relocations of populations are already underway in anticipation of future climate impacts (de Sherbinin et al., 2011), while the government of Indonesia decided in 2019 to move its capital city, Jakarta, in anticipation of future floods.

Shifting livelihoods is a typical adaptation strategy but can also reflect a social tipping point if this shift affects the community as a whole. Therefore, social tipping points should not be confused with the carrying capacity of a community. Whilst the carrying capacity of a community is a fixed, predetermined limit, social tipping points are dynamic, and constantly evolving under the influence of different social and political factors—such as solidarity networks or governance mechanisms. The carrying capacity of a community can evolve over time, but remains a static concept, unlike social tipping points. Social tipping points have also been applied to adaptation, through the concept of adaptation tipping points, which indicate how much pressure a socio-environmental system is able to absorb (Ahmed et al., 2018). Beyond the adaptation tipping point, the efficiency of adaptation responses will be limited, and can even transform into maladaptive options.

8.4.5 Projected risks for livelihoods and consequences for equity and sustainability

8.4.5.1 Projected risks for livelihoods

There is *robust evidence with high agreement* that future climate change impacts will have severe consequences for poor households, particularly those situated in areas highly exposed to actual or future climate hazards, such as low lying coastal communities (see also Cross-Chapter Paper 1 COASTS), drylands (see also Cross-Chapter Paper 3 DRYLANDS) or remote mountain (see also Cross-Chapter Paper 5 MOUNTAINS) settlements with low levels of connectivity to markets, poor infrastructure and high dependence upon poor quality natural capital (Barbier and Hochard, 2018; Gioli et al., 2019). While livelihoods operate in a dynamic context characterised by multiple interacting structures and processes, climate change can act as a risk multiplier. When current livelihood activities become untenable as a result of both long trends and short-term shocks and climate hazards (e.g., droughts, floods), shifting livelihoods is a common response and in many cases can be unavoidable due to the negative consequences of these climate hazards on specific livelihood capitals (see Section 8.5). Such shifts can involve a change in livelihood activities (e.g., continuing in agriculture but growing different kinds of crops), or a change to broader livelihood strategies (e.g., diversifying into handicrafts or paid employment, specialising in one particular activity, or migrating, seasonally or permanently in search of other livelihood opportunities) or even an entire change of the livelihood activity, for example, abandoning agriculture altogether (McLeman and Smit, 2006; Black et al., 2011). Shifting livelihoods can therefore involve mobility or take place in situ. Some of these shifts also lead to social tipping points.

8.4.5.1.1. Proactive and reactive livelihood shifts and their relevance for future risks due to climate change

Livelihood shifts may also take place proactively as new opportunities emerge and reduce climate impacts by providing buffers of financial capital. For example, (Hirons, 2014) assesses artisanal and small-scale mining as an emerging livelihood opportunity in Ghana. Evidence challenges the popular assertion around the idea of wealth seeking for short term profit and reveals an alternative scenario whereby artisanal and small-scale mining can be a poverty-driven activity, particularly in areas in which agricultural employment has not delivered sufficient income or where crops are highly exposed and sensitive to climate change impacts. Income from new livelihood activities can support recovery following specific events (major flooding or drought) linked to climate hazards and climate change. Livelihood shifts therefore take place in a highly dynamic and heterogeneous context. Another example comes from (Okpara et al., 2016a) the Small Lake Chad, Republic of Chad. Fluctuating water levels linked to seasonal flood pulses and droughts were shown to link closely to livelihood dynamics. Lake drying led to new adaptive behaviours based on seasonality (e.g., migration of herders to different areas of the lake shore to access water resources, in line with more predictable seasonal changes) as well as linking to opportunism supported by climate change impacts. For example, during times of lake flooding, new opportunities for fishing opened for people that were otherwise operating primarily as pastoral or agricultural households. However, these kinds of livelihood shifts remain largely reactive and can bring negative as well as positive impacts. In the Lake Chad case, it resulted in social clashes between different groups, while in other examples from Tanzania, livelihood shifts towards extensification of farming led to deforestation (Suckall et al., 2014), which could constitute a maladaptive shift. Such findings have important implications for the types of government and institutional support that can enable livelihood shifts and highlight the need to consider trade-offs for climate change mitigation, as well as with other adaptation options (see Section 8.6).

8.4.5.2 Future risks, vulnerabilities, differentiated inequalities and livelihood shifts

Overall, there is *high agreement* that future climate change impacts are going to worsening poverty and exacerbating inequalities within and between nations with projections that by 2030 these will increase significantly (Olsson et al., 2014; Hallegatte and Rozenberg, 2017; Roy et al., 2018). In addition, the COVID-19 pandemic and consequences linked to measures to reduce the spreading of the virus are *likely* to increase poverty, particularly in regions already facing high levels of vulnerability and poverty (Laborde et al., 2020b; Sumner et al., 2020).

Key risks due to future climate change, exposure and vulnerability are difficult to assess and are based on evidence from the past and *likely* future vulnerabilities and livelihood challenges. The assessment of Representative Key Risks (see Section 16.5.2.3.4) underscores that risks to living standards are potentially severe as measured by the magnitude of impacts in comparison to historical events or as inferred from the number of people currently vulnerable (see in detail Chapter 16). Table 8.4 provides an overview of what is known in the literature assessed about future risks, inequalities and particularly future vulnerabilities, including potential challenges for climate justice and adaptation barriers. For example, barriers for gender, ethnicity and class have been addressed for a long time yet need substantive intervention. Gender, along with many other structural inequalities (Table 8.4) that are deeply rooted, pose future threats to people/groups in vulnerable situations from, for example, the loss of land/assets, exposure to extreme events and so on. These people will also *likely* be highly exposed to future climate risks unless there are significant and new avenues for action on climate change now. For example, recent studies suggest that the total population of all countries classified as most highly vulnerable is projected to grow significantly. A study using 5 vulnerability categories globally concludes that the total population of all countries with very high vulnerability (see Figure 8.6) is projected to increase from 2019 numbers approximately by 102% by 2050 (i.e., roughly double) and 257% by 2100, while the population of all countries with very low vulnerability is projected to decrease by 9% by 2050 and 17% by 2100 (based on UN medium probabilistic projections). Another study estimates that the total population of all countries classified at most vulnerable (top 2 categories; using 7 vulnerability categories globally) is predicted to increase by 82% by 2050 and 192% by 2100. In contrast the population of all countries classified as least vulnerable (bottom 2 categories) is projected to only increase by 9% by 2050 and 1% by 2100 (see in detail UN-DESA, 2019; Birkmann et al., 2021a; Birkmann et al., 2022).

That means that, based on current population growth estimates and if vulnerability levels are not reduced significantly, more people will be living in more vulnerable context conditions in the future compared to those living in less vulnerable contexts. This is independent of the development of climatic hazard exposure. If significant reductions of vulnerability are achieved, this projection will change. However, the vulnerability and poverty of some regions and countries has proved over decades to be persistent, such as Haiti or Afghanistan. Consequently, the estimated future population growth is another factor that points towards the urgent need to reduce vulnerability and to narrow the adaptation gap.

While future adaptation options can also encompass measures or tools that emerge in future, most of the future adaptation options and their relevance for reducing vulnerability, poverty and inequality are known. Evidence exists that the importance of social networks that organise social protection and leverage resources in terms of reducing risks to climate change is increasing, particularly for most vulnerable people/groups in countries that have limited social security measures in place.

Table 8.4: Summary of interlocking categories differentiation future risks, vulnerabilities, inequality and adaptation

Future risks	Inequalities	Future vulnerabilities, future livelihood, future exposure (examples)	References
Increasing risk of displacement and damages to women and girls in floods	Gender inequality leaves women and girls hidden, forgotten, exposed, resulting in displacement impacts and limited resources, including social capital and increasing risk of human trafficking	Increasing future vulnerability of Women and girls due to high hazard exposure; gender differentiated vulnerability to urban flood in India); Increasing risk of human trafficking associated with exposure to future extreme events	(Singh, 2020; Cross-Chapter Box GENDER in Chapter 18)
Increasing risks of exacerbating inequalities and tensions	Differentiation based on Ethnicity and race leads to groups in society less visible, less rights, in particularly livelihoods that expose them to extremes. Unequal access to adaptation opportunities and benefits.	Increasing future vulnerability of Indigenous Peoples due to exposure to extreme events. Communities of colour are *likely* to be exposed to increased climate change impacts, e.g., differentiated health impacts on black and hispanic communities heat-related mortality rates and poverty for neighborhoods in New York City.	(Hsu et al., 2021; Section 8.3)
Increasing risk of loss of homes and assets in the case of floods	Class differences in exposure and awareness of flood risks. Lower caste disproportionately impacted by climate change	Increasing differentiated exposure among classes to events such as flooding.	(Jones and Boyd, 2011; Fielding, 2018)
Risks to loss of lives in cases where there is no agency	Religious and beliefs impact experience of climate change	Increasing vulnerability to climate change among different religious groups.	(Schuman et al., 2018)
Risk of premature mortality, risk of loss of livelihoods in employment	Age and aging populations. Elderly and young are disproportionately impacted by climate change, e.g., heatwave in France 2003 and Japan 2018. Youth	Increasing future vulnerability among elderly, underage youth and children vulnerable to increasing risks of health	(Hsu et al., 2021; Section 8.3)

	underemployed or in vulnerable livelihoods could be vulnerable to climate related risks which adversely affects the economy.	impacts of pollutants or floods, heatwaves	
Risks to mobility in a climate extreme	People with disabilities, for instance shows evidence emerging in the disaster risk reduction and humanitarian sector.	Increasing risks to people with disabilities disadvantaged exposed to extreme events. .	(King et al., 2019)
Risks of isolation for communities remote from centres of power	Geographical exposure. The location of people and societies within a particular territory is a determinant of inequality e.g., disruptions to food supplies to the Caribbean when there are climate extreme events.	Increasing risk and exposure among communities remote from urban centres far from resources and exposed to climate impacts	(Section 8.3; Cross-Chapter Box GENDER in Chapter 18)
Risks of food insecurity	Differentiation of asset / ownership / access among groups where unclear status.	Increasing risks to tenurial landless. If tenurial status is unclear, groups may experience loss of land and displacement.	(Section 8.2; Cross-Chapter Box GENDER in Chapter 18).

8.4.5.3 Future limits to adaptation

Local perceptions of losses from adverse effects of climate variability and change can help to assess the magnitude of impacts that individuals and communities have not been able to cope with or adapt to (James et al., 2014; Barnett et al., 2016; McNamara and Jackson, 2019 McNamara et al. 2021, Mecheler et al. 2020).

The IPCC Special Report on a 1.5°C warming world shows with *high confidence* that for the Arctic systems, if average temperature increase exceeds 1.5°C by the end of the century, compromising people's livelihoods and will exceed limits to adaptation and residual impacts can be expected (Ford et al., 2015; O'Neill et al., 2017b; Roy et al., 2018; Hoegh-Guldberg et al., 2019a). The loss and degradation of the Amazon forest concerning global warming temperatures (beyond 1.5°C) is another clear example of irreversible loss, with significant impact to people's livelihoods today and in the future (Hoegh-Guldberg et al., 2018; Roy et al., 2018). Moreover, the losses and damage from climate change impacts are also felt heavily by women, children and elderly given the intersectionality with socio-economic and gender inequalities (Li et al., 2016; Roy et al., 2018). For instance, gender and wealth inequality offers challenges to scale up the Maasai pastoralist community autonomous adaptive practices (Wangui and Smucker, 2018). These authors found that most female-headed and poorest households couldn't access the land, water for irrigation, and financial assets required to access adaptive practices that are available in the wider community. Consequently, future impacts of climate change are *likely* to increase rather than decrease inequality based on already observed impacts on adaptive capacities that constrain also future adaptation options particularly for the poor (Roy et al., 2018).

8.4.5.4 Future livelihood challenges in the context of risks and adaptation limits

The climate change risks in this section are addressed through the lens of livelihoods, human, food, water, and ecosystem security, building on key impacts and risks since AR5 (Oppenheimer et al., 2014), and key findings from SR1.5°C (Hoegh-Guldberg et al., 2018; Roy et al., 2018), SROCC (IPCC, 2019b), and SRCCL (IPCC, 2019a). The AR5 WGII risk tables (IPCC, 2014b), updated in SR1.5°C (Roy et al., 2018) offer an interesting entry point as it shows high confidence on key observed impacts and limits to the adaptation of natural and social systems that are compounded by the effects of poverty and inequality on water scarcity, ecosystems alteration and degradation, coastal cities in relation to sea-level rise, cyclones and coastal erosion, food systems and human health (Hoegh-Guldberg et al., 2018; Roy et al., 2018). As a consequence, the climate change risks substantially pose negative impacts on climate-sensitive livelihoods of smallholder farmers, fisheries communities, urban poor, Indigenous Peoples, informal settlements, with limits to adaptation evidenced on the loss income, ecosystems, health, and increasing migration (Roy et al., 2018). The compounded effects of socio-economic development patterns and climate change impacts are worse experienced among climate-sensitive ecosystems in the Arctic and Small Island Developing States (SIDS) (Roy et al., 2018). The future risks to these climate-sensitive ecosystems and livelihoods are potentially severe given their current high exposure to climate hazards, and high number of vulnerable of people exposed for example in the SIDS (see also Chapter 16 Living Standard; (Ahmadalipour et al., 2019); Liu and Chen 2021). Residual losses then may be unavoidable for some ecosystems and livelihoods affecting the vulnerable groups of people and countries as consequences of structural poverty, socio-economic, gender, and ethnics inequalities, that marginalize and exclude and limit the development of adaptive capacity for future changes (Olsson et al., 2014; Roy et al., 2018).

In Small Islands States (SDIS) key risks are represented by losses of livelihoods of coastal settlements, ecosystem services, infrastructure, and economic stability, exhibiting limits to adaptation in face of local's coping strategies capacity (Hoegh-Guldberg et al., 2019a). There is *high confidence* that sea-level rise in SIDS combined with extreme flooding events will threaten the future livelihoods of coastal communities (Hoegh-Guldberg et al., 2018; Roy et al., 2018).

In the global south, the increasing heat associated with warming of global temperature represents an important risks due to losses of labour productivity, crop failures and livelihood security, involving economic losses, and health effects as well as increasing deaths that are anticipated to have significant implications for poverty, inequality and equity (Carleton, 2017; Roy et al., 2018). The increasing temperature, droughts, and excessive rain lead to successive crop failures and lack of productivity that are affecting children's growth and health in developing countries (Hanna and Oliva, 2016). Likewise, the expected global temperature increase by the end of the century will have devastating health consequences for children, associated with sea-level rise, heatwaves, and incidence of malaria and dengue, and malnutrition, especially in Asia (Ghosh et al., 2018) and African countries as Chad, Somalia, Niger and Mali (Hanna and Oliva, 2016; Ghosh et al., 2018; Clark et al., 2020).

The incidence of floods also increases the occurrence of diseases (e.g., diarrhoea and respiratory infections) and undernutrition in children living in informal settlements and slums in Asia (Ghosh, 2018) and Africa (Clark et al., 2020). Women and children are currently bearing the worst impacts from climate hazards, and are unable to move due to assigned gender roles to avoid flooding risks in highly vulnerable slums in Bangladesh, causing them emotional distress and poor living conditions (Ayeb-Karlsson et al., 2020). In this region, the experienced severe floods associated with death, injury, infectious disease, mental and emotional stress and cultural disruptions—dimensions of noneconomic losses are often not accounted for in the disaster relief policies (Chiba et al., 2017) and these severely influence the ability to build adaptive capacities for future hazards (Roy et al., 2018). In the same way, risks to female-headed households with insecurity in tenure rights is greater, as these group were the most affected by flooding in 2018 in Dar es Salaam, Tanzania, that cost 3-4% of the country's gross domestic product (GDP) and affecting 4.5 million people (Erman et al., 2019).

In the Himalayas mountain range (part of the Hindu-Kush Himalaya, HKH) temperature warming is expected to increase up to 2°C by 2050 (*high confidence*), increasing flooding and bringing larger risks to food and water security on mountain communities that are already highly vulnerable given limited livelihood options and supporting infrastructure in these regions (Mishra et al., 2017). In Nepal, agriculture-oriented livelihoods are reported to be negatively affected by an increase in landslide frequency (92.6%) and intensity (97.3%) over a 20 years period (1996-2016) (van Der Geest and Schindler, 2016). The catastrophic landslide in 2014, the material losses experienced by poor households were 14 times greater than their annual gains associated with loss of crops and land; The NELD losses were emotional distress and fear of new event occurrence, showing that most poor households may not fully recover in their lifetime post an extreme event. This example is indicative of the representative future climate risks to these populations; Albeit livelihood diversification is commonly adopted by the poor households to reduce the impacts of extreme rainfall and landslides smallholders in Nepal, there are limits to these strategies given poor household infrastructure that challenge risk reduction and as so it is expected that migration to neighbouring countries as Bhutan or India will increase (van Der Geest and Schindler, 2016).

Expected future risks to vulnerable communities and Indigenous Peoples includes losses across a range of impacts. A larger household comparative analysis across countries in Southeast Asia, Africa, and Asia Mountain regions shows that more than 60% of the population reported losses from residual impacts concerning droughts, floods, cyclones, sea-level rise, glacier retreat, and desertification, despite autonomous adaptation involving changing food consumption, and relying on formal aid from government support (Warner and Van der Geest, 2013). Among Indigenous Peoples across the Global South as in the Brazilian Amazon, Australia and Botswana, locally autonomous adaptive measures, were not sufficient to avoid significant losses (some irreversible in case of lost habitats). The barriers and insufficient adaptive capacities are also intrinsically linked to historical marginalization and vulnerability of the population in these countries (Maru et al., 2014).

In the Arctic, temperature warming, and sea level rising constitute a key risk to the loss of identity and culture of Indigenous People, associated to migration and or relocation due to livelihoods deterioration from coastal erosion, permafrost thaw, and reduced fisheries productivity (Roberts and Andrei, 2015; Roy et al., 2018). These risks and losses often encompass various non-economic losses, such as the loss of identity that cannot be replaced or economically compensated (see also Section 8.3.5).

Likewise, in the Amazon basin, climate change hazards of severe droughts and floods (*high confidence*) (Cox et al., 2004; IPCC, 2019a), are exhibiting limits to adaptation among the majority of riverine communities, and smallholders farmers with residual impacts associated with losses of income, fisheries, and agriculture productivity as well as affecting non-economic livelihood dimensions, such as the ability to attend school and losses of place and identity through forced migration (Maru et al., 2014; Pinho et al., 2015; Lapola et al., 2018). Furthermore, the expansion of the agricultural frontier and construction of large dams to supply energy needs in the Amazon basin are amplifying the vulnerabilities and reducing future adaptive capacities, of smallholders, and the fisheries communities to climate risk (Bro et al., 2018; Castro-Diaz et al., 2018). It is expected that the global temperature warming level of 2ºC by 2050 in the Amazon will lead to a significant reduction of major rivers' water flow and leading to further food and water insecurity (Betts et al., 2018) likely to affect forest and river dependent livelihoods in the Region (Box 8.6; Lapola et al., 2018).

The glacier retreat associated with the increase in global warming temperature has also shown losses that are permanent and related to a sense of belonging and cultural heritage for the Glacier countries but with the most negative livelihood impacts experienced among poor households in the Peruvian Andes and Himalayas (Jurt et al., 2015). The risks for the glacier smallholder's livelihoods are expected to increase in the future once the shrinking glaciers are expected to increase water competition, crop failure, and extreme flooding (Kraaijenbrink et al., 2017). For example, in Bhutan adaptive measures such as changing crops, developing irrigation channels, and sharing water among the community members still insufficient to avoid loss and damage associated with the dramatically reduced water availability (Kusters and Wangdi, 2013; Warner and Van der Geest, 2013). In high Mountain Regions, the intersections of agro-pastoralists marginalization, difficult in access, and ecological sensitivity contribute to residual impacts associated with extreme climate hazards which can lead to irreversible losses and challenge poverty reduction efforts (Mishra et al., 2019).

In semi-arid West Africa, poor households have in place longer term local adaptation to deal with severe droughts that involves reducing household and cattle water consumption, planting drought-tolerant crops, and adopting integrated crop-livestock for efficiency, with migration either seasonal and or permanent mostly effective (van der Geest et al., 2019). Likewise, Senegal, Ethiopia, and Northern Kenya adaptation have advanced with external government and non-government organisation (NGO) support (Schäfer et al., 2019), including technological innovations and insurance to households (Schäfer et al., 2019) but not enough in preventing losses to already impoverished households (Schäfer et al., 2019).

There is *robust evidence* that future risks to climate-sensitive livelihoods as agriculture, livestock and fisheries are amplified by gender, age, and wealth inequalities (Wangui and Smucker, 2018), ethical background and geography (Piggott-McKellar et al., 2020; Thomas and Benjamin, 2020) as well as by ecological thresholds that challenge autonomous adaptation among vulnerable disadvantaged communities mostly in the Global South (Roy et al., 2018; Mechler et al., 2020).

The assessment also points towards the fact that there exist strong linkages between national level vulnerability (see e.g., Figure 8.6) and individual vulnerability at household or livelihood scale. Various disadvantaged and marginalized groups or communities within a society are significantly constrained in terms of the ability to build adaptive capacities for future climate change threats due to limited access to resources or government support for planned adaptation. Consequently, these linkages between regional, national and local vulnerability need more attention in research and practical adaptation strategies (vertical integration).

The next section discusses how risks emerge as a result of the failure in adaptation or when it is not implemented, with particular attention to risks that are impossible to adapt to and lead to inevitable loss and damage among the poor households, livelihoods and countries.

[START BOX 8.6 HERE]

Box 8.6: Social dimensions of the Amazonia Forest Fires and Future Risks

The Amazon ecosystem, together with the Arctic, is listed as the first out of five IPCC Reasons for Concern (RFCs) due to climate change, given the *high confidence* level that different temperature warming and greenhouse emissions will offer significant risks that threaten these unique ecosystems (O'Neill et al., 2017b; Roy et al., 2018). In addition to the scientific evidence, a resurgence of cross-national collective expressions about the fate of the Amazon forest, Indigenous Peoples and traditional communities, in the context of an unprecedented climate crisis and sustainable future, have gained pronounced importance. On 19 August 2019, the skies of Sao Paulo State were dark by 3pm due to the formation of a 'smoke corridor' associated with the extensive burning of the Amazon forest (Seymour and Harris, 2019). The fire outbreaks were a consequence of multiple factors related to political, social, economic and environmental scenarios concomitant with the weakening of environmental governance such as control and monitoring of deforestation and fire incidences programs (Escobar, 2019; Seymour and Harris, 2019). The deforestation rate and incidences of fire are both increasing in the Amazon of Brazil, Colombia and Peru (Seymour and Harris, 2019). Accordingly, 2019 registered an increase of 60% on the number of cumulative fire count in Brazil, Bolivia and Peru in comparison with the same period in 2018, and a 12% increase in comparison with the same period in an extremely dry year in 2016 (GFED, 2019). In this context, looking at this case study through the lenses of poverty, inequality and the Sustainable Development Goals (SDGs) addresses the compound effect of climate and land-use change in the Amazon forest fires and its cascading impacts and risks on the social domain in the region. There is evidence that both climate and land-use change impacts and risks are disproportionately borne by poor and vulnerable ethnical groups, remote rural communities and poor urban households in the Amazon(Pinho et al., 2015; Brondízio et al., 2016; Mansur et al., 2016; Pinho, 2016).

Fires are not a natural phenomenon in the Amazon region (Bush et al., 2004; McMichael et al., 2012) albeit used for food security, hunting and religious rituals among Indigenous Peoples and traditional communities (Hecht, 2006; Carmenta et al., 2019; da Cunha, 2020), and also as a widespread technique for land clearing for small and large-scale farms for agriculture (Morello et al., 2019). The dramatically increased forest burning observed in the Amazon recently are the results of illegal land grabbing, the small and large-scale cattle ranching sector and agribusiness practices coupled with loosening land tenure policies and decision making neglect of deforestation and burning monitoring data (Nobre et al., 2016; Lovejoy and Nobre, 2018; Leal Filho et al., 2020a). The fire outbreaks intensified substantially to the point that in August 2019 there were approximately 3500 fires in 148 Indigenous territories (DETER and INPE, 2019; ISA, 2019). Although most of the burning in the Legal Amazon in Brazil occurred on private land of medium and larger sizes (about 67%), around 33% was observed within Indigenous territories and protected areas called conservation units (UCs) (DETER and INPE, 2019; ISA, 2019). In 2019, 40% of the deforestation occurred in public forests, which encompasses undesignated forest lands, Indigenous territories and conservation units (UCs). This deforestation came accompanied by fires: 18% of the 2019 fires occurred on undesignated lands, 7% on Indigenous territories and 6% on UCs, where many traditional populations live (Alencar et al., 2020). It is also important to note that during 2019, 46% of the deforestation and 52% of the fires occurred on private rural properties and settlements, respectively, where the legal accountability of these crimes is possible. The 2020 deforestation rate presented an increase of 47% and 9.5% compared to 2018 and 2019, respectively, and was the highest in the decade (Silveira et al., 2020). The clear-cut inside indigenous territories more than doubled from 2018 to 2019 (Brasilis, 2021) and despite it decreasing from the 2019 rate, during 2020 it was the highest since 2008. It has been demonstrated that on average, at least 50% of yearly active fires being up to 5 km from deforested areas in the same year, reaching 74% during 2019 (Silveira et al., 2020). This means, that fires and deforestation have an increased threat to indigenous population (Oliveira et al., 2020), particularly during the year 2020 and currently in 2021 since, COVID-19 and air pollution from agricultural burnings greatly impacts respiratory health in the Amazon (Morello, 2021).

Health impacts, economic and non-economic losses

The health impacts and economic losses estimates are not homogeneously gathered for the entire Amazon basin countries, but some recent evidence associated with this knowledge gap shows the magnitude of the forest fire impacts, as well as where they spatially occur and who are the most affected by it. Fires associated with deforestation in the Amazon have been related to 1065-4714 deaths annually in South America (Reddington et al., 2015). The recent fires in the Amazon basin are directly affecting 24 million Amazonians with the worst impacts felt by children, and the elderly (Machado-Silva et al., 2020). Indigenous Peoples and traditional communities (Fellows et al., 2020). Children under five years old and the elderly in rural areas are respectively 11 and 22 times more affected by the smoke from fire outbreaks and temperature increase in the Amazon (Machado-Silva et al., 2020).

In the Acre State, the fire incidence coupled with extreme droughts in 2005 and 2010 led to an increase—from 1.2% to 27%—in hospitalizations of children (under 5 years) due to respiratory diseases (Smith et al., 2015). The same evidence was found among the rapidly deforested areas known as ‘Arc of Deforestation’ that have dramatically led to a higher number of respiratory diseases mainly in children under 5 years (do Carmo et al., 2013). There is also evidence for interlinked dynamics between deforestation, urbanization and incidence of fire episodes providing an appropriate environment for *Anopheles darlingi* vector propagation and the increased incidence of malaria in the region (Hahn et al., 2014). In the 2005 drought, burning in Acre alone recorded 400,000 people affected and the loss of 300,000 hectares of forest with direct costs of US$50 million (Brown et al., 2006). In 2010, the fires during the drought were approximately 16 times larger than that in the meteorologically normal years (Campanharo et al., 2019). The estimated total economic loss in 2010 was about US$243.36 ± 85.05 million, representing 9.07 ± 2.46% of Acre's gross domestic product (GDP) (Campanharo et al., 2019). The economic and non-economic losses associated with the impacts of climate change and future risks of fires outbreaks on native food crops (açai, guaraná), livelihoods, tourism, medicinal and spiritual sites, culture, migration patterns, place-based attachments, emotional and mental distress among the most affected and vulnerable population as Indigenous Peoples and traditional communities are still to be fully estimated for the region (Pinho et al., 2015; Brondízio et al., 2016). Also relevant is a trend of Amazonian forest fires spreading from the southern Brazilian Amazon to Bolivia and Peru, indicating that transboundary burning increases are systemic and will lead to extensive economic losses of wildcrops, infrastructure and livelihoods, and requiring a landscape level approach for deforestation and fire management and control (Kalamandeen et al., 2018).

Future vulnerabilities and risks for Indigenous Peoples and traditional communities

In the future, it is expected that by 2030 the incidence of extreme droughts in the Amazon will increase the costs of the health sector associated with treatment costs of respiratory diseases (20%-50%) and malaria incidence (5%-10%) incurring a high social cost as people will be impaired to carry out their livelihoods (Lapola et al., 2018). It is also expected that extreme droughts in the Amazon by 2030 will accelerate and intensify rural (traditional communities and Indigenous Peoples) migration to urban centres where their living standards are expected to decrease once they will occupy marginal areas within larger urban centres (Lapola et al., 2018).

In terms of adaptation and risk reduction, priority should be given to strengthening multi-scale governance and partnerships among different private and public actors. Also policies at national and sub-national levels are needed, such as control strategies to reduce deforestation and fire incidence, demarcating new Indigenous territories, payment for ecosystem services (REDD+) and investment in traceability for commodities productive chain market are needed (Morello et al., 2017; Scarano, 2017; Carmenta et al., 2019; Seymour and Harris, 2019). The increase in global temperature level up to 2°C will exacerbate food and water insecurity in the Amazon (Betts et al., 2018; Hoegh-Guldberg et al., 2018) (*medium confidence*). Thus, curbing fire incidence and deforestation rate will make it easier for the Indigenous Peoples and traditional and vulnerable population to reach the Sustainable Development Goals (SDGs), especially in terms of reducing poverty (SDG1), food security (SDG2), wellbeing and health (SDG3) and protecting terrestrial ecosystem (SDG15) (Roy et al., 2018).

[END BOX 8.6 HERE]

8.4.5.5 Maladaptation as a projected future risk particularly for the poor and marginalized

There is increasing evidence that maladaptation can lead to future risks to socio-ecological security when adaptation measures focusing on short -term action that may lead to adverse longer-term impacts to livelihoods and failures to address transboundary scales to avoid negative consequences for social and ecological systems (Warner and Van der Geest, 2013; Roy et al., 2018; Mechler et al., 2019a; see also Section 5.13.3). Hence, maladaptation can intensify and even accelerate future risks as a result from climate change mitigation and adaptation policies when responses to climate change hazards are embedded within 'business as usual' development approaches (Work et al., 2019). For instance, in Cambodia, the conventional development strategies intertwined with climate change mitigation and adaptation initiatives are increasing the probability of maladaptive outcomes in a context of high informality, and conflicts among poor farmers exposed and vulnerable to flooding (Work et al., 2019). The potential for maladaptation emerges from the vulnerability of precarious living conditions of poor farmers in informality, not accounted for in climate mitigation and adaptation strategies for irrigation, protected areas management and reforestation projects funded by multilateral donors (Work et al., 2019). (Work et al., 2019). As a consequence, losses emerge despite actions to prevent adverse impacts and maladaptation instead became a vector of increased vulnerability for poor and vulnerable communities (Mechler et al., 2019a).

The maladaptation outcome also emerges as a failure of adaptation. In Ghana, poor farmers in face of crop yield failure during severe droughts further exacerbate water use for irrigation and livelihood diversification, including selling firewood for charcoal production, forms of maladaptation as it can furthering increasing their vulnerability to climate risks, compromising food production, income generation, and sustainability (Antwi-Agyei et al., 2018b). In Cambodia, governmental adaptation strategies focusing on reforestation and conservation measures are eroding the local biodiversity, and the crop irrigation strategies are compromising scarce water resources and also excluding poor farmers susceptible to flooding from decision-making and benefits (Work et al., 2019). Likewise, in Ethiopia, efforts of adaptation programs to droughts contribute to current unsustainable development trajectories among pastoralist communities, resulting in charcoal production, overgrazing, migration and conflict with other groups and marginalization of livelihood (Magnan et al., 2016). In the Sudan, maladaptation outcomes to the poor population are linked to a dependency on war economy and post- conflict power dynamics that are and will affect sustainability and equity in the context of drought incidence (Young and Ismail, 2019).

In Bangladesh, a highly expensive Coastal Climate-Resilient Infrastructure Project can potentially increase the vulnerability of urban poor as they will remain in areas that are highly susceptible to flooding brought by sea level rise (Magnan et al., 2016). In Central America, the lack of assessments of future climate variability on crop yield scenarios coupled with lack of policy makers to incorporate autonomous local adaptation practices could lead to an unsustainable trajectory to local communities and risk of maladaptation (Beveridge et al., 2018). In Bhutan, small-scale rice farmers have adopted water -sharing measures to avoid the impacts of reduced and uncertain precipitation levels associated with monsoons, but these measures led to disruptions in social cohesion as conflicts over water sharing escalated (Mathew and Akter, 2015). In the same region, local governments prioritize the glacier retreat as a perceived risk to flooding on dams but overlook the slow and gradual impact of the deficit in precipitation affecting negatively the rice productivity (Mathew and Akter, 2015). In Burkina Faso, a region highly impacted by severe droughts, local communities have become less able to cope with droughts given a decline in cultural pastoralism and increased dependence on crops (van der Geest et al., 2019).

As seen, maladaptive responses to droughts, sea-level rise and flooding are negatively affecting poor farmers, pastoralists, and rural and urban informal workers, increasing loss of crops, infrastructure, income, conflict and migration. Given the high risks of maladaptation to poor people this agenda should be given priority among the development sector and planning (Magnan et al., 2016). The categories in Table 8.5 also represent important future compounding and complex risks that can emerge due to maladaptation (high confidence).

Table 8.5: Categories of Maladaptation as future risk and examples of outcomes and world regions based on literature assessment evidence. Confidence Level ** Medium (5-9 papers).

Categories of Risks to Maladaptation	Examples of Outcomes
Uncertainty (climate events)	Lack of knowledge of future climate extreme events hinder adaptation actions for the poor.
Inequalities	The exclusion of rights and access and benefits of adaptation
Sustainability	Further ecological degradation and biodiversity loss.
Informality	Reinforces vulnerabilities to the poor and marginalized population.
Poverty	It increase vulnerabilities and risks of maladaptation.
Scales (Temporal and Spatial)	There is negative trade-offs across short and longer term decisions as well as transboundary issues that increase likelihood of maladaptation.
Regions Evidence	South Asia and Southeast Asia (Bangladesh, India, Nepal, Maldives, Indonesia and Thailand) (6) **
	Africa (Ethiopia, Gahna, Malawaii) (3)
	Central America (1)
	Global South (2)
	Global (1)

8.4.5.6 Future challenges for vulnerability and livelihood security due to adaptation-limits of people and ecosystems

The risks and future losses of communities and livelihoods with higher exposure to the risks posed by climate change and with lower adaptive capacity will experience a higher burden of loss and damage in comparison to others (Tschakert et al., 2017). In Asia (Indonesia) and Arctic region, a decline of marine fisheries by approximately 3 million metric tons per degree of warming is expected to have severe negative regional impacts, especially on Indigenous People (Cheung et al., 2016).

It is projected that climate change impacts on incidence of disasters will push 122 million additional people into extreme poverty with global temperatures increase by 2030 (Hallegatte and Rozenberg, 2017; Hoegh-Guldberg et al., 2018; Jafino et al., 2020). It is also expected that around 330-396 million people will be exposed to lower agricultural yields at warming beyond 1.5°C (Hoegh-Guldberg et al., 2018), most of them in South Asia and Sub-Saharan Africa (Chapter 16; Roy et al., 2018; World Bank, 2019a). There is also *medium evidence* that tens to hundreds of millions of people that are dependent upon climate-sensitive livelihoods could out-migrate as a consequence of global temperature increasing, mostly in Africa, Asia and Latin America—posing additional risks to unsustainable urbanization and/or group conflict (Chapter 16; Hoegh-Guldberg et al., 2018; Roy et al., 2018).

The multi-intersectionality of inequalities (socioeconomic, caste, ethnicity, among others) and marginalization, in most of the cases exhibit adaptation limits, emerge through differential capacity to avoid risks that amongst the world's poor and vulnerable communities are highly deficient and at the brick of falling into poverty traps affecting future generations (Hallegatte and Rozenberg, 2017; Roy et al., 2018; Tschakert et al., 2019). For instance, the poorest communities in the Global South, whose livelihoods are dependent upon thriving ecosystems for health, food, water, energy, are disproportionately more exposed to temperature extremes, and droughts compromising the food and water security (Byers et al., 2018). There are also inequalities associated with the opportunities to adapt to risks that are unevenly distributed among global regions, with richer and more equal societies in the Global North presenting superior capacities than

Global South communities, sectors, ecological systems, and species where the most detrimental climate change impacts are experienced (Hoegh-Guldberg et al., 2018; Roy et al., 2018). The climate-sensitive livelihoods of poor and vulnerable communities in the global south, and the unprecedented ecosystems losses are examples of multiple limits of adaptation that emerge simultaneously also linked to the differential access to assets and resources, such as physical (propriety, income), social (health, age, education) , cultural (shared community values and norms, ethnicity), ecological (linked to land use change and productivity) and institutional (market, policies and governance) (Roy et al., 2018; Hoegh-Guldberg et al., 2019a; Olsson et al., 2019). The adaptation limits emerges mostly in the Global South countries, and disproportionately affect specific groups, with high poverty incidence, that are constrained by inadequate financial resources and institutional instruments (Tian and Lemos, 2018; Volpato and King, 2019), including lack of understanding and preparedness of the risks posed by climate change (Ayeb-Karlsson et al., 2016; Maharjan et al., 2020).

In other situations, adaptation limits to household's livelihoods emerge from ecological thresholds associated with global warming temperatures, such as deterioration of land and water resources, extinction of species and biodiversity that can lead to systemic crop failures, declined fisheries productivity and water availability and substantial risks to households' livelihoods (Roy et al., 2018). However, it is also important to note that limits are associated with development, technology, and cultural norms and values that can change over time to enhance or reduce the capacity of systems to avoid limits (Adger et al., 2014; Roy et al., 2018). It could also include aspects of maintaining security of air or water quality; as well as equity, cultural cohesion, and preservation of livelihoods (Adger et al., 2014; Tschakert et al., 2019). For soft limits, however, adaptation options could become available in the future owing to changing attitudes or values or as a result of innovation or other resources becoming available to most vulnerable and poor actors, households and countries. However, when compounded with lack of finance, and high costs associated with disasters and poverty and environmental degradation, soft limits might become hard ones in the future (see Figure 8.5; Gracia et al., 2018).

Table 8.6, built from SR1.5°C (Roy et al., 2018), illustrates how ecological thresholds and socio-economic determinants are linked to soft and hard adaptation limits and what are the potential and magnitude of livelihoods risks in the future. For instance, in the SR1.5°C (IPCC, 2018b) and SROCC (IPCC, 2019b), hard limits are expected with global warming beyond 1.5°C associated with the losses of coral reefs, that will lead to substantial loss of income and livelihoods for coastal communities (Roy et al., 2018; Mechler et al., 2019b; Oppenheimer et al., 2019). The loss of coral reefs in remote islands of Boigu in Australia are affecting low-lying communities facing financial, institutional (Evans et al., 2016) and cultural place-based attachment adaptation limits (McNamara et al., 2017). Another hard limit to adaptation and implications for income, and culture-and place-based livelihoods is related to the sensitivity of global fish to global temperature increase with losses of fish reproduction expected to 10% (SSP1–1.9) to about 60% (SSP5–8.5) potentially cascading into severe risks for fisheries livelihoods (Dahlke et al., 2020). In West African fisheries, the loss of coastal ecosystems and productivity are estimated to require 5–10% of countries' gross domestic product (GDP) in adaptation costs (Zougmoré et al., 2016), incurring financial limits in the poor countries to avoid socio-economic risks. The SROCC (IPCC, 2019b) showed that scientific knowledge limitations can constrain management of coastlines, mainly in the context of lack of data with affect most of the vulnerable and poor communities in the global south (Perkins et al., 2015; Sutton-Grier et al., 2015; Wigand et al., 2017; Romañach et al., 2018). The hard and soft adaptation limits are challenging to be defined, given the rate and intensity of climate change hazards and the mitigation and adaptation options available, but also the level and rate of non-climatic stresses increasing vulnerabilities and undermining adaptive capacity of poorest members of society and sensitive ecosystems (*medium evidence, high agreement*) (Klein et al., 2014; Roy et al., 2018).

The recent evidence show that adaptation limits can also be associated to financial and institutional mechanisms, and related to structural poverty and inequalities among rural farmers in India (Singh et al., 2019a) and among low-income countries (Tenzing, 2020), agro -pastoralists communities (Volpato and King, 2019), women (Balehey et al., 2018), slum informal settlements in Latin America (Núñez Collado and Wang, 2020), and informal workers in Southeast Asia (Balehey et al., 2018). For SIDS countries, multiple adaptation limits also emerge as a combination of political-institutional, and cultural aspects (Robinson and Wren, 2020) such as preserving national identity and sovereignty in the context of migration in the Marshall Islands (Bordnera et al., 2020). The widespread narrative that migration in the SIDS countries given sea level rise and global temperature increase by 2050 is inevitable, desirable and economically necessary, many more people will be exposed to migration and affected by multiple physiological and emotional distress (Bordnera et al., 2020). In the same way, the Mohawk community of Kanesatake, Canada, is faced with institutional and socio-political adaptation limits such as lack of land ownership rights, insurance and social institutions, to name only a few (Fayazi et al., 2020).

New emerging considerations to ecological limits to adaptation associated with severe glacier retreat in the Peruvian Andes, is expected to reduce lake discharge by 2-11% (7-14%) until 2050 (2100) affecting smallholders farmers, through crops yield failures and severely reduced hydropower capacity (Drenkhan et al., 2019). Also, the study showed very high risk of glacier lakes affected by Glacial Lake Outburst Floods (GLOF) in RCP8.5, posing serious threat to rural people's livelihoods (Drenkhan et al., 2019).

Table 8.6 represents different types of adaptation limits (Soft and/or Hard) that emerge over time and sometimes concomitantly and are leading to severe risks to livelihoods in a high poverty, unequal and hotter future, especially among the poor and vulnerable population in that, the Indigenous People, women, and children (see Section 16.5.2.3.4). The confidence statements is assessed through the evidence on papers as High (≥ 10 papers), Medium (5-9 papers), Low (≤ 4 papers) to ensure traceability on what are the nature of livelihoods barriers and ecological thresholds associated to 'soft" and or "hard" limits to adaption under a warming global world. The determinants of livelihood barriers are linked to: *Gender-based inequality or discrimination, poverty and inequality, Indigeneity and cultural place attachment, Artic Hunting and fishing, Urban Slum and Informal Settlements* incurring in soft and hard limits to adaptation. The Ecological thresholds assessed are associated to *Glacier Retreat, Loss of Coral Reefs, Biodiversity Loss, Ocean Acidification and warming, Sea Level Rise (SLR)* and *Heat Stress* incurring into hard limits to adaptation severe risks to people's livelihoods; The severity of risks to livelihoods is assessed by presenting a magnitude indicator either through the current number of people exposure and vulnerable to climate-sensitive livelihoods. The supporting literature has been provided in the Table SM8.1.

Table 8.6: Synthesis of hard and soft limits to adaptation and risks to livelihoods, equity and sustainability adapted from Chapter 5 of SR1.5°C (Roy et al., 2018).

Determinant	Nature of barrier to livelihood adaptation	Magnitude + Indicator	Soft Limit	Hard Limit	Confidence Level Based on Number of Papers
Socioeconomic and human-geographical determinants					
Gender-based inequality or discrimination	Gender-based inequalities constrain women's access to resources, thus limiting ability to invest in adaptive capacity and heightening vulnerability	World Bank: 62.151% [Employment in agriculture, female (% of female employment) (modelled ILO estimate) - Low income, 2020]; 25.409% [Employment in agriculture, female (% of female employment) (modelled ILO estimate)],	X		***High (≥ 10 papers)
Poverty and socioeconomic inequality	Poverty and lack of financial resources constrain ability to invest in livelihood diversification, resilience or adaptive capacity	World Bank: 10% [Poverty headcount ratio at $1.90 a day (2011 PPP) (% of population)]; 26.498% [Employment in agriculture (% of total employment) (modeled ILO estimate)]; 58.783% [Employment in agriculture (% of total employment) (modeled ILO estimate) - Low income], Low income countries, 2020	X		***High (≥ 10 papers)
Indigeneity and other cultural place-based attachments	Indigenous and other populations with strong cultural or economic attachments to place face barriers to adaptation due to noneconomic losses associated with migration,	SIDS total population of ca. 65 million(UN-OHRLLS, 2015); 476 million indigenous people worldwide (World Bank, 2016)		X	***High (≥ 10 papers)

	urbanisation, and some forms of livelihood transformation				
Arctic hunting and fishing communities	Residents of Arctic regions dependent on hunting and fishing livelihoods interrelated cultural and economic vulnerability due to risk crossing Arctic ecosystem thresholds and tipping points	Global arctic population, ca. 4 million (Larsen, 2015)	X	X	***High (≥ 10 papers)
Urban slum and informal settlement populations	Residents of slums and informal urban settlements are particularly vulnerable due to limited infrastructure and limited employment opportunities	33.331% [Population living in slums (% of urban population)], World, 2009; It is estimated that 50–57 million urban Africans (47% (44–50%) of the urban population analysed) were living in unimproved housing in 2015 mostly in the sub-Saharan Africa (Tusting et al., 2019)	X		***High (≥ 10 papers)
Ecological determinants					
Glacier Retreat	Seasonal water scarcity and/or Glacial Lake Outburst Floods (GLOF) pose a serious threat for highly exposed and vulnerable smallholders in the Peruvian Andes (Drenkhan et al., 2019). Tibetan Plateau region will reach peak water between 2030 and 2050 (Yao et al., 2020)	The flow decrease of the Tibetan Plateau region would affect water availability for 1.7 billion people with a gross domestic product (GDP) of US$ 12.7 trillion (Yao et al. 2019).In 2050, the number of people that will be living in water scarce regions will increase to 2.7 to 3.2 billion people (Luterbacher et al., 2020). As for 2010, 27% of global population (˜1.9 billion people) lived in severely water-scarce areas (Luterbacher et al., 2020).	X	X	***High (≥ 10 papers)
Loss of Coral reefs	Loss of 70-90% of tropical coral reefs by mid-century under 1.5°C scenario (total loss under 2°C scenario) (see SR1.5°C in Chapter 3, Sections 3.4.4 and 3.5.2.1, Box 3.4 (Hoegh-Guldberg et al., 2018), (Magnan et al., 2019).; Chapter 5, Section 5.2 (Roy et al., 2018)).	The Coral reef fisheries-dependent and coastal livelihoods, sustain 6 million direct fishing jobs and more than $6 billion in revenues globally (Teh et al., 2013), often among disadvantaged populations (Hoegh-Guldberg et al., 2018). In tropical regions, there are 1.3 billion people living by coast and depending upon fisheries for food and livelihoods (Sale et al., 2014). In Africa and Asia over 400 million people are dependent upon protein intake from fisheries (Hoegh-Guldberg et al., 2019b). Approximately 850 million people live within 100 kilometres of reefs and more than 275 million reside within 30 kilometres, many of whom are likely to be highly dependent on coral reefs, especially those who look to these marine ecosystems for food and livelihoods (Burke et al., 2011).		X	***High (≥ 10 papers)

Biodiversity Loss	Terrestrial species on average lose 20-27% of their range at 1.5°C (significantly higher range losses projected for some species at 2°C) (see IPCC SR 1.5°C Chapter 3, Section 3.4.3.2 (Hoegh-Guldberg et al., 2018); Chapter 4, Section 4.3.2 (de Coninck et al., 2018)). Tropical forests (vegetation shifts due mainly to drying), and high latitude and altitude ecosystems and Mediterranean-climate ecosystems (high vulnerability	The forest dependent livelihoods of 1.6 billion rural people (in 2012) is likely to be affected to risks of terrestrial forest and biodiversity loss (Newton et al., 2020).		X	**Medium (5-9 papers)
Ocean acidification and warming	Large-scale changes in oceanic systems (temperature, acidification) inflict damage and losses to livelihoods, income, cultural identity and health for island and coastal-dependent communities at 1.5°C (potential for higher losses increases from 1.5- 2°C and above) (see Chapter 3, Section 3.4.4.2.4 (Hoegh-Guldberg et al., 2018); Chapter 4, Section 4.3.5 (de Coninck et al., 2018); Section 5.2.2 (Roy et al., 2018).	500 million people who derive food, income, coastal protection, and a range of other services from coral reefs (Hoegh-Guldberg et al., 2017)	X	X	**Medium (5-9 papers)
Sea level rise (SLR)	Sea level rise and increased wave run up combined with increased aridity and decreased freshwater availability at 1.5°C warming potentially leaving several atoll islands uninhabitable (see IPCC SR. 1.5°C; Chapter 3, Box 3.5 (Hoegh-Guldberg et al., 2018); Chapter 4, Cross-chapter Box 4.1 (de Coninck et al., 2018)); The projected SLR is projected to affect human health and wellbeing, cultural and natural heritage, freshwater, biodiversity, agriculture, and fisheries (IPCC, 2018b; WHO, 2018; IDMC, 2019; McMichael et al., 2020).	It is projected that ~316–411 million people in 2060 will be living in areas to be affected by SLR, with most of them in South and Southeast Asia and in Africa (Neumann et al., 2015; Oppenheimer et al., 2019).The number of people at risk of floods will increase from its current level of 1.2 billion to 1.6 billion by 2050 (Luterbacher et al., 2020). It is estimated that 6–8% of Latin America and the Caribbean's population, face high risk associated with coastal hazards (Oppenheimer et al., 2019).		X	***High (≥ 10 papers)
Heat Stress	It is expected that by 2070 over 30% of global poor population will be living outside the human thermal comfort, beyond adaptive capacity, and affecting crop	It is projected that by 2100, human mortality from heat will affect increase and affect 1/4 of the population (-1/448% under drastic mitigation scenario) and to almost 1/5 in a higher emission scenario (-1/474% under a		X	**Medium (5-9 papers)

	and livestock productivity (Xu et al., 2020)	scenario of growing emissions) (Mora et al., 2017). Heat Stress contributes to deaths and health problems among the elderly and children. Specifically, heat stress is currently responsible for 38,000 annual deaths mostly among the elderly, and 48,000 from diarrhoea, 60,000 from malaria, and 95,000 from childhood undernutrition (WHO, 2014a; Roy et al., 2018).

8.4.5.7 Compounding future risks on equity and sustainability

The compounding future effects on equity and sustainability emerge when multiple stressors linked to environmental and/or climate change, together with underlying structural poverty, exclusion, marginalization, and conflicts creating risks that need to be addressed simultaneously. Compounding risks of climate change received attention in AR5 (Oppenheimer et al., 2014) including risks associated with compound hazards (O'Neill et al., 2017b), and their implications for future risk when repeated impacts erode human and ecosystem capacity, including through transboundary effects. In SRCCL (IPCC, 2019a), land degradation and climate change compounded to highly expose the livelihoods of the poor to climate hazards and caused food insecurity (*high confidence*), migration, conflict and loss of cultural heritage (*low confidence*) (Olsson et al., 2019).

The evidence of compounded risks emerge from specific climate and environmental hazards as in relation to heatwaves, droughts, altered precipitation regimes, and increasing aridity, cyclones, floods, hurricanes and wildfires (Table 8.7). Other evidence shows that the structural poverty and socio-economic inequalities (Lusseau and Mancini, 2019), disability (Sun et al., 2017), corruption (Markkanen, 2019) and isolation (Reyer et al., 2017) (Table 8.7) compound to amplify climate risks among rural and urban poor, smallholder farms, coastal settlements, with health impacts in children's development (Perera, 2017) and urban elderly (Sun et al., 2017). In Tanzania, a greater exposure of households to climate change impacts and risks is associated with increasing land value and variable tenure, compounded with declining farm yields, accelerating the negative effects among the population (Röschel et al., 2018). In India, extreme droughts and heatwaves compound extreme poverty, and high dependence on agriculture for income and food production will affect crop productivity, income and increase of food price among smallholder farms (Singh and Leua, 2017). Soil degradation and fertility compounded with incidence of droughts increase the vulnerability of already poor smallholders in Mozambique that lack access to technological advances for crop yield management and drought resistance crops (Kidane et al., 2019).

Table 8.7: Effects of compounded risks on the poor. Climate hazards: flooding, hurricanes, drought, heatwave. Confidence level: *** High (≥ 10 papers); ** Medium (5-9 papers); * Low (≤ 4 papers); NE (No evidence)

Dimensions of compounding risk effects to the poor	Equity	Sustainability
Poverty (9) **	✓	✓
Environmental (Ecological Change, Soil degradation, fertility and aridity) and Socioeconomic changes (8) **	✓	✓
Inequalities (4) *	✓	
Governance (3) *	✓	✓
Geographical (isolation) (1)	✓	✓
Population Growth (3) *		✓
Diseases (3)	✓	✓
Uncertainty (1)		
Finance (1)		
Informality urban (2) *	✓	✓

Disability (1)	✓	
Climate-sensitive livelihoods (1)		✓
Infrastructure (1)		✓

In the context of urbanization, in fast growing cities in Asia, Africa and Latin America that are highly socially and economically unequal, the climate change impacts from events such as flooding, and droughts, are amplified on water crisis mostly among the poor and marginalized population, and challenging governance for risk reduction (Gore, 2015; Dodman et al., 2017; Jiang and O'Neill, 2017; Pelling et al., 2018; Solecki et al., 2018). In the Global South, over 880 million people are living in precarious and informal conditions without access to water and sanitation mostly in sub-Saharan Africa and South Asia (see Chapter 6; Rosenzweig et al., 2018; Satterthwaite et al., 2018; Tusting et al., 2019). In rapid urbanization sub Saharan African countries, around 53 (50–57) million urban inhabitants (50% of urban population) and 595 (585–607) million rural inhabitants (82% of the rural population) are still living in unimproved housing in 2015 (Tusting et al., 2019).

Experienced losses and damage from climate extremes, such as fatalities or economic losses due to droughts or floods (see also Fig. 8.6), also matter for future vulnerability and risk, since the poorest segments of society take longer to recover after shocks (Gupta and Sharma, 2006; van der Geest, 2018). In some cases, poor households might never be able to fully recover from post disaster, especially in the context of increasing global temperature increase (van der Geest, 2018). Another example of compounding effects of climate change to equity and sustainability is migration, which is underpinned by the underlying socio-economic and political context of vulnerability (see Section 8.2).

In Latin America, compounding effects of climate change impacts (disasters) and armed conflict has contributed to increase forced migration to the point that in 2018 alone, 1.7 million people migrated due to extremes events, four times as high as the number of people leaving their homeland due to armed conflict (Serraglio and Schraven, 2019). In South America, migration within and between countries can stem from climate extremes primarily felt by the poorest and marginalized (by gender, age, ethnicity) populations that might not be able to adapt to the fast pace and scale of changes at the local level (Maru et al., 2014; Pinho et al., 2015; Serraglio and Schraven, 2019). In Mountain Regions, intersections of people's marginalization, difficulty in access, and environmental sensitivity in the context of incidence of climate extremes have combined to reduce the ability of mountain agro-pastoralists to cope with climate extremes (Mishra et al., 2019). Mountain ecosystems are also highly susceptible to disasters and disturbances, which can lead to irreversible loss, and challenge poverty reduction efforts (Mishra et al., 2019) Some risks associated with the degradation and loss of habitats and ecosystem services associated with land use changes and commodities in many countries have compounding impacts on equity and sustainability, associated with permanent losses to the livelihood of poor and marginalized groups such as Indigenous Peoples and traditional communities around the world (Roy et al., 2018). For instance, high deforestation rates and increased forest burning in many of the Amazonian countries are further exposing vulnerable Indigenous Peoples and Traditional populations to health problems, crop failures and shortages of freshwater supply, especially in the context of extreme droughts and non-supportive governance (Leal Filho et al., 2020a; Walker et al., 2020).

Overall, there is increasing evidence that the compounding effects of climate hazards intertwined with dimensions of poverty, environmental degradation, and inequalities, represent a key risk to equity and sustainability among poor and vulnerable populations (*medium evidence and high agreement*). Compounding risks - compared to compounding hazards - can also be significantly influenced by societal tipping points and by different factors of human vulnerability that determine underlying destabilization processes of societies and communities exposed to climate change, including issues of governance.

8.5 Adaptation Options and Enabling Environments for Adaptation with a Particular Focus on the Poor, Different Livelihood Capitals and Vulnerable Groups

This section focuses on adaptation at household and community scales, including options, capacity and enabling environment, which include actions required towards building resilience. The emphasis is on the decision-making space and governance including the role of the state, private sector and other actors. Successful adaptation requires not only identifying adaptation options and assessing their costs and benefits, but also exploiting available mechanisms for expanding the adaptive capacity of human and natural systems (Klein et al., 2014). At the same time, developing suitable responses to hazards for communities and users of climate services is important in ensuring the success of adaptation measures. But despite this, knowledge about adaptation options, including possible actions that can be implemented to improve adaptation and reduce the impacts of climate change hazards, is still limited.

8.5.1 Adaptation options to climate change hazards focusing on vulnerable groups

In light of the severe adverse consequences of climate change for the poorest populations whose livelihoods are frequently dependent on vulnerable ecosystems, it is essential to enhance knowledge about sustainable and appropriate adaptation strategies and measures, as well as recognise and respond to limits to adaptation as reported in AR5 (Somorin, 2010; Noble et al., 2014; Connolly-Boutin and Smit, 2016). There is increasing evidence on the adaptation options that enhance the ability of different socio-ecological systems to become resilient in the long-term in ways that do not exacerbate poverty and inequality, and which adaptations may have little or no impact, or even adverse effects (maladaptation). Analysis of climate hazards can provide an indication of required adaptation strategies, however, most importantly is the focus on exposure, vulnerability, however the novelty of the AR6 is assessing existing response capacities to cope and adapt to climate changes and associated hazards. There is increasing knowledge about the differential adaptation options within and across social groups and the influence of (enabling) conditions that enhance or limit these options.

From the analysis in the IPCC AR5, there is *high agreement* that engineered and technological adaptation options are still the most common adaptation responses, although there is increased recognition of the value of ecosystem-based, institutional and social measures, including the provision of climate-linked safety nets for those who are most vulnerable (IPCC, 2014a). It is important to note that climate adaptation measures are increasingly integrated within wider policy, development strategies and spatial planning frameworks. Such integration streamlines the adaptation planning and decision-making process and embeds climate-sensitive thinking in existing and new institutions and organizations across scales and levels.

In the past decades a number of categories of adaptation options have been identified and are also discussed in Section 8.5. Adaptation options are categorized in various ways, such as in terms of grey and green adaptation or hard and soft measures (Depietri et al., 2013; Chambwera et al., 2014; Grimm et al., 2015). Grey measures refer for example to technological and engineering solutions to improve adaptation of infrastructures or to protect a specific land use or city from adverse consequences of climate hazards (OECD, 2018). It is accordingly explained that ecosystem-based approaches, including natural infrastructure, can provide an effective complement or substitute for traditional built (or "grey") infrastructure. For example, watershed restoration can protect sources of drinking water and reduce the need for subsequent treatment. Green measures are often encompassing ecosystem-based (or nature-based) approaches. These make use of the multiple services provided by ecosystems to improve resilience and adaptive capacity or to reduce risk. Soft adaptation measures include policy, legal, social, management and financial measures that can alter human behaviour and support adaptive governance, contributing to improved adaptation capacity, increased awareness and change in values and actions on climate change issues.

Adaptation actions frequently include deliberate, coordinated, proactive policy decisions based on the awareness that conditions have changed or will change and that action is required to avert impacts or return to, maintain, or achieve a desired state (Carter et al., 1994). Noteworthy, governance provides an important contextual framing, particularly in contexts where it is weak or contested (e.g., some of the Sahel zone). In these cases, it can mean that adaptation options stem largely from the local level. Adaptation processes can be categorised as individual, collective, proactive, reactive, autonomous, coordinated, and natural (Chambwera et al., 2014). Apart from governments, other actors, organizations and institutions (including non-state agencies and private industry actors) also play an important part in adaptation processes, consequently also the discussion of enabling environments for sustainable or successful adaptation has to deal and consider these different scales and actors. For example, while autonomous adaptations are mainly undertaken by private actors, triggered by climate change induced market or welfare changes, planned adaptations can be carried out by both private and public actors. Natural adaptations appear within ecosystems as a reaction to climate change as well as other factors and incorporate innumerable possible actions that are context specific, ranging from managerial approaches, technological innovations, and ecosystem based approaches (Huq et al., 2004). Sanchez et al. (2017) draws attention to preconceived ideas about some adaptation measures that are either considered good or bad without proper evaluation. It is argued that the association ‘hard-bad’ and ‘soft-good’ is not necessarily true; the impacts of adaptation can only be established through a case-by-case assessment. The decision to select a more or less intensive adaptation measure should integrate all approaches, social, environmental, technical and economic, in a multi-criteria analysis. This analysis should value, inter alia, social and environmental sensitivity, benefits and drawbacks or trade-offs with climate, including all the adaptation options, among them the ‘no action’ alternative.

Adaptation frequently responds to an observed or anticipated ‘trigger’ for response, such as the looming loss of land to sea level rise (Barnett et al., 2014). Identifying adaptation needs stemming from climate risks and vulnerabilities provides a foundation for selecting a sequence of adaptation options that connect through time, a long-term adaptation pathway (Wise et al., 2014; Turnheim et al., 2015). National, sectoral, or local adaptation plans are *likely* to include a number of measures that are implemented jointly from across various categories including structural, institutional, and social options. While structural or physical adaptation encompasses measures for the engineered built environment it also can encompass nature based solutions, which include ecosystem based protection measures, for example to buffer risks and hazard exposure to extreme weather events. The category of ‘soft’ adaptation measures—changes in societal values or practices—are often linked to issues of education, information and behavioural changes to support communities within specific adaptation processes to climate change and climate hazards. Institutional adaptation deals with adaptation actions and measures introduced through new legal frameworks, laws and regulations for new institutions or policies for risk reduction and adaptation. This category can also encompass the development of new organizations that have the mandate to support adaptation (Noble et al., 2014). The appropriateness and accessibility of adaptation options under these categories for supporting the poor and most vulnerable groups differs. In many cases large scale structural measures are not affordable for many poor communities. Despite this important potential of Indigenous Knowledge for disaster risk reduction of the communities, it is often shunned by practitioners (Dube and Munsaka, 2018). It is further argued by practitioners that Indigenous Knowledge lacks documentation, it is not found in all generational classes, it is contextualised to particular communities and the knowledge cannot be scientifically validated. However, there is also evidence that both local communities and disaster risk reduction practitioners can benefit from the Indigenous Knowledge of communities (Dube and Munsaka, 2018).

In practice, adaptation refers to initiatives such as a policy, plan, project or decision that are designed to change and/or respond to something in the context of existing risks and hazards. For example, a farmer might adapt to drought by deciding to harvest their crop earlier; a municipality can decide to build a sea wall to adapt to increased flood risk.

The increasing complexity of adaptation practice means that institutional learning is an important component of effective adaptation (Noble et al., 2014). It is paramount that approaches to selecting adaptation options continue to emphasize incremental change to reduce impacts while achieving co-benefits. There is increasing evidence that transformative changes may be necessary in order to prepare for climate change impacts and adaptation options in the context of climate hazards (Noble et al., 2014). Transformation for some actors at some levels may equate with incremental change and transitions for other actors and scales. While attention to flexibility and safety margins is becoming more common in selecting adaptation options, many see the need for more urgent and transformative changes in our perception and paradigms about the nature of climate change, adaptation and their relationship to other natural and human systems.

In this context, there are many potential adaptation options available for marginal change of existing agricultural and other livelihood systems, often variations of existing climate risk management. According to Howden et al. (2007) implementation of these options is *likely* to have substantial benefits under moderate climate change for some existing cropping systems. Apparently, there are limits to their effectiveness under more severe climate changes. Hence, more systemic changes in resource allocation need to be considered, such as targeted diversification of production systems and livelihoods. Howden et al. (2007) further argue that achieving increased adaptation action will necessitate integration of climate change-related issues with other risk factors, which implies integrating non-climatic factors, such as climate variability and market risk, and with other policy domains, such as sustainable development. Noteworthy, an increasing number of research programs seek to support adaptation to climate change through the engagement of large-scale transdisciplinary networks that span countries and continents (Cundill et al., 2019).

Based on analysis of different adaptation options, there is *high agreement* that the many barriers to effective adaptation will require a comprehensive and dynamic policy approach covering a range of geographical scales and multiple actors across scales, taking into consideration both climatic and non-climatic stress factors (Eriksen et al., 2015). For instance, from the agricultural perspective this could imply the understanding by farmers of change in risk profiles to the establishment of efficient markets that facilitate response strategies. It is also important to note that Science, too, has to adapt employing a range of approaches, based on the fact that multidisciplinary problems require multidisciplinary solutions. Towards enhancing resilience, a focus on integrated rather than disciplinary science alone could be of utmost importance as well as strengthening of the interface with key stakeholders, ranging from decision makers, practitioners, policymakers, and scientists.

8.5.2 Enabling environments for adaptation in different socio-economic contexts

8.5.2.1 Factors that support enabling environments for adaptation

This section assesses the literature on components of the enabling environment for adaptation. The point of departure considers findings in both the SR1.5°C report, which note that adaptation becomes increasingly difficult (and expensive) at temperatures more than 1.5ºC warmer (IPCC, 2018a), and noting also that (IPCC, 2014a) underscores that there is no one-size-fits-all approach to adaptation for all contexts, and that mitigation and adaptation must be pursued in tandem.

Climate change affects people inequitably, and everyone does not contribute equally to climate change. A range of economic and non-economic impacts can be experienced. This has led some researchers to call for a more central role for rights-based approaches to adaptation, to help secure space for those marginalised from adaptation decision making and to prioritise access to resources and information for those most vulnerable to, or affected by, the social, cultural or economic consequences of climate change (Bee et al., 2013; Da Costa, 2014; Toussaint and Martinez Blanco, 2020; Box 8.7; Section 5.12). In terms of international law, the human rights obligations of states have been subject to multiple recommendations relating to climate change by UN treaty bodies in the reporting period. More broadly, rights-based approaches rely on the normative framework of human rights, requiring adaptation to be non-discriminatory, participatory, transparent and accountable in both formal (e.g., legal and regulatory) and informal (e.g., social or cultural norms) settings and at international, national and sub-national scales (Ensor et al., 2015; Arts, 2017). Sovacool et al. (2015) note that unless critical competing interests are addressed during planning, adaptations may fail to achieve the desired outcomes. This is increasingly seen at a political level within efforts to implement the Paris Agreement, in relation to the principle of 'Common but Differentiated Responsibilities and Respective Capacities' (CBDR-RC) (Box 8.7).

[START BOX 8.7 HERE]

Box 8.7: Addressing Inequalities in National Capabilities: Common but Differentiated Responsibilities and Respective Capabilities Relating to Adaptation and the Paris Agreement

Common but differentiated responsibilities and respective capabilities (CBDR-RC) is a key principle within the UNFCCC, and attempts to acknowledge countries' diverse development situations. The Convention and its Kyoto Protocol operationalized the principle by committing developed (Annex I) countries to absolute emission reduction or limitation targets and exempting developing countries from any binding reductions in emissions (Huggins and Karim, 2016; Pauw et al., 2019). In contrast, the Paris Agreement distinguishes between 'developed' and 'developing' countries instead of Annex I and non-Annex I countries and acknowledges significant asymmetries and inequalities not only between developed and developing countries, but also between developed and developing countries themselves, both in terms of vulnerability to climate change impacts, and capacity to mitigate the problem. The literature contains extensive analyses of CBDR-RC in relation to equity in mitigation efforts in the post-2020 regime (e.g., Michaelowa and

Michaelowa, 2015; du Pont et al., 2017; Liu et al., 2017; Holz et al., 2018; Sælen et al., 2019), but little in relation to adaptation, particularly relating to how it plays out in the Paris Agreement.

The somewhat static interpretation of CBDR-RC prior to the Paris COP was overcome through the introduction of a qualification to the CBDR-RC principle: the phrase ‘in the light of different national circumstances’. Without changing the original principle, the qualifier adds a dynamic element (Rajamani, 2016). Common but differentiated responsibilities and respective capabilities of Parties are therefore recognised not to be ‘tied to the annexes’, but instead evolve alongside national circumstances (Maljean-Dubois, 2016; Voigt and Ferreira, 2016 p.301). The Paris Agreement also recognises context, considering differentiation in relation to each of the Durban pillars, i.e., mitigation, adaptation, finance, technology, capacity building and transparency (Rajamani and Guérin, 2017).

Article 7 of the Paris Agreement acknowledges adaptation as a ‘global challenge faced by all’, recognising, for the first time, a global aspiration of ‘enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change’. It calls for a balance between mitigation and adaptation funding and emphasises the need to provide developing country Parties, especially the most vulnerable, with ‘[c]ontinuous and enhanced international support’ for adaptation. The basis for differentiation under Article 7 therefore relies mostly on diverse national circumstances, capabilities and vulnerabilities. Least Developed Countries (LDCs), as well as Small Island Developing States (SIDS), are assumed by the literature, to be part of this category (Maljean-Dubois, 2016).

The literature offers two main perspectives when evaluating the effectiveness of these provisions on adaptation in the context of the post-Paris climate change regime. One argument follows that the Paris Agreement gives priority attention to the most vulnerable Parties and, unlike previous international agreements in the climate change regime, places adaptation on equal footing to mitigation (Magnan and Ribera, 2016; Pérez and Kallhauge, 2017; Morgan, 2018). Article 7 is interpreted here as a breakthrough, containing unprecedented provisions that give adaptation prominence and which elevate the importance of undertaking adequate action to cope with current and future climate change impacts. A second view argues that the Article 7 marks little departure from previous efforts to support adaptation efforts in developing countries (Doelle, 2016) or that it could have included stronger provisions, such as a quantitative goal with respect to adaptation needs and costs (Bodansky, 2016).

The literature nevertheless shows *high agreement* that other parts of the Paris Agreement do contain consequential provisions on adaptation and the operationalization of the CBDR-RC principle. Those provisions covering financial support are arguably the most pertinent, as they replace the dichotomy between developing countries and developed countries with a trichotomy which also includes ‘other Parties’ (Maljean-Dubois, 2016). While provision of support from developed Parties continues to be mandatory, these ‘other Parties’, apparently developing country Parties, are ‘encouraged to provide or continue to provide such support voluntarily’ (Article 9.2). Parties themselves determine whether they belong to this category. So far, several developing countries have made contributions to the Green Climate Fund, ranging from Indonesia and Mexico to Mongolia and Panama (Green Climate Fund, 2017). Expanding the donor base to these ‘other parties’ and breaking down the wall between donor and recipient countries marks a departure from previous practice, under which developing countries had no formal role in climate finance and support (Bodansky, 2016; Voigt and Ferreira, 2016).

[END BOX 8.7 HERE]

The scale of analysis, baseline conditions prior to adaptation and scale of action matter too when assessing the key components of an enabling environment for adaptation. At a national scale, it is well established that low income countries are less well positioned to manage climate change impacts, being variously attributed to a lack of institutional, economic or financial capacity to adapt effectively (Tol and Yohe, 2007; Barr et al., 2010). It can be particularly difficult to adapt to drought, for example, when it occurs in the pre-conditions of poor water supplies and sanitation (see Box 8.5 and Section 8.3.2), and in a context of corruption, governance failure and a lack of accountability. Adaptation productivity in higher income countries is further supported by better infrastructure and stronger institutions—low adaptation efficiency is linked to lower government spending, higher inequalities in income distribution and poor governance (Fankhauser and

McDermott, 2014). At smaller scales, even within a single socio-economic setting, different groups require different kinds of adaptation support and exhibit different vulnerabilities to climate change impacts. Huynh and Stringer (2018) found that households vulnerable to climate change impacts linked to sea-level rise and flooding in Da Nang City and Ngu Hanh Son District, Vietnam, had limited access to human, natural, physical, financial and social assets and lacked a diversified livelihood portfolio. An enabling environment for household level adaptation would need to address these factors in this context. However, the same authors found that at District scale, different challenges persisted, including obstacles to multidirectional flows of climate information, poor vertical interplay both upward and downward, and a lack of citizen participation in the governance of climate change.

Acknowledging that context and scale matter, it is nevertheless possible to set out the core components of a generic enabling environment (Figure 8.12), linking them to the literature on climate change and recognising how they can support adaptation in different socio-economic and environmental settings in which different emphases are required. This broad set of enablers requires different emphases according to the specific context, yet the interdependence between them is universally applicable.

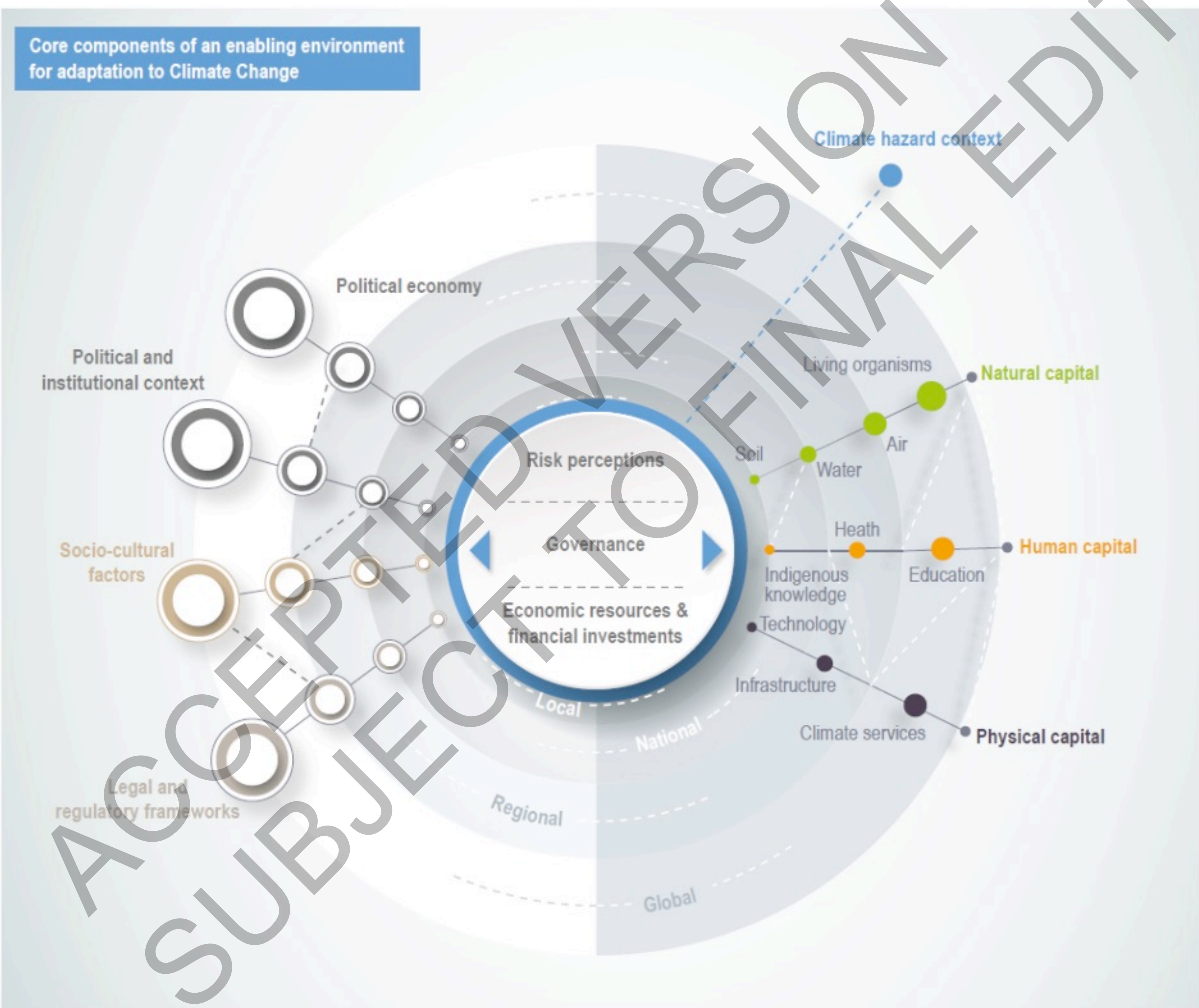


Figure 8.12: Core components of the enabling environment for adaptation to climate change (key interactions are illustrated but it should be noted that there are overlaps, interactions and feedbacks both within and between each item; and that different countries have different capacities and starting points in addressing these enablers and the interlinkages between them).

The specific political economy of each country and its underpinning philosophies shape the national political context in which public policy supporting adaptation is developed and implemented. It further shapes the context for private adaptation. Public policy targeting climate change seeks to address market failures, amend policy distortions and offer incentives for private adaptation, as well as provide climate-resilient public goods, climate services and safety nets for the poor and vulnerable (Fankhauser, 2017). In some countries that have a more stable institutional context, such policies are more straightforward to develop and implement; while in countries with weaker institutions (e.g., those emerging from conflict) a larger role may be needed for regional economic commissions and transnational networks to support the governance of 'borderless climate risks' (Benzie and Persson, 2019) particularly where these countries also are most vulnerable to climate change (see also Figure 8.6). To support enabling conditions in highly vulnerable countries that are also characterized by state fragility (see Figure 8.8), funding and projects designed to support adaptation may need to be modified to effectively promote regional cooperation and transboundary adaptation. Nevertheless, such interventions can also reinforce particularly powerful agendas and fail to assist and empower those with the greatest need to adapt(Biermann et al., 2010; Burch et al., 2019) neglecting community voices and sovereignty (Schlosberg and Collins, 2014). It is therefore important that the relevance of people and community empowerment to effectively achieve vulnerability reduction and climate change adaptation is recognised.

It is also insufficient to consider countries as stand-alone entities, due to links such as those provided by international trade. Taking Europe as an example, the continent has strong links to major trade partners such as India, Indonesia, Nigeria and Vietnam, so failure to assist adaptation in other locations opens up important vulnerabilities through supply chains (Lung et al., 2017). Policies seeking to protect national interests alone (e.g., in terms of food security) are seen as causes of negative impacts at a global scale (Puma et al., 2015; Challinor et al., 2017), with those nations and individuals least able to adapt to evolving climate changes experiencing exacerbation of existing imbalances (Elbehri et al., 2015). Least developed countries are projected to suffer greater import losses in more connected networks (Puma et al., 2015). In the food sector, poorer net food buyers are anticipated to experience the worst impacts of climate change (Gitz et al., 2015).

Behind each policy are decisions about the magnitude of financial resource investments in specific adaptation actions, and their allocation between different sectors and groups in society, both spatially and temporally. The IPCC has estimated that limiting the rise in global average surface temperatures to 1.5°C would require between $1.6 trillion to $3.8 trillion of annual investment in supply-side energy systems (those that generate energy) between 2016 and 2050 (IPCC, 2018b). Resource allocations however, are shaped by perceptions of the risks of climate change and the urgency of actions, as well as other motivational factors such as descriptive norms and perceived self-efficacy (van Valkengoed and Steg, 2019) and the underlying approaches taken to valuing human wellbeing (e.g., see work from Bhutan on Gross National Happiness and climate change actions (Kamei et al., 2021)).

An increase in finance mobilised, however, does not automatically equate to adaptation interventions on the ground, nor does guarantee the effectiveness of those adaptations deployed (Berrang-Ford et al., 2021). Unintended negative consequences may arise due to lack of understanding of the drivers of vulnerability (such as gender inequality or inequitable access to natural resources), non-involvement of marginalised local groups, retrofitting adaptation into existing development agendas, and insufficiently defining adaptation success (Eriksen et al., 2021). A 2017 study estimated that less than 10 percent of climate finance committed from international, regional and national climate funds to developing countries between 2003 and 2016 went to locally focused projects, suggesting a need to rethink approaches if the most affected groups are to build sufficient resilience to the impacts of climate change (Soanes et al., 2017).

The literature shows with *high confidence* that the poorest groups in society often lose out, and require greater planned adaptation support, having less capacity to adapt than better off groups with easy access to assets (Barbier and Hochard, 2018; Ziervogel, 2019b; Box 8.5). Developing countries such as Burkina Faso, Mali and Zambia are not only among the most vulnerable to climate change, they are also the least able to mobilise the finance needed to adapt to its impacts (ND-GAIN, 2019). Women and girls are often most heavily burdened. When building adaptive capacity these groups can require different support such that their knowledge, capacities and skills can be harnessed, in such a way that does not feminise responsibility and add to their burdens (Clissold et al., 2020; McNamara et al., 2021a).

There is broad support for the notion, enshrined in the Paris Agreement, that adaptation finance flowing to developing countries of the Global South should primarily benefit the most climate-vulnerable among them due to their limited technical capacity and financial capabilities, yet such countries are often insufficiently considered in funding decisions. There are nevertheless concerns regarding institutional fit: that foreign funding regimes may not map onto more recently developed administrative traditions, leading to dominance of governance models emanating from donors (Vink and Schouten, 2018). Research has found multilateral donors do not prioritise vulnerable developing countries at the project selection stage and they have received smaller allocations of adaptation finance from bilateral donors than less vulnerable countries (Saunders, 2019), leaving the poor vulnerable to climate impacts. The lack of climate finance flowing to LDCs and SIDs (currently 14 and two percent of the total, respectively) is compounded by access issues due to the inability of domestic institutions to meet specific fiduciary standards and other access requirements, insufficient human resource support and the inflexibility of current approaches which are biased in favour of governments and against non-traditional actors such as local enterprise and grassroots organisations (Shakya et al., 2021). Further, vulnerable developing countries shoulder additional financial burden, embodied in higher interest payments to service public and private debt, due to the increased cost of capital brought about by greater exposure to climate risks (Buhr et al., 2018). This has been further exacerbated by the recession and debt distress accompanying the Covid-19 pandemic (Kose et al., 2021). A range of reforms, including comprehensive debt relief by public creditors, green recovery bonds, debt-for-climate swaps and new SDG-aligned debt instruments may address unsustainable debt burdens, freeing up investment in climate adaptation and a green economic recovery (Volz et al., 2020; see Section 8.6.3.1)..

Greater investment is also needed in the developed countries of the Global North. For example, both the 2018 forest fires in Sweden, the 2019-2020 Australian bushfire season and the 2020 forest fire season along the US West Coast were unusually long and severe, resulting in unprecedented damage to natural habitats and human livelihoods and, relatedly, significant economic cost, particularly given interlinkages with other stressors such as Covid-19. While a range of drivers underpin annual fire seasons, including greater water withdrawal and years of fire suppression, early research indicates that climate change increases their likelihood due to long-term warming trends (van Oldenborgh et al., 2021a).

However, investing in poverty reduction does not necessarily lead to climate change adaptation and where adaptation does result, it does not always reduce vulnerability of the most marginalised, such as documented in case studies from Northeast Brazil (Nelson et al., 2016). Poverty also affects private adaptation options. For example, research from Portugal highlights the importance of private financial assets in helping older adults to adapt to extreme temperatures (Nunes, 2018).

Policies and investments that are adopted are embedded within the relevant legal and regulatory frameworks, which extend beyond national jurisdictions upward to the regional scale (such as the Southern Africa Development Community's Southern Africa Regional Framework of Climate Change Programmes, (2010)) and international scale, for example, UNFCCC, the 2015 Paris Agreement, the Sendai Framework for Disaster Risk Reduction, the New Urban Agenda and the SDGs. Legal and regulatory concerns also extend downward to shape local- and city-scale adaptation efforts (e.g., Sao Paulo's municipal policy and new master plan). Nevertheless, only a minority of countries have dedicated legal frameworks supporting adaptation (Lesnikowski et al., 2017) and these often lack in both precision and obligation—largely because adaptation is a contested global public good but also because adaptation is commonly bundled in with mitigation commitments (Hall and Persson, 2018). Coherence, horizontally and vertically in both policy and law is often lacking. At the same time, bottom-up, private, autonomous adaptation efforts are being better tracked, with different actors motivated by growing experiences of local climate change impacts (Berrang-Ford et al., 2014).While the emergent polycentricity of adaptation governance is beginning to take shape, wherein both state and non-state actors share a common adaptation goal and interact coherently, yet often independently, to advance progress towards it (Morrison et al., 2019), understandings of how various centres of decision making with different degrees of autonomy support an enabling environment for adaptation, remain at a nascent stage . Multiple scales and forms of adaptation occur, with attributes such as self-organisation, appreciation of site-specific conditions, and the need for learning and experimentation, alongside building of trust, increasingly shown to be vital (Dorsch and Flachsland, 2017). Literature indicates that professional and learning networks are important groups supporting adaptation in cities and can help harness resources (Woodruff, 2018); while (Hauge et al., 2019) research in Norway underscores the importance of working across multiple disciplines and the inclusion of actors from different levels of authority in multilevel municipal networks. They found that these factors can help to identify specific adaptation actions as well support knowledge sharing within participating organisations, which in turn helps garner commitment to adaptation and its implementation. They also found that it is important to involve local leaders in polycentric adaptation networks.

Among the many institutions, actors and roles associated with successful adaptation, two play an increasingly important role: local governments and the private sector (Noble et al., 2014). These groups often define the flows of information and finance from the top down, as well as supporting the scaling up of community and household adaptation. In some countries, for example, in South America (Argentina, Brazil, Paraguay) vocational agricultural schools, often in remote rural locations, play a key part in knowledge sharing activities that support adaptation. Similar valuable contributions are made by universities through their outreach activities, particularly those offering programs in environmental and agricultural fields. Many actors face a lack of resources and capacity, particularly at the local level. Local institutions, including local governments, non-government organizations (NGOs) and civil society organizations, are hampered by ongoing challenges in gaining support from higher governance levels—from national government or the international community, particularly in developing countries. At the same time, private sector actors, from individual farmers and small/medium enterprises (SMEs) as well as large multinational businesses, will seek to protect and enhance their production systems, supply chains and markets by pursuing adaptation-related opportunities. Yet, while these goals will help expand adaptation activities, they may not align with government or community objectives and priorities without coordination and incentives, and in the process, can reinforce existing capacities, inequalities and power relations (Sovacool et al., 2015). Similarly, an enabling environment for businesses' adaptation is highly differentiated and often requires structural deficits (such as limited market access, finance and transport and communications infrastructure) to be tackled (Gannon et al., 2020).

The challenges of climate change have driven governments around the world to emphasise climate services as a route to enhance decision-making and reduce climate-related risks, as well as inform adaptation, supporting calls for the right to information (Tall and Njinga, 2013). While there have been some efforts to evaluate the economic impact of climate services alongside other impacts (e.g, Tall et al., 2018), little is known about the institutional contexts in which investments in climate services have taken place, nor those groups that are most vulnerable or marginalised in relation to specific climate risks. Vincent et al. (2017) offer preliminary insights from Malawi, identifying that barriers to improved integration of climate services in national policy planning include factors relating to spatial and temporal scale, accessibility and timing of information provision, credibility and mismatches in time-frames between planning cycles and climate projections. An understanding of the factors that enable climate service investment is important for the development of climate services at local, national and international levels (Vaughan et al., 2017) but this area of literature is not yet well developed.

Overall, adaptation entails financial (and non-financial) costs not just in implementing adaptation actions, but also in designing, facilitating and preparing for actions—costs to create and maintain an enabling environment (see also Section 8.2.2.3, Cross-Chapter Box LOSS in Chapter 17). Financial and economic investments target the whole range of other types of asset (natural capital, physical capital, human capital, social capital). AR5 reports that aggregate economic losses accelerate with increasing temperatures (IPCC, 2014a). Costs may be borne when gaining information (e.g., investments in climate services), while adjustment costs are incurred as adaptations take place. Nevertheless, to enable adaptation, investment is needed in various natural, human, physical and social assets, as considered below. The importance of investment in each of these different types of asset varies according to the scale and livelihood system in need of adaptation and the ways in which livelihood resilience is framed and power is distributed, within each specific setting (Carr, 2020).

8.5.2.2 Natural capital

It is well established that climate change compounds the impacts of pressures that humans place on the environment (*high confidence*) and that environmental degradation can undermine options for adaptation and an enabling environment, with poor and natural resource dependent groups most acutely affected (see e.g., CCP3 for insights from deserts and semi-arid areas). Sustainable management of natural capital contributes to building resilience and the natural ability of ecosystems to adapt to climate change (IPCC, 2014a) and see also IPCC SROCC Chapter 5, Section 5.3.2 (Bindoff et al., 2019). Some systems like mangroves (found in 123 countries, many of which are in the developing world) offer a broad range of vital ecosystem services(Hamza et al., 2020). Mangroves provide regulating services by acting as a natural defence against sea level rise and storm surges; and by sequestering carbon in both the trees and sediments they capture. Provisioning services (e.g., fish, crabs, timber and fuelwood) from mangroves support livelihoods and livelihood adaptation options especially for those with few other livelihood opportunities, while these systems also provide important habitat (breeding, spawning and nursery grounds for fish) and biodiversity, and offer cultural services in the forms of education, recreation and spiritual benefits (Quinn et al., 2017). As the frequency of events such as hurricanes, storms and typhoons rises with climate change, natural capital assets like mangroves become increasingly important in protecting coastlines and supporting adaptation. While not reducing the hazard itself, the mangroves reduce exposure and in some cases also vulnerability. The literature shows with *high confidence* that environmental assets support both climate change mitigation (at a large scale) and adaptation (at a smaller scale), particularly for the poorest groups in society who directly depend upon natural capital for their subsistence (e.g., Angelsen et al., 2014). In turn, the legal and regulatory context and institutional set up determines who has access rights to different aspects of the natural resource base. This shows how different aspects of the enabling environment work in tandem to constitute one another.

In a market economy, human activities tend to exacerbate degradation of natural capital, despite its role in buffering climate change impacts, supporting mitigation and providing adaptation options. Economic agents base their decisions on market prices, even though market prices do not incorporate the costs of deteriorating natural capital because of externalities and other market failures, i.e., environmental degradation is not internalised (Bowen et al., 2012). At the same time, expanding populations, capitalism and consumption choices affect the condition of natural capital, alongside short-termism stemming from poverty, linked to the need for survival. All these factors therefore interact, with the aggregate effect of worsening the impacts of climate change, while also undermining future adaptation options, particularly for the poor. Adaptation policies should, but do not always, compensate for the prevalent market failures. For example, in Melanesia, sea walls have been built out of coral by local people in an attempt to reduce the impacts of rising sea levels, leading to outright destruction of some of the world's most productive and biodiverse coral reefs (Martin and Watson, 2016). Similarly, in the Congo Basin, farmers are adapting to increasingly variable rainfall by expanding their cropping activities into forested areas, releasing carbon into the atmosphere through forest clearance activities and threatening biodiversity. Agricultural land is also being degraded globally (see the IPCC's SRCCL (IPCC, 2019a)), and this too closes down adaptation and livelihood options for the poorest, natural resource dependent populations, while jeopardising food security, biodiversity and human health at wider scales. An enabling environment for adaptation therefore demands investment in sustaining natural capital at multiple scales, internalising the costs of degradation, as well as establishing the necessary legal and regulatory frameworks (and associated enforcement) to reduce its degradation(IPBES, 2018).

The literature increasingly shows that approaches such as nature-based solutions (NBS) and ecosystem-based adaptation (see Chapter 2 and Chapter 6) can offer value for money in tackling climate change from both a mitigation and adaptation standpoint (Seddon et al., 2020). According to the Global Commission on Adaptation, a global investment of $1.8 trillion between 2020 and 2030 into adaptation measures such as early warning systems, climate-resilient infrastructure, improved dryland agriculture, mangrove protection, and resilient water resources can yield $7.1 trillion in total net benefits (Global Commission on Adaptation, 2019). NBS operate by harnessing natural processes, sometimes in combination with technological or engineered solutions. Examples encompass green public spaces and parks (Sahakian and Anantharaman, 2020), green infrastructure, such as urban forests and street trees (Richards and Edwards, 2017) which create shade and reduce urban heat island effects whereby urban areas are warmer than their surroundings (Depietri et al., 2013), and support human health and wellbeing by keeping people in cities more closely linked with nature (Gulsrud et al., 2018). NBS also encompasses blue infrastructure including constructed wetlands, bioswales, rain gardens etc., which can reduce flood risks (Haase, 2015). While the literature is generally positive about the ability of NBS to support climate risk reduction and deliver multiple other benefits (Connop et al., 2016) such as green job opportunities, improved provision of recreational space, cleaner air, habitat provision and increased property values (Emmanuel and Loconsole, 2015), more research is required to specifically assess and evaluate the conditions and contexts in which these kinds of potential benefits are realised and how they can be mainstreamed into policy (Frantzeskaki et al., 2019). Similarly, there is *limited evidence* on unintended consequences (e.g., methane production, creation of habitat for disease vectors, increased human-wildlife conflict) and how these can be avoided (Wolch et al., 2014).

8.5.2.3 Human capital

Successful adaptation requires support to be directed towards human capital and socio-economic capabilities and competences, in terms of education, knowledge, experience, health and wellbeing, and migration, enabling people to contribute meaningfully towards development (Bowen et al., 2012). At the same time, strong human capital and investment in actions that build human capacities to deal with climate change, can further enhance adaptation activities linked to other capitals, and contribute positively to overall disaster risk reduction.

Analyses of educational attainment distributions with datasets reaching back as far as 1970 show that improving educational attainment in people of working age has been the most consistent and significant driver of economic growth globally (Lutz et al., 2008), showing the importance of the right to education. Education has further supported sustainable development by fostering empowerment, yielding access to information (including on climate change) and has clear links to other aspects of human capital, including health and mortality (Samir and Lutz, 2017). There is *medium evidence and high agreement* that education reduces vulnerability and enhances adaptive capacity (Frankenberg et al., 2013; Sharma et al., 2013), with *high agreement* that climate change impacts can have negative effects on existing levels of human capital, with some development pathways affected more than others (Samir and Lutz, 2017). Education can help to shape people's risk perception and assessment, as well as affecting knowledge sharing and the development of problem-solving abilities (Striessnig et al., 2013).

At the same time, Indigenous Knowledge and Local Knowledge can inform adaptation actions (Apgar et al., 2018), but is poorly integrated into formal educational systems and in some cases is insufficient to adapt to new hazards that are emerging as a consequence of climate change. Education further feeds into livelihood options, with close relationships between people's earning capacities, the livelihood choices they can make and their levels of financial capital. It also supports food security (Lutz et al., 2004). There is *medium evidence* that climate change can undermine human capital and education. For example, studies have shown that higher temperatures reduce exam educational performance (Park, 2020), while extreme weather events such as snow storms disrupt learning, yielding long lasting and multidimensional effects (Maccini and Yang, 2009; Cho, 2017; Graff Zivin et al., 2018).

As well as studies examining formal education, a large body of research has focused on social learning and its role in building adaptive capacity through joint knowledge production and reflexivity. Foregrounding the need for continuous changes in response to emerging conditions, this literature identifies the potential of shared learning for co-constructing policy and practice responses to complex, multi-stakeholder environmental problems, and highlights both the necessity and challenge of including non-dominant values, knowledge and expertise in adaptation decision making, considering the role of power dynamics therein (Collins and Ison, 2009; Ensor and Harvey, 2015; Phuong et al., 2017; Apgar et al., 2018; Brymer et al., 2018; Fisher and Dodman, 2019). A growing body of evidence also links to on organisational learning and adaptation. It was found that organisations' adaptive behaviours, like those of households and individuals, do not operate in a vacuum, with organisations' behaviours shaped by policy and market conditions amongst other factors. Mudombi et al. (2017) highlight further barriers in their study in South Africa, linked to inadequate resourcing, political interference, governance shortcomings and knowledge/expertise gaps within organisations, alongside short timeframes for implementing projects.

Adaptations that support human health and wellbeing require investments in physical assets and infrastructure linked to water and sanitation (see Chapter 4), particularly in rapidly urbanizing areas in the Global South, alongside specific pro-poor investment strategies given disproportionate climate change impacts on women (See Cross-Chapter Box GENDER in Chapter 18), other marginalized groups and low income households who lack access to healthcare. Climate change facilitates the spread of vector borne diseases such as malaria, as well as illnesses such as meningitis (Rocklöv and Dubrow, 2020). Impacts on health are also experienced, through food insecurity resulting from climate change, including malnutrition, as well as through loss of livelihoods, making it more difficult to afford and to access health services. Health aspects are considered in-depth in chapter 7 but we underscore the importance of a rights based lens on adaptation in supporting the right to health and food in the context of inequality.

A key dimension of human capital is local understanding of climate risk, which includes knowledge systems outside western scientific approaches. For millennia, local communities have relied heavily upon culturally accumulated Indigenous Knowledge participating in landscapes as stewards of their environment, engaged in profoundly detailed livelihood strategies that deal with natural hazards (Ajayi and Mafongoya, 2017). Indigenous Knowledge systems as they are embedded in culture, and are passed from generation to generation in various ways: livelihoods, traditions, spiritual practices and oral tradition, cultural identity, and historical memory. Indigenous Knowledge is known or learnt from experience, or acquired through observation and practice, and handed down from generation to generation. It is acknowledged that Indigenous Peoples communities, particularly those in hazard-prone areas, have developed a profound understanding and knowledge of disaster prevention and mitigation, early warning, preparedness and response, and post disaster recovery. While Indigenous Knowledge systems, themselves, are an indispensable dimension of capacity for adaptation, and where threatened represent a major risk to Indigenous Peoples communities. While still robust among Indigenous Peoples in many parts of Africa, Asia and Latin America, Indigenous Knowledge is not well reflected or incorporated in assessments such as this, and stands in danger of being lost as its custodians are passing away.

Indigenous Knowledge about natural hazards enables communities at risk to take steps to reduce climate risk. Indigenous Knowledge systems are locally indispensable resources for adaptation to climate change, yet are often misunderstood and undervalued. Generally, Indigenous Peoples and other local groups hold relevant local-scale knowledge about environmental change, the impacts of those changes on ecosystems and livelihoods at local scales, and possible locally effective adaptive responses. However, it is important that Indigenous Knowledge and Local Knowledge is situated within knowledge from other scales in order to assess its broader relevance and applicability (Ahlborg and Nightingale, 2012). Some authors suggest including Indigenous Knowledge in the IPCC assessment process should be of high priority, as it is becoming increasingly relevant for climate services (*high confidence*) (Strauss and Orlove, 2003; Crate and Nuttall, 2009; Crate, 2011). Their knowledge can draw attention to climate baselines and change, and identify adaptation priorities, such as plant and animal species that should be protected given local contextual environmental considerations. For example, using Indigenous Knowledge in weather and climate prediction, local communities in different parts of Tanzania have been coping with and adapting to increased climate variability normally manifested in the form of increased frequency and magnitude of various exigencies including droughts and floods, and outbreak of pests and diseases (Kijazi et al., 2013). Prediction of impending hazards has been an integral part of Indigenous Peoples' adaptation strategies. Various environmental and astronomical indicators are used to predict rainfall, including plant phenology, behaviour and movement of birds, animal and insects are widely used in many parts of Tanzania (Kijazi et al., 2013).

There are efforts in developing adaptation plans that utilize local knowledge. Local knowledge-based adaptation is focused primarily on the use of traditional knowledge to increase adaptive capacity at the community level and less on integration (Mimura et al., 2014). Hence, there is need to increase effectiveness of policy processes that work towards integration of local and scientific knowledge (Nakashima et al., 2013; IPCC, 2014a).

8.5.2.4 Physical capital

Ensuring sufficient investment in physical capital is vital to support development pathways at the national level, but for the poorest and most marginalised in society, physical capital represents an invaluable source of adaptation options (Hallegatte et al., 2019). Physical capital constitutes assets such as land, roads and other infrastructure (e.g., water supplies, electricity, mobile phone connectivity), housing and other buildings, as well as the materials and tools needed to make a living (e.g., farming, forestry and fishing equipment, transportation vehicles, technology). It can also help to foster a sense of place, and can support wellbeing. Climate change impacts on physical capital are often widespread, as well as economically and emotionally costly, particularly when communities afflicted by hardship (inadequate levels of sustainable human development through access to essential public goods and services and access to income opportunities (Abbott and Pollard, 2004).

Given the massive scale of investments required to build and sustain physical capital at the state level, it is imperative to ensure physical capital decisions take into account climate resilience; not least because retrofitting and replacing are both highly costly. The World Bank estimates that adapting over the period 2010-2050 to a world that is 2 °C warmer by 2050 will cost $70 billion to $100 billion per annum, with the infrastructure sector accounting for the largest share of costs (World Bank, 2010). At the same time, every $1 invested in preventive measures can save $5 of repairs (PRIF, 2013). While adequate financing and technical expertise are required, as well as foresight in planning and design and climate risk screening, successful adaptation relating to physical capital also demands legal and institutional enablers (e.g., development and enforcement of building codes and regulations; roll out of insurance options; planning restrictions to reduce construction in locations that are highly exposed to climate hazards etc). In some situations, these are lacking. For example, low-lying least developed countries such as Bangladesh, as well as small island nations, regularly suffer from climate events such as floods, typhoons, cyclones, hurricanes and saline intrusion (see chapter 15 on small islands). Hazards such as typhoons cause substantial damage and destruction, impede mobility, reduce connectivity, disrupt communications, food, water and energy supplies and render people homeless and without the assets they rely on to make a living. In the absence of adequate legal and institutional enablers, as well as livelihood assets, it makes the maintenance of physical capital far more challenging, as the case of Cyclone Aila in Box 8.8 demonstrates.

[START BOX 8.8 HERE]

Box 8.8: Cyclone Aila in Bangladesh: Impact, Adaptation and Way Forward

Historically, southern coastal Bangladesh, where the 1970 Bhola Cyclone killed 500,000 people, has been considered among the most climate vulnerable environments on Earth. However in recent decades, extreme weather events, like Cyclone Aila, though still destructive and destabilizing, have resulted in lower death tolls thanks to a concerted investment in flood mitigation infrastructure, a dense network of cyclone shelters and a robust early warning system (Chowdhury et al., 1993; Paul, 2009). Cyclone Aila struck the south-west coast of Bangladesh on 25 May 2009 with a wind speed of 120km/hour (Islam and Hasan, 2016). With tidal surges of up to 6.5 m, occurring over dry pre-monsoon soils, 11 coastal districts and more than 3.9 million people were affected (United Nations, 2010), 190 people died, and 7,100 people suffered injuries (Saha, 2017).

Aila greatly damaged the region's physical capital, including 6000 km of roads and 17,000 km of embankments. The cyclone polluted and damaged sources of drinking water and destroyed 243,000 houses and thousands of schools (Mallick et al., 2017; Paul and Chatterjee, 2019). In Satkhira and Khulna districts alone, 165,000 houses were destroyed and households were forced to live on damaged embankments in makeshift shanties(UNDP, 2015). Many people had to live in these temporary shelters for years (Saha, 2017). Aila occurred during a high tide and the surge of saline water inundated not only the roads, embankments and houses but also vast areas of agricultural field and shrimp farms (Paul and Chatterjee, 2019) leaving many areas waterlogged for months (Abdullah et al., 2016; Mallick et al., 2017). The effect of saline water logging inside embankments caused further harm to houses, roads, and culverts, adding more barriers to the post-disaster reconstruction activities (Roy, 2020). In the same area, tube-wells were damaged. Women had to travel up to 2 km every day to collect safe water, spending 30–90 minutes on this activity daily (Alam and Rahman, 2019). The distribution of costs across different socio-economic groups was not always as expected. A study in Aila affected Koyra sub-district of Khulna found that households with higher incomes were more vulnerable to Aila in both relative and absolute terms compared to middle- and low-income groups mainly due to damage to shrimp farming which underpinned their livelihoods (Abdullah et al., 2016). This highlights how specialised livelihoods can leave people more vulnerable as they have fewer options. However, the same study found that the damage to physical capital such as fishing nets and boats was statistically significantly greater for middle- and low-income groups. Damage to houses was statistically significantly more among poorer households followed by middle and higher-income groups.

A range of coping and adaptation actions were enacted in response to losses of and damage to physical capital (Table Box8.8.1). Actions varied across the different affected areas and were taken by the households themselves, by the Government, and NGOs.

Table Box 8.8.1: Coping and adaptation actions enacted in the cyclone Aila affected area in response to losses of and damage to physical capital

Coping and adaptation actions	Action group	References

Human migration—mostly forced due to loss of houses as well as other resources and livelihood activities	Households	(Abdullah et al., 2016; Mallick et al., 2017; Paul and Chatterjee, 2019)
Alternative livelihood activities such as crafts, and honey and wood collection from the Sundarbans, due to irreparable damage to fishing gear	Households	(Alam et al., 2015)
Saving money for house repairs or construction	Households	(Alam et al., 2015)
Underground storage of emergency items such as foods, matchbox, cooker and cooking fuel	Households	(Alam et al., 2015)
Selection of high land to build shelter along both sides of the embankments	Households	(Alam et al., 2015)
Tree plantation in the homestead periphery to protect the house from gusty winds and to use as a source of wood for house repair/construction	Households	(Alam et al., 2015)
Increasing height of the house plinth	Households	(Alam et al., 2015)
Changing of house roofing material from thatched to corrugated iron sheet or asbestos	Households	(Alam et al., 2015)
Informally allowing people to harvest Sundarbans forest wood without any charge so they could make makeshift houses	Forest Department	(Abdullah et al., 2016)
Rainwater harvesting using plastic or clay pots and artificial aquifer tube-wells for securing drinking water.	NGOs and Households	(Sultana and Mallick, 2015)
Replacement of mud walls of houses with wood or bamboo sticks to enhance durability	NGOs and households	(Sultana and Mallick, 2015)
Making thick shelterbelts along coastal embankments	NGOs and households	(Rahman and Rahman, 2015)

The impacts of some of these adaptations, particularly engagement in new livelihood activities after Aila, were varied, with income of the affected households increasing in some cases and decreasing in others. In Koyra, the income of the poorest and middle-income households increased by 16 % and 4% respectively, while the income of richer households (many of whom lost physical capital assets that they use to pursue their livelihoods) decreased by 50% (Abdullah et al., 2016).

Research into adaptation projects led by various actors has shown that adaptations taken by the households and community themselves are effective only to address typical challenges (such as seasonal shifts in temperature or rainfall) but are less effective in addressing extreme events that have long-lasting impacts. This is mainly due to lack of adequate resources and institutional support (Alam et al., 2015). At the same time, some coping mechanisms are harmful in the longer term, for example, harvesting Sundarbans forest wood after Aila for reconstruction could have negative impacts on the forest.

As of 2017, many of the affected areas had not yet been able to recover from the effects of Aila (Paul and Chatterjee, 2019). A transformative approach needs to be taken not only to help them recover in livelihoods terms, but also to support people’s wellbeing. Suggestions of physical interventions that are needed include higher and stronger dykes, cyclone-resistant housing, active maintenance and strict policing of embankment use and good governance (Abdullah et al., 2016). Enabling formal institutions could help, for instance, by improving the climate-resilience of physical capital (e.g., by developing and enforcing building codes for houses). Other institutional mechanisms could help to improve access to low interest credit, prevent maladaptation, improve enforcement of laws, and provide insurance. However, such institutional reforms need to be co-developed with local people and incorporate local cultural mechanisms (Islam and Nursey-Bray, 2017). Future adaptation strategies also need to take into account the limits to autonomous adaptation (i.e. that without external intervention) and differential level of impacts and adaptive capacities among different groups of households in the Aila affected areas. This example illustrates the importance of a more comprehensive approach to resilience building, and the need to better understand the interlinkages between the core components of an enabling environment for adaptation (see Figure 8.12).

[END BOX 8.8 HERE]

Physical capital in the form of technology is increasingly supporting climate change adaptation, despite that innovations can be rolled out under high uncertainty, opening up new risks (e.g., hacking). Moreover, deployment of technology is closely tied to other forms of capital, especially human capital, and innovations cannot just be rolled out in the absence of suitable institutional and technical support and training. Similarly, access to finance is vital. Some technological adaptations require a pre-existing level of infrastructure and literacy, raising important questions about inequality (Taylor, 2018). Rotz et al. (2019) warn of automation impacts on rural labour, especially in places with high youth unemployment, while Taylor (2018) notes that social classes and gender are impacted differently by technological change, and failure to address underlying inequalities will shape who becomes vulnerable. Adequate testing of technologies in terms of their applicability to different contexts is also required, ensuring they do not become maladaptive when applied at scale.

Similarly, technology must always be grounded in an appreciation of the cultural context. Research in the European Arctic with the Indigenous Sami Peoples found that use of GPS technology on reindeer, together with supplementary feeding, offer useful adaptations for some herders. However, there are fears such technologies may, over time, reduce the skills, cultural knowledge and Indigenous adaptations of the Sami (Andersson and Keskitalo, 2017), as, for example, reindeer become more tame through supplementary feeding, affecting their range selection. Overall, technology and other adaptations should seek not to erode Sami culture's adaptive capacity (Vuojala-Magga et al., 2011; Risvoll and Hovelsrud, 2016), particularly because reindeer grazing as a land management practice can play a useful climate change mitigation role too. Reindeer grazing protects tundra from tree line and bush encroachment, while summer grazing increases surface albedo by delaying snowmelt (Jaakkola et al., 2018).

8.5.2.4.1 Socio-cultural factors

Social and cultural factors are closely linked to values, beliefs and identities (Heimann and Mallick, 2016) and mediate the ways in which people respond to climate variability and change (Adger et al., 2013). There is *limited evidence* but medium agreement about the importance and role of social and cultural factors in shaping adaptation, in terms of both the need to adapt and the way it is presented and communicated, although evidence is somewhat mixed in terms of how experiences of weather affect opinions and perceptions of climate change (Howe et al., 2019). Research also highlights the importance of context in understanding relations between perceptions of risks and behaviour, arguing that power relations and other obstacles and opportunities play a vital role in shaping actions (Rufat et al., 2020). In general, nonetheless, adaptation is spurred when people perceive that there is an action they can take to make a difference (Kuruppu and Liverman, 2011; Mayer and Smith, 2019), although it cannot be assumed that action will be taken if the socio-cultural setting is not amenable and it contravenes the values underlying people's perceptions (Kwon et al., 2019). Research testing for the effect of beliefs on behavioural change from 48 countries highlighted the need for policy leaders to present climate change as solvable yet challenging, if fatalistic beliefs that act as barriers to adaptation were to be reduced (Mayer and Smith, 2019). This demonstrates how beliefs do not always reinforce actions, even when risks are perceived. Similarly, research from Burkina Faso working with the Fulbe ethnic group found that cultural norms restricted engagement in four of the most successful livelihood strategies that support adaptation to climate change (labour migration, working for development projects, gardening and female engagement in economic activities) (Nielsen and Reenberg, 2010). Cultural factors therefore play an important but under-researched role in adaptation.

Social factors in the context of adaptation, by contrast, are more widely studied. The literature on adaptation and the role of social capital as an enabler is diverse. There is *high confidence* that during disasters, social capital plays an important role in linking those who are affected to external supports and resources, while on small islands social networks can be dense and support adaptation (Petzold and Ratter, 2015), with traditional knowledge and societal cohesion helping small island communities to have self-belief and build resilience even in the absence of external interventions (Nunn and Kumar, 2018). Even the development of weak ties (e.g., one-way information transfer) can lead to establishment of mutual collaboration relations that can be more easily draw on in times of climate change related shocks and stresses (Ingold, 2017), while collective shared disaster experiences can cause new social groups to emerge and spur action, linked to a perceived common fate (Ntontis et al., 2020). However, this can exacerbate inequalities and create new ones, with those who are more connected having enhanced access to, for example, shelters following storm evacuations or earthquakes (Rahill et al., 2014). In adapting to more incremental changes, social capital has been shown to increase shared Local Knowledge and awareness, support participatory processes and strengthen ties to corporate and political institutions, increasing their responsiveness to local concerns, as shown by examples from Aldrich et al. (2016). They describe how in Houma, Louisiana, located west of New Orleans, rising sea levels and hurricane risks have drawn on and built social capital at the community level. Having what was perceived locally as insufficient federal government support, residents, church groups and town council members collaborated to spur adaptation. Community mobilisation led to construction of self-funded levees and water projects to protect 200,000 residents from storm surges. Projects include marshland restoration, the elevation of existing housing, improved pumping systems and canal drainage, as well as buyouts and relocations of businesses and housing that has been repetitively damaged. Funds were raised from households through donations via a self-imposed sales tax. While this example paints a positive picture of the role of social capital and collective action in adaptation activities, it also raises questions about the coherence of actions across levels, again, highlighting a role for polycentric governance if risks of maladaptation are to be reduced. The danger in the example presented here is that should federal plans in future conflict with the community level work, local efforts may have been in vain if installations have to be removed. This highlights the importance of careful evaluation of all adaptation options on an ongoing basis.

Further warnings about social capital as an adaptation enabler come from Acosta et al. (2016) who recognise that it may be detrimental to private adaptation in some cases. Their research in rural Ethiopia found that qualitative measures of trust predict contributions to public goods, supporting theories about collective action, but that the effects of social capital are not homogenous: it can be helpful in some contexts, but unhelpful, or even detrimental in others. This led them to highlight the need for policymakers to consider these potentially different outcomes. Other research, also from Ethiopia, suggested that households with more social capital are more specialised in their livelihood strategies. This could leave them more vulnerable to climate change impacts (as per the cyclone Aila example where shrimp farmers were specialised and hit hardest by the cyclone's impacts), though social capital acts as a kind of informal insurance (Wuepper et al., 2018).

8.6 Climate Resilient Development for the Poor and Pro-poor Adaptation Finance: Ensuring Climate Justice and Sustainable Development

This section evaluates climate-resilient development (CRD) focussing on potential synergies between adaptation and mitigation in different sectors, decision making approaches and adaptation finance especially for the poor. It examines whether climate change response options, meaning mitigation and adaptation, in different development sectors, create development synergies or trade-offs for low-income households and people living in poverty.

The link between development and climate change was not evaluated comprehensively until the first decades of the twenty first century (Figure 8.13; Klein et al., 2005; Tol, 2005). Until recently mitigation and adaptation, the two primary approaches to climate action, have been dealt with separately in climate change science and policy (Landauer et al., 2015). Nevertheless, synergistic "co-benefits" between mitigation and adaptation may be enhanced, and trade-offs reduced, through the holistic empirical evaluation of actions for climate change response (Runhaar et al., 2018). The synergetic effect of mitigation and adaptation has been documented for a few interventions across the globe, however, evidence-based quantification of the synergies and trade-offs are rare.

Where co-benefits have emphasized identifying mitigation-adaptation synergies, a key turn has been evaluating Climate Compatible Development (CCD), 'development that minimises the harm caused by climate change impacts, while maximising the many human development opportunities presented by a low emission, more resilient future' (Mitchell and Maxwell, 2010). CCD calls for triple wins, resulting in synergies between mitigation-adaptation-development through single interventions (Figure 8.13; Ellis and Tschakert, 2019). Climate compatible development offers specific entry points for identifying ways on how to strengthen synergies between mitigation and adaptation particularly within the context of low income countries. Effective integration of emission reductions and accommodation actions for mitigation and adaptation can be win-win strategies and may be cost-efficient (Runhaar et al., 2018) and have the potential to create opportunities to foster sustainable development (Denton et al., 2014).

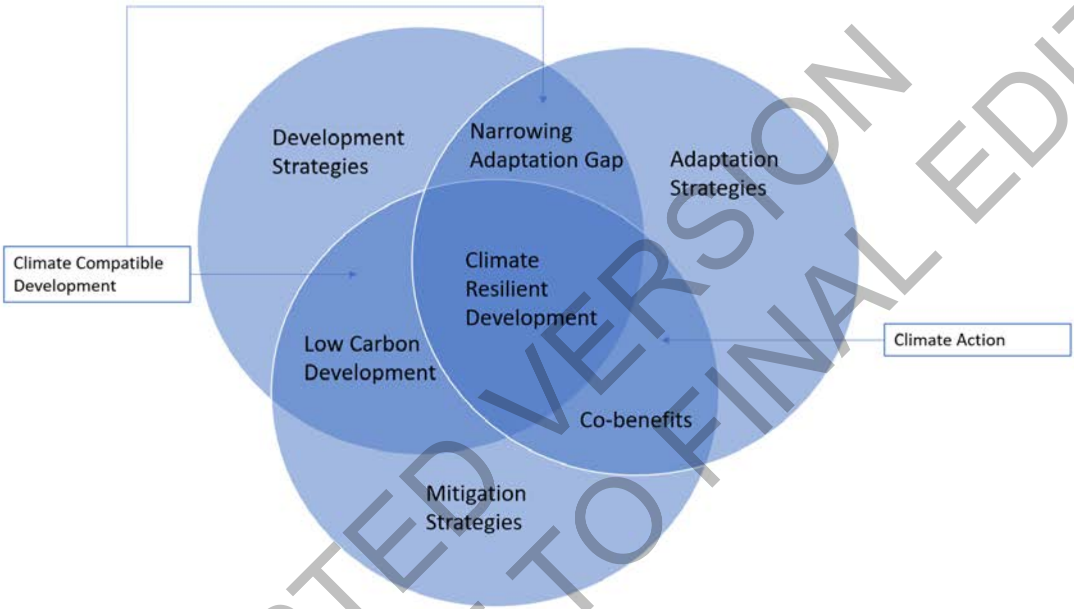


Figure 8.13: Climate Resilient Development (CRD). Actions and strategies consider both Climate Compatible Development and Climate Action.

This assessment identifies and evaluates approaches to Climate Resilient Development (CRD) "that deliberately adopt mitigation and adaptation measures to secure a safe climate, meet basic needs, eliminate poverty and enable equitable, just and sustainable development". The body of literature on the synergies and trade-offs between adaptation, mitigation, poverty, equity and sustainable development has grown steadily since the AR5 (IPCC, 2014a). The IPCC Special Report on the impacts of global warming of 1.5°C (IPCC, 2018c), suggests that 'Limiting warming to 1.5°C can be achieved synergistically with poverty alleviation and improved energy security and can provide large public health benefits through improved air quality, preventing millions of premature deaths'.

Implementing the integrative concept of CRD will likely produce transformative benefits affecting the poorest populations primarily (Roy et al., 2018; Leal Filho et al., 2019). The risks of transformative actions to the poor are diminished when undertaken in the context of good governance at multiple levels, within existing top-down and bottom-up processes, and making use of available levers of policy, technology, education and financial/economic systems (Stringer et al., 2020).

8.6.1 Synergies and trade-offs between adaptation and mitigation in different sectors with implications for poverty, livelihoods and sustainable development

8.6.1.1 Climate Resilient Development

Climate Resilient Development relies on identifying synergies between different strategies and actions in the field of climate change, primarily between mitigation actions with adaptation benefits (Locatelli et al., 2015), adaptation actions with mitigation benefits (Denton et al., 2014; Sánchez and Izzo, 2017), processes that promote both mitigation and adaptation measures, and policies and strategies that promote integrated mitigation and adaptation measures (Zhao et al., 2018). At the same time, adaptation and mitigation actions can be evaluated in terms of their co-benefits, the social, economic or other benefits of actions in addition to avoiding climate change impacts (Karlsson et al., 2020). The clearest co-benefits of mitigation are associated with economic development through low-carbon industrialization (IPCC, 2014c; Jakob et al., 2014; Lu, 2017). Co-benefits can include contributing to economic growth, reducing competition for resources, improved integration of scientific input to policy development and implementation, or improving political participation and social licensing in large-scale projects (e.g., hydropower) (Hennessey et al., 2017). Adaptation can support mitigation and contribute to co-benefits in various ways: ensuring development-based natural resource management (Denton et al., 2014; Suckall et al., 2015; Reang et al., 2021) , integrating water resources management (Liang et al., 2016; Sharifi, 2021), practicing sustainable agriculture (Bustamante et al., 2014; Duguma et al., 2014a; Di Gregorio et al., 2017; Reang et al., 2021), ensuring the protection of ecosystem services (Pandey et al., 2017a; Baumber et al., 2019), conserving biodiversity (Di Gregorio et al., 2017; Loboguerrero et al., 2019; Smith et al., 2019) and managing bioenergy resource (Dovie, 2019).

The key challenge for CRD is addressing climate change from the perspective of development: addressing the fundamental development obstacles that limit capacity for adaptation. Where development is not sustainable, especially if it is not equitable, capacity for adapting is greatly reduced—a phenomenon known as the adaptation gap (Figure 8.14; Birkmann et al., 2021a; UNEP, 2021). Figure 8.14 depicts the effect of development trajectories (as described in the Shared Socioeconomic Pathways framework) on capacity for adaptation, a key determinant of eventual outcomes. Achieving CRD through coupling adaptation with equitable sustainable development under and low emissions profiles that limit warming to 1.5°C (i.e., sustainability scenario) is necessary to close the adaptation gap. Even if emissions are kept low and 1.5°C emissions targets are achieved, if poverty and inequality remain high, then impacts are likely to remain high and may overwhelm capacity for adaptation. High poverty and high inequality in a society (i.e., inequality scenario) reduce the likelihood that countries are able to manage risk and avoid residual impacts, such as also documented in the assessment above (see Sections 8.2, 8.3, 8.4). Unsustainable development trajectories reduce capacity for adaptation and may result in highly unequally distributed residual impacts from climate change. Even despite rapid, equitable development and modest emissions reductions efforts necessary to limit warming to 2°C (i.e. the middle of the road scenario), there is still risk of unequal distribution of impacts. Under all high emissions scenarios (>3°C warming), universal residual impacts are unavoidable.

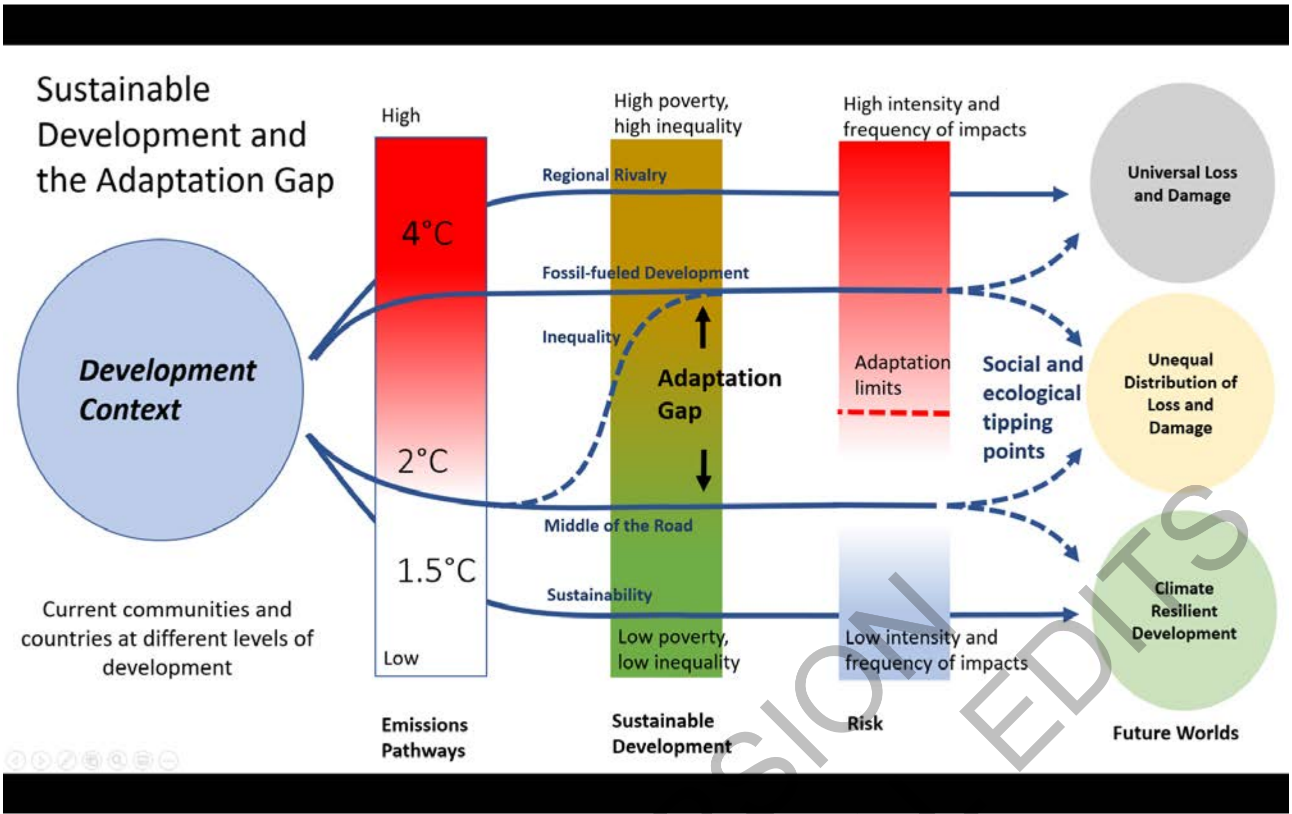


Figure 8.14: Conceptual figure illustrating the link between sustainable development and the adaptation gap. Even if emissions are kept low, if poverty and inequality remain high, then impacts are likely to remain high and may overwhelm capacity for adaptation.

Mitigation planning has not sufficiently considered poverty reduction policies, the basis for narrowing the adaptation gap (see also Figure 8.14). Many synergies between climate change mitigation and poverty reduction have been identified, although sometimes with *limited evidence*. The mitigation measures that have been most evaluated include clean development mechanisms (CDM), programs aimed at reduction of emissions from deforestation and forest degradation (REDD+), voluntary carbon offsets and biofuel production. However, while these mitigation programs stimulate economic growth, they may contribute to processes that trade-off against equitable development and threaten to further impoverish forest communities, such as large-scale land acquisitions (Carter et al., 2017; Schaafsma et al., 2021) and fortress conservation (see IPCC SR 1.5°C Chapter 5 (Roy et al., 2018) and see also Chapter 6 of this report).

The IPCC Special Report on Climate Change and Land (IPCC, 2019a) states that agriculture, food production and deforestation are major drivers of climate change and calls for coordinated action to tackle climate change that can simultaneously improve land, food security and nutrition, and help to end hunger. There are five land challenges identified including climate change mitigation, adaptation, desertification, land degradation and food security. This report identified three major categories of climate response options that show promise for achieving mitigation and increasing capacity for adaptation while addressing poverty: sustainable land management options, value chain management and risk management options (IPCC, 2019a). For example, programs supporting no-till agriculture and residue retention allows small-scale farmers to participate in mitigation and adaptation activities, with long-term benefits to soil health and food, energy and water security (Wright et al., 2014). Likewise, the installation of a solar powered drip irrigation system simultaneously reduces emission, improves water security and increases farmers' income; (Locatelli et al., 2015). Response options in terms of sustainable land management options, and value chain and risk management involves interlinkages between land-based climate strategies, synergies and trade-offs (see Chapter 6). On the other hand, a key trade-off for consideration CRD is the potential for maladaptation, where one adaptation intervention at one time, location or sector could increase the vulnerability at another time, location or sector, or increase the vulnerability of the target group to future climate change (*medium evidence, high agreement*) (Eriksen et al., 2011). A cause of increasing concern to adaptation planners, the understanding of maladaptation has changed subtly to recognize that it arises inadvertently, from poorly planned adaptation actions, but also from carefully deliberated decisions where wider considerations place greater emphasis on singular or short-term outcomes ahead of broader, longer-term threats, or that discount, or fail to consider, the full range of interactions arising from the planned actions across scales (Eriksen et al., 2021). Research identifies the challenge of avoiding maladaptation as one of reducing long-term structural vulnerability. Accordingly, one can consider that CCD and maladaptation as two sides of the same coin. Scholars of 'sustainable adaptation' define it as adaptation that contributes to socially and environmentally sustainable development pathways, which takes into account both social justice and environmental integrity (Eriksen et al., 2011). The parallels in maladaptation include the underlying drivers of vulnerability, namely socio-environmental processes such as conflict, marginalization, economic restructuring, exploitation, institutional fragility, etc (Antwi-Agyei et al., 2018b; Neef et al., 2018).

Harnessing opportunities for mitigation, adaptation and development in an effective manner may lead to 'triple-wins' under CRD, though empirical evidence is extremely rare for such 'triple-wins' strategies that address mitigation, adaptation and development in an effective manner (Tompkins et al., 2013). Integration of mitigation, adaptation and development is being initiated and operationalised through projects by several developing countries for achieving main national development priorities, such as poverty reduction, increased employment opportunities, energy security, transportation (Denton et al., 2014; Stringer et al., 2014). Important follow-on questions from that are pressing social questions about how trade-offs are deliberated, who wins and losses and who decides (see Section 8.4 and Ellis and Tschakert, 2019). Likewise, the efficiency, effectiveness and feasibility trade-offs of climate policies must be considered (i.e., can programs in developing countries be economically efficient and provide opportunities to achieve sustainable development targets for developing countries?) (Dang et al., 2003). Moreover, questions about co-benefits must consider the benefit-cost ratio of mitigative versus adaptive action for assets saved from destruction by climate impacts, for example (Stadelmann et al., 2014). Implementing a mitigation or adaptation option may affect positively or negatively, directly or indirectly, the feasibility and effectiveness of other options such as soil management leads to soil organic carbon (Locatelli et al., 2015; de Coninck et al., 2018). Farmers and local people are often also being encouraged to undertake mitigation and adaptation activities leading to long term benefits such as cultivation of no-till wheat with residue retention leading to low emission along with energy and water saving (Wright et al., 2014).

Moreover, regulatory structure for evaluation of mitigation and adaptation actions is required for understanding the co-benefits of these two actions such as choice of adaptation actions can be made according to their effectiveness per unit of money invested such as economic assets saved from destruction of climate change impacts and benefits can be evaluated in terms of economies, people, and the environment such as human lives and health protected contrary to the emission reduction by mitigation strategies (Stadelmann et al., 2014).

8.6.1.2. Climate Resilient Development Synergies and Trade-offs by Sector

Some sectors—such as agriculture, forestry, energy—are found to have more potential for CRD synergies than others, although trade-offs are also identified. Climate-smart agriculture, carbon-forestry programmes and the water-energy-climate nexus show trade-offs across levels and sectors with identified winners and losers (*high confidence*) (IPCC, 2018a). Mitigation can be designed to provide opportunities for enhanced adaptation with comparable co-benefits, even while adaptation portfolios can maximize co-benefits around sustainable resource management that reduce emissions (Dovie, 2019). Climate policy integration can be considered as the integration of multiple policy objectives, governance arrangements and policy processes of climate change mitigation and adaptation along with other policy domains (Di Gregorio et al., 2017) as well as sector policies integrating climate change adaptation and mitigation (England et al., 2018). Integrating climate policies may require balancing multiple sectoral goals, such as REDD+ projects, climate smart agriculture, water sector strategies, national policies on climate change and national conservation plans (Duguma et al., 2014a). Within the scientific discourse increasing attention is given to the question of the synergies and mismatches between mitigation and adaptation policies.

The assessed literature underscores that for synergies to be realized, mitigation and adaptation policies must be institutionally supported within a multi-level governance architecture (national to sub-national to municipal levels) with other priorities, and identify sustainable financing mechanisms within the country or via the international community (Dovie and Lwasa, 2017). Integrating and mainstreaming adaptation and mitigation across agencies within countries can bridge the divide between climate policy and sustainable development (Venema and Rehman, 2007).

The Paris Agreement recognized that the agreement will reflect equity and common but differentiated responsibilities (CBDR-RC) of national circumstances, (Voigt and Ferreira, 2016). The Paris Climate Agreement should be broadened to include mitigation co-benefits (Dovie, 2019). Integrating adaptation with mitigation may possibly contribute to amend or reduce the discursive rift between climate policy and sustainable development (Venema and Rehman, 2007).

Integrated climate change actions or responses can be inefficient and infeasible in the absence of enabling conditions, including the policy conditions that reinforce unified climate action, and sustainable financial mechanism for implementation of the programs and policies (Duguma et al., 2014b). In the absence of strong coordination, integrating mitigation and adaptation may undermine the overall or individual objectives of either climate response (Kongsager, 2018). A lack of coordination in mitigation and adaptation may also exacerbate the threats of climate change to sustainable development (Ayers and Huq, 2009; Kongsager, 2018). Therefore, for successful integration of CRD, it is necessary to move beyond considering either adaptation or mitigation towards better understanding the linkages between adaptation and mitigation projects and policies at multiple levels of governance, to identify potential trade-offs in projects and policies (Suckall et al., 2015) and to identify the enabling conditions for designing and implementing action leading to synergies (Denton et al., 2014; Kongsager, 2018).

Despite the potential effectiveness and efficiency of integrating mitigation and adaptation under a common CRD framework, gaps persist in our knowledge about the enabling conditions for synergies, due to the limited number of examples and even fewer evaluations. Potential benefits may be achieved by pursuing multi-level governance approaches, that means integrating decision-making at the local level with coordination at other levels, by actors and agencies simultaneously pursuing multiple other priorities (see Section 8.5.2 Shaw et al., 2014). For example, pursuing climate-resilient land-use pathways integrating climate policy within the land use sector requires a governance policy environment that combines multiple policy aims, including urban growth, soil conservation and water management alongside mitigation and adaptation. Facilitating climate resilient land use pathways combining the aims of climate change adaptation, mitigation and sustainable development requires a governance environment requires: i) internal climate policy coherence between mitigation and adaptation objectives and policies; ii) external climate policy coherence between climate change and development objectives; iii) vertical policy integration that to mainstreams climate change into sectoral policies; and; iv) overarching governance structures that facilitate horizontal policy integration cross-sectoral coordination by overarching governance structures for cross-sectoral coordination (Di Gregorio et al., 2017) as well as sector policies integrating climate change adaptation and mitigation (England et al., 2018).

Within sector policies and economic sectors (such as land-use, transportation, and technology) mitigation and adaptation have many positive, negative, direct and indirect linkages within and beyond the sector (Locatelli et al., 2015). The land-use sector, for example, includes agriculture and forestry and encompasses the management of a mosaic of interacting urban environments and ecosystems with a diversity of cultural and institutional attributes (Locatelli et al., 2015). The land-use sector is key to climate adaptation, where policy coordination can enhance food production, regulate urban microclimates, affect water security, and, in the case of mangroves, buffer the impacts of extreme climate events in coastal areas (Locatelli et al., 2015). City-level actions can also be pivotal for reduction in emissions and improvement in resilience (UCLG, 2015) such as zoning and planning that promotes green development and green and efficient energy use. Urban planning and transport policies are crucial to support a transition towards a low-carbon and resilient future (Ford et al., 2018) such as means of transportation as public and private transport facilities are crucial for emission reduction.

CRD may require multi-sectoral coordination, including public-private partnerships (Campbell et al., 2018). In the food system, for example, under a CRD framework transformative actions may require (1) incentives for expanded private sector activities and/or public-private partnerships; (2) publicly-backed credit and/or insurance; (3) public institutional support for strong local organisations and networking; (4) climate-informed weather advisories and early warning systems; (5) digital investments in technological transformation for agriculture (e.g., “digital agriculture” and virtual markets); (6) investments in climate-resilient and low-emission practices and technologies (Duguma et al., 2014b); (7) prioritisation and pathways of change; (8) capacity and enabling policy and institutions are crucial with careful consideration of trade-offs between adaptation and mitigation, and amongst other SDGs for achieving SDG13 'urgent action to combat climate change and its impacts' (Campbell et al., 2018). Moreover, the risks of transformative actions to the farmers is addressed by strong good governance at multiple levels, combining top-down and bottom-up processes along with by a mix of levers that combine policy, technology, education and awareness-raising, dietary shifts and financial/economic mechanisms, attending to multiple time dimensions (Stringer et al., 2020).

8.6.1.2.1 Agriculture and food production

Integrated CRD approaches in agriculture, such as climate smart agriculture (CSA), can reduce trade-offs and exploit synergies with biodiversity and food security to reduce the risk of climate change (Di Gregorio et al., 2017; Loboguerrero et al., 2019). There are many technologies and approaches in agriculture that leverage synergies relevant for CRD, including agroecology (Pandey et al., 2017a; Saj et al., 2017), climate smart agriculture (CSA), climate smart landscapes, organic agriculture mitigating climate change, conservation agriculture, ecological intensification and sustainable intensifications, which in many cases aim to address both adaptation and mitigation to climate change simultaneously (Kongsager, 2018). From these approaches, a number of scalable agriculture technologies have emerged that simultaneously achieve mitigation and adaptation goals, such as reducing water consumption while maintaining grain yield, including alternate wetting and drying (AWD) irrigation technology (Liang et al., 2016) and aerobic rice production (Wichelns, 2016). Likewise, a number of these approaches have been supported within international and national institutional frameworks (e.g., through incentives) to harness synergies (Kongsager et al., 2016).

Climate-smart agriculture (CSA) is discussed in the scientific literature as an approach that could transform agricultural production systems and food value chains in line with sustainable development and food security under climate change. However, concerns and critique have been raised, such as the insufficient consideration of the access to entitlements within CSA and the question who wins and loses when applying CSA in different country contexts (see Karlsson et al., 2017; Sain et al., 2017). CSA has three main objectives: sustainably increase agricultural productivity and incomes; adapt and build resilience to climate change and reduce and/or remove greenhouse gas emissions (FAO, 2017). Various CSA technologies are capable of improving crop yields, increasing net income, increasing input use efficiencies and reducing emissions (Khatri-Chhetri et al., 2017). However, up-take and adoption of CSA by local farmers in poor developing countries remains a challenge (Palanisami et al., 2015) due to the difficulty of identifying and prioritising of technologies suiting local climate risks and accommodating the farming practices of locals (Dougill et al., 2017; Khatri-Chhetri et al., 2017). An analysis of CSA implementation in Mali, for example, identified major challenges to policy makers' efforts to adopt CSA, including difficulties identifying CSA options and portfolios, valuing them, and prioritizing investments (Andrieu et al., 2017).

Potential opportunities from CSA may also result from Integration of "technological packages" (Totin et al., 2018), which include new market structures; knowledge infrastructure and agriculture extension services; and capacity building programs (Dougill et al., 2017; Totin et al., 2018); institutional support for key enabling programs, such as crop insurance, agro-advisories and rainwater harvesting (Khatri-Chhetri et al., 2017). CSA is able—if carefully designed—to achieve transformative "triple wins" for climate and development when it is accompanied by new governance architectures that are socially inclusive and respectful of traditions and livelihoods, and accommodate traditional institutions that underpin the bargaining power of the poorest and most vulnerable groups (Karlsson et al., 2017).

Conservation Agriculture (CA), another framework for achieving CRD, is based on three synergistic principles: a) soil management to reduce soil physical disturbance and reduce its degradation; b) crop management such as residue management to protect the soil top layers; and c) genetic management to increase agricultural systems' biodiversity and in consequences their resilience (DeLonge and Basche, 2017). In the cereal systems of the Indo-Gangetic Plains, India, Conservation Agriculture has increased crop yields, returns from crop cultivation, input-use efficiency, in spite of heat stress even while reducing GHGs emissions (Sapkota et al., 2015). However, also challenges with CA are documented in the scientific literature. For example, an evaluation of CA in Malawi noted that adoption of CA was challenged by weak integration of CA in agricultural policies; lack of institutional arrangements of promoters; and farmers' experiences (Chinseu et al., 2019).

Locally appropriate agroecological practices have clear potential to increase the resilience of livelihoods and enhance adaptation to climate change at field and farm levels across a wide range of contexts, often with significant mitigation co-benefits (Sinclair et al., 2019). Relatedly, agroforestry systems are the intentional integration of trees and shrubs into crop and animal production systems to solve societal challenges including climate change (Raymond et al., 2017). For example, in the tropics, such systems offer viable opportunities to mitigate and adapt to climate change for farmers through transforming into resilient farming systems and improving farm economy while securing environmental benefits to local and global communities (Swamy and Tewari, 2017). In Western Africa, the high plant functional diversity of agroforestry systems with a mix of trees and crops having different roles, such as shade provision, soil fertilization, fruit production, or timber value, maximises benefits and allows alternative adaptation strategies (Tschora and Cherubini, 2020). In spite of various benefits of agroforestry, the expansion of existing areas of agroforestry and the establishment of new agroforestry systems has remained limited (Martineau et al., 2016), mainly due to a lack of institutional supports, a lack of expert support to ensure adequate management, weak capacity for monitoring and regulation, and a lack of financial support (Hernández-Morcillo et al., 2018).

The enabling conditions for the expansion of agroforestry include training and expert support programmes for managers and sharing of best practices (Ashraf et al., 2015; Hernández-Morcillo et al., 2018; Tschora and Cherubini, 2020). Other scalable frameworks integrating food and agriculture within CRD include Sustainable Intensification (SI), which emphasizes sustainable practices to safeguard sustainable use of natural resources, and meet the growing demand for agricultural production, even while building resilience (Thierfelder et al., 2018). Integrated Agricultural Systems (IAS) aim to increase farm diversity and lower reliance on external inputs, enhancing nutrient cycling and increasing natural resource use efficiency (Smith et al., 2017), and may have the potential to enhance resilience against climate change impacts and risks (Gil et al., 2017). Policy frameworks that aim to integrate any of these approaches climate actions must account for the costs associated throughout the up-take and adoption process (Gil et al., 2017).

8.6.1.2.2 Livestock

As the consumption of animal protein and products rises along with global standards of living, CRD will require transformations in livestock-centred livelihoods. Livestock are a key contributor to global food security especially in marginal lands where animal products are a unique source of energy, protein and micronutrients (FAO, 2017; IPCC, 2019a), but also contribute disproportionately to the total annual anthropogenic GHG emissions globally and influence climate through land use change, processing and transport by emitting CO2; animal production by increasing methane emissions; and feed production, manure by emitting CO2, nitrous oxide, and methane, (Rojas-Downing et al., 2017). Mitigation of livestock emissions can be achieved by implementation of various technologies and practices such as improving diets to reduce enteric fermentation, improving manure management, improvement in animal nutrition and genetics (Rojas-Downing et al., 2017); altering land use for grazing and feed production, feeding practices, manure treatment and herd size reduction (Zhang et al., 2017). Adaptation strategies in the livestock sector include changes in animal feeding, genetic manipulation, alterations in species and/or breeds (Zhang et al., 2017); shifting to mixed crop-livestock systems (Rojas-Downing et al., 2017), production and management system modifications, breeding strategies, institutional and policy changes, science and technology advances, and changing farmers' perception and adaptive capacity (USDA, 2013).

Policies supporting sustainable rangeland management and the livelihood strategies of rangeland users have an outsized influence on both development and climate action (Gharibvand et al., 2015). Climate change adaptation, mitigation practices and livestock production can be supported by policies that encourage diversification of livestock animals (within species), support sustainable foraging and feed varieties (Rivera-Ferre et al., 2016), strengthen institutions such as agricultural support programs, markets and intra- and inter-regional trade (Zhang et al., 2017). For example, sustainable pastoralism can contribute to mitigation both by increasing carbon sequestration through improved soil management and by reducing methane emissions through changing the mix and distribution of the herd. Likewise sustainable pastoralism can also contribute to adaptation by changing grazing management, introducing alternative livestock breeds, pest management, and modified production structures (Joyce et al., 2013). Another example of rangeland adaptation is diversifying the use of rangelands such as supplementing with payments for ecosystem services, carbon sequestration, tourism or supplementary assistance for all land based activities (Gharibvand et al., 2015). However, challenges for climate smart livestock production systems remain due to a lack of information, limited access to technology and insufficient capital (FAO, 2017). Small-holders in cropping and livestock systems in Saharan Africa and South Asia, for example, face obstacles obtaining climate change mitigation and adaptation synergies due to poor access to markets and relevant knowledge, land tenure insecurity and the common property status of most grazing resources (Descheemaeker et al., 2016). Consequently, the appropriateness of these strategies and measures need to be further evaluated, particularly in terms of their usefulness for the poor and most vulnerable.

Different farming and pastoral systems can achieve reductions in the emissions intensity of livestock products. Depending on the farming and pastoral systems and level of development, reductions in the emissions intensity of livestock products may lead to absolute reductions in GHG emissions (IPCC, 2019a) (*medium confidence*). Significant synergies exist between adaptation and mitigation, for example, through sustainable land management approaches (*high confidence*). {4.8, 5.3.3, 5.5.1, 5.6}.

8.6.1.2.3 Forestry

Forests can support CRD in rural communities and households: they support consumption of energy, food and fibre; provide a safety net in cases of shocks; fill gaps during seasonal shortfalls; and are a means to accumulate assets and provide support to emerge out of poverty (Angelsen et al., 2014; Adams et al., 2020). Forest ecosystems are an essential element of climate change mitigation and adaptation, with the potential for synergy and conflict between the two climate action objectives (Morecroft et al., 2019). However, there are varied perspectives on the role of the forests, with some treating conservation and forest management practices as a barrier to livelihood resilience (Few et al., 2017) despite the broader role of forest management in climate mitigation (Houghton, 2012).

Forestry mitigation projects such as forest conservation, reduced deforestation, protected area management and sustainable forest management, can promote adaptation and can also have consequences for the development objectives of other sectors (for example, expansion of farmland) (Smith et al., 2014). REDD+ (reducing emissions from deforestation and forest degradation and fostering conservation, sustainable management of forest and enhancement of carbon stocks) is a payment programmes and may provide adaptation benefits by enhancing households' economic resilience (Sills et al., 2014; Duchelle et al., 2018) and also produce positive livelihood impacts through the employment benefits of supporting conservation and sustainable management of forests (Caplow et al., 2011). Furthermore, the management of ecosystem services may contribute to both mitigation and adaptation. For example, REDD+ projects, such as mangrove conservation and restoration simultaneously contribute to carbon storage and diversification of incomes and economic activities. At the same time, mangroves protect coastal areas against flooding and hydrological variations, improving capacity for adaptation in local livelihoods (Locatelli et al., 2016).

However, while studies of existing REDD+ programs noted the moderately encouraging impacts for mitigation and small or insignificant impacts for adaptation options (especially well-being), they underscored the potentially damaging impacts to local livelihoods (Milne et al., 2019; Skutsch and Turnhout, 2020) and suggested improved engagement with local communities, increased funding to strengthen the interventions on the ground, and more attention to both mitigation and adaptation outcomes in implementation for achieving the benefits of REDD+ program (Duchelle et al., 2018). Moreover, to effectively counter local threats to forests and biodiversity and attain positive biodiversity and development outcomes, REDD+ programs must be focused on better institutional support for governance, coordinating interventions and monitoring of plans, as well as making explicit linkages between REDD+ activities and national biodiversity conservation efforts (Panfil and Harvey, 2016) and assuring a fair distribution of benefits to local communities (Myers et al., 2018). An analysis of country-specific REDD+ programs in Cameroon for synergistic approaches to REDD+ with other national goals such as poverty reduction identifies two principal modes of strategic interaction management among actors. The first prioritizes relates to specific structures for designing REDD+ giving high priority to social safeguards, and the second relates to programming that builds trust, communication and confidence of participants creating an environment for enabling management through commitment and behavioural interaction by creating an overarching institutional framework and unilateral management (Somorin et al., 2016).

To achieve CRD, forestry conservation strategies need to be driven by climate action and forest management policies that benefit both ecological and human systems, and above all, involve forest communities in program and project implementation (Cordeiro-Beduschi, 2020). Synergies between mitigation and adaptation of the forestry sector can be enhanced by considering on-the-ground contexts of constraints and social trade-offs that may undermine implemented actions (Few et al., 2017). However, the lack of knowledge about trade-offs and synergies at the local level and between local and global scales makes this challenging.

Despite these constraints, forestry can serve as a foundation for CRD when adaptation and mitigation activities are effectively integrated from the stage of policy formulation with consideration of specific institutional structures and procedures that can assist to facilitate such integration (Locatelli et al., 2015). Effectively integrated adaptation and mitigation activities can be achieved by encouraging collaboration between the two activities, promoting research on the impacts of the integrated activities, their cost-effectiveness and their synergies within the complex setting of risks and uncertainty concerning the magnitude of climate change impacts (Bakkegaard et al., 2016), along with facilitating participation of communities in the two activities and defining forest policies (Ngum et al., 2019). Moreover, international donors and funds are also critical to guide countries to identify adaptation-mitigation synergies, through consultation processes, dialogue and awareness raising (Locatelli et al., 2016). Moreover, in order to be effective, nature-based climate solutions such as mixed species plantation, forest expansion and REDD+, must be people-centric and respond to the needs of the rural and Indigenous Peoples who manage ecosystems for their livelihoods while supporting at the same time the biodiversity of the ecosystems (Temperton et al., 2019; Fleischman et al., 2020).

8.6.1.2.4 Energy

The continued dependence on fossil energy sources for economic development is the primary source of increasing GHGs (Hansen et al., 2017). There is an emerging agreement in terms of the importance of the bioenergy sector for climate change mitigation (Jackson et al., 2016; Hansen et al., 2017), however, the options and limitations in terms of transforming the energy systems to support both mitigation and adaptation are still contested.

About 1 billion people globally (12.5% of the world's population) do not have access to electricity (World Bank, 2021), and yet access to electricity is required for basic adaptation strategies, such as the use of air conditioning and fans in homes and working spaces to mitigate heat stress and enable healthier lives, daytime activities, and night-time sleep quality. Electrification enables farmers to mechanically pump water from the underground to boost agricultural productivity, stabilise yields and make food security less reliant on erratic rainfall patterns and less vulnerable to dry spells. Access to electricity enables the spread of valuable information through television, radio, computers, and smartphones, including weather forecasts and disasters prevention and response (Dagnachew et al., 2018). The increasing access to electricity facilitates the SDG 7 coupled with other SDGs and societal goals, including mitigation of climate change (van Vuuren et al., 2018) through reducing energy consumption by the use of efficient technology and appliances. Electricity access can be an important enabler of adaptation action for different purposes in different sectors (Mastrucci et al., 2019).

Low-carbon development strategies can also be compatible with ecological sustainability, as proponents of bioenergy have claimed. Bioenergy can contribute to reducing emissions and energy inefficiencies in agricultural food and bioenergy sectors, even while safeguarding food and energy security. However, recent literature also points towards significant tensions and mismatches between increasing bioenergy on agricultural land and local livelihoods and food security (Yildiz, 2019). A growing list of studies have documented the detrimental trade-offs between small-holder food systems and large-scale biofuel production, which include dispossession and impoverishment of small-holder farmers, food insecurity, food shortages, and social instability (Hunsberger et al., 2017). Nevertheless, synergies between bioenergy and food security can be promoted by integrated resource management designed to improve both food and water security and access to bioenergy; investments in technology, rural extension, promotion of stable prices to incentivize local production; use of double cropping and flex crops that provide food and energy (Souza et al., 2017).

Trade-offs of bioenergy can be minimised by replacing land-intensive first generation biofuels (e.g., oil palm) with second and subsequent generations (e.g., microalgae). However, there are costs of relying on 'sustainable biofuels' as most of the agricultural and non-agricultural land would be needed for cultivation of biofuels along with reduction in pattern of energy consumption as well as attainment to a significant reduction in population (Gomiero, 2015). Contrasting impacts on environmental, economic and social sustainability are reported for production and use of biofuels (Azapagic and Perdan, 2011) ranging from positive impacts such as reduction in GHG emissions, energy security and rural development and negative impacts such as risk of increase of food prices, the risk of increase in GHG emissions through direct and indirect land-use change from production of biofuel feedstocks, as well as the risks of degradation of land, forests, water resources and ecosystems (UNEP, 2009). Biofuel production may cause loss of biodiversity (Jeswani et al., 2020) and may also impact on various ecosystem services, such as land, water and food, however biofuel production and use may pollute air, water and soil (Scovronick and Wilkinson, 2014). The collective benefits of biofuels may be realized by developing future policies based on integrated systems view with clear understanding about the interactions across sectors and land uses by analysing complete value chains (Jeswani et al., 2020).

Clean sources of energy such as solar and wind can facilitate both mitigation and adaptation. For example, in South Africa, clean sources of energy provide energy security with huge water savings along with creation of employment, proximity to point-of-use and, in many cases, less reliance on concentrated sources of energy (Mpandeli et al., 2018). Overall, the increased use of thermal solar panels contributes to reducing GHG emissions and improves air quality as well as providing benefits to the community and the environment. The differential adoption of solar panels can be managed by simultaneous investment in other technologies that utilize renewable energy along with investment in solar panels (Kaya et al., 2019). Development of a smart electricity grid connected to a renewable energy source reduces GHG emissions and decreases vulnerability to climate change by enhancing response to changing conditions and providing more reliable service to the population (Hennessey et al., 2017). Moreover, in the policy development for a low-carbon and climate resilient power system, a local nexus between mitigation and adaptation can be explored (Handayani et al., 2020). For example, use of efficient fuel in urban areas facilitates air pollution reduction and also provides health benefits for urban populations (Ramaswami et al., 2017). Green buildings substantially reduce energy consumption and also improve indoor environmental quality and thus contribute to mitigation and provide societal value in terms of health (MacNaughton et al., 2018). Besides, green roofed building contributes to keeping local temperatures cooler during the hot days and thereby reducing energy use for air-conditioning and thus contributing to both mitigation and adaptation (Sharma et al., 2016).

Positive synergies between adaptation and mitigation in the energy sector can include changes in production technologies and utilization of technologies by various industries, change in consumer or corporate behaviour, and the development of policies that alter the energy sector activities sufficiently to achieve a combination of reduced GHGs emissions and increased benefits for communities (Morand et al., 2015). However, the policy perspective must be based on the country circumstances, especially urbanization, economic growth and energy consumption matching with the income level of the country (Wang et al., 2018).

8.6.2 Decision making approaches for Climate Resilient Development

A range of different traditional economic decision support tools can be used to help guide resource allocation in relation to climate change adaptation (e.g., cost benefit analysis, cost-effectiveness analysis, multi criteria analysis) (Watkiss et al., 2016), with a strong focus on monetary values and the present and near-term. There are also tools to assess uncertainty (e.g., iterative risk management) and to guide decision making under uncertainty over longer time frames (through e.g., real options analysis, robust decision making involving substantial numbers of scenarios, portfolio analysis and rule based decision support for uncertainty where maximum regrets are minimised). Use of these tools nevertheless requires human capital and skills and more commonly they are applied to public rather than private (individual/ household) adaptation decision processes. Tools grounded in economics can lack sufficient consideration of which groups in society might gain and lose out from particular options (Sovacool et al., 2015; Stringer et al., 2019), neglecting to appreciate non-monetary factors (like wellbeing) which are non-economic, less tangible and harder to put a value on (see Section 8.3).

This section lists several groups of the strategies, ranging from mainstreaming and coherence, to dealing with the complexities through broader and innovative governance and scale, to provision of funding and the associated cost and benefit analysis, through focussing on the community and addressing underlying equity through transformational adaptation.

8.6.2.1 Policy coherence, policy integration and broader governance approaches

Mainstreaming and policy coherence is one of the most proposed strategies in dealing with adaptation and mitigation as a coherent approach, in the context of good governance. Politics, power and interests influence the prospects of achieving integrated climate policy and development goals in practice (Naess et al., 2015). Institutional incoherence has led to inefficiency and ineffectiveness (Di Gregorio et al., 2017). To achieve more coherent institutions and synergies, four major enabling conditions have been identified: (1) planned and/or existing national laws, policies and strategies; (2) existing and planned financial means and measures; (3) institutional arrangements in the country with specific reference to climate change issues; and (4) planned and/or existing plans, programmes and initiatives in the country (Kabisch et al., 2016). Another strategy offered is to develop a 'dual track approach' at local/municipality/city level through having a local climate plan and/or mainstreaming plan (Duguma et al., 2014b). This can lead to effective implementation of climate actions and diffusion of climate issues into local sector policies (Reckien et al., 2019). Effective climate policy integration (CPI) calls for four ways of coherence (Di Gregorio et al., 2017), namely between internal coherence (mitigation and adaptation policies objectives and policies), external coherence (climate change and development objectives), vertical integration (mainstream climate change into sectoral policies) and horizontal integration (overarching governance structures for cross-sectoral coordination).

Progress of policy integration varies from the global to local level. Progress in mainstreaming and coherence is emerging globally and has slowly made it down to the national level (Di Gregorio et al., 2017). Adaptation and mitigation should be mainstreamed into planning and implementation on food security programmes, and cross-cutting oversights are required to integrate land restoration, climate policy, food security and disaster risk management into a coherent policy framework (Woolf et al., 2015).

There has been an increase in the literature examining adaptation and mitigation synergy in the Nationally Determined Contributions (NDCs) submitted by countries to the UNFCCC. Agriculture and energy are the two priority sectors for which there have been significant pledges and commitments from countries, with, to some extent, good alignment between adaptation and mitigation. This alignment can provide good opportunities to integrate both into national sectoral policies (Antwi-Agyei et al., 2018a). This suggests that inclusive and sustainable economic and social development can be achieved if national governments focus on developing coherent, cross-sector approaches that deliver potential triple wins of mitigation, adaptation and development.

Different governance approaches such as polycentric governance, adaptive governance, multi-level governance, collaborative governance, or network governance are increasingly utilised to understand the processes of transitioning towards CRD. The potential of polycentric governance approaches for promoting both climate mitigation and adaptation is well established (Cole, 2015; Abbott, 2017; Morrison et al., 2017a; Warner et al., 2018). Polycentric governance deals with active steering of local, regional, national, and international actors and instigates learning from experience across multiple actors, levels of decision-making, and temporal scales (Ostrom, 2010). It is the source of power to achieve collective goals. Polycentric actors have the framing power, power by design and pragmatic power (Morrison et al., 2017b). It offers new opportunities for climate action through more opportunities for communication, trust-building, policy experimentation and learning (Cole, 2015). Adaptive governance is understood as various interactions between actors, networks, organizations, and institutions toward achieving a desired state of social-ecological systems (Chaffin et al., 2014). It requires a structure of nested institutions, diversity at different levels, connected by formal and informal social networks (Dietz et al., 2003). As Brunner and Lynch (2010) observe, the emergence of community-based initiatives in addressing climate change marks the emergence of adaptive governance.

8.6.2.2 The water-energy-food-nexus approach

Increasing demands for water, energy, food and materials are putting pressure on resource supply, and hence the nexus approach can inform transition pathways for interlinked resource systems (Johnson et al., 2019). Nexus approach, especially the water-energy-food nexus, is used to examine synergies and trade-offs between adaptation and mitigation (Howells and Rogner, 2014). As reviewed by (Wiegleb and Bruns, 2018), early use of the concept was by the World Economic Forum in 2008 where it was emphasised that issues of economic growth need to be considered within water, energy and food resource systems. This was later published as Water Security: The Water-Food-Energy-Climate Nexus. Another key activity was the Bonn2011 Nexus conference. Then in 2015, The Nexus Dialogue Programme was held by the UN and EU Commissions as an approach to implement the SDGs. UN Water underscores the water-food-energy nexus as central to development (Newell et al., 2019). It notes that demand for water, food and energy are rising due to a growing population, rapid urbanisation, changing diets and economic growth, and in most cases, the lack of knowledge on water-food-energy nexus has often led to mismatches in prioritization and decision-making which hinders sustainable development (Mitra et al., 2020). It is important to note, however, benefits of nexus approach are not always easily quantified and often accrue to local communities over time (Amjath-Babu et al., 2019).

A well-coordinated and integrated nexus approach offers opportunities to build resilient systems while harmonising interventions, mitigating trade-offs and hence improving sustainability (Biggs et al., 2015). This can be achieved through greater resource mobilisation and coordination, policy convergence across sectors, and targeting nexus points in the broader landscape (Mpandeli et al., 2018). Studies utilizing the nexus approach to climate change in different places show considerably different results. In the Southern African Region, climate change is already affecting water-energy-food resources and exerting further pressure on already scarce resources. It is proposed that adaptation can be achieved through cross-sectoral management of resources, by adopting water management practices, by aiming to produce more food and energy with less water resources, and through the adoption of cleaner and renewable sources of energy resulting in saving water and ensuring energy security in a region that depends on hydro and coal energy sources (Mpandeli et al., 2018). A study in developing Asian countries (Bangladesh, India and Vietnam), found following factors inhibit ability to govern the nexus consideration (i) absence of institutional coordination; (ii) influence of political priorities on decisions rather than use of scientific knowledge to shape the decisions; (iii) lack of capacity to understand interlinkages between sectors; (iv) lack of multi-stakeholder engagement in planning and decision-making processes; and (v) lack of incentive mechanisms and adequate finance to support the approach` (Bao et al., 2018). Applying the nexus approach on the Hindu-Kush Himalayan region identified three challenges: increasing population and declining agricultural land, stagnating or declining food production, and increasingly water and energy intensive food production despite water and energy scarcity (Rasul and Sharma, 2016). Nexus smart adaptation policies need to be complemented with system-wide adaptation, policy coherence and sectoral coordination, and targeting poverty and vulnerability linkages (Rasul and Sharma, 2016).

8.6.2.3 Community-based approach

Another important strategy to better determine impacts of adaptation and mitigation and promote inclusivity, ensure transparency and accountability is a community based approach. This approach also supports adaptation and mitigation indirectly through the strengthening of capacity and social capital. For example, in Bangkalan, Indonesia, the presence of high social capacity and readily available free agricultural inputs are the two decisive factors for effective climate change mitigation and adaptation as well as enhancing community livelihood (Sunkar and Santosa, 2018). The calls for considering Indigenous Knowledge and Indigenous People to support integrated strategies in adaptation and mitigation are increasing (Ford et al., 2016; Altieri and Nicholls, 2017; Brugnach et al., 2017). Detailed knowledge of local socio-ecological contexts may offer transformational processes to harness synergies (Thornton and Comberti, 2017). A study in the Ukraine on cooperatives shows that it offers a well-established livelihood strategy and means to support agriculture small holders. Moreover, social capital fulfils key roles in the process of capacity building and implementation of sustainable measures (Kopytko, 2018). In Indonesia, a well-known program focussing on community-led adaptation and mitigation activities is Proklim. It empowers communities to learn about climate change impacts, record data and plan actions for climate change (Muttaqin and Yulianti, 2019). Multi-stakeholder, participatory planning processes are beneficial to help farmers to screen and prioritise rural livelihood strategies in Indonesia. The necessity of CRD is reflected in standard development interventions: water management, intensification and diversification of agriculture and aquaculture, education, health, food security and skill building for farmers (Wise et al., 2016).

8.6.3. Future adaptation finance and social and economic changes within the context of poverty, livelihoods, equity, equality and justice

8.6.3.1 Coverage of adaptation finance

There is still some debate on what qualifies as adaptation finance and how such finance should be measured (UNFCCC, 2016). According to the Climate Policy Initiative, adaptation finance is 'finance with the aim of improving preparation and reducing climate-related risk and damage, for both human and natural systems, as short-term climate impacts will continue to exact economic, social, and environmental costs even if appropriate mitigation actions are taken.' (CPI, 2019). According to UNEP, the annual costs of adaptation in developing countries could range from $140 billion to $300 billion by 2030. Globally, adaptation costs are estimated to be even greater, with up to $500 billion per year by 2050 under a business-as-usual scenario (UNEP, 2021). While global climate finance flows reached $579 billion on average over the 2017/18 period, there has been a continued heavy imbalance in favour of mitigation finance, with adaptation finance totalling around $30 billion (compared to $532 billion for mitigation), or five percent of tracked climate finance. The World Bank has however, committed itself to increase direct adaptation finance to $50 billion over the 2020-25 period, putting the Bank's adaptation finance in developing countries on par with its mitigation investments (World Bank, 2019a). Adaptation finance is also growing alongside finance for actions with both mitigation and adaptation benefits, for example in forestry or agriculture, which rose to just over $12 billion (CPI, 2019), as well as increasing focus on adaptation and cross-sectoral projects. Looking only at climate finance flows from developed to developing countries, the OECD estimates a total of $78.9 billion mobilised in 2018, with mitigation accounting for 70 percent ($55 billion) of the total, adaptation 21 percent ($16.8 billion) and cross-cutting finance making up the remainder(OECD, 2020a).

Adaptation finance funds actions to adapt to the impacts of climate change, yet such actions are heavily context-, scale- and time-specific. Many mitigation actions in the energy sector can be easily quantified and employed across different jurisdictions. For example, solar photovoltaic (PV) presents an established way across a multitude of countries to produce low-carbon energy at a profit and reduce global GHG emissions. Adaptation needs, however, vary greatly from location to location and short-term solutions, for example investments in irrigation technologies to improve water availability for specific crops in a growing season, may differ from longer-term solutions, for example switching to different crops altogether. Benefits are not always easily quantified and often accrue to local communities over time rather than to investors looking for the kind of returns realised in mitigation actions.

Development finance institutions (DFIs) mainly draw on market-rate loans and, to a lesser extent, concessional lending and grants to finance adaptation actions. There are regional differences in the choice of instruments, too, owing to the degree of economic development: while most of the adaptation finance flowing to the Asia-Pacific is market-rate debt, the vast majority of adaptation finance flowing to sub-Saharan Africa is in the form of concessional debt or grants (Richmond et al., 2020).

Globally, the main sectors benefiting from adaptation finance to date include water and waste water management; agriculture, forestry, land use, and natural resource management; disaster risk management; and infrastructure, energy, and other built environment (Oliver et al., 2018). In recent years, this finance has moved away from a concentration on water and wastewater management to spread out more evenly across the sectors. Between 2015/16 and 2017/18, investment in water and wastewater management dropped from $11 billion to $9 billion, while investment in agriculture, forestry, land use and natural resource management grew from $5 billion to $7 billion, and investment in disaster risk management more than doubled from $3 billion to $7 billion (CPI, 2019). In addition, while mitigation actions are more easily delineated, for example wind farms in the energy sector, adaptation measures often need to be mainstreamed across a number of sectors and investment decisions.

There are strong interconnections between nature-based solutions, climate adaptation and mitigation actions. Ecosystem-based adaptation is a nature-based solution that uses ecosystem services to help communities adapt to climate change. Examples of such approaches were covered in Section 8.5.2.2. For example, mangrove restoration provides both climate mitigation (as carbon sinks) and adaptation to climate change (increasing the resilience of coastal communities) while also supporting the implementation of a range of other SDGs (for example through increased food security). Research has found that without mangroves, global flood damage costs would increase by more than $65 billion a year (Menéndez et al., 2020). There is, therefore, an urgent need to invest in a range of nature-based solutions.

[START BOX 8.9 HERE]

Box 8.9: Adaptation Fnancing for the Poor and the Need for Systems Transition: Eastern Indonesian Islands

Summary

A 4-year project in Nusa Tenggara Barat Province, Indonesia, aimed to stimulate an adaptation pathways process. The goal was to support climate resilient development in a context with low stakeholder capacity, high poverty, and rapid environmental and social change. On these archipelagic islands, livelihoods are predominantly rural, far from political and urban centres. The project focused on the integrated top-down and bottom-up development planning that could enable climate resilient development at the local level, linked to provincial and national plans.

Lessons learned

- Substantial gradients in both climate and livelihoods in the island geographies necessitate fine-scale planning and make it difficult to scale up.
- Infrastructural investments, including roads, ports, and irrigation, are crucial to climate-resilient development. If not well designed, such investments are prone to maladaptation, such as exposure to sea level rise.
- Although some development interventions are delivering climate resilience, such outcomes are often haphazard, rather than strategically conceived, coordinated, and delivered. (Butler et al., 2016)

[END BOX 8.9 HERE]

New financial instruments can help to support investment in, for example, ecosystem-based adaptation. For example, green bonds have shown their ability to raise significant amounts of capital in support of projects with environmental/ climate benefits. The green bond market has quickly developed since the European Investment Bank launched the first green bond in 2007, with issuance growing to $257.7 billion in 2019, up more than 50 percent on the previous year (CPI, 2019). Most green bonds focus on energy, buildings and transport infrastructure but green bond issuance to support sustainable agriculture and forestry has grown from $208 million in 2013 to $7.4 billion in 2018 (Wilkins, 2019). The Seychelles issued the world's first 'blue' bond in 2018 with the support of the World Bank. Similar to green bonds, blue bonds earmark the use of bond proceeds for specific purposes, here the sustainable use of marine resources (World Bank, 2018). In 2019, the European Bank for Reconstruction and Development issued the world's first ever dedicated climate resilience bond, raising $700 million. The five-year bond will be used to finance the Bank's projects in climate resilient infrastructure (e.g., water, energy and transport), climate-resilient business, commercial operations, climate-resilient agriculture and ecological systems (Bennett, 2019). While these issuances are still small compared to the overall green bond market, their rapid growth points to enormous opportunities for ecosystem-based adaptation.

Despite the growth of official adaptation funding at international and national levels, for the world's poorest, adaptation to the impacts and opportunities of climate change frequently occurs in response to losses and damages at the individual or household scale, without coordination at larger institutional scales (Section 8.3, 8.4; Barrett, 2014). Discussions of adaptation finance often occur in the context of dwindling resources, and trade-offs: triage decisions about the other investments that societies can tolerate suspending (Warner and Van der Geest, 2013; Tanner et al., 2015). In many poor, vulnerable countries, complex governance challenges, such as budget austerity or corruption, hamper the provision of such support. In the absence of adaptation funding for the poor coordinated at higher scales, the costs of adaptation are borne by the poor at community, kin-group and household scales. Bearing the cost of adaptation, thus, can become, in the short-term, an erosive process of coping that ultimately increases the likelihood that communities and households will remain trapped in poverty (Antwi-Agyei et al., 2018b). In the long-term, these measures financing adaptation may be maladaptive, meaning they ultimately leave the poor at greater risk of experiencing climate change impacts (Section 8.4.5; Rahman and Hickey, 2019). Such circumstances highlight the governance gap that drive the poorest to rely on extreme measures to finance adaptation.

Since the AR5, there is greater documentation of the extreme measures and high-risk income alternatives that the world's poorest commonly take to finance adaptation (Dawson, 2017; Ahmed et al., 2019). While still a controversial topic, clear examples of extreme adaptation finance measures include:

- unauthorized international migration (McLeman, 2018)
- informal small-scale mining of precious metals and minerals (Hilson and Van Bockstael, 2012; Osumanu, 2020)
- illegal poaching of flora and fauna, including participation in illegal timber harvesting (Bolognesi et al., 2015)
- illegal, unregulated or unreported (IUU) fishing, including within marine protected areas, or the coastal zones of neighbouring countries(Tanner et al., 2014)
- utilizing livelihood resources, such as boats, in smuggling activities, including drug and arms trafficking(Belhabib et al., 2020)
- participation in piracy, extortion or kidnapping economies (Staff, 2017)

Enabling conditions for formal adaptation finance for the poorest are needed to reduce reliance on high-risk, extra-legal sources of income (see Section 8.5.2). In general, the antidote to this emerging problem is access to living wages that the poor can rely on to finance adaptation. There are few examples of pro-poor mechanisms, programs or institutions that prioritize coordinated, access to credit for proactively adapting livelihoods of the poor (Agrawal and Perrin, 2009). Institutions can reduce incentives for vulnerable people to engage in high risk activities by including them in the process of adaptation governance, which aims not only at supporting sustainable livelihood practices (such as farming, fishing and forestry), but also guaranteeing land tenure (Wrathall et al., 2019). Critical for risk reduction to the poor is also the ability of authorities across multiple spatial and temporal scales to maintain social protection that are able to reduce the dependency of illegal sources of income at the same time facilitate adaptation (Tenzing, 2020). A range of tools exists for opening access to credit to poor and marginalized people whose livelihoods are most highly vulnerable (Ribot, 2013): climate insurance tools that are designed and targeted at the poorest and which have been properly assessed to ensure they do not undermine other coping strategies such as risk spreading, programs that ease access or subsidize loans for adaptation, mobile banking and mobile-based financial and risk-management tools, impact pay-outs in the form of direct transfers, and institutional supports for hometown associations. International governance arrangements, such as the Warsaw International Mechanism on Loss and Damage, might aim primarily to clear the financing gap between global financial and risk management institutions and the pocketbooks of the poorest (Wrathall et al., 2015).

8.7 Conclusion

The chapter has moved beyond the IPCC WGII AR5 in that the chapter lays out structural elements of vulnerability and provides quantitative information about climate-related vulnerability hotspots globally complemented with the assessment of poverty, local livelihood vulnerability and sustainable development. Also the assessment of non-economic losses and enabling and supportive environments for adaptation are new aspects.

The chapter provides additional evidence on the livelihood resources at local levels that have been impacted by different climate hazards, and globally, that specific hazards (namely, drought and rising temperatures) are more threatening and destabilizing to livelihoods than others. There is robust evidence that coping and adaptive capacities erode with increasing global mean temperature (GMT)—substantial differences are expected between a GMT increase of less than 1.5°C compared to an increase of more than 3°C— and the frequencies of climate hazards, such as heat waves, droughts or floods is likely to increase substantially. Nevertheless, this assessment also revealed that the adverse impacts of climate change for livelihoods and multidimensional poverty differ substantially between different population groups exposed to climate hazards, based on the socio-economic and governance context. Consequently, societal impacts of climate change need to be understood in the broader context of development and the development challenges that influence exposure, vulnerability and adaptation.

There is robust evidence of the impacts of all climate hazards on the key livelihood resources that the poor depend on. There is high confidence that two climate hazards pose high risk to a broad range of livelihood resources: warming trends and droughts. Meanwhile, the livelihood resources that are globally at greatest risk include people's bodily health, food security and agricultural productivity (high confidence). Evidence suggests that the fundamental challenge of climate change to livelihoods is that rising temperatures, drought and other hazards endanger human life, and the lives of plants and animals that humans rely on to survive (high confidence). There is now robust evidence that the impacts of climate change on livelihoods are driving people to migrate in search of alternative incomes, and this tendency will increase with rising temperatures. Of greatest concern are people whose development context is compromised by war, conflict and extreme poverty and inequality, such as refugee populations and displaced people.

This chapter reports quantitative evidence about human vulnerability and therefore identifies various spatial hotspots of vulnerability emerging in regional clusters, and reports that significantly more people are living in highly vulnerable context conditions compared to those living in low vulnerability contexts. The assessment revealed that approximately more than 3 million people are living in countries classified as very highly or highly vulnerable (depending on the assessment method and the number of classes used and countries included). In contrast approximately 2 billion people reside in low or very low vulnerable country contexts. Studies estimate the population in the most vulnerable regions to almost double by the year 2100 (Section 8.4.5.2). When near-term estimates are used, the population growth in highly vulnerable countries is still significantly higher compared to less vulnerable countries. Consequently, this assessment points towards the fact that even if we do not know how societal or community vulnerability will develop in specific areas, it is highly likely that in the future, more people will live in destabilized and highly vulnerable country contexts compared to the population today. However, it is important to note that the scientific literature also underscores that trends in vulnerability differ significantly between different world regions and within countries.

The chapter also advances knowledge in terms of the interconnections between human vulnerability and observed losses and adverse consequences. The assessment shows that statistically relevant differences in observed fatalities per hazard events can not only be explained by hazard intensity and frequency, but are also linked to different levels of vulnerability of a region exposed. Despite all uncertainties about future change, the assessed literature clearly provides an accurate picture of the expected societal impacts of climate change, the requirements for successful adaptation, and the need to address the adaptation gap through the perspective of vulnerability.

The chapter shows that intersectionality approaches are becoming increasingly central to grasping how differential vulnerability to climate hazards is experienced by different social groups. Intersectionality recognises that age, gender, class, race and ethnicity are reinforcing social phenomena shaping social inequalities and experiences of the world which also intersect with climate hazards and vulnerability. Our assessment reveals the central role of maladaptation with *robust new evidence* on negative consequences of interventions on different social groups. Well intentioned adaptation can exacerbate past and existing vulnerabilities and undermine livelihoods. There is also evidence that despite maladaptation, inclusive and sustainable development at the local level can reduce vulnerability.

Since AR5 loss and damage has taken much more central stage in sustainable development, policy and poverty and livelihoods discourse. While there is ambiguity about what constitutes loss and damage the chapter illustrates there is new evidence of observed losses and damages, including slow-onset impacts (e.g., sea level rise and drought). Our assessment reveals that there exists a body of literature that explicitly addresses non-economic losses and that these are experienced everywhere now due to human induced climate change. These are coupled with advancements in the science of extreme event attribution with new focus on adaptation metrics and vulnerability assessments.

This assessment also identifies emerging evidence of linkages between extreme and slow onset events, non-economic loss and damage, and livelihood shifts. Evidence suggests that losses are leading to a range of shifts in livelihoods, which may be easier for some social groups than others and with implications for livelihoods security across transboundary scales. Yet, climate change is only one driver. Untangling the drivers of vulnerability is also critical with use of intersectionality approaches. Our quantification of vulnerability hotspots supports this concern and it will be critical to seek further knowledge on the extent of livelihood shifts among the most vulnerable resulting from specific non-economic loss and damage, for whom, where and at what scale. Gaps in knowledge highlight this as an area that needs further work in order to develop and understand further the full extent and reach of the relationships between extreme and slow onset climate events, non-economic losses, and shifting livelihoods.

This chapter builds from AR5 and 1.5°C Report on key limits to the adaptation of natural and social systems since that are compounded by the effects of poverty and inequality such as on water scarcity, ecosystems alteration and degradation, coastal cities in relation to sea-level rise, cyclones and coastal erosion, food systems and human health (*high confidence*). The climate change risks substantially pose negative impacts on climate-sensitive livelihoods of smallholder farmers, fisheries communities, Indigenous People, urban poor, informal settlements, with limits to adaptation evidenced on the loss income, ecosystems, health, and increasing migration (*high confidence*). It also addresses how ecological thresholds and socio-economic determinants of vulnerabilities are linked to soft and hard adaptation limits, including the potential and magnitude to livelihoods risks in the future. For instance, a hard limit associated to losses of coral reefs at 1.5°C warmer world will lead to substantial loss of income and livelihoods for coastal communities (*high confidence*), including loss of culture and place-based attachment (*medium confidence*). The adaptation hard limits are expected for the Arctic ecosystem, whose threshold will affect residents of Arctic regions dependent on hunting and fishing livelihoods (*high confidence*). New emerging considerations to ecological limits to adaptation such as severe glacier retreat and Amazon Forest dieback, is expected to affect the livelihoods of smallholder's farmers, and Indigenous People through crops yield failures, biodiversity loss, reduced hydropower capacity and heath (*medium evidence*). While a knowledge gap remains on the projected risks of increasing global temperature to climate-sensitive livelihoods among global south countries and specific groups of people, current observations show negative impacts to livelihoods for tens to hundreds of millions of people. Thus, without sustainable, equitable and urgent adaptation measures, maladaptation risks are likely to further increase vulnerability, marginalization, and ecological tipping points among the poor within countries (*medium confidence*).

Evidence on the kinds of enabling environment required paints a complex picture. The assessment highlights the interaction of different capital assets with the broader context of key enablers in shaping the overall enabling environment for adaptation, which itself is highly context-dependent. In this regard, countries present different starting points for adaptation, with some requiring, for example, more of an emphasis on institutional capacity building; others requiring transformation to the broader legal and political conditions. Capitals are not necessarily substitutable but rather act as an assemblage in shaping both perceptions of climate risk and the necessity and appropriateness of actions. At the same time there is *robust evidence* that livelihoods that depend strongly on natural capital for both subsistence and as a source of income are particularly sensitive to climate risks; and are where perhaps adaptive actions are most urgently needed, even with smaller rises in temperature under the most optimistic scenarios. This applies to both the global south and the global north. Investments in any form of capital asset to support adaptation need to be mindful of reinforcing existing inequalities and introducing new ones, particularly if transformation takes place. This also underscores the importance of inclusive, polycentric governance in ensuring the voices of all groups are heard and that wide ranging knowledge types are incorporated in decision making, nevertheless recognising that trade-offs are inevitable.

The chapter also highlights and provides quantitative evidence that adaptation strategies need to go beyond the idea of adapting to warming levels only. Adaptation strategies have to reduce the adaptation gap and therewith reduce human vulnerability independent of a specific climatic hazard. It has been shown that adaptation strategies that explicitly address poverty, inequities and consider also right based approaches can generate co-benefits for resilience building of most vulnerable groups and for sustainable development.

[START FAQ8.1 HERE]

FAQ 8.1: Why are people who are poor and disadvantaged especially vulnerable to climate change and why do climate change impacts worsen inequality?

Poor people and their livelihoods are especially vulnerable to climate change because they usually have fewer assets and less access to funding, technologies and political influence. Combined, these constraints mean they have fewer resources to adapt to climate change impacts. Climate change impacts tend to worsen inequalities due to the fact that they disproportionately affect disadvantaged groups. This in turn further increases their vulnerability to climate change impacts and reduces their ability to cope and recover.

Climate change and related hazards (e.g., droughts, floods, heat stress, etc.) affect many aspects of people's lives—such as their health, access to food and housing, or their source of income such as crops or fish stocks—and many will have to adapt their way of life in order to deal with these impacts. People who are poor and have few resources with which to adapt are thus much more seriously negatively affected by climate-related hazards. If a person or community are not able to cope and adapt to climate-related hazards, this is referred to as 'vulnerability'. For example, if someone who is very rich has their house washed away in a flood, this is terrible, but they often have more resources to rebuild, have insurances that support recovery and maybe even build a house that is no longer in a flood-prone area. Whereas for someone who is very poor and who does not live in a state that provides support, the loss of their house in a flood could mean homelessness. This example shows that the same climate hazard (flood) can have a very different impact on people depending on their vulnerability (their capacity to cope and adapt to hazards).

It is not just poverty that can make people more vulnerable to climate change and climate-related hazards. Disadvantage due to discrimination, gender and income inequalities and lack of access to resources, for example, those with disabilities or of minority groups, can mean these groups have fewer resources with which to prepare and react to climate change and to cope with and recover from its adverse effects and are therefore more vulnerable. This vulnerability can then increase due to climate change impacts in a vicious cycle, unless adaptation measures are supported and made possible.

[END FAQ8.1 HERE]

[START FAQ8.2 HERE]

FAQ 8.2: Which world regions are highly vulnerable and how many people live there?

A mix of multiple development challenges, such as poverty, hunger, conflict and environmental degradation, make countries and whole regions vulnerable to climate change. Many of the people in the most vulnerable situations and in the most vulnerable regions are also highly exposed to climate hazards, such as droughts, floods or sea-level rise at present and will become increasingly so in the future. Studies estimate that around 1.6 to 3.3 billion people are living in regions classified as highly vulnerable to climate change impacts, which is almost twice as many as the approximately 0.8 to 2 billion people who reside in regions classified as least vulnerable. The most vulnerable regions include East, Central and West Africa, South Asia, Micronesia and Melanesia and in Central America.

When a country or region is considered 'vulnerable' to climate change this means that climate hazards (e.g., drought, flood, heatwaves) have a very negative impact because there are a high number of people in these areas lacking the ability or opportunity to cope and adapt to such events, due, for example, to high average poverty, inequality and lack of institutional support. This vulnerability could be due to many different development challenges that all come together and influence each other, such as poverty, lack of access to basic infrastructure services, high numbers of uprooted people, state fragility, low or below average life expectancy and biodiversity degradation. These structural social issues often affect regions for many decades and make it difficult for the state and for individuals to respond to climate change and climate-related hazards.

For example, if a region is already characterized by poverty and struggling to feed its population and provide adequate access to basic infrastructure services such as water and sanitation, this makes them vulnerable. If this region is then faced with an increased number of extremely dry years, this exposes them to drought and will make things even harder and cause more hunger, poverty and worsen health—these are climate impacts. Most vulnerable regions are in Africa, as well as in South Asia, the Pacific and the Caribbean. In these regions there are often multiple neighbouring countries that all are highly vulnerable, for example in Central- and West-Africa. These regional clusters require special attention.

There are also highly vulnerable groups and individuals within less vulnerable regions. For example, marginalised, disadvantaged and poor minorities within highly affluent cities. Programmes that aim to support adaptation to climate change need to focus on reducing the vulnerability of individuals, groups, countries and regions.

[END FAQ8.2 HERE]

[START FAQ8.3 HERE]

FAQ 8.3: How does and will climate change interact with other global trends (e.g., urbanization, economic globalization) and shocks (e.g., COVID-19) to influence livelihoods of the poor?

A range of local, regional and global economic and political processes already underway have put at risk the livelihoods of the poor (which include urbanization, industrialization, technological transformation, monetization of rural economies, increasing reliance on wages, and inequality at national and international levels), and climate change intersects with these processes.

The world's poorest already struggle providing for themselves and their families in their pursuit of livelihoods. Despite hard work there are many factors beyond an individual's control that can make earning a living very difficult. Climate change is one problem among many that put stress on livelihoods. Poor and marginal groups disproportionately bear impacts of climate change, in ways that accelerate transitions from traditional livelihoods, such as rural farming, to wage jobs in urban areas. Where adaptation measures are insufficient and where the poor are excluded from decision-making, these livelihood transitions can be severely destabilizing.

For example, climate change may alter the frequency or intensity of hazards that threaten the viability of a community's traditional farming or fishing livelihoods. Local farmers or fishers are then forced to adapt how they farm or fish or abandon livelihood practices entirely. The latter may mean migrating to a city to find work. As many communities face the same challenge, this intersects with a global trend that is affecting billions of lives and livelihoods—urbanization—as seen in the rapid growth of informal settlements at the peripheries of cities around the world, particularly rapidly growing megacities in Africa, Asia and Latin America. These developments will be accelerated by negative impacts of climate change and increase risks that larger segments of the population enter conditions of persistent poverty.

At the same time, people whose livelihoods have been upended by climate change are subject to new threats, such as the global COVID-19 pandemic, which has shined a light on the plight of the most vulnerable people. Disproportionately severely impacted by COVID-19 were for example the elderly, Indigenous Peoples and Communities of Colour and also the indirect economic consequences particularly hit the poor. Hence, COVID-19 demonstrates that the livelihoods of the poorest and most marginalized are vulnerable to other global trends beyond climate change. Also, most severe impacts are expected in regions that are already characterized by high levels of systemic human vulnerability.

[END FAQ8.3 HERE]

[START FAQ8.4 HERE]

FAQ 8.4: What can be done to help reduce the risks from climate change, especially for the poor?

Public and private investment in different types of assets can help reduce risks from climate change. Exactly which assets require investment depends on the specific situation. However, the provision of access to basic services, such as water and sanitation, education and health care as well as the importance of reducing inequity is shown within the assessment for many regions. The poor have fewer resources to invest, so in poorer countries greater public investment is needed. Legal, social, political, institution and economic interventions can alter human behaviour, though care must be taken that these do not amplify existing inequalities, create new inequalities, or reduce future adaptation options.

Adaptation can help to reduce risks for the poor and requires both public and private investment in various natural assets (e.g., mangroves, farmland, wetlands); human assets (e.g., health, skills, Indigenous Knowledge), physical assets (e.g., mobile phone connectivity, housing, electricity, technology), financial assets (e.g., savings, credit) and social assets (e.g., social networks, membership of organisations such as farmer cooperatives). Often, the poor have the least to invest, so poverty can reduce adaptation options. Sometimes people migrate as a reaction to floods or droughts, though the poorest groups often lack the resources to move. Exactly what needs investing in to reduce risks varies according to the scale and livelihood system in need of adaptation. In general, risks can be reduced through a range of different technological and engineering approaches (for example, building sea defences to reduce storm surge impacts), as well as ecosystem based approaches (such as replanting mangroves, altering the types of crops grown, changing the timing of farming activities, or using climate smart agriculture or agroforestry approaches).

At the same time, legal, social, political, institutional and economic solutions can alter human behaviour (for example, through enforcement of building codes to prevent construction on low lying land prone to flooding; timely provision of weather information and early warning systems; knowledge sharing activities, including adaptation strategies grounded in Indigenous Knowledge; crop insurance schemes; incentives such as payments to stop people cutting down trees or to enable them to plant them, and social protection to provide a safety net in times of crisis).

The poorest groups often require greater public adaptation investments. Efforts to support adaptation need to be mindful of reinforcing existing inequalities and introducing new ones, making sure they are inclusive, culturally sensitive, and that the voices of all groups of people are heard. It is also important that adaptations which reduce immediate risks for the poor do not rule out adaptation options that could help them later on, or which could cause them to increase their emissions. Political will is needed to put people at the centre of climate change risk reduction efforts, including support for their livelihoods.

[END FAQ8.4 HERE]

[START FAQ8.5 HERE]

FAQ 8.5: How do present adaptation and future responses to climate change affect poverty and inequality?

Present adaptation can help to reduce the current and possibly future impacts of climate change. Future responses to climate change can reduce poverty and inequality and even help transition toward climate resilient livelihoods and climate resilient development. Pro-poor adaptation planning is necessary to ensure future risks for the poor are being accounted for and the inequality underlying the poverty is being addressed.

There are many ways in which poverty and inequality are influenced by climate change. The livelihood sources of the poor are likely to be affected and cumulative effects of losses and damages and may influence future poverty. There are cases when present adaptation worsens future poverty and exacerbates inequality—this is called maladaptation. The risks of maladaptation are greater in societies characterized by high inequality, and in many cases the poor and most vulnerable groups are the ones most adversely affected.

Effective decision making in adaptation should be informed by past, present and future climate data, information and scenarios to cater for reliable plans and actions for climate-resilient livelihoods. Adaptation lessons from the past play an important role in decision making regarding responses to climate change. There is an emerging debate on the role of learning, particularly forward-looking (anticipatory) learning, as a key element or important aspect for adaptation and resilience in the context of climate change. Memory, monitoring of key drivers of change, scenario planning, and measuring anticipatory capacity are seen as crucial ingredients for future adaptation and resilience pathways and hence overcoming maladaptation. Moreover, climate resilient development calls for ensuring synergies between adaptation, mitigation and development are maximised, while trade-offs, especially those to the poor, are minimised.

[END FAQ8.5 HERE]

References

Abbott, D. and S. Pollard, 2004: *Hardship and Poverty in the Pacific*. Asian Development Bank, Manila, Philippines, 151 pp. Available at: https://www.adb.org/sites/default/files/publication/28800/hardship-poverty.pdf.

Abbott, K. W., 2017: Orchestration: strategic ordering in polycentric climate governance. *Available at SSRN 2983512*, doi:http://dx.doi.org/10.2139/ssrn.2983512.

Abdullah, A. N. M. et al., 2016: A short-term decrease in household income inequality in the Sundarbans, Bangladesh, following Cyclone Aila. *Natural Hazards*, **83**(2), 1103-1123, doi:https://doi.org/10.1007/s11069-016-2358-1.

Abel, G. J., M. Brottrager, J. Crespo Cuaresma and R. Muttarak, 2019: Climate, conflict and forced migration. *Global Environmental Change*, **54**, 239-249, doi:https://doi.org/10.1016/j.gloenvcha.2018.12.003.

Abrahamse, W. and R. Shwom, 2018: Domestic energy consumption and climate change mitigation. *WIRES Climate Change*, **9**(4), doi:https://doi.org/10.1002/wcc.525.

Acharya, P., B. Boggess and K. Zhang, 2018: Assessing Heat Stress and Health among Construction Workers in a Changing Climate: A Review. *Int J Environ Res Public Health*, **15**, 247, doi:10.3390/ijerph15020247.

Acosta, L. A. et al., 2016: Loss and damage from typhoon-induced floods and landslides in the Philippines: community perceptions on climate impacts and adaptation options. *International Journal of Global Warming*, **9**(1), 33-65, doi:10.1504/ijgw.2016.074307.

Adamo, S. et al., 2021: Slow Onset Events related to Climate Change. *Current Opinion in Environmental Sustainability*, **50**, https://www.sciencedirect.com/journal/current-opinion-in-environmental-sustainability/vol/50/suppl/C.

Adams, H., 2016: Why populations persist: mobility, place attachment and climate change. *Population and Environment*, **37**(4), 429-448, doi:https://doi.org/10.1007/s11111-015-0246-3.

Adams, H. et al., 2020: Multi-dimensional well-being associated with economic dependence on ecosystem services in deltaic social-ecological systems of Bangladesh. *Regional Environmental Change*, **20**, 42, doi:10.1007/s10113-020-01620-x.

ADB, 2005: *The Asian Development Bank Annual Report 2004*. Asian Development Bank (ADB), Singapore, 250 pp. Available at: https://www.adb.org/sites/default/files/institutional-document/31327/ar2004.pdf.

Adger, W. N. et al., 2013: Cultural dimensions of climate change impacts and adaptation. *Nature climate change*, **3**(2), 112-117, doi:https://doi.org/10.1038/nclimate1666.

Adger, W. N. et al., 2020: Urbanization, Migration, and Adaptation to Climate Change. *One Earth*, **3**(4), 396-399, doi:https://doi.org/10.1016/j.oneear.2020.09.016.

Adger, W. N., R. S. de Campos and C. Mortreux, 2018: Mobility, displacement and migration, and their interactions with vulnerability and adaptation to environmental risks. In: *Routledge handbook of environmental displacement and migration*, 1st ed. [McLeman, R. and F. Gemenne (eds.)]. Routledge, London, pp. 29-41. ISBN https://doi.org/10.4324/9781315638843.

Adger, W. N. et al., 2014: Human Security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA pp. 755-791. ISBN 9781107058071.

Afifi, T. et al., 2016: Human mobility in response to rainfall variability: opportunities for migration as a successful adaptation strategy in eight case studies. *Migration and Development*, **5**(2), 254-274, doi:https://doi.org/10.1080/21632324.2015.1022974.

Agrawal, A. and N. Perrin, 2009: Climate adaptation, local institutions and rural livelihoods. In: *Adapting to climate change: thresholds, values, governance* [Adger, N. W., I. Lorenzoni and K. L. O'Brien (eds.)]. Cambridge University Press, Cambridge, pp. 350-367. ISBN 9780521764858.

Ahlborg, H. and A. J. Nightingale, 2012: Mismatch between scales of knowledge in Nepalese forestry: epistemology, power, and policy implications. *Ecology and Society*, **17**(4), doi:http://dx.doi.org/10.5751/ES-05171-170416.

Ahmadalipour, A., H. Moradkhani, A. Castelletti and N. Magliocca, 2019: Future drought risk in Africa: Integrating vulnerability, climate change, and population growth. *Science of the Total Environment*, **662**, 672-686, doi:https://doi.org/10.1016/j.scitotenv.2019.01.278.

Ahmed, F. et al., 2018: Integrated Adaptation Tipping Points (IATPs) for urban flood resilience. *Environment and Urbanization*, **30**(2), 575-596, doi:10.1177/0956247818776510.

Ahmed, I. et al., 2019: Climate change, environmental stress and loss of livelihoods can push people towards illegal activities: a case study from coastal Bangladesh. *Climate and Development*, **11**(10), 907-917, doi:https://doi.org/10.1080/17565529.2019.1586638.

Aipira, C., A. Kidd and K. Morioka, 2017: Climate change adaptation in pacific countries: Fostering resilience through gender equality. In: *Climate change adaptation in Pacific countries* [W, L. F. (ed.)]. Springer, Cham, pp. 225-239. ISBN 978-3-319-50093-5.

Aitsi-Selmi, A. and V. Murray, 2016: Protecting the Health and Well-being of Populations from Disasters: Health and Health Care in The Sendai Framework for Disaster Risk Reduction 2015-2030. *Prehospital and Disaster Medicine*, **31**(01), 74-78, doi:10.1017/s1049023x15005531.

Ajayi, O. and P. Mafongoya, 2017: *Indigenous knowledge systems and climate change management in Africa*. CTA, Wageningen, The Netherlands, 316 pp. ISBN 978-92-9081-619-5.
Alam, A. F. M. A., R. Asad and A. Parvin, 2015: Climate Change Adaptation Through Grassroots Responses: Learning from the "Aila" Affected Coastal Settlement of Gabura, Bangladesh. In: *Handbook of Climate Change Adaptation* [Leal Filho, W. (ed.)]. Springer, Berlin, Heidelberg, pp. 2011-2034.
Alam, G. M. M., K. Alam, S. Mushtaq and W. Leal Filho, 2018: How do climate change and associated hazards impact on the resilience of riparian rural communities in Bangladesh? Policy implications for livelihood development. *Environmental science & policy*, **84**, 7-18, doi:https://doi.org/10.1016/j.envsci.2018.02.012.
Alam, K. and M. H. Rahman, 2019: Post-disaster recovery in the cyclone Aila affected coastline of Bangladesh: women's role, challenges and opportunities. *Natural Hazards*, **96**(3), 1067–1090, doi:10.1007/s11069-019-03591-7.
Alaniz, R., 2017: *From strangers to neighbors: Post-disaster resettlement and community building in Honduras*. University of Texas Press, Texas. ISBN 978-1-4773-1409-8.
Aldrich, D. P., C. M. Page-Tan and C. J. Paul, 2016: Social capital and climate change adaptation. *Oxford Research Encyclopedia of Climate Science*, doi:https://doi.org/10.1093/acrefore/9780190228620.013.342.
Aleksandrova, M., 2020: Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries. *Climate and Development*, **12**(6), 511-520, doi:https://doi.org/10.1080/17565529.2019.1642180.
Alencar, A., P. Moutinho, V. Arruda and D. Silverio, 2020: *Amazônia Em Chamas O Fogo E O Desmatamento Em 2019 E O Que Vem Em 2020*. Nota Tecnica, IPAM, Ipam, Brasilia- DF. Available at: https://ipam.org.br/wp-content/uploads/2020/04/NT3-Fogo-em-2019.pdf.
Alexander, M., E. Zagheni and K. Polimis, 2019: The impact of Hurricane Maria on out-migration from Puerto Rico: Evidence from Facebook data. *Population and Development Review*, **45**(3), 617–630, doi:https://doi.org/10.1111/padr.12289.
Alston, M., 2012: Rural male suicide in Australia. *Social science & medicine*, **74**(4), 515-522, doi:https://doi.org/10.1016/j.socscimed.2010.04.036.
Alston, P., 2019: *Climate change and poverty: Report of the Special Rapporteur on extreme poverty and human rights*. United Nations General Assembly, Forty-first session 24 June–12 July 2019 ed., New York City, 19 pp. Available at: https://digitallibrary.un.org/record/3810720?ln=en.
Altieri, M. A. and C. I. Nicholls, 2017: The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change*, **140**(1), 33-45, doi:https://doi.org/10.1007/s10584-013-0909-y.
Alves, F. et al., 2020: Climate change policies and agendas: Facing implementation challenges and guiding responses. *Environmental Science & Policy*, **104**, 190-198, doi:https://doi.org/10.1016/j.envsci.2019.12.001.
Amjad, K., 2019: Mental stress of climate migrant's poor women living in slums of Dhaka city. *International Journal of Multidisciplinary Research and Development*, **6**(8), 131–138.
Amjath-Babu, T. et al., 2019: Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. *Applied Energy*, **239**, 494-503, doi:https://doi.org/10.1016/j.apenergy.2019.01.147.
Anderson, M., M. Mckee and E. Mossialos, 2020: Covid-19 exposes weaknesses in European response to outbreaks. **368**, m1075, doi:https://doi.org/10.1136/bmj.m1075.
Andersson, E. and E. C. H. Keskitalo, 2017: Technology use in Swedish reindeer husbandry through a social lens. *Polar Geography*, **40**(1), 19-34, doi:10.1080/1088937x.2016.1261195.
Andrić, I., M. Koc and S. G. Al-Ghamdi, 2018: A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries. *Journal of Cleaner Production*, **211**, 83-102, doi:https://doi.org/10.1016/j.jclepro.2018.11.128.
Andrieu, N. et al., 2017: Prioritizing investments for climate-smart agriculture: Lessons learned from Mali. *Agricultural Systems*, **154**, 13-24, doi:https://doi.org/10.1016/j.agsy.2017.02.008.
Andrijevic, M., J. Crespo Cuaresma, R. Muttarak and C. F. Schleussner, 2020: Governance in socioeconomic pathways and its role for future adaptive capacity. *Nature Sustainability*, **3**, 35-41, doi:https://doi.org/10.1038/s41893-019-0405-0.
Angelsen, A. et al., 2014: Environmental Income and Rural Livelihoods: A Global-Comparative Analysis. *World Development*, **64**, S12-S28, doi:doi.org/10.1016/j.worlddev.2014.03.006.
Anjum, G. and A. Fraser, 2021: Vulnerabilities associated with slow-onset events (SoEs) of climate change: multi-level analysis in the context of Pakistan. *Current Opinion in Environmental Sustainability*, **50**, 54-63, doi:https://doi.org/10.1016/j.cosust.2021.02.004.
Ansah, E. W., E. Ankomah-Appiah, M. Amoadu and J. O. Sarfo, 2021: Climate change, health and safety of workers in developing economies: A scoping review. *The Journal of Climate Change and Health*, **3**, doi:10.1016/j.joclim.2021.100034.
Antwi-Agyei, P., A. J. Dougill, T. P. Agyekum and L. C. Stringer, 2018a: Alignment between nationally determined contributions and the sustainable development goals for West Africa. *Climate policy*, **18**(10), 1296-1312, doi:https://doi.org/10.1080/14693062.2018.1431199.

Antwi-Agyei, P., A. J. Dougill, L. C. Stringer and S. N. A. Codjoe, 2018b: Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Climate Risk Management*, **19**, 83-93, doi:https://doi.org/10.1016/j.crm.2017.11.003.
Apgar, M. et al., 2018: *Learning to Engage With Inequality in the Context of Resilience-Building Programming: Experiences from Isiolo, Kenya*. Institute of Development Studies (IDS), Studies, I. o. D., Brighton. Available at: https://opendocs.ids.ac.uk/opendocs/handle/20.500.12413/14096.
Archie, K. M., R. Chapman and S. Flood, 2018: Climate change response in New Zealand communities: Local scale adaptation and mitigation planning. *Environmental development*, **28**, 19-31, doi:https://doi.org/10.1016/j.envdev.2018.09.003.
Arts, K., 2017: Inclusive sustainable development: a human rights perspective. *Current Opinion in Environmental Sustainability*, **24**, 58-62, doi:https://doi.org/10.1016/j.cosust.2017.02.001.
Asante, W. A., E. Acheampong, E. Kyereh and B. Kyereh, 2017: Farmers' perspectives on climate change manifestations in smallholder cocoa farms and shifts in cropping systems in the forest-savannah transitional zone of Ghana. *Land use policy*, **66**, 374-381, doi:https://doi.org/10.1016/j.landusepol.2017.05.010.
Ashraf, J., R. Pandey, W. de Jong and B. Nagar, 2015: Factors influencing farmers' decisions to plant trees on their farms in Uttar Pradesh, India. *Small-scale forestry*, **14**(3), 301-313, doi:https://doi.org/10.1007/s11842-015-9289-7.
Atteridge, A. and E. Remling, 2018: Is adaptation reducing vulnerability or redistributing it? *WIRES Climate Change*, **9**(1), e500, doi:https://doi.org/10.1002/wcc.500.
Aune, K. T., D. Gesch and G. S. Smith, 2020: A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. *Environmental research*,(185), 109384, doi:https://doi.org/10.1016/j.envres.2020.109384.
Australian-Government, Farming, food and drought, Australian Government. Available at: https://www.agriculture.gov.au/ag-farm-food (accessed 30-06-2021).
Axelsson-Linkowski, W. et al., 2020: Shifting strategies between generations in Sami Reindeer Husbandry: The challenges of maintaining traditions while adapting to a changing context. *Human Ecology*, **48**(4), 481-490, doi:https://doi.org/10.1007/s10745-020-00171-3.
Ayal, D. Y., S. Desta and L. Robinson, 2020: Governance Dimensions of Climate Change Adaptation: The Case of Didahara, Borana, Southern Ethiopia. In: *Handbook of Climate Change Resilience* [Leal Filho, W. (ed.)]. Springer, Cham, pp. 2059-2074. ISBN 978-3-319-93336-8.
Ayeb-Karlsson, S., D. Kniveton and T. Cannon, 2020: Trapped in the prison of the mind: Notions of climate-induced (im) mobility decision-making and wellbeing from an urban informal settlement in Bangladesh. *Palgrave Communications*, **6**(1), 1-15, doi:https://doi.org/10.1057/s41599-020-0443-2.
Ayeb-Karlsson, S. et al., 2016: A people-centred perspective on climate change, environmental stress, and livelihood resilience in Bangladesh. *Sustainability Science*, **11**(4), 679-694, doi:https://doi.org/10.1007/s11625-016-0379-z.
Ayers, J. M. and S. Huq, 2009: Supporting adaptation to climate change: what role for official development assistance? *Development Policy Review*, **27**(6), 675-692, doi:https://doi.org/10.1111/j.1467-7679.2009.00465.x.
Azapagic, A. and S. Perdan, 2011: *Sustainable development in practice: Case studies for engineers and scientists / editors, Adisa Azapagic and Slobodan Perdan*, 2nd ed. ed., Wiley-Blackwell, Oxford. ISBN 9780470718711.
Bailey, I. and L. E. Buck, 2016: Managing for resilience: a landscape framework for food and livelihood security and ecosystem services. *Food security*, **8**(3), 477-490, doi:https://doi.org/10.1007/s12571-016-0575-9.
Bakkegaard, R. K., L. R. Møller and F. Bakhtiari, 2016: *Joint Adaptation and Mitigation in Agriculture and Forestry*. UNEP DTU Partnership Working Papers series; Climate Resilient Development Programme, United Nations Environmental Program Technical University of Denmark, Partnershi, U. D., Lyngby, 36 pp. Available at: https://backend.orbit.dtu.dk/ws/portalfiles/portal/157400483/Joint_adaptation_and_mitigation_updated_09_08_16_1_.pdf.
Balehey, S., G. Tesfay and M. Balehegn, 2018: Traditional gender inequalities limit pastoral women's opportunities for adaptation to climate change: Evidence from the Afar pastoralists of Ethiopia. *Pastoralism*, **8**(1), 23, doi:https://doi.org/10.1186/s13570-018-0129-1.
Balint, T. et al., 2017: Complexity and the economics of climate change: a survey and a look forward. *Ecological Economics*, **138**, 252-265, doi:https://doi.org/10.1016/j.ecolecon.2017.03.032.
Banerjee, S., R. Black, A. Mishra and D. Kniveton, 2019a: Assessing vulnerability of remittance-recipient and nonrecipient households in rural communities affected by extreme weather events: Case studies from South-West China and North-East India. *Population, Space and Place*, **25**(2), doi:10.1002/psp.2157.
Banerjee, S., A. Hussain, S. Tuladhar and A. Mishra, 2019b: Building capacities of women for climate change adaptation: Insights from migrant-sending households in Nepal. *Climatic Change*, **157**(3), 587-609, doi:https://doi.org/10.1007/s10584-019-02572-w.
Bao, P. N. et al., 2018: *Governing the Water-Energy-Food Nexus Approach for Creating Synergies and Managing Trade-offs*. **Issue Brief**, Institute of Global Environmental Strategies, Berlin, 7 pp. Available at: https://www.apn-gcr.org/wp-content/uploads/2020/09/2ddd451c4775e2e8604d29a82878fe28.pdf.
Barange, M. et al., 2014: Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nature Climate Change*, **4**(3), 211-216, doi:https://doi.org/10.1038/nclimate2119.

Barbier, E. B., 2015: *Climate change impacts on rural poverty in low-elevation coastal zones*. Policy Research Working Paper, The World Bank, Bank, T. W., Washington DC. Available at: https://openknowledge.worldbank.org/handle/10986/23443.

Barbier, E. B. and J. P. Hochard, 2018: The impacts of climate change on the poor in disadvantaged regions. *Review of Environmental Economics and Policy*, **12**(1), 26-47, doi:doi: 10.1093/reep/rex023.

Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4**(12), 1103-1108, doi:https://doi.org/10.1038/nclimate2383.

Barnett, J. and S. J. O'neill, 2012: Islands, resettlement and adaptation. *Nature Climate Change*, **2**(1), 8, doi:https://doi.org/10.1038/nclimate1334.

Barnett, J., P. Tschakert, L. Head and W. N. Adger, 2016: A science of loss. *Nature Climate Change*, **6**, 976-978, doi:10.1038/nclimate3140.

Barr, R., S. Fankhauser and K. Hamilton, 2010: Adaptation investments: a resource allocation framework. *Mitigation and Adaptation Strategies for Global Change*, **15**(8), 843-858, doi:doi.org/10.1007/s11027-010-9242-1.

Barreca, A. et al., 2016: Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century. *Journal of Political Economy*, **124**(1), 105-159, doi:10.1086/684582.

Barrett, C. B. and P. Santos, 2014: The impact of changing rainfall variability on resource-dependent wealth dynamics. *Ecological Economics*, **105**, 48-54, doi:https://doi.org/10.1016/j.ecolecon.2014.05.009.

Barrett, S., 2014: Subnational climate justice? Adaptation finance distribution and climate vulnerability. *World Development*, **58**, 130-142, doi:https://doi.org/10.1016/j.worlddev.2014.01.014.

Barrett, S. and A. Dannenberg, 2014: Sensitivity of collective action to uncertainty about climate tipping points. *Nature Climate Change*, **4**, 36-36, doi:https://doi.org/10.1038/nclimate2059.

Bauer, K., 2013: Are preventive and coping measures enough to avoid loss and damage from flooding in Udayapur district, Nepal? *International Journal of Global Warming*, **5**(4), 433-451, doi:doi/pdf/10.1504/IJGW.2013.057292.

Baumber, A. et al., 2019: Promoting co-benefits of carbon farming in Oceania: Applying and adapting approaches and metrics from existing market-based schemes. *Ecosystem Services*, **39**, 100982, doi:10.1016/j.ecoser.2019.100982.

Beckman, M. and M. V. T. Nguyen, 2016: Upland development, climate-related risk and institutional conditions for adaptation in Vietnam. *Climate and Development*, **8**(5), 413-422, doi:https://doi.org/10.1080/17565529.2015.1067178.

Bee, B., M. Biermann and P. Tschakert, 2013: Gender, development, and rights-based approaches: Lessons for climate change adaptation and adaptive social protection. In: *Research, action and policy: Addressing the gendered impacts of climate change* [Alston, M. and K. Whittenbury (eds.)]. Springer, pp. 95-108. ISBN 978-94-007-5518-5.

Beillouin, D. et al., 2020: Impact of extreme weather conditions on European crop production in 2018. *Philosophical Transactions of the Royal Society B*, **375**(1810), 20190510, doi:https://doi.org/10.1098/rstb.2019.0510.

Bel, G. and S. Joseph, 2018: Climate change mitigation and the role of technological change: Impact on selected headline targets of Europe's 2020 climate and energy package. *Renewable and Sustainable Energy Reviews*, **82**, 3798-3807, doi:https://doi.org/10.1016/j.rser.2017.10.090.

Belhabib, D., P. Le Billon and D. J. Wrathall, 2020: Narco-Fish: Global fisheries and drug trafficking. *Fish and Fisheries*, **21**(5), 992–1007, doi:10.1111/faf.12483.

Bell, A. R., C. Calvo-Hernandez and M. Oppenheimer, 2019: Migration, intensification, and diversification as adaptive strategies. *Socio-Environmental Systems Modelling*, **1**, 16102-16102, doi:https://doi.org/10.18174/sesmo.2019a16102.

Bell, A. R. et al., 2021: Migration towards Bangladesh coastlines projected to increase with sea-level rise through 2100. *Environmental Research Letters*, **16**(2), 024045, doi:https://doi.org/10.1088/1748-9326/abdc5b.

Bellprat, O., V. Guemas, F. Doblas-Reyes and M. G. Donat, 2019: Towards reliable extreme weather and climate event attribution. *Nature communications*, **10**(1), 1-7, doi:https://doi.org/10.1038/s41467-019-09729-2.

Béné, C. et al., 2016: Contribution of fisheries and aquaculture to food security and poverty reduction: assessing the current evidence. *World Development*, **79**, 177-196, doi:https://doi.org/10.1016/j.worlddev.2015.11.007.

Benjaminsen, T. A., K. Alinon, H. Buhaug and J. T. Buseth, 2012: Does climate change drive land-use conflicts in the Sahel? *Journal of Peace Research*, **49**(1), 97-111, doi:10.1177/0022343311427343.

Bennett, M. M. and L. C. Smith, 2017: Advances in using multitemporal night-time lights satellite imagery to detect, estimate, and monitor socioeconomic dynamics. *Remote Sensing of Environment*, **192**, 176-197, doi:https://doi.org/10.1016/j.rse.2017.01.005.

Bennett, V., World's first dedicated climate resilience bond, for US$ 700m, is issued by EBRD, European Bank for Reconstruction and Development. Available at: https://www.ebrd.com/news/2019/worlds-first-dedicated-climate-resilience-bond-for-us-700m-is-issued-by-ebrd-.html.

Bentley, R. A. et al., 2014: Social tipping points and Earth systems dynamics. *Frontiers in Environmental Science*, **2**, 35-35, doi:https://doi.org/10.3389/fenvs.2014.00035.

Benzie, M. and Å. Persson, 2019: Governing borderless climate risks: moving beyond the territorial framing of adaptation. *International Environmental Agreements: Politics, Law and Economics*, **19**(4-5), 369-393, doi:https://doi.org/10.1007/s10784-019-09441-y.

Bergmann, J. et al., 2021: Assessing the Evidence: Climate Change and Migration in Peru. Potsdam Institute for Climate Impact Research International Organization for Migration, Potsdam; Geneva, 238 pp.
Berkhout, F. et al., 2014: Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments. *Regional Environmental Change*, **14**(3), 879-893, doi:https://doi.org/10.1007/s10113-013-0519-2.
Berrang-Ford, L. et al., 2014: What drives national adaptation? A global assessment. *Climatic Change*, **124**(1-2), 441-450, doi:doi.org/10.1007/s10584-014-1078-3.
Berrang-Ford, L. et al., 2021: Mapping evidence of human adaptation to climate change. *Nature climate change*, **Accepted. In press**, doi:10.21203/rs.3.rs-100873/v1.
Betts, R. A. et al., 2018: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5 C and 2 C global warming with a higher-resolution global climate model. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160452, doi:https://doi.org/10.1098/rsta.2016.0452.
Beveridge, L., S. Whitfield and A. Challinor, 2018: Crop modelling: towards locally relevant and climate-informed adaptation. *Climatic change*, **147**(3-4), 475-489, doi:https://doi.org/10.1007/s10584-018-2160-z.
Bhatta, G. D., P. K. Aggarwal, S. Poudel and D. A. Belgrave, 2016: Climate-induced migration in South Asia: Migration decisions and the gender dimensions of adverse climatic events. *Journal of Rural and Community Development*, **10**(4).
Biermann, F., F. Zelli, P. Pattberg and H. van Asselt, 2010: The Architecture of Global Climate Governance: Setting the Stage. In: *Global Climate Governance Beyond 2012: Architecture, Agency and Adaptation* [Biermann, F., P. Pattberg and F. Zelli (eds.)]. Cambridge University Press, Cambridge, pp. 15-24. ISBN 9781139107150.
Biggs, E. M. et al., 2015: Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science & Policy*, **54**, 389-397, doi:https://doi.org/10.1016/j.envsci.2015.08.002.
Billi, M., G. Blanco and A. Urquiza, 2019: What is the 'Social' in Climate Change Research? A Case Study on Scientific Representations from Chile. *Minerva*, **57**(3), 293-315, doi:https://doi.org/10.1007/s11024-019-09369-2.
Bindoff, N. et al., 2019: Changing ocean, marine ecosystems, and dependent communities. In: *IPCC special report on the ocean and cryosphere in a changing climate*. Cambridge University Press.
Birkmann, J. et al., 2021a: Regional clusters of vulnerability show the need for transboundary cooperation. *Environmental Research Letters*, **16**, 094052, doi:https://doi.org/10.1088/1748-9326/ac1f43.
Birkmann, J. et al., 2022: Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning. *Science of The Total Environment*, **803**, 150065, doi:https://doi.org/10.1016/j.scitotenv.2021.150065.
Birkmann, J. et al., 2021b: New methods for local vulnerability scenarios to heat stress to inform urban planning—case study City of Ludwigsburg/Germany. *Climatic Change*, **165**(1-2), doi:10.1007/s10584-021-03005-3.
Birkmann, J. et al., 2020: Strengthening risk-informed decision-making: scenarios for human vulnerability and exposure to extreme events. *Disaster Prevention and Management: An International Journal*, **29**(5), 663–679, doi:10.1108/dpm-05-2020-0147.
Birkmann, J. and T. Welle, 2016: The WorldRiskIndex 2016: Reveals the necessity for regional cooperation in vulnerability reduction. *Journal of Extreme Events*, **3**(02), 1650005, doi:https://doi.org/10.1142/S2345737616500056.
Birkmann, J. et al., 2016: Boost resilience of small and mid-sized cities. *Nature*, **537**(7622), 605–608, doi:10.1038/537605a.
Black, R., S. R. G. Bennett, S. M. Thomas and J. R. Beddington, 2011: Migration as adaptation. *Nature*, **478**, 447-449, doi:https://doi.org/10.1038/478477a.
Blattman, C. and J. Annan, 2016: Can Employment Reduce Lawlessness and Rebellion? A Field Experiment with High-Risk Men in a Fragile State. *American Political Science Review*, **110**(1), 1-17, doi:10.1017/s0003055415000520.
Blench, R., 2001: *You Can't Go Home Again': Pastoralism in the New Millennium*. Overseas Development Institute London, London, O. D. I., London, 104 pp. Available at: https://cdn.odi.org/media/documents/6329.pdf.
Boda, C. S. et al., 2020: Framing Loss and Damage from climate change as the failure of Sustainable Development. *Climate and Development*, 1–8, doi:10.1080/17565529.2020.1851640.
Bodansky, D., 2016: The Paris climate change agreement: a new hope? *American Journal of International Law*, **110**(2), 288-319, doi:https://doi.org/10.5305/amerjintelaw.110.2.0288.
Boer, M. M., V. R. de Dios and R. A. Bradstock, 2020: Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, **10**(3), 171-172, doi:https://doi.org/10.1038/s41558-020-0716-1.
Bohra-Mishra, P., M. Oppenheimer and S. M. Hsiang, 2014: Nonlinear permanent migration response to climatic variations but minimal response to disasters. *Proceedings of the National Academy of Sciences*, **111**(27), 9780-9785, doi:https://doi.org/10.1073/pnas.1317166111.
Bollin, C. and R. Hidajat, 2013: Community-Based Risk Index: Pilot Implementation in Indonesia. In: *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies*, Second ed. [Birkmann, J. (ed.)]. United Nations University Press, Tokyo, Japan, pp. 383–400. ISBN 978-92-808-1202-2.

Bolognesi, M., A. Vrieling, F. Rembold and H. Gadain, 2015: Rapid mapping and impact estimation of illegal charcoal production in southern Somalia based on WorldView-1 imagery. *Energy for sustainable development*, **25**, 40-49, doi:https://doi.org/10.1016/j.esd.2014.12.008.

Booth, L. et al., 2020: Simulating synergies between Climate Change Adaptation and Disaster Risk Reduction stakeholders to improve management of transboundary disasters in Europe. *International journal of disaster risk reduction*, **49**, 101668, doi:https://doi.org/10.1016/j.ijdrr.2020.101668.

Booysen, M., C. Ripunda and M. Visser, 2019a: Results from a water-saving maintenance campaign at Cape Town schools in the run-up to Day Zero. *Sustainable Cities and Society*, **50**, 101639, doi:https://doi.org/10.1016/j.scs.2019.101639.

Booysen, M., M. Visser and R. Burger, 2019b: Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data. *Water research*, **149**, 414-420, doi:https://doi.org/10.1016/j.watres.2018.11.035.

Borderon, M. et al., 2019: Migration influenced by environmental change in Africa: A systematic review of empirical evidence. *Demographic Research*, **41**(18), 491-544, doi:10.4054/DemRes.2019.41.18.

Bordnera, A. S., C. E. Fergusona and L. Ortolanoa, 2020: Colonial dynamics limit climate adaptation in Oceania: Perspectives from the Marshall Islands. *Global Environmental Change*, **61**(102054), doi:doi.org/10.1016/j.gloenvcha.2020.102054.

Boullion, G. Q. et al., 2020: Meaning, social support, and resilience as predictors of posttraumatic growth: A study of the Louisiana flooding of August 2016. *The American journal of orthopsychiatry*, **90**(5), 578–585, doi:10.1037/ort0000464.

Bouwer, L. M., 2019: Observed and projected impacts from extreme weather events: implications for loss and damage. In: *Loss and damage from climate change* [Mechler, R., L. Bouwer, T. Schinko, S. Surminski and L.-B. J (eds.)]. Springer, Cham, pp. 63-82. ISBN 978-3-319-72025-8.

Bowen, A., S. Cochrane and S. Fankhauser, 2012: Climate change, adaptation and economic growth. *Climatic Change*, **113**(2), 95-106, doi:doi.org/10.1007/s10584-011-0346-8.

Boyd, E. et al., 2017: A typology of loss and damage perspectives. *Nature Climate Change*, **7**(10), 723-729, doi:10.1038/nclimate3389.

Boyd, E. et al., Recasting the Disproportionate Impacts of Climate Extremes, Lund University Centre For Sustainabilty Studies (LUCSUS), Lund. Available at: https://www.lucsus.lu.se/research/research-themes/climate-change-and-resilience/dice.

Brasilis, P. T., 2021: PRODES/Terra Brasilis. Available at: http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/amazon/increments (accessed 26/04/2021).

Brazil Ministry of Environment, 2016: *National Adaptation Plan to Climate Change: Volume I - General strategy*. Brazil Ministry of Enviroment, Brasilia, 310 pp. Available at: https://www4.unfccc.int/sites/NAPC/Documents/Parties/Brazil%20NAP%20English.pdf (accessed 18-05-2021).

Brida, A.-B., T. Owiyo and Y. Sokona, 2013: Loss and damage from the double blow of flood and drought in Mozambique. *International Journal of Global Warming*, **5**(4), 514–531, doi:http://dx.doi.org/10.1504/IJGW.2013.057291.

Bro, A. S., E. Moran and M. F. Calvi, 2018: Market participation in the age of big dams: the Belo Monte Hydroelectric Dam and its impact on rural agrarian households. *Sustainability*, **10**(5), 1592, doi:https://doi.org/10.3390/su10051592.

Bro, A. S., D. L. Ortega, D. C. Clay and R. B. Richardson, 2020: Understanding individuals' incentives for climate change adaptation in Nicaragua's coffee sector. *Climate and Development*, **12**(4), 332-342, doi:https://doi.org/10.1080/17565529.2019.1619506.

Brondízio, E. S., A. C. B. de Lima, S. Schramski and C. Adams, 2016: Social and health dimensions of climate change in the Amazon. *Annals of Human Biology*, **43**(4), 405-414, doi:10.1080/03014460.2016.1193222.

Brooks, N., J. Clarke, G. W. Ngaruiya and E. E. Wangui, 2020: African heritage in a changing climate. *Azania: Archaeological Research in Africa*, **55**(3), 297-328, doi:https://doi.org/10.1080/0067270X.2020.1792177.

Brown, I. F. et al., 2006: Monitoring fires in southwestern Amazonia Rain Forests. *Eos, Transactions American Geophysical Union*, **87**(26), 253-253, doi:10.1029/2006eo260001.

Brugnach, M., M. Craps and A. Dewulf, 2017: Including indigenous peoples in climate change mitigation: addressing issues of scale, knowledge and power. *Climatic change*, **140**(1), 19-32, doi:https://doi.org/10.1007/s10584-014-1280-3.

Brunner, R. and A. Lynch, 2010: *Adaptive governance and climate change*. American Meteorological Society, Boston. ISBN 978-1-935704-01-0.

Bryan, E., Q. Bernier, M. Espinal and C. Ringler, 2018: Making climate change adaptation programmes in sub-Saharan Africa more gender responsive: insights from implementing organizations on the barriers and opportunities. *Climate and Development*, **10**(5), 417-431, doi:https://doi.org/10.1080/17565529.2017.1301870.

Bryan, E. et al., 2017: Gender-Sensitive, Climate-Smart Agriculture for Improved Nutrition in Africa South of the Sahara. In: *A thriving agricultural sector in a changing climate: Meeting Malabo Declaration goals through climate-smart agriculture* [De Pinto, A. a. and J. M. Ulimwengu (eds.)]. International Food Policy Research Institute (IFPRI), Washington, D.C., pp. 114-135. ISBN 9780896292949.

Bryant, L. and B. Garnham, 2015: The fallen hero: masculinity, shame and farmer suicide in Australia. *Gender, Place & Culture*, **22**(1), 67-82, doi:https://doi.org/10.1080/0966369X.2013.855628.
Brymer, A. L. B., J. Wulfhorst and M. W. Brunson, 2018: Analyzing stakeholders' workshop dialogue for evidence of social learning. *Ecology and Society*, **23**(1), 42, doi:https://doi.org/10.5751/ES-09959-230142.
Buhaug, H. et al., 2014: One effect to rule them all? A comment on climate and conflict. *Climatic Change*, **127**(3), 391-397, doi:10.1007/s10584-014-1266-1.
Buhr, B. et al., 2018: *Climate Change and the Cost of Capital in Developing Countries: Assessing the Impact of Climate Risks on Sovereign Borrowing Costs*. Imperial College Business School SOAS University of London and UN Environment, School, I. C. B., London, 38 pp. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/26007/Climate_Change_Costs.pdf?sequence=1&isAllowed=y.
Burby, R. J., 2006: Hurricane Katrina and the Paradoxes of Government Disaster Policy: Bringing About Wise Governmental Decisions for Hazardous Areas. *The ANNALS of the American Academy of Political and Social Science*, **604**(1), 171-191, doi:10.1177/0002716205284676.
Burch, S. et al., 2019: New directions in earth system governance research. *Earth System Governance*, **1**, 100006, doi:https://doi.org/10.1016/j.esg.2019.100006.
Burke, L., K. Reytar, M. Spalding and A. Perry, 2011: Reefs at Risk Revisited. World Resources Institute, Washington, DC, pp. 113. ISBN 978-1-56973-762-0.
Burke, M., S. M. Hsiang and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**(7577), 235-239, doi:https://doi.org/10.1038/nature15725.
Burrows, K. and P. L. Kinney, 2016: Exploring the climate change, migration and conflict nexus. *International journal of environmental research and public health*, **13**(4), 443, doi:https://doi.org/10.3390/ijerph13040443.
Bush, M. B. et al., 2004: Amazonian paleoecological histories: one hill, three watersheds. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **214**(4), 359-393, doi:10.1016/j.palaeo.2004.07.031.
Bustamante, M. et al., 2014: Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Global change biology*, **20**(10), 3270–3290, doi:10.1111/gcb.12591.
Butler, J. et al., 2016: Building capacity for adaptation pathways in eastern Indonesian islands: synthesis and lessons learned. *Climate Risk Management*, **12**, A1-A10, doi:https://doi.org/10.1016/j.crm.2016.05.002.
Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, **13**(5), 055012, doi:https://doi.org/10.1088/1748-9326/aabf45.
Caetano, T., H. Winker and J. Depledge, 2020: Towards zero carbon and zero poverty: integrating national climate change mitigation and sustainable development goals. *Climate Policy*, **20**(7), 773-778, doi:https://doi.org/10.1080/14693062.2020.1791404.
Cai, R., S. Feng, M. Oppenheimer and M. Pytlikova, 2016: Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management*, **79**, 135-151, doi:https://doi.org/10.1016/j.jeem.2016.06.005.
Call, M. A., C. Gray, M. Yunus and M. Emch, 2017: Disruption, not displacement: environmental variability and temporary migration in Bangladesh. *Global environmental change*, **46**, 157-165, doi:https://doi.org/10.1016/j.gloenvcha.2017.08.008.
Cambaza, E. et al., 2019: Outbreak of Cholera Due to Cyclone Kenneth in Northern Mozambique, 2019. *International journal of environmental research and public health*, **16**(16), 2925, doi:https://dx.doi.org/10.3390%2Fijerph16162925.
Campanharo, W. et al., 2019: Translating Fire Impacts in Southwestern Amazonia into Economic Costs. *Remote Sensing*, **11**(7), 764-764, doi:10.3390/rs11070764.
Campbell, B. M. et al., 2018: Urgent action to combat climate change and its impacts (SDG 13): transforming agriculture and food systems. *Current opinion in environmental sustainability*, **34**, 13-20, doi:https://doi.org/10.1016/j.cosust.2018.06.005.
Cannon, T. and D. Müller-Mahn, 2010: Vulnerability, resilience and development discourses in context of climate change. *Natural Hazards*, **55**(3), 621-635, doi:10.1007/s11069-010-9499-4.
Cao, A. et al., 2021: Future of Asian Deltaic Megacities under sea level rise and land subsidence: current adaptation pathways for Tokyo, Jakarta, Manila, and Ho Chi Minh City. *Current Opinion in Environmental Sustainability*, **50**, 87-97, doi:https://doi.org/10.1016/j.cosust.2021.02.010.
Caplow, S., P. Jagger, K. Lawlor and E. Sills, 2011: Evaluating land use and livelihood impacts of early forest carbon projects: Lessons for learning about REDD+. *Environmental Science & Policy*, **14**(2), 152-167, doi:https://doi.org/10.1016/j.envsci.2010.10.003.
Cardona , A. O. D. et al., 2020: Slope Instability and Landslides. In: Adaptation to Climate Change Risks in Ibero-American Countries In: *RIOCCADAPT Report* [Moreno, J. M., C. Laguna-Defior, V. Barros, E. Calvo Buendía, J. A. Marengo and O. U. Spring (eds.)]. McGraw-Hill, Madrid, pp. 397-434. ISBN 9788448621667)

Cardona, O. D., 2017: *World at Risk: Revealing latent disasters*. 203 pp. Available at: https://www.researchgate.net/publication/322887085_World_at_Risk_Revealing_latent_disasters.

Cardona, O. D. et al., 2012: Determinants of risk: exposure and vulnerability. In: *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change* [Field, C. B., V. Barros, Stocker, T.F, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, pp. 65-108. ISBN ISBN 978-1-107-02506-6.
Carleton, T. A., 2017: Crop-damaging temperatures increase suicide rates in India. *Proceedings of the National Academy of Sciences*, **114**(33), 8746-8751, doi:https://doi.org/10.1073/pnas.1701354114.
Carmenta, R., E. Coudel and A. M. Steward, 2019: Forbidden fire: Does criminalising fire hinder conservation efforts in swidden landscapes of the Brazilian Amazon? *Geographical Journal*, doi:10.1111/geoj.12255.
Carmona, M. et al., 2017: Assessing the effectiveness of Multi-Sector Partnerships to manage droughts: The case of the Jucar river basin. *Earth's Future*, **5**(7), 750-770, doi:https://doi.org/10.1002/2017EF000545.
Carr-Hill, R., 2013: Missing millions and measuring development progress. *World Development*, **46**, 30-44, doi:https://doi.org/10.1016/j.worlddev.2012.12.017.
Carr, E. R., 2020: Resilient livelihoods in an era of global transformation. *Global Environmental Change*, **64**, 102155, doi:https://doi.org/10.1016/j.gloenvcha.2020.102155.
Carrao, H., G. Naumann and P. Barbosa, 2016: Mapping global patterns of drought risk: an empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change*, **39**, 108-124, doi:https://doi.org/10.1016/j.gloenvcha.2016.04.012.
Carter, S. et al., 2017: Large scale land acquisitions and REDD+: a synthesis of conflicts and opportunities. *Environmental Research Letters*, **12**(3), 035010, doi:https://doi.org/10.1088/1748-9326/aa6056.
Carter, T. R. et al., 2016: Characterising vulnerability of the elderly to climate change in the Nordic region. *Regional Environmental Change*, **16**(1), 43-58, doi:10.1007/s10113-014-0688-7.
Carter, T. R., M. Parry, H. Harasawa and S. Nishioka, 1994: *IPCC technical guidelines for assessing climate change impacts and adaptations*. IPCC technical guidelines for assessing climate change impacts and adaptations, University College London, London. ISBN 0 904813 11 8.
Castro-Diaz, L., M. C. Lopez and E. Moran, 2018: Gender-differentiated impacts of the Belo Monte hydroelectric dam on downstream fishers in the Brazilian Amazon. *Human ecology*, **46**(3), 411-422, doi:https://doi.org/10.1007/s10745-018-9992-z.
Caton, C. L., C. Wilkins and J. Anderson, 2007: *People who experience long-term homelessness: Characteristics and interventions*. Toward understanding homelessness: The 2007 national symposium on homelessness research, US Department of Health and Human Services and US Department of Housing, 44 pp. Available at: https://www.aspe.hhs.gov/sites/default/files/migrated_legacy_files//139161/report.pdf?_ga=2.258156106.1347889478.1630538260-577195147.1630538259.
Cattaneo, C. and G. Peri, 2016: The migration response to increasing temperatures. *Journal of Development Economics*, **122**, 127-146, doi:https://doi.org/10.1016/j.jdeveco.2016.05.004.
Chaffin, B. C., H. Gosnell and B. A. Cosens, 2014: A decade of adaptive governance scholarship: synthesis and future directions. *Ecology and Society*, **19**(3), doi:http://dx.doi.org/10.5751/ES-06824-190356.
Challinor, A. J., W. N. Adger and T. G. Benton, 2017: Climate risks across borders and scales. *Nature Climate Change*, **7**(9), 621-623, doi:https://doi.org/10.1038/nclimate3380.
Chambers, R. and G. R. Conway, 1992: *Sustainable rural livelihoods: practical concepts for the 21st century*. **IDS Discussion Paper**, Institute of Development Studies (IDS), Brighton, 33 pp. Available at: https://opendocs.ids.ac.uk/opendocs/bitstream/handle/20.500.12413/775/Dp296.pdf?sequence=1.
Chambwera, M. et al., 2014: Economics of Adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977. ISBN 9781107058071.
Chandra, A. et al., 2017: Gendered vulnerabilities of smallholder farmers to climate change in conflict-prone areas: A case study from Mindanao, Philippines. *Journal of Rural Studies*, **50**, 45-59, doi:https://doi.org/10.1016/j.jrurstud.2016.12.011.
Chanza, N. et al., 2020: Closing the Gaps in Disaster Management and Response: Drawing on Local Experiences with Cyclone Idai in Chimanimani, Zimbabwe. *International Journal of Disaster Risk Science*, 1-12, doi:https://doi.org/10.1007/s13753-020-00290-x.
Chapman, S. et al., 2019: The impact of climate change and urban growth on urban climate and heat stress in a subtropical city. *International Journal of Climatology*, **39**(6), 3013-3030, doi:10.1002/joc.5998.
Cheeseman, J., 2016: Food security in the face of salinity, drought, climate change, and population growth. In: *Halophytes for food security in dry lands* [Khan, M. A., M. Ozturk, B. Gul and M. Z. Ahmed (eds.)]. Elsevier, Oxford, pp. 111-123. ISBN 978-0-12-801854-5.
Cheung, W. W. L., G. Reygondeau and T. L. Frölicher, 2016: Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science*, **354**(6319), 1591-1594, doi:10.1126/science.aag2331.
Chiba, Y., R. Shaw and S. Prabhakar, 2017: Climate change-related non-economic loss and damage in Bangladesh and Japan. *International Journal of Climate Change Strategies and Management*, doi:10.1108/ijccsm-05-2016-0065.

Chin-Yee, S., 2019: *Climate change and human security: case studies linking vulnerable populations to increased security risks in the face of the global climate challenge*. EUCERS Strategy Paper, King's College London The European Centre for Energy and Resource Security (EUCERS), Eucers, London, 2-31 pp.
Chinowsky, P. S., A. E. Schweikert, N. L. Strzepek and K. Strzepek, 2015: Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia. *Climatic Change*, **130**(1), 49-62, doi:https://doi.org/10.1007/s10584-014-1219-8.
Chinseu, E. L., L. C. Stringer and A. J. Dougill, 2019: An Empirically Derived Conceptual Framework to Assess Dis-Adoption of Conservation Agriculture: Multiple Drivers and Institutional Deficiencies. *Journal of Sustainable Development*, **12**(5), 48-64, doi:10.5539/jsd.v12n5p48.
Cho, H., 2017: The effects of summer heat on academic achievement: A cohort analysis. *Journal of Environmental Economics and Management*, **83**, 185-196, doi:doi.org/10.1016/j.jeem.2017.03.005.
Choudhary, B. K., A. K. Tripathi and J. Rai, 2019: Can 'poor'cities breathe: Responses to climate change in low-income countries. *Urban Climate*, **27**, 403-411, doi:https://doi.org/10.1016/j.uclim.2019.01.001.
Chowdhury, A. M. R., A. U. Bhuyia, A. Y. Choudhury and R. Sen, 1993: The Bangladesh cyclone of 1991: why so many people died. *Disasters*, **17**(4), 291-304, doi:https://doi.org/10.1111/j.1467-7717.1993.tb00503.x.
Chu, E. and K. Michael, 2019: Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. *Environment and Urbanization*, **31**(1), 139–156, doi:10.1177/0956247818814449.
Cinner, J. E. et al., 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, **8**(2), 117, doi:https://doi.org/10.1038/s41558-017-0065-x.
Clark, H. et al., 2020: A future for the world's children? A WHO–UNICEF–Lancet Commission. *The Lancet*, **395**(10224), 605-658, doi:https://doi.org/10.1016/S0140-6736(19)32540-1.
Clarke, B. J., F. E. Otto and R. G. Jones, 2021: Inventories of extreme weather events and impacts: Implications for loss and damage from and adaptation to climate extremes. *Climate Risk Management*, **32**, 100285, doi:https://doi.org/10.1016/j.crm.2021.100285.
Clemens, J. and S. Veuger, 2020: Implications of the Covid-19 Pandemic for State Government Tax Revenues. *National Tax Journal*, **73**(3), 619-644, doi:10.17310/ntj.2020.3.01.
Clissold, R., R. Westoby and K. E. McNamara, 2020: Women as recovery enablers in the face of disasters in Vanuatu. *Geoforum*, **113**, 101-110, doi:https://doi.org/10.1016/j.geoforum.2020.05.003.
CoCT, 2019: *Cape Town Resilience Strategy*. City of Cape Town CoCT, Cape Town, 156 pp. Available at: https://resource.capetown.gov.za/documentcentre/Documents/City%20strategies%2C%20plans%20and%20frameworks/Resilience_Strategy.pdf.
Cole, D. H., 2015: Advantages of a polycentric approach to climate change policy. *Nature Climate Change*, **5**(2), 114, doi:https://doi.org/10.1038/nclimate2490.
Cole, H. D. et al., 2021: Managing city-scale slow-onset disasters: Learning from Cape Town's 2015–2018 drought disaster planning. *International Journal of Disaster Risk Reduction*, **63**, 102459, doi:10.1016/j.ijdrr.2021.102459.
Collins, K. and R. Ison, 2009: Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. *Environmental Policy and Governance*, **19**(6), 358-373, doi:10.1002/eet.523.
Connolly-Boutin, L. and B. Smit, 2016: Climate change, food security, and livelihoods in sub-Saharan Africa. *Regional Environmental Change*, **16**(2), 385-399, doi:https://doi.org/10.1007/s10113-015-0761-x.
Connop, S. et al., 2016: Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure. *Environmental Science & Policy*, **62**, 99-111, doi:10.1016/j.envsci.2016.01.013.
Conway, D. et al., 2019: The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions. *Nature Climate Change*, **9**(7), 503-511, doi:10.1038/s41558-019-0502-0.
Conway, D. et al., 2015: Climate and southern Africa's water–energy–food nexus. *Nature Climate Change*, **5**(9), 837-846, doi:https://doi.org/10.1038/nclimate2735.
Cordeiro-Beduschi, L. E., 2020: Forest Governance in Brazil and Chile: Institutions and Practices in the Implementation of Sustainable Management of Native Forests. In: *Ecological Economic and Socio Ecological Strategies for Forest Conservation* [Fuders, F. and P. J. Donoso (eds.)]. Springer International Publishing, Cham, pp. 213–226. ISBN 978-3-030-35378-0.
Cox, P. M. et al., 2004: Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical and applied climatology*, **78**(1-3), 137-156, doi:https://doi.org/10.1007/s00704-004-0049-4.
CPI, 2019: *Global Landscape of Climate Finance* [Buchner, B., A. Clark, A. Falconer, R. Macquarie, C. Meat tle, R. Tolentino and C. Wetherbee (eds.)]. Climate Policy Initiative, London, 38 pp. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2019/11/2019-Global-Landscape-of-Climate-Finance.pdf.
Cramer, W. et al., 2014: Detection and Attribution of Observed Impacts. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 979-1037. ISBN 9781107058071.
Craparo, A. et al., 2015: Coffea arabica yields decline in Tanzania due to climate change: Global implications. *Agricultural and Forest Meteorology*, **207**, 1-10, doi:https://doi.org/10.1016/j.agrformet.2015.03.005.

Crate, S. A., 2011: Climate and culture: anthropology in the era of contemporary climate change. *Annual Review of Anthropology*, **40**, 175-194, doi:10.1146/annurev.anthro.012809.104925.
Crate, S. A. and M. Nuttall, 2009: Epilogue: anthropology, science, and climate change policy. In: *Anthropology & Climate change. From encounters to actions* [Crate, S. A. and M. Nuttall (eds.)]. Left Coast Press, Inc., California, pp. 394-400. ISBN 978-1-59874-333-3.
Crawford, A. et al., 2015: *Promoting Climate-Resilient Peacebuilding in Fragile States*. The International Institute for Sustainable Development, Development, T. I. I. f. S., Manitoba. Available at: https://www.iisd.org/system/files/publications/promoting-climate-resilient-peacebuilding-fragile-states.pdf.
CRED, 2015: *Human Cost of Natural Disasters: An Overview of the last 20 Years 2000-2019*. Center for Research on the Epidemiology of Disasters (CRED) UN Office for Disaster Risk Reduction (UNDRR), Disasters, C. f. R. o. t. E. o., Louvain. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/Human%20Cost%20of%20Disasters%202000-2019%20Report%20-%20UN%20Office%20for%20Disaster%20Risk%20Reduction.pdf.
CRED, 2020: Emergency Events Database (EM-DAT), Centre for Research on the Epidemiology of Disasters (CRED). Available at: https://public.emdat.be/data.
CRED and UNDRR, 2020: *2020: The Non-COVID Year in Disasters - Global Trends and Perspectives*. Centre for Research on the Epidemiology of Disasters (CRED) and UN Office for Disaster Risk Reduction, Louvain and Geneva, 8 pp. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/2020%20-%20the%20non-COVID%20Year%20in%20Disasters%20-%20Global%20Trends%20and%20Perspectives.pdf.
Cronin, J., G. Anandarajah and O. Dessens, 2018: Climate change impacts on the energy system: a review of trends and gaps. *Climatic Change*, **151**, 79–93, doi:https://doi.org/10.1007/s10584-018-2265-4.
Cundill, G. et al., 2019: Large-scale transdisciplinary collaboration for adaptation research: Challenges and insights. *Global Challenges*, **3**(4), 1700132, doi:https://doi.org/10.1002/gch2.201700132.
Curtain, R. and M. Dornan, 2019: *A pressure release valve? Migration and climate change in Kiribati, Nauru and Tuvalu*. Development Policy Centre, The Australian National University, Development Policy Centre, T. A. N. U., Canberra. Available at: https://devpolicy.org/publications/reports/Migration-climate%20change-Kiribati-Nauru-Tuvalu.pdf.
Curtis, K. J., E. Fussell and J. DeWaard, 2015: Recovery migration after Hurricanes Katrina and Rita: Spatial concentration and intensification in the migration system. *Demography*, **52**(4), 1269-1293, doi:https://doi.org/10.1007/s13524-015-0400-7.
Cutter, S. L., 2018: Linkages between vulnerability and resilience. In: *Vulnerability and resilience to natural hazards* [Fuchs, S. and T. Thaler (eds.)]. Cambridge University Press, Cambridge, pp. 257-270. ISBN 9781107154896
Cutter, S. L., K. D. Ash and C. T. Emrich, 2016: Urban-Rural Differences in Disaster Resilience. *Annals of the American Association of Geographers*, **106**(6), 1236–1252, doi:https://doi.org/10.1080/24694452.2016.1194740.
Cutter, S. L., B. J. Boruff and W. L. Shirley, 2003: Social Vulnerability to Environmental Hazards*. *Social Science Quarterly*, **84**(2), 242–261, doi:10.1111/1540-6237.8402002.
Cutter, S. L. and C. Finch, 2008: Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the national academy of sciences*, **105**(7), 2301-2306, doi:https://doi.org/10.1073/pnas.0710375105.
Da Costa, K., 2014: Can the observance of human rights of individuals enhance their resilience to cope with natural disasters? In: *4th International Conference on Building Resilience, Building Resilience 2014*, Salford Quays, UK, Procedia Economics and Finance, **18**, pp. 62-70, doi:doi: 10.1016/S2212-5671(14)00914-9.
da Cunha, M. C., 2020: Chapter 8. Antidomestication in the Amazon: Swidden and its Foes. *Hau: Journal of Ethnographic Theory*, **9**(1), 36–182, doi:https://doi.org/10.1086/703870.
Dagnachew, A. G., P. L. Lucas, A. F. Hof and D. P. van Vuuren, 2018: Trade-offs and synergies between universal electricity access and climate change mitigation in Sub-Saharan Africa. *Energy Policy*, **114**, 355–366, doi:10.1016/j.enpol.2017.12.023.
Dahlke, F. T., S. Wohlrab, M. Butzin and H.-O. Pörtner, 2020: Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, **369**(2), 65–70, doi:10.1126/science.aaz3658.
Dang, H. H., A. Michaelowa and D. D. Tuan, 2003: Synergy of adaptation and mitigation strategies in the context of sustainable development: the case of Vietnam. *Climate policy*, **3**(sup1), S81-S96, doi:https://doi.org/10.1016/j.clipol.2003.10.006.
Dasgupta, S., M. D. Moqbul Hossain, M. Huq and D. Wheeler, 2016: Facing the Hungry Tide: Climate Change, Livelihood Threats, and Household Responses in Coastal Bangladesh. *Climate Change Economics*, **07**(03), doi:10.1142/s201000781650007x.
Dawson, A., 2017: *Extreme cities: The peril and promise of urban life in the age of climate change*. Verso Books, London, 385 pp. ISBN 1784780375.
De Brauw, A., V. Mueller and H. L. Lee, 2014: The role of rural–urban migration in the structural transformation of Sub-Saharan Africa. *World Development*, **63**, 33-42, doi:https://doi.org/10.1016/j.worlddev.2013.10.013.
de Coninck, H. et al., 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R.

Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
De Longueville, F. et al., 2020: Comparing climate change perceptions and meteorological data in rural West Africa to improve the understanding of household decisions to migrate. *Climatic Change*, **160**(1), 123-141, doi:https://doi.org/10.1007/s10584-020-02704-7.
de Sherbinin, A., 2014: Climate change hotspots mapping: what have we learned? *Climatic Change*, **123**(1), 23-37, doi:https://doi.org/10.1007/s10584-013-0900-7.
de Sherbinin, A., A. Apotsos and J. Chevrier, 2017: Mapping the future: Policy applications of climate vulnerability mapping in West Africa. *The Geographical Journal*, **183**(4), 414-425, doi:https://doi.org/10.1111/geoj.12226.
de Sherbinin, A. et al., 2019: Climate vulnerability mapping: A systematic review and future prospects. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(5), e600, doi:https://doi.org/10.1002/wcc.600.
de Sherbinin, A. et al., 2011: Preparing for Resettlement Associated with Climate Change. *Science*, **334**, 456-457, doi:10.1126/science.1208821.
DEDAT, 2018: *Potential economic impacts of the water crisis in the Western Cape, with a specific focus on Cape Town: Synthesis Report*. Department of Economic Development and Tourism of the Western Cape Government (DEDAT), Cape Town, South Africa, 1-17 pp. Available at: https://www.westerncape.gov.za/documents.
DeFries, R. S. et al., 2019: *The missing economic risks in assessments of climate change impacts*. The Grantham Research Institute on Climate Change and the Environment; The Earth Institute; The Potsdam Institute for Climate Impact Research, Environment, G. R. I. o. C. C. a. t., London, 15 pp. Available at: https://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2019/09/The-missing-economic-risks-in-assessments-of-climate-change-impacts-1.pdf.
DeLonge, M. and A. Basche, 2017: Leveraging agroecology for solutions in food, energy, and water. *Elementa: Science of the Anthropocene*, **5**, doi:10.1525/elementa.211.
Demski, C. et al., 2017: Experience of extreme weather affects climate change mitigation and adaptation responses. *Climatic Change*, **140**(2), 149-164, doi:https://doi.org/10.1007/s10584-016-1837-4.
Dennig, F. et al., 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proc Natl Acad Sci U S A*, **112**(52), 15827-15832, doi:10.1073/pnas.1513967112.
Denton, F. et al., 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131. ISBN 9781107058071.
Depietri, Y., T. Welle and F. G. Renaud, 2013: Social vulnerability assessment of the Cologne urban area (Germany) to heat waves: links to ecosystem services. *International Journal of Disaster Risk Reduction*, **6**, 98-117, doi:10.1016/j.ijdrr.2013.10.001.
Descheemaeker, K. et al., 2016: Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments. *Regional Environmental Change*, **16**(8), 2331-2343, doi:https://doi.org/10.1007/s10113-016-0957-8.
DETER and INPE, Alertas do DETER na Amazônia em junho somam 2.072,03 km², Instituto Nacional de Pesquisas Espaciais. Available at: http://www.inpe.br/noticias/noticia.php?Cod_Noticia=5147.
Devictor, X. and Q.-T. Do, 2016: *How many years have refugees been in exile?* Policy Research Working Paper, The World Bank, Bank, T. W., 17 pp. Available at: https://elibrary.worldbank.org/doi/pdf/10.1596/1813-9450-7810.
Di Baldassarre, G. et al., 2010: Flood fatalities in Africa: from diagnosis to mitigation. *Geophysical Research Letters*, **37**(22), doi:http://dx.doi.org/10.1029/2010GL045467.
Di Gregorio, M. et al., 2017: Climate policy integration in the land use sector: Mitigation, adaptation and sustainable development linkages. *Environmental Science & Policy*, **67**, 35-43, doi:https://doi.org/10.1016/j.envsci.2016.11.004.
Dietz, T., E. Ostrom and P. C. Stern, 2003: The struggle to govern the commons. *Science*, **302**(5652), 1907-1912, doi:10.1126/science.1091015.
Djalante, R., 2019: Key assessments from the IPCC special report on global warming of 1.5° C and the implications for the Sendai framework for disaster risk reduction. *Progress in Disaster Science*, **1**, 100001, doi:https://doi.org/10.1016/j.pdisas.2019.100001.
Djalante, R., R. Shaw and A. DeWit, 2020: Building resilience against biological hazards and pandemics: COVID-19 and its implications for the Sendai Framework. *Progress in Disaster Science*, **6**, 100080, doi:https://doi.org/10.1016/j.pdisas.2020.100080.
Djoudi, H. et al., 2016: Beyond dichotomies: Gender and intersecting inequalities in climate change studies. *Ambio*, **45**(3), 248-262, doi:https://doi.org/10.1007/s13280-016-0825-2.
do Carmo, C. N., M. B. Alves and S. d. S. Hacon, 2013: Impact of biomass burning and weather conditions on children's health in a city of Western Amazon region. *Air Quality, Atmosphere and Health*, doi:10.1007/s11869-012-0191-6.

Dodman, D., H. Leck, M. Rusca and S. Colenbrander, 2017: African urbanisation and urbanism: Implications for risk accumulation and reduction. *International journal of disaster risk reduction*, **26**, 7-15, doi:https://doi.org/10.1016/j.ijdrr.2017.06.029.
Doelle, M., 2016: The Paris Agreement: historic breakthrough or high stakes experiment? *Climate Law*, **6**(1-2), 1-20, doi:http://dx.doi.org/10.1163/18786561-00601001.
Dogru, T., E. A. Marchio, U. Bulut and C. Suess, 2019: Climate change: Vulnerability and resilience of tourism and the entire economy. *Tourism Management*, **72**, 292-305, doi:https://doi.org/10.1016/j.tourman.2018.12.010.
Dong, W. et al., 2015: New climate and socio-economic scenarios for assessing global human health challenges due to heat risk. *Climatic Change*, **130**(4), 505-518, doi:10.1007/s10584-015-1372-8.
Dorsch, M. J. and C. Flachsland, 2017: A Polycentric Approach to Global Climate Governance. *Global Environmental Politics*, **17**(2), 45-64, doi:10.1162/GLEP_a_00400.
Dougill, A. J. et al., 2017: Mainstreaming conservation agriculture in Malawi: Knowledge gaps and institutional barriers. *Journal of environmental management*, **195**, 25-34, doi:https://doi.org/10.1016/j.jenvman.2016.09.076.
Douglass, K. and J. Cooper, 2020: Archaeology, environmental justice, and climate change on islands of the Caribbean and southwestern Indian Ocean. *Proceedings of the National Academy of Sciences*, **117**(15), 8254-8262, doi:10.1073/pnas.1914211117.
Dovie, D. B. K., 2019: Case for equity between Paris Climate agreement's Co-benefits and adaptation. *Science of the Total Environment*, **656**, 732-739, doi:https://doi.org/10.1016/j.scitotenv.2018.11.333.
Dovie, D. B. K. and S. Lwasa, 2017: Correlating negotiation hotspot issues, Paris climate agreement and the international climate policy regime. *Environmental Science & Policy*, **77**, 1-8, doi:https://doi.org/10.1016/j.envsci.2017.07.010.
Drenkhan, F., C. Huggel, L. Guardamino and W. Haeberli, 2019: Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin. *Science of the Total Environment*, **665**, 465-483, doi:https://doi.org/10.1016/j.scitotenv.2019.02.070.
du Pont, Y. R. et al., 2017: Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, **7**(1), 38-43, doi:https://doi.org/10.1038/nclimate3186.
Dube, E. and E. Munsaka, 2018: The contribution of indigenous knowledge to disaster risk reduction activities in Zimbabwe: A big call to practitioners. *Jàmbá: Journal of Disaster Risk Studies*, **10**(1), 493, doi:10.4102/jamba.v10i1.493.
Duchelle, A. E., G. Simonet, W. D. Sunderlin and S. Wunder, 2018: What is REDD+ achieving on the ground? *Current Opinion in Environmental Sustainability*, **32**, 134-140, doi:https://doi.org/10.1016/j.cosust.2018.07.001.
Dückers, M., G. Frerks and J. Birkmann, 2015: Exploring the plexus of context and consequences: An empirical test of a theory of disaster vulnerability. *International Journal of Disaster Risk Reduction*, **13**, 85–95, doi:https://doi.org/10.1016/j.ijdrr.2015.04.002.
Duguma, L. A., P. A. Minang and M. van Noordwijk, 2014a: Climate change mitigation and adaptation in the land use sector: from complementarity to synergy. *Environmental management*, **54**(3), 420-432, doi:https://doi.org/10.1007/s00267-014-0331-x.
Duguma, L. A., S. W. Wambugu, P. A. Minang and M. Van Noordwijk, 2014b: A systematic analysis of enabling conditions for synergy between climate change mitigation and adaptation measures in developing countries. *Environmental Science & Policy*, **42**, 138-148, doi:https://doi.org/10.1016/j.envsci.2014.06.003.
Dzebo, A., 2019: Effective governance of transnational adaptation initiatives. *International Environmental Agreements: Politics, Law and Economics*, **19**(4-5), 447-466, doi:https://doi.org/10.1007/s10784-019-09445-8.
Earle, A. et al., 2015: *Transboundary water management and the climate change debate*. Routledge, London. ISBN 9780415835152.
Ebi, K. L., J. J. Hess and P. Watkiss, 2017: Health risks and costs of climate variability and change. In: *Injury Prevention and Environmental Health.*, 3rd ed. [Mock, C. N., R. Nugent, O. Kobusingye and K. R. Smith (eds.)]. The International Bank for Reconstruction and Development / The World Bank;, Washington DC, pp. 153-169. ISBN 978-1-4648-0521-9.
EC-DRMKC, INFORM Risk, European Commission Joint Research Center. Available at: https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk/Results-and-data/moduleId/1782/id/419/controller/Admin/action/Results.
Eckstein, D., V. Künzel, L. Schäfer and M. Winges, 2019: *Global climate risk index 2020: Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2018 and 1999 to 2018*. **20**, Germanwatch e.V., Briefing Paper ed., Bonn, 44 pp. Available at: https://germanwatch.org/sites/default/files/20-2-01e%20Global%20Climate%20Risk%20Index%202020_14.pdf.
Eklöw, K. and F. Krampe, 2019: *Climate-related security risks and peacebuilding in Somalia*. **SIPRI Policy Paper**, Stockholm International Peace Research Institute (SIPRI), Institute, S. I. P. R., Solna. Available at: https://www.sipri.org/sites/default/files/2019-10/sipripp53_2.pdf.
Elbehri, A., J. Elliott and T. Wheele, 2015: Climate change, food security and trade: An overview of global assessments and policy insights. In: *Climate change and food systems: global assessments and implications for food security and trade.* [Elbehri, A. (ed.)]. Food Agriculture Organization of the United Nations (FAO), Rome, pp. 1-27. ISBN 978-92-5-108699-5.

Ellis, N. R. and P. Tschakert, 2019: Triple-wins as pathways to transformation? A critical review. *Geoforum*, **103**, 167-170, doi:https://doi.org/10.1016/j.geoforum.2018.12.006.
Eloy, L., S. Hecht, A. Steward and J. Mistry, 2019: Firing up: Policy, politics and polemics under new and old burning regimes. *The Geographical Journal*, **185**(1), 2-9, doi:10.1111/geoj.12293.
Emmanuel, R. and A. Loconsole, 2015: Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley Region, UK. *Landscape and Urban Planning*, **138**, 71-86, doi:10.1016/j.landurbplan.2015.02.012.
England, M. I. et al., 2018: Climate change adaptation and cross-sectoral policy coherence in southern Africa. *Regional Environmental Change*, **18**(7), 2059-2071, doi:https://doi.org/10.1007/s10113-018-1283-0.
Enqvist, J. P. and G. Ziervogel, 2019: Water governance and justice in cape town: An overview. *Wiley Interdisciplinary Reviews: Water*, **6**, e1354, doi:https://doi.org/10.1002/wat2.1354.
Ensor, J. and B. Harvey, 2015: Social learning and climate change adaptation: evidence for international development practice. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(5), 509-522, doi:10.1002/wcc.348.
Ensor, J. E., S. E. Park, E. T. Hoddy and B. D. Ratner, 2015: A rights-based perspective on adaptive capacity. *Global Environmental Change*, **31**, 38-49, doi:https://doi.org/10.1016/j.gloenvcha.2014.12.005.
Eriksen, C. et al., 2020: Rethinking the interplay between affluence and vulnerability to aid climate change adaptive capacity. *Climatic Change*, **162**, 25-39, doi:https://doi.org/10.1007/s10584-020-02819-x.
Eriksen, S. et al., 2011: When not every response to climate change is a good one: Identifying principles for sustainable adaptation. *Climate and Development*, **3**(1), 7–20, doi:10.3763/cdev.2010.0060.
Eriksen, S. et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: help, hindrance or irrelevance? *World Development*, **141**, 105383, doi:https://doi.org/10.1016/j.worlddev.2020.105383.
Eriksen, S. H., A. J. Nightingale and H. Eakin, 2015: Reframing adaptation: The political nature of climate change adaptation. *Global Environmental Change*, **35**, 523-533, doi:https://doi.org/10.1016/j.gloenvcha.2015.09.014.
Erman, A. et al., 2019: *Wading out the storm: The role of poverty in exposure, vulnerability and resilience to floods in Dar Es Salaam*. **Policy Research Working Paper**, The World Bank, Washington, DC., 8976 pp. Available at: https://openknowledge.worldbank.org/handle/10986/32269.
Escarcha, J. F., J. A. Lassa, E. P. Palacpac and K. K. Zander, 2020: Livelihoods transformation and climate change adaptation: The case of smallholder water buffalo farmers in the Philippines. *Environmental Development*, **33**, 100468, doi:https://doi.org/10.1016/j.envdev.2019.100468.
Escobar, H., 2019: Amazon fires clearly linked to deforestation, scientists say. *Science*, **365**(6456), 853, doi:https://doi.org/10.1126/science.365.6456.853.
Eugenio, E. A. et al., 2016: Adaptive capacity of Philippine communities vulnerable to flash floods and landslides: assessing loss and damage from typhoon Bopha in Eastern Mindanao. *International Journal of Sustainable Development & World Ecology*, **19**(3), 279-314, doi:https://doi.org/10.1504/IJSD.2016.078290.
Evans, L. S. et al., 2016: Structural and psycho-social limits to climate change adaptation in the Great Barrier Reef Region. *PloS one*, **11**(3), e0150575, doi:https://doi.org/10.1371/journal.pone.0150575.
Evers, J. and A. Pathirana, 2018: Adaptation to climate change in the Mekong River Basin: introduction to the special issue. *Climatic Change*, **419**, 1-11, doi:https://doi.org/10.1007/s10584-018-2242-y.
Ezeh, A. et al., 2017: The history, geography, and sociology of slums and the health problems of people who live in slums. *The lancet*, **389**(10068), 547-558, doi:https://doi.org/10.1016/s0140-6736(16)31650-6.
Fang, J. et al., 2019: Natural disasters, climate change, and their impact on inclusive wealth in G20 countries. *Environmental Science and Pollution Research*, **26**(2), 1455-1463, doi:https://doi.org/10.1007/s11356-018-3634-2.
Fankhauser, S., 2017: Adaptation to Climate Change. *Annual Review of Resource Economics*, **9**, 209-230, doi:https://doi.org/10.1146/annurev-resource-100516-033554.
Fankhauser, S. and T. K. J. McDermott, 2014: Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change*, **27**, 9-18, doi:doi.org/10.1016/j.gloenvcha.2014.04.014.
FAO, 2017: *Climate Smart Agriculture Source Book*, 2nd ed., Food and Agriculture Organization of the United Nations (FAO), Rome, 56 pp. ISBN 978-92-5-109988-9.
FAO, 2018: *Mongolia, Impact of Early Warning Early Action: Protecting the livelihoods of herders from a dzud winter*. Food and Agriculture Organization (FAO), Food and O. Agriculture, Rome, 32 pp. Available at: http://www.fao.org/3/ca2181en/CA2181EN.pdf (accessed 15-03-2021).
FAO, 2020: *Addressing inequality in times of COVID-19*. **Policy Brief**, Food and Agriculture Organization of the United Nations (FAO), Rome, 11 pp. Available at: http://www.fao.org/3/ca8843en/CA8843EN.pdf.
Fayazi, M., I.-A. Bisson and E. Nicholas, 2020: Barriers to climate change adaptation in indigenous communities: A case study on the mohawk community of Kanesatake, Canada. *International Journal of Disaster Risk Reduction*, **49**, 101750, doi:doi.org/10.1016/j.ijdrr.2020.101750.
Feeny, E. and T. Chagutah, 2016: The Longest Lean Season': How urgent action is needed to counter the devastating humanitarian impacts of the El Nino drought in Southern Africa. Oxfam International, Oxford.
Fekete, A., 2019: Social Vulnerability (Re-)Assessment in Context to Natural Hazards: Review of the Usefulness of the Spatial Indicator Approach and Investigations of Validation Demands. *International Journal of Disaster Risk Science*, **10**(2), 220–232, doi:10.1007/s13753-019-0213-1.

Feldmeyer, D. et al., 2021: Global vulnerability hotspots: differences and agreement between international indicator-based assessments. *Climatic Change*,(In press), doi:10.1007/s10584-021-03203-z
Feldmeyer, D., J. Birkmann and T. Welle, 2017: Development of Human Vulnerability 2012–2017. *Journal of Extreme Events*, **4**(04), 1850005, doi:https://doi.org/10.1142/S2345737618500057.
Fellows, M. et al., 2020: *They Are not Numbers. They Are Lives! COVID-19 threatens indigenous peoples in the Brazilian Amazon*. Amazon Environmental Research Institute (IPAM) Coordination of the Indigenous Organizations of the Brazilian Amazon (COIAB), 22 pp. Available at: https://ds.saudeindigena.icict.fiocruz.br/bitstream/bvs/2806/1/Fellows%20et%20al.%20-%202020%20-%20They%20Are%20not%20Numbers.%20They%20Are%20Lives%21%20COVID-19%20thr.pdf.
Ferrante, L. and P. M. Fearnside, 2019: Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate. *Environmental Conservation*, **46**(4), 261-263, doi:https://doi.org/10.1017/S0376892919000213.
Few, R. et al., 2017: Transformation, adaptation and development: relating concepts to practice. *Palgrave Communications*, **3**, doi:doi.org/10.1057/palcomms.2017.92.
FFP, 2020: *Fragile State Index: Annual Report 2020*. The Fund for Peace, Washington, D.C. Available at: https://fragilestatesindex.org/wp-content/uploads/2020/05/fsi2020-report.pdf.
Fielding, J. L., 2018: Flood risk and inequalities between ethnic groups in the floodplains of England and Wales. *Disasters*, **42**(1), 101-123, doi:https://doi.org/10.1111/disa.12230.
Filkov, A. I. et al., 2020: Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science and Resilience*, **1**(1), 44-56, doi:https://doi.org/10.1016/j.jnlssr.2020.06.009.
Finkbeiner, E. M. et al., 2018: Exploring trade-offs in climate change response in the context of Pacific Island fisheries. *Marine Policy*, **88**, 359-364, doi:https://doi.org/10.1016/j.marpol.2017.09.032.
Fischel de Andrade, J. H. and A. de Lima Madureira, 2021: Protection in Natural Disasters: the response to Cyclone Idai in Mozambique. *Journal of Refugee Studies*, **feab056**, doi:https://doi.org/10.1093/jrs/feab056.
Fisher, S. and D. Dodman, 2019: Urban climate change adaptation as social learning: Exploring the process and politics. *Environmental Policy and Governance*, **29**(3), 235-247, doi:https://doi.org/10.1002/eet.1851.
Flavell, A., S. Melde and A. Milan, 2020: *Migration, environment and climate change: Impacts Second report in the "Migration, environment and climate change" series*. Migration, environment and climate change, Global Migration Data Analysis Centre (GMDAC) International Organization for Migration (IOM), Agency, G. E., Dessau-Roßlau. Available at: http://www.umweltbundesamt.de/publikationen.
Fleischman, F. et al., 2020: Pitfalls of tree planting show why we need people-centered natural climate solutions. *BioScience*, **70**(11), 947–950, doi:https://doi.org/10.1093/biosci/biaa094.
Ford, A., R. Dawson, P. Blythe and S. Barr, 2018: Land-use transport models for climate change mitigation and adaptation planning. *Journal of Transport and Land Use*, **11**(1), 83-101, doi:https://doi.org/10.5198/jtlu.2018.1209.
Ford, J. D. et al., 2016: Including indigenous knowledge and experience in IPCC assessment reports. *Nature Climate Change*, **6**(4), 349, doi:https://doi.org/10.1038/nclimate2954.
Ford, J. D., G. McDowell and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5**(12), 1046-1053, doi:https://doi.org/10.1038/nclimate2723.
Formetta, G. and L. Feyen, 2019: Empirical evidence of declining global vulnerability to climate-related hazards. *Global Environmental Change*, **57**, 101920, doi:https://doi.org/10.1016/j.gloenvcha.2019.05.004.
Forster, P. M. et al., 2020: Current and future global climate impacts resulting from COVID-19. . *Nature Climate Change*, **10**, 913-919, doi:https://doi.org/10.1038/s41558-020-0883-0.
Forzieri, G. et al., 2016: Multi-hazard assessment in Europe under climate change. *Climatic Change*, **137**(1-2), 105-119, doi:https://doi.org/10.1007/s10584-016-1661-x.
Frame, B. et al., 2018: Adapting global shared socio-economic pathways for national and local scenarios. *Climate Risk Management*, **21**, 39-51, doi:10.1016/j.crm.2018.05.001.
Frankenberg, E. et al., 2013: Education, Vulnerability, and Resilience after a Natural Disaster. *Ecology and Society*, **18**(2), 16, doi:10.5751/es-05377-180216.
Frantzeskaki, N. et al., 2019: Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making. *BioScience*, **69**(6), 455-466, doi:https://doi.org/10.1093/biosci/biz042.
Fraser, T., D. P. Aldrich and A. Small, 2021: Seawalls or social recovery? The role of policy networks and design in disaster recovery. *Global Environmental Change*, **70**, 102342, doi:https://doi.org/10.1016/j.gloenvcha.2021.102342.
Friedman, R., M. A. Hirons and E. Boyd, 2019: Vulnerability of Ghanaian women cocoa farmers to climate change: a typology. *Climate and Development*, **11**(5), 446-458, doi:https://doi.org/10.1080/17565529.2018.1442806.
Fritzell, J., J. Rehnberg, J. B. Hertzman and J. Blomgren, 2015: Absolute or relative? A comparative analysis of the relationship between poverty and mortality. *International journal of public health*, **60**(1), 101-110, doi:https://doi.org/10.1007/s00038-014-0614-2.
Frose, R. and J. Schiling, 2019: The Nexus of Climate Change, Land Use, and Conflicts. *Current Climate Change Reports*, **5**(1), 24–35, doi:https://doi.org/10.1007/s40641-019-00122-1.

Funk, C. et al., 2018: Anthropogenic Enhancement of Moderate-to-Strong El Niño Events Likely Contributed to Drought and Poor Harvests in Southern Africa During 2016. *Bulletin of the American Meteorological Society*, **99**(1), S91-S96, doi:10.1175/bams-d-17-0112.1.
Fussell, E., 2015: The long-term recovery of New Orleans' population after Hurricane Katrina. *American Behavioral Scientist*, **59**(10), 1231-1245, doi:https://dx.doi.org/10.1177%2F0002764215591181.
Galappaththi, E. K., J. D. Ford and E. M. Bennett, 2020: Climate change and adaptation to social-ecological change: the case of indigenous people and culture-based fisheries in Sri Lanka. *Climatic Change*, **162**(2), 279-300, doi:10.1007/s10584-020-02716-3.
Gamble, J. et al., 2016: Populations of concern. In: *The impacts of climate change on human health in the Untited States: A scientific assessment* [Program, U. S. G. C. R. (ed.)]. US Global Change Research Program, Washington, DC, pp. 247-286. ISBN 978-0-16-093241-0.
Gannon, K. E. et al., 2020: Private adaptation in semi-arid lands: a tailored approach to 'leave no one behind'. *Global Sustainability*, **3**, e6, doi:https://doi.org/10.1017/sus.2019.26.
Garcia-Aristizabal, A. et al., 2015: Analysis of non-stationary climate-related extreme events considering climate change scenarios: an application for multi-hazard assessment in the Dar es Salaam region, Tanzania. *Natural Hazards*, **75**(1), 289-320, doi:http://dx.doi.org/10.1007/s11069-014-1324-z.
García-Herrera, R. et al., 2010: A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, **40**(4), 267-306, doi:https://doi.org/10.1080/10643380802238137.
Garcia, A., P. Tschakert and N. A. Karikari, 2020: 'Less able': how gendered subjectivities warp climate change adaptation in Ghana's Central Region. *Gender, Place & Culture*, **27**(11), 1602-1627, doi:https://doi.org/10.1080/0966369X.2020.1786017.
García, I., 2021: Deemed Ineligible: Reasons Homeowners in Puerto Rico Were Denied Aid After Hurricane María. *Housing Policy Debate*, 1-21, doi:10.1080/10511482.2021.1890633.
Garg, T., M. Gibson and F. Sun, 2020: Extreme temperatures and time use in China. *Journal of Economic Behavior & Organization*, **180**, 309-324, doi:10.1016/j.jebo.2020.10.016.
Garschagen, M., D. Doshi, J. Reith and M. Hagenlocher, 2021: Comparing global climate and disaster risk indices – How consistent and robust are their results? *Climatic Change*, **In Press**.
Gautam, Y., 2017: Seasonal migration and livelihood resilience in the face of climate change in Nepal. *Mountain Research and Development*, **37**(4), 436-445, doi:https://doi.org/10.1659/MRD-JOURNAL-D-17-00035.1.
Gemenne, F., J. Barnett, W. Neil and G. D. Dabelko, 2014: Climate and security: evidence, emerging risks, and a new agenda. *Climatic Change*, **123**(1), 1-9, doi:10.1007/s10584-014-1074-7.
Gemenne, F. and J. Blocher, 2017: How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *The Geographical Journal*, **183**(4), 336-347, doi:http://dx.doi.org/10.1111/geoj.12205.
GFED, 2019 Fire Season Updates, Global Fire Emissions Database (GFED). Available at: https://www.globalfiredata.org/forecast.html#totals.
Gharibvand, H. K., H. Azadi and F. Witlox, 2015: Exploring appropriate livelihood alternatives for sustainable rangeland management. *The Rangeland Journal*, **37**(4), 345-356, doi:https://doi.org/10.1071/RJ15027.
Ghosh, A., 2018: Recipe of a Disaster: Peripheral Lives in the Epicentre of Changing Climate. In: *Sustainability Conflicts in Coastal India* [Ghosh, A. (ed.)]. Springer International Publishing, Cham, pp. 35-66. ISBN 978-3-319-63892-8.
Ghosh, U., L. S. Vadrevu and A. Mandal, 2018: *Children of an Uncertain Climate*. Future Health System, System, F. H., Brighton, 52 pp. Available at: https://opendocs.ids.ac.uk/opendocs/bitstream/handle/20.500.12413/14327/CCH%20Report_Final%20version_UG%20revisions.pdf?sequence=3&isAllowed=y.
Giannini, A. et al., 2017: Climate risk and food security in Mali: A historical perspective on adaptation. *Earth's Future*, **5**(2), 144-157, doi:https://doi.org/10.1002/2016EF000404.
Gil, J. D. B. et al., 2017: The resilience of integrated agricultural systems to climate change. *WIREs Climate Change*, **8**(4), doi:10.1002/wcc.461.
Gioli, G. et al., 2019: Understanding and Tackling Poverty and Vulnerability in Mountain Livelihoods in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment* [Wester, P., A. Mishra, A. Mukherji and A. Shrestha (eds.)]. Springer, Cham, pp. 421-455. ISBN 978-3-319-92288-1.
Gitz, V. et al., 2015: *Climate change and food security: risks and responses*. Food and Agriculture Organization of the United Nations (FAO), Rome, 110 pp. Available at: http://www.fao.org/3/i5188e/i5188e.pdf.
GIZ, 2019: *Cities Fit for Climate Change: A source book for climate proof urban development*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Bonn and Eschborn, 286 pp. Available at: https://www.giz.de/climate-proof-cities/epaper/ausgabe.pdf.
GIZ, 2021: *Diving into the gap: Gender dimensions of Climate Risk Management*. Deutsche Gesellschaft für Internationale Zusammenarbeit, Bonn, 60 pp. Available at: https://www.giz.de/en/downloads/GIZ-GP-(2021)_Diving%20into%20the%20gap_Genderdimensions%20of%20Climate%20RiskManagement.pdf (accessed 01-09-2021).
GIZ and BMZ, 2017: *Adapting to climate change: Promising Ways to Tackle Climate Risks*. Deutsche Gesellschaft für Internationale Zusammenarbeit Federal Ministry for Economic Cooperation and Development, Bonn, 32 pp. Available at:

https://www.bmz.de/resource/blob/18754/5fc4c285ff5b178cfd307fd3e04d6ad5/Materilie325_Adaptation-to-Climate-Change.pdf.

Glazebrook, T., S. Noll and E. Opoku, 2020: Gender matters: Climate change, gender bias, and women's farming in the global South and North. *Agriculture*, **10**(7), 267, doi:https://doi.org/10.3390/agriculture10070267.

Global Commission on Adaptation, 2019: *Adapt Now: Global Call for Leadership on Climate Resilience*. Global Center on Adaptation World Resources Institute, Rotterdam Washington, DC. Available at: https://gca.org/wp-content/uploads/2019/09/GlobalCommission_Report_FINAL.pdf.

Godde, C. et al., 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global food security*, **28**, 100488, doi:https://doi.org/10.1016/j.gfs.2020.100488.

Golrokhian, A. et al., 2016: National Adaptation Programme of Action: Ethiopia's responses to climate change. *World Development*, **1**, 53-57, doi:https://doi.org/10.1016/j.wdp.2016.05.005.

Gomiero, T., 2015: Are biofuels an effective and viable energy strategy for industrialized societies? A reasoned overview of potentials and limits. *Sustainability*, **7**(7), 8491-8521, doi:https://doi.org/10.3390/su7078491.

Gore, C., 2015: Climate Change Adaptation and African Cities: Understanding the Impact of Government and Governance on Future Action. In: *The urban climate challenge* [Johnson, C., N. Toly and H. Schroeder (eds.)]. Routledge, New York, pp. 205–226. ISBN 9781317680062.

GovSA, Government programmes, projects and campaigns, South Africa. Available at: https://www.gov.za/about-government/government-programmes/projects-and-campaigns#Rural.

Gracia, A., N. Rangel-Buitrago, J. A. Oakley and A. T. Williams, 2018: Use of ecosystems in coastal erosion management. *Ocean & Coastal Management*, **156**, 277–289, doi:10.1016/j.ocecoaman.2017.07.009.

Graff Zivin, J., S. M. Hsiang and M. Neidell, 2018: Temperature and human capital in the short and long run. *Journal of the Association of Environmental and Resource Economists*, **5**(1), 77-105, doi:10.1086/694177.

Graff Zivin, J. and M. Neidell, 2014: Temperature and the Allocation of Time: Implications for Climate Change. *Journal of Labor Economics*, **32**(1), 1-26, doi:10.1086/671766.

Gralepois, M. et al., 2016: Is flood defense changing in nature? Shifts in the flood defense strategy in six European countries. *Ecology and Society*, **21**(4), 37, doi:https://doi.org/10.5751/ES-08907-210437.

Granderson, A. A., 2017: The role of traditional knowledge in building adaptive capacity for climate change: Perspectives from Vanuatu. *Weather, Climate, and Society*, **9**(3), 545-561, doi:https://doi.org/10.1175/WCAS-D-16-0094.1.

Grasham, C. F., M. Korzenevica and K. J. Charles, 2019: On considering climate resilience in urban water security: A review of the vulnerability of the urban poor in sub-Saharan Africa. *WIREs Water*, **6**(3), doi:10.1002/wat2.1344.

Gray, C. and E. Wise, 2016: Country-specific effects of climate variability on human migration. *Climatic change*, **135**(3-4), 555-568, doi:https://doi.org/10.1007/s10584-015-1592-y.

Green Climate Fund, 2018: Resource mobilization. Available at: https://www.greenclimate.fund/how-we-work/resource-mobilization.

Grimm, N. B., E. M. Cook, R. L. Hale and D. M. Iwaniec, 2015: A broader framing of ecosystem services in cities: Benefits and challenges of built, natural or hybrid system function. In: *The Routledge handbook of urbanization and global environmental change* [Seto, K. C., Solecki, W. D and C. A. Griffith (eds.)]. Routledge, pp. 227-236. ISBN 9780415732260.

Guido, Z., C. Knudson and K. Rhiney, 2020: Will COVID-19 be one shock too many for smallholder coffee livelihoods? *World Development*, **136**, 105172, doi:https://doi.org/10.1016/j.worlddev.2020.105172.

Gulsrud, N. M., K. Hertzog and I. Shears, 2018: Innovative urban forestry governance in Melbourne?: Investigating "green placemaking" as a nature-based solution. *Environmental Research*, **161**, 158-167, doi:10.1016/j.envres.2017.11.005.

Gupta, A. K. et al., 2020: Mapping socio-environmental vulnerability to climate change in different altitude zones in the Indian Himalayas. *Ecological Indicators*, **109**, 105787, doi:https://doi.org/10.1016/j.ecolind.2019.105787.

Gupta, J., 2016: Climate change governance: history, future, and triple-loop learning? *Wiley Interdisciplinary Reviews: Climate Change*, **7**(2), 192-210, doi:https://doi.org/10.1002/wcc.388.

Gupta, J. et al., 2021: COVID-19, poverty and inclusive development. *World Development*, **145**, 105527, doi:https://doi.org/10.1016/j.worlddev.2021.105527.

Gupta, M. and A. Sharma, 2006: Compounded loss: the post tsunami recovery experience of Indian island communities. *Disaster Prevention and Management: An International Journal*, **15**(1), 67-78, doi:10.1108/09653560610654248.

Haase, D., 2015: Reflections about blue ecosystem services in cities. *Sustainability of Water Quality and Ecology*, **5**, 77-83, doi:10.1016/j.swaqe.2015.02.003.

Hagerman, S. M. and T. Satterfield, 2014: Agreed but not preferred: expert views on taboo options for biodiversity conservation, given climate change. *Ecological Applications*, **24**(3), 548-559, doi:https://doi.org/10.1890/13-0400.1.

Hahn, M. B. et al., 2014: Influence of deforestation, logging, and fire on malaria in the Brazilian Amazon. *PloS one*, **9**(1), e85725, doi:10.1371/journal.pone.0085725.

Hahn, M. B. et al., 2021: Wildfire Smoke Is Associated With an Increased Risk of Cardiorespiratory Emergency Department Visits in Alaska. *GeoHealth*, **5**(5), e2020GH000349, doi:10.1029/2020gh000349.

Haile, A. T., K. Kusters and N. Wagesho, 2013: Loss and damage from flooding in the Gambela region, Ethiopia. *International Journal of Global Warming*, **5**(4), 483-497, doi:http://dx.doi.org/10.1504/IJGW.2013.057290.

Hall, N. and Å. Persson, 2018: Global climate adaptation governance: Why is it not legally binding? *European Journal of International Relations*, **24**(3), 540-566, doi:doi.org/10.1177/1354066117725157.
Hallegatte, S. et al., 2015: *Shock waves: managing the impacts of climate change on poverty*. The World Bank, Washington, DC, 227 pp. ISBN 146480673X.
Hallegatte, S., M. Fay and E. B. Barbier, 2018: Poverty and climate change: Introduction. *Environment and Development Economics*, **23**(3), 217-233, doi:https://doi.org/10.1017/S1355770X18000141.
Hallegatte, S., J. Rentschler and J. Rozenberg, 2019: *LIFELINES: The resilient infrastructure opportunity*. The World Bank, Washington, DC, 200 pp. ISBN 978-1-4648-1431-0.
Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**(4), doi:10.1038/nclimate3253.
Hallegatte, S., A. Vogt-Schilb, M. Bangalore and J. Rozenberg, 2017: *Unbreakable: building the resilience of the poor in the face of natural disasters Building the resilience of the poor in the face of natural disasters*. The World Bank, Washington, DC, 187 pp. ISBN 978-1-4648-1003-9.
Hamza, A. J., L. S. Esteves, M. Cvitanovic and J. Kairo, 2020: Past and Present Utilization of Mangrove Resources in Eastern Africa and Drivers of Change. *Journal of Coastal Research*, **95**(SI), 39-44, doi:https://doi.org/10.2112/SI95-008.1.
Handayani, K., T. Filatova, Y. Krozer and P. Anugrah, 2020: Seeking for a climate change mitigation and adaptation nexus: Analysis of a long-term power system expansion. *Applied energy*, **262**, 114485, doi:https://doi.org/10.1016/j.apenergy.2019.114485.
Handmer, J. and J. Nalau, 2019: Understanding loss and damage in Pacific Small Island developing states. In: *Loss and Damage from Climate Change* [Mechler, R., L. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer, Cham, pp. 365-381. ISBN 978-3-319-72026-5.
Hanigan, I. C., C. D. Butler, P. N. Kokic and M. F. Hutchinson, 2012: Suicide and drought in new South Wales, Australia, 1970–2007. *Proceedings of the National Academy of Sciences*, **109**(35), 13950-13955, doi:https://doi.org/10.1073/pnas.1112965109.
Hanna, R. and P. Oliva, 2016: Implications of Climate Change for Children in Developing Countries. *The Future of Children*, **26**(1), 115-132, doi:10.1353/foc.2016.0006.
Hansen, J. et al., 2017: Young people's burden: requirement of negative CO 2 emissions. *Earth System Dynamics*, **8**(3), 577-616, doi:https://doi.org/10.5194/esd-8-577-2017.
Harrington, L. J., D. Frame, A. D. King and F. E. Otto, 2018: How uneven are changes to impact-relevant climate hazards in a 1.5° C world and beyond? *Geophysical Research Letters*, **45**(13), 6672-6680, doi:https://doi.org/10.1029/2018GL078888.
Harrington, L. J. and F. E. Otto, 2020: Reconciling theory with the reality of African heatwaves. *Nature Climate Change*, **10**(9), 796-798, doi:https://doi.org/10.1038/s41558-020-0851-8.
Hasegawa, T. et al., 2018: Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, **8**(8), 699-703, doi:https://doi.org/10.1038/s41558-018-0230-x.
Hauge, Å. L., G. S. Hanssen and C. Flyen, 2019: Multilevel networks for climate change adaptation–what works? *International Journal of Climate Change Strategies and Management*, doi:https://doi.org/10.1108/IJCCSM-10-2017-0194.
Healy, N. and J. Barry, 2017: Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition". *Energy Policy*, **108**, 451-459, doi:https://doi.org/10.1016/j.enpol.2017.06.014.
Hecht, S. B., 2006: Indigenous Soil Management and the Creation of Amazonian Dark Earths: Implications of Kayapó Practice. In: *Amazonian Dark Earths* [Lehmann, J., D. C. Kern, B. Glaser and W. I. Wodos (eds.)]. Springer, Dordrecht, pp. 355-372. ISBN 978-1-4020-1839-8.
Heesen, J. et al., 2014: Blind Spots on Achilles' Heel: The Limitations of Vulnerability and Resilience Mapping in Research. *International Journal of Disaster Risk Science*, **5**(1), 74-85, doi:10.1007/s13753-014-0014-5.
Heimann, T. and B. Mallick, 2016: Understanding Climate Adaptation Cultures in Global Context: Proposal for an Explanatory Framework. *Climate*, **4**(4), 59, doi:doi.org/10.3390/cli4040059.
Hellberg, S., 2020: Scarcity as a means of governing: Challenging neoliberal hydromentality in the context of the South African drought. *Environment and Planning E: Nature and Space*, **3**(1), 186-206, doi:https://doi.org/10.1177%2F2514848619853551.
Hennessey, R., J. Pittman, A. Morand and A. Douglas, 2017: Co-benefits of integrating climate change adaptation and mitigation in the Canadian energy sector. *Energy Policy*, **111**, 214-221, doi:http://dx.doi.org/10.1016/j.enpol.2017.09.025.
Henrique, K. P. and P. Tschakert, 2020: Pathways to urban transformation: From dispossession to climate justice. *Progress in Human Geography*, 1-30, doi:10.1177/0309132520962856.
Hernández-Morcillo, M. et al., 2018: Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science & Policy*, **80**, 44-52, doi:https://doi.org/10.1016/j.envsci.2017.11.013.
Hertel, T. W., 2015: Food security under climate change. *Nature Climate Change*, **6**(1), 10, doi:http://dx.doi.org/10.1038/nclimate2834.

Hertel, T. W. and D. B. Lobell, 2014: Agricultural adaptation to climate change in rich and poor countries: Current modeling practice and potential for empirical contributions. *Energy Economics*, **46**, 562-575, doi:https://doi.org/10.1016/j.eneco.2014.04.014.
Hilson, G. and S. Van Bockstael, 2012: Poverty and livelihood diversification in rural Liberia: exploring the linkages between artisanal diamond mining and smallholder rice production. *Journal of Development Studies*, **48**(3), 413-428, doi:https://doi.org/10.1080/00220388.2011.604414.
Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8**(7), 570-578, doi:https://doi.org/10.1038/s41558-018-0176-z.
Hirons, M., 2014: Shifting sand, shifting livelihoods? Reflections on a coastal gold rush in Ghana. *Resources Policy*, **40**, 83-89, doi:10.1016/j.resourpol.2013.08.005.
Hochrainer-Stigler, S. and S. Hanger-Kopp, 2017: Subsidized drought insurance in Austria: recent reforms and future challenges. *Wirtschaftspolitische Blätter*, **6**(4), 599-614.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. Cambridge University Press, pp. In press. ISBN 9789291691517
Hoegh-Guldberg, O. et al., 2019a: The human imperative of stabilizing global climate change at 1.5° C. *Science*, **365**(6459), eaaw6974, doi:10.1126/science.aaw6974.
Hoegh-Guldberg, O., L. Pendleton and A. Kaup, 2019b: People and the changing nature of coral reefs. *Regional Studies in Marine Science*, **30**, 100699, doi:https://doi.org/10.1016/j.rsma.2019.100699.
Hoegh-Guldberg, O., E. S. Poloczanska, W. Skirving and S. Dove, 2017: Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science*, **4**, 158, doi:https://doi.org/10.3389/fmars.2017.00158.
Holz, C., S. Kartha and T. Athanasiou, 2018: Fairly sharing 1.5: national fair shares of a 1.5 C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18**(1), 117-134, doi:https://doi.org/10.1007/s10784-017-9371-z.
Horton, R. M., A. d. Sherbinin, D. Wrathall and M. Oppenheimer, 2021: Assessing human habitability and migration. *Science*, **372**(6548), 1279–1283, doi:10.1126/science.abi8603.
Houghton, R. A., 2012: Carbon emissions and the drivers of deforestation and forest degradation in the tropics. *Current Opinion in Environmental Sustainability*, **4**(6), 597–603, doi:10.1016/j.cosust.2012.06.006.
Howard, A. J., E. Hancox, J. Hanson and R. Jackson, 2017: Protecting the Historic Environment from Inland Flooding in the UK: Some Thoughts on Current Approaches to Asset Management in the Light of Planning Policy, Changing Catchment Hydrology and Climate Change. *The Historic Environment: Policy & Practice*, **8**(2), 125–142, doi:10.1080/17567505.2017.1320855.
Howden, S. M. et al., 2007: Adapting agriculture to climate change. *Proceedings of the national academy of sciences*, **104**(50), 19691-19696, doi:https://dx.doi.org/10.1073%2Fpnas.0701890104.
Howe, P. D., J. R. Marlon, M. Mildenberger and B. S. Shield, 2019: How will climate change shape climate opinion? *Environmental Research Letters*, **14**(11), 113001, doi:http://dx.doi.org/10.1088/1748-9326/ab466a.
Howells, M. and H.-H. Rogner, 2014: Assessing integrated systems. *Nature Climate Change*, **4**(4), 246-247, doi:https://doi.org/10.1038/nclimate2180.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356**(6345), 1362-1369, doi:10.1126/science.aal4369.
Hsiang, S. M., M. Burke and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science* **341**(6151), 1235367, doi:10.1126/science.1235367.
Hsu, A., G. Sheriff, T. Chakraborty and D. Manya, 2021: Disproportionate exposure to urban heat island intensity across major US cities. *Nature communications*, **12**(1), 2721, doi:10.1038/s41467-021-22799-5.
Huggins, A. and M. S. Karim, 2016: Shifting traction: Differential treatment and substantive and procedural regard in the international climate change regime. *Transnational Environmental Law*, **5**(2), 427-448, doi:http://dx.doi.org/10.1017/S2047102516000170.
Hunsberger, C. et al., 2017: Climate change mitigation, land grabbing and conflict: towards a landscape-based and collaborative action research agenda. *Canadian Journal of Development Studies/Revue canadienne d'études du développement*, **38**(3), 305-324, doi:https://doi.org/10.1080/02255189.2016.1250617.
Hunter, L. M. and D. H. Simon, 2017: Might climate change the "healthy migrant" effect? *Global Environmental Change*, **47**, 133-142, doi:https://doi.org/10.1016/j.gloenvcha.2017.10.003.
Huq, S. et al., 2004: Mainstreaming adaptation to climate change in least developed countries (LDCs). *Climate Policy*, **4**(1), 25-43, doi:https://doi.org/10.1080/14693062.2004.9685508.
Huynh, L. and L. C. Stringer, 2018: Multi-scale assessment of social vulnerability to climate change: An empirical study in coastal Vietnam. *Climate Risk Management*, **20**, 165-180, doi:doi.org/10.1016/j.crm.2018.02.003.
Ide, T., 2019: The impact of environmental cooperation on peacemaking: Definitions, mechanisms, and empirical evidence. *International Studies Review*, **21**(3), 327-346, doi:https://doi.org/10.1093/isr/viy014.

Ide, T., M. Brzoska, J. F. Donges and C.-F. Schleussner, 2020: Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk. *Global Environmental Change*, **62**, doi:10.1016/j.gloenvcha.2020.102063.

IDMC, 2019: *Global Report on Internal Displacement 2019*. International Displacement Monitoring Center (IDMC) Norwegian Refugee Council (NRC), Center, I. D. M., Geneva, 148 pp. Available at: https://www.internal-displacement.org/sites/default/files/publications/documents/2019-IDMC-GRID.pdf.

IDMC, 2020: *Global Report on Internal Displacement 2020*. International Displacement Monitoring Center (IDMC) Norwegian Refugee Council (NRC), Center, I. D. M., Geneva, 126 pp. Available at: https://www.internal-displacement.org/sites/default/files/publications/documents/2020-IDMC-GRID.pdf (accessed 20-11-2020).

IDMC, 2021: *Global Report on Internal Displacement 2021*. International Displacement Monitoring Center (IDMC) Norwegian Refugee Council (NRC), Center, I. D. M., Geneva, 160 pp. Available at: https://www.internal-displacement.org/sites/default/files/publications/documents/grid2021_idmc.pdf (accessed 20-11-2020).

INFORM, INFORM Index for Risk Management, European Commission Joint Research Center. Available at: https://drmkc.jrc.ec.europa.eu/inform-index/Results/Global.

Ingold, K., 2017: How to create and preserve social capital in climate adaptation policies: A network approach. *Ecological Economics*, **131**, 414-424, doi:10.1016/j.ecolecon.2016.08.033.

IPBES, 2018: Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. [Scholes, R., L. Montanarella, A. Brainich, N. Barger, B. ten Brink, M. Cantele, B. Erasmus, J. Fisher, T. Gardner, T. G. Holland, F. Kohler, J. S. Kotiaho, G. Von Maltitz, G. Nangendo, R. Pandit, J. Parrotta, M. D. Potts, S. Prince, M. Sankaran and L. Willemen (eds.)]. Itergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany, pp. 44. ISBN 978-3-947851-04-1.

IPCC, 2014a: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B. (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp. ISBN 9781107058071.

IPCC, 2014b: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing, T., R. K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp pp.

IPCC, 2014c: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. v. Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30. ISBN 9781107058217.

IPCC, 2018a: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.

IPCC, 2018b: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V. (ed.)]. In press pp. ISBN 9789291691517.

IPCC, 2018c: Technical Summary In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V. Z., P. ;Pörtner, H.-O. ;Roberts, D. ;Skea, J. ;Shukla, P.R. ;Pirani, A. ;Moufouma-Okia, W. ;Péan, C. ;Pidcock, R. ;Connors, S. ;Matthews, J.B.R. ;Chen, Y. ;Zhou, X. ;Gomis, M.I. ;Lonnoy, E. ;Maycock, T. ;Tignor, M. ;Waterfield, T. (ed.)], pp. In press. ISBN 9789291691517 [Add to Citavi project by ISBN]

IPCC, 2019a: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R. (ed.)]. Cambridge University Press, In press pp. ISBN 978-92-9169-154-8.

IPCC, 2019b: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. In press pp.

IPCC, 2021: Summary for Policy Makers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V. Z., P.; Pirani, A.; Connors, S.L; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.

I.; Huang, M.; Leitzell, K.; Lonney, E.; Matthews, J.B.R.; Maycock, T. K.; Watefield, T.; Yelekçi, O.; Yu, R.; Zhou, B. (ed.)]. Cambridge University Press, In Press.

ISA, ISA mostra Terras Indígenas mais afetadas por incêndios na Amazônia brasileira, Instituto Socioambiental (ISA). Available at: https://www.socioambiental.org/pt-br/noticias-socioambientais/isa-mostra-terras-indigenas-mais-afetadas-por-incendios-na-amazonia-brasileira.

Islam, M. M., S. Sallu, K. Hubacek and J. Paavola, 2014: Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: insights from coastal Bangladesh. *Regional Environmental Change*, **14**(1), 281-294, doi:https://doi.org/10.1007/s10113-013-0487-6.

Islam, M. R. and M. Hasan, 2016: Climate-induced human displacement: a case study of Cyclone Aila in the south-west coastal region of Bangladesh. *Natural Hazards*, **81**(2), 1051-1071, doi:10.1007/s11069-015-2119-6.

Islam, M. T. and M. Nursey-Bray, 2017: Adaptation to climate change in agriculture in Bangladesh: The role of formal institutions. *Journal of Environmental Management*, **200**, 347-358, doi:10.1016/j.jenvman.2017.05.092.

Islam, N. and J. Winkel, 2017: *Climate change and social inequality*. **DESA Working Paper**, United Nations Department of Economic and Social Affairs (UN-DESA), New York, 32 pp. Available at: https://www.un.org/esa/desa/papers/2017/wp152_2017.pdf.

Jaakkola, J. J. K., S. Juntunen and K. Näkkäläjärvi, 2018: The Holistic Effects of Climate Change on the Culture, Well-Being, and Health of the Saami, the Only Indigenous People in the European Union. *Current Environmental Health Reports*, **5**(4), 401-417, doi:10.1007/s40572-018-0211-2.

Jackson, R. B. et al., 2016: Reaching peak emissions. *Nature Climate Change*, **6**(1), 7-10, doi:http://dx.doi.org/doi:10.1038/nclimate2892.

Jafino, B. A., B. Walsh, J. Rozenberg and S. Hallegatte, 2020: *Revised estimates of the impact of climate change on extreme poverty by 2030*. Policy Research Working Paper, World Bank, Bank, W., Washington DC, 17 pp. Available at: http://hdl.handle.net/10986/34555.

Jakob, M. et al., 2014: Feasible mitigation actions in developing countries. *Nature Climate Change*, **4**(11), 961–968, doi:10.1038/nclimate2370.

James, R. et al., 2014: Characterizing loss and damage from climate change. *Nature Climate Change*, **4**, 938-938, doi:https://doi.org/10.1038/nclimate2411.

James, R. A. et al., 2019: Attribution: How Is It Relevant for Loss and Damage Policy and Practice? In: *Loss and Damage from Climate Change* [Mechler, R., L. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer, Cham, pp. 113-154. ISBN 978-3-319-72026-5.

Jamshed, A., J. Birkmann, I. Ahmad Rana and D. Feldmeyer, 2020a: The effect of spatial proximity to cities on rural vulnerability against flooding: An indicator based approach. *Ecological indicators*, **118**, 106704, doi:10.1016/j.ecolind.2020.106704.

Jamshed, A. et al., 2020b: The Impact of Extreme Floods on Rural Communities: Evidence from Pakistan. In: *Climate Change, Hazards and Adaptation Options*, 1 ed. [Leal, W. F., G. Nagy, M. Borga, D. Chavez and A. Magnuszewski (eds.)]. Springer, Cham, pp. 585–613. ISBN 9783030374242.

Jamshed, A., J. Birkmann, I. A. Rana and J. M. McMillan, 2020c: The relevance of city size to the vulnerability of surrounding rural areas: An empirical study of flooding in Pakistan. *International Journal of Disaster Risk Reduction*, 101601, doi:10.1016/j.ijdrr.2020.101601.

Jamshed, A., I. A. Rana, J. Birkmann and O. Nadeem, 2017: Changes in Vulnerability and Response Capacities of Rural Communities After Extreme Events: Case of Major Floods of 2010 and 2014 in Pakistan. *Journal of Extreme Events*, **04**(03), 1750013, doi:10.1142/s2345737617500130.

Jantarasami, L. et al., 2018: Tribes and Indigenous Peoples. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, B. C. Stewart, D. J. Wuebbles, D. W. Fahey and K. A. Hibbard (eds.)]. U.S. Global Change Research Program (USGCRP), Washington, DC, pp. 572–603.

Jean, N. et al., 2016: Combining satellite imagery and machine learning to predict poverty. *Science*, **353**(6301), 790-794, doi:10.1126/science.aaf7894.

Jeschonnek, L. et al. (eds.), 2014: *WorldRiskReport 2014: Focus: The city as a risk area*, Bündnis Entwicklung hilft e.V and United Nations University – Institute for Environment and Human Security (UNU-EHS), Berlin, 70 Seiten pp. ISBN 978-3-9814495-4-9.

Jeswani, H. K., A. Chilvers and A. Azapagic, 2020: Environmental sustainability of biofuels: a review. *Proceedings. Mathematical, physical, and engineering sciences*, **476**(2243), 20200351, doi:10.1098/rspa.2020.0351.

Jiang, L. and B. C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 193-199, doi:10.1016/j.gloenvcha.2015.03.008.

Johnson, N. et al., 2019: Integrated solutions for the Water-Energy-Land Nexus: Are global models rising to the challenge? *Water*, **11**(11), 2223, doi:https://doi.org/10.3390/w11112223.

Jones, L. and E. Boyd, 2011: Exploring social barriers to adaptation: insights from Western Nepal. *Global Environmental Change*, **21**(4), 1262-1274, doi:https://doi.org/10.1016/j.gloenvcha.2011.06.002.

Joseph, S. R. et al., 2020: Colonial Neglect and the Right to Health in Puerto Rico After Hurricane Maria. *Am J Public Health*, **110**(10), 1512-1518, doi:10.2105/AJPH.2020.305814.

Jost, C. et al., 2016: Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, **8**(2), 133-144, doi:https://doi.org/10.1080/17565529.2015.1050978.

Joyce, L. A. et al., 2013: Climate change and North American rangelands: assessment of mitigation and adaptation strategies. *Rangeland Ecology & Management*, **66**(5), 512-528, doi:https://doi.org/10.2111/REM-D-12-00142.1.
Jurt, C. et al., 2015: Cultural values of glaciers. In: *The High-Mountain Cryosphere: Environmental Changes and Human Risks* [Huggel, C., M. Carey, J. J. Clague and A. Kaab (eds.)]. Cambridge University Press, Cambridge, pp. 90-106. ISBN 9781107588653.
Kabisch, N. et al., 2016: Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, **21**(2), doi:http://dx.doi.org/10.5751/ES-08373-210239.
Kaczan, D. J. and J. Orgill-Meyer, 2020: The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change*, **158**(3), 281-300, doi:https://doi.org/10.1007/s10584-019-02560-0.
Kaijser, A. and A. Kronsell, 2014: Climate change through the lens of intersectionality. *Environmental politics*, **23**(3), 417-433, doi:https://doi.org/10.1080/09644016.2013.835203.
Kalamandeen, M. et al., 2018: Pervasive Rise of Small-scale Deforestation in Amazonia. *Scientific Reports*, doi:10.1038/s41598-018-19358-2.
Kamei, M., T. Wangmo, B. D. Leibowicz and S. Nishioka, 2021: Urbanization, carbon neutrality, and Gross National Happiness: Sustainable development pathways for Bhutan. *Cities*, **111**, 102972, doi:https://doi.org/10.1016/j.cities.2020.102972.
Kandic, S., 2020: Heat - an invisible hazard : perceived effects of the 2019 heatwave on construction workers in the Netherlands. Master Thesis Series in Environmental Studies and Sustainability Science. Lund University.
Karlsson, L., A. Nightingale, L. O. Naess and J. Thompson, 2017: Triple wins' or'triple faults'? Analysing policy discourse on climate-smart agriculture (CSA). *The Journal of Peasant Studies*, **45**(1), 150-174, doi:https://doi.org/10.1080/03066150.2017.1351433.
Karlsson, M., E. Alfredsson and N. Westling, 2020: Climate policy co-benefits: a review. *Climate Policy*, **20**(3), 292-316, doi:https://doi.org/10.1080/14693062.2020.1724070.
Kasecker, T. P., M. B. Ramos-Neto, J. M. C. da Silva and F. R. Scarano, 2018: Ecosystem-based adaptation to climate change: defining hotspot municipalities for policy design and implementation in Brazil. *Mitigation and adaptation strategies for global change*, **23**(6), 981–993, doi:https://doi.org/10.1007/s11027-017-9768-6.
Kaya, O., A. M. Klepacka and W. J. Florkowski, 2019: Achieving renewable energy, climate, and air quality policy goals: Rural residential investment in solar panel. *Journal of environmental management*, **248**, 109309, doi:https://doi.org/10.1016/j.jenvman.2019.109309.
Keegan, R. et al., 2018: Case Study of Resilient Baton Rouge: Applying Depression Collaborative Care and Community Planning to Disaster Recovery. *International journal of environmental research and public health*, **15**(6), doi:10.3390/ijerph15061208.
Khan, M. et al., 2019: Twenty-five years of adaptation finance through a climate justice lens. *Climatic Change*, 1-19, doi:https://doi.org/10.1007/s10584-019-02563-x.
Khan, U. and Y. Zhang, 2021: The global inequalities and climate change. *Environmental Science and Pollution Research International*, doi:https://doi.org/10.1007/s11356-020-12333-3.
Khatri-Chhetri, A., P. K. Aggarwal, P. Joshi and S. Vyas, 2017: Farmers' prioritization of climate-smart agriculture (CSA) technologies. *Agricultural systems*, **151**, 184-191, doi:https://doi.org/10.1016/j.agsy.2016.10.005.
Kidane, S. et al., 2019: Conservation agriculture and maize production risk: The case of Mozambique smallholders. *Agronomy Journal*, **111**, 1–11, doi:doi.org/10.2134/agronj2018.05.0331.
Kihara, J. et al., 2020: Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. *Environmental geochemistry and health*, 1-19, doi:https://doi.org/10.1007/s10653-019-00499-w.
Kijazi, A. et al., 2013: The use of indigenous knowledge in weather and climate prediction in Mahenge and Ismani wards, Tanzania. *Journal of Geography and Regional Planning*, **6**(7), 274-279, doi:http://dx.doi.org/10.5897/JGRP2013.0386.
Kinay, P. et al., 2019: Direct and indirect health impacts of climate change on the vulnerable elderly population in East China. *Environmental Reviews*, **27**(3), 295–303, doi:10.1139/er-2017-0095.
King-Okumu, C. et al., 2021a: How can we stop the slow-burning systemic fuse of loss and damage due to land degradation and drought in Africa? *Current Opinion in Environmental Sustainability*, **50**, 289-302, doi:https://doi.org/10.1016/j.cosust.2021.04.008.
King-Okumu, C. et al., 2021b: How can we stop the slow-burning systemic fuse of loss and damage due to land degradation and drought in Africa? *Current Opinion in Environmental Sustainability*, **50**, 289–302, doi:10.1016/j.cosust.2021.04.008.
King, J., N. Edwards, H. Watling and S. Hair, 2019: Barriers to disability-inclusive disaster management in the Solomon Islands: Perspectives of people with disability. *International Journal of Disaster Risk Reduction*, **34**, 459-466, doi:10.1016/j.ijdrr.2018.12.017.
Kishore, N. et al., 2018: Mortality in puerto rico after hurricane maria. *New England journal of medicine*, **379**(2), 162-170, doi:10.1056/NEJMsa1803972.
Klein, R. J., E. L. F. Schipper and S. Dessai, 2005: Integrating mitigation and adaptation into climate and development policy: three research questions. *Environmental science & policy*, **8**(6), 579-588, doi:https://doi.org/10.1016/j.envsci.2005.06.010.

Klein, R. J. T. et al., 2014: Adaptation Opportunities, Constraints, and Limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943. ISBN 9781107058071.

Klinenberg, E., M. Araos and L. Koslov, 2020: Sociology and the Climate Crisis. *Annual Review of Sociology*, **46**(1), 649–669, doi:10.1146/annurev-soc-121919-054750.

Koh, I., R. Garrett, A. Janetos and N. D. Mueller, 2020: Climate risks to Brazilian coffee production. *Environmental Research Letters*, **15**(10), 104015, doi:http://dx.doi.org/10.1088/1748-9326/aba471.

Kohlitz, J. et al., 2019: *Climate, Sanitation and Health*. Discussion Paper, World Health Organization WHO, Who, W. H. O., Geneva, 25 pp. Available at: https://cdn.who.int/media/docs/default-source/climate-change/discussion-paper-climate-sanitation-and-healthfb841397-121b-42dc-88ad-2a7eb8ab544f.pdf?sfvrsn=7bbd007f_1&download=true.

Kongsager, R., 2018: Linking Climate Change Adaptation and Mitigation: A Review with Evidence from the Land-Use Sectors. *Land*, **7**(4), 158, doi:https://doi.org/10.3390/land7040158.

Kongsager, R., B. Locatelli and F. Chazarin, 2016: Addressing climate change mitigation and adaptation together: A global assessment of agriculture and forestry projects. *Environmental management*, **57**(2), 271-282, doi:https://doi.org/10.1007/s00267-015-0605-y.

Kopytko, N., 2018: What role can a livelihood strategy play in addressing climate change? Lessons in improving social capital from an agricultural cooperative in Ukraine. *Climate and Development*, **10**(8), 717-728, doi:https://doi.org/10.1080/17565529.2018.1442787.

Kose, M. A., P. Nagle, F. Ohnsorge and N. Sugawara, 2021: *Global Waves of Debt: Causes and Consequences*. The World Bank, Washington DC, 310 pp. ISBN 978-1-4648-1544-7.

Kraaijenbrink, P., M. Bierkens, A. Lutz and W. Immerzeel, 2017: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, **549**(7671), 257-260, doi:https://doi.org/10.1038/nature23878.

Kreft, S., D. Eckstein and I. Melchior, 2016: *Global Climate Risk Index 2017: Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2015 and 1996 to 2015*. Germanwatch e.V., Bonn, 32 pp. Available at: https://germanwatch.org/sites/germanwatch.org/files/publication/16411.pdf.

Krishnapillai, M., 2018: Enhancing Adaptive Capacity and Climate Change Resilience of Coastal Communities in Yap. In: *Climate Change Impacts and Adaptation Strategies for Coastal Communities* [Leal Filho, W. (ed.)]. Springer, Cham, pp. 87-118. ISBN 978-3-319-70702-0.

Krishnapillai, M. and R. Gavenda, 2014: From barren land to biodiverse home gardens. *Farming Matters*, **30**(1), 26-28.

Krishnapillai, M. V., 2017: Climate-friendly adaptation strategies for the displaced Atoll population in Yap. In: *Climate Change Adaptation in Pacific Countries* [Leal Filho, W. (ed.)]. Springer, Cham, pp. 101-117. ISBN 978-3-319-84316-2.

Kuffer, M., K. Pfeffer and R. Sliuzas, 2016: Slums from space—15 years of slum mapping using remote sensing. *Remote Sensing*, **8**(6), 455, doi:https://doi.org/10.3390/rs8060455.

Kugler, T. A. et al., 2019: People and Pixels 20 years later: the current data landscape and research trends blending population and environmental data. *Population and Environment*, **41**(2), 209-234, doi:https://doi.org/10.1007/s11111-019-00326-5.

Kulp, S. A. and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature communications*, **10**(1), 1-12, doi:https://doi.org/10.1038/s41467-019-12808-z.

Kuruppu, N. and D. Liverman, 2011: Mental preparation for climate adaptation: The role of cognition and culture in enhancing adaptive capacity of water management in Kiribati. *Global Environmental Change*, **21**(2), 657-669, doi:10.1016/j.gloenvcha.2010.12.002.

Kusters, K. and N. Wangdi, 2013: The costs of adaptation: changes in water availability and farmers' responses in Punakha district, Bhutan. *International Journal of Global Warming*, doi:10.1504/ijgw.2013.057287.

Kwon, S. A., K. Seoyong and J. E. Lee, 2019: Analyzing the Determinants of Individual Action on Climate Change by Specifying the Roles of Six Values in South Korea. *Sustainability*, **11**, 1834, doi:10.3390/su11071834.

Laaidi, K. et al., 2011: The impact of heat islands on mortality in Paris during the August 2003 heat wave. *Environmental health perspectives*, **120**(2), 254-259, doi:https://doi.org/10.1289/ehp.1103532.

Laborde, D., W. Martin, J. Swinnen and R. Vos, 2020a: COVID-19 risks to global food security. *Science*, **369**(6503), 500-502, doi:10.1126/science.abc4765.

Laborde, D., W. Martin and R. Vos, 2020b: Poverty and food insecurity could grow dramatically as COVID-19 spreads. In: *COVID-19 and global food security* [Swinnen, J. and J. McDermott (eds.)]. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 16-19. ISBN 9780896293878.

Lakner, C., D. G. Mahler, M. Negre and E. B. Prydz, 2020: *How Much Does Reducing Inequality Matter for Global Poverty?* Global Poverty Monitoring Technical Note, World Bank, Bank, W., Washington, DC., 32 pp. Available at: https://openknowledge.worldbank.org/handle/10986/33902.

Landauer, M., S. Juhola and M. Söderholm, 2015: Inter-relationships between adaptation and mitigation: a systematic literature review. *Climatic Change*, **131**(4), 505-517, doi:https://doi.org/10.1007/s10584-015-1395-1.

Lapola, D. M. et al., 2018: Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proceedings of the National Academy of Sciences*, **115**(46), 11671-11679, doi:https://doi.org/10.1073/pnas.1721770115.
Larsen, J. N., Fondahl, G., 2015: *Arctic Human Development Report: Regional Processes and Global Linkages*. Nordisk Ministerråd, Copenhagen, 500 pp. Available at: http://norden.diva-portal.org/smash/get/diva2:788965/FULLTEXT03.pdf.
Le, T. D. N., 2019: Climate change adaptation in coastal cities of developing countries: characterizing types of vulnerability and adaptation options. *Mitigation and Adaptation Strategies for Global Change*, 1-23, doi:https://doi.org/10.1007/s11027-019-09888-z.
Leal-Filho, W., G. J. Nagy and D. Y. Ayal, 2020: Viewpoint: climate change, health and pandemics–a wake-up call from COVID-19. *International Journal of Climate Change Strategies and Management*, **12**(4), 533-535, doi:https://doi.org/10.1108/IJCCSM-08-2020-212.
Leal Filho, W., 2018: *Climate change impacts and adaptation strategies for coastal communities*. Climate Change Management, Springer, Cham, IX, 478 pp. ISBN 3319707035.
Leal Filho, W. et al., 2018: Strengthening climate change adaptation capacity in Africa-case studies from six major African cities and policy implications. *Environmental Science & Policy*, **86**, 29-37, doi:https://doi.org/10.1016/j.envsci.2018.05.004.
Leal Filho, W. et al., 2019: Assessing the impacts of climate change in cities and their adaptive capacity: Towards transformative approaches to climate change adaptation and poverty reduction in urban areas in a set of developing countries. *Science of the Total Environment*, **692**, 1175-1190, doi:https://doi.org/10.1016/j.scitotenv.2019.07.227.
Leal Filho, W., V. T. King and I. B. de Lima, 2020a: *Indigenous Amazonia, Regional Development and Territorial Dynamics*. The Latin American Studies Book Series, Springer, Cham, 433 pp. ISBN 978-3-030-29153-2.
Leal Filho, W. et al., 2021a: Poverty: a central barrier to the implementation of the UN Sustainable Development Goals. *Environmental Science and Policy*, **125**, 96-104, doi:10.1016/j.envsci.2021.08.020.
Leal Filho, W. et al., 2017: Climate change responses among the maasai community in Kenya. *Climatic change*, **145**(1), 71-83, doi:https://doi.org/10.1007/s10584-017-2087-9.
Leal Filho, W. et al., 2020b: Introducing experiences from African pastoralist communities to cope with climate change risks, hazards and extremes: Fostering poverty reduction. *International Journal of Disaster Risk Reduction*, **50**, 101738, doi:https://doi.org/10.1016/j.ijdrr.2020.101738.
Leal Filho, W. et al., 2021b: The impacts of the early outset of the COVID-19 pandemic on climate change research: Implications for policy-making. *Environmental Science & Policy*, **124**, 267-278, doi:https://doi.org/10.1016/j.envsci.2021.06.008.
Leichenko, R. and K. O'Brien, 2019: *Climate and Society: Transforming the Future*. Polity Press, Cambridge, 248 pp. ISBN 978-0-745-68438-3.
Leichenko, R. and J. A. Silva, 2014: Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(4), 539-556, doi:https://doi.org/10.1002/wcc.287.
Lenton, T. M. et al., 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, **105**(6), 1786-1793, doi:https://doi.org/10.1073/pnas.0705414105.
Lenton, T. M. et al., 2019: Climate tipping points—too risky to bet against. *Nature*, **575**(7784), 592-595, doi:https://doi.org/10.1038/d41586-019-03595-0.
Lesnikowski, A. et al., 2017: What does the Paris Agreement mean for adaptation? *Climate Policy*, **17**(7), 825-831, doi:10.1080/14693062.2016.1248889.
Levy, B. S. and J. A. Patz, 2015: Climate Change, Human Rights, and Social Justice. *Annals of Global Health*, **81**(3), 310-322, doi:https://doi.org/10.1016/j.aogh.2015.08.008.
.
Li, S. et al., 2021: Anthropogenic climate change contribution to wildfire-prone weather conditions in the Cerrado and Arc of deforestation. *Environmental Research Letters*, doi:10.1088/1748-9326/ac1e3a.
Li, T. et al., 2016: Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China. *Scientific Reports*, **6**, doi:https://doi.org/10.1038/srep28161.
Liang, H. et al., 2016: An integrated soil-crop system model for water and nitrogen management in North China. *Scientific reports*, **6**, 25755, doi:https://doi.org/10.1038/srep25755.
Liang, L. and P. Gong, 2017: Climate change and human infectious diseases: A synthesis of research findings from global and spatio-temporal perspectives. *Environment international*, **103**, 99-108, doi:https://doi.org/10.1016/j.envint.2017.03.011.
Liu, L., T. Wu and Y. Huang, 2017: An equity-based framework for defining national responsibilities in global climate change mitigation. *Climate and Development*, **9**(2), 152-163, doi:https://doi.org/10.1080/17565529.2015.1085358.
Loboguerrero, A. M. et al., 2019: Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems. *Sustainability*, **11**(5), 1372, doi:https://doi.org/10.3390/su11051372.
Locatelli, B., G. Fedele, V. Fayolle and A. Baglee, 2016: Synergies between adaptation and mitigation in climate change finance. *International Journal of Climate Change Strategies and Management*, doi:https://doi.org/10.1108/IJCCSM-07-2014-0088.

Locatelli, B., C. Pavageau, E. Pramova and M. Di Gregorio, 2015: Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(6), 585-598, doi:https://doi.org/10.1002/wcc.357.

Lovejoy, T. E. and C. Nobre, 2018: Amazon Tipping Point. *Science Advances*, doi:10.1126/sciadv.aat2340.

Lu, C., Y. Sun, N. Christidis and P. A. Stott, 2020: Contribution of Global Warming and Atmospheric Circulation to the Hottest Spring in Eastern China in 2018. *Advances in Atmospheric Sciences*, **37**(11), 1285–1294, doi:10.1007/s00376-020-0088-5.

Lu, W.-C., 2017: Greenhouse gas emissions, energy consumption and economic growth: a panel cointegration analysis for 16 Asian countries. *International journal of environmental research and public health*, **14**(11), 1436, doi:https://doi.org/10.3390/ijerph14111436.

Lu, X. et al., 2016: Unveiling hidden migration and mobility patterns in climate stressed regions: A longitudinal study of six million anonymous mobile phone users in Bangladesh. *Global Environmental Change*, **38**, 1-7, doi:https://doi.org/10.1016/j.gloenvcha.2016.02.002.

Lucci, P., T. Bhatkal and A. Khan, 2018: Are we underestimating urban poverty? *World Development*, **103**, 297-310, doi:https://doi.org/10.1016/j.worlddev.2017.10.022.

Lund, D., 2021: Navigating slow-onset risks through foresight and flexibility in Fiji: emerging recommendations for the planned relocation of climate-vulnerable communities. *Current Opinion in Environmental Sustainability*, **50**, 12–20, doi:10.1016/j.cosust.2020.12.004.

Lung, T., H.-M. Füssel and L. Eichle, 2017: Europe's vulnerability to climate change impacts outside Europe. In: *Climate change, impacts and vulnerability in Europe 2016: An indicator-based report* [European Environment Agency (ed.)]. European Environment Agency (EEA), Luxembourg, pp. 288-293. ISBN 978-92-9213-835-6.

Lusseau, D. and F. Mancini, 2019: Income-based variation in Sustainable Development Goal interaction networks. *Nature Sustainability*, **2**, 242–247, doi:https://doi.org/10.1038/s41893-019-0231-4.

Luterbacher, J., L. Paterson, K. Solazzo and S. Castonguay, 2020: *United in Science 2020: A multi-organization high-level compilation of the latest climate science information*. World Meteorological Organization (WMO), Nations, U., Geneva, 28 pp. Available at: https://www.unep.org/resources/report/united-science-report-climate-change-has-not-stopped-covid-19.

Lutz, W., J. C. Cuaresma and W. Sanderson, 2008: The demography of educational attainment and economic growth. *Science*, **319**(5866), 1047-1048, doi:10.1126/science.1151753.

Lutz, W., S. Scherbov, P. K. Makinwa-Adebusoye and G. Reniers, 2004: Population–environment–development–agriculture interactions in Africa: a case study on Ethiopia. In: *The End of World Population Growth in the 21st Century: New Challenges for Human Capital Formation and Sustainable Development* [Lutz, W., W. C. Sanderson and S. Scherbov (eds.)]. Earthscan, London, pp. 187-225. ISBN 9781844070992.

Ma, F., X. Yuan, Y. Jiao and P. Ji, 2020: Unprecedented Europe Heat in June–July 2019: Risk in the Historical and Future Context. *Geophysical Research Letters*, **47**(11), doi:10.1029/2020gl087809.

Maccini, S. and D. Yang, 2009: Under the weather: Health, schooling, and economic consequences of early-life rainfall. *American Economic Review*, **99**(3), 1006-1026, doi:10.1257/aer.99.3.1006.

Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-197, doi:https://doi.org/10.1038/s41586-019-1300-6.

Machado-Silva, F. et al., 2020: Drought and fires influence the respiratory diseases hospitalizations in the Amazon. *Ecological Indicators*, **109**, doi:10.1016/j.ecolind.2019.105817.

MacNaughton, P. et al., 2018: Energy savings, emission reductions, and health co-benefits of the green building movement. *Journal of Exposure Science & Environmental Epidemiology*, **28**(4), 307-318, doi:https://doi.org/10.1038/s41370-017-0014-9.

Madonsela, B., S. Koop, K. Van Leeuwen and K. Carden, 2019: Evaluation of Water Governance Processes Required to Transition towards Water Sensitive Urban Design—An Indicator Assessment Approach for the City of Cape Town. *Water*, **11**(2), 292, doi:https://doi.org/10.3390/w11020292.

Magnan, A. et al., 2016: Addressing the risk of maladaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **7**(5), 646-665, doi:https://doi.org/10.1002/wcc.409.

Magnan, A. K. et al., 2019: Cross-Chapter Box 9: Integrative Cross-Chapter Box on Low-Lying Islands and Coasts. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.

Magnan, A. K. and T. Ribera, 2016: Global adaptation after Paris. *Science*, **352**(6291), 1280-1282, doi:https://doi.org/10.1126/science.aaf5002.

Maharjan, A. et al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, 1-16, doi:https://doi.org/10.1007/s40641-020-00153-z.

Malhi, Y. et al., 2020: Climate change and ecosystems: threats, opportunities and solutions. *Philosophical Transactions of Royal Society B*, **375**, 20190104, doi:https://doi.org/10.1098/rstb.2019.0104.

Malik, A. A. and J. Stolove, In South Asian slums, women face the consequences of climate change, LEAD Pakistan, Islamabad. Available at: https://www.urban.org/urban-wire/south-asian-slums-women-face-consequences-climate-change.

Maljean-Dubois, S., 2016: The Paris Agreement: A new step in the gradual evolution of differential treatment in the climate regime? *Review of European, Comparative & International Environmental Law*, **25**(2), 151-160, doi:https://doi.org/10.1111/reel.12162.
Mall, R. K. et al., 2019: Disaster Risk Reduction Including Climate Change Adaptation Over South Asia: Challenges and Ways Forward. *International Journal of Disaster Risk Science*, **10**(1), 14-27, doi:https://doi.org/10.1007/s13753-018-0210-9.
Mallick, B., B. Ahmed and J. Vogt, 2017: Living with the Risks of Cyclone Disasters in the South-Western Coastal Region of Bangladesh. *Environments*, **4**(1), 13, doi:doi.org/10.3390/environments4010013.
Mansur, A. V. et al., 2016: An assessment of urban vulnerability in the Amazon Delta and Estuary: a multi-criterion index of flood exposure, socio-economic conditions and infrastructure. *Sustainability Science*, **11**(4), 625-643, doi:10.1007/s11625-016-0355-7.
Marchiori, L., J.-F. Maystadt and I. Schumacher, 2012: The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management*, **63**(3), 355-374, doi:https://doi.org/10.1016/j.jeem.2012.02.001.
Marin-Ferrer, M., L. Vernaccini and K. Poljanšek, 2017: *Index for risk management - INFORM: Concept and methodology, version 2017*. Scientific and technical research series, Joint Research Center of European Commission, Luxembourg, 85 pp. ISBN 978-92-79-69697-8.
Markkanen, S. A.-K., A., 2019: Social Impacts of climate change mitigation policies and their implications for inequality. *Climate Policy*, **19**(7), 827–844, doi:https://doi.org/10.1080/14693062.2019.1596873.
Markolf et al., 2019: Transportation resilience to climate change and extreme weather events–Beyond risk and robustness. *Transport Policy*, **74**, 174-186, doi:https://doi.org/10.1016/j.tranpol.2018.11.003.
Marsha, A. et al., 2018: Influences of climatic and population changes on heat-related mortality in Houston, Texas, USA. *Climatic change*, **146**(3-4), 471-485, doi:https://doi.org/10.1007/s10584-016-1775-1.
Marshall, N. et al., 2019: Reef Grief: investigating the relationship between place meanings and place change on the Great Barrier Reef, Australia. *Sustainability Science*, **14**(3), 579-587, doi:https://doi.org/10.1007/s11625-019-00666-z.
Martha, T. R. et al., 2015: Landslides triggered by the June 2013 extreme rainfall event in parts of Uttarakhand state, India. *Landslides*, **12**(1), 135-146, doi:https://doi.org/10.1007/s10346-014-0540-7.
Martin, T. G. and J. E. M. Watson, 2016: Intact ecosystems provide best defence against climate change. *Nature Climate Change*, **6**, 122-124, doi:https://doi.org/10.1038/nclimate2918.
Martineau, H. et al., 2016: *Effective Performance of Tools for Climate Action Policy− Meta-review of Common Agricultural Policy (CAP) Mainstreaming*. Ricardo-AEA IEEP, Oxfordshire, 287 pp. Available at: https://ec.europa.eu/clima/sites/clima/files/forests/lulucf/docs/cap_mainstreaming_en.pdf.
Martyr-Koller, R. et al., 2021: Loss and damage implications of sea-level rise on Small Island Developing States. *Current Opinion in Environmental Sustainability*, **50**, 245-259, doi:https://doi.org/10.1016/j.cosust.2021.05.001.
Maru, Y. T. et al., 2014: A linked vulnerability and resilience framework for adaptation pathways in remote disadvantaged communities. *Global Environmental Change*, **28**, 337-350, doi:https://doi.org/10.1016/j.gloenvcha.2013.12.007.
Mastrucci, A., E. Byers, S. Pachauri and N. D. Rao, 2019: Improving the SDG energy poverty targets: Residential cooling needs in the Global South. *Energy and Buildings*, **186**, 405–415, doi:10.1016/j.enbuild.2019.01.015.
Mathew, L. M. and S. Akter, 2015: Loss and Damage Associated with Climate Change Impacts. In: *Handbook of Climate Change Mitigation and Adaptation* [Chen, W.-Y., T. Suzuki and M. Lackner (eds.)]. Springer, New York, pp. 1-23. ISBN 978-3-319-14408-5.
Matikinca, P., G. Ziervogel and J. P. Enqvist, 2020: Drought response impacts on household water use practices in Cape Town, South Africa. *Water Policy*, doi:https://doi.org/10.2166/wp.2020.169.
Mavhura, E., 2017: Applying a systems-thinking approach to community resilience analysis using rural livelihoods: The case of Muzarabani district, Zimbabwe. *International Journal of Disaster Risk Reduction*, **25**, 248-258, doi:https://doi.org/10.1016/j.ijdrr.2017.09.008.
Mawejje, J. and A. J. Finn, 2020: *South Sudan Economic Update: Poverty and Vulnerability in a Fragile Environment*. World Bank, Bank, W., Washington, DC., 65 pp. Available at: http://hdl.handle.net/10986/33453.
Mayer, A. and E. K. Smith, 2019: Unstoppable climate change? The influence of fatalistic beliefs about climate change on behavioural change and willingness to pay cross-nationally. *Climate Policy*, **19**(4), 511-523, doi:10.1080/14693062.2018.1532872.
Mbow, C. et al., 2019: Food Security. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. R. D. C. Pörtner, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], In press.
McCloskey, B. et al., 2020: Mass gathering events and reducing further global spread of COVID-19: a political and public health dilemma. *The Lancet*, **395**(10230), 1096-1099, doi:https://doi.org/10.1016/S0140-6736(20)30681-4.
McDonnell, S., 2021: The importance of attention to customary tenure solutions: slow onset risks and the limits of Vanuatu's climate change and resettlement policy. *Current Opinion in Environmental Sustainability*, **50**, 281-288, doi:https://doi.org/10.1016/j.cosust.2021.06.008.

McLeman, R., 2018: Thresholds in climate migration. *Population and Environment*, **39**(4), 319-338, doi:https://doi.org/10.1007/s11111-017-0290-2.
McLeman, R. and B. Smit, 2006: Migration as an adaptation to climate change. *Climatic change*, **76**(1-2), 31-53, doi:https://doi.org/10.1007/s10584-005-9000-7.
McMichael, C., S. Dasgupta, S. Ayeb-Karlsson and I. Kelman, 2020: A review of estimating population exposure to sea-level rise and the relevance for migration. *Environmental Research Letters*, doi:https://doi.org/10.1088/1748-9326/abb398.
McMichael, C. H. et al., 2012: Sparse pre-Columbian human habitation in Western Amazonia. *Science*, **336**(6087), 1429-1431, doi:10.1126/science.1219982.
McNamara, K. E., R. Clissold and R. Westoby, 2021a: Women's capabilities in disaster recovery and resilience must be acknowledged, utilized and supported. *Journal of Gender Studies*, **30**(1), 119-125, doi:https://doi.org/10.1080/09589236.2020.1801397.
McNamara, K. E. and H. J. Des Combes, 2015: Planning for Community Relocations Due to Climate Change in Fiji. *International Journal of Disaster Risk Science*, **6**(3), 315–319, doi:https://doi.org/10.1007/s13753-015-0065-2.
McNamara, K. E. and G. Jackson, 2019: Loss and damage: A review of the literature and directions for future research. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(2), e564-e564, doi:10.1002/wcc.564.
McNamara, K. E. and S. S. Prasad, 2014: Coping with extreme weather: communities in Fiji and Vanuatu share their experiences and knowledge. *Climatic change*, **123**(2), 121-132, doi:https://doi.org/10.1007/s10584-013-1047-2.
McNamara, K. E., R. Westoby and A. Chandra, 2021b: Exploring climate-driven non-economic loss and damage in the Pacific Islands. *Current Opinion in Environmental Sustainability*, **50**, 1-11, doi:https://doi.org/10.1016/j.cosust.2020.07.004.
McNamara, K. E., R. Westoby and S. G. Smithers, 2017: Identification of limits and barriers to climate change adaptation: case study of two islands in Torres Strait, Australia. *Geographical Research*, **55**(4), 438-455, doi:https://doi.org/10.1111/1745-5871.12242.
McNeeley, S. M., 2017: Sustainable Climate Change Adaptation in Indian Country. *Weather, Climate, and Society*, **9**(3), 393-404, doi:10.1175/wcas-d-16-0121.1.
McOmber, C., 2020: Women and climate change in the Sahel. doi:https://doi.org/10.1787/24142026.
McPherson, M., M. Counahan and J. L. Hall, 2015: Responding to Typhoon Haiyan in the Philippines. *Western Pacific surveillance and response journal: WPSAR*, **6**(Suppl 1), 1, doi:https://dx.doi.org/10.5365%2FWPSAR.2015.6.4.HYN_026.
Mechler, R. et al., 2019a: *Loss and damage from climate change: Concepts, methods and policy options*. Springer, Cham, XXII, 557 pp. ISBN 978-3-319-72025-8.
Mechler, R. et al., 2019b: Science for loss and damage. Findings and propositions. In: *Loss and Damage from Climate Change* [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer, Cham, pp. 3-37. ISBN 978-3-319-72025-8.
Mechler, R. et al., 2020: Loss and Damage and limits to adaptation: recent IPCC insights and implications for climate science and policy. *Sustainability Science*, doi:https://doi.org/10.1007/s11625-020-00807-9.
Melde, S., F. Laczko and F. Gemenne, 2017: *Making mobility work for adaptation to environmental changes: Results from the MECLEP global research*. International Organization for Migration (IOM), Geneva, 144 pp. Available at: https://environmentalmigration.iom.int/making-mobility-work-adaptation-environmental-changes-results-meclep-global-research.
Méndez, M., G. Flores-Haro and L. Zucker, 2020: The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and indigenous immigrants. *Geoforum*, **116**, 50–62, doi:10.1016/j.geoforum.2020.07.007.
Menéndez, P. et al., 2020: The global flood protection benefits of mangroves. *Scientific Reports*, **10**(1), 1-11, doi:https://doi.org/10.1038/s41598-020-61136-6.
Meyer, L. and D. Jose, September/October: Sowing Seeds of Stability in Micronesia, United States Agency for International Development (USAID). Available at: https://www.usaid.gov/news-information/frontlines/september-october-2017.
Michaelowa, A. and K. Michaelowa, 2015: Do rapidly developing countries take up new responsibilities for climate change mitigation? *Climatic Change*, **133**(3), 499-510, doi:https://doi.org/10.1007/s10584-015-1528-6.
Miguel, E., S. Satyanath and E. Sergenti, 2004: Economic Shocks and Civil Conflict: An Instrumental Variables Approach. *Journal of Political Economy*, **112**(4), 725-753, doi:10.1086/421174.
Mikulewicz, M., 2020: The discursive politics of adaptation to climate change. *Annals of the American Association of Geographers*, **110**(6), 1807-1830, doi:https://doi.org/10.1080/24694452.2020.1736981.
Milkoreit, M. et al., 2018: Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. *Environmental Research Letters*, **13**(3), 033005, doi:https://doi.org/10.1088/1748-9326/aaaa75.
Milne, S. et al., 2019: Learning from 'actually existing'REDD+ A synthesis of ethnographic findings. *Conservation & Society*, **17**(1), 84-95, doi:https://doi.org/10.4103/cs.cs_18_13.
Mimura, N. et al., 2014: Adaptation Planning and Implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A.

N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869-898. ISBN 9781107058071.
Mishra, A. et al., 2019: Adaptation to Climate Change in the Hindu Kush Himalaya: Stronger Action Urgently Needed. In: *The Hindu Kush Himalaya Assessment* [Wester, P., A. Mishra, A. Mukherji and A. Shrestha (eds.)]. Springer International Publishing, Cham, pp. 457-490. ISBN 978-3-319-92287-4.
Mishra, V., S. Mukherjee, R. Kumar and D. A. Stone, 2017: Heat wave exposure in India in current, 1.5 C, and 2.0 C worlds. *Environmental Research Letters*, **12**(12), 124012, doi:https://doi.org/10.1088/1748-9326/aa9388.
Mitchell, T. and S. Maxwell, 2010: *Defining climate compatible development*. Policy Brief, Climate and Development Knowledge Network (CKDN) Overseas Development Institute (ODI), Climate and N. Development Knowledge, London, 6 pp. Available at: https://cdkn.org/wp-content/uploads/2012/10/CDKN-CCD-Planning_english.pdf.
Mitra, B. K. et al., 2020: Water-energy-food nexus perspective: Pathway for Sustainable Development Goals (SDGs) to country action in India. *APN Science Bulletin*, 34-40, doi:https://doi.org/10.30852/sb.2020.1067.
Moleti, C. A., L. Contreras Sollazzo, M. Minick and C. L. Esposito, 2020: In the Aftermath of Maria: An Ethnographic Review of Rescue, Recovery, Climate, and Social Justice in Puerto Rico. *Journal of the New York State Nurses Association*, **47**(1), 45-56.
Monroe, M. C. et al., 2017: Identifying effective climate change education strategies: a systematic review of the research. *Environmental Education Research*, doi:https://doi.org/10.1080/13504622.2017.1360842.
Mora, C. et al., 2017: Global risk of deadly heat. *Nature climate change*, **7**(7), 501-506, doi:https://doi.org/10.1038/nclimate3322.
Mora, C. et al., 2018: Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change*, **8**(12), 1062–1071, doi:10.1038/s41558-018-0315-6.
Morand, A., R. Hennessey, J. Pittman and A. Douglas, 2015: *Linking Mitigation and Adaptation Goals in the Energy Sector: A Case Study Synthesis Report*. The Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR), Ontario, 122 pp. Available at: http://www.climateontario.ca/doc/reports/Adaptation-MitigationSynthesisReport-FINAL.pdf.
Morecroft, M. D. et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366**(6471), doi:https://doi.org/10.1126/science.aaw9256.
Morello, T. et al., 2019: Fire, Tractors, and Health in the Amazon: A Cost-Benefit Analysis of Fire Policy. *Land Economics*, **95**(3), 409–434, doi:10.3368/le.95.3.409.
Morello, T. F., 2021: COVID-19 and agricultural fire pollution in the Amazon: Puzzles and solutions. *World Development*, **138**, 105276, doi:https://doi.org/10.1016/j.worlddev.2020.105276.
Morello, T. F., L. Parry, N. Markusson and J. Barlow, 2017: Policy instruments to control Amazon fires: A simulation approach. *Ecological Economics*, **138**, 199-222, doi:10.1016/j.ecolecon.2017.03.043.
Morgan, J., 2019: 4 Signs the Paris Agreement Is the Start of a New Era in International Climate Action, World Resources Institute, Washington, D.C. Available at: https://www.wri.org/insights/4-signs-paris-agreement-start-new-era-international-climate-action.
Morrison, D. et al., 2017a: Predicting the reward value of faces and bodies from social perception. *PloS one*, **12**(9), e0185093, doi:https://doi.org/10.1371/journal.pone.0185093.
Morrison, T. H. et al., 2017b: Mitigation and adaptation in polycentric systems: sources of power in the pursuit of collective goals. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(5), e479, doi:https://doi.org/10.1002/wcc.479.
Morrison, T. H. et al., 2019: The black box of power in polycentric environmental governance. *Global Environmental Change*, **57**, doi:10.1016/j.gloenvcha.2019.101934.
Moser, S. C., 2014: Communicating adaptation to climate change: the art and science of public engagement when climate change comes home. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(3), 337-358, doi:https://doi.org/10.1002/wcc.276.
Mpandeli, S. et al., 2018: Climate change adaptation through the water-energy-food nexus in southern Africa. *International journal of environmental research and public health*, **15**(10), 2306, doi:https://doi.org/10.3390/ijerph15102306.
Mudombi, S., C. Fabricius, V. van Zyl-Bulitta and A. Patt, 2017: The use of and obstacles to social learning in climate change adaptation initiatives in South Africa. *Jamba*, **9**(1), 292, doi:10.4102/jamba.v9i1.292.
Mueller, V., C. Gray and K. Kosec, 2014: Heat stress increases long-term human migration in rural Pakistan. *Nature climate change*, **4**(3), 182-185, doi:https://doi.org/10.1038/nclimate2103.
Mueller, V., G. Sheriff, X. Dou and C. Gray, 2020: Temporary migration and climate variation in eastern Africa. *World development*, **126**, 104704, doi:https://doi.org/10.1016/j.worlddev.2019.104704.
Mukheibir, P. and G. Ziervogel, 2007: Developing a Municipal Adaptation Plan (MAP) for climate change: the city of Cape Town. *Environment and Urbanization*, **19**(1), 143-158, doi:https://doi.org/10.1177%2F0956247807076912.
Muller, M., 2008: Free basic water — a sustainable instrument for a sustainable future in South Africa. *Environment and Urbanization*, **20**(1), 67–87, doi:10.1177/0956247808089149.
Muller, M., 2017: Understanding the origins of Cape Town's water crisis: water engineering. *Civil Engineering= Siviele Ingenieurswese*, **2017**(v25i5), 11-16, doi:https://hdl.handle.net/10520/EJC-a549bf214.
Muller, M., 2018: Lessons from Cape Town's drought. *Nature*, **559**(7713), 174-176, doi:https://doi.org/10.1038/d41586-018-05649-1.

Muller, M., 2019: Some systems perspectives on demand management during Cape Town's 2015–2018 water crisis. *International Journal of Water Resources Development*, 1-19, doi:https://doi.org/10.1080/07900627.2019.1667754.
Murray, U., Z. Gebremedhin, G. Brychkova and C. Spillane, 2016: Smallholder farmers and climate smart agriculture: Technology and labor-productivity constraints amongst women smallholders in Malawi. *Gender, Technology and Development*, **20**(2), 117-148, doi:https://doi.org/10.1177/0971852416640639.
Mustafa, D. and D. Wrathall, 2011: Indus basin floods of 2010: Souring of a Faustian bargain? *Water Alternatives*, **4**(1).
Muttaqin, Z. and A. Yulianti (eds.), Climate village program (ProKlim) in Simurugul Sub-Village, Margawati Village, Garut Kota Sub-Regency, Garut Regency, West Java Province, Indonesia. IOP Conference Series: Earth and Environmental Science, IOP Publishing, 012046 pp. ISBN 1755-1315.
Mutyambizi, C., T. Mokhele, C. Ndinda and C. Hongoro, 2020: Access to and Satisfaction with Basic Services in Informal Settlements: Results from a Baseline Assessment Survey. *International journal of environmental research and public health*, **17**(12), doi:10.3390/ijerph17124400.
Myers, R. et al., 2018: Messiness of forest governance: How technical approaches suppress politics in REDD+ and conservation projects. *Global Environmental Change*, **50**, 314-324, doi:https://doi.org/10.1016/j.gloenvcha.2018.02.015.
Mysiak, J. et al., 2016: Brief communication: Sendai framework for disaster risk reduction–success or warning sign for Paris? *Natural Hazards and Earth System Sciences*, **16**(10), 2189-2193, doi:https://doi.org/10.5194/nhess-16-2189-2016.
Nadin, R. and E. Roberts, 2018: *Moving towards a growing global discourse on transboundary adaptation*. Briefing note, Overseas Development Institute, Institute, O. D., London, 12 pp. Available at: https://cdn.odi.org/media/documents/12139.pdf.
Nadiruzzaman, M. and D. Wrathall, 2015: Participatory exclusion–cyclone Sidr and its aftermath. *Geoforum*, **64**, 196-204, doi:https://doi.org/10.1016/j.geoforum.2015.06.026.
Naess, L. O. et al., 2015: Climate policy meets national development contexts: Insights from Kenya and Mozambique. *Global Environmental Change*, **35**, 534-544, doi:https://doi.org/10.1016/j.gloenvcha.2015.08.015.
Nakashima, D. et al., 2013: *Weathering uncertainty: traditional knowledge for climate change assessment and adaptation*. United Nations Educational, Scientific and Cultural Organization (UNESCO) United Nations University, Paris, 120 pp. ISBN 978-92-3-001068-3.
Nand, M. M. and D. K. Bardsley, 2020: Climate change loss and damage policy implications for Pacific Island Countries. *Local Environment*, 1-16, doi:https://doi.org/10.1080/13549839.2020.1825357.
Nawrotzki, R. J. and J. DeWaard, 2016: Climate shocks and the timing of migration from Mexico. *Population and Environment*, **38**(1), 72-100, doi:https://doi.org/10.1007/s11111-016-0255-x.
Nawrotzki, R. J. and J. DeWaard, 2018: Putting trapped populations into place: Climate change and inter-district migration flows in Zambia. *Regional environmental change*, **18**(2), 533-546, doi:https://doi.org/10.1007/s10113-017-1224-3.
Nawrotzki, R. J., J. DeWaard, M. Bakhtsiyarava and J. T. Ha, 2017: Climate shocks and rural-urban migration in Mexico: exploring nonlinearities and thresholds. *Climatic change*, **140**(2), 243-258, doi:https://doi.org/10.1007/s10584-016-1849-0.
ND-GAIN, ND-GAIN Country Index, University of Notre Dame, Notre Dame. Available at: https://gain.nd.edu/our-work/country-index/.
Neef, A. et al., 2018: Climate adaptation strategies in Fiji: The role of social norms and cultural values. *World Development*, **107**, 125-137, doi:10.1016/j.worlddev.2018.02.029.
Nel, E. and C. M. Rogerson, 2005: *Local Economic Development in the Changing World: The Experience of Southern Africa*. Routledge, New York NY. ISBN 9781351322607.
Nelson, D. R., M. C. Lemos, H. Eakin and Y. J. Lo, 2016: The limits of poverty reduction in support of climate change adaptation. *Environmental Research Letters*, **11**, 094011, doi:doi.org/10.1088/1748-9326/11/9/094011.
Nett, K. and L. Rüttinger, 2016: *Insurgency, terrorism and organised crime in a warming climate: analysing the links between climate change and non-State armed groups*. adelphi, Berlin, 66 pp. Available at: https://climate-diplomacy.org/sites/default/files/2020-10/CD%20Report_Insurgency_170724_web.pdf.
Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. *PloS one*, **10**(3), e0118571, doi:https://doi.org/10.1371/journal.pone.0118571.
Newell, J. P., B. Goldstein and A. Foster, 2019: A 40-year review of food–energy–water nexus literature and its application to the urban scale. *Environmental Research Letters*, **14**(7), 073003, doi:https://doi.org/10.1088/1748-9326/ab0767.
Newell, P. et al., 2021: Toward transformative climate justice: An emerging research agenda. *WIREs Climate Change*, e733, doi:10.1002/wcc.733.
Newton, P. et al., 2020: The number and spatial distribution of forest-proximate people globally. *One Earth*, **3**(3), 363-370, doi:https://doi.org/10.1016/j.oneear.2020.08.016.
Ngum, F. et al., 2019: Synergizing climate change mitigation and adaptation in Cameroon. *International Journal of Climate Change Strategies and Management*, doi:http://dx.doi.org/10.1108/IJCCSM-04-2017-0084.

Nhamo, G. and A. O. Agyepong, 2019: Climate change adaptation and local government: Institutional complexities surrounding Cape Town's Day Zero. *Jàmbá: Journal of Disaster Risk Studies*, **11**(3), 1-9, doi:https://doi.org/10.4102/jamba.v11i3.717.
Nielsen, J. Ø. and A. Reenberg, 2010: Cultural barriers to climate change adaptation: A case study from Northern Burkina Faso. *Global Environmental Change*, **20**(1), 142-152, doi:10.1016/j.gloenvcha.2009.10.002.
Noble, I. R. et al., 2014: Adaptation Needs and Options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 833-868. ISBN 9781107058071.
Nobre, C. A. et al., 2016: Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences of the United States of America*, **113**(39), 10759-10768, doi:10.1073/pnas.1605516113.
Nogueira, E. M. et al., 2018: Carbon stocks and losses to deforestation in protected areas in Brazilian Amazonia. *Regional Environmental Change*, **18**(1), 261-270, doi:10.1007/s10113-017-1198-1.
Nogués-Bravo et al., 2019: Cracking the code of biodiversity responses to past climate change. *Trends in Ecology & Evolution*, **33**(10), 765-776, doi:https://doi.org/10.1016/j.tree.2018.07.005.
Ntontis, E. et al., 2020: Endurance or decline of emergent groups following a flood disaster: Implications for community resilience. *International Journal of Disaster Risk Reduction*, **45**(101493), 10.1016, doi:https://doi.org/10.1016/j.ijdrr.2020.101493.
Nunes, A. R., 2018: The contribution of assets to adaptation to extreme temperatures among older adults. *PloS one*, **13**(11), e0208121, doi:https://doi.org/10.1371/journal.pone.0208121.
Núñez Collado, J. R. and H.-H. Wang, 2020: Slum upgrading and climate change adaptation and mitigation: Lessons from Latin America. *Cities*, **104**, 102791, doi:10.1016/j.cities.2020.102791.
Nunn, P. and R. Kumar, 2018: Understanding climate-human interactions in Small Island Developing States (SIDS): Implications for future livelihood sustainability. *International Journal of Climate Change Strategies and Management*, doi:http://dx.doi.org/10.1108/IJCCSM-01-2017-0012.
Nurse, L. A. et al., 2014: Small Islands. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1613-1654. ISBN 9781107058163.
Nyantakyi-Frimpong, H. and R. Bezner-Kerr, 2015: The relative importance of climate change in the context of multiple stressors in semi-arid Ghana. *Global Environmental Change*, **32**, 40-56, doi:https://doi.org/10.1016/j.gloenvcha.2015.03.003.
O'Neill, B. C. et al., 2017a: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169-180, doi:https://doi.org/10.1016/j.gloenvcha.2015.01.004.
O'Neill, B. C. et al., 2017b: IPCC reasons for concern regarding climate change risks. *Nature Climate Change*, **7**(1), 28-37, doi:https://doi.org/10.1038/nclimate3179.
O'Neill, B. C. et al., 2020: Achievements and needs for the climate change scenario framework. *Nature climate change*, **10**(12), 1074-1084, doi:https://doi.org/10.1038/s41558-020-00952-0.
O'Neill, B. C. et al., 2014: A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic change*, **122**(3), 387-400, doi:https://doi.org/10.1007/s10584-013-0905-2.
OECD, 2018: Climate-resilient Infrastructure: Policy Perspectives. Environment Directorate: Organisation for Economic Co-operation and Development (OECD), 48 pp.
OECD, 2020a: *Climate Finance Provided and Mobilised by Developed Countries in 2013-18*. OECD Publishing, Paris. Available at: https://www.oecd-ilibrary.org/finance-and-investment/climate-finance-provided-and-mobilised-by-developed-countries-in-2013-18_f0773d55-en (accessed 22-04-2021).
OECD, 2020b: *Coronavirus (COVID-19): SME policy responses*. SME policy responses to Coronavirus (COVID-19), Organisation for Economic Co-operation and Development (OECD), Paris, 169 pp. Available at: https://www.oecd.org/coronavirus/policy-responses/coronavirus-covid-19-sme-policy-responses-04440101/.
Ojwang, L. et al., 2017: Assessment of coastal governance for climate change adaptation in Kenya. *Earth's Future*, **5**(11), 1119-1132, doi:https://doi.org/10.1002/2017EF000595.
Okpara, U. T., L. C. Stringer and A. J. Dougill, 2016a: Lake drying and livelihood dynamics in Lake Chad: Unravelling the mechanisms, contexts and responses. *Ambio*, **45**(7), 781-795, doi:https://doi.org/10.1007/s13280-016-0805-6.
Okpara, U. T., L. C. Stringer and A. J. Dougill, 2016b: Perspectives on contextual vulnerability in discourses of climate conflict. *Earth System Dynamics*, **7**(1), 89-102, doi:doi.org/10.5194/esd-7-89-2016.
Oliveira, G. et al., 2020: Smoke pollution's impacts in Amazonia. *Science*, **369**(6504), 634-635., doi:https://doi.org/10.1126/science.abd5942.

Oliver, P., A. Clark and C. Meattle, 2018: *Global Climate Finance: An Updated View 2018 Climate Policy Initiative*. Climate Policy Initiative, London, 15 pp. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2018/11/Global-Climate-Finance-_-An-Updated-View-2018.pdf.

Olsson, L. et al., 2019: Land degradation. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.

Olsson, L. et al., 2014: Livelihoods and Poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793-832. ISBN 9781107058071.

Onwutuebe, C. J., 2019: Patriarchy and women vulnerability to adverse climate change in Nigeria. *Sage Open*, **January-March 2019**, 1-7, doi:https://doi.org/10.1177%2F2158244019825914.

Opare, S., 2018: Adaptation to climate change impacts: coping strategies of an indigenous community in Ghana to declining water supply. *Climate and Development*, **10**(1), 73-83, doi:https://doi.org/10.1080/17565529.2016.1184610.

Opondo, D. O., 2013: Erosive coping after the 2011 floods in Kenya. *International Journal of Global Warming*, **5**(4), 452, doi:10.1504/ijgw.2013.057285.

Oppenheimer, M. et al., 2014: Emergent Risks and Key Vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099. ISBN 9781107058071.

Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.

Orimoloye, I. R. et al., 2019: Implications of climate variability and change on urban and human health: A review. *Cities*, **91**, 213-223, doi:https://doi.org/10.1016/j.cities.2019.01.009.

Osbahr, H., C. Twyman, W. N. Adger and D. S. Thomas, 2010: Evaluating successful livelihood adaptation to climate variability and change in southern Africa. *Ecology and Society*, **15**(2), doi:http://dx.doi.org/10.5751/ES-03388-150227.

Ostrom, E., 2010: Beyond markets and states: polycentric governance of complex economic systems. *American economic review*, **100**(3), 641-672, doi:10.1257/aer.100.3.641

Osumanu, I. K., 2020: Small-scale Mining and Livelihood Dynamics in North-eastern Ghana: Sustaining Rural Livelihoods in a Changing Environment. *Progress in Development Studies*, **20**(3), 208-222, doi:https://doi.org/10.1177/1464993420934223.

Otto, F. E. et al., 2020a: Challenges to understanding extreme weather changes in lower income countries. *Bulletin of the American Meteorological Society*, **101**(10), E1851-E1860, doi:https://doi.org/10.1175/BAMS-D-19-0317.1.

Otto, F. E. et al., 2020b: Toward an Inventory of the Impacts of Human-Induced Climate Change. *Bulletin of the American Meteorological Society*, **101**(11), E1972-E1979, doi:https://doi.org/10.1175/BAMS-D-20-0027.1.

Otto, F. E. et al., 2016: The attribution question. *Nature Climate Change*, **6**(9), 813, doi:https://doi.org/10.1038/nclimate3089.

Otto, F. E. et al., 2018a: Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. *Environmental Research Letters*, **13**(12), 124010, doi:https://doi.org/10.1088/1748-9326/aae9f9.

Otto, F. E. L., 2020: Extreme Weather Events and Local Impacts of Climate Change: The Scientific Perspective. In: *Global Warming in Local Discourses: How Communities around the World Make Sense of Climate Change* [Brueggemann, M. and S. Roedder (eds.)]. Open Book Publishers, Cambridge, pp. 245-262. ISBN 978-1-78374-960-7.

Otto, F. E. L. et al., 2018b: Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond—a real-time event attribution revisited. *Environmental Research Letters*, **13**(2), 024006, doi:10.1088/1748-9326/aa9663.

Ouweneel, B., K. Winter and K. Carden, 2020: How different Cape Town residential suburbs helped avert Day Zero. *H2Open Journal*, **3**(1), 118–134, doi:10.2166/h2oj.2020.018.

Palanisami, K., K. R. Kakumanu, C. Ranganathan and N. Udaya Sekhar, 2015: Farm-level cost of adaptation and expected cost of uncertainty associated with climate change impacts in major river basins in India. *International Journal of Climate Change Strategies and Management*, **7**(1), 76-96, doi:https://doi.org/10.1108/IJCCSM-04-2013-0059.

Palinkas, L. A., 2020: *Global Climate Change, Population Displacement, and Public Health: The Next Wave of Migration*. Springer International Publishing, Basel. ISBN 3030418901.
Pandey, R. et al., 2017a: Agroecology as a climate change adaptation strategy for smallholders of Tehri-Garhwal in the Indian Himalayan region. *Small-scale forestry*, **16**(1), 53-63, doi:https://doi.org/10.1007/s11842-016-9342-1.
Pandey, R. et al., 2017b: Sustainable livelihood framework-based indicators for assessing climate change vulnerability and adaptation for Himalayan communities. *Ecological indicators*, **79**, 338–346, doi:10.1016/j.ecolind.2017.03.047.
Panfil, S. N. and C. A. Harvey, 2016: REDD+ and Biodiversity Conservation: A Review of the Biodiversity Goals, Monitoring Methods, and Impacts of 80 REDD+ Projects. *Conservation Letters*, **9**(2), 143–150, doi:10.1111/conl.12188.
Pascale, S., S. B. Kapnick, T. L. Delworth and W. F. Cooke, 2020: Increasing risk of another Cape Town "Day Zero" drought in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(47), 29495–29503, doi:10.1073/pnas.2009144117.
Pasquini, L., G. Ziervogel, R. M. Cowling and C. Shearing, 2015: What enables local governments to mainstream climate change adaptation? Lessons learned from two municipal case studies in the Western Cape, South Africa. *Climate and Development*, **7**(1), 60-70, doi:https://doi.org/10.1080/17565529.2014.886994.
Passel, J. S., 2006: *The size and characteristics of the unauthorized migrant population in the US*. **7**, Pew Hispanic Center, Center, P. H., Washington , DC, 23 pp. Available at: https://www.pewresearch.org/wp-content/uploads/sites/5/reports/61.pdf.
Patnaik, U., P. K. Das and C. S. Bahinipati, 2019: Development interventions, adaptation decisions and farmers' well-being: evidence from drought-prone households in rural India. *Climate and Development*, **11**(4), 302-318, doi:https://doi.org/10.1080/17565529.2017.1410084.
Patterson, J. J. and D. Huitema, 2019: Institutional innovation in urban governance: The case of climate change adaptation. *Journal of Environmental Planning and Management*, **62**(3), 374-398, doi:https://doi.org/10.1080/09640568.2018.1510767.
Pattyn, F. and M. Morlighem, 2020: The uncertain future of the Antarctic Ice Sheet. *Science*, **367**(6484), 1331-1335, doi:10.1126/science.aaz5487.
Paul, B. K., 2009: Why relatively fewer people died? The case of Bangladesh's Cyclone Sidr. *Natural Hazards*, **50**(2), 289-304, doi:https://doi.org/10.1007/s11069-008-9340-5.
Paul, B. K. and S. Chatterjee, 2019: Climate Change-Induced Environmental Hazards and Aila Relief Measures Undertaken to Sundarbans in Bangladesh and India. In: *The Sundarbans: A Disaster-Prone Eco-Region* [H.S, S. (ed.)]. Springer, Switzerland, pp. 469-490. ISBN 978-3-030-00679-2.
Pauw, P., K. Mbeva and H. van Asselt, 2019: Subtle differentiation of countries' responsibilities under the Paris Agreement. *Palgrave Communications*, **5**, 86, doi:10.1057/s41599-019-0298-6.
Pelling, M. et al., 2018: Africa's urban adaptation transition under a 1.5° climate. *Current Opinion in Environmental Sustainability*, **31**, 10-15, doi:10.1016/j.cosust.2017.11.005.
Pepermans, Y., Maeseele and P., 2016: The politicization of climate change: problem or solution? *WIREs Climate Change*, **7**, 478-485, doi:doi.org/10.1002/wcc.405.
Pereira, L. M. et al., 2020: Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. *People and Nature*, **2**(4), 1172–1195, doi:10.1002/pan3.10146.
Perera, F. P., 2017: Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. *International Journal of Environmental Research and Public Health*, **15**(1), 16, doi:10.3390/ijerph15010016.
Pérez, I. S. and A. C. Kallhauge, 2017: Part II Analysis of the Provisions of the Agreement, 12 Adaptation (Article 7). In: *The Paris Agreement on Climate Change: Analysis and Commentary* [Klein, D., M. P. Carazo, M. Doelle, J. Bulmer and A. Higham (eds.)]. Oxford University Press, Oxford, pp. 196-223. ISBN 9780198789338.
Perfecto, I., M. E. Jiménez-Soto and J. Vandermeer, 2019: Coffee landscapes shaping the Anthropocene: forced simplification on a complex agroecological landscape. *Current Anthropology*, **60**(S20), S236-S250, doi:https://doi.org/10.1086/703413.
Perkins, M. J. et al., 2015: Conserving intertidal habitats: What is the potential of ecological engineering to mitigate impacts of coastal structures? *Estuarine, Coastal and Shelf Science*, **167**, 504–515, doi:10.1016/j.ecss.2015.10.033.
Persson, S., D. Harnesk and M. Islar, 2017: What local people? Examining the Gállok mining conflict and the rights of the Sámi population in terms of justice and power. *Geoforum*, **86**, 20-29, doi:https://doi.org/10.1016/j.geoforum.2017.08.009.
Peters, K. et al., 2019: *Double vulnerability: the humanitarian implications of intersecting climate and conflict risk.* , **Working paper**, Overseas Development Institute (ODI), London, 18 pp. Available at: https://cdn.odi.org/media/documents/12647.pdf.
Petzold, J. and B. M. W. Ratter, 2015: Climate change adaptation under a social capital approach – An analytical framework for small islands. *Ocean & Coastal Management*, **112**, 36-43, doi:10.1016/j.ocecoaman.2015.05.003.
Phillips, C. A. et al., 2020: Compound climate risks in the COVID-19 pandemic. *Nature Climate Change*, **10**(7), 586-588, doi:https://doi.org/10.1038/s41558-020-0804-2.

Phuong, L. T. H., G. R. Biesbroek and A. E. J. Wals, 2017: The interplay between social learning and adaptive capacity in climate change adaptation: A systematic review. *NJAS - Wageningen Journal of Life Sciences*, **82**, 1-9, doi:10.1016/j.njas.2017.05.001.

Piggott-McKellar, A. E., J. Pearson, K. E. McNamara and P. D. Nunn, 2020: A livelihood analysis of resettlement outcomes: lessons for climate-induced relocations. *Ambio*, **49**(9), 1474-1489, doi:https://doi.org/10.1007/s13280-019-01289-5.

Pinho, P. F., 2016: Watching Brazil but missing the story: An Amazonian inferno. *Latin American Studies Association - Special Issue on Environmental Justice and Climate Change in Latin America LASAFORUM, Fall 2016*, **XLVIII**(4), 21-25.

Pinho, P. F., J. A. Marengo and M. S. Smith, 2015: Complex socio-ecological dynamics driven by extreme events in the Amazon. *Regional Environmental Change*, **15**(4), doi:10.1007/s10113-014-0659-z.

Pinho, P. F. et al., 2014: Ecosystem protection and poverty alleviation in the tropics: Perspective from a historical evolution of policy-making in the Brazilian Amazon. *Ecosystem Services*, **8**, 97-109, doi:10.1016/j.ecoser.2014.03.002.

Plagányi, É., 2019: Climate change impacts on fisheries. *Science*, **363**(6430), 930-931, doi:https://doi.org/10.1126/science.aaw5824.

Pogacar, T. et al., 2018: The effect of hot days on occupational heat stress in the manufacturing industry: implications for workers' well-being and productivity. *International Journal of Biometeorol*, **62**(7), 1251-1264, doi:10.1007/s00484-018-1530-6.

Porst, L. and P. Sakdapolrak, 2020: Gendered translocal connectedness: Rural–urban migration, remittances, and social resilience in Thailand. *Population, Space and Place*, **26**(4), e2314, doi:https://doi.org/10.1002/psp.2314.

Poumadere, M., C. Mays, S. Le Mer and R. Blong, 2005: The 2003 heat wave in France: dangerous climate change here and now. *Risk Analysis: an International Journal*, **25**(6), 1483-1494, doi:https://doi.org/10.1111/j.1539-6924.2005.00694.x.

Poupeau, F. et al., 2017: *Water bankruptcy in the land of plenty*. CRC Press, Leiden, 432 pp. ISBN 9781138029699.

PRIF, 2013: *Infrastructure maintenance in the pacific: Challenging the Build-Neglect-Rebuild paradigm*. Pacific Region Infrastructure Facility (PRIF) Pacific Infrastructure Advisory Centre (PIAC), Centre, P. I. A., Sydney, Australia. Available at: https://www.theprif.org/sites/default/files/documents/build_neglect_rebuild_revised_full_report_2014.pdf.

Puma, M. J., S. Bose, S. Y. Chon and B. I. Cook, 2015: Assessing the evolving fragility of the global food system. *Environmental Research Letters*, **10**(2), 024007, doi:https://doi.org/10.1088/1748-9326/10/2/024007.

Quinn, C. H. et al., 2017: Unpacking changes in mangrove social-ecological systems: lessons from Brazil, Zanzibar, and Vietnam. *Resources*, **6**(1), 14, doi:https://doi.org/10.3390/resources6010014.

Rabbani, G., A. Rahman and K. Mainuddin, 2013: Salinity-induced loss and damage to farming households in coastal Bangladesh. *International Journal of Global Warming*, **5**(4), 400, doi:10.1504/ijgw.2013.057284.

Rahill, G. J., N. E. Ganapati, J. C. Clérismé and A. Mukherji, 2014: Shelter recovery in urban Haiti after the earthquake: the dual role of social capital. *Disasters*, **38**, S73-S93, doi:10.1111/disa.12051.

Rahman, H. and G. M. Hickey, 2019: What does autonomous adaptation to climate change have to teach public policy and planning about avoiding the risks of maladaptation in Bangladesh? *Frontiers in Environmental Science*, **7**, 2, doi:https://doi.org/10.3389/fenvs.2019.00002.

Rahman, M. A., 2018: Governance matters: climate change, corruption, and livelihoods in Bangladesh. *Climatic change*, **147**(1-2), 313-326, doi:https://doi.org/10.1007/s10584-018-2139-9.

Rahman, M. A. and S. Rahman, 2015: Natural and traditional defense mechanisms to reduce climate risks in coastal zones of Bangladesh. *Weather and Climate Extremes*, **7**, 84-95, doi:https://doi.org/10.1016/j.wace.2014.12.004.

Rai, A., A. J. Sharma and M. A. Subramanyam, 2021: Droughts, cyclones, and intimate partner violence: A disastrous mix for Indian women. *International Journal of Disaster Risk Reduction*, **53**, 102023, doi:10.1016/j.ijdrr.2020.102023.

Rajamani, L., 2016: Ambition and differentiation in the 2015 Paris Agreement: Interpretative possibilities and underlying politics. *International & Comparative Law Quarterly*, **65**(2), 493-514, doi:https://doi.org/10.1017/S0020589316000130.

Rajamani, L. and E. Guérin, 2017: Central concepts in the Paris Agreement and how they evolved. In: *The Paris Agreement on Climate Change: Analysis and Commentary; Eds* [Klein, D., M. P. Carazo, M. Doelle, J. Bulmer and A. Higham (eds.)]. Oxford University Press, Oxford, pp. 74-90. ISBN 9780198789338.

Raju, E., 2019: Gender as fundamental to climate change adaptation and disaster risk reduction: Experiences from South Asia. In: *Climate Hazards, Disasters, and Gender Ramifications*. Routledge, London, pp. 16
ISBN 9780429424861.

Raju, E., 2020: Five years post-Sendai: Where is the Sendai framework for Disaster Risk Reduction in the COVID-19 response? *Disaster Prevention and Management: An International Journal*, **29**(4), 421-423, doi:https://doi.org/10.1108/DPM-08-2020-400.

Raju, E., A. Dutta and S. Ayeb-Karlsson, 2021: COVID-19 in India: Who are we leaving behind? *Progress in Disaster Science*, **10**, 100163, doi:https://doi.org/10.1016/j.pdisas.2021.100163.

Raker, E. J. et al., 2019: Twelve years later: The long-term mental health consequences of Hurricane Katrina. *Social Science & Medicine*, **242**, 112610, doi:https://doi.org/10.1016/j.socscimed.2019.112610.

Ramaswami, A. et al., 2017: Urban cross-sector actions for carbon mitigation with local health co-benefits in China. *Nature Climate Change*, **7**(10), 736-742, doi:https://doi.org/10.1038/nclimate3373.

Rana, I. A., M. Asim, A. B. Aslam and A. Jamshed, 2021: Disaster management cycle and its application for flood risk reduction in urban areas of Pakistan. *Urban Climate*, **38**, 100893, doi:10.1016/j.uclim.2021.100893.

Randall, S., 2015: Where have all the nomads gone? Fifty years of statistical and demographic invisibilities of African mobile pastoralists. *Pastoralism*, **5**(1), 22, doi:https://doi.org/10.1186/s13570-015-0042-9.

Räsänen, A. et al., 2016: Climate change, multiple stressors and human vulnerability: a systematic review. *Regional Environmental Change*, **16**(8), 2291-2302, doi:https://doi.org/10.1007/s10113-016-0974-7.

Rasul, G. and B. Sharma, 2016: The nexus approach to water–energy–food security: an option for adaptation to climate change. *Climate Policy*, **16**(6), 682-702, doi:https://doi.org/10.1080/14693062.2015.1029865.

Ray, B. and R. Shaw (eds.), 2019a: *Urban Drought*, Disaster Risk Reduction, Springer Singapore, Singapore. ISBN 978-981-10-8946-6.

Ray, B. and R. Shaw, 2019b: Water Insecurity in Asian Cities. In: *Urban Drought* [Ray, B. and R. Shaw (eds.)]. Springer Singapore, Singapore, pp. 17–32. ISBN 978-981-10-8946-6.

Raymond, C. M. et al., 2017: A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy*, **77**, 15-24, doi:https://doi.org/10.1016/j.envsci.2017.07.008.

Reang, D. et al., 2021: Assessing tree diversity and carbon storage during land use transitioning from shifting cultivation to indigenous agroforestry systems: Implications for REDD+ initiatives. *Journal of Environmental Management*, **298**, 113470, doi:https://doi.org/10.1016/j.jenvman.2021.113470.

Reckien, D. et al., 2018: Equity, environmental justice, and urban climate change. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, Cynthia, W. D. Solecki, L. Romero, Patricia, Mehrotra, Shagun, Dhakal, Shobhakar and S. A. Ibrahim (eds.)]. Cambridge University Press, New York, pp. 173-224. ISBN 9781316603338.

Reckien, D. et al., 2019: Dedicated versus mainstreaming approaches in local climate plans in Europe. *Renewable and Sustainable Energy Reviews*, **112**, 948-959, doi:https://doi.org/10.1016/j.rser.2019.05.014.

Reddington, C. L. et al., 2015: Air quality and human health improvements from reductions in deforestation-related fire in Brazil. *Nature Geoscience*, **8**, 768–771, doi:https://doi.org/10.1038/ngeo2535.

Reichel, D. and L. Morales, 2017: Surveying immigrants without sampling frames–evaluating the success of alternative field methods. *Comparative migration studies*, **5**, 1, doi:https://doi.org/10.1186/s40878-016-0044-9.

Reichstein, M., A. D. Richardson, M. Migliavacca and N. Carvalhais, 2014: Plant–environment interactions across multiple scales. In: *Ecology and the Environment* [Monson, R. K. (ed.)]. Springer, New York, pp. 1-27. ISBN 978-1-4614-7500-2.

Rentschler, J., 2016: Incidence and impact: The regional variation of poverty effects due to fossil fuel subsidy reform. *Energy Policy*, **96**, 491-503, doi:https://doi.org/10.1016/j.enpol.2016.06.025.

Reyer, C. P. O. et al., 2017: Climate change impacts in Central Asia and their implications for development. *Regional Environmental Change*, **17**(6), 1639-1650, doi:https://doi.org/10.1007/s10113-015-0893-z.

Reyes-Fox, M. et al., 2014: Elevated CO2 further lengthens growing season under warming conditions. *Nature*, **510**, 259-262, doi:https://doi.org/10.1038/nature13207.

Rhiney, K., A. Eitzinger and A. D. Farrell, 2016: Assessing the vulnerability of Caribbean farmers to climate change impacts: a comparative study of cocoa farmers in Jamaica and Trinidad. In: *Climate Change and Food Security: Africa and the Caribbean*, 1st ed. [Hope, E. T. (ed.)]. Routledge, London, pp. 75-85. ISBN 9781315469737.

Ribot, J., 2013: Vulnerability does not just fall from the sky: Toward multi-scale pro-poor climate policy. In: *Handbook on climate change and human security* [Redclift, M. R. G. M. (ed.)]. Edward Elgar Publishing, Cheltenham, pp. 164–199. ISBN 9780857939104.

Richards, D. R. and P. J. Edwards, 2017: Quantifying street tree regulating ecosystem services using Google Street View. *Ecological Indicators*, **77**, 31-40, doi:10.1016/j.ecolind.2017.01.028.

Richmond, M. et al., 2020: *A Snapshot of Global Adaptation Investment and Tracking Methods*. Climate Policy Initiative, Initiative, C. P., 21 pp. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2020/04/A-Snapshot-of-Global-Adaptation-Investment-and-Tracking-Methods-April-2020.pdf.

Ricketts, T. H. et al., 2010: Indigenous lands, protected areas, and slowing climate change. *PLoS biology*, **8**(3), e1000331, doi:https://doi.org/10.1371/journal.pbio.1000331.

Risvoll, C. and G. K. Hovelsrud, 2016: Pasture access and adaptive capacity in reindeer herding districts in Nordland, Northern Norway. *The Polar Journal*, **6**(1), 87-111, doi:10.1080/2154896x.2016.1173796.

Rivera-Ferre, M. et al., 2016: Re-framing the climate change debate in the livestock sector: Mitigation and adaptation options. *Wiley Interdisciplinary Reviews: Climate Change*, **7**(6), 869-892, doi:https://doi.org/10.1002/wcc.421.

Roberts, E. and S. Andrei, 2015: The rising tide: migration as a response to loss and damage from sea level rise in vulnerable communities. *International Journal of Global Warming*, **8**(2), 258-258, doi:10.1504/ijgw.2015.071965.

Robinson, M. and T. Shine, 2018: Achieving a climate justice pathway to 1.5 °C. *Nature Climate Change*, **8**, 564-569, doi:https://doi.org/10.1038/s41558-018-0189-7.

Robinson, S.-a. and C. Wren, 2020: Geographies of vulnerability: a research note on human system adaptations to climate change in the Caribbean. *Geografisk Tidsskrift-Danish Journal of Geography*, **102**(1), 1-8, doi:https://doi.org/10.1080/00167223.2020.1733432.

Rocklöv, J. and R. Dubrow, 2020: Climate change: an enduring challenge for vector-borne disease prevention and control. *Nature immunology*, **21**(5), 479-483, doi:https://doi.org/10.1038/s41590-020-0648-y.
Rodina, L., 2016: Human right to water in Khayelitsha, South Africa–Lessons from a 'lived experiences' perspective. *Geoforum*, **72**(2016), 58-66, doi:https://doi.org/10.1016/J.GEOFORUM.2016.04.003.
Rodina, L., 2019a: Planning for water resilience: Competing agendas among Cape Town's planners and water managers. *Environmental Science & Policy*, **99**, 10-16, doi:10.1016/j.envsci.2019.05.016.
Rodina, L., 2019b: Water resilience lessons from Cape Town's water crisis. *Wiley Interdisciplinary Reviews: Water*, **6**(6), e1376, doi:https://doi.org/10.1002/wat2.1376.
Rodríguez-Díaz, C. E., 2018: Maria in Puerto Rico: natural disaster in a colonial archipelago. *American Public Health Association*, **108**(1), 30-32, doi:https://dx.doi.org/10.2105%2FAJPH.2017.304198.
Rodriguez Lopez, J. M. et al., 2019: A transdisciplinary approach to identifying transboundary tipping points in a contentious area: experiences from across the Jordan river region. *Sustainability*, **11**(4), 1184, doi:https://doi.org/10.3390/su11041184.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163, doi:https://doi.org/10.1016/j.crm.2017.02.001.
Romañach, S. S. et al., 2018: Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean & Coastal Management*, **154**, 72–82, doi:10.1016/j.ocecoaman.2018.01.009.
Röschel, L. et al., 2018: Individual Local Farmers' Perceptions of Environmental Change in Tanzania. *Water*, **10**(4), 525, doi:https://doi.org/10.3390/w10040525.
Rosenzweig, C. et al., 2018: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, Cambridge New York, 811 pp. ISBN 978-1-316-60333-8.
Rossiello, M. R. and A. Szema, 2019: Health effects of climate change-induced wildfires and heatwaves. *Cureus*, **11**(5), e4771, doi:https://dx.doi.org/10.7759%2Fcureus.4771.
Rotz, S. et al., 2019: Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. *Journal of Rural Studies*, **68**, 112-122, doi:10.1016/j.jrurstud.2019.01.023.
Roy, J. et al., 2018: Sustainable Development, Poverty Eradication and Reducing Inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
Roy, S., 2020: Livelihood Resilience of the Indigenous Munda Community in the Bangladesh Sundarbans Forest. In: *Handbook of Climate Change Resilience* [W, L. F. (ed.)]. Springer, Cham, pp. 51-72. ISBN 978-3-319-93336-8.
Rozenberg, J., C. Guivarch, R. Lempert and S. Hallegatte, 2014: Building SSPs for climate policy analysis: a scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation. *Climatic change*, **122**(3), 509-522, doi:https://doi.org/10.1007/s10584-013-0904-3.
Rufat, S. et al., 2020: Swimming alone? Why linking flood risk perception and behavior requires more than "it's the individual, stupid". *Wiley Interdisciplinary Reviews: Water*, **7**(5), e1462, doi:https://doi.org/10.1002/wat2.1462.
Rufat, S., E. Tate, C. G. Burton and A. S. Maroof, 2015: Social vulnerability to floods: Review of case studies and implications for measurement. *International Journal of Disaster Risk Reduction*, **14**, 470–486, doi:10.1016/j.ijdrr.2015.09.013.
Rufat, S., E. Tate, C. T. Emrich and F. Antolini, 2019: How valid are social vulnerability models? *Annals of the American Association of Geographers*, **109**(4), 1131-1153, doi:https://doi.org/10.1080/24694452.2018.1535887.
Runhaar, H. et al., 2018: Mainstreaming climate adaptation: taking stock about "what works" from empirical research worldwide. *Regional Environmental Change*, **18**(4), 1201-1210, doi:https://doi.org/10.1007/s10113-017-1259-5.
Sælen, H., V. Tørstad, C. Holz and T. D. Nielsen, 2019: Fairness conceptions and self-determined mitigation ambition under the Paris Agreement: Is there a relationship? *Environmental science & policy*, **101**, 245-254, doi:https://doi.org/10.1016/j.envsci.2019.08.018.
Saha, S. K., 2017: Cyclone Aila, livelihood stress, and migration: empirical evidence from coastal Bangladesh. *Disasters*, **41**(3), 505-526, doi:10.1111/disa.12214.
Sahakian, M. and M. Anantharaman, 2020: What space for public parks in sustainable consumption corridors? Conceptual reflections on need satisfaction through social practices. *Sustainability: Science, Practice and Policy*, **16**(1), 128-142, doi:https://doi.org/10.1080/15487733.2020.1788697.
Sain, G. et al., 2017: Costs and benefits of climate-smart agriculture: The case of the Dry Corridor in Guatemala. *Agricultural Systems*, **151**, 163-173, doi:10.1016/j.agsy.2016.05.004.
Saj, S. et al., 2017: The way forward: An agroecological perspective for Climate-Smart Agriculture. *Agriculture, Ecosystems & Environment*, **250**, 20-24, doi:https://doi.org/10.1016/j.agee.2017.09.003.
Sakaguchi, K., A. Varughese and G. Auld, 2017: Climate wars? A systematic review of empirical analyses on the links between climate change and violent conflict. *International Studies Review*, **19**(4), 622-645, doi:https://doi.org/10.1093/isr/vix022.

Sale, P. F. et al., 2014: Transforming management of tropical coastal seas to cope with challenges of the 21st century. *Marine Pollution Bulletin*, **85**(1), 8-23, doi:https://doi.org/10.1016/j.marpolbul.2014.06.005.
Salim, W., K. Bettinger and M. Fisher, 2019: Maladaptation on the waterfront: Jakarta's growth coalition and the Great Garuda. *Environment and Urbanization Asia*, **10**(1), 63-80, doi:https://doi.org/10.1177%2F0975425318821809.
Sam, A. G., B. O. Abidoye and S. Mashaba, 2021: Climate change and household welfare in sub-Saharan Africa: empirical evidence from Swaziland. *Food Security*, **13**(2), 439-455, doi:https://doi.org/10.1007/s12571-020-01113-z.
Samir, K. C. and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, **42**, 181-192, doi:10.1016/j.gloenvcha.2014.06.004.
Sanchez, Á., R. Díaz-Sierra, R. M. Martín-Aranda and M. J. Santos, 2017: Environmental impacts of climate change adaptation. *Environmental Impact Assessment Review*, **64**, 87-96, doi:https://doi.org/10.1016/j.eiar.2017.03.005.
Sánchez, A. and M. Izzo, 2017: Micro hydropower: an alternative for climate change mitigation, adaptation, and development of marginalized local communities in Hispaniola Island. *Climatic Change*, **140**(1), 79-87, doi:10.1007/s10584-016-1865-0.
Sapkota, T. B. et al., 2015: Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: some examples from cereal systems of Indo-Gangetic Plains. *Journal of Integrative Agriculture*, **14**(8), 1524-1533, doi:https://doi.org/10.1016/S2095-3119(15)61093-0.
Sarker, M. N. I., M. Wu, G. M. Alam and R. C. Shouse, 2019: Livelihood vulnerability of riverine-island dwellers in the face of natural disasters in Bangladesh. *Sustainability*, **11**(6), 1623, doi:https://doi.org/10.3390/su11061623.
Satterthwaite, D. et al., 2018: *Responding to climate change in cities and in their informal settlements and economies*. International Institute for Environment and Development Instituto Internacional de Medio Ambiente y Desarrollo - América Latina, London, 61 pp. Available at: https://pubs.iied.org/sites/default/files/pdfs/migrate/G04328.pdf (accessed 05-02-2020).
Saunders, N., 2019: *Climate change adaptation finance: are the most vulnerable nations prioritised?* SEI working paper, Stockholm Environment Institute, Institute, S. E., Stockholm, 42 pp. Available at: https://www.sei.org/wp-content/uploads/2019/04/climate-change-adaptation-finance-are-the-most-vulnerable-nations-prioritised.pdf.
Savo, V. et al., 2016: Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change*, **6**(5), 462-473, doi:https://doi.org/10.1038/nclimate2958.
Scarano, F. R., 2017: Ecosystem-based adaptation to climate change: concept, scalability and a role for conservation science. *Perspectives in Ecology and Conservation*, **15**(2), 65-73, doi:10.1016/j.pecon.2017.05.003.
Schaafsma, M. et al., 2021: Trade-off decisions in ecosystem management for poverty alleviation. *Ecological Economics*, **187**, 107103, doi:10.1016/j.ecolecon.2021.107103.
Schäfer, L., K. Warner and S. Kreft, 2019: Exploring and Managing Adaptation Frontiers with Climate Risk Insurance. In: *Loss and Damage from Climate Change*. [Mechler, R., L. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer, Cham, pp. 317-341. ISBN 978-3-319-72026-5.
Scheba, S. and N. Millington, 2018: Crisis temporalities: Intersections between infrastructure and inequality in the Cape Town Water Crisis. *International Journal of Urban and Regional Research*, doi:http://www.ijurr.org/spotlight-on-overview/parched-cities-parched-citizens/crisis-temporalities/.
Scheffer, M. et al., 2012: Anticipating critical transitions. *science*, **338**(6105), 344-348, doi:10.1126/science.1225244.
Schell, C. J. et al., 2020: The ecological and evolutionary consequences of systemic racism in urban environments. *Science*, **369**(6510), doi:https://doi.org/10.1126/science.aay4497.
Schipper, E. L. F., 2020: Maladaptation: when adaptation to climate change goes very wrong. *One Earth*, **3**(4), 409-414, doi:https://doi.org/10.1016/j.oneear.2020.09.014.
Schleussner, C.-F. et al., 2021: Pathways of climate resilience over the 21st century. *Environmental Research Letters*, **16**(5), 054058, doi:https://doi.org/10.1088/1748-9326/abed79.
Schlosberg, D. and L. B. Collins, 2014: From environmental to climate justice: climate change and the discourse of environmental justice. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(3), 359-374, doi:https://doi.org/10.1002/wcc.275.
Schmid, B., E. Raju and P. K. M. Jensen, 2021: COVID-19 and business continuity-learning from the private sector and humanitarian actors in Kenya. *Progress in Disaster Science*, 100181, doi:https://doi.org/10.1016/j.pdisas.2021.100181.
Schuldt, B. et al., 2020: A first assessment of the impact of the extreme 2018 summer drought on Central European forests. *Basic and Applied Ecology*, **45**, 86–103, doi:10.1016/j.baae.2020.04.003.
Schuman, S., J.-V. Dokken, D. van Niekerk and R. A. Loubser, 2018: Religious beliefs and climate change adaptation: A study of three rural South African communities. *Jàmbá: Journal of Disaster Risk Studies*, **10**(1), a509, doi:https://doi.org/10.4102/jamba.v10i1.509.
Schutte, S., J. Vestby, J. Carling and H. Buhaug, 2021: Climatic conditions are weak predictors of asylum migration. *Nature communications*, **21**, 2067, doi:https://doi.org/10.1038/s41467-021-22255-4.
Schwerdtle, P. N. et al., 2020: Health and migration in the context of a changing climate: a systematic literature assessment. *Environmental Research Letters*, **15**(10), 103006, doi:https://doi.org/10.1088/1748-9326/ab9ece.
Scovronick, N. and P. Wilkinson, 2014: Health impacts of liquid biofuel production and use: A review. *Global Environmental Change*, **24**, 155–164, doi:10.1016/j.gloenvcha.2013.09.011.

Sealey-Huggins, L., 2018: The climate crisis is a racist crisis: structural racism, inequality and climate change. In: *The Fire Now: Anti-Racist Scholarship in Times of Explicit Racial Violence* [Johnson, A., R. Joseph-Salisbury and B. Kamunge (eds.)]. Zed Books, London, pp. 99-113. ISBN 9781786993793.

Seddon, A. W. R. et al., 2016: Sensitivity of global terrestrial ecosystems to climate variability. *Nature*, **531**, 229 - 232, doi:https://doi.org/10.1038/nature16986.

Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B*, **375**(1794), 20190120, doi:https://doi.org/10.1098/rstb.2019.0120.

Selby, J., O. S. Dahi, C. Fröhlich and M. Hulme, 2017: Climate change and the Syrian civil war revisited. *Political Geography*, **60**, 232-244, doi:https://doi.org/10.1016/j.polgeo.2017.05.007.

Semde, I. et al., 2021: Enhancing Food Security and Disaster Risk Resilience in Burkina Faso: New Resilience Pathways to Disaster Risk and Food Security in the Sahel for Public Action. *IOSR Journal of Environmental Science, Toxicology and Food Technology (***15**(6), 39–50.

Serdeczny, O., 2019: Non-economic loss and damage and the Warsaw international mechanism. In: *Loss and Damage from Climate Change* [Mechler, R., L. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer, pp. 205-220. ISBN 978-3-319-72026-5.

Serdeczny, O., E. Waters and S. Chan, 2016: *Non-economic loss and damage in the context of climate change: understanding the challenges*. German Development Institute (DIE), Bonn, 38 pp. Available at: https://www.die-gdi.de/uploads/media/DP_3.2016.pdf.

Serdeczny, O. M., S. Bauer and S. Huq, 2018: Non-economic losses from climate change: opportunities for policy-oriented research. *Climate and Development*, **10**(2), 97-10, doi:10.1080/17565529.2017.1372268.

Serraglio, D. and B. Schraven, 2019: *Why we need to talk more about "climate migration"in Latin America*. German Development Institute Deutsches Institut für Entwicklungspolitik (DIE), Bonn, 2 pp. Available at: https://www.die-gdi.de/uploads/media/German_Development_Institute_Serraglio_Schraven_09.09.2019.pdf.

Seymour, F. and N. L. Harris, 2019: Reducing tropical deforestation. *Science*, **365**(6455), 756-757, doi:10.1126/science.aax8546.

Shaffril, H. A. M., S. E. Krauss and S. F. Samsuddin, 2018: A systematic review on Asian's farmers' adaptation practices towards climate change. *Science of the Total Environment*, **644**, 683–695, doi:https://doi.org/10.1016/j.scitotenv.2018.06.349.

Shakya, C. et al., 2021: *Access to climate finance* **Workshop Report** International Institute for Environment and Development (IIED), London, 15 pp. Available at: https://pubs.iied.org/10213iied (accessed 22-04-2021).

Sharifi, A., 2021: Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. *Science of The Total Environment*, **750**, 141642, doi:10.1016/j.scitotenv.2020.141642.

Sharma, A. et al., 2016: Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters*, **11**(6), 064004, doi:https://doi.org/10.1088/1748-9326/11/6/064004.

Sharma, U., A. Patwardhan and A. G. Patt, 2013: Education as a determinant of response to cyclone warnings: Evidence from coastal zones in India. *Ecology and Society*, **18**(2), 18, doi:10.5751/es-05439-180218.

Shaw, A. et al., 2014: Accelerating the sustainability transition: Exploring synergies between adaptation and mitigation in British Columbian communities. *Global Environmental Change*, **25**, 41-51, doi:http://dx.doi.org/10.1016/j.gloenvcha.2014.01.002.

Shepherd, M. and B. KC, 2015: Climate change and African Americans in the USA. *Geography Compass*, **9**(11), 579-591, doi:https://doi.org/10.1111/gec3.12244.

Siddiqi, M. N. A., M. N. Haque and M. A. Goni, 2011: Malnutrition of Under-Five Children: Evidence from Bangladesh. *Asian Journal of Medical Sciences*, **2**(2), 113–119, doi:10.3126/ajms.v2i2.3662.

Sills, E. O. et al., 2014: *REDD+ on the ground: A case book of subnational initiatives across the globe*. Center for International Forestry Research (CIFOR), Bogor. ISBN 978-602-1504-55-0.

Silveira, m. V. F. et al., 2020: Drivers of Fire Anomalies in the Brazilian Amazon: Lessons Learned from the 2019 Fire Crisis. *Land*, **9**(12), 516, doi:https://doi.org/10.3390/land9120516.

Simpson, N. P., C. D. Shearing and B. Dupont, 2019a: Climate gating: A case study of emerging responses to Anthropocene Risks. *Climate Risk Management*, **26**, 100196, doi:https://doi.org/10.1016/j.crm.2019.100196.

Simpson, N. P., C. D. Shearing and B. Dupont, 2020a: Gated adaptation during the cape town drought: mentalities, transitions and pathways to partial nodes of water security. *Society & Natural Resources*, **33**(8), 1041-1049, doi:https://doi.org/10.1080/08941920.2020.1712756.

Simpson, N. P., C. D. Shearing and B. Dupont, 2020b: 'Partial functional redundancy': An expression of household level resilience in response to climate risk. *Climate Risk Management*, **28**, doi:10.1016/j.crm.2020.100216.

Simpson, N. P., C. D. Shearing and B. Dupont, 2020c: When Anthropocene shocks contest conventional mentalities: a case study from Cape Town. *Climate and Development*, **12**(2), 163-169, doi:https://doi.org/10.1080/17565529.2019.1609402.

Simpson, N. P., K. J. Simpson, C. D. Shearing and L. R. Cirolia, 2019b: Municipal finance and resilience lessons for urban infrastructure management: a case study from the Cape Town drought. *International Journal of Urban Sustainable Development*, **11**(3), 257-276, doi:https://doi.org/10.1080/19463138.2019.1642203.

Sinclair, F. et al., 2019: *The Contribution of Agroecological Approaches to Realizing Climate-Resilient Agriculture.*, Global Commission on Adaptation, Adaptation, G. C. o., Rotterdam and Washington, DC, 46 pp. Available at: https://www.shareweb.ch/site/Agriculture-and-Food-Security/focusareas/Documents/cra_keydocs_sinclair_agroecology.pdf.
Singh, C., 2019: Migration as a driver of changing household structures: Implications for local livelihoods and adaptation. *Migration and Development*, **8**(3), 301-319, doi:https://doi.org/10.1080/21632324.2019.1589073.
Singh, C., G. Jain, V. Sukhwani and R. Shaw, 2021: Losses and damages associated with slow-onset events: urban drought and water insecurity in Asia. *Current Opinion in Environmental Sustainability*, **50**, 72-86, doi:https://doi.org/10.1016/j.cosust.2021.02.006.
Singh, C. et al., 2019a: What shapes vulnerability and risk management in semi-arid India? Moving towards an agenda of sustainable adaptation. *Environmental Development*, **30**, 35-50, doi:https://doi.org/10.1016/j.envdev.2019.04.007.
Singh, C. et al., 2019b: Exploring methodological approaches to assess climate change vulnerability and adaptation: reflections from using life history approaches. *Regional Environmental Change*, **19**(8), 2667-2682, doi:https://doi.org/10.1007/s10113-019-01562-z.
Singh, D., 2020: Gender relations, urban flooding, and the lived experiences of women in informal urban spaces. *Asian Journal of Women's Studies*, **26**(3), 326-346, doi:10.1080/12259276.2020.1817263.
Singh, N. and A. Leua, 2017: Adaptation and climate change: Challenges for doubling the farmers income. *Indian Journal of Economics and Development*, **13**((2a)), 437-442, doi:10.5958/2322-0430.2017.00109.3.
Singh, R. K. et al., 2020: Perceived Climate Variability and Compounding Stressors: Implications for Risks to Livelihoods of Smallholder Indian Farmers. *Environmental Management*, **66**(5), 826-844, doi:https://doi.org/10.1007/s00267-020-01345-x.
Singleton, B. E., N. Rask, G. L. Magnusdottir and A. Kronsell, 2021: Intersectionality and climate policy-making: The inclusion of social difference by three Swedish government agencies. *Environment and Planning C: Politics and Space*, **In Press**, 1-21, doi:https://doi.org/10.1177%2F23996544211005778.
Siqueira-Gay, J., L. J. Sonter and L. E. Sánchez, 2020: Exploring potential impacts of mining on forest loss and fragmentation within a biodiverse region of Brazil's northeastern Amazon. *Resources Policy*, **67**, 101662, doi:https://doi.org/10.1016/j.resourpol.2020.101662.
Skutsch, M. and E. Turnhout, 2020: REDD+: If communities are the solution, what is the problem? *World Development*, **130**, 104942, doi:https://doi.org/10.1016/j.worlddev.2020.104942.
Smirnov, O. et al., 2016: The relative importance of climate change and population growth for exposure to future extreme droughts. *Climatic Change*, **138**(1-2), 41-53, doi:https://doi.org/10.1007/s10584-016-1716-z.
Smith, A. et al., 2017: Measuring sustainable intensification in smallholder agroecosystems: A review. *Global Food Security*, **12**, 127–138, doi:10.1016/j.gfs.2016.11.002.
Smith, L. T., L. E. O. C. Aragão, C. E. Sabel and T. Nakaya, 2015: Drought impacts on children's respiratory health in the Brazilian Amazon. *Scientific Reports*, **4**(1), 3726-3726, doi:10.1038/srep03726.
Smith, P. et al., 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 811-922. ISBN 9781107058217.
Smith, R. et al., 2019: Ensuring Co-benefits for Biodiversity, Climate Change and Sustainable Development. In: *Handbook of Climate Change and Biodiversity* [Leal Filho, W., J. Barbir and R. Preziosi (eds.)]. Springer International Publishing, Cham, pp. 151–166. ISBN 978-3-319-98680-7.
Smucker, T. A. et al., 2015: Differentiated livelihoods, local institutions, and the adaptation imperative: Assessing climate change adaptation policy in Tanzania. *Geoforum*, **59**, 39-50, doi:https://doi.org/10.1016/j.geoforum.2014.11.018.
Soanes, M. et al., 2017: *Delivering real change: getting international climate finance to the local level.* **Working Paper**, International Institute for Environment and Development (IIED), London. Available at: https://pubs.iied.org/sites/default/files/pdfs/migrate/10178IIED.pdf.
Solecki, W. et al., 2018: City transformations in a 1.5°C warmer world. *Nature Climate Change*, **8**(3), 177-181, doi:10.1038/s41558-018-0101-5.
Solow, A. R., 2013: A call for peace on climate and conflict. *Nature*, **497**, 179-180, doi:https://doi.org/10.1038/497179a.
Somanathan, E., R. Somanathan, A. Sudarshan and M. Tewari, 2021: The Impact of Temperature on Productivity and Labor Supply: Evidence from Indian Manufacturing. *Journal of Political Economy*, **129**(6), 1797-1827, doi:10.1086/713733.
Somorin, O. A., 2010: Climate impacts, forest-dependent rural livelihoods and adaptation strategies in Africa: A review. *African Journal of Environmental Science and Technology*, **4**(13), 903-912, doi:http://hdl.handle.net/10625/46178.

Somorin, O. A. et al., 2016: Integration through interaction? Synergy between adaptation and mitigation (REDD+) in Cameroon. *Environment and Planning C: Government and Policy*, **34**(3), 415-432, doi:https://doi.org/10.1177%2F0263774X16645341.
Sorensen, P., 2017: The chronic water shortage in Cape Town and survival strategies. *International Journal of Environmental Studies*, **74**(4), 515-527, doi:https://doi.org/10.1080/00207233.2017.1335019.
Sousa, P. M. et al., 2018: The 'Day Zero'Cape Town drought and the poleward migration of moisture corridors. *Environmental Research Letters*, **13**(12), 124025, doi:https://doi.org/10.1088/1748-9326/aaebc7.
Southard, Nicole, 2017: The Socio-Political and Economic Causes of Natural Disasters. CMC Senior Thesis. Claremont McKenna College, 119 pp.
Souza, G. M. et al., 2017: The role of bioenergy in a climate-changing world. *Environmental development*, **23**, 57-64, doi:https://doi.org/10.1016/j.envdev.2017.02.008.
Sovacool, B. K., B. Linnér and M. E. Goodsite, 2015: The political economy of climate adaptation. *Nature Climate Change*, **5**, 616-618, doi:https://doi.org/10.1038/nclimate2665.
Sovacool, B. K., M. Tan-Mullins and W. Abrahamse, 2018: Bloated bodies and broken bricks: Power, ecology, and inequality in the political economy of natural disaster recovery. *World Development*, **110**, 243-255, doi:https://doi.org/10.1016/j.worlddev.2018.05.028.
Sovacool, B. K. et al., 2021: Dispossessed by decarbonisation: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways. *World Development*, **137**, 105116, doi:https://doi.org/10.1016/j.worlddev.2020.105116.
Spielman, S. E. et al., 2020: Evaluating social vulnerability indicators: criteria and their application to the Social Vulnerability Index. *Natural Hazards*, **100**(1), 417-436, doi:https://doi.org/10.1007/s11069-019-03820-z.
Stadelmann, M., Å. Persson, I. Ratajczak-Juszko and A. Michaelowa, 2014: Equity and cost-effectiveness of multilateral adaptation finance: are they friends or foes? *International Environmental Agreements: Politics, Law and Economics*, **14**(2), 101-120, doi:https://doi.org/10.1007/s10784-013-9206-5.
Staff, H., 2017: The emergence of private security governance. Assessing facilitating conditions in the case of Somali piracy. *Global Change, Peace & Security*, **29**(1), 21-37, doi:https://doi.org/10.1080/14781158.2016.1231174.
Steege, H. T. et al., 2015: Estimating the global conservation status of more than 15,000 Amazonian tree species. *Science Advances*, doi:10.1126/sciadv.1500936.
Steele, J. E. et al., 2017: Mapping poverty using mobile phone and satellite data. *Journal of The Royal Society Interface*, **14**(127), 20160690, doi:https://doi.org/10.1098/rsif.2016.0690.
Steenbergen, D. J. et al., 2020: COVID-19 restrictions amidst cyclones and volcanoes: A rapid assessment of early impacts on livelihoods and food security in coastal communities in Vanuatu. *Marine policy*, **121**, 104199, doi:https://doi.org/10.1016/j.marpol.2020.104199.
Steffen, W. et al., 2018: Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, **115**(33), 8252-8259, doi:https://doi.org/10.1073/pnas.1810141115.
Stott, P. A. et al., 2016: Attribution of extreme weather and climate-related events. *Wiley Interdisciplinary Reviews: Climate Change*, **7**(1), 23-41, doi:https://doi.org/10.1002/wcc.380.
Strauss, S. and B. S. Orlove, 2003: *Weather, climate, culture*, 1st ed., Routledge, London, 326 pp. ISBN 9781859736975.
Striessnig, E., W. Lutz and A. G. Patt, 2013: Effects of educational attainment on climate risk vulnerability. *Ecology and Society*, **18**(1), 16, doi:10.5751/es-05252-180116.
Stringer, C. et al., 2019: High-dimensional geometry of population responses in visual cortex. bioRxiv. *Nature*, **571**, 361–365, doi:https://doi.org/10.1038/s41586-019-1346-5.
Stringer, L. C. et al., 2014: Advancing climate compatible development: lessons from southern Africa. *Regional Environmental Change*, **14**(2), 713-725, doi:https://doi.org/10.1007/s10113-013-0533-4.
Stringer, L. C. et al., 2020: Adaptation and development pathways for different types of farmers. *Environmental Science & Policy*, **104**, 174-189, doi:https://doi.org/10.1016/j.envsci.2019.10.007.
Suckall, N., E. Fraser and P. Forster, 2017: Reduced migration under climate change: Evidence from Malawi using an aspirations and capabilities framework. *Climate and Development*, **9**(4), 298-312, doi:https://doi.org/10.1080/17565529.2016.1149441.
Suckall, N., L. C. Stringer and E. L. Tompkins, 2015: Presenting triple-wins? assessing projects that deliver adaptation, mitigation and development co-benefits in rural Sub-Saharan Africa. *Ambio*, **44**(1), 34-41, doi:https://dx.doi.org/10.1007%2Fs13280-014-0520-0.
Suckall, N., E. Tompkins and L. Stringer, 2014: Identifying trade-offs between adaptation, mitigation and development in community responses to climate and socio-economic stresses: Evidence from Zanzibar, Tanzania. *Applied Geography*, **46**, 111-121, doi:https://doi.org/10.1016/j.apgeog.2013.11.005.
Sujakhu, N. M. et al., 2019: Assessing the Livelihood Vulnerability of Rural Indigenous Households to Climate Changes in Central Nepal, Himalaya. *Sustainability*, **11**(10), 2977, doi:https://doi.org/10.3390/su11102977.
Sultana, F., 2021: Climate change, COVID-19, and the co-production of injustices: a feminist reading of overlapping crises. *Social & Cultural Geography*, **22**(4), 447-460, doi:https://doi.org/10.1080/14649365.2021.1910994.
Sultana, Z. and B. Mallick, 2015: Adaptation strategies after cyclone in southwest coastal Bangladesh–pro poor policy choices. *American Journal of Rural Development*, **3**(2), 24-33, doi:10.12691/ajrd-3-2-2.

Sumner, A., C. Hoy and E. Ortiz-Juarez, 2020: *Estimates of the Impact of COVID-19 on Global Poverty*. **WIDER Working Paper**, United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki, 800-809 pp. Available at: http://dx.doi.org/10.35188/UNU-WIDER/2020/800-9.

Sun, Y., P. H. Chau, M. Wong and et al., 2017: Place-and Age-Responsive Disaster Risk Reduction for Hong-Kong: Collaborative Place Audit and Social Vulnerability Index for Elders. *International Journal of Disaster Risk Science*, **8**, 121–133, doi:doi.org/10.1007/s13753-017-0128-7.

Sunkar, A. and Y. Santosa, 2018: Low Resource Use and High Yield Concept in Climate-Smart Community Empowerment. In: *Sustainable Future for Human Security* [McLellan, B. (ed.)]. Springer, Singapore, pp. 319-332. ISBN 978-981-10-5433-4.

Sutton-Grier, A. E., K. Wowk and H. Bamford, 2015: Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, **51**, 137–148, doi:10.1016/j.envsci.2015.04.006.

Swamy, S. and V. Tewari, 2017: Mitigation and adaptation strategies to climate change through agroforestry practices in the tropics. In: *Agroforestry* [Dagar, J. and V. Tewari (eds.)]. Springer, Singapore, pp. 725-738. ISBN 978-981-10-7650-3.

Tacoli, C., G. McGranahan and D. Satterthwaite, 2015: *Urbanisation, rural-urban migration and urban poverty*. **Working Paper**, International Institute for Environment and Development (IIED), Lonodn, 34 pp. Available at: https://pubs.iied.org/sites/default/files/pdfs/migrate/10725IIED.pdf.

Tall, A., J. Y. Coulibaly and M. Diop, 2018: Do climate services make a difference? A review of evaluation methodologies and practices to assess the value of climate information services for farmers: Implications for Africa. *Climate Services*, **11**, 1-12, doi:https://doi.org/10.1016/j.cliser.2018.06.001.

Tall, A. and J.-L. Njinga, 2013: *Developing a methodology to evaluate climate services for farmers in Africa and South Asia workshop report*. **Workshop Report**, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Cgiar Research Program on Climate Change, A., Food, Security, Copenhagen, 27 pp. Available at: https://hdl.handle.net/10568/33442.

Tanner, T. et al., 2015: Livelihood resilience in the face of climate change. *Nature Climate Change*, **5**, 23-26, doi:https://doi.org/10.1038/nclimate2431.

Tanner, T. et al., 2014: Political Economy of Climate Compatible Development: Artisanal Fisheries and Climate Change in Ghana. *IDS Working Papers*, **2014**(446), 1–30, doi:10.1111/j.2040-0209.2014.00446.x.

Taylor, M., 2018: Climate-smart agriculture: what is it good for? *The Journal of Peasant Studies*, **45**, 89-107, doi:10.1080/03066150.2017.1312355.

Teh, L., L. Teh and U. Sumaila, 2013: A Global Estimate of the Number of Coral Reef Fishers. *PLoS ONE*, **8**(6), e65397, doi:https://doi.org/10.1371/journal.pone.0065397.

Temperton, V. M. et al., 2019: Step back from the forest and step up to the Bonn Challenge: how a broad ecological perspective can promote successful landscape restoration. *Restoration ecology*, **27**(4), 705-719, doi:https://doi.org/10.1111/rec.12989.

Tenzing, J. D., 2020: Integrating social protection and climate change adaptation: A review. *Wiley Interdisciplinary Reviews: Climate Change*, **11**(2), e626, doi:https://doi.org/10.1002/wcc.626.

Thiede, B., C. Gray and V. Mueller, 2016: Climate variability and inter-provincial migration in South America, 1970–2011. *Global Environmental Change*, **41**, 228-240, doi:https://doi.org/10.1016/j.gloenvcha.2016.10.005.

Thierfelder, C. et al., 2018: Complementary practices supporting conservation agriculture in southern Africa. A review. *Agronomy for Sustainable Development*, **38**(2), doi:10.1007/s13593-018-0492-8.

Thomas, A. and L. Benjamin, 2020: Non-economic loss and damage: Lessons from displacement in the Caribbean. *Climate Policy*, **20**(6), 715-728, doi:https://doi.org/10.1080/14693062.2019.1640105.

Thomas, K. et al., 2019: Explaining differential vulnerability to climate change: A social science review. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(2), e565, doi:https://doi.org/10.1002/wcc.565.

Thomas, K. A. and B. P. Warner, 2019: Weaponizing vulnerability to climate change. *Global Environmental Change*, **57**, 101928, doi:https://doi.org/10.1016/j.gloenvcha.2019.101928.

Thornton, T. F. and C. Comberti, 2017: Synergies and trade-offs between adaptation, mitigation and development. *Climatic Change*, **140**(1), 5-18, doi:10.1007/s10584-013-0884-3.

Tian, Q. and M. C. Lemos, 2018: Household Livelihood Differentiation and Vulnerability to Climate Hazards in Rural China. *World Development*, **108**, 321-331, doi:https://doi.org/10.1016/j.worlddev.2017.10.019.

Tilleard, S. and J. Ford, 2016: Adaptation readiness and adaptive capacity of transboundary river basins. *Climatic Change*, **137**(3), 575-591, doi:https://doi.org/10.1007/s10584-016-1699-9.

Tol, R. S., 2005: Adaptation and mitigation: trade-offs in substance and methods. *Environmental Science & Policy*, **8**(6), 572-578, doi:https://doi.org/10.1016/j.envsci.2005.06.011.

Tol, R. S. J. and G. W. Yohe, 2007: The weakest link hypothesis for adaptive capacity: An empirical test. *Global Environmental Change*, **17**(2), 218-227, doi:doi.org/10.1016/j.gloenvcha.2006.08.001.

Tompkins, E. L. et al., 2013: *An investigation of the evidence of benefits from climate compatible development*. **Working paper**, Sustainability Research Institute Centre for Climate Change Economics and Policy, London, 27 pp. Available at: https://eprints.soton.ac.uk/349080/1/SRIPs-44-Tompkinsetal-triplewins-Jan2013.pdf.

Toolkit, U. C. R., Meet the Challenges of a Changing Climate: Learn about potential climate hazards so you can protect vulnerable asset, United States Global Change Research Program. Available at: https://toolkit.climate.gov/.

Totin, E. et al., 2018: Institutional perspectives of climate-smart agriculture: A systematic literature review. *Sustainability*, **10**(6), 1990, doi:https://doi.org/10.3390/su10061990.
Toussaint, P. and A. Martinez Blanco, 2020: A human rights-based approach to loss and damage under the climate change regime. *Climate policy*, **20**(6), 743-757, doi:https://doi.org/10.1080/14693062.2019.1630354.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(5), e476, doi:https://doi.org/10.1002/wcc.476.
Tschakert, P. et al., 2019: One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change*, **55**, 58-72, doi:https://doi.org/10.1016/j.gloenvcha.2018.11.006.
Tschora, H. and F. Cherubini, 2020: Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. *Global Ecology and Conservation*, **22**, e00919, doi:https://doi.org/10.1016/j.gecco.2020.e00919.
Tucker, J. et al., 2015: Social vulnerability in three high-poverty climate change hot spots: What does the climate change literature tell us? *Regional Environmental Change*, **15**(5), 783-800, doi:https://doi.org/10.1007/s10113-014-0741-6.
Turnheim, B. et al., 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change*, **35**, 239-253, doi:https://doi.org/10.1016/j.gloenvcha.2015.08.010.
Tusting, L. S. et al., 2019: Mapping changes in housing in sub-Saharan Africa from 2000 to 2015. *Nature*, **568**(7752), 391-394, doi:https://doi.org/10.1038/s41586-019-1050-5.
Tvinnereim, E. et al., 2018: Citizens' preferences for tackling climate change. Quantitative and qualitative analyses of their freely formulated solutions. *Global Environmental Change*, **46**, 34-41, doi:https://doi.org/10.1016/j.gloenvcha.2017.06.005.
UCLG, 2015: *Paris City Hall Declaration: A decisive contribution to COP21*. World Organization of United Cities and Local Governments, Paris. Available at: https://www.uclg.org/sites/http://default/files/climate_summit_final_declaration.pdf.
Uddin, M. S. et al., 2021: "Disasters threaten livelihoods, and people cope, adapt and make transformational changes": Community resilience and livelihoods reconstruction in coastal communities of Bangladesh. *International Journal of Disaster Risk Reduction*, **63**, 102444, doi:https://doi.org/10.1016/j.ijdrr.2021.102444.
UN-DESA, 2019: *World Population Prospects 2019: Methodology of the United Nations population estimates and projections* United Nations, Department of Economic and Social Affairs (UN-DESA), Population Division, New York. Available at: https://population.un.org/wpp/Download/Probabilistic/Population/.
UN-DESA, 2020: *World Social Report 2020. Inequality in a Rapidly Changing*. United Nations, New York, 216 pp. Available at: https://www.un.org/development/desa/dspd/wp-content/uploads/sites/22/2020/02/World-Social-Report2020-FullReport.pdf.
UN-OHRLLS, 2015: *Small Island Developing States in Numbers*. Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States (UN-OHRLLS), Climate Change Edition 15 ed., Nations, U., New York. Available at: https://sustainabledevelopment.un.org/content/documents/2189SIDS-IN-NUMBERS-CLIMATE-CHANGE-EDITION_2015.pdf.
UNDP, 2015: Following up on cyclone recovery in Bangladesh. Available at: https://www.undp.org/content/undp/en/home/ourwork/ourstories/following-up-on-cyclone-recovery-in-bangladesh.html (accessed 29 Aug 2019).
UNDRR, 2019: *Global Assessment Report on Disaster Risk Reduction 2019*. United Nations Office for Disaster Risk Reduction (UNDRR), Geneva, Switzerland, 425 pp. Available at: https://www.undrr.org/publication/global-assessment-report-disaster-risk-reduction-2019.
UNEP, 2009: *Towards Sustainable Production and Use of Resources: Assessing Biofuels*. United Nations Environment Programm (UNEP), Milan and Paris, 40 pp. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/8680/Biofuels_EN.pdf?sequence=1&isAllowed=y.
UNEP, 2016: *The Adaptation Gap Report 2016: Finance*. United Nations Environment Programme (UNEP) Nairobi, 50 pp. Available at: https://climateanalytics.org/media/agr2016.pdf.
UNEP, 2018: *Adaptation Gap Report 2018: Health*. United Nations Environment Programme (UNEP), Nairobi, 84 pp. Available at: https://www.unep.org/resources/adaptation-gap-report-2018.
UNEP, 2021: *Adaptation Gap Report 2020*. United Nations Environment Programme, Nairobi, 99 pp. Available at: https://www.unep.org/adaptation-gap-report-2020 (accessed 27-04-2021).
UNFCCC, 2016: *UNFCCC Standing Committee on Finance 2016 Biennial Assessment and Overview of Climate Finance Flows Report.*, United Nations Framework Convention on Climate Change (UNFCCC), Bonn, 150 pp. Available at: https://unfccc.int/files/cooperation_and_support/financial_mechanism/standing_committee/application/pdf/2016_ba_technical_report.pdf.
UNHCR, 2020: *Global Trends: Forced Displacement in 2019*. United Nations High Commissioner for Refugee (UNHCR), Copenhagen, 84 pp. Available at: https://www.unhcr.org/be/wp-content/uploads/sites/46/2020/07/Global-Trends-Report-2019.pdf.

UNISDR, 2009: *Global Assessment Report on Disaster Risk Reduction 2009*. United Nations International Strategy for Disaster Reduction (UNISDR), Reduction, U. N. I. S. f. D., Geneva, 207 pp. Available at: https://www.undrr.org/publication/global-assessment-report-disaster-risk-reduction-2009.

UNISDR, 2015: *Global Assessment Report on Disaster Risk Reduction 2015*. United Nations International Strategy for Disaster Reduction (UNISDR), Reduction, U. N. I. S. f. D., Geneva, 312 pp. Available at: https://www.un-ilibrary.org/content/books/9789210572699.

United Nations, 2010: *Cyclone Aila: Joint UN Multi-sector Assessment and Response Framework*. United Nations. Available at: https://www.scribd.com/document/79662690/Aila-UN-Assessment-Framework-FINAL (accessed 28 Aug 2019).

United Nations, 2015: *Transforming our world: the 2030 Agenda for Sustainable Development*. United Nations, New York, 35 pp. Available at: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.

United Nations, 2018: *Sustainable Development Goals Report 2018*. United Nations Publications, New York, NY. ISBN 978-92-1-101390-0.

UNTTSDCC, 2014: *Social Dimensions of Climate Change*. United Nations, Nations, U., New York. Available at: https://www.unsystem.org/content/social-dimensions-climate-change-0?page=4.

USDA, 2013: *Climate Change and Agriculture in the United States: Effects and Adaptation*. USDA Technical Bulletin, United States Department of Agriculture (USDA), Washington, DC, 216 pp. Available at: http://www.usda.gov/oce/climate_change/effects_2012/CC%20and%20Agriculture%20Report%20%2802-04-2013%29b.pdf.

USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, B. C. Stewart, D. J. Wuebbles, D. W. Fahey and K. A. Hibbard (eds.)]. **II**, U.S. Global Change Research Program (USGCRP), Washington, DC, 1515 pp. Available at: https://nca2018.globalchange.gov/.

Vallejo, L. and M. Mullan, 2017: *Climate-resilient infrastructure: Getting the policies right*. Organisation for Economic Co-operation and Development (OECD), Paris, 74 pp. Available at: https://www.oecd-ilibrary.org/docserver/02f74d61-en.pdf?expires=1629456211&id=id&accname=guest&checksum=5CD362C237A25087741F4AEBEE1698DE.

van der Geest, K., 2018: Landslide Loss and Damage in Sindhupalchok District, Nepal: Comparing Income Groups with Implications for Compensation and Relief. *International Journal of Disaster Risk Science*, **9**(2), 157-166, doi:10.1007/s13753-018-0178-5.

van der Geest, K. et al., 2019: The Impacts of Climate Change on Ecosystem Services and Resulting Losses and Damages to People and Society. In: *Loss and Damage from Climate Change. Climate Risk Management, Policy and Governance* [Mechler, R., L. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer, Cham, pp. 221-236. ISBN 978-3-319-72026-5.

van Der Geest, K. and M. Schindler, 2016: Brief communication: Loss and damage from a catastrophic landslide in Nepal. *Natural Hazards and Earth System Sciences*, **16**, 2347–2350, doi:10.5194/nhess-16-2347-2016.

van der Geest, K. and K. Warner, 2020: Loss and damage in the IPCC Fifth Assessment Report (Working Group II): a text-mining analysis. *Climate Policy*, **20**(6), 729-742, doi:https://doi.org/10.1080/14693062.2019.1704678.

Van Lange, P. A., J. Joireman and M. Milinski, 2018: Climate change: What psychology can offer in terms of insights and solutions. *Current directions in psychological science*, **27**(4), 269-274, doi:https://doi.org/10.1177%2F0963721417753945.

van Noordwijk, M., 2019: Integrated natural resource management as pathway to poverty reduction: Innovating practices, institutions and policies. *Agricultural Systems*, **172**, 60-71, doi:https://doi.org/10.1016/j.agsy.2017.10.008.

van Oldenborgh, G. J. et al., 2021a: Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences*, **21**(3), 941–960, doi:https://doi.org/10.5194/nhess-21-941-2021.

van Oldenborgh, G. J. et al., 2021b: Pathways and pitfalls in extreme event attribution. *Climatic Change*, **166**(1), 1-27, doi:https://doi.org/10.1007/s10584-021-03071-7.

van Ruijven, B. J., E. De Cian and I. S. Wing, 2019: Amplification of future energy demand growth due to climate change. *Nature communications*, **10**(1), 1-12, doi:https://doi.org/10.1038/s41467-019-10399-3.

van Valkengoed, A. M. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, **9**(2), 158-163, doi:https://doi.org/10.1038/s41558-018-0371-y.

van Vuuren, D. P. et al., 2018: Alternative pathways to the 1.5 C target reduce the need for negative emission technologies. *Nature Climate Change*, **8**(5), 391, doi:https://doi.org/10.1038/s41558-018-0119-8.

Vaughan, C. et al., 2017: Creating an enabling environment for investment in climate services: The case of Uruguay's National Agricultural Information System. *Climate Services*, **8**, 62-71, doi:https://doi.org/10.1016/j.cliser.2017.11.001.

Venema, H. D. and I. H. Rehman, 2007: Decentralized renewable energy and the climate change mitigation-adaptation nexus. *Mitigation and Adaptation Strategies for Global Change*, **12**(5), 875-900, doi:https://doi.org/10.1007/s11027-007-9104-7.

Verschuur, J., S. Li, P. Wolski and F. E. Otto, 2021: Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. *Scientific reports*, **11**, 3852, doi:https://doi.org/10.1038/s41598-021-83375-x.

Versey, H. S., 2021: Missing Pieces in the Discussion on Climate Change and Risk: Intersectionality and Compounded Vulnerability. *Policy Insights from the Behavioral and Brain Sciences*, **8**(1), 67-75, doi:https://doi.org/10.1177%2F2372732220982628.
Vetlesen, A. J., 2019: *Cosmologies of the Anthropocene: panpsychism, animism, and the limits of posthumanism*. Routledge, London, 270 pp. ISBN 9780367545345.
Vij, S. et al., 2017: Climate adaptation approaches and key policy characteristics: Cases from South Asia. *Environmental Science & Policy*, **78**, 58-65, doi:https://doi.org/10.1016/j.envsci.2017.09.007.
Vincent, K. et al., 2017: Identifying climate services needs for national planning: insights from Malawi. *Climate Policy*, **17**(2), 189-202, doi:https://doi.org/10.1080/14693062.2015.1075374.
Vink, M. and G. Schouten, 2018: Foreign-Funded Adaptation to Climate Change in Africa: Mirroring Administrative Traditions or Traditions of Administrative Blueprinting? *Review of Policy Research*, **35**(6), 792-834, doi:https://doi.org/10.1111/ropr.12291.
Visser, H. et al., 2020: What users of global risk indicators should know. *Global Environmental Change*, **62**, 102068, doi:https://doi.org/10.1016/j.gloenvcha.2020.102068.
Vogt, J. et al., 2018: *Drought Risk Assessment and Management: A conceptual Framework*. Publications Office of the European Union, Luxembourg, 68 pp. Available at: file:///C:/Users/IREUS-~1/AppData/Local/Temp/vogt_etal_2018_drought_risk_assessment_final-online_1.pdf (accessed 09-04-2021).
Voigt, C. and F. Ferreira, 2016: 'Dynamic differentiation': The principles of CBDR-RC, progression and highest possible ambition in the Paris Agreement. *Transnational Environmental Law*, **5**(2), 285-303, doi:https://doi.org/10.1017/S2047102516000212.
Volpato, G. and E. G. King, 2019: From cattle to camels: trajectories of livelihood adaptation and social-ecological resilience in a Kenyan pastoralist community. *Regional Environmental Change*, **19**(3), 849-865, doi:https://doi.org/10.1007/s10113-018-1438-z.
Volz, U. et al., 2020: *Debt Relief for a Green and Inclusive Recovery: A Proposal* [Center for Sustainable Finance, S. U. o. L. and B. U. Global Development Policy Center (eds.)]. Heinrich Böll Foundation; Center for Sustainable Finance, SOAS, University of London; Global Development Policy Center, Boston University, Foundation, H. B., Berlin LondonBoston, 58 pp. Available at: https://www.boell.de/sites/default/files/2021-01/Endf%20DRGR%20Hauptreport%20%28klein%29.pdf (accessed 22-04-2021).
von Uexkull, N., M. Croicu, H. Fjelde and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proc Natl Acad Sci U S A*, **113**(44), 12391-12396, doi:10.1073/pnas.1607542113.
Vuojala-Magga, T., M. Turunen, R. T. and M. Tennberg, 2011: Resonance Strategies of Sámi Reindeer Herders in Northernmost Finland during Climatically Extreme Years. *Arctic*, **64**(2), 227-241, doi:https://doi.org/10.14430/arctic4102.
Walker, H. M., M. G. Reed and A. J. Fletcher, 2021: Applying intersectionality to climate hazards: a theoretically informed study of wildfire in northern Saskatchewan. *Climate Policy*, **21**(2), 171-185, doi:https://doi.org/10.1080/14693062.2020.1824892.
Walker, W. S. et al., 2020: The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. *Proceedings of the National Academy of Sciences*, **117**(6), 3015-3025, doi:https://doi.org/10.1073/pnas.1913321117.
Wallemacq, P. and R. House, 2018: *Economic losses, poverty & disasters: 1998-2017*. United Nations Office for Disaster Risk Reduction UNDRR Centre for Research on the Epidemiology of Disasters CRED, Geneva. Available at: https://www.undrr.org/publication/economic-losses-poverty-disasters-1998-2017 (accessed 19-04-2021).
Wang, S., G. Li and C. Fang, 2018: Urbanization, economic growth, energy consumption, and CO2 emissions: Empirical evidence from countries with different income levels. *Renewable and Sustainable Energy Reviews*, **81**, 2144-2159, doi:https://doi.org/10.1016/j.rser.2017.06.025.
Wang, S. Y. S., L. Zhao and R. R. Gillies, 2016: Synoptic and quantitative attributions of the extreme precipitation leading to the August 2016 Louisiana flood. *Geophysical Research Letters*, **43**(22), doi:10.1002/2016gl071460.
Wangui, E. E. and T. A. Smucker, 2018: Gendered opportunities and constraints to scaling up: a case study of spontaneous adaptation in a pastoralist community in Mwanga District, Tanzania. *Climate and Development*, **10**(4), 369-376, doi:10.1080/17565529.2017.1301867.
Ward, P. S., 2016: Transient poverty, poverty dynamics, and vulnerability to poverty: An empirical analysis using a balanced panel from rural China. *World development*, **78**, 541-553, doi:https://doi.org/10.1016/j.worlddev.2015.10.022.
Warner, J. F., A. J. Wesselink and G. D. Geldof, 2018: The politics of adaptive climate management: Scientific recipes and lived reality. *Wiley Interdisciplinary Reviews: Climate Change*, **9**(3), e515, doi:https://doi.org/10.1002/wcc.515.
Warner, K. and K. Van der Geest, 2013: Loss and damage from climate change: local-level evidence from nine vulnerable countries. *International Journal of Global Warming*, **5**(4), 367-386, doi:https://dx.doi.org/10.1504/IJGW.2013.057289.
Watkiss, P. and H. A., 2016: Assessing Climate-Resilient Development Options. In: *The Economics of Climate-Resilient Development* [Fankhauser, S. and e. T. McDermott (eds.)]. Edward Elgar, Cheltenham. ISBN 9781785360305.

Watts, M. J. and H. G. Bohle, 1993: The space of vulnerability: the causal structure of hunger and famine. *Progress in human geography*, **17**(1), 43-67, doi:https://doi.org/10.1177%2F030913259301700103.
Welle, T. and J. Birkmann, 2015: The World Risk Index – An Approach to Assess Risk and Vulnerability on a Global Scale. *Journal of Extreme Events*, **02**(01), 1550003, doi:10.1142/s2345737615500037.
WHO, 2014a: *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*. World Health Organization, Geneva. ISBN 978 92 4 150769 1.
WHO, 2014b: *WHO guidance to protect health from climate change through health adaptation planning.*, World Health Organization, Organization, W. H., Geneva, 23 pp. Available at: https://apps.who.int/iris/handle/10665/137383.
WHO, 2018: *World health statistics 2018: monitoring health for the SDGs, sustainable development goals*. World Health Organization, Geneva, 86 pp. ISBN 978-92-4-156558-5.
Wichelns, D., 2016: Managing water and soils to achieve adaptation and reduce methane emissions and arsenic contamination in Asian rice production. *Water*, **8**(4), 141, doi:https://doi.org/10.3390/w8040141.
Wiegleb, V. and A. Bruns, 2018: What is driving the Water-Energy-Food Nexus? Discourses, knowledge and politics of an emerging resource governance concept. *Frontiers in Environmental Science*, **6**, 128, doi:https://doi.org/10.3389/fenvs.2018.00128.
Wigand, C. et al., 2017: A Climate Change Adaptation Strategy for Management of Coastal Marsh Systems. *Estuaries and Coasts*, **40**(3), 682–693, doi:10.1007/s12237-015-0003-y.
Wilkins, M., S&P Global Ratings Adds Agriculture, Forestry, And Waste To Its Green Evaluation, S&P News. Available at: https://www.spglobal.com/ratings/en/research/articles/191204-s-p-global-ratings-adds-agriculture-forestry-and-waste-to-its-green-evaluation-11267665.
Windfeld, E. J., J. D. Ford, L. Berrang-Ford and G. McDowell, 2019: How do community-level climate change vulnerability assessments treat future vulnerability and integrate diverse datasets? A review of the literature. *Environmental Reviews*, **27**(4), 427-434, doi:https://doi.org/10.1139/er-2018-0102.
Wise, R. et al., 2016: How climate compatible are livelihood adaptation strategies and development programs in rural Indonesia? *Climate Risk Management*, **12**, 100-114, doi:https://doi.org/10.1016/j.crm.2015.11.001.
Wise, R. M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325-336, doi:https://doi.org/10.1016/j.gloenvcha.2013.12.002.
Wisner, B., 2016: Vulnerability as concept, model, metric, and tool. *Oxford Research Encyclopedia of Natural Hazard Science*, doi:https://doi.org/10.1093/acrefore/9780199389407.013.25.
Wisner, B., 2020: Five years beyond Sendai—Can we get beyond frameworks? *International Journal of Disaster Risk Science*, **11**(2), 239-249, doi:https://doi.org/10.1007/s13753-020-00263-0.
Wolch, J. R., J. Byrne and J. P. Newell, 2014: Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning*, **125**, 234-244, doi:10.1016/j.landurbplan.2014.01.017.
Wolf, A. T., K. Stahl and M. F. Macomber, 2003: Conflict and cooperation within international river basins: The importance of institutional capacity. *Water Resources Update*, **125**(2), 31-40.
Wolski, P., 2018: How severe is Cape Town's "Day Zero" drought? *Significance*, **15**(2), 24-27, doi:https://doi.org/10.1111/j.1740-9713.2018.01127.x.
Woodruff, S. C., 2018: City membership in climate change adaptation networks. *Environmental Science & Policy*, **84**, 60-68, doi:https://doi.org/10.1016/j.envsci.2018.03.002.
Woolf, D. et al., 2015: *Climate Change Mitigation Potential of Ethiopia's Productive Safety-Net Program (PSNP) . A World Bank Climate Smart Initiative (CSI) Report*. Technical Report, Cornell University Colorado State University, University, C., Ithaca. Available at: https://hdl.handle.net/1813/41296.
Work, C., V. Rong, D. Song and A. Scheidel, 2019: Maladaptation and development as usual? Investigating climate change mitigation and adaptation projects in Cambodia. *Climate Policy*, **19**(sup1), S47-S62, doi:https://doi.org/10.1080/14693062.2018.1527677.
World Bank, 2008: *The World Bank annual report 2008: Year in review*. World Bank Annual Report, World Bank, Bank, W., Washington, D.C., 68 pp. Available at: https://documents1.worldbank.org/curated/en/452391468323718231/pdf/462560WBAR00EN1ry0Sept020080English.pdf.
World Bank, 2010: *Economics of Adaptation to Climate Change: Synthesis Report*. World Bank, Washington, DC., 136 pp. Available at: https://openknowledge.worldbank.org/handle/10986/12750.
World Bank, 2016: *The Inspection Panel. 2016. Indigenous Peoples. Emerging Lessons*. **Emerging Lessons Series**, World Bank, Washington, DC. , 44 pp. Available at: http://hdl.handle.net/10986/25328.
World Bank, Seychelles launches World's First Sovereign Blue Bond, World Bank, Seychelles. Available at: https://www.worldbank.org/en/news/press-release/2018/10/29/seychelles-launches-worlds-first-sovereign-blue-bond (accessed 14-08-2019).
World Bank, 2019a: *Action Plan on Climate Change Adaptation and Resilience: Managing Risks for a more Resilient Future*. World Bank, 24, Washington DC. Available at: http://documents1.worldbank.org/curated/en/519821547481031999/The-World-Bank-Groups-Action-Plan-on-Climate-Change-Adaptation-and-Resilience-Managing-Risks-for-a-More-Resilient-Future.pdf.

World Bank, World Development Indicators: Population, total. Available at: https://data.worldbank.org/indicator/SP.POP.TOTL.
World Bank, 2020: *Poverty and Shared Prosperity 2020 : Reversals of Fortune*. World Bank, Washington, DC. ISBN 978-1-4648-1602-4.
World Bank, 2021: *Tracking the SDG 7: The Energy Progress Report 2021*. World Bank, Washington DC 234 pp. Available at: https://trackingsdg7.esmap.org/data/files/download-documents/2021_tracking_sdg7_report.pdf (accessed 25-08-2021).
Wrathall, D. et al., 2019: Meeting the looming policy challenge of sea-level change and human migration. *Nature Climate Change*, **9**(12), 898-901, doi:https://doi.org/10.1038/s41558-019-0640-4.
Wrathall, D. J. et al., 2014: Migration amidst climate rigidity traps: Resource politics and social–ecological possibilism in Honduras and Peru. *Annals of the Association of American Geographers*, **104**(2), 292-304, doi:https://doi.org/10.1080/00045608.2013.873326.
Wrathall, D. J. et al., 2015: Problematising loss and damage. *International Journal of Global Warming*, **8**(2), 274-294, doi:https://doi.org/10.1504/IJGW.2015.071962.
Wrathall, D. J., J. Van Den Hoek, A. Walters and A. Devenish, 2018: *Water Stress and Human Migration: A Global, Georeferenced Review of Empirical Research*. **Land and Water Discussion Paper**, Food and Agriculture Organization of the United Nations, Rome, 26 pp. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/I8867EN.pdf.
Wright, H. et al., 2014: Farmers, food and climate change: ensuring community-based adaptation is mainstreamed into agricultural programmes. *Climate and development*, **6**(4), 318-328, doi:https://doi.org/10.1080/17565529.2014.965654.
Wuepper, D., H. Y. Ayenew and J. Sauer, 2018: Social Capital, Income Diversification and Climate Change Adaptation: Panel Data Evidence from Rural Ethiopia. *Journal of Agricultural Economics*, **69**(2), 458-475, doi:10.1111/1477-9552.12237.
Xie, M. et al. (eds.), Transfer learning from deep features for remote sensing and poverty mapping. Thirtieth AAAI Conference on Artificial Intelligence, Phoenix, Arizona USA, Association for the Advancement of Artificial Intelligence AAAI. ISBN 978-1-57735-760-5.
Xu, C. et al., 2020: Future of the human climate niche. *Proceedings of the National Academy of Sciences*, **117**(21), 11350-11355, doi:https://doi.org/10.1073/pnas.1910114117.
Yao, T. et al., 2020: Third Pole climate warming and cryosphere system changes. *World Meteorological Organization Bulletin*, **69**(1), 38-44.
Yildiz, I., 2019: Review of climate change issues: A forcing function perspective in agricultural and energy innovation. *International Journal of Energy Research*, **43**(6), 2200-2215, doi:https://doi.org/10.1002/er.4435.
Young, B. E., N. S. DuBois and E. L. Rowland, 2015: Using the Climate Change Vulnerability Index to Inform Adaptation Planning: Lessons, Innovations, and Next Steps. *Wildlife Society Bulletin*, **39**(1), 174-181, doi:10.1002/wsb.478.
Young, H. M. and M. A. Ismail, 2019: Complexity, continuity and change: livelihood resilience in the Darfur region of Sudan. *Disasters*, **43**(S3), 318-344, doi:10.1111/disa.12337.
Yu, Y. et al., 2021: Increased Risk of the 2019 Alaskan July Fires due to Anthropogenic Activity. *Bulletin of the American Meteorological Society*, **102**(1), S1-S7, doi:10.1175/bams-d-20-0154.1.
Yun, X. et al., 2020: Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin. *Journal of Hydrology*, **590**, 125472, doi:10.1016/j.jhydrol.2020.125472.
Zhang, H. et al., 2021: The role of spiritual fortitude in meaning and mental health symptoms following a natural disaster. *Psychology of Religion and Spirituality*, doi:10.1037/rel0000420.
Zhang, Y., B. McCarl and J. Jones, 2017: An Overview of Mitigation and Adaptation Needs and Strategies for the Livestock Sector. *Climate*, **5**(4), 95, doi:10.3390/cli5040095.
Zhao, C. et al., 2018: Adaptation and mitigation for combating climate change–from single to joint. *Ecosystem Health and Sustainability*, **4**(4), 85-94, doi:https://doi.org/10.1080/20964129.2018.1466632.
Zhukova, E., 2020: Vulnerability. In: *Humanitarianism: Keywords* [Lauri, A. d. (ed.)]. Koninklijke Brill NV, Leiden, pp. 230–232. ISBN 9789004431133.
Zickgraf, C., 2021: Climate change, slow onset events and human mobility: reviewing the evidence. *Current Opinion in Environmental Sustainability*, **50**, 21-30, doi:https://doi.org/10.1016/j.cosust.2020.11.007.
Ziervogel, G., 2019a: Building transformative capacity for adaptation planning and implementation that works for the urban poor: Insights from South Africa. *Ambio*, **48**(5), 494-506, doi:https://doi.org/10.1007/s13280-018-1141-9.
Ziervogel, G., 2019b: *Unpacking the Cape Town drought: lessons learned*. African Centre for Cities, Cities, A. C. f., Cape Town. Available at: https://www.africancentreforcities.net/wp-content/uploads/2019/02/Ziervogel-2019-Lessons-from-Cape-Town-Drought_A.pdf.
Zimmermann, A., J. Benda, H. Webber and Y. Jafari, 2018: *Trade, food security and climate change: conceptuallinkages and policy implications*. Food and Agriculture Organization (FAO), Food and O. Agriculture, Rome, 48 pp. Available at: http://www.fao.org/3/CA2370EN/ca2370en.pdf.
Zougmoré, R. et al., 2016: Toward climate-smart agriculture in West Africa: a review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agriculture & Food Security*, **5**, 26, doi:https://doi.org/10.1186/s40066-016-0075-3.

Zuñiga, R. A. A., G. N. Lima and A. M. G. Villoria, 2021: Impact of slow-onset events related to Climate Change on food security in Latin America and the Caribbean. *Current Opinion in Environmental Sustainability*, **50**, 215-224, doi:https://doi.org/10.1016/j.cosust.2021.04.011.

Chapter 9: Africa

Coordinating Lead Authors: Christopher H. Trisos (South Africa), Ibidun O. Adelekan (Nigeria), Edmond Totin (Benin).

Lead Authors: Ayansina Ayanlade (Nigeria), Jackson Efitre (Uganda), Adugna Gemeda (Ethiopia), Kanungwe Kalaba (Zambia), Christopher Lennard (South Africa), Catherine Masao (Tanzania), Yunus Mgaya (Tanzania), Grace Ngaruiya (Kenya), Daniel Olago (Kenya), Nicholas P. Simpson (Zimbabwe/South Africa), Sumaya Zakieldeen (Sudan).

Contributing Authors: Philip Antwi-Agyei (Ghana), Aaron Atteridge (Sweden/Australia), Rachel Bezner Kerr (Canada/USA), Max Callaghan (United Kingdom/Germany), Tamma Carleton (USA), Colin Carlson (USA), Hayley Clements (South Africa), Declan Conway (United Kingdom), Sean Cooke (South Africa), Matthew Chersich (South Africa), David Chiawo (Kenya), Joanne Clarke (Australian/United Kingdom), Marlies Craig (South Africa), Olivier Crespo (South Africa), James Cullis (South Africa), Jampel Dell'Angelo (Italy/USA), Luleka Dlamini (South Africa) Hussen Seid Endris (Kenya), Christien Engelbreht (South Africa), Aidan Farrell (Trinidad and Tobago/Ireland), James Franke (USA), Thian Yew Gan (Malaysia/Canada), Christopher Golden (USA), Kerry Grey (South Africa), Toshihiro Hasegawa (Japan), Ryan Hogarth (Canada/United Kingdom), Nadia, Hassan O. Kaya (South Africa), Khalaf (United Kingdom), Mercy Kinyua (Kenya), Scott Kulp (USA), William F. Lamb (United Kingdom/Germany), Charne Lavery (South Africa), Johan Maritz (South Africa), Guy Midgley (South Africa), Danielle Millar (South Africa), Jan Minx (Germany), Glenn Moncrieff (South Africa), Rachid Moussadek (Morocco), Mzime Ndebele-Murisa (Zimbabwe), Emily Nicklin (South Africa), Michelle North (South Africa), Mary Nyasimi (Kenya), Elizabeth Nyboer (Canada), Romaric Odoulami (Benin/South Africa), Andrew Okem (South Africa/Nigeria), Gladys Okemwa (Kenya), Kulthoum Omari (Botswana/South Africa), Esther Onyango (Kenya/Australia), Birgitt Ouweneel (Netherlands/South Africa), Indra Øverland (Norway), Lorena, Pasquini (South Africa), Belynda Petrie (South Africa), Alex Pigot (United Kingdom), Wilfried Pokam (Cameroon), Bronwen Powell (Canada/USA), Jeff Price (United Kingdom), Heather Randell (USA), Maren Radeny (Kenya), Jonathan Rawlins (South Africa), Kanta Kumari Rigaud (Malaysia/USA), Carla Roncoli (USA), Olivia Rumble (South Africa), Elisa Sainz de Murieta (Spain), Georgia Savvidou (Sweden/Cyprus), Lucia Schlemmer (South Africa), Laura Schmitt Olabisi (USA), Chandni Singh (India), Thomas Smucker (USA), Nicola Stevens (South Africa), Anna Steynor (South Africa), Bamba Sylla (Rwanda/Senegal), Arame Tall (Senegal/USA), Richard Taylor (Canada/United Kingdom), Meryem Tenarhte (Morocco/Germany), Mia Thom (South Africa), Jessica Thorn (Namibia/South Africa), Katharina Waha (Germany/Australia), Hitomi Wakatsuki (Japan), Edna Wangui (Kenya/USA), Portia Adade Williams (Ghana), Kevin Winter (South Africa), Caradee Wright (South Africa), Luckson Zvobgo (Zimbabwe/South Africa).

Review Editors: Stuart Mark Howden (Australia), Robert (Bob) J. Scholes (South Africa), Pius Yanda (Tanzania).

Chapter Scientists: Michelle North (South Africa), Luckson Zvobgo (Zimbabwe/South Africa).

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Overall Key Messages

Africa has contributed among the least to greenhouse gas emissions, yet key development sectors have already experienced widespread loss and damage attributable to anthropogenic climate change, including biodiversity loss, water shortages, reduced food production, loss of lives and reduced economic growth (*high confidence*[1]). {9.1.1, 9.2, 9.6.1, 9.8.2, 9.10.2, 9.11.1; Box 9.4}

Between 1.5°C and 2°C global warming—assuming localised and incremental adaptation—impacts are projected to become widespread and severe for reduced food production, reduced economic growth, increased inequality and poverty, biodiversity loss, increased human morbidity and mortality (*high confidence*)**. Limiting global warming to 1.5°C is expected to substantially reduce damages to African economies and ecosystems** (*high confidence*). {9.2, 9.6.2, 9.8.2, 9.8.5, 9.10.2, 9.11.2}

Exposure and vulnerability to climate change in Africa are multi-dimensional with socioeconomic, political and environmental factors intersecting (*very high confidence*). Africans are disproportionately employed in climate-exposed sectors: 55–62% of the sub-Saharan workforce employed is in agriculture and 95% of cropland rainfed. In rural Africa, poor and female-headed households face greater livelihood risks from climate hazards. In urban areas, growing informal settlements without basic services increases the vulnerability of large populations to climate hazards, especially women, children and the elderly. {9.8.2, 9.9.1, 9.9.3, 9.11.4; Box 9.1}

Adaptation in Africa has multiple benefits, and most assessed adaptation options have medium effectiveness at reducing risks for present-day global warming, but their efficacy at future warming levels is largely unknown (*high confidence*). {9.3, 9.6.4, 9.8.3, 9.11.4}

Enabling Climate-Resilient Development

Climate-related research in Africa faces severe data constraints, as well as inequities in funding and research leadership that reduce adaptive capacity (*very high confidence*)**.** Many countries lack regularly reporting weather stations, and data access is often limited. From 1990–2019 research on Africa received just 3.8% of climate-related research funding globally: 78% of this funding went to EU and North American institutions and only 14.5% to African institutions. The number of climate research publications with locally-based authors are among the lowest globally and research led by external researchers may focus less on local priorities. Increased funding for African partners, and direct control of research design and resources can provide more actionable insights on climate risks and adaptation options in Africa. {9.1, 9.4.5, 9.5.2}

Adaptation generally is cost effective, but annual finance flows targeting adaptation for Africa are billions of USD less than the lowest adaptation cost estimates for near-term climate change (*high confidence*). Finance has not targeted more vulnerable countries. From 2014–2018 more finance commitments were debt than grants and—excluding multilateral development banks—only 46% of commitments were disbursed (compared to 96% for other development projects). {9.4.1}

Adaptation costs will rise rapidly with global warming (*very high confidence*)**. Increasing public and private finance flows by billions of dollars per year, increasing direct access to multilateral funds, strengthening project pipeline development, and shifting finance from readiness activities to project implementation would help realise transformative adaptation in Africa** (*high confidence*). Concessional finance will be required for adaptation in low-income settings. Aligning sovereign debt relief with climate goals could increase finance by redirecting debt-servicing payments to climate resilience. {9.4.1}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Governance for climate resilient development includes: long-term planning, all-of-government approaches, transboundary cooperation and benefit-sharing, development pathways that increase adaptation and mitigation and reduce inequality, and NDC implementation (*high confidence*). {9.3.2, 9.4.2, 9.4.3}

Cross-sectoral 'nexus' approaches provide significant opportunities for large co-benefits and/or avoided damages (*very high confidence*). For example, climate change adaptation benefits pandemic preparedness; 'One Health' approaches benefit human and ecosystem health; and Ecosystem-based Adaptation can deliver adaptation and emissions mitigation (*high confidence*). {9.4.3, 9.6.4, 9.11.5; Box 9.6}

Without cross-sectoral, transboundary and long-term planning, response options in one sector can become response risks, exacerbating impacts in other sectors and causing maladaptation (*very high confidence*)**.** For example, maintaining indigenous forest benefits biodiversity and emissions mitigation, but afforestation—or wrongly targeting ancient grasslands and savannas for reforestation—harms water security and biodiversity, and can increase carbon loss to fire and drought. Planned hydropower projects may increase risk as rainfall changes impact water, energy and food security exacerbating trade-offs between users, including across countries. {9.4.3; Boxes 9.3, 9.5}

Robust legislative frameworks that develop or amend laws to mainstream climate change into their empowerment and planning provisions will facilitate effective design and implementation of climate change responses (*high confidence*). {9.4.4}

Climate information services that are demand-driven and context-specific (e.g., for agriculture or health) combined with climate change literacy can affect the difference between coping and informed, adaptation responses (*high confidence*). Across 33 African countries, 23–66% of people are aware of anthropogenic climate change—with larger variation at subnational scales (e.g., 5–71% among states in Nigeria). Climate change literacy increases with education level but is undermined by poverty, and rates average 12.8% lower for women than men. 71% of Africans aware of climate change agree it should be stopped. Production of salient climate information in Africa is hindered by limited availability of and access to weather and climate data. {9.4.5, 9.5.1, 9.8.4, 9.10.3}

Ecosystem-based adaptation can reduce climate risk while providing social, economic and environmental benefits (*high confidence*). Direct human dependence on ecosystem services in Africa is high. Ecosystem protection and restoration, conservation agriculture practices, sustainable land management, and integrated catchment management can support climate resilience. Ecosystem-based adaptation can cost less than grey infrastructure in human settlements (e.g., using wetlands and mangroves as coastal protection). {9.6.4, 9.7.3, 9.8.3, 9.9.5, 9.12.3; Box 9.7}

Observed Impacts and Projected Risks

Climate

Increasing mean and extreme temperature trends across Africa are attributable to human-induced climate change (*high confidence*). {9.5.1, 9.5.2}

Climate change has increased heat waves (*high confidence*) **and drought** (*medium confidence*) **on land, and doubled the probability of marine heatwaves around most of Africa** (*high confidence*). Multi-year droughts have become more frequent in West Africa, and the 2015–2017 Cape Town drought was three times more *likely*[2] due to human-induced climate change. {9.5.3–7, 9.5.10}

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

Above 2°C global warming, meteorological drought frequency will increase and duration will double from 2 to 4 months over North Africa, the western Sahel and southern Africa (*medium confidence*). {9.5.2, 9.5.3, 9.5.6.}

Frequency and intensity of heavy rainfall events will increase at all levels of global warming (except in North and southwestern Africa), increasing exposure to pluvial and riverine flooding (*high confidence).* {9.5.3–7, 9.7}

Glaciers on the Rwenzoris and Mt. Kenya are projected to disappear by 2030, and by 2040 on Kilimanjaro *(medium confidence*). {9.5.8}

In East and southern Africa, tropical cyclones making landfall are projected to become less frequent but have more intense rainfall and higher wind speeds at increasing global warming (*medium confidence*). {9.5.7}

Heat waves on land, in lakes, and in the ocean will increase considerably in magnitude and duration with increasing global warming (*very high confidence*). Under a 1.5°C-compatible scenario, children born in Africa in 2020 are *likely* to be exposed to 4–8 times more heat waves compared to people born in 1960, increasing to 5–10 times for 2.4°C global warming. The annual number of days above potentially lethal heat thresholds reaches 50–150 in west Africa at 1.6°C global warming, 100–150 in Central Africa at 2.5°C, and 200–300 over tropical Africa for >4°C. {9.5.2, 9.5.3, 9.5.4, 9.5.5, 9.5.6, 9.7.2.1}

Most African countries will enter unprecedented high temperature climates earlier in this century than generally wealthier, higher latitude countries, emphasising the urgency of adaptation measures in Africa (*high confidence*). {9.5.1}

Compound risks

Multiple African countries are projected to face compounding risks from: reduced food production across crops, livestock and fisheries; increasing heat-related mortality; heat-related loss of labour productivity; and flooding from sea level rise, especially in West Africa (*high confidence*). {9.8.2, 9.8.5, 9.9.4, 9.10.2, 9.11.2}

Water

Recent extreme variability in rainfall and river discharge (c. -50% to +50% relative to long-term historical means) across Africa have had largely negative and multi-sector impacts across water-dependent sectors (*high confidence*) {9.7.2, 9.10.2}. Hydrological variability and water scarcity have induced cascading impacts from water-supply provision and/or hydro-electric power production to health, economies, tourism, food, disaster risk response capacity and increased inequality of water access. {Box 9.4}

Extreme hydrological variability is projected to progressively amplify under all climate scenarios relative to the current baseline, depending on region (*high confidence*). Projections of numbers of people exposed to water stress by the 2050s vary widely—decreases/increases by hundreds of millions, with higher numbers for increases—with disagreement among global climate models the major factor driving these large ranges. Populations in drylands are projected to more than double. Projected changes present heightened cross-cutting risks to water-dependent sectors, and require planning under deep uncertainty for the wide range of extremes expected in future. {9.7.1, 9.7.2}

Economy and Livelihoods

Climate change has reduced economic growth across Africa, increasing income inequality between African countries and those in temperate, Northern Hemisphere climates (*high confidence*)**.** One estimate suggests GDP per capita for 1991–2010 in Africa was on average 13.6% lower compared to if climate change had not occurred. Impacts manifest largely through losses in agriculture, as well as tourism, manufacturing, and infrastructure. {9.6.3, 9.11.1}

Climate variability and change undermine educational attainment (*high agreement, medium evidence*). High temperatures, low rainfall, and flooding, especially in the growing season, may mean children are removed from school to assist income generation. Early life undernutrition associated with low harvests can impair cognitive development. {9.11.1.2}

Limiting global warming to 1.5°C is *very likely* to positively impact GDP per capita across Africa. Increasing economic damage forecasts under high-emissions diverge from low-emissions pathways by 2030. Inequalities between African countries are projected to widen with increased warming. Across nearly all African countries, GDP per capita is projected to be at least 5% higher by 2050 and 10–20% higher by 2100 if global warming is held to 1.5°C versus 2°C. {9.11.2}

Food systems

In Africa, climate change is reducing crop yields and productivity (*medium confidence*). Agricultural productivity growth has been reduced by 34% since 1961 due to climate change, more than any other region. Maize and wheat yields decreased on average 5.8% and 2.3%, respectively in sub-Saharan Africa due to climate change in the period 1974–2008. Farmers and pastoralists perceive the climate to have changed and over two thirds of Africans perceive climate conditions for agricultural production have worsened over the past ten years. Woody plant encroachment has reduced fodder availability. {9.4.5, 9.6.1, 9.8.2}

Future warming will negatively affect food systems in Africa by shortening growing seasons and increasing water stress (*high confidence)*. By 1.5°C global warming, yields are projected to decline for olives (North Africa) and Sorghum (West Africa) with a decline in suitable areas for coffee and tea (East Africa). Although yield declines for some crops may be partially compensated by increasing atmospheric CO_2 concentrations, global warming above 2°C will result in yield reductions for staple crops across most of Africa compared to 2005 yields (e.g., 20–40% decline in West African maize yields), even when considering adaptation options and increasing CO_2 (*medium confidence*). Relative to 1986–2005, global warming of 3°C is projected to reduce labour capacity in agriculture by 30–50% in sub-Saharan Africa. {9.8.2}

Climate change threatens livestock production across Africa (*high agreement, low evidence***).** Rangeland net primary productivity is projected to decline 42% for west Africa by 2050 at 2ºC global warming. Vector-borne livestock diseases and the duration of severe heat stress are both projected to become more prevalent under warming. {9.8.2}

Climate change poses a significant threat to African marine and freshwater fisheries (*high confidence*). Fisheries provide the main source of protein for ~30% of Africa's population and support the livelihoods of 12.3 million people. At 1.5°C global warming, marine fish catch potential (MFCP) decreases 3–41% by 2081–2100 relative to 1986–2005, increasing to 12–69% at 4.3°C, with the highest declines for tropical countries. Under 1.7°C global warming, reduced fish harvests could leave 1.2–70 million people vulnerable to iron deficiencies, up to 188 million for vitamin A deficiencies, and 285 million for vitamin B_{12} and omega-3 fatty acids by mid-century. For inland fisheries, 55–68% of commercially harvested fish species are vulnerable to extinction under 2.5°C global warming by 2071–2100. {9.8.5}

Health

Climate variability and change already impacts the health of tens of millions of Africans through exposure to non-optimal temperatures and extreme weather, and increased range and transmission of infectious diseases (*high confidence).* {9.10.1}

Mortality and morbidity will escalate with further global warming, placing additional strain on health and economic systems (*high confidence*). At 1.5°C of global warming, distribution and seasonal transmission of vector-borne diseases is expected to increase, exposing tens of millions more people, mostly in East and Southern Africa (*high confidence*). Above 1.5°C risk of heat-related deaths rises sharply (*high confidence*), with at least 15 additional deaths per 100,000 annually across large parts of Africa. At 2.1°C degrees, thousands to tens of thousands of additional cases of diarrhoeal disease are projected, mainly in Central and East Africa (*medium confidence*). These changes risk undermining improvements in health from future socio-economic development (*high agreement, medium evidence*).{9.10.2}

Human Settlements

Exposure of people, assets and infrastructure to climate hazards is increasing in Africa with rapid urbanisation, infrastructure deficit, and growing population in informal settlements (*high confidence***).**

About one-third of African cities with populations over 300,000 are located in areas that are at high risk from climate hazards. Sub-Saharan Africa is the only region that has recorded increasing rates of flood mortality since the 1990s. {9.9.1, 9.9.2}

High population growth and urbanisation in low-elevation coastal zones will be a major driver of exposure to sea level rise in the next 50 years (*high confidence*). By 2030, 108–116 million people in Africa will be exposed to sea level rise in Africa (compared to 54 million in 2000), increasing to 190–245 million by 2060. {9.9.1, 9.9.4}

Africa's rapidly growing cities will be hotspots of risks from climate change and climate-induced in-migration, which could amplify pre-existing stresses related to poverty, informality, exclusion and governance (*high confidence*)**.** Urban population exposure to extreme heat is projected to increase from 2 billion person-days per year in 1985–2005 to 45 billion person-days by the 2060s (1.7℃ global warming with low population growth) and to 95 billion person-days (2.8℃ global warming with medium-high population growth), with greatest exposure in West Africa. Sensitive populations under 5 and over 64 years old in African cities exposed to heat waves are projected to increase from around 27 million in 2010 to 360 million (SSP1) and 440 million (SSP5) by 2100, for global warming of 1.8℃ and >4℃, respectively. Compared to 2000, urbanization is projected to increase urban land extent exposed to arid conditions by around 700% and exposure to high-frequency flooding by 2,600% across West, Central and East Africa by 2030. {9.9.1, 9.9.2, 9.9.4; Box 9.8}

Migration

Most climate-related migration observed currently is within countries or between neighbouring countries, rather than to distant high-income countries (*high confidence*)**.** Urbanisation has increased when rural livelihoods were negatively impacted by low rainfall. Over 2.6 million and 3.4 million new weather-related displacements occurred in sub-Saharan Africa in 2018 and 2019. {Box 9.8}

Climate change is projected to increase migration, especially internal and rural-to-urban migration (*high agreement, medium evidence*)**.** With 1.7°C global warming by 2050, 17–40 million people could migrate internally in sub-Saharan Africa, increasing to 56–86 million for 2.5°C (>60% in West Africa) due to water stress, reduced crop productivity, and sea level rise. This is a lower-bound estimate excluding rapid-onset hazards such as floods and tropical cyclones. {Box 9.8}

Infrastructure

Climate-related infrastructure damage and repairs will be a financially significant burden to countries (*high confidence*)**.** Without adaptation, aggregate damages from sea level rise and coastal extremes to 12 major African coastal cities in 2050 under medium and high emissions scenarios will be USD 65 billion and USD 86.5 billion, respectively. Potential costs of up to USD 183.6 billion may be incurred through 2100 to maintain existing road networks damaged from temperature and precipitation changes due to climate change. Increased rainfall variability is expected to affect electricity prices in countries highly dependent on hydropower. {9.9.4; Boxes 9.4, 9.5}

Ecosystems

Increasing CO_2 levels and climate change are destroying marine biodiversity, reducing lake productivity, and changing animal and vegetation distributions (*high confidence*)**.** Impacts include repeated mass coral bleaching events in east Africa, and uphill (birds) or poleward (marine species) shifts in geographic distributions. For vegetation, the overall observed trend is woody plant expansion, particularly into grasslands and savannas, reducing grazing land and water supplies. {9.6.1}

The outcome of interacting drivers operating in opposing directions on future biome distributions is highly uncertain. Further increasing CO2 concentrations could increase woody plant cover, but increasing aridity could counteract this, destabilising forest and peatland carbon stores in central Africa (*low confidence*). {9.6.2.1}

African biodiversity loss is projected to be widespread and escalating with every 0.5ºC increase above present-day global warming (*high confidence***).** Above 1.5°C, half of assessed species are projected to lose over 30% of their population or area of suitable habitat. At 2°C, 36% of freshwater fish species are vulnerable to local extinction, 7–18% of species assessed are at risk of extinction, and over 90% of East African coral reefs could be destroyed by bleaching. Above 2°C, risk of sudden and severe biodiversity losses becomes widespread in West, Central and East Africa. Climate change is also projected to change patterns of invasive species spread. {9.6.2}

Climate security

There is increasing evidence linking increased temperatures and drought to conflict risk in Africa (*high confidence*)**.** Agriculturally dependent and politically excluded groups are especially vulnerable to drought-associated conflict risk. However, climate is one of many interacting risk factors, and may explain a small share of total variation in conflict incidence. Ameliorating ethnic tensions, strengthening political institutions, and investing in economic diversification could mitigate future impacts of climate change on conflict. {Box 9.9}

Heritage

African cultural heritage is already at risk from climate hazards, including sea level rise and coastal erosion. Most African heritage sites are neither prepared for, nor adapted to, future climate change (*high confidence*). {9.12}

Adaptation

With global warming increasing above present-day levels the ability of adaptation responses to offset risk is substantially reduced (*high confidence***).** Crop yield losses, even after adaptation, are projected to rise rapidly above 2°C global warming. Limits to adaptation are already being reached in coral reef ecosystems. Immigration of species from elsewhere may partly compensate for local extinctions and/or lead to local biodiversity gains in some regions. However, more African regions face net losses than net gains. At 1.5°C global warming, over 46% of localities face net losses in terrestrial vertebrate species richness with net increases projected for under 15% of localities. {9.6.1.4, 9.6.2.2, 9.8.2.1, 9.8.2.2, 9.8.4}

Technological, institutional, and financing factors are major barriers to climate adaptation feasibility in Africa (*high confidence*). {9.3, 9.4.1}

There is limited evidence for economic growth alone reducing climate damages, but under scenarios of inclusive and sustainable development, millions fewer people in Africa will be pushed into extreme poverty by climate change and negative impacts to health and livelihoods can be reduced by 2030 (*medium confidence*). {9.10.3, 9.11.4}

Gender-sensitive and equity-based adaptation approaches reduce vulnerability for marginalised groups across multiple sectors in Africa, including water, health, food systems and livelihoods (*high confidence*). {9.7.3, 9.8.3, 9.9.5, 9.10.3, 9.11.4; Boxes 9.1, 9.2}

Integrating climate adaptation into social protection programs, such as cash transfers, public works programmes and healthcare access, can increase resilience to climate change (*high confidence*). Nevertheless, social protection programs may increase resilience to climate-related shocks, even if they do not specifically address climate risks. {9.4.2, 9.10.3, 9.11.4}

The diversity of African indigenous knowledge and local knowledge systems provide a rich foundation for adaptation actions at local scales (*high confidence*). African indigenous knowledge systems are exceptionally rich in ecosystem-specific knowledge used for management of climate variability. Integration of indigenous knowledge systems within legal frameworks, and promotion of indigenous land tenure rights can reduce vulnerability. {9.4.4; Box 9.1, Box 9.2}

Early warning systems based on targeted climate services can be effective for disaster risk reduction, social protection programmes, and managing risks to health and food systems (e.g., vector-borne disease and crops) (*high confidence*). {9.4.5, 9.5.1, Box 9.2, 9.8.4, 9.8.5, 9.10.3, 9.11.4}

Risk-sensitive infrastructure delivery and equitable provision of basic services can reduce climate risks and provide net financial savings (*high confidence*). However, there is limited evidence of pro-active climate adaptation in African cities. Proactive adaptation policy could reduce road repair and maintenance costs by 74% compared to a reactive policy. Adapting roads for increased temperatures and investment in public transport are assessed as 'no regret' options. In contrast, hydropower development carries risk of regrets due to damages when a different climate than was expected materializes. Energy costs for cooling demands are projected to accumulate to USD 51.3 billion in 2035 at 2°C global warming and to USD 486.5 billion in 2076 at 4°C. {9.8.5}

Reduced drought and flood risk, and improved water and sanitation access, can be delivered by: water-sensitive and climate scenario planning, monitored groundwater use, waterless on-site sanitation, rainwater harvesting and water reuse, reducing risk to human settlements, food systems, economies, and human health (*high confidence*). {9.8, 9.9, 9.10, 9.11}

Water sector adaptation measures show medium social and economic feasibility but low feasibility for most African cities due to technical and institutional restrictions, particularly for large supply dams and centralised distribution systems (*medium confidence*). {9.3.1, 9.7.3} Use of integrated water management, water supply augmentation, and establishment of decentralised water management systems can reduce risk. Integrated water management measures including sub-national financing, demand management through subsidies, rates and taxes, and sustainable water technologies can reduce water insecurity caused by either drought or floods (*medium confidence*). {9.7.3; Box 9.4}

Agricultural and livelihood diversification, agroecological and conservation agriculture practices, aquaculture, on-farm engineering, and agroforestry can increase resilience and sustainability of food systems in Africa under climate change (*medium confidence*). However, smallholder farmers tend to address short-term shocks or stresses by deploying coping responses rather than transformative adaptations. Climate information services, institutional capacity building, and strategic financial investment can help overcome these barriers to adaptation (*medium confidence*). {9.4.5, 9.8.3, 9.8.5}

African countries and communities are inadequately insured against climate risk, but innovative index-based insurance schemes can help transfer risk and aid recovery, including in food systems (*medium confidence*). Despite their potential, uptake of climate insurance products remains constrained by lack of affordability, awareness and product diversity. {9.4.5, 9.8.4, 9.11.4.1}

Human migration is a potentially effective adaptation strategy across food systems, water, livelihoods and in climate-induced conflict areas, but can also be maladaptive if vulnerability is increased, particularly for health and human settlements (*high confidence*). Migration of men from rural areas can aggravate the work burden faced by women. The more agency migrants have (that is, degree of voluntarity and freedom of movement) the greater the potential benefits for sending and receiving areas (*high agreement, medium evidence*).{9.3, 9.8.3, 9.9.1–3, 9.10.2.2.2; Boxes 9.8, 9.9; Cross-Chapter Box MIGRATE in Chapter 7}

9.1 Introduction

9.1.1 Point of Departure

This chapter assesses the scientific evidence on observed and projected climate change impacts, vulnerability and adaptation options in Africa. The assessment refers to five African sub-regions – North, West, Central, East and southern – closely following the African Union (AU), but including Mauritania in West Africa and Sudan in North Africa because much of the literature assessed places these countries in these regions (Figure 9.1). Madagascar and other island states are addressed in Chapter 15.

Africa has contributed among the least to historical greenhouse gas emissions (GHG) responsible for anthropogenic climate change and has the lowest per capita GHG emissions of all regions currently (*high confidence*) (Figure 9.2). Yet Africa has already experienced widespread impacts from anthropogenic climate change (*high confidence*) (Table 9.1; Figure 9.2).

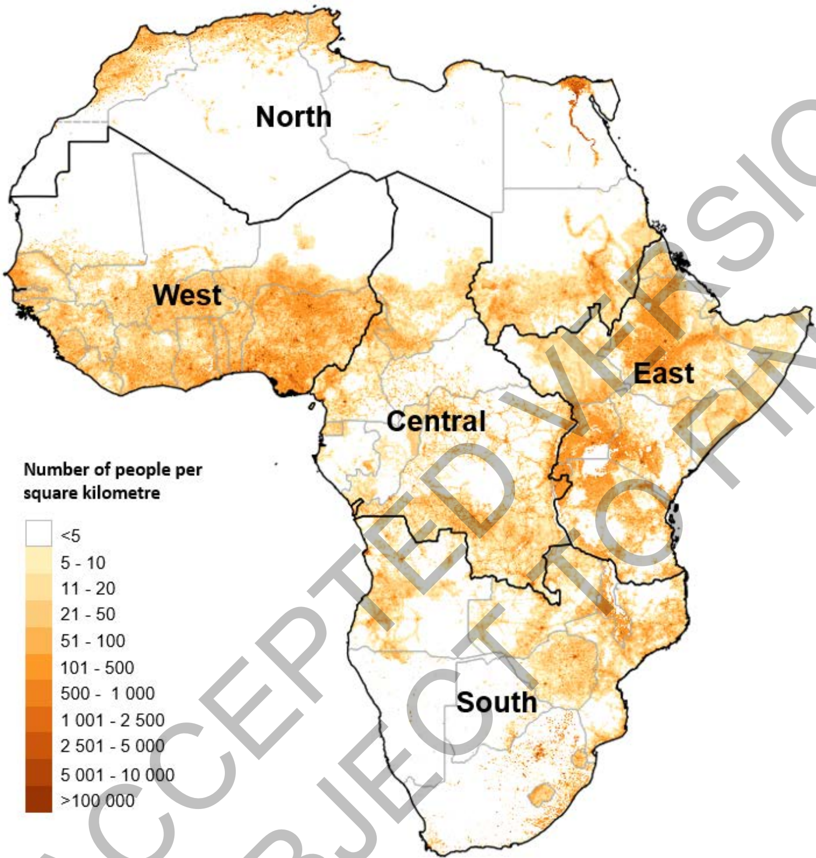


Figure 9.1: The 5 Regions of Africa used in this chapter, also showing estimated population density in 2019. The population of Africa was estimated at 1.312 billion for 2020, which is about 17% of the world population but this is projected to grow to around 40% of world population by 2100 (UNDESA, 2019a). Although 57% of the African population currently live in rural areas (43% urban), Africa is the most rapidly urbanising region globally and is projected to transition to a majority urban population in the 2030s with a 60% urban population by 2050 (UNDESA, 2019b). The 2019 Gross Domestic Product (GDP) per capita in constant 2010 averaged USD 2,250 across 43 countries reporting data, ranging from USD 202 (Burundi) to USD 8,840 (Gabon), with 40% of the population of sub-Saharan Africa living below the international poverty line of USD 1,90 per day in 2018 (World Bank, 2018). The highest life expectancy at birth is 67 (Botswana and Senegal) and the lowest is 52 (Central African Republic) (World Bank, 2018). Grid-cell population density data for mapping are from (Tatem, 2017; WorldPop, 2021).

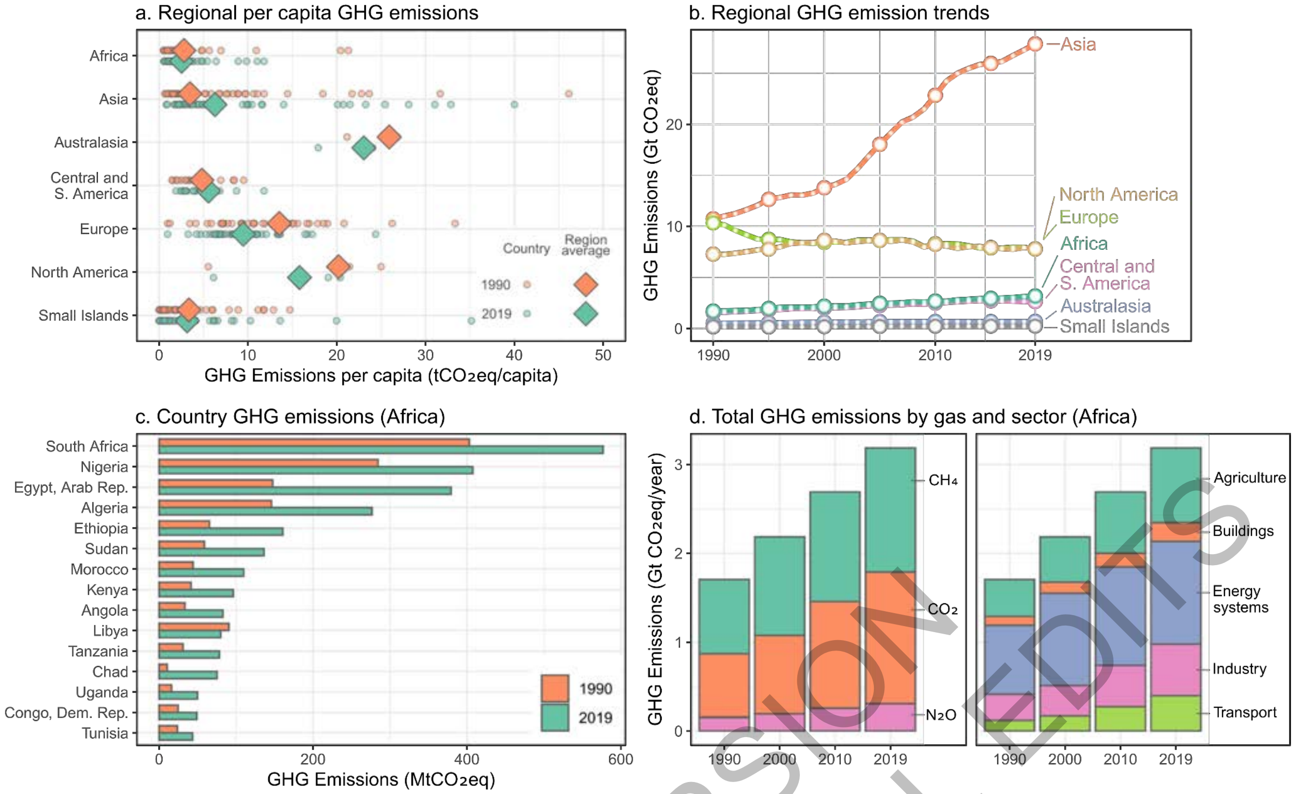


Figure 9.2: Historical greenhouse gas (GHG) emission trends for Africa compared to other world regions: (a) Per person GHG emissions by region and growth from 1990-2018 (circles represent countries, diamonds represent the region average). (b) Total GHG emissions by region since 1990. (c) The total GHG emissions in 1990 and 2018 for the 15 highest emitting countries within Africa. (d) Total emissions in Africa since 1990, broken down by GHG (left) and sector (right). Methane and CO_2 emissions comprise an almost equal share of greenhouse gas emissions in Africa, with the largest emissions sectors being energy and agriculture (Crippa et al., 2021). Agriculture emissions in panel (d) do not include land use, land use change and forestry (LULUCF CO2). One-hundred-year global warming potentials consistent with WGI estimates are used. Emissions data are from (Crippa et al., 2021), compiled by Chapter 2 of WGIII.

Since AR5, there have been notable policy changes in Africa and globally. The Paris Agreement, 2030 Sustainable Development Goals (SDGs), the Sendai Framework and Agenda 2063 emphasise interlinked aims to protect the planet, reduce disaster risk, end poverty and ensure all people enjoy peace and prosperity (AU, 2015; UNFCCC Paris Agreement, 2015; UNISDR Sendai Framework, 2015; United Nations General Assembly, 2015). To match these interlinked ambitions, this chapter assesses risks and response options both for individual sectors and cross-sectorally to assess how risks can compound and cascade across sectors, as well as the potential feasibility and effectiveness, co-benefits and trade-offs and potential for maladaptation from response options (Simpson et al., 2021b; Williams et al., 2021).

9.1.2 Major Conclusions from Previous Assessments

Based on an analysis of 1,022 mentions of Africa or African countries across the three AR6 Special Reports, the following main conclusions emerged.

- Hot days, hot nights and heatwaves have become more frequent; heatwaves have also become longer (*high confidence*). Drying is projected particularly for West and southwestern Africa (*high confidence*) (IPCC, 2018c; Shukla et al., 2019).
- Climate change is contributing to land degradation, loss of biodiversity, bush encroachment and spread of pests and invasive species (SR1.5, SRCCL, SROCC).
- Climate change has already reduced food security through losses in crop yields, rangelands, livestock and fisheries, deterioration in food nutritional quality, access and distribution and price spikes. Risks to crop yields are substantially less at 1.5°C compared with 2°C of global warming, with a large reduction

in maize cropping areas projected even for 1.5°C, as well as reduced fisheries catch potential (SR1.5, SRCCL, SROCC).
- Increased deaths from undernutrition, malaria, diarrhoea, heat stress and diseases related to exposure to dust, fire smoke and other air pollutants are projected from further warming (IPCC, 2018c; Shukla et al., 2019).
- The largest reductions in economic growth for an increase from 1.5°C to 2°C of global warming are projected for low- and middle-income countries, including in Africa (IPCC, 2018c).
- Climate change interacts with multidimensional poverty, among other vulnerabilities. Africa is projected to bear an increasing proportion of the global exposed and vulnerable population at 2°C and 3°C of global warming (IPCC, 2018c).
- Poverty and limited financing continue to undermine adaptive capacity, particularly in rapidly growing African cities (Shukla et al., 2019).
- Large-scale afforestation and bioenergy can reduce food availability and ecosystem health (IPCC, 2018c) (SRCCL 2019).
- Transitioning to renewable energy would reduce reliance on wood fuel and charcoal, especially in urban areas, with co-benefits including reduced deforestation, desertification, fire risk and improved indoor air quality, local development and agricultural yield (Shukla et al., 2019).
- Sustainable use of biodiversity, conservation agriculture, reduced deforestation, land and watershed restoration, rainwater harvesting and well-planned reforestation can have multiple benefits for adaptation and mitigation, including water security, food security, biodiversity, soil conservation and local surface cooling (IPBES, 2018; Shukla et al., 2019).
- Climate resilience can be enhanced through improvements to early warning systems, insurance, investment in safety nets, secure land tenure, transport infrastructure, communication, access to information and investments in education and strengthened local governance (Shukla et al., 2019).
- Scenarios of socio-environmental change are underused in decision-making in Africa (IPBES, 2018).
- Africa's rich biodiversity together with a wealth of indigenous knowledge and local knowledge is a key strategic asset for sustainable development (IPBES, 2018).

9.1.3 What's New on Africa in AR6?

1. Increased confidence in observed and projected changes in climate hazards, including heat and precipitation.
2. Increased regional, national and sub-national observed impacts and projected risks.
3. Loss and damage assessment.
4. Increased quantification of projected risks at 1.5°C, 2°C, 3°C and 4°C of global warming (Section 9.2; Figure 9.6).
5. Improved assessment of sea level rise risk (Sections 9.9 and 9.12).
6. Increased quantification of risk across all sectors assessed.
7. Expanded assessment of adaptation feasibility and effectiveness and limits to adaptation (Figure 9.7).
8. Assessment of adaptation finance (Section 9.4.1).
9. Increased assessment of how climate risk and adaptation and mitigation response options are interlinked across multiple key development sectors (Section 9.4.3; Boxes 9.4 and 9.5).

9.1.4 Extent of Climate Change Impacts Across Africa

In many parts of southern, East and West Africa, temperature or precipitation trends since the 1950s are attributable to anthropogenic climate change and several studies document the impacts of these climate trends on human and natural systems (*high confidence*) (Figure 9.3; Sections 9.5.6 and 9.5.7). Nevertheless, research into attribution of trends to anthropogenic climate change or climate impacts remains scarce for multiple regions, especially in North and Central Africa. This illustrates an 'attribution gap' where robust evidence for attributable impacts is twice as prevalent in high compared to low-income countries globally (Callaghan et al., 2021). Most studies on climate impacts in Africa have focused on terrestrial ecosystems or water, with fewer on marine ecosystems, agriculture, migration and health and well-being (Callaghan et al., 2021). Specific factors driving these knowledge gaps include limited data collection, data access and research funding for African researchers (see next section).

Figure 9.3: Climate impacts on human and natural systems are widespread across Africa, as are climate trends attributable to human-induced climate change. This machine-learning-assisted evidence map shows the presence of historical trends in temperature and precipitation attributable to human-induced climate change (pinks vs. greys) and the amount of evidence (intensity of colours) documenting the impacts of these climate trends on human and natural systems (e.g., ecosystems, agriculture, health) across Africa. 'Robust' indicates more than 5 studies document impacts per grid cell. A 'high' amount of evidence indicates more than 20 studies documented impacts for a grid cell. Climate impact studies from the literature were identified and categorised using machine learning. A language representation model was trained on a set of 2,373 climate impact studies coded by hand. This supervised machine learning model identified 102,160 published studies predicted to be relevant for climate impacts globally; references to places in Africa were found in 5,081 studies (5% of global studies). Temperature trends were calculated from 1951-2018 and precipitation from 1951-2016. Hatching shows regions where trends in both temperature and precipitation are attributable to human-induced climate change. Data from (Callaghan et al., 2021).

9.1.5 Extent of Climate Change Data and Research Gaps Across Africa

Since AR5, there have been rapid advances in climate impacts research due to increased computing power, data access and new developments in statistical analysis (Carleton and Hsiang, 2016). However, sparse and intermittent weather station data limit attribution of climate trends to anthropogenic climate change for large areas of Africa, especially for precipitation and extreme events, and hinder more accurate climate change projections (Otto et al., 2020) (Section 9.5.2; Figure 9.3). Outside of South Africa and Kenya, digitally accessible data on biodiversity is limited (Meyer et al., 2015). Lack of comprehensive socioeconomic data also limits researchers' ability to predict climate change impacts. Ideally, multiple surveys over time are needed to identify effects of a location's changing climate on changing socioeconomic conditions. Twenty-five African countries conducted only one nationally representative survey that could be used to construct measures of poverty during 2000-2010 and 14 conducted none over this period (Jean et al., 2016). Because of these challenges, much of what is known about climate impacts and risks in Africa relies on evidence from global studies that use data largely from outside Africa (e.g., Zhao et al., 2021). These studies generate estimates of average impacts across the globe, but may not have the statistical power to distinguish whether African nations display differential vulnerability, exposure or adaptive capacity. In sections of this chapter, we have relied when necessary on such studies, as they often provide best available evidence for Africa.

Increasing data coverage and availability would increase the ability to discern important differences in risk both among and within African countries.

Climate-related research in Africa faces severe funding constraints with unequal funding relationships between countries and with research partners in Europe and North America (*high confidence*). Based on analysis of over 4 million research grants from 521 funding organisations globally, it is estimated from 1990-2020 USD 1,26 billion funded Africa-related research on climate impacts, mitigation and adaptation. This represents only 3.8% of global funding for climate-related research – a figure incommensurate with Africa's high vulnerability to climate change (Overland et al., 2021) (Box 9.1; Chapter 8). Almost all funding for Africa-related climate research originates outside Africa and goes to research institutions outside Africa (Blicharska et al., 2017; Bendana, 2019; Siders, 2019; Overland et al., 2021). From 1990–2020, 78% of funding for Africa-related climate research flowed to institutions in Europe and the United States – only 14.5% flowed to institutions in Africa (Overland et al., 2021) (Figure 9.4). Kenya (2.3% of total funding) and South Africa (2.2%) are the only African countries among the top 10 countries in the world in terms of hosting institutions receiving funding for climate-related research on Africa (Overland et al., 2021).

These unequal funding relations influence inequalities in climate-related research design, participation, and dissemination between African researchers and researchers from high-income countries outside Africa, in ways that can reduce adaptive capacity in Africa (*very high confidence*). Those empowered to shape research agendas can shape research answers: climate research agendas, skills gaps and eligible researchers are frequently defined by funding agencies, often from a Global North perspective (Vincent et al., 2020a). Larger funding allocations for research focused on Ghana, South Africa, Kenya, Tanzania and Ethiopia are reflected in higher concentrations of empirical research on impacts and adaptation options in these countries, and there is a general lack of adaptation research for multiple of the most vulnerable countries in Africa (Figure 9.5) (Callaghan et al., 2021; Overland et al., 2021; Sietsma et al., 2021; Vincent and Cundill, 2021). The combination of Northern-led identification of both knowledge and skills gaps can result in projects where African partners are positioned primarily as recipients engaged to support research and/or have their 'capacity built' rather than also leading research projects on an equal basis (Vincent et al., 2020a; Trisos et al., 2021). Analysis of >15,000 climate change publications found for over 75% of African countries 60–100% of climate change publications on these countries did not include a single local author, with authorship dominated by researchers from richer countries outside Africa (Pasgaard et al., 2015). This can reduce adaptive capacity in Africa as researchers at Global North institutions may shape research questions and outputs for a Northern audience rather than providing actionable insights on priority issues for African partners (Pasgaard et al., 2015; Nago and Krott, 2020). Moreover, in order to access research publications in a timely manner, many researchers in Africa are forced to use shadow websites bypassing journal paywalls (Bohannon, 2016). Ways to enhance research partnerships to produce actionable insights on climate impacts and solutions in Africa include increased funding from African and non-African sources, projects funded by non-African agencies, increasing direct control of resources for African partners and having African research and user priorities set research questions, identify skills gaps and lead research, open access policies for research outputs (ESPA Directorate, 2018; Vogel et al., 2019; Vincent et al., 2020a; IDRC, 2021; Trisos et al., 2021).

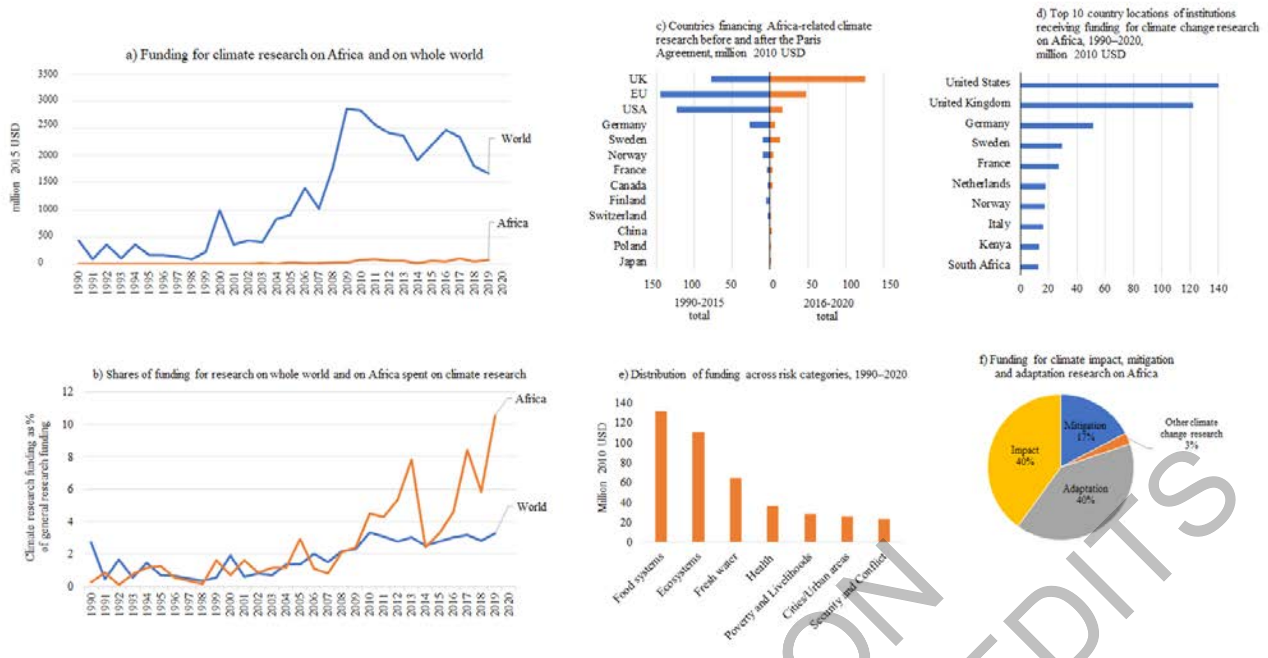


Figure 9.4: Climate-related research on Africa receives a small proportion of global climate research funding (a, b), with most funding for climate-related research on Africa flowing to institutions based in the Europe and the USA (d). Major funding countries are the UK, EU, USA, Germany and Sweden (d) . Funding comes mainly from government organisations with private philanthropy providing only around 1% (Overland et al., 2021). Africa-related climate research funding focuses mostly on food systems, ecosystems and freshwater, while security and conflict and urban areas have received the least (e). Research on climate mitigation received only 17% of funding while climate impacts and adaptation each received 40% (f). Since 2010, climate research has made up a larger share (5%) of Africa-related research funding than is the case for research globally (3%) with a greater proportion of this Africa-focused climate funding going to social sciences and humanities (28%) than is the case globally (12%) (Overland et al., 2021). Data are from an analysis of 4,458,719 research grants in the Dimensions database with a combined value of USD 1.51 trillion awarded by 521 funding organisations globally (Overland et al. 2021). The Dimensions database is the world's largest database on research funding flows (Overland et al. 2021). It draws on official data from all major funding organisations in the world, mainly government research councils or similar institutions. Note: The South African National Research Foundation is the only African research funding body that is sufficiently large to be included in Dimensions.

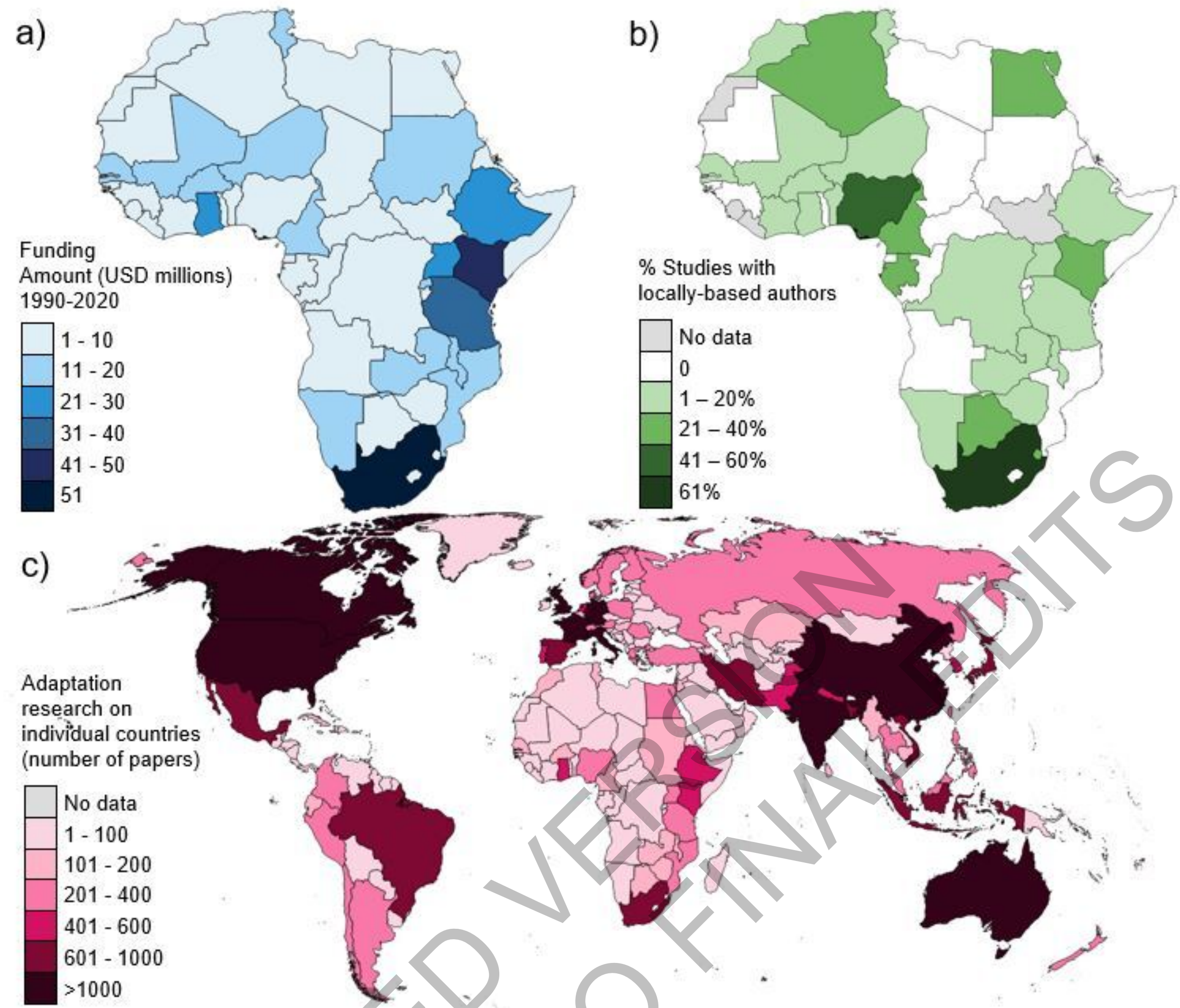


Figure 9.5: Major gaps in climate change research funding, participation and publication exist within Africa, and for Africa compared to the rest of the world. (a) Funding: Amount of climate change research funding focused on African countries 1990-2020 (Overland et al., 2021). Considering population size, research on Egypt and Nigeria stands out as particularly underfinanced (b) Participation: Percentage of climate change papers (impacts and adaptation) published on a given country that also include at least one based in that country (Pasgaard et al. 2015). (c) Number of publications of climate change adaptation research focused on individual countries identified from a global sample of 62,191 adaptation-relevant peer-reviewed articles published from 1988-2020 (Sietsma et al., 2021). There is a general lack of adaptation-related research on many vulnerable countries in Africa. Topic biases in adaptation-relevant research also exist where research focuses more on disaster and development-related topics in Southern countries (but published authors from the global North), while Northern countries dominate governance topics (Sietsma et al., 2021).

9.1.6 Loss and Damage from Climate Change

Assessment of impacts, vulnerability, risks and adaptation highlights climate change is leading to irreversible and existential impacts across Africa which breach current and projected adaptation limits (Table 9.1) (Cross-Chapter Box LOSS in Chapter 17).

Table 9.1: Loss and damage from climate change across sectors covered in this report. Loss and damage arise from adverse climate-related impacts and risks from both sudden-onset events, such as floods and cyclones, and slower-onset processes, including droughts, sea level rise, glacial retreat and desertification and includes both include both economic (e.g., loss of assets and crops) and non-economic types (e.g., loss of biodiversity, heritage and health) (UNFCCC Paris Agreement, 2015; IPCC, 2018a; Mechler et al., 2020). Section marked with * and in bold highlights Loss and Damage attributed to anthropogenic climate change (16.1.3).

Sector	**Loss and damage from climate change**	**Observed**	**Projected**
Ecosystems	Local, regional and global extinction	9.6.2	9.6.2

	Reduced ecosystem goods and services	9.6.1; 9.6.2	9.6.2
	Declining natural coastal protection and habitats	9.6.1; 9.6.2	9.6.2
	Altered ecosystem structure and declining ecosystem functioning	9.6.1	9.6.2
	Nature–based tourism	9.6.3	9.6.3
	Biodiversity loss	**9.6.2***	
Water	Declining lake and river resources	9.7.1	9.7.2
	Reduced hydro-electricity and irrigation	9.7.2; 9.9.1 -	9.7.2; 9.9.3; Box 9.5
	Disappearing glaciers	**9.5.9***; 9.7.1	9.5.9
	Reduced groundwater recharge and salinization	-	9.7.2
	Drought	**Box 9.4***	
Food systems	Reduced crop productivity and revenues	**9.7.2***, 9.8.1; 9.8.2; 9.11.1; Box 9.5	9.8.2; 9.8.3; Box 9.5
	Increased livestock mortality and price shocks	9.8.2	9.8.2
	Decreased fodder and pasture availability	9.8.2	9.8.2
	Reduced fisheries catch and fisher livelihoods	9.6.1; 9.8.5	9.8.5
Human settlements and Infrastructure	Loss or damage to formal and informal dwellings	9.9.2	9.9.4
	Damage to transport systems	9.9.2	9.9.4
	Damage to energy systems	9.9.2	9.7.2; 9.9.4
	Water supply, sanitation, education and health infrastructure	9.9.2; 9.10; 9.11.1	9.7.3; 9.9.4; 9.10; 9.11.1
	Migration	9.9.1; Box 9.8	9.9.4; Box 9.8
Health	Loss of life	**9.9.2***; 9.10.2; Box 9.9	9.9.4; 9.10.2
	Loss of productivity	9.10.3; 9.11.1	9.10.2; 9.11.2
	Reduced nutrition	9.8.1; 9.10.2	9.10.2
Economy, poverty and Livelihoods	Loss of livelihoods, jobs and income	9.9.2; 9.10.2; 9.11.1	9.10.2; 9.11.2
	Reduced productive land	9.8.2	9.8.2
	Reduced economic growth and increased inequality	**9.11.1***; Box 9.5	9.11.2
	Community and involuntary displacement	9.9.3; Box 9.8	9.9.4; Box 9.8
	Reduced labour productivity and earning potential	9.11.1	9.11.2
	Delayed and poorer education progress	9.11.1	9.11.1
	Reduced tourism	9.6.3	9.5.9, 9.6.3, 9.12.2
	Increased urban in-migration	9.8.1; 9.9.1; Table Box 9.8	9.9.4; Table Box 9.8
Heritage	Loss of traditional cultures and ways of life	Box 9.2; 9.12.1	9.12.2
	Loss of language and knowledge systems	-	9.12.1
	Damage to heritage sites	9.12.1	9.12.2

9.2 Key Risks for Africa

A key risk is defined as a potentially severe risk. In line with AR5, 'severity' relates to dangerous anthropogenic interference with the climate system, the prevention of which is the ultimate objective of the UNFCCC as stated in its Article 2 (Oppenheimer et al., 2014). The process for identifying key risks for Africa included reviewing risks from the Africa chapter of AR5, and assessing new evidence on observed impacts and projected risks in this chapter.

Several key risks were identified for both ecosystems and people including species extinction and ecosystem disruption, loss of food production, reduced economic output and increased poverty, increased disease and loss of human life, increased water and energy insecurity, loss of natural and cultural heritage, and compound extreme events harming human settlements and critical infrastructure (Table 9.2). In order to provide a sector and continent-level perspective, the key risks aggregate across different regions and combine multiple risks within sectors. For detailed assessments of observed impacts and future risks within each sector and each sub-region of Africa, see the sector-specific sections of this chapter (Sections 9.6.1 and 9.12.1).

Several expert elicitation workshops of lead and contributing authors were held to develop 'burning embers' assessing how risk increases with further global warming for a subset of key risks, specifically risk of food production losses, risk of biodiversity loss and risk of mortality and morbidity from heat and infectious disease (Figure 9.6). These key risks were selected in part because of underlying assessment work in the chapter to connect multiple studies to observed impacts and/or risk at increasing global warming levels (Sections 9.6.2, 9.8.2, 9.8.5.2 and 9.10.2).

All three of these key risks are assessed to have already transitioned completely into moderate risk—that is, negative impacts have been detected and attributed to climate change—before the 2010–2020 level of global warming (1.09°C) (IPCC, 2021), with *medium confidence* for increased mortality and morbidity and *high confidence* for losses of food productivity and biodiversity (Figure 9.6). For biodiversity, these impacts include repeated mass die-offs of coral reefs due to marine heat (Section 9.6.1.4), reductions in lake productivity due to warming (Section 9.6.1.3), and woody encroachment of grasslands and savannas due to increased atmospheric CO_2 concentrations (Section 9.6.1.1), with negative impacts on livelihoods (Section 9.6.1). For food production, climate change impacts include up to 5.8% mean reduction in maize productivity due to increased temperatures in sub-Saharan Africa (Section 9.8.2.1 and 9.8.2.2) and reduced fisheries catches due to increased temperatures, especially in tropical regions (Section 9.8.2). For health, climate change impacts include increased mortality and morbidity from changes in the distribution and incidence of malaria and cholera and the direct effects of increasing temperatures (Section 9.10.2).

In scenarios with low adaptation (that is largely localised and incremental), the transition to high risk—widespread and severe impacts—has already begun at the current level of global warming for biodiversity loss (*high confidence*), and begins below 1.5°C global warming for both food production (*medium confidence*) and mortality and morbidity from heat and infectious disease (*high confidence*). Across all risks, the best estimate for the transition to high risk is at 1.5°C of global warming, with transition to high risk completing before 2°C (Figure 9.6). Projected impacts considered high risk around 1.5°C include: across more than 90% of Africa, more than 10% of species are at risk of local extinction (Figure 9.6; Table 9.1); the further expansion of woody plants into grass-dominated biomes (Section 9.6.2.1); 9% declines in maize yield for West Africa and 20–60% decline in wheat yield for southern and northern Africa, as well as declines in coffee and tea in East Africa and sorghum in West Africa (Figures 9.22 and 9.23; Section 9.8.2.1 and 9.8.2.2), and >12% decline in marine fisheries catch potential for multiple West African countries, potentially leaving millions at risk of nutritional deficiencies (Figure 9.25; Section 9.8.5); tens of millions more people exposed to vector-borne diseases in East and southern Africa (malaria), and North, East and southern Africa (dengue, zika), increased risk of malnutrition in Central, East and West Africa, and more than 15 additional deaths per 100,000 annually due to heat in parts of West, East and North Africa (Figures 9.32 and 9.35; Sections 9.10.2 and 9.9.4.1).

The transition from high to very high risk—that is severe and widespread impacts with limited ability to adapt—begins either at or just below 2°C for all three risks (Figure 9.6). The assessed temperature range for the transition to very high risk is wider for food production than for biodiversity and health. Projected impacts for food include: 10–30% decline in marine fisheries catch potential for the Horn of Africa region and southern Africa and more than 30% decline for West Africa at 2°C global warming, with greater declines at higher levels of warming (Section 9.8.2). Beyond 2°C global warming, over 50% of commercially important freshwater fish species across Africa are projected to be vulnerable to extinction (Figure 9.26). Between 2°C and 4°C, wheat, maize and rice yields are projected, on average, to be lower than 2005 yields across all regions of Africa. From 2°C global warming, over 40% losses in rangeland productivity are projected for western Africa. By 3.75°C, severe heat stress may be near year-round for cattle across tropical Africa (Figure 9.24). Multiple countries in West, Central and East Africa are projected to be at risk from simultaneous negative impacts on crops, fisheries and livestock (Thiault et al., 2019) (9.8.2; 9.8.5).

The best estimate for the onset of very high risk for biodiversity and health is at 2.1°C. Projected impacts considered very high risk for biodiversity include potential destabilisation of the African tropical forest carbon sink, risk of local extinction of more than 50% of plants, vertebrate and insect species across one-fifth of Africa, 7–18% of African species at risk of total extinction including, a third of freshwater fish, and more than 90% warm-water coral reefs lost (Section 9.6.2). For health, projected impacts considered high risk include potentially lethal heat exposure for more than 100 days per year in West, Central and East Africa, with more than 50 additional heat-related deaths per 100,000 annually across large parts of Africa, and hundreds of millions more people exposed to extreme heat in cities (Section 9.5, 9.10.2 and 9.9.4.1; Figure 9.35), tens to hundreds of thousands of additional cases of diarrhoeal disease in East, Central and West Africa, and tens of millions more people exposed to mosquito-borne arboviruses like dengue or zika in North, East and southern Africa (Section 9.10.2).

The feasibility and effectiveness of existing adaptation options under current levels of warming are assessed in Section 9.10.2 and adaptation options considering future levels of warming are assessed in the chapter section for each sector.

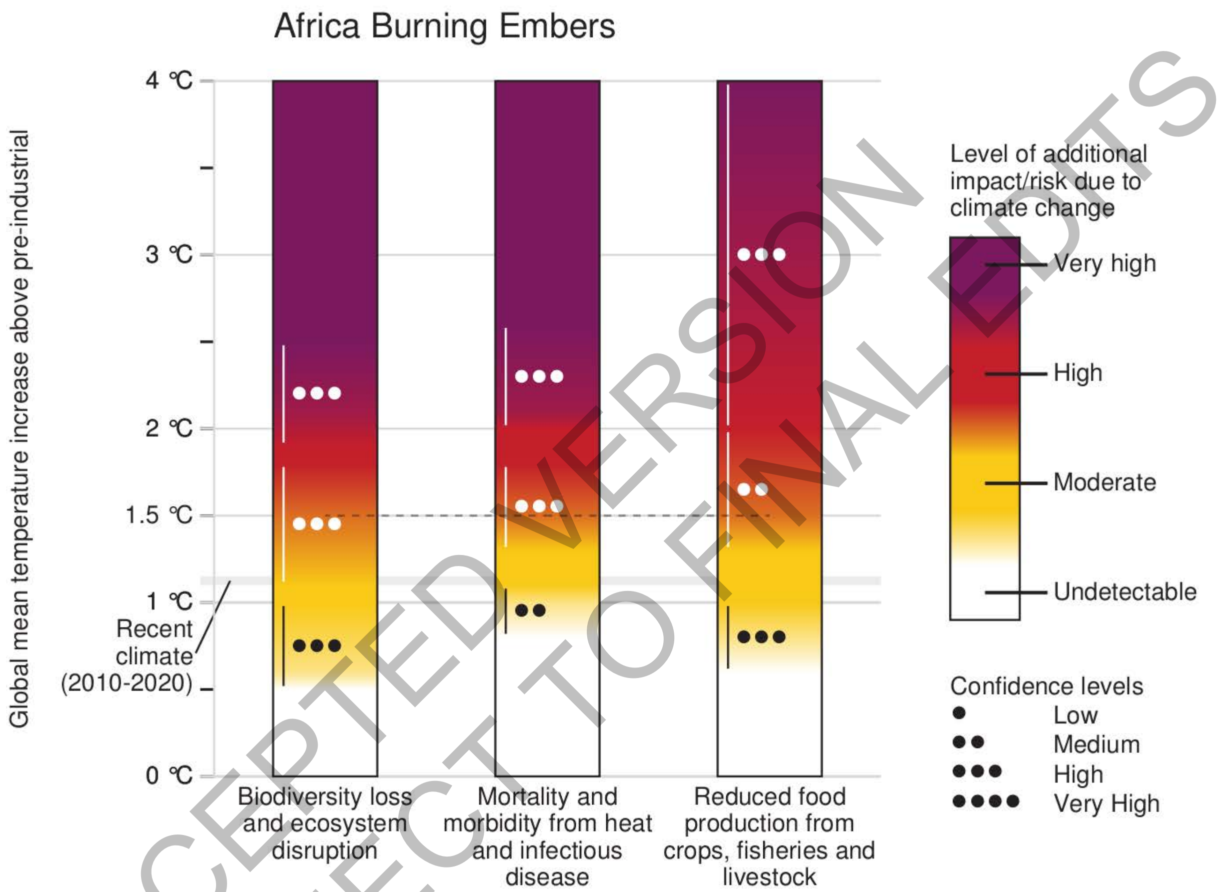


Figure 9.6: Burning Embers showing increasing risk due to climate change for selected key risks in Africa. Projected increase is assessed for global warming increasing above pre-industrial levels (1850–1900). All three risks are assessed to have already transitioned to moderate risk by the recent level of global warming 2010–2020 (1.09°C). Risks are characterized as undetectable, moderate, high, or very high, and the transition between risk levels as a function of global warming is represented by the colour change of each bar (IPCC, 2021). For range of global warming levels for each risk transition used to make this figure see Supplementary Material Table SM 9.1.

Table 9.2: Key risks from climate change in Africa

Key climate change risk	Climate impact driver	Vulnerability	Chapter section
Local or global extinction of species and reduction or irreversible loss of ecosyste§ms and their services, including freshwater, land and ocean ecosystems	Increasing temperatures of freshwaters, ocean and on land; heatwaves; precipitation changes (both increases and decreases); increased atmospheric CO_2	Vulnerability highest among poorly dispersing organisms (plants) and species with narrow and disappearing niches (e.g. mountain endemics), and is exacerbated by non-	9.6

	concentrations; sea level rise; ocean acidification	climate hazards (e.g. habitat loss for agriculture or afforestation projects); Vulnerability is high for Protected Areas surrounded by transformed land preventing species' dispersal and areas with limited elevational gradients that reduce their potential to act as climate refugia	
Loss of food production from crops, livestock and fisheries	Increasing temperatures and heat waves for freshwaters, ocean and on land; precipitation changes; drought; increased atmospheric CO_2 concentrations	High for low-income coastal and riparian communities whose livelihood depends on healthy ocean and freshwater ecosystems, and for populations reliant on fish for protein and micronutrients. Vulnerability is high for many food producers dependent on rainfall and temperature conditions, including subsistence farmers, the rural poor, and pastoralists. Lack of access to climate information and services increases vulnerability.	9.8
Mortality and morbidity from heat and infectious diseases	Increasing temperatures; heatwaves; precipitation change (both increases and decreases)	Vulnerability is highest for the elderly, pregnant women, individuals with underlying conditions, immune-compromised individuals (e.g., from HIV), and young children. Regions without vector control programmes in place or without detection and treatment regimens. Inadequate insulation in housing in informal settlements in urban heat islands. Inadequate improvements in public health systems. Inadequate water and sanitation infrastructure, especially in rapidly expanding urban areas and informal settlements.	9.10

Reduced economic output and growth, and increased inequality and poverty rates	Increased temperatures; reduced rainfall; extreme weather events	Conditions underlying severe risk are lower income growth, higher population levels, low rates of structural economic change with more of the labour force engaged in agriculture and other more climate-exposed sectors due in part to physical labour outdoors.	9.11
Water and energy insecurity due to shortage of irrigation and hydropower.	Heat and drought	High reliance on hydropower for national electricity generation, especially East and Southern African countries. Planned for high reliance on irrigated food production. Concentrations of hydropower plants within river basins experiencing similar rainfall and run-off patterns. Limited electricity trade between major river basins.	9.7, 9.9, Box 9.5
Cascading and compounding risks of loss of life, livelihoods and infrastructure in human settlements.	Extreme heat; floods; drought; sea level rise and associated coastal hazards; compound climate hazards (e.g., coinciding heat and drought)	Coastal and low-lying urban areas and those in dryland regions with rapidly growing populations. People living in informal settlements. Increased magnitude of heat waves due to urban heat island effects. Climate-shocks to municipal revenues (e.g., from water). Unaffordable maintenance of transport and protective infrastructure with increasing climate impacts. Greater water resource demand from urban and non-urban populations and key economic sectors	9.9

9.3 Climate Adaptation Options

9.3.1 Adaptation Feasibility and Effectiveness

Based on a systematic assessment of observed climate adaptation responses in the scientific literature covering 827 adaptation response types in 553 studies (2013–2021), and expert elicitation process, 24 categories of adaptation responses in Africa were identified (Williams et al., 2021). This assessment excluded autonomous adaptation in ecosystems, such as migration and evolution of animal and plant species.

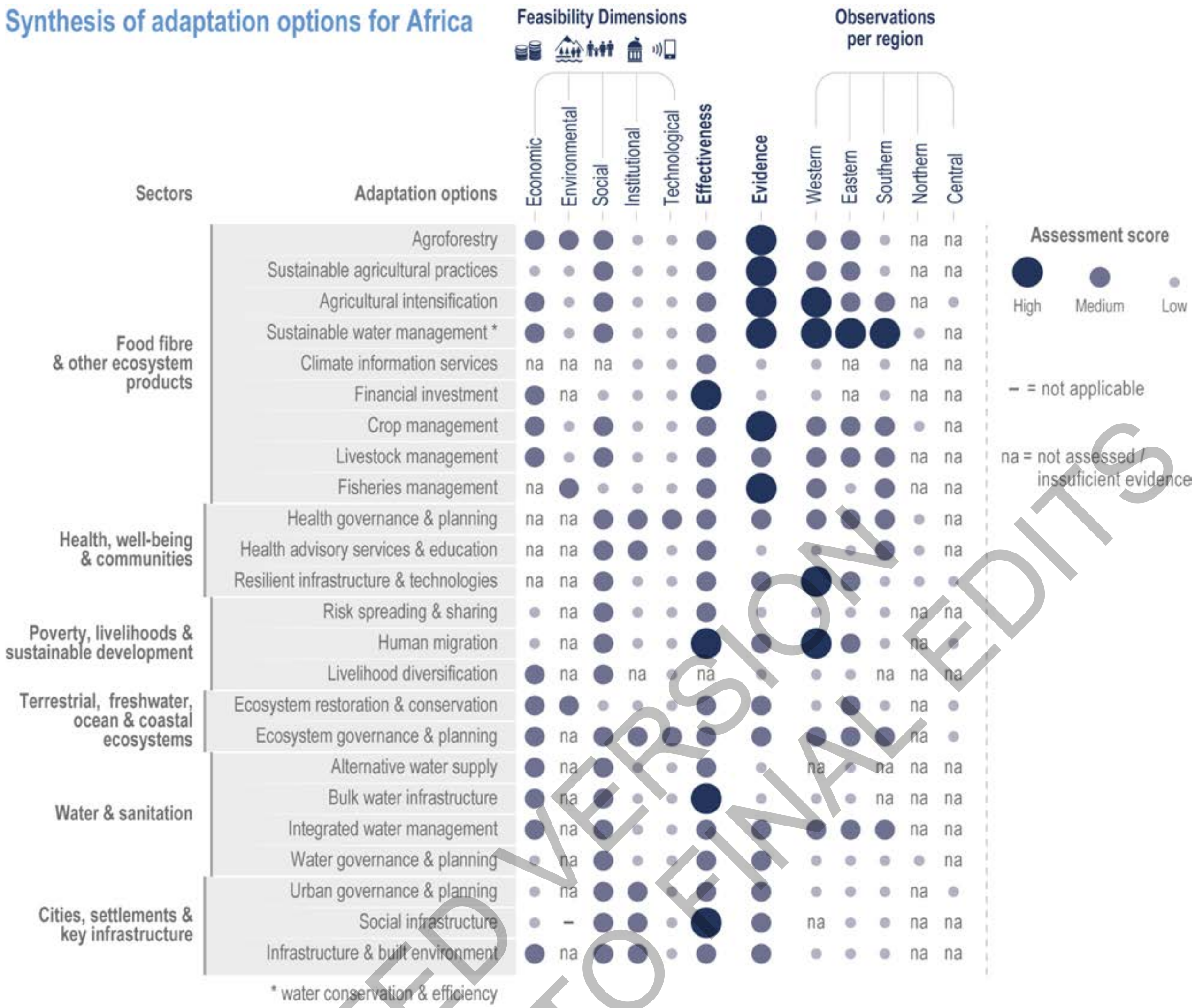


Figure 9.7: Assessment of feasibility of observed climate adaptation responses under current climate conditions for 24 categories of adaptation responses across regions of Africa. The assessment comprised evaluation of each adaptation category along six feasibility dimensions: economic viability, environmental sustainability, social validity, institutional relevance, technological availability, and potential for risk reduction (considering current climate conditions) (Williams et al., 2021). Fifty-six experts on the African region were consulted using a structured, expert-driven elicitation process to increase the coverage and robustness of the continent-wide adaptation feasibility and effectiveness assessment in Williams et al. (2021). Assessment included both peer-reviewed articles and grey literature.

At the current global warming level, 83% of adaptation response categories assessed showed medium potential for risk reduction (that is, mixed evidence of effectiveness). Bulk water infrastructure (including managed aquifer recharge, dams, pipelines, pump stations, water treatment plants and distribution networks), human migration, financial investment for agricultural intensification, and social infrastructure (including decentralised management, strong community structures and informal support networks) show high potential for risk reduction (high evidence of option's effectiveness) (Sections 9.6.4 and 9.7.3; Boxes 9.8, 9.9, 9.10 and 9.11). However, there was limited evidence to assess the continued effectiveness of these options at higher global warming levels (Williams et al., 2021) with some options, such as bulk water infrastructure (particularly large dams), expected to face increasing risk with continued warming with damages cascading to other sectors (see Box 9.5), while others, such as crop irrigation and adjusting planting times, may increasingly reach adaptation limits above 1.5°C and 2°C global warming (Sections 9.8.3 and 9.8.4)

The majority of adaptation studies were in West and East Africa (Ghana, Ethiopia, Kenya and Tanzania), followed by southern Africa, with the least coming from Central and North Africa (Figure 9.7) (Williams et al., 2021). Most studies were on adaptation actions in the food sector, with the least on health (Figure 9.7). The five adaptation response categories with the highest number of reported actions were sustainable water management (food sector), resilient infrastructure and technologies (health sector), agricultural intensification (food sector), human migration (poverty and livelihoods) and crop management (food sector).

No adaptation response categories were assessed to have high feasibility of implementation. Technological barriers dominate factors limiting implementation (92% of adaptation categories have low technological feasibility) followed by institutional barriers (71% of adaptation categories have low institutional feasibility). This assessment matches review studies finding institutional responses to be least common in Africa and highlight inadequate institutional capacities as key limits to human adaptation (Berrang-Ford et al., 2021; Thomas et al., 2021) (Cross-Chapter Box FEASIB in Chapter 18). Feasibility is higher for the social dimension of adaptation responses (with moderate feasibility for 88% of categories). The largest evidence gap is for environmental feasibility for which 67% could not be assessed due to insufficient evidence (Figure 9.7).

Sustainable Water Management (SWM) includes rainwater harvesting for irrigation, watershed restoration, water conservation practices (e.g., efficient irrigation) and less water-intensive cropping (also see Section 9.8.3), and was the most reported adaptation response in the food sector. SWM was assessed with medium economic and social feasibility and low environmental, institutional and technological feasibility. The feasibility of this adaptation category may depend largely on socioeconomic conditions (Amamou et al., 2018; Harmanny and Malek, 2019; Schilling et al., 2020), as many African farmers cannot afford the cost of sustainable water management facilities (Section 9.8.4).

Resilient Infrastructure and Technologies (RIT) for health include improved housing to limit exposure to climate hazards (Stringer et al., 2020), and improved water quality, sanitation and hygiene infrastructure (e.g., technology across all sectors to prevent contamination and pollution of water, improved water, sanitation and hygiene (WASH) approaches such as promotion of diverse water sources for water supply, improving health infrastructure) (Section 9.10.3). Overall, RIT had medium social feasibility and low institutional and technological feasibility. Bulk water infrastructure was assessed to have high effectiveness, but low institutional and technological feasibility. Increasing variability in climate and environmental challenges has made sustainable and resilient infrastructure design a key priority (Minsker et al., 2015). RIT is, however, generally new in the African context (Cumming et al., 2017) and that may be why there is limited evidence to assess some of its dimensions (economic and environmental feasibility). Construction of resilient public water infrastructures that include safeguards for sanitation and hygiene are expensive and, across national and local levels, planning for its construction poses multiple challenges (Choko et al., 2019).

Agricultural intensification (including mixed cropping, mixed farming, no soil disturbance, mulching) in many smallholder farming systems remains a key response option to secure food for the growing African population (Nziguheba et al., 2015; Ritzema et al., 2017). Yet this option faces low environmental, institutional and technological feasibility (Figure 9.7). Social and economic feasibility is higher, but barriers include high cost of farm inputs (land, capital and labour), lack of access to timely weather information and lack of water resources can make this option quite challenging for African smallholder farmers (Kihila, 2017; Williams et al., 2019b) (Sections 9.8.1 and 9.11.4).

Crop management includes adjusting crop choices, planting times, or the size, type and location of planted areas (Altieri et al., 2015; Nyagumbo et al., 2017; Dayamba et al., 2018). This option faces environmental, institutional and technological barriers to feasibility. Social and economic barriers to implementation are fewer. Factors such as tenure and ownership rights, labour requirements, high investment costs and lack of skills and knowledge on how to use the practices are reported to hinder implementation of crop management options by smallholder farmers (Muller and Shackleton, 2013; Nyasimi et al., 2017). For instance, when improved seed varieties are available, high price limits access for rural households (Amare et al., 2018) (see Sections 9.8.3 and 9.8.4).

Human migration was assessed to have high potential for risk reduction (Rao et al., 2019; Sitati et al., 2021) (Cross-Chapter Box MIGRATE in Chapter 7, Box 9.8). However, it had low feasibility for economic, institutional and technological dimensions, with limited evidence on environmental feasibility. Institutional factors such as the implementation of top-down policies have been reported as limiting options for coping locally, resulting in migration (Brockhaus et al., 2013). Limited financial and technical support for migration limits the extent to which it can make meaningful contributions to climate resilience (Djalante et al., 2013;

Trabacchi and Mazza, 2015). International and domestic remittances are an important resource that can help aid recovery from climate shocks, but inadequate finance and banking infrastructure can limit cash transfers (Box 9.8). Male migration can increase burdens of household and agricultural work, especially for women (Poudel et al., 2020; Rao et al., 2020; Zhou et al., 2020). The more agency migrants have (that is, degree of voluntarity and freedom of movement), the greater the potential benefits for sending and receiving areas (*high agreement, medium evidence*) (Cross-Chapter Box MIGRATE in Chapter 7, Box 9.8)

Adaptation options within a number of categories, including sustainable agriculture practices, agricultural intensification, fisheries management, health advisory services and education, social infrastructure, infrastructure and built environment and livelihood diversification were observed to reduce socioeconomic inequalities (Williams et al., 2021). Whether adaptation options reduce inequality can be a key consideration enhancing acceptability of policies and adaptation implementation (Islam and Winkel, 2017) (Box 9.1; Section 9.11.4).

9.3.2 Adaptation Co-Benefits and Trade-Offs with Mitigation and SDGs

Synergies between the adaptation and progress towards the Sustainable Development Goals (SDGs) present potential co-benefits for realising multiple objectives towards Climate Resilient Development in Africa, increasing the efficiency and cost-effectiveness of climate actions (Cohen et al., 2021). However, designing adaptation policy under conditions of scarcity, common to many African countries, can inadvertently lead to trade-offs between adaptation options, as well as between adaptation and mitigation options, can reinforce inequality, and fail to address underlying social vulnerabilities (Kuhl, 2021).

Adaptation options such as access to climate information, provision of climate information services, growing of early maturing varieties, agroforestry systems, agricultural diversification and growing of drought-resistant varieties of crops may deliver co-benefits, providing synergies that result in positive outcomes. For instance, in SSA drylands including northern Ghana and Burkina Faso and large parts of the Sahel, migration as a result of unfavourable environmental conditions closely linked to climate change has often provided opportunities for farmers to earn income (SDG 1) and mitigate the effects of climate-related fluctuations in crop and livestock productivity (SDG 2) (Zampaligré et al., 2014; Antwi-Agyei et al., 2018; Wiederkehr et al., 2018). Renewable energy can mitigate climate effects (SDG 13), improve air quality (SDG 3), wealth and development (SDGs 1, 2).

Different types of irrigation including drip and small-scale irrigation can contribute towards increased agricultural productivity (SDG 2), improved income (SDG 1) and food security (SDG 2) and increase resilience to long-term changes in precipitation (SDG 13) (Bjornlund et al., 2020). In Kenya and Tanzania, small-scale irrigation provides employment opportunities and income to both farmers and private businesses (SDGs 8 and 9) (Lefore et al., 2021; Simpson et al., 2021c). Land management practices including the use of fertilizers and mulching have also been highlighted as adaptation options improving soil fertility for better yields (SDG 2) and delivering opportunities to reduce the climate change effects (SDG 13) (Muchuru and Nhamo, 2019).

Climate smart agriculture (CSA) offers opportunities for smallholder farmers to increase productivity (SDG 2), build adaptive capacity whilst reducing the emission of greenhouse gases (SDG 13) from agricultural systems (Lipper et al., 2014; Mutenje et al., 2019). CSA practices including conservation agriculture, access to climate information, agroforestry systems, drip irrigation, planting pits and erosion control techniques (Partey et al., 2018; Antwi-Agyei et al., 2021) can improve soil fertility, increase yield and household food security (Zougmoré et al., 2016; Zougmoré et al., 2018), thereby contributing to the realisation of SDG 2 in Africa (Mbow et al., 2014).

On the contrary, adaptation actions may induce trade-offs with mitigation objectives, as well as other adaptation and developmental outcomes, delivering negative impacts and compromising the attainment of the SDGs. For example, increased deployment of renewable energy technologies can drive future land use changes (Frank et al., 2021) and threaten important biodiversity areas if poorly deployed (Rehbein et al., 2020). The use of early-maturing or drought-tolerant crop varieties may increase resilience (SDGs 1, 2), but adoption by smallholder farmers can also be hindered by affordability of seed. Cultivation of biodiesel crops also can hinder food security (SDG 2) at local and national levels (Tankari, 2017; Brinkman et al., 2020).

Additionally, the use of fertilizers in intense systems can result in increased environmental degradation (Akinyi et al., 2021). When farmers migrate, it puts pressure on inadequate social services provision and facilities at their destination (SDG 8) and leads to reduced farm labour and a deterioration of the workforce and assets (SDG 2) (Gemenne and Blocher, 2017a), which negatively affects farm operations and non-migrants, particularly women, elderly and children, at the point of origin (Nyantakyi-Frimpong and Bezner-Kerr, 2015; Ahmed et al., 2016; Otto et al., 2017; Eastin, 2018). Farmers may also miss critical periods during the farming season that eventually makes them food insecure (SDG 2) and vulnerable to climate change (SDG 13) (Antwi-Agyei et al., 2018). Migrants should be supported to reduce their overall shocks to climate vulnerability at the points of origin and destination. Small-scale irrigation infrastructure if not managed properly, may lead to negative environmental effects and compromise the integrity of riparian ecosystems (SDG 15) (Loucks and van Beek, 2017) and serve as breeding grounds for malaria-causing mosquitoes (SDG 3) (Attu and Adjei, 2018).

9.4 Climate Resilient Development

Climate resilient development (CRD) is a process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all (Denton et al., 2014; Andrijevic et al., 2020; Owen, 2020; Cornforth et al., 2021). It emphasises equity as a core element of sustainable development as well as conditions for inclusive and sustained economic growth, shared prosperity and decent work for all, taking into account different levels of national development and capacities as encoded in the SDGs (Section 9.3.2; Chapter 18, Section 18.1). This chapter section identifies five key dimensions of CRD for Africa: climate finance, governance, cross-sectoral and transboundary solutions, adaptation law and climate services and literacy.

9.4.1 Climate Finance

Access to adequate financial resources is crucial for climate change adaptation (Cross-Chapter Box FINANCE in Chapter 17). Since the Copenhagen Accord (UNFCCC, 2009), and then extended by the Paris Agreement (UNFCCC Paris Agreement, 2015 see Article 4.4, and also 4.8, 4.9), developed countries are expected to scale up climate finance for developing countries toward a collective goal of USD 100 billion per year by 2020, with a balanced allocation between adaptation and mitigation.

9.4.1.1 How Much Adaptation Finance is Needed?

There is limited research providing quantitative estimates of adaptation costs across Africa. Adaptation costs in Africa have been estimated at USD 7–15 billion per year by 2020 (Schaeffer et al., 2013), corresponding to USD 5–11 per capita per year. The African Development Bank estimates costs of near-term adaptation needs identified in the Intended NDCs (INDCS) of African countries as USD 7.4 billion per year from 2020, recognising INDCs describes only a limited subset of adaptation needs (AfDB, 2019). Many African countries, particularly Least Developed Countries (LDCs), express a stronger demand for adaptation finance – a study of financial demands in INDCs for 16 African countries suggests a ratio around 2:1 for adaptation to mitigation finance with demand for Eritrea and Uganda approximately 80% for adaptation (Zhang and Pan, 2016).

Adaptation costs in Africa are expected to rise rapidly as global warming increases (*high confidence*). A meta-analysis of adaptation costs identified in 44 NDCs and NAPs from developing countries estimated a median adaptation cost around USD 17 per capita per year for 2020–2030 (Chapagain et al., 2020). Adaptation cost estimates for Africa increase from USD 20–50 billion per year for RCP2.6 in 2050 (around 1.5°C of warming), to USD18–60 billion per year for just over 2°C, to USD 100–437 billion per year for 4°C of global warming above pre-industrial levels (Schaeffer et al., 2013; UNEP, 2015; Chapagain et al., 2020). Focusing on individual sectors, the average country-level cost is projected to be USD 0.8 billion per year for adapting to temperature-related mortality under 4°C global warming (Carleton et al., 2018), with cumulative energy costs for cooling demand projected to reach USD 51 billion by 2°C and USD 486 billion by 4°C global warming (Parkes et al., 2019). Transport infrastructure repair costs are also projected to be substantial (Section 9.8.2) More precise estimates are limited by methodological difficulties and data gaps for costing adaptation, uncertainties about future levels of global warming and associated climate hazards, and ethical choices such as the desired level of protection achieved (Fankhauser, 2010; Hallegatte et al., 2018; UNFCCC, 2018) (Cross-Chapter Box FINANCE in Chapter 17). As such, existing estimates are expected to substantially underestimate eventual costs with adaptation costs possibly 2–3 times higher than current global estimates by 2030, and 4–5 times higher by 2050 (UNEP, 2016a).

9.4.1.2 Benefit-Cost Ratios in Adaptation

Although analysts face challenges related to the nature of climate change impacts (Sussman et al., 2014) and data limitations (Li et al., 2014) when estimating all costs and benefits for adaptation measures in specific contexts, adaptation generally is cost-effective (*high confidence*). The Global Commission on Adaptation estimated the benefits and costs of five illustrative investments and found benefit-cost ratios ranging from 2:1 to 10:1. However, it also noted that 'actual returns depend on many factors, such as economic growth and demand, policy context, institutional capacities and condition of assets' (The Global Commission on Adaptation, 2019). A review of ex-ante cost-benefit analyses for 19 adaptation-focused projects in Africa financed by the Green Climate Fund (GCF) shows benefit-cost ratios in a similar range. Using a 10% discount rate, as used by many of GCF's accredited entities, the benefit-cost ratio for individual projects ranges from 0.9:1 to 7.3:1, the median benefit-cost ratio is 1.8:1 and total ratio across all 19 projects is 2.6:1. When using lower discount rates, as some entities do for climate projects, the benefit-cost ratio is even higher, reflecting the front-loaded costs and back-loaded benefits of many adaptation investments. Using a 5% discount rate, the overall benefit-cost ratio of the GCF projects is 3.5:1, with a range from 1:1 to 11.5:1 and a median ratio of 2.4:1 (Breitbarth, 2020). In addition, many proposals have activities for which further benefits were not estimated due to the difficulty of attributing benefits directly to the intervention. The benefits of adaptation measures for infrastructure and others with clear market impacts are often easier to estimate than for policy interventions and where markets may not exist, such as ecosystem services (Li et al., 2014).

9.4.1.3 How Much Finance is Being Mobilised?

The amounts of finance being mobilised internationally to support adaptation in African countries are billions of USD less than adaptation cost estimates, and finance has targeted mitigation more than adaptation (*high confidence*). The OECD (2020) estimates an average of USD 17.3 billion per year in public finance targeting mitigation and adaptation from developed countries to Africa from 2016-2018, with adaptation expected to be a small share of this amount: Of the global total only 21% in 2018 targeted adaptation (there is no breakdown provided for Africa). Analysis of OECD data that is reported by the funders, covering bilateral and multilateral funding sources, estimated international public finance (grants and concessional lending) committed to Africa for climate change for 2014-2018 at USD 49.9 billion: 61% (30.6 billion) for mitigation, 33% (16.5 billion) for adaptation and 5% (2.7 billion) for both objectives simultaneously (Savvidou and Atteridge, 2021) (Figure 9.8a). This equates to an average of USD 3.8 billion per year targeting adaptation (Savvidou and Atteridge, 2021). In per capita terms, only two countries (Djibouti and Gabon) were supported with more than USD 15 per person per year, most were supported with less than USD 5 per person per year (Savvidou and Atteridge, 2021).

The multilateral development banks (MDBs) report 43% of their climate-related commitments to sub-Saharan Africa in 2018 targeted adaptation (EBRD et al., 2021). Sources other than international public finance are more difficult to track and there is limited data on Africa (Cross-Chapter Box FINANCE in Chapter 17). Considering a wider range of finance types (including private flows and domestic mobilisation), an estimated annual average of roughly USD 19 billion in climate finance for 2017-2018 went to sub-Saharan Africa, of which only 5% was for adaptation (CPI, 2019; Adhikari and Safaee Chalkasra, 2021). The mobilisation of private finance by developed country governments, through bilateral and multilateral financial support, is lower in Africa relative to other world regions. Globally, in 2016-2018, Africa made up only 17% of mobilised private finance relevant for climate change (OECD, 2020).

Strong differences exist among African sub-regions. Finance commitments targeting adaptation increased from 2014-2018 for East and West Africa but decreased in Central Africa (Savvidou and Atteridge, 2021) (Figure 9.8b). Climate-related finance was >50% for adaptation in 19 countries, while 26 received >50% for mitigation (Savvidou and Atteridge, 2021).

African countries expect grants to play a crucial role in supporting adaptation efforts because loans add to already high debt levels that exacerbate fiscal challenges, especially in light of high sovereign debt levels from the COVID-19 pandemic (Bulow et al., 2020; Estevão, 2020). From 2014-2018, more finance commitments targeting adaptation in Africa were debt instruments (57%) than grants (42%) (Savvidou and Atteridge, 2021) (Figure 9.8c).

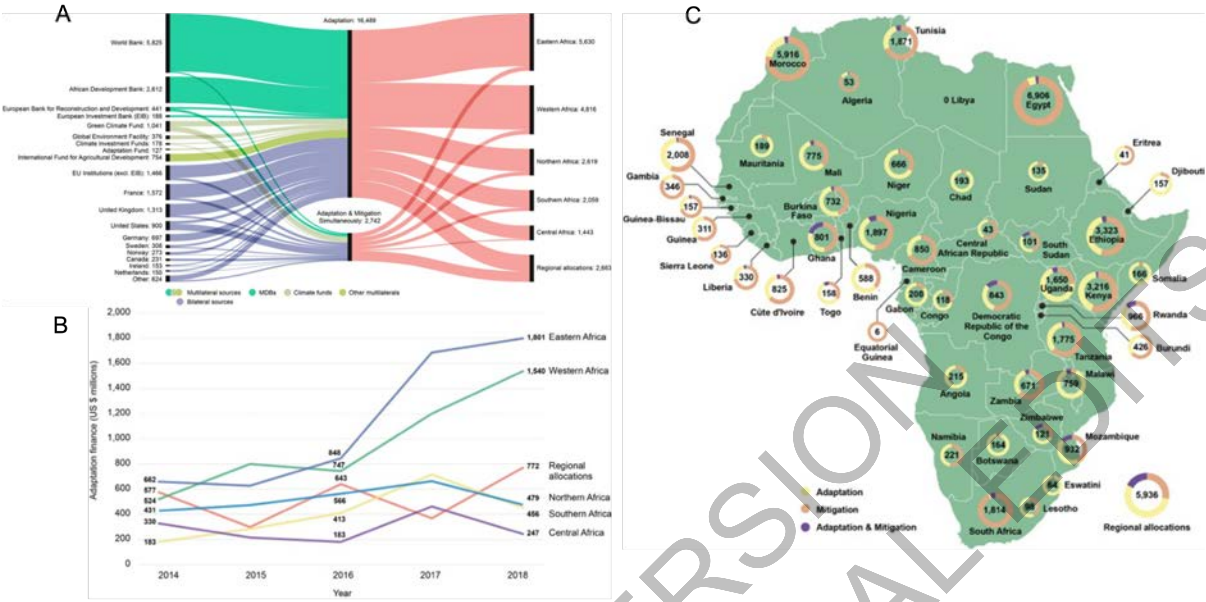


Figure 9.8: Finance targeting climate adaptation by sector and percentages of climate finance commitments that have been disbursed in Africa (2014-2018) as reported to OECD. (a) Flows of committed finance targeting adaptation, (b) trend over time in international development finance commitments targeting adaptation in Africa, and (c) country-level shares of total climate finance that targeted adaptation or mitigation or both simultaneously. Source: (Savvidou and Atteridge, 2021).

For Africa combined, the sectors targeted with most support for adaptation are Agriculture and Water Supply and Sanitation, which account for half of total adaptation finance from 2014-2018 (Figure 9.9a). The sectoral distribution has changed little over these years, suggesting adaptation planners and funders are maintaining a relatively narrow view of where support is needed and how to build climate resilience (Savvidou and Atteridge, 2021).

However, to understand actual expenditure on adaptation, it is necessary to look at disbursements (that is, the amounts paid out versus committed amounts). Low ratios of disbursements to commitments suggest difficulties in project implementation. Disbursement ratios for climate-related finance from all funders other than MDBs (for which data is not published) in Africa are very low (Savvidou and Atteridge, 2021) (Figure 9.9b). Only 46% of 2014–2018 commitments targeting adaptation were dispersed (Savvidou and Atteridge, 2021). Regions faring worst are North Africa (15%), Central Africa (33%) and West Africa (33%) (Figure 9.9c). These disbursement ratios for adaptation and mitigation finance in Africa are lower than the global average (Savvidou and Atteridge, 2021), which suggests greater capacity problems in implementing climate-related projects and, in turn, means lost opportunities to build resilience and adaptive capacity and a wider gap in adaptation finance for Africa (Omari-Motsumi et al., 2019).

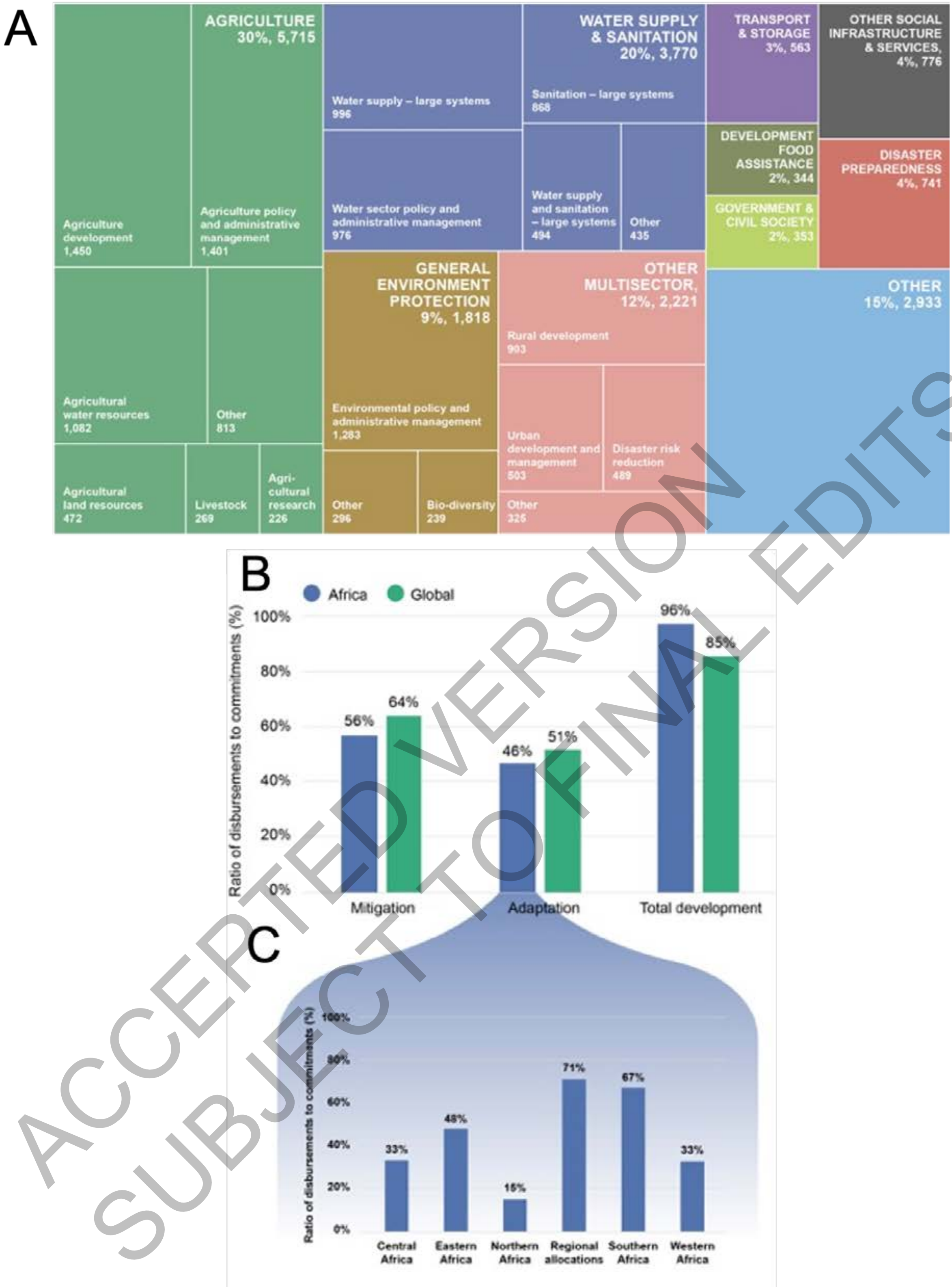


Figure 9.9: (a) Sectoral distribution of adaptation finance commitments to Africa 2014-2018 (Savvidou and Atteridge, 2021). Disbursement ratio (disbursements expressed as percentage of commitments) targeting mitigation, adaptation and for total development finance, (b) disbursement ratios for Africa compared to global average, and (c) disbursement ratios for adaptation finance broken down by each African sub-region. 2014-2018 (for all funders reporting to OECD except Multilateral Development Banks). Source: (Savvidou and Atteridge, 2021).

9.4.1.4 What are the Barriers and Enabling Conditions for Adaptation Finance?

The present situation reflects not only an insufficient level of finance being mobilised to support African adaptation needs (Section 9.4.1) but also problems in accessing and using funding that is available. The direct access modality introduced by the Adaptation Fund and GCF, whereby national and regional entities from developing countries can be accredited to access funds directly, is aimed at reducing transaction costs for recipient countries, increasing national ownership and agency for adaptation actions, and enhancing decision-making responsibilities by national actors, thereby contributing to strengthening local capacity for sustained and transformational adaptation (CDKN, 2013; Masullo et al., 2015). Indeed, direct-access projects from the Adaptation Fund tend to be more community focussed than indirect-access projects (Manuamorn and Biesbroek, 2020). Country institutions in Africa, however, are struggling to be accredited for direct access because of the complicated, lengthy and bureaucratic processes of accreditation, which requires, for example, strong institutional and fiduciary standards and capacity to be in place (Brown et al., 2013; Omari-Motsumi et al., 2019). As of December 2019, over 80% of all developing countries had no national Direct Access Entities (DAEs) (Asfaw et al., 2019). Capacity to develop fundable projects in Africa is also inadequate. An analysis of proposals submitted to the GCF up to 2017 revealed that, while African countries were able to submit proposals to the GCF, they had the lowest percentage of approvals (39%) compared to all other regions (Fonta et al., 2018). This suggests the quality of proposals and therefore the capacity to develop fundable proposals remains inadequate in the region.

Even when accredited, some countries experience significant institutional and financial challenges in programming and implementing activities to support concrete adaptation measures (Omari-Motsumi et al., 2019). Low disbursement ratios suggest inadequate capacity to implement projects once they are approved (Savvidou and Atteridge, 2021). Systemic barriers have been highlighted in relation to the multilateral climate funds, including funds not providing full-cost adaptation funding, capacity barriers in the design and implementation of adaptation actions (including the development of fundable project proposals) and barriers in recognising and enabling the involvement of sub-national actors in the delivery and implementation of adaptation action (Omari-Motsumi et al., 2019). As of 2017, most GCF disbursements to Africa (61.9%) were directed to support national stakeholders' engagement with regards to readiness activities, with only 11% directed to support DAEs in implementation of concrete projects/pipeline development (Fonta et al., 2018). While supporting readiness activities is important for strengthening country ownership and institutional development, research suggests adaptation finance needs to shift towards implementation of concrete projects and more pipeline development if the goal of transformative and sustained adaptation in Africa is to be realised (Fonta et al., 2018; Omari-Motsumi et al., 2019). The source of these problems needs to be better understood so that the prospects for future climate-related investments can be improved and institutional strengthening and targeted project preparation can be supported (Omari-Motsumi et al., 2019; Doshi and Garschagen, 2020; Savvidou and Atteridge, 2021).

Some progress has been made in supporting developing countries to enhance their adaptation actions. The process to formulate and implement NAPs was established by parties under the UNFCCC to support developing countries identify their vulnerabilities, and determine their medium- and long-term adaptation needs (UNFCCC Paris Agreement, 2015). NAPs provide a means of developing and implementing strategies and programmes to address those needs. In 2016, the parties agreed for the GCF to fund up to USD 3 million per country for adaptation planning instruments, including NAPs. However, accessing funding through the GCF for NAP formulation is challenging (Fonta et al., 2018) and, as of October 2020, four years after the decision to fund NAPs, only six African countries had completed their NAPs (UNFCCC NAP Central). The next step is to convert adaptation planning documents into programming pipeline projects that are fundable and implementable, which presents a significant barrier to enhanced adaptation action (Omari-Motsumi et al., 2019).

Adaptation finance has not been targeted more towards more vulnerable countries (Barrett, 2014; Weiler and Sanubi, 2019; Doshi and Garschagen, 2020; Savvidou and Atteridge, 2021). Reasons for this include fast-growing middle-income countries offering larger gains in emission reductions, so finance has favoured mitigation in these economies, even within sub-Saharan Africa, and as more climate finance uses debt instruments, mitigation projects are further preferred because returns are perceived to be more certain (Rai et al., 2016; Lee and Hong, 2018; Carty et al., 2020; Simpson et al., 2021c).

Many adaptation interventions for most vulnerable countries and communities provide no adequate financial return on investments and can therefore only be funded with concessional public finance (Cross-Chapter Box

FINANCE in Chapter 17). Yet, public funds alone are insufficient to meet rapidly growing adaptation needs. Public mechanisms can help leverage private sector finance for adaptation by reducing regulatory, cost and market barriers through blended finance approaches, public-private partnerships, or innovative financial instruments and structuring in support of private sector requirements for risk and investment returns, such as green bonds (Cross-Chapter Box FINANCE in Chapter 17). Subnational actors can be core agents to conceptualize, drive, and deliver adaptation responses and unlock domestic resources in the implementation of adaptation action (CoM SSA, 2019; Omari-Motsumi et al., 2019), provided they are sufficiently resourced and their participation and agency are supported.

Many African countries are at high risk of debt distress, especially due to the COVID-19 pandemic, and will need to decrease their debt levels to have the fiscal space to invest in climate resilience (Estevão, 2020; Dibley et al., 2021). As of mid-2021, the G20's Debt Service Suspension Initiative is providing temporary relief for repayment of bilateral credit, but this has largely not been taken up by private lenders (Dibley et al., 2021; World Bank, 2021). The total external debt servicing payments combined for 44 African countries in 2019 were USD 75 billion (World Bank, 2018), far exceeding discussed levels of near-term climate finance. Aligning debt relief with Paris Agreement goals could provide an important channel for increased financing for climate action, for example, by allowing African countries to use their debt-servicing payments to finance climate change mitigation and adaptation (Fenton et al., 2014). Governments can disclose climate risks when taking on sovereign debt, and debt-for-climate resilience swaps could be used to reduce debt burdens for low-income countries while supporting adaptation and mitigation (Dibley et al., 2021).

9.4.2 Governance

9.4.2.1 Governance Barriers

Overcoming governance barriers is a precondition to ensure successful adaptation and climate-resilient development (Pasquini et al., 2015; Owen, 2020). Despite the ambitious climate targets across African countries and renewed commitments in recent years (Zheng et al., 2019; Ozor and Nyambane, 2020), governance barriers include, among others, slow policy implementation progress (Shackleton et al., 2015; Taylor, 2016), incoherent and fragmented approaches (Zinngrebe et al., 2020; Nemakonde et al., 2021), inadequate governance systems to manage climate finance (Granoff et al., 2016; Banga, 2019), poor stakeholder participation (Sherman and Ford, 2014), gender inequalities (Andrijevic et al., 2020), unaligned development and climate agendas (Musah-Surugu et al., 2019; Robinson, 2020), elite capture of climate governance systems (Kita, 2019), hierarchical and complex state bureaucracy (Meissner and Jacobs, 2016; Biesbroek et al., 2018) and weak, non-existent or fragmented subnational institutions (Paterson et al., 2017; Musah-Surugu et al., 2019). Further, adaptation planning involves cross-cutting themes, multiple actors and institutions with different objectives, jurisdictional authority and levels of power and resources, yet there is often a lack of coordination, clear leadership or governance mandates (Shackleton et al., 2015; Leck and Simon, 2018) and unequal power relations between African countries and developed countries can hinder progress on governance of financial markets, budget allocations and technology transfer to address addressing climate technology gaps in Africa (Rennkamp and Boyd, 2015; Olawuyi, 2018).

Policy implementation can be slow due to the absence of support mechanisms and dependency on funding by international partners (Leck and Roberts, 2015; Ozor and Nyambane, 2020). In many countries, commitment to climate policy objectives is low (Naess et al., 2015), particularly in light of competing development imperatives and post-COVID-19 recovery efforts (Caetano et al., 2020), although COVID-19 recovery efforts offer significant opportunities for health, economic and climate resilience co-benefits (Sections 9.4.3 and 9.11.5; Cross-Chapter Box COVID in Chapter 7). Another challenge relates to long-term planning and decision-making which is hampered by uncertainty related to future socio-economic and GHG emissions scenarios (Coen, 2021), political cycles and short-term political appointment terms (Pasquini et al., 2015).

Lack of community agency in climate governance affects ability for citizen-led climate interventions in Africa (Antwi-Agyei et al., 2015; Mersha and Van Laerhoven, 2016). This is attributed partly to low civic education, limited participation power of citizens and tokenism due to perceived lack of immediate benefits (Odei Erdiaw-Kwasie et al., 2020), as well as low rates of climate change literacy in many regions (Simpson et al., 2021a) (Section 9.4.3). Participation in climate policy also extends to the private sector, which has been relatively uninvolved in adaptation discussions to date (Crick et al., 2018).

Africa requires substantial resources and support to adapt to the unavoidable consequences of climate change, a pertinent climate justice concern for governments. However, the mechanisms needed to redress current power imbalances, structural and systemic inequality are often absent (Saraswat and Kumar, 2016) (see Section 9.11.4) and policies that underpin environmental justice concerns, including distributive justice, participation, recognition and capability (Shi et al., 2016; Chu et al., 2017) are also needed.

9.4.2.2 Good Governance

Good governance can contribute to positive climate outcomes and climate-resilient development in Africa through long-term planning, development-focused policy environments, the development of robust and transformational policy architecture, inclusive participation and timely implementation of NDCs (Bataille et al., 2016; Werners et al., 2021) (see Table 9.3 for examples).

Table 9.3: Characteristics and examples of governance that contribute towards climate-resilient development in Africa

Governance characteristic	Example
Long-term development planning	Countries are mainstreaming adaptation into their long-term development cycles (UNFCCC Adaptation Committee, 2019). For example, Burkina Faso's National Adaptation Plan elaborates its perspective to 2050 and links to its development pathways (Government of Burkina Faso, 2015). Many African countries are also enhancing the adaptation components of their long-term low emissions strategies.
Climate justice and inequality-focused policies	Climate policies can be designed to include specific policy mechanisms (e.g., carbon taxes, renewable energy subsidies) to maximise developmental gains while reducing inequality (Andrijevic et al., 2020). For example, revenues from a carbon tax can be used to increase social assistance programs that benefit poor people and reduce their vulnerability to climate change (Hallegatte et al., 2016). Climate risk management can be integrated into social protection and assistance programs, such as public works programs that increase climate resilience (9.11)
Interlinkages between adaptation and development pathways	Cross-sectoral and multi-level governance approaches can harness synergies with the SDGs, Paris Agreement and Agenda 2063 aspirations, helping to counter the adaptation deficit, promote sustainable resource use and contribute to poverty reduction (Niang et al., 2014; IPBES, 2018; Roy et al., 2018b). Ghana, Namibia, Rwanda and Uganda all link adaptation with disaster risk reduction in their NDCs (UNFCCC Adaptation Committee, 2019).
High-level engagement	Climate policies, traditionally overseen by environment ministries, are increasingly receiving priority from finance and planning ministries. Zambia's Climate Change Secretariat is currently led by the Ministry of Finance (Government of the Republic of Zambia, 2010), while Tanzania's environmental division sits in the office of the Vice-President (Governmet of the United Republic of Tanzania, 2011).
All-of-government approach	In Kenya, the Climate Change Directorate is the secretariat for the National Climate Change Commission, serving as an overarching mechanism to coordinate sectoral and county level action (Government of the Republic of Kenya, 2018). In South Africa, the National Committee on Climate Change, the Intergovernmental Committee on Climate Change and the Presidential Climate Change Commission have been established to enhance intergovernmental and multisectoral coordination on climate action (Climate Action Tracker, 2021).
Participatory engagement	Polycentric, bottom-up and locally implemented approaches are more able to include the emergence of new actors (e.g., city networks, multinational companies and sub-state entities), new instruments and levels (soft law instruments or transnational dynamics) and new guiding principles and values (fairness, transparency and co-participation) (Leal Filho et al., 2018; Sapiains et al., 2021). Case studies include the community-based, participatory scenario planning approach used in Malawi to generate information for farmers from seasonal forecasts, as well as the integration of climate risk into Lusaka's Strategic Plan through engagement with city planners (Conway and Vincent, 2021; Vincent and Conway, 2021). Many innovative solutions have been designed to promote participation, such as Pamoja Voices toolkits in pastoralist communities in Northern Tanzania (Greene et al., 2020).

Inclusive and diverse stakeholders	Kenya's Climate Change Directorate has a designated team to integrate gender into its national climate policies (Murray, 2019), while Seychelles' National Climate Change Council has allocated a seat exclusively for a youth candidate (Government of The Seychelles, 2020). Tanzanian Climate-Smart Agriculture Alliance supports the integration of farmers and builds strategic alliances to support climate processes (Nyasimi et al., 2017).
Partnerships	Ghana, Kenya, Uganda and Zambia are developing anticipatory scenarios for low-carbon climate-resilient development pathways for the agricultural sector, aimed at informing input into national climate policy (Balié et al., 2019). This science to policy to practice interface is bridged through the inclusion of policymakers, practitioners and academics (Dinesh et al., 2018). In Lusaka, Durban and other African cities, processes of engagement and learning have built the trust and capacities needed to inform city-scale, climate-resilient decisions and associated actions (Taylor et al., 2021a; Taylor et al., 2021b).
NDC implementation	Rwanda has developed an indicator-based Monitoring, Reporting and Verification (MRV) framework for tracking its NDC implementation and associated financial flows (Government of Republic of Rwanda, 2020). Zambia has also integrated gender indicators into its NDC implementation plan and is incorporating gender considerations into its MRV framework (Murray, 2019).

African governments are developing and revising ambitious adaptation policies that are enforceable and aligned with wider societal development goals, including an enabling environment for finance and investment in the jobs and skills development necessary to support a just transition (ILO, 2019) (Section 9.4.5). If appropriately designed, such institutions offer the opportunity to foster adaptive governance which is collaborative, multi-level and decentralised, offering integration of policy domains, flexibility and an emphasis on non-coerciveness and adaptation (Ruhl, 2010).

Coordination across multiple sectors, supported with leadership from the highest levels of government, has shown to improve implementation effectiveness and anticipated scaling up (Rigaud et al., 2018). This high-level engagement promotes the inclusion of climate resilience and adaptation targets in national planning and budgeting. Financial and capacity support is essential (Adenle et al., 2017; UNEP, 2021), as is the tracking of national progress towards development goals (Box 9.6).

In Africa, climate governance occurs in a context of deep inequality and asymmetric power relations – both within countries and between countries – making adequate mechanisms for multi-stakeholder participation essential (Sapiains et al., 2021). This requires creation of avenues for the voices of marginalised groups in policy processes and enabling policy environments that can catalyse inclusive action and transformational responses to climate change (Totin et al., 2018; Revi et al., 2020; Ziervogel et al., 2021), safeguarding protection against the climate harms of the most vulnerable in society, particularly of women and children (see also Box 9.1). Community-based natural resource management in pastoral communities was observed to improve institutional governance outcomes through involving community members in decision-making, increasing the capacity of these communities to respond to climate change (Reid, 2014).

Specific indicators can be included in the performance metrics and monitoring frameworks for each sector, policy intervention and budget planning cycle (Wojewska et al., 2021). Many countries in Africa are also revamping their institutional coordination mechanisms to reflect an all-of-government approach and partnership with non-State stakeholders with diverse capabilities and expertise (see examples from Rwanda and Zambia in Table 9.3). This includes Cape Town's drought response in 2017/2018 where non-State actors actively partnered with the state response around water management/savings practices (Simpson et al., 2020a; Simpson et al., 2020b; Cole et al., 2021b).

9.4.3 Cross-Sectoral and Transboundary Solutions

Climate change does not present its problems and opportunities conveniently aligned with traditional sectors, so mechanisms are needed to facilitate interactions and collaborations between people working in widely different sectors (Simpson et al., 2021b). Traditional risk assessments typically only consider one climate hazard and one sector at a time, but this can lead to substantial misestimation of risk because multiple climate risks can interact to cause extreme impacts (Zscheischler et al., 2018; Simpson et al., 2021b).

Because multiple risks are interlinked and can cascade and amplify risk across sectors, cross-sectoral approaches that consider these interlinkages are essential for climate-resilient development, especially for managing trade-offs and co-benefits between SDGs, mitigation and adaptation responses (Liu et al., 2018a).

In Africa, placing cross-sectoral approaches at the core of climate-resilient development provides significant opportunities to deliver large benefits and/or avoids damages across multiple sectors including water, health, ecosystems and economies (*very high confidence*) (Boxes 9.5, 9.6 and 9.7). They can also prevent adaptation or mitigation action in one sector, exacerbating risks in other sectors and resulting in maladaptation, for example, from large-scale dam construction or large-scale re/afforestation (e.g., water-energy-food nexus and large-scale tree planting efforts) (Boxes 9.3 and 9.5).

Cross-sectoral or 'nexus' approaches can improve the ability of decision-makers to foresee and prevent major climate impacts. Barriers to developing nexus approaches arise from rigid sectoral planning, regulatory and implementation procedures, entrenched interests and power structures and established sectoral communication structures. Opportunities for overcoming these barriers include creating a dedicated home for co-development of nexus risk assessment and solutions, promoting co-leadership of projects by multiple sectors, specific budget allocations for nexus projects, facilitating and coordinating services, compiling useful strategies into toolkits, ameliorating inequitable power relations among participants and measuring progress on nexus approaches through metrics (Palmer et al., 2016; Baron et al., 2017).

Beyond cross-sectoral collaboration, international cooperation is vital to avert dangerous climate change as its impacts reach beyond the jurisdiction of individual states. International good practice and regional agreements, protocols and policies together recognise that regional integration, cooperative governance and benefit-sharing approaches are cornerstones of effective resource security and climate change responses in Africa (Jensen and Lange, 2013; World Bank, 2017a; Dombrowsky and Hensengerth, 2018). Natural resource development, particularly governance of shared river basins, exemplifies opportunities for governance responses for African nations that can be cooperative, regionally integrated and climate-resilient.

In Africa, climate vulnerability crosses geopolitical divides as regional clusters of fragile and high vulnerability countries exist, emphasising the need for transboundary cooperation (Birkmann et al., 2021; Buhaug and von Uexkull, 2021). Natural resource security is increasingly reliant on transboundary governance, regional integration and cooperation (Namara and Giordano, 2017). There are 60 international or shared river basins on the continent, a function of colonial divides and topography, with some basins shared by four or more countries (UNECA, 2016; Popelka and Smith, 2020). Climate changes which result in impact and risk pathways across country boundaries and regions (although with different levels of impact) accelerate the urgency for integrated approaches to manage and benefit from shared resources and promote their security for populations and economies (Namara and Giordano, 2017; Frame et al., 2018; Carter et al., 2021). At the same time, natural resources such as water generate economic benefits shared across boundaries, such as hydroelectric power generation and regional food security (Dombrowsky and Hensengerth, 2018).

Poor governance, particularly at the transboundary level, can undermine water security and climate change is likely to add new challenges to pre-existing dynamics, emphasising the necessity of formal transboundary arrangements (Jensen and Lange, 2013; UNECA, 2016). Further, it can constrain access to critical financial resources at a time when it is needed most. This is particularly the case when climate impact pathways manifest at the transboundary level (Challinor et al., 2018; Simpson et al., 2021b), but where the need to protect sovereign interests can block regionally integrated institutional arrangements that are pivotal for accessing the multilateral climate funds for transboundary climate investments that include resilient infrastructure and greater water benefits across Africa's shared river basins (Carter et al., 2021) (Cross-Chapter Box INTEREG in Chapter 16).

In response, the African Development Bank is supporting two of the most climate-vulnerable and larger African river basins to leverage GCF and GEF funds to finance Programmes for Integrated Development and Adaptation to Climate Change (PIDACC). PIDACC finance is approved at the multinational level in the Niger basin which is shared by 9 West and Central African States (AfDB, 2018c; GCF, 2018a), while a PIDACC proposal is currently under development for the Zambezi basin (Zambezi Watercourse Commission, 2021).

Stakeholders across Africa are recognising the scale and severity of transboundary risks to water. Such risks are twofold in nature, arising both from potential impacts due to climate change and from responses to climate change (Simpson et al., 2021b). This awareness amongst stakeholders is leading to increasingly progressive approaches to natural resource development which can also reduce risk across boundaries within regions. For example, river basin organisations (RBOs) in southern Africa such as the Orange-Senqu and the Okavango River Basin Commissions are revising treaties considered to predate the interrelated issues of climate change, growing populations and water scarcity (OKACOM, 2020). In parts of West Africa, where climate change is characterised by reduction of precipitation (Barry et al., 2018), regionally integrated and climate-resilient economic investments for water resource development are enabled by the Senegal River Basin Organisation (OMVS) which emphasises programme and project development, financing and implementation in ensuing work plans (World Bank, 2020e), as does the Nile Basin Initiative (NBI) in North and East Africa (Schmeier, 2017; Blumstein and Petersen-Perlman, 2021).

Enhanced transboundary governance arrangements suggest that countries are joining forces to coherently manage and protect natural resources (Spalding-Fecher et al., 2014; AfDB, 2021). Underlying governance issues and political economy interests block or advance such transitions to regionally integrated resource management and benefit-sharing, the market drivers of water security (AMCOW, 2012; Soliev et al., 2015). Angola, for example, outlines regional adaptation as a priority and one of its unconditional adaptation strategies (which is already funded) is enhancing resilience in the Benguela fisheries system, a project shared with Namibia and South Africa (GEF and FAO, 2021). Another example is The Great Green Wall for the Sahara and Sahel Initiative which was launched in 2007, with the aim of tackling land degradation in Africa (UNCCD, 2020). This transboundary project, led by the African Union Commission, is being implemented in more than 20 countries across Africa's Sahel region, in cooperation with international partners including UNCCD, GEF and the World Bank among others. Approximately USD 10 billion have been mobilised and/or promised for this initiative (UNCCD, 2020). Such statements demonstrate the increasing identification of transboundary risks and approaches to manage and adapt to them as areas of 'common concern' that require cooperative adaptation actions. Accelerating strengthened transboundary water and climate governance needs to integrate these climate drivers of compromised water security. The role of institutions such as OVMS and the NBI have demonstrated they can be played in influencing economic behaviour among riparian countries of shared river basins highlighting that institutions are an integral part of climate governance in evolving economic systems (Hodgson, 2000).

9.4.4 Climate Change Adaptation Law in Africa

9.4.4.1 The Rise of Climate Change Adaptation Law

Robust legislative frameworks, both climate change specific and non-specific, can foster adaptive responses to climate change, particularly in Least Developed Countries (LDCs) (Nachmany et al., 2017). As discussed in Chapter 17, there are multiple reasons for this. The successful implementation of policy objectives across the continent is often contingent upon or at least supported by an underlying legislative framework (Averchenkova and Matikainen, 2017; Scotford et al., 2017). There are also wider systemic and structural reasons for developing climate change legislation, including the promotion of coordination within government, its policy entrenching role, its symbolic value and its potential to support climate finance flows (Nachmany et al., 2017; Scotford and Minas, 2019).

Legal systems, however, also have the potential to be maladaptive. Laws may be brittle, often assuming and reinforcing a static state, and the boundary of the law may not align to the relevant location, scale or impact (Craig, 2010; Arnold and Gunderson, 2013; Wenta et al., 2019). This necessitates the review and revision of existing laws to remove such barriers and foster adaptive management (Craig, 2010; Ruhl, 2010; Cosens et al., 2017) and, where necessary, the promulgation of new laws.

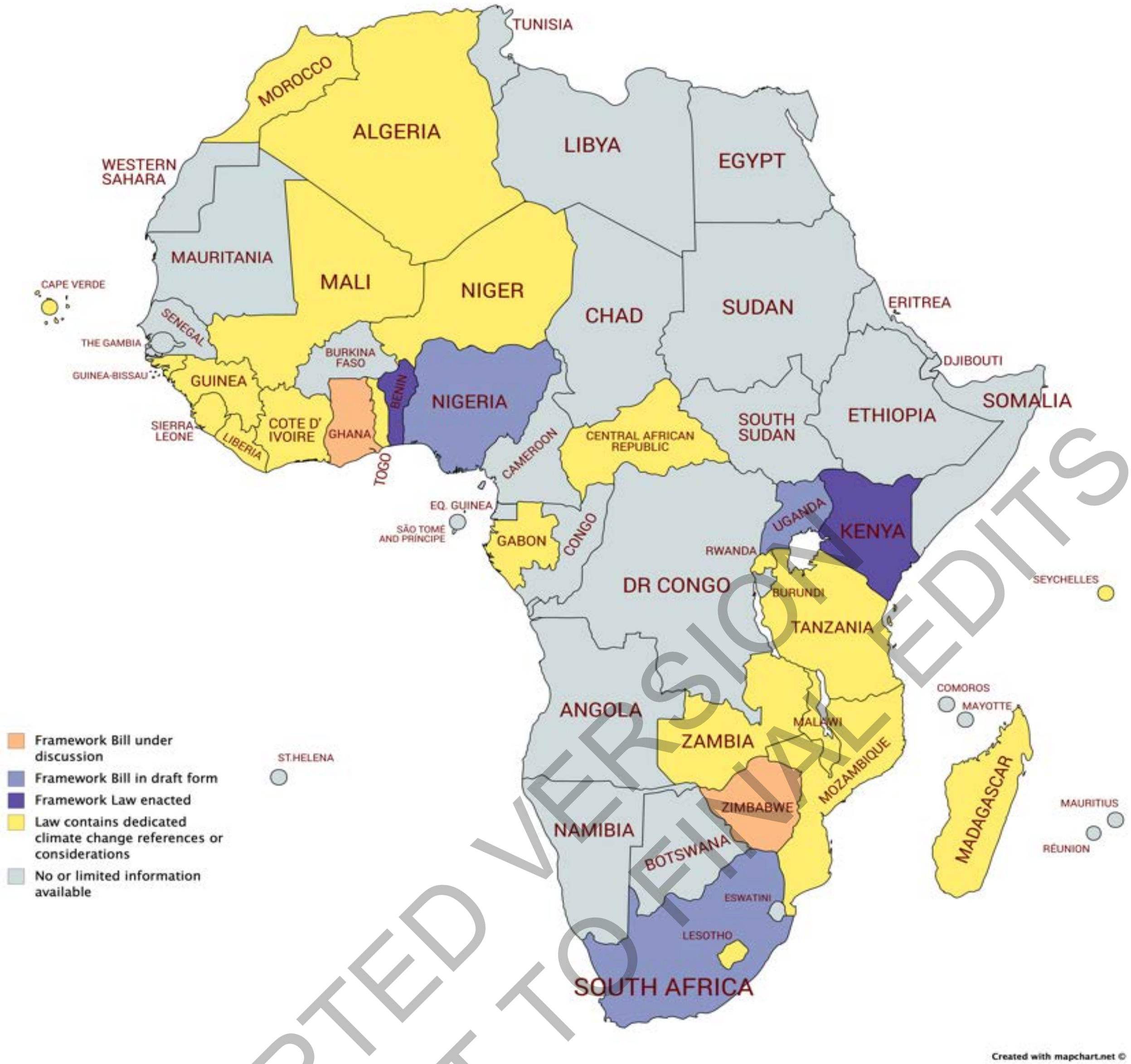


Figure 9.10: Progress in development of climate change framework law in Africa derived from an analysis of public databases of African laws (author's own map), data drawn from (Government of Niger, 1998; Government of Liberia, 2002; Government of Algeria, 2004; Government of Tanzania, 2004; Government of Central African Republic, 2008; Government of Lesotho, 2008; Government of Togo, 2008; Government of Guinea Bissau, 2011; Government of Ivory Coast, 2012; Government of Rwanda, 2012; Government of Sierra Leone, 2012; Government of Cape Verde, 2014; Government of Morocco, 2014; Government of Mozambique, 2014; Government of Madagascar, 2015; Government of the Seychelles, 2015; Government of Gabon, 2016; Government of Kenya, 2016; Government of Mali, 2016; Government of Zambia, 2016; Government of Malawi, 2017; Government of Nigeria, 2017; Government of Benin, 2018; Government of Ghana, 2018; Government of South Africa, 2018; Government of Uganda, 2018; Government of Zimbabwe, 2019 sources quoted as of September 2019).

There has been a rise in framework and sectoral climate change laws across Africa, as illustrated in Figure 9.10 above. The map illustrates the two framework statutes which have been promulgated in Benin and Kenya, as well as the three framework Bills which have been drafted in Nigeria, South Africa and Uganda. There are also discussions taking place in Zimbabwe and Ghana regarding the potential development of a draft framework Climate Change Bill. A review of the climate change framework laws indicates evidence of cross-pollination in design across African jurisdictions, creating the potential for a unique and regionally appropriate body of law with a strong focus on adaptation responses (Rumble, 2019). As discussed in Chapter 17, however, there remains the need for in-country expert input on how the domestic legal landscape may influence their operation, and for each jurisdiction to independently interrogate its adaptation needs and objectives (Scotford et al., 2017).

Numerous African states have also included dedicated climate change-related provisions within various existing statutes which regulate the environment or disaster management. For example, Tanzania's Environmental Management Act 20 of 2004 contains dedicated provisions to address climate change. Rwanda's Law on Environment 48/2018 also contains detailed provisions on mainstreaming climate change into development planning processes, education on climate change, vulnerability assessments and the promotion of measures to enhance adaptive capacity. Some countries have also developed laws dedicated to a specific aspect of adaptation. For example, the Conservation and Climate Adaptation Trust of Seychelles Act 18 of 2015 establishes a trust fund to finance climate change adaptation responses in Seychelles. Similarly, many countries including Algeria, Burkina Faso, Djibouti, Ghana, Namibia, Malawi, Mauritius, Madagascar, Mozambique, Tanzania and South Africa have dedicated disaster management laws. At this stage, it is still too early to determine whether these laws are having any substantive influence in strengthening resilience and reducing vulnerability and, as discussed in Chapter 17, this is identified as a knowledge gap requiring further research.

9.4.4.2 Common Themes in Framework Laws

Laws are now being developed to formalise and entrench institutional structures, specifying their mandate, function, membership and related procedures. A useful example of such an approach can be found in the Nigerian Climate Change Bill which establishes the National Climate Council on Climate Change headed and chaired by the Vice-President, with a wide membership of Ministers, the Chairmen of the Governors' Forum and Association of Local Governments, as well as the private sector and non-governmental organisation (NGO) representatives.

Climate change framework laws can play an instrumental role in achieving mainstreaming by directing relevant actors to integrate adaptation considerations into existing mandates, operations and planning instruments (Rumble, 2019). By way of example, the South African Draft Climate Change Bill contains a general duty to 'coordinate and harmonise the policies, plans, programmes and decisions of the national, provincial and local spheres of government' to achieve, among other things, the climate change objectives of the Bill and national adaptation objectives.

Another common theme is the requirement to develop national climate change adaptation strategies and plans. Many laws further entrench their longevity by requiring them to be subject to strong community participation and consultation, as demonstrated by the Kenyan Climate Change Act and the Nigerian Climate Change Bill.

9.4.4.3 Local Climate Change Laws and Indigenous Knowledge Systems

The Paris Agreement acknowledges, in Article 7.5, that adaptation should be based on and guided by, among other things, 'traditional knowledge, knowledge of indigenous peoples and local knowledge systems'. The accumulated knowledge within indigenous knowledge systems is particularly important as it can assist governments in determining how the climate is changing, how to characterise these impacts and provide lessons for adaptation (Salick and Ross, 2009). In this context, indigenous knowledge systems can play an important role in the effective design of local laws (Mwanga, 2019) as well as national laws. Doing so can contribute to the success of climate change response strategies, including enhancing local participation and the implementation of community-based and ecosystem-based adaptations (Chanza and de Wit, 2016; Mwanga, 2019). For example, the Makorongo Village Forest Management By-Law in Tanzania codifies local customary practices relating to forest management and sustainable harvesting with associated dual adaptation and mitigation benefits and includes all villagers in the decision-making processes relating to forest management (Mwanga, 2019). The inclusion of beneficial indigenous knowledge systems within local by-laws is contingent on the active involvement of members of the indigenous community and awareness of climate change considerations within the local sphere of government, and a willingness to foster such practices (Mwanga, 2019).

In addition to the advancement of indigenous knowledge in adaptive responses, it has been suggested that the protection of the rights of indigenous peoples can have adaptive benefits, in particular through the protection of land tenure rights (Ayanlade and Jegede, 2016). It has been argued that doing so will protect indigenous peoples' lands and resources from overconsumption, secure the recognition of their cultural stewardship over the environment, provide the financial incentive for land stewardship and promote the application of their unique knowledge on the sustainable development of that land and its preservation (Jaksa, 2006; Ayanlade and Jegede, 2016). Not only can a lack of protection of indigenous legal tenure undermine these objectives, but a number of African laws may actively work against them. For example, a review of Tanzanian and Zambian laws highlighted existing provisions that empowered the state to terminate or criminalise the occupation of vacant, undeveloped or fallow lands, which undermined the occupation by indigenous peoples of forests and other uncultivated lands (Ayanlade and Jegede, 2016).

9.4.5 Climate Services, Perception and Literacy.

Policy actors across Africa perceive that anthropogenic climate change is already impacting their locales through a range of negative socioeconomic and environmental effects (Pasquini, 2020; Steynor and Pasquini, 2020). They are highly concerned about and motivated to address these impacts (Hambira and Saarinen, 2015; Pasquini, 2020). Transformative responses to the impacts of climate change facilitate climate-resilient development and are informed by perceptions of climate variability and change and climate change literacy (Figure 9.11).

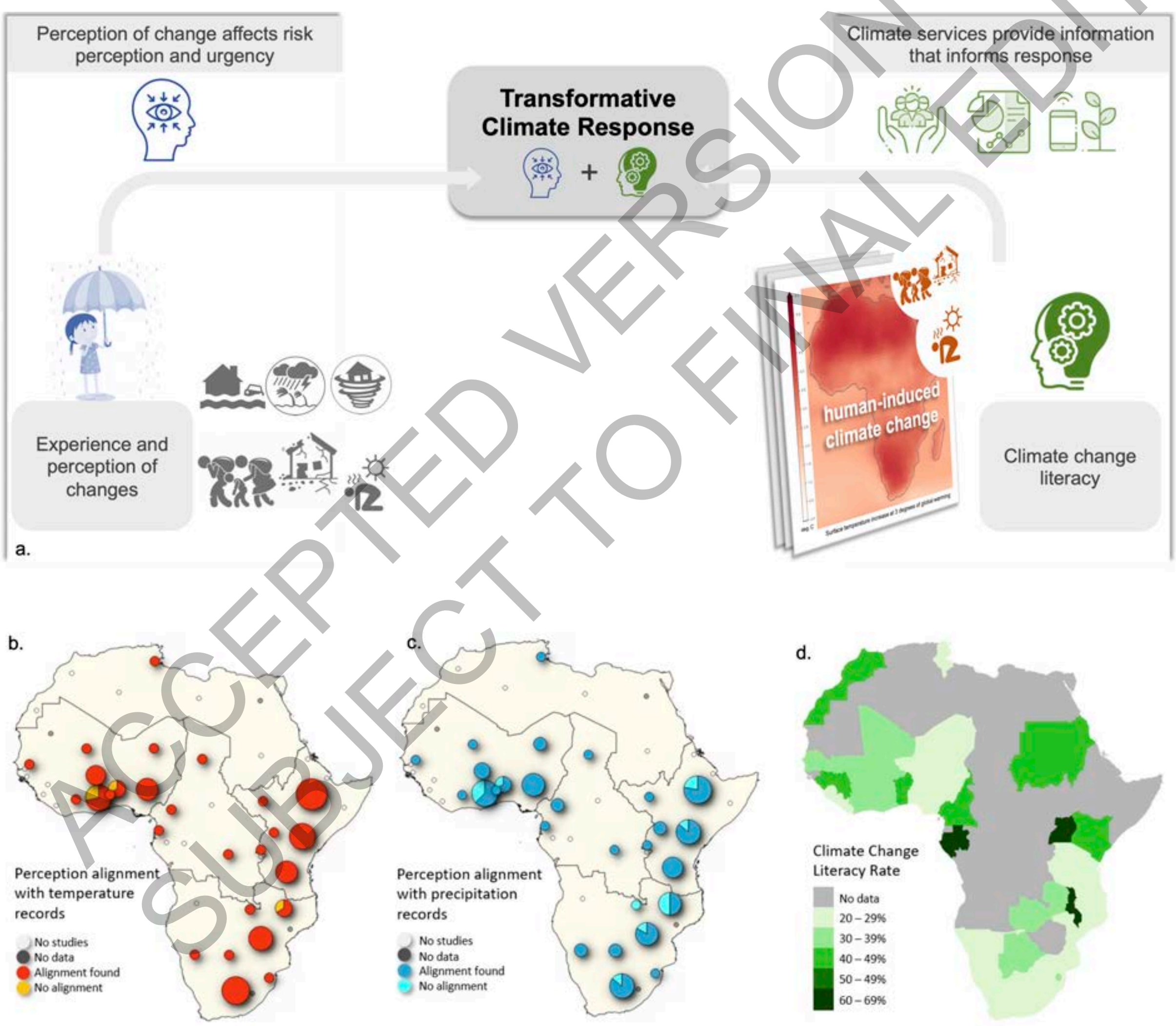


Figure 9.11: The importance of climate services and climate change literacy for more transformative responses to climate change in Africa (adapted from Simpson et al., 2021a). Climate services promote Climate Resilient Development by providing climate information for adaptation decision-making (Street, 2016; Vaughan et al., 2018). However, scalable uptake of climate services relies on climate risk perception of users which is largely driven in Africa by experience and perception of local climate changes (Jacobs and Street, 2020; Steynor et al., 2020b; Steynor and Pasquini, 2020). Perception of climate change in Africa can occur without the knowledge of its anthropogenic causes and its effect on risk, as awareness of the concept of climate change is generally low across Africa (Lee et al., 2015; Alemayehu and Bewket, 2017; Andrews and Smirnov, 2020). This can lead to coping responses to climate change which fall short of adaptation. Climate change literacy can fill this knowledge gap and, together with climate services,

extend responses to climate change to include consideration of future risk through awareness of the anthropogenic cause of climate change and its effect on risk (IPCC, 2019b; Simpson et al., 2021a). Maps a-c: (a) Percentage of times scholarship on Africa record that perception of temperature changes (left), (b) precipitation changes (centre), aligned with available meteorological or climate records for 144 country studies across 33 African countries (Size of bubble indicates number of studies per country for both Panels a and b; Panel b, alignment with temperature changes is indicated for all studies within a country in red, and articles indicating no alignment in orange; while in panel c, alignment with precipitation changes is indicated per country in dark blue and articles indicating no alignment in light blue). Panel c) country-level rates of climate change literacy for 33 African countries (that is, percentage of the population that have heard about climate change and think that human activity is wholly or partly the cause of climate change) (adapted from Simpson et al., 2021a).

9.4.5.1 Climate Information and Services

Climate services (CS) broadly include the generation, tailoring and provision of climate information for use in decision-making at all levels of society (Street, 2016; Vaughan et al., 2018). There is a range of climate service providers in Africa, including primarily National Meteorological and Hydrological Services (NMHS) and partner institutions, complemented by NGOs, the private sector and research institutions (Snow et al., 2016; Harvey et al., 2019), which offer the potential for public-private partnerships (Winrock, 2018; Harvey et al., 2019).

International development funding has progressed the provision of climate services and, together with technological advances and capacity-building initiatives, has increased the reliability of climate services across Africa (Vogel et al., 2019). Most CS investments have been towards the agricultural sector, with other focal sectors including pastoralism, health, water, energy and disaster risk reduction having only small CS initiatives directed towards them (Nkiaka et al., 2019; Carr et al., 2020). Despite this focus and investment, however, there remains a mismatch between the supply and uptake of CS in Africa as information is often inaccessible, unaffordable, not relevant to context or scale and is poorly communicated (Singh et al., 2018; Antwi-Agyei et al., 2021) (Table 9.4; Sections 9.4.1.5.1 and 9.13.4.1). Observational data required for effective regional climate services, including trend analyses, seasonal climate assessment, modelling and model evaluation, is sparse and often of poor quality (Figure 9.11) and usually requires payment which renders it unaffordable (Winrock, 2018).

A number of these challenges may be addressed through the transdisciplinary co-production of climate services (Alexander and Dessai, 2019; Vogel et al., 2019; Carter et al., 2020). Co-production of climate services involves climate information producers, practitioners and stakeholders, and other knowledge holders participating in equitable partnerships and dialogues to collaboratively identify climate-based risk and develop scale-relevant climate information to address this risk (Table 9.4) (Vincent et al., 2018; Carter et al., 2020).

Table 9.4: Challenges and opportunities for Climate Services in Africa for the supply and uptake of climate services.

Challenges	*Opportunities/Solutions*	*References*	*Examples of Programmes that address these challenges. Reproduced from (Carter et al., 2020) with permission.*
Supply of climate services			
Poor infrastructure (e.g., non-functioning observational networks; limited Internet bandwidth; lack of climate modelling capacity; keeping pace with changing technology).	• International funding for observation networks, data rescue and data sharing • Regular NMHS budgets from governments • Public-private partnerships	(Winrock, 2018; Harvey et al., 2019) (Snow et al., 2016; World Bank Group, 2016; Winrock, 2018; Cullmann et al., 2020; Meque et al., 2021)	*East Africa and the West African Sahel (ENACTS programme).* Work with NMHS to provide enhanced services by overcoming the challenges of data quality, availability and access. Creation of reliable climate information suitable for national and local decision-making using station observations and satellite data to provide greater accuracy in smaller space and time scales.

Fragmented delivery of climate services.	• Greater collaboration between the NMHS and sector-specific specialists to create a central database of sector-based climate services	(Winrock, 2018; Hansen et al., 2019a)	*Rwanda (RCSA programme).* improving climate services and agricultural risk management at local and national government levels in the face of a variable and changing climate
Mismatch in timescales: short-term information more desirable, e.g., seasonal predictions as opposed to decadal or end of century projections.	• Co-production of CS climate service products	(Jones et al., 2015; Vincent et al., 2018; Hansen et al., 2019a; Carr et al., 2020; Sultan et al., 2020)	*Burkina Faso (BRACED project).* Strengthening technical and communication capacities of national meteorological services to enable partners to jointly develop forecasts tailored to support agro-pastoralists.
Development funding interventions operate on timescales that inhibit or restrict effective adaptation and neglect to build in considerations for sustainability post the funded intervention.	• Co-production of climate service CS products • Endogenously driven climate services (services that are developed by regional actors, not by remote, usually developed nation actors)	(Vincent et al., 2018; Vogel et al., 2019) (Vincent et al., 2020a)	*Burkina Faso (BRACED project).* Actors recognised the need to ensure continuation of climate services post-project. Burkina Faso NMHS (ANAM) and National Council for Emergency Assistance and Rehabilitation (CONASUR) budgeted for the continued communication of climate services and training of focal weather intermediaries. Local radio stations agreed to continue transmitting climate services.
Use of climate services			
Insufficient access to usable data, including station data, and information suited to the decision context (including accessibility limitations based on gender and social inequalities)	• Capacity development initiatives for CS providers, intermediaries (including extension agents, NGO workers and others) and users • User needs assessments • Consistent monitoring and evaluation of climate services interventions	(Jones et al., 2015; Winrock, 2018; Hansen et al., 2019a; Hansen et al., 2019c; Mercy Corps, 2019; Nkiaka et al., 2019; Carr et al., 2020; Cullmann et al., 2020; Gumucio et al., 2020; Sultan et al., 2020) (Figure 9.11)	*Kenya, Ethiopia, Ghana, Niger and Malawi (ALP Programme).* Co-production of relevant information for decision-making and planning at seasonal time scales. The methods and media for communication and messages differ between different users. Strong emphasis on participation by women.
Limited capacity of users to understand or request appropriate CS products	• Co-production of climate service products • Capacity development	(Snow et al., 2016; Singh et al., 2018; Vincent et al., 2018; Nkiaka et al., 2019; Daniels et al., 2020)	*Cities in Zambia, Namibia, Mozambique, Zimbabwe, Botswana, Malawi and South Africa (FRACTAL programme).* Repeated interactions between each represented sector to learn and more completely understand the different contexts of each represented party and build understanding through an ethic of collaboration for solving climate-related problems in each unique city.

Lack of user trust in the information	• Co-production of climate service products • Combine scientific and indigenous forecasts • Demonstrate added value of the climate service	(Vincent et al., 2018; Nkiaka et al., 2019; Vaughan et al., 2019; Vogel et al., 2019; Nyadzi et al., 2021)	*Tanzania (ENACTS programme).* Co-production to inform malaria decisions systematically and change relationships, trust, and demand in a manner that had not been realised through previous singular and siloed approaches.
Socio-economic, and institutional barriers (limited professional mandates, financing limitations, institutional cooperation)	• Regular NMHS budgets from governments • Public-private partnerships • Supportive institutions, policy frameworks and individual capacity and agency	(Snow et al., 2016; World Bank Group, 2016; Winrock, 2018; Harvey et al., 2019; Vincent et al., 2020b)	

However, the effectiveness of co-production processes are hindered by aspects such as inequitable power relationships between different types of knowledge holders (e.g., scientists and practitioners), inequitable distribution of funding between developed country versus African partners that favours developed country partners, an inability to develop sustained trust relationships as a result of short-funding cycles, a lack of flexibility due to product-focused engagements and the scalability of co-production to enable widespread reach across Africa as the process is usually context-specific (*high confidence*) (Vincent et al., 2018; Vogel et al., 2019; Vincent et al., 2020a).

Despite these challenges, the inclusive nature of co-production has had a positive influence on the uptake of climate services into decision-making where it has been applied (Vincent et al., 2018; Vogel et al., 2019; Carter et al., 2020; Chiputwa et al., 2020) (Table 9.4; Figure 9.12) (*medium confidence*), through sustained inter/transdisciplinary relationships and capacity development (Norström et al., 2020), strategic financial investment (Section 9.13.4.1), fostering of ownership of resulting products and the combining of scientific and other knowledge systems (Carter et al., 2020; Steynor et al., 2020a). There is *high confidence* that together with improved institutional capacity building and strategic financial investment, climate services can help African stakeholders adapt to projected climate risks (Section 9.13.4.1; Figure 9.11).

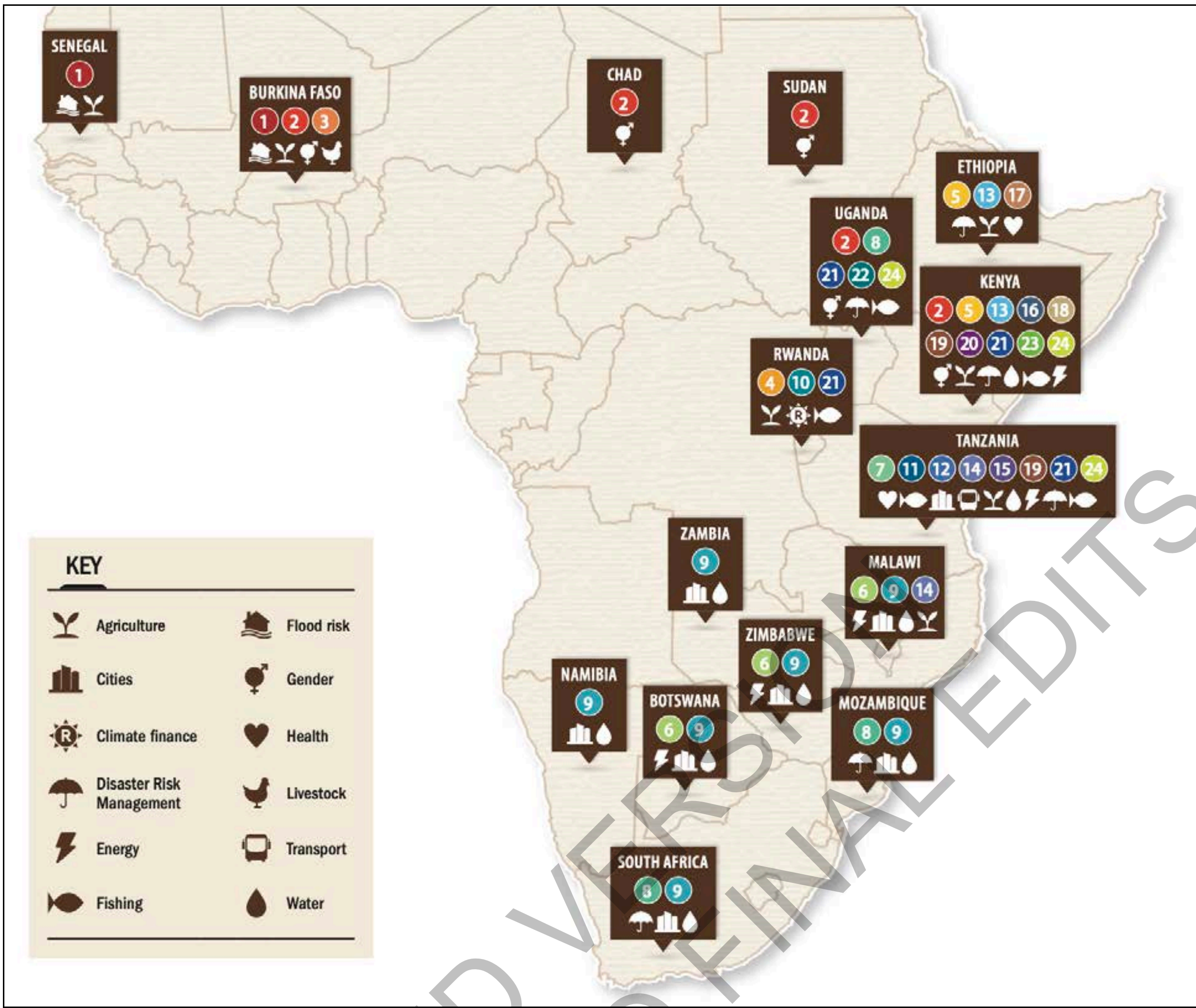


Figure 9.12: Case studies of co-production programmes, the countries they occurred in, sectors involved (icons – see key) and programmes under which the engagements occurred (numbers). Programmes listed are (1) AMMA-2050, (2,3) BRACED, (4) RCSA, (5) ALP, (6) Climate Risk Narratives, (7) ENACTS, (8) FATHUM, (9) FRACTAL, (10) FONERWA, (11) MHEWS, (12) Resilient Transport Strategic Assessment , (13) RRA, (14) UMFULA, (15) IRRP, (16) PRISE, (17) NMA ENACTS, (18) REACH, (19) DARAJA, (20) ForPAc, (21) HIWAY, (22) HyCRYSTAL, (23) SCIPEA, (24) Weather Wise. See Carter et al. (2020) for details and outcomes of each engagement. Source (Carter et al., 2020).

9.4.5.2 Community Perceptions of Climate Variability and Change

Perceptions of climate variability and change affect whether and how individuals and institutions act, and thus contribute to the success or failure of adaptation policies related to weather and climate (Silvestri et al., 2012; Arbuckle et al., 2015; Simpson et al., 2021a).

A recent Afrobarometer study covering 34 African countries found 67% of Africans perceive climate conditions for agricultural production to have worsened over time, and report drought as the main extreme weather event to have worsened in the past decade (Selormey et al., 2019). Of these participants, across all socioeconomic strata, 71% of those who were aware of the concept of climate change agreed that it needs to be stopped, but only 51% expressed confidence about their ability to make a difference. East Africans (63%) were almost twice as likely as North Africans (35%) to report that the weather for growing crops had worsened. Additionally, people engaged in occupations related to agriculture (farming, fishing or forestry) were more likely to report negative weather effects (59%) than those with other livelihoods (45%) (Selormey et al., 2019). Similar perceptions have been reported among a diversity of rural communities in many sub-Saharan African countries (Asiyanbi, 2015; Mahl et al., 2020; Simpson et al., 2021a).

Rural communities, particularly farmers, have been the most studied groups for climate change perception. They perceive the climate to be changing, most often reporting changes in rainfall variability, increased dry spells, decreases in rainfall and increased temperatures or temperature extremes, and perceive these changes to bring a range of negative socioeconomic and environmental effects (Alemayehu and Bewket, 2017; Liverpool-Tasie et al., 2020; Simpson et al., 2021a). In some cases, farmers' perceptions of changes in weather and climate frequently match climate records for decreased precipitation totals, increased drought frequency, shorter rainy season and rainy season delay and increased temperatures (Rurinda et al., 2014; Boansi et al., 2017; Ayanlade et al., 2018) (Figure 9.11), but not in all cases or not for all perceived changes, with common discrepancies in perceived lower rainfall totals (Alemayehu and Bewket, 2017; Ayal and Leal Filho, 2017; Simpson et al., 2021a).

Farming experience, access to extension services and increasing age are the most frequently cited factors positively influencing the perceptions of climate changes (Alemayehu and Bewket, 2017; Oduniyi and Tekana, 2019). Personal experience of climate-related changes and their impacts appears to be an important factor influencing perceptions through shaping negative associations, for example, experience of flash floods (Elshirbiny and Abrahamse, 2020) or direct effect on economic activity, indicating that perception is not restricted to crop farmers (Liverpool-Tasie et al., 2020). However, perception commonly has misconceptions about the causes of climate change which has implications for climate action (Elshirbiny and Abrahamse, 2020), highlighting the importance of climate change literacy.

9.4.5.3 Climate Change Literacy

Understanding the human cause of climate change has been shown to be a strong predictor of climate change risk perception (Lee et al., 2015) and a critical knowledge foundation that can affect the difference between coping responses and more informed and transformative adaptation (Oladipo, 2015; Mutandwa et al., 2019) (Figure 9.11). At a minimum, climate change literacy includes both having heard of climate change and understanding it is, at least in part, caused by people (Simpson et al., 2021a). However, large inequalities in climate change literacy exist between and within countries and communities across Africa.

The average national climate change literacy rate in Africa is only 39% (country rates range from 23-66%) (Figure 9.11). Of 394 sub-national regions surveyed by Afrobarometer, 8% (37 regions in 16 countries) have a climate change literacy rate lower than 20%, while only 2% (8 regions) score higher than 80% which is common across European countries (Simpson et al., 2021a). Striking differences exist when comparing sub-national units within countries. Climate change literacy rates in Nigeria range from 71% in Kwara to 5% in Kano, and within Botswana from 69% in Lobatse to only 6% in Kweneng West (Simpson et al., 2021a). Education is the strongest positive predictor of climate change literacy, particularly tertiary education, but poverty decreases climate change literacy and climate change literacy rates average 12.8% lower for women than men (Simpson et al., 2021a).

As the identified drivers of climate change literacy overlap with broader developmental challenges on the continent, policies targeting these predictors can potentially yield co-benefits for both climate change adaptation as well as progress towards SDGs, particularly education and gender equality (Simpson et al., 2021a). Progress towards greater climate change literacy affords a concrete opportunity to mainstream climate change within core national and sub-national developmental agendas in Africa towards more climate-resilient development pathways. Synergies with climate services can also overcome gendered deficits, for example, although women are generally less climate change aware and more vulnerable to climate change than men in Africa, they are generally more likely to adopt climate-resilient crops when they are climate change aware and have exposure to extension services (Acevedo et al., 2020; Simpson et al., 2021a).

[START BOX 9.1 HERE]

Box 9.1: Vulnerability Synthesis

Vulnerability in Africa is socially, culturally and geographically differentiated among climatic regions, countries and local communities, with climate change impacting the health, livelihoods and food security of different groups to different extents (Gan et al., 2016; Onyango et al., 2016a; Gumucio et al., 2020). This synthesis emphasises intersectional diversity within vulnerable groups as well as their position within dynamic social and cultural contexts (Wisner, 2016; Kuran et al., 2020), and highlights the differential impacts of climate change and restricted adaptation options available to vulnerable groups across African countries (see also Cross-Chapter Box GENDER in Chapter 18).

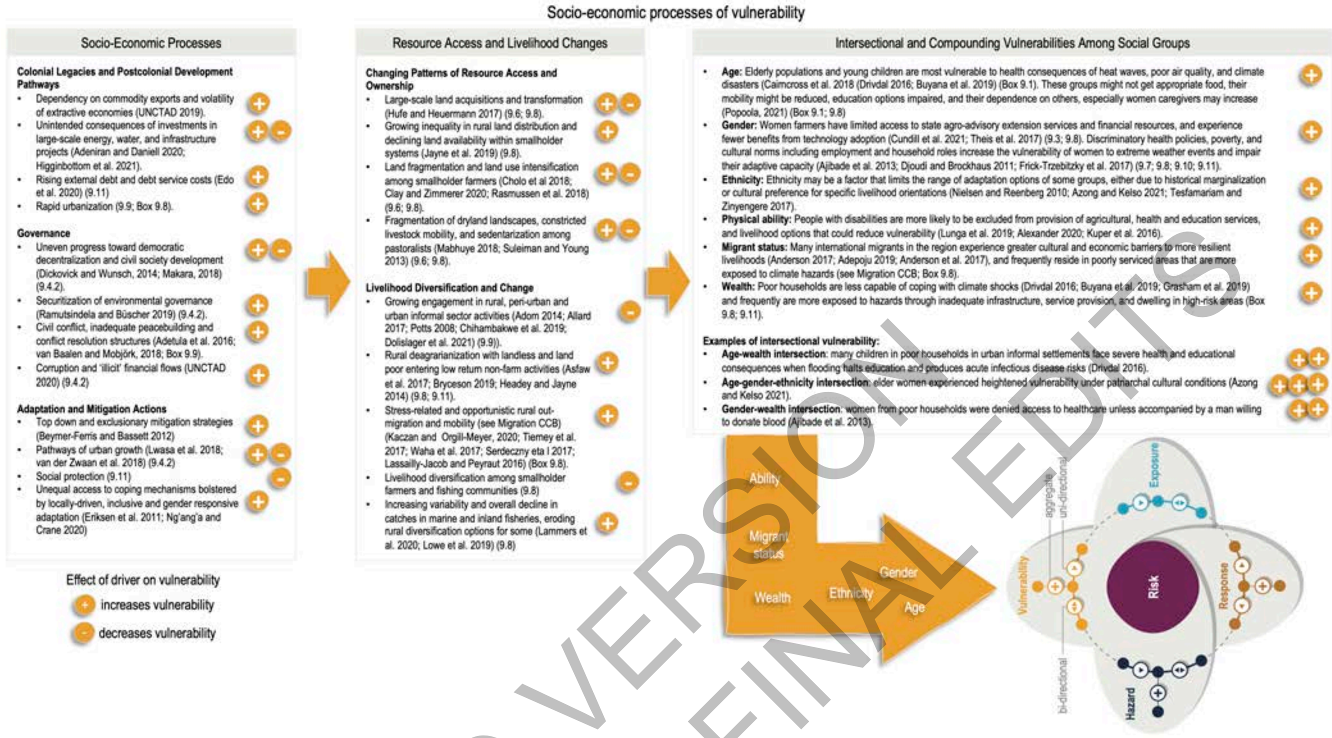


Figure Box 9.1.1: Factors contributing to the progression of vulnerability in African contexts considering their socioeconomic processes, resource access and livelihood changes, and intersectional vulnerability among social groups. Figure reflects a synthesis of vulnerability across sections of this chapter and highlights the compounding interactions of multiple dimensions of vulnerability (Potts, 2008; Nielsen and Reenberg, 2010; Akresh et al., 2011; Eriksen et al., 2011; Beymer-Farris and Bassett, 2012; Davis et al., 2012; Adom, 2014; Akello, 2014; Dickovick, 2014; Headey and Jayne, 2014; Otzelberger, 2014; Conteh, 2015; Huntjens and Nachbar, 2015; Spencer, 2015; Adetula et al., 2016; Djoudi et al., 2016; Kuper et al., 2016; Stark and Landis, 2016; Allard, 2017; Anderson, 2017; Asfaw et al., 2017; Hufe and Heuermann, 2017; Hulme, 2017; Paul and wa Gĩthĩnji, 2017; Rao et al., 2017; Serdeczny et al., 2017; Tesfamariam and Zinyengere, 2017; Tierney et al., 2017; Waha et al., 2017; Chihambakwe et al., 2018; Cholo et al., 2018; Jenkins et al., 2018; Keahey, 2018; Lwasa et al., 2018; Makara, 2018; Nyasimi et al., 2018; Petesch et al., 2018; Schuman et al., 2018; Theis et al., 2018; van Baalen and Mobjörk, 2018; van der Zwaan et al., 2018; Adepoju, 2019; Adzawla et al., 2019b; Bryceson, 2019; Grasham et al., 2019; Jayne et al., 2019a; Lowe et al., 2019; Lunga et al., 2019; OGAR and Bassey, 2019; Onwutuebe, 2019; Ramutsindela and Büscher, 2019; Sulieman and Young, 2019; Torabi and Noori, 2019; Adeniran and Daniell, 2020; Alexander, 2020; Clay and Zimmerer, 2020; Devonald et al., 2020; Dolislager et al., 2020; Edo et al., 2020; Kaczan and Orgill-Meyer, 2020; Lammers et al., 2020; World Bank, 2020b; Asiama et al., 2021; Azong and Kelso, 2021; Birgen, 2021; Paalo and Issifu, 2021).

Vulnerability and exposure to the impacts of climate change are complex and affected by multiple, interacting non-climatic processes, which together influence risk including socioeconomic processes (Lwasa et al., 2018; UNCTAD, 2020), resource access and livelihood changes (Jayne et al., 2019b), and intersectional vulnerability among social groups (Rao et al., 2020) (Figure Box 9.1.1). Socioeconomic processes encompass broader social, economic and governance trends, such as expanded investment in large energy and transportation infrastructure projects (Adeniran and Daniell, 2020), rising external debt (Edo et al., 2020), changing role of the state in social development (Dickovick, 2014), environmental management (Ramutsindela and Büscher, 2019) and conflict, as well as those emanating from climate change mitigation and adaptation projects (Beymer-Farris and Bassett, 2012; van Baalen and Mobjörk, 2018; Simpson et al., 2021b). These macro trends shape both urban and rural livelihoods, including the growing diversification of rural livelihoods through engagement in the informal sector and other non-farm activities, and are mediated by complex and intersecting factors like gender, ethnicity, class, age, disability and other dimensions of social status that influence access to resources (Luo et al., 2019). Research increasingly highlights the intersectionality of multiple dimensions of social identity and status that are associated with greater susceptibility to loss and harm (Caparoci Nogueira et al., 2018; Li et al., 2018).

Arid and semi-arid countries in the Sahelian belt and the greater Horn of Africa are often identified as the most vulnerable regions on the continent (Closset et al., 2017; Serdeczny et al., 2017). Particularly vulnerable groups include pastoralists (Wangui, 2018; Ayanlade and Ojebisi, 2019), fishing communities (Belhabib et al., 2016; Muringai et al., 2019a), small-scale farmers (Ayanlade et al., 2017; Mogomotsi et al., 2020) (see Section 9.8.1) and residents of formal and informal urban settlements (see Section 9.9.2). Research has identified key macro drivers as well as the multiple dimensions of social status that mediate differential vulnerability in different African contexts. For example, the contemporary vulnerability of small-scale rural producers in semi-arid northern Ghana has been shaped by colonial economic transformations (Ahmed et al., 2016), more recent neoliberal reforms reducing state support (Fieldman, 2011) and the disruption of local food systems due to increasing grain imports (Nyantakyi-Frimpong and Bezner-Kerr, 2015). Age interacts with other dimensions of social status, shaping differential vulnerability in several ways. Projected increases in mean temperatures and longer and more intense heat waves (Figure Box 9.1.1) may increase health risks for children and elderly populations by increasing risks associated with heat stress (Bangira et al., 2015; Cairncross et al., 2018). Temperature extremes are associated with increased risk of mortality in Ghana, Burkina Faso, Kenya and South Africa, with greatest increases among children and the elderly (Bangira et al., 2015; Amegah et al., 2016; Omonijo, 2017; Wiru et al., 2019) (see Section 9.10.2.3.1).

Rural African women are often disadvantaged by traditional, patriarchal decision-making processes and lack of access to land – issues compounded by kinship systems (that, is matrilineal or patrilineal), migrant status, age, type of household, livelihood orientation and disability in determining their adaptive options (Ahmed et al., 2016) (sees Section 9.8.1 and 9.11.1.2; Box 9.8). Differential agricultural productivity between men and women is about 20–30% or more in dryland regions of Ethiopia and Nigeria (Ghanem, 2011) and challenges women's ability to adapt to climate change. Limited access to agricultural resources and limited benefits from agricultural policies, compounded by other social and cultural factors, make women more vulnerable to climatic risks (Shukla et al., 2021). Kinship systems can contribute to their vulnerability and capacity to adapt. Women in matrilineal systems have greater bargaining power and have access to more resources than those in patrilineal systems (Chigbu, 2019; Robinson and Gottlieb, 2021) (see Sections 9.8.1 and 9.11.1.2).

Knowledge Gaps and Recommendations

The differential impacts of climate change on and adaptation options available to vulnerable groups in Africa are a critical knowledge gap. More research is needed to examine the intersection of different dimensions of social status on climate change vulnerability in Africa (Thompson-Hall et al., 2016; Oluwatimilehin and Ayanlade, 2021). More analysis of vulnerability based on gender and other social and cultural factors is needed to fully understand the impacts of climate change, the interaction of divergent adaptive strategies, as well as the development of targeted adaptation and mitigation strategies, for example, for women in patrilineal kinship systems, people living with disabilities, youth, girls and the elderly. Finally, there is an urgent need to build capacity among those conducting vulnerability assessments, so that they are familiar with this intersectionality lens.

Additional information and capacity development through education and early warning systems could enhance vulnerable groups' ability to cope and adapt their livelihoods (Jaka and Shava, 2018). However, some groups of people may struggle to translate information into actual changes (Makate et al., 2019; McOmber et al., 2019). Lack of access to assets and social networks, for example, among older populations, are critical limitations to locally-driven or autonomous adaptation and limit potential benefits from planned adaptation actions (e.g., adoption of agricultural technologies or effective use of early warning systems). There is an urgent need for societal and political change to realise potential benefits for these vulnerable groups in the long term (Nyasimi et al., 2018). There is a need for gender-sensitive climate change policies in many African countries and gender-responsive policies, implementation plans and budgets for all local-level initiatives (Wrigley-Asante et al., 2019).

[END BOX 9.1 HERE]

9.5 Observed and Projected Climate Change

This section assesses observed and projected climate change over Africa. In Working Group I of the IPCC AR6 (WGI), four chapters make regional assessments of observed and projected climate change (Doblas-Reyes et al., 2021; Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021), which facilitates a more nuanced assessment in this section of climate and ocean phenomena that impact African systems.

9.5.1 Climate Hazards in Africa

Human-caused temperature increases are detected across Africa and many regions have warmed more rapidly than the global average (Figure 9.13a) (Ranasinghe et al., 2021) and a signal of increased annual heatwave frequency has already emerged from the background natural variability over the whole continent (Engdaw et al., 2021) (Figure 9.14). However, detection of statistically significant rainfall trends is evident in only a few regions (Figure 9.13b), and in some regions different observed precipitation datasets disagree on the direction of rainfall trends (Panitz et al., 2013; Sylla et al., 2013; Contractor et al., 2020). The uncertainty of observed rainfall trends results from a number of sources, including high interannual and decadal rainfall variability, different methodologies used in developing rainfall products and a lack of and poor quality of rainfall station data (Figure 9.15) (Gutiérrez et al., 2021).

With increased greenhouse gas emissions, mean temperature is projected to increase over the whole continent, as are temperature extremes over most of the continent (Figure 9.16a,b). Increased mean annual rainfall is projected over the eastern Sahel, eastern East Africa and Central Africa (Figures 9.16c and 9.14). In contrast, reduced mean annual rainfall and increased drought (meteorological and agricultural) are projected over southwestern Southern Africa and coastal North Africa, with drought in part as a result of increasing atmospheric evaporative demand due to higher temperatures (Figure 9.16e) (Ukkola et al., 2020; Ranasinghe et al., 2021; Seneviratne et al., 2021). The frequency and intensity of heavy precipitation are projected to increase across most of Africa, except northern and southwestern Africa (Figures 9.16d and 9.14).

Most African countries are expected to experience high temperatures unprecedented in their recent history earlier in this century than generally wealthier, higher latitude countries (*high confidence*). As low latitudes have lower internal climate variability (e.g. low seasonality), low-latitude African countries are projected to have their populations exposed to large increases in frequency of daily temperature extremes (hotter than 99.9% of their historical records) earlier in the 21st century compared to generally wealthier nations at higher latitudes (Harrington et al., 2016; Chen et al., 2021; Doblas-Reyes et al., 2021; Gutiérrez et al., 2021). Although higher warming rates are projected over high latitudes during the first half of this century, societies and environments in low-latitude, low-income countries are projected to become exposed to unprecedented climates before those in high latitude, developed countries (Frame et al., 2017; Harrington et al., 2017; Gutiérrez et al., 2021). For example, beyond 2050, in Central Africa and coastal West Africa 10 months of every year will be hotter than any month in the period 1950–2000 under a high emissions scenario (RCP8.5) (Harrington et al., 2017; Gutiérrez et al., 2021). Ambitious, near-term mitigation will provide the largest reductions in exposure to unprecedented high temperatures for populations in low-latitude regions, such as across tropical Africa (Harrington et al., 2016; Frame et al., 2017).

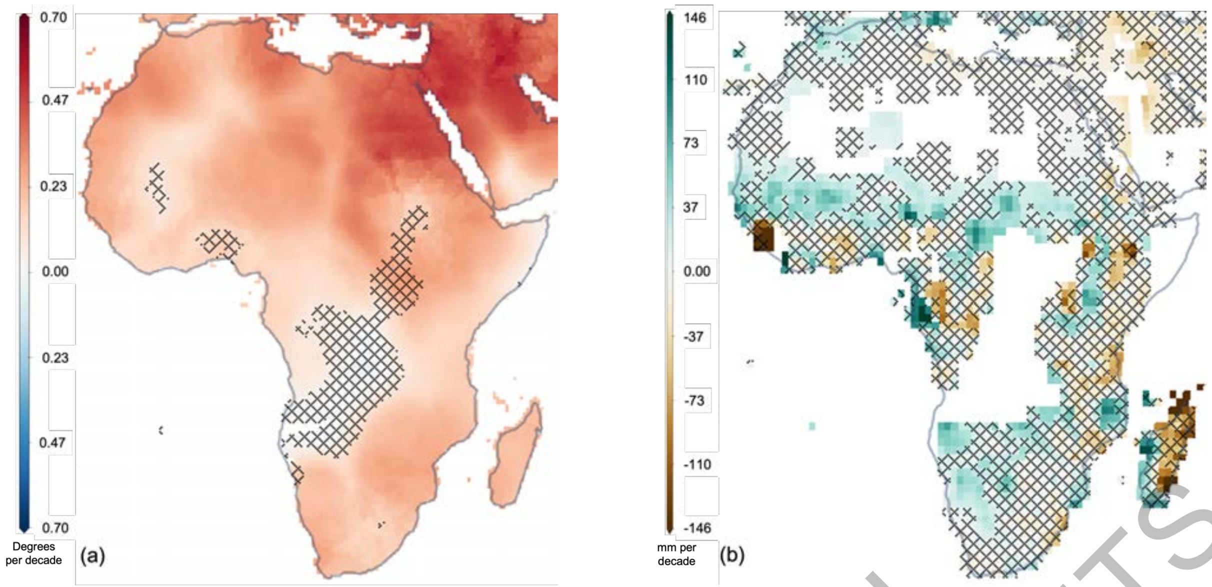


Figure 9.13: Mean observed trends calculated for the common 1980-2015 period in (a) 2-meter temperature in degrees Celsius per decade and (b) precipitation in millimetres per decade with respect to the climatological mean over this period. The Climate Research Unit Time Series data (CRU TS) are used to compute temperature trends and the Global Precipitation Climatology Centre data (GPCC) precipitation trends. Regions with no 'x' hatching indicate statistically significant trends over this period. The figures are derived from (Gutiérrez et al., 2021).

9.5.1.1 Station Data Limitations

Sustained station observation networks (Figure 9.15) are essential for the long-term analysis of local and regional climate trends, including for temperature and rainfall, the calibration of satellite-derived climate products, development of gridded climate datasets using interpolated and blended station-satellite products that form the baseline from which climate change departures are measured, development and running of early warning systems, climate projection and impact studies and extreme event attribution studies (Harrison et al., 2019; Otto et al., 2020). However, production of salient climate information in Africa is hindered by limited availability of and access to weather and climate data, especially in Central and North Africa (Figure 9.15) (Coulibaly et al., 2017; Hansen et al., 2019a). Existing weather infrastructure remains suboptimal for development of reliable early warning systems (Africa Adaptation Initiative, 2018; Krell et al., 2021). For example, it is estimated only 10% of ground-based observation networks are in Africa, and that 54% of Africa's surface weather stations cannot capture data accurately (Africa Adaptation Initiative, 2018; World Bank, 2020d). Some programmes are trying to address this issue, including the trans-African hydro-meteorological observatory (van de Giesen et al., 2014), the West African Science Service Centre on Climate Change and Adaptive Land Management (WASCAL) (Salack et al., 2019), the Southern African Science Service Centre for Climate Change, Adaptive Land Management (SASSCAL) (Kaspar et al., 2015) and AMMA-CATCH (Galle et al., 2018). However, the sustainability of observation networks beyond the life of these programmes is uncertain as many African National Meteorological and Hydrology Services experience structural, financial and technical barriers to maintaining these systems (Section 9.4.5).

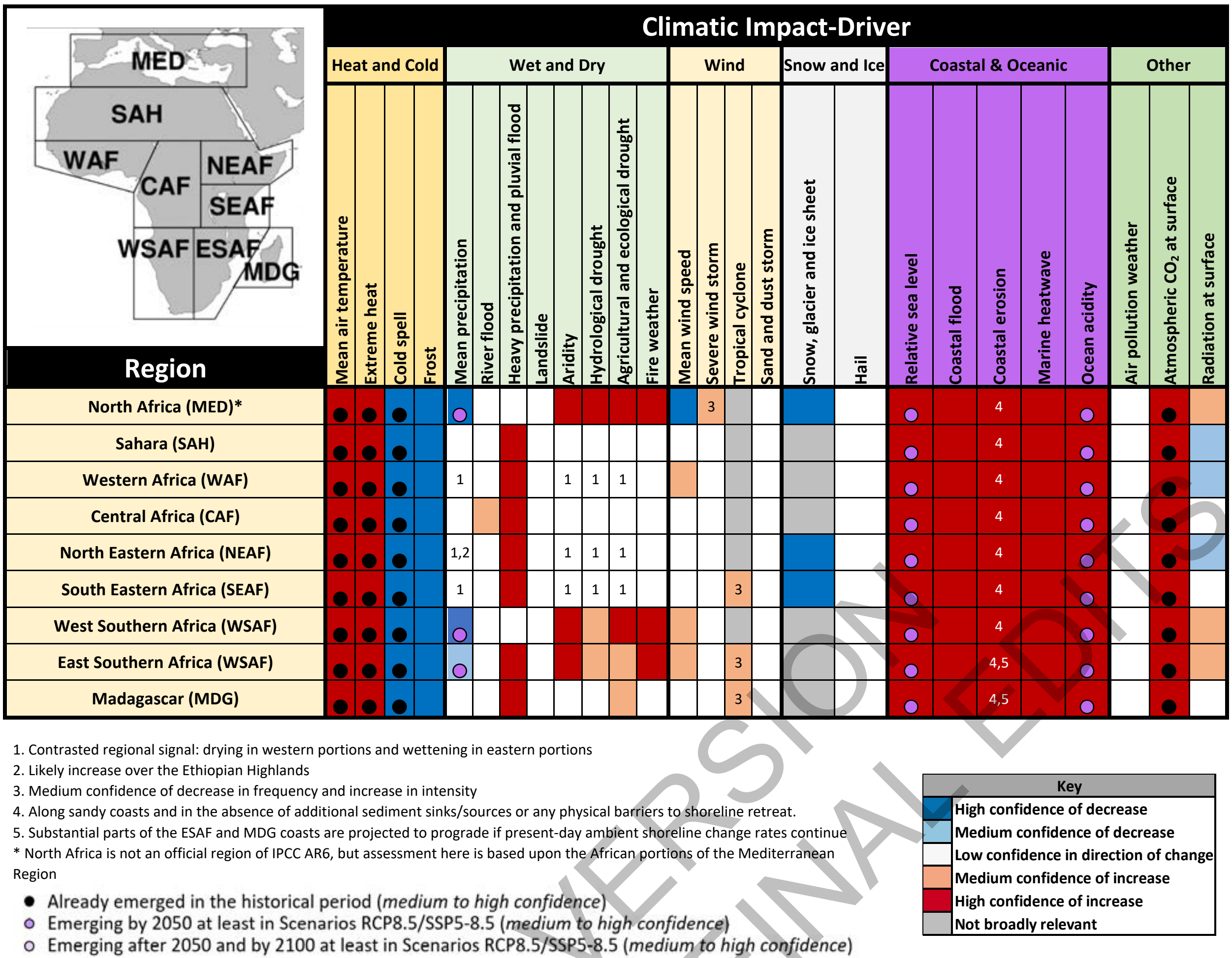


Figure 9.14: Summary of confidence in direction of projected change in climatic impact-drivers (CIDs) in Africa, representing their aggregate characteristic changes for mid-century for medium emission scenarios RCP4.5, SSP3–4.5, SRES A1B, or higher emissions scenarios (e.g., RCP8.5, SSP5–RCP8.5), within each AR6 WGI region (inset map) approximately corresponding to global warming levels between 2°C and 2.4°C (for CIDs that are independent of sea-level rise). CIDs are drivers of impacts that are of climatic origin (that is, physical climate system conditions including means and extremes) that affect an element of society or ecosystems. The table also includes the assessment of observed or projected time-of-emergence of the CID change signal from the natural inter-annual variability if found with at least *medium confidence* (dots). Emergence of a climate change signal or trend refers to when a change in climate (the 'signal') becomes larger than the amplitude of natural or internal variations (the 'noise'). The figure is a modified version of Table 12.3 in Chapter 12 (Ranasinghe et al., 2021), please see this chapter for definitions of the various climate impact drivers and the basis for confidence levels of the assessment. Please note these WGI regions do not directly correspond to the regionalisation in this chapter nor do we assess climate risks for Madagascar.

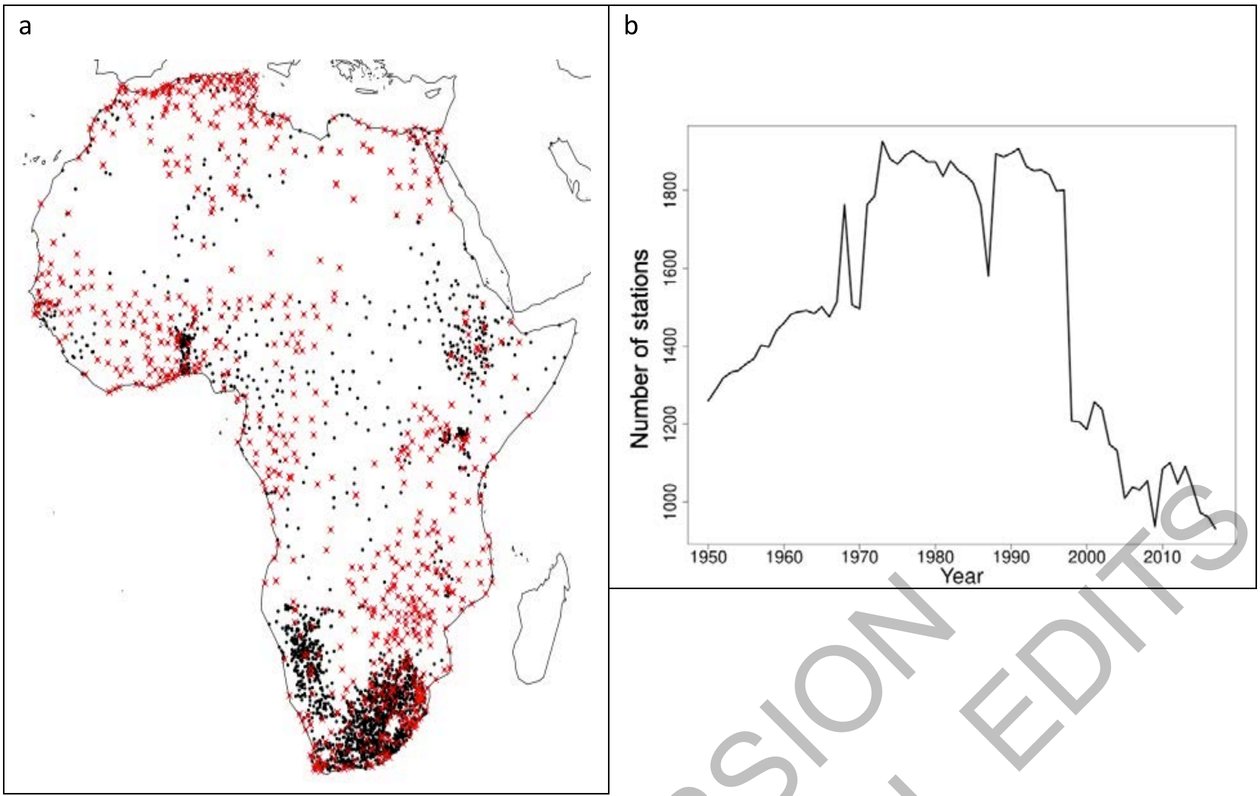


Figure 9.15: Large regions of Africa lack regularly reporting and quality-controlled weather station data. Stations in Africa with quality-controlled station data used in developing the Rainfall Estimates on a Gridded Network (REGEN) interpolated rainfall product (Harrison et al., 2019). Panel (a) provides a spatial representation of stations across the continent since 1950 as black dots and red crosses, where red crosses represent stations that were still active in 2017. Panel (b) demonstrates the decline in operational stations or stations with quality-controlled data since *circa* 1998, which is largely a function of declining networks in a subset of countries. Figure is derived from (Contractor et al., 2020).

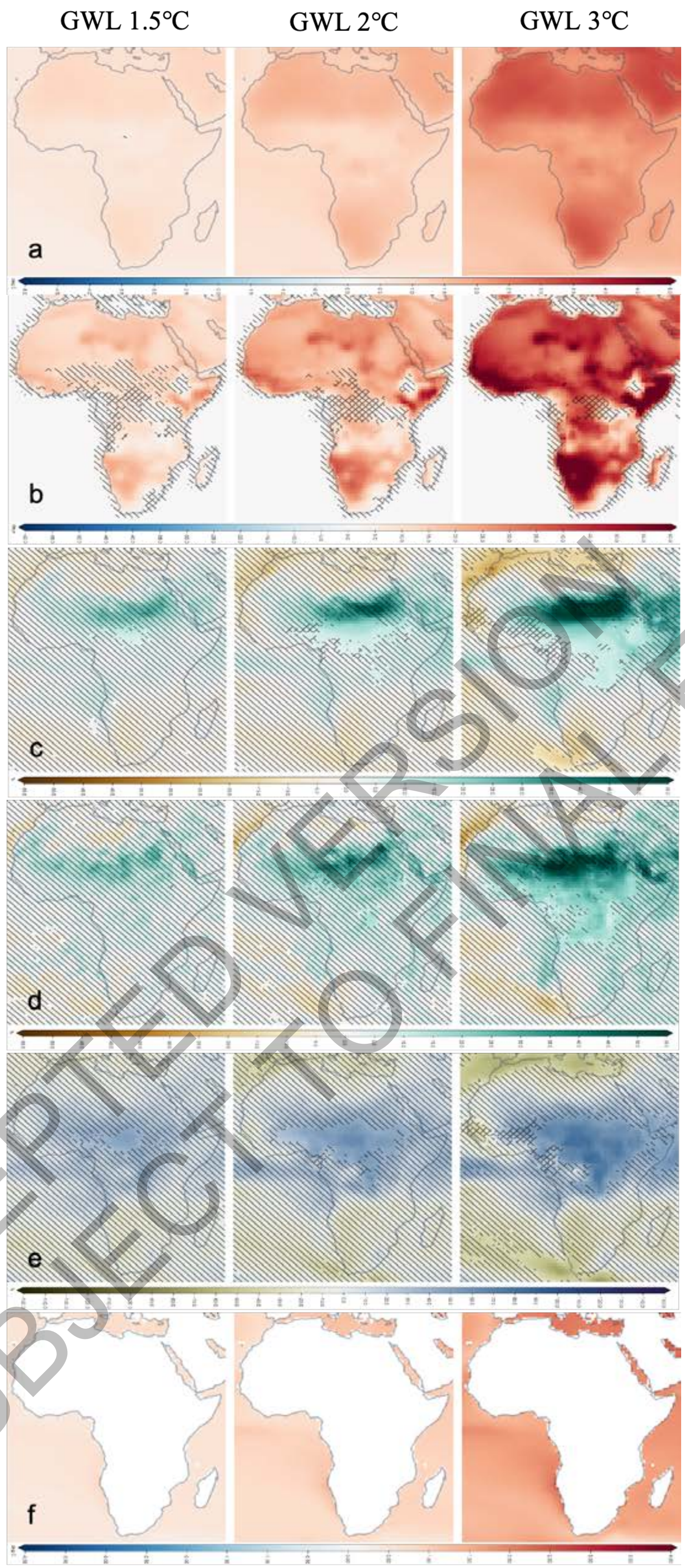


Figure 9.16: Projected changes of climate variables and hazards (relative to 1995–2014 average) at 1.5°C, 2°C and 3°C of global warming above pre-industrial (1850–1900). Rows are (a) Increase in mean annual temperature; (b) Increase in number of days per year above 35 °C; (c) Change in average annual rainfall (%); (d) Change in heavy precipitation represented by maximum 5-day precipitation (%); (e) Change in drought represented as the six-month standardized precipitation index (%). Negative changes indicate areas where drought frequency, intensity and/or duration is projected to increase. Positive changes show the opposite; (f) Increase in mean annual sea surface temperature (°C). All figures are derived from the WGI Interactive Atlas and show results from between 26 to 33 CMIP6 global climate models, depending on the climate variable. CMIP6 models include improved representations of physical, biological and chemical processes as well as higher spatial resolutions compared to previous CMIP5 models (WGI CH3). Three

categories of trend robustness are shown in the projection figures: (1) No hatching indicates a projected change is robust and likely greater than natural climate variability (that is, ≥66% of models show change greater than natural variability, and ≥80% of all models agree on sign of change); (2) Diagonal lines (\) indicate no robust change (<66% of models show change greater than natural variability); (3) Crossed lines (X) indicate conflicting signals where at least 66% of the models show change greater than natural variability, but <80% of all models agree on direction of change (Gutiérrez et al., 2021).

9.5.2 North Africa

9.5.2.1 Temperature

Observations

Mean and seasonal temperatures have increased at twice the global rate over most regions in North Africa due to anthropogenic climate change (Ranasinghe et al., 2021) (Figures 9.13a and 9.14) (*high confidence).* Increasing temperature trends are particularly strong since the 1970s (between 0.2°C/decade and 0.4°C/decade), especially in the summer (Tanarhte et al., 2012; Donat et al., 2014a; Lelieveld et al., 2016). Similar warming signals have been observed since the mid-1960s over the Sahara and the Sahel (Fontaine et al., 2013; Moron et al., 2016). Trends in mean maximum (TX) and minimum (TN) temperatures range between +2°C and +3°C per century over North Africa, and the frequencies of hot days (TX >90th percentile, TX90p) and tropical nights (TN >20°C), as well as the frequencies of warm days and nights, roughly follow these mean TX and TN trends (Fontaine et al., 2013; Moron et al., 2016; Ranasinghe et al., 2021; Seneviratne et al., 2021). Warm spell duration has increased in many North African countries (Donat et al., 2014a; Filahi et al., 2016; Lelieveld et al., 2016; Nashwan et al., 2018) and heatwave magnitude and spatial extent have increased across North Africa since 1980, with an increase in the number of events since 2000 that is beyond the level of natural climate variability (Russo et al., 2016; Ceccherini et al., 2017; Engdaw et al., 2021).

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in North Africa are projected to be on average, 0.9°C, 1.5°C and 2.6°C warmer than the 1994–2005 average respectively (Figure 9.16a). Warming is projected to be stronger in summer than winter (Lelieveld et al., 2016; Dosio, 2017). The number of hot days is *likely* to increase by up to 90% by the end of the century under RCP8.5 (global warming level [GWL] 4.4°C) (Gutiérrez et al., 2021; Ranasinghe et al., 2021) and hot nights and the duration of warm spells to increase in the first half of the 21st century in both intermediate and high emission scenarios (Patricola and Cook, 2010; Vizy and Cook, 2012; Lelieveld et al., 2016; Dosio, 2017; Filahi et al., 2017). Heatwaves are projected to become more frequent and intense even at 1.5°C of global warming (Gutiérrez et al., 2021; Ranasinghe et al., 2021). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 4–6 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 9–10 times more heatwaves for emission reduction pledges, limiting global warming to 2.4°C (Thiery et al., 2021).

9.5.2.2 Precipitation

Observations

Mean annual precipitation decreased over most of North Africa between 1971–2000 (Donat et al., 2014a; Hertig et al., 2014; Nicholson et al., 2018; Zittis, 2018), with a gradual recovery to normal or wetter conditions in Algeria and Tunisia since 2000 and over Morocco since 2008 (Nouaceur and Murărescu, 2016). Since the 1960s days with more than 10 mm of rainfall have decreased and the number of consecutive dry days have increased in the eastern parts of North Africa, while in the western parts of North Africa heavy rainfall and flooding has increased (Donat et al., 2014a). Aridity, the ratio of potential evaporation to precipitation, has increased over the Mediterranean and North Africa due to significant decreases in precipitation (Greve et al., 2019).

Projections

Mean annual precipitation is projected to decrease in North Africa at warming levels of 2°C and higher (*high confidence*) with the most pronounced decreases in the northwestern parts (Schilling et al., 2012; Filahi et al., 2017; Barcikowska et al., 2018; Ranasinghe et al., 2021) (Figures 9.14 and 9.16c). Meteorological drought over Mediterranean North Africa in CMIP5 and CMIP6 models are projected to increase in duration from approximately 2 months during 1950–2014 to approximately 4 months in the period 2050–2100 under RCP8.5 and SSP5-85 (Ukkola et al., 2020). Extreme rainfall (monthly maximum 1-day rainfall – RX1day) in the region is projected to decrease (Donat et al., 2019).

During 1984–2012, North Africa experienced a decreasing dust trend with North African dust explaining more than 60% of global dust variations (Shao et al., 2013). Dust loadings and related air pollution hazards (from fine particles that affect health) are projected to decrease in many regions of the Sahara as a result of decreased wind speeds (Evan et al., 2016; Ranasinghe et al., 2021).

9.5.3 West Africa

9.5.3.1 Temperature

Observations

Observed mean annual and seasonal temperatures have increased 1–3°C since the mid-1970s with the highest increases in the Sahara and Sahel (Cook and Vizy, 2015; Lelieveld et al., 2016; Dosio, 2017; Nikiema et al., 2017; Gutiérrez et al., 2021; Ranasinghe et al., 2021) (Figure 9.13a) and positive trends in mean annual maximum (TX) and minimum (TN) of 0.16°C and 0.28°C per decade, respectively (Mouhamed et al., 2013; Moron et al., 2016; Russo et al., 2016; Barry et al., 2018). The frequency of very hot days (TX >35°C) and tropical nights has increased by 1–9 days and 4–13 nights per decade between 1961–2014 (Moron et al 2016), and cold nights have become less frequent (Fontaine et al., 2013; Mouhamed et al., 2013; Barry et al., 2018). In the 21st century, heatwaves have become hotter, longer and more extended compared to the last two decades of the 20th century (Mouhamed et al., 2013; Moron et al., 2016; Russo et al., 2016; Barbier et al., 2018).

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in West Africa are projected to be on average, 0.6°C, 1.1°C and 2.1°C warmer than the 1994–2005 average respectively (Figure 9.16a). Under mid- and high-emission scenarios end of century summer temperatures are projected to increase by 2°C and 5°C, respectively (Sylla et al., 2015a; Russo et al., 2016; Dosio, 2017). The annual number of hot days is projected to increase at all global warming levels with larger increases at higher warming levels (Figure 9.16b). By 2060 the frequency of hot nights is projected to be almost double the 1981–2010 average at GWL 2°C (Dosio, 2017; Bathiany et al., 2018; Gutiérrez et al., 2021; Ranasinghe et al., 2021). Heatwave frequency and intensity are projected to increase under all scenarios, but limiting global warming to 1.5°C leads to a decreased heatwave magnitude (–35%) and frequency (–37%) compared to 2°C global warming (Dosio, 2017; Weber et al., 2018; Nangombe et al., 2019). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 4–6 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 7–9 times more heatwaves at GWL 2.4°C (Thiery et al., 2021).

The number of dangerous heat days (TX >40.6°C) is projected to increase from approximately 60 per year in 1985–2005 to approximately 110, 130 and 140 under RCPs 2.6, 4.5 and 8.5, respectively, in the 2060s and to 105, 145 and 196 in the 2090s (Rohat et al., 2019). Over tropical West Africa, heat-related mortality risk through increased heat and humidity is 6–9 times higher than the 1950–2005 average at GWL 2°C, 8–15 times at GWL 2.65°C and 15–30 times at GWL 4.12°C (Ahmadalipour and Moradkhani, 2018) (Coffel et al., 2018). The number of potentially lethal heat days per year is projected to increase from <50 during 1995–2005 to 50–150 at GWL 1.6°C, 100–250 at GWL 2.5°C and 250–350 at GWL 4.4°C, with highest increases in coastal regions (Mora et al., 2017). Increasing urbanization concentrates this exposure in cities, such as Lagos, Niamey, Kano and Dakar (Coffel et al., 2018; Rohat et al., 2019) (Section 9.9.3.1).

9.5.3.2 Precipitation

Observations

Negative trends in rainfall accompanied by increased rainfall variability were observed between 1960s–1980s over West Africa (Nicholson et al., 2018; Thomas and Nigam, 2018), caused by a combination of anthropogenic aerosols and greenhouse gases emitted between 1950s–1980s (Booth et al., 2012; Wang et al., 2016; Giannini and Kaplan, 2019; Douville et al., 2021). Declining rainfall trends ended by 1990 due to the growing influence of greenhouse gasses and reduced cooling effect of aerosol emissions, with a trend to wetter conditions emerging in the mid-1990s accompanied by more intense, but fewer precipitation events (Sanogo et al., 2015; Sylla et al., 2016; Kennedy et al., 2017; Barry et al., 2018; Bichet and Diedhiou, 2018a; Bichet and Diedhiou, 2018b; Thomas and Nigam, 2018). A shift to a later onset and end of the West African monsoon is also reported in West Africa and Sahel (*low confidence*) (Chen et al., 2021; Ranasinghe et al., 2021). Between 1981–2014 the Gulf of Guinea and the Sahel have experienced more intense precipitation events (Panthou et al., 2014; Bichet and Diedhiou, 2018a; Panthou et al., 2018) and the frequency of mesoscale storms has tripled (Taylor et al., 2017; Callo-Concha, 2018). Extreme heavy precipitation indices show increasing trends from 1981–2010 (Barry et al., 2018), increasing high flow events in large Sahelian rivers as well as small to mesoscale catchments leading to pluvial and riverine flooding (Douville et al., 2021). Meteorological, agricultural and hydrological drought in the region has increased in frequency since the 1950s (*medium confidence*) (Seneviratne et al., 2021).

Projections

West African rainfall projections show a gradient of precipitation decrease in the west and increase in the east (*medium confidence*) (Dosio et al., 2021; Gutiérrez et al., 2021; Ranasinghe et al., 2021) (Figure 9.14). This pattern is evident at 1.5°C of global warming and the magnitude of change increases at higher warming levels (Schleussner et al., 2016b; Kumi and Abiodun, 2018; Sylla et al., 2018) (Figure 9.16c). A reduction in length of the rainy season is projected over the western Sahel through delayed rainfall onset by 4 to 6 days at global warming levels of 1.5°C and 2°C (Kumi and Abiodun, 2018; Douville et al., 2021; Gutiérrez et al., 2021). Although there are uncertainties in rainfall projections over the Sahel (Klutse et al., 2018; Gutiérrez et al., 2021), CMIP6 models project monsoon rainfall amounts to increase by approximately 2.9% per degree of warming (Jin et al., 2020; Wang et al., 2020a), therefore, at higher levels of warming and towards the end of the century, a wetter monsoon is projected in the eastern Sahel (*medium confidence*).

The frequency and intensity of extremely heavy precipitation are projected to increase under mid- and high-emission scenarios (Sylla et al., 2015b; Diallo et al., 2016; Akinsanola and Zhou, 2019; Giorgi et al., 2019; Dosio et al., 2021; Li et al., 2021; Seneviratne et al., 2021) (Figure 9.16d). However, heavy rainfall statistics from global and regional climate models may be conservative as very-high-resolution, convection-permitting climate models simulate more intense rainfall than these models (Stratton et al., 2018; Berthou et al., 2019; Han et al., 2019; Kendon et al., 2019).

At 2°C global warming, West Africa is projected to experience a drier, more drought-prone and arid climate, especially in the last decades of the 21st century (Sylla et al., 2016; Zhao and Dai, 2016; Klutse et al., 2018). The duration of meteorological drought duration is projected to increase from approximately 2 months during 1950–2014 to approximately 4 months in the period 2050–2100 under RCP8.5 and SSP5–8.5 (Ukkola et al., 2020). Increased intensity of heavy precipitation events combined with increasing drought occurrences will substantially increase the cumulative hydroclimatic stress on populations in West Africa during the late 21st century (Giorgi et al., 2019).

9.5.4 Central Africa

9.5.4.1 Temperature

Observations

Mean annual temperature across Central Africa has increased by 0.75°C–1.2°C since 1960 (Aloysius et al., 2016; Gutiérrez et al., 2021). The number of hot days, heatwaves and heatwave days increased between 1979–2016 (Hu et al., 2019) and cold extremes have decreased (Aguilar et al., 2009; Seneviratne et al., 2021) (Figure 9.14). Uncertainties associated with the poor ground-based observation networks in the region and associated observational uncertainties (Section 9.5.1.1) result in an assessment of *medium confidence* in an increase in the number of heat extremes over the region.

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in Central Africa are projected to be on average, 0.6°C, 1.1°C and 2.1°C warmer than the 1994–2005 average, respectively (Figure 9.16a). By the end of the century (2070–2099), warming of 2°C (RCP4.5) to 4°C (RCP8.5) is projected over the region (Aloysius et al., 2016; Fotso-Nguemo et al., 2017; Diedhiou et al., 2018; Mba et al., 2018; Tamoffo et al., 2019) and the number of days with maximum temperature exceeding 35°C is projected to increase by 150 days or more at GWL 4.4°C (Gutiérrez et al., 2021; Ranasinghe et al., 2021). According to CMIP6 and CORDEX models, the annual average number of days with maximum temperature exceeding 35°C will increase between 14–27 days at GWL 2°C and 33–59 days at GWL 3°C above the 61–63 days for 1995–2014 (Gutiérrez et al., 2021; Ranasinghe et al., 2021) (*high confidence*). The number of heatwave days is projected to increase and extreme heatwave events may last longer than 180 days at GWL 4.1°C (Dosio, 2017; Weber et al., 2018; Spinoni et al., 2019). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 6–8 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 7–9 times more heatwaves at GWL 2.4°C (Thiery et al., 2021). The number of potentially lethal heat days per year is projected to increase from <50 during 1995–2005 to 50–75 at GWL 1.6°C, 100–150 at GWL 2.5°C and 200–350 at GWL 4.4°C (Mora et al., 2017).

9.5.4.2 Precipitation

Observations

The severe lack of station data over the region leads to large uncertainty in the estimation of observed rainfall trends and *low confidence* in changes in extreme rainfall (Figure 9.13b) (Creese and Washington, 2018; Gutiérrez et al., 2021; Ranasinghe et al., 2021). There is some evidence of drying since the mid-20th century through decreased mean rainfall and increased precipitation deficits (Gutiérrez et al., 2021), as well as increases in meteorological, agricultural and ecological drought (*medium confidence*) (Seneviratne et al., 2021). However, there is spatial heterogeneity in annual rainfall trends between 1983–2010 ranging from –10 to +39 mm per year (Maidment et al., 2015), with a decline in mean seasonal April–June precipitation of –69 mm per year in most regions except in the northwest (Zhou et al., 2014; Hua et al., 2016; Klotter et al., 2018; Hu et al., 2019). Southern and eastern Central Africa were identified as drought hotspots between 1991–2010 (Spinoni et al., 2014).

Projections

Under low emission scenarios and at GWL 1.5 and GWL 2°C there is *low confidence* in projected mean rainfall change over the region (Figure 9.16c). At GWL 3°C and GWL 4.4°C an increased mean annual rainfall of 10–25% is projected by regional climate models (Coppola et al., 2014; Pinto et al., 2015) and the intensity of extreme precipitation will increase (*high confidence*) (Sylla et al., 2015a; Diallo et al., 2016; Dosio et al., 2019; Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021) (Figure 9.16c,d). This is projected to increase the likelihood of widespread flood occurrences before, during and after the mature monsoon season (Figure 9.14).

Convection permitting simulations (4.5 km spatial resolution) simulate increased dry spell length not apparent at coarser resolutions, suggesting drying in addition to more intense extreme rainfall (Stratton et al., 2018). Although reduced drought frequency is indicated in Figure 9.16e, the SPI metric does not account for the effect of increased temperature on drought (increased moisture deficit), and metrics that account for this indicate slightly increased drought frequency or no change (Spinoni et al., 2020). Therefore, there is *low confidence* in projected changes of drought frequency over the region (Figure 9.14).

9.5.5 East Africa

9.5.5.1 Temperature

Observations

Mean temperatures over the region have increased by 0.7°C–1°C from 1973 to 2013, depending on the season (Ayugi and Tan, 2018; Camberlin, 2018). Increases in TX and TN are evident across the region accompanied by significantly increasing trends of warm nights, warm days and warm spells (Russo et al., 2016; Gebrechorkos et al., 2019; Nashwan and Shahid, 2019). The greatest increases are found in northern and central regions.

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in East Africa are projected to be on average, 0.6°C, 1.1°C and 2.1°C warmer than the 1994–2005 average respectively (Figure 9.16a). Highest increases are projected over the northern and central parts of the region and the lowest increase over the coastal regions (Otieno and Anyah, 2013; Dosio, 2017). The magnitude and frequency of hot days are projected to increase from GWL 2°C and above with larger increases at higher GWLs (Dosio, 2017; Bathiany et al., 2018; Dosio et al., 2018; Kharin et al., 2018) (Figure 9.16a,b). At GWL 4.6°C a number of East African cities are projected to have an up to 2000-fold increase in exposure to dangerous heat (days >40.6 °C) compared to 1985–2005 including Blantyre-Limbe, Lusaka and Kampala, (Mora et al., 2017; Rohat et al., 2019). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 3–5 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 4–9 times more heatwaves at GWL 2.4°C (Thiery et al., 2021). The number of potentially lethal heat days per year is projected to increase from <50 during 1995–2005 to <50 at GWL 1.6°C, 50–120 at GWL 2.5°C and 150–350 at GWL 4.4°C with largest increases at the coast (Mora et al., 2017), highlighting the new emergence of dangerous heat conditions in these areas.

9.5.5.2 Precipitation

Observations

Over Equatorial East Africa the short rains (October–November–December) have shown a long-term wetting trend from the 1960s until present (Manatsa and Behera, 2013; Nicholson, 2015; Nicholson, 2017), which is linked with western Indian Ocean warming and a steady intensification of Indian Ocean Walker Cell (Liebmann et al., 2014; Nicholson, 2015).

In contrast, the long rainfall season (March-April-May) has experienced a long-term drying trend between 1986 and 2007, with rainfall declines in each of these months and a shortening of the wet season (Rowell et al., 2015; Wainwright et al., 2019). Unlike previous decades, since around 2000 the long rains have exhibited a significant relationship with the El Niño-Southern Oscillation (Park et al., 2020), as multiple droughts have occurred during recent La Niña events and when the western to central Pacific SST gradient was La Niña-like (Funk et al., 2015; Funk et al., 2018a). Wetter-than-average rainfall years within this long-term drying trend are often associated with a stronger amplitude of the Madden-Julian Oscillation (Vellinga and Milton, 2018).

In the northern, summer rainfall region (June–September), a decline in rainfall occurred in the 1960s and rainfall has remained relatively low, while interannual variability has increased since the late 1980s (Nicholson, 2017); the cause of this drying trend is uncertain.

Since 2005, drought frequency has doubled from once every six to once every three years and has become more severe during the long and summer rainfall seasons than during the short rainfall season (Ayana et al., 2016; Gebremeskel Haile et al., 2019). Several prolonged droughts have occurred predominantly within the arid and semi-arid parts of the region over the past three decades (Nicholson, 2017).

Projections

Higher mean annual rainfall, particularly in the eastern parts of east Africa are projected at GWL 1.5°C and 2°C by 25 CORDEX models (Nikulin et al., 2018; Osima et al., 2018). The additional 0.5°C of warming from 1.5°C increases average dry spell duration by between two and four days, except over southern Somalia where this is reduced by between two to three days (Hoegh-Guldberg et al., 2018; Nikulin et al., 2018; Osima et al., 2018; Weber et al., 2018).

During the short rainy season, a longer rainfall season (Gudoshava et al., 2020) and increased rainfall of up to over 100 mm on average is projected over the eastern horn of Africa and regions of high/complex topography at GWL 4.5° C (Dunning et al., 2018; Endris et al., 2019; Ogega et al., 2020).

During the long rainy season, there is *low confidence* in projected mean rainfall change (Gutiérrez et al., 2021). Although some studies report projected increased end of century rainfall (Otieno and Anyah, 2013; Kent et al., 2015), the mechanisms responsible for this are not well-understood and a recent regional model study has detected no significant change (Cook et al., 2020b). Projected wetting is opposite to the observed drying trends, giving rise to the 'East African rainfall paradox' (Rowell et al., 2015; Wainwright et al., 2019). In other parts of East Africa, no significant trend is evident (Ogega et al., 2020), agreement on the sign of change is low, and in some regions, CMIP5 and CORDEX data show opposite signs of change (Lyon et al., 2017; Lyon and Vigaud, 2017; Osima et al., 2018; Kendon et al., 2019; Ogega et al., 2020).

Heavy rainfall events are projected to increase over the region at global warming of 2°C and higher (*high confidence*) (Nikulin et al., 2018; Finney et al., 2020; Ogega et al., 2020; Li et al., 2021). Drought frequency, duration and intensity are projected to increase in Sudan, South Sudan, Somalia and Tanzania but decrease or not change over Kenya, Uganda and Ethiopian highlands (Liu et al., 2018c; Nguvava et al., 2019; Haile et al., 2020; Spinoni et al., 2020).

9.5.6 Southern Africa

9.5.6.1 Temperature

Observations
Mean annual temperatures over the region have increased by between 1.04°C and 1.44°C over the period 1961–2015 depending on the observational dataset (Gutiérrez et al., 2021) and in northern Botswana and Zimbabwe increasing 1.6°C–1.8°C between 1961–2010 (Engelbrecht et al 2015). The annual number of hot days have increased in southern Africa over the last four decades (Ceccherini et al., 2017; Kruger and Nxumalo, 2017b; Kruger and Nxumalo, 2017a) and there is increasing evidence of increased heat stress impacting agriculture and human health (Section 9.10.2). The occurrence of cold extremes, including frost days, have decreased (Kruger and Nxumalo, 2017b) (Figure 9.14).

Projections
At 1.5℃, 2℃ and 3°C of global warming above pre-industrial levels, mean annual temperatures in southern Africa are projected to be on average, 1.2℃, 2.3℃ and 3.3℃ warmer than the 1994–2005 average respectively (Figure 9.16a). The annual number of heatwaves is projected to increase by between 2–4 (GWL 1.5°C), 4–8 (GWL 2°C) and 8–12 (GWL 3°C) and hot and very hot days are *virtually certain* to increase under 1.5°C and 2°C of global warming (Engelbrecht et al., 2015; Russo et al., 2016; Dosio, 2017; Weber et al., 2018; Seneviratne et al., 2021). Cold days and cold extremes are projected to decrease under all emission scenarios with the strongest decreases associated with low mitigation (Iyakaremye et al., 2021). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 3–4 times more heatwaves in their lifetimes compared to people born in 1960, although in Angola this is 7–8 times; at GWL 2.4°C this exposure increases to 5–9 times more heatwaves (>10 times in Angola) (Thiery et al., 2021).

9.5.6.2 Precipitation

Observations
Mean annual rainfall has increased over parts of Namibia, Botswana and southern Angola during 1980–2015 by between 128 and 256 mm (Figure 9.13b). Since the 1960s decreasing precipitation trends have been detected over the South African winter rainfall region (*high confidence*) and the far eastern parts of South Africa (*low confidence*) (Engelbrecht et al., 2009; Kruger and Nxumalo, 2017b; Burls et al., 2019; Lakhraj-Govender and Grab, 2019; Gutiérrez et al., 2021; Ranasinghe et al., 2021). The frequency of dry spells and agricultural drought in the region has increased over the period 1961–2016 (Yuan et al., 2018; Seneviratne et al., 2021), the frequency of meteorological drought increased by between 2.5–3 events per decade since 1961 (Spinoni et al 2019) and the probability of the multi-year drought over the southwestern cape of South Africa increased by a factor of three in response to global warming (Otto et al., 2018). The number and intensity of extreme precipitation events have increased over the last century (Kruger and Nxumalo, 2017b; Ranasinghe et al., 2021; Sun et al., 2021), and in the Karoo region of southern South Africa, long-term station data show an increasing trend in annual rainfall of greater than 5 mm per decade over the period 1921–2015 (Kruger and Nxumalo, 2017b).

Projections
Mean annual rainfall in the summer rainfall region is projected to decrease by 10–20%, accompanied by an increase in the number of consecutive dry days during the rainy season under RCP8.5 (Kusangaya et al., 2014; Engelbrecht et al., 2015; Lazenby et al., 2018; Maúre et al., 2018; Spinoni et al., 2019). The western parts of the region are projected to become drier, with increasing drought frequency, intensity and duration

likely under RCP8.5 (*high confidence*) (Engelbrecht et al., 2015; Liu et al., 2018b; Liu et al., 2018c; Ukkola et al., 2020) (Figures 9.16c,e and 9.14), including multi-year droughts (Zhao and Dai, 2016; Dosio, 2017).

Dryness in the summer rainfall region is expected to increase at 1.5°C and higher levels of global warming (Hoegh-Guldberg et al., 2018) and together with higher temperatures will enhance evaporation from the region's mega-dams and reduce soil-moisture content (Engelbrecht et al., 2015) (Section 9.7.1). Increases in drought frequency and duration are projected over large parts of southern Africa at GWL 1.5°C (Liu et al., 2018b; Liu et al., 2018c; Seneviratne et al., 2021) and unprecedented extreme droughts (compared to the 1981–2010 period) emerge at GWL 2°C (Spinoni et al., 2021). Meteorological drought duration is projected to increase from approximately 2 months during 1950–2014 to approximately 4 months in the mid-to-late-21st century future under RCP8.5 (Ukkola et al., 2020). Heavy precipitation in the southwestern region is projected to decrease (Donat et al., 2019) and increase in the eastern parts of southern Africa at all warming levels (Li et al., 2021; Seneviratne et al., 2021).

9.5.7 Tropical cyclones

There is limited evidence of an increased frequency of Category 5 tropical cyclones in the southwestern Indian Ocean (Fitchett et al., 2016; Ranasinghe et al., 2021; Seneviratne et al., 2021) and more frequent landfall of tropical cyclones over central to northern Mozambique (Malherbe et al., 2013; Muthige et al., 2018). There is a projected decrease in the number of tropical cyclones making landfall in the region at 1°C, 2°C and 3°C of global warming, however, they are projected to become more intense with higher wind speeds so when they do make landfall the impacts are expected to be high (*medium confidence*) (Malherbe et al., 2013; Muthige et al., 2018; Ranasinghe et al., 2021).

9.5.8 Glaciers

Total glacial area on Mount Kenya decreased by 121×10^3 m^2 (44%) during 2004–2016 (Prinz et al., 2016), Kilimanjaro from 4.8 km^2 in 1984 to 1.7 km^2 in 2011 (Cullen et al., 2013) and, in the Rwenzori Mountains, from ~2 km^2 in 1987 to ~1 km^2 in 2003 (Taylor et al., 2006). Declining glacial areas in East Africa are linked to rising air temperatures (Taylor et al., 2006; Hastenrath, 2010; Veettil and Kamp, 2019), and in the case of Kilimanjaro and Mount Kenya, declining precipitation and atmospheric moisture (Mölg et al., 2009a; Mölg et al., 2009b; Prinz et al., 2016; Veettil and Kamp, 2019).

Glacial ice cover is projected to disappear before 2030 on the Rwenzori Mountains (Taylor et al., 2006) and Mount Kenya (Prinz et al., 2018) and by 2040 on Kilimanjaro (Cullen et al., 2013). The loss of glaciers is expected to result in a loss in tourism revenues, especially in mountain tourism (Wang and Zhou, 2019).

9.5.9 Teleconnections and Large-Scale Drivers of African Climate Variability

The El Niño-Southern Oscillation (ENSO), Indian Ocean dipole (IOD) and southern annular mode (SAM) are the primary large-scale drivers of African seasonal and interannual climate variability. The diurnal temperature range tends to be greater during La Niña than El Niño in northeastern Africa (Hurrell et al., 2003; Donat et al., 2014a), and in southern Africa, the El Niño warming effect has been stronger for more recent times (1979–2016) compared to earlier period (1940–1978) (Lakhraj-Govender and Grab, 2019). In East Africa, ENSO and IOD exert an interannual control on particularly October–November–December (short rains) and June–July–August–September seasons. In southern Africa, El Niño is associated with negative rainfall and positive temperature anomalies with the opposite true for La Niña. The SAM exerts control on rainfall in the southwestern parts of the region and a positive SAM mode is often associated with lower seasonal rainfall in the region (Reason and Rouault, 2005). The SAM shows a systematic positive trend over the last five decades (Niang et al., 2014).

There is no clear indication that climate change will impact the frequencies of ENSO and IOD (Stevenson et al., 2012; Endris et al., 2019), although there is some indication that extreme ENSO events and extreme phases of the IOD, particularly the positive phase, may become more frequent with implications for extreme events associated with these features, such as drought (Collins et al., 2019; Cai et al., 2021; Seneviratne et al., 2021). Under high emission scenarios, a positive trend in SAM is projected to continue through the 21st century, however, under low emission scenarios, this trend is projected to be weak or even negative given the potential for ozone hole recovery (Arblaster et al., 2011).

9.5.10 African Marine Heatwaves

Marine heatwaves are periods of extreme warm sea surface temperature that persist for days to months and can extend up to thousands of kilometres (Hobday et al., 2016; Scannell et al., 2016), negatively impacting marine ecosystems (Section 9.6.1.4).

The number of marine heatwaves doubled in Mediterranean North Africa and along the Somalian and southern African coastlines from 1982–2016 (Frölicher et al., 2018; Laufkötter et al., 2020) (Oliver et al., 2018), *very likely* as a result of human-induced climate change (Seneviratne et al., 2021). Marine heatwave intensity has increased along the southern African coastline (Oliver et al., 2018). In the ecologically sensitive region west of southern Madagascar, the longest and most intense marine heatwave in the past 35 years was recorded during the austral summer of 2017 in the region, it lasted 48 days and reached a maximum intensity of 3.44°C above climatology (Mawren et al., 2021). Satellite-derived measurements of coastal marine heatwaves may under-report their intensity as measured against coastal *in situ* measurements (Schlegel et al., 2017).

Sea surface temperatures around Africa are projected to increase 0.5°C–1.3°C under GWL1.5 and 1.3°C–2.0°C under GWL3 (Figure 9.16f). Globally, 87% of observed MHWs have been attributed to anthropogenic forcing, and at GWL2.0, nearly all MHWs would be attributable to anthropogenic heating (Frölicher et al., 2018; Laufkötter et al., 2020). Increases in frequency, intensity, spatial extent and duration of marine heatwaves are projected for all coastal zones of Africa. At 1°C and 3.5°C of global warming, the probability of MHW days is between 4–15 times and 30–60 times higher compared to the preindustrial (1861–1880) 99th percentile probability, with highest increases over equatorial and sub-tropical coastal regions (Frölicher et al., 2018) (Figure 9.16). These events are expected to overwhelm the ability of marine organisms and ecosystems to adapt to these changes (Frölicher et al., 2018) (Sections 9.6.1). Reducing emissions and limiting warming to lower levels reduces risk to these systems (*high confidence*) (Hoegh-Guldberg et al., 2018).

[START BOX 9.2 HERE]

Box 9.2: Indigenous Knowledge and Local Knowledge

This box aims at mapping the diversity of indigenous and local knowledge systems in Africa and highlights the potential of this knowledge to enable sustainability and effective climate adaptation. This box builds on the framing of the IPCC system for which 'indigenous knowledge (IK) refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings' (IPCC, 2019b), while 'local knowledge (LK) refers to the understandings and skills developed by individuals and populations, specific to the place where they live' (IPCC, 2019b) (Cross-Chapter Box INDIG in Chapter 18).

Early warning systems and indicators of climate variability

In most African indigenous agrarian systems, local communities integrate IK to anticipate or respond to climate variability (Mafongoya et al., 2017). This holds potential for a more holistic response to climate change, as IK and LK approaches seek solutions that increase resilience to a wide range of shocks and community stresses (IPCC, 2019b). In Africa, IK and LK are exceptionally rich in ecosystem-specific knowledge, with the potential to enhance the management of natural hazards and climate variability (*high confidence*), but there is uncertainty about IK and LK for adaptation under future climate conditions.

Common indicators for the quality of the rain season for local communities in Africa include flower and fruit production of local trees (Nkomwa et al., 2014; Jiri et al., 2015; Kagunyu et al., 2016), insect, bird and animal behaviour and occurrence (Jiri et al., 2016; Mwaniki and Stevenson, 2017; Ebhuoma, 2020) and dry season temperatures (Kolawole et al., 2016; Okonya et al., 2017). Fulani herders in West Africa believe that when 'nests hang high on trees, then rains will be heavy; when nests hang low, rains will be scarce' (Roncoli et al., 2002). In South Africa, LK on weather forecasting is based on the hatching of insects, locust swarm movements and the arrival of migratory birds, which has enabled farmers to make adjustments to cropping practices (Muyambo et al., 2017; Tume et al., 2019). Most of these IK indicators apply to specific communities, and are used for short-term forecasting (e.g., event-specific predictions, such as a violent storm, and onset rain predictions) (Zuma-Netshiukhwi et al., 2013; Mutula et al., 2014). There is evidence of communities that rely heavily on IK and LK indicators to forecast seasonal variability across the continent (Kagunyu et al., 2016; Mwaniki and Stevenson, 2017; Tume et al., 2019). However, their accuracy is debatable, with evidence of both accuracy and inaccuracies due to age-old knowledge losing accuracy because of recent changes in weather conditions (Shaffer, 2014; Adjei and Kyerematen, 2018). There are also some limitations in the transferability of IK across geographical scales, as its understanding is framed by traditional beliefs and cultural practices, historical and social conditions of each community, which vary significantly across communities. This has direct implications for the adoption of IK and LK in national policy and planned adaptation by governments. However, in some parts of Africa, evidence of the integration of IK and LK and scientific-based weather forecasting is increasing (Jiri et al., 2016; Mapfumo et al., 2017; Williams et al., 2020).

IK and LK and climate adaptation

Communities across Africa have long histories of using IK and LK to cope with climate variability, reduce vulnerability and improve the capacity to cope with climate variability (Iloka Nnamdi, 2016; Mapfumo et al., 2017). The adaptation is mostly incremental, such as customary rainwater harvesting practices and planting ahead of rains (Ajibade and Eche, 2017; Makate, 2019), which are used to address the late-onset rains and rainfall variability. Although IK and LK adaptation practices implemented by African communities are incremental, such practices record higher evidence of climate risk reduction compared to practices influenced by other knowledge types (Williams et al., 2020). African communities have used IK and LK to cope, adapt to and manage climate hazards, mainly floods, wildfires, rainfall variability and droughts (see Table Box 9.2.1) (IPCC, 2018b; IPCC, 2019b).

Table Box 9.2.1: Selected studies where IK and LK have been used to cope with climate variability and climate change impacts in Africa.

Climate Hazard	Adaptation/Coping Strategy	Indigenous Group, Community, Country	Evidence
Floods	Use IK to predict floods (village elders acted as meteorologists) and use LK to prepare coping mechanisms (social capital); place valuable goods on higher ground, raise the floor level; leave the field uncultivated when facing flood/drought; indigenous earthen walls to protect homesteads from flooding; planting of culturally flood-immunising indigenous plants.	Coastal communities in Nigeria; Oshiwambo communities in the northern region of Namibia; Matabeleland and Mashonaland provinces in Zimbabwe; communities in Nyamwamba watershed, Uganda; subsistent farmers in Mount Oku and Mbaw, Cameroon; Akobo in South Sudan.	(Fabiyi and Oloukoi, 2013; Hooli, 2016; Lunga and Musarurwa, 2016; Bwambale et al., 2018; Tume et al., 2019)
Wildfires	Early burning to prevent the intensity of the late-season fires	Smallholders in Mutoko, Zimbabwe; Khwe and Mbukushu communities in Namibia	(Mugambiwa, 2018; Humphrey et al., 2021)
Rainfall variability	Change crop type (from maize to traditional millet and sorghum); no weeding; forecasting, rainwater harvesting; women perform rituals rainmaking, seed dressing and crop maintenance as adaptation measures; mulching	Communities in Accra, Ghana; small-scale farmers in Ngamiland in Botswana; Malawi; Zimbabwe; Women in Dikgale, South Africa, agropastoral smallholders in Ntungamo, Kamuli and Sembabule in Uganda.	(Codjoe et al., 2014; Nkomwa et al., 2014; Lunga and Musarurwa, 2016; Rankoana, 2016b; Mugambiwa, 2018; Mfitumukiza et al., 2020; Mogomotsi et al., 2020)
Droughts	Traditional drying of food for preservation (to consume during short	Communities in Accra, Ghana; Malawi; South Africa, Uganda; Smallholder	(Egeru, 2012; Gebresenbet and Kefale, 2012; Codjoe et al., 2014; Kamwendo and

	term droughts); harvesting wild fruits and vegetables; herd splitting by pastorals	farmers in Mutoko, Zimbabwe; Agro-pastoralists in Makueni, Kenya; Pastoralists in South Omo, Ethiopia	Kamwendo, 2014; Okoye and Oni, 2017; Mugambiwa, 2018)
Drought related water scarcity	Traditional rainwater harvesting to supplement both irrigation and domestic water; indigenous water bottle technology for irrigation.	Smallholder farmers in Beaufort, South Africa	(Ncube, 2018)

IK and LK and coping strategies in Table Box 9.2.1 are supportive measures that communities cannot solely rely upon, but which can be used to complement other adaptation options to increase community resilience.

African indigenous language and climate change adaptation

The diversity of African languages is crucial for climate adaptation. Africa has over 30% of the world's indigenous languages (Seti et al., 2016) which are exceptionally rich in ecosystem-specific knowledge on biodiversity, soil systems and water (Oyero, 2007; Mugambiwa, 2018). Taking into consideration the low level of literacy in Africa, especially among women and girls, indigenous languages hold great potential for more effective climate change communication and services that enable climate adaptation (Brooks et al., 2005; Ologeh et al., 2018; IPCC, 2019b). African traditional beliefs and cultural practices place great value on the natural environment, especially land as the dwelling place of the ancestors and source of livelihoods (Tarusarira, 2017) (see Section 9.12).

Limitations of African IK *and* ***LK in climate adaptation***

Studies on IK and LK and climate change adaptation conducted in various African countries and across ecosystems indicate that indigenous environmental knowledge is negatively affected by several factors. Local farmers who depend on this knowledge system for their livelihoods hold the view that African governments do not support and promote it in policy development. Most government agricultural extension workers still consider IK as unscientific and unreliable (Seaman et al., 2014; Mafongoya et al., 2017). At the national level, there is a lack of recognition and inclusion of IK and LK in adaptation planning by African governments, partly because most of the IK and LK in African local communities remains undocumented, but also because IK and LK are inadequately captured in the literature (Ford et al., 2016; IPCC, 2019b). It is predominantly preserved in the memories of the elderly and is handed down orally or by demonstration from generation to generation. It gradually disappears due to memory gaps, and when those holding the knowledge die or refuse to pass it to another generation, the knowledge becomes extinct (Rankoana, 2016a). The way in which IK is transmitted, accessed and shared in most African societies is not smooth (IIED, 2015). IK is also threatened by urbanisation, which attracts rural migrants to urban areas where IK and LK use is limited (Fernández-Llamazares et al., 2015). Further, most African societies that use IK were once colonised, whereby the African indigenous ways of knowing were devalued and marginalised (Bolden et al., 2018). There are concerns about the effectiveness of both IK indicators and related adaptation responses by communities to predict and adapt to weather events under future climate conditions (Speranza et al., 2009; Shaffer, 2014; Hooli, 2016).

Figure Box 9.2.1: Indigenous earth walls *(hayit)* built by indigenous people in Akobo, Jonglei Region, South Sudan to protect their houses/ infrastructure from the worst flood in 25 years occurred in 2019. The wall is 1–2 m high. Photo credit, **Laurent-Charles Levesque**.

[END BOX 9.2 HERE]

9.6 Ecosystems

9.6.1 Observed Impacts of Climate Change on African Biodiversity and Ecosystem Services

9.6.1.1 Terrestrial Ecosystems

The overall continental trend is woody plant expansion, particularly in grasslands and savannas, with woody plant cover increasing at a rate of 2.4% per decade (Stevens et al., 2017; Axelsson and Hanan, 2018) (Figure 9.17). There is also increased grass cover in arid regions in southwestern Africa (Masubelele et al., 2014). There is *high agreement* that this is attributable to increased CO_2, warmer and wetter climates, declines in burned area and release from herbivore browsing pressure, but the relative importance of these interacting drivers remains uncertain (O'Connor et al., 2014; Stevens et al., 2016; García Criado et al., 2020). Woody encroachment is the dominant trend in the western and central Sahel, occurring over 24% of the region, driven primarily by shifts in rainfall timing and recovery from drought (Anchang et al., 2019; Brandt et al., 2019). Remote sensing studies demonstrate greening in southern Africa and forest expansion into water-limited savannas in Central and West Africa (Baccini et al., 2017; Aleman et al., 2018; Piao et al., 2020), with increases in precipitation and atmospheric CO_2 the likely determinants of change (Venter et al., 2018; Brandt et al., 2019; Zhang et al., 2019). These trends of greening and woody plant expansion stand in contrast to the desertification and contraction of vegetated areas highlighted in AR5 (Niang et al., 2014), but are based on multiple studies and longer time series of observations. Reported cases of desertification and vegetation loss, for example, in the Sahel, appear transitory and localised rather than widespread and permanent (Dardel et al., 2014; Pandit et al., 2018; Sterk and Stoorvogel, 2020).

Shifts in demography, geographic ranges and abundance of plants and animals consistent with expected impacts of climate change are evident across Africa. These include uphill contractions of elevational range limits of birds (Neate-Clegg et al., 2021), changes in species distributions previously reported in AR5 (Niang et al., 2014) and the death of many of the oldest and largest African Baobabs (Patrut et al., 2018). An increase in frequency and intensity of hot, dry weather after wildfires led to a long-term decline in plant biodiversity in Fynbos since the 1960s (Slingsby et al., 2017). Increasing temperatures may have contributed to the declining abundance and range size of South African birds (Milne et al., 2015), including Cape Rock-jumper (*Chaetops frenatus*) and Protea Canary (*Serinus leucopterus*), from increased risk of reproductive failure (Lee and Barnard, 2016; Oswald et al., 2020). For hot and dry regions (e.g., Kalahari), there is strong evidence increased temperatures are having chronic sublethal impacts, including reduced foraging efficiency and loss of body mass (du Plessis et al., 2012; Conradie et al., 2019), and are approaching species physiological limits, with heat extremes driving mass mortality events in birds and bats (McKechnie et al., 2021). Vegetation change linked to climate change and increasing atmospheric CO_2 has had an indirect impact on animals. Increased woody cover has decreased the occurrence of bird, reptile and mammal species that require grassy habitats (Péron and Altwegg, 2015; McCleery et al., 2018). Decreased fruit production linked to rising temperatures has decreased the body condition of fruit-dependent forest elephants by 11% from 2008–2018 (Bush et al., 2020).

There is *high agreement* that land use activities counteract or exacerbate climate-driven vegetation change (Aleman et al., 2017; Timm Hoffman et al., 2019). Decreased woody plant biomass in 11% of sub-Saharan Africa was attributed to land clearing for agriculture (Brandt et al., 2017; Ordway et al., 2017). Localised loss of tree cover in Miombo woodlands and 16.6±0.5 Mha of forest loss in the Congo basin between 2000-2014 was driven largely by forest clearing and drought mortality (McNicol et al., 2018; Tyukavina et al., 2018).

Vegetation changes interacting with climate and land use change have impacted fire regimes across Africa. The frequency of weather conducive for fire has increased in southern and West Africa and is expected to continue increasing in the 21st century under both RCP2.6 and RCP8.5 (Betts et al., 2015; Abatzoglou et al., 2019). Increased grass cover in arid regions introduced fire into regions where fuel was previously insufficient to allow fire spread, such as the arid Karoo in South Africa (du Toit et al., 2015; Strydom and Savage, 2016). In contrast, shrub encroachment, increased precipitation (Zubkova et al., 2019), vegetation fragmentation and cropland expansion have reduced fire activity in many African grasslands and savannas (Andela and van der Werf, 2014; Probert et al., 2019). These drivers are expected to negate the effect of increasing fire weather and ultimately lead to a reduction in the total burned area under RCP4.5 and RCP8.5 (Knorr et al., 2016; Moncrieff et al., 2016; Wu et al., 2016).

9.6.1.2 Vegetation Resilience

African ecosystems have a long evolutionary association with fire, large mammal herbivory and drought (Maurin et al., 2014; Charles-Dominique et al., 2016). The maintenance of biodiversity depends on natural disturbance regimes. Natural regrowth of savanna plant biomass in southern Africa compensated for biomass removal through human activities (McNicol et al., 2018), and rapid recovery occurred after the 2014-2016 extreme drought (Abbas et al., 2019). During the same drought event, browsing and mixed feeder herbivores were resilient, but grazers declined by approximately 60% and were highly dependent on drought refugia (Abraham et al., 2019). African tropical forests remained a carbon sink through the record drought and temperature experienced in the 2015–2016 El Niño, indicating resilience in the face of extreme environmental conditions (Bennett et al., 2021). This is likely due to the presence of drought-tolerant species and floristic and functional shifts in tree species assemblages (Fauset et al., 2012; Aguirre-Gutiérrez et al., 2019). This resilience indicates that there is the capacity to recover from disturbances and short-term change. But resilience has limits and beyond certain points, change can lead to irreversible shifts to different states (Figure 9.18).

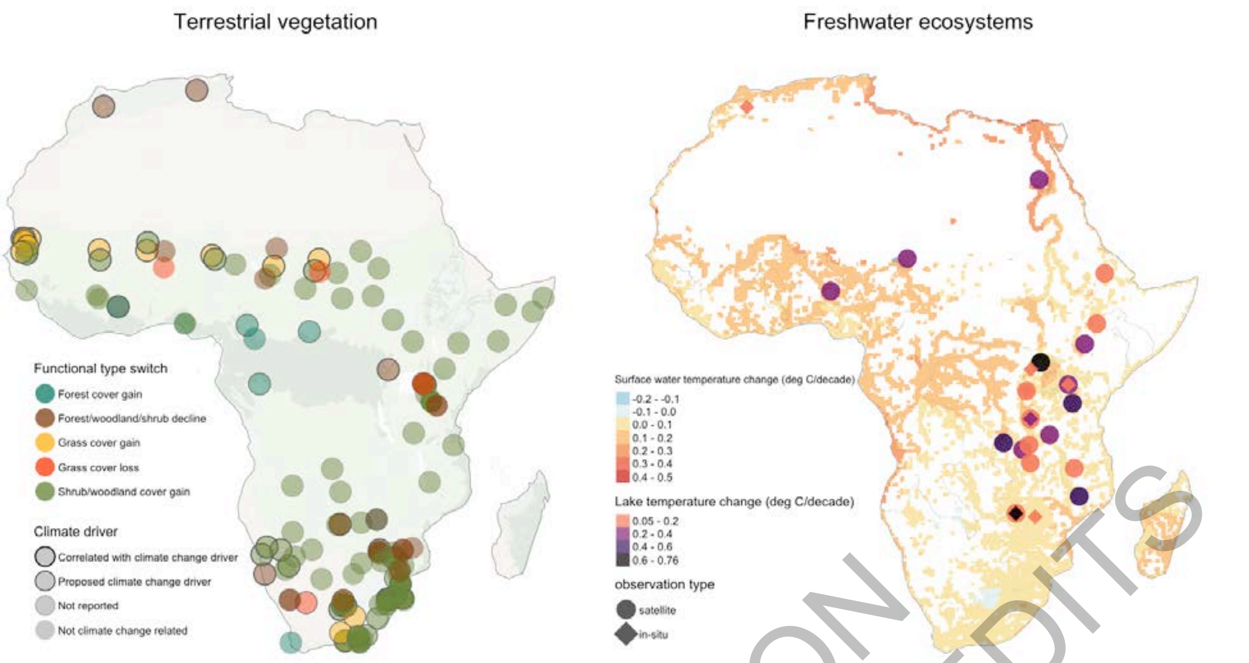


Figure 9.17: Widespread changes to African vegetation have been reported, especially increasing woody plant cover in many savannas and grasslands, with 37% of these changes proposed to be driven by anthropogenic climate change and increased CO_2. The warming of lakes and rivers has been detected across Africa and is attributed to climate change. Data on vegetation change was gathered from 156 studies published between 1989 and 2021. Climatic changes, mostly associated with changes in rainfall, are enhancing grass production in arid grasslands and savannas, and causing grass expansion into semi-desert regions with notable increases in the Sahel and southern Africa. Tropical forest expansion into mesic savannas is occurring on the fringes of the central African tropical forest. Interactions between land use, climate change and increasing atmospheric CO_2 concentrations are causing a widespread increase in woody plant cover encroachment in tropical savannas and grasslands. Some tree death and woody cover decline associated with climate and land use change have also been recorded across biomes. Of the reported changes to terrestrial vegetation, 24% were explicitly linked to climate change and a further 13% were proposed to be driven by climate change. In 48% of studies, no climate driver was mentioned and in 15% climate change was ruled out as the driver of change. Annual surface water temperatures in African lakes have warmed at a rate of 0.05°C–0.76°C per decade. Both satellite-based measures spanning 1985-2011 and *in situ* measurements spanning 1927-2014 agree on this warming trend. Other surface waters across Africa warmed from 1979-2018 at a rate of between 0.05°C and 0.5°C per decade (Woolway and Maberly, 2020). Vegetation change data were taken from a larger, global literature survey of existing databases supplemented with newer studies documenting changes in tree, shrub and grass cover linked to climate and land use change in natural and semi-natural areas (for further details 2.4.3.5 and Table 2.S.1 in Chapter 2, and see Supplementary Material Table SM 9.2 for Africa vegetation change data and Table SM 9.3 for studies reporting lake warming data).

9.6.1.3 Freshwater Ecosystems

Small climatic variations have large impacts on ecosystem function in Africa's freshwaters (Ndebele-Murisa, 2014; Ogutu-Ohwayo et al., 2016). Warming of water temperatures from 0.2°C to 3.2°C occurred in several lakes over 1927–2014 and has been attributed to anthropogenic climate change (Ogutu-Ohwayo et al., 2016); Figure 9.17). Increased temperature, changes in rainfall, and reduced wind speed altered the physical and chemical properties of inland water bodies, affecting water quality and productivity of algae, invertebrates and fish (*high confidence*). In deeper lakes, warmer surface waters and decreasing wind speeds reduced shallow waters mixing with nutrient-rich deeper waters, reducing biological productivity in the upper sunlit zone (Ndebele-Murisa, 2014; Saulnier-Talbot et al., 2014). In several lakes, climate change was identified as causing changes in insect emergence time (Dallas and Rivers-Moore, 2014) and in loss of fish habitats (Natugonza et al., 2015; Gownaris et al., 2016). This set of changes can harm human livelihoods, for example, from reduced fisheries productivity (Ndebele-Murisa, 2014; Ogutu-Ohwayo et al., 2016) (9.8.5) and reduced water supply and quality (Section 9.7.1).

9.6.1.4 Marine Ecosystems

Anthropogenic climate change is already negatively impacting Africa's marine biodiversity, ecosystem functioning and services by changing physical and chemical properties of seawater (increased temperature, salinity and acidification, and changes in oxygen concentration, ocean currents and vertical stratification) (*high confidence*) (Hoegh-Guldberg et al., 2014; Hoegh-Guldberg et al., 2018). Coastal ecosystems in West Africa are among the most vulnerable because of extensive low-lying deltas exposed to sea level rise, erosion, saltwater intrusion and flooding (Belhabib et al., 2016; UNEP, 2016b; Kifani et al., 2018). In southern Africa, shifting distributions of anchovy, sardine, hake, rock lobster and seabirds have been partly attributed to climate change (Crawford et al., 2015; van der Lingen and Hampton, 2018; Vizy et al., 2018), including southern shifts of 30 estuarine and marine fish species attributed to increased temperature and changes in water circulation from decreased river inflow (Augustyn et al., 2018). Warming sea surface temperatures inhibiting nutrient mixing reduced phytoplankton biomass in the western Indian Ocean by 20% since the 1960s, potentially reducing tuna catches (Roxy et al., 2016).

Mangroves, seagrasses and coral reefs support nursery habitats for fish, sequester carbon, trap sediment and provide shoreline protection (Ghermandi et al., 2019). Climate change is compromising these ecosystem services (*medium confidence*). Marine heatwaves associated with El Niño-Southern Oscillation (ENSO) events triggered massive coral bleaching and mortality over the past 20 years (Oliver et al., 2018). Mass coral bleaching in the western Indian Ocean occurred in 1998, 2005, 2010 and 2015/2016 with coral cover just 30–40% of 1998 levels by 2016 (Obura et al., 2017; Moustahfid et al., 2018). The northern Mozambique Channel has served as a refuge from climate change and biological reservoir for the entire coastal East African region (McClanahan et al., 2014; Hoegh-Guldberg et al., 2018). A southern shift of mangrove species has been observed in South Africa (Peer et al., 2018) with loss in total suitable coastal habitats for mangroves and shifts in the distribution of some species of mangroves and a gain for others (Record et al., 2013). Mangrove cover was reduced 48% in Mozambique in 2000 from tropical cyclone Eline, with 100% mortality of seaward mangroves dominated by *Rhizophora mucronata* (Macamo et al., 2016). Recovery of mangrove species was observed 14 years later in sheltered sites. There is *low confidence* these cyclone-induced impacts are attributable to climate change owing, in part, to a lack of reliable long-term data sets (Macamo et al., 2016). In West Africa, oil and gas extraction, deforestation, canalisation and de-silting of waterways have been the largest factors in mangrove destruction (Numbere, 2019).

9.6.2 Projected Risks of Climate Change for African Biodiversity and Ecosystem Services

9.6.2.1 Projected Biome Distribution

African biomes are projected to shift due to changes in atmospheric CO_2 concentrations and aridity (Figure 9.18). Grassland expansion into the desert, woody expansion into grasslands and forest expansion into savannas are projected for areas of reduced aridity, caused by reduced moisture stress from CO_2 fertilisation under medium (RCP4.5) and high (SRES A2) emissions scenarios (Heubes et al., 2011; Moncrieff et al., 2016). This greening trend may slow or reverse with continued temperature increase and/or in areas of increased aridity (Berdugo et al., 2020). The net impact of these effects on vegetation is highly uncertain (Trugman et al., 2018; Cook et al., 2020a; Martens et al., 2021). The maintenance or re-establishment of natural fire and large mammal herbivory processes can mitigate projected CO_2 and climate-driven changes (Scheiter and Savadogo, 2016; Stevens et al., 2016). Expansion of croplands and pastures will reduce ecosystem carbon storage in Africa, potentially reversing climate- and CO_2-driven greening in savannas (Aleman et al., 2018; Quesada et al., 2018).

Vegetation growth simulated by dynamic vegetation models is often highly sensitive to CO_2 fertilisation. These models project the African tropical forest carbon sink to be stable or strengthened under scenarios of future climate change (Huntingford et al., 2013; Martens et al., 2021). In contrast, statistical modelling suggests it has begun to decline and will weaken further, decreasing from current estimates of 0.66 tonnes of carbon removed from the atmosphere per hectare per year to 0.55 tonnes of carbon (Hubau et al., 2020). Increasing rainfall seasonality and aridity over central Africa (Haensler et al., 2013) threatens the massive carbon store in the Congo Basin's Cuvette Centrale peatlands, estimated at 30.6 billion tonnes (Dargie et al., 2019).

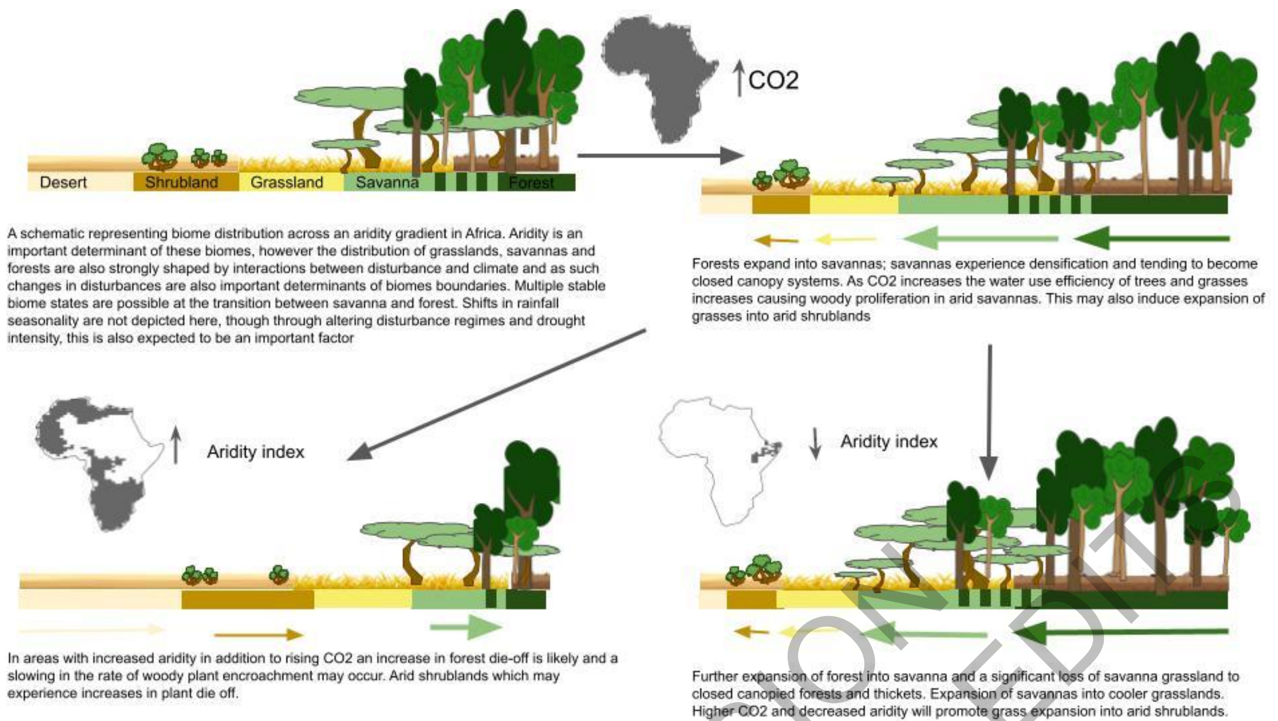


Figure 9.18: Increases in atmospheric CO_2 and changes in aridity are projected to shift the geographic distribution of major biomes across Africa (*high confidence*). Arrows in the diagram indicate possible pathways of biome change from current conditions resulting from changes in CO_2 and aridity. Changes need not be gradual or linear and may occur rapidly if tipping points are crossed. Currently, widespread greening observed in Africa has been at least partially attributed to increasing atmospheric CO_2 concentrations. Future projected increases in aridity are expected to cause desertification in many regions, but it is highly uncertain how this will interact with the greening effect of CO_2. Inset maps show the projected geographical extent of changes in CO_2 concentrations and aridity. CO_2 is projected to increase globally under all future emission scenarios. Aridity index maps show projected change in aridity (calculated as annual precipitation/annual potential evapotranspiration) at around 4°C global warming relative to 1850–1900 (RCP8.5 in 2070–2099) from 34 CMIP5 models (Scheff et al., 2017). Shaded areas indicate regions where >75 % of models agree on the direction of change.

9.6.2.2 Terrestrial Biodiversity

Local extinction is when a species is extirpated from a local site. The magnitude and extent of local extinctions predicted across Africa increase substantially under all future global warming levels (*high confidence*) (Table 9.5; Figure 9.19). Above 2°C the risk of sudden disruption or loss of local biodiversity, increases and becomes more widespread, especially in Central, West and East Africa (Trisos et al., 2020).

Global extinction is when a species is extirpated from all areas. At 2°C global warming, 11.6% of African species (mean 11.6%, 95% CI 6.8–18.2%) assessed are at risk of global extinction, placing Africa second only to South America in the magnitude of projected biodiversity losses (Urban, 2015). At >2°C, 20% of North African mammals may lose all suitable climates (Soultan et al., 2019), and over half of the dwarf succulents in South African Karoo may lose >90% of their suitable habitat (Young et al., 2016). Among the thousands of species at risk, many are species of ecological, cultural and economic importance such as African wild dogs (Woodroffe et al., 2017) and Arabica Coffee (Moat et al., 2019).

With increasing warming, there is a lower likelihood species can migrate rapidly enough to track shifting climates, increasing global extinction risk and biodiversity loss across more of Africa (*high confidence*). Immigration of species from elsewhere may partly compensate for local extinctions and lead to local biodiversity gains in some regions (Newbold, 2018; Warren et al., 2018). However, more regions face net losses than net gains. At 1.5°C global warming, >46% of localities face net declines in vertebrate species richness of >10%, with net increases projected for less than 15% of localities (Barbet-Massin and Jetz, 2015; Newbold, 2018). At >2°C, 9% of species face complete range loss by 2100, regardless of their dispersal ability (Urban, 2015). With >4°C global warming, a net loss of >10% of vertebrate species richness is projected across 85% of Africa (Barbet-Massin and Jetz, 2015; Mokhatla et al., 2015; Newbold, 2018; Warren et al., 2018). Mountain top endemics and species in North and southern Africa are at risk due to disappearing cold climates (Milne et al., 2015; Garcia et al., 2016; Bentley et al., 2018; Soultan et al., 2019). For hot regions such as the Sahara, Congo Basin and Kalahari, no warmer-adapted species are available elsewhere to compensate for local extinctions, so the resilience of local biodiversity will depend entirely on the persistence of species (Burrows et al., 2014; Garcia et al., 2014). The capacity for species to avoid extinction through behavioural thermoregulation, plasticity or evolution is uncertain but will become increasingly *unlikely* under higher warming scenarios (Conradie et al., 2019).

Table 9.5: Risk of local extinction risk increases across Africa with increasing global warming.

Global Warming Level (relative to 1850-1900)	Taxa	% of species at a site at risk of local extinction	Extent across Africa (% of the land area of Africa)	Areas at risk	References
1.5°C	Plants, insects, vertebrates	>10%	>90%	Widespread. Hot and/or arid regions especially at risk, including Sahara, Sahel and Kalahari	Fig. 9.29b (Newbold, 2018; Warren et al., 2018)
>2°C	Plants, insects, vertebrates	>50%	18%	Widespread	(Newbold, 2018; Warren et al., 2018)
>4°C	Plants, insects, vertebrates	>50%	45-73%	Widespread. Higher uncertainty for central African tropical forests due to lower agreement between biodiversity models	Fig. 9.29c (Barbet-Massin and Jetz, 2015; Newbold, 2018; Warren et al., 2018)

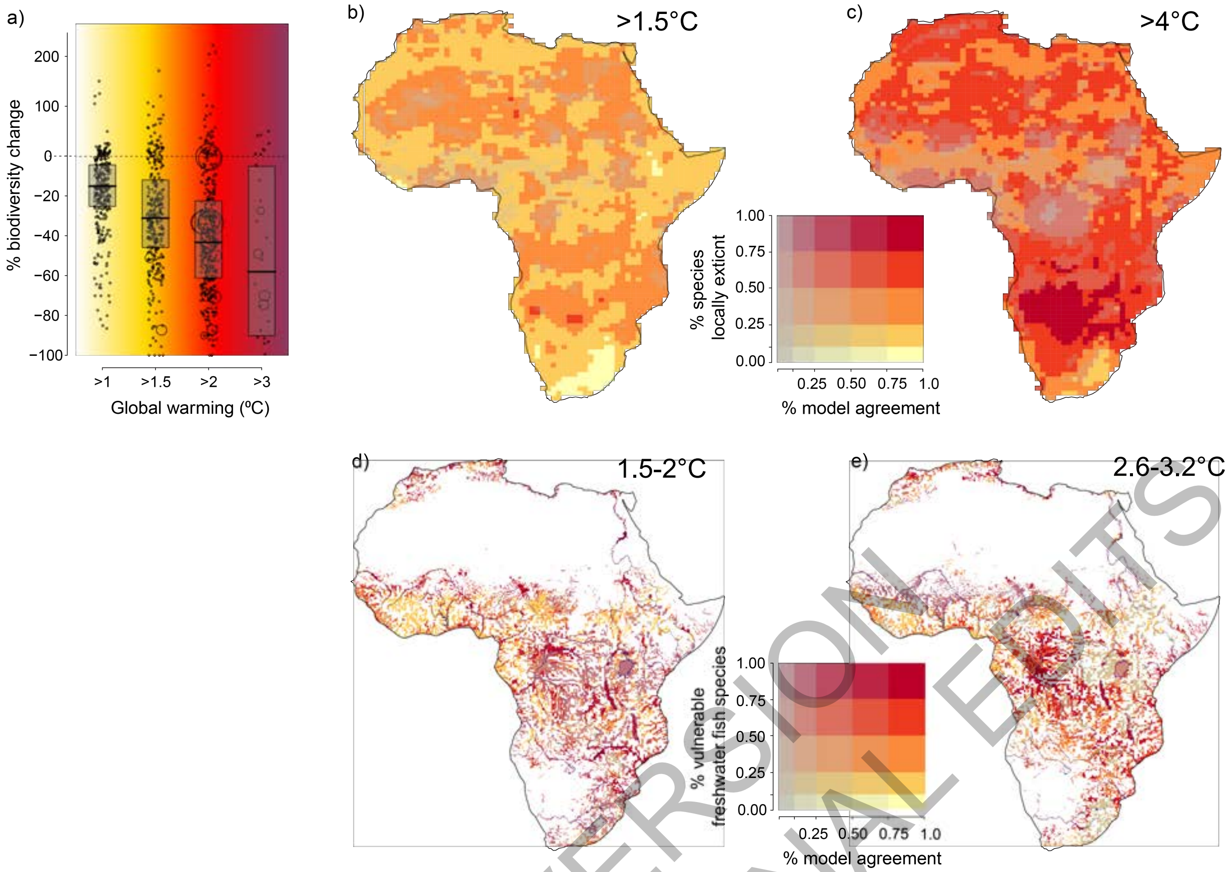


Figure 9.19: The loss of African biodiversity under future climate change is projected to be widespread and increasing substantially with every 0.5°C above the current (2001–2020) level of global warming (*high confidence*). (a) Projected biodiversity loss, quantified as percentage change in species abundance, range size or area of suitable habitat increases with increasing global warming levels (relative to 1850–1900). Above 1.5°C global warming, half of all assessed species are projected to lose >30% of their population, range size or area of suitable habitat, with losses increasing to >40% for >3°C. The 2001–2020 level of global warming is around 1°C higher than 1850–1900 (IPCC, 2021). Boxplots show the median (horizontal line), 50% quantiles (box), and points are studies of individual species or of multiple species (symbol size indicates the number of species in a study). (b–c) The mean projected local extinction of vertebrates, plants and insects within 100 km grid cells increases in severity and extent under increased global warming (relative to 1850–1900). Local extinction >10% is widespread by 1.5°C. Pixel colour shows the projected percentage of species undergoing local extinction and the agreement between multiple biodiversity models. (d–e) The mean projected increase in species of freshwater fish vulnerable to local extinction within 10 km grid cells for future global warming. Around a third of fish species are projected to be vulnerable to extinction by 2°C global warming. Pixel colour shows the projected percentage of species vulnerable to extinction and agreement between multiple vulnerability models. In (a), data were obtained from 22 peer-reviewed papers published since 2012 investigating the impacts of projected climate change on African biodiversity. When a paper provided impact projections for several time periods, climate change scenarios or for more than one species, each impact was recorded as an individual biodiversity impact projection, resulting in a database of 1,165 biodiversity impact projections. Data were initially collected by Manes et al. (2021) as part of a larger literature review for Cross-Chapter Paper 1 on Biodiversity Hotspots and then expanded to include areas outside of African priority conservation areas (see Supplementary Material Table SM 9.4). The literature review was limited to peer-reviewed publications that reported quantifiable risks to biodiversity, eliminating non-empirical studies. In (b–c), projections are based on intersecting current and future modelled species distributions at ~10 km spatial resolution from two recent global assessments of climate change impacts on terrestrial vertebrates (Newbold, 2018; Warren et al., 2018). In (d-e) projections are based on intersecting future species vulnerabilities from two recent assessments of climate change vulnerability of freshwater fish species (Nyboer et al., 2019; Barbarossa et al., 2021).

9.6.2.3 *Marine Ecosystems*

African coastal and marine ecosystems are highly vulnerable to climate change (*high confidence*). At 1.5°C of global warming, mangroves will be exposed to sedimentation and sea level rise, while seagrass ecosystems will be most affected by heat extremes (*high confidence*) (Hoegh-Guldberg et al., 2018) and turbidity (Wong et al., 2014). These risks will be amplified at 2°C and 3°C (*virtually certain*) (Hoegh-

Guldberg et al., 2018). Over 90% of East African coral reefs are projected to be destroyed by bleaching at 2°C of global warming (*very high confidence*) (Hoegh-Guldberg et al., 2018). At around 2.5°C global warming, an important reef-building coral (*Diploastrea heliopora*) in the central Red Sea is projected to stop growing altogether (Cantin et al., 2010). By 2.5°C, suitable habitat of >50% of species are projected to decline for coastal lobster in East and North Africa, with large declines for commercially important *J. lalandii* in southern Africa (Boavida-Portugal et al., 2018). More generally, tropical regions, especially exclusive economic zones in West Africa, are projected to lose large numbers of marine species and may experience sudden declines with extratropical regions having potential net increases as species track shifting temperatures poleward (García Molinos et al., 2016; Trisos et al., 2020).

9.6.2.4 Freshwater Ecosystems

Above 2°C global warming, the proportion of freshwater fish species vulnerable to climate change increases substantially (*high confidence*) (Figure 9.19). At 2°C, 36.4% of fish species are projected to be vulnerable to local or global extinction by 2100, increasing to 56.4% under 4°C warming (average of values from (Nyboer et al., 2019; Barbarossa et al., 2021) (Figure 9.19). Global warming reduces available habitat for freshwater species due to reduced precipitation and increased drought leading to increasing water temperatures above optimal physiological limits in floodplains, estuaries, wetlands, ephemeral pools, rivers and lakes (Dalu et al., 2017; Kalacska et al., 2017; Nyboer and Chapman, 2018). Along the Zambezi River, projected flow reductions could cause a 22% reduction in annual spawning habitat and depletion of food resources for fry and juvenile fish that could impede fish migration and reduce stocks (Kangalawe, 2017; Martínez-Capel et al., 2017; Tamatamah and Mwedzi, 2020). More aquatic species will have the capacity to cope with 2°C compared to 4°C global warming, with more negative effects on physiological performance at 4°C (Dallas, 2016; Pinceel et al., 2016; Zougmoré et al., 2016; Nyboer and Chapman, 2017; Ross-Gillespie et al., 2018). Endemic, specialised fish species will have a lower capacity to adjust to elevated water temperatures compared to hardier generalist fishes (McDonnell and Chapman, 2015; Nyboer and Chapman, 2017; Lapointe et al., 2018; Reizenberg et al., 2019). More work is needed to understand the risk for invertebrates (Dallas and Rivers-Moore, 2014; Cohen et al., 2016), and to understand the potential effects of reduced mixing of water and other climate risks on freshwater biodiversity.

9.6.2.5 Climate Change & Ecosystem Services

Direct human dependence on provisioning ecosystem services in Africa is high (Egoh et al., 2012; IPBES, 2018). For example, natural forests provided 21% of rural household income across 11 African countries (Angelsen et al., 2014) and wild-harvested foods (including fisheries) provide important nutrition to millions of Africans, including through important micronutrients and increased dietary diversity (Powell et al., 2013; Baudron et al., 2019a) (Sections 9.8.2.3 and 9.8.5)

Climate change has affected ecosystem services in Africa by reducing fish stocks, crop and livestock productivity and water provisioning due to heat and drought (see Sections 9.8.2.1, 9.8.2.2, 9.8.2.4 and 9.8.5.1). Woody encroachment is decreasing cattle production and water supply (Smit and Prins, 2015; Stafford et al., 2017), but can also provide forage for goat production, as well as resins, fuelwood and charcoal (Reed et al., 2015; Stafford et al., 2017; Charis et al., 2019). Local communities perceive climate change to have decreased crop and livestock productivity, reduced wild food availability and reduced forest resources across Africa (Onyekuru and Marchant, 2014) (see Sections 9.8.2.1, 9.8.2.2, 9.8.2.4 and 9.8.2.3).

With global warming >3°C, and with high population growth and agricultural expansion (SSP3, 2081–2100), 1.2 billion Africans are projected to be negatively affected by pollution of drinking water from reduced water quality regulation by ecosystems and 27 million people affected by reduced coastal protection by ecosystems (Chaplin-Kramer et al., 2019). The number of people affected reduces to 0.4 billion and 22 million under a sustainable development scenario with global warming below 2°C (SSP1, 2081–2100). The African tropical forest carbon sink has been more resilient than Amazonia to recent warming but may already have peaked, and this service is predicted to decline with further warming, reducing 14% by the 2030s (Hubau et al., 2020; Sullivan et al., 2020). This declining carbon storage may be offset by CO_2 fertilisation (*low confidence*) (Martens et al., 2021). Climate change is projected to shift the geographic distribution of important human and livestock disease vectors (see Section 9.8.2.4 and 9.10.2). Changes in rainfall seasonality compounded with land privatisation and population growth may adversely impact nomadic and semi-nomadic pastoralists who follow shifting patterns of greening vegetation (Van Der Ree et al., 2015).

9.6.2.6 Invasive Species

Invasive species threaten African ecosystems and livelihoods (Ranasinghe et al., 2021). For instance, economic impacts were estimated at USD 1 billion per year for smallholder maize farmers in East Africa (Pratt et al., 2017). Climate change is projected to change patterns of invasive species spread (*high confidence*). The area of suitable climate for *Lantana camara* is projected to contract (Taylor et al., 2012) and to expand for *Prosopis juliflora* (Sintayehu et al., 2020). Bioclimatic suitability for fall armyworm, a major threat to maize, is projected to decrease in Central Africa but expand in southern and West Africa (Zacarias, 2020), and to expand for coffee berry borer (*H. hampei*) in Uganda and around Mount Kenya (Jaramillo et al., 2011). Climate suitability for tephritid fruit flies is projected to decrease in central Africa (Hill et al., 2016). Increased water temperature is projected to favour invasive over local freshwater fish populations and shift the range of invasive aquatic plants in South Africa (Hoveka et al., 2016; Shelton et al., 2018). Alterations to lake and river connectivity are predicted to modify invasion pathways in Lake Tanganyika and water hyacinth coverage may increase with warmer waters in Lake Victoria (Masters and Norgrove, 2010; Plisnier et al., 2018).

9.6.3 Nature-Based Tourism in Africa

Nature-based tourism is important for African economies and jobs. Tourism contributed 8.5% of Africa's 2018 GDP (World Travel and Tourism Council, 2019a) with Wildlife tourism contributing a third of tourism revenue (USD 70.6 billion), supporting 8.8 million jobs (World Travel and Tourism Council, 2019b).

Climate change is already negatively affecting tourism in Africa (*high confidence*). The 2015–2018 Cape Town drought caused severe water restrictions, reducing tourist arrivals and spending with associated job losses (Dube et al., 2020). Anthropogenic climate change increased the likelihood of drought by a factor of five to six (Pascale et al., 2020). Extreme heat days have increased across South African national parks since the 1990s (van Wilgen et al., 2016). This reduces animal mobility, decreasing animal viewing opportunities (Dube and Nhamo, 2020). Tourists and employees also fear heat stress (Dube and Nhamo, 2020). Visitors to South Africa's national parks preferred to visit in cool-to-mild temperatures (Coldrey and Turpie, 2020). Extreme weather conditions disrupted tourist activities and damaged infrastructure at Victoria Falls, Hwange National Park, Kruger National Park and the Okavango Delta (Dube et al., 2018; Dube and Nhamo, 2018; Mushawemhuka et al., 2018; Dube and Nhamo, 2020). Rainfall variability and drought alters wildlife migrations, affecting tourist visits to the Serengeti (Kilungu et al., 2017). Reduced tourism decreases revenue for national park management (van Wilgen et al., 2016).

Future climate change is projected to further negatively affect nature-based tourism. Decreased snow and forest cover may reduce visits to Kilimanjaro National Park (Kilungu et al., 2019). Woody plant expansion in savanna and grasslands reduce tourist's game viewing experience and negatively impact conservation revenues (Gray Emma and Bond William, 2013; Arbieu et al., 2017). Visitation rates to South African national parks, based on mean monthly temperatures, are projected to decline 4% with 2°C global warming (Coldrey and Turpie, 2020). Sea level rise and increased intensity of storms is projected to reduce beach tourism due to beach erosion (Grant, 2015; Amusan and Olutola, 2017). Tourism in the Victoria Falls, Okavango and Chobe hydrological systems may be negatively affected by heat and increased variability of rainfall and river flow (Saarinen et al., 2012; Dube and Nhamo, 2019). Increased extreme heat will increase air turbulence and weight restrictions on aircraft, which could make air travel more uncomfortable and expensive to African destinations (Coffel and Horton, 2015; Dube and Nhamo, 2019).

9.6.3.1 Protected Areas and Climate Change

African protected areas store around 1.5% of global land ecosystem carbon stocks and support biodiversity (Gray et al., 2016; Melillo et al., 2016; Sala et al., 2018). They also support livelihoods and economies, such as through nature-based tourism and improved fisheries (Brockington and Wilkie, 2015; Mavah et al., 2018; Ban et al., 2019).

Climate change and land use change will interact to influence the effectiveness of African protected areas (*high confidence*). Species representation in the existing African protected area network is projected to decrease due to species range shifts for mammals, bats, birds and amphibians (Hole et al., 2009; Baker et al., 2015; Payne and Bro-Jørgensen, 2016; Smith et al., 2016; Phipps et al., 2017). Species ability to disperse between areas to track shifting climates is increasingly impaired by land transformation and fencing, which also impact seasonal wildlife migrations (Lovschal et al., 2017; Sloan et al., 2017). On land, only 0.5% of the African protected area network is connected through low-impact landscapes (Ward et al., 2020). Linear transport infrastructure (e.g., roads, railways, pipelines) and fencing from proposed 'development corridors' are projected to bisect over 400 protected areas and degrade around 1,800 more (Laurance et al., 2015). Climate change could increase human-wildlife conflict as resultant resource shortages cause communities to move into protected areas for harvesting or livestock grazing, or wildlife to move out of protected areas and into contact with people (Mukeka et al., 2018; Kupika et al., 2019; Hambira et al., 2020). See Section 9.1.4 for the role of land and ocean protected areas in climate change adaptation.

9.6.4 Ecosystem-Based Adaptation in Africa

Ecosystem-based adaptation (EbA) uses biodiversity and ecosystem services to assist people to adapt to climate change (Swanepoel and Sauka, 2019). Africa's Nationally Determined Contributions (NDCs) show 36% of adaptation actions identified by 52 countries are considered to be EbA (Figure 9.20).

EbA can reduce climate impacts and there is high agreement EbA can be more cost-effective than traditional grey infrastructure when a range of economic, social and environmental benefits are also accounted for (Table 9.6) (Baig et al., 2016; Emerton, 2017; Chausson et al., 2020). This is particularly relevant in Africa where climate vulnerabilities are strongly linked to natural resource-based livelihood practices and existing grey infrastructure levels are low in many regions (Dube et al., 2016; Reid et al., 2019). However, financial constraints limit EbA project implementation (Mumba et al., 2016; Swanepoel and Sauka, 2019).

Evidence for EbA in Africa is largely case study based and often anecdotal (Reid et al., 2018). There is *high agreement* that costs, challenges and negative outcomes of EbA interventions are still poorly understood (Reid, 2016; Chaplin-Kramer et al., 2019), despite limited evidence for the efficacy of context-specific applications at different scales (Doswald et al., 2014).

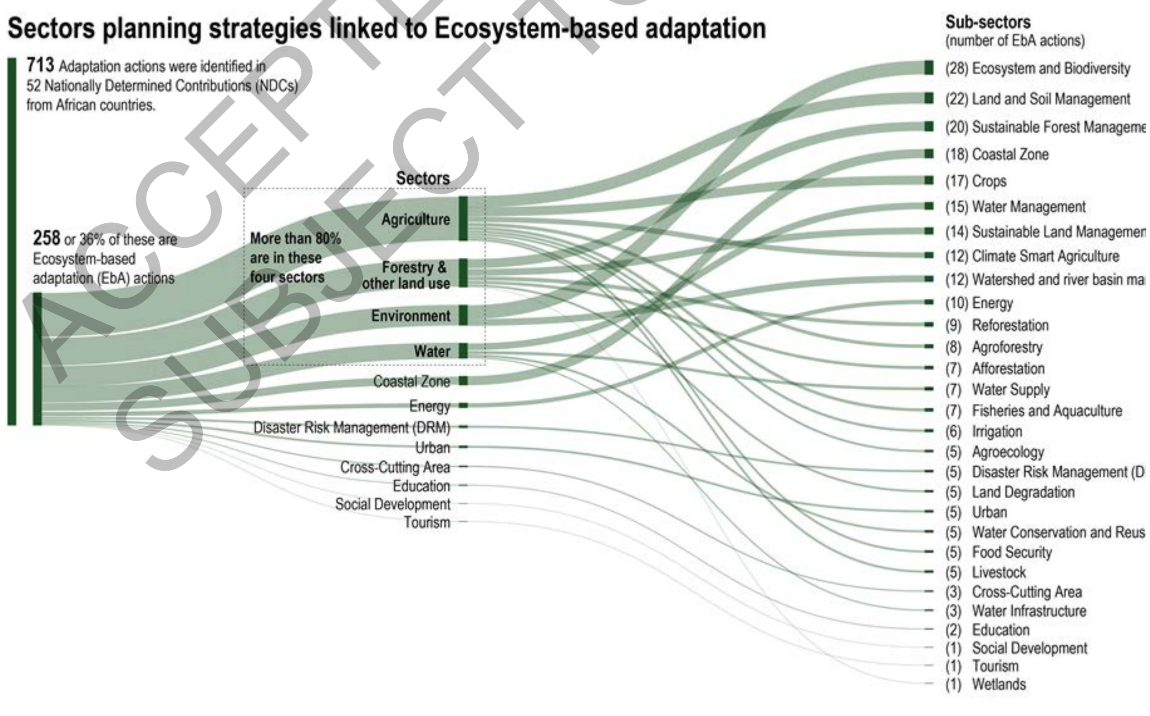


Figure 9.20: Over a third (36%) of all adaptation actions identified in the NDCs of 52 African countries are Ecosystem-based Adaptations (EbA). Of these actions ± 83% fall within the Agriculture, Land Use/Forestry, Environment and Water sectors. The EbA actions identified from the NDCs span 12 primary sectors and 29 sub-sectors.

Table 9.6: The beneficial outcomes of Ecosystem-based Adaptation (EbA) actions and assessed confidence in these outcomes. Assessment is provided for EbA options in the four most prevalent EbA sectors identified in the Nationally Determined Contributions of 52 African countries (Figure 9.20). See Chapter 2.6.3 and 3.6.2 of this report for further assessment of EbA approaches in terrestrial, freshwater and marine systems.

Sector	EbA Action(s)	Outcome(s)	Confidence	Source(s)
Agriculture	Conservation agriculture	Improved soil and water conservation	*High*	(Thierfelder et al., 2017)
		Improved agricultural productivity and drought resilience	*Medium*	(Pittelkow et al., 2015; Thierfelder et al., 2017; Adenle et al., 2019)
	Diversified crop varieties	Improved agricultural productivity and drought resilience	*High*	(Shiferaw et al., 2014; Tesfaye et al., 2016; Thierfelder et al., 2017)
Environment	Ecosystem protection and restoration	Carbon sequestration and storage	*High*	(Melillo et al., 2016; Griscom et al., 2017; FAO, 2018a)
		Stepping stones for species migrating due to climate change	*Medium*	(Beale et al., 2013; Roberts et al., 2020)
		Increased ecosystem resilience to disturbance	*High*	(Anthony et al., 2015; Sierra-Correa and Cantera Kintz, 2015; Kroon et al., 2016; Roberts et al., 2017)
		Livelihood diversification opportunities from ecotourism, resource harvesting, and rangelands (among others)	*Medium*	(Lunga and Musarurwa, 2016; Bedelian and Ogutu, 2017; Agyeman, 2019; Kupika et al., 2019; Naidoo et al., 2019)
Forestry & Other Land Use	Restoration/ Reforestation Sustainable forestry and land management	Restoration of degraded ecosystems and enhanced carbon sequestration	*High*	(Mugwedi et al., 2018)
		Reducing pressure on forests for food and energy needs	*Medium*	(Peprah, 2017; Zegeye, 2018)
Water	Integrated catchment management	Improved flood attenuation capacity	*High*	(Bradshaw et al., 2007; Mwenge Kahinda et al., 2016; Rawlins et al., 2018)
		Improved resilience of freshwater ecosystems	*High*	(Ndebele-Murisa, 2014; Natugonza et al., 2015; Lowe et al., 2019; Tamatamah and Mwedzi, 2020)

9.6.4.1 Terrestrial Ecosystems

Improved ecosystem care and restoration are cost-effective for carbon sequestration while providing multiple environmental, social and economic co-benefits (Griscom et al., 2017; Shukla et al., 2019). Protecting and restoring natural forests and wetlands reduces flood risk across multiple African countries (Bradshaw et al., 2007). In Kenya, enclosures for rangeland regeneration diversified income sources, which could increase the adaptive capacity of local people (Mureithi et al., 2016; Wairore et al., 2016). Sustainable agroforestry in semi-arid regions provides income sources from fuelwood, fruit and timber and reduces exposure to drought, floods and erosion (Quandt et al., 2017). Forest protection in Zimbabwe maintains honey production during droughts, providing food supply options if crops fail (Lunga and Musarurwa, 2016). Community-based natural resource management in pastoral communities improved institutional governance outcomes through involving community members in decision-making, increasing the capacity of these communities to respond to climate change (Reid, 2014).

EbA can also increase ecological resilience. Re-introduction of fire and large mammals can restore ecosystem services, enhance adaptive capacity and benefit people by combatting woody encroachment, restoring grazing and increasing streamflow (Asner et al., 2016; Stafford et al., 2017; Cromsigt et al., 2018). Herbivores can also reduce fuel loads in areas facing increased fire risk (Hempson et al., 2017).

Protected areas can be ‘stepping stones' that facilitate climate-induced species range shifts (Roberts et al., 2020), preserve medicinal plant diversity despite climate change (Kaky and Gilbert, 2017) and provide livelihood diversification opportunities (Table 9.6). Protecting 30% of sub-Saharan Africa's land area could reduce the proportion of species at risk of extinction by around 60% in both low and high warming scenarios (Hannah et al., 2020). The role of protected areas in EbA can be strengthened by: (i) increasing coverage of diverse environments and high carbon storage ecosystems, (ii) habitat restoration, (iii) maintaining intact habitat, (iv) participatory, equitable conservation and adaptation strategies; (v) cooperation across borders and (vi) adequate monitoring (Gillson et al., 2013; Rannow et al., 2014; Midgley and Bond, 2015; Pecl et al., 2017; Dinerstein et al., 2019; Roberts et al., 2020).

[START BOX 9.3 HERE]

Box 9.3: Tree Planting in Africa

Due to widespread deforestation and forest degradation (Malhi et al., 2014), future scenarios to limit global warming include large-scale reforestation and afforestation (Griscom et al., 2017; Bastin et al., 2019). Africa has been targeted through the AFR100 (https://afr100.org) to plant ~1 million km^2 of trees by 2030 (Bond et al 2019). Maintaining existing indigenous forest and indigenous forest restoration is a win-win, maximising benefits to biodiversity, adaptation and mitigation (Griscom et al., 2017; Watson et al., 2018; Lewis et al., 2019) (*high confidence)*.

Yet many areas targeted by AFR100 erroneously mark Africa's open ecosystems (grasslands, savannas, shrublands) as degraded and suitable for afforestation (Figure Box 9.3.1) (Veldman et al., 2015; Bond et al., 2019) *(high confidence)*. These ecosystems are not degraded, they are ancient ecosystems that evolved in the presence of disturbances (fire/herbivory) (Maurin et al., 2014; Bond and Zaloumis, 2016; Charles-Dominique et al., 2016). Afforestation prioritises carbon sequestration at the cost of biodiversity and other ecosystem services (Veldman et al., 2015; Bond et al., 2019). Furthermore, it remains uncertain how much carbon can be sequestered as, compared to grassy ecosystems, afforestation can reduce belowground carbon stores and increase aboveground carbon loss to fire and drought (Yang et al., 2019; Wigley et al., 2020b; Nuñez et al., 2021). Thus, afforested areas may store less carbon than ecosystems they replace (Dass et al., 2018; Heilmayr et al., 2020). Afforestation would reduce livestock forage, eco-tourism potential and water availability (Gray Emma and Bond William, 2013; Anadón et al., 2014; Cao et al., 2016; Stafford et al., 2017; Du et al., 2021), and may reduce albedo thereby increasing warming (Baldocchi and Penuelas, 2019; Bright et al., 2015).

Exotic tree species are often selected for planting (e.g., *Pinus* spp or *Eucalyptus* spp), but in parts of Africa, they have become invasive (Zengeya, 2017; Witt et al., 2018), increasing fire hazards and decreasing biodiversity and water resources (Nuñez et al., 2021) *(high confidence)*. Negative impacts of afforestation on ecosystems are not restricted to plantations of exotic species; they extend to inappropriate planting of native forest species (Slingsby et al., 2020).

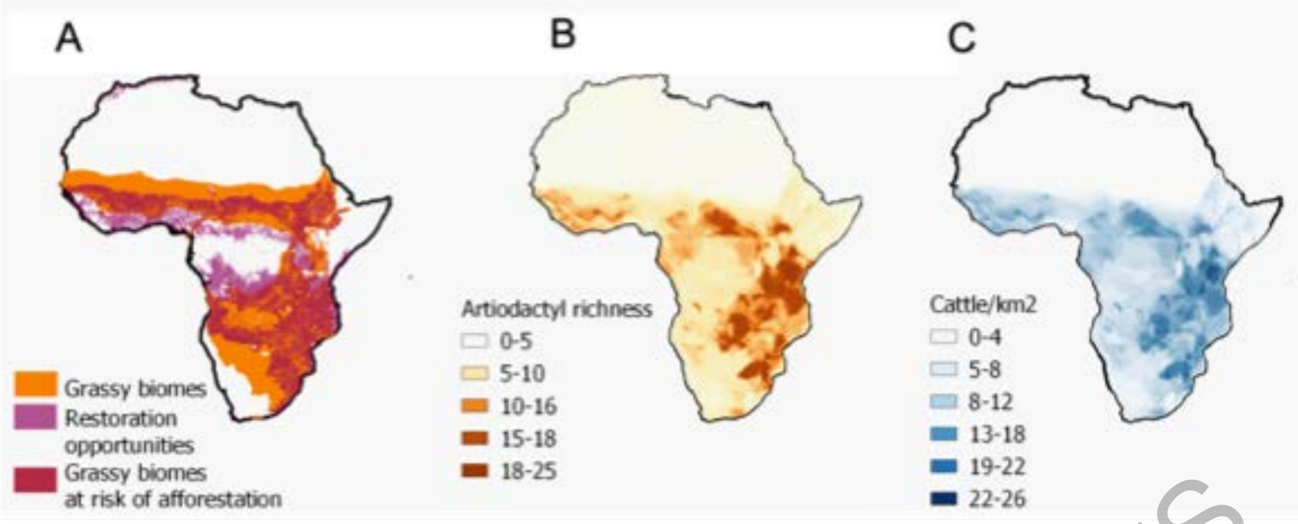


Figure Box 9.3.1: Proposed tree planting plans in Africa are focused on (a) non-forested ecosystems like savannas, grasslands and shrublands which (b) host uniquely adapted biodiversity and (c) offer important ecosystem services like grazing which supports subsistence and commercial agriculture. Figure adapted from (Bond et al., 2019).

[END BOX 9.3 HERE]

9.6.4.2 Freshwater Ecosystems

EbA can mitigate flooding and increase the resilience of freshwater ecosystems (Table 9.6). Adaptation in African freshwater ecosystems is heavily influenced by non-climate anthropogenic factors, including land use change, water abstraction and diversion, damming and overfishing (Dodds et al., 2013; Kimirei et al., 2020; UNESCO and UN-Water, 2020). Wetlands and riparian areas support biodiversity, act as natural filtration systems and serve as buffers to changes in the hydrological cycle, thereby increasing the resilience of freshwater ecosystems and the people that rely on them (Ndebele-Murisa, 2014; Musinguzi et al., 2015; Lowe et al., 2019). However, national adaptation programmes of action, national adaptation plans and national communications rarely consider the ecological stability of ecosystems safeguarding the very water resources they seek to preserve (Kolding et al., 2016). Some countries have mandated the protection of riparian zones, but implementation is low (Musinguzi et al., 2015; Muchuru and Nhamo, 2018). Protecting terrestrial areas surrounding Lake Tanganyika benefited fish diversity (Britton et al., 2017). Afforestation reduces water availability but forest restoration and removing invasive plant species can increase water flows in regions facing water insecurity from climate change (Chausson et al., 2020; Le Maitre et al., 2020). Regular, long-term monitoring of African freshwaters would improve understanding of responses to climate change. General principles for this type of monitoring were developed for Lake Tanganyika (Plisnier et al., 2018) and could be applied to develop harmonised, regional monitoring of African lakes, rivers and wetlands (Tamatamah and Mwedzi, 2020)

9.6.4.3 Marine and Coastal Ecosystems

Marine and coastal ecosystems such as mangroves, seagrass and coral reefs provide storm protection and food security for coastal communities (*high confidence*) (IPCC, 2019c). Restoring reef systems reduced wave height in Madagascar (Narayan et al., 2016), but there is limited evidence for the efficacy of coral reef restoration at large scales with increased warming (3.6.3). Populations at risk from storm surge and/or sea level rise coincide with areas of high coastal EbA potential from Mozambique to Somalia, and coastlines of the Gulf of Guinea, Gambia, Guinea-Bissau and Sierra Leone (Jones et al., 2020). Understanding hotspots of EbA potential is particularly important for West Africa with some of the highest levels of human dependence on marine ecosystems at high risk from climate change and large populations vulnerable to sea level rise (Selig et al., 2018; Trisos et al., 2020) (Sections 9.9.3.1 and 9.8.5.2).

Marine protected areas (MPAs) can yield multiple adaptation benefits, such as buffering species from extinction and increasing fish stocks, as well as storing large amounts of carbon (Edgar et al., 2014; Roberts et al., 2017; Lovelock and Duarte, 2019). However, this potential of MPAs will reach limits with increased warming (Roberts et al., 2017). For example, MPAs cannot prevent coral bleaching at scale and mass die-offs are well-described from MPAs following climate shocks (Bates et al., 2019; Bruno et al., 2019). Although prioritising MPA coverage of climate refugia, such as the northern Mozambique channel, may offer some increased resilience (McClanahan et al., 2014).

9.7 Water

Much of Africa experiences very high hydrological variability in all components of the water cycle, with important implications for people and ecosystems. Most of the continent's water is stored in groundwater (660,000 km^3), which is 20 times more than the water stored in the lakes and 100 times more than the annual renewable water resources (MacDonald et al., 2012). The accessible volume of groundwater via wells and springs is smaller than these estimates (Xu et al., 2019). Africa has 63 transboundary river basins (UNEP, 2010), 72 mapped transboundary aquifers (Nijsten et al., 2018) and 33 transboundary lakes (ILEC and UNEP, 2016), reflecting a highly water-connected and interdependent socio-ecological system across countries, extending also to the coastal areas of the continent (see Section 4.1, Figure 4.1).

9.7.1 Observed Impacts from Climate Variability and Climate Change

Climate impacts on water are occurring against a backdrop of increasing temperatures and changes in rainfall, with increased seasonal and interannual variability, droughts in some regions, and increased frequency of heavy rainfall events (see Section 9.5). In West Africa, declines in river flows have been attributed to declining rainfall and increasing temperature, drought frequency and water demand (Biao, 2017; Thompson et al., 2017; Descroix et al., 2018). In Central Africa, the Congo river demonstrates inter-decadal shifts but no long-term trend (Mahe et al., 2013; Alsdorf et al., 2016), however, recently observed falling water levels in its upper and middle reaches are attributed to climate change (von Lossow, 2017).

A review of river flow and lake level changes in 82 basins in eastern and southern Africa regions for 1970–2010 showed mixed trends: 51% had decreasing trends ranging from 10–49% and 11% increasing trends ranging from 7–60% (Schäfer et al., 2015). However, in southern Africa as a whole, river flows have mostly decreased *(high confidence)* (Dallas and Rivers-Moore, 2014). In East Africa, large rivers such as the Tana show increasing flow (1941–2016) related to increased rainfall in the highlands, with little influence of flow regulation by a series of dams (Langat et al., 2017). The Nile river basin has been experiencing a mainly increasing rainfall trend upstream and decreasing trend downstream (Onyutha et al., 2016). The observed changes are driven by a complex coupling of changes in climate, land use and water demand.

Observed climate changes in Africa (see Section 9.5) have led to changes in river flow and runoff (Dallas and Rivers-Moore, 2014; Wolski et al., 2014) and high fluctuations in lake levels *(high confidence)* (Natugonza et al., 2016; Ogutu-Ohwayo et al., 2016; Gownaris et al., 2018). Shallow lakes respond dramatically to hydrological changes, for example, Lake Chilwa has dried up completely nine times in the last century (Wilson, 2014), while Lake Chad shrunk by 90% between 1963 and 2000 (Gao et al., 2011). However, recent analyses indicate that Lake Chad's water levels have been stable since 2000 due to infilling from groundwater resources (Buma et al., 2018; Pham-Duc et al., 2020). Other factors such as deforestation and increased water use in upstream tributaries also contribute to lake shrinking (Mvula et al., 2014). Water levels in Kenya's mostly shallow rift lakes have been rising since 2010, with some exceeding historical record high levels (Schagerl and Renaut, 2016; Olago et al., 2021). The recent 10-year rising trend is partly attributed to increased rainfall and changing land uses (Onywere and John M. Mironga, 2012; Olago et al., 2021). Changes in water level fluctuations of 13 African lakes have been positively correlated with primary and overall production (Gownaris et al., 2018), and will have important consequences for freshwater ecosystems and related ecosystem goods and services (see Sections 9.6.1.3 and 9.8.5). Other effects of observed climate changes in Africa include higher episodic groundwater recharge, particularly in drylands, from heavy rainfall events that are in some cases related to El Niño-Southern Oscillation and the Indian Ocean Dipole (Taylor et al., 2013; Fischer and Knutti, 2016; Cuthbert et al., 2019; Kotchoni et al., 2019; Myhre et al., 2019), reduced soil moisture, more frequent and intense floods, more persistent and frequent droughts (Douville et al., 2021) and the steady decline and projected disappearance by 2040 of African tropical glaciers (see Section 9.5.9).

The mixed-signal in river flow trends (increase/decrease/no-change) across Africa mirrors the results seen globally for runoff and streamflow (see Section 4.2.3 in Chapter 4). Hydrological extremes are, however, of increasing concern. There has been an increase in drought frequency, severity and spatial extent in recent decades. From 1900–2013, Africa suffered the largest number of drought events globally and registered the second largest number of people affected after Asia (Masih et al., 2014). The likelihood of recent severe climate conditions such as the multi-year Cape Town Drought has increased to due to human-induced climate change (Otto et al., 2018; Pascale et al., 2020) (see Box 9.4), and regional and urban floods (Yuan et al., 2018; Tiitmamer, 2020) and droughts (Funk et al., 2018b; Siderius et al., 2018; Uhe et al., 2018) are expected to increase.

However, between 2010–2020 more people across Africa have been impacted by floods (e.g., related to Cyclone Idai in March 2019) compared to droughts (Lumbroso, 2020). Coastal cities are vulnerable to floods related to rainfall and sea level rise (Musa et al., 2014), as exemplified by the flood disasters experienced in the Niger delta in 2012 which displaced more than 3 million people and destroyed schools, clinics, markets and electricity installations (Amadi and Ogonor, 2015). From 2000–2015, the proportion of people exposed to floods grew by 20–24%, mostly in Africa and Asia, and these numbers will increase under climate change (Tellman et al., 2021). Sectoral impacts from flooding within Africa and globally are further elaborated on in Sections 9.8.2 and 9.8.5.1, Table 9.3 and Section 4.3 in Chapter 4.

[START BOX 9.4 HERE]

Box 9.4: African Cities Facing Water Scarcity

Many African cities will face increasing water scarcity under climate change (Grasham et al., 2019). The Cape Town and Dodoma cases illustrate challenges for both surface and groundwater supply and what adaptation responses have been employed.

The Cape Town Drought (2015-2018)

The Cape Town drought illustrates how a highly diverse African city and its citizens responded to protracted and unanticipated water scarcity. Anthropogenic climate change made the drought five to six times more *likely* (Pascale et al., 2020; Doblas-Reyes et al., 2021). After three consecutive years of low precipitation, Cape Town braced for a 'Day Zero' where large portions of the city would lose water supply (Cole et al., 2021a). The risk of day zero was anticipated to cascade to affect risks to health, economic output and security (Simpson et al., 2021b). The case study highlights the importance of communication, budgetary flexibility, robust financial buffers and insurance mechanisms, disaster planning, intergovernmental cooperation, nature-based solutions, infrastructure transformations and equitable access for climate adaptation in African cities facing water scarcity.

A substantial media campaign was launched to inform residents about the severity of the drought and urge water conservation (Booysen et al., 2019; Hellberg, 2019; Ouweneel et al., 2020). Together with stringent demand management through higher water tariffs, this communication campaign played an important role in reducing consumption from 540 to 280 litres per household per day (Booysen et al., 2019; Simpson et al., 2019a). Revenue from water sales contributes 14% of Cape Town's total revenue, making it the third-largest source of 'own' revenue for the city (Simpson et al., 2019b). However, with an unprecedented reduction in water use, the municipal budget was undermined (Simpson et al., 2020b). Collecting less revenue created a financial shock as the city struggled to recover operating finance, even while new capital requirements were needed for the development of expensive new water supply projects (Simpson et al., 2019b). This financial shock was compounded by the economic stress of poor agricultural and tourism performance brought about by the drought (Shepherd, 2019; Simpson et al., 2021b). As wealthy residents invested in private, off-grid water supplies, the risk of reduced municipal revenue collections from newly off-grid households aggregated with the risk of reduced tourism, increasing the risk to the reputation of the incumbent administration (Simpson et al., 2021b). This demonstrates how a population cohort with a high response capability to water scarcity can reduce risk while simultaneously increasing risks to the municipality and its capacity to provide water to vulnerable residents (Simpson et al., 2020b). Given that city populations in Africa pay 5–7 times more for water than the average price paid in the United States or Europe (Adamu and Ndi, 2017; Lwasa et al., 2018), municipal finance needs to delink operating revenue from potential climate shocks (see Box 8.6 in Chapter 8).

The drought led the municipality to consider a broader diversity of water supply options, including groundwater (CoCT, 2019), developing city-scale slow-onset disaster planning (Cole et al., 2021a) and building an enhanced 'relationship with water' (CoCT, 2019; Madonsela et al., 2019). This shift in approach is displayed in the recognition of nature-based solutions as a priority in water resilience-building efforts (Rodina, 2019) and is signalled in Cape Town's Water Strategy which aims to become a 'water sensitive city' that makes 'optimal use of stormwater and urban waterways for flood control, aquifer recharge, water reuse and recreation' (CoCT, 2019).

The drought required cooperation between multiple spheres of government, and the management of a broad range of stakeholders and political entities (Nhamo and Agyepong Adelaide, 2019; Cole et al., 2021a). The case highlights how a lack of coordination between essential organs of state and political entities can reduce response efficacy (Rodina, 2019). Despite significant investments in water security by public and private entities, one-quarter of Cape Town's population remains in persistent conditions of water stress, emphasising the challenge and importance of inclusive solutions that address the persistent social and economic stressors which affect vulnerability to water scarcity (Enqvist and Ziervogel, 2019).

Sustaining intensive groundwater use in a dryland city under climate change: Dodoma, Tanzania

Since 1954, the Makutapora wellfield in semi-arid, central Tanzania has supplied safe water to the city of Dodoma. Substantial rises in wellfield pumping and population growth have increased freshwater demand in Dodoma and dependence upon the Makutapora Wellfield, currently the sole perennial source of piped water to the city. Yet, there is high uncertainty of groundwater recharge rates (Nkotagu, 1996; Taylor et al., 2013) which rely on intense seasonal rainfall associated with the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) modes of climate variability (e.g., 2 to 7 years) to contribute disproportionately to recharge (Taylor et al., 2013; Kolusu et al., 2019).

Defining a sustainable pumping rate for the Makutapora wellfield is complicated by the variable and episodic nature of groundwater replenishment in this dryland environment. For example, groundwater recharge during the 1997/1998 El Niño event, the strongest El Niño event of the 20th century, accounted for nearly 20% of all of the recharge received from 1955–2010 (Taylor et al., 2013), highlighting the vital role interannual groundwater storage plays in enabling adaptation to climate variability and change in drylands. The disproportionate contribution of intense seasonal rainfalls to the replenishment of the Makutapora wellfield, consistent with observations from across sub-Saharan Africa (Cuthbert et al., 2019), suggests that groundwater in drylands are currently naturally resilient to climate change. However, it remains unclear whether climate change will strengthen or weaken the influence of ENSO and IOD on rainfall (Brown et al., 2020) and thereby affect the predictability of groundwater recharge.

As freshwater demand in Tanzania's rapidly growing capital is projected to increase substantially in the coming decades, questions remain as to whether the capacity of the Makutapora wellfield can meet some or all of this demand. Nature-based solutions to improve the resilience of wellfield abstraction to increased pumpage and climate change include Managed Aquifer Recharge (MAR). The sharing of general lessons learned from other cities in dryland Africa employing MAR, such as Windhoek in Namibia (Murray et al., 2018), could prove invaluable.

[END BOX 9.4 HERE]

9.7.2 Projected Risks and Vulnerability

9.7.2.1 Projected Risks

By 2050, up to 921 million additional people in Africa could be exposed to climate change-related water stress, while up to 459 million could experience reduced exposure (Dickerson et al., 2021). This large variance in numbers and direction of change is related to uncertainties in climate models and non-climate factors like population growth and water withdrawals (Dickerson et al., 2021). The baseline for most of the projected risks presented here is 1971–2000.

In West Africa, significant spatial variability in river flow is projected in the upper reaches of several rivers, with no clear pattern overall (Roudier et al., 2014) and large uncertainties in estimations of change in runoff (Roudier et al., 2014; Bodian et al., 2018). In some higher altitude regions, like the Niger Inland Delta in West Africa, river flows and water levels are expected to increase (*medium confidence*) (Aich et al., 2014; Thompson et al., 2017). In the Lower Niger Basin, combined average annual rainfall and erosivity for all the climatic models in all scenario shows increasing rainfall amounts are projected to result in an increasing average change in rainfall-runoff erosivity of about 14%, 19% and 24% for the 2030s, 2050s and 2070s, with concomitant increase in soil loss of 12%, 19% and 21% (Amanambu et al., 2019). In the Volta River system, increasing wet season river flows (+36% by 2090s) and Volta lake outflow (+5% by 2090s) are anticipated under RCP8.5 (*medium confidence*) (Awotwi A et al., 2015; Jin et al., 2018). In the Volta River basin, compared to 1976–2005, drought events are projected to increase by 1.2 events per decade at around 2°C to 1.6 events per decade at around 2.5°C global warming, and drought area extent is projected to increase by 24% to 34% (Oguntunde et al., 2017). In Central Africa, runoff in the Congo River system may increase by up to 50% (RCP8.5), especially in the wet season, enhancing flood risks in the entire Congo basin, particularly in the central and western parts (CSC, 2013). Average river flows are expected to increase in most parts of Central Africa, with expected increases in total potential hydropower production (Ludwig et al., 2013).

In North Africa, in the upper White Nile basin, Olaka et al. (2019) project a 25% and 5 to 10% (RCP4.5) increase in the intensification of future annual rainfall in the eastern and western parts of the Lake Victoria Basin, respectively, with corresponding variability in future river discharge ranging from 5 to 26%. In the upper Blue Nile basin, models also indicate up to 15% increase in runoffs in wet-season and up to −24% decreasing in dry-season 2021–2040 (RCP8.5) (Ayele et al., 2016; Siam and Eltahir, 2017; Meresa and Gatachew, 2018). The increase of precipitation in wet-season indicates a higher possibility of flash floods while decreased runoffs in dry-season further intensify existing shortage of irrigation water demand (Ayele et al., 2016; Siam and Eltahir, 2017; Meresa and Gatachew, 2018). The annual flow and revenues from hydropower production and irrigated agriculture of the Blue Nile River at Khartoum are projected to increase under maximum but are expected to decrease under minimum and median projected changes in streamflow for 2041–2070 and 2071–2100, respectively (Tariku et al., 2021). The Middle Draa valley in Morocco is expected to experience more severe droughts and the estimation of the water balance suggests a lack of supply in the future (Karmaoui et al., 2016).

In East Africa, Liwenga et al. (2015) show that it will *likely* be warmer and wetter in the Great Ruaha River region and with increasing seasonal variation and extremes towards the end of the century. A similar observation is made for the River Pangani, with mean river flow being about 10% higher in the 2050s relative to the 1980–1999 period, associated with a 16–18% increase in rainfall in its upper catchment (Kishiwa et al., 2018). However, at more local scales, the projections cover a range of slight declines to significant increases in mean annual rainfall amounts (Gulacha and Mulungu, 2017). In the Tana River basin in Kenya, water yield is projected to increase progressively under RCP4.5 and RCP8.5 relative to the baseline period 1983–2011 but is characterised by distinct spatial heterogeneity (Muthuwatta et al., 2018).

In southern Africa, reductions in rainfall over the Limpopo and Zambezi river basins under 1.5°C and 2°C global warming could have adverse impacts on hydropower generation, irrigation, tourism, agriculture and ecosystems (Figure Box 9.5.1) (Maúre et al., 2018), although model projections of strong early summer drying trends remain uncertain (Munday and Washington, 2019).

Changes in the amplitude, timing and frequency of extreme events such as droughts and floods will continue to affect lake levels, rates of river discharge and runoff and groundwater recharge (*high confidence*) (Gownaris et al., 2016; Darko et al., 2019), but with disparate effects at regional, basin and sub-basin scales, and at seasonal, annual and longer timescales. The increased frequency of extreme rainfall events under climate change (Myhre et al., 2019) is projected to amplify groundwater recharge in drylands (Jasechko and Taylor, 2015; Cuthbert et al., 2019). However, declining trends in rainfall and snowfall in some areas of North Africa (Donat et al., 2014b) are projected to continue in a warming world (Seif-Ennasr et al., 2016), restricting groundwater recharge from meltwater flows, exacerbating the salinisation and depletion of groundwater (Hamed et al., 2018) and increasing the risk of reduced soil moisture (Petrova et al., 2018) in this region where groundwater abstraction is greatest (Wada et al., 2014).

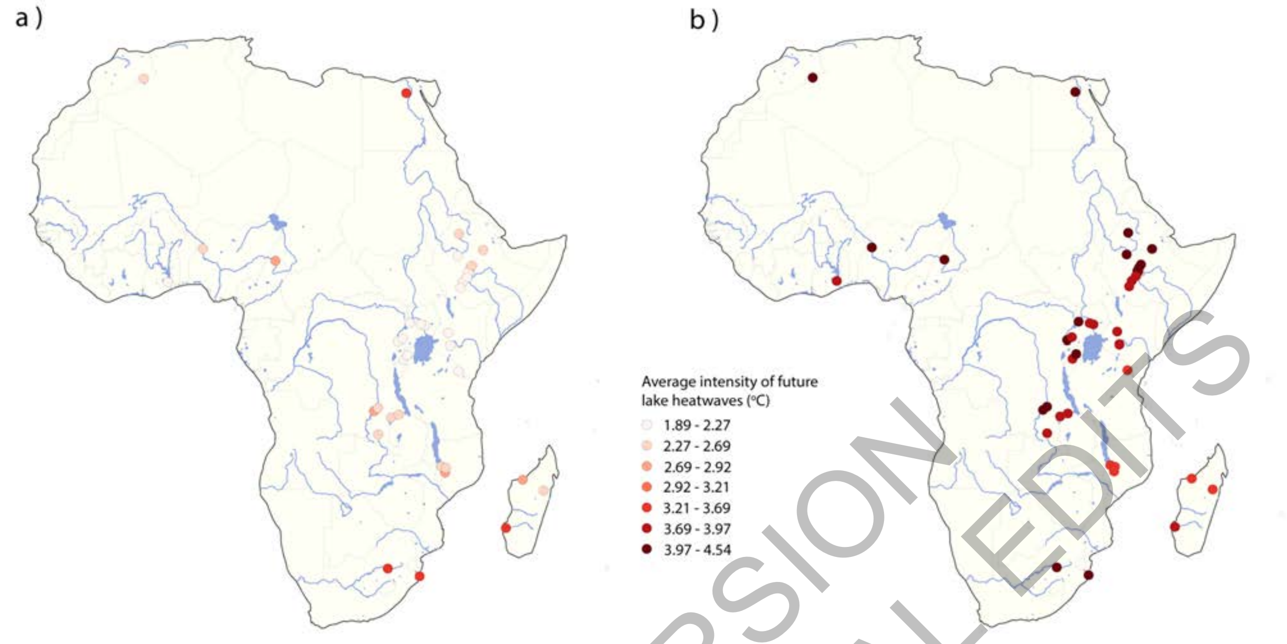


Figure 9.21: Climate change is projected to increase the intensity of lake heatwaves across Africa. Projected increases in average intensity of lake heatwaves (°C) under (a) 1.8°C global warming (RCP2.6 in 2070–2099) and (b) 4.2°C global warming (RCP8.5 in 2070–2099). Each lake is represented by a point. Data were extracted from (Woolway et al., 2021).

Lake surface temperatures across Africa are expected to rise in tandem with increasing global warming. Lake heatwaves, periods of extreme warm lake surface water temperature, are projected to become hotter and longer (Figure 9.21), with heatwaves more than 300 days per year in many lakes for global warming of 4.2°C (Woolway et al., 2021). Lake warming is expected to have adverse consequences for aquatic biodiversity, habitats, water quality and disruption of current lake physical processes and circulation patterns (Kraemer et al., 2021).

9.7.2.2 Vulnerability

Climate change is projected to reduce water availability and increase the extent of water scarcity (Mekonnen and Hoekstra, 2016), particularly in southern and North Africa, while other regions will be more affected by increased hydrological variability over temporally short to interannual timescales (see Section 9.6.2). African countries are considered to be particularly at risk due to their underlying vulnerabilities (IPCC, 2014; UNESCO and UN-Water, 2020), yet the continents' water resources are still inadequately quantified and modelled (Müller Schmied et al., 2016; Reinecke et al., 2019), constraining sustainable management practices (Cuthbert et al., 2019; Hughes, 2019).

Hydrological fluctuations are associated with drought, flood and cyclone events which have had multi-sector impacts (Siderius et al., 2021) (see Sections 4.3 and 4.5 in Chapter 4), including: reduced crop production (D'Odorico et al., 2018), migration and displacement (Siam and Eltahir, 2017; IDMC, 2018), food insecurity and extensive livestock deaths (Nhamo et al., 2018), electricity outages (Gannon et al., 2018), increased incidence of cholera (Olago et al., 2007; Sorensen et al., 2015; Houéménou et al., 2020) and increased groundwater abstraction amplifying the risk from sea level rise of saline intrusion (Hamed et al., 2018; Ouhamdouch et al., 2019).

The literature shows significant gender-differentiated vulnerability and intersectional vulnerability to climate change impacts on water in Africa (Fleifel et al., 2019; Grasham et al., 2019; Mackinnon et al., 2019; Dickin et al., 2020; Lund Schlamovitz and Becker, 2020), although studies are generally lacking in northern Africa (Daoud, 2021). Women and girls are in most cases more impacted than men/boys by customary water practices as adult females are the primary water collectors (46% in Liberia to 90% in Cote d'Ivoire), while more female than male children are associated with water collection (62% compared with 38%, respectively) (Graham et al., 2016). Women and girls face barriers toward accessing basic sanitation and hygiene resources, and 71% of studies reported a negative health outcome, reflecting a water-gender-health nexus (Pouramin et al., 2020). These differential vulnerabilities are crucial for informing adaptation, but are still relatively under-researched, more so for the urban poor than rural communities (Grasham et al., 2019; Mackinnon et al., 2019; Lund Schlamovitz and Becker, 2020).

9.7.3 Water Adaptation Options and their Feasibility

9.7.3.1 Reducing Risk through a Systems Approach to Water Resources Planning and Management

An integrated systems and risk-based approach to the design and management of water resources at scale is generally accepted as a practical and viable way of underpinning the resilience of water systems to climate change and human pressures (Duffy, 2012; García et al., 2014). Such approaches confer multiple benefits to nature and society at scale and enhance efficiency gains through technology and management improvements, but their full implementation has not yet been realised (Weinzierl and Schilling, 2013; McDonald et al., 2014; UN Environment, 2019). Drylands are particularly singled out as ignored areas that require Integrated Water Resource Management approaches (Stringer et al., 2021) (Section 9.3.1). Appropriate nature-based solutions that are applicable at scale should be identified and strongly embedded in these approaches to deliver multiple benefits while maintaining the integrity of ecosystems and biodiversity (UN Environment, 2019) (see Sections 9.6.4, 9.8.5, and Box 4.6). Furthermore, adaptation options are often influenced or constrained by institutions, regulation, availability, distribution, price and technologies (McCarl et al., 2016). Thus, institutional capacity to manage complex water supply systems under rapidly increasing demand and climate change stress is critical in achieving water security for African cities, particularly as cities become more dependent on alternative and distant water sources (Padowski et al., 2016).

9.7.3.2 Adopting Nexus Lenses

The water-energy-food (WEF) nexus explicitly recognises the strong interdependencies of these three sectors and their high levels of exposure to climate change (Zografos et al., 2014; Dottori et al., 2018) (see Box 9.5). With increasing societal demands on more variable water resources under climate change, an intensification of WEF competition and trade-offs are projected (D'Odorico et al., 2018; Dottori et al., 2018). Other interacting factors, for example, the increasing number of transnational investments in land resources can lead to localised increased competition for water resources (Messerli et al., 2014; Breu et al., 2016; Chiarelli et al., 2016). Understanding such nexus inter-linkages can help characterise risks to water resource security, identify co-benefits and clarify the range of multi-sectoral actors involved in and affected by development decisions (Kyriakarakos et al., 2020). Major barriers and entry points for greater integration include coordination of horizontal policy and integration of climate change adaptation actions (England et al., 2018), capturing the scarcity values of water and energy embedded in food/energy products (Allan et al., 2015), and inclusion of community-based organisations such as water resource user associations (Villamayor-Tomas et al., 2015) and agricultural cooperatives (Kyriakarakos et al., 2020).

[START BOX 9.5 HERE]

Box 9.5: Water-Energy-Food Nexus

The water-energy-food (WEF) nexus explicitly recognises the strong interdependencies of these three sectors and their high levels of exposure to climate change. Risks can be transmitted from one WEF sector to the other two with cascading risks to human health, cities and infrastructure (Conway et al., 2015; Mpandeli et al., 2018; Nhamo et al., 2018; Yang and Wi, 2018; Ding et al., 2019; Simpson et al., 2021b). For example, increasing demand for water for agricultural and energy production is driving an increasing competition over water resources between food and energy industries which, among other effects, compromises the nutritional needs of local populations (Zografos et al., 2014; Dottori et al., 2018). Drought events, such as in southern

Africa during the 2015/16 El Niño, have been associated with major multi-sector impacts on food security (over 40 million food-insecure people and extensive livestock deaths) and reduced energy security through disruption to hydropower generation (associated in Zambia with the lowest rate of real economic growth in over 15 years)(Nhamo et al., 2018). The WEF nexus of the Nile and Zambezi river basins, which include many of Africa's largest existing hydropower dams, have received the most attention. In these two regions where socioeconomic development is already driving up demand, projections indicate that water scarcity may be exacerbated by drying (Munday and Washington, 2019) and increased flow variability (Siam and Eltahir, 2017). However, for Africa more widely, very few studies fully integrate all three WEF nexus sectors and rarely include an explicit focus on climate change.

In Africa, the climate risks that the water, energy and food sectors will face in the future are heavily influenced by the infrastructure decisions that governments make in the near term. The African Union's Programme for Infrastructure Development (PIDA), along with other national energy plans (jointly referred to as PIDA+), aim to increase hydropower capacity nearly six-fold, irrigation capacity by over 60% and hydropower storage capacity by over 80% in major African river basins (Cervigni et al., 2015). The vast majority of hydropower additions would occur in the Congo, Nile, Zambezi and Niger river basins, and the majority of the irrigation capacity additions would occur in the Niger, Nile and Zambezi River basins (Huber-Lee et al., 2015) (Figure Box 9.5.1).

Climate change risk to the productivity of this rapidly expanding hydropower and irrigation infrastructure compound the overall WEF nexus risk. Future levels of rainfall, evaporation and runoff will have a substantial impact on hydropower and irrigation production. Climate models disagree on whether climates will become wetter or dryer in each river basin. Cervigni et al. (2015) modelled revenues from the sale of hydroelectricity and irrigated crops in major African river basins under different climate scenarios between 2015 and 2050 (Figure Box 9.5.1). The study found that hydropower revenues in the driest climate scenarios could be 58% lower in the Zambezi River basin, 30% lower in the Orange basin and 7% lower in the Congo basin relative to a scenario with current climate conditions. Hydropower revenues in the wettest climate scenario could be more than 20% higher in the Zambezi River basin and 50% higher in the Orange basin. The biggest risk to the production of irrigated crops is in the eastern Nile where irrigation revenue could be 34% lower in the driest scenario and 11% higher in the wettest than in a scenario without climate change (Cervigni et al., 2015).

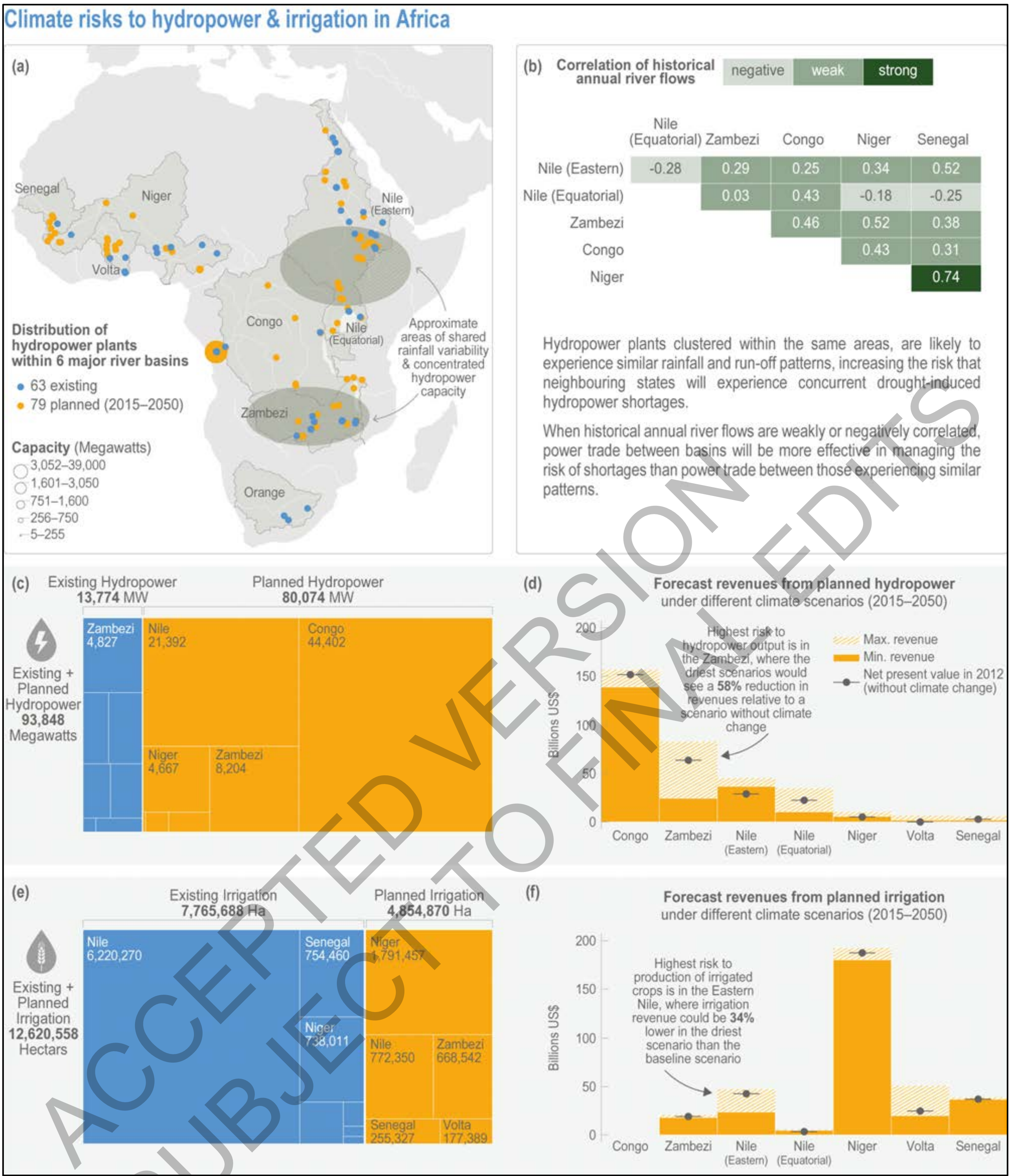


Figure Box 9.5.1: Climate risks to hydropower and irrigation in Africa. The map shows the location and size of existing (blue) and planned (red) hydropower plants in African governments' infrastructure expansion plans, 2015–2050. The bar graphs show the forecast revenues for hydropower and irrigation infrastructure from 2015-2050 in each river basin. Hydropower revenues refer to net present value of hydroelectricity produced in each river basin over the period, and irrigation revenues refer to the crop revenues per hectare for each crop multiplied by the number of hectares of each crop across the basin. Dark blue dots show forecasted revenues from 2015–2050 of existing irrigation and hydropower in major African river basins in a scenario without further climate change (i.e., based on historical data). Red dots show how hydropower and irrigation revenues are expected to increase as new hydropower and irrigation infrastructure is added in a scenario without climate change. Blue and green bars illustrate the range of forecasted revenue from 2015–2050 from new and existing hydropower and irrigation under 121 different climate futures. In river basins with a wide range of potential outcomes, such as the eastern Nile and Zambezi River, there is significant uncertainty around revenue forecasts based on historical trends. All figures are estimates of the net present value of revenues, using a discount rate of 3%, and are in 2012 USD billions. The 121 potential climate futures were derived using different General Circulation Models (GCMs), Representative Concentration Pathways (RCPs), and downscaling methods. IPCC AR4 and AR5 provided data from 22 and 23 GCMs, respectively. These were evaluated across two or three emissions pathways, including RCP4.5 and RCP8.5. The Bias Corrected Spatial Disaggregation (BCSD) method of downscaling was then used to derive 99 potential climate futures. An additional 22 climate futures (11 GCMs driven by the RCP4.5 and RCP8.5 emissions pathways) were produced using the Empirical Statistical Downscaling Methods developed at the Climate Systems Analysis Group at the University of Cape Town.. Data sourced from (Cervigni et al., 2015).

Studies have used the river basin as a unit of analysis and adopted sophisticated techniques to assess and present trade-offs between competing uses. For example, Yang and Wi (2018) consider the WEF nexus in the Great Ruaha tributary of the Rufiji River in Tanzania motivated by an observed decrease in streamflow during the dry season in the 1990s, but without an explicit focus on climate. Yang and Wi (2018) show sensitivity of water availability for irrigated crop production to warming, and sensitivity of hydropower generation and ecosystem health to changes in precipitation and dam development. Understanding of WEF nexus interlinkages can help characterise risks and identify entry points and the relevant institutional levels for cross-sectoral climate change adaptation actions (England et al., 2018). An integrated response can be enhanced through the inclusion of community-based organisations, such as water resource user associations and the wide range of other multi-sectoral actors involved in and affected by development decisions. Capturing the scarcity values of water and energy embedded in food and other products can help identify the co-benefits and costs of integrated adaptation (Allan et al., 2015).

[END BOX 9.5 HERE]

9.7.3.3 Climate-Proofing Water Infrastructure

While natural variability in the hydrological cycle has always been considered by water resources planners and engineers (Müller Schmied et al., 2016; Muller, 2018), many countries will have to take into consideration the range of historically unprecedented extremes expected in the future. Increasingly, the provision of urban water security is dependent on the functioning of complex bulk water infrastructure systems consisting of dams, inter-basin transfers, pipelines, pump stations, water treatment plants and distribution networks (McDonald et al., 2014). Risk-based studies on the potential climate change risks for water security show that there are benefits when risks are reduced at the tails of the distribution - floods and droughts—even if there is little benefit in terms of changes in the mean (Arndt et al., 2019). When risk is taken into account in an integrated (national) bulk water infrastructure supply system, the overall impact of climate change on the average availability of water to meet current and future demands is significantly reduced (Cullis et al., 2015). Further, stemming leakages and enhancing efficiency through technology and management improvements is important in building climate-resilient water conveyance systems (UN Environment, 2019). African cities could leap-frog through the development phases to achieve a water sensitive city ideal, reaping benefits such as improved liveability, reduced flooding impacts, safe water and overall lower net energy requirements and avoid making the mistakes developed countries' cities have made (Fisher-Jeffes et al., 2017) (Brodnik et al., 2018). However, the challenge of large proportions of the population lacking access to even basic water supply and sanitation infrastructure (Armitage et al., 2014) must be simultaneously and effectively addressed, particularly in light of other major exacerbating factors like the COVID-19 pandemic (Section 9.11.5).

9.7.3.4 Decision Support Tools for Managing Complex Water Systems

Many studies in Africa use the river basin as a unit of analysis at scale and adopt sophisticated model-based techniques to assess climate change impacts on hydrology under different climate and development scenarios, thereby presenting trade-offs between competing uses such as hydropower generation, irrigation and ecosystem requirements (Yang and Wi, 2018; Ahmed, 2020) (Section 9.12.1). However, longer (multi-decadal) hydrological datasets and model improvements are required (Taye et al., 2015), and models should incorporate the quantification of the wider benefits, risks and political opportunities arising from reservoir development to better inform decision-makers to achieve a higher level of (transboundary) cooperation (Digna et al., 2016; Nijsten et al., 2018). Collaboration between scientists and policy-makers to address the complexity of decision-making under uncertainty (Steynor et al., 2016) (Pienaar and Hughes, 2017), coupled with community involvement in participatory scenario development and participatory GIS to aid in collaborative planning that is context-specific (Muhati et al., 2018; Álvarez Larrain and McCall, 2019) are powerful tools for more beneficial adaptive and resilience building actions.

9.7.3.5 Other Adaptation Options

Climate change is projected to increase dependence upon groundwater withdrawals in most parts of Africa as an adaptive strategy to amplified variability in precipitation and surface water resources, highlighting the need for conjunctive surface-groundwater management and rainwater harvesting (Cobbing and Hiller, 2019; Taylor et al., 2019). Alternative water supply options such as desalination, managed aquifer recharge, stormwater harvesting and re-use (direct and indirect, potable and non-potable), all require significant amounts of energy and are complex to operate and maintain. A failure to provide a source of reliable energy and the capacity to implement, maintain, and operate these systems is a significant contributor to water scarcity risks in Africa (Muller and Wright, 2016). Soft adaptation options include increasing water use efficiency, chaning agricultural practices, more appropriate water pricing (Olmstead, 2014) and enhancing capacity to tackle groundwater overexploitation (Kuper et al., 2016), among others (see Section 9.10.2.4; Sections 4.6 and 4.7 in Chapter 4).

9.7.3.6 Mainstreaming Gender Across all Adaptation Options

Gender is important in building resilience and adaptation pathways to global environmental change (Ravera et al., 2016). It is well-established that women, in most societies, have accumulated considerable knowledge about water resources, including location, quality and storage methods because they are primarily responsible for the management of water for household water supply, sanitation and health, and for productive uses in subsistence agriculture (UN-Water, 2006). As gender-differentiated relationships are complex, adaptation should take into account intersectional differences such as homeownership, employment and age (Harris et al., 2016), educational, infrastructural and programmatic interventions (Pouramin et al., 2020), aspects of protection and safety (Mackinnon et al., 2019), barriers to adaptation and gendered differences in the choice of adaptation measures (Mersha and Van Laerhoven, 2016), the complex power dynamics of existing social and political relations (Djoudi et al., 2016; Rao et al., 2017) and inclusion and empowerment of women in the management of environmental resources (Makina and Moyo, 2016). Incorporation of gender and water inequities into climate change adaptation would have a significant impact on achieving the SDGs (particularly 1,3,4, 5 and 6), while failure to incorporate gender will undermine adaptation efforts (Bunce and Ford, 2015; Fleifel et al., 2019; Pouramin et al., 2020).

9.8 Food Systems

Ideally, a systems approach (Ericksen, 2008; Rosenzweig et al., 2020) could be used to assess how global environmental changes affect the food sector in Africa, emphasising the complex interactions that exist within the components of the food supply system, including its enabling socioeconomic and biophysical environment (Ingram, 2011; Foran et al., 2014; Tendall et al., 2015), and how food is connected to other critical systems such as energy, water and transportation (Albrecht et al., 2018) (see Box 9.5). Production will not be the only aspect of food security that is impacted by climate change. Processing, storage, distribution and consumption will also be affected. Access to healthy and adequate food in the face of climate change requires resilience across these components of the food system (Adenle et al., 2017). However, most studies on climate change impacts on food in Africa are heavily focused on production only. A significant knowledge gap, therefore, exists around the complex ways in which climate change will interact with broader components of African food systems, and strategies for making these systems more resilient, particularly in a context of rapid population growth and urbanisation across the continent (Adenle et al., 2017; Schmitt Olabisi et al., 2018).

9.8.1 Vulnerability to Observed and Projected Impacts from Climate Change

Agricultural activities are mainly rainfed and subsistence across Africa. The dominant farming system is mixed cereal-livestock (Thornton and Herrero, 2015; Nematchoua et al., 2019), with pastoral systems in East Africa, and commercial livestock and crop systems also representing a significant proportion of the food system in southern Africa (Thornton and Herrero, 2015). Many African regions are vulnerable to food insecurity, facing dwindling food production, food access, stocks and income due to low adaptive capacity (Evariste et al., 2018; Fuller et al., 2018; Bang et al., 2019; Gebre and Rahut, 2021).

Across regions with food systems highly vulnerable to climate change, female farmers, cocoa farmers, pastoralists, plantain farmers, coastal zone communities, rural households and forest communities in central Africa indicate higher vulnerability (Chia et al., 2016; Schut et al., 2016; Nematchoua et al., 2019). Their vulnerability is multidimensional and affected by low adaptive capacity, location, livelihood system, socioeconomic status, gender, age and ethnicity (Perez et al., 2015; Weston et al., 2015; Gebre and Rahut, 2021) (see also Box 9.1).

Across Africa, including West Africa, adverse climate conditions for agricultural and pastoral livelihoods have contributed to rural-to-urban migration patterns and migration among African regions (see Box 9.8) (Baudoin et al., 2014; Abbas, 2017; Gemenne and Blocher, 2017b). Rural to urban migration may increase vulnerability of migrants through exposure to additional risks, including food insecurity (Amadi and Ogonor, 2015; Abbas, 2017). In general, West African countries are characterised by the poor adaptive capacity of rural households (Douxchamps et al., 2015; Dumenu and Obeng, 2016).

In North Africa, livelihoods and economies are strongly dependent on agriculture. Pressure on water demand due to climate change and variability is threatening income, development processes and food security in the region (*high confidence*) (Mohmmed et al., 2018; Khedr, 2019). Increased temperatures and droughts have enhanced the vulnerability of the irrigation sector (Verner et al., 2018; İlseven et al., 2019), and the combined effect of these hazards negatively affects crop and animal production (Mohmmed et al., 2018; Verner et al., 2018). For example, dairy farms in Tunisia are experiencing warmer temperatures above the thermoneutral zone of cows for more than 5 months each year, reducing production efficiency and resulting in significant economic losses (Amamou et al., 2018).

Non-climatic stressors aggravate food insecurity in many parts of the continent, including lack of access to production inputs and land, lack of education and limited income sources, with adverse climate impacts on agriculture reducing education attainment for children (Evariste et al., 2018; Fuller et al., 2018) (Section 9.11.1.2). Geographic and social isolation is another type of social vulnerability, especially for pastoralist communities in East and southern Africa (Sonwa et al., 2017; Basupi et al., 2019). Rural communities often have poor transport networks, limited access to markets or information and fewer livelihood alternatives, and are less able to be informed of risks or be assisted in the event of extreme climate events (Sonwa et al., 2017; Basupi et al., 2019).

Extreme climate events have been key drivers in rising acute food insecurity and malnutrition of millions of people requiring humanitarian assistance in Africa (*high confidence*). Between 2015 and 2019, an estimated 45.1 million people in the Horn of Africa and 62 million people in eastern and southern Africa required humanitarian assistance due to climate-related food emergencies. Children and pregnant women experience disproportionately greater adverse health and nutrition impacts (*very high confidence*) (Gebremeskel Haile et al., 2019) (see Chapter 7, Section 7.2.4).

Future climate warming will *likely* have a substantial impact on food security in Africa and is anticipated to coincide with low adaptive capacity as climate change intensifies anthropogenic stressors, as 85% of Africa's poor live in rural areas and mostly depend on agriculture for their livelihoods (Adams, 2018; Mahmood et al., 2019). This highlights the need to prioritise innovative measures for reducing vulnerabilities in Africa food systems (Fuller et al., 2018; Mahmood et al., 2019).

Climate change impacts could increase the global number of people at risk of hunger in 2050 by 8 million people under a scenario of sustainable development (SSP1) and 80 million people under a scenario of reduced international cooperation and low environmental protection (SSP3), with populations concentrated in sub-Saharan Africa, South Asia and Central America (see Chapter 5, Sections 5.2.2, 5.4.2 and 5.4.3). Global climate impacts on food availability are expected to lead to higher food prices, increasing the risk of hunger for people in African countries, and slow progress towards eradicating child undernutrition and malnutrition in all its forms (see Chapter 7, Section 7.4).

9.8.2 Observed Impacts and Projected Risks to Crops and Livestock

9.8.2.1 Observed Impacts and Projected Risks for Staple Crops

Climate change is already negatively impacting crop production and slowing productivity growth in Africa (*high confidence*) (Iizumi et al., 2018; Ray et al., 2019; Sultan et al., 2019; Ortiz-Bobea et al., 2021). Climate change has reduced total agricultural productivity growth in Africa by 34% since 1961, more than in any other region (Ortiz-Bobea et al., 2021), more than in any other region. Maize yields have decreased 5.8% and wheat yields 2.3%, on average, in sub-Saharan Africa due to climate change in the period 1974–2008 (Ray et al., 2019). Overall, climate change has decreased food total calories across all crops in sub-Saharan Africa by 1.4% on average compared to a no climate change counterfactual since 1970, with up to 10% reductions in Ghana and Zimbabwe (Ray et al., 2019).

Farmers perceive a wide variety of climate threats to crop production including droughts, precipitation variability, a delayed onset and overall reductions in early growing season rainfall and excess heat (Rankoana, 2016a; Elum et al., 2017; Kichamu et al., 2017; Alvar-Beltrán et al., 2020). Farmers attribute these perceived changes as a major driver of yield losses (Ayanlade and Jegede, 2016) (see Section 9.4.5). Over half of surveyed farmers in West Africa perceive increases in crop pests and diseases as due to climate change as the range and seasonality of many pests and diseases change under warming (Callo-Concha, 2018),. Pests and diseases contribute between 10–35% yield losses for wheat, rice, maize, potato and soybean in sub-Saharan Africa (Savary et al., 2019). Recent locust outbreaks in 2019 in East Africa have been linked to climate conditions caused in part by ocean warming (Wang et al., 2020b) (see Box 5.8 in Chapter 5).

Future climate change may increase insect pest-driven losses in Africa for maize, rice and wheat: Compared to 1950–2000, losses may increase by up to 50% at 2°C of global warming (Deutsch et al., 2018). However, many challenges remain in modelling pest and disease under climate change with additional research needed expanding the range of crops and diseases studied (Newbery et al., 2016).

Agriculture in Africa is especially vulnerable to future climate change in part because 90–95% of African food production is rainfed (Adams, 2018). Maize, rice, wheat and soybean yields in tropical regions (20S-20N) are projected to decrease approximately 5% per °C of global warming in a multi-model ensemble (Rosenzweig et al., 2014; Franke et al., 2020). Dryland agricultural areas are especially sensitive to changes in rainfall. For example, without adaptation, substantial yield declines are projected for staple crops in North Africa (Figure 9.3). A recent meta-analysis of 56 studies indicates that, compared to 1995–2005, economic welfare in the agriculture sector in North Africa is projected to decline 5% for 2℃ global warming and 20% for 3℃ global warming, and in sub-Saharan Africa by 5% (2℃) and 10% (3℃) (Moore et al., 2017a), both more pessimistic than previous economic estimates.

A synthesis of projected staple crop impacts across 35 studies for nearly 1040 locations and cases shows on average decreases in crop yields with increasing global warming across staple crops in Africa, including when accounting for CO_2 increases and adaptation measures. For example for maize in West Africa, compared to 2005 yield levels, median projected yields decrease 9% at 1.5℃ global warming and 41% at 4℃, without adaptation (Figure 9.22). However, uncertainties in projected impacts across crops and regions are driven by uncertainties in crop responses to increasing CO_2 and adaptation response, especially for maize in East Africa and wheat in North Africa and East Africa (Figure 9.22) (Hasegawa et al., 2021).

There is also growing evidence that climate change is *likely* beginning to outpace adaptation in agricultural systems in parts of Africa (Rippke et al., 2016). For example, despite the use of adjusted sowing dates and existing heat-tolerant varieties, Sudan's domestic production share of wheat may decrease from 16.0% to 4.5–12.2% by 2050 under RCP8.5 (2.4℃ global warming) (Iizumi et al., 2021).

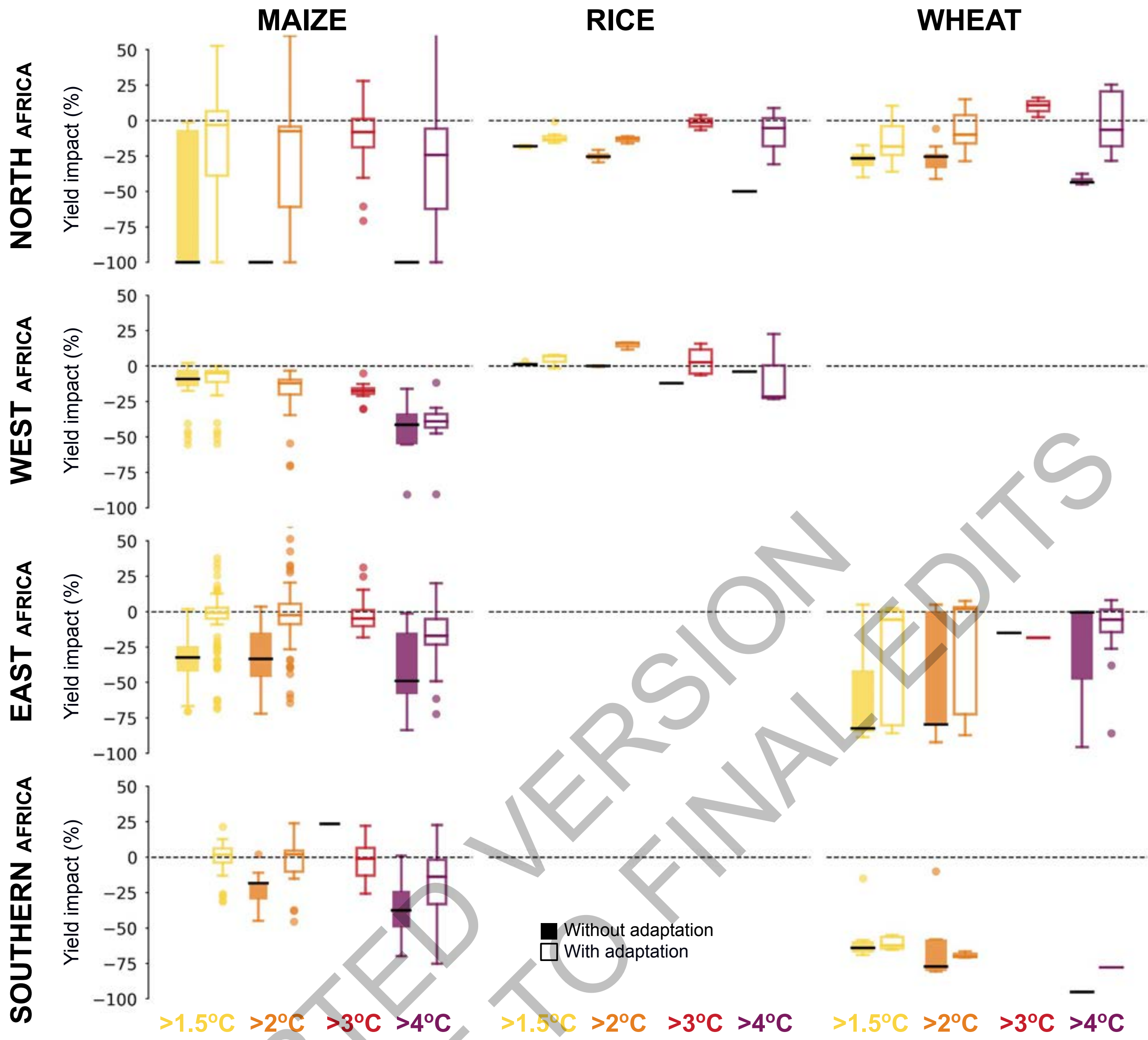


Figure 9.22: Projected yield changes for major crops in Africa due to climate change (compared to 2005 yield levels). Impacts are binned into global warming levels above pre-industrial global mean temperature (1850–1900). Boxplots show a synthesis of projected staple crop impacts, with and without adaptation measures (e.g. planting date, cultivar, tillage or irrigation). On average crop yields are projected to decrease with increasing global warming across staple crops in Africa. The overall adaptation potential to offset yield losses across Africa for rice, maize and wheat reduces with increasing global warming. On average, in projections including adaptation options and yield losses, in the median case, are reduced from –33% to –10% of 2005 levels at 2°C of global warming and from –46% to –23% at 4°C. Data are a synthesis across 35 studies for nearly 1040 locations and cases of projected impacts for regions of Africa for maize, rice and wheat (Hasegawa et al., 2021) (Supplementary Material Table SM 9.5).

Elevated CO_2 concentrations in the atmosphere might mitigate some or all climate-driven losses (Swann et al., 2016; Durand et al., 2018), but there is considerable uncertainty around the CO_2 response (Deryng et al., 2016; Toreti et al., 2020), especially when nutrients such as nitrogen and phosphorus are limiting crop growth. Additional Free-Air Carbon dioxide Enrichment (FACE) experiments are needed in the tropics, particularly on the African continent, to better understand the impacts of increased CO_2 concentrations on the productivity of crops and cultivars grown in Africa under additional temperature impacts and water and nutrient limitations (Ainsworth and Long, 2021). Warming and elevated CO_2 may also change the nutritional content of some crops. By 2050 under RCP8.5 (2.4°C global warming), overall wheat yields and grain protein content may decrease by 10% and 15%, respectively, in North and East Africa, and by over 15% in southern Africa (Asseng et al., 2019). See Chapter 5 for more details on CO_2 impacts and uncertainties.

9.8.2.2 Observed Impacts and Projected Risks on Regional Cash Crops and Food Crops

Few studies have attributed changes in yields of cash crops and other regionally important food crops in Africa to anthropogenic climate change, but recent research suggests yields of cash crops in Africa have already been impacted by climate change, in both a negative and positive manner (Falco et al., 2012; Traore et al., 2013; Ray et al., 2019). For example, between the period 1974–2008, sugarcane yields decreased on average by 3.9% and 5.1% in sub-Saharan Africa and North Africa, respectively, due to climate change, while sorghum yields increased 0.7%, and cassava yield increased 1.7% in sub-Saharan Africa and 18% in North Africa (Ray et al., 2019).

There are also limited studies for assessing projected climate change impacts on important cash crops and food crops other than maize, rice and wheat (Jarvis et al., 2012; Schroth et al., 2016; Awoye et al., 2017). These studies often represent changes at specific sites in a country or assess changes in the yield and/or suitability for cultivating a specific crop across a larger geographic area. Climate change is projected to have overall positive impacts on sugarcane and Bambara nuts in southern Africa, oil palm in Nigeria and chickpea in Ethiopia (*low confidence*) (Figure 9.23).

Climate change is projected to reduce sorghum yields in West Africa (Figure 9.23). For example, across the West African Sahel savanna sorghum yields are projected to decline on average 2% at 1.5°C and 5% at 2°C global warming (Faye et al., 2018). For coffee and tea in eastern Africa, olives in Algeria and sunflower in Botswana and Morocco, we find studies indicating mostly negative impacts on production systems. For example, in Kenya, compared to 2000, optimal habitat for tea production is projected to decrease in area by 27% with yields declining 10% for global warming of 1.8–1.9°C, although yield declines may be reduced at higher levels of warming (Beringer et al., 2020; Jayasinghe and Kumar, 2020; Rigden et al., 2020). Suitable area for tea production may reduce by half in Uganda (Eitzinger et al., 2011; Läderach et al., 2013). In East Africa, the coffee-growing area is projected to shift up in elevation with suitability decreasing 10–30% between 1.5–2°C of global warming (Bunn et al., 2015; Ovalle-Rivera et al., 2015).

For all other crops, there is at least one study that finds low to highly negative impacts for one or several warming levels (Figure 9.23). Mixed results on the direction of change often occur when several contrasting sites with varying baseline climates are studied, and when a study considers the full range of climate scenarios. For example, there are mixed results on the direction of change for impacts of 1.5°C global warming on cassava, cotton, cocoa and millet in West Africa (*low confidence*) (Figure 9.23). In general, there is limited evidence in the direction of change, due to single studies being available for most crop-country combinations (Knox et al., 2010; Chemura et al., 2013; Asaminew et al., 2017; Bouregaa, 2019). Occasionally, two studies agree on the direction and magnitude of change, for example, for potatoes in East Africa, yields are projected to decrease by 11–17% with 3°C of warming (Fleisher et al., 2010; Tatsumi et al., 2011).

Crop	Region (Country)	Global warming levels >1.5 Direction of change	>1.5 Level of confidence in the direction of change	>1.5 Level of risk	>2 Direction of change	>2 Level of confidence in the direction of change	>2 Level of risk	>3°C Direction of change	>3°C Level of confidence in the direction of change	>3°C Level of risk	>4°C Direction of change	>4°C Level of confidence in the direction of change	>4°C Level of risk	Adaptation options
Cassava	EA	Negative	Low	HN	ID	ID	ID	Positive	Low	MP	ID	ID	ID	
	WA	Mixed	Low	Mixed	ID	ID	ID	Negative	Low	MN	ID	ID	ID	
	CA	Negative	Low	LN	ID	ID	ID	Negligible	Low	Negligible	ID	ID	ID	
	SA	Positive	Low	HP	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	NA	ID	ID	ID	ID	ID	ID	Negligible	Low	Negligible	ID	ID	ID	
	SSA	Mixed	Low	Mixed	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	
	Sahel	Positive	Low	LP	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID
Sugarcane	SA (South Africa & Swaziland)	ID	ID	ID	Positive	Low	LP	Mixed	Medium	Mixed	ID	ID	ID	ID
Cotton	WA (Benin & Cameroon)	Mixed	Medium	Mixed	Positive	Low	MP	ID	ID	ID	Positive	Low	VP	Late planting can reduce the impact of CC
	EA (Ethiopia)	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	Mixed	Low		
	NA (Sudan)	ID	ID	ID	Negative	Low	HN	ID	ID	ID	ID	ID	ID	
	SSA	Positive	Low	LP	ID	ID	ID	ID	ID	ID	ID	ID	ID	
Oil Palm	WA (Nigeria)	Positive	Low	Negligible*	Positive	Low	HP	ID	ID	ID	Positive	Low	VP	ID
Tobacco	SA (Zimbabwe)	ID	ID	ID	Negative	Low	LN	ID	ID	ID	ID	ID	ID	ID
Cocoa	WA (Ghana & Côte d'Ivoire)	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	ID	ID	ID	ID
Coffee	EA	Negative	Low	HN	Negligible	Low	Negligible	ID	ID	ID	Negative	Low	VN	ID
Tea	EA (Kenya & Uganda)	Negative	Medium	MN	Negative	Medium	MN	Negative	Medium	MN	ID	ID	ID	ID
Groundnut	SSA	ID	ID	ID	Negative	Low	MN	ID	ID	ID	ID	ID	ID	
	WA (Benin)	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	NA (Sudan)	ID	ID	ID	Negative	Low	LN	ID	ID	ID	ID	ID	ID	ID
Bambara nut	SA	ID	ID	ID	Positive	Low	VP	ID	ID	ID	ID	ID	ID	ID
Chickpea	EA (Ethiopia)	Positive	Low	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID
Olive	NA (Algeria)	Negative	Low	HN	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID
Millet	WA	Mixed	Low	Mixed	Negligible	Medium	Negligible	ID	ID	ID	ID	ID	ID	ID
Sorgulm	WA	Negative	Low	MN	Negative	Low	MN	Negative	Low	LN	ID	ID	ID	Crop modelling suggests that shifts in sowing date and fertilizer rate can be effective in reducing negative impacts on soghum yield in Southern Africa
	SA	Mixed	Low	Mixed	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	NA (Sudan)	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	
Potato	Africa	Negative	Low	LN	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	
	EA	Negative	Low	LN	ID	ID	ID	Negative	Medium	MN	Negative	Low	HN	
	SA	Mixed	Low	Mixed	ID	ID	ID	Negative	Low	HN	ID	ID	ID	
	WA	Negative	Low	LN	ID	ID	ID	Positive	Low	LP	ID	ID	ID	
	Sahel	Mixed	Low	Mixed	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	CA	Negative	Low	LN	ID	ID	ID	Negative	Low	MN	ID	ID	ID	ID
Sunflower	SA (Botswana)	Negative	Low	HN	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	NA (Morocco)	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID
Cowpea	WA (Benin)	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID

Direction of impact	Level of confidence		Level of risk	% Change in Climate suitability (area)	% Yield change (biomass, sucrose)	% Change in current real GDP (due cost of inaction on adaptation)
Positive	Low	4	Very positive (VP)	>40%	>40%	>4%
Negative	Medium	3	Highly positive (HP)	>20%	>20%	>2%
Mixed	High	2	Moderately positive (MP)	>10%	>10%	>1%
Insufficient data (ID)		1	Low positive (LP)	>5%	>5%	>0.5%
		0	Negligible			
		-1	Low negative (LN)	>5%	>5%	>0.5%
		-2	Moderately negative (MN)	>10%	>10%	>1%
		-3	Highly negative (HN)	>20%	>20%	>2%
		-4	Very negative (VN)	>40%	>40%	>4

Figure 9.23: Projected risks at increasing global warming levels for regionally important cash and food crops in Africa. Insufficient data (ID) indicates there were limited to no published studies that have quantified projected climate change impacts or adaptation options for specific crops under different warming levels (see Supplementary Material Table SM 9.6).

9.8.2.3 Observed Impacts and Projected Risks for Wild-Harvested Food

Wild-harvested foods (e.g., fruits, vegetables and insects) provide dietary diversification and for many people in Africa, wild-harvested food plants may provide a livelihood and/or nutritional safety net when other sources of food fail, such as during drought (Sunderland et al., 2013; Shumsky et al., 2014; Wunder et al., 2014; Baudron et al., 2019b). In Zimbabwe, during lean times, consumption of wild fruits increases, as does their sale to generate income for additional food expenses in poor, rural households (Mithöfer and Waibel, 2004). In Zambia, Mali and Tanzania, household surveys indicate that forest products including wild foods can play an important role in reducing household vulnerability to climate shocks by providing alternative sources of food and income during droughts and floods (Robledo et al., 2012). In the Parklands of West Africa, wild trees are a significant source of wild foods and are thus a place where one might expect wild plant foods to make an important contribution to diets and nutrition (Boedecker et al., 2014; Leßmeister et al., 2015). Non-timber forest products are consumed by an estimated 43% of all households in Burkina Faso (FAO, 2019), and wild vegetables accounted for about 50% of total vegetable consumption in southeastern Burkina Faso (Mertz et al., 2001).

The focus of projected climate change impacts has been almost exclusively on agricultural production, yet climate change could have substantial impacts on the distribution and availability of wild-harvested food plants in Africa (Wessels et al., 2021). Non-cultivated species in Africa are vulnerable to current and future climate changes, with widespread changes in woody plant cover already observed (see Section 9.6.1.1). Evidence about the impacts of climate change on individual wild food species is less consistent. Communities in the Kalahari (Crate and Nuttall, 2016) and Zimbabwe (Sango and Godwell, 2015) report growing scarcity of wild foods (such as wild meat and fruit) perceived to be, at least in part, due to drought and climate change. Shea tree (*Vitellaria paradoxa*) nuts provide fats and oils for the diets of many rural populations in West Africa. In Burkina Faso, global warming of 3°C is projected to reduce area of suitable habitat for the Shea tree by 14% (Dimobe et al., 2020). In southern Africa, 40% of native, wild-harvested food plant species are projected to decrease in geographic range extent at 1.7°C global warming with range reductions for 66% of species projected for 3.5°C (Wessels et al., 2021).

9.8.2.4 Observed Impacts and Projected Risks on Livestock

Livestock systems in Africa are already being affected by changes in climate through increased precipitation variability decreasing fodder availability (Sloat et al., 2018; Stanimirova et al., 2019). More than twice as many countries in Africa have experienced increases in precipitation variability in the last century than decreases (Sloat et al., 2018). Fodder availability is also being impacted by Woody Plant Encroachment—the increase in shrub and tree cover—which has increased by 10% on subsistence grazing lands and 20% on economically important grazing lands in South Africa in the last 60 years (Stevens et al., 2016), and is driven in part by climatic factors (see Section 9.6.1.1). Increased temperature and precipitation have contributed to the expanding range, especially in East and southern Africa, of several ixodid tick species which carry economically important livestock diseases (Nyangiwe et al., 2018).

Pastoralists in Africa perceive the climate as already changing and report more erratic and reduced rainfall, prolonged and more frequent droughts and a rise in temperature (Sanogo et al., 2017; Kimaro et al., 2018). They also report reduced milk production, increased deaths and disease outbreaks in their herds due to malnutrition and starvation resulting from the shortages in forage and water (Kimaro et al., 2018). Additional research is required to attribute precipitation variability to anthropogenic forcing (see Section 9.3), and to evaluate the relative contributions of climate change and management to disease vector extent.

Future climate change will have compounding impacts on livestock, including negative impacts on fodder availability and quality, availability of drinking water, direct heat stress and the prevalence of livestock diseases (Nardone et al., 2010; Rojas-Downing et al., 2017; Godde et al., 2021). Climate change is projected to negatively affect fodder availability (Briske, 2017) because overall rangeland net primary productivity (NPP) by 2050 is projected to decrease 42% under RCP4.5 (2°C global warming) and 46% under RCP8.5 (2.4°C global warming) for western sub-Saharan Africa, compared to a 2000 baseline (Boone et al., 2018). NPP is also projected to decline by 37% in southern Africa, 32% in North Africa and 5% in both East Africa and Central Africa by 2050 under RCP8.5 (2.4°C global warming) (Boone et al., 2018). For example, in Zimbabwe by 2040–2070, net revenues from livestock production, compared to a 2011 survey, are projected to decline by 8–32% under RCP4.5 for 2°C and 11–43% under RCP8.5 for 2.7°C global warming due to a decline in fodder availability (Descheemaeker et al., 2018). The available literature does not comprehensively capture the economic implications of climate-related impacts on livestock production across Africa.

Fodder quality, critical for animal health and weight gain, is at risk from climate change as increases in temperature, elevated CO_2 and water stress have been shown to reduce dry matter digestibility and nitrogen content for C_3 grasses (Augustine et al., 2018), tropical C_4 grasses (Habermann et al., 2019) and fodder crops such as Lucerne/Alfalfa (Polley et al., 2013; Thivierge et al., 2016).

Climate change is projected to threaten water availability for livestock. Droughts in Africa have become more intense, frequent and widespread in the last 50 years (Masih et al., 2014), and progressive increase in droughts between three- and twenty-fold under climate change up to 3°C of warming are projected for most of Africa (9.5). In the Klela basin in Mali by 2050, groundwater recharge is projected to decline by 49% and groundwater storage by 24% under RCP8.5 (2.4°C global warming) compared to the 2006 baseline (Toure et al., 2017). Water availability for livestock during drought is a major concern for many African pastoralists including but not limited to those in Zimbabwe (Dzavo et al., 2019) and Nigeria (Ayanlade and Ojebisi, 2019). Increased livestock mortality and livestock price shocks have been associated with droughts in Africa, as well as being a potential pathway for climate-related conflict (Catley et al., 2014; Maystadt and Ecker, 2014) (see Box 9.9).

Heat stress may already be the largest factor impacting livestock production in many regions in Africa (El-Tarabany et al., 2017; Pragna et al., 2018), as the combination of high temperatures and high relative humidity can be dangerous for livestock and has already decreased dairy production in Tunisia (Amamou et al., 2018). Climate change is projected to increase heat stress for all types of livestock, especially in the tropics (Lallo et al., 2018) (Figure 9.24). More studies quantifying the impact of heat stress on other types of livestock production loss are needed in Africa (Rahimi et al., 2021).

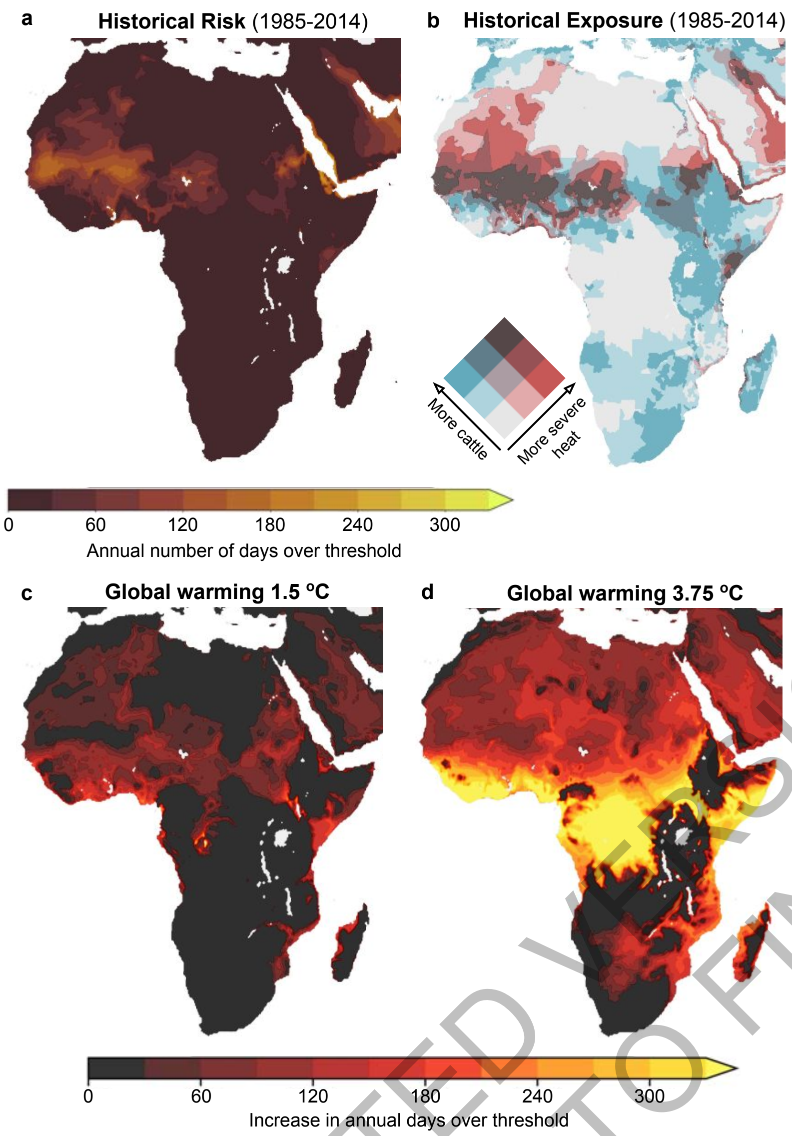


Figure 9.24: Severe heat stress duration for cattle in Africa is projected to increase with increased global warming. (a) Number of days per year with severe heat stress in the historical climate (1985-2014). (b) Historical cattle exposure to severe heat. (Cattle density fromGilbert et al., 2018) . (c and d) Increase in the number of days per year with severe heat stress for global warming of 1.5C and 3.75C above pre-industrial levels (1850-2100). Severe heat stress for cattle is projected to become much more extensive in the future in Africa at increased global warming levels. Strong mitigation would substantially limit the spatial extent and the duration of cattle heat stress across Africa. Heat stress is estimated using THI (Temperature Humidity Index) with a value greater than 79 considered the onset of severe heat stress (Livestock Weather Safety Index) (Lallo et al., 2018). Global warming of 1.5°C used scenario SSP1–2.6 and global warming of 3.75°C used SSP5–8.5, both for 2070–2099 (12 climate models fromO'Neill et al., 2016; Tebaldi et al., 2021) .

Climate change will impact livestock disease prevalence primarily through changes in vector dynamics or range (Abdela and Jilo, 2016; Semenza and Suk, 2018). African Rift Valley Fever (RVF) and Trypanosomiasis are positively associated with extreme climate events (droughts and ENSO) (Bett et al., 2017) and are projected to expand in range under climate change (Kimaro et al., 2017; Mweya et al., 2017). More quantitative estimates of projected risk from diseases are needed.

9.8.3 Adapting to Climate Variability and Change

Agricultural and livelihood diversification are strategies used by African households to cope with climate change, enabling them to spread risks and adjust to shifting climate conditions (Thierfelder et al., 2017; Thornton et al., 2018). This includes adjusting cropping choices, planting times, or size, type and location of planted areas (Altieri et al., 2015; Nyagumbo et al., 2017; Dayamba et al., 2018). In southern Africa, changes in planting dates provide farmers with greater yield stability in uncertain climate conditions (Nyagumbo et al., 2017). In Ghana, farmers are changing planting schedules and using early maturing varieties to cope with late-onset and early cessation of the rainy season (Antwi-Agyei et al., 2014; Bawakyillenuo et al., 2016).

The use of drought-tolerant crop varieties is another adaptation available to African farmers (Hove and Gweme, 2018; Choko et al., 2019). Adoption, however, is hindered by lack of information and training, availability or affordability of seed, inadequate labelling and packaging size for seed supplies and financial constraints (Fisher et al., 2015). Moreover, drought-tolerant varieties do not address changing temperature regimes (Guan et al., 2017).

Crop diversification enhances crop productivity and resilience and reduces vulnerability in smallholder farming systems (McCord et al., 2015; Mulwa and Visser, 2020). In Tanzania, diversified crop portfolios are associated with greater food security and dietary quality (Brüssow et al., 2017). In Kenya, levels of crop diversity are higher in villages affected by frequent droughts, which are the main cause of crop failure (Bozzola and Smale, 2020). They also help control pest outbreaks, which may become more frequent and severe under increased climate variability and extreme events (Schroth and Ruf, 2014). High farming diversity enables households to better meet food needs, but only up to a certain level of diversity (Waha et al., 2018), and the viability of and benefits from mixed-farming are highly context-dependent (Thornton and Herrero, 2015; Weindl et al., 2015).

Agroecological and conservation agriculture practices, such as intercropping, integration of legumes, mulching and incorporation of crop residues, are associated with household food security and improved health status (Nyantakyi-Frimpong et al., 2017; Shikuku et al., 2017). These practices can enhance the benefits of other adaptations, such as planting drought- and heat-tolerant or improved varieties, although effects vary across soil types, geographical zones and social groups (Makate et al., 2019; Mutenje et al., 2019). Non-climatic variables, such as financial resources, access to information and technology, level of education, land security and gender dynamics affect feasibility and adoption (Makate et al., 2019; Mutenje et al., 2019).

To mitigate growing water stress, countries like Tanzania, Uganda, Rwanda and Ethiopia are striving to improve irrigation efficiency (McCarl et al., 2015; Connolly-Boutin and Smit, 2016; Herrero et al., 2016). The feasibility and effectiveness of this adaptation depend on biophysical and socioeconomic conditions (Amamou et al., 2018; Harmanny and Malek, 2019; Schilling et al., 2020). Irrigation is unaffordable for many smallholder farmers and only covers a negligible proportion of the total cultivated area. Nonetheless, in some regions of West Africa, small-scale irrigation, including the digging of ditches, holes and depressions to collect rainwater (Makondo and Thomas, 2018), is widely adopted and promoted to support national food security (Dowd-Uribe et al., 2018).

African farmers are also diversifying their income sources to offset reduced yields or crop losses by shifting labour resources to off-farm work, or by migrating seasonally or longer-term (Kangalawe et al., 2017; Hove and Gweme, 2018). Off-farm activities provide financial resources that rural households need to cope with extreme climate variability (Hamed et al., 2018; Rouabhi et al., 2019). However, in some cases, these off-farm activities can be maladaptive at larger scales, such as when households turn to charcoal production which contributes to deforestation (Egeru, 2016). Whether off-farm activities constitute maladaptation depends on whether resources are available to upgrade skills or support investments that make a new business more lucrative. Without such resources, this option may lead to impoverishment (see Box 5.8 on AFOLU in Chapter 5).

Smallholder farmers' responses tend to address short-term shocks or stresses by deploying coping responses (e.g., selling labour, reducing consumption and temporary migration), rather than longer-term sustainable adaptations (Ziervogel and Parnell, 2014; Jiri et al., 2017). This is partly due to institutional barriers (e.g., markets, credit, infrastructure and information) and resource requirements that are unaffordable to smallholder farmers (Pauline et al., 2017). There is a need for policies that strengthen natural, financial, human and social capitals, the latter being key to household and community resilience, especially where government services may be limited (Mutabazi et al., 2015; Alemayehu and Bewket, 2017). There is evidence that collective action, local organizations and climate information are associated with higher food security, and that institutional interventions are needed to ensure scaling up of adaptations (Thornton et al., 2018).

A range of options is considered potentially effective in reducing future climate change risk, including plant breeding, crop diversification alongside livestock, mixed planting, intercrops, crop rotation and integrated crop-livestock systems (Thornton and Herrero, 2014; Cunningham et al., 2015; Himanen et al., 2016; Farrell et al., 2018; Snowdon et al., 2021) (Chapter 5, Sections 5.4.4 and 5.14.1). However, adaptation limits for crops in Africa are increasingly reached for global warming above 2°C (*high confidence*), and in tropical Africa may already be reached at current levels of global warming (*low confidence*).

Global warming beyond 2°C will place nearly all of sub-Saharan Africa cropland substantially outside of its historical Safe Climate Zone (Kummu et al., 2021) and may exponentially increase the cost of adaptation and residual damage for major crops (Iizumi et al., 2020). Without accounting for CO_2 increases, global-scale studies employing ensembles of gridded crop models for 2°C of global warming find that for adaptation using genetic cultivar change in most of Africa net losses are projected, even with adaptation up to 2°C of global warming for rice, maize, soybean, and wheat (Minoli et al., 2019; Zabel et al., 2021), although model uncertainty is still high (Müller et al., 2021). In contrast, when accounting for CO_2 increases, applying new genetics for rice under warming is projected to fully counteract all climate change-induced losses in Africa up to 3.5°C of global warming, except in West Africa (van Oort and Zwart, 2018).

However, compared to temperate regions, risks of adaptation shortfalls – that is climate change impacts even after adaptation – are generally greater for current agricultural conditions across much of Africa (tropical, arid and semi-arid) (Sun et al., 2019). The overall adaptation potential to offset yield losses across Africa for rice, maize, and wheat wheat reduces with increasing global warming. On average, in projections including adaptation options, yield losses, in the median case, are reduced from –33% to –10% of 2005 levels at 2°C of global warming and from –46% to –23% at 4°C, but estimates vary widely (Hasegawa et al., 2021) (Figure 9.22). Across Africa, the risks of no available genetic varieties of maize for growing season adaptation are higher for East Africa and southern Africa than for Central or West Africa (Zabel et al., 2021). To keep pace with expected rates of climate change, crop breeding, development and adoption must accelerate to meet the challenge (Challinor et al., 2016). Regional modelling has shown very little efficacy for late sowing, intensification of seeding density and fertilizers, water harvesting and other measures for cereals in West Africa at 2°C of global warming (Sultan and Gaetani, 2016; Guan et al., 2017). Historical climate change adaptation by crop migration has been shown in some cases (Sloat et al., 2020) but poses risks to biodiversity and water resources and this option may be limited for maize in Africa by suitable climate shifting completely across national borders and available land at the edges of the continent (Franke et al., 2021). More research is required to evaluate the potential effectiveness and limits of adaptation options in African agriculture under future climate change (see Chapter 5, Section 5.4.4 for more details)

9.8.4 Climate Information Services and Insurance for Agriculture Adaptation

In addition to adaptation in crop, soil and water management, the combination of (i) Climate Information Services (CIS), (ii) institutional capacity building and (iii) strategic financial investment can help African food producers adapt to projected climate risks (Carter et al., 2015; Surminski et al., 2016; Scott et al., 2017; Cinner et al., 2018; Diouf et al., 2019; Hansen et al., 2019a). There is growing evidence of farmers' use of weather and climate information, especially at the short- and medium-time horizon (Carr et al., 2016; Singh et al., 2018). Digital services can contribute to the sustainable intensification of food production globally (Duncombe, 2018; Klerkx et al., 2019). This points to the need for the scientific and development communities to better understand the conditions that enable widespread adoption in Africa.

Although climate services have the potential to strengthen farmers' resilience, barriers to accessibility, affordability and utilisation remain (Krell et al., 2021). Often the information offered is not consistent with what farmers need to know and how they access and process information (Meadow et al., 2015; Singh et al., 2018). Production of salient and credible climate information is hindered by the limited availability of and access to weather and climate data (Coulibaly et al., 2017; Hansen et al., 2019a). The existing weather infrastructure remains suboptimal to enable the development of reliable early warning systems (Africa Adaptation Initiative, 2018; Krell et al., 2021). Of the 1,017 land-based observational networks in the world, only 10% are in Africa, and 54% of Africa's surface weather stations cannot capture data accurately (Africa Adaptation Initiative, 2018; World Bank, 2020d).

Advances in remote sensing and climate analysis tools have allowed the development of weather index insurance products as a potential adaptation option, with Malawi and Ethiopia being early testbeds (Tadesse et al., 2015). These pilot projects were initially sponsored by NGOs, but in the last decade, the private sector has become more active in this sector. The Ghana Agricultural Insurance Pool (GAIP) and Agriculture and Climate Risk Enterprise (ACRE) in Kenya, Tanzania and Rwanda are examples. Despite the potential for weather index insurance, uptake by smallholder farmers in Africa remains constrained by several factors. These include the failure to capture actual crop loss as in traditional crop insurance products, as well as the inability of poor farmers to pay premiums (Elum et al., 2017; Weber, 2019). Weather index insurance could be part of a wider portfolio of risk mitigation services offered to farmers (Tadesse et al., 2015; Weber, 2019). Strategic partnerships between key players (e.g., credit institutions, policymakers, meteorologists, farmer associations, extension services, NGOs) are needed to develop better products and build capacity among smallholder farmers to engage more beneficially with weather index insurance (Singh et al., 2018; Tesfaye et al., 2019).

9.8.5 Marine and Inland Fisheries

9.8.5.1 Observed Impacts of Climate Variability and Change on Marine and Inland Fisheries

Marine and freshwater fisheries provide 19.3% of animal protein intake (Chan et al., 2019) and support the livelihoods of 12.3 million people (de Graaf and Garibaldi, 2015) across Africa. Estimates suggest that fish provides ~30% of the continent's population (approximately 200 million people) with their main source of animal protein and key micronutrients (Obiero et al., 2019). Although marine fisheries account for >50 % of total capture fishery production (Obiero et al., 2019), 2.9 million tonnes of fish are harvested annually from inland water bodies constituting the highest per-capita inland fishery production of any continent (2.56 kg / year / person) (Harrod et al., 2018a; Funge-Smith and Bennett, 2019).

Climate change poses a significant threat to marine and freshwater fisheries and aquaculture in Africa (Blasiak et al., 2017; Harrod et al., 2018a). Severe (>30%) coral bleaching has impacted ~80% of major reef areas in the western Indian Ocean and Red Sea along Africa's eastern coast (Hughes et al., 2018). Biological effects (e.g., changes in primary production, fish distribution) have also occurred (Hidalgo et al., 2018). Range shifts in marine fish species can exacerbate boundary conflicts among fisher communities (Penney et al., 2017; Belhabib et al., 2019). Changes in fish distribution and reductions in catch across inland fisheries are associated with climatic variability by fishing communities (Okpara et al., 2017b; Lowe et al., 2019; Muringai et al., 2019b). Floods and reduced river flow reduces fish catches (Kolding et al., 2019), which scale positively with discharge rates in rivers across Africa (McIntyre et al., 2016). Warming air and water temperatures have altered water stratification patterns in African lakes causing reductions in or redistirbutions of primary productivity and leading to reduced fish biomass (Section 9.6.1.3). Such changes, partially explain reduced fish catches in Lake Tanganyika (Cohen et al., 2016). In some regions, water scarcity has resulted in conflict within and among food production sectors (pastoralists, fishers and farmers) in this region (Okpara et al., 2017b). Small-scale and artisanal fisher communities are ill-equipped to adapt to climate impacts because there are few financially-accessible alternative livelihoods (Belhabib et al., 2016; Ndhlovu and Saito, 2017).

9.8.5.2 Projected Risks of Climate Change to Fisheries

At 4.3°C global warming, maximum catch potential (MCP) from marine fisheries in African Exclusive Economic Zones (EEZs) would decrease by 12–69% by the end of the 21st century relative to recent decades (1986–2005) whereas maintaining warming levels below 1.6°C would decrease MCP by 3–41% (Cheung William et al., 2016) (Figure 9.25). However, by mid-century under 2°C global warming, MCP would decrease by 10 to >30% on the western coast of South Africa, the Horn of Africa and West Africa, indicating these regions could be at risk to declines in MCP earlier in the century than other parts of Africa (Cheung et al., 2016) (Figure 9.25). Declining fish harvests due to sea temperature rise could leave 1.2–70 (median 11.1) million people in Africa vulnerable to deficiencies in iron, and up to 188 million to vitamin A and 285 million to vitamin B_{12} and omega-3 fatty acids by mid-century under 1.7°C global warming (Golden et al., 2016). Maire et al. (2021) assessed the nutritional vulnerabilities of African countries to climate change and overfishing, and found that the four most vulnerable countries ranked on a scale from 0 (low vulnerability) to 100 (high vulnerability) were Mozambique (87), Madagascar (76), Tanzania (61) and Sierra Leone (58). Coral reef habitat in East Africa is projected to decrease, resulting in negative impacts on demersal fish stocks and invertebrates (Hoegh-Guldberg et al., 2018). Central, West and East Africa appear to be at the greatest nutritional risk from sea temperature rise, leading to reduced catch in coastal waters (Golden et al., 2016) (Figure 9.25). In North Africa, a rise in water temperatures is expected to impact the phenology and migratory patterns of large pelagic species (e.g., bluefin tuna, *Thunnus thynnus*) (Hidalgo et al., 2018). Increased sea surface temperatures have been associated with increases in spring and summer upwelling intensity reducing the abundance and larval survival of small pelagic fishes and shellfish in West Africa (Bakun et al., 2015; Tiedemann et al., 2017; Atindana et al., 2020). Ocean warming, acidification and hypoxia are predicted to affect the early life history stages of several marine food species, including fish and crustaceans (Kifani et al., 2018). Climate warming is projected to impact water temperature and horizontal and vertical mixing on the southern Benguela ecosystem, with marked negative effects on the biomass of several important fishery resources by 2050 amplified under 2.5°C compared to 1.7°C global warming (Ortega-Cisneros et al., 2018).

For inland fisheries, 55–68% of commercially harvested fish species will be vulnerable to extinction under 2.5°C global warming by the end of the 21st century (2071–2100) compared to 77–97% under 4.4°C global warming (Figure 9.26). This will increase the number of countries that are at food security risk due to fishery species declines from 10 to 13 (Figure 9.26). Other recent analyses suggest that African countries with the highest inland fisheries production have low- to mid-range projected climate risk (2.4℃–2.6°C local temperature increase compared to other regions with 2.7℃–3.3°C increase by end of centruy) based on a 3.9°C global warming scenario (Harrod et al., 2018b). In regions where inland fishery production is derived primarily from lakes, there is a lower likelihood of reduced catch, especially where precipitation is projected to increase (e.g., African Great Lakes region) (Harrod et al., 2018b). Regions reliant on rivers and floodplains (e.g., Zambezi and Niger basins) are more *likely* to experience downturns in catch, as hydrological dynamics may be altered (Harrod et al., 2018b). Projections suggest that opportunistic species that do well in modified systems (Escalera-vázquez et al., 2017) and small pelagic fishes will remain important components to inland fishery food systems (Kolding et al., 2016; Gownaris et al., 2018; Kolding et al., 2019). Climate adaptation responses that rely on freshwater resources (e.g., hydroelectric power generation, agricultural irrigation) represent threats to inland fisheries (Cowx et al., 2018; Harrod et al., 2018c), by changing flow regimes, reducing water levels, and increasing runoff of pesticides and nutrients (Harrod et al., 2018c).

For both marine and freshwater fisheries, climate-related extreme weather events and flooding may drive the loss of fishing days, cause damage and loss to fishing gear, endanger the lives of fishers and block transportation from damaged roads (Muringai et al., 2021). Fish processing via weather-dependent techniques such as sun drying may be hampered, causing post-harvest losses (Akintola and Fakoya, 2017; Chan et al., 2019).

9.8.5.3 Current and Future Adaptation Responses for Fisheries

Patterns of vulnerability and adaptive capacity are highly context-dependent and vary within and among fishing communities in coastal and riparian areas (Ndhlovu and Saito, 2017; Lowe et al., 2019; D'agata et al., 2020). Interventions that integrate scientific knowledge and fishers' local knowledge while focusing on vulnerable groups are more *likely* to be more successful (Musinguzi et al., 2018; Muringai et al., 2019b). Infrastructure improvements (e.g., storage facilities, processing technologies, transport systems) could reduce post-harvest losses and improve food safety (Chan et al., 2019). Fisher safety can be aided by early warning of severe weather conditions (Thiery et al., 2017), enhanced through communication via mass media and mobile phones (Thiery et al., 2017; Kiwanuka-Tondo et al., 2019). Although changing fishing gears and shifting target species are important adaptation options for artisanal fishers, many have instead expanded their fishing range or increased effort (Musinguzi et al., 2015; Belhabib et al., 2016). Adapting to the impacts of climate change on marine fisheries productivity requires management reforms accounting for shifting productivity and species distributions, such as increasing marine protected areas, strengthening regional trade networks, and increasing the investment and innovation in climate-resilient aquaculture production (Golden et al., 2021). This could yield higher catch and profits in the future relative to today in

50% of African countries with marine territories under 2°C global warming and in 35% under 4.3°C global warming (Free et al., 2020). For inland fisheries, opportunities for adaptation include better integration of inland fisheries into management plans from other sectors (e.g., hydropower and irrigation) (Harrod et al., 2018c; Cowx and Ogutu-Ohwayo, 2019; McCartney et al., 2019). There is growing interest in enhancing the supply of freshwater fishery production from small water bodies and reservoirs in dryland regions of sub-Saharan Africa (Kolding et al., 2016).

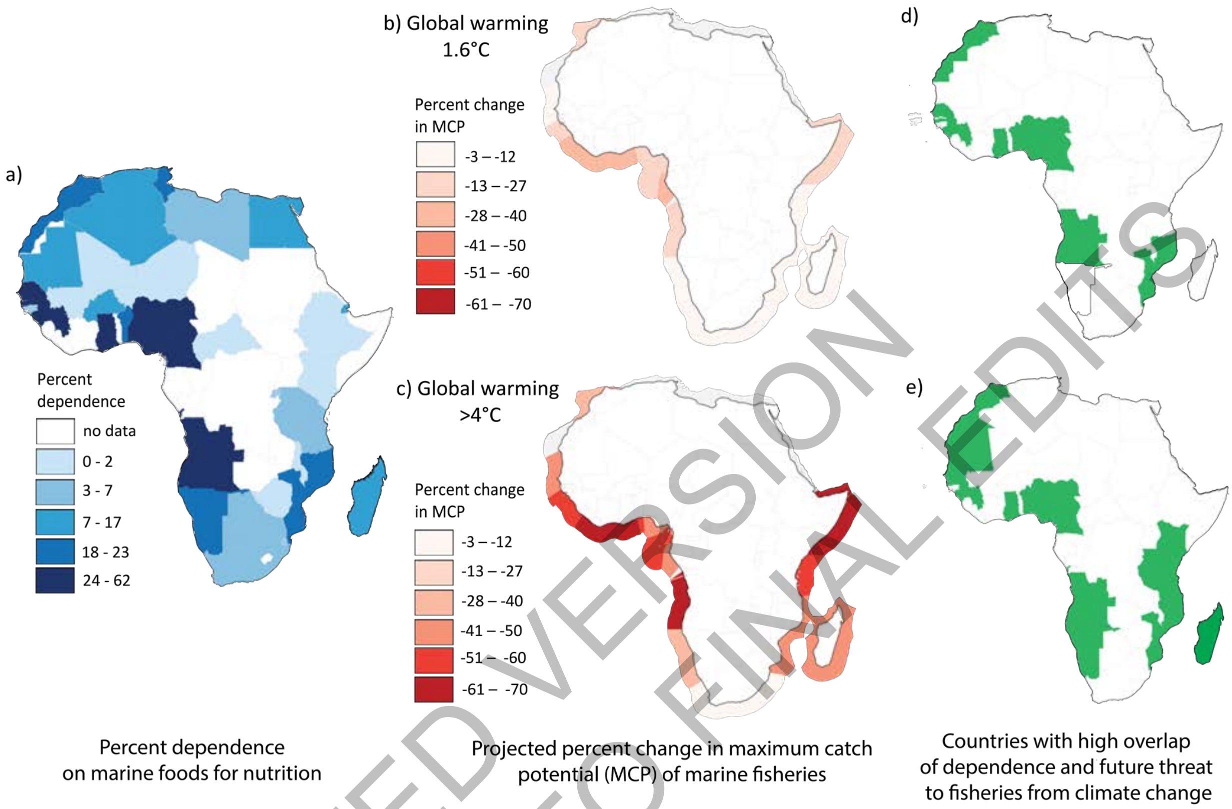


Figure 9.25: Climate change risk to nutrition and catch potential from Marine Fisheries: Panels comparing countries current percent dependence on marine foods for nutrition compared with projected change in maximum catch potential (MCP) from marine fisheries. (a) The percentage of animal sources foods consumed that originate from a marine environment. Countries with higher dependence are indicated by darker shades of blue (Golden et al., 2016). (b–c) Projected percent change in maximum catch potential (MCP) of marine fisheries under 1.6°C global warming (b) and >4°C global warming (c) from recent past (1986–2005) to end of 21st century (2081-2100) in countries' Exclusive Economic Zones (EEZs)(Cheung William et al., 2016). Darker red indicates greater percent reduction [negative values]. (d–e) Countries (in green) that have overlap between high nutritional dependence and high reduction in MCP under two warming scenarios.

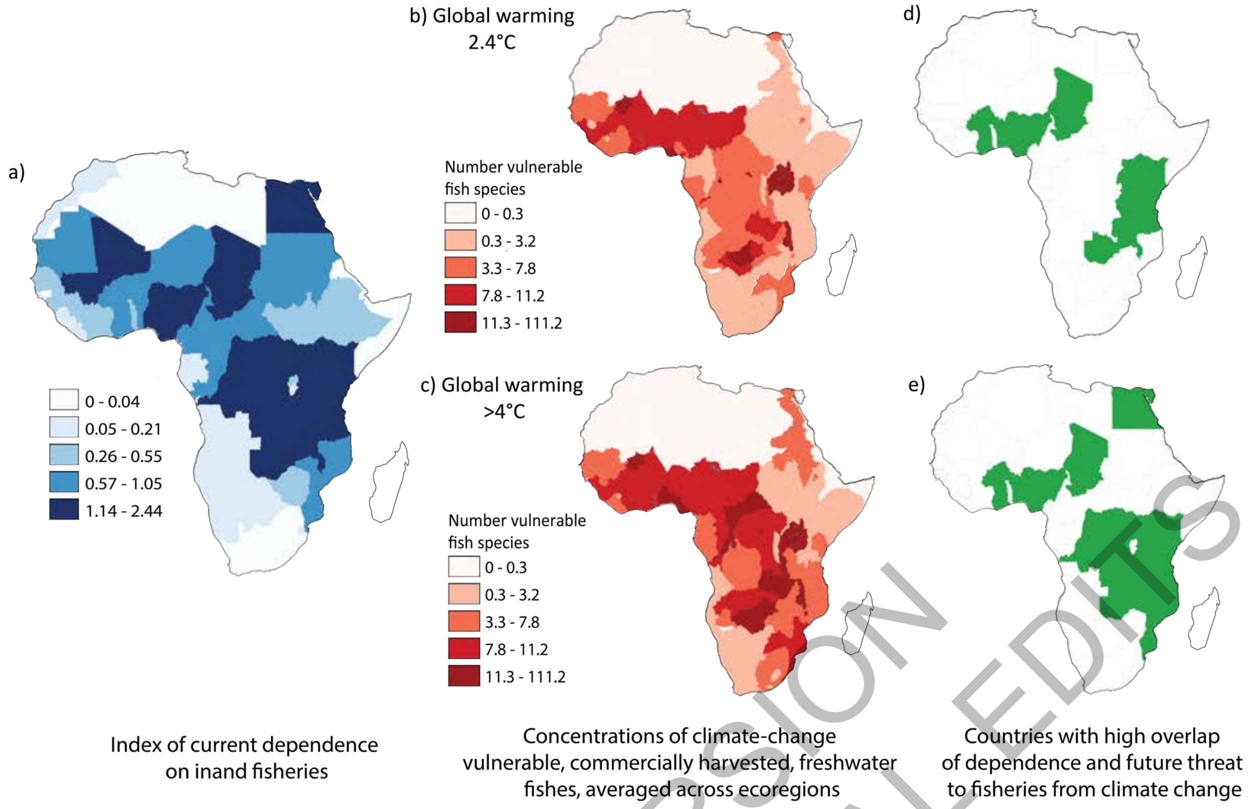


Figure 9.26: Climate change risk to Freshwater Fisheries: Panels comparing countries current dependence on inland fisheries compared with climate change vulnerability of important fishery species. (a) Countries' reliance on inland fisheries was estimated by catch (total, tonnes) (FAO, 2018b; Fluet-Chouinard et al., 2018), per capita catch (kg/person/year) (FAO, 2018b), percent reliance on fish for micronutrients, and percent consumption per household (Golden et al., 2016). Z-scores of each metric were averaged for each country to create a composite index describing 'current dependence on freshwater fish' for each country with darker blue colours indicating higher dependence. (b–c) Projected concentrations (numbers) of vulnerable freshwater fishery species averaged within freshwater ecoregions under >2°C global warming (b) and >4°C global warming (c) estimated from recent past (1961–1992) to the end of the 21st century (2071 to 2100) (Nyboer et al., 2019). Numbers of vulnerable fish species translate to an average of 55–68% vulnerable at >2°C and 77–97% vulnerable at <4°C global warming. Darker reds indicate higher concentrations of vulnerable fish species. (d–e) Countries (in green) that have an overlap between high dependence on freshwater fish and high concentrations of fishery species that are vulnerable to climate change under two warming scenarios

9.9 Human Settlements and Infrastructure

This section assesses climate impacts, risks and adaptation options for human settlements comprising human populations and infrastructure such as buildings, roads and energy across Africa.

9.9.1 Urbanisation, Population and Development Trends

Africa is the most rapidly urbanising region in the world, with an annual urban population growth rate of 3.6% for 2005–2015 (UN-Habitat, 2016). About 57% of the population currently lives in rural areas, the proprotion of the population living in urban areas is projectted to exceed 60% by 2050 (UNDESA, 2019b) (UN-Habitat, 2016). Much of the rapid rate of urbanisation has resulted from the growth of small towns and intermediary cities (African Development Bank et al., 2016).

Approximately 59% of sub-Saharan Africa's urban population resides in informal settlements (in some cities up to 80%), and the population in informal settlements is expected to increase (*very high confidence*) (Taylor and Peter, 2014; UN-Habitat, 2014; UN-Habitat, 2016; UNDP, 2019). These urbanisation trends are compounding the increasing exposure to climate hazards, particularly floods and heatwaves (*high confidence*) (Dodman et al., 2015).

Globally, the highest rates of population growth and urbanisation are taking place in Africa's coastal zones (*high confidence*) (Merkens et al., 2016). Coastal urban populations account for 25–29% of the total population in West, North and southern Africa (OECD/SWAC, 2020). Accounting for a continuing young population, stagnant economies and migration to regional growth centres, projections indicate that the low-lying coastal zone population of sub-Saharan Africa could increase by 175% (2030) and 625% (2060) relative to 24 million in 2000 (Neumann et al., 2015).

Climate-related displacement is widespread in Africa, with increased migration to urban areas in sub-Saharan Africa linked to decreased rainfall in rural areas, increasing urbanisation and affecting household vulnerability (see Box 9.9). Much of this growth can occur in informal settlements which are growing due to both climatic and non-climatic drivers, and which often house temporary migrants, including internally displaced people. Such informal settlements are located in areas exposed to climate change and variability and are exposed to floods, landslides, sea level rise and storm surges in low-lying coastal areas, or alongside rivers that frequently overflow, thereby exacerbating existing vulnerabilities (Satterthwaite et al., 2020).

Sub-Saharan Africa's large infrastructure deficit (quantity, quality and access) with respect to road transport, electricity, water supply and sanitation places the region at the lowest of all developing regions (AfDB, 2018a; Calderon et al., 2018). Adequate infrastructure to support Africa's rapidly growing population is important to raise living standards and productivity in informal settlements (AfDB, 2018b; UN Environment, 2019). Yet planned infrastructure developments, including those related to African Union's Programme for Infrastructure Development (PIDA), along with other energy plans, and China's Belt and Road Initiative (BRI), may increase or decrease both climate change mitigation and adaptation depending on whether infrastructure planning integrates current and future climate change risks (Cervigni et al., 2015; Addaney, 2020) (see Box 9.5).

9.9.2 Observed Impacts on Human Settlements and Infrastructure

African human settlements are particularly exposed to floods (pluvial and fluvial), droughts and heat waves. Other climate hazards are sea level rise and storm surges in coastal areas, tropical cyclones and convective storms. This sub-section provides an assessment of observed impacts and risks from climate hazards in different sub-regions to underscore the relevance of climate-sensitive planning and actions to advance social and economic development, and reduce the loss and damage of property, assets and critical infrastructure.

9.9.2.1 Observed Impacts on Human Settlements

The spatial distribution of climate hazards and observed impacts in terms of total people affected (displaced persons and deaths) during 2010–2020 is shown in Figure 9.27. From 2000–2019 , floods and droughts accounted for 80% and 16%, respectively, of the 337 million affected persons, and a further 32% and 46%, respectively, of 46,078 deaths from natural disasters in Africa (CRED, 2019). Flooding is a major hazard across Africa (Kundzewicz et al., 2014; Douglas, 2017) and is increasing (Zevenbergen et al., 2016; Elboshy et al., 2019). An increase in extreme poverty and up to a 35% decrease in consumption has been associated with exposure to flood shocks (Azzarri and Signorelli, 2020). Globally, only sub-Saharan Africa has recorded increasing rates of flood mortality since the 1990s (Tellman et al., 2021). Economic opportunities, transportation of goods and services, and mobility and access to essential services, including health and education, are greatly hindered by flooding (Gannon et al., 2018). Severe impacts from tropical cyclone landfalls have been recorded in East and southeastern Africa (Rapolaki and Reason, 2018; Cambaza et al., 2019; Chatiza, 2019; Hope, 2019). Cyclones Idai and Kenneth in early 2019 caused flooding of districts in Mozambique, Zimbabwe and Malawi, with substantial loss and damage to infrastructure in the energy, transport, water supply, communication services, housing, health and education sectors, particularly in Mozambique (Figure 9.27; see also Cross-Chapter Box DISASTER in Chapter 4) (Warren, 2019; Dube et al., 2021; Phiri et al., 2021).

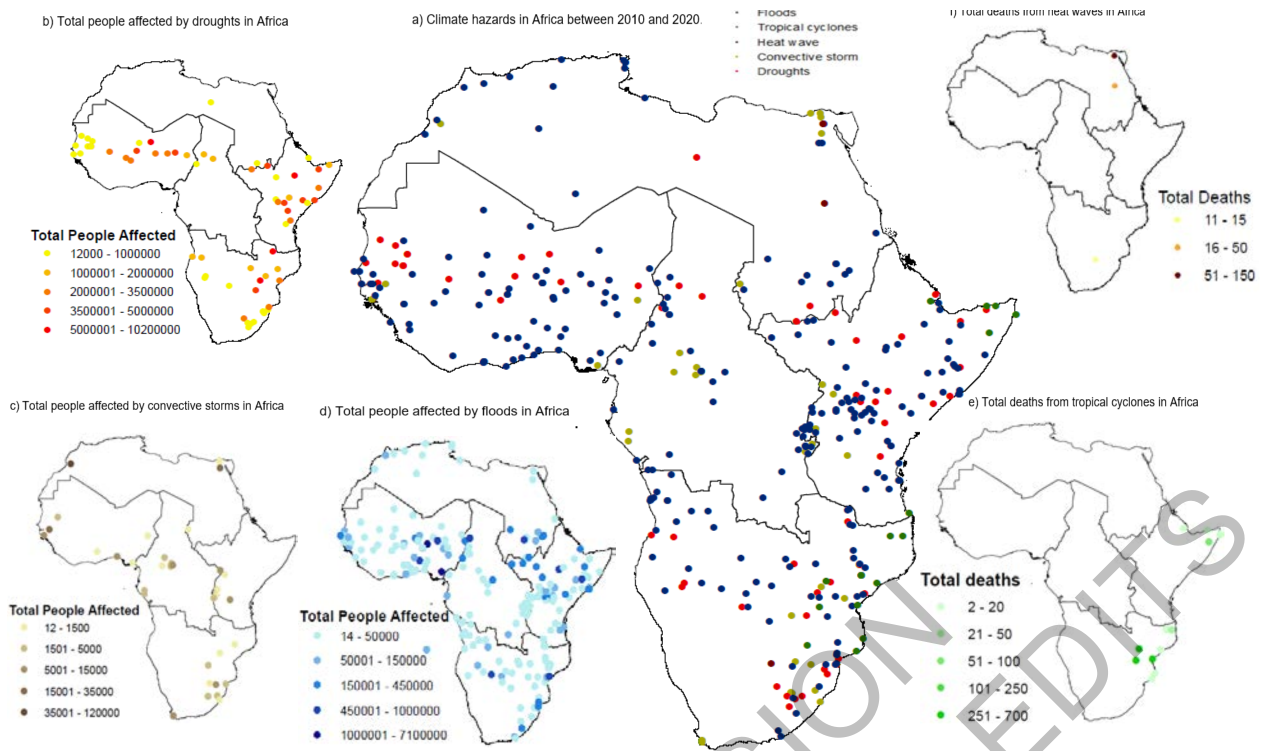


Figure 9.27: From 2010–2020, over 166 million people were reported to be affected by climate hazards across Africa. Maps show (a) location of all reported climate hazards, (b) people affected by droughts, (c) people affected by convective storms, (d) people affected by floods, (e) total deaths from tropical cyclones, and (f) total deaths from heat waves. Source (EMDAT and CRED, 2020). Note, although extreme weather damage databases under report heatwaves (which is indicated in panel (f) by very few deaths), the region has experienced a number of heatwaves and will be affected disproportionately by them in the future under climate change (Harrington and Otto, 2020).

Table 9.7: Case studies of climate hazard impacts and risks to selected human settlements in Africa

Hazard	Country/City	Impact on Human Settlement and Infrastructure	Source
Sea level rise and storm surge	Egypt (North Africa)	December 2010, January 2011, and October 2015: Storm surge of 1.2 m above MSL (typical of the Nile Delta coast: 0.4–0.5 m). Coastal flooding and damage to some coastal structures. Moderate flooding of the Nile Delta lowlands. Alexandria city: Flooding generated by heavy rainfall (2015). Increased turbidity of water sources affected efficiency of water treatment plants leading to reduction of water supplies affecting public health systems. Potable water supply affected by saltwater intrusion. Coastal erosion and property damage.	(Kloos and Baumert, 2015; Abutaleb et al., 2018) (Eldeberky Y, 2015; Yehia et al., 2017)
Drought	Southern Africa	**El Niño Drought 2015–2016**: Western Cape Region Affected 8.6 million people. Losses: >USD 2.2 billion. Power generation reduced by 75% at Kariba dam (Zambia) in 2016, and the Cahora Bassa dam (Mozambique) reduced to 34% of its capacity with widespread impact on electricity supplies across southern Africa.	(Davis-Reddy et al., 2017; Spalding-Fecher et al., 2017) (Brooks, 2019)
	Somalia (East Africa)	**Somalia drought 2016-2017**: 926,000 newly displaced persons reported (Nov. 2016–Oct. 2017). 40% of total drought-related displacements accommodated in Mogadishu, Baidoa, Kismayo; 60% hosted in other secondary cities. Increased population density and overcrowding in Somalia's urban areas. Explosion of new shelters and tents for displaced persons within and in outskirts of cities. In Mogadishu, 34% of new settlements developed within six months.	(Government of Somalia, 2018)
Flooding	Malawi (East Africa)	**Floods 2019**: Approximately 975,600 people affected, 672 injured, 60 persons killed, and 86,976 people displaced. 288,371 houses	(Government of Malawi, 2019)

		damaged. 129 bridges and 68 culverts destroyed. 1841 km of road network estimated at USD 36.1 million destroyed. Total cost of damage and losses: housing sector - USD 106.9 million, energy - USD 3.1 million; water and sanitation - USD 6.4 million; transport - USD 37.0 million. Total cost of destroyed physical assets – USD 157.7 million. Damage and Losses in Blantyre city: housing sector - USD 29.87 million, energy sector - USD 0.38 million and transport sector - USD 1.72 million.	
Tropical cyclone	Mozambique, Zimbabwe and Malawi (Southern Africa)	**Cyclones Idai and Kenneth 2019:** Severe flooding of districts in Mozambique, Zimbabwe, and Malawi; 233,900 houses completely destroyed or damaged in Mozambique. Cyclone Kenneth - about 40,000 houses and 19 health facilities destroyed. Cyclone Idai - destroyed or damaged 1,345 km of transmission lines, 10,216 km of distribution lines, two 90MW generation plants, 30 sub-stations and 4,000 transformers, resulting in estimated damage of USD 133.5 million and loss of USD 47.9 million in the energy sector in Mozambique. 602 and 299 people killed in Mozambique and Zimbabwe respectively; Affected persons - about 1.5 million in Mozambique and 270,000 in Zimbabwe. In Beira (Mozambique) - 60% of city was inundated, 70% of houses damaged or totally destroyed, mostly in the poorest neighbourhood, and 90% of the city's power grid affected. Huge losses and damages to infrastructures in the energy, transport, water supply, communication services, housing, health and education sector were also recorded.	(Cambaza et al., 2019; Chatiza, 2019; Government of Mozambique, 2019; Hope, 2019; Lequechane et al., 2020; Phiri et al., 2021) (Enenkel et al., 2020)
Landslide	Freetown (West Africa)	**August 2017**: At least 500 persons killed and over 600 persons declared missing, >3,000 residents rendered homeless; 349 houses destroyed. Damage to health facilities and educational buildings. Economic cost of landslide and flood: USD 31.6 million.	(Cui et al., 2019) (World Bank, 2017b)
	Uganda (East Africa)	Slopes of Mt. Elgon (2010): More than 350 deaths and 500,000 persons needed to be relocated	(Croitoru et al., 2019)

From 2005–2020, flood-induced damage over Africa was estimated at over USD 4.4 billion, with eastern and western Africa being the most affected regions (EMDAT and CRED, 2020). Total damages in four West African countries (Benin, Cote d'Ivoire, Senegal and Togo) in 2017 were estimated at USD 850 million for pluvial floods and USD 555 million for fluvial floods (Croitoru et al., 2019). Unprecedented economic loss, in terms of goods and properties, estimated by the Nigerian insurance industry at USD 200 million resulted from floods in Lagos in 2011 (Adelekan, 2016). In southern Africa, the highest costs were incurred from flood losses during the period 2000-2015 (UNEP-FI, 2019b; Simpson, 2020).

Business disruptions from climate impacts have implications for deepening poverty (Adelekan and Fregene, 2015). Small and medium enterprises (SMEs) employ 60–90% of workers in many African countries and contribute 40% or more to the GDP in Ghana, Kenya, Nigeria, Zimbabwe, South Africa and Tanzania (Muriithi, 2017). The viability of businesses and economic well-being of large populations employed in SMEs is severely affected by climate hazards as reported for local wind storms in Ibadan (Adelekan, 2012), El Niño-related flooding (Nairobi), drought-induced water supply disruption (Gaborone) and power outages (Lusaka) (Gannon et al., 2018). High water demand due to high rates of urbanisation and population growth, coupled with drought, reduce groundwater levels in cities (e.g., Bouake, Harare, Tripoli, Niamey) and increase saltwater intrusion into groundwater in coastal areas, reducing water availability and water security, particularly for poorer populations not connected to municipal water networks (Aswad et al., 2019; Claon et al., 2020).

Evidence of the impact of heat waves in urban Africa in the current climate is sparse, due in part to low reporting and monitoring (Engelbrecht et al., 2015; Harrington and Otto, 2020). Knowledge is also limited on the interaction of climate change, urban growth and the urban heat island effect in Africa (Chapman et al., 2017). In North Africa, the present day number of high heat-stress nights is around 10 times larger in urban than rural areas (Fischer et al., 2012).

9.9.2.2 Observed Impacts to Road and Energy Infrastructure

The highest transport infrastructure exposures are from floods (Koks et al., 2019), with potentially severe consequences for food security (Fanzo et al., 2018), communication and the economy of affected regions (*high confidence*) (Koks et al., 2019). Eight of the twenty countries with the highest expected annual damages to road and rail assets, relative to the country's GDP, are located in East, West and Central Africa (Koks et al., 2019). Transport impacts compound climate impacts, such as heat stress and air pollution linked to vehicle emissions in Dar es Salaam (Ndetto and Matzarakis, 2014).

African economies that rely primarily on hydropower for electricity generation are particularly sensitive to climate variability (Brooks, 2019). This sensitivity was already felt during the 2015/16 El Niño, in which Malawi, Tanzania, Zambia and Zimbabwe all experienced widespread and prolonged load shedding due to low rainfall. The impact was felt throughout the economy and reflected in reduced GDP growth in Zambia (Conway et al., 2017).

9.9.3 Observed Vulnerabilities of Human Settlements to Climate Risks

Urban vulnerabilities and exposure to climate change are increasing (*medium to high confidence*) and are influenced by patterns of urban settlement and housing characteristics (Satterthwaite, 2017; Godsmark et al., 2019; Williams et al., 2019a). About 70% of African cities are highly vulnerable to climate shocks of which small- and medium-sized towns and cities are more at risk (Verisk Maplecroft, 2018). Flooding was perceived as the most prominent water risk in 75% of 36 sampled cities across African sub-regions, while drought-related water scarcity was indicated as very important/important in 66.7% of cities (OECD, 2021). Almost one-third of African cities with populations of 300,000 or more are located in areas of high exposure to at least one natural hazard, including floods (12%) and droughts (20–25%) (Gu et al., 2015). The coastal cities of East, West and North Africa are particularly vulnerable to the effects of rising sea levels (Abutaleb et al., 2018; IPCC, 2019a).

Globally, sub-Saharan Africa has the largest population living in extreme poverty that are exposed to high flood risk (~71 million people or 55% of global total) (Rentschler and Salhab, 2020). Poverty is a significant factor of flood-induced displacement in Africa, where even small flood exposure can lead to high numbers of displacement (Kakinuma et al., 2020). Africa's large population of urban poor and marginalised groups and informal sector workers, further contribute to high vulnerability to extreme weather and climate change in many settlements (*high confidence*) (Adelekan and Fregene, 2015; IPCC, 2019a; UNDP, 2019).

Other non-climatic stressors which exacerbate vulnerabilities, especially in urban areas, include poor socioeconomic development, weak municipal governance, poor resource and institutional capacities, together with multi-dimensional, location-specific inequalities (*high confidence*) (Dodman et al., 2017; Satterthwaite, 2017).

9.9.4 Projected Risks for Human Settlements and Infrastructure

9.9.4.1 Projected Risks for Human Settlements

The extent of urban areas in Africa exposed to climate hazards will increase considerably and cities will be hotspots of climate risks, which could amplify pre-existing stresses related to poverty, exclusion and governance (*high confidence*) (IPCC, 2018b).

Flooding

Continuing current population and GDP growth trends, the extent of urban land exposed to high-frequency flooding is projected to increase around 270% in North Africa, 800% in southern Africa, and 2600% in mid-latitude Africa by 2030 when compared to 2000, without considering climate change (Güneralp et al., 2015). In addition, global warming is projected to increase frequency and magnitude of river floods in East, Central and West Africa (Alfieri et al., 2017; Gu et al., 2020; Kam et al., 2021). On average across large African river basins, the frequency of flood events with a current return period of 100 years is projected to increase to 1 in 40 years at 1.5°C and 2°C global warming, and 1 in 21 years at 4°C warming, with Egypt, Nigeria, Sudan and DRC in the top 20 countries globally for projected damages (Alfieri et al., 2017). Compared to population in 2000, human displacement due to river flooding in Sub-Saharan Africa is projected to increase 600% by 2066–2096 with moderate-to-high population growth and 2.6°C global warming, with risk reducing to a 200% increase for low population growth and 1.6°C global warming (Kam et al., 2021).

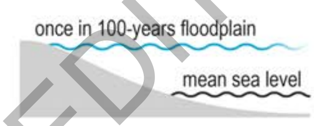
Urban population exposure to tropical cyclone hazards in southeastern Africa, in particular Mozambique, is projected to increase due to the intensification of cyclones and their extended duration associated with warmer sea surface temperatures (Fitchett, 2018; Vidya et al., 2020). Urban damage assessment based on a 10-year flood protection level for Accra shows that without flood protection, there is a 10% probability of a flood occurring annually which could cause USD 98.5 million urban damage, affect GDP by USD 50.3 million and affect 34,000 people (Asumadu-Sarkodie et al., 2015). Many urban households and Africa's growing assets could therefore be exposed to increased flooding (IPCC, 2018b).

Population in low-elevation coastal zones (LECZ) projected for 2030 and 2060

Exposed population: 1 million people – >200 million people

Population growth scenarios:
I = growth at lowest end of forecasts
II = growth at low end of forecasts
III = growth at high end of forecasts
IV = growth towards highest end of forecasts

Low-elevation coastal zones



(a) Population exposed to sea level rise in LECZ.

	Year 2000	Year 2030				Year 2060			
	Baseline	I	II	III	IV	I	II	III	IV
Africa	**54.2**	**108.5**	**108.9**	**117.6**	**116.8**	**190.0**	**185.6**	**229.3**	**245.2**
Eastern Africa	17.1	45.3	43.6	47.1	47.2	95.0	88.9	111.7	122.3
Middle Africa	30.3	46.6	48.6	52.3	52.3	56.3	61.4	72.4	74.8
Northern Africa	5.2	13.8	13.8	15.1	14.1	34.8	31.1	39.9	42.5
Southern Africa	1.1	2.0	2.0	2.2	2.2	3.0	3.0	3.8	4.1
Western Africa	0.5	0.8	0.9	0.9	1.0	0.9	1.1	1.5	1.7

(b) African countries in the global top 25 with highest populations within LECZ and in the 100-year floodplains, under growth scenario IV.

	Populations within LECZ				Populations within 100-year floodplains			
	Baseline 2000	Year 2030	Year 2060	*Growth 2000–2060*	Baseline 2000	Year 2030	Year 2060	*Growth 2000–2060*
Egypt	25.5	45.0	63.5	*0.25*	7.4	13.8	20.7	*0.28*
Nigeria	7.4	19.8	57.7	*0.79*	0.1	0.3	0.9	*0.84*
Senegal	2.9	8.5	19.2	*0.66*	0.4	1.1	2.7	*0.76*
Benin	1.4	5.4	15.0	*1.06*	0.1	0.6	1.6	*1.12*
Tanzania	0.6	2.8	14.0	*2.2*	0.2	0.9	4.3	*2.3*
Somalia	0.6	2.2	9.8	*1.68*	0.2	0.6	2.7	*1.7*
Cote d'Ivoire	1.2	3.0	7.6	*0.64*	0.1	0.3	0.7	*0.65*
Mozambique	2.3	4.4	7.5	*0.33*	0.7	1.4	2.5	*0.36*

Figure 9.28: Tens to hundreds of millions of people in Africa are projected to be exposed to sea level rise, with a major risk driver being increased exposure due to population increase in low-lying areas. (a) Population in the low-elevation coastal zone (LECZ) projected for 2030 (+10cm SLR) and 2060 (+21 cm SLR). (b) African countries with highest population in LECZ, and additional population exposed in the 100-year floodplain. Data sourced from (Neumann et al., 2015).

Sea level rise and coastal flooding

Africa's low-lying coastal zone population is expected to grow more than any other region from 2000 to 2060 (see Figure 9.28) (Neumann et al., 2015). Future rapid coastal development is expected to increase existing high vulnerabilities to sea level rise (SLR) and coastal hazards, particularly in East Africa (*high confidence*) (Figure 9.29) (Hinkel et al., 2012; Kulp and Strauss, 2019). By 2100, sea levels are projected to rise at least 40 cm above those in 2000 in a below 2°C scenario, and possibly up to 1 m by the end of the century under a 4°C warming scenario (Serdeczny et al., 2017) (see also Cross-Chapter Box SLR in Chapter 3).

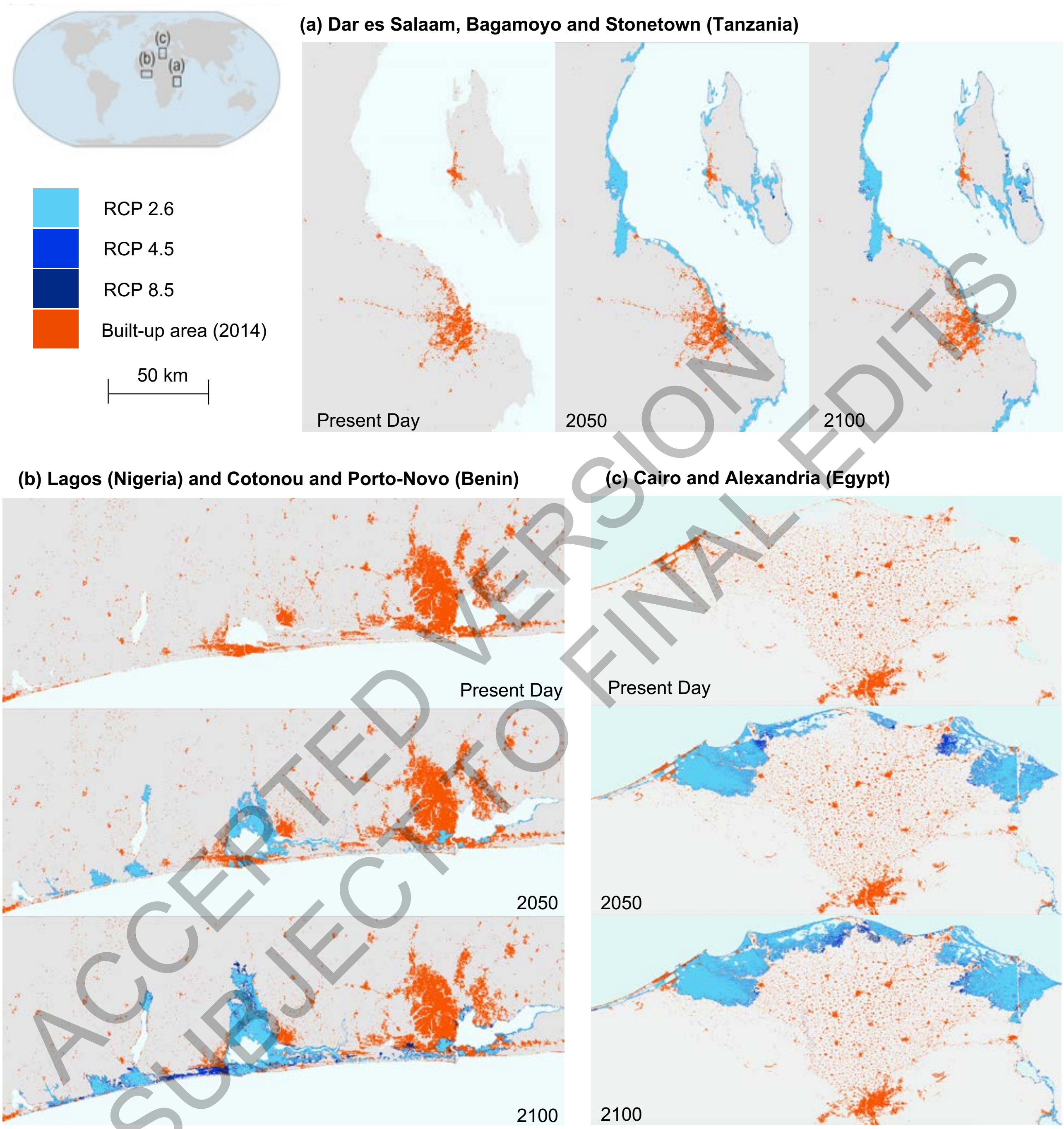


Figure 9.29: Selected African cities exposed to sea level rise include (a) Dar es Salaam, Bagamoyo, and Stone Town in Tanzania (East Africa), (b) Lagos in Nigeria, and Cotonou and Porto-Novo in Benin (West Africa), and (c) Cairo and Alexandria in Egypt (North Africa). Orange shows built-up area in 2014. Shades of blue show permanent flooding due to sea level rise by 2050 and 2100 under low (RCP2.6), medium (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenarios. Darker colours for higher emissions scenarios show areas projected to be flooded in addition to those for lower emissions scenarios. The figure assumes failure of coastal defences in 2050 and 2100. Some areas are already below current sea level rise and coastal defences need to be upgraded as sea level rises (e.g., in Egypt), others are just above mean sea levels and they do not necessarily have high protection levels, so these defences need to be built (e.g., Dar Es Salam and Lagos). Blue shading shows permanent inundation surfaces predicted by Coastal DEM and SRTM given the 95th percentile K14/RCP2.6, RCP4.5, and RCP8.5, for present day, 2050, and 2100 sea level projection for permanent inundation (inundation without a storm surge event), and RL10 (10-year return level storm) (Kulp and Strauss, 2019). Low-lying areas isolated from the ocean are removed from the inundation surface using

connected components analysis. Current water bodies are derived from the SRTM Water Body Dataset. Orange areas represent the extent of coastal human settlements in 2014 (Corbane et al., 2018). See Figure CCP4.7 for projections including subsidence and worst-case scenario projections for 2100.

In the absence of any adaptation, Egypt, Mozambique, and Nigeria are projected to be worst affected by SLR in terms of the number of people at risk of flooding annually in a 4°C warming scenario (Hinkel et al., 2012). Recent estimates have explored the potential damages due to SLR and coastal extreme events in 12 major African cities using a stochastic approach to account for uncertainty (Abadie et al., 2020). Expected aggregate damages to these cities in 2050 are USD 65 billion for RCP4.5 and USD 86.5 billion for RCP8.5, and USD 137.5 billion under a high-end scenario that incorporates expert opinion on additional ice sheet melting (Table 9.8). When considering low-probability, high-damage events, aggregate damage risks can be more than twice as high, reaching USD 187 billion and USD 206 billion under RCP4.5 and RCP8.5 scenarios, respectively, and USD 397 billion under the high-end scenario. City characteristics and exposure play a larger role in expected damages and risk than changes in sea level. The city of Alexandria in North Africa leads the ranking, with aggregate expected damage of USD 36 billion and USD 50 billion under RCP4.5 and RCP8.5 scenarios, respectively, and USD 79.4 billion under the high-end scenario.

Table 9.8: Regional relative sea level rise and associated damage risks in 12 major African coastal cities under four SLR scenarios. Panel (a) Regional relative sea level rise by 2050 and 2100. For SLR, median and 95th percentiles are presented, in centimetres. Panel (b) Probabilistic damage estimations by 2050 include expected average damages (EAD), damages at the 95th percentile (VaR) and the Expected Shortfall (ES), which represents the average damages of the 5% worst cases. Four relative sea level projections were considered under no adaptation: the RCP2.6, 4.5 and 8.5 scenarios from the IPCC AR5, and a high-end RCP8.5 scenario that incorporates expert opinion on additional ice sheet melting. Note that figures are provided in undiscounted millions of US dollars (2005) and have been rounded off to avoid a false sense of precision (Abadie et al., 2020; Abadie et al., 2021).

a) Regional relative sea level rise (cm)

City	Year	RCP2.6		RCP4.5		RCP8.5		High end	
		Median	P95	Median	P95	Median	P95	Median	P95
Abidjan	2050	21	30	22	32	24	34	28	48
	2100	44	69	53	86	75	114	86	206
Alexandria	2050	18	26	18	28	21	30	25	43
	2100	36	58	46	73	67	102	78	186
Algiers	2050	19	27	19	29	22	31	25	45
	2100	39	62	47	76	66	98	78	192
Cape Town	2050	20	30	21	31	23	33	27	48
	2100	44	69	53	87	75	117	86	199
Casablanca	2050	19	27	20	29	22	31	26	46
	2100	39	63	47	78	65	99	77	198
Dakar	2050	21	31	21	31	23	33	27	48
	2100	43	69	53	86	73	111	85	209
Dar-es-Salam	2050	20	29	21	31	24	33	27	47
	2100	45	70	54	86	76	117	87	206
Durban	2050	20	30	22	32	25	34	28	49
	2100	46	72	55	90	78	119	89	207
Lagos	2050	21	30	22	32	24	34	28	48
	2100	44	69	54	86	75	113	86	205
Lome	2050	21	30	22	32	24	34	28	48
	2100	44	69	53	86	76	115	87	205
Luanda	2050	21	30	23	32	25	35	29	49
	2100	45	70	55	88	78	119	90	205
Maputo	2050	21	31	22	32	24	34	28	49
	2100	45	71	55	89	78	120	89	209

b) Expected damages and risk measures (USD millions)

City	RCP2.6			RCP4.5			RCP8.5			High-end scenario		
	EAD	VaR(95%)	ES(95%)	EAD	VaR(95%)	ES(95%)	EAD	VaR(95%)	ES(95%)	EAD	VaR(95%)	ES(95%)
Abidjan	14,290	33,910	41,690	16,730	38,230	46,390	20,910	42,140	49,550	32,670	77,750	96,570
Alexandria	32,840	74,100	92,470	36,220	83,700	104,270	49,990	99,500	117,580	79,360	180,090	221,390
Algiers	270	620	760	300	700	870	390	810	960	640	1,540	1,920
Cape Town	110	310	400	130	360	450	170	410	490	300	800	1,010
Casablanca	350	1,150	1,520	420	1,340	1,740	610	1,570	1,930	1,230	3,590	4,630
Dakar	590	1,310	1,590	620	1,390	1,690	760	1,530	1,800	1,180	2,880	3,610
Dar-es-Salam	880	2,100	2,600	1,050	2,440	2,970	1,360	2,760	3,250	2,140	5,120	6,360
Durban	110	370	470	150	420	530	210	490	590	370	970	1,230
Lagos	3,680	6,790	7,950	4,200	7,660	8,930	4,920	8,270	9,420	6,750	13,820	16,730
Lome	3,230	10,480	13,460	4,280	12,580	15,780	5,980	14,430	17,380	10,720	28,580	36,010
Luanda	160	380	470	200	440	530	260	510	600	400	910	1,130
Maputo	650	1,990	2,530	700	2,080	2,620	980	2,410	2,910	1,790	4,830	6,110
Aggregate damage and risk	57,160	133,510	165,910	65,000	151,340	186,770	86,540	174,830	206,460	137,550	320,880	396,700

Sea level rise and associated episodic flooding are identified as key drivers of projected net migration of 750,000 people out of the East African coastal zone between 2020 and 2050 (IPCC, 2019a). These trends, alongside the emergence of 'hotspots' of climate in and out-migration (Box 9.8), will have major implications for climate-sensitive sectors and the adequacy of human settlements, including urban infrastructure and social support systems. Actions which could help reduce the number of people being forced to move in distress, include adoption of inclusive and climate-resilient development policies, together with targeted investments to manage the reality of climate migration; and mainstreaming climate migration in development planning (Box 9.8).

Drought

Although an increase in drought hazard is projected for North and southwest southern Africa with increased global warming (Figure 9.15), Central African countries may have the highest drought risk because of high vulnerability and high population growth (Ahmadalipour et al., 2019). Among continents, Africa contains the second largest population of people living in drylands, which is expected to double by 2050 (IPCC, 2019a). Continuing current population and GDP growth trends, the extent of urban land in arid zones is projected to increase around 180% in Southern Africa, 300% in North Africa, and 700% in mid-latitude Africa by 2030 when compared to 2000, without considering climate change (Güneralp et al., 2015). At 1.5°C warming, urban populations exposed to severe droughts in West Africa are projected to increase (65±34 million) and increase further at 2°C (IPCC, 2018b; Liu et al., 2018b). Risks associated with increases in drought frequency and magnitudes are projected to be substantially larger at 2°C than at 1.5°C for North Africa and Southern Africa (IPCC, 2018b; Oppenheimer et al., 2019). Dryland populations exposed (vulnerable) to water stress, heat stress, and desertification are projected to reach 951 (178) million at 1.5°C, 1,152 (220) million at 2°C, and 1,285 (277) million at 3°C of global warming (IPCC, 2019a). At global warming of 2°C under a scenario of low populaton growth and sustainable development (SSP1), the exposed (vulnerable) dryland population is 974 (35) million and for higher population growth and low environmental protections (SSP3) it is 1.27 billion (522 million), a majority of which is in West Africa (IPCC, 2019a).

Extreme heat

Projections for 173 African cities show that around 25 cities will have over 150 days per year with an apparent temperature above 40.6°C for 1.7°C global warming, increasing to 35 cities for 2.1°C and 65 cities for 4.4°C warming, with West African cities most affected (Rohat et al., 2019). Across Africa, urban population exposure to extreme heat is expected to increase from 2 billion person-days per year for 1985–2005 to 45 billion person-days for 1.7°C global warming with low population growth (SSP1) and to 95 billion person-days for 2.8°C and medium-high population growth (SSP4) by the 2060s, with increases of 20–52 times 1985–2005 levels by 2080–2100, depending on the scenario (Rohat et al., 2019). West Africa (especially Nigeria) has the highest absolute exposure and Southern Africa the least. Considering the urban heat island effect, the more vulnerable populations under 5 and over 64 exposed to heat waves of >15 days over 42°C are projected to increase from 27 million in 2010 to 360 million by 2100 for 1.8°C global warming, increasing to 440 million for >4°C global warming, with West Africa most affected (Marcotullio et al., 2021). This portends increased vulnerability to risk of heat stress in big cities of Central, East and West Africa (*very high confidence*) (Gasparrini et al., 2015; Liu et al., 2017; Rohat et al., 2019). Shifting to a low urban population growth pathway is projected to achieve a greater reduction in aggregate exposure to extreme heat for most cities in West Africa whereas limiting warming through lower emissions pathways achieves greater reductions in exposure in Central and East Africa (Rohat et al., 2019).

The African population exposed to compound climate extremes, such as coincident heat waves and droughts or drought followed immediately by extreme rainfall, is projected to increase 47-fold by 2070–2099 compared to 1981–2010 for a scenario with high population growth and 4°C global warming (SSP3/RCP8.5) and only 12-fold for low population growth and 1.6°C global warming (SSP1/RCP2.6), with West, Central-East, northeastern and southeastern Africa especially exposed (Weber et al., 2020). Coincident heat waves and drought is the compound event to which the most people are projected to be exposed: ~1.9 billion person-events (a 14-fold increase) for SSP1/RCP2.6 and ~7.3 billion person-events (52-fold increase) for SSP3/RCP8.5 (Weber et al., 2020).

9.9.4.2 Projected Risks to Electricity Generation and Transmission

Climate change poses an increased risk to energy security for human settlements in Africa (*high confidence*). With burgeoning urban populations and growing economies, sub-Saharan Africa's electricity needs are growing. The IEA projects total generation capacity in Africa must grow 2.5 times from 244 GW in 2018 to 614 GW by 2040 (IEA, 2019). African nations plan to add significant generation capacity from natural gas, hydropower, wind and solar power. Each of these technologies is associated to a varying degree with climate risk.

The long lifespan of hydropower dams exposes them to decades of climatic variability. There is a wide range of uncertainty around the future climate of Africa's major river basins, but in several basins, there is the likelihood of increased rainfall variability and a drier climate (see Box 9.5). In countries that rely primarily on hydropower, climate change could have considerable impacts on electricity prices and as a result, consumers' expenditure (Sridharan et al., 2019). With increasing societal demands on limited water resources and future climate change, it is expected that there will be an intensification of water-energy-food competition and trade-offs (*high confidence*) (Section 9.7; Box 9.5).

9.9.4.3 Projected Risks to Road Infrastructure

Climate change and sea level rise will result in high economic costs for road infrastructure in sub-Saharan Africa (*medium confidence*) (Chinowsky et al., 2015). Across Africa as a whole, potential cumulative costs estimates through 2100 range from USD 183.6 billion (with adaptation) to USD 248.3 billion (no adaptation) to repair and maintain existing roads damaged by temperature and precipitation changes directly related to projected climate change (see Figure 9.30) (Chinowsky et al., 2013). Climate-related road damage and associated repairs will be a significant financial burden to countries, but to varying degrees according to flood risk, existing road asset liability, topography and rural connectivity, among other factors (Chinowsky et al., 2015; Cervigni et al., 2017; Koks et al., 2019). For example, Mozambique is projected to face estimated annual average costs of USD 123 million for maintaining and repairing roads damaged directly by precipitation and temperature changes from climate change through 2050 in a median climate change scenario for a policy that does not consider climate impacts during road design and construction (Chinowsky et al., 2015). Risk of river flooding to bridges in Mozambique under current conditions is estimated to be USD 200 million, equal to 1.5% of its GDP per year, and could rise to USD 400 million per year in the worst-case climate change scenario by 2050 (Schweikert et al., 2015).

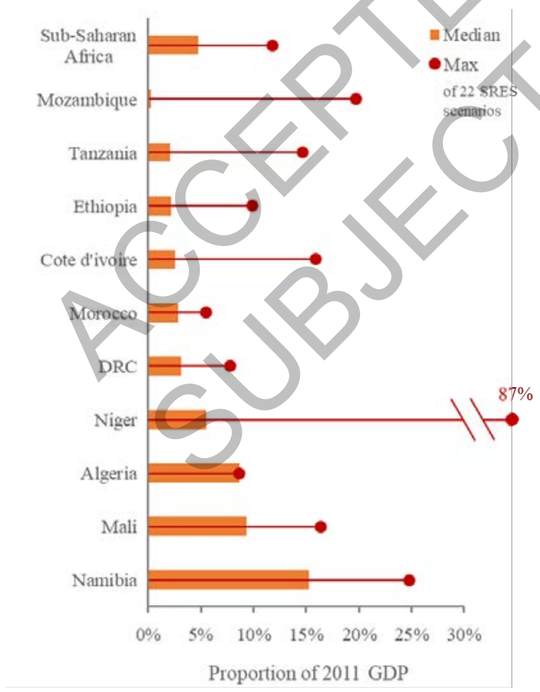


Figure 9.30: Projected costs for repair and maintenance of pre-2011 road infrastructure in selected African countries as a result of projected climate-change-related damages due directly to precipitation and temperature changes through to 2100 (Data sources: (Chinowsky et al., 2013). The analysis was run for 22 SRES climate scenarios and the median, and maximum results of the analyses are represented as proportions of the 2011 GDP of each country.

9.9.5 Adaptation in Human Settlements and for Infrastructure

9.9.5.1 Solutions and Residual Risk Observed in Human Settlements

Autonomous responses to climate impacts in 40 African cities show that excess rainfall is the primary climate driver of adaptation, followed by multi-hazard impacts, with 72% of responses focused on excess rainfall (Hunter et al., 2020). Innovation for adaptation in areas such as home design, social networks, organisations and infrastructure, is evident (Swanepoel and Sauka, 2019). Social learning platforms also increase communities' adaptive capacities and resilience to risk (Thorn et al., 2015).

There is limited evidence of successful, proactively planned climate change adaptation in African cities (Simon and Leck, 2015), particularly for those countries highly vulnerable to climate change (Ford et al., 2014). Planned adaptation initiatives in African cities since 2006 have been predominantly determined at the national level with negligible participation of lower levels of government (Ford et al., 2014). Adaptation action directed at vulnerable populations is also rare (Ford et al., 2014). There are emerging examples of cities planned climate adaptation measures, such as those advanced by Durban (Roberts, 2010), Cape Town (Taylor et al., 2016) and Lagos (Adelekan, 2016). There are also examples of community-led projects such as those in Maputo (Broto et al., 2015), which have seen meaningful help from a range of policy networks, dialogue forums and urban learning labs (Pasquini and Cowling, 2014; Shackleton et al., 2015). These researched cities can be lighthouses for wider exchange and the basis for a deeper synthesis of evidence (Lindley et al., 2019). However, planned adaptation progress is slow, especially in West and Central Africa (Tiepolo, 2014).

Nature-based solutions are also being deployed in mitigating and adapting to climate change, with demonstrated long-term health, ecological and social co-benefits (Swanepoel and Sauka, 2019) (Section 9.6.4). The cost-benefit analysis of nature-based solutions, compared to purely grey infrastructure initiatives, is discussed in Chapter 6 (Section 6.3.3). Nature-based solutions can also lengthen the life of existing built infrastructure (du Toit et al., 2018). Since 2014, an increasing number of ecosystem-based adaptation projects involving the restoration of mangrove, wetland and riparian ecosystems have been initiated across Africa, a majority of which address water-related climate risks (Table 9.9).

Table 9.9: Examples of ecosystem-based solutions to climate impacts in African cities.

Project	City	Solution	Reference
Green Urban Infrastructure (GUI)	Beira (Mozambique)	Mitigating against increased flood risks through restoration of mangrove and other natural habitats along the Chiveve river and the development of urban green spaces.	(IPCC, 2019a; CES Consulting Engineers Salzgitter GmbH and Inros Lackner SE, 2020) .
The Msimbazi Opportunity Plan (MOP) 2019-2024	Dar es Salaam, Tanzania	Enhancing urban resilience to flood risk by reducing flood hazard, and reducing people, properties and critical infrastructure exposed to flood hazard.	(Croitoru et al., 2019)
Tanzania Ecosystem Based Adaptation	Dar es Salaam and five coastal districts, Tanzania	Rehabilitation of over 3,000 hectares of climate-resilient mangrove species.	(UNEP, 2019)
Building Resilience in the Coastal Zone through Ecosystem–based approaches to adaptation	Maputo, Mozambique	Restoration of mangrove and riparian ecosystems for flood control and protection from coastal flooding enhanced water supply.	(GEF, 2019)
Addressing Urgent Coastal Adaptation Needs and Capacity Gaps in Angola	Five coastal communities in Angola	Restoration of 561 hectares of wetland, mangroves and other ecological habitats to promote flood defence and mitigate the threat of drought.	(UNEP, 2020)

Green City Kigali 2016-	Kigali (Rwanda)	600 hectares planned neighbourhood which integrates green building and design, efficient and renewable energy, recycling and inclusive living.	(SWECO, 2019)
Urban Natural Assets for Africa - Rivers for Life	Kampala (Uganda)	Preservation of natural buffers to enhance the protective functions offered by natural ecosystems that support disaster resilience benefit.	(World Bank, 2015)

For green infrastructure to be successful, however, sustainable landscapes and regions require both stewardship and management at multiple levels of governance and social scales (Brink et al., 2016).

Currently planned climate change adaptation to coastal hazards in Africa's large coastal cities has mainly been achieved through expensive coastal engineering efforts such as sea walls, revetments, breakwaters, spillways, dikes and groynes. Examples are found in West Africa (Adelekan, 2016; Alves et al., 2020). Beach nourishment efforts have also been undertaken in Egypt, Banjul and Lagos (Frihy et al., 2016; Alves et al., 2020). However, the use of vegetated coastal ecosystems presents greater opportunities for African cities because of the lower costs (Duarte et al., 2013).

Most (>80%) of Africa's large coastal cities have no adaptation policies and, where available, these are mostly, except for South Africa, dominated by national plans (Olazabal et al., 2019). Coastal adaptation actions minimally consider socioeconomic projections and are not at all aligned with future climate scenarios and risks, which is highly limiting for adaptation planning (Olazabal et al., 2019).

9.9.5.2 Anticipated Adaptation and Residual Risk for Human Settlements

Africa's smaller towns and cities have received far less scholarly and policy development attention for adaptation (Clapp and Pillay, 2017; White and Wahba, 2019). Smaller towns also have less ability to partner effectively with private entities for adaptation initiatives (Wisner et al., 2015). Political will to address climate change and information flows between key stakeholders, professional and political decision-makers may be easier to establish in smaller cities than in the megacity context (Wisner et al., 2015).

Exposure and vulnerability are particularly acute in informal areas, making coordinated adaptation challenging. Yet, there is growing recognition of the potential for bottom-up adaptation that embraces informality in order to more effectively reduce risk (Taylor et al., 2021a) (Figure 9.31). This can provide an opportunity for change towards more risk-sensitive urban development and transformative climate adaptation (Leck et al., 2018). Addressing social vulnerability is particularly important for ensuring the resilience of populations at risk. Improved monitoring, modelling and communication of climate risks is needed to reduce the impacts of climate hazards (Tramblay et al., 2020; Cole et al., 2021a).

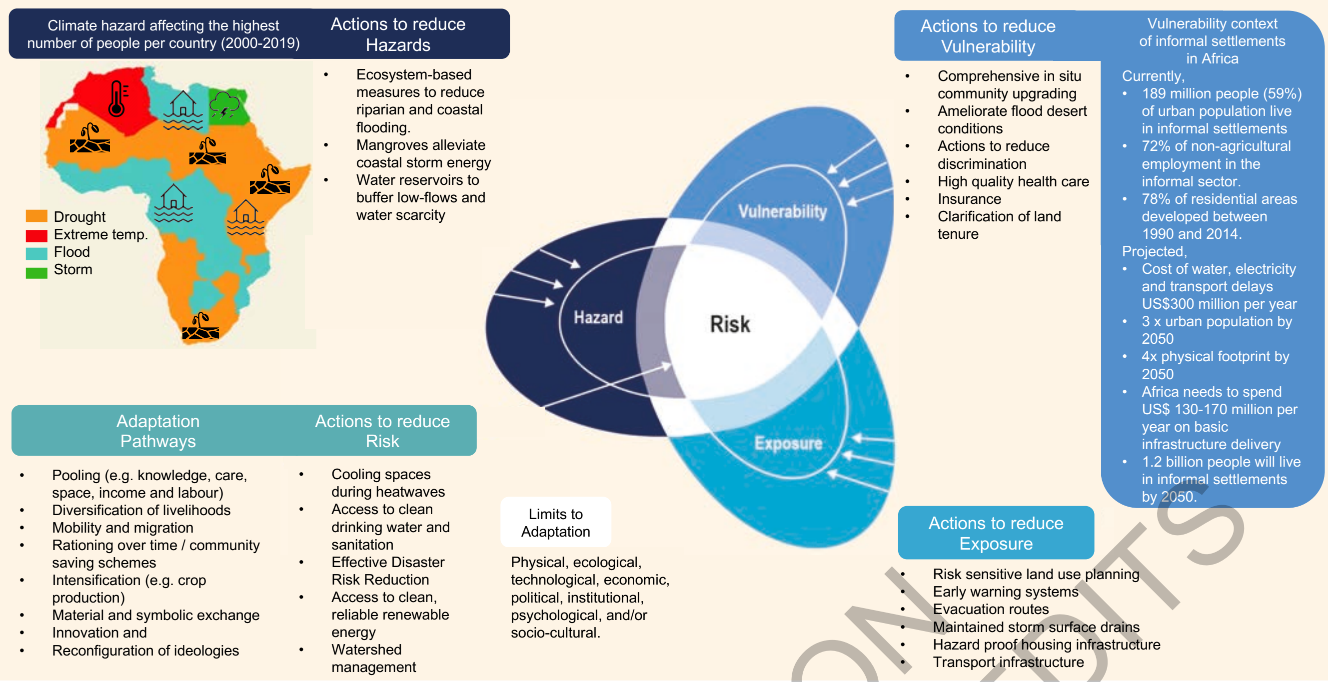


Figure 9.31: Key elements of adaptation in informal settlements in Africa. Adapted from (Thorn et al., 2015; Fedele et al., 2019; Satterthwaite et al., 2020)

9.9.5.3 Anticipated Adaptation for Transport Systems in Africa

Higher costs will be incurred to maintain and repair damages caused to existing roads as a result of climate change for countries with no adaptation policy for transport infrastructure (*very high confidence*) (Chinowsky et al., 2013; Cervigni et al., 2017; Koks et al., 2019). Countries with a greater percentage of unpaved roads will, however, incur higher economic costs through adaptation policy when compared to no adaptation policy (Cervigni et al., 2017).

Adaptation measures in the transport sector have focused on the climate resilience of road infrastructure. Modelling suggests that proactive adaptation of road designs to account for temperature increases is a ‘no regret’ option in all cases, but accounting for precipitation increases should be assessed on a case-by-case basis (*medium confidence*) (Cervigni et al., 2017). African governments will need climate adaptation financing options to meet the higher capital requirements of resilient road infrastructure interventions (Hearn, 2016).

Under the Nationally Appropriate Mitigation Action (NAMA) programme, investments in public transport and transit-oriented development are highlighted as desired mitigation-adaptation interventions within cities of South Africa, Ethiopia and Burkina Faso (UNFCCC, 2020). These interventions simultaneously reduce the vulnerability of low-income residents to climate shocks, prevent lock-ins into carbon-intensive development pathways and reduce poverty (*high confidence*) (Hallegatte et al., 2016; Rozenberg et al., 2019). The combined mitigation-adaptation interventions in the land use transport systems of African cities are also expected to have sufficient short-term co-benefits (reducing air pollution, congestion and traffic fatalities) to be ‘no regret’ investments (*very high confidence*) (Hallegatte et al., 2016; Rozenberg et al., 2019). Only eight African countries have transport-specific adaptation measures in their NDCs (Nwamarah, 2018). Five African countries have submitted National Adaptation Plans (NAPs) (Table 9.10).

Table 9.10: Transport sector references in the National Adaptation Plans of five African countries. Source: (Government of Burkina Faso, 2015; Government of Cameroon, 2015; Government of Togo, 2016; Government of Kenya, 2017; Government of Ethiopia, 2019).

Country	Identify climate change impacts	Promote transport as a disaster risk	Transport-specific adaptation measures			
			Climate resilient	Promote public transport	Promote non-motorized transport	Urban land use planning

		reduction measure	design standards			
Burkina Faso	X		X	X		X
Cameroon			X	X		
Ethiopia	X	X	X	X		
Kenya	X					
Togo				X	X	

9.9.5.4 Projected Adaptation for Electricity Generation and Transmission in Africa

Most electricity infrastructure in Africa has been designed to account for historical climatic patterns. Failure to take into account future climate scenarios in power system planning increases the climate risk facing infrastructure and supplies. Yet, energy demand for cooling over Africa, for example, is expected to increase, with a potential increase in heat stress, population growth and rapid urbanisation to 1.2% of total final energy demand by 2100 compared to 0.4% in 2005 (Parkes et al., 2019). Integrated energy system costs from increased demand for cooling to mitigate heat stress are projected to accumulate from 2005 to USD 51.3 billion by 2035 at 2°C and to USD 486.5 billion by 2076 at 4°C global warming (Parkes et al., 2019).

For hydropower, adaptations to different climate conditions can be made at the level of the power plant, turbine size and reservoir storage capacities, and can be adjusted to projected hydrological patterns (Lempert et al., 2015). At the river basin level, integrated water resource management practices can be implemented across sectors that compete for the same water resources (Howells et al., 2013). At the power system level, the energy mix and the protocol through which different power plants are dispatched can be adapted to different climate scenarios (Spalding-Fecher et al., 2017; Sridharan et al., 2019).

Given the uncertainty around future hydroclimate conditions, hydropower development decisions carry risk of 'regrets' (that is, damages or missed opportunities) when a different climate than was expected materialises. 'Robust adaptation' refers to an adaptation strategy that balances risks across different climate scenarios (Cervigni et al., 2015) (Cross-Chapter Box DEEP in Chapter 17). Development bank lending principles require consideration of the regional picture and interactions with other developments along a river when they determine the social and environmental impacts of the proposed hydropower project. However, these principles often do not explicitly consider climate change, so the risk of reoccurring drought-induced hydropower shortages could be missed (Box 9.5).

Lastly, given the degree to which hydropower competes with other sectors and ecosystems for the same water resources, it is critical that hydropower planning and adaptation does not occur in isolation. As discussed in Section 9.7, it must be part of an integrated water management system that balances the needs of different water-reliant sectors with other societal and ecological demands under increasingly variable climate and hydrological conditions (Section 9.7.3).

9.10 Health

The health section is organised by disease or health outcome, with observed impacts and projected risks described for each condition. All adaptation options are presented at the end of the section, highlighting prevention and preparedness, community engagement and disease-specific adaptation options.

9.10.1 The Influence of Social Determinants of Health on the Impacts of Climate Change

The social determinants of health are 'the conditions in which people are born, grow, live, work and age' as well as the drivers of these, including the social circumstances which profoundly affect health and drive health disparities (Commission of Social Determinants of Health, 2008; Gurewich et al., 2020). Social features (e.g., health-related behaviours), socioeconomic factors (e.g., income, wealth and education) and environmental determinants (e.g., air or water quality) are critical for shaping health outcomes. These factors are inextricably linked (Schulz and Northridge, 2004; Moore and Diaz, 2015) and are largely outside the domain of the health sector. Climate change is already challenging the health and well-being of African communities, compounding the effects of underlying inequalities (*high confidence*). The interlinkage between climate change and social determinants of health are largely discussed at a global level (Commission of Social Determinants of Health, 2008), or for developed countries (Ahdoot et al., 2015; Levy and Patz, 2015; Department of Economic and Social Affairs, 2016), with scant evidence for Africa. Nevertheless, there is robust evidence that the health impacts of climate change disproportionately affect the poorest people and children and, in some situations, can differ by gender and age (St Louis and Hess, 2008; Nyahunda et al., 2020; Ragavan et al., 2020) (see Box 9.1). Unequal access to health care particularly affects rural communities (Falchetta et al., 2020), vulnerable women and children (Wigley et al., 2020a) and challenges the achievement of development priorities such as universal health care access (SDG 3) (Weiss et al., 2020).

9.10.2 Observed Impacts and Projected Risks

Climate change is already impacting certain health outcomes in Africa (e.g. temperature-related mortality) and risks for most (but not all) health outcomes are projected to increase with increasing global warming (Figure 9.32), with young children (<5 years old), the elderly (>65 years old), pregnant women, individuals with pre-existing morbidities, physical labourers and people living in poverty or affected by other socioeconomic determinants of health being the most vulnerable (*high confidence*). Women may be more vulnerable to climate change impacts than men (Chersich et al., 2018; Jaka and Shava, 2018; Adzawla et al., 2019a). Contextualising projected impacts of climate change on health requires an understanding of observed impacts (Figure 9.32). Without management and mitigation, current and projected morbidities and mortalities will put additional strain on health, social and economic systems (Hendrix, 2017; Alonso et al., 2019).

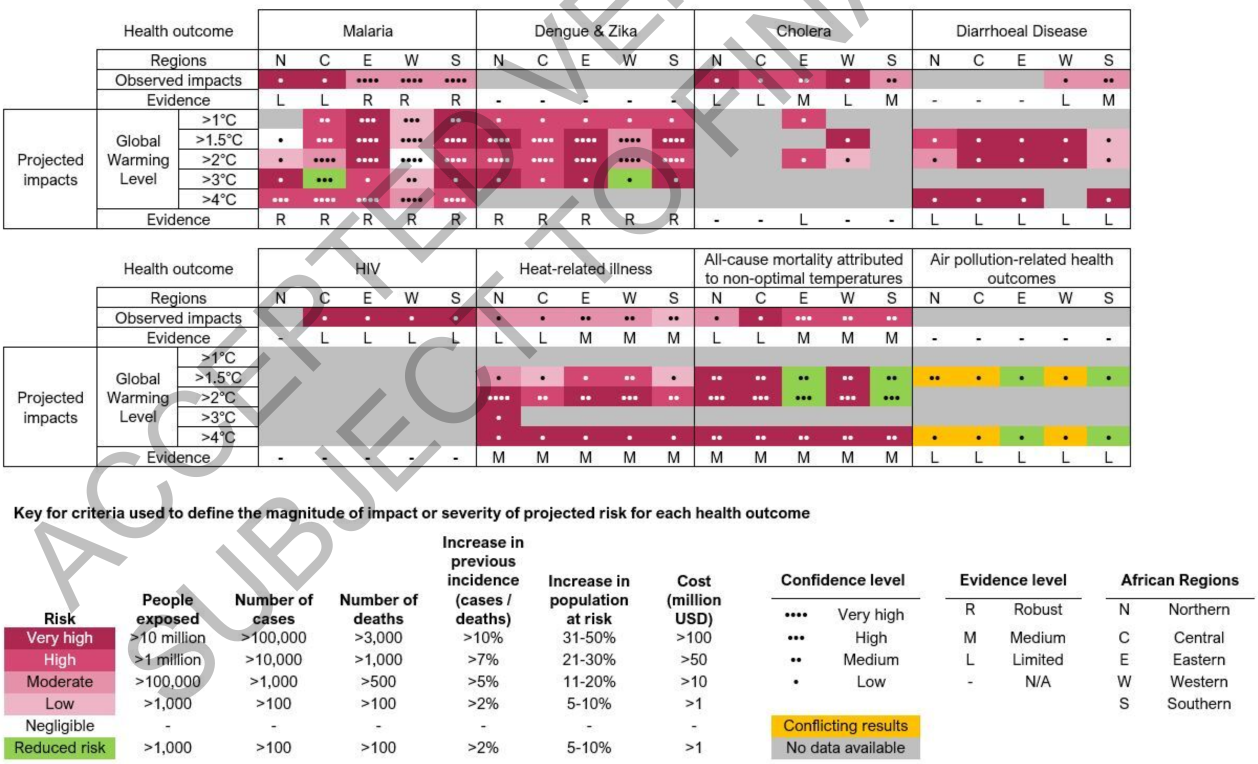


Figure 9.32: Observed climate impacts and projected climate change risks across African regions for eight key health outcomes. Increased global warming levels are shown relative to pre-industrial 1850–1900. This list of health impacts and risks is not intended to be exhaustive, but instead focusses on well-documented conditions. This assessment is a synthesis across 58 studies on observed impacts and 29 studies on projected risks for health (see Supplementary Material Table SM 9.7). The category of air pollution-related health outcomes includes health impacts from changing particulate matter concentrations due to climate change.

9.10.2.1 Vector-Borne Diseases

9.10.2.1.1 Malaria

Observed impacts

Higher temperatures and shifting patterns of rainfall influence the distribution and incidence of malaria in sub-Saharan Africa (*high confidence*) (Agusto et al., 2015; Beck-Johnson et al., 2017). Up to 10.9 million km^2 of sub-Saharan Africa is optimally suitable for year-round malaria transmission (Mordecai et al., 2013; Ryan et al., 2015). Current climate suitability for endemic malaria transmission is concentrated in the central African region, some areas along the Southern coast of West Africa and the East African coast (Ryan et al., 2020).

In East Africa, there has been an expansion of the *Anopheles* vector into higher altitudes (Gone et al., 2014; Carlson et al., 2019) and increasing incidence of infection with *P. falciparum* with higher temperatures (*high confidence*) (Alemu et al., 2014; Lyon et al., 2017). Over Southern Africa, changes in temperature and rainfall are increasing malaria transmission (Abiodun et al., 2018). In West Africa, studies show both positive (Adu-Prah and Kofi Tetteh, 2015; Darkoh et al., 2017) and negative (M'Bra et al., 2018) correlations of malaria incidence with increases in mean monthly temperatures, and an abundance of *Anopheles gambiae s.s.* associated with mean diurnal temperature (Akpan et al., 2018).

Malaria incidence and outbreaks in East Africa were linked with both moderate monthly rainfall and extreme flooding (Boyce et al., 2016; Amadi et al., 2018; Simple et al., 2018), and increase one to two months after periods of rainfall in Southern and West Africa (Diouf et al., 2017; Ferrão et al., 2017; Adeola et al., 2019). The years following La Niña events (Southern Africa) (Adeola et al., 2017)) and high relative humidity (West Africa) (Adu-Prah and Kofi Tetteh, 2015; Darkoh et al., 2017) have been positively linked with malaria incidence.

Projected risks

Since AR5, significant progress has been made in understanding how changes in climate influence the seasonal and geographical range of malaria vectors, transmission intensity and burden of disease of malaria across Africa. Yet projecting changes remains challenging given the range of factors that influence transmission and disease patterns, and model outputs contain high degrees of uncertainty (Zermoglio et al., 2019; Giesen et al., 2020). Models have limited ability to account for population changes and development trends (Kibret et al., 2015; Kibret et al., 2017), investments in health sectors and interventions (McCord, 2016; Colborn et al., 2018; Caminade et al., 2019), and confounders such as age, socioeconomic status, employment and labour migration and climate variability (Bennett et al., 2016; Karuri and Snow, 2016; Byass et al., 2017; Chuang et al., 2017; Colborn et al., 2018). Nevertheless, available models do allow for projections of malaria transmission under different climate change scenarios to be made with high levels of certainty.

In East and southern Africa and the Sahel, malaria vector hotspots and prevalence are projected to increase under RCP4.5 and RCP8.5 by 2030 (1.5°C–1.7°C global warming) (*high confidence*) (Leedale et al., 2016; Semakula et al., 2017b; Zermoglio et al., 2019), becoming more pronounced later in the century (2.4°C–3.9°C global warming) (Ryan et al., 2020). Under RCP4.5, 50.6–62.1 million people in East and Southern Africa will be at risk of malaria by the 2030s (1.5°C global warming), and 196–198 million by the 2080s (2.4°C global warming) (Ryan et al., 2020). Northern Angola, Southern DRC, western Tanzania and central Uganda are predicted to be worst impacted in 2030, extending to western Angola, upper Zambezi River Basin, northeastern Zambia and the East African highlands by 2080 (Ryan et al., 2020). Under rising temperatures, by the 2050s, the greatest shifts in suitability for malaria transmission will be seen in East, Southern and Central Africa (2°C global warming) (Tonnang et al., 2014; Zermoglio et al., 2019; Ryan et al., 2020).

Conversely, in some regions, changing climatic conditions are projected to reduce malaria hotspots and prevalence. With continued greenhouse gas emissions, these include: West Africa by 2030 (1.7°C global warming) (*high confidence*) (Yamana et al., 2016; Semakula et al., 2017b; Ryan et al., 2020), parts of Southern Central Africa and dryland regions in East Africa by 2050 (2.5°C global warming) (*high confidence*) (Semakula et al., 2017b; Ryan et al., 2020), and large areas of southern Central Africa and the western Sahel by 2100 (>4°C global warming) (Yu et al., 2015; Tourre et al., 2019). These reductions in transmission correspond with decreasing environmental suitability for the malaria vector and parasite in these regions (Ryan et al., 2015; Mordecai et al., 2020). Most areas in Burkina Faso, Cameroon, Ivory Coast, Ghana, Sierra Leone, Niger, Nigeria, Zambia and Zimbabwe will have almost zero malaria transmission under RCP8.5 (Semakula et al., 2017b; Tourre et al., 2019).

The El Niño-Southern Oscillation (ENSO) cycle currently contributes to seasonal epidemic malaria in epidemic-prone areas (*high confidence*), and is projected to shift the malaria epidemic fringe southward and into higher altitudes by mid- to end-century (*high confidence*) (Bouma et al., 2016; Semakula et al., 2017b; Caminade et al., 2019). More evidence is needed, however, of climate variability impacts through ENSO cycles in future risk projections, as well as a deeper understanding of how climate change will impact the length of transmission season for mosquitoes, particularly in areas where increases in spring and autumn temperatures may increase suitability for the reproduction of malaria vectors (Ryan et al., 2020). Other gaps in knowledge include a better understanding of mosquito thermal biology and thermal limits for a variety of species, potential adaptations to extreme temperatures and how landscape changes contribute to malaria transmission (Tompkins and Caporaso, 2016).

9.10.2.1.2 Mosquito-borne viruses

Observed impacts

Climate variability has driven a global intensification of mosquito-borne viruses (e.g., dengue, Zika and Rift Valley Fever), including expansion into areas with higher altitudes (Leedale et al., 2016; Mweya et al., 2016; Messina et al., 2019). Concerns centre on diseases vectored by the yellow fever mosquito (*Aedes aegypti*), common throughout most of sub-Saharan Africa, and the tiger mosquito (*Aedes albopictus*), currently largely confined to western Central Africa (Kraemer et al., 2019; Mordecai et al., 2020).

Although warming temperatures are largely responsible for increasing environmental suitability for mosquito vectors (Mordecai et al., 2019), droughts can augment transmission when open water storage provides breeding sites near human settlements, and when flooding enables mosquitoes to proliferate and spread viruses further (Mweya et al., 2017; Bashir and Hassan, 2019). Within Africa's rapidly growing cities, diseases vectored by urban-adapted *Aedes* mosquitoes pose a major threat, especially in West Africa (Zahouli et al., 2017; Weetman et al., 2018; Messina et al., 2019). Dengue virus expansion may cause explosive outbreaks but the burden of dengue haemorrhagic fever and associated mortality is higher in areas where transmission is already endemic (Murray et al., 2013).

Projected risks

Populations of *Aedes aegypti* and *Aedes albopictus* mosquitoes and epidemics of dengue and yellow fever and other *Aedes*-borne viruses are expected to increase, including at high altitudes (Weetman et al., 2018; Messina et al., 2019; Ryan et al., 2019; Gaythorpe et al., 2020; Mordecai et al., 2020). *Aedes albopictus* may expand beyond western Central Africa into Chad, Mali and Burkina Faso by mid-century at >2°C global warming (Kraemer et al., 2019). Shifts projected in *Aedes* range due to changing environmental suitability, combined with rapid urbanisation and population growth, suggest that by 2050 populations exposed to these vectors in Africa may double, and by 2080 nearly triple at >2°C global warming (Kraemer et al., 2019). Southern limits of dengue transmission in Namibia and Botswana, and the western Sahel, may show the greatest expansions in environmental suitability under 1.8°C–2.6°C global warming (Messina et al., 2019). In the warmest scenarios (RCP8.5), however, some parts of Central Africa may become too hot for mosquitoes to transmit dengue, and thus at-risk populations may peak at intermediate warming levels (Ryan et al., 2019). Climatic conditions favourable for mosquitoes, combined with the increase of animal trade, may result in the expansion of the geographic range of zoonotic diseases like Rift Valley fever (Martin et al., 2008), a threat for human and animal health with strong socioeconomic impacts (Peyre, 2015).

9.10.2.2 Diarrhoeal Diseases, HIV and Other Infectious Diseases

9.10.2.2.1 Diarrhoeal diseases

Observed impacts

Africa has the highest rates of death due to diarrhoeal diseases in the world (Havelaar et al., 2015; Troeger et al., 2018) and many children have repeated diarrhoeal episodes with impaired growth, stunting, immune dysfunction and reduced cognitive performance (Squire and Ryan, 2017). High land and sea temperatures (Paz, 2009; Musengimana et al., 2016) and precipitation extremes increase transmission of bacterial and protozoal diarrhoeal disease agents (Boeckmann et al., 2019) through contamination of drinking water and food preparation and preservation practices (Figure 9.33) (Levy et al., 2016; Soneja et al., 2016; Walker, 2018).

Cholera incidence has been shown to increase with temperature (Trærup et al., 2011). Outbreaks, however, are most frequent in East and Southern Africa following tropical cyclones (Moore et al., 2017b; Troeger et al., 2018; Ajayi and Smith, 2019; Cambaza et al., 2019).

Africa's rapidly urbanising population increases the demand for freshwater and is occurring in places that already have stretched water and sanitation infrastructure (Howard et al., 2016). These conditions, especially during periods of water scarcity, can reduce the frequency and adequacy of hand washing and thereby increase disease transmission.

Projected risks

Disruptions in water availability, such as during droughts or infrastructure breakdown, will jeopardise access to safe water and adequate sanitation, undermine hygiene practices and increase environmental contamination with toxins (Howard et al., 2016; WWF-SA, 2016; Miller and Hutchins, 2017).

Climate change is projected to cause 20,000–30,000 additional diarrhoeal deaths in children (<15 years old) by mid-century under 1.5°C–2.1°C global warming (WHO, 2014), with West Africa most affected, followed by East, Central and southern Africa. Cholera outbreaks are anticipated to impact East Africa most severely during and particularly after ENSO events (Moore et al., 2017b).

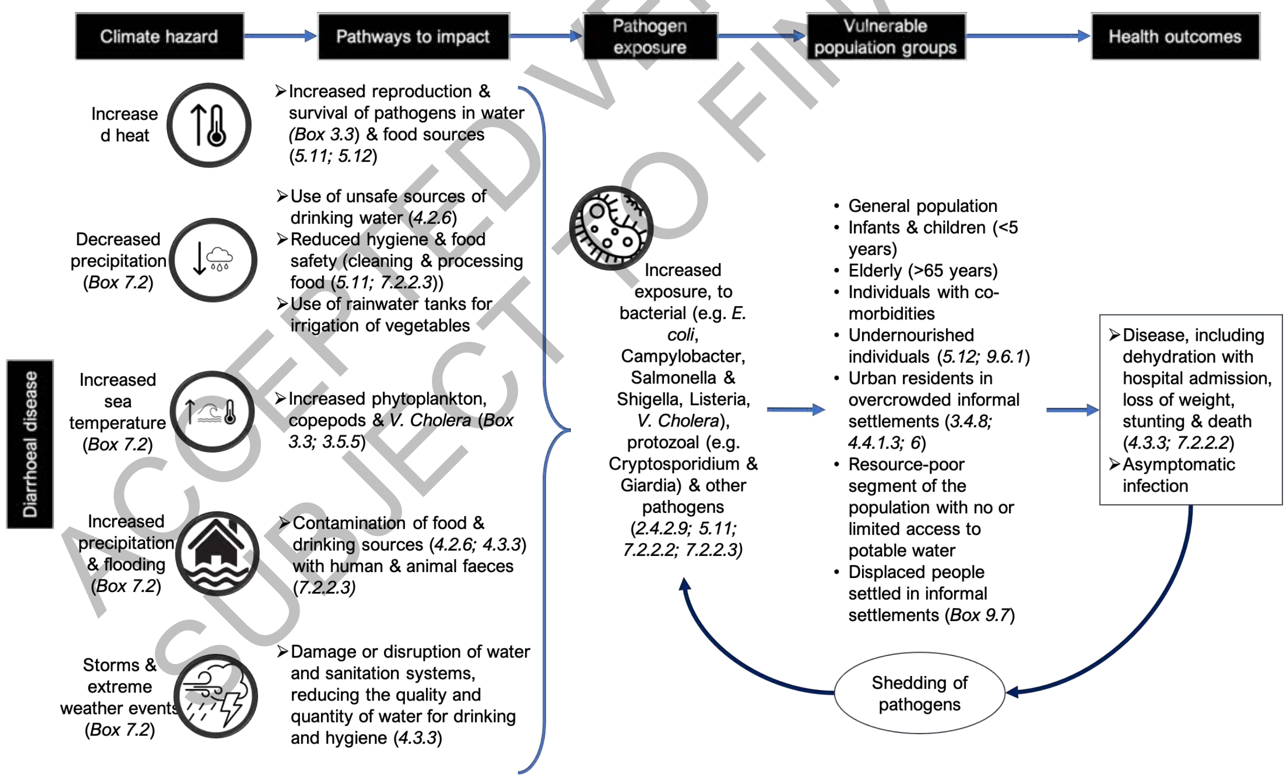


Figure 9.33: Pathways to impact: diarrhoeal disease. Schematic showing the pathways of impact diarrhoeal disease in Africa as a result of exposure to climate hazards.

[START BOX 9.6 HERE]

Box 9.6: Pandemic Risk in Africa: COVID-19 and Future Threats

Rapid advances in vaccination and other control measures in high-income countries means that the burden of COVID-19 is increasingly concentrated in low- and middle-income countries, including those in Africa. The extent to which the COVID-19 pandemic is influenced by weather or by future changes in climate remains contested (WMO, 2021). In time, COVID-19 may develop seasonal dynamics (Baker et al., 2020; Kissler et al., 2020) similar to other respiratory infections (Carlson et al., 2020b).

Early work interpreted low-reported cases of COVID-19 in Africa as suggesting evidence of a protective climatic effect, but increasing evidence indicates the role of climate is secondary to the timing of disease introduction, the pace of implementation of non-pharmaceutical interventions, and surveillance gaps (Evans et al., 2020; WMO, 2021). Going forward, testing coverage, reporting, governance, non-pharmaceutical interventions and vaccine distribution and uptake are *likely* to be far more significant for Africa's COVID-19 trajectory than climate change. Compounding risks, where climate hazards and natural disasters impair outbreak responses, may disrupt interventions or cause additional deaths (Phillips et al., 2020; Salas et al., 2020).

Emerging and future pandemic threats

Future influenza pandemics are highly *likely*, as are regional epidemics and pandemics of novel zoonotic viruses (including coronaviruses and flaviviruses) (*high confidence*). In the next decades, climate change will reshape the risk landscape for emerging zoonotic threats as wildlife-livestock-human interfaces shift, facilitating the emergence of novel zoonotic threats and spillover of known zoonoses into novel geographies (Carlson et al., 2020a; Mordecai et al., 2020). Characteristics of urban development and level of service provision, for example, crowded living spaces and transport facilities, and access to water and sanitation will influence the transmission of COVID-19 and future disease outbreaks (Wilkinson, 2020). Historically, West and Central Africa were considered especially at risk of outbreaks given their high biodiversity, high intensity of human-wildlife contact including wild meat trade, vulnerable health systems and history of Ebola virus disease outbreaks (Paige et al., 2014; Allen et al., 2017; Pigott et al., 2017). However, as the Middle East respiratory syndrome coronavirus (MERS-CoV) and COVID-19 pandemics have shown, there are multiple hotspots of viruses with pandemic potential globally, many of which are not in Africa. Thus, labelling African rainforests as unique 'hotspots' undermines global health work and pandemic preparedness.

[END BOX 9.6 HERE]

9.10.2.2.2 HIV

Observed impacts

Although levels of new HIV infections declined sharply during the last decade, still more than a million adults and children become infected each year (UNAIDS, 2020). Climate influences on HIV are predominately indirect such as through heightened migration due to climate variability, or extreme weather events leading to increased transactional sex to replace lost sources of income. Changes in climate affect each of the main drivers of HIV transmission in women, including poverty, inequity and gender-based violence (Burke et al., 2015a; Loevinsohn, 2015; Fiorella et al., 2019).

Projected risks

'Oscillating' or 'circular' migration for migrant workers in urban and mining centres drove HIV transmission in the 1990s and 2000s (Lurie, 2006), and climate-related displacement may have similar effects (see Box 9.7) (Gray and Mueller, 2012; Loevinsohn, 2015; Low et al., 2019). Food insecurity and nutritional deficiencies, projected to increase with increasingly variable climates, has been shown to increase sexual risk-taking and migration, as well as increase susceptibility to other infections (Lieber et al., 2021). Projected increases in exposure to infectious diseases pose considerable threats to HIV-infected people who may already have compromised immune function. Additionally, reduced lung function in people with HIV from previous tuberculosis infection may put them at high risk for morbidity and death during extreme heat (Abayomi and Cowan, 2014). Moreover, extreme weather events accompanied by damage to health system infrastructure could compromise the continuity of antiretroviral treatment (Weiser et al., 2010; Pozniak et al., 2020).

9.10.2.2.3 Other infectious diseases

Poor populations in the western Sahel have the highest burden of bacterial meningitis worldwide, with seasonal dynamics driven by the dry Harmattan winds that transport dust long distances across the continent (Agier et al., 2013; García-Pando et al., 2014). In Nigeria, rising temperatures are projected to increase meningitis cases by about 50% for 1.8°C global warming (RCP2.6 in 2060–2075), and by almost double for 3.4°C global warming (RCP8.5 in 2060-2075) (Abdussalam et al., 2014). Bilharzia is also highly climate-sensitive, with its distribution influenced by changes in temperature and precipitation, as well as development, such as the introduction of freshwater projects (e.g., canals, hydroelectric dams and irrigation schemes) (Adekiya et al., 2019).

9.10.2.3 Temperature-Related Impacts

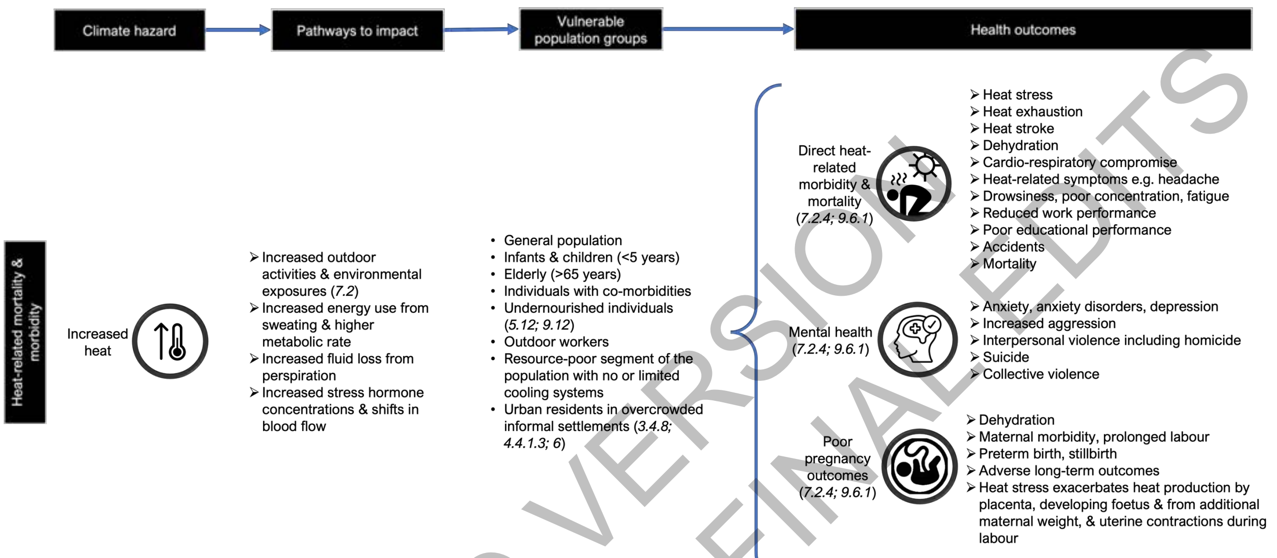


Figure 9.34: Pathways to impact: heat-related morbidities. Schematic showing the pathways of impact for heat-related morbidities in Africa as a result of exposure to climate hazards. Numbers in the figure refer to chapter sections of this report. Indirect health impacts of heat are not shown. For example, risk of malnutrition from reduced crop yields or reduced fisheries catches (see Section 9.8.5).

9.10.2.3.1 Mortality and morbidity

Observed impacts

Emergency department visits and hospital admissions have been shown to increase at moderate to high temperatures (Bishop-Williams et al., 2018; van der Linden et al., 2019), with increased levels of mortality recorded on days with raised temperatures in Burkina Faso (Kynast-Wolf et al., 2010; Diboulo et al., 2012; Bunker et al., 2017), Ghana (Azongo et al., 2012), Kenya (Egondi et al., 2012; Egondi et al., 2015), South Africa (Wichmann, 2017; Scovronick et al., 2018), Tanzania (Mrema et al., 2012) and Tunisia (Bettaieb et al., 2010; Leone et al., 2013). Cause of death most commonly involves cardiovascular diseases (Kynast-Wolf et al., 2010; Scovronick et al., 2018), but increased incidences of respiratory (Scovronick et al., 2018), stroke (Longo-Mbenza et al., 1999) and non-communicable diseases (Bunker et al., 2017) have also been linked with heat.

Excess death rates from non-optimal temperature in sub-Saharan Africa are estimated to be nearly double the global average, with 24% of the more than 5 million annual deaths associated with non-optimal temperature occurring in Africa (Zhao et al., 2021). The region had the world’s highest cold-related excess death ratio and lowest heat-related excess death ratio over the period 2000–2019. However, during this time, cold-related excess deaths declined more rapidly than the increase in heat-related excess deaths, resulting in a net decrease in the excess death ratio from temperature.

Recent estimates of the burden of mortality associated with the additional heat exposure from recent human-induced warming suggest approximately 43.8% of heat-related mortality in South Africa was attributable to anthropogenic climate change from 1991–2018 (Vicedo-Cabrera et al., 2021). In many of South Africa's 52 districts, this equates to dozens of deaths per year. The elderly and children under five years are most vulnerable to heat exposure (Sewe et al., 2015; Scovronick et al., 2018).

Projected risks

Globally, Africa is predicted to suffer disproportionately higher all-cause mortality risk from higher temperature-related all-cause mortality from global warming, compared to temperate, Northern Hemisphere countries (Carleton et al., 2018). The number of days projected to exceed potentially lethal heat thresholds per year reaches 50–150 days in West Africa at 1.6°C global warming, up to 200 days in West Africa and 100–150 days in Central Africa and parts of coastal East Africa at 2.5°C, and over 200 days for parts of West, Central and East Africa for >4°C global warming (Mora et al., 2017) (see Sections 9.5.3–7; Figure 9.15). Projected rates of heat-related mortality among people in the Middle East and North Africa who are older than 65 years increase by 8–20 fold in 2070–2099, compared with 1951–2005, based on RCP4.5 and RCP8.5 (both at >2°C global warming) (Ahmadalipour and Moradkhani, 2018).

Temperature-related mortality across Africa is projected to escalate with global warming, reaching 50–180 additional deaths per 100,000 people annually in regions of North, West, and East Africa for 2.5°C global warming, and increasing to 200-600 per 100,000 people annually for 4.4°C global warming (Carleton et al., 2018) (Figure 9.35). However, some regions that currently experience cold-related mortality (e.g., Lesotho and Ethiopian highlands) are projected to have reduced temperature-related mortality risk from warming. Greenhouse gas mitigation is projected to save tens of thousands of lives: limiting warming to RCP4.5 (2.5°C) rather than RCP8.5 (4.4°C) at the end of the century is projected to avoid on average 71 deaths per 100,000 people annually across Africa with larger reductions in risk in North, West, Central and parts of East Africa (Figure 9.35). The cost of mitigating heat stress using energy-intensive cooling methods is expected to be to be unachievable for many African countries (Parkes et al., 2019) (see Section 9.9.4).

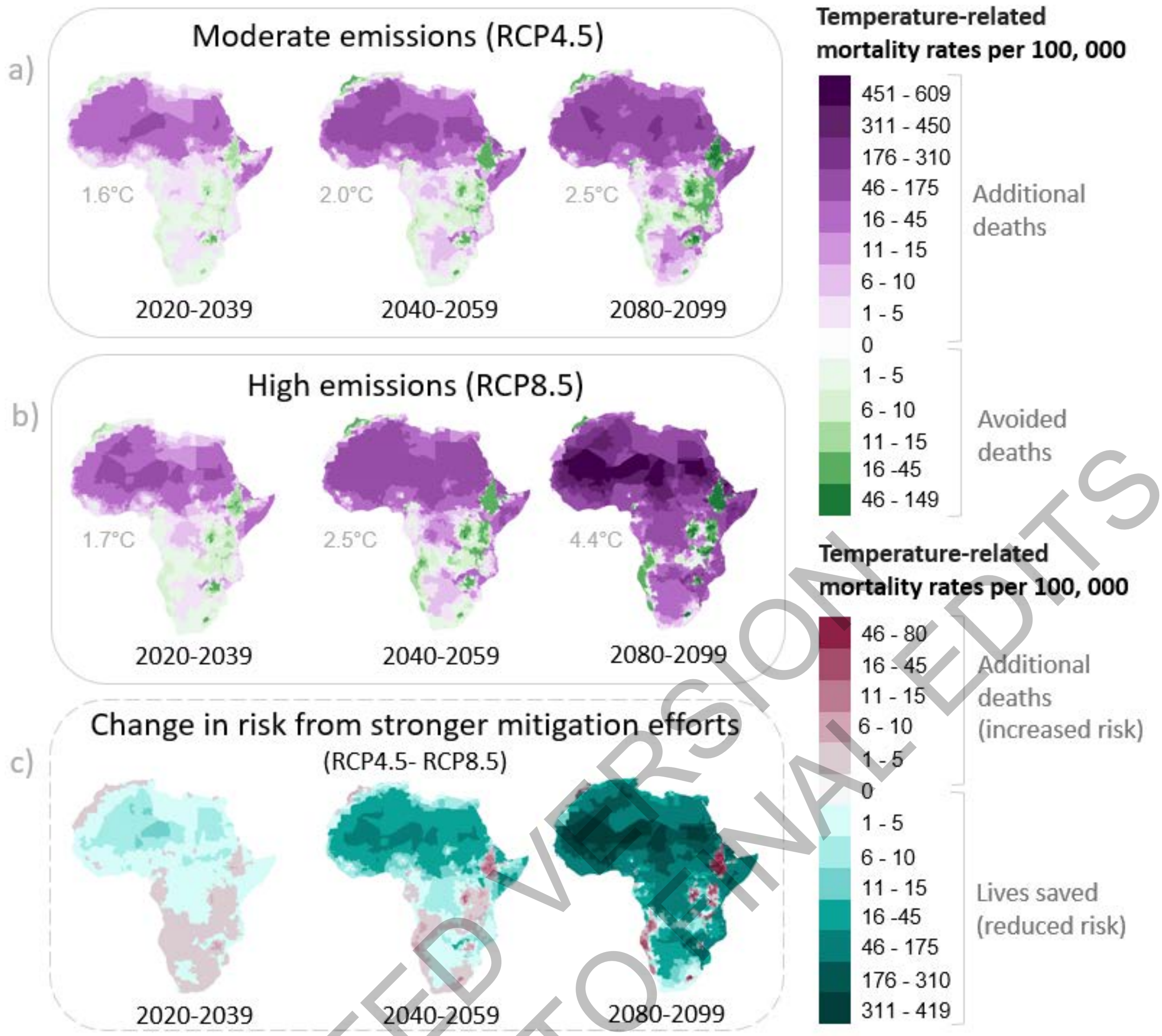


Figure 9.35: Temperature-related mortality risk in Africa with increased global warming. Maps showing changes in mortality rates in deaths per 100 000 for global warming in the years 2020–2039, 2040–2059, and 2080–2099 for (a) medium emissions scenario (RCP 4.5); (b) a high emissions scenario (RCP 8.5); and (c) showing avoidable deaths due to increased emissions mitigation to achieve reduced global warming (RCP4.5–RCP8.5). These estimates of climate change impacts on mortality rates include temperature-related impacts only. They account for the benefits of income growth and incremental adaptation to climate change, both of which reduce mortality sensitivity to extreme temperatures. Projections were based on income and demographics from Shared Socioeconomic Pathway 3 (SSP3), with future adaptation based on adaptation actions observed in the global historical record. The estimates do not include the costs of the behaviours and investments required to achieve such adaptation (Carleton et al., 2018). Areas shown in green in c) have fewer deaths due to temperature under RCP8.5 than RCP4.5. This is because cold is currently the greatest driver of temperature-related deaths in these countries, which will be alleviated with increasing levels of global warming (Zhao et al., 2021).

9.10.2.3.2 Heat stress in specific settings

Heat stress symptoms are prevalent among people in buildings that are poorly ventilated or insulated, or constructed with unsuitable materials (e.g., corrugated metal sheeting). These features are common to many structures in Africa, including in slums, informal and low-income settlements, as well as schools and healthcare facilities (Bidassey-Manilal et al., 2016; Naicker et al., 2017; Wright et al., 2019). Temperatures inside these structures can exceed outdoor temperatures by 4°C or more and have large diurnal fluctuations (Mabuya and Scholes, 2020). Daily wage labourers and residents of urban informal settlements are among the most vulnerable to heat stress because of the urban heat island effect, with congestion, little ventilation, shade, open space and vegetation (Bartlett, 2008) being associated with impacts of both hot and cold conditions on public health (Ramin, 2009), and the number of years lived depending on age, sex and comorbidities (Egondi et al., 2015). Temperature extremes are *likely* to result in relatively more deaths in informal settlements than in other settlement types (Scovronick and Armstrong, 2012).

The urban heat island effect exacerbates current and projected heat stress in Africa's rapidly growing cities (Mitchell, 2016) and is discussed in more detail in Section 9.9.3.

Escalating temperatures and longer-duration heatwaves are *likely* to heavily affect workers already exposed to extreme temperatures, e.g., outdoor workers (Kjellstrom et al., 2018) and miners (El-Shafei et al., 2018; Nunfam et al., 2019a; Nunfam et al., 2019b). Vulnerability may also be high for women who cook food for a living, and children who accompany them, due to prolonged exposure to high temperatures (Parmar et al., 2019). Prisons, commonly poorly ventilated and overcrowded, are also high-risk settings (Van Hout and Mhlanga-Gunda, 2019).

9.10.2.3.3 Maternal and child health

Exposure to high temperatures during pregnancy has been linked with adverse birth outcomes, including stillbirths or miscarriages (Asamoah et al., 2018) and long-term behavioural and developmental deficiencies (Duchoslav, 2017; MacVicar et al., 2017).

9.10.2.4 Impacts of Extreme Weather

During extreme conditions, for example, Cyclone Kenneth (Codjoe et al., 2020) and El Niño 2015-2016 (WHO, 2016; Pozniak et al., 2020), direct physical injury, loss of life, destruction of property and population displacement can occur. Flooding and landslides are common after extreme rainfall and are the most frequently described impact of climate variability in Africa's cities currently, with residents of poorly serviced or informal settlements most vulnerable (Hunter et al., 2020). Post-traumatic stress disorders in affected individuals are common, including in children (Rother, 2020). In rural areas, the resulting damage to health facilities, access routes and transport services can severely compromise health service delivery (WHO, 2016). The effects of extreme weather on urban health infrastructure depends on the characteristics, location and adaptive capacity of cities (see Section 9.9.4).

9.10.2.5 Malnutrition

Observed impacts

Africa has experienced the greatest impacts of climate change on acute food insecurity and malnutrition (FAO and ECA, 2018). Adverse climatic conditions exacerbate the impacts of an unstable global economy, conflict and pandemics on food insecurity (AfDB, 2018b; Food Security Information Network (FSIN), 2019; Fore et al., 2020) (see Chapter 5, Section 5.12.4).

More than 250 million Africans are undernourished, mostly in Central and East Africa (FAO et al., 2020), which increases childhood stunting, affects cognition and has trans-generational sequelae (IFPRI, 2016; UNICEF et al., 2019). Undernutrition is strongly linked with hot climates (Hagos et al., 2014; Tusting et al., 2020). In Burkina Faso, low crop yields resulted in around 110 deaths per 10,000 children under five, with 72% of this impact attributable to adverse climate conditions in the growing season (Belesova et al., 2019).

Increasing incidence and expanded distributions of vector-borne livestock diseases (e.g., bluetongue, trypanosomiasis and Rift Valley Fever) in response to changes in rainfall and increasing temperatures, undermine food security, especially among subsistence farmers (Samy and Peterson, 2016; Caminade et al., 2019). Locust infestations linked with changes in climate (Salih et al., 2020) are a major risk for food security in Africa.

Projected risks

Projected risks for malnutrition in Africa are high (FAO, 2016) (see Section 9.8.1): 433 million people in Africa are anticipated to be undernourished by 2030 (FAO et al., 2020) and, compared to 1961–1990, 1.4 million additional African children will suffer from severe stunting by 2050 under 2.1°C global warming (WHO, 2014). In Burkina Faso, the mortality burden due to low crop yields could double by 2100 with 1.5°C of global warming (Belesova et al., 2019). Drought risks will include crop and livestock failures

(Ahmadalipour et al., 2019). Additionally, increasing concentrations of atmospheric CO_2 will affect the nutritional quality of C_3 plant staples, lowering levels of protein and minerals like zinc and iron (Myers et al., 2014; Weyant et al., 2018). Declining fish catches due to ocean warming, illegal fishing and poor stock management are projected to increase deficiencies of zinc, iron and vitamin A for millions of people across Mozambique, Angola and multiple West African countries (Golden et al., 2016) (see Section 9.8.5).

9.10.2.6 Non-Communicable Diseases and Mental Health

Links between climate change and the environmental risk factors for non-communicable diseases (NCDs) may be direct (e.g., extreme heat exposure in people with cardiovascular disease) or indirect, such as via the global agriculture and food industry (Landrigan et al., 2018). These effects are largely unreported for Africa (Amegah et al., 2016), where the burden of many NCDs is growing rapidly with increasing urbanisation and pollution (Rother, 2020).

Many urban poor populations have unhealthy dietary practices, which present major risks for obesity, type II diabetes and hypertension. Paradoxically, despite growing levels of undernutrition, the incidence of overweight and obesity continues to rise in Africa, particularly in children under five from the northern and southern parts of the continent (FAO and ECA, 2018). Diabetes is increasingly prevalent and outcomes may worsen if climate change undermines health infrastructure and the range of available foods (Keeling et al., 2012; Kula et al., 2013; Chersich and Wright, 2019).

The relationship between cancer and climate change is complex and indirect. Changing temperature and humidity may alter the distribution of Aflatoxin-producing fungi, contaminating food (grains, maize) and causing cancer (see Box 5.9 in Chapter 5) (Sserumaga et al., 2020; Valencia-Quintana et al., 2020). Severe storms and flooding may disrupt wastewater treatment or disposal, potentially contaminating drinking water with carcinogenic substances.

Areas with low service provision (e.g., informal settlements in Africa) suffer from increased infestations of pests such as flies, cockroaches, rats, bedbugs and lice, which may be controlled by chemical pesticides (Rother et al., 2020) and may become more prevalent with a changing climate (Mafongoya et al., 2019). Inappropriate pesticide use and disposal cause endocrine disruption and increased incidences of some cancers (Rother et al., 2020).

9.10.2.6.1 Mental health and well-being
Mental health and well-being are affected by local climate conditions and are therefore sensitive to climate change (Burke et al., 2018b; Obradovich et al., 2018). High temperatures are strongly associated with poor mental health and suicide in South Africa (Kim et al., 2019). Exposure to extreme heat directly influences emotional control, aggression and violent behaviour, escalating rates of interpersonal violence, with homicides rising by as much as 18% in South Africa when temperatures are above 30°C compared with temperatures below 20°C (Burke et al., 2015a; Chersich et al., 2019b; Gates et al., 2019).

Extreme weather events are often severely detrimental to mental health (Scheerens et al., 2020), with elevated rates of anxiety, post-traumatic stress disorder and depression in impacted individuals (Schlenker and Lobell, 2010; Nuvey et al., 2020). Youth may be at especially high risk (Barkin et al., 2021).

Loss of livestock from disease or lack of pastures is strongly linked with poor mental health among farmers (Nuvey et al., 2020). Climate change impacts on mental health among refugees is concerning but remains under-researched (Matlin et al., 2018).

9.10.2.7 Air Quality-Related Health Impacts

Links between air quality and climate change are complex (Smith et al., 2014; Szopa et al., 2021). Increases in particulate matter concentrations are driven more by vehicle emissions, solid waste, biomass burning and development (Abera et al., 2021) than by climate change, and these factors vary widely across regions of the continent (West et al., 2013). Women and children who are exposed to high particulate matter concentrations when cooking indoors and HIV-infected people are more vulnerable to the health impacts of air pollution (Abera et al., 2021). Information on the direction of change of air quality in different African regions attributable to climate change are contradictory (Westervelt et al., 2016; Silva et al., 2017). Additionally, much uncertainty remains about interactions between air quality and climate change and relative impacts of different modes of development and climate change on pollutants. However, increasing temperatures combined with a reduction in rainfall are *likely* to increase particulate matter concentrations (Abera et al., 2021), particularly in North Africa (Westervelt et al., 2016; Silva et al., 2017).

Nevertheless, continued dependence on fossil-fuelled power plants will result in tens of thousands of avoidable deaths due to air pollution by 2030 (Marais and Wiedinmyer, 2016), and accelerate climate change. Actions to reduce air pollution can both mitigate climate change and have major co-benefits for health (West et al., 2013; Rao et al., 2016; Markandya et al., 2018; Rauner et al., 2020a; Rauner et al., 2020b) (see also AR6 WGIII, Chapters 3, 4, 8 and 10). Investing in renewable energy resources rather than reliance on the combustion of fossil fuels would mark an important step forward for African population health (Marais et al., 2019). This is especially important in South Africa which emits approximately half the total carbon emissions for Africa, ranking 12th in the world for carbon emissions (Mohsin et al., 2019).

Dust events in West Africa have severe health impacts (cardiorespiratory and infectious diseases, including meningitis) (Ayanlade et al., 2020) given the proximity of the Sahara, which produces about half of the yearly global mineral dust (de Longueville et al., 2013). Wildfires are projected to become the main source of particulate matter in West, Central and southern Africa under both the lowest and highest future emissions scenarios, whereas, under intermediate scenarios (i.e., SSP3/RCP4.5), anthropogenic sources of particulate matter are projected to exceed that produced by wildfires (Knorr et al., 2017).

[START BOX 9.7 HERE]

Box 9.7: The Health-Climate Change Nexus in Africa

The intersections between climate change and human health are involve interactions of numerous systems and sectors (Lindley et al., 2019; Yokohata et al., 2019). This complexity means that holistic, transdisciplinary and cross-sectoral (systems) approaches like One Health, EcoHealth and Planetary Health can improve the long-term effectiveness of responses to health risks (Zinsstag, 2012; Whitmee et al., 2015; Nantima et al., 2019). More research is needed to identify sustainable solutions (Rother et al., 2020), as recently re-emphasised by the Intergovernmental Panel on Biodiversity in its report on the COVID-19 pandemic (IPBES, 2020). The close dependency of many Africans on their livestock and surrounding ecosystems forms a context where integrated health approaches are especially critical for addressing climate change risks to health (Figure Box 9.7.1) (Watts et al., 2015; Cissé, 2019).

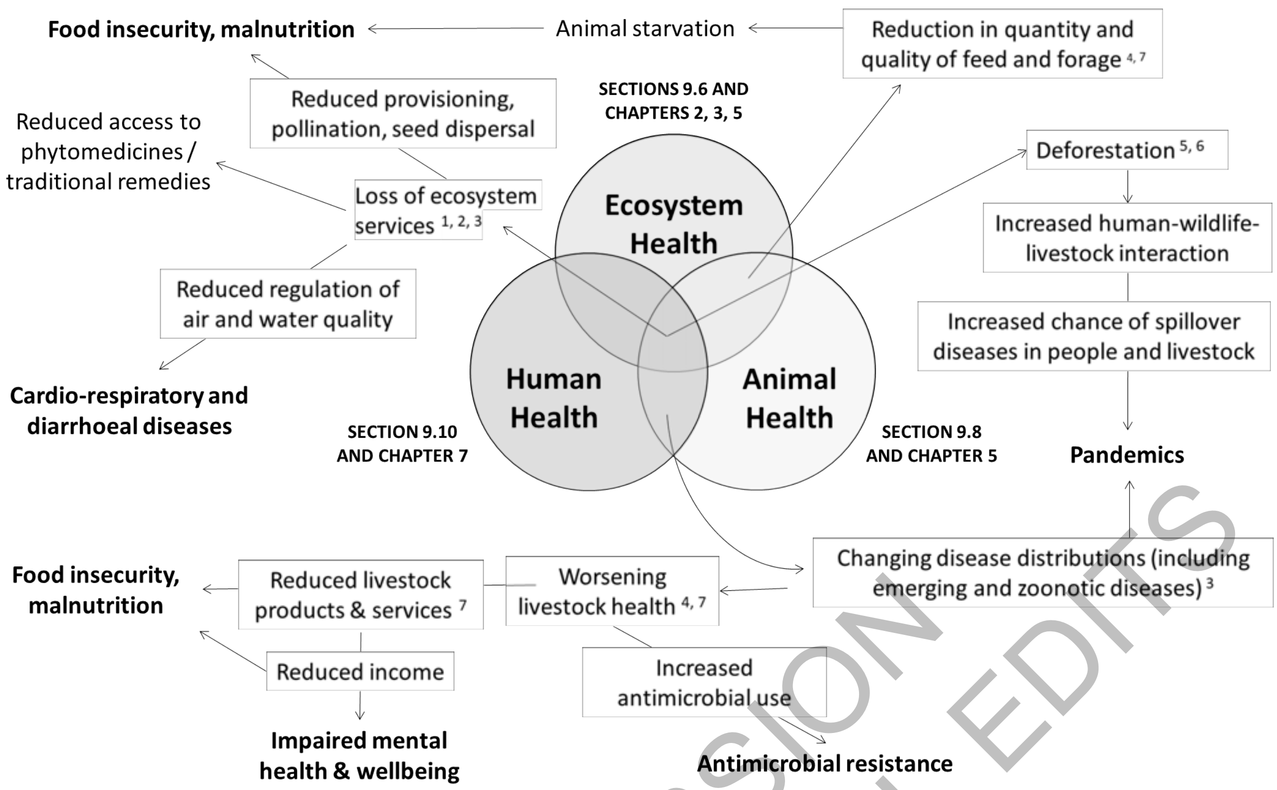


Figure Box 9.7.1: Human, ecosystem and animal health are intimately interlinked, and require transdisciplinary approaches such as One Health, EcoHealth and Planetary Health for effective, sustainable, long-term management. This schematic shows some examples of these interlinkages, and how they impact human health, highlighting the complex interactions and the importance of holistic, systems approaches to health interventions, including for climate change adaptation. Supporting literature: 1 (Egoh et al., 2012); 2 (Wangai et al., 2016); 3 (Failler et al., 2018); 4 (Ifejika Speranza, 2010); 5 (Brancalion et al., 2020); 6 (Bloomfield et al., 2020); 7 (Rojas-Downing et al., 2017).

Integrated approaches to health in Africa can deliver multiple benefits for humans and ecosystems For example, rather than addressing micronutrient deficiencies with supplements, which may not be accepted culturally and can be disrupted by stockouts or similar, addressing nutrient deficiencies in staple crops by selecting or breeding more nutritious varieties (e.g., orange-fleshed sweet potatoes or 'golden rice' for vitamin A deficiency) may prove to be more sustainable options (Datta et al., 2003; Nair et al., 2016; Laurie et al., 2018; Oduor et al., 2019; Stokstad, 2019). Additionally, some micro- or macronutrient deficiencies and food insecurities may be improved by addressing the depletion of soils through better management, including the incorporation of holistic, sustainable principles, such as those promoted by agroforestry or regenerative agriculture (Rhodes, 2017; Elevitch et al., 2018; LaCanne and Lundgren, 2018) (5.12.4).

[END BOX 9.7 HERE]

9.10.3 Adaptation for Health and Well-Being in Africa

In this section, we focus on adaptation actions that are well-documented or shown to have the potential for substantially improving health or well-being. These adaptation options are assessed in Figure 9.36 and Table 9.11.

In Africa, adaptive responses have begun to be implemented by local, national and international entities (Ebi and Otmani Del Barrio, 2017). With strong leadership, these initiatives can be used as an opportunity for comprehensive, transformative change rather than incremental improvements to existing systems. Adaptation responses are necessarily context-specific and can focus on providing services for vulnerable and high-risk populations (Dumenu and Obeng, 2016; Herslund et al., 2016).

Adaptation actions in the health sector range from building resilient health systems to preparing responses to health impacts of extreme weather events to reducing effects of increasing temperatures in residential and occupational settings (Kjellstrom et al., 2016; Chersich and Wright, 2019). A climate-resilient health system involves functional and effective health systems (WHO, 2015), national and local policy plans with resources for implementation, and long- and short-term communication strategies to raise awareness around climate change (Nhamo and Muchuru, 2019).

Many health conditions associated with climate change are not new, and existing evidence-based interventions can be modified to address shifting disease patterns (Ebi and Otmani Del Barrio, 2017). Adaptation options can build on a long tradition of community-based services in Africa (Ebi and Otmani Del Barrio, 2017). Indeed, strengthening many of the services already provided (e.g., childhood vaccinations and vector control) will help curtail emerging burdens of climate-sensitive conditions. However, a disproportionate focus on emerging zoonotic and vector-borne viruses could undermine climate change adaptation efforts in Africa if it shifts the focus away from health system strengthening and leaves few resources for addressing other health impacts of climate change.

Core components of an adaptation response include rapid impact packages (e.g., mass drug administration for schistosomiasis), education of women and direct poverty alleviation (Bailey et al., 2019). Where droughts are more frequent and rainfall patterns have shifted, adaptation support can be provided for strategies developed by communities, including the adaptation of livelihoods and diversification of crops and livestock (Mbereko et al., 2018; Bailey et al., 2019). Continued efforts through partnerships, blending adaptation and disaster risk reduction, and long-term international financing are needed to bridge humanitarian and sustainable development priorities (Lindley et al., 2019) (Cross-Chapter Box HEALTH in Chapter 7).

9.10.3.1 Risk Assessment and Warning Systems

Improved institutional capacity for risk monitoring and early warning systems is key to support emergency preparedness and responsiveness in Africa, as well as shock-responsive and long-term social protection (FAO and ECA, 2018). Climate risk assessments grounded in evidence and locally appropriate technologies are important for identifying priority actions, the scale of intervention needed and high-risk geographical areas and populations. Potential tools include those developed by WHO (Ceccato et al., 2018) and the Strategic Tool for Analysis of Risk (Ario et al., 2019).

Warning systems that predict seasonal to intra-seasonal climate risks could assist in improving response times to extreme weather events (such as droughts, flooding or heat waves) and shifts in infectious diseases. Weather and other types of forecasting provide an advanced warning – a central tenet of disaster risk reduction (Funk et al., 2017; Okpara et al., 2017a; Lumbroso, 2018). Models encompassing each component of the human-animal-environmental interface, including disease surveillance in humans and animals and remote sensing of vegetation indexes, water and soil can be used to project patterns of zoonose outbreaks (UNDP, 2016; Bashir and Hassan, 2019; Durand et al., 2019). Early warning systems may help better prepare for these and other forms of infectious disease outbreaks (Thomson et al., 2006) but adaptation is possible in the absence of statistical tools through vaccination and surveillance, for example.

Surveillance systems for diseases and vectors are well-established in many parts of Africa (Ogden, 2017). However, many data gaps remain, especially in monitoring climate-sensitive conditions such as diarrheal- and arbovirus-related diseases, and morbidity and mortality stemming from heat exposure (Ogden, 2017; Buchwald et al., 2020).

Climate and health adaptation indicators are required for Africa to strengthen institutional capacity for risk monitoring and early warning systems, emergency preparedness and response, vulnerability reduction measures, shock-responsive and long-term social protection and planning and implementing resilience building measures (FAO and ECA, 2018). National-level progress is assessed through the Lancet Countdown indicators (Watts et al., 2018), however, district- and local-level indicators are needed to measure levels of vulnerability and response effectiveness at a local level, and for informing planning local service delivery. Potential indicators include monitoring the number of excess health conditions during extreme heat events. Indoor temperature monitoring in sentinel houses and health facilities is a related indicator (Ebi and Otmani Del Barrio, 2017), linked with threshold temperature levels at which health impacts occur, and the ability of the built environment to protect against these impacts (e.g., for heatwaves).

Measuring climate-health linkages is challenging due to the considerable diversity of the exposures, impacts and outcomes, as well as constraints in key technical areas. Increasing our understanding of this diversity and how this is influenced by adaptative changes is a major knowledge gap. This could be facilitated through a pan-African database of climate and other environmental exposures, together with real-time statistical support for analyses of climate and health associations.

9.10.3.2 Community Engagement

Increased awareness can facilitate community engagement and action (see Section 9.4.3). In Ghana, for example, local communities understand the climate hazards that drive outbreaks of meningitis and adapt accordingly by improving housing to limit heat and exposure, changing funeral practices during outbreaks, increased vaccination uptake and afforestation (Codjoe and Nabie, 2014). Similarly, participation in community organisations improved child nutrition in vulnerable rural households in Eswatini (Anchang et al., 2019). Interventions specifically targeting women are beneficial for food security, although they may be undermined by harmful gender norms in communities that are patriarchal, led by chiefs or have high rates of gender-based violence (Jaka and Shava, 2018; Kita, 2019; Masson et al., 2019). The BRACED project in Burkina Faso and Ethiopia specifically adopted a gender-transformative approach as an integral part of resilience-building (McOmber et al., 2019). Improving 'climate literacy' could empower youth, women and men to be active citizens in promoting adherence of governments to international agreements in climate change (Mudombi et al., 2017; Chersich et al., 2019a).

9.10.3.3 9.10.3.1Health Financing

Poor and low-income households often are not able to afford high out-of-pocket costs for medical care, or it consumes a large portion of their income. As a result, without financial aid, peoples' health needs may not be met after a climate shock (Hallegatte and Rozenberg, 2017). Microfinance (the provision of small-scale financial products to low income and otherwise disadvantaged groups by financial institutions) and disaster contingency funds can serve to reduce health risks of climate change for low-income communities (Agrawala and Carraro, 2010; Ozaki, 2016), as can different forms of insurance and disaster relief (Fenton et al., 2015; Dowla, 2018). Unconditional cash transfers in Kenya, Uganda and Zambia assisted vulnerable groups to absorb the negative impacts of climate-related shocks or stress and to prepare for these (Lawlor et al., 2019; Ulrichs et al., 2019). Based on several case studies in Africa, the Food and Agriculture Organization recommends a 'Cash+' approach which combines cash transfers with productive assets, inputs or technical training to address the needs of vulnerable households in emergency situations, and enhance livelihoods potential, income generation and food security (FAO, 2017). New economic models have been implemented in North Africa, focused on poor households, youth and women that enable access to credit and support the implementation of policies that balance cash and food crops, social safety nets and social protection (Mumtaz and Whiteford, 2017; Narayanan and Gerber, 2017) (see also Sections 9.4, 9.8 and 9.11).

9.10.3.4 Disease-Specific Adaptations

Adaptation to prevent malaria
Increasing distribution and coverage of long-lasting insecticide-treated bed nets, improved diagnostic tests and increasing health service access could mitigate the impacts of climate change on malaria if aligned with the predicted or actual burden of malaria (*medium confidence*) (Kienberger and Hagenlocher, 2014; Thwing et al., 2017). Understanding seasonal shifts in malaria transmission suitability as a result of climate change can guide more targeted seasonal public health responses and better planning for different types of management and control interventions based on the impact. For example, an increase in the number of months where climate conditions are suitable for mosquito survival will require public health responses for an extended period of time (Ryan et al., 2020).

In malaria-endemic areas, repeated malaria infections can provide temporary immunity, which reduces new clinical cases (Laneri et al., 2015; Yamana et al., 2016). Conversely, where people have little or no immunity, exposure to malaria can lead to epidemics (Semakula et al., 2017a; Ryan et al., 2020). Pregnant women and infants remain at risk for severe malaria, regardless of immunity status. Vector control and case management capacity should be rapidly scaled up in newly affected areas where risks for epidemics are high and populations are especially vulnerable. Poverty-alleviation initiatives underpin malaria control as the malaria burden is strongly tied to socioeconomic status (Huldén et al., 2014; Degarege et al., 2019).

Contextualised risk studies on local drivers of transmission are still lacking and present a major gap in developing appropriate adaptation strategies (*high confidence*). Progress has been made identifying and ranking vulnerability and exposure indicators (Protopopoff et al., 2009; Onyango et al., 2016a), however, better linking of biophysical and socioeconomic determinants of risk in integrated assessment models are needed (Caminade et al., 2019; Zermoglio et al., 2019), as are applied approaches to develop adaptation strategies for risk management (Leedale et al., 2016; Onyango et al., 2016b; Sadoine et al., 2018).

Adaptation to reduce diarrhoeal disease

Reducing pathogen concentrations in water and across food chains is fundamental for controlling diarrhoeal diseases (van den Berg et al., 2019). Diarrhoea prevention and treatment post-disaster, encompass social mobilisation campaigns, water treatment, enhanced surveillance and vaccination and treatment centres for cholera (Cambaza et al., 2019) and typhoid (Neuzil et al., 2019).

Improved water, sanitation and hygiene (WASH) requires robust water and sanitation infrastructure (Duncker, 2017; Kohlitz et al., 2017; Venema and Temmer, 2017) and technological adaptations (Gabert, 2016; van Wyk et al., 2017), such as waterless on-site sanitation (Sutherland et al., 2021), diversification of water sources (e.g., rainwater harvesting (Lasage and Verburg, 2015) and groundwater abstraction (MacDonald et al., 2012)), and sharing of best practices across the continent (WASH Alliance International, 2015; Jack et al., 2016) (see also Section 9.7.3; Chapter 4, Section 4.6.4). Hand hygiene can be improved through the creation of handwashing stations, increased access to soap and simple technologies such as the foot-operated Tippy taps (Coultas and Iyer, 2020; Mbakaya et al., 2020).

Adaptation to reduce conditions related to heat exposure

Reducing morbidity and mortality during extreme heat events requires changes in behaviour and health promotion initiatives, health system interventions and modifications to the built and natural environment. Health promotion initiatives include promoting adequate hydration and simple cooling measures such as drinking cold liquids, water sprays and raising awareness of the symptoms and importance of heat stress, including heatstroke (Aljawabra and Nikolopoulou, 2018). Adaptive measures are especially important for high-risk groups such as outdoor workers, the elderly, pregnant women and infants. Health systems interventions may include early warning systems, heat health regulation, and health workers providing cooling interventions, such as supplying cool water or fans, during heat waves. Changes to the built environment include painting the roofs of houses white and improving ventilation during extreme heat (Codjoe et al., 2020), the use of insulation materials or altering the building materials used for the construction of housing to improve their ability to moderate indoor temperatures (Mathews et al., 1995; Makaka and Meyer, 2006).

Adaptation to prevent malnutrition

Transformative adaptation requires integration of resilience and mitigation across all parts of the food system including production, supply chains, social aspects and dietary choices (IPCC, 2019a). Adaptation to prevent malnutrition goes hand-in-hand with adaptation to prevent food insecurity, as is discussed in Section 9.8.3 and Chapter 5, Section 5.12.5.

Urban agriculture and forestry can improve nutrition and food security, household income and mental health of urban farmers while mitigating against some of the impacts of climate change like flooding and landslides (by stabilising the soil and reducing runoff, for example), heat (by providing shade and through evapotranspiration) and diversifying food sources in case of drought (Zezza and Tasciotti, 2010; Lwasa et al., 2014; Battersby and Hunter-Adams, 2020).

The health sector needs to collaborate and coordinate adaptation activities with other sectors, as well as civil society and international agencies, to engage communities in health promotion (Irwin et al., 2006; Commission of Social Determinants of Health, 2008; Braveman and Gottlieb, 2014). The importance of social determinants of health, such as socioeconomic status, education and the physical environment in which people live and work and their consideration during development are highlighted in Chapter 7 (see Sections 7.1.6 and 7.4.2)

Figure 9.36: Adaptation options across multiple sectors have potential for reducing risk across multiple health outcomes, considering their potential to reduce vulnerability, and potential barriers to implementation (e.g., lack of social acceptance). Reduced risk for health may result from targeted actions or as a result of co-benefits (see Supplementary Material Table SM9.8 for a full list of references).

Table 9.11: Co-benefits, barriers and enablers of adaptation responses to climate change impacts on human health in Africa (see Supplementary Material Table SM 9.9 for a full list of references).

Response category	Co-benefits	Inter-sectoral trade-offs and/or drawbacks	Enablers	Barriers
Policy development	Policies and plans that facilitate service delivery and guide national and international funding; decreased number of work hours lost; improved work performance, increased productivity		Willingness of policymakers; political support; politically willing environment; inter-sectoral collaboration	Lack of implementation; poor governance
Education & awareness	Promotion of sustainable living and circular economy		Guarantee to sustained funding; political support; politically willing environment; increased accessibility of learning institutions	Lack of implementation; historical and colonisation-related insensitivities
Health systems & primary healthcare services	Capacity building in communities; buffered economic impact of outbreaks/ disasters; job creation	Increased GHG from building; increased energy demand; decreased productivity and increased work hours lost due to waiting times	Guarantee to sustained funding; political support; politically willing environment	Corruption and fraudulent activities around resource allocation
Surveillance, risk assessments, monitoring, & research	Evidence to improve adaptation response; fast post-disaster recovery; increased awareness and disease prevention; improved health system functioning post-disasters		Requires effective institutional arrangements and inter-sectoral collaboration; guarantee to sustained funding; requires skills development	May be limited by uncertainty in modelled predictions and thresholds
Resource management	Improved health system functioning post-disasters; capacity building in communities; promotes economic growth/stability; increases the tourism potential of the area; increased accessibility/ mobility of the community; reduced land degradation, desertification, and bush encroachment; food security; decreased emissions	Increased GHG from building; increased energy demand; increased crowding/ population density; land use; microclimate and ecosystem disruption	Guarantee to sustained funding; political support; politically willing environment; requires effective institutional arrangements and inter-sectoral collaboration; requires skills development	Corruption and fraudulent activities around resource allocation
Vector control & disease prevention	Decreased mortality; improved work performance; increased productivity; improved mental health	Increased GHG; decreased biodiversity; environmental impacts of production, packaging, and delivery; potentially detrimental to health	Guarantee to sustained funding; funding and resources; future planning or retrofit required	Last-mile access; cost per capita and capacity for service delivery

9.11 Economy, Poverty and Livelihoods

9.11.1 Observed Impacts of Climate Change on African Economies and Livelihoods

9.11.1.1 Economic Output and Growth

Increased average temperatures and lower rainfall have reduced economic output and growth in Africa, with larger negative impacts than other regions of the world (Abidoye and Odusola, 2015; Burke et al., 2015a; Acevedo et al., 2017; Kalkuhl and Wenz, 2020). In one estimate, GDP per capita is on average 13.6% lower for African countries than it would be if anthropogenic warming since 1991 had not occurred (Diffenbaugh and Burke, 2019), although impacts vary substantially across countries (see Figure 9.37). As such, global warming has increased economic inequality between temperate, Northern Hemisphere countries and those in Africa (Diffenbaugh and Burke, 2019). Warming also leads to differential economic damages within Africa (Baarsch et al., 2020). One estimate found a 1°C increase in 20-year average temperature reduced GDP growth by 0.67 percentage points, with the greatest impacts in Central African Republic, Democratic Republic of Congo and Zimbabwe (Abidoye and Odusola, 2015). Changes in rainfall patterns also influence individual and national incomes. Had total rainfall not declined between 1960 and 2000, the gap between African GDP and that of the rest of the developing world would be 15–40% smaller than today, with the largest impacts in countries heavily dependent on agriculture and hydropower (Barrios et al., 2010).

Aggregate macroeconomic impacts manifest through many channels (Carleton et al., 2016). Macroeconomic evidence suggests aggregate impacts occurred largely through losses in agriculture with a smaller role for manufacturing (Barrios et al., 2010; Burke et al., 2015b; Acevedo et al., 2017). Sector-specific analyses confirm that declines in productivity of food crops, commodity crops and overall land productivity contribute to lower macroeconomic performance under rising temperatures (Schlenker and Lobell, 2010; Bezabih et al., 2011; Jaramillo et al., 2011; Lobell et al., 2011; Adhikari et al., 2015). Labour supply and productivity declines in manufacturing, industry, services and daily wage labour have been observed in other regions (Graff Zivin and Neidell, 2014; Somanathan et al., 2015; Day et al., 2019; Nath, 2020) and contribute to aggregate economic declines, countering aggregate poverty reduction strategies and other sustainable development goals (Satterthwaite and Bartlett, 2017; Day et al., 2019). In a case study of a rural town in South Africa, over 80% of businesses (both formal and informal) lost over 50% of employees and revenue due to agricultural drought (Hlalele et al., 2016). Drought and extreme heat events have also reduced tourism revenues in Africa (Section 9.6.3). Infrastructure damage and transport disruptions from adverse climate events reduce access to services and growth opportunities (Chinowsky et al., 2014). In global datasets including Africa, tropical cyclones have been shown to have large and long-lasting negative impacts on GDP growth (Hsiang and Jina, 2014).

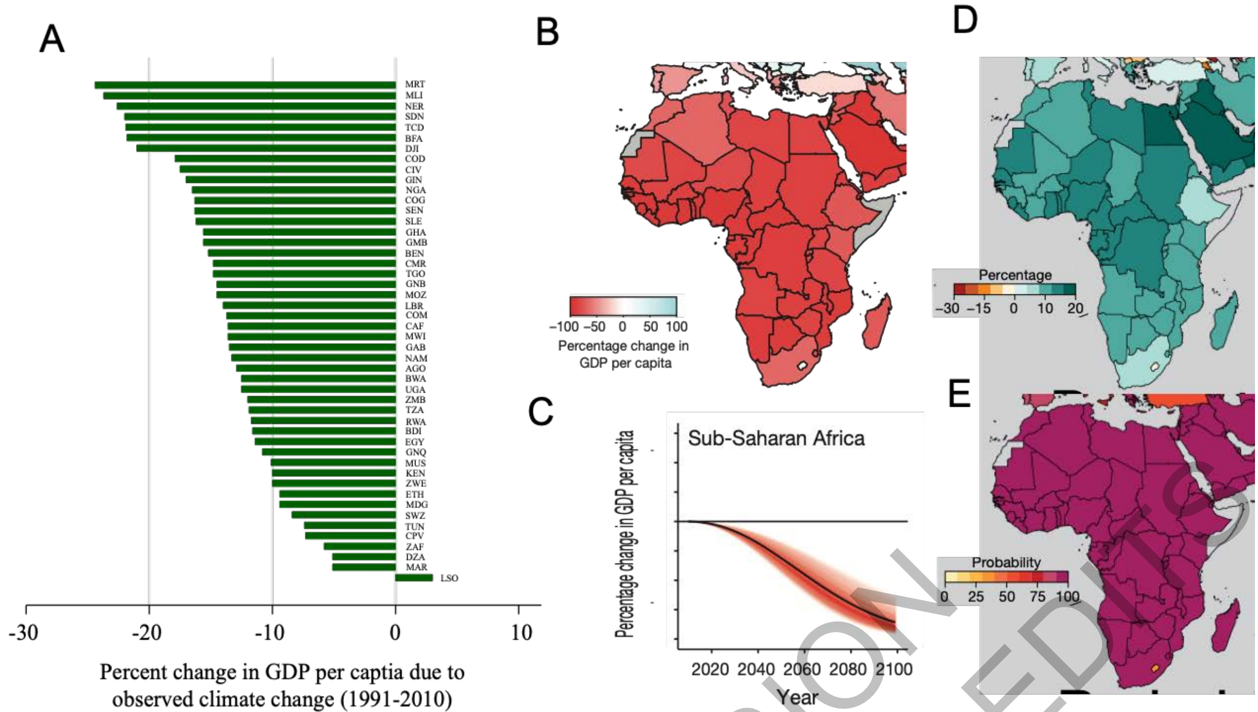


Figure 9.37: Observed aggregate economic impacts and projected risks from climate change in Africa. (A) Estimated effect of anthropogenic climate change on GDP per capita for 48 African countries between 1991 and 2010. (B, C) Projected effect on GDP per capita of global warming of ~4°C by 2100 compared to no global warming after 2010 at country level (B) and averaged across sub-Saharan Africa (C). (D) Benefits to GDP per capita of holding warming to 1.5°C versus 2°C above pre-industrial. (E) Probability of realising any economic benefits by holding warming to 1.5°C versus 2°C. Data sources: (Burke et al., 2015b; Burke et al., 2018a; Diffenbaugh and Burke, 2019).

9.11.1.2 Human Capital Development and Education

Investments in human capital, particularly education, are critical for socioeconomic development and poverty reduction by providing valuable skills and expanding labour market opportunities. Much progress has been made in improving education access, however, in sub-Saharan Africa, 32% of children, adolescents and youth (~97 million people) remain out of school (UNESCO Institute of Statistics, 2018). Climate variability and change can undermine educational attainment with negative impacts on later life earning potential and adaptive capacity to future climate change (Lutz et al., 2014) (Figure 9.11).

Several studies indicate experiencing low rainfall, warming temperatures or extreme events reduce education attainment and that future climate change may reduce children's school participation, particularly for agriculturally-dependent and poor urban households. In West and Central Africa, experiencing lower-than-average rainfall during early life is associated with up to 1.8 fewer years of completed schooling in adolescence while more rainfall and milder temperatures during the main agricultural season were positively associated with educational attainment for boys and girls in rural Ethiopia (Randell and Gray, 2016; Randell and Gray, 2019). In Uganda, low rainfall reduced primary school enrolment by 5% for girls (Björkman-Nyqvist, 2013), and in Malawi, in utero drought exposure was associated with delayed school entry among boys (Abiona, 2017). In rural Zimbabwe, experiencing drought conditions during the first few years of life was associated with fewer grades of completed schooling in adolescence, which translates into a 14% reduction in lifetime earnings (Alderman et al., 2006). In Cameroon, warming temperatures have negatively affected plantain yields, which in turn is linked to lower educational attainment (Fuller et al., 2018). One suggested mechanism underlying the relationship between climate and schooling is that adverse climatic conditions can reduce income among farming households, leading them to pull children out of school (Randell and Gray, 2016; Marchetta et al., 2019). Other potential mechanisms are poor harvests from droughts or supply interruptions from extreme weather events leading to undernutrition among young children, negatively affecting cognitive development and schooling potential (Alderman et al., 2006; Bartlett, 2008).

More research is needed on climate change impacts on education in Africa. This information can help ensure families keep children in school amidst climate-related income shocks. For example, in Mexico, a conditional cash transfer program mitigated the negative effect of natural disasters on school attendance (de Janvry et al., 2006).

9.11.2 Projected Risks of Climate Change for African economies and livelihoods

Future warming will have negative consequences for economic growth in Africa, relative to a future without additional climate change and assuming current levels of adaptation (*high confidence*) (Dell et al., 2012; Burke et al., 2015a; Burke et al., 2015b; Acevedo et al., 2017; Baarsch et al., 2020). Statistically-based empirical analyses project that global warming of 2.3°C by 2050 could lower GDP per capita across sub-Saharan Africa by 12% (SSP2) (Baarsch et al., 2020) and 80% for warming >4°C by 2100 (SSP5, 75% for MENA) (Burke et al., 2015b). Depending on the future socioeconomic scenario, this could increase global inequality and leave some African countries poorer than at present (Burke et al., 2015b). Inequalities between African countries are projected to widen under climate change, with negative impacts estimated to be largest in West and East Africa (Baarsch et al., 2020). While negative impacts across African economies are highly *likely* under climate change, precise magnitudes are debated in the literature. Alternative statistical analyses suggest a 12% reduction of GDP per capita by 2100 under RCP8.5 across African countries relative to a future without climate change (Kahn et al., 2019), while computable general equilibrium models generate smaller damages as well, ranging from 3.8% reduction across sub-Saharan Africa in 2060 under warming of 2.5°C (Dellink et al., 2019) to 12% across all of Africa in 2100 under warming of 5°C (SSP4) (Takakura et al., 2019).

Substantial avoided economic damages to African countries are projected from ambitious, near-term global mitigation limiting global warming well below 2°C above pre-industrial levels (*high confidence*). Increased economic damage forecasts for Africa under high emissions scenarios start diverging rapidly from low emissions scenarios by the 2030s (Baarsch et al., 2020). Across nearly all African countries, GDP per capita is projected to be at least 5% higher by 2050 and 10–20% higher by 2100 if global warming is held to 1.5°C versus 2°C (Burke et al., 2018a; Baarsch et al., 2020) (Figure 9.37). The probability of this positive gain to GDP per capita from achieving 1.5°C versus 2°C is reported as close to 100% (Burke et al., 2018a). While these estimates rely on temperature and rainfall-driven damages, sea level rise also poses a risk for Africa. By 2050, damages from sea level rise across sub-Saharan Africa could reach 2–4% of GDP, depending on the socioeconomic, adaptation and emissions scenario (Parrado et al., 2020).

Heat stress is projected to reduce working hours and work capacity under climate change, with among the largest declines in sub-Saharan Africa and for workers in vulnerable occupation groups, such as those working outdoors (Kjellstrom et al., 2014; Kjellstrom et al., 2016; de Lima et al., 2021) (AR6 WGII, Chapter 5). Global warming of 3°C is projected to reduce labour capacity in agriculture by 30–50% in sub-Saharan Africa (relative to the baseline in 1986–2005) (de Lima et al., 2021). These effects lead to substantial aggregate losses, for example, in West Africa, labour productivity impacts under a 3°C temperature increase are estimated to cost up to 8% of GDP (Roson and Sartori, 2016). Manufacturing productivity across Africa is projected to decline under RCP8.5 by 0–15% by 2080–2099, with the largest effects in the Democratic Republic of Congo, Ethiopia, Somalia, Mozambique and Malawi (Nath, 2020).

Large risks to road, rail and water infrastructure are projected from climate change with substantial economic cost implications (see Section 9.9.3; Box 9.5).

9.11.3 Informality

Aggregate GDP data capture formal economic activity but informal employment is the main source of employment in Africa, accounting for 85.8% of all employment (71.9%, excluding agriculture), which is 21.4% higher than the global average (ILO, 2018b). Estimates of national levels of informal employment range from 30% in South Africa, to 94.6% in Burkina Faso (ILO, 2018b), with high variability within countries such as South Africa and Nigeria (Etim and Daramola, 2020). Informal employment is a greater source of employment for women than for men in sub-Saharan Africa and young and old have especially high rates of informal employment: 94.9% of persons between ages 15 and 24 in employment and 96% of persons aged 65 and older (ILO, 2018b).

Informal sector impacts are omitted from GDP-based impacts projections. Yet informal sector activity and small to medium-sized enterprises can be highly exposed to climate extremes, as they are often located in low-lying areas, coastal areas, sloped or other hazardous zones (Thorn et al., 2015; Satterthwaite et al., 2020). Businesses and individuals in the informal sector, including construction workers, domestic workers, street vendors and transport workers, often cannot operate during climate shocks due to interruptions in transportation and commodity flows and, without the ability to insure against risk, struggle to recover assets from extreme events such as flooding, landslides and waterlogging (Chen, 2014; Thorn et al., 2015; Roy et al., 2018a). Women are overrepresented in the more poorly remunerated sections of the informal economy (Satterthwaite et al., 2020).

There is scope for governments to better harness the role of the informal sector in mitigation and adaptation (Douxchamps et al., 2015; Satterthwaite et al., 2020). Multi-level governance that includes informal service providers, such as informal water and sanitation networks, into planned adaptation programmes can increase climate resilience, in part because these networks can respond with more flexibility than hard infrastructure projects (Satterthwaite et al., 2020; Peirson and Ziervogel, 2021). Climate risk is often concentrated in urban informal settlements (Section 9.9.4). Here, informal land markets influence development patterns and can help ensure adherence to building codes to ensure safety of informally built structures at high risks of landslides and floods and enforce compliance with regulations relating to planning and land use (Thorn et al., 2015; Satterthwaite et al., 2020). Improving land management practices of charcoal producers and artisanal gold miners, combined with appropriate alternative livelihood and energy sources, can reduce emissions and increase resilience (e.g., reduce erosion and sedimentation, increase water infiltration) and benefit health (Atteridge, 2013; Paz et al., 2015; Macháček, 2019; Barenblitt et al., 2021; Eniola, 2021). Providing concessional loans, commercial financing or equity investment to informal brick makers can boost delivery of low emission social housing while the use of crop residues or renewable energy for brick making can replace wood biomass and reduce pressure on forests (Alam, 2006; Paz et al., 2015).

9.11.4 Climate Change Adaptation to Reduce Vulnerability, Poverty and Inequality

High temperature-related income losses have been observed in low- and high-income countries, suggesting optimistic economic development trajectories may not substantially reduce climate change impacts on aggregate economic performance in Africa (*low confidence*) (Burke et al., 2015b; Deryugina and Hsiang, 2017; Henseler and Schumacher, 2019). Nevertheless, climate change impacts on poverty in Africa will depend on how socioeconomic development unfolds over the coming decades (*medium confidence*) (Rozenberg and Hallegatte, 2015; Hallegatte and Rozenberg, 2017; Henseler and Schumacher, 2019). Climate change by 2030 is projected to push 39.7 million Africans into extreme poverty[3] under a baseline scenario of delayed and non-inclusive growth, with food prices acting as the dominant channel of impact, but this number is cut roughly in half under an inclusive economic growth scenario (Rozenberg and Hallegatte, 2015; Hallegatte and Rozenberg, 2017; Jafino et al., 2020).

People in Africa are disproportionately employed in highly climate-sensitive sectors: 55–62% of the sub-Saharan African workforce is employed in agriculture and while between 90–95% of cropland is rainfed (Woodhouse et al., 2017; ILO, 2018a; International Institute of Water Management, 2019; World Bank, 2020c), there has been an expansion of small-scale 'farmer-led irrigation' (Woodhouse et al., 2017). Agricultural GDP also appears more strongly affected by increasing temperatures than non-agricultural GDP, implying livelihood diversification out of agriculture may help minimise future economic damage (Bezabih et al., 2011; Burke et al., 2015b; Acevedo et al., 2017; Deryugina and Hsiang, 2017), although such workforce reallocation requires careful management and planning depending on the overall livelihood portfolios, type of farmer and profitability (Stringer et al., 2020). De-agrarianisation can feed urbanisation, which may exacerbate inequality within and between countries (Stringer et al., 2020).

Changes in trade patterns may help mitigate projected aggregate economic losses by reallocating agricultural production abroad and encouraging economic diversification toward less affected sectors. Temperature increases have been shown to lower agriculture and manufacturing exports with especially large declines in

3 Extreme poverty is defined using a consumption poverty line at US$1.25 per day, using 2005 purchasing power parity exchange rates.

poor countries (Jones and Olken, 2010; Roberts and Schlenker, 2013). Further, imports of agricultural products are projected to rise across most of Africa by 2080-2099 under a high emissions scenario (RCP8.5), with increases ranging from ~30% of GDP in the Central African Republic to ~5% of GDP in South Africa and Nigeria, although some countries will experience increases in net agricultural exports (Nath, 2020). While these reallocation effects may be large, current evidence is mixed regarding whether such adjustment of production will dampen or amplify overall social costs of climate change in Africa (Costinot et al., 2012; Bren d'Amour et al., 2016; Wenz and Levermann, 2016; Nath, 2020), as food prices are projected to rise by 2080-2099 across all African countries under a scenario with high challenges to mitigation and adaptation (SSP3 and RCP8.5), with the largest price effects (up to 120%) experienced in Niger, Chad and Sudan (Nath, 2020). Moreover, reallocating production of agriculture abroad could be maladaptive if it leads to decline or replacement of traditional sectors by industrial and service sectors which could lead to land abandonment, food insecurity and loss of traditional practices and cultural heritage (Thorn et al., 2020; Gebre and Rahut, 2021; Nyiwul, 2021).

African countries have high inequality: the average within-country share of income accruing to the top 10% of households was estimated at 50% for 2019 (Robilliard, 2020). However, analysis of INDCs across 54 African countries suggests current climate policies do not, on average, target social inequality in energy, water and food security; proposed mitigation and adaptation actions fell about 23% for every 1% rise in social inequality across these sectors (Nyiwul, 2021). In contrast, adaptation actions can be designed in ways that actively work towards reducing inequality, whether gender, income, employment, education or otherwise (Andrijevic et al., 2020).

In rural Africa, poor and female-headed households face greater livelihood risks from climate hazards (*high confidence*). Women often constitute a high proportion of the informal workforce and are also more *likely* to be unemployed than men (ILO, 2018a). These factors leave women, and particularly female-headed households, at greater risk of poverty and food insecurity from climate hazards. Controlling for multiple factors, income of female-headed households in agricultural districts in South Africa is more vulnerable to precipitation variability than those headed by men (Davidson, 2016; Flatø et al., 2017). Across nine countries in East and West Africa women tend to control smaller plots of land that is often of poorer quality, have less access to inputs such as fertilizer, tools and improved seeds, have lower educational attainment and benefit less from extension services, government agencies and non-governmental organisations (Perez et al., 2015). Gender assessments prior to adaptation programmes can identify disparities in division of labour and income and socio-cultural norms, hindering women from holding leadership positions or determining livelihood and resource-use activities, thereby helping ensure equitable benefits from livelihood diversification and improving women's working conditions (ILO, 2018a). Gender-responsive policy instruments can measure success using sex-disaggregated data to monitor impact and meaningful participation in decision-making (GCF, 2018b).

Exposure to climate hazards can trap poorer households in a cycle of poverty (Dercon and Christiaensen, 2011; Sesmero et al., 2018) and poor people in Africa are often more exposed to climate hazards than non-poor people. For example, poor people live in hotter areas in Nigeria and in multiple African countries, poor households are more exposed to flooding (Hallegatte et al., 2016) (Section 9.9.2). Daily wage labourers and residents of urban informal settlements are vulnerable to heat stress because of the urban heat-island effect combined with congestion, little shade and ventilation (Bartlett, 2008). Climate change can negatively affect household poverty through price spikes, destroying assets or ability to invest in new assets and reducing productivity (Hallegatte et al., 2016) with important impact pathways operating through agriculture, ecosystem functioning and health (Sections 9.6, 9.8, 9.10; Chapters 5, 7, 8). Non-poor people can lose more in absolute terms from climate shocks because of having more assets and higher incomes, but in relative terms, poor people often lose more than the non-poor. These relative losses matter most for livelihoods and welfare (Hallegatte et al., 2016).

In Malawi, wealthier households were able to maintain more diversified livelihoods, buffering them from extreme weather-related income losses (Sesmero et al., 2018). Poorer households have limited access to resources such as savings, credit, irrigation technologies and insurance, which can lead to larger crop and other income losses from climate hazards, preventing investments to improve resilience to future climate shocks (Castells-Quintana et al., 2018). Poor households may reduce risk or aid recovery by cooperating with other households in their community to adapt collectively to climate change, for example, through informal insurance networks (Paul et al., 2016; Wuepper et al., 2018). Prioritising poor households for interventions including social protection, ecosystem-based adaptation, universal healthcare, climate-smart buildings and agriculture, flexible work hours under extreme heat and early warning systems will increase adaptation to climate shocks (Angula and Menjono, 2014; Moosa and Tuana, 2014; Hallegatte et al., 2016; Day et al., 2019) (Section 9.6.4; Chapter 6). Pro-poor policies that link mitigation and adaptation, such as using renewable energy to increase rural electrification or using revenues from a carbon tax, combined with international financial support to increase social assistance, could support sustainable eradication of poverty under near-term climate change (Hallegatte et al., 2016; Aklin et al., 2018; Simpson et al., 2021c). Integrating urban green infrastructure into adaptation planning in informal settlements can simultaneously unlock pathways for inclusivity and social justice (Tozer et al., 2020; Wijesinghe and Thorn, 2021) (Section 9.9.5).

Social protection has been used for decades, particularly in eastern and southern Africa, to safeguard poor and vulnerable populations from poverty and food insecurity (Niño-Zarazúa et al., 2012). Instruments of social protection include public works programs, cash transfers, in-kind transfers, social insurance and microinsurance schemes that assist individuals and households to cope during times of crisis and minimise social inequality. Evidence from Kenya, Ethiopia and Uganda indicates national social protection programmes are effective in improving individual and household resilience to climate-related shocks, regardless of whether they aim specifically to address climate risks (Ulrichs et al., 2019). Strengthening social protection and better integrating climate risk management into design of social protection programs can help build long-term resilience to climate change (Hallegatte et al., 2016; Agrawal et al., 2019). For example, Public Works programs can build climate resilience by targeting soil, water and ecosystem conservation and carbon sequestration, such as South Africa's Working for Water Programme that restores river catchments to reduce fire risk and increase water supplies (Turpie et al., 2008; Norton et al., 2020).

9.11.4.1 Climate Insurance

African countries and communities are inadequately insured against climate risk. Insurance penetration is less than 2% of GDP (Swis Re, 2019) and 90% of natural catastrophe losses were uninsured in Africa in 2018 (Swis Re, 2019) leaving a large risk protection gap. The cost of reinsurance in Africa's most mature insurance market – South Africa – has increased since 2017 due to climate-related payouts (SAIA, 2018; Simpson, 2020), *likely* to further reduce the extent of insurance coverage. Emerging trends that seek to address this gap include innovative weather and drought index-based insurance schemes to transfer risk, forward-looking climate data and models to manage risk and insurers transitioning from risk transfer providers to proactive risk managers.

The most significant area of climate risk insurance innovation has occurred in weather and drought index-based insurance schemes that pay out fixed amounts based on the occurrence of an event instead of full indemnification against assessed losses (Table 9.12). However, despite the relatively low cost, uptake remains low due to affordability constraints, lack of awareness, access to and trust in products, distribution challenges, basis risk, poor transparency, challenges regarding the integration of complementary interventions (e.g., access to improved inputs or informal savings/credit) and poor perceptions/norms of insurance and risk transfer. Lack of data and models further hinders insurers' ability to price risk correctly, which reduces value to clients (Greatrex et al., 2015; Di Marcantonio and Kayitakire, 2017; WEF, 2021). Impact assessments point to potential but remain context-specific (Awondo, 2019; Hansen et al., 2019b; Noritomo and Takahashi, 2020). In addition, there is no comprehensive overview of the number of people covered by such schemes, nor of the value they provide in terms of actual claims payouts. Lastly, donor and/or public funds still play an outsized role in launching and/or sustaining these schemes and schemes beyond weather and drought remain limited (Table 9.12).

Insurers and their clients are often unaware of their risk exposure, partly due to data and modelling gaps. Climate information services and related collaborations are increasingly helping to address this problem (see Section 9.4.5). Climate change attribution methods to estimate the contribution of anthropogenic climate change to the cost of parametric insurance offers possibilities for a sharing of the premium between the impacted African country and a global climate fund, such as the Green Climate Fund (New et al., 2020). Technology companies and start-ups (including fintechs) are also emerging as solutions to fill risk gaps, leveraging new approaches to data and technology through the use of sensors, drones and satellite imaging to speak to mainly agricultural risks, but also urban risks such as informal settlement fires, exacerbated by heat and drought (Table 9.12).

Ten African insurers formally committed to help manage climate risk on the continent through the Nairobi declaration of the UNEP Principles for Sustainable Insurance (PSI) in 2021 (UNEP PSI, 2021). Some early examples of public-private partnerships with municipalities and governments to better manage climate risk are also emerging (Table 9.12).

Table 9.12: Insurance opportunities to mitigate climate risk.

Initiatives	Drought/ heatwave	Flood	Cyclone	Fire	Example	Policyholders/ beneficiaries	Reference
Index and parametric schemes – smallholder farmer	x	x			ACRE Africa, Pula, R4 Rural Resilience Initiative, KLIP, FISP, Ghana Agricultural Insurance Pool, Oko Crop Assurance	Smallholder farmers	(Greatrex et al., 2015; CTA, 2019; Global Index Insurance Facility, 2019; WFP, 2020; Fava et al., 2021; OKO Finance, 2021; Pula, 2021; Tsan et al., 2021)
Index and parametric schemes – sovereign and sub-sovereign	x	x	x		African Risk Capacity	Governments	(ARC, 2019)
Index and parametric schemes – global	x	x			African and Asian Resilience in Disaster Insurance Scheme (ARDIS)	Individuals and smallholder farmers	(Global Parametrics, 2018)
Risk management and data collaboration	x	x	x	x	UNEP PSI Santam Tripartite Agreement	Insurers and reinsurers, local municipalities, governments	(Santam, 2018; Forsyth et al., 2019; UNEP-FI, 2019a; InsurResilience, 2020; Simpson, 2020)
FinTech	x	x		x	Lumkani, WorldCover, Econet, PlaNet Guarantee	Individuals, smallholder farmers	(Greatrex et al., 2015; Hunter et al., 2018; CTA, 2019; UK Space Agency, 2020; Tsan et al., 2021)

[START BOX 9.8 HERE]

Box 9.8: Climate Change, Migration and Displacement in Africa

Climatic conditions are important drivers of migration and displacement with migration responses to climate hazards strongly influenced by economic, social, political and demographic processes (Cross-Chapter Box MIGRATE in Chapter 7).

Most climate-related migration and displacement observed currently is within countries or between neighbouring countries, rather than to more geographically distant high-income countries (Hoffmann et al., 2020; Kaczan and Orgill-Meyer, 2020). Natural-related disaster displacements in sub-Saharan Africa were over 2.6 million in 2018 and 3.4 million in 2019 (13.9% of the global total and one of the highest historical figures for the region), with East (1,437,7000) and West Africa (798,000) being hotspots in 2018 (Mastrorillo et al., 2016; IDMC, 2019; IDMC, 2020) (Table Box 9.8.1). Estimates indicate future climate change effects on internal migration in Africa will be considerable (Rigaud et al., 2018) (Table Box 9.8.2).

Internal migration, displacement and urbanisation

Climate change can have opposing influences on migration flows. Deteriorating economic conditions caused by climate hazards can encourage out-migration (Wiederkehr et al., 2018). However, these same economic losses undermine household resources needed to migrate (Cattaneo and Peri, 2016). The net effect of these two forces leads to mixed results across study methodologies and contexts (Carleton and Hsiang, 2016; Borderon et al., 2019; Cattaneo et al., 2019; Hoffmann et al., 2020).

Urbanisation in Africa is affected by climate conditions in rural agricultural areas (*high confidence*). Urbanisation can increase when reduced moisture availability depresses farm incomes or pastoral livelihoods become unviable (Marchiori et al., 2012; Henderson et al., 2014; Mastrorillo et al., 2016). The influence of rainfall on rural-urban migration increased since decolonisation, possibly due to more lenient legislation on internal mobility, with each 1% reduction in precipitation below a long-term average associated with a 0.45% increase in urbanisation (Barrios et al., 2006). Rate of rural-urban migration is anticipated to increase (Neumann et al., 2015) as a result of increasing vulnerability of agricultural livelihoods to climate change (Serdeczny et al., 2017). Nevertheless, rural-urban migration is not a simple one-way process. Peri-urban and rural areas provide developmental feedback loops, helping create a 'regional agglomeration' effect, for instance, through growing food demand, family and social connections, and flows back to rural areas of goods and services and financial investments (UN-Habitat, 2016; Dodman et al., 2017).

Migration is an important and potentially effective climate change adaptation strategy in Africa and must be considered in adaptation planning (*high confidence)* (Williams et al., 2021). The more agency migrants have (that is, degree of voluntarity and freedom of movement), the greater the potential benefits for sending and receiving areas (*high agreement, medium evidence*) (Cross-Chapter Box MIGRATE in Chapter 7). In a synthesis of 63 studies covering over 9,700 rural households in dryland sub-Saharan Africa, 23% of households employed migration (primarily temporary economic) to adapt to changes in rainfed agriculture (Wiederkehr et al., 2018). Migration responses to climate change tend to be stronger among wealthier households, as poorer households often lack financial resources necessary to migrate (Kaczan and Orgill-Meyer, 2020).

International migration

Studies on propensity to emigrate have uncovered conflicting results. Some findings suggest in low-income countries high temperatures 'trap' people at home and lower migration rates abroad, but in middle-income countries, these same high temperatures encourage emigration (Cattaneo and Peri, 2016). However, other research finds in poor and agriculturally-dependent countries, high temperatures encourage international out-migration, particularly to the OECD (Cai et al., 2016). Some evidence indicates people who leave tend to be more educated, possibly leading to 'brain drain' (Mbaye, 2017). Recent evidence suggests hotter-than-normal temperatures across 103 countries, including many in Africa, increased asylum applications to the European Union (Missirian and Schlenker, 2017). Assuming no change in present-day vulnerability, asylum applications are projected to increase 34% across Africa (relative to 2000–2014) at 2.2°C global warming (Missirian and Schlenker, 2017), although this finding has been challenged in the literature (Abel et al., 2019; Boas et al., 2019).

International remittances are a vital resource for developing countries that can help aid recovery from climate shocks (Hallegatte et al. 2016). Estimated at USD 48 billion in 2019 their importance is expected to grow further due to foreign direct investment declines during the COVID-19 pandemic (World Bank, 2020a). Furthermore, domestic remittances from rural-urban migration can help rural households respond to climate risks (KNOMAD, 2016). However, adequate finance and banking infrastructure are essential for remittances and, on average, cash transfer costs for sub-Saharan African countries remain the highest globally (World Bank, 2020a). Mobile money technologies and regulation that promotes competition in the remittances market can reduce transaction costs (World Bank, 2020a). Governments can further address challenges facing internal and international migrants by including them in health services and other social programmes and protecting them from discrimination (World Bank, 2020a).

Table Box 9.8.1: Reported impacts of climate on migration in Africa (Findings on the linkages between climatic conditions and migration vary greatly across countries in Africa)

Climate driver	Country	Climate - Migration linkages	Reference
Temperature	Kenya	Cool temperatures linked to internal labour migration among males	(Gray and Wise, 2016)
	Uganda	High temperatures linked to increased non-labour migration among females. Short hot spells linked to increased temporary migration. Long-term heat stress linked to permanent migration through an agricultural livelihoods pathway.	(Gray and Wise, 2016; Call and Gray, 2020)
	Tanzania	Temperature-induced income shocks linked to decreased long-term rural-urban migration among men.	(Hirvonen, 2016)
Precipitation	Kenya	Increased precipitation linked to decreased rural-urban migration.	(Mueller et al., 2020)
	Zambia	Increased precipitation linked to increased internal migration.	(Mueller et al., 2020)
	Burkina Faso	Drier regions linked to increased temporary and permanent migrations to other rural areas. Short-term precipitation deficits linked to increased long-term migration to rural areas and decreased risk of short-term migration to distant destinations.	(Henry et al., 2004)
	Ethiopia	Drought linked to men's labour migration from rural to urban areas, especially in land-poor households. Drought linked to decreased marriage-related migration by women. Precipitation variability and drought linked to labour migration from rural to urban areas. Precipitation variability and drought linked to out-migration to communities where precipitation variability and drought probability are lower. High precipitation variability linked to increased migration, either through increased non-farm activities, which enable migration through economic resources or through insufficient agricultural production, which increase migration needs.	(Gray and Mueller, 2012; Morrissey, 2013; Hermans-Neumann et al., 2017; Groth et al., 2021)
	Ghana	Increased severity of drought and household insecurity linked to reduced future migration intentions of households.	(Adger et al., 2021)
	Malawi	Precipitation shocks linked to rural out-migration to communities where precipitation variability and drought probability are lower. Precipitation shocks (flood and droughts) linked to longer-term urban migration and/or reverse (i.e., urban-rural) migration.	(Lewin et al., 2012; Suckall et al., 2015)
	Mali	Decreased precipitation linked to overall increase in out-migration – where farming families or individuals from farming communities will leave their origin community – and some changes in duration and destination of trips. These moves can be either permanent or short-term, domestic or international.	(Grace et al., 2018)

	Niger	Drought linked to economically-induced migration of households from rural areas to cities. Drought also linked to temporary international migration.	(Afifi, 2011)
Temperature and precipitation	Burkina Faso	High temperatures linked to negative effects on all migration streams including international migration, much of which is to neighbouring countries. International migration also declines with precipitation.	(Gray and Wise, 2016)
	Senegal	No detected linkages between climate and migration.	(Gray and Wise, 2016)
	Nigeria	No detected linkages between climate and migration.	(Gray and Wise, 2016)
	Botswana	Increased temperatures and precipitation linked to decreased internal migration.	(Mueller et al., 2020)
	South Africa	Higher temperatures and precipitation extremes linked to increased rural out-migration, especially among black and low-income South Africans.	(Mastrorillo et al., 2016)
	Senegal	Precipitation variability, drought and increased temperatures linked to seasonal migration from rural to urban areas.	(Hummel, 2016)
	Zambia	Hotter and drier climate linked to inter-district migration of wealthy districts. Poor districts characterised by climate-related immobility.	(Nawrotzki and DeWaard, 2018)

Table Box 9.8.2: Projected numbers and shares of internal climate migrants in 2050 by sub-regions of sub-Saharan Africa. Projections are for internal migration driven by three slow-onset climate hazards (water stress, crop failure, and sea level rise), and excluding rapid-onset hazards such as floods and tropical cyclones. As such, they present a lower-bound estimate of potential climate change impacts on internal migration. Projections are for two warming scenarios: low emissions (RCP2.6) and high emissions (RCP8.5), both coupled with a socioeconomic pathway (SSP4) in which low-income countries have high population growth, high rates of urbanisation, and increasing inequality within and among countries. By 2050, between 17.4 million (RCP2.6) and 85 million (RCP8.5) people (up to 4% of the region's total population) could be moving as a consequence of climate impacts on water stress, crop productivity and sea level rise. More inclusive socioeconomic pathways with lower population growth are projected to reduce these risks. West Africa has the highest levels of climate migrants, potentially reaching more than 50 million, suggesting that climate impacts will have a particularly pronounced impact on future migration in the region. In East Africa, out-migration hotspots include coastal regions of Kenya and Tanzania, western Uganda and parts of the northern highlands of Ethiopia. Kampala, Nairobi and Lilongwe may become hotspots of climate in-migration, coupled with existing rural to urban migration trends, and a high likelihood of movement toward non-climate-related sources of income in cities. Source: (Rigaud et al., 2018).

Region		Global warming around 2.5°C above pre-industrial by 2050 (RCP8.5)	Global warming around 1.7°C above pre-industrial by 2050 (RCP2.6)
East Africa	Average number of internal migrants by 2050 (million)	10.1	6.9
	Internal climate migrants as percent of population	1.28%	0.87%
West Africa	Average number of internal migrants by 2050 (million)	54.4	17.9
	Internal climate migrants as percent of population	6.87%	2.27%

Central Africa	Average number of internal migrants by 2050 (million)	5.1			2.6		
	Internal climate migrants as percent of population	1.31%			0.66%		
Southern Africa	Average number of internal migrants by 2050 (million)	1.5			0.9		
	Internal climate migrants as percent of population	2.31%			1.40%		
Sub-Saharan Africa	Average number of internal migrants by 2050 (million)	71.1			28.3		
	Minimum (left) and maximum (right) million	56.6	85.7		17.4	39.9	
	Internal climate migrants as percent of population	3.49%			1.39%		
	Minimum (left) and maximum (right) percent	2.71%		4.03%	0.91%		2.04%

[END BOX 9.8 HERE]

9.11.5 COVID-19 Recovery Stimulus Packages for Climate Action

The COVID-19 pandemic recovery effort includes significant opportunities for African countries to reduce future vulnerability to compound climate, economic and health risks. Fiscal recovery packages could set economies on a pathway towards net-zero emissions, reducing future climate risk or entrench fossil-fuel intensive systems, exacerbating risk (Hepburn et al., 2020; Dibley et al., 2021; IEA, 2021). Investments in renewable energy, building efficiency retrofits, education and training, natural capital (that is, ecosystem restoration and ecosystem-based adaptation), R&D, connectivity infrastructure and sustainable agriculture can help meet both economic recovery and climate goals (Hepburn et al., 2020; Dibley et al., 2021).

The impacts of the COVID-19 pandemic have been substantially worsened by climate hazards in many places. In others, outbreak response has been disrupted (Phillips et al., 2020; Kruczkiewicz et al., 2021). These vulnerabilities are rooted in insufficient disaster preparedness infrastructure but are almost always worsened by social and economic inequality. Ensuring the most vulnerable populations are properly protected from climate change has co-benefits for recovery from the COVID-19 pandemic (Manzanedo and Manning, 2020). In particular, efforts to reduce syndemic vulnerabilities across key sectors (especially health, livelihoods and food security) will lessen climate change impacts and will also reduce the risk and impacts of future epidemics and pandemics, for example, during the pandemic, water scarcity has been a barrier to a key risk mitigation behaviour (handwashing). In the long-term, development efforts focused on water, sanitation and hygiene (WASH) will reduce this vulnerability and also reduce the health toll of diarrheal disease linked to climate change (Anim and Ofori-Asenso, 2020; Zvobgo and Do, 2020). Spending recovery funds on social safety nets will reduce inequality and protect the most vulnerable communities (especially women and low-income and marginalised communities) from the social and economic impacts of disasters. Key among these safety nets is universal health coverage, including low- or no-cost access to essential medicine, high-quality preventative care, financial protections against medical debt and increased geographic and population coverage for all services (Hallegatte et al., 2016). All of these are key components of climate change adaptation for health and will reduce both the rate at which future outbreaks start and their total scope and impact (Carlson et al., 2021). The co-benefits of multilateral cooperation on the attainment of universal health coverage will be a key determinant of success or failure in both climate change adaptation and pandemic preparedness.

[START BOX 9.9 HERE]

Box 9.9: Climate Change and Security: Interpersonal Violence and Large-scale Civil Conflict

There is substantial evidence that climate variability influences human security across Africa (see Chapter 7 WGII Section 7.2.7 and 7.3.3 7). However, the strength and nature of this link depend on socioeconomic and institutional conditions, and climate is just one of many factors influencing violence and civil conflict (Schleussner et al., 2016a; von Uexkull et al., 2016; Linke et al., 2018; Mach et al., 2019; van Weezel, 2019; Ide et al., 2020).

Projections of security implications of long-run climate change in Africa are uncertain, as they rely on extrapolating observed effects of short-run climate variability (Burke et al., 2014). Lack of detection and attribution studies limit assessment of the impacts of observed anthropogenic climate change on security.

Interpersonal violent crime

Evidence from across the globe finds that interpersonal violence, ranging from use of profanity to violent crime, increases with temperature and sometimes low rainfall (Hsiang et al., 2013a; Burke et al., 2014; Gates et al., 2019). The effect of temperature may be driven by a physiological mechanism (Morrison et al., 2008; Seo et al., 2008; Ray et al., 2011), while effects of rainfall may operate through an agricultural yield impacts channel (Burke et al., 2014). While few studies link interpersonal violence to climate in Africa, Gates et al. (2019) documents homicide risks increasing under high temperatures in South Africa, and similarity across diverse study settings suggests temperature-induced violent crime *likely* generalizes to Africa (Burke et al., 2014).

Large-scale intergroup conflict

Climatic conditions also change the risk of large-scale conflicts such as riots, ethnic conflicts and civil war (Burke et al., 2014; Koubi, 2019). The effects of temperature are particularly well-studied in Africa. Risk of violent conflict rises with temperature in Sudan and South Sudan (Maystadt and Ecker, 2014; Maystadt et al., 2014; Scheffran et al., 2014), Kenya (Hsiang et al., 2013b; Scheffran et al., 2014), the East African region (O'Loughlin et al., 2012) and across sub-Saharan Africa (Burke et al., 2009; O'Loughlin et al., 2014; Witmer et al., 2017). Estimates indicate that warming trends since 1980 have elevated conflict risk across sub-Saharan Africa by 11% (Burke et al., 2009; Carleton et al., 2016).

Periods of low rainfall or flooding also contribute to social instability and upheaval across Africa (Miguel et al., 2004; Ralston, 2015; von Uexkull et al., 2016; Harari and Ferrara, 2018; van Weezel, 2019; Ide et al., 2020). The link between rainfall and conflict appears *likely* due to crop losses and declines in economic opportunity. One study finds that dry growing seasons increase conflict incidence across 36 African nations, with spillover effects from the location of climate shock to neighbouring communities (Harari and Ferrara, 2018). Conflict-inducing impacts of drought have also been uncovered in Somalia (Maystadt and Ecker, 2014), Uganda, Sudan, Ethiopia and Kenya (Fjelde and von Uexkull, 2012; Hendrix and Salehyan, 2012; Couttenier and Soubeyran, 2014; Ralston, 2015; Linke et al., 2018; van Weezel, 2019), the Democratic Republic of Congo (von Uexkull et al., 2020) and in a pooled sample of African and Asian countries (von Uexkull et al., 2016). Extremely high rainfall may also incite conflict risk, although results are mixed (Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012). This uncertainty, combined with large uncertainties in rainfall projections under climate change, render future impacts of anthropogenic emissions on rainfall-induced conflict in Africa highly uncertain.

While conflict-climate links have been repeatedly identified in Africa, climate is one of many interacting conflict risk factors and appears to explain only a small share of total variation in conflict incidence (von Uexkull et al., 2016; Mach et al., 2019; van Weezel, 2019).

Opportunities for adaptation

Adaptive capacity with respect to climate and conflict remains low in Africa (Sitati et al., 2021). For example, one study finds that relative to each country's optimal annual temperature, realized temperatures across sub-Saharan Africa increase the annual incidence of war by 29.3% on average (Carleton et al., 2016). Another finds that rising temperatures due to climate change may lead to higher levels of violence in sub-Saharan Africa if political rights do not improve from current conditions (Witmer et al., 2017). Available studies on adaptation in conflict-affected areas tend to have a narrow focus, particularly on agriculture-related adaptation in rural contexts and adaptation by low-income actors, with little known beyond these contexts (Sitati et al., 2021). Literature on the gender dimension of climate adaptation in conflict-affected countries is also limited (Sitati et al., 2021).

Migration is a common response (Sitati et al., 2021) and may be an effective adaptive response to climate-induced conflict. Bosetti et al. (2018) find that countries with high emigration propensity display lower sensitivity of conflict to temperature, with no evidence of detrimental impacts on the destination countries. Indigenous knowledge has also been applied to enable adaptation amidst conflict, for example, in Libya, to deal with erratic rainfall (Biagetti, 2017).

Other socioeconomic factors have been identified as adaptive opportunities. Rising incomes may mitigate conflict-climate relationships (Carleton et al., 2016), while weak institutions, lack of political freedom, agricultural dependence and exclusion of ethnic groups increase their strength (Schleussner et al., 2016a; von Uexkull et al., 2016; Witmer et al., 2017; Ide et al., 2020). In particular, agriculturally dependent and politically excluded groups in Africa are especially vulnerable to the impact of drought on conflict (von Uexkull et al., 2016; Koubi, 2019). Household-level resilience to economic shocks has been shown to lower support for violence after drought (von Uexkull et al., 2020). Local-level institutions have also been shown to support non-violence under adverse climate conditions (Bogale and Korf, 2007).

These findings suggest that ameliorating ethnic tensions, improving political institutions, and investing in economic diversification and household resilience could mitigate future impacts of climate change on conflict.

[END BOX 9.9 HERE]

9.12 Heritage

Africa is a rich reservoir of heritage resources and indigenous knowledge, showcased by about 96 sites inscribed by UNESCO as World Heritage Sites (UNESCO, 2018b). These include 53 sites specifically denoted as having great cultural importance and 5 sites with mixed heritage values. Unfortunately, valuable cultural heritage in forms of tangible evidence of past human endeavour, and the intangible heritage encapsulated by diverse cultural practices of many communities (Feary et al., 2016), is under great threat from climate change.

9.12.1 Observed Impacts on Cultural Heritage.

For more than 10,000 years, Africans recorded over 8,000 painted and engraved images on rock shelters and rock outcroppings across 800 exceptional rock art sites of incalculable value (Hall et al., 2007; di Lernia and Gallinaro, 2011; di Lernia, 2017; Clarke and Brooks, 2018; Barnett, 2019), but which are exceptionally fragile to the elements. Unfortunately, there has been a poor study of direct climate change impacts on rock art across Africa.

Underwater heritage includes shipwrecks and artefacts lost at sea and extends to prehistoric sites, sunken towns and ancient ports that are now submerged due to climatic or geological changes (Spalding, 2011). Off the shores of Africa, about 111 shipwrecks have been documented, with South Africa having a major share of about 41 sites. The sunken Egyptian city of Thonis-Heracleion and its associated 60+ shipwrecks reflect the richness of Africa's waters. Unfortunately, increased storm surges and violent weather currently threaten the integrity of shipwrecks by accelerating the destruction of wooden parts and other features (Harkin et al., 2020). However, climate change impacts on underwater cultural heritage sites are poorly studied, as it requires specialist assessment techniques (Feary et al., 2016), and marine archaeology studies are not well-established in Africa.

Intangible heritage includes instruments, objects, artefacts and cultural spaces associated with communities, and are almost always held orally (UNESCO, 2003). Loss of heritage assets may be a direct consequence of climate change/variability (Markham et al., 2016), or a consequence of indirect factors resulting from climate change, for example, economic instability and poor decision-making in areas of governance. In northern Nigeria, climate change exacerbates the impact of poor land use decisions, reducing the flow of the Yobe River and negatively impacting the Bade fishing festival because the available fish species continue to decline (Oruonye, 2010). Similarly, Lake Sanké in Mali has been degraded by a combination of urban development and poor rainfall, threatening the Sanké mon collective fishing rite (UNESCO, 2018b).

Migration related to climate change and climatic events could offer openings to women and young people to become de facto family heads (Kaag et al., 2019). However, such societal changes also increase community vulnerability to the loss of cultural knowledge held by village elders. For example, in Mauritius, the Sega tambour Chagos music is at risk, as elders familiar with the landscape pass on (Boswell, 2008).

Case study: Traditional earthen 'green energy' buildings

Historically, Africa has had a unique and sustainable architecture (Diop, 2018) characterised by area-specific, traditional earthen materials and associated indigenous technology. Key examples include Tiébélé in Burkina Faso, Walata in Mauritania, Akan in Ghana, Ghadames in Libya, Old Towns of Djenné in Mali (World Heritage Site) and other diverse earthen architecture across sub-Saharan Africa. Adegun and Adedeji (2017) indicate that earthen materials provide advantages in thermal conductivity, resistivity and diffusivity, indoor and outdoor temperature, as well as cooling and heating capacities. Moreover, earthen materials are recyclable and environmentally 'cleaner' (Sanya, 2012) because of the absence or small quantity of cement in production, thus reducing carbon emissions. Despite these advantages, the expertise and socio-cultural ceremonies that accompany building and renewal of earthen architecture are disappearing fast (Adegun and Adedeji, 2017). Further, earthen construction is being threatened by extreme climatic variability and changing climate that exacerbates decay (Brimblecombe et al., 2011; Bosman and Van der Westhuizen, 2014; Brooks et al., 2020).

9.12.2 Projected Risks

Sea level rise and its associated hazards will present increasing climate risk to African heritage in the coming decades (Marzeion and Levermann, 2014; Reimann et al., 2018; Brito and Naia, 2020) (Figure 9.38). Although no continental assessment has quantified climate risk to African heritage and little is known of near term exposure to hazards such as sea level rise and erosion, for a handful of coastal heritage sites included in global or Mediterranean studies, 10 cultural sites are identified to be physically exposed to sea level rise by 2100 at high emissions scenarios (RCP8.5) (Marzeion and Levermann, 2014; Reimann et al., 2018), of which, 7 World Heritage Sites in the Mediterranean are also projected to face medium or high risk of erosion (Reimann et al., 2018) (Figure 9.38). Further, Brito and Naia (2020) identify natural heritage sites across 27 African countries that will be affected by sea level rise by 2100 (RCP8.5), of which 15 sites covering eight countries demonstrated a high need for proactive management actions because of high levels of biodiversity, international conservation relevance and exposure to sea level rise (Figure 9.38). These nascent studies highlight the potential severity of risk and loss and damage from climate change to African heritage, as well as gaps in knowledge of climate risk to African cultural and natural, particularly concerning bio-cultural heritage.

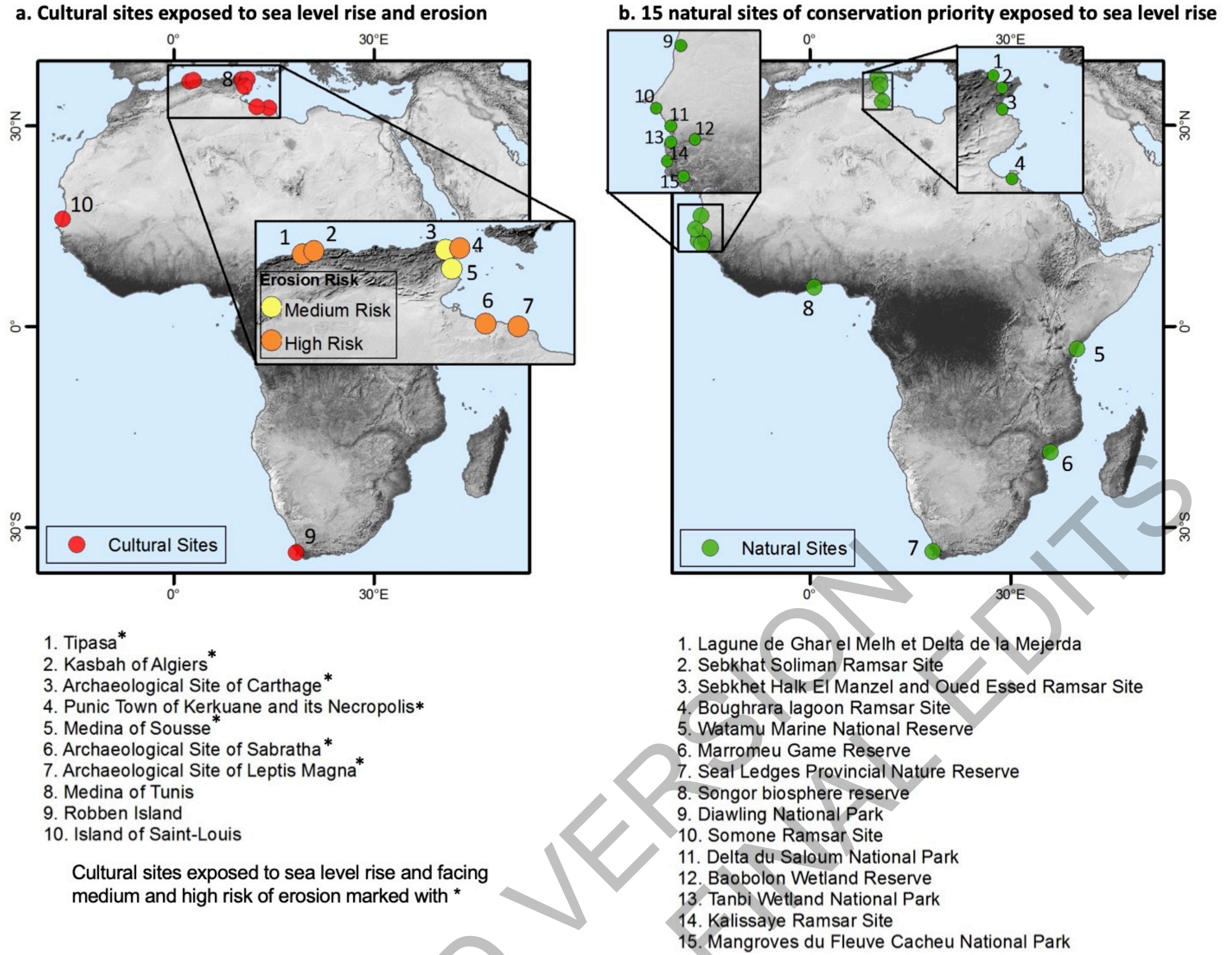


Figure 9.38: Risk to Africa's cultural and natural coastal heritage sites from sea level rise and erosion by 2100 (RCP8.5). Panel (a) Exposed World Heritage sites projected to be affected by sea level rise under a high-end sea level rise scenario (RCP8.5, 2100) (Marzeion and Levermann, 2014; Reimann et al., 2018). Panel a call out) Sites identified to be also exposed to medium and high erosion risk under current and future conditions (2000 and 2100) under a high-end sea level rise scenario (Reimann et al., 2018). Panel (b) The 15 topmost African natural sites (coastal protected areas) identified to be exposed to negative impacts from sea level rise and as priority for conservation (Brito and Naia, 2020).

Although climate change is a significant risk to heritage sites (Brito and Naia, 2020), there is little research on how heritage management is adapting to climate change, and particularly, whether the capacity of current heritage management systems can prepare for and deal with consequences of climate change (Phillips, 2015) (see also Cross-Chapter Box SLR in Chapter 3).

Worsening climate impacts are cumulative and often exacerbate the vulnerability of cultural heritage sites to other existing risks, including conflict, terrorism, poverty, invasive species, competition for natural resources and pollution (Markham et al., 2016). These issues may affect a broad range of tourism segments, including beach vacation sites, safari tourism, cultural tourism and visits to historic cities (UNWTO, 2008). Climate change impacts have the potential to increase tourist safety concerns, especially at sites where increased intensity of extreme weather events or vulnerability to floods and landslides are projected (Markham et al., 2016) (see also Cross-Chapter Box EXTREMES in Chapter 2). There may also be circumstances where interventions required to preserve and protect the resource alter its cultural significance (van Wyk, 2017).

9.12.3 Adaptation

Research highlights potential in integrating indigenous knowledge, land use practices, scientific knowledge and heritage values to co-produce tools that refine our understanding of climate change and variability and develop comprehensive heritage adaptation policy (Ekblom et al., 2019) (Table 9.13).

Table 9.13: Examples of responses to climate change impacts to heritage sites.

Heritage	Type	Example		Type of Climate Impact	Intervention Focus or Activity	Main Intervention Activity	State of Materials	Final State of Heritage	Literature
Tangible	Ancient	Historic buildings	Ounga Byzantine Fort and associated archaeological remains, Tunisia	Coastal erosion	Archaeological conservation of fort	Building repairs to outer walls of fort but other archaeological areas no intervention	Mixed. Fort is in good condition, but other parts of the site are under threat of coastal erosion, particularly lesser archaeological remains of other periods	Some aspects of site well preserved, other parts damaged	(Slim et al., 2004)
		Archaeological sites	Sabratha, Roman City, Libyan coast	Sea level rise, local flooding and coastal erosion	Monitoring of condition	None	Loss of archaeological remains into the sea	Some aspects of site well preserved, other parts damaged	(Abdalahh, 2011)
	Living	Cities / towns	Lamu Old Town and archipelago, Kenya	Sea Level Rise impacting low lying areas and climate variability impacting protective mangroves	Lamu Old Town managed by National Museums of Kenya the mangrove forests by Community Forest Associations and Forest Conservation and Management Act of 2016. Changes in biodiversity and cultural resilience to climate shocks.	Draft for National Policy for Disaster Management in Kenya	Mangrove forests provide protection from storm surges and coastal erosion. Changing biodiversity of mangroves is threatening mangroves which threaten Lamu Old Town	Continuing deterioration	(Wanderi, 2019)
		Mud buildings	Tiébélé, Burkina Faso	Climate variability causing flooding, erosion.	Local community conservation	Improvements to drainage and land security, development of conservation and management plans.	Current and ongoing conservation	Stable	(Birabi and Nawangwe, 2011)
Bio-cultural		Rock art	Golden Gate Highlands, South Africa	Precipitation and atmospheric changes	Monitoring of condition	No known intervention	Biodeterioration of condition of rock surface	Increasing loss of rock surfaces	(Viles and Cutler, 2012)

			causing luxuriant lichen growth				and images on the rock surfaces	
Intangible (indigenous)	Language	!Xun and Khwe Indigenous Youth of South Africa	Climate variability causing drought and loss of plants	Groups (youth)	Documentation	Non-formal, local	Enhancement, promotion	(Bodunrin, 2019)
		Indigenous Language Use in Agricultural Radio Programming in Nigeria	Climate variability increasing frequency of drought	Farmer groups, communities	Research, documentation	Formal, local	Promotion, transmission	(Adeyeye et al., 2020)
	Rituals	Enkipaata, Eunoto and Olng'esherr Maasai male rites of passage	Climate variability causing drought	Maasai community groups	Identification, documentation, research	Formal, non-formal, local, foreign	promotion	(UNESCO, 2018a)
	Customs & beliefs	Sanké mon fishing festival in Mali	Climate variability reducing rainfall	Malinkés, Bambara and Buwa communities	Identification, documentation, preservation	Formal, non-formal, local	promotion	(UNESCO, 2009)
	Indigenous engineering systems	Water measurers of the Foggara irrigation system in Algeria	Increased siltation and sandstorms Climate variability causing flooding	Touat and Tidikelt communities	Research, identification, documentation	Formal, local	transmission	(Mokadem et al., 2018)
	Arts and crafts	Traditional crafts made from various parts of the Date Palm in Egypt, Mauritania, Morocco, Sudan, Tunisia and other countries outside Africa	Climate variability causing shift in plant habitats	Residents of oases, groups, communities, agricultural cooperative societies	Research, identification, documentation, preservation, protection	Formal, non-formal, local, foreign	Transmission, promotion, enhancement, revitalization	(UNESCO, 2003) (Shabani et al., 2012)

Conservation of heritage may require offsetting the impact of loss through partial or total excavation under certain circumstances, like environment instability, or where *in situ* heritage preservation is exorbitant in cost (Maarleveld and Guérin, 2013).

Although many underwater shipwrecks and ruins of cities are currently preserved better *in situ* than similar sites on land (Feary et al., 2016), preserving such heritage is often financially prohibitive with many physical and technical challenges. Further, skill capacities of heritage agencies are limited to a few qualified archaeologists in Africa (Maarleveld and Guérin, 2013).

For centuries, Africans have drawn on intangible heritage to enhance their resilience to climatic variability and support adaptation practices. For example, pastoralist communities have historically translated their experiences into memories that can be 'translated' into diverse adaptive practices (Oba, 2014). In coastal Kenya, Mijikenda communities rely on indigenous knowledge and practices used in the management of the sacred Kaya Forests to adapt their farming to a changing climate (Wekesa et al., 2015).

Hence, preservation measures for transforming oral information into written records should ensure viability of intangible cultural heritage by giving due consideration to the confidentiality of culturally sensitive information and intellectual property rights (Feary et al., 2016).

Inclusion of cultural landscapes and intangible heritage in the landscape approach at the regional scale development planning processes may have significant impacts on protected area management (Feary et al., 2016). For example, at the Domboshava rock art site in Zimbabwe, all management decisions are taken in direct consultation with traditional leaders and other stakeholders from surrounding communities (Chirikure et al., 2010). Such adaptation strategies promote a more open-minded approach to heritage by leveraging local development (UNESCO, 2018b).

Lack of expertise and resources, together with legislation that privileges certain typologies of heritage, seem to limit implementation of approved policies (Ndoro, 2015). Additionally, cultural heritage has least priority in terms of budgetary allocation, capacity building and inclusion into school curricula. Failure to consider the views of people who attach spiritual significance to places is detrimental to the conservation of heritage places (Bwasiri, 2011). In particular, documented cases of local people having to pay an entrance fee, like tourists, to access burial grounds and places of pilgrimage negate local participation in cultural site management (Ndoro, 2015).

In the long term, heritage managers and local authorities could shift from planning primarily for disaster response and recovery to strategies that focus on disaster preparedness, reducing the vulnerability of sites and strengthening resilience of local communities (UNFCCC, 2007; Domke and Pretzsch, 2016). This could evolve into innovative approaches that integrate community, government and the research sector in productive cultural heritage management partnerships.

There is a need for institutions to establish, maintain and update a comprehensive inventory of underwater cultural heritage. This can be done using non-intrusive, detailed mapping of the wreck site and a 3D model from which scientists can reconstruct the site in detail (Maarleveld and Guérin, 2013).

[START FAQ9.1 HERE]

FAQ 9.1: Which climate hazards impact African livelihoods, economies, health and well-being the most?

Climate extremes, particularly extreme heat, drought, and heavy rainfall events, impact the livelihoods, health, and well-being of millions of Africans. They will also continue to impact African economies, limiting adaptation capacity. Interventions based on resilient infrastructure and technologies can achieve numerous developmental and adaptation co-benefits.

Rainfall impacts African livelihoods and well-being primarily through drought and heavy rainfall events. Drought frequency, duration and intensity is projected to increase in most parts of Africa, but particularly in

West Africa and the Sahel. By 2030, about 250 million people may experience high water stress in Africa, with up to 700 million people displaced as a result. In sub-Saharan Africa, floods are expected to displace an average of 2.7 million people in any given year in the future. Changing rainfall distributions together with warming temperatures will alter the distributions of disease vectors like mosquitoes and midges. Malaria vector hotspots and prevalence are projected to increase in East and southern Africa and the Sahel under RCP4.5 by the 2030s, exposing an additional 50.6–62.1 million people to malaria risk.

Increases in the number of hot days and nights, as well as in heatwave intensity and duration, have had negative impacts on agriculture, human health, water availability, energy demand and livelihoods. By some estimates, African countries' GDP per capita is on average 13.6% lower since 1991 than if anthropogenic warming had not occurred. In the future, high temperatures combined with high humidity exceed the threshold for human and livestock tolerance over larger parts of Africa and with greater frequency. Increased average temperatures and lower rainfall will further reduce economic output and growth in Africa, with larger negative impacts than on other regions of the world.

Resilient infrastructure and technologies are required to cope with the increasing climate variability and change (Figure FAQ 9.1). These include improving housing to limit heat and exposure, along with improving water and sanitation infrastructure. Such interventions to ensure that the most vulnerable are properly protected from climate change have many co-benefits, including for pandemic recovery and prevention.

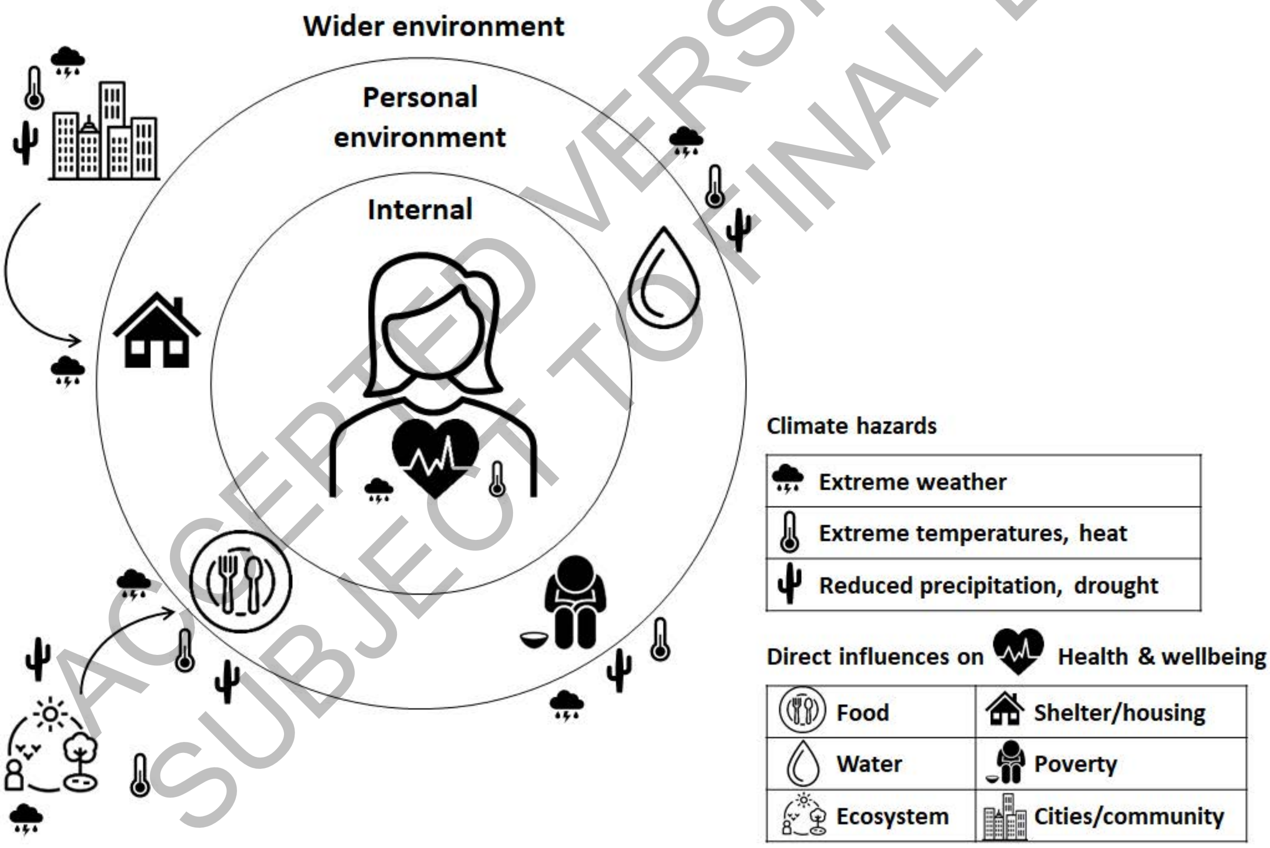


Figure FAQ9.1.1: A schematic illustration of the interconnectedness of different sectors and impacts that spillover to affect the health and well-being of African people.

[END FAQ9.1 HERE]

[START FAQ9.2 HERE]

FAQ9.2: What are the limits and benefits of climate change adaptation in Africa?

The capacity for African ecosystems to adapt to changing environmental conditions is limited by a range of factors, from heat tolerance to land availability. Adaptation across human settlements and food systems are further constrained by insufficient planning and affordability. Integrated development planning and increasing finance flows can improve African climate change adaptation.

Many species will lose all suitable habitats due to increases in temperature by 2100. Coupled with projected losses of Africa's protected areas, higher temperatures will also reduce carbon sinks and other ecosystem services. Many nature-based adaptation measures (e.g., for coral reefs, mangroves, marshes) are no longer effective at 1.5ºC of global warming. Human-based adaptation strategies for ecosystems reach their limits as availability and affordability of land decreases, resulting in migration, displacement and relocation.

The limits to adaptation for human settlements arise largely from developmental challenges associated with Africa's rapid urbanisation, poor development planning, and increasing numbers of urban poor residing in informal settlements. Further limits arise from insufficient consideration of climate change in adaptation planning and infrastructure investment and insufficient financial resources. There are also limits to adaptation for food production strategies. Increasing climate events – droughts and floods – impose specific adaptation responses which poorer households cannot afford. For instance, the use of early-maturing or drought-tolerant crop varieties may increase resilience, but adoption by smallholder farmers is hindered by the unavailability or unaffordability of seed.

Adaptation in Africa can reduce risks at current levels of global warming. However, there is very limited evidence for the effectiveness of current adaptation at increased global warming levels. Ambitious, near-term mitigation would yield the largest single contribution to successful adaptation in Africa.

Current adaptation finance flows are billions of USD less than the needs of African countries and around half of finance commitments to Africa reported by developed countries remain undisbursed. Increasing adaptation finance flows by billions of dollars (including public and private sources), removing barriers to accessing finance and providing targeted country support can improve climate change adaptation across Africa.

[END FAQ9.2 HERE]

[START FAQ9.3 HERE]

FAQ 9.3: How can African countries secure enough food in changing climate conditions for their growing populations?

Climate change is already impacting African food systems and will worsen food insecurity in sub-Saharan Africa in the future. An integrated approach to adaptation planning can serve as a flexible and cost-effective solution for addressing African food security challenges.

Maize and wheat yields have decreased on average 5.8% and 2.3%, respectively, in Sub-Saharan Africa due to climate change. Among the 135 million acutely food-insecure people in crisis globally, more than half (73 million) are in Africa. This is partly due to the growing severity of drought. Adding to these challenges, Africa has the fastest-growing population in the world. Its population is expected to increase by roughly 50% over the next fifteen years, growing from 1.2 billion people to over 1.8 billion by 2035.

Sustainable agricultural development combined with enabling institutional conditions, such as supportive governance systems and policy, can provide farmers with greater yield stability in uncertain climate conditions. It is also widely acknowledged that an integrated approach for adaptation planning that combines (i) emerging Climate Information Services, (ii) capacity building, (iii) local and indigenous knowledge systems and (iv) strategic financial investment can serve as a flexible and cost-effective solution for addressing African food security challenges (Section 9.4.1.2; Box 9.2).

[END FAQ9.3 HERE]

[START FAQ9.4 HERE]

FAQ9.4: How can African local knowledge serve climate adaptation planning more effectively?

A strong relationship between scientific knowledge and local knowledge is desirable, especially in developing contexts where technology for prediction and modelling is least accessible.

In many African settings, farmers use the local knowledge gained over time – through experience and passed on orally from generation to generation – to cope with climate challenges. Indigenous knowledge systems of weather and climate patterns include early warning systems, agroecological farming systems and observation of natural or non-natural climate indicators. For instance, biodiversity and crop diversification are used as a buffer against environmental challenges: if one crop fails, another will survive. Local knowledge of seasons, storms, and wind patterns is used to guide and plan farming and other activities.

Collaborative partnerships between research, agricultural extension services and local communities would create new avenues for the co-production of knowledge in climate change adaptation to better inform adaptation policies and practices across Africa (Section 9.4.3; Box 9.2).

[END FAQ9.4 HERE]

References

Abadie, L. M. et al., 2020: Comparing urban coastal flood risk in 136 cities under two alternative sea-level projections: RCP 8.5 and an expert opinion-based high-end scenario. *Ocean & Coastal Management*, **193**, 105249, doi:https://doi.org/10.1016/j.ocecoaman.2020.105249.

Abadie, L. M. et al., 2021: Additional dataset to "Comparing urban coastal flood risk in 136 cities under two alternative sea-level projections: RCP 8.5 and an expert opinion-based high-end scenario", Zenodo. Available at: https://doi.org/10.5281/zenodo.4733499.

Abatzoglou, J. T., A. P. Williams and R. Barbero, 2019: Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophysical Research Letters*, **46**(1), 326-336, doi:10.1029/2018GL080959.

Abayomi, A. and M. N. Cowan, 2014: The HIV/AIDS epidemic in South Africa: Convergence with tuberculosis, socioecological vulnerability, and climate change patterns. *S Afr Med J*, **104**(8), 583, doi:10.7196/samj.8645.

Abbas, A. M. (ed.), Climate Change and Forced Migration from Ngala and Kala-Balge LGAs, N.E. Borno State, Nigeria. Global Changes and Natural Disaster Management: Geo-information Technologies, 2017, Cham, Springer International Publishing, 141-151 pp. ISBN 978-3-319-51844-2.

Abbas, H. A., W. J. Bond and J. J. Midgley, 2019: The worst drought in 50 years in a South African savannah: Limited impact on vegetation. *African Journal of Ecology*, **57**(4), 490-499, doi:10.1111/aje.12640.

Abdalahh, M., 2011: Impact of coastal environmental conditions on building materials of The Roman Theater at the archaeological site of Sabratha, Libya. *Yearbook of the General Union of Archaeologists*, **14**(14), 288-323, doi:10.21608/cguaa.2011.35625.

Abdela, N. and K. Jilo, 2016: Impact of Climate Change on Livestock Health: A Review. *Global Veterinaria*, **16**(5), 419-424, doi:http://dx.doi.org/10.5829/idosi.gv.2016.16.05.10370.

Abdussalam, A. F. et al., 2014: The impact of climate change on meningitis in Northwest Nigeria: An assessment using CMIP5 climate model simulations. *Weather, Climate, and Society*, **6**(3), 371–379, doi:https://doi.org/10.1175/WCAS-D-13-00068.1.

Abel, G. J., M. Brottrager, J. Crespo Cuaresma and R. Muttarak, 2019: Climate, conflict and forced migration. *Global Environmental Change*, **54**, 239-249, doi:https://doi.org/10.1016/j.gloenvcha.2018.12.003.

Abera, A. et al., 2021: Air Quality in Africa: Public Health Implications. *Annual Review of Public Health*, **42**(1), 193-210, doi:10.1146/annurev-publhealth-100119-113802.

Abidoye, B. O. and A. F. Odusola, 2015: Climate Change and Economic Growth in Africa: An Econometric Analysis. *Journal of African Economies*, **24**(2), 277-301, doi:10.1093/jae/eju033.

Abiodun, G. J. et al., 2018: Exploring the Influence of Daily Climate Variables on Malaria Transmission and Abundance of *Anopheles arabiensis* over Nkomazi Local Municipality, Mpumalanga Province, South Africa. *Journal of Environmental and Public Health*, **2018**, 3143950, doi:10.1155/2018/3143950.

Abiona, O., 2017: Adverse effects of early life extreme precipitation shocks on short-term health and adulthood welfare outcomes. *Review of Development Economics*, **21**, 1229-1254, doi:10.1111/rode.12310.

Abraham, J. O., G. P. Hempson and A. C. Staver, 2019: Drought-response strategies of savanna herbivores. *Ecol Evol*, **9**(12), 7047-7056, doi:10.1002/ece3.5270.

Abutaleb, K. A. A., A. H. E. Mohammed and M. H. M. Ahmed, 2018: Climate Change Impacts, Vulnerabilities and Adaption Measures for Egypt's Nile Delta. *Earth Systems and Environment*, **2**(2), 183-192, doi:10.1007/s41748-018-0047-9.

Acevedo, M. et al., 2020: A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nat Plants*, **6**(10), 1231-1241, doi:10.1038/s41477-020-00783-z.

Acevedo, S. et al., 2017: The effects of weather shocks on economic activity: How can low-income countries cope? In: *World Economic Outlook, October 2017 : Seeking Sustainable Growth: Short-Term Recovery, Long-Term Challenges* [IMF (ed.)]. International Monetary Fund. Research Dept., New York, pp. 117-183.

Adams, L., 2018: *Unlocking the potential of enhanced rainfed agriculture*. SIWI, Stockholm. Available at: https://www.siwi.org/wp-content/uploads/2018/12/Unlocking-the-potential-of-rainfed-agriculture-2018-FINAL.pdf

Adamu, B. and H. N. Ndi, 2017: Changing trends in water sources and related pathologies in small to medium size African cities. *GeoJournal*, **83**(4), 885-896, doi:10.1007/s10708-017-9808-5.

Addaney, M., 2020: Strengthening Africa's Adaptive Capacity to Climate Change: African Union Law and Implications of China's Belt and Road Policy. In: *Climate Change, Hazards and Adaptation Options* [Filho, W. L., G. J. Nagy, M. Borga, P. D. C. Muñoz and A. Magnuszewski (eds.)]. Springer Nature Switzerland AG, pp. 481-503.

Adegun, O. B. and Y. M. D. Adedeji, 2017: Review of economic and environmental benefits of earthen materials for housing in Africa. *Frontiers of Architectural Research*, **6**(4), 519-528, doi:https://doi.org/10.1016/j.foar.2017.08.003.

Adekiya, T. A. et al., 2019: The Effect of Climate Change and the Snail-Schistosome Cycle in Transmission and Bio-Control of Schistosomiasis in Sub-Saharan Africa. *International journal of environmental research and public health*, **17**(1), 181, doi:10.3390/ijerph17010181.

Adelekan, I. and T. Fregene, 2015: Vulnerability of artisanal fishing communities to flood risks in coastal southwest Nigeria. *Climate and Development*, **7**(4), 322-338, doi:10.1080/17565529.2014.951011.

Adelekan, I. O., 2012: Vulnerability to wind hazards in the traditional city of Ibadan, Nigeria. *Environment and Urbanization*, **24**(2), 597-617, doi:10.1177/0956247812454247.
Adelekan, I. O., 2016: Flood risk management in the coastal city of Lagos, Nigeria. *Journal of Flood Risk Management*, **9**(3), 255-264, doi:10.1111/jfr3.12179.
Adeniran, A. B. and K. A. Daniell, 2020: Transaqua: power, political change and the transnational politics of a water megaproject. *International Journal of Water Resources Development*, **37**(2), 234-255, doi:10.1080/07900627.2020.1747408.
Adenle, A. A. et al., 2017: Managing Climate Change Risks in Africa - A Global Perspective. *Ecological Economics*, **141**, 190-201, doi:https://doi.org/10.1016/j.ecolecon.2017.06.004.
Adenle, A. A., K. Wedig and H. Azadi, 2019: Sustainable agriculture and food security in Africa: The role of innovative technologies and international organizations. *Technology in Society*, **58**, 101143, doi:https://doi.org/10.1016/j.techsoc.2019.05.007.
Adeola, A. M. et al., 2019: Predicting malaria cases using remotely sensed environmental variables in Nkomazi, South Africa. *Geospatial Health*, **14**(1), doi:10.4081/gh.2019.676.
Adeola, A. M. et al., 2017: Climatic Variables and Malaria Morbidity in Mutale Local Municipality, South Africa: A 19-Year Data Analysis. *International journal of environmental research and public health*, **14**(11), 1360, doi:10.3390/ijerph14111360.
Adepoju, A., 2019: Migrants and Refugees in Africa. In: *Oxford Research Encyclopedia of Politics*. ISBN 9780190228637.
Adetula, V. A. O., R. Bereketeab and O. Jaiyebo, 2016: *Regional economic communities and peacebuilding in Africa : the experiences of ECOWAS and IGAD*. NAI Policy Dialogue, Nordiska Afrikainstitutet, Uppsala, 50 pp. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:nai:diva-2103 (accessed 2017-01-25t16:44:07.290+01:00).
Adeyeye, B. et al., 2020: A SWOT analysis of indigenous language use in agricultural radio programming in Nigeria. In: *Emerging Trends in Indigenous Language Media, Communication, Gender, and Health* [Adesina, E., O. Afolabi, N. C. Asogwa, F. Falobi, A. C. Ifeanyichukwu, K. Kadiri, P. Mpofu, O. Ogunyombo, K. Onyenankeya, O. Oredola, T. Owolabi and O. Oyero (eds.)]. IGI Global, pp. 188-209. ISBN 9781799820918.
Adger, W. N. et al., 2021: Perceived environmental risks and insecurity reduce future migration intentions in hazardous migration source areas. *One Earth*, **4**(1), 146-157, doi:10.1016/j.oneear.2020.12.009.
Adhikari, B. and L. S. Safaee Chalkasra, 2021: Mobilizing private sector investment for climate action: enhancing ambition and scaling up implementation. *Journal of Sustainable Finance & Investment*, 1-18, doi:10.1080/20430795.2021.1917929.
Adhikari, U., A. P. Nejadhashemi and S. A. Woznicki, 2015: Climate change and eastern Africa: a review of impact on major crops. *Food and Energy Security*, **4**(2), 110-132, doi:https://doi.org/10.1002/fes3.61.
Adjei, V. and R. Kyerematen, 2018: Impacts of Changing Climate on Maize Production in the Transitional Zone of Ghana. *American Journal of Climate Change*, **7**(3), 14, doi:10.4236/ajcc.2018.73028.
Adom, K., 2014: Beyond the Marginalization Thesis: An Examination of the Motivations of Informal Entrepreneurs in Sub-Saharan Africa. *The International Journal of Entrepreneurship and Innovation*, **15**(2), 113-125, doi:10.5367/ijei.2014.0144.
Adu-Prah, S. and E. Kofi Tetteh, 2015: Spatiotemporal analysis of climate variability impacts on malaria prevalence in Ghana. *Applied Geography*, **60**, 266-273, doi:10.1016/j.apgeog.2014.10.010.
Adzawla, W., S. B. Azumah, P. Y. Anani and S. A. Donkoh, 2019a: Gender perspectives of climate change adaptation in two selected districts of Ghana. *Heliyon*, **5**(11), e02854, doi:10.1016/j.heliyon.2019.e02854.
Adzawla, W., H. Baumüller, S. A. Donkoh and R. Serra, 2019b: Effects of climate change and livelihood diversification on the gendered productivity gap in Northern Ghana. *Climate and Development*, **12**(8), 743-755, doi:10.1080/17565529.2019.1689093.
AfDB, 2018a: *The Africa Infrastructure Develoment Index 2018*. Available at: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/Economic_Brief_-_The_Africa_Infrastructure_Development_Index.pdf.
AfDB, 2018b: *African Economic Outlook 2018*. 200 pp. Available at: https://www.afdb.org/en/documents/document/african-economic-outlook-aoe-2018-99877.
AfDB, 2018c: *Multinational Appraisal Report for Programme for Integrated Development and Adaptation to Climate Change (PIDACC)*. African Development Bank (AfDB), AfDB, Abidjan, Côte d'Ivoire, 56 pp. Available at: https://www.afdb.org/en/documents/document/multinational-programme-for-integrated-development-and-adaptation-to-climate-change-in-the-niger-basin-pidacc-appraisal-report-109273.
AfDB, 2019: *Analysis of adaptation components of Africa's Nationally Determined Contributions (NDCs)*. African Development Bank, Abijan. Available at: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/Analysis_of_Adaptation_Components_in_African_NDCs_2019.pdf.
AfDB, 2021: *African Development Report 2015 - Growth, Poverty and Inequality Nexus: Overcoming Barriers to Sustainable Development*. African Development Bank, Bank, A. D., Abidjan, Côte d'Ivoire, 270 pp. Available at: https://www.afdb.org/en/documents/document/african-development-report-2015-growth-poverty-and-inequality-nexus-overcoming-barriers-to-sustainable-development-89715.
Afifi, T., 2011: Economic or Environmental Migration? The Push Factors in Niger. *International Migration*, **49**(s1), e95-e124, doi:https://doi.org/10.1111/j.1468-2435.2010.00644.x.

Africa Adaptation Initiative, 2018: Africa State of Adaptation Report. Africa Adaptation Initiative (AAI), New York, USA., 32 pp.
African Development Bank, OECD and United Nations Development Programme, 2016: *African Economic Outlook 2016*. Sustainable Cities and Structural Transformation, 400 pp. ISBN 9789264256477.
Agier, L. et al., 2013: Seasonality of meningitis in Africa and climate forcing: aerosols stand out. *Journal of the Royal Society Interface*, **10**(79), 20120814, doi:https://doi.org/10.1098/rsif.2012.0814.
Agrawal, A. et al., 2019: *Climate resilience through social protection. Background paper to the 2019 report of the Global Commission on Adaptation*. Rotterdam and Washington, DC. Available at: www.gca.org.
Agrawala, S. and M. Carraro, 2010: Assessing the Role of Microfinance in Fostering Adaptation to Climate Change. *Fondazione Eni Enrico Mattei, Working Papers*, doi:10.2139/ssrn.1646883.
Aguilar, E. et al., 2009: Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955–2006. *J Geophys Res-Atmos*, **114**(D2), doi:https://doi.org/10.1029/2008JD011010.
Aguirre-Gutiérrez, J. et al., 2019: Drier tropical forests are susceptible to functional changes in response to a long-term drought. *Ecology Letters*, **22**(5), 855-865, doi:https://doi.org/10.1111/ele.13243.
Agusto, F. B., A. B. Gumel and P. E. Parham, 2015: Qualitative assessment of the role of temperature variations on malaria transmission dynamics. *J. Biol. Syst.*, **23**(04), 1550030, doi:10.1142/S0218339015500308.
Agyeman, Y. B., 2019: Ecotourism as an Adaptation Strategy for Mitigating Climate Change Impacts on Local Communities Around Protected Areas in Ghana. In: *Handbook of Climate Change Resilience* [Filho, W. L. (ed.)]. Springer, Cham, Switzerland, pp. 537-555. ISBN 978-3-319-93336-8
Ahdoot, S., S. E. Pacheco and T. C. O. E. HEALTH, 2015: Global Climate Change and Children's Health. *Pediatrics*, peds.2015-3233, doi:10.1542/peds.2015-3233.
Ahmadalipour, A. and H. Moradkhani, 2018: Escalating heat-stress mortality risk due to global warming in the Middle East and North Africa (MENA). *Environment International*, **117**, 215-225, doi:https://doi.org/10.1016/j.envint.2018.05.014.
Ahmadalipour, A., H. Moradkhani, A. Castelletti and N. Magliocca, 2019: Future drought risk in Africa: Integrating vulnerability, climate change, and population growth. *Sci Total Environ*, **662**, 672-686, doi:10.1016/j.scitotenv.2019.01.278.
Ahmed, A. et al., 2016: Adaptation to climate change or non-climatic stressors in semi-arid regions? Evidence of gender differentiation in three agrarian districts of Ghana. *Environmental Development*, **20**, 45-58, doi:https://doi.org/10.1016/j.envdev.2016.08.002.
Ahmed, S. M., 2020: Impacts of drought, food security policy and climate change on performance of irrigation schemes in Sub-saharan Africa: The case of Sudan. *Agricultural Water Management*, **232**, doi:10.1016/j.agwat.2020.106064.
Aich, V. et al., 2014: Comparing impacts of climate change on streamflow in four large African river basins. *Hydrology and Earth System Sciences*, **18**(4), 1305-1321, doi:10.5194/hess-18-1305-2014.
Ainsworth, E. A. and S. P. Long, 2021: 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Global Change Biology*, **27**(1), 27-49, doi:10.1111/gcb.15375.
Ajayi, A. and S. I. Smith, 2019: Recurrent cholera epidemics in Africa: which way forward? A literature review. *Infection*, **47**(3), 341-349, doi:https://doi.org/10.1007/s15010-018-1186-5.
Ajibade, L. T. and J. O. Eche, 2017: Indigenous knowledge for climate change adaptation in Nigeria. In: *Indigenous knowledge systems and climate change management in Africa* [Mafongoya, P. L. and O. C. Ajayi (eds.)]. CTA, Wageningen, The Netherlands, pp. 316.
Akello, S., 2014: Effects of floods on students access to secondary education in Nyando district, Kisumu county, Kenya. University of Nairobi, Nairobi, 84 pp.
Akinsanola, A. A. and W. Zhou, 2019: Projections of West African summer monsoon rainfall extremes from two CORDEX models. *Clim Dyn*, **52**(3), 2017-2028, doi:10.1007/s00382-018-4238-8.
Akintola, S. L. and K. A. Fakoya, 2017: Small - scale fisheries in the context of traditional post - harvest practice and the quest for food and nutritional security in Nigeria. *Agriculture & Food Security*, **6**(34), 1-17, doi:10.1186/s40066-017-0110-z.
Akinyi, D. P., S. K. Ng'ang'a and E. H. Girvetz, 2021: Trade-offs and synergies of climate change adaptation strategies among smallholder farmers in sub-Saharan Africa: A systematic review. *Regional Sustainability*, **2**(2), 130-143, doi:https://doi.org/10.1016/j.regsus.2021.05.002.
Aklin, M., P. Bayer, S. P. Harish and J. Urpelainen, 2018: *Escaping the Energy Poverty Trap When and How Governments Power the Lives of the Poor*. MIT Press, Cambridge, MA ISBN 9780262535861.
Akpan, G. E., K. A. Adepoju, O. R. Oladosu and S. A. Adelabu, 2018: Dominant malaria vector species in Nigeria: Modelling potential distribution of Anopheles gambiae sensu lato and its siblings with MaxEnt. *PLOS ONE*, **13**(10), e0204233, doi:10.1371/journal.pone.0204233.
Akresh, R., P. Verwimp and T. Bundervoet, 2011: Civil War, Crop Failure, and Child Stunting in Rwanda. *Economic Development and Cultural Change*, **59**(4), 778-810, doi:https://www.journals.uchicago.edu/doi/full/10.1086/660003.
Alam, S. A., 2006: Use of biomass fuels in the brick-making industries of Sudan: Implications for deforestation and greenhouse gas emission. University of Helsinki, Finland, Helsinki, Finland, 87 pp.

Albrecht, T. R., A. Crootof and C. A. Scott, 2018: The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, **13**(4), 043002, doi:10.1088/1748-9326/aaa9c6.
Alderman, H., J. Hoddinott and B. Kinsey, 2006: Long term consequences of early childhood malnutrition. *Oxford Economic Papers*, **58**(3), 450-474, doi:10.1093/oep/gpl008.
Aleman, J. C. et al., 2017: Tree cover in Central Africa: determinants and sensitivity under contrasted scenarios of global change. *Scientific Reports*, **7**(1), 1-12, doi:10.1038/srep41393.
Aleman, J. C., M. A. Jarzyna and A. C. Staver, 2018: Forest extent and deforestation in tropical Africa since 1990. *Nature Ecology and Evolution*, **2**(1), 26-33, doi:10.1038/s41559-017-0406-1.
Alemayehu, A. and W. Bewket, 2017: Smallholder farmers' coping and adaptation strategies to climate change and variability in the central highlands of Ethiopia. *Local Environment*, **22**(7), 825-839, doi:10.1080/13549839.2017.1290058.
Alemu, K., A. Worku, Y. Berhane and A. Kumie, 2014: Spatiotemporal clusters of malaria cases at village level, northwest Ethiopia. *Malar. J.*, **13**, 223, doi:10.1186/1475-2875-13-223.
Alexander, M., 2020: Pandemics, climate change, and disability related to SCI. *Spinal Cord Ser Cases*, **6**(1), 36, doi:10.1038/s41394-020-0285-6.
Alexander, M. and S. Dessai, 2019: What can climate services learn from the broader services literature? *Climatic Change*, **157**(1), 133-149, doi:10.1007/s10584-019-02388-8.
Alfieri, L. et al., 2017: Global projections of river flood risk in a warmer world. *Earth's Future*, **5**(2), 171-182, doi:https://doi.org/10.1002/2016EF000485.
Aljawabra, F. and M. Nikolopoulou, 2018: Thermal comfort in urban spaces: a cross-cultural study in the hot arid climate. *Int J Biometeorol*, **62**(10), 1901-1909, doi:10.1007/s00484-018-1592-5.
Allan, T., M. Keulertz and E. Woertz, 2015: The water–food–energy nexus: an introduction to nexus concepts and some conceptual and operational problems. *International Journal of Water Resources Development*, **31**(3), 301-311, doi:10.1080/07900627.2015.1029118.
Allard, C., 2017: The Informal Economy in Sub-Saharan Africa. In: *Regional Economic Outlook* [Robinson, D. (ed.)], pp. 122. ISBN 9781475574463.
Allen, T. et al., 2017: Global hotspots and correlates of emerging zoonotic diseases. *Nat Commun*, **8**(1), 1124, doi:10.1038/s41467-017-00923-8.
Alonso, S. et al., 2019: The economic burden of malaria on households and the health system in a high transmission district of Mozambique. *Malaria Journal*, **18**(1), 360, doi:10.1186/s12936-019-2995-4.
Aloysius, N. R. et al., 2016: Evaluation of historical and future simulations of precipitation and temperature in central Africa from CMIP5 climate models. *J Geophys Res-Atmos*, **121**(1), 130-152, doi:10.1002/2015JD023656.
Alsdorf, D. et al., 2016: Opportunities for hydrologic research in the Congo Basin. *Reviews of Geophysics*, **54**(2), 378-409, doi:10.1002/2016rg000517.
Altieri, M. A., C. I. Nicholls, A. Henao and M. A. Lana, 2015: Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, **35**(3), 869-890, doi:10.1007/s13593-015-0285-2.
Alvar-Beltrán, J. et al., 2020: Farmers' Perceptions of Climate Change and Agricultural Adaptation in Burkina Faso. *Atmosphere*, **11**(8), 827, doi:10.3390/atmos11080827.
Álvarez Larrain, A. and M. K. McCall, 2019: Participatory mapping and participatory GIS for historical and archaeological landscape studies: a critical review. *Journal of Archaeological Method and Theory*, **26**(2), 643-678, doi:10.1007/s10816-018-9385-z.
Alves, B., D. B. Angnuureng, P. Morand and R. Almar, 2020: A review on coastal erosion and flooding risks and best management practices in West Africa: what has been done and should be done. *Journal of Coastal Conservation*, **24**(3), doi:10.1007/s11852-020-00755-7.
Amadi, J. A. et al., 2018: Sensitivity of vegetation to climate variability and its implications for malaria risk in Baringo, Kenya. *PLOS ONE*, **13**(7), e0199357, doi:10.1371/journal.pone.0199357.
Amadi, L. and U. M. Ogonor, 2015: Climate change, environmental security and displacement in Nigeria: Experience from the Niger Delta Flood Disaster, 2012. *African Journal of Environmental Science and Technology*, **9**(1), 53-64, doi:https://doi.org/10.5897/AJEST2014.1749.
Amamou, H. et al., 2018: Climate change-related risks and adaptation strategies as perceived in dairy cattle farming systems in Tunisia. *Climate Risk Management*, **20**, 38-49, doi:10.1016/j.crm.2018.03.004.
Amanambu, A. C. et al., 2019: Spatio-temporal variation in rainfall-runoff erosivity due to climate change in the Lower Niger Basin, West Africa. *CATENA*, **172**, 324-334, doi:https://doi.org/10.1016/j.catena.2018.09.003.
Amare, Z. Y., J. O. Ayoade, I. O. Adelekan and M. T. Zeleke, 2018: Barriers to and determinants of the choice of crop management strategies to combat climate change in Dejen District, Nile Basin of Ethiopia. *Agriculture & Food Security*, **7**(1), 37, doi:10.1186/s40066-018-0188-y.
AMCOW, 2012: *Water Security and Climate Resilient Development: Strategic Framework*. Water Climate Development Programme, The African Ministers' Council on Water (AMCOW), AMCOW, Abuja Nigeria, 52 pp. Available at: https://www.preventionweb.net/files/43470_watersecurityandclimateresilientdev.pdf.
Amegah, A. K., G. Rezza and J. J. K. Jaakkola, 2016: Temperature-related morbidity and mortality in Sub-Saharan Africa: A systematic review of the empirical evidence. *Environment International*, **91**, 133-149, doi:https://doi.org/10.1016/j.envint.2016.02.027.

Amusan, L. and O. Olutola, 2017: Climate change and sustainable tourism: South Africa caught in-between. *African Journal of Hospitality, Tourism and Leisure*, **6**(4).

Anadón, J. D., O. E. Sala, B. L. Turner and E. M. Bennett, 2014: Effect of woody-plant encroachment on livestock production in North and South America. *Proceedings of the National Academy of Sciences*, **111**(35), 12948, doi:10.1073/pnas.1320585111.

Anchang, J. Y. et al., 2019: Trends in Woody and Herbaceous Vegetation in the Savannas of West Africa. *Remote Sensing*, **11**(5), 576, doi:10.3390/rs11050576.

Andela, N. and G. R. van der Werf, 2014: Recent trends in African fires driven by cropland expansion and El Niño to La Niña transition. *Nature Climate Change*, **4**(9), 791-795, doi:10.1038/nclimate2313.

Anderson, A., 2017: Mean streets: migration, xenophobia and informality in South Africa. *Ethnic and Racial Studies*, **40**(8), 1343-1345, doi:10.1080/01419870.2016.1243252.

Andrews, T. M. and O. Smirnov, 2020: Who feels the impacts of climate change? *Global Environmental Change*, **65**, 102164, doi:https://doi.org/10.1016/j.gloenvcha.2020.102164.

Andrijevic, M. et al., 2020: Overcoming gender inequality for climate resilient development. *Nature Communications*, **11**(1), 6261, doi:10.1038/s41467-020-19856-w.

Angelsen, A. et al., 2014: Environmental Income and Rural Livelihoods: A Global-Comparative Analysis. *World Development*, **64**, S12-S28, doi:https://doi.org/10.1016/j.worlddev.2014.03.006.

Angula, M. N. and E. Menjono, 2014: *Gender, culture and climate change in Namibia*. 225-238 pp. Available at: http://journals.unam.edu.na/index.php/JSHSS/article/view/980.

Anim, D. O. and R. Ofori-Asenso, 2020: Water scarcity and COVID-19 in sub-Saharan Africa. *J Infect*, **81**(2), e108-e109, doi:10.1016/j.jinf.2020.05.032.

Anthony, K. R. N. et al., 2015: Operationalizing resilience for adaptive coral reef management under global environmental change. *Global Change Biology*, **21**(1), 48-61, doi:10.1111/gcb.12700.

Antwi-Agyei, P., A. J. Dougill, J. Doku-Marfo and R. C. Abaidoo, 2021: Understanding climate services for enhancing resilient agricultural systems in Anglophone West Africa: The case of Ghana. *Climate Services*, **22**, 100218, doi:10.1016/j.cliser.2021.100218.

Antwi-Agyei, P., A. J. Dougill and L. C. Stringer, 2015: Barriers to climate change adaptation: evidence from northeast Ghana in the context of a systematic literature review. *Climate and Development*, **7**(4), 297-309, doi:10.1080/17565529.2014.951013.

Antwi-Agyei, P., A. J. Dougill, L. C. Stringer and S. N. A. Codjoe, 2018: Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Climate Risk Management*, **19**, 83-93, doi:https://doi.org/10.1016/j.crm.2017.11.003.

Antwi-Agyei, P., L. C. Stringer and A. J. Dougill, 2014: Livelihood adaptations to climate variability: insights from farming households in Ghana. *Regional Environmental Change*, **14**(4), 1615-1626, doi:10.1007/s10113-014-0597-9.

Arbieu, U., C. Grünewald, M. Schleuning and K. Böhning-Gaese, 2017: The importance of vegetation density for tourists' wildlife viewing experience and satisfaction in African savannah ecosystems. *PLoS ONE*, **12**(9), doi:10.1371/journal.pone.0185793.

Arblaster, J. M., G. A. Meehl and D. J. Karoly, 2011: Future climate change in the Southern Hemisphere: Competing effects of ozone and greenhouse gases. *Geophysical Research Letters*, **38**(2), doi:https://doi.org/10.1029/2010GL045384.

Arbuckle, J. G., Jr., L. W. Morton and J. Hobbs, 2015: Understanding Farmer Perspectives on Climate Change Adaptation and Mitigation: The Roles of Trust in Sources of Climate Information, Climate Change Beliefs, and Perceived Risk. *Environ Behav*, **47**(2), 205-234, doi:10.1177/0013916513503832.

ARC, 2021: ARC Risk Pools, African Risk Capacity. Available at: https://www.africanriskcapacity.org/countries/arc-risk-pools/.

Ario, A. R. et al., 2019: The logic model for Uganda's health sector preparedness for public health threats and emergencies. *Glob Health Action*, **12**(1), 1664103, doi:10.1080/16549716.2019.1664103.

Armitage, N. et al., 2014: *Water Sensitive Urban Design (WSUD) for South Africa: Framework and Guidelines*. University of Cape Town.

Arndt, C. et al., 2019: Climate change and developing country growth: the cases of Malawi, Mozambique, and Zambia. *Climatic Change*, **154**(3-4), 335-349, doi:10.1007/s10584-019-02428-3.

Arnold, C. A. and L. H. Gunderson, 2013: Adaptive law and resilience. *Envtl. L. Rep. News & Analysis*, **43**, 10426-10443.

Asaminew, T. G., A. Araya, G. Atkilt and H. Solomon, 2017: Modeling the Potential Impact of Climate Change on Cotton (Gossypium hirsutum) Production in Northeastern Semi-Arid Afar and Western Tigray
Regions of Ethiopia. *J Earth Sci Clim Change*, **8**(3), doi:10.4172/2157-7617.1000390.

Asamoah, B., T. Kjellstrom and P. O. Ostergren, 2018: Is ambient heat exposure levels associated with miscarriage or stillbirths in hot regions? A cross-sectional study using survey data from the Ghana Maternal Health Survey 2007. *Int J Biometeorol*, **62**(3), 319-330, doi:10.1007/s00484-017-1402-5.

Asfaw, A., B. Simane, A. Hassen and A. Bantider, 2017: Determinants of non-farm livelihood diversification: evidence from rainfed-dependent smallholder farmers in northcentral Ethiopia (Woleka sub-basin). *Development Studies Research*, **4**(1), 22-36, doi:10.1080/21665095.2017.1413411.

Asfaw, S. et al., 2019: *Independent Evaluation of the Green Climate Fund's Country Ownership Approach*. **21**, Independent Evaluation Unit, Green Climate Fund, GCF, Songdo, South Korea.
Asiama, K. O., W. Voss, R. Bennett and I. Rubanje, 2021: Land consolidation activities in Sub-Saharan Africa towards the agenda 2030: A tale of three countries. *Land Use Policy*, **101**, doi:10.1016/j.landusepol.2020.105140.
Asiyanbi, A. P., 2015: 'I don't get this climate stuff!' Making sense of climate change among the corporate middle class in Lagos. *Public Underst Sci*, **24**(8), 1007-1024, doi:10.1177/0963662514565332.
Asner, G. P., N. Vaughn, I. P. Smit and S. Levick, 2016: Ecosystem-scale effects of megafauna in African savannas. *Ecography*, **39**(2), 240-252, doi:http://dx.doi.org/10.1111/ecog.01640.
Asseng, S. et al., 2019: Climate change impact and adaptation for wheat protein. *Global Change Biology*, **25**(1), 155-173, doi:10.1111/gcb.14481.
Asumadu-Sarkodie, S., P. A. Owusu and P. Rufangura, 2015: Impact analysis of flood in Accra, Ghana. *Advances in Applied Science Research*, **6**(9), 53-78.
Aswad, N. A. E., T. A. Mohammad, A. H. Ghazali and Z. M. Yusoff, 2019: Modelling of Groundwater Pumping Scenarios and their Impact on Saline Water Intrusion in a Tripoli Coastal Aquifer, Libya. *Pertanika J. Sci. & Technol.* , **27**(3), 1407-1427.
Atindana, S. A., P. K. Ofori-danson and S. Brucet, 2020: Modelling the effects of climate change on shellfish production in marine artisanal fisheries of Ghana. *AAS Open Research*, **2**(16), 1-13, doi:https://doi.org/10.12688/aasopenres.12956.1.
Atteridge, A., 2013: Transforming household energy practices to reduce climate risks: Charcoal use in Lusaka, Zambia. *Climate Change: Adaptation, Resilience and Energy Security*, **61**, 5-7.
Attu, H. and J. K. Adjei, 2018: Local knowledge and practices towards malaria in an irrigated farming community in Ghana. *Malar J*, **17**(1), 150, doi:10.1186/s12936-018-2291-8.
AU, 2015: *Agenda 2063*. The African Union Commission, Addis Ababa, Ethiopia. Available at: https://au.int/sites/default/files/documents/36204-doc-agenda2063_popular_version_en.pdf.
Augustine, D. J. et al., 2018: Elevated CO2 induces substantial and persistent declines in forage quality irrespective of warming in mixedgrass prairie. *Ecological Applications*, **28**(3), 721-735, doi:10.1002/eap.1680.
Augustyn, J. et al., 2018: South Africa. In: *Climate change impacts on fisheries and aquaculture: a global analysis* [Phillips, B. and M. Perez-Ramirez (eds.)]. John Wiley and Sons Inc, pp. 479-522. ISBN 978-1-119-15404-4.
Averchenkova, A. and S. Matikainen, 2017: Climate legislation and international commitments. In: *Trends in Climate Change Legislation* [Averchenkova, A., Fankhauser, S., Nachmany, M (ed.)]. Edward Elgar, London, pp. 193-208. ISBN 978 1 78643 577 4.
Awondo, S. N., 2019: Efficiency of region-wide catastrophic weather risk pools: Implications for African Risk Capacity insurance program. *Journal of Development Economics*, **136**, 111-118, doi:https://doi.org/10.1016/j.jdeveco.2018.10.004.
Awotwi A et al., 2015: Predicting Hydrological Response to Climate Change in the White Volta Catchment, West Africa. *Journal of Earth Science & Climatic Change*, **06**(01), doi:10.4172/2157-7617.1000249.
Awoye, O. H. R., F. Pollinger, E. K. Agbossou and H. Paeth, 2017: Dynamical-statistical projections of the climate change impact on agricultural production in Benin by means of a cross-validated linear model combined with Bayesian statistics. *Agricultural and Forest Meteorology*, **234-235**, 80-94, doi:https://doi.org/10.1016/j.agrformet.2016.12.010.
Axelsson, C. R. and N. P. Hanan, 2018: Rates of woody encroachment in African savannas reflect water constraints and fire disturbance. *Journal of Biogeography*, **45**(6), 1209-1218, doi:https://doi.org/10.1111/jbi.13221.
Ayal, D. Y. and W. Leal Filho, 2017: Farmers' perceptions of climate variability and its adverse impacts on crop and livestock production in Ethiopia. *Journal of Arid Environments*, **140**, 20-28, doi:10.1016/j.jaridenv.2017.01.007.
Ayana, E. K., P. Ceccato, J. R. B. Fisher and R. DeFries, 2016: Examining the relationship between environmental factors and conflict in pastoralist areas of East Africa. *Science of The Total Environment*, **557-558**, 601-611, doi:https://doi.org/10.1016/j.scitotenv.2016.03.102.
Ayanlade, A. and M. O. Jegede, 2016: Climate Change Education and Knowledge among Nigerian University Graduates. *Weather, Climate, and Society*, **8**(4), 465-473, doi:10.1175/wcas-d-15-0071.1.
Ayanlade, A. et al., 2020: Early warning climate indices for malaria and meningitis in tropical ecological zones. *Scientific Reports*, **10**(1), 14303, doi:10.1038/s41598-020-71094-8.
Ayanlade, A. and S. M. Ojebisi, 2019: Climate change impacts on cattle production: analysis of cattle herders' climate variability/change adaptation strategies in Nigeria. *Change and Adaptation in Socio-Ecological Systems*, **5**(1), 12-23, doi:doi:10.1515/cass-2019-0002.
Ayanlade, A., M. Radeny and A. I. Akin-Onigbinde, 2018: Climate variability/change and attitude to adaptation technologies: a pilot study among selected rural farmers' communities in Nigeria. *GeoJournal*, **83**(2), 319-331, doi:10.1007/s10708-017-9771-1.
Ayanlade, A., M. Radeny and J. F. Morton, 2017: Comparing smallholder farmers' perception of climate change with meteorological data: A case study from southwestern Nigeria. *Weather and Climate Extremes*, **15**, 24-33, doi:https://doi.org/10.1016/j.wace.2016.12.001.
Ayele, H., M.-H. Li, C.-P. Tung and T.-M. Liu, 2016: Impact of climate change on runoff in the Gilgel Abbay watershed, the Upper Blue Nile Basin, Ethiopia. *Water*, **8**(9), doi:10.3390/w8090380.

Ayugi, B. O. and G. Tan, 2018: Recent trends of surface air temperatures over Kenya from 1971 to 2010. *Meteorology and Atmospheric Physics*, **131**(5), 1401-1413, doi:10.1007/s00703-018-0644-z.
Azong, M. N. and C. J. Kelso, 2021: Gender, ethnicity and vulnerability to climate change: The case of matrilineal and patrilineal societies in Bamenda Highlands Region, Cameroon. *Global Environmental Change*, **67**, doi:10.1016/j.gloenvcha.2021.102241.
Azongo, D. K. et al., 2012: A time series analysis of weather variables and all-cause mortality in the Kasena-Nankana Districts of Northern Ghana, 1995–2010. *Global Health Action*, **5**(1), 19073, doi:10.3402/gha.v5i0.19073.
Azzarri, C. and S. Signorelli, 2020: Climate and poverty in Africa South of the Sahara. *World Development*, **125**, 104691, doi:https://doi.org/10.1016/j.worlddev.2019.104691.
Baarsch, F. et al., 2020: The impact of climate change on incomes and convergence in Africa. *World Development*, **126**, 104699, doi:https://doi.org/10.1016/j.worlddev.2019.104699.
Baccini, A. et al., 2017: Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science (New York, N.Y.)*, **358**(6360), 230, doi:10.1126/science.aam5962.
Baig, S., M. J. Pangilinan, A. R. Rizvi and R. P. Tan, 2016: *Cost and benefits of ecosystem based adaptation*. IUCN, Gland, Switzerland. Available at: https://portals.iucn.org/library/node/45925 (accessed 2019/09/18/13:26:33).
Bailey, K. M., R. A. McCleery, G. Barnes and S. L. McKune, 2019: Climate-Driven Adaptation, Household Capital, and Nutritional Outcomes among Farmers in Eswatini. *Int J Environ Res Public Health*, **16**(21), doi:10.3390/ijerph16214063.
Baker, D. J. et al., 2015: Assessing climate change impacts for vertebrate fauna across the West African protected area network using regionally appropriate climate projections. *Diversity and Distributions*, **21**(9), 991-1003, doi:https://doi.org/10.1111/ddi.12337.
Baker, R. E. et al., 2020: Susceptible supply limits the role of climate in the early SARS-CoV-2 pandemic. *Science (New York, N.Y.)*, **369**(6501), 315-319, doi:10.1126/science.abc2535.
Bakun, A. et al., 2015: Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems. *Current Climate Change Reports*, **1**(2), 85-93, doi:10.1007/s40641-015-0008-4.
Balié, J. et al., 2019: Exploring opportunities around climate-smart breeding for future food and nutrition security, Wageningen, Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
Ban, N. C. et al., 2019: Well-being outcomes of marine protected areas. *Nature Sustainability*, **2**(6), 524-532, doi:10.1038/s41893-019-0306-2.
Bang, H., L. Miles and R. Gordon, 2019: Evaluating local vulnerability and organisational resilience to frequent flooding in Africa: the case of Northern Cameroon. *Foresight*, **21**(2), 266-284, doi:https://doi.org/10.1108/FS-06-2018-0068.
Banga, J., 2019: The green bond market: a potential source of climate finance for developing countries. *Journal of Sustainable Finance & Investment*, **9**(1), 17-32, doi:10.1080/20430795.2018.1498617.
Bangira, T., B. H. P. Maathuis, T. Dube and T. W. Gara, 2015: Investigating flash floods potential areas using ASCAT and TRMM satellites in the Western Cape Province, South Africa. *Geocarto International*, **30**(7), 737-754, doi:10.1080/10106049.2014.997302.
Barbarossa, V. et al., 2021: Threats of global warming to the world's freshwater fishes. *Nature Communications*, **12**(1), 1701, doi:10.1038/s41467-021-21655-w.
Barbet-Massin, M. and W. Jetz, 2015: The effect of range changes on the functional turnover, structure and diversity of bird assemblages under future climate scenarios. *Glob Chang Biol*, **21**(8), 2917-2928, doi:10.1111/gcb.12905.
Barbier, J. et al., 2018: Detection of Intraseasonal Large-Scale Heat Waves: Characteristics and Historical Trends during the Sahelian Spring. *Journal of Climate*, **31**(1), 61-80, doi:10.1175/JCLI-D-17-0244.1.
Barcikowska, M. J., S. B. Kapnick and F. Feser, 2018: Impact of large-scale circulation changes in the North Atlantic sector on the current and future Mediterranean winter hydroclimate. *Clim Dyn*, **50**(5), 2039-2059, doi:10.1007/s00382-017-3735-5.
Barenblitt, A. et al., 2021: The large footprint of small-scale artisanal gold mining in Ghana. *Science of The Total Environment*, **781**, 146644, doi:https://doi.org/10.1016/j.scitotenv.2021.146644.
Barkin, J. L. et al., 2021: Effects of extreme weather events on child mood and behavior. *Developmental Medicine & Child Neurology*, **63**(7), 785-790, doi:https://doi.org/10.1111/dmcn.14856.
Barnett, T., 2019: *An Engraved Landscape. Rock Carvings in the Wadi al-Ajal, Libya.* vol. 1, Society of Libyan Studies, London. ISBN 978-1-900971-51-5.
Baron, J. S. et al., 2017: Synthesis Centers as Critical Research Infrastructure. *BioScience*, **67**(8), 750-759, doi:10.1093/biosci/bix053.
Barrett, S., 2014: Subnational Climate Justice? Adaptation Finance Distribution and Climate Vulnerability. *World Development*, **58**, 130-142, doi:https://doi.org/10.1016/j.worlddev.2014.01.014.
Barrios, S., L. Bertinelli and E. Strobl, 2006: Climatic change and rural–urban migration: The case of sub-Saharan Africa. *Journal of Urban Economics*, **60**(3), 357-371, doi:10.1016/j.jue.2006.04.005.
Barrios, S., L. Bertinelli and E. Strobl, 2010: Trends in rainfall and economic growth in Africa: A neglected cause of the African growth tragedy. *The Review of Economics and Statistics*, **92**(2), 350-366, doi:https://doi.org/10.1162/rest.2010.11212.

Barry, A. A. et al., 2018: West Africa climate extremes and climate change indices. *International Journal of Climatology*, **38**(S1), e921-e938, doi:10.1002/joc.5420.
Bartlett, S., 2008: Climate change and urban children: impacts and implications for adaptation in low- and middle-income countries. *Environment and Urbanization*, **20**(2), 501-519, doi:10.1177/0956247808096125.
Bashir, R. S. E. and O. A. Hassan, 2019: A One Health perspective to identify environmental factors that affect Rift Valley fever transmission in Gezira state, Central Sudan. *Tropical Medicine and Health*, **47**(1), 54, doi:10.1186/s41182-019-0178-1.
Bastin, J.-F. et al., 2019: The global tree restoration potential. *Science (New York, N.Y.)*, **365**(6448), 76, doi:10.1126/science.aax0848.
Basupi, L. V., C. H. Quinn and A. J. Dougill, 2019: Adaptation strategies to environmental and policy change in semi-arid pastoral landscapes: Evidence from Ngamiland, Botswana. *Journal of Arid Environments*, **166**, 17-27, doi:https://doi.org/10.1016/j.jaridenv.2019.01.011.
Bataille, C. et al., 2016: The need for national deep decarbonization pathways for effective climate policy. *Climate Policy*, **16**(sup1), S7-S26, doi:10.1080/14693062.2016.1173005.
Bates, A. E. et al., 2019: Climate resilience in marine protected areas and the 'Protection Paradox'. *Biological Conservation*, **236**, 305-314, doi:https://doi.org/10.1016/j.biocon.2019.05.005.
Bathiany, S., V. Dakos, M. Scheffer and T. M. Lenton, 2018: Climate models predict increasing temperature variability in poor countries. *Science Advances*, **4**, eaar5809, doi:10.1126/sciadv.aar5809.
Battersby, J. and J. Hunter-Adams, 2020: No Looking Back: [Food]ways Forward for Healthy African Cities in Light of Climate Change. *Journal of urban health : bulletin of the New York Academy of Medicine*, **97**(2), 226-229, doi:10.1007/s11524-020-00429-7.
Baudoin, M.-A., A. C. Sanchez and B. Fandohan, 2014: Small scale farmers' vulnerability to climatic changes in southern Benin: the importance of farmers' perceptions of existing institutions. *Mitigation and Adaptation Strategies for Global Change*, **19**(8), 1195-1207, doi:10.1007/s11027-013-9468-9.
Baudron, F. et al., 2019a: Testing the Various Pathways Linking Forest Cover to Dietary Diversity in Tropical Landscapes. *Frontiers in Sustainable Food Systems*, **3**, 97, doi:10.3389/fsufs.2019.00097.
Baudron, F. et al., 2019b: Understanding the factors influencing fall armyworm (Spodoptera frugiperda J.E. Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in Eastern Zimbabwe. *Crop Protection*, **120**, 141-150, doi:https://doi.org/10.1016/j.cropro.2019.01.028.
Bawakyillenuo, S., J. A. Yaro and J. Teye, 2016: Exploring the autonomous adaptation strategies to climate change and climate variability in selected villages in the rural northern savannah zone of Ghana. *Local Environment*, **21**(3), 361-382, doi:10.1080/13549839.2014.965671.
Beale, C. M., N. E. Baker, M. J. Brewer and J. J. Lennon, 2013: Protected area networks and savannah bird biodiversity in the face of climate change and land degradation. *Ecol Lett*, **16**(8), 1061-1068, doi:10.1111/ele.12139.
Beck-Johnson, L. M. et al., 2017: The importance of temperature fluctuations in understanding mosquito population dynamics and malaria risk. *Royal Society Open Science*, **4**(3), 160969-160969, doi:10.1098/rsos.160969.
Bedelian, C. and J. O. Ogutu, 2017: Trade-offs for climate-resilient pastoral livelihoods in wildlife conservancies in the Mara ecosystem, Kenya. *Pastoralism*, **7**(1), 10, doi:10.1186/s13570-017-0085-1.
Belesova, K. et al., 2019: Mortality impact of low annual crop yields in a subsistence farming population of Burkina Faso under the current and a 1.5°C warmer climate in 2100. *Sci Total Environ*, **691**, 538-548, doi:10.1016/j.scitotenv.2019.07.027.
Belhabib, D., V. W. Y. Lam and W. W. L. Cheung, 2016: Overview of West African fisheries under climate change: Impacts, vulnerabilities and adaptive responses of the artisanal and industrial sectors. *Marine Policy*, **71**, 15-28, doi:https://doi.org/10.1016/j.marpol.2016.05.009.
Belhabib, D., U. R. Sumaila and P. Le Billon, 2019: The fisheries of Africa: Exploitation, policy, and maritime security trends. *Marine Policy*, **101**, 80-92, doi:https://doi.org/10.1016/j.marpol.2018.12.021.
Bendana, C., 2019: African research projects are failing because funding agencies can't match donor money. *Science (New York, N.Y.)*, doi:https://doi:10.1126/science.aax6796.
Bennett, A. et al., 2016: The relative contribution of climate variability and vector control coverage to changes in malaria parasite prevalence in Zambia 2006–2012. *Parasites & Vectors*, **9**(1), 431-431, doi:10.1186/s13071-016-1693-0.
Bennett, A. C. et al., 2021: Resistance of African tropical forests to an extreme climate anomaly. *Proceedings of the National Academy of Sciences*, **118**(21), e2003169118, doi:10.1073/pnas.2003169118.
Bentley, L. K., M. P. Robertson and N. P. Barker, 2018: Range contraction to a higher elevation: the likely future of the montane vegetation in South Africa and Lesotho. *Biodiversity and Conservation*, **28**(1), 131-153, doi:10.1007/s10531-018-1643-6.
Berdugo, M. et al., 2020: Global ecosystem thresholds driven by aridity. *Science (New York, N.Y.)*, **367**(6479), 787-790, doi:10.1126/science.aay5958.
Beringer, T. et al., 2020: First process-based simulations of climate change impacts on global tea production indicate large effects in the World's major producer countries. *Environmental Research Letters*, **15**(3), 034023, doi:10.1088/1748-9326/ab649b.
Berrang-Ford, L. et al., 2021: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, doi:https://doi.org/10.21203/rs.3.rs-100873/v1.

Berthou, S. et al., 2019: Larger Future Intensification of Rainfall in the West African Sahel in a Convection-Permitting Model. *Geophysical Research Letters*, **46**(22), 13299-13307, doi:https://doi.org/10.1029/2019GL083544.
Bett, B. et al., 2017: Effects of climate change on the occurrence and distribution of livestock diseases. *Preventive Veterinary Medicine*, **137**(Pt B), 119-129, doi:10.1016/j.prevetmed.2016.11.019.
Bettaieb, J. et al., 2010: [Relationship between temperature and mortality in the city of Tunis: 2005-2007]. *Archives de l'Institut Pasteur de Tunis*, **87**(1-2), 25-33.
Betts, R. A. et al., 2015: Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences*, **12**(5), 1317-1338, doi:10.5194/bg-12-1317-2015.
Beymer-Farris, B. A. and T. J. Bassett, 2012: The REDD menace: Resurgent protectionism in Tanzania's mangrove forests. *Global Environmental Change*, **22**(2), 332-341, doi:10.1016/j.gloenvcha.2011.11.006.
Bezabih, M., M. Chambwera and J. Stage, 2011: Climate change and total factor productivity in the Tanzanian economy. *Climate Policy*, **11**(6), 1289-1302, doi:10.1080/14693062.2011.579300.
Biagetti, S., 2017: Resilience in a Mountain Range: The Case of the Tadrart Acacus (Southwest Libya). *Nomadic Peoples*, **21**(2), 268-285, doi:https://doi.org/10.3197/np.2017.210205.
Biao, E., 2017: Assessing the impacts of climate change on river discharge dynamics in Oueme River Basin (Benin, West Africa). *Hydrology*, **4**(4), doi:10.3390/hydrology4040047.
Bichet, A. and A. Diedhiou, 2018a: Less frequent and more intense rainfall along the coast of the Gulf of Guinea in West and Central Africa (1981-2014). *Climate Research*, **76**(3), 191-201, doi:10.3354/cr01537.
Bichet, A. and A. Diedhiou, 2018b: West African Sahel has become wetter during the last 30 years, but dry spells are shorter and more frequent. *Climate Research*, **75**(2), 155-162, doi:https://doi.org/10.3354/cr01515.
Bidassey-Manilal, S. et al., 2016: Students' Perceived Heat-Health Symptoms Increased with Warmer Classroom Temperatures. *Int J Environ Res Public Health*, **13**(6), doi:10.3390/ijerph13060566.
Biesbroek, R., B. G. Peters and J. Tosun, 2018: Public Bureaucracy and Climate Change Adaptation. *Review of Policy Research*, **35**(6), 776-791, doi:https://doi.org/10.1111/ropr.12316.
Birabi, A. K. and B. Nawangwe (eds.), Mitigating threats to local knowledge embedded in earthen architecture: the case of preserving African architectural semiotics. 2011, Getty Publications, 104 pp. ISBN 1606060430.
Birgen, M. K., 2021: A Christian Ecological Theology from an African Christian Perspective. *ShahidiHub International Journal of Theology & Religious Studies*, **1**(1), 1-14.
Birkmann, J. et al., 2021: Regional clusters of vulnerability show the need for transboundary cooperation. *Environmental Research Letters*, **16**(9), 094052, doi:10.1088/1748-9326/ac1f43.
Bishop-Williams, K. E. et al., 2018: Understanding Weather and Hospital Admissions Patterns to Inform Climate Change Adaptation Strategies in the Healthcare Sector in Uganda. *Int J Environ Res Public Health*, **15**(11), doi:10.3390/ijerph15112402.
Björkman-Nyqvist, M., 2013: Income shocks and gender gaps in education: Evidence from Uganda. *Journal of Development Economics*, **105**, 237-253, doi:https://doi.org/10.1016/j.jdeveco.2013.07.013.
Bjornlund, H. et al., 2020: Institutional innovation and smart water management technologies in small-scale irrigation schemes in southern Africa. *Water International*, **45**(6), 621-650, doi:10.1080/02508060.2020.1804715.
Blasiak, R. et al., 2017: Climate change and marine fisheries: Least developed countries top global index of vulnerability. *PLOS ONE*, **12**(6), e0179632, doi:10.1371/journal.pone.0179632.
Blicharska, M. et al., 2017: Steps to overcome the North–South divide in research relevant to climate change policy and practice. *Nature Climate Change*, **7**(1), 21-27, doi:10.1038/nclimate3163.
Bloomfield, L. S. P., T. L. McIntosh and E. F. Lambin, 2020: Habitat fragmentation, livelihood behaviors, and contact between people and nonhuman primates in Africa. *Landscape Ecology*, **35**(4), 985-1000, doi:10.1007/s10980-020-00995-w.
Blumstein, S. and J. D. Petersen-Perlman, 2021: When the water runs dry: supporting adaptive governance in transboundary river basins. *Water International*, **46**(3), 306-324, doi:10.1080/02508060.2021.1877984.
Boansi, D., J. A. Tambo and M. Müller, 2017: Analysis of farmers' adaptation to weather extremes in West African Sudan Savanna. *Weather and Climate Extremes*, **16**(March), 1-13, doi:10.1016/j.wace.2017.03.001.
Boas, I. et al., 2019: Climate migration myths. **9**, 901-903, doi:10.1038/s41558-019-0633-3.
Boavida-Portugal, J. et al., 2018: Climate change impacts on the distribution of coastal lobsters. *Marine Biology*, **165**(12), 186, doi:10.1007/s00227-018-3441-9.
Bodian, A. et al., 2018: Future Climate Change Impacts on Streamflows of Two Main West Africa River Basins: Senegal and Gambia. *Hydrology*, **5**(1), doi:10.3390/hydrology5010021.
Bodunrin, I. A., 2019: Hip-hop and Decolonized Practices of Language Digitization among the Contemporary !Xun and Khwe Indigenous Youth of South Africa. *Critical Arts*, **33**(4-5), 174-190, doi:10.1080/02560046.2019.1702070.
Boeckmann, M. et al., 2019: Climate change and control of diarrhoeal diseases in South Africa: Priorities for action. *South African Medical Journal*, **109**, 359, doi:10.7196/SAMJ.2019.v109i6.14075.
Boedecker, J. et al., 2014: Dietary contribution of Wild Edible Plants to women's diets in the buffer zone around the Lama forest, Benin – an underutilized potential. *Food Security*, **6**(6), 833-849, doi:10.1007/s12571-014-0396-7.
Bogale, A. and B. Korf, 2007: To share or not to share? (non-)violence, scarcity and resource access in Somali Region, Ethiopia. *The Journal of Development Studies*, **43**(4), 743-765, doi:10.1080/00220380701260093.

Bohannon, J., 2016: Who's downloading pirated papers? Everyone. *Science (New York, N.Y.)*, **352**(6285), 508-512, doi:10.1126/science.352.6285.508.
Bolden, I. W. et al., 2018: Climate-related community knowledge networks as a tool to increase learning in the context of environmental change. *Climate Risk Management*, **21**, 1-6, doi:https://doi.org/10.1016/j.crm.2018.04.004.
Bond, W. and N. P. Zaloumis, 2016: The deforestation story: testing for anthropogenic origins of Africa's flammable grassy biomes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1696), 20150170, doi:10.1098/rstb.2015.0170.
Bond, W. J., N. Stevens, G. F. Midgley and C. E. R. Lehmann, 2019: The Trouble with Trees: Afforestation Plans for Africa. *Trends in Ecology & Evolution*, **34**(11), 963-965, doi:https://doi.org/10.1016/j.tree.2019.08.003.
Boone, R. B. et al., 2018: Climate change impacts on selected global rangeland ecosystem services. *Global Change Biology*, **24**(3), 1382-1393, doi:10.1111/gcb.13995.
Booth, B. B. B. et al., 2012: Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, **484**(7393), 228-232, doi:10.1038/nature10946.
Booysen, M. J., M. Visser and R. Burger, 2019: Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data. *Water Research*, **149**, 414-420, doi:https://doi.org/10.1016/j.watres.2018.11.035.
Borderon, M. et al., 2019: Migration influenced by environmental change in Africa: A systematic review of empirical evidence. *Demographic Research*, **41**, 491-544, doi:10.4054/DemRes.2019.41.18.
Bosetti, V., C. Cattaneo and G. Peri, 2018: Should they stay or should they go? Climate Migrants and Local Conflicts. *National Bureau of Economic Research Working Paper Series No. 24447*, doi:10.3386/w24447.
Bosman, G. and D. Van der Westhuizen, 2014: The effects of climatic conditions on attitudinal changes towards earth construction in South Africa: review article. *Acta Structilia : Journal for the Physical and Development Sciences*, **21**(1), 117-141, doi:10.10520/EJC160907.
Boswell, R., 2008: *Challenges to identifying and managing intangible cultural heritage in Mauritius, Zanzibar and Seychelles*. CODESRIA Monograph Series, CODESRIA, Dakar, Senegal. ISBN 978-2-86978-215-0.
Bouma, M. J., A. S. Siraj, X. Rodo and M. Pascual, 2016: El Niño-based malaria epidemic warning for Oromia, Ethiopia, from August 2016 to July 2017. *Tropical Medicine & International Health*, **21**(11), 1481-1488, doi:10.1111/tmi.12776.
Bouregaa, T., 2019: Impact of climate change on yield and water requirement of rainfed crops in the Setif region. *Management of Environmental Quality: An International Journal*, **30**(4), 851-863, doi:10.1108/MEQ-06-2018-0110.
Boyce, R. et al., 2016: Severe Flooding and Malaria Transmission in the Western Ugandan Highlands: Implications for Disease Control in an Era of Global Climate Change. *Journal of Infectious Diseases*, **214**(9), 1403-1410, doi:10.1093/infdis/jiw363.
Bozzola, M. and M. Smale, 2020: The welfare effects of crop biodiversity as an adaptation to climate shocks in Kenya. *World Development*, **135**, 105065, doi:https://doi.org/10.1016/j.worlddev.2020.105065.
Bradshaw, C. J. A., N. S. Sodhi, K. S. H. Peh and B. W. Brook, 2007: Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology*, **13**(11), 2379-2395, doi:https://doi.org/10.1111/j.1365-2486.2007.01446.x.
Brancalion, P. H. S. et al., 2020: Emerging threats linking tropical deforestation and the COVID-19 pandemic. *Perspectives in Ecology and Conservation*, **18**(4), 243-246, doi:https://doi.org/10.1016/j.pecon.2020.09.006.
Brandt, M. et al., 2019: Changes in rainfall distribution promote woody foliage production in the Sahel. *Communications Biology*, **2**(1), 133, doi:10.1038/s42003-019-0383-9.
Brandt, M. et al., 2017: Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. *Nature Ecology & Evolution*, **1**(4), 1-6, doi:10.1038/s41559-017-0081.
Braveman, P. and L. Gottlieb, 2014: The Social Determinants of Health: It's Time to Consider the Causes of the Causes. *Public Health Reports*, **129**(1_suppl2), 19-31, doi:10.1177/00333549141291S206.
Breitbarth, T., 2020: *Analysis of ex-ante economic models for Green Climate Fund adaptation projects in Africa*. Green Climate Fund, Incheon, Republic of Korea.
Bren d'Amour, C. et al., 2016: Teleconnected food supply shocks. *Environmental Research Letters*, **11**(3), 035007, doi:10.1088/1748-9326/11/3/035007.
Breu, T. et al., 2016: Large-scale land acquisition and its effects on the water balance in investor and host countries. *PLoS One*, **11**(3), e0150901, doi:10.1371/journal.pone.0150901.
Brimblecombe, P. et al., 2011: Impact of Climate Change on Earthen Buildings. In: *Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architectural Heritage "* [Rainer, L. H., A. B. Rivera and D. Gandreau (eds.)]. Getty Conservation Institute, Getty Publications, Los Angeles, pp. 278-282.
Brink, E. et al., 2016: Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, **36**, 111-123, doi:10.1016/j.gloenvcha.2015.11.003.
Brinkman, M. et al., 2020: The distribution of food security impacts of biofuels, a Ghana case study. *Biomass and Bioenergy*, **141**, 105695, doi:https://doi.org/10.1016/j.biombioe.2020.105695.
Briske, D. D., 2017: *Rangeland Systems: Processes, Management and Challenges* [Briske, D. D. (ed.)]. Springer Series on Environmental Management, Springer International Publishing, Cham. ISBN 978-3-319-46707-8 978-3-319-46709-2.

Brito, J. C. and M. Naia, 2020: Coping with Sea-Level Rise in African Protected Areas: Priorities for Action and Adaptation Measures. *BioScience*, **70**(10), 924-932, doi:10.1093/biosci/biaa087.
Britton, A. W. et al., 2017: Terrestrial-focused protected areas are effective for conservation of freshwater fish diversity in Lake Tanganyika. *Biological Conservation*, **212**, 120-129, doi:10.1016/j.biocon.2017.06.001.
Brockhaus, M., H. Djoudi and B. Locatelli, 2013: Envisioning the future and learning from the past: Adapting to a changing environment in northern Mali. *Environmental Science & Policy*, **25**, 94-106, doi:https://doi.org/10.1016/j.envsci.2012.08.008.
Brockington, D. and D. Wilkie, 2015: Protected areas and poverty. *Philos Trans R Soc Lond B Biol Sci*, **370**(1681), doi:10.1098/rstb.2014.0271.
Brodnik, C. et al., 2018: Jumping to the top: catalysts for leapfrogging to a water sensitive city. *IOP Conference Series: Earth and Environmental Science*, **179**, 012034, doi:10.1088/1755-1315/179/1/012034.
Brooks, C., 2019: *Will climate change undermine the potential for hydropower in Africa?*, Oxford Management Policy. Available at: https://www.opml.co.uk/blog/the-impact-of-climate-change-on-hydropower-in-africa.
Brooks, N., J. Clarke, G. W. Ngaruiya and E. E. Wangui, 2020: African heritage in a changing climate. *Azania: Archaeological Research in Africa*, **55**(3), 297-328, doi:10.1080/0067270x.2020.1792177.
Brooks, N., W. Neil Adger and P. Mick Kelly, 2005: The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*, **15**(2), 151-163, doi:https://doi.org/10.1016/j.gloenvcha.2004.12.006.
Broto, V. C., E. Boyd and J. Ensor, 2015: Participatory urban planning for climate change adaptation in coastal cities: lessons from a pilot experience in Maputo, Mozambique. *Current Opinion in Environmental Sustainability*, **13**, 11-18, doi:10.1016/j.cosust.2014.12.005.
Brown, J. R. et al., 2020: Comparison of past and future simulations of ENSO in CMIP5/PMIP3 and CMIP6/PMIP4 models. *Climate of the Past Discussions*, doi:https://doi.org/10.5194/cp-2019-155.
Brown, L., C. Polycarp and M. Spearman, 2013: *Within Reach. Strengthening Country Ownership and Accountability in Accessing Climate Finance*. Working Paper, World Resources Institute, Washington, DC. Available at: wri.org/publication/ownership-andaccountability-in-climate-finance.
Bruno, J. F., I. M. Côté and L. T. Toth, 2019: Climate Change, Coral Loss, and the Curious Case of the Parrotfish Paradigm: Why Don't Marine Protected Areas Improve Reef Resilience? *Annual Review of Marine Science*, **11**(1), 307-334, doi:10.1146/annurev-marine-010318-095300.
Brüssow, K., A. Faße and U. Grote, 2017: Implications of climate-smart strategy adoption by farm households for food security in Tanzania. *Food Security*, **9**(6), 1203-1218, doi:10.1007/s12571-017-0694-y.
Bryceson, D. F., 2019: Gender and generational patterns of African deagrarianization: Evolving labour and land allocation in smallholder peasant household farming, 1980–2015. *World Development*, **113**, 60-72, doi:10.1016/j.worlddev.2018.08.021.
Buchwald, A. G. et al., 2020: Aedes-borne disease outbreaks in West Africa: A call for enhanced surveillance. *Acta tropica*, **209**, 105468, doi:10.1016/j.actatropica.2020.105468.
Buhaug, H. and N. von Uexkull, 2021: Vicious Circles: Violence, Vulnerability, and Climate Change. *Annual Review of Environment and Resources*, **46**(1), doi:10.1146/annurev-environ-012220-014708.
Bulow, J., C. Reinhart, K. Rogoff and C. Trebesch, 2020: The Debt Pandemic. *Finance & Development*, **0057**(003), A004, doi:10.5089/9781513544595.022.A004.
Buma, W. G., S.-I. Lee and J. Y. Seo, 2018: Recent Surface Water Extent of Lake Chad from Multispectral Sensors and GRACE. *Sensors*, **18**(7), doi:10.3390/s18072082.
Bunce, A. and J. Ford, 2015: How is adaptation, resilience, and vulnerability research engaging with gender? *Environmental Research Letters*, **10**(12), doi:10.1088/1748-9326/10/12/123003.
Bunker, A. et al., 2017: Excess burden of non-communicable disease years of life lost from heat in rural Burkina Faso: a time series analysis of the years 2000-2010. *BMJ open*, **7**(11), e018068, doi:10.1136/bmjopen-2017-018068.
Bunn, C., P. Läderach, O. Ovalle Rivera and D. Kirschke, 2015: A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change*, **129**(1), 89-101, doi:10.1007/s10584-014-1306-x.
Burke, M., W. M. Davis and N. S. Diffenbaugh, 2018a: Large potential reduction in economic damages under UN mitigation targets. *Nature*, **557**(7706), 549-553, doi:10.1038/s41586-018-0071-9.
Burke, M., E. Gong and K. Jones, 2015a: Income Shocks and HIV in Africa. *The Economic Journal*, **125**(585), 1157-1189, doi:10.1111/ecoj.12149.
Burke, M. et al., 2018b: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8**(8), 723-729, doi:10.1038/s41558-018-0222-x.
Burke, M., S. Hsiang and E. Miguel, 2014: Climate and Conflict. *Annual Review of Economics*, **7**(1), 577-617, doi:10.3386/w20598.
Burke, M., S. M. Hsiang and E. Miguel, 2015b: Global non-linear effect of temperature on economic production. *Nature*, **527**(7577), 235-239, doi:10.1038/nature15725.
Burke, M. B. et al., 2009: Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences*, **106**(49), 20670, doi:10.1073/pnas.0907998106.
Burls, N. J. et al., 2019: The Cape Town "Day Zero" drought and Hadley cell expansion. *npj Climate and Atmospheric Science*, **2**(1), 27, doi:10.1038/s41612-019-0084-6.

Burrows, M. T. et al., 2014: Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**(7493), 492-495, doi:10.1038/nature12976.
Bush, E. R. et al., 2020: Long-term collapse in fruit availability threatens Central African forest megafauna. *Science (New York, N.Y.)*, **370**(6521), 1219, doi:10.1126/science.abc7791.
Bwambale, B., M. Muhumuza and M. Nyeko, 2018: Traditional ecological knowledge and flood risk management: A preliminary case study of the Rwenzori. *Jamba*, **10**(1), 536, doi:10.4102/jamba.v10i1.536.
Bwasiri, E. J., 2011: *The challenge of managing intangible heritage: Problems in Tanzanian legislation and administration*. vol. 66, South African Archaeological Society, 129–135 pp. ISBN 0038-1969.
Byass, P. et al., 2017: The long road to elimination: malaria mortality in a South African population cohort over 21 years. *Global Health, Epidemiology and Genomics*, **2**, e11-e11, doi:10.1017/gheg.2017.7.
Caetano, T., H. Winker and J. Depledge, 2020: Towards zero carbon and zero poverty: integrating national climate change mitigation and sustainable development goals. *Climate Policy*, **20**(7), 773-778, doi:10.1080/14693062.2020.1791404.
Cai, R., S. Feng, M. Oppenheimer and M. Pytlikova, 2016: Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management*, **79**, 135-151, doi:https://doi.org/10.1016/j.jeem.2016.06.005.
Cai, W. et al., 2021: Opposite response of strong and moderate positive Indian Ocean Dipole to global warming. *Nature Climate Change*, **11**(1), 27-32, doi:10.1038/s41558-020-00943-1.
Cairncross, E. et al., 2018: Climate Change, Air Pollution and Health in South Africa. In: *Climate Change and Air Pollution* [Akhtar R. and C. Palagiano (eds.)]. Springer Climate, pp. 327-347. ISBN 978-3-319-61345-1.
Calderon, C., C. Cantu and P. Chuhan-Pole, 2018: *Infrastructure Development in Sub-Saharan Africa : A Scorecard*. Policy Research Working Papers, World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/29770.
Call, M. and C. Gray, 2020: Climate anomalies, land degradation, and rural out-migration in Uganda. *Population and Environment*, **41**(4), 507-528, doi:10.1007/s11111-020-00349-3.
Callaghan, M. et al., 2021: AI based evidence and attribution mapping of 100,000 climate impact studies. *Nature Climate Change*.
Callo-Concha, D., 2018: Farmer Perceptions and Climate Change Adaptation in the West Africa Sudan Savannah: Reality Check in Dassari, Benin, and Dano, Burkina Faso. *Climate*, **6**(2), doi:10.3390/cli6020044.
Cambaza, E. et al., 2019: Outbreak of Cholera Due to Cyclone Kenneth in Northern Mozambique, 2019. *International Journal of Environmental Research and Public Health*, **16**(16), doi:10.3390/ijerph16162925.
Camberlin, P., 2018: Climate of Eastern Africa. Oxford University Press.
Caminade, C., K. M. McIntyre and A. E. Jones, 2019: Impact of recent and future climate change on vector-borne diseases. *Annals of the New York Academy of Sciences*, **1436**(1), 157-173, doi:10.1111/nyas.13950.
Cantin, N. E. et al., 2010: Ocean warming slows coral growth in the central Red Sea. *Science (New York, N.Y.)*, **329**(5989), 322-325, doi:10.1126/science.1190182.
Cao, S., J. Zhang, L. Chen and T. Zhao, 2016: Ecosystem water imbalances created during ecological restoration by afforestation in China, and lessons for other developing countries. *Journal of Environmental Management*, **183**, 843-849, doi:https://doi.org/10.1016/j.jenvman.2016.07.096.
Caparoci Nogueira, S. M., M. A. Moreira and M. M. Lordelo Volpato, 2018: Evaluating Precipitation Estimates from Eta, TRMM and CHRIPS Data in the South-Southeast Region of Minas Gerais State—Brazil. *Remote Sensing*, **10**(2), doi:10.3390/rs10020313.
Carleton, T. et al., 2018: Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits. *University of Chicago, Becker Friedman Institute for Economics Working Paper No. 2018-51.*, doi:10.2139/ssrn.3224365.
Carleton, T., S. M. Hsiang and M. Burke, 2016: Conflict in a changing climate. *The European Physical Journal Special Topics*, **225**(3), 489-511, doi:10.1140/epjst/e2015-50100-5.
Carleton, T. A. and S. M. Hsiang, 2016: Social and economic impacts of climate. *Science (New York, N.Y.)*, **353**(6304), doi:10.1126/science.aad9837.
Carlson, C. J. et al., 2020a: Climate change will drive novel cross-species viral transmission. *bioRxiv*, 2020.2001.2024.918755, doi:10.1101/2020.01.24.918755.
Carlson, C. J., G. F. Albery and A. Phelan, 2021: Preparing international cooperation on pandemic prevention for the Anthropocene. *BMJ Global Health*, **6**(3), e004254, doi:10.1136/bmjgh-2020-004254.
Carlson, C. J. et al., 2019: Rapid range shifts in African Anopheles mosquitoes over the last century. doi:10.1101/673913.
Carlson, C. J., A. C. R. Gomez, S. Bansal and S. J. Ryan, 2020b: Misconceptions about weather and seasonality must not misguide COVID-19 response. *Nature Communications*, **11**(1), 4312, doi:10.1038/s41467-020-18150-z.
Carr, E. R., G. Fleming and T. Kalala, 2016: Understanding women's needs for weather and climate information in agrarian settings: The case of Ngetou Maleck, Senegal. *Weather, Climate, and Society*, **8**(3), 247-264, doi:https://doi.org/10.1175/WCAS-D-15-0075.1.
Carr, E. R. et al., 2020: Identifying climate information services users and their needs in Sub-Saharan Africa: a review and learning agenda. *Climate and Development*, **12**(1), 23-41, doi:10.1080/17565529.2019.1596061.

Carter, J. G. et al., 2015: Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, **95**, 1-66, doi:https://doi.org/10.1016/j.progress.2013.08.001.
Carter, S. et al., 2020: *Co-production of African weather and climate services*. Future Climate for Africa and Weather and Climate Information Services for Africa 2ed., Cape Town, 160 pp. Available at: https://futureclimateafrica.org/coproduction-manual/downloads/WISER-FCFA-coproduction-manual.pdf.
Carter, T. R. et al., 2021: A conceptual framework for cross-border impacts of climate change. *Global Environmental Change*, **69**, 102307, doi:https://doi.org/10.1016/j.gloenvcha.2021.102307.
Carty, T., J. Kowalzig and B. Zagema, 2020: *Climate Finance Shadow Report 2020: Assessing progress towards the $100 billion commitment*. Oxfam International, Oxford, UK, 32 pp. Available at: https://oxfamilibrary.openrepository.com/bitstream/handle/10546/621066/bp-climate-finance-shadow-report-2020-201020-en.pdf.
Castells-Quintana, D., M. d. P. Lopez-Uribe and T. K. J. McDermott, 2018: Adaptation to climate change: A review through a development economics lens. *World Development*, **104**, 183-196, doi:https://doi.org/10.1016/j.worlddev.2017.11.016.
Catley, A., B. Admassu, G. Bekele and D. Abebe, 2014: Livestock mortality in pastoralist herds in Ethiopia and implications for drought response. *Disasters*, **38**(3), 500-516, doi:10.1111/disa.12060.
Cattaneo, C. et al., 2019: Human migration in the era of climate change. *Review of Environmental Economics and Policy*, **13**(2), 189-206, doi:https://dx.doi.org/10.1093/reep/rez008.
Cattaneo, C. and G. Peri, 2016: The migration response to increasing temperatures. *Journal of Development Economics*, **122**, 127-146, doi:https://doi.org/10.1016/j.jdeveco.2016.05.004.
CDKN, 2013: *Enhancing direct access to the Green Climate Fund*. Climate and Devleopment Knowledge Network. Available at: https://cdkn.org/wp-content/uploads/2013/06/CDKN_GCFPolicyBrief_Pr2_21-06-13_WEB.pdf.
Ceccato, P. et al., 2018: Data and tools to integrate climate and environmental information into public health. *Infectious diseases of poverty*, **7**(1), 126, doi:10.1186/s40249-018-0501-9.
Ceccherini, G. et al., 2017: Heat waves in Africa 1981-2015, observations and reanalysis. *Natural Hazards and Earth System Sciences*, **17**, 115-125, doi:10.5194/nhess-17-115-2017.
Cervigni, R., R. Liden, J. E. Neumann and K. M. Strzepek, 2015: *Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors*. Africa Development Forum, The World Bank, Washington, DC, 216 pp. ISBN 978-1-4648-0466-3.
Cervigni, R., A. Losos, P. Chinowsky and J. E. Neumann, 2017: *Enhancing the Climate Resilience of Africa's Infrastructure: The Roads and Bridges Sector*. **1**, World Bank Group, Washinton, DC. Available at: http://documents.worldbank.org/curated/en/270671478809724744/Enhancing-the-climate-resilience-of-Africa-s-Infrastructure-the-roads-and-bridges-sector.
CES Consulting Engineers Salzgitter GmbH and Inros Lackner SE, 2020: *Upscaling Nature-Based Flood Protection in Mozambique's Cities* [Zangerling, B. M., B. Jongman, M. Matera, L. Carrera, X. A. Chavana, S. A. Carrion, A. Midgley, A. E. Erman, B. T. V. Zanten and M. V. Ledden (eds.)]. World Bank Group,, Washington, DC, 45 pp. Available at: http://documents.worldbank.org/curated/en/401611585291379085/Upscaling-Nature-Based-Flood-Protection-in-Mozambique-s-Cities-Knowledge-Note.
Challinor, A. J. et al., 2018: Transmission of climate risks across sectors and borders. *Phil. Trans. R. Soc. A*, **376**(2121), 20170301, doi:10.1098/rsta.2017.0301.
Challinor, A. J. et al., 2016: Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nature Climate Change*, **6**(10), 954-958, doi:10.1038/nclimate3061.
Chan, C. Y. et al., 2019: Prospects and challenges of fish for food security in Africa. *Global Food Security*, **20**(May 2018), 17-25, doi:10.1016/j.gfs.2018.12.002.
Chanza, N. and A. de Wit, 2016: Enhancing climate governance through indigenous knowledge: Case in sustainability science. *South African Journal of Science*, **112**, 1-7, doi:http://dx.doi.org/10.17159/sajs.2016/20140286.
Chapagain, D., F. Baarsch, M. Schaeffer and S. D'Haen, 2020: Climate change adaptation costs in developing countries: insights from existing estimates. *Climate and Development*, **12**(10), 934-942, doi:10.1080/17565529.2020.1711698.
Chaplin-Kramer, R. et al., 2019: Global modeling of nature's contributions to people. *Science (New York, N.Y.)*, **366**(6462), 255, doi:10.1126/science.aaw3372.
Chapman, D., B. V. Purse, H. E. Roy and J. M. Bullock, 2017: Global trade networks determine the distribution of invasive non-native species. *Global Ecology and Biogeography*, **26**, 907-917, doi:10.1111/geb.12599.
Charis, G., G. Danha and E. Muzenda, 2019: Waste valorisation opportunities for bush encroacher biomass in savannah ecosystems: A comparative case analysis of Botswana and Namibia. *Procedia Manufacturing*, **35**, 974-979, doi:https://doi.org/10.1016/j.promfg.2019.06.044.
Charles-Dominique, T. et al., 2016: Spiny plants, mammal browsers, and the origin of African savannas. *Proceedings of the National Academy of Sciences*, **113**(38), E5572, doi:10.1073/pnas.1607493113.
Chatiza, K., 2019: Cyclone Idai in Zimbabwe: An analysis of policy implications for post-disaster institutional development. Oxfam, 30 pp.
Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, **26**(11), 6134-6155, doi:https://doi.org/10.1111/gcb.15310.

Chemura, A. et al., 2013: Assessing the impact of climate change on the suitability of rainfed flu-cured tobacco (Nicotiana tobacum) production in Zimbabwe. In: *1st Climate Science Symposium of Zimbabwe.*, Harare, **1**, pp. 1-14.

Chen, D. et al., 2021: *Framing, Context, and Methods* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, **In Press**, Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_01.pdf.

Chen, M., 2014: Informal Employment and Development: Patterns of Inclusion and Exclusion. *The European Journal of Development Research*, **26**(4), 397-418, doi:10.1057/ejdr.2014.31.

Chersich, M. F. et al., 2019a: Climate change and adolescents in South Africa: The role of youth activism and the health sector in safeguarding adolescents' health and education. *S Afr Med J*, **109**(9), 615-619, doi:10.7196/SAMJ.2019.v109i9.14327.

Chersich, M. F. et al., 2019b: *Violence in hot weather: Will climate change exacerbate rates of violence in South Africa?* 2019, vol. 109. ISBN 2078-5135.

Chersich, M. F. and C. Y. Wright, 2019: Climate change adaptation in South Africa: a case study on the role of the health sector. *Global Health*, **15**(1), 22, doi:10.1186/s12992-019-0466-x.

Chersich, M. F. et al., 2018: Impacts of Climate Change on Health and Wellbeing in South Africa. *International Journal of Environmental Research and Public Health*, **15**(9), 14, doi:10.3390/ijerph15091884.

Cheung William, W. L., G. Reygondeau and L. Frölicher Thomas, 2016: Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science (New York, N.Y.)*, **354**(6319), 1591-1594, doi:10.1126/science.aag2331.

Cheung, W. W. L. et al., 2016: Structural uncertainty in projecting global fisheries catches under climate change. *Ecological Modelling*, **325**, 57-66, doi:10.1016/j.ecolmodel.2015.12.018.

Chia, E. L. et al., 2016: Securing well-being with the advent of climate hazards. *International Journal of Climate Change Strategies and Management*, **8**(2), 175-193, doi:10.1108/IJCCSM-04-2014-0048.

Chiarelli, D. D., K. F. Davis, M. C. Rulli and P. D'Odorico, 2016: Climate change and large-scale land acquisitions in Africa: Quantifying the future impact on acquired water resources. *Advances in Water Resources*, **94**, 231-237, doi:https://doi.org/10.1016/j.advwatres.2016.05.016.

Chigbu, U. E., 2019: Anatomy of women's landlessness in the patrilineal customary land tenure systems of sub-Saharan Africa and a policy pathway. *Land Use Policy*, **86**, 126-135, doi:https://doi.org/10.1016/j.landusepol.2019.04.041.

Chihambakwe, M., P. Mafongoya and O. Jiri, 2018: Urban and Peri-Urban Agriculture as A Pathway to Food Security: A Review Mapping the Use of Food Sovereignty. *Challenges*, **10**(1), doi:10.3390/challe10010006.

Chinowsky, P. et al., 2013: Climate change adaptation advantage for African road infrastructure. *Climatic Change*, **117**(1), 345-361, doi:10.1007/s10584-012-0536-z.

Chinowsky, P. S., A. E. Schweikert, N. L. Strzepek and K. Strzepek, 2014: Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia. *Climatic Change*, **130**(1), 49-62, doi:10.1007/s10584-014-1219-8.

Chinowsky, P. S., A. E. Schweikert, N. L. Strzepek and K. Strzepek, 2015: Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia. *Climatic Change*, **130**(1), 49-62, doi:10.1007/s10584-014-1219-8.

Chiputwa, B. et al., 2020: Transforming climate science into usable services: The effectiveness of co-production in promoting uptake of climate information by smallholder farmers in Senegal. *Climate Services*, **20**, 100203, doi:https://doi.org/10.1016/j.cliser.2020.100203.

Chirikure, S., M. Manyanga, W. Ndoro and G. Pwiti, 2010: Unfulfilled promises? Heritage management and community participation at some of Africa's cultural heritage sites. *International Journal of Heritage Studies*, **16**(1-2), 30-44, doi:10.1080/13527250903441739.

Choko, O. P. et al., 2019: A Resilience Approach to Community-Scale Climate Adaptation. *Sustainability*, **11**(11), doi:10.3390/su11113100.

Cholo, T., L. Fleskens, D. Sietz and J. Peerlings, 2018: Is Land Fragmentation Facilitating or Obstructing Adoption of Climate Adaptation Measures in Ethiopia? *Sustainability*, **10**(7), doi:10.3390/su10072120.

Chu, E., I. Anguelovski and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**, 378-387, doi:https://doi.org/10.1016/j.cities.2016.10.016.

Chuang, T.-W. et al., 2017: Assessment of climate-driven variations in malaria incidence in Swaziland: toward malaria elimination. *Malaria Journal*, **16**(1), 232, doi:10.1186/s12936-017-1874-0.

Cinner, J. E. et al., 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, **8**(2), 117-123, doi:10.1038/s41558-017-0065-x.

Cissé, G., 2019: Food-borne and water-borne diseases under climate change in low- and middle-income countries: Further efforts needed for reducing environmental health exposure risks. *Acta tropica*, **194**, 181-188, doi:10.1016/j.actatropica.2019.03.012.

Claon, J. S. et al., 2020: Water scarcity in African cities: anthropic factors or climate change? Case of Bouake (Côte d'Ivoire). In: *Second International Conference. Water, Megacities and Global Change*, 7-11 December 2020.

Clapp, C. and K. Pillay, 2017: Green Bonds and Climate Finance. In: *Climate Finance*. World Scientific, pp. 79-105. ISBN 978-981-4641-80-7.
Clarke, J. and N. Brooks, 2018: *The Archaeology of Western Sahara*. A Synthesis of Fieldwork, 2002 to 2009, Oxbow Books, Oxford.
Clay, N. and K. S. Zimmerer, 2020: Who is resilient in Africa's Green Revolution? Sustainable intensification and Climate Smart Agriculture in Rwanda. *Land use policy*, **97**, 104558, doi:10.1016/j.landusepol.2020.104558.
Climate Action Tracker, 2021: *Climate governance assessment of the government's ability and readiness to transform South Africa into a zero emissions society*. Climate Action Tracker,, Cologne, Germany, 23 pp. Available at: https://climateactiontracker.org/documents/837/2020_12_CAT_Governance_Report_South_Africa.pdf.
Closset, M., S. FEINDOUNO, P. Guillaumont and C. Simonet, 2017: A Physical Vulnerability to Climate Change Index: Which are the most vulnerable developing countries?
Cobbing, J. and B. Hiller, 2019: Waking a sleeping giant: Realizing the potential of groundwater in Sub-Saharan Africa. *World Development*, **122**, 597-613, doi:https://doi.org/10.1016/j.worlddev.2019.06.024.
CoCT, 2019: *Cape Town Water Strategy (2019): Our shared water future*. City of Cape Town,, Cape Town. Available at: https://resource.capetown.gov.za/documentcentre/Documents/City%20strategies,%20plans%20and%20frameworks/Cape%20Town%20Water%20Strategy.pdf.
Codjoe, S. and V. Nabie, 2014: Climate change and cerebrospinal meningitis in the Ghanaian meningitis belt. *International journal of environmental research and public health*, **11**(7), 6923–6939, doi:https://doi.org/10.3390/ijerph110706923.
Codjoe, S. N. A. et al., 2020: Impact of extreme weather conditions on healthcare provision in urban Ghana. *Social Science & Medicine*, **258**, 113072, doi:https://doi.org/10.1016/j.socscimed.2020.113072.
Codjoe, S. N. A., G. Owusu and V. Burkett, 2014: Perception, experience, and indigenous knowledge of climate change and variability: The case of Accra, a sub-Saharan African city. *Regional Environmental Change*, **14**(1), 369-383, doi:http://dx.doi.org/10.1007/s10113-013-0500-0.
Coen, D. R., 2021: A brief history of usable climate science. *Climatic Change*, **167**(3), 51, doi:10.1007/s10584-021-03181-2.
Coffel, E. and R. Horton, 2015: Climate Change and the Impact of Extreme Temperatures on Aviation. *Weather, Climate, and Society*, **7**(1), 94-102, doi:10.1175/WCAS-D-14-00026.1.
Coffel, E. D., R. M. Horton and A. de Sherbinin, 2018: Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21(st) century. *Environ Res Lett*, **13**(1), 014001, doi:10.1088/1748-9326/aaa00e.
Cohen, A. S. et al., 2016: Climate warming reduces fish production and benthic habitat in Lake Tanganyika, one of the most biodiverse freshwater ecosystems. *Proceedings of the National Academy of Sciences*, **113**(34), 9563-9568, doi:10.1073/pnas.1603237113.
Cohen, B. et al., 2021: Co-benefits and trade-offs of climate change mitigation actions and the Sustainable Development Goals. *Sustainable Production and Consumption*, **26**, 805-813, doi:10.1016/j.spc.2020.12.034.
Colborn, K. L. et al., 2018: Spatio-temporal modelling of weekly malaria incidence in children under 5 for early epidemic detection in Mozambique. *Sci. Rep.*, **8**(1), 9238, doi:10.1038/s41598-018-27537-4.
Coldrey, K. M. and J. K. Turpie, 2020: Potential impacts of changing climate on nature-based tourism: A case study of South Africa's national parks. *Koedoe*, **62**(1), doi:https://doi.org/10.4102/koedoe.v62i1.1629
Cole, H. D. et al., 2021a: Managing city-scale slow-onset disasters: Learning from Cape Town's 2015–2018 drought disaster planning. *International Journal of Disaster Risk Reduction*, **63**, doi:10.1016/j.ijdrr.2021.102459.
Cole, H. D. et al., 2021b: Managing city-scale slow-onset disasters: Learning from Cape Town's 2015-2018 drought disaster planning. *International Journal of Disaster Risk Reduction*, **63**(September 2021), doi:10.1016/j.ijdrr.2021.102459.
Collins, M. et al., 2019: *Extremes, Abrupt Changes and Managing Risk. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D. C. R., V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (ed.)]. **In press**. Available at: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/10_SROCC_Ch06_FINAL.pdf.
CoM SSA, 2019: *Climate Finance Landscape for sub-Saharan Cities*. Covenant of Mayors for Sub-Saharan Africa (CoM SSA),, Covenant of Mayors for Sub-Saharan Africa (CoM SSA), Cape Town, South Africa. Available at: https://africa.iclei.org/wp-content/uploads/2020/06/2020_Publication_Financing-SEACAPs-Mapping-Report-English.pdf.
Commission of Social Determinants of Health, 2008: *Closing the gap in a generation: health equity through action on the social determinants of health. Final Report of the Commission on Social Determinants of Health*. World Health Organization, Geneva, Switzerland, 256 pp. Available at: http://apps.who.int/iris/bitstream/handle/10665/43943/9789241563703_eng.pdf;jsessionid=4A55149E474B1A3C8BD54A190F5F5891?sequence=1.
Connolly-Boutin, L. and B. Smit, 2016: Climate change, food security, and livelihoods in sub-Saharan Africa. *Regional Environmental Change*, **16**(2), 385-399, doi:http://dx.doi.org/10.1007/s10113-015-0761-x.

Conradie, S. R., S. M. Woodborne, S. J. Cunningham and A. E. McKechnie, 2019: Chronic, sublethal effects of high temperatures will cause severe declines in southern African arid-zone birds during the 21st century. *Proceedings of the National Academy of Sciences*, **116**(28), 14065, doi:10.1073/pnas.1821312116.
Conteh, I. K., 2015: Natural Hazards and Education. The Impact of Floods on Primary School Education in Zambia. Maastricht University, Boekenplan.
Contractor, S. et al., 2020: Rainfall Estimates on a Gridded Network (REGEN)–a global land-based gridded dataset of daily precipitation from 1950 to 2016. *Hydrology and Earth System Sciences (HESS)*, **24**(2), 919-943, doi:https://doi.org/10.5194/hess-24-919-2020.
Conway, D., C. Dalin, W. A. Landman and T. J. Osborn, 2017: Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption. *Nature Energy*, **2**(12), 946-953, doi:10.1038/s41560-017-0037-4.
Conway, D. et al., 2015: Climate and southern Africa's water–energy–food nexus. *Nature Climate Change*, **5**(9), 837-846, doi:10.1038/nclimate2735.
Conway, D. and K. Vincent, 2021: *Climate Risk in Africa: Adaptation and Resilience*, 1 ed., Palgrave Macmillan, Cham, Switzerland. ISBN 978-3-030-61160-6.
Cook, B. I. et al., 2020a: Twenty-First Century Drought Projections in the CMIP6 Forcing Scenarios. *Earth's Future*, **8**(6), e2019EF001461, doi:https://doi.org/10.1029/2019EF001461.
Cook, K. H., R. G. J. Fitzpatrick, W. Liu and E. K. Vizy, 2020b: Seasonal asymmetry of equatorial East African rainfall projections: understanding differences between the response of the long rains and the short rains to increased greenhouse gases. *Clim Dyn*, **55**(7), 1759-1777, doi:10.1007/s00382-020-05350-y.
Cook, K. H. and E. K. Vizy, 2015: Detection and Analysis of an Amplified Warming of the Sahara Desert. *Journal of Climate*, **28**(16), 6560-6580, doi:10.1175/JCLI-D-14-00230.1.
Coppola, E. et al., 2014: Present and future climatologies in the phase I CREMA experiment. *Climatic Change*, **125**(1), 23-38, doi:10.1007/s10584-014-1137-9.
Corbane, C. et al., 2018: GHS built-up grid, derived from Landsat, multitemporal (1975-1990-2000-2014), R2018A, European Commission, Joint Research Centre (JRC), Brussels.
Cornforth, R. J., C. Petty and G. Walker, 2021: Supporting Climate-Resilient Planning at National and District Levels: A Pathway to Multi-stakeholder Decision-Making in Uganda. In: *Climate Risk in Africa: Adaptation and Resilience* [Conway, D. and K. Vincent (eds.)]. Springer International Publishing, Cham, pp. 131-145. ISBN 978-3-030-61160-6.
Cosens, B. A. et al., 2017: The role of law in adaptive governance. *Ecol Soc*, **22**(1), 1-30, doi:10.5751/ES-08731-220130.
Costinot, A., D. Donaldson and C. Smith, 2012: Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from a 9 Million-Field Partition of the Earth. *Journal of Political Economy*.
Coulibaly, J. Y., B. Chiputwa, T. Nakelse and G. Kundhlande, 2017: Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agricultural Systems*, **155**, 52-69, doi:https://doi.org/10.1016/j.agsy.2017.03.017.
Coultas, M. and R. Iyer, 2020: Handwashing Compendium for Low Resource Settings: A Living Document. The Sanitation Learning Hub.
Couttenier, M. and R. Soubeyran, 2014: Drought and Civil War in Sub-Saharan Africa. *The Economic Journal*, **124**(575), 201-244, doi:10.1111/ecoj.12042.
Cowx, I. G., A. Lungu and M. Kalonga, 2018: Optimising hydropower development and ecosystem services in the Kafue River, Zambia. *Marine and Freshwater Research*, **69**(12), 1974-1982, doi:https://doi.org/10.1071/MF18132.
Cowx, I. G. and R. Ogutu-Ohwayo, 2019: Towards sustainable fisheries and aquaculture management in the African Great Lakes. *Fisheries Management and Ecology*, **26**(August), 397-405, doi:10.1111/fme.12391.
CPI, 2019: *Global Landscape of Climate Finance 2019* [Buchner, B., A. Clark, A. Falconer, R. Macquarie, C. Meattle, R. Tolentino and C. Wetherbee (eds.)]. Climate Policy Initiative (CPI), London, UK, 38 pp. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2019/11/2019-Global-Landscape-of-Climate-Finance.pdf.
Craig, R. K., 2010: Stationarity is Dead - Long Live Transformation: Five Principles for Climate Change Adaptation Law. *Harvard Environmental Law Review*, **34**(1), 9-74.
Crate, S. A. and M. Nuttall, 2016: From local to global: perceptions and realities of environmental change among Kalahari San. In: *Anthropology and Climate Change*. Routledge, pp. 250-262.
Crawford, R. J. M. et al., 2015: A changing distribution of seabirds in South Africa—the possible impact of climate and its consequences. *Frontiers in Ecology and Evolution*, **3**(10), doi:10.3389/fevo.2015.00010.
CRED, 2019: Disasters in Africa: 20 year review (2000–2019). *CRED Crunch Newsletter*,(56), 2. Available at: https://www.emdat.be/cred-crunch-56-disasters-africa-20-year-review-2000-2019.
Creese, A. and R. Washington, 2018: A Process-Based Assessment of CMIP5 Rainfall in the Congo Basin: The September–November Rainy Season. *Journal of Climate*, **31**(18), 7417-7439, doi:10.1175/jcli-d-17-0818.1.
Crick, F., K. E. Gannon, M. Diop and M. Sow, 2018: Enabling private sector adaptation to climate change in sub-Saharan Africa. *WIREs Climate Change*, **9**(2), e505, doi:https://doi.org/10.1002/wcc.505.

Crippa, M. et al., 2021: *EDGAR v6.0 Greenhouse Gas Emissions*. European Commission Joint Research Centre (JRC), Ispra, Italy. Available at: http://data.europa.eu/89h/97a67d67-c62e-4826-b873-9d972c4f670b.
Croitoru, L., J. J. Miranda and M. Sarraf, 2019: *The Cost of Coastal Zone Degradation In West Africa: Benin, Côte D'ivoire, Senegal And Togo*. Economic and Sector Work (ESW) Studies, World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/31428.
Cromsigt, J. et al., 2018: Trophic rewilding as a climate change mitigation strategy? *Philos Trans R Soc Lond B Biol Sci*, **373**(1761), doi:10.1098/rstb.2017.0440.
CSC, 2013: *Climate Change Scenarios for the Congo Basin* [Haensler, A., D. Jacob, P. Kabat and F. Ludwig (eds.)]. Climate Service Centre, Hamburg, Germany.
CTA, 2019: *The digitalisation of African agriculture report 2018-2019*. The Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, The Netherlands, 241 pp. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/101498/CTA-Digitalisation-report.pdf.
Cui, Y. et al., 2019: The cost of rapid and haphazard urbanization: lessons learned from the Freetown landslide disaster. *Landslides*, **16**(6), 1167-1176, doi:10.1007/s10346-019-01167-x.
Cullen, N. J. et al., 2013: A century of ice retreat on Kilimanjaro: the mapping reloaded. *The Cryosphere*, **7**(2), 419-431, doi:10.5194/tc-7-419-2013.
Cullis, J. et al., 2015: An Uncertainty Approach to Modelling Climate Change Risk in South Africa. UNU-WIDER, Helsinki, Finland.
Cullmann, J. et al., 2020: *State of Climate Services: Risk Information and Early Warning Systems*. World Meteorological Organisation, Geneva, Switzerland, 25 pp. Available at: https://library.wmo.int/doc_num.php?explnum_id=10385.
Cumming, T. L. et al., 2017: Achieving the national development agenda and the Sustainable Development Goals (SDGs) through investment in ecological infrastructure: A case study of South Africa. *Ecosystem Services*, **27**, 253-260, doi:https://doi.org/10.1016/j.ecoser.2017.05.005.
Cunningham, S. C. et al., 2015: Reforestation with native mixed-species plantings in a temperate continental climate effectively sequesters and stabilizes carbon within decades. *Global Change Biology*, **21**(4), 1552-1566, doi:https://doi.org/10.1111/gcb.12746.
Cuthbert, M. O. et al., 2019: Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. *Nature*, **572**(7768), 230-234, doi:10.1038/s41586-019-1441-7.
D'Odorico, P. et al., 2018: The global food-energy-water nexus. *Reviews of Geophysics*, **56**(3), 456-531, doi:10.1029/2017rg000591.
D'agata, S. et al., 2020: Multiscale determinants of social adaptive capacity in small-scale fishing communities. *Environmental Science & Policy*, **108**, 56-66, doi:https://doi.org/10.1016/j.envsci.2020.03.006.
Dallas, H. F., 2016: The influence of thermal history on upper thermal limits of two species of riverine insects: the stonefly, Aphanicerca capensis, and the mayfly, Lestagella penicillata. *Hydrobiologia*, **781**(1), 95-108, doi:10.1007/s10750-016-2826-3.
Dallas, H. F. and N. Rivers-Moore, 2014: Ecological consequences of global climate change for freshwater ecosystems in South Africa. *South African Journal of Science*, **110**(5/6), doi:10.1590/sajs.2014/20130274.
Dalu, T., R. J. Wasserman and M. T. B. Dalu, 2017: Agricultural intensification and drought frequency increases may have landscape-level consequences for ephemeral ecosystems. *Global Change Biology*, **23**(3), 983-985, doi:https://doi.org/10.1111/gcb.13549.
Daniels, E. et al., 2020: Refocusing the climate services lens: Introducing a framework for co-designing "transdisciplinary knowledge integration processes" to build climate resilience. *Climate Services*, **19**, doi:10.1016/j.cliser.2020.100181.
Daoud, M., 2021: Is vulnerability to climate change gendered? And how? Insights from Egypt. *Regional Environmental Change*, **21**(2), doi:10.1007/s10113-021-01785-z.
Dardel, C. et al., 2014: Re-greening Sahel: 30years of remote sensing data and field observations (Mali, Niger). *Remote Sensing of Environment*, **140**, 350-364, doi:https://doi.org/10.1016/j.rse.2013.09.011.
Dargie, G. C. et al., 2019: Congo Basin peatlands: threats and conservation priorities. *Mitigation and Adaptation Strategies for Global Change*, **24**(4), 669-686, doi:10.1007/s11027-017-9774-8.
Darko, D. et al., 2019: The context and politics of decision making on large dams in Ghana: an overview, Manchester.
Darkoh, E. L., J. A. Larbi and E. A. Lawer, 2017: A Weather-Based Prediction Model of Malaria Prevalence in Amenfi West District, Ghana. *Malar. Res. Treat.*, **2017**, 7820454, doi:10.1155/2017/7820454.
Dass, P., B. Z. Houlton, Y. Wang and D. Warlind, 2018: Grasslands may be more reliable carbon sinks than forests in California. *Environmental Research Letters*, **13**(7), 074027, doi:10.1088/1748-9326/aacb39.
Datta, K. et al., 2003: Bioengineered 'golden' indica rice cultivars with beta-carotene metabolism in the endosperm with hygromycin and mannose selection systems. *Plant Biotechnol J*, **1**(2), 81-90, doi:10.1046/j.1467-7652.2003.00015.x.
Davidson, D., 2016: Gaps in agricultural climate adaptation research. *Nature Climate Change*, **6**(5), 433-435, doi:10.1038/nclimate3007.
Davis-Reddy, C. L., K. Vincent and J. Mambo, 2017: Socio-economic impacts of extreme weather events in Southern Africa. In: *Climate Risk and Vulnerability: A Handbook for Southern Africa*. CSIR, Pretoria, South Africa, pp. 30-47.

Davis, J., B. Crow and J. Miles (eds.), Measuring water collection times in Kenyan informal settlements. Fifth International Conference on Information and Communication Technologies and Development, Atlanta, GA, USA, 114–121 pp.

Day, E. et al., 2019: Upholding labour productivity under climate change: an assessment of adaptation options. *Climate Policy*, **19**(3), 367-385, doi:10.1080/14693062.2018.1517640.

Dayamba, D. S. et al., 2018: Assessment of the use of Participatory Integrated Climate Services for Agriculture (PICSA) approach by farmers to manage climate risk in Mali and Senegal. *Climate Services*, **12**, 27-35, doi:https://doi.org/10.1016/j.cliser.2018.07.003.

de Graaf, G. and L. Garibaldi, 2015: *THE VALUE OF AFRICAN FISHERIES*. FAO Fisheries and Aquaculture Circular, Food and Agriculture Organization of the United Nations, Rome, 76 pp. Available at: https://www.proquest.com/scholarly-journals/value-african-fisheries/docview/1703270253/se-2?accountid=14500.

de Janvry, A., F. Finan, E. Sadoulet and R. Vakis, 2006: Can conditional cash transfer programs serve as safety nets in keeping children at school and from working when exposed to shocks? *Journal of Development Economics*, **79**(2), 349-373, doi:10.1016/j.jdeveco.2006.01.013.

de Lima, C. Z. et al., 2021: Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters*, **16**(4), 044020, doi:10.1088/1748-9326/abeb9f.

de Longueville, F., P. Ozer, S. Doumbia and S. Henry, 2013: Desert dust impacts on human health: an alarming worldwide reality and a need for studies in West Africa. *Int J Biometeorol*, **57**(1), 1-19, doi:10.1007/s00484-012-0541-y.

Degarege, A. et al., 2019: Improving socioeconomic status may reduce the burden of malaria in sub Saharan Africa: A systematic review and meta-analysis. *PLoS One*, **14**(1), e0211205, doi:10.1371/journal.pone.0211205.

Dell, M., B. F. Jones and B. A. Olken, 2012: Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, **4**(3), 66-95, doi:10.1257/mac.4.3.66.

Dellink, R., E. Lanzi and J. Chateau, 2019: The Sectoral and Regional Economic Consequences of Climate Change to 2060. *Environmental and Resource Economics*, **72**(2), 309-363, doi:10.1007/s10640-017-0197-5.

Denton, F. et al., 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131. ISBN 9781107058071.

Department of Economic and Social Affairs, 2016: *World Economic and Social Survey 2016: Climate Change Resilience: An Opportunity for Reducing Inequalities*. United Nations, 1 ed., New York. Available at: https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/WESS_2016_Report.pdf.

Dercon, S. and L. Christiaensen, 2011: Consumption risk, technology adoption and poverty traps: Evidence from Ethiopia. *Journal of Development Economics*, **96**(2), 159-173, doi:10.1016/j.jdeveco.2010.08.003.

Deryng, D. et al., 2016: Regional disparities in the beneficial effects of rising CO2 concentrations on crop water productivity. *Nature Climate Change*, **6**(8), 786-790, doi:10.1038/nclimate2995.

Deryugina, T. and S. Hsiang, 2017: *The marginal product of climate*. Nber Working Paper Series, National Bureau of Economic Research, Inc., Cambridge, MA. Available at: https://www.nber.org/papers/w24072.pdf.

Descheemaeker, K. et al., 2018: Effects of climate change and adaptation on the livestock component of mixed farming systems: A modelling study from semi-arid Zimbabwe. *Agricultural Systems*, **159**, 282-295, doi:10.1016/j.agsy.2017.05.004.

Descroix, L. et al., 2018: Evolution of surface hydrology in the Sahelo-Sudanian strip: An updated review. *Water*, **10**(6), doi:10.3390/w10060748.

Deutsch, C. A. et al., 2018: Increase in crop losses to insect pests in a warming climate. *Science (New York, N.Y.)*, **361**(6405), 916-919, doi:10.1126/science.aat3466.

Devonald, M., N. Jones and W. Yadete, 2020: *'The first thing that I fear for my future is lack of rain and drought': climate change and its impacts on adolescent capabilities in low-and middle-income countries*. London. Available at: https://www.gage.odi.org/wp-content/uploads/2020/12/Climate-change-report-for-web-1.pdf.

di Lernia, S., 2017: The Archaeology of Rock Art in Northern Africa. In: *The Oxford Handbook of the Archaeology and Anthropology of Rock Art* [David, B. and I. J. McNiven (eds.)]. Oxford University Press, Oxford.

di Lernia, S. and M. Gallinaro, 2011: Working in a UNESCO WH Site. Problems and Practices on the Rock Art of Tadrart Akakus (SW Libya, Central Sahara). *Journal of African Archaeology*, **9**(2), 159-175, doi:https://doi.org/10.3213/2191-5784-10198.

Di Marcantonio, F. and F. Kayitakire, 2017: Review of Pilot Projects on Index-Based Insurance in Africa: Insights and Lessons Learned. In: *Renewing Local Planning to Face Climate Change in the Tropics* [Tiepolo, M., A. Pezzoli and V. Tarchiani (eds.)]. Springer, Cham, pp. 323-341. ISBN 978-3-319-59095-0.

Diallo, I. et al., 2016: Projected changes of summer monsoon extremes and hydroclimatic regimes over West Africa for the twenty-first century. *Clim Dyn*, **47**(12), 3931-3954, doi:10.1007/s00382-016-3052-4.

Dibley, A., T. Wetzer and C. Hepburn, 2021: National COVID debts: climate change imperils countries' ability to repay. *Nature*, **596**(August 2021), 184-187, doi:https://doi.org/10.1038/d41586-021-00871-w.

Diboulo, E. et al., 2012: Weather and mortality: a 10 year retrospective analysis of the Nouna Health and Demographic Surveillance System, Burkina Faso. *Global Health Action*, **5**(1), 19078, doi:10.3402/gha.v5i0.19078.
Dickerson, S., M. Cannon and B. O'Neill, 2021: Climate change risks to human development in sub-Saharan Africa: a review of the literature. *Climate and Development*, 1-19, doi:10.1080/17565529.2021.1951644.
Dickin, S., L. Segnestam and M. Sou Dakouré, 2020: Women's vulnerability to climate-related risks to household water security in Centre-East, Burkina Faso. *Climate and Development*, **13**(5), 443-453, doi:10.1080/17565529.2020.1790335.
Dickovick, T. J. W., James S. , 2014: Decentralization: Theoretical, Conceptual, and Analytical Issues. In: *Decentralization in Africa: The Paradox of State Strength* [Dickovick, T. J. and J. S. Wunsch (eds.)]. Lynne Rienner Publishers. ISBN 978-1-62637-053-1.
Diedhiou, A. et al., 2018: Changes in climate extremes over West and Central Africa at 1.5 °C and 2 °C global warming. *Environmental Research Letters*, **13**(6), 065020, doi:10.1088/1748-9326/aac3e5.
Diffenbaugh, N. S. and M. Burke, 2019: Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences*, **116**(20), 9808-9813, doi:10.1073/pnas.1816020116.
Digna, R. F. et al., 2016: Nile River Basin modelling for water resources management – a literature review. *International Journal of River Basin Management*, **15**(1), 39-52, doi:10.1080/15715124.2016.1228656.
Dimobe, K. et al., 2020: Climate change reduces the distribution area of the shea tree (Vitellaria paradoxa C.F. Gaertn.) in Burkina Faso. *Journal of Arid Environments*, **181**, 104237, doi:https://doi.org/10.1016/j.jaridenv.2020.104237.
Dinerstein, E. et al., 2019: A Global Deal For Nature: Guiding principles, milestones, and targets. *Science Advances*, **5**(4), eaaw2869, doi:10.1126/sciadv.aaw2869.
Dinesh, D. et al., 2018: Facilitating Change for Climate-Smart Agriculture through Science-Policy Engagement. *Sustainability*, **10**(8), 2616, doi:https://doi.org/10.3390/su10082616.
Ding, K., J. M. Gilligan and G. M. Hornberger, 2019: "Avoiding "day-zero": A Testbed for Evaluating Integrated Food-energy-water Management in Cape Town, South Africa. *IEEE*, 866-877, doi:10.1109/WSC40007.2019.9004889.
Diop, A., 2018: Tombouctou: l'avenir des maçons traditionnels. In: *World Heritage for Sustainable Development in Africa*. United Nations Educational, Scientific and Cultural Organization. UNESCO, Paris, pp. 99-103.
Diouf, I. et al., 2017: Comparison of Malaria Simulations Driven by Meteorological Observations and Reanalysis Products in Senegal. *International journal of environmental research and public health*, **14**(10), 1119, doi:10.3390/ijerph14101119.
Diouf, N. S. et al., 2019: Factors influencing gendered access to climate information services for farming in Senegal. *Gender, Technology and Development*, **23**(2), 93-110, doi:10.1080/09718524.2019.1649790.
Djalante, R., C. Holley, F. Thomalla and M. Carnegie, 2013: Pathways for adaptive and integrated disaster resilience. *Natural Hazards*, **69**, 2105-2135, doi:10.1007/s11069-013-0797-5.
Djoudi, H. et al., 2016: Beyond dichotomies: Gender and intersecting inequalities in climate change studies. *Ambio*, **45**(3), 248-262, doi:10.1007/s13280-016-0825-2.
Doblas-Reyes, F. J. et al., 2021: *Linking Global to Regional Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, **In Press**, Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_10.pdf.
Dodds, W. K., J. S. Perkin and J. E. Gerken, 2013: Human Impact on Freshwater Ecosystem Services: A Global Perspective. *Environmental Science & Technology*, **47**(16), 9061-9068, doi:10.1021/es4021052.
Dodman, D., H. Leck, M. Rusca and S. Colenbrander, 2017: African Urbanisation and Urbanism: Implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction*, **26**, 7-15, doi:10.1016/j.ijdrr.2017.06.029.
Dodman, D. et al., 2015: *Understanding the assessment and reduction of vulnerability to climate change in African cities: A focus on low-income and informal settlements*. Environment and Urbanization, **24**, International Institute for Environment and Development (IIED), 77-97 pp. Available at: https://www.afd.fr/en/understanding-assessment-and-reduction-vulnerability-climate-change-african-cities-focus-low-income-and-informal-settlements.
Dolislager, M. et al., 2020: Youth and Adult Agrifood System Employment in Developing Regions: Rural (Peri-urban to Hinterland) vs. Urban. *The Journal of Development Studies*, **57**(4), 571-593, doi:10.1080/00220388.2020.1808198.
Dombrowsky, I. and O. Hensengerth, 2018: Governing the Water-Energy-Food Nexus Related to Hydropower on Shared Rivers—The Role of Regional Organizations. *Frontiers in Environmental Science*, **6**(153), doi:10.3389/fenvs.2018.00153.
Domke, M. and J. Pretzsch, 2016: Knowledge Management on Climate Change Adaptation. Analysis of Information Exchange Processes and Collaboration Networks in Rural Ethiopia. In: *Climatic and Environmental Challenges: Learning from the Horn of Africa*. Centre français des études éthiopiennes, Addis-Abeba. ISBN 9782821873001.
Donat, M. G., O. Angélil and A. M. Ukkola, 2019: Intensification of precipitation extremes in the world's humid and water-limited regions. *Environmental Research Letters*, **14**(6), 065003, doi:10.1088/1748-9326/ab1c8e.

Donat, M. G. et al., 2014a: Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO. *International Journal of Climatology*, **34**(3), 581-592, doi:10.1002/joc.3707.
Donat, M. G. et al., 2014b: Consistency of temperature and precipitation extremes across various global gridded in situ and reanalysis datasets. *Journal of Climate*, **27**(13), 5019-5035, doi:10.1175/jcli-d-13-00405.1.
Doshi, D. and M. Garschagen, 2020: Understanding Adaptation Finance Allocation: Which Factors Enable or Constrain Vulnerable Countries to Access Funding? *Sustainability*, **12**(10), 4308, doi:10.3390/su12104308.
Dosio, A., 2017: Projection of temperature and heat waves for Africa with an ensemble of CORDEX Regional Climate Models. *Clim Dyn*, **49**, 493-519, doi:10.1007/s00382-016-3355-5.
Dosio, A. et al., 2019: What can we know about future precipitation in Africa? Robustness, significance and added value of projections from a large ensemble of regional climate models. *Clim Dyn*, doi:10.1007/s00382-019-04900-3.
Dosio, A. et al., 2021: Projected future daily characteristics of African precipitation based on global (CMIP5, CMIP6) and regional (CORDEX, CORDEX-CORE) climate models. *Clim Dyn*, doi:10.1007/s00382-021-05859-w.
Dosio, A., L. Mentaschi, E. M. Fischer and K. Wyser, 2018: Extreme heat waves under 1.5 °C and 2 °C global warming. *Environmental Research Letters*, **13**(5), 054006, doi:10.1088/1748-9326/aab827.
Doswald, N. et al., 2014: Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, **6**(2), 185-201, doi:10.1080/17565529.2013.867247.
Dottori, F. et al., 2018: Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, **8**(9), 781-786, doi:10.1038/s41558-018-0257-z.
Douglas, I., 2017: Flooding in African cities, scales of causes, teleconnections, risks, vulnerability and impacts. *International Journal of Disaster Risk Reduction*, **26**, 34-42, doi:10.1016/j.ijdrr.2017.09.024.
Douville, H. et al., 2021: *Water Cycle Changes* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change **In Press**, Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_08.pdf.
Douxchamps, S. et al., 2015: Linking agricultural adaptation strategies, food security and vulnerability: evidence from West Africa. *Regional Environmental Change*, **16**(5), 1305-1317, doi:10.1007/s10113-015-0838-6.
Dowd-Uribe, B., M. Sanon, C. Roncoli and B. Orlove, 2018: Grounding the Nexus: Examining the Integration of Small-Scale Irrigators into a National Food Security Programme in Burkina Faso. *Water Alternatives*, **11**(2).
Dowla, A., 2018: Climate change and microfinance. *BUSINESS STRATEGY & DEVELOPMENT*, **1**(2), 78-87, doi:10.1002/bsd2.13.
Du, L. et al., 2021: Effects of anthropogenic revegetation on the water and carbon cycles of a desert steppe ecosystem. *Agricultural and Forest Meteorology*, **300**, 108339, doi:https://doi.org/10.1016/j.agrformet.2021.108339.
du Plessis, K. L. et al., 2012: The costs of keeping cool in a warming world: implications of high temperatures for foraging, thermoregulation and body condition of an arid-zone bird. *Global Change Biology*, **18**(10), 3063-3070, doi:https://doi.org/10.1111/j.1365-2486.2012.02778.x.
du Toit, J. C. O., L. van den Berg and T. G. O'Connor, 2015: Fire effects on vegetation in a grassy dwarf shrubland at a site in the eastern Karoo, South Africa. *African Journal of Range & Forage Science*, **32**(1), 13-20, doi:10.2989/10220119.2014.913077.
du Toit, M. J. et al., 2018: Urban green infrastructure and ecosystem services in sub-Saharan Africa. *Landscape and Urban Planning*, **180**, 249-261, doi:10.1016/j.landurbplan.2018.06.001.
Duarte, C. M. et al., 2013: The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, **3**(11), 961-968, doi:10.1038/nclimate1970.
Dube, K., L. Chapungu and J. M. Fitchett, 2021: Meteorological and Climatic Aspects of Cyclone Idai and Kenneth. In: *Cyclones in Southern Africa: Volume 2: Foundational and Fundamental Topics* [Nhamo, G. and K. Dube (eds.)]. Springer International Publishing, Cham, pp. 19-36. ISBN 978-3-030-74262-1.
Dube, K., K. Mearns, S. Mini and L. Chapungu, 2018: Tourists' knowledge and perceptions on the impact of climate change on tourism in Okavango Delta, Botswana'. *African Journal of Hospitality, Tourism and Leisure*, **7**(4), 1-18.
Dube, K. and G. Nhamo, 2018: Climate variability, change and potential impacts on tourism: Evidence from the Zambian side of the Victoria Falls. *Environmental Science & Policy*, **84**, 113-123, doi:https://doi.org/10.1016/j.envsci.2018.03.009.
Dube, K. and G. Nhamo, 2019: Climate change and potential impacts on tourism: evidence from the Zimbabwean side of the Victoria Falls. *Environment, Development and Sustainability*, **21**(4), 2025-2041, doi:10.1007/s10668-018-0118-y.
Dube, K. and G. Nhamo, 2020: Evidence and impact of climate change on South African national parks. Potential implications for tourism in the Kruger National Park. *Environmental Development*, **33**, 100485, doi:https://doi.org/10.1016/j.envdev.2019.100485.

Dube, K., G. Nhamo and D. Chikodzi, 2020: Climate change-induced droughts and tourism: Impacts and responses of Western Cape province, South Africa. *Journal of Outdoor Recreation and Tourism*, 100319, doi:https://doi.org/10.1016/j.jort.2020.100319.
Dube, T., P. Moyo, M. Ncube and D. Nyathi, 2016: The Impact of Climate Change on Agro-Ecological Based Livelihoods in Africa: A Review. *Journal of Sustainable Development*, **9**(1), doi:10.5539/jsd.v9n1p256.
Duchoslav, J., 2017: Prenatal Temperature Shocks Reduce Cooperation: Evidence from Public Goods Games in Uganda. *Frontiers in behavioral neuroscience*, **11**, 249, doi:10.3389/fnbeh.2017.00249.
Duffy, M., 2012: The "One Water" Approach.
Dumenu, W. K. and E. A. Obeng, 2016: Climate change and rural communities in Ghana: Social vulnerability, impacts, adaptations and policy implications. *Environmental Science & Policy*, **55**, 208-217, doi:https://doi.org/10.1016/j.envsci.2015.10.010.
Duncker, L. C., 2017: The Effect of Consumer Expectations and Perceptions Regarding Sanitation on Access to Clean Water. *Journal of Ethical Urban Living*, **1**(1), 19-36.
Duncombe, R., 2018: *Digital Technologies for Agricultural and Rural Development in the Global South*. CAB International, , UK, 160 pp.
Dunning, C. M., E. Black and R. P. Allan, 2018: Later wet seasons with more intense rainfall over Africa under future climate change. *Journal of Climate*, **31**(23), 9719-9738, doi:https://doi.org/10.1175/JCLI-D-18-0102.1.
Durand, B. et al., 2019: Rift Valley fever in northern Senegal : a modelling approach to analyse the processes underlying virus circulation recurrence. *bioRxiv*, 2019.2012.2023.886978, doi:10.1101/2019.12.23.886978.
Durand, J.-L. et al., 2018: How accurately do maize crop models simulate the interactions of atmospheric CO2 concentration levels with limited water supply on water use and yield? *European Journal of Agronomy*, **100**, 67-75, doi:10.1016/j.eja.2017.01.002.
Dzavo, T., T. J. Zindove, M. Dhliwayo and M. Chimonyo, 2019: Effects of drought on cattle production in sub-tropical environments. *Trop Anim Health Prod*, **51**(3), 669-675, doi:10.1007/s11250-018-1741-1.
Eastin, J., 2018: Climate change and gender equality in developing states. *World Development*, **107**, 289-305, doi:10.1016/j.worlddev.2018.02.021.
Ebhuoma, E. E., 2020: A framework for integrating scientific forecasts with indigenous systems of weather forecasting in southern Nigeria. *Development in Practice*, **30**(4), 472-484, doi:https://doi.org/10.1080/09614524.2020.1723494.
Ebi, K. L. and M. Otmani Del Barrio, 2017: Lessons Learned on Health Adaptation to Climate Variability and Change: Experiences Across Low- and Middle-Income Countries. *Environ Health Perspect*, **125**(6), 065001, doi:10.1289/EHP405.
EBRD et al., 2021: *Joint report on multilateral development banks' climate finance*. World Bank Group, Washington DC, USA, 64 pp. Available at: https://thedocs.worldbank.org/en/doc/9234bfc633439d0172f6a6eb8df1b881-0020012021/original/2020-Joint-MDB-report-on-climate-finance-Report-final-web.pdf.
Edgar, G. J. et al., 2014: Global conservation outcomes depend on marine protected areas with five key features. *Nature*, **506**(7487), 216-220, doi:10.1038/nature13022.
Edo, S., N. E. Osadolor and I. F. Dading, 2020: Growing external debt and declining export: The concurrent impediments in economic growth of Sub-Saharan African countries. *International Economics*, **161**, 173-187, doi:10.1016/j.inteco.2019.11.013.
Egeru, A., 2012: Role of indigenous knowledge in climate change adaptation: A case study of the Teso Sub-Region, Eastern Uganda. *Indian J. Tradit. Knowl.*, **11**(2), 217-224.
Egeru, A., 2016: Climate risk management information, sources and responses in a pastoral region in East Africa. *Climate Risk Management*, **11**, 1-14, doi:10.1016/j.crm.2015.12.001.
Egoh, B. N. et al., 2012: An African account of ecosystem service provision: Use, threats and policy options for sustainable livelihoods. *Ecosystem Services*, **2**, 71-81, doi:10.1016/j.ecoser.2012.09.004.
Egondi, T. et al., 2012: Time-series analysis of weather and mortality patterns in Nairobi's informal settlements. *Global Health Action*, **5**(1), 19065, doi:10.3402/gha.v5i0.19065.
Egondi, T., C. Kyobutungi and J. Rocklov, 2015: Temperature variation and heat wave and cold spell impacts on years of life lost among the urban poor population of Nairobi, Kenya. *Int J Environ Res Public Health*, **12**(3), 2735-2748, doi:10.3390/ijerph120302735.
Eitzinger, A. et al., 2011: *Future climate scenarios for Uganda's tea growing areas*. International Center for Tropical Agriculture, Cali, Columbia.
Ekblom, A. et al., 2019: Conservation through Biocultural Heritage—Examples from Sub-Saharan Africa. *Land*, **8**(1), doi:10.3390/land8010005.
El-Shafei, D. A., S. A. Bolbol, M. B. Awad Allah and A. E. Abdelsalam, 2018: Exertional heat illness: knowledge and behavior among construction workers. *Environ Sci Pollut Res Int*, **25**(32), 32269-32276, doi:10.1007/s11356-018-3211-8.
El-Tarabany, M. S., A. A. El-Tarabany and M. A. Atta, 2017: Physiological and lactation responses of Egyptian dairy Baladi goats to natural thermal stress under subtropical environmental conditions. *Int J Biometeorol*, **61**(1), 61-68, doi:10.1007/s00484-016-1191-2.
Elboshy, B. et al., 2019: A framework for pluvial flood risk assessment in Alexandria considering the coping capacity. *Environment Systems and Decisions*, **39**(1), 77-94, doi:10.1007/s10669-018-9684-7.

Eldeberky Y, H. B. (ed.), Vulnerability of the Nile delta to recent and future climate change. . 36th IAHR WORLD CONGRESS, The Hague, Netherlands, International Association for Hydro-Environment Engineering & Research (IAHR).
Elevitch, C. R., D. N. Mazaroli and D. Ragone, 2018: Agroforestry Standards for Regenerative Agriculture. *Sustainability*, **10**(9), 3337, doi:https://doi.org/10.3390/su10093337.
Elshirbiny, H. and W. Abrahamse, 2020: Public risk perception of climate change in Egypt: a mixed methods study of predictors and implications. *Journal of Environmental Studies and Sciences*, **10**, 242–254, doi:10.1007/s13412-020-00617-6.
Elum, Z. A., D. M. Modise and A. Marr, 2017: Farmer's perception of climate change and responsive strategies in three selected provinces of South Africa. *Climate Risk Management*, **16**, 246-257, doi:10.1016/j.crm.2016.11.001.
EMDAT and CRED, 2020: EM-DAT Drought Disaster Occurances: Africa query [UCLouvain (ed.)], UCLouvain, Brussels, Belgium. Available at: www.emdat.be.
Emerton, L., 2017: *Valuing the Benefits, Costs and Impacts of Ecosystem-based Adaptation Measures: A sourcebook of methods for decision-making*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn and Eschborn, Germany.
Endris, H. S. et al., 2019: Future changes in rainfall associated with ENSO, IOD and changes in the mean state over Eastern Africa. *Clim Dyn*, **52**(3), 2029-2053, doi:10.1007/s00382-018-4239-7.
Enenkel, M. et al., 2020: Emergencies do not stop at night: Advanced analysis of displacement based on satellite-derived nighttime light observations. *IBM Journal of Research and Development*, **64**(1/2), 8:1-8:12, doi:10.1147/JRD.2019.2954404.
Engdaw, M. M., A. P. Ballinger, G. C. Hegerl and A. K. Steiner, 2021: Changes in temperature and heat waves over Africa using observational and reanalysis data sets. *International Journal of Climatology*, **n/a**(n/a), doi:https://doi.org/10.1002/joc.7295.
Engelbrecht, F. et al., 2015: Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10**(8), 085004, doi:10.1088/1748-9326/10/8/085004.
Engelbrecht, F. A., J. L. McGregor and C. J. Engelbrecht, 2009: Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *International Journal of Climatology*, **29**(7), 1013-1033, doi:https://doi.org/10.1002/joc.1742.
England, M. I. et al., 2018: Climate change adaptation and cross-sectoral policy coherence in southern Africa. *Regional Environmental Change*, **18**(7), 2059-2071, doi:10.1007/s10113-018-1283-0.
Eniola, P. O., 2021: Menace and Mitigation of Health and Environmental Hazards of Charcoal Production in Nigeria. In: *African Handbook of Climate Change Adaptation* [Oguge, N., D. Ayal, L. Adeleke and I. da Silva (eds.)]. Springer International Publishing, Cham, pp. 2293-2310. ISBN 978-3-030-45106-6.
Enqvist, J. P. and G. Ziervogel, 2019: Water governance and justice in Cape Town: An overview. *WIREs Water*, **6**(4), e1354, doi:https://doi.org/10.1002/wat2.1354.
Ericksen, P. J., 2008: Conceptualizing food systems for global environmental change research. *Global Environmental Change*, **18**(1), 234-245, doi:https://doi.org/10.1016/j.gloenvcha.2007.09.002.
Eriksen, S. et al., 2011: When not every response to climate change is a good one: Identifying principles for sustainable adaptation. *Climate and Development*, **3**(1), 7-20, doi:10.3763/cdev.2010.0060.
Escalera-vázquez, L. H., N. Calderón-cortés and L. Zambrano-gonzález, 2017: Fish population responses to hydrological variation in a seasonal wetland in southeast México. *Neotropical Ichthyology*, **15**(June), 1-10, doi:10.1590/1982-0224-20160129.
ESPA Directorate, 2018: *Research into Results for the ESPA Directorate. Ecosystem Services for Poverty Alleviation Programme Highlights 2009–2018.* ESPA Directorate,, Edinburgh, UK. Available at: https://www.espa.ac.uk/files/espa/ESPA%20Programme%20Highlights%20Report%202009_2018.pdf.
Estevão, M., 2020: Climate-Smart Fiscal Policy Can Foster a Lasting Economic Recovery. *One Earth*, **3**(3), 273-276, doi:https://doi.org/10.1016/j.oneear.2020.08.017.
Etim, E. and O. Daramola, 2020: The Informal Sector and Economic Growth of South Africa and Nigeria: A Comparative Systematic Review. *Journal of Open Innovation: Technology, Market, and Complexity*, **6**(4), doi:10.3390/joitmc6040134.
Evan, A. T., C. Flamant, M. Gaetani and F. Guichard, 2016: The past, present and future of African dust. *Nature*, **531**(7595), 493-495, doi:10.1038/nature17149.
Evans, M. et al., 2020: *Reconciling model predictions with low reported cases of COVID-19 in Sub-Saharan Africa: Insights from Madagascar*.
Evariste, F. F., S. Denis Jean, K. Victor and M. Claudia, 2018: Assessing climate change vulnerability and local adaptation strategies in adjacent communities of the Kribi-Campo coastal ecosystems, South Cameroon. *Urban Climate*, **24**, 1037-1051, doi:10.1016/j.uclim.2017.12.007.
Fabiyi, O. O. and J. Oloukoi, 2013: Indigenous knowledge system and local adaptation strategies to flooding in coastal rural communities of Nigeria. *Journal of Indigenous Social Development*, **2**(1).
Failler, P. et al., 2018: *The IPBES regional assessment report on biodiversity and ecosystem services for Africa* [Archer, E., L. Dziba, K. J. Mulongoy, M. A. Maoela and M. Walters (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 77–130 pp.

Falchetta, G., A. T. Hammad and S. Shayegh, 2020: Planning universal accessibility to public health care in sub-Saharan Africa. *Proc Natl Acad Sci U S A*, **117**(50), 31760-31769, doi:10.1073/pnas.2009172117.
Falco, S. D. et al., 2012: Estimating the Impact of Climate Change on Agriculture in Low-Income Countries: Household Level Evidence from the Nile Basin, Ethiopia. *Environmental and Resource Economics*, **52**(4), 457-478, doi:10.1007/s10640-011-9538-y.
Fankhauser, S., 2010: The costs of adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **1**(1), 23-30, doi:10.1002/wcc.14.
Fanzo, J., C. Davis, R. McLaren and J. Choufani, 2018: The effect of climate change across food systems: Implications for nutrition outcomes. *Global Food Security*, **18**, 12-19, doi:10.1016/j.gfs.2018.06.001.
FAO, 2016: *The State of Food and Agriculture: Climate Change, Agriculture and Food Security*. Food and Agriculture Organization of the United Nations, Rome, 173 pp. Available at: www.fao.org/3/a-i6030e.pdf.
FAO, 2017: *Cash+: FAO's Approach* Food and Agriculture Organization of the United Nations (FAO), Rome, 20 pp. Available at: http://www.fao.org/3/a-i7864e.pdf.
FAO, 2018a: Climate change and its impacts on the work and activities of FAO forestry. FAO, Rome.
FAO, 2018b: *The State of World Fisheries and Aquaculture: Meeting the sustainable development goals* [Barange, M., J. Alder, U. Barg, S. Funge-Smith, P. Mannini, M. Taconet and J. Plummer (eds.)]. The State of World Fisheries and Aquaculture (SOFIA), FAO, Rome, Italy, 277 pp. Available at: http://www.fao.org/3/i9540en/i9540en.pdf.
FAO, 2019: *The State of the World's Biodiversity for Food and Agriculture* [Bélanger, J. and D. Pilling (eds.)]. FAO Commission on Genetic Resources for Food and Agriculture Assessments, FAO Rome, 575 pp. Available at: http://www.fao.org/3/CA3129EN/CA3129EN.pdf.
FAO and ECA, 2018: *Africa: Regional Overview of Food Security and Nutrition. Addressing the threat from climate variability and extremes for food security and nutrition*. Food and Agriculture Organization of the United Nations, Accra, 116 pp. Available at: http://www.fao.org/3/CA2710EN/ca2710en.pdf.
FAO et al., 2020: *The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets*. The State of Food Security and Nutrition in the World (SOFI), FAO, Rome, Italy, 320 pp. Available at: https://doi.org/10.4060/ca9692en.
Farrell, A. D., K. Rhiney, A. Eitzinger and P. Umaharan, 2018: Climate adaptation in a minor crop species: is the cocoa breeding network prepared for climate change? *Agroecology and Sustainable Food Systems*, **42**(7), 812-833, doi:10.1080/21683565.2018.1448924.
Fauset, S. et al., 2012: Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana. *Ecology Letters*, **15**(10), 1120-1129, doi:https://doi.org/10.1111/j.1461-0248.2012.01834.x.
Fava, F. et al., 2021: *Building Financial Resilience in Pastoral Communities in Africa*. The Financial Protection Forum and Disaster Risk Financing and Insurance Program (DRFIP) and World Bank Group Global Facility for Disaster Reduction and Recovery, Washington, DC. Available at: https://www.financialprotectionforum.org/publication/building-financial-resilience-in-pastoral-communities-in-africa.
Faye, B. et al., 2018: Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna. *Environmental Research Letters*, **13**(3), 034014, doi:10.1088/1748-9326/aaab40.
Feary, S. et al., 2016: *Earth's cultural heritage*. Protected Area Governance and Management, ANU Press, Canberra, Australia ISBN 9781925021691.
Fedele, G. et al., 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116-125, doi:https://doi.org/10.1016/j.envsci.2019.07.001.
Fenton, A., J. Paavola and A. Tallontire, 2015: Microfinance and climate change adaptation: An overview of the current literature. *Enterprise Development and Microfinance*, **26**, 262-273, doi:10.3362/1755-1986.2015.023.
Fenton, A. et al., 2014: Debt relief and financing climate change action. *Nature Climate Change*, **4**(8), 650-653, doi:10.1038/nclimate2303.
Fernández-Llamazares, Á. et al., 2015: Rapid ecosystem change challenges the adaptive capacity of Local Environmental Knowledge. *Global Environmental Change*, **31**, 272-284, doi:https://doi.org/10.1016/j.gloenvcha.2015.02.001.
Ferrão, J. L., J. M. Mendes, M. Painho and S. Zacarias, 2017: Malaria mortality characterization and the relationship between malaria mortality and climate in Chimoio, Mozambique. *Malaria Journal*, **16**(1), 212, doi:10.1186/s12936-017-1866-0.
Fieldman, G., 2011: Neoliberalism, the production of vulnerability and the hobbled state: Systemic barriers to climate adaptation. *Climate and Development*, **3**(2), 159-174, doi:10.1080/17565529.2011.582278.
Filahi, S. et al., 2016: Trends in indices of daily temperature and precipitations extremes in Morocco. *Theoretical and Applied Climatology*, **124**(3-4), 959-972, doi:https://doi.org/10.1007/s00704-015-1472-4.
Filahi, S., Y. Tramblay, L. Mouhir and E. P. Diaconescu, 2017: Projected changes in temperature and precipitation indices in Morocco from high-resolution regional climate models. *International Journal of Climatology*, **37**(14), 4846-4863, doi:https://doi.org/10.1002/joc.5127.
Finney, D. L. et al., 2020: Effects of Explicit Convection on Future Projections of Mesoscale Circulations, Rainfall, and Rainfall Extremes over Eastern Africa. *Journal of Climate*, **33**(7), 2701-2718, doi:10.1175/JCLI-D-19-0328.1.
Fiorella, K. J. et al., 2019: A review of transactional sex for natural resources: Under-researched, overstated, or unique to fishing economies? *Global public health*, **14**(12), 1803-1814, doi:10.1080/17441692.2019.1625941.

Fischer, E. M. and R. Knutti, 2016: Observed heavy precipitation increase confirms theory and early models. *Nature Climate Change*, **6**(11), 986-991, doi:10.1038/nclimate3110.
Fischer, E. M., K. W. Oleson and D. M. Lawrence, 2012: Contrasting urban and rural heat stress responses to climate change. *Geophysical Research Letters*, **39**(3), doi:https://doi.org/10.1029/2011GL050576.
Fisher-Jeffes, L., K. Carden and N. Armitage, 2017: A water sensitive urban design framework for South Africa. *Town and Regional Planning*, **71**, 1-10, doi:https://doi.org/10.18820/2415-0495/trp71i1.1.
Fisher, M. et al., 2015: Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change*, **133**(2), 283-299, doi:10.1007/s10584-015-1459-2.
Fitchett, J. M., 2018: Recent emergence of CAT5 tropical cyclones in the South Indian Ocean. *South African Journal of Science*, **114**(11-12), 1-6, doi:http://dx.doi.org/10.17159/sajs.2018/4426.
Fitchett, J. M., B. Grant and G. Hoogendoorn, 2016: Climate change threats to two low-lying South African coastal towns: Risks and perceptions. *South African Journal of Science*, **112**(n.5-6), 1-9, doi:http://dx.doi.org/10.17159/sajs.2016/20150262
Fjelde, H. and N. von Uexkull, 2012: Climate triggers: Rainfall anomalies, vulnerability and communal conflict in Sub-Saharan Africa. *Political Geography*, **31**(7), 444-453, doi:10.1016/j.polgeo.2012.08.004.
Flatø, M., R. Muttarak and A. Pelser, 2017: Women, Weather, and Woes: The Triangular Dynamics of Female-Headed Households, Economic Vulnerability, and Climate Variability in South Africa. *World Development*, **90**, 41-62, doi:https://doi.org/10.1016/j.worlddev.2016.08.015.
Fleifel, E., J. Martin and A. Khalid, 2019: Gender Specific Vulnerabilities to Water Insecurity. Available at: https://ic-sd.org/wp-content/uploads/2019/11/eliana-fleifel.pdf.
Fleisher, D. et al., 2010: Effects of CO2 and temperature on crops: Lessons from SPAR growth chambers. In: *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, And Mitigation* [Hillel, D. and C. Rosenzweig (eds.)]. Imperial College Press, Singapore, pp. 55-86.
Fluet-Chouinard, E., S. Funge-Smith and P. B. McIntyre, 2018: Global hidden harvest of freshwater fish revealed by household surveys. *Proceedings of the National Academy of Sciences*, **115**(29), 7623, doi:10.1073/pnas.1721097115.
Fonta, W. M., E. T. Ayuk and T. van Huysen, 2018: Africa and the Green Climate Fund: current challenges and future opportunities. *Climate Policy*, **18**(9), 1210-1225, doi:10.1080/14693062.2018.1459447.
Fontaine, B., S. Janicot and P.-A. Monerie, 2013: Recent changes in air temperature, heat waves occurrences, and atmospheric circulation in Northern Africa. *J Geophys Res-Atmos*, **118**(15), 8536-8552, doi:10.1002/jgrd.50667.
Food Security Information Network (FSIN), 2019: *Global Report on Food Crises*. World Food Programme, Rome, Italy. Available at: https://ec.europa.eu/knowledge4policy/publication/global-report-food-crises-2019_en.
Foran, T. et al., 2014: Taking Complexity in Food Systems Seriously: An Interdisciplinary Analysis. *World Development*, **61**, 85-101, doi:https://doi.org/10.1016/j.worlddev.2014.03.023.
Ford, J. D. et al., 2014: The status of climate change adaptation in Africa and Asia. *Regional Environmental Change*, **15**(5), 801-814, doi:10.1007/s10113-014-0648-2.
Ford, J. D. et al., 2016: Including indigenous knowledge and experience in IPCC assessment reports. *Nature Climate Change*, **6**(4), 349-353, doi:https://doi.org/10.1038/nclimate2954.
Fore, H. H., Q. Dongyu, D. M. Beasley and T. A. Ghebreyesus, 2020: Child malnutrition and COVID-19: the time to act is now. *The Lancet*, **396**(10250), 517-518, doi:10.1016/S0140-6736(20)31648-2.
Forsyth, G. et al., 2019: *The Knysna fires of 2017: learning from this disaster*. CSIR, Stellenbosch University & Santam Insurance, Stellenbosch, South Africa. Available at: https://cisp.cachefly.net/assets/articles/attachments/78574_the_knysna_fires_of_2017_learnings_from_the_disaster.pdf.
Fotso-Nguemo, T. C. et al., 2017: On the added value of the regional climate model REMO in the assessment of climate change signal over Central Africa. *Clim Dyn*, **49**(11-12), 3813-3838, doi:10.1007/s00382-017-3547-7.
Frame, B. et al., 2018: Adapting global shared socio-economic pathways for national and local scenarios. *Climate Risk Management*, **21**, 39-51, doi:https://doi.org/10.1016/j.crm.2018.05.001.
Frame, D. et al., 2017: Population-based emergence of unfamiliar climates. *Nature Climate Change*, **7**(6), 407-411, doi:10.1038/nclimate3297.
Frank, S. et al., 2021: Land-based climate change mitigation potentials within the agenda for sustainable development. *Environmental Research Letters*, **16**(2), 024006, doi:10.1088/1748-9326/abc58a.
Franke, J. A. et al., 2020: The GGCMI Phase 2 experiment: global gridded crop model simulations under uniform changes in CO_2, temperature, water, and nitrogen levels (protocol version 1.0). *Geosci. Model Dev.*, **13**(5), 2315-2336, doi:10.5194/gmd-13-2315-2020.
Franke, J. A. et al., 2021: Agricultural breadbaskets shift poleward given adaptive farmer behavior under climate change. *Global Change Biology*, doi:https://doi.org/10.1111/gcb.15868.
Free, C. M. et al., 2020: Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLOS ONE*, **15**(3), e0224347, doi:10.1371/journal.pone.0224347.
Frihy, O., W. Moufaddal, E. Deabes and E. E. D. Helmy, 2016: Economic evaluation of using marine dredged material for erosion control along the northeast coast of the Nile Delta, Egypt. *Arabian Journal of Geosciences*, **9**(14), 637, doi:10.1007/s12517-016-2660-y.

Frölicher, T. L., E. M. Fischer and N. Gruber, 2018: Marine heatwaves under global warming. *Nature*, **560**(7718), 360-364, doi:10.1038/s41586-018-0383-9.
Fuller, T. L. et al., 2018: Climate warming causes declines in crop yields and lowers school attendance rates in Central Africa. *Science of The Total Environment*, **610-611**, 503-510, doi:https://doi.org/10.1016/j.scitotenv.2017.08.041.
Funge-Smith, S. and A. Bennett, 2019: A fresh look at inland fisheries and their role in food security and livelihoods. *Fish and Fisheries*, **20**(6), 1176-1195, doi:https://doi.org/10.1111/faf.12403.
Funk, C. et al., 2018a: 18. Anthropogenic enhancement of moderate-to-strong El Niño events likely contributed to drought and poor harvests in southern Africa during 2016. *Bull. Am. Meteorol. Soc*, **99**, S91-S96, doi:10.1175/bams-d-17-0112.1.
Funk, C. et al., 2017: *Climate Change Vulnerability, Impacts and Adaptation Assessment for East Africa: Summary for Policy Makers*. USAID, Burlington, Vermont, 31 pp. Available at: https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID-PREPARED-TetraTech_Vulnerability-Impacts-Adaptation-Assessment-East-Africa-Water.pdf.
Funk, C. et al., 2018b: Examining the role of unusually warm Indo-Pacific sea-surface temperatures in recent African droughts. *Quarterly Journal of the Royal Meteorological Society*, **144**(S1), 360-383, doi:https://doi.org/10.1002/qj.3266.
Funk, C., S. Shukla, A. Hoell and B. Livneh, 2015: 16. ASSESSING THE CONTRIBUTIONS OF EAST AFRICAN AND WEST PACIFIC WARMING TO THE 2014 BOREAL SPRING EAST AFRICAN DROUGHT. *Bulletin of the American Meteorological Society*, **96**(12), S77-S82.
Gabert, J. (ed.), How to make urban and sanitation planning work? Lessons learnt from West Africa, South East Asia, Madagascar, and Haiti. BORDA Symposium - Integrated Management of Used Water and Sanitation, 10 and 11 November 2015, Bremen, Germany, Bremen Overseas Research & Development Association (BORDA), 50-53 pp.
Galle, S. et al., 2018: AMMA-CATCH, a Critical Zone Observatory in West Africa Monitoring a Region in Transition. *Vadose Zone Journal*, **17**(1), 180062, doi:https://doi.org/10.2136/vzj2018.03.0062.
Gan, T. Y. et al., 2016: Possible climate change/variability and human impacts, vulnerability of drought-prone regions, water resources and capacity building for Africa. *Hydrological Sciences Journal*, **61**(7), 1209-1226, doi:10.1080/02626667.2015.1057143.
Gannon, K. E. et al., 2018: Business experience of floods and drought-related water and electricity supply disruption in three cities in sub-Saharan Africa during the 2015/2016 El Niño. *Global Sustainability*, **1**(e14), 1–15, doi:10.1017/sus.2018.14.
Gao, H. et al., 2011: On the causes of the shrinking of Lake Chad. *Environmental Research Letters*, **6**(3), doi:10.1088/1748-9326/6/3/034021.
García-Pando, C. P. et al., 2014: Soil dust aerosols and wind as predictors of seasonal meningitis incidence in Niger. *Environmental health perspectives*, **122**(7), 679–686, doi:https://doi.org/10.1289/ehp.1306640.
García Criado, M. et al., 2020: Woody plant encroachment intensifies under climate change across tundra and savanna biomes. *Global Ecology and Biogeography*, **29**(5), 925-943, doi:https://doi.org/10.1111/geb.13072.
García, L. E. et al., 2014: *Beyond Downscaling: A Bottom-Up Approach to Climate Adaptation for Water Resources Management*. World Bank Group, Washington DC.
Garcia, R. A., M. Cabeza, R. Altwegg and M. B. Araújo, 2016: Do projections from bioclimatic envelope models and climate change metrics match? *Global Ecology and Biogeography*, **25**(1), 65-74, doi:https://doi.org/10.1111/geb.12386.
Garcia, R. A., M. Cabeza, C. Rahbek and M. B. Araújo, 2014: Multiple Dimensions of Climate Change and Their Implications for Biodiversity. *Science (New York, N.Y.)*, **344**(6183), 1247579, doi:10.1126/science.1247579.
García Molinos, J. et al., 2016: Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, **6**(1), 83-88, doi:10.1038/nclimate2769.
Gasparrini, A. et al., 2015: Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet*, **386**(9991), 369-375, doi:10.1016/S0140-6736(14)62114-0.
Gates, A. et al., 2019: Short-term association between ambient temperature and homicide in South Africa: a case-crossover study. *Environmental Health*, **18:109**, doi:10.1186/s12940-019-0549-4.
Gaythorpe, K. A. M. et al., 2020: The effect of climate change on yellow fever disease burden in Africa. *eLife*, **9**, e55619, doi:10.7554/eLife.55619.
GCF, 2018a: *Programme for integrated development and adaptation to climate change in the Niger Basin (PIDACC/NB)*. Green Climate Fund (GCF), Incheon, Republic of Korea, 3 pp. Available at: https://www.greenclimate.fund/project/fp092.
GCF, 2018b: *Updated Gender Policy and Action Plan 2018–2020*. Green Climate Fund, Manama, Bahrain, 24 pp. Available at: https://www.greenclimate.fund/sites/default/files/document/gcf-b21-02.pdf.
Gebre, G. G. and D. B. Rahut, 2021: Prevalence of household food insecurity in East Africa: Linking food access with climate vulnerability. *Climate Risk Management*, **33**, 100333, doi:https://doi.org/10.1016/j.crm.2021.100333.
Gebrechorkos, S. H., S. Hülsmann and C. Bernhofer, 2019: Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. *International Journal of Climatology*, **39**(1), 18-30, doi:10.1002/joc.5777.
Gebremeskel Haile, G. et al., 2019: Droughts in East Africa: Causes, impacts and resilience. *Earth-Science Reviews*, **193**, 146-161, doi:https://doi.org/10.1016/j.earscirev.2019.04.015.

Gebresenbet, F. and A. Kefale, 2012: Traditional coping mechanisms for climate change of pastoralists in South Omo, Ethiopia. *Indian J. Tradit. Knowl.*, **11**(4), 573-579.
GEF, 2019: *Mozambique: Building Resilience in the Coastal Zone through Ecosystem Based Approaches to Adaptation (EbA)*. Global Environment Facility, Washington, DC, 2 pp. Available at: https://www.thegef.org/project/mozambique-building-resilience-coastal-zone-through-ecosystem-based-approaches-adaptation.
GEF and FAO, 2021: *Enhancing Climate Change Resilience in the Benguela Current Fisheries System*. FAO and the GEF Partnering for Sustainable Agriculture and the Environment, **2021**, FAO and the GEF, FAO, Rome, Italy, 2 pp. Available at: http://www.fao.org/gef/projects/detail/en/c/1056798/.
Gemenne, F. and J. Blocher, 2017a: How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *The Geographical Journal*, **183**(4), 336-347, doi:10.1111/geoj.12205.
Gemenne, F. and J. a. Blocher, 2017b: Climate change, natural disasters and population displacements in West Africa. *Geo-Eco-Trop*, **41**(3), 317-337.
Ghanem, H., 2011: The State of Food and Agriculture: Women in Agriculture–Closing the Gender Gap for Development. *Rome: Food and agricultural organization of the United Nations (FAO)*.
Ghermandi, A., D. Obura, C. Knudsen and P. A. L. D. Nunes, 2019: Marine ecosystem services in the Northern Mozambique Channel: A geospatial and socio-economic analysis for policy support. *Ecosystem Services*, **35**, 1-12, doi:10.1016/j.ecoser.2018.10.009.
Giannini, A. and A. Kaplan, 2019: The role of aerosols and greenhouse gases in Sahel drought and recovery. *Climatic Change*, **152**(3), 449-466, doi:10.1007/s10584-018-2341-9.
Giesen, C. et al., 2020: The impact of climate change on mosquito-borne diseases in Africa. *Pathogens and Global Health*, **114**(6), 287-301, doi:10.1080/20477724.2020.1783865.
Gilbert, M. et al., 2018: Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data*, **5**(1), 180227, doi:10.1038/sdata.2018.227.
Gillson, L., T. P. Dawson, S. Jack and M. A. McGeoch, 2013: Accommodating climate change contingencies in conservation strategy. *Trends Ecol Evol*, **28**(3), 135-142, doi:10.1016/j.tree.2012.10.008.
Giorgi, F., F. Raffaele and E. Coppola, 2019: The response of precipitation characteristics to global warming from climate projections. *Earth System Dynamics*, **10**(1), 73-89, doi:10.5194/esd-10-73-2019.
Global Index Insurance Facility, 2019: *Zambia*. Global Index Insurance Facility, Washington, DC, 2 pp. Available at: https://www.indexinsuranceforum.org/sites/default/files/29947_CountryProfile_Zambia_March30.pdf.
Global Parametrics, 2021: Global Parametrics Natural Disaster Fund launched with Vision Fund initiative, Global Parametrics, London, UK. Available at: https://www.globalparametrics.com/news/global-parametrics-natural-disaster-fund-launched-with-vision-fund-initiative/.
Godde, C. M. et al., 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488, doi:https://doi.org/10.1016/j.gfs.2020.100488.
Godsmark, C. N. et al., 2019: Priority focus areas for a sub-national response to climate change and health: A South African provincial case study. *Environment International*, **122**, 31-51, doi:https://doi.org/10.1016/j.envint.2018.11.035.
Golden, C. D. et al., 2016: Nutrition: Fall in fish catch threatens human health. *Nature*, **534**(7607), 317-320, doi:10.1038/534317a.
Golden, C. D. et al., 2021: Aquatic foods to nourish nations. *Nature*, doi:https://doi.org/10.1038/s41586-021-03917-1.
Gone, T., M. Balkew and T. Gebre-Michael, 2014: Comparative entomological study on ecology and behaviour of Anopheles mosquitoes in highland and lowland localities of Derashe District, southern Ethiopia. *Parasites & Vectors*, **7**(1), doi:10.1186/s13071-014-0483-9.
Government of Algeria, 2004: Law No. 04-20 relative to the Prevention of Major Risks and the Management of Catastrophes in the Framework of Sustainable Development, Algeria.
Government of Benin, 2018: Regulating Climate Change, Benin.
Government of Burkina Faso, 2015: *Burkina Faso National Climate Change Adaptation Plan (NAP)*, Burkina Faso Ministry of Environment and Fishery Resources, UNFCCC, Ouagadougou. Available at: https://www4.unfccc.int/sites/NAPC/Documents/Parties/PNA_Version_version%20finale%5BTransmission%5D.pdf.
Government of Cameroon, 2015: *Plan National d'Adaptation aux Changements Climatiques du Cameroun*, Cameroun Ministere de l'Environnement de Laprotection de la Nature et du Developpement Durable, Government of Cameroon,, Yaounde. Available at: https://www4.unfccc.int/sites/NAPC/Documents/Parties/PNACC_Cameroun_VF_Validée_24062015%20-%20FINAL.pdf.
Government of Cape Verde, 2014: Resolution no. 87/2014 (creating the Steering Committee of the project 'Strengthening Capacity of Adaptation and Resilience to Climate Change in the Water Sector in Cape Verde'), Cape Verde.
Government of Central African Republic, 2008: Law no. 08.222 (on the forestry code), Central African Republic.
Government of Ethiopia, 2019: *Ethiopia's Climate Resilient Green Economy: National Adaptation Plan*, Commission, E. E. F. a. C. C., Federal Democratic Republic of Ethiopia, Addis Ababa. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=10&cad=rja&uact=8&ved=2ahUKEwi_r

9-UnIDlAhWgSRUIHYosAQYQFjAJegQIARAC&url=https%3A%2F%2Fwww4.unfccc.int%2Fsites%2FNAPC%2FDocuments%2FParties%2FFinal%2520Ethiopia-national-adaptation-plan%2520%25281%2529.pdf&usg=AOvVaw1u-dBNOG1S-N1MuQObwZ7o.

Government of Gabon, 2016: Decree No. 0122 setting the responsibilities, organization and functioning of the National Council on Climate Change, Gabon.

Government of Ghana, 2018: Public statement that a climate change law is under consideration, Ghana.

Government of Guinea Bissau, 2011: Law No. 1/2011 approving the Basic Legislation on Environment, Guinea Bissau.

Government of Ivory Coast, 2012: Decree No. 2012-1049 of 24 October 2012 establishing the organization and functioning of the National Commission for the reduction of greenhouse gas emissions from deforestation and forest degradation, Ivory Coast.

Government of Kenya, 2016: Climate Change Act No 11 of 2016, Kenya.

Government of Kenya, 2017: *National Climate Change Action Plan 2013-2017*, Resources, M. o. E. a. N., Government Printer, Nairobi. Available at: http://www.environment.go.ke/wpcontent/uploads/2018/08/nationalclimatechangeactionplan2013-2017.pdf

Government of Lesotho, 2008: Lesotho: Environment Act 2008 (No. 10 of 2008), Lesotho.

Government of Liberia, 2002: Environmental Protection and Management Law of the Republic of Liberia, Liberia.

Government of Madagascar, 2015: Law no. 2015-031 on the National Policy of Risk Management and Catastrophes, Madagascar.

Government of Malawi, 2017: Environment Management Act, 2017 (No. 19 of 2017), Malawi.

Government of Malawi, 2019: *Malawi 2019 Floods Post Disaster Needs Assessment (PDNA)*, 106 pp. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/Malawi%202019%20Floods%20Post%20Disaster%20Needs%20Assessment%20Report.pdf.

Government of Mali, 2016: Ordinance No. 2016-007 P-RM of 25 February 2016 establishing the Project to Strengthen Resilience to Food Insecurity and Decree No. 2011-107-PM-RM of March 11, 2011 establishing the National Climate Change Committee Mali, Mali.

Government of Morocco, 2014: Framework Law 99-12 on the National Charter for the Environment and Sustainable Development, Morocco.

Government of Mozambique, 2014: Law No. 15/2014 establishing the legal framework for disaster management, Mozambique.

Government of Mozambique, 2019: *Mozambique Cyclone Idai: Post Disaster Needs Assessment*. Government of Mozambique, Maputo. Available at: https://www.undp.org/content/dam/undp/library/Climate%20and%20Disaster%20Resilience/PDNA/PDNA%20Mozambique%20Cyclone%20Idai%20-%20Post-Disaster%20Needs%20Assessment_Executive%20Summary.pdf.

Government of Niger, 1998: Law no. 98-56 (Framework Law on Environmental Management), Niger.

Government of Nigeria, 2017: Climate Change Bill 2017, Nigeria.

Government of Republic of Rwanda, 2020: *Updated Nationally Determined Contribution* Minister of Environment Republic of Rwanda, Rwanda, M. o. E. R. o., 96 pp. Available at: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Rwanda%20First/Rwanda_Updated_NDC_May_2020.pdf.

Government of Rwanda, 2012: Law No. 16 of 22 May 2012, determining the Organisation, Functioning and Mission of the National Fund for Environment, Rwanda.

Government of Sierra Leone, 2012: The National Protected Area Authority and Conservation Trust Fund Act, 2012 (No. 11 of 2012), Sierra Leone.

Government of Somalia, 2018: *Somalia Drought Impact and Needs Assessment (DINA) Vol. 2*, **2**, 180 pp. Available at: https://www.undp.org/content/undp/en/home/librarypage/climate-and-disaster-resilience-/somalia-drought-impact-and-needs-assessment.html.

Government of South Africa, 2018: Climate Change Bill, South Africa.

Government of Tanzania, 2004: Environmental Management Act 20 of 2004, Tanzania.

Government of the Republic of Kenya, 2018: *National Climate Change Action Plan (Kenya): 2018-2022*. Ministry of Environment and Forestry, Forestry, M. o. E. a., Nairobi, Kenya, 110 pp. Available at: https://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2018/10/8737.pdf.

Government of the Republic of Zambia, 2010: *National Climate Change Response Strategy (NCCRS) Zambia*. Ministry of Tourism, Environment and Natural Resources, Ministry of Tourism, E. a. N. R., Lusaka, Zambia, 135 pp. Available at: https://www.adaptation-undp.org/sites/default/files/downloads/zambia-climate_change_response_strategy.pdf.

Government of the Seychelles, 2015: Conservation and Climate Adaptation Trust of Seychelles Act 18 of 2015, Seychelles.

Government of The Seychelles, 2020: *Seychelles National Climate Change Strategy*. Seychelles Ministry of Environment, Energy and Climate Change, Seychelles, G. o. T., 32 pp. Available at: http://www.meecc.gov.sc/wp-content/uploads/2019/10/seychelles-national-climate-change-policy-may-2020.pdf.

Government of Togo, 2008: Law 2008-005 - Framework Law on the Environment, Togo.

Government of Togo, 2016: *Plan National d'Adaption aux Changements Climatiques du Togo (PNACC)*, Forestieres, M. d. l. E. e. d. R., Ministere de l'Environment et des Ressources Forestieres, Lome. Available at: https://www.preventionweb.net/files/12232_TogoNAPA.pdf.
Government of Uganda, 2018: Climate Change Bill 2018, Uganda.
Government of Zambia, 2016: Constitution of Zambia (Amendment) Act No. 2 of 2016, Zambia.
Government of Zimbabwe, 2019: Draft Climate Change Bill, 2019, Zimbabwe.
Governmet of the United Republic of Tanzania, 2011: *National Climate Change Strategy and Action Plan*, President, O. o. t. V., Dar es Salaam, Tanzania, 100 pp. Available at: http://www.tzdpg.or.tz/fileadmin/_migrated/content_uploads/TZ_CC_strategy_draft_Jan_2012_01.pdf.
Gownaris, N. J. et al., 2016: Fisheries and water level fluctuations in the world's largest desert lake. *Ecohydrology*, **10**(1), e1769, doi:10.1002/eco.1769.
Gownaris, N. J. et al., 2018: Water level fluctuations and the ecosystem functioning of lakes. *Journal of Great Lakes Research*, **44**(6), 1154-1163, doi:10.1016/j.jglr.2018.08.005.
Grace, K., V. Hertrich, D. Singare and G. Husak, 2018: Examining rural Sahelian out-migration in the context of climate change: An analysis of the linkages between rainfall and out-migration in two Malian villages from 1981 to 2009. *World Development*, **109**, 187-196, doi:https://doi.org/10.1016/j.worlddev.2018.04.009.
Graff Zivin, J. and M. Neidell, 2014: Temperature and the Allocation of Time: Implications for Climate Change. *Journal of Labor Economics*, **32**(1), 1-26, doi:10.1086/671766.
Graham, J. P., M. Hirai and S. S. Kim, 2016: An Analysis of Water Collection Labor among Women and Children in 24 Sub-Saharan African Countries. *PLoS One*, **11**(6), e0155981, doi:10.1371/journal.pone.0155981.
Granoff, I., J. R. Hogarth and A. Miller, 2016: Nested barriers to low-carbon infrastructure investment. *Nature Climate Change*, **6**(12), 1065-1071, doi:10.1038/nclimate3142.
Grant, B. C., 2015: Investigating tourism and climate change: the case of St Francis Bay and Cape St Francis. University of the Witwatersrand, Johannesburg.
Grasham, C. F., M. Korzenevica and K. J. Charles, 2019: On considering climate resilience in urban water security: A review of the vulnerability of the urban poor in sub-Saharan Africa. *Wiley Interdisciplinary Reviews: Water*, **6**(3), doi:10.1002/wat2.1344.
Gray, C. and V. Mueller, 2012: Drought and population mobility in rural Ethiopia. *World Dev*, **40**(1), 134-145, doi:10.1016/j.worlddev.2011.05.023.
Gray, C. and E. Wise, 2016: Country-specific effects of climate variability on human migration. *Climatic Change*, **135**((3–4)), 555–568, doi:10.1007/s10584-015-1592-y.
Gray, C. L. et al., 2016: Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nature Communications*, **7**(1), 12306, doi:10.1038/ncomms12306.
Gray Emma, F. and J. Bond William, 2013: Will woody plant encroachment impact the visitor experience and economy of conservation areas? : original research. *Koedoe : African Protected Area Conservation and Science*, **55**(1), 1-9, doi:10.4102/koedoe.v55i1.1106.
Greatrex, H. et al., 2015: *Scaling up index insurance for smallholder farmers: Recent evidence and insights*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), CCAFS, Copenhagen, Denmark, 32 pp. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/53101/CCAFS_Report14.pdf.
Greene, S. et al., 2020: *Understanding local climate priorities. Applying a gender and generation focused planning tool in mainland Tanzania and Zanzibar*. International Institute for Environment and Development (IIED). Available at: http://www.jstor.org/stable/resrep29063 (accessed 2021/08/30/).
Greve, P., M. L. Roderick, A. M. Ukkola and Y. Wada, 2019: The aridity Index under global warming. *Environmental Research Letters*, **14**(12), 124006, doi:10.1088/1748-9326/ab5046.
Griscom, B. W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114**(44), 11645, doi:10.1073/pnas.1710465114.
Groth, J. et al., 2021: Investigating environment-related migration processes in Ethiopia – A participatory Bayesian network. *Ecosystems and People*, **17**(1), 128-147, doi:10.1080/26395916.2021.1895888.
Gu, D., P. Gerland, Pelletier and B. Cohen, 2015: *Risks of Exposure and Vulnerability to Natural Disasters at the City Level: A Global Overview*. Nations, U., 48 pp. Available at: https://population.un.org/wup/Publications/Files/WUP2014-TechnicalPaper-NaturalDisaster.pdf.
Gu, X. et al., 2020: Impacts of anthropogenic warming and uneven regional socio-economic development on global river flood risk. *Journal of Hydrology*, **590**, 125262, doi:https://doi.org/10.1016/j.jhydrol.2020.125262.
Guan, K. et al., 2017: Assessing climate adaptation options and uncertainties for cereal systems in West Africa. *Agricultural and Forest Meteorology*, **232**, 291-305, doi:10.1016/j.agrformet.2016.07.021.
Gudoshava, M. et al., 2020: Projected effects of 1.5 C and 2 C global warming levels on the intra-seasonal rainfall characteristics over the Greater Horn of Africa. *Environmental Research Letters*, **15**(3), 034037, doi:https://doi.org/10.1088/1748-9326/ab6b33.
Gulacha, M. M. and D. M. M. Mulungu, 2017: Generation of climate change scenarios for precipitation and temperature at local scales using SDSM in Wami-Ruvu River Basin Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C*, **100**, 62-72, doi:https://doi.org/10.1016/j.pce.2016.10.003.
Gumucio, T., J. Hansen, S. Huyer and T. van Huysen, 2020: Gender-responsive rural climate services: a review of the literature. *Climate and Development*, **12**(3), 241-254, doi:10.1080/17565529.2019.1613216.

Güneralp, B., İ. Güneralp and Y. Liu, 2015: Changing global patterns of urban exposure to flood and drought hazards. *Global Environmental Change*, **31**, 217-225, doi:10.1016/j.gloenvcha.2015.01.002.

Gurewich, D., A. Garg and N. R. Kressin, 2020: Addressing Social Determinants of Health Within Healthcare Delivery Systems: a Framework to Ground and Inform Health Outcomes. *Journal of General Internal Medicine*, **35**(5), 1571-1575, doi:10.1007/s11606-020-05720-6.

Gutiérrez, J. M. et al., 2021: *Atlas* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change **In Press**, Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Atlas.pdf.

Habermann, E. et al., 2019: Warming and water deficit impact leaf photosynthesis and decrease forage quality and digestibility of a C4 tropical grass. *Physiologia Plantarum*, **165**(2), 383-402, doi:10.1111/ppl.12891.

Haensler, A., F. Saeed and D. Jacob, 2013: Assessing the robustness of projected precipitation changes over central Africa on the basis of a multitude of global and regional climate projections. *Climatic Change*, **121**(2), 349-363, doi:10.1007/s10584-013-0863-8.

Hagos, S. et al., 2014: Climate change, crop production and child under nutrition in Ethiopia; a longitudinal panel study. *BMC public health*, **14**, 884, doi:10.1186/1471-2458-14-884.

Haile, G. G. et al., 2020: Projected Impacts of Climate Change on Drought Patterns Over East Africa. *Earth's Future*, **8**(7), e2020EF001502, doi:https://doi.org/10.1029/2020EF001502.

Hall, K., I. Meiklejohn and J. Arocena, 2007: The thermal responses of rock art pigments: Implications for rock art weathering in southern Africa. *Geomorphology*, **91**(1), 132-145, doi:https://doi.org/10.1016/j.geomorph.2007.02.002.

Hallegatte, S. et al., 2016: *"Shock Waves" Managing the Impacts of Climate Change on Poverty*. Climate Change and Development Series, The World Bank,, Washington, DC, 227 pp. ISBN 978-1-4648-0674-2.

Hallegatte, S. et al., 2018: *The Economics of (and Obstacles to) Aligning Development and Climate Change Adaptation: A World Bank Group Contribution to the Global Commission on Adaptation*. Global Commission on Adaptation, Rotterdam and Washington, DC, 22 pp. Available at: https://gca.org/wp-content/uploads/2018/10/18_WP_GCA_Economics_1001_final.pdf.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**(4), 250-256, doi:10.1038/nclimate3253.

Hambira, W. L. and J. Saarinen, 2015: Policy-makers' perceptions of the tourism–climate change nexus: Policy needs and constraints in Botswana. *Development Southern Africa*, **32**(3), 350-362, doi:10.1080/0376835X.2015.1010716.

Hambira, W. L., J. Saarinen and O. Moses, 2020: Climate change policy in a world of uncertainty: changing environment, knowledge, and tourism in Botswana. *African Geographical Review*, **39**(3), 252-266, doi:10.1080/19376812.2020.1719366.

Hamed, Y. et al., 2018: Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. *Euro-Mediterranean Journal for Environmental Integration*, **3**(1), doi:10.1007/s41207-018-0067-8.

Han, F., K. H. Cook and E. K. Vizy, 2019: Changes in intense rainfall events and dry periods across Africa in the twenty-first century. *Clim Dyn*, **53**(5), 2757-2777, doi:10.1007/s00382-019-04653-z.

Hannah, L. et al., 2020: 30% land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography*, **43**(7), 943-953, doi:https://doi.org/10.1111/ecog.05166.

Hansen, J. et al., 2019a: *Scaling Climate Services to Enable Effective Adaptation Action*. Adaptation, G. C. o., Rotterdam, the Netherlands & Washington, DC, United States. Available at: https://hdl.handle.net/10568/105763.

Hansen, J. et al., 2019b: Climate risk management and rural poverty reduction. *Agricultural Systems*, **172**, 28-46, doi:https://doi.org/10.1016/j.agsy.2018.01.019.

Hansen, J. W. et al., 2019c: Climate Services Can Support African Farmers' Context-Specific Adaptation Needs at Scale. *Frontiers in Sustainable Food Systems*, **3**(21), 1-16, doi:10.3389/fsufs.2019.00021.

Harari, M. and E. L. Ferrara, 2018: Conflict, Climate, and Cells: A Disaggregated Analysis. *The Review of Economics and Statistics*, **100**(4), 594-608, doi:10.1162/rest_a_00730.

Harkin, K. et al., 2020: Impacts of climate change on cultural heritage. *MCCIP Sci. Rev*, **16**, 24-39, doi:10.14465/2020.arc26.che.

Harmanny, K. S. and Ž. Malek, 2019: Adaptations in irrigated agriculture in the Mediterranean region: an overview and spatial analysis of implemented strategies. *Regional Environmental Change*, **19**(5), 1401-1416, doi:10.1007/s10113-019-01494-8.

Harrington, L. J. et al., 2016: Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. *Environmental Research Letters*, **11**(5), 055007, doi:10.1088/1748-9326/11/5/055007.

Harrington, L. J., D. J. Frame, E. Hawkins and M. Joshi, 2017: Seasonal cycles enhance disparities between low- and high-income countries in exposure to monthly temperature emergence with future warming. *Environmental Research Letters*, **12**(11), 114039, doi:10.1088/1748-9326/aa95ae.

Harrington, L. J. and F. E. L. Otto, 2020: Reconciling theory with the reality of African heatwaves. *Nature Climate Change*, **10**(9), 796-798, doi:10.1038/s41558-020-0851-8.
Harris, L. et al., 2016: Intersections of gender and water: comparative approaches to everyday gendered negotiations of water access in underserved areas of Accra, Ghana and Cape Town, South Africa. *Journal of Gender Studies*, **26**(5), 561-582, doi:10.1080/09589236.2016.1150819.
Harrison, L., C. Funk and P. Peterson, 2019: Identifying changing precipitation extremes in Sub-Saharan Africa with gauge and satellite products. *Environmental Research Letters*, **14**(8), 085007, doi:10.1088/1748-9326/ab2cae.
Harrod, C., A. Ramirez, J. Valbo-Jorgensen and S. Funge-Smith, 2018a: How climate change impacts inland fisheries. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. FAO, Rome, pp. 375-391. ISBN 9789251306079.
Harrod, C., A. Ramirez, J. Valbo-Jorgensen and S. F. Smith, 2018b: Current anthropogenic stress and projected effect of climate change on global inland fisheries. [Barange, M., T. Bahri, M. Beveridge, K. Cochrane and S. Funge-Smith (eds.)]. Food and Agriculture organization of the United Nations, Rome, pp. 393-448. ISBN 9789251306079.
Harrod, C., F. Simmance, S. Funge-Smith and J. Valbo-Jorgensen, 2018c: Options and opportunities for supporting inland fisheries to cope with climate change adaptation in other sectors. [Barange, M., T. Bahri, M. Beveridge, K. Cochrane and S. Funge-Smith (eds.)]. FAO, Rome, pp. 567-584. ISBN 9789251306079.
Harvey, B., L. Jones, L. Cochrane and R. Singh, 2019: The evolving landscape of climate services in sub-Saharan Africa: What roles have NGOs played. *Climatic Change*, **157**, 81–98, doi:10.1007/s10584-019-02410-z.
Hasegawa, T. et al., 2021: A global dataset for the projected impacts of climate change on four major crops. *bioRxiv*, 2021.2005.2027.444762, doi:10.1101/2021.05.27.444762.
Hastenrath, S., 2010: Climatic forcing of glacier thinning on the mountains of equatorial East Africa. *International Journal of Climatology*, **30**(1), 146-152, doi:https://doi.org/10.1002/joc.1866.
Havelaar, A. H. et al., 2015: World Health Organization global estimates and regional comparisons of the burden of foodborne disease in 2010. *PLoS medicine*, **12**(12), e1001923.
Headey, D. D. and T. S. Jayne, 2014: Adaptation to land constraints: Is Africa different? *Food Policy*, **48**, 18-33, doi:10.1016/j.foodpol.2014.05.005.
Hearn, G., 2016: Managing road transport in a world of changing climate and land use. *Proceedings of the Institution of Civil Engineers - Municipal Engineer*, **169**(3), 146-159, doi:10.1680/muen.15.00009.
Heilmayr, R., C. Echeverría and E. F. Lambin, 2020: Impacts of Chilean forest subsidies on forest cover, carbon and biodiversity. *Nature Sustainability*, **3**(9), 701-709, doi:10.1038/s41893-020-0547-0.
Hellberg, S., 2019: Scarcity as a means of governing: Challenging neoliberal hydromentality in the context of the South African drought. *Environment and Planning E: Nature and Space*, **3**(1), 186-206, doi:10.1177/2514848619853551.
Hempson, G. P., S. Archibald and W. J. Bond, 2017: The consequences of replacing wildlife with livestock in Africa. *Scientific Reports*, **7**(1), 17196, doi:10.1038/s41598-017-17348-4.
Henderson, J., A. Storeygard and U. Deichmann, 2014: 50 years of urbanization in Africa : examining the role of climate change. *World Bank Policy Research Working Paper*,(6925), doi:10.1596/1813-9450-6925.
Hendrix, C. S., 2017: The streetlight effect in climate change research on Africa. *Global Environmental Change*, **43**, 137-147, doi:10.1016/j.gloenvcha.2017.01.009.
Hendrix, C. S. and I. Salehyan, 2012: Climate change, rainfall, and social conflict in Africa. *Journal of Peace Research*, **49**(1), 35-50, doi:10.1177/0022343311426165.
Henry, S., B. Schoumaker and C. Beauchemin, 2004: The Impact of Rainfall on the First Out-Migration: A Multi-level Event-History Analysis in Burkina Faso. *Population and Environment*, **25**(5), 423-460, doi:10.1023/B:POEN.0000036928.17696.e8.
Henseler, M. and I. Schumacher, 2019: The impact of weather on economic growth and its production factors. *Climatic Change*, **154**(3), 417-433, doi:10.1007/s10584-019-02441-6.
Hepburn, C. et al., 2020: Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Review of Economic Policy*, **36**(Supplement_1), S359-S381, doi:10.1093/oxrep/graa015.
Hermans-Neumann, K., J. Priess and M. Herold, 2017: Human migration, climate variability, and land degradation: hotspots of socio-ecological pressure in Ethiopia. *Regional Environmental Change*, **17**(5), 1479-1492, doi:10.1007/s10113-017-1108-6.
Herrero, M. et al., 2016: Climate change and pastoralism: impacts, consequences and adaptation. *Rev Sci Tech*, **35**(2), 417-433, doi:10.20506/rst.35.2.2533.
Herslund, L. B. et al., 2016: A multi-dimensional assessment of urban vulnerability to climate change in Sub-Saharan Africa. *Natural Hazards*, **82**(2), 149-172, doi:10.1007/s11069-015-1856-x.
Hertig, E. et al., 2014: Statistical modelling of extreme precipitation indices for the Mediterranean area under future climate change. *International Journal of Climatology*, **34**(4), 1132-1156, doi:10.1002/joc.3751.
Heubes, J. et al., 2011: Modelling biome shifts and tree cover change for 2050 in West Africa. *Journal of Biogeography*, **38**(12), 2248-2258, doi:10.1111/j.1365-2699.2011.02560.x.
Hidalgo, M., V. Mihneva, M. Vasconcellos and M. Bernal, 2018: *Climate change impacts, vulnerabilities and adaptations: Mediterranean Sea and the Black Sea marine fisheries* [Barange, M., T. Bahri, M. C. M. Beveridge,

K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options, FAO, Rome. Available at: http://www.fao.org/3/i9705en/I9705EN.pdf.
Hill, M. P. et al., 2016: Predicted decrease in global climate suitability masks regional complexity of invasive fruit fly species response to climate change. *Biological Invasions*, **18**(4), 1105-1119, doi:10.1007/s10530-016-1078-5.
Himanen, S. J., H. Mäkinen, K. Rimhanen and R. Savikko, 2016: Engaging Farmers in Climate Change Adaptation Planning: Assessing Intercropping as a Means to Support Farm Adaptive Capacity. *Agriculture*, **6**(3), doi:10.3390/agriculture6030034.
Hinkel, J. et al., 2012: Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. *Regional Environmental Change*, **12**(1), 207-224, doi:10.1007/s10113-011-0249-2.
Hirvonen, K., 2016: Temperature Changes, Household Consumption, and Internal Migration: Evidence from Tanzania. *American Journal of Agricultural Economics*, **98**(4), 1230-1249, doi:https://doi.org/10.1093/ajae/aaw042.
Hlalele, B., I. Mokhatle and R. Motlogeloa, 2016: Assessing Economic Impacts of Agricultural Drought: A Case of Thaba Nchu, South Africa. *Journal of Earth Science and Climate Change*, **7**(1), 327, doi:10.4172/2157-7617.1000327.
Hobday, A. J. et al., 2016: A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, **141**, 227-238, doi:https://doi.org/10.1016/j.pocean.2015.12.014.
Hodgson, G. M., 2000: What Is the Essence of Institutional Economics? *Journal of Economic Issues*, **34**(2), 317-329, doi:10.1080/00213624.2000.11506269.
Hoegh-Guldberg, O. et al., 2014: *The Ocean* [Barros, V. R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L. L. White (eds.)]. Climate Change 2014: Impacts, Adaptation, and Vulnerability Part B: Regional Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change, USA: Cambridge University Press, Cambridge University Press, Cambridge, United Kingdom and New York, NY, 1655-1731 pp. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap30_FINAL.pdf.
Hoegh-Guldberg, O. et al., 2018: *Impacts of 1.5ºC global warming on natural and human systems* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter3_Low_Res.pdf.
Hoffmann, R. et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change*, **10**(10), 904-912, doi:10.1038/s41558-020-0898-6.
Hole, D. G. et al., 2009: Projected impacts of climate change on a continent-wide protected area network. *Ecol Lett*, **12**(5), 420-431, doi:10.1111/j.1461-0248.2009.01297.x.
Hooli, L. J., 2016: Resilience of the poorest: coping strategies and indigenous knowledge of living with the floods in Northern Namibia. *Regional Environmental Change*, **16**(3), 695-707, doi:10.1007/s10113-015-0782-5.
Hope, M., 2019: Cyclones in Mozambique may reveal humanitarian challenges of responding to a new climate reality. *The Lancet Planetary Health*, **3**(8), e338-e339, doi:https://doi.org/10.1016/S2542-5196(19)30131-7.
Houéménou, H. et al., 2020: Degradation of groundwater quality in expanding cities in West Africa. A case study of the unregulated shallow aquifer in Cotonou. *Journal of Hydrology*, **582**, 124438, doi:https://doi.org/10.1016/j.jhydrol.2019.124438.
Hove, M. and T. Gweme, 2018: Women's food security and conservation farming in Zaka District-Zimbabwe. *Journal of Arid Environments*, **149**, 18-29, doi:https://doi.org/10.1016/j.jaridenv.2017.10.010.
Hoveka, L. N. et al., 2016: Effects of climate change on the future distributions of the top five freshwater invasive plants in South Africa. *South African Journal of Botany*, **102**, 33-38, doi:10.1016/j.sajb.2015.07.017.
Howard, G., R. Calow, A. Macdonald and J. Bartram, 2016: Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action. *Annual Review of Environment and Resources*, **41**(1), 253-276, doi:10.1146/annurev-environ-110615-085856.
Howells, M. et al., 2013: Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, **3**(7), 621-626, doi:10.1038/nclimate1789.
Hsiang, S. M., M. Burke and E. Miguel, 2013a: Quantifying the influence of climate on human conflict. *Science (New York, N.Y.)*, **341**(6151), 1235367, doi:10.1126/science.1235367.
Hsiang, S. M., M. Burke and E. Miguel, 2013b: *Reconciling Temperature-conflict Results in Kenya*. UC Berkeley, Berkeley, CA. Available at: http://www.escholarship.org/uc/item/9ct8g2zr.
Hsiang, S. M. and A. S. Jina, 2014: *The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones*. National Bureau of Economic Research, Cambridge, MA. Available at: https://www.nber.org/system/files/working_papers/w20352/w20352.pdf.
Hu, L., J.-J. Luo, G. Huang and M. C. Wheeler, 2019: Synoptic Features Responsible for Heat Waves in Central Africa, a Region with Strong Multidecadal Trends. *Journal of Climate*, **32**(22), 7951-7970, doi:https://doi.org/10.1175/JCLI-D-18-0807.1.

Hua, W. et al., 2016: Possible causes of the Central Equatorial African long-term drought. *Environmental Research Letters*, **11**(12), 124002, doi:10.1088/1748-9326/11/12/124002.
Hubau, W. et al., 2020: Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, **579**(7797), 80-87, doi:10.1038/s41586-020-2035-0.
Huber-Lee, A. et al., 2015: Reference Investment Scenario. In: *Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors* [Cervigni, R., R. Liden, J. E. Neumann and K. M. Strzepek (eds.)]. The World Bank, Washington, DC, pp. 77-83. ISBN 978-1-4648-0466-3.
Hufe, P. and D. F. Heuermann, 2017: The local impacts of large-scale land acquisitions: a review of case study evidence from Sub-Saharan Africa. *Journal of Contemporary African Studies*, **35**(2), 168-189, doi:10.1080/02589001.2017.1307505.
Hughes, D. A., 2019: Facing a future water resources management crisis in sub-Saharan Africa. *Journal of Hydrology: Regional Studies*, **23**, doi:10.1016/j.ejrh.2019.100600.
Hughes, T. P. et al., 2018: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science (New York, N.Y.)*, **359**(6371), 80, doi:10.1126/science.aan8048.
Huldén, L., R. McKitrick and L. Huldén, 2014: Average household size and the eradication of malaria. *J. R. Stat. Soc. Ser. A Stat. Soc.*, **177**(3), 725-742.
Hulme, M., 2017: Climate Change and the Significance of Religion. *Economic and Political Weekly*, **52**(28), 14-17.
Hummel, D., 2016: Climate change, land degradation and migration in Mali and Senegal – some policy implications. *Migration and Development*, **5**(2), 211-233, doi:10.1080/21632324.2015.1022972.
Humphrey, G. J., L. Gillson and G. Ziervogel, 2021: How changing fire management policies affect fire seasonality and livelihoods. *Ambio*, **50**(2), 475-491, doi:10.1007/s13280-020-01351-7.
Hunter, N. B., M. A. North, D. C. Roberts and R. Slotow, 2020: A systematic map of responses to climate impacts in urban Africa. *Environmental Research Letters*, **15**(10), 103005, doi:10.1088/1748-9326/ab9d00.
Hunter, R. e., K. Nordin and M. Thom, 2018: *Inclusive insurance enhanced through the use of client data; typologies, use cases and adoption challenges*. insight2impact, Nairobi, Kenya. Available at: https://cenfri.org/wp-content/uploads/2018/10/Inclusive-insurance-enhanced-through-the-use-of-client-data_i2i-FSDA_October-2018_SINGLE.pdf.
Huntingford, C. et al., 2013: Simulated resilience of tropical rainforests to CO2-induced climate change. *Nature Geoscience*, **6**(4), 268-273, doi:10.1038/ngeo1741.
Huntjens, P. and K. Nachbar, 2015: *Climate Change as a Threat Multiplier for Human Disaster and Conflict. The Hague Institute for Global Justice*. **Working Paper 9**. Available at: http://www.thehagueinstituteforglobaljustice.org/working-paper-9.
Hurrell, J. W., Y. Kushnir, G. Ottersen and M. Visbeck, 2003: *An Overview of the North Atlantic Oscillation*. The North Atlantic Oscillation: Climatic Significance and Environmental Impact, vol. 134, American Geophysical Union, Washington, D.C.
Ide, T., M. Brzoska, J. F. Donges and C.-F. Schleussner, 2020: Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk. *Global Environmental Change*, **62**, 102063, doi:https://doi.org/10.1016/j.gloenvcha.2020.102063.
IDMC, 2018: *Global Report on Internal Displacement - GRID 2018*. Internal Displacment Monitoring Centre, Norwegian Refugee Council, Geneva, Switzerland.
IDMC, 2019: *Global Report on Internal Displacement GRID 2019*. Internal Displacement Monitoring Center, Geneva, Switzerland, 159 pp. Available at: https://www.internal-displacement.org/global-report/grid2019/.
IDMC, 2020: *Global Report on Internal Displacement GRID 2020.* . Internal Displacement Monitoring Centre,, Geneva, Switzerland,, 136 pp. Available at: https://www.internal-displacement.org/sites/default/files/publications/documents/grid2021_idmc.pdf.
IDRC, 2021: Open Access Policy for IDRC-Funded Project Outputs. Available at: https://www.idrc.ca/en/open-access-policy-idrc-funded-project-outputs.
IEA, 2019: *Africa Energy Outlook 2019*. World Energy Outlook Special Report, International Energy Agency, Paris. Available at: https://www.iea.org/reports/africa-energy-outlook-2019.
IEA, 2021: *Sustainable Recovery Tracker*. IEA, Paris, 25 pp. Available at: https://www.iea.org/reports/sustainable-recovery-tracker.
Ifejika Speranza, C., 2010: Drought Coping and Adaptation Strategies: Understanding Adaptations to Climate Change in Agro-pastoral Livestock Production in Makueni District, Kenya. *The European Journal of Development Research*, **22**(5), 623-642, doi:10.1057/ejdr.2010.39.
IFPRI, 2016: *2016 Global Nutrition Report. From Promise to Impact: Ending Malnutrition by 2030*. International Food Policy Research Institute (IFPRI), Washington, DC. Available at: http://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/130354/filename/130565.pdf.
IIED, 2015: *Vulnerable Communities: Getting their Needs and Knowledge into Climate Policy*. IIED Briefing, International Institute for Environment and Development (IIED), London, UK. Available at: https://pubs.iied.org/pdfs/17328IIED.pdf.
Iizumi, T. et al., 2021: Rising temperatures and increasing demand challenge wheat supply in Sudan. *Nature Food*, **2**(1), 19-27, doi:10.1038/s43016-020-00214-4.

Iizumi, T. et al., 2020: Climate change adaptation cost and residual damage to global crop production. *Climate Research*, **80**(3), 203-218.
Iizumi, T. et al., 2018: Crop production losses associated with anthropogenic climate change for 1981–2010 compared with preindustrial levels. *International Journal of Climatology*, **38**(14), 5405-5417, doi:https://doi.org/10.1002/joc.5818.
ILEC and UNEP, 2016: *Transboundary Lakes and Reservoirs: Status and Trends, Summary for Policy Makers.*, United Nations Environment Programme (UNEP), Nairobi. Available at: https://www.unep.org/resources/report/transboundary-lakes-and-reservoirs-status-and-future-trends-volume-2-lake-basins.
ILO, 2018a: *The employment Impact of climate change adaptation*. International Labour Organisation, Geneva, Switzerland. Available at: https://www.ilo.org/wcmsp5/groups/public/---ed_emp/documents/publication/wcms_645572.pdf.
ILO, 2018b: *Women and men in the informal economy: a statistical picture*. **3**, International Labour Office, Geneva, Switzerland, 164 pp. Available at: https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/documents/publication/wcms_626831.pdf.
ILO, 2019: *Skills for a greener future: a global view*. International Labout Office, Geneva, Switzerland. Available at: https://www.ilo.org/wcmsp5/groups/public/---ed_emp/documents/publication/wcms_732214.pdf.
Iloka Nnamdi, G., 2016: Indigenous knowledge for disaster risk reduction : an African perspective : original research. *Jamba : Journal of Disaster Risk Studies*, **8**(1), 1-7, doi:10.4102/jamba.v8i1.272.
İlseven, S. et al., 2019: Attitude and risk perception of climate change in farming communities in Tripoli, Libya. *Chimica Oggi/Chemistry Today*, 91-96.
Ingram, J., 2011: A food systems approach to researching food security and its interactions with global environmental change. *Food Security*, **3**(4), 417-431, doi:10.1007/s12571-011-0149-9.
InsurResilience, 2021: Tripartite Agreement: A public-private partnership between BMZ, UNDP and IDF leveraging financing, expertise and risk capital for the fulfilment of Vision 2025, InsurResilience Global Partnership, Bonn, Germany. Available at: https://annualreport.insuresilience.org/tripartite-agreement/.
International Institute of Water Management, Rainfed Agriculture Summary. Available at: https://www.iwmi.cgiar.org/issues/rainfed-agriculture/summary/.
IPBES, 2018: *Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for Africa of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.* [E. Archer, L. E. D., K. J. Mulongoy, M. A. Maoela, M. Walters, R. Biggs, M-C. Cormier-Salem, F. DeClerck, M. C. Diaw, A. E. Dunham, P. Failler, C. Gordon, K. A. Harhash, R. Kasisi, F. Kizito, W. D. Nyingi, N. Oguge, B. Osman-Elasha, L. C. Stringer, L. Tito de Morais, A. Assogbadjo, B. N. Egoh, M. W. Halmy, K. Heubach, A. Mensah, L. Pereira and N. Sitas (ed.)]. IPBES secretariat, Bonn, Germany, 49 pp. Available at: https://ipbes.net/sites/default/files/spm_africa_2018_digital.pdf.
IPBES, 2020: *IPBES workshop on biodiversity and pandemics: Executive summary*. Intergovernmental SciencePolicy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany. Available at: https://ipbes.net/sites/default/files/2020-10/IPBES%20Pandemics%20Workshop%20Report%20Executive%20Summary%20Final.pdf.
IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Pachauri, R. K. and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. Available at: https://www.ipcc.ch/report/ar5/syr/.
IPCC, 2018a: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
IPCC, 2018b: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (ed.)]. In Press pp. Available at: https://www.ipcc.ch/sr15/download/.
IPCC, 2018c: *Summary for Policymakers* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, In press pp. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf.

IPCC, 2019a: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Skea, J., E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)]. Shukla, P. R., In press pp. Available at: https://www.ipcc.ch/srccl-report-download-page/.
IPCC, 2019b: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. In press pp. Available at: https://www.ipcc.ch/srocc/download/.
IPCC, 2019c: *Technical Summary* [H.-O. Pörtner, D. C. R., V. Masson-Delmotte, P. Zhai, E. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (ed.)]. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate **In press**, 39-69 pp. Available at: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/04_SROCC_TS_FINAL.pdf
IPCC, 2021: *Summary for Policymakers* [MassonDelmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, **In press**, Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.
Irwin, A. et al., 2006: The commission on social determinants of health: tackling the social roots of health inequities. *PLoS Med*, **3**(6), e106, doi:10.1371/journal.pmed.0030106.
Islam, N. S. and J. Winkel, 2017: *Climate Change and Social Inequality*. Building Resilience to Climate Change – An Opportunity to Reduce Inequalities, UNITED NATIONS, New York, USA, 32 pp. Available at: https://www.un.org/esa/desa/papers/2017/wp152_2017.pdf.
Iyakaremye, V., G. Zeng and G. Zhang, 2021: Changes in extreme temperature events over Africa under 1.5 and 2.0°C global warming scenarios. *International Journal of Climatology*, **41**(2), 1506-1524, doi:https://doi.org/10.1002/joc.6868.
Jack, C., P. Wolski, I. Pinto and V. Indasi, 2016: Southern Africa: Tools for observing and modelling climate. In: *Africa's climate: Helping decision-makers make sense of climate information*. Future Climate for Africa, Cape Town, South Africa, pp. 23-30.
Jacobs, K. L. and R. B. Street, 2020: The next generation of climate services. *Climate Services*, **20**, 100199, doi:10.1016/j.cliser.2020.100199.
Jafino, B. A., B. Walsh, J. Rozenberg and S. Hallegatte, 2020: *Revised Estimates of the Impact of Climate Change on Extreme Poverty by 2030*. Poverty and Shared Prosperity 2020, World Bank Group, Group, W. B., Washington DC, USA, 17 pp. Available at: https://documents1.worldbank.org/curated/en/706751601388457990/pdf/Revised-Estimates-of-the-Impact-of-Climate-Change-on-Extreme-Poverty-by-2030.pdf.
Jaka, H. and E. Shava, 2018: Resilient rural women's livelihoods for poverty alleviation and economic empowerment in semi-arid regions of Zimbabwe. *Jamba*, **10**(1), 524, doi:10.4102/jamba.v10i1.524.
Jaksa, M. F., 2006: Putting the Sustainable Back in Sustainable Development: Recognizing and Enforcing Indigenous Property Rights as a Pathway to Global Environmental Sustainability Notes & Comments. *Journal of Environmental Law and Litigation*, **21**(1), 157-206.
Jaramillo, J. et al., 2011: Some Like It Hot: The Influence and Implications of Climate Change on Coffee Berry Borer (Hypothenemus hampei) and Coffee Production in East Africa. *PLoS ONE*, **6**(9), e24528-e24528, doi:10.1371/journal.pone.0024528.
Jarvis, A., J. Ramirez-Villegas, B. V. H. Campo and C. Navarro-Racines, 2012: Is Cassava the Answer to African Climate Change Adaptation? *Tropical Plant Biology*, **5**(1), 9-29, doi:10.1007/s12042-012-9096-7.
Jasechko, S. and R. G. Taylor, 2015: Intensive rainfall recharges tropical groundwaters. *Environmental Research Letters*, **10**(12), doi:10.1088/1748-9326/10/12/124015.
Jayasinghe, S. L. and L. Kumar, 2020: Climate Change May Imperil Tea Production in the Four Major Tea Producers According to Climate Prediction Models. *Agronomy*, **10**(10), doi:10.3390/agronomy10101536.
Jayne, T. S. et al., 2019a: Are medium-scale farms driving agricultural transformation in sub-Saharan Africa? *Agricultural Economics*, **50**(S1), 75-95, doi:10.1111/agec.12535.
Jayne, T. S., S. Snapp, F. Place and N. Sitko, 2019b: Sustainable agricultural intensification in an era of rural transformation in Africa. *Global Food Security*, **20**, 105-113, doi:https://doi.org/10.1016/j.gfs.2019.01.008.
Jean, N. et al., 2016: Combining satellite imagery and machine learning to predict poverty. *Science (New York, N.Y.)*, **353**(6301), 790-794, doi:10.1126/science.aaf7894.
Jenkins, W., E. Berry and L. B. Kreider, 2018: Religion and Climate Change. *Annual Review of Environment and Resources*, **43**(1), 85-108, doi:10.1146/annurev-environ-102017-025855.
Jensen, K. M. and R. B. Lange, 2013: *Transboundary Water Governance in a Shifting Development Context New Development Finance, Development Spaces and Commitment to Cooperation: A Comparative Study of the Mekong And the Zambezi River Basins*. **20**, Danish Institute for International Studies (DIIS), DIIS, Copenhagen, 134 pp. Available at: http://www.jstor.org/stable/resrep13303 (accessed 2021/09/01/).

Jin, C., B. Wang and J. Liu, 2020: Future Changes and Controlling Factors of the Eight Regional Monsoons Projected by CMIP6 Models. *Journal of Climate*, **33**(21), 9307-9326, doi:10.1175/JCLI-D-20-0236.1.
Jin, L. et al., 2018: Modeling future flows of the Volta River system: Impacts of climate change and socio-economic changes. *Sci Total Environ*, **637-638**, 1069-1080, doi:10.1016/j.scitotenv.2018.04.350.
Jiri, O., P. Mafongoya and P. Chivenge, 2015: Indigenous knowledge systems, seasonal 'quality'and climate change adaptation in Zimbabwe. *Climate Research*, **66**(2), 103-111, doi:https://doi.org/10.3354/cr01334.
Jiri, O., P. L. Mafongoya and P. Chivenge, 2017: Building climate change resilience through adaptation in smallholder farming systems in semi-arid Zimbabwe. *International Journal of Climate Change Strategies and Management*, **9**(2), 151-165, doi:10.1108/IJCCSM-07-2016-0092.
Jiri, O., P. L. Mafongoya, C. Mubaya and O. Mafongoya, 2016: Seasonal climate prediction and adaptation using indigenous knowledge systems in agriculture systems in Southern Africa: a review. *Journal of Agricultural Science*, **8**(5), 156.
Jones, B. F. and B. A. Olken, 2010: Climate Shocks and Exports. *American Economic Review*, **100**(2), 454-459, doi:10.1257/aer.100.2.454.
Jones, H. P. et al., 2020: Global hotspots for coastal ecosystem-based adaptation. *PLoS One*, **15**(5), e0233005, doi:10.1371/journal.pone.0233005.
Jones, L. et al., 2015: Ensuring climate information guides long-term development. *Nature Climate Change*, **5**(9), 812-814, doi:10.1038/nclimate2701.
Kaag, M., G. Baltissen, G. Steel and A. Lodder, 2019: Migration, Youth, and Land in West Africa: Making the Connections Work for Inclusive Development. *Land*, **8**(4), 60, doi:10.3390/land8040060.
Kaczan, D. J. and J. Orgill-Meyer, 2020: The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change*, **158**(3), 281-300, doi:10.1007/s10584-019-02560-0.
Kagunyu, A., S. Wandibba and J. G. Wanjohi, 2016: The use of indigenous climate forecasting methods by the pastoralists of Northern Kenya. *Pastoralism*, **6**(1), doi:10.1186/s13570-016-0054-0.
Kahn, M. E. et al., 2019: *Long-term macroeconomic effects of climate change: A cross-country analysis* [Catherine, P. (ed.)]. International Monetary Fund,, IMF. Available at: https://www.imf.org/en/Publications/WP/Issues/2019/10/11/Long-Term-Macroeconomic-Effects-of-Climate-Change-A-Cross-Country-Analysis-48691.
Kakinuma, K. et al., 2020: Flood-induced population displacements in the world. *Environmental Research Letters*, **15**(12), 124029, doi:10.1088/1748-9326/abc586.
Kaky, E. and F. Gilbert, 2017: Predicting the distributions of Egypt's medicinal plants and their potential shifts under future climate change. *PLOS ONE*, **12**(11), e0187714, doi:10.1371/journal.pone.0187714.
Kalacska, M., J. Arroyo-Mora, O. Lucanus and M. Kishe-Machumu, 2017: Land Cover, Land Use, and Climate Change Impacts on Endemic Cichlid Habitats in Northern Tanzania. *Remote Sensing*, **9**(6), doi:10.3390/rs9060623.
Kalkuhl, M. and L. Wenz, 2020: The impact of climate conditions on economic production. Evidence from a global panel of regions. *Journal of Environmental Economics and Management*, **103**, 102360, doi:https://doi.org/10.1016/j.jeem.2020.102360.
Kam, P. M. et al., 2021: Global warming and population change both heighten future risk of human displacement due to river floods. *Environmental Research Letters*, **16**(4), 044026, doi:10.1088/1748-9326/abd26c.
Kamwendo, G. and J. Kamwendo, 2014: Indigenous Knowledge-Systems and Food Security: Some Examples from Malawi. *Journal of Human Ecology*, **48**(1), 97-101, doi:10.1080/09709274.2014.11906778.
Kangalawe, R. Y. M., 2017: Climate change impacts on water resource management and community livelihoods in the southern highlands of Tanzania. *Climate and Development*, **9**(3), 191-201, doi:10.1080/17565529.2016.1139487.
Kangalawe, R. Y. M. et al., 2017: Climate change and variability impacts on agricultural production and livelihood systems in Western Tanzania. *Climate and Development*, **9**(3), 202-216, doi:10.1080/17565529.2016.1146119.
Karmaoui, A. et al., 2016: Analysis of the Water Supply-demand Relationship in the Middle Draa Valley, Morocco, under Climate Change and Socio-economic Scenarios. *Journal of Scientific Research and Reports*, **9**(4), 1-10, doi:10.9734/jsrr/2016/21536.
Karuri, S. W. and R. W. Snow, 2016: Forecasting paediatric malaria admissions on the Kenya Coast using rainfall. *Glob Health Action*, **9**, 29876, doi:10.3402/gha.v9.29876.
Kaspar, F. et al., 2015: The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in science and research*, **12**, 171-177, doi:https://doi.org/10.5194/asr-12-171-2015.
Keahey, J., 2018: Gendered livelihoods and social change in post-apartheid South Africa. *Gender, Place & Culture*, **25**(4), 525-546, doi:10.1080/0966369x.2018.1460328.
Keeling, A., K. Dain and L. Hadley, 2012: *Diabetes and Climate Change Report*. International Diabetes Foundation (IDF), (IDF), I. D. F. Available at: https://www.idf.org/our-activities/advocacy-awareness/resources-and-tools/144:diabetes-and-climate-change-report.html.
Kendon, E. J. et al., 2019: Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale. *Nature communications*, **10**(1794), 1-14, doi:https://doi.org/10.1038/s41467-019-09776-9.
Kennedy, J. et al., 2017: Global and regional climate in 2016. *Weather*, **72**(8), 219-225, doi:10.1002/wea.3042.
Kent, C., R. Chadwick and D. P. Rowell, 2015: Understanding Uncertainties in Future Projections of Seasonal Tropical Precipitation. *Journal of Climate*, **28**(11), 4390-4413, doi:10.1175/JCLI-D-14-00613.1.

Kharin, V. V. et al., 2018: Risks from Climate Extremes Change Differently from 1.5°C to 2.0°C Depending on Rarity. *Earth's Future*, **6**(5), 704-715, doi:10.1002/2018ef000813.

Khedr, M., 2019: Challenges and Issues in Water, Climate Change, and Food Security in Egypt. In: *Conventional Water Resources and Agriculture in Egypt* [Negm, A. M. (ed.)]. Springer International Publishing, Cham, pp. 229-243. ISBN 978-3-319-95065-5.

Kibret, S. et al., 2015: Malaria impact of large dams in sub-Saharan Africa: maps, estimates and predictions. *Malaria Journal*, **14**(1), 339-339, doi:10.1186/s12936-015-0873-2.

Kibret, S. et al., 2017: The Influence of Dams on Malaria Transmission in Sub-Saharan Africa. *EcoHealth*, **14**(2), 408-419, doi:10.1007/s10393-015-1029-0.

Kichamu, E. A., J. S. Ziro, G. Palaniappan and H. Ross, 2017: Climate change perceptions and adaptations of smallholder farmers in Eastern Kenya. *Environment, Development and Sustainability*, **20**(6), 2663-2680, doi:10.1007/s10668-017-0010-1.

Kienberger, S. and M. Hagenlocher, 2014: Spatial-explicit modeling of social vulnerability to malaria in East Africa. *Int. J. Health Geogr.*, **13**, 29, doi:10.1186/1476-072X-13-29.

Kifani, S. et al., 2018: *Chapter 8: Climate change impacts, vulnerabilities and adaptations: Eastern Central Atlantic marine fisheries* [Barange, M., T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options, FAO Fisheries and Aquaculture, Italy, 159-183 pp. Available at: http://www.fao.org/3/i9705en/I9705EN.pdf.

Kihila, J. M., 2017: Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review. *Climate and Development*, **10**(5), 406-416, doi:10.1080/17565529.2017.1318739.

Kilungu, H., R. Leemans, P. K. Munishi and B. Amelung, 2017: Climate change threatens major tourist attractions and tourism in Serengeti National Park, Tanzania. In: *Climate Change Adaptation in Africa* [Leal Filho, W., S. Belay, J. Kalangu, W. Menas, P. Munishi and K. Musiyiwa (eds.)]. Springer, Cham, pp. 375-392. ISBN 978-3-319-49520-0.

Kilungu, H. et al., 2019: Forty Years of Climate and Land-Cover Change and its Effects on Tourism Resources in Kilimanjaro National Park. *Tourism Planning & Development*, **16**(2), 235-253, doi:10.1080/21568316.2019.1569121.

Kim, Y. et al., 2019: Suicide and Ambient Temperature: A Multi-Country Multi-City Study. *Environ Health Perspect*, **127**(11), 117007, doi:10.1289/ehp4898.

Kimaro, E. G., S. M. Mor and J.-A. L. M. L. Toribio, 2018: Climate change perception and impacts on cattle production in pastoral communities of northern Tanzania. *Pastoralism*, **8**(1), 19, doi:10.1186/s13570-018-0125-5.

Kimaro, E. G., J.-A. L. M. L. Toribio and S. M. Mor, 2017: Climate change and cattle vector-borne diseases: Use of participatory epidemiology to investigate experiences in pastoral communities in Northern Tanzania. *Preventive Veterinary Medicine*, **147**, 79-89, doi:10.1016/j.prevetmed.2017.08.010.

Kimirei, I. A. et al., 2020: Trends in Ecological Changes: Implications for East and Southern Africa. In: *Ecological Changes in the Zambezi River Basin* [Ndebele-Murisa, M., I. A. Kimirei, C. P. Mubaya and T. Bere (eds.)]. CODESRIA, Dakar, pp. 49-82. ISBN 978-2-86978-713-1.

Kishiwa, P., J. Nobert, V. Kongo and P. Ndomba, 2018: Assessment of impacts of climate change on surface water availability using coupled SWAT and WEAP models: case of upper Pangani River Basin, Tanzania. *Proceedings of the International Association of Hydrological Sciences*, **378**, 23-27, doi:10.5194/piahs-378-23-2018.

Kissler, S. M. et al., 2020: Projecting the transmission dynamics of SARS-CoV-2 through the post-pandemic period. *medRxiv*, 2020.2003.2004.20031112, doi:10.1101/2020.03.04.20031112.

Kita, S. M., 2019: Barriers or enablers? Chiefs, elite capture, disasters, and resettlement in rural Malawi. *Disasters*, **43**(1), 135-156, doi:10.1111/disa.12295.

Kiwanuka-Tondo, J., F. Semazzi and K. Pettiway, 2019: Climate risk communication of navigation safety and climate conditions over Lake Victoria basin: Exploring perceptions and knowledge of indigenous communities. *Cogent Social Sciences*, **5**(1), 1588485, doi:10.1080/23311886.2019.1588485.

Kjellstrom, T. et al., 2016: Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. *Annual Review of Public Health*, **37**(1), 97-112, doi:10.1146/annurev-publhealth-032315-021740.

Kjellstrom, T. et al., 2018: Estimating population heat exposure and impacts on working people in conjunction with climate change. *Int J Biometeorol*, **62**(3), 291-306, doi:10.1007/s00484-017-1407-0.

Kjellstrom, T. et al., 2014: *Occupational Heat Stress Contribution to WHO project on "Global assessment of the health impacts of climate change", which started in 2009*. ClimateChip Technical Report, Ruby Coast Research Centre, Mapua, Nelson, New Zealand, 52 pp. Available at: http://climatechip.org/sites/default/files/publications/TP2014_4_Occupational_Heat_Stress_WHO.pdf.

Klerkx, L., E. Jakku and P. Labarthe, 2019: A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen Journal of Life Sciences*, **90-91**, 100315, doi:https://doi.org/10.1016/j.njas.2019.100315.

Kloos, J. and N. Baumert, 2015: Preventive resettlement in anticipation of sea level rise: a choice experiment from Alexandria, Egypt. *Natural Hazards*, **76**(1), 99-121, doi:10.1007/s11069-014-1475-y.

Klotter, D., S. E. Nicholson, A. K. Dezfuli and L. Zhou, 2018: New Rainfall Datasets for the Congo Basin and Surrounding Regions. *Journal of Hydrometeorology*, **19**(8), 1379-1396, doi:10.1175/jhm-d-18-0015.1.
Klutse, N. A. B. et al., 2018: Potential impact of 1.5 °C and 2 °C global warming on consecutive dry and wet days over West Africa. *Environmental Research Letters*, **13**(5), 055013, doi:10.1088/1748-9326/aab37b.
KNOMAD, 2016: *Migration and Development Brief 26: Migration and Remittances Recent Developments and Outlook*. World Bank, The Global Knowledge Partnership on Migration and Development (KNOMAD), Washington, DC, 48 pp. Available at: http://pubdocs.worldbank.org/en/661301460400427908/MigrationandDevelopmentBrief26.pdf.
Knorr, W., A. Arneth and L. Jiang, 2016: Demographic controls of future global fire risk. *Nature Climate Change*, **6**(8), 781-785, doi:10.1038/nclimate2999.
Knorr, W. et al., 2017: Wildfire air pollution hazard during the 21st century. *Atmos. Chem. Phys.*, **17**(14), 9223-9236, doi:10.5194/acp-17-9223-2017.
Knox, J. W., J. A. Rodríguez Díaz, D. J. Nixon and M. Mkhwanazi, 2010: A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems*, **103**(2), 63-72, doi:https://doi.org/10.1016/j.agsy.2009.09.002.
Kohlitz, J., J. Chong and J. Willetts, 2017: Climate change vulnerability and resilience of water, sanitation, and hygiene services: A theoretical perspective. *Journal of Water Sanitation and Hygiene for Development*, **7**, washdev2017134, doi:10.2166/washdev.2017.134.
Koks, E. E. et al., 2019: A global multi-hazard risk analysis of road and railway infrastructure assets. *Nat Commun*, **10**(1), 2677, doi:10.1038/s41467-019-10442-3.
Kolawole, O. D. et al., 2016: Climate Variability and Rural Livelihoods: How Households Perceive and Adapt to Climatic Shocks in the Okavango Delta, Botswana. *Weather, Climate, and Society*, **8**(2), 131-145, doi:10.1175/WCAS-D-15-0019.1.
Kolding, J., P. van Zwieten, F. Marttin and F. Poulain, 2016: *Fisheries in the Drylands of sub-Saharan Africa: "fish come with the rains" - Building resilience for sheries-dependent livelihoods to enhance food security and nutrition in the drylands*. FAO Fisheries and Aquaculture Circular Food and Agricultural Organization of the United Nations, Rome, 64 pp. Available at: http://www.fao.org/3/a-i5616e.pdf.
Kolding, J. et al., 2019: *Freshwater small pelagic fish and their fisheries in major African lakes and reservoirs in relation to food security and nutrition*. FAO Fisheries and Aquaculture Technical Paper, FAO, Rome, Italy, 122 pp. Available at: http://www.fao.org/documents/card/en/c/CA0843EN/.
Kolusu, S. R. et al., 2019: The El Niño event of 2015–2016: climate anomalies and their impact on groundwater resources in East and Southern Africa. *Hydrology and Earth System Sciences*, **23**(3), 1751-1762, doi:10.5194/hess-23-1751-2019.
Kotchoni, D. O. V. et al., 2019: Relationships between rainfall and groundwater recharge in seasonally humid Benin: a comparative analysis of long-term hydrographs in sedimentary and crystalline aquifers. *Hydrogeology Journal*, **27**(2), 447-457, doi:10.1007/s10040-018-1806-2.
Koubi, V., 2019: Climate Change and Conflict. *Annual Review of Political Science*, **22**(1), 343-360, doi:10.1146/annurev-polisci-050317-070830.
Kraemer, B. M. et al., 2021: Climate change drives widespread shifts in lake thermal habitat. *Nature Climate Change*, **11**(6), 521-529, doi:10.1038/s41558-021-01060-3.
Kraemer, M. U. G. et al., 2019: Past and future spread of the arbovirus vectors Aedes aegypti and Aedes albopictus. *Nature Microbiology*, **4**(5), 854-863, doi:10.1038/s41564-019-0376-y.
Krell, N. T. et al., 2021: Smallholder farmers' use of mobile phone services in central Kenya. *Climate and Development*, **13**(3), 215-227, doi:10.1080/17565529.2020.1748847.
Kroon, F. J., P. Thorburn, B. Schaffelke and S. Whitten, 2016: Towards protecting the Great Barrier Reef from land-based pollution. *Global Change Biology*, **22**(6), 1985-2002, doi:10.1111/gcb.13262.
Kruczkiewicz, A. et al., 2021: Opinion: Compound risks and complex emergencies require new approaches to preparedness. *Proceedings of the National Academy of Sciences*, **118**(19), e2106795118, doi:10.1073/pnas.2106795118.
Kruger, A. C. and M. Nxumalo, 2017a: Historical rainfall trends in South Africa: 1921–2015. *Water SA*, **43**(2), 285-297, doi:https://doi.org/10.4314/wsa.v43i2.12.
Kruger, A. C. and M. Nxumalo, 2017b: Surface temperature trends from homogenized time series in South Africa: 1931-2015. *International Journal of Climatology*, **37**(5), 2364-2377, doi:10.1002/joc.4851.
Kuhl, L., 2021: Policy making under scarcity: reflections for designing socially just climate adaptation policy. *One Earth*, **4**(2), 202-212, doi:https://doi.org/10.1016/j.oneear.2021.01.008.
Kula, N., A. Haines and R. Fryatt, 2013: Reducing Vulnerability to Climate Change in Sub-Saharan Africa: The Need for Better Evidence. *PLoS medicine*, **10**(1), 5, doi:10.1371/journal.pmed.1001374.
Kulp, S. A. and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, **10**(1), 4844, doi:10.1038/s41467-019-12808-z.
Kumi, N. and B. J. Abiodun, 2018: Potential impacts of 1.5 °C and 2 °C global warming on rainfall onset, cessation and length of rainy season in West Africa. *Environmental Research Letters*, **13**(5), 055009, doi:10.1088/1748-9326/aab89e.

Kummu, M. et al., 2021: Climate change risks pushing one-third of global food production outside the safe climatic space. *One Earth*, **4**(5), 720-729, doi:https://doi.org/10.1016/j.oneear.2021.04.017.
Kundzewicz, Z. W. et al., 2014: Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, **59**(1), 1-28, doi:10.1080/02626667.2013.857411.
Kuper, H. et al., 2016: Social protection for people with disabilities in Tanzania: a mixed methods study. *Oxford Development Studies*, **44**(4), 441-457, doi:10.1080/13600818.2016.1213228.
Kupika, O. L., E. Gandiwa, G. Nhamo and S. Kativu, 2019: Local Ecological Knowledge on Climate Change and Ecosystem-Based Adaptation Strategies Promote Resilience in the Middle Zambezi Biosphere Reserve, Zimbabwe. *Scientifica*, **2019**, 3069254, doi:10.1155/2019/3069254.
Kuran, C. H. A. et al., 2020: Vulnerability and vulnerable groups from an intersectionality perspective. *International Journal of Disaster Risk Reduction*, **50**, 101826, doi:https://doi.org/10.1016/j.ijdrr.2020.101826.
Kusangaya, S., M. L. Warburton, E. Archer van Garderen and G. P. W. Jewitt, 2014: Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth, Parts A/B/C*, **67-69**, 47-54, doi:https://doi.org/10.1016/j.pce.2013.09.014.
Kynast-Wolf, G. et al., 2010: Seasonal patterns of cardiovascular disease mortality of adults in Burkina Faso, West Africa. *Trop Med Int Health*, **15**(9), 1082-1089, doi:10.1111/j.1365-3156.2010.02586.x.
Kyriakarakos, G., A. T. Balafoutis and D. Bochtis, 2020: Proposing a Paradigm Shift in Rural Electrification Investments in Sub-Saharan Africa through Agriculture. *Sustainability*, **12**(8), doi:10.3390/su12083096.
LaCanne, C. E. and J. G. Lundgren, 2018: Regenerative agriculture: merging farming and natural resource conservation profitably. *PeerJ*, **6**(e4428), doi:10.7717/peerj.4428.
Läderach, P., A. Martinez-Valle, G. Schroth and N. Castro, 2013: Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. *Climatic Change*, **119**(3-4), 841-854, doi:10.1007/s10584-013-0774-8.
Lakhraj-Govender, R. and S. W. Grab, 2019: Rainfall and river flow trends for the Western Cape Province, South Africa. *South African Journal of Science*, **115**(9/10), 1-6, doi:http://dx.doi.org/10.17159/sajs.2019/6028
Lakhraj-Govender, R. and S. W. Grab, 2019: Assessing the impact of El Niño–Southern Oscillation on South African temperatures during austral summer. *International Journal of Climatology*, **39**(1), 143-156, doi:https://doi.org/10.1002/joc.5791.
Lallo, C. H. O. et al., 2018: Characterizing heat stress on livestock using the temperature humidity index (THI)—prospects for a warmer Caribbean. *Regional Environmental Change*, **18**(8), 2329-2340, doi:10.1007/s10113-018-1359-x.
Lammers, P. L., T. Richter and J. Mantilla-Contreras, 2020: From Safety Net to Point of No Return—Are Small-Scale Inland Fisheries Reaching Their Limits? *Sustainability*, **12**(18), doi:10.3390/su12187299.
Landrigan, P. J. et al., 2018: The *Lancet* Commission on pollution and health. *The Lancet*, **391**(10119), 462-512, doi:10.1016/S0140-6736(17)32345-0.
Laneri, K. et al., 2015: Dynamical malaria models reveal how immunity buffers effect of climate variability. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(28), 8786-8791, doi:10.1073/pnas.1419047112.
Langat, P., L. Kumar and R. Koech, 2017: Temporal Variability and Trends of Rainfall and Streamflow in Tana River Basin, Kenya. *Sustainability*, **9**(11), doi:10.3390/su9111963.
Lapointe, D. et al., 2018: Predicted impacts of climate warming on aerobic performance and upper thermal tolerance of six tropical freshwater fishes spanning three continents. *Conserv Physiol*, **6**(1), coy056, doi:10.1093/conphys/coy056.
Lasage, R. and P. H. Verburg, 2015: Evaluation of small scale water harvesting techniques for semi-arid environments. *Journal of Arid Environments*, **118**, 48-57, doi:https://doi.org/10.1016/j.jaridenv.2015.02.019.
Laufkötter, C., J. Zscheischler and T. L. Frölicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science (New York, N.Y.)*, **369**(6511), 1621-1625, doi:https://doi.org/10.1126/science.aba0690.
Laurance, W. F., S. Sloan, L. Weng and J. A. Sayer, 2015: Estimating the Environmental Costs of Africa's Massive "Development Corridors". *Current Biology*, **25**(24), 3202-3208, doi:https://doi.org/10.1016/j.cub.2015.10.046.
Laurie, S. M., M. Faber and N. Claasen, 2018: Incorporating orange-fleshed sweet potato into the food system as a strategy for improved nutrition: The context of South Africa. *Food Research International*, **104**, 77-85, doi:https://doi.org/10.1016/j.foodres.2017.09.016.
Lawlor, K., S. Handa and D. Seidenfeld, 2019: Cash Transfers Enable Households to Cope with Agricultural Production and Price Shocks: Evidence from Zambia. *The Journal of Development Studies*, **55**(2), 209-226, doi:10.1080/00220388.2017.1393519.
Lazenby, M. J., M. C. Todd, R. Chadwick and Y. Wang, 2018: Future Precipitation Projections over Central and Southern Africa and the Adjacent Indian Ocean: What Causes the Changes and the Uncertainty? *Journal of Climate*, **31**(12), 4807-4826, doi:10.1175/JCLI-D-17-0311.1.
Le Maitre, D. C. et al., 2020: Impacts of Plant Invasions on Terrestrial Water Flows in South Africa. In: *Biological Invasions in South Africa* [van Wilgen, B. W., J. Measey, D. M. Richardson, J. R. Wilson and T. A. Zengeya (eds.)]. Springer International Publishing, Cham, pp. 431-457. ISBN 978-3-030-32394-3.

Leal Filho, W. et al., 2018: Strengthening climate change adaptation capacity in Africa-case studies from six major African cities and policy implications. *Environmental Science & Policy*, **86**, 29-37, doi:https://doi.org/10.1016/j.envsci.2018.05.004.
Leck, H. et al., 2018: Towards Risk-Sensitive and Transformative Urban Development in Sub Saharan Africa. *Sustainability*, **10**(8), doi:10.3390/su10082645.
Leck, H. and D. Roberts, 2015: What lies beneath: understanding the invisible aspects of municipal climate change governance. *Current Opinion in Environmental Sustainability*, **13**, 61-67, doi:https://doi.org/10.1016/j.cosust.2015.02.004.
Leck, H. and D. Simon, 2018: Local Authority Responses to Climate Change in South Africa: The Challenges of Transboundary Governance. *Sustainability*, **10**(7), 2542, doi:10.3390/su10072542.
Lee, A. T. K. and P. Barnard, 2016: Endemic birds of the Fynbos biome: a conservation assessment and impacts of climate change. *Bird Conservation International*, **26**(1), 52-68, doi:10.1017/S0959270914000537.
Lee, K. W. and M. Hong, 2018: Relative Effectiveness of Various Development Finance Flows: A Comparative Study. *KD Journal of Economic Policy*, **40**(3), 91-115, doi:10.23895/KDIJEP.2018.40.3.91.
Lee, T. M. et al., 2015: Predictors of public climate change awareness and risk perception around the world. *Nature Climate Change*, **5**(11), 1014-1020, doi:10.1038/nclimate2728.
Leedale, J., A. Jones, C. Caminade and A. Morse, 2016: A dynamic, climate-driven model of Rift Valley fever. *Geospatial health*, **11**, 394, doi:10.4081/gh.2016.394.
Lefore, N., A. Closas and P. Schmitter, 2021: Solar for all: A framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture. *Energy Policy*, **154**, 112313, doi:https://doi.org/10.1016/j.enpol.2021.112313.
Lelieveld, J. et al., 2016: Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. *Climatic Change*, **137**(1-2), 245–260, doi:https://doi.org/10.1007/s10584-016-1665-6.
Lempert, R. et al., 2015: Adaptation to Climate Change in Infrastructure Planning. In: *Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors* [Cervigni, R., R. Liden, J. E. Neumann and K. M. Strzepek (eds.)]. The World Bank, Washington, DC, pp. 103-130. ISBN 978-1-4648-0466-3.
Leone, M. et al., 2013: A time series study on the effects of heat on mortality and evaluation of heterogeneity into European and Eastern-Southern Mediterranean cities: results of EU CIRCE project. *Environmental health : a global access science source*, **12**, 55, doi:10.1186/1476-069x-12-55.
Lequechane, J. D. et al., 2020: Mozambique's response to cyclone Idai: how collaboration and surveillance with water, sanitation and hygiene (WASH) interventions were used to control a cholera epidemic. *Infectious Diseases of Poverty*, **9**(1), 68, doi:10.1186/s40249-020-00692-5.
Leßmeister, A. et al., 2015: Substitution of the most important and declining wild food species in southeast Burkina Faso. *Flora et Vegetatio Sudano-Sambesica*, **18**, 11-20, doi:https://doi.org/10.21248/fvss.18.29.
Levy, B. S. and J. A. Patz, 2015: Climate Change, Human Rights, and Social Justice. *Ann Glob Health*, **81**(3), 310-322, doi:10.1016/j.aogh.2015.08.008.
Levy, K., A. P. Woster, R. S. Goldstein and E. J. Carlton, 2016: Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. *Environmental science & technology*, **50**(10), 4905-4922, doi:https://doi.org/10.1021/acs.est.5b06186.
Lewin, P. A., M. Fisher and B. Weber, 2012: Do rainfall conditions push or pull rural migrants: evidence from Malawi. *Agricultural Economics*, **43**(2), 191-204, doi:https://doi.org/10.1111/j.1574-0862.2011.00576.x.
Lewis, S. L., C. E. Wheeler, E. T. Mitchard and A. Koch, 2019: Restoring natural forests is the best way to remove atmospheric carbon. *Nature*, **568**, 25-28, doi:https://doi.org/10.1038/d41586-019-01026-8.
Li, C. et al., 2021: Changes in Annual Extremes of Daily Temperature and Precipitation in CMIP6 Models. *Journal of Climate*, **34**(9), 3441-3460, doi:10.1175/JCLI-D-19-1013.1.
Li, D., G. Christakos, X. Ding and J. Wu, 2018: Adequacy of TRMM satellite rainfall data in driving the SWAT modeling of Tiaoxi catchment (Taihu lake basin, China). *Journal of Hydrology*, **556**, 1139-1152, doi:https://doi.org/10.1016/j.jhydrol.2017.01.006.
Li, J., M. Mullan and J. Helgeson, 2014: Improving the practice of economic analysis of climate change adaptation. *Journal of Benefit-Cost Analysis*, **5**(3), 445, doi:https://doi.org/10.1515/jbca-2014-9004.
Lieber, M. et al., 2021: The Synergistic Relationship Between Climate Change and the HIV/AIDS Epidemic: A Conceptual Framework. *AIDS and Behavior*, **25**(7), 2266-2277, doi:10.1007/s10461-020-03155-y.
Liebmann, B. et al., 2014: Understanding Recent Eastern Horn of Africa Rainfall Variability and Change. *Journal of Climate*, **27**(23), 8630-8645, doi:10.1175/jcli-d-13-00714.1.
Lindley, S. J., P. A. Cook, M. Dennis and A. Gilchrist, 2019: Biodiversity, Physical Health and Climate Change: A Synthesis of Recent Evidence. In: *Biodiversity and Health in the Face of Climate Change* [Marselle, M. R., J. Stadler, H. Korn, K. N. Irvine and A. Bonn (eds.)]. Springer International Publishing, Cham, pp. 17-46. ISBN 978-3-030-02317-1.
Linke, A. M. et al., 2018: Drought, Local Institutional Contexts, and Support for Violence in Kenya. *Journal of Conflict Resolution*, **62**(7), 1544-1578, doi:10.1177/0022002717698018.
Lipper, L. et al., 2014: Climate-smart agriculture for food security. *Nature Climate Change*, **4**(12), 1068-1072, doi:10.1038/nclimate2437.

Liu, B., Y. L. Siu and G. Mitchell, 2017: A quantitative model for estimating risk from multiple interacting natural hazards: an application to northeast Zhejiang, China. *Stochastic Environmental Research and Risk Assessment*, **31**, 1319-1340, doi:10.1007/s00477-016-1250-6.
Liu, J. et al., 2018a: Nexus approaches to global sustainable development. *Nature Sustainability*, **1**(9), 466-476, doi:10.1038/s41893-018-0135-8.
Liu, W. et al., 2018b: Global Freshwater Availability Below Normal Conditions and Population Impact Under 1.5 and 2 °C Stabilization Scenarios. *Geophysical Research Letters*, **45**(18), 9803-9813, doi:https://doi.org/10.1029/2018GL078789.
Liu, W. et al., 2018c: Global drought and severe drought-affected populations in 1.5 and 2 C warmer worlds. *Earth System Dynamics*, **9**(1), 267-283, doi:https://doi.org/10.5194/esd-9-267-2018.
Liverpool-Tasie, L. S. O. et al., 2020: Perceptions and exposure to climate events along agricultural value chains: Evidence from Nigeria. *Journal of Environmental Management*, **264**(January), doi:10.1016/j.jenvman.2020.110430.
Liwenga, E. et al., 2015: Climate related projections on future water resources and human adaptation in the Great Ruaha River Basin in Tanzania.
Lobell, D. B., M. Bänziger, C. Magorokosho and B. Vivek, 2011: Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, **1**(1), 42-45, doi:10.1038/nclimate1043.
Loevinsohn, M., 2015: The 2001-03 Famine and the Dynamics of HIV in Malawi: A Natural Experiment. *PLoS One*, **10**(9), e0135108, doi:10.1371/journal.pone.0135108.
Longo-Mbenza, B. et al., 1999: Hematocrit and stroke in black Africans under tropical climate and meteorological influence. *Ann Med Interne (Paris)*, **150**(3), 171-177.
Loucks, D. P. and E. van Beek, 2017: Water Resource Systems Modeling: Its Role in Planning and Management. In: *Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications*. Springer International Publishing, Cham, pp. 51-72. ISBN 978-3-319-44234-1.
Lovelock, C. E. and C. M. Duarte, 2019: Dimensions of Blue Carbon and emerging perspectives. *Biology Letters*, **15**(3), 20180781, doi:10.1098/rsbl.2018.0781.
Lovschal, M. et al., 2017: Fencing bodes a rapid collapse of the unique Greater Mara ecosystem. *Sci Rep*, **7**, 41450, doi:10.1038/srep41450.
Low, A. J. et al., 2019: Association between severe drought and HIV prevention and care behaviors in Lesotho: A population-based survey 2016–2017. *PLoS medicine*, **16**(1), e1002727, doi:10.1371/journal.pmed.1002727.
Lowe, B. S. et al., 2019: Adapting to change in inland fisheries: analysis from Lake Tanganyika, East Africa. *Regional Environmental Change*, **19**(6), 1765-1776, doi:10.1007/s10113-019-01516-5.
Ludwig, F. et al., 2013: *Climate change impacts on the Congo Basin region* [Haensler, A., D. Jacob, P. Kabat and F. Ludwig (eds.)]. Climate Change Scenarios for the Congo Basin, Climate Service Centre, Hamburg, Germany.
Lumbroso, D., 2018: How can policy makers in sub-Saharan Africa make early warning systems more effective? The case of Uganda. *International Journal of Disaster Risk Reduction*, **27**, 530-540, doi:https://doi.org/10.1016/j.ijdrr.2017.11.017.
Lumbroso, D., 2020: Flood risk management in Africa. *Journal of Flood Risk Management*, **13**(3), doi:10.1111/jfr3.12612.
Lund Schlamovitz, J. and P. Becker, 2020: Differentiated vulnerabilities and capacities for adaptation to water shortage in Gaborone, Botswana. *International Journal of Water Resources Development*, **37**(2), 278-299, doi:10.1080/07900627.2020.1756752.
Lunga, W. and C. Musarurwa, 2016: Exploiting indigenous knowledge commonwealth to mitigate disasters: from the archives of vulnerable communities in Zimbabwe. *Indian J. Tradit. Knowl.*, **15**(1), 22-29.
Lunga, W., P. Pathias Bongo, D. van Niekerk and C. Musarurwa, 2019: Disability and disaster risk reduction as an incongruent matrix: Lessons from rural Zimbabwe. *Jamba*, **11**(1), 648, doi:10.4102/jamba.v11i1.648.
Luo, X. et al., 2019: Hydrological Simulation Using TRMM and CHIRPS Precipitation Estimates in the Lower Lancang-Mekong River Basin. *Chinese geographical science*, **29**(1), 13-25, doi:https://doi.org/10.1007/s11769-019-1014-6.
Lurie, M. N., 2006: The Epidemiology of Migration and HIV/AIDS in South Africa. *Journal of Ethnic and Migration Studies*, **32**(4), 649-666.
Lutz, W., R. Muttarak and E. Striessnig, 2014: Universal education is key to enhanced climate adaptation. *Science (New York, N.Y.)*, **346**(6213), 1061-1062, doi:10.1126/science.1257975.
Lwasa, S., K. Buyana, P. Kasaija and J. Mutyaba, 2018: Scenarios for adaptation and mitigation in urban Africa under 1.5 °C global warming. *Current Opinion in Environmental Sustainability*, **30**, 52-58, doi:10.1016/j.cosust.2018.02.012.
Lwasa, S. et al., 2014: Urban and peri-urban agriculture and forestry: Transcending poverty alleviation to climate change mitigation and adaptation. *Urban Climate*, **7**, 92-106, doi:10.1016/j.uclim.2013.10.007.
Lyon, B., T. Dinku, A. Raman and M. C. Thomson, 2017: Temperature suitability for malaria climbing the Ethiopian Highlands. *Environmental Research Letters*, **12**(6), 064015, doi:10.1088/1748-9326/aa64e6.
Lyon, B. and N. Vigaud, 2017: Unraveling East Africa's Climate Paradox. In: *Climate Extremes* [Wang, S. S., J. Yoon, C. C. Funk and R. R. Gillies (eds.)]. John Wiley & Sons, Inc, pp. 265-281. ISBN 9781119068020.

M'Bra, R. K. et al., 2018: Impact of climate variability on the transmission risk of malaria in northern Côte d'Ivoire. *PLOS ONE*, **13**(6), e0182304, doi:10.1371/journal.pone.0182304.
Maarleveld, T. J. and U. Guérin, 2013: *Manual for Activities directed at Underwater Cultural Heritage* [Egger, B. (ed.)]. UNESCO, France, 351 pp. Available at: http://www.unesco.org/culture/en/underwater/pdf/UCH-Manual.pdf (accessed 2019/03/22/08:30:46).
Mabuya, B. and M. Scholes, 2020: The Three Little Houses: A Comparative Study of Indoor and Ambient Temperatures in Three Low-Cost Housing Types in Gauteng and Mpumalanga, South Africa. *International journal of environmental research and public health*, **17**(10), 3524, doi:10.3390/ijerph17103524.
Macamo, C. C. F. et al., 2016: Mangrove's response to cyclone Eline (2000): What is happening 14 years later. *Aquatic Botany*, **134**, 10-17, doi:10.1016/j.aquabot.2016.05.004.
MacDonald, A. M., H. C. Bonsor, B. É. Ó. Dochartaigh and R. G. Taylor, 2012: Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, **7**(2), doi:10.1088/1748-9326/7/2/024009.
Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**, 193-197, doi:10.1038/s41586-019-1300-6.
Macháček, J., 2019: Typology of Environmental Impacts of Artisanal and Small-Scale Mining in African Great Lakes Region. *Sustainability*, **11**(11), doi:10.3390/su11113027.
Mackinnon, E. et al., 2019: 21st century research in urban WASH and health in sub-Saharan Africa: methods and outcomes in transition. *Int J Environ Health Res*, **29**(4), 457-478, doi:10.1080/09603123.2018.1550193.
MacVicar, S. et al., 2017: Whether weather matters: Evidence of association between in utero meteorological exposures and foetal growth among Indigenous and non-Indigenous mothers in rural Uganda. *PLoS One*, **12**(6), e0179010, doi:10.1371/journal.pone.0179010.
Madonsela, B., S. Koop, K. Van Leeuwen and K. Carden, 2019: Evaluation of Water Governance Processes Required to Transition towards Water Sensitive Urban Design—An Indicator Assessment Approach for the City of Cape Town. *Water*, **11**(2), 14, doi:10.3390/w11020292.
Mafongoya, P. et al., 2019: Climate Change and Rapidly Evolving Pests and Diseases in Southern Africa. pp. 41-57.
Mafongoya, P. L., O. Jiri, C. P. Mubaya and O. Mafongoya, 2017: Using indigenous knowledge for seasonal quality prediction in managing climate risk in sub-Saharan Africa. In: *Indigenous knowledge systems and climate change management in Africa* [Mafongoya, P. L. and O. C. Ajayi (eds.)]. The Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, The Netherlands, pp. 43.
Mahe, G. et al., 2013: The rivers of Africa: witness of climate change and human impact on the environment. *Hydrological Processes*, **27**(15), 2105-2114, doi:10.1002/hyp.9813.
Mahl, D. et al., 2020: "We are a Bit Blind About it": A Qualitative Analysis of Climate Change-Related Perceptions and Communication Across South African Communities. *Environmental Communication*, **14**(6), 802-815, doi:10.1080/17524032.2020.1736116.
Mahmood, R., S. Jia and W. Zhu, 2019: Analysis of climate variability, trends, and prediction in the most active parts of the Lake Chad basin, Africa. *Scientific Reports*, **9**(1), 6317, doi:10.1038/s41598-019-42811-9.
Maidment, R. I., R. P. Allan and E. Black, 2015: Recent observed and simulated changes in precipitation over Africa. *Geophysical Research Letters*, **42**(19), 8155-8164, doi:10.1002/2015gl065765.
Maire, E. et al., 2021: Micronutrient supply from global marine fisheries under climate change and overfishing. *Current Biology*, doi:https://doi.org/10.1016/j.cub.2021.06.067.
Makaka, G. and E. Meyer, 2006: Temperature Stability of Traditional and Low-cost Modern Housing in the Eastern Cape, South Africa. *Journal of Building Physics*, **30**(1), 71-86, doi:10.1177/1744259106065674.
Makara, S., 2018: Decentralisation and good governance in Africa: A critical review. *African Journal of Political Science and International Relations*, **12**(2), 22-32, doi:https://doi.org/10.5897/AJPSIR2016.0973.
Makate, C., 2019: Local institutions and indigenous knowledge in adoption and scaling of climate-smart agricultural innovations among sub-Saharan smallholder farmers. *International Journal of Climate Change Strategies and Management*, **12**(2), 270-287, doi:10.1108/IJCCSM-07-2018-0055.
Makate, C., M. Makate, N. Mango and S. Siziba, 2019: Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa. *Journal of Environmental Management*, **231**, 858-868, doi:https://doi.org/10.1016/j.jenvman.2018.10.069.
Makina, A. and T. Moyo, 2016: Mind the gap: institutional considerations for gender-inclusive climate change policy in Sub-Saharan Africa. *Local Environment*, **21**(10), 1185-1197, doi:10.1080/13549839.2016.1189407.
Makondo, C. C. and D. S. G. Thomas, 2018: Climate change adaptation: Linking indigenous knowledge with western science for effective adaptation. *Environmental Science & Policy*, **88**, 83-91, doi:https://doi.org/10.1016/j.envsci.2018.06.014.
Malherbe, J., F. A. Engelbrecht and W. A. Landman, 2013: Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean region under enhanced anthropogenic forcing. *Clim Dyn*, **40**(11), 2867-2886, doi:https://doi.org/10.1007/s00382-012-1635-2.
Malhi, Y. et al., 2014: Tropical Forests in the Anthropocene. *Annual Review of Environment and Resources*, **39**(1), 125-159, doi:10.1146/annurev-environ-030713-155141.
Manatsa, D. and S. K. Behera, 2013: On the Epochal Strengthening in the Relationship between Rainfall of East Africa and IOD. *Journal of Climate*, **26**(15), 5655-5673, doi:10.1175/jcli-d-12-00568.1.

Manes, S. et al., 2021: Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, **257**, 109070, doi:https://doi.org/10.1016/j.biocon.2021.109070.
Manuamorn, O. P. and R. Biesbroek, 2020: Do direct-access and indirect-access adaptation projects differ in their focus on local communities? A systematic analysis of 63 Adaptation Fund projects. *Regional Environmental Change*, **20**(4), 139, doi:10.1007/s10113-020-01716-4.
Manzanedo, R. D. and P. Manning, 2020: COVID-19: Lessons for the climate change emergency. *Science of the Total Environment*, **742**, 140563-140563, doi:10.1016/j.scitotenv.2020.140563.
Mapfumo, P. et al., 2017: Pathways to transformational change in the face of climate impacts: an analytical framework. *Climate and Development*, **9**(5), 439-451, doi:https://doi.org/10.1080/17565529.2015.1040365.
Marais, E. A. et al., 2019: Air Quality and Health Impact of Future Fossil Fuel Use for Electricity Generation and Transport in Africa. *Environmental Science & Technology*, **53**(22), 13524-13534, doi:10.1021/acs.est.9b04958.
Marais, E. A. and C. Wiedinmyer, 2016: Air Quality Impact of Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa). *Environmental Science & Technology*, **50**(19), 10739-10745, doi:10.1021/acs.est.6b02602.
Marchetta, F., D. E. Sahn and L. Tiberti, 2019: The Role of Weather on Schooling and Work of Young Adults in Madagascar. *American Journal of Agricultural Economics*, **101**(4), 1203-1227, doi:10.1093/ajae/aaz015.
Marchiori, L., J.-F. Maystadt and I. Schumacher, 2012: The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management*, **63**(3), 355-374, doi:https://doi.org/10.1016/j.jeem.2012.02.001.
Marcotullio, P. J., C. Keßler and B. M. Fekete, 2021: The future urban heat-wave challenge in Africa: Exploratory analysis. *Global Environmental Change*, **66**, 102190, doi:https://doi.org/10.1016/j.gloenvcha.2020.102190.
Markandya, A. et al., 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. *The Lancet Planetary Health*, **2**(3), e126-e133, doi:10.1016/S2542-5196(18)30029-9.
Markham, A., E. Osipova, K. Lafrenz Samuels and A. Caldas, 2016: *World Heritage and Tourism in a Changing Climate.*, United Nations Environment Programme, Nairobi, Kenya.
Martens, C. et al., 2021: Large uncertainties in future biome changes in Africa call for flexible climate adaptation strategies. *Global Change Biology*, **27**(2), 340-358, doi:https://doi.org/10.1111/gcb.15390.
Martin, V. et al., 2008: The impact of climate change on the epidemiology and control of Rift Valley fever. *Rev Sci Tech*, **27**(2), 413-426.
Martínez-Capel, F., L. García-López and M. Beyer, 2017: Integrating Hydrological Modelling and Ecosystem Functioning for Environmental Flows in Climate Change Scenarios in the Zambezi River (Zambezi Region, Namibia). *River Research and Applications*, **33**(2), 258-275, doi:https://doi.org/10.1002/rra.3058.
Marzeion, B. and A. Levermann, 2014: Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environmental Research Letters*, **9**(3), doi:10.1088/1748-9326/9/3/034001.
Masih, I., S. Maskey, F. E. F. Mussá and P. Trambauer, 2014: A review of droughts on the African continent: a geospatial and long-term perspective. *Hydrology and Earth System Sciences*, **18**(9), 3635-3649, doi:10.5194/hess-18-3635-2014.
Masson, V. L., C. Benoudji, S. S. Reyes and G. Bernard, 2019: How violence against women and girls undermines resilience to climate risks in Chad. *Disasters*, **43 Suppl 3**(Suppl 3), S245-s270, doi:10.1111/disa.12343.
Masters, G. and L. Norgrove, 2010: *Climate change and invasive alien species*. **1**, CABI, Switzerland, 30 pp. Available at: https://www.cabi.org/Uploads/CABI/expertise/invasive-alien-species-working-paper.pdf.
Mastrorillo, M. et al., 2016: The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change*, **39**, 155-169, doi:https://doi.org/10.1016/j.gloenvcha.2016.04.014.
Masubelele, M. L., M. T. Hoffman, W. J. Bond and J. Gambiza, 2014: A 50 year study shows grass cover has increased in shrublands of semi-arid South Africa. *Journal of Arid Environments*, **104**, 43-51, doi:https://doi.org/10.1016/j.jaridenv.2014.01.011.
Masullo, I., G. Larsen, L. Brown and L. Dougherty-Choux, 2015: *"Direct Access" To Climate Finance: Lessons Learned By National Institutions*. World Resources Institute, 1-32 pp. Available at: https://wriorg.s3.amazonaws.com/s3fs-public/22DIRECT_ACCESS_TO_CLIMATE_FINANCE_LESSONS_LEARNED_BY_NATIONAL_INSTITUTIONS.pdf.
Mathews, E. H., P. G. Richards, S. L. Van Wyk and P. G. Rousseau, 1995: Energy efficiency of ultra-low-cost housing. *Building and Environment*, **30**(3), 427-432, doi:10.1016/0360-1323(94)00061-V.
Matlin, S. A. et al., 2018: Migrants' and refugees' health: towards an agenda of solutions. *Public Health Rev.*, **39**(1), 55, doi:10.1186/s40985-018-0104-9.
Maúre, G. et al., 2018: The southern African climate under 1.5 °C and 2 °C of global warming as simulated by CORDEX regional climate models. *Environmental Research Letters*, **13**(6), 065002, doi:10.1088/1748-9326/aab190.
Maurin, O. et al., 2014: Savanna fire and the origins of the 'underground forests' of Africa. *New Phytologist*, **204**(1), 201-214, doi:https://doi.org/10.1111/nph.12936.
Mavah, G. A. et al., 2018: Food and livelihoods in park-adjacent communities: The case of the Odzala Kokoua National Park. *Biological Conservation*, **222**, 44-51, doi:10.1016/j.biocon.2018.03.036.
Mawren, D., J. Hermes and C. J. C. Reason, 2021: Marine heatwaves in the Mozambique Channel. *Clim Dyn*, doi:10.1007/s00382-021-05909-3.

Maystadt, J.-F. and O. Ecker, 2014: Extreme Weather and Civil War: Does Drought Fuel Conflict in Somalia through Livestock Price Shocks? *American Journal of Agricultural Economics*, **96**(4), 1157-1182, doi:10.1093/ajae/aau010.
Maystadt, J. F., M. Calderone and L. You, 2014: Local warming and violent conflict in North and South Sudan. *Journal of Economic Geography*, **15**(3), 649-671, doi:10.1093/jeg/lbu033.
Mba, W. P. et al., 2018: Consequences of 1.5 °C and 2 °C global warming levels for temperature and precipitation changes over Central Africa. *Environmental Research Letters*, **13**(5), 055011, doi:10.1088/1748-9326/aab048.
Mbakaya, B. C., F. W. Kalembo and M. Zgambo, 2020: Use, adoption, and effectiveness of tippy-tap handwashing station in promoting hand hygiene practices in resource-limited settings: a systematic review. *BMC public health*, **20**(1), 1005, doi:10.1186/s12889-020-09101-w.
Mbaye, L. M., 2017: *Climate change, natural disasters, and migration*. African Development Bank, Côte d'Ivoire.
Mbereko, A., M. J. Chimbari and S. Mukaratirwa, 2018: The political ecology of stakeholder-driven climate change adaptation: Case study from Ntalale ward, Gwanda district, in Zimbabwe. *Jamba*, **10**(1), 419, doi:10.4102/jamba.v10i1.419.
Mbow, C. et al., 2014: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in africa. *Current Opinion in Environmental Sustainability*, **6**, 8-14, doi:10.1016/j.cosust.2013.09.002.
McCarl, B. A. et al., 2015: Climate change vulnerability and adaptation strategies in Egypt's agricultural sector. *Mitigation and Adaptation Strategies for Global Change*, **20**(7), 1097-1109, doi:10.1007/s11027-013-9520-9.
McCarl, B. A., A. W. Thayer and J. P. H. Jones, 2016: The challenge of climate change adaptation for agriculture: An economically oriented review. *Journal of Agricultural and Applied Economics*, **48**(4), 321-344, doi:10.1017/aae.2016.27.
McCartney, M. P. et al., 2019: Rethinking irrigation modernisation: realising multiple objectives through the integration of fisheries. *Marine and Freshwater Research*, **70**(9), 1201-1210, doi:https://doi.org/10.1071/MF19161.
McClanahan, T. R. et al., 2014: Biogeography and change among regional coral communities across the Western Indian Ocean. *PLoS One*, **9**(4), e93385, doi:10.1371/journal.pone.0093385.
McCleery, R. et al., 2018: Animal diversity declines with broad-scale homogenization of canopy cover in African savannas. *Biological Conservation*, **226**, 54-62, doi:10.1016/j.biocon.2018.07.020.
McCord, G. C., 2016: Malaria ecology and climate change. *Eur. Phys. J. Spec. Top.*, **225**(3), 459-470, doi:10.1140/epjst/e2015-50097-1.
McCord, P. F., M. Cox, M. Schmitt-Harsh and T. Evans, 2015: Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya. *Land Use Policy*, **42**, 738-750, doi:https://doi.org/10.1016/j.landusepol.2014.10.012.
McDonald, R. I. et al., 2014: Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change*, **27**, 96-105, doi:10.1016/j.gloenvcha.2014.04.022.
McDonnell, L. H. and L. J. Chapman, 2015: At the edge of the thermal window: effects of elevated temperature on the resting metabolism, hypoxia tolerance and upper critical thermal limit of a widespread African cichlid. *Conserv Physiol*, **3**(1), cov050, doi:10.1093/conphys/cov050.
McIntyre, P. B., C. A. Reidy and C. Revenga, 2016: Linking freshwater fishery management to global food security and biodiversity conservation. *Proceedings of the National Academy of Sciences*, **113**(45), doi:10.1073/pnas.1521540113.
McKechnie, A. E., I. A. Rushworth, F. Myburgh and S. J. Cunningham, 2021: Mortality among birds and bats during an extreme heat event in eastern South Africa. *Austral Ecology*, **46**(4), 687-691, doi:https://doi.org/10.1111/aec.13025.
McNicol, I. M., C. M. Ryan and E. T. A. Mitchard, 2018: Carbon losses from deforestation and widespread degradation offset by extensive growth in African woodlands. *Nature Communications*, **9**(1), 3045, doi:10.1038/s41467-018-05386-z.
McOmber, C., C. Audia and F. Crowley, 2019: Building resilience by challenging social norms: integrating a transformative approach within the BRACED consortia. *Disasters*, **43 Suppl 3**, S271-s294, doi:10.1111/disa.12341.
Meadow, A. M. et al., 2015: Moving toward the deliberate coproduction of climate science knowledge. *Climate, and Society*, **7**(2), 179-191, doi:https://doi.org/10.1175/WCAS-D-14-00050.1.
Mechler, R. et al., 2020: Loss and Damage and limits to adaptation: recent IPCC insights and implications for climate science and policy. *Sustainability Science*, doi:10.1007/s11625-020-00807-9.
Meissner, R. and I. Jacobs, 2016: Theorising complex water governance in Africa: the case of the proposed Epupa Dam on the Kunene River. *International Environmental Agreements: Politics, Law and Economics*, **16**(1), 21-48, doi:10.1007/s10784-014-9250-9.
Mekonnen, M. M. and A. Y. Hoekstra, 2016: Four billion people facing severe water scarcity. *Science Advances*, **2**(2), e1500323, doi:10.1126/sciadv.1500323.
Melillo, J. M. et al., 2016: Protected areas' role in climate-change mitigation. *Ambio*, **45**(2), 133-145, doi:10.1007/s13280-015-0693-1.
Meque, A. et al., 2021: Numerical weather prediction and climate modelling: Challenges and opportunities for improving climate services delivery in Southern Africa. *Climate Services*, **23**, 100243, doi:https://doi.org/10.1016/j.cliser.2021.100243.

Mercy Corps, 2019: *Climate Information Services Research Initiative: Final Report. A Learning Agenda for Climate Information Services in Sub-Saharan Africa (USAID)*. Mercy Corps, Washington DC, USA. Available at: https://www.climatelinks.org/sites/default/files/asset/document/2020_USAID_Mercy-CorpsC-CISRI.pdf.
Meresa, H. K. and M. T. Gatachew, 2018: Climate change impact on river flow extremes in the Upper Blue Nile River basin. *Journal of Water and Climate Change*, **10**(4), 759-781, doi:10.2166/wcc.2018.154.
Merkens, J.-L., L. Reimann, J. Hinkel and A. T. Vafeidis, 2016: Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, **145**, 57-66, doi:https://doi.org/10.1016/j.gloplacha.2016.08.009.
Mersha, A. A. and F. Van Laerhoven, 2016: A gender approach to understanding the differentiated impact of barriers to adaptation: responses to climate change in rural Ethiopia. *Regional Environmental Change*, **16**(6), 1701-1713, doi:10.1007/s10113-015-0921-z.
Mertz, O., A. Lykke and A. Reenberg, 2001: Importance and seasonality of vegetable consumption and marketing in Burkina Faso. *Economic Botany*, **55**(2), 276-289, doi:10.1007/BF02864565.
Messerli, P. et al., 2014: The geography of large-scale land acquisitions: Analysing socio-ecological patterns of target contexts in the global South. *Applied Geography*, **53**, 449-459, doi:10.1016/j.apgeog.2014.07.005.
Messina, J. P. et al., 2019: The current and future global distribution and population at risk of dengue. *Nature Microbiology*, **4**(9), 1508-1515, doi:10.1038/s41564-019-0476-8.
Meyer, C., H. Kreft, R. Guralnick and W. Jetz, 2015: Global priorities for an effective information basis of biodiversity distributions. *Nature Communications*, **6**, doi:10.1038/ncomms9221.
Mfitumukiza, D. et al., 2020: The role of indigenous knowledge (IK) in adaptation to drought by agropastoral smallholder farmers in Uganda. *Indian J. Tradit. Knowl.*, **19**(1), 44-52.
Midgley, G. F. and W. J. Bond, 2015: Future of African terrestrial biodiversity and ecosystems under anthropogenic climate change. *Nature Climate Change*, **5**(9), 823-829, doi:10.1038/nclimate2753.
Miguel, E., S. Satyanath and E. Sergenti, 2004: Economic Shocks and Civil Conflict: An Instrumental Variables Approach. *Journal of Political Economy*, **112**(4), 725-753, doi:10.1086/421174.
Miller, J. D. and M. Hutchins, 2017: The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. *Journal of Hydrology: Regional Studies*, **12**, 345-362, doi:10.1016/j.ejrh.2017.06.006.
Milne, R., S. J. Cunningham, A. T. K. Lee and B. Smit, 2015: The role of thermal physiology in recent declines of birds in a biodiversity hotspot. *Conservation Physiology*, **3**(1), doi:10.1093/conphys/cov048.
Minoli, S. et al., 2019: Global Response Patterns of Major Rainfed Crops to Adaptation by Maintaining Current Growing Periods and Irrigation. *Earth's Future*, **7**(12), 1464-1480, doi:https://doi.org/10.1029/2018EF001130.
Minsker, B. et al., 2015: Progress and Recommendations for Advancing Performance-Based Sustainable and Resilient Infrastructure Design. *Journal of Water Resources Planning and Management*, **141**(12), A4015006, doi:10.1061/(ASCE)WR.1943-5452.0000521.
Missirian, A. and W. Schlenker, 2017: Asylum applications respond to temperature fluctuations. *Science (New York, N.Y.)*, **358**(6370), 1610-1614, doi:10.1126/science.aao0432.
Mitchell, D., 2016: Human Influences on Heat-Related Health Indicators During the 2015 Egyptian Heat Wave. *Bulletin of the American Meteorological Society*, **97**, S70-S74, doi:10.1175/BAMS-D-16-0132.1.
Mithöfer, D. and H. Waibel (eds.), Seasonal vulnerability to poverty and indigenous fruit use in Zimbabwe. Rural poverty reduction through research for development and transformation, Berlin, Germany, University of Hannover, 5-7 pp.
Moat, J., T. W. Gole and A. P. Davis, 2019: Least concern to endangered: Applying climate change projections profoundly influences the extinction risk assessment for wild Arabica coffee. *Glob Chang Biol*, **25**(2), 390-403, doi:10.1111/gcb.14341.
Mogomotsi, P. K., A. Sekelemani and G. E. Mogomotsi, 2020: Climate change adaptation strategies of small-scale farmers in Ngamiland East, Botswana. *Climatic Change*, **159**, 441–460, doi:https://doi.org/10.1007/s10584-019-02645-w.
Mohmmed, A. et al., 2018: Assessing drought vulnerability and adaptation among farmers in Gadaref region, Eastern Sudan. *Land Use Policy*, **70**, 402-413, doi:https://doi.org/10.1016/j.landusepol.2017.11.027.
Mohsin, M. et al., 2019: Developing low carbon economies: An aggregated composite index based on carbon emissions. *Sustainable Energy Technologies and Assessments*, **35**, 365-374, doi:https://doi.org/10.1016/j.seta.2019.08.003.
Mokadem, N. et al., 2018: Impact of climate change on groundwater and the extinction of ancient "Foggara" and springs systems in arid lands in North Africa: a case study in Gafsa basin (Central of Tunisia). *Euro-Mediterranean Journal for Environmental Integration*, **3**(1), 28, doi:10.1007/s41207-018-0070-0.
Mokhatla, M. M., D. Rödder and G. J. Measey, 2015: Assessing the effects of climate change on distributions of Cape Floristic Region amphibians. *South African Journal of Science*, **111**(11), 1-7, doi:http://dx.doi.org/10.17159/sajs.2015/20140389.
Mölg, T., J. C. H. Chiang, A. Gohm and N. J. Cullen, 2009a: Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modelling. *Quarterly Journal of the Royal Meteorological Society*, **135**(643), 1439-1455, doi:https://doi.org/10.1002/qj.461.

Mölg, T. et al., 2009b: Quantifying Climate Change in the Tropical Midtroposphere over East Africa from Glacier Shrinkage on Kilimanjaro. *Journal of Climate*, **22**(15), 4162-4181, doi:10.1175/2009JCLI2954.1.
Moncrieff, G. R. et al., 2016: The future distribution of the savannah biome: model-based and biogeographic contingency. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150311, doi:10.1098/rstb.2015.0311.
Moore, F. and D. Diaz, 2015: Temperature Impacts on Economic Growth Warrant Stringent Mitigation Policy. *Nature Climate Change*, **5**, doi:10.1038/nclimate2481.
Moore, F. C., U. Baldos, T. Hertel and D. Diaz, 2017a: New science of climate change impacts on agriculture implies higher social cost of carbon. *Nature Communications*, **8**(1), doi:10.1038/s41467-017-01792-x.
Moore, S. M. et al., 2017b: El Niño and the shifting geography of cholera in Africa. *Proceedings of the National Academy of Sciences*, **114**(17), 4436-4441, doi:10.1073/pnas.1617218114.
Moosa, C. S. and N. Tuana, 2014: Mapping a Research Agenda Concerning Gender and Climate Change: A Review of the Literature. *Hypatia*, **29**(3), 677-694, doi:10.1111/hypa.12085.
Mora, C. et al., 2017: Global risk of deadly heat. *Nature Climate Change*, **7**(7), 501-506, doi:10.1038/nclimate3322.
Mordecai, E. A. et al., 2019: Thermal biology of mosquito-borne disease. *Ecology Letters*, **22**(10), 1690-1708, doi:10.1111/ele.13335.
Mordecai, E. A. et al., 2013: Optimal temperature for malaria transmission is dramatically lower than previously predicted. *Ecol. Lett.*, **16**(1), 22-30, doi:10.1111/ele.12015.
Mordecai, E. A. et al., 2020: Climate change could shift disease burden from malaria to arboviruses in Africa. *The Lancet Planetary Health*, **4**(9), e416-e423, doi:10.1016/S2542-5196(20)30178-9.
Moron, V. et al., 2016: Trends of mean temperatures and warm extremes in northern tropical Africa (1961-2014) from observed and PPCA-reconstructed time series. *J Geophys Res-Atmos*, **121**(10), 5298-5319, doi:10.1002/2015jd024303.
Morrison, S. F., K. Nakamura and C. J. Madden, 2008: Central control of thermogenesis in mammals. *Exp Physiol*, **93**(7), 773-797, doi:10.1113/expphysiol.2007.041848.
Morrissey, J. W., 2013: Understanding the relationship between environmental change and migration: The development of an effects framework based on the case of northern Ethiopia. *Global Environmental Change*, **23**(6), 1501-1510, doi:https://doi.org/10.1016/j.gloenvcha.2013.07.021.
Mouhamed, L., S. B. Traore, A. Alhassane and B. Sarr, 2013: Evolution of some observed climate extremes in the West African Sahel. *Weather and Climate Extremes*, **1**, 19-25, doi:10.1016/j.wace.2013.07.005.
Moustahfid, H., F. Marsac and A. Gangopadhyay, 2018: *Climate change impacts, vulnerabilities and adaptations: Western Indian Ocean marine fisheries* [Barange, M., T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options, FAO, Rome, Italy, 251-259 pp. Available at: http://www.fao.org/3/i9705en/I9705EN.pdf.
Mpandeli, S. et al., 2018: Climate Change Adaptation through the Water-Energy-Food Nexus in Southern Africa. *Int J Environ Res Public Health*, **15**(10), doi:10.3390/ijerph15102306.
Mrema, S., A. Shamte, M. Selemani and H. Masanja, 2012: The influence of weather on mortality in rural Tanzania: a time-series analysis 1999-2010. *Glob Health Action*, **5**, 33-43, doi:10.3402/gha.v5i0.19068.
Muchuru, S. and G. Nhamo, 2018: Climate change adaptation and the African fisheries: evidence from the UNFCCC National Communications. *Environment, Development and Sustainability*, **20**(4), 1687-1705, doi:10.1007/s10668-017-9960-6.
Muchuru, S. and G. Nhamo, 2019: A review of climate change adaptation measures in the African crop sector. *Climate and Development*, **11**(10), 873-885, doi:10.1080/17565529.2019.1585319.
Mudombi, S., C. Fabricius, V. van Zyl-Bulitta and A. Patt, 2017: The use of and obstacles to social learning in climate change adaptation initiatives in South Africa. *Jamba (Potchefstroom, South Africa)*, **9**(1), 292-292, doi:10.4102/jamba.v9i1.292.
Mueller, V., C. Gray and D. Hopping, 2020: Climate-Induced migration and unemployment in middle-income Africa. *Global Environmental Change*, **65**, 102183, doi:https://doi.org/10.1016/j.gloenvcha.2020.102183.
Mugambiwa, S. S., 2018: Adaptation measures to sustain indigenous practices and the use of indigenous knowledge systems to adapt to climate change in Mutoko rural district of Zimbabwe. *Jamba-J. Disaster Risk Stud.*, **10**(1), 1-9, doi:10.4102/jamba.v10i1.388.
Mugwedi, L. F. et al., 2018: Restoration planning for climate change mitigation and adaptation in the city of Durban, South Africa. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **14**(1), 132-144, doi:10.1080/21513732.2018.1483967.
Muhati, G. L., D. Olago and L. Olaka, 2018: Participatory scenario development process in addressing potential impacts of anthropogenic activities on the ecosystem services of Mt. Marsabit forest, Kenya. *Global Ecology and Conservation*, **14**, doi:10.1016/j.gecco.2018.e00402.
Mukeka, J. M., J. O. Ogutu, E. Kanga and E. Roskaft, 2018: Characteristics of Human-Wildlife Conflicts in Kenya: Examples of Tsavo and Maasai Mara Regions. *Environment and Natural Resources Research*, **8**(3), doi:10.5539/enrr.v8n3p148.
Muller, A. M. and A. Wright, 2016: *Unlocking Africa's Transboundary Water Potential* Bank, A. D., Abidjan. Available at: https://ssrn.com/abstract=2856605.

Müller, C. et al., 2021: Exploring uncertainties in global crop yield projections in a large ensemble of crop models and CMIP5 and CMIP6 climate scenarios. *Environmental Research Letters*, **16**(3), 034040, doi:10.1088/1748-9326/abd8fc.

Muller, C. and S. E. Shackleton, 2013: Perceptions of climate change and barriers to adaptation amongst commonage and commercial livestock farmers in the semi-arid Eastern Cape Karoo. *African Journal of Range & Forage Science*, **31**(1), 1-12, doi:10.2989/10220119.2013.845606.

Muller, M., 2018: Cape Town's drought: don't blame climate change. *Nature*, **559**(7713), 174-176, doi:10.1038/d41586-018-05649-1.

Müller Schmied, H. et al., 2016: Variations of global and continental water balance components as impacted by climate forcing uncertainty and human water use. *Hydrology and Earth System Sciences*, **20**(7), 2877-2898, doi:10.5194/hess-20-2877-2016.

Mulwa, C. K. and M. Visser, 2020: Farm diversification as an adaptation strategy to climatic shocks and implications for food security in northern Namibia. *World Development*, **129**, 104906, doi:https://doi.org/10.1016/j.worlddev.2020.104906.

Mumba, M. et al., 2016: Ecosystem-based Adaptation (EbA) of African Mountain Ecosystems: Experiences from Mount Elgon, Uganda. In: *Climate Change Adaptation Strategies – An Upstream-downstream Perspective* [Salzmann, N., C. Huggel, S. U. Nussbaumer and G. Ziervogel (eds.)]. Springer, Cham, pp. 121-140. ISBN 978-3-319-40773-9.

Mumtaz, Z. and P. Whiteford, 2017: Social safety nets in the development of a welfare system in Pakistan: an analysis of the Benazir Income Support Programme. *Asia Pacific Journal of Public Administration*, **39**(1), 16-38, doi:10.1080/23276665.2017.1290902.

Munday, C. and R. Washington, 2019: Controls on the diversity in climate model projections of early summer drying over Southern Africa. *Journal of Climate*, **32**(12), 3707-3725, doi:10.1175/JCLI-D-18-0463.1.

Mureithi, S. M. et al., 2016: Benefits Derived from Rehabilitating a Degraded Semi-Arid Rangeland in Communal Enclosures, Kenya. *Land Degradation & Development*, **27**(8), 1853-1862, doi:https://doi.org/10.1002/ldr.2341.

Muriithi, S. M., 2017: African small and medium enterprises (SMEs) contributions, challenges and solutions. *European Journal of Research and Reflection in Management Sciences*, **5**(1), 36-48.

Muringai, R. T., P. L. Mafongoya and R. Lottering, 2021: Climate Change and Variability Impacts on Sub-Saharan African Fisheries: A Review. *Reviews in Fisheries Science & Aquaculture*, 1-21, doi:10.1080/23308249.2020.1867057.

Muringai, R. T., D. Naidoo, P. Mafongoya and S. Lottering, 2019a: The Impacts of Climate Change on the Livelihood and Food Security of Small-Scale Fishers in Lake Kariba, Zimbabwe. *Journal of Asian and African Studies*, **55**(2), 298-313, doi:10.1177/0021909619875769.

Muringai, R. T., D. Naidoo, P. Mafongoya and M. Sibanda, 2019b: Small-scale fishers' perceptions of climate change and its consequences on fisheries: the case of Sanyathi fishing basin, Lake Kariba, Zimbabwe. *Transactions of the Royal Society of South Africa*, **74**(3), 248-257, doi:10.1080/0035919x.2019.1639564.

Murray, N. E., M. B. Quam and A. Wilder-Smith, 2013: Epidemiology of dengue: past, present and future prospects. *Clin Epidemiol*, **5**, 299-309, doi:10.2147/clep.s34440.

Murray, R., D. Louw, B. van der Merwe and I. Peters, 2018: Windhoek, Namibia: from conceptualising to operating and expanding a MAR scheme in a fractured quartzite aquifer for the city's water security. *Sustainable Water Resources Management*, **4**(2), 217-223, doi:10.1007/s40899-018-0213-0.

Murray, U., 2019: *Gender and NDCs: Country Progress and Key Findings*. UNDP, Nairobi, Kenya. Available at: https://www.international-climate-initiative.com/fileadmin/Dokumente/2020/200302_undp-ndcsp-gender-ndc-country-progress-key-findings.pdf.

Musa, Z. N., I. Popescu and A. Mynett, 2014: The Niger Delta's vulnerability to river floods due to sea level rise. *Natural Hazards and Earth System Sciences*, **14**(12), 3317-3329, doi:10.5194/nhess-14-3317-2014.

Musah-Surugu, I. J., A. Ahenkan and J. N. Bawole, 2019: Too weak to lead: motivation, agenda setting and constraints of local government to implement decentralized climate change adaptation policy in Ghana. *Environment, Development and Sustainability*, **21**(2), 587-607, doi:10.1007/s10668-017-0049-z.

Musengimana, G., F. K. Mukinda, R. Machekano and H. Mahomed, 2016: Temperature Variability and Occurrence of Diarrhoea in Children under Five-Years-Old in Cape Town Metropolitan Sub-Districts. *Int J Environ Res Public Health*, **13**(9), doi:10.3390/ijerph13090859.

Mushawemhuka, W., J. M. Rogerson and J. Saarinen, 2018: Nature-based tourism operators' perceptions and adaptation to climate change in Hwange National Park, Zimbabwe. *Bulletin of Geography. Socio-economic Series*,(42), 115-127, doi:http://dx.doi.org/10.1515/bog-2018-0034.

Musinguzi, L. et al., 2015: Fishers' perceptions of climate change, impacts on their livelihoods and adaptation strategies in environmental change hotspots: a case of Lake Wamala, Uganda. *Environment, Development and Sustainability*, **18**(4), 1255-1273, doi:10.1007/s10668-015-9690-6.

Musinguzi, L., V. Natugonza, J. Efitre and R. Ogutu-Ohwayo, 2018: The role of gender in improving adaptation to climate change among small-scale fishers. *Climate and Development*, **10**(6), 556-576, doi:10.1080/17565529.2017.1372262.

Mutabazi, K. D., T. S. Amjath-Babu and S. Sieber, 2015: Influence of livelihood resources on adaptive strategies to enhance climatic resilience of farm households in Morogoro, Tanzania: an indicator-based analysis. *Regional Environmental Change*, **15**(7), 1259-1268, doi:10.1007/s10113-015-0800-7.
Mutandwa, E., B. Hanyani-Mlambo and J. Manzvera, 2019: Exploring the link between climate change perceptions and adaptation strategies among smallholder farmers in Chimanimani district of Zimbabwe. *International Journal of Social Economics*, **46**(7), 850-860, doi:10.1108/ijse-12-2018-0654.
Mutenje, M. J. et al., 2019: A cost-benefit analysis of climate-smart agriculture options in Southern Africa: Balancing gender and technology. *Ecological Economics*, **163**, 126-137, doi:https://doi.org/10.1016/j.ecolecon.2019.05.013.
Muthige, M. S. et al., 2018: Projected changes in tropical cyclones over the South West Indian Ocean under different extents of global warming. *Environmental Research Letters*, **13**(6), 065019, doi:10.1088/1748-9326/aabc60.
Muthuwatta, L. et al., 2018: Understanding the impacts of climate change in the Tana River Basin, Kenya. *Proceedings of the International Association of Hydrological Sciences*, **379**, 37-42, doi:10.5194/piahs-379-37-2018.
Mutula, S., C. Stilwell and E. F. Elia, 2014: Indigenous Knowledge use in seasonal weather forecasting in Tanzania: the case of semi-arid central Tanzania. *South African Journal of Libraries and Information Science*, **80**(1), 18-27.
Muyambo, F., Y. T. Bahta and A. J. Jordaan, 2017: The role of indigenous knowledge in drought risk reduction: A case of communal farmers in South Africa. *Jamba*, **9**(1), 420, doi:10.4102/jamba.v9i1.420.
Mvula, P. et al., 2014: *Towards Defragmenting the Management System of Lake Chilwa Basin, Malawi*. Defragmenting African Resource Management, LIT Verlag. ISBN 978-3643903983.
Mwanga, E., 2019: The Role of By-Laws in Enhancing the Integration of Indigenous Knowledge. *Carbon & Climate Law Review*, **13**(1), 19-30, doi:10.21552/cclr/2019/1/5.
Mwaniki, F. and R. B. Stevenson, 2017: Farmers' uses of indigenous knowledge and practices to cope with climate change in Kilifi County, Kenya. *International Journal of Climate Change: impacts and responses*, **9**(4), 53-65, doi:http://dx.doi.org/10.18848/1835-7156/CGP/v09i04/53-65.
Mwenge Kahinda, J., R. Meissner and F. A. Engelbrecht, 2016: Implementing Integrated Catchment Management in the upper Limpopo River basin: A situational assessment. *Physics and Chemistry of the Earth, Parts A/B/C*, **93**, 104-118, doi:https://doi.org/10.1016/j.pce.2015.10.003.
Mweya, C. N. et al., 2016: Climate Change Influences Potential Distribution of Infected Aedes aegypti Co-Occurrence with Dengue Epidemics Risk Areas in Tanzania. *PLOS ONE*, **11**(9), e0162649, doi:10.1371/journal.pone.0162649.
Mweya, C. N., L. E. G. Mboera and S. I. Kimera, 2017: Climate Influence on Emerging Risk Areas for Rift Valley Fever Epidemics in Tanzania. *Am J Trop Med Hyg*, **97**(1), 109-114, doi:10.4269/ajtmh.16-0444.
Myers, S. S. et al., 2014: Increasing CO2 threatens human nutrition. *Nature*, **510**, 139, doi:10.1038/nature13179.
Myhre, G. et al., 2019: Frequency of extreme precipitation increases extensively with event rareness under global warming. *Sci Rep*, **9**(1), 16063, doi:10.1038/s41598-019-52277-4.
Nachmany, M., A. Abeysinghe and S. Barakat, 2017: Climate change legislation in the least developing countries. In: *Trends in Climate Change Legislation* [Averchenkova, A. F., Sam and M. Nachmany (eds.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 59–82. ISBN 9781786435774.
Naess, L. O. et al., 2015: Climate policy meets national development contexts: Insights from Kenya and Mozambique. *Global Environmental Change*, **35**, 534-544, doi:https://doi.org/10.1016/j.gloenvcha.2015.08.015.
Nago, M. and M. Krott, 2020: Systemic failures in north–south climate change knowledge transfer: a case study of the Congo Basin. *Climate Policy*, 1-14, doi:10.1080/14693062.2020.1820850.
Naicker, N. et al., 2017: Indoor Temperatures in Low Cost Housing in Johannesburg, South Africa. *Int J Environ Res Public Health*, **14**(11), doi:10.3390/ijerph14111410.
Naidoo, R. et al., 2019: Evaluating the impacts of protected areas on human well-being across the developing world. *Science Advances*, **5**(4), eaav3006, doi:10.1126/sciadv.aav3006.
Nair, M. K., L. F. Augustine and A. Konapur, 2016: Food-Based Interventions to Modify Diet Quality and Diversity to Address Multiple Micronutrient Deficiency. *Frontiers in Public Health*, **3**(277), doi:10.3389/fpubh.2015.00277.
Namara, R. E. and M. Giordano, 2017: *Economic Rationale for Cooperation on International Waters in Africa*. World Bank Group, Washington DC.
Nangombe, S. S. et al., 2019: High-Temperature Extreme Events Over Africa Under 1.5 and 2 °C of Global Warming. *J Geophys Res-Atmos*, **124**(8), 4413-4428, doi:10.1029/2018jd029747.
Nantima, N. et al., 2019: The importance of a One Health approach for prioritising zoonotic diseases to focus on capacity-building efforts in Uganda. *Rev Sci Tech*, **38**(1), 315-325, doi:10.20506/rst.38.1.2963.
Narayan, S. et al., 2016: The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLoS One*, **11**(5), e0154735, doi:10.1371/journal.pone.0154735.
Narayanan, S. and N. Gerber, 2017: Social safety nets for food and nutrition security in India. *Global Food Security*, **15**, 65-76, doi:https://doi.org/10.1016/j.gfs.2017.05.001.
Nardone, A. et al., 2010: Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science*, **130**(1-3), 57-69, doi:10.1016/j.livsci.2010.02.011.
Nashwan, M. S. and S. Shahid, 2019: Spatial distribution of unidirectional trends in climate and weather extremes in Nile river basin. *Theoretical and Applied Climatology*, **137**(1-2), 1181-1199, doi:https://doi.org/10.1007/s00704-018-2664-5.

Nashwan, M. S., S. Shahid and N. Abd Rahim, 2018: Unidirectional trends in annual and seasonal climate and extremes in Egypt. *Theoretical and Applied Climatology*, **136**(1-2), 457-473, doi:10.1007/s00704-018-2498-1.

Nath, I. B., 2020: *The food problem and the aggregate productivity consequences of climate change*. Cambridge University Press, Cambridge, MA. ISBN 9788578110796.

Natugonza, V. et al., 2016: Implications of climate warming for hydrology and water balance of small shallow lakes: A case of Wamala and Kawi, Uganda. *Aquatic Ecosystem Health & Management*, **19**(4), 327-335, doi:10.1080/14634988.2016.1142167.

Natugonza, V. et al., 2015: The responses of Nile tilapia *Oreochromis niloticus* (Linnaeus, 1758) in Lake Wamala (Uganda) to changing climatic conditions. *Lakes Reserv Res Manage*, **20**(2), 101-119, doi:10.1111/lre.12091.

Nawrotzki, R. J. and J. DeWaard, 2018: Putting trapped populations into place: climate change and inter-district migration flows in Zambia. *Regional Environmental Change*, **18**(2), 533-546, doi:10.1007/s10113-017-1224-3.

Ncube, B., 2018: Insights into indigenous knowledge strategies for coping and adapting to drought in agriculture: A Karoo scenario, South Africa. *Indilinga African Journal of Indigenous Knowledge Systems*, **17**(1), 92-108.

Ndebele-Murisa, M. R., 2014: Associations between Climate, Water Environment and Phytoplankton Production in African Lakes. In: *Phytoplankton: Biology, Classification and Environmental Impacts* [Teresa, M. S. (ed.)]. Nova Science Publishers, Inc. , NewYork, pp. 37-64. ISBN 978-1-62948-655-0.

Ndetto, E. L. and A. Matzarakis, 2014: Urban atmospheric environment and human biometeorological studies in Dar es Salaam, Tanzania. *Air Quality, Atmosphere & Health*, **8**(2), 175-191, doi:10.1007/s11869-014-0261-z.

Ndhlovu, N. and O. Saito, 2017: Assessing the Sensitivity of Small-Scale Fishery Groups to Climate Change in Lake Kariba , Zimbabwe. *Sustainability*, **9**(2209), 1-18, doi:10.3390/su9122209.

Ndoro, W., 2015: Heritage laws: Whose heritage are we protecting? In: *South African Archaeological Bulletin*. South African Archaeological Society, pp. 136–137. ISBN 0038-1969.

Neate-Clegg, M. H. C. et al., 2021: Afrotropical montane birds experience upslope shifts and range contractions along a fragmented elevational gradient in response to global warming. *PLOS ONE*, **16**(3), e0248712, doi:10.1371/journal.pone.0248712.

Nemakonde, L. D., D. Van Niekerk, P. Becker and S. Khoza, 2021: Perceived Adverse Effects of Separating Government Institutions for Disaster Risk Reduction and Climate Change Adaptation Within the Southern African Development Community Member States. *International Journal of Disaster Risk Science*, **12**(1), 1-12, doi:10.1007/s13753-020-00303-9.

Nematchoua, M. K., J. A. Orosa and S. Reiter, 2019: Climate change: Variabilities, vulnerabilities and adaptation analysis - A case of seven cities located in seven countries of Central Africa. *Urban Climate*, **29**, 100486, doi:https://doi.org/10.1016/j.uclim.2019.100486.

Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. *PLoS One*, **10**(3), e0118571, doi:10.1371/journal.pone.0118571.

Neuzil, K. M., A. J. Pollard and A. A. Marfin, 2019: Introduction of Typhoid Conjugate Vaccines in Africa and Asia. *Clin Infect Dis*, **68**(Suppl 1), S27-s30, doi:10.1093/cid/ciy878.

New, M., S. Dorbor, R. C. Odoulami and D. Maslo, 2020: Towards attribution-based climate insurance: Redefining who should pay for weather-related insurance. In: *Criminology and Climate: Insurance, Finance and the Regulation of Harmscapes*, 1st ed. [Holley, C., L. Phelan and C. Shearing (eds.)]. Routledge, London, pp. 15. ISBN 9780429201172.

Newbery, F., A. Qi and B. D. L. Fitt, 2016: Modelling impacts of climate change on arable crop diseases: progress, challenges and applications. *Current Opinion in Plant Biology*, **32**, 101-109, doi:10.1016/j.pbi.2016.07.002.

Newbold, T., 2018: Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. *Proceedings of the Royal Society B: Biological Sciences*, **285**(1881), 20180792, doi:10.1098/rspb.2018.0792.

Nguvava, M., B. J. Abiodun and F. Otieno, 2019: Projecting drought characteristics over East African basins at specific global warming levels. *Atmospheric Research*, **228**, 41-54, doi:https://doi.org/10.1016/j.atmosres.2019.05.008.

Nhamo, G. and O. Agyepong Adelaide, 2019: Climate change adaptation and local government : institutional complexities surrounding Cape Town's Day Zero. *Jamba : Journal of Disaster Risk Studies*, **11**(3), 1-9, doi:10.4102/jamba.v11i3.717.

Nhamo, G. and S. Muchuru, 2019: Climate adaptation in the public health sector in Africa: Evidence from United Nations Framework Convention on Climate Change National Communications. *Jamba*, **11**(1), 644, doi:10.4102/jamba.v11i1.644.

Nhamo, L. et al., 2018: The water-energy-food nexus: Climate risks and opportunities in Southern Africa. *Water*, **10**(5), doi:10.3390/w10050567.

Niang, I. et al., 2014: *Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1199-1266 pp. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap22_FINAL.pdf.

Nicholson, S. E., 2015: Long-term variability of the East African 'short rains' and its links to large-scale factors. *International Journal of Climatology*, **35**(13), 3979-3990, doi:10.1002/joc.4259.
Nicholson, S. E., 2017: Climate and climatic variability of rainfall over eastern Africa. *Reviews of Geophysics*, **55**(3), 590-635, doi:10.1002/2016rg000544.
Nicholson, S. E., C. Funk and A. H. Fink, 2018: Rainfall over the African continent from the 19th through the 21st century. *Global and Planetary Change*, **165**, 114-127, doi:https://doi.org/10.1016/j.gloplacha.2017.12.014.
Nielsen, J. Ø. and A. Reenberg, 2010: Cultural barriers to climate change adaptation: A case study from Northern Burkina Faso. *Global Environmental Change*, **20**(1), 142-152, doi:10.1016/j.gloenvcha.2009.10.002.
Nijsten, G.-J. et al., 2018: Transboundary aquifers of Africa: Review of the current state of knowledge and progress towards sustainable development and management. *Journal of Hydrology: Regional Studies*, **20**, 21-34, doi:10.1016/j.ejrh.2018.03.004.
Nikiema, P. M. et al., 2017: Multi-model CMIP5 and CORDEX simulations of historical summer temperature and precipitation variabilities over West Africa. *International Journal of Climatology*, **37**(5), 2438-2450, doi:10.1002/joc.4856.
Nikulin, G. et al., 2018: The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble. *Environmental Research Letters*, **13**(6), 065003, doi:10.1088/1748-9326/aab1b1.
Niño-Zarazúa, M., A. Barrientos, S. Hickey and D. Hulme, 2012: Social Protection in Sub-Saharan Africa: Getting the Politics Right. *World Development*, **40**(1), 163-176, doi:10.1016/j.worlddev.2011.04.004.
Nkiaka, E. et al., 2019: Identifying user needs for weather and climate services to enhance resilience to climate shocks in sub-Saharan Africa. *Environmental Research Letters*, **14**(12), 123003, doi:10.1088/1748-9326/ab4dfe.
Nkomwa, E. C. et al., 2014: Assessing indigenous knowledge systems and climate change adaptation strategies in agriculture: A case study of Chagaka Village, Chikhwawa, Southern Malawi. *Physics and Chemistry of the Earth*, **67-69**, 164-172, doi:https://doi.org/10.1016/j.pce.2013.10.002.
Nkotagu, H., 1996: Application of environmental isotopes to groundwater recharge studies in a semi-arid fractured crystalline basement area of Dodoma, Tanzania. *Journal of African Earth Sciences*, **22**(4), 443-457, doi:https://doi.org/10.1016/0899-5362(96)00022-X.
Noritomo, Y. and K. Takahashi, 2020: Can Insurance Payouts Prevent a Poverty Trap? Evidence from Randomised Experiments in Northern Kenya. *The Journal of Development Studies*, **56**(11), 2079-2096, doi:10.1080/00220388.2020.1736281.
Norström, V. A. et al., 2020: Principles for knowledge co-production in sustainability research. *Nature Sustainability*, **3**(3), 182-190, doi:10.1038/s41893-019-0448-2.
Norton, A. et al., 2020: Harnessing employment-based social assistance programmes to scale up nature-based climate action. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190127, doi:doi:10.1098/rstb.2019.0127.
Nouaceur, Z. and O. Murărescu, 2016: Rainfall Variability and Trend Analysis of Annual Rainfall in North Africa. *International Journal of Atmospheric Sciences*, **2016**, 1-12, doi:10.1155/2016/7230450.
Numbere, A. O., 2019: Mangrove Habitat Loss and the Need for the Establishment of Conservation and Protected Areas in the Niger Delta, Nigeria. In: *Habitats of the World-Biodiversity and Threats* [Musarella, C. M., A. C. Ortiz and R. Q. Canas (eds.)]. IntechOpen, pp. 49-63. ISBN 978-1-78984-487-0.
Nuñez, M. A. et al., 2021: Should tree invasions be used in treeless ecosystems to mitigate climate change? *Frontiers in Ecology and the Environment*, **19**(6), 334-341, doi:https://doi.org/10.1002/fee.2346.
Nunfam, V. F. et al., 2019a: Perceptions of climate change and occupational heat stress risks and adaptation strategies of mining workers in Ghana. *Sci Total Environ*, **657**, 365-378, doi:10.1016/j.scitotenv.2018.11.480.
Nunfam, V. F. et al., 2019b: Climate change and occupational heat stress risks and adaptation strategies of mining workers: Perspectives of supervisors and other stakeholders in Ghana. *Environ Res*, **169**, 147-155, doi:10.1016/j.envres.2018.11.004.
Nuvey, F. S. et al., 2020: Poor mental health of livestock farmers in Africa: a mixed methods case study from Ghana. *BMC public health*, **20**(1), 825, doi:10.1186/s12889-020-08949-2.
Nwamarah, U., 2018: *Gap analysis report: African Nationally Determined Contributions (NDCs)* [Dorsouma, A.-H., G. Phillips, S. Wade, G. Jeal, S. Bruton, S. Borrini and G. Esambe (eds.)]. African Development Bank, Abidjan, Côte d'Ivoire, 66 pp. Available at: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Events/Cop24/african_ndcs_gap_analysis_report.pdf.
Nyadzi, E., S. E. Werners, R. Biesbroek and F. Ludwig, 2021: Techniques and skills of indigenous weather and seasonal climate forecast in Northern Ghana. *Climate and Development*, **13**(6), 551-562, doi:10.1080/17565529.2020.1831429.
Nyagumbo, I., S. Mkuhlani, W. Mupangwa and D. Rodriguez, 2017: Planting date and yield benefits from conservation agriculture practices across Southern Africa. *Agricultural Systems*, **150**, 21-33, doi:https://doi.org/10.1016/j.agsy.2016.09.016.
Nyahunda, L., J. C. Makhubele, V. Mabvurira and F. K. Matlakala, 2020: Vulnerabilities and Inequalities Experienced by Women in the Climate Change Discourse in South Africa's Rural Communities: Implications for Social Work. *The British Journal of Social Work*, doi:10.1093/bjsw/bcaa118.
Nyangiwe, N., M. Yawa and V. Muchenje, 2018: Driving forces for changes in geographic range of cattle ticks (Acari: Ixodidae) in Africa: A review. *SA J. An. Sci.*, **48**(5), 829, doi:10.4314/sajas.v48i5.4.

Nyantakyi-Frimpong, H. and R. Bezner-Kerr, 2015: The relative importance of climate change in the context of multiple stressors in semi-arid Ghana. *Global Environmental Change*, **32**, 40-56, doi:10.1016/j.gloenvcha.2015.03.003.
Nyantakyi-Frimpong, H. et al., 2017: Agroecology and healthy food systems in semi-humid tropical Africa: Participatory research with vulnerable farming households in Malawi. *Acta tropica*, **175**, 42-49, doi:https://doi.org/10.1016/j.actatropica.2016.10.022.
Nyasimi, M. et al., 2018: Inclusion of Gender in Africa's Climate Change Policies and Strategies. In: *Handbook of Climate Change Communication* [Leal Filho W., M. E., Azul A., Azeiteiro U., McGhie H. (ed.)]. Springer, Cham, pp. 171-185. ISBN 978-3-319-69837-3.
Nyasimi, M. et al., 2017: Adoption and Dissemination Pathways for Climate-Smart Agriculture Technologies and Practices for Climate-Resilient Livelihoods in Lushoto, Northeast Tanzania. *Climate*, **5**(3), doi:10.3390/cli5030063.
Nyboer, E. A. and L. J. Chapman, 2017: Elevated temperature and acclimation time affect metabolic performance in the heavily exploited Nile perch of Lake Victoria. *The Journal of Experimental Biology*, **220**(20), 3782-3793, doi:10.1242/jeb.163022.
Nyboer, E. A. and L. J. Chapman, 2018: Cardiac plasticity influences aerobic performance and thermal tolerance in a tropical, freshwater fish at elevated temperatures. *J Exp Biol*, **221**(Pt 15), jeb178087, doi:10.1242/jeb.178087.
Nyboer, E. A., C. Liang and L. J. Chapman, 2019: Assessing the vulnerability of Africa's freshwater fishes to climate change: A continent-wide trait-based analysis. *Biological Conservation*, **236**, 505-520, doi:https://doi.org/10.1016/j.biocon.2019.05.003.
Nyiwul, L., 2021: Climate change adaptation and inequality in Africa: Case of water, energy and food insecurity. *Journal of Cleaner Production*, **278**, 123393, doi:https://doi.org/10.1016/j.jclepro.2020.123393.
Nziguheba, G. et al., 2015: Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification. *Nutrient Cycling in Agroecosystems*, **104**(3), 321-340, doi:10.1007/s10705-015-9729-y.
O'Connor, T. G., J. R. Puttick and M. T. Hoffman, 2014: Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science*, **31**(2), 67-88, doi:10.2989/10220119.2014.939996.
O'Loughlin, J., A. M. Linke and F. D. Witmer, 2014: Effects of temperature and precipitation variability on the risk of violence in sub-Saharan Africa, 1980-2012. *Proceedings of the National Academy of Sciences*, **111**(47), 16712-16717, doi:10.1073/pnas.1411899111.
O'Loughlin, J. et al., 2012: Climate variability and conflict risk in East Africa, 1990-2009. *Proceedings of the National Academy of Sciences* **109**(45), 18344-18349, doi:10.1073/pnas.1205130109.
O'Neill, B. C. et al., 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.*, **9**(9), 3461-3482, doi:10.5194/gmd-9-3461-2016.
Oba, G., 2014: *Climate change adaptation in Africa: an historical ecology*. Routledge, London. ISBN 9781315794907.
Obiero, K. et al., 2019: The Contribution of Fish to Food and Nutrition Security in Eastern Africa: Emerging Trends and Future Outlooks. *Sustainability*, **11**(6), doi:10.3390/su11061636.
Obradovich, N., R. Migliorini, M. P. Paulus and I. Rahwan, 2018: Empirical evidence of mental health risks posed by climate change. *Proceedings of the National Academy of Sciences*, **115**(43), 10953-10958, doi:10.1073/pnas.1801528115.
Obura, D. et al., 2017: *Coral reef status report for the Western Indian Ocean. Global Coral Reef Monitoring Network (GCRMN)/International Coral Reef Initiative (ICRI)*. 144 pp. Available at: https://nairobiconvention.org/clearinghouse/sites/default/files/Coral%20reef%20status%20report%20for%20the%20Western%20Indian%20Ocean%20%282017%29.pdf.
Odei Erdiaw-Kwasie, M., M. Abunyewah, J. Edusei and E. Buernor Alimo, 2020: Citizen participation dilemmas in water governance: An empirical case of Kumasi, Ghana. *World Development Perspectives*, **20**, 100242, doi:https://doi.org/10.1016/j.wdp.2020.100242.
Oduniyi, O. S. and S. S. Tekana, 2019: Adoption of agroforestry practices and climate change mitigation strategies in North West province of South Africa. *International Journal of Climate Change Strategies and Management*, **11**(5), 716-729, doi:10.1108/IJCCSM-02-2019-0009.
Oduor, F. O., J. Boedecker, G. Kennedy and C. Termote, 2019: Exploring agrobiodiversity for nutrition: Household on-farm agrobiodiversity is associated with improved quality of diet of young children in Vihiga, Kenya. *PLOS ONE*, **14**(8), e0219680, doi:10.1371/journal.pone.0219680.
OECD, 2020: *Climate Finance Provided and Mobilised by Developed Countries in 2013-18*. Climate Finance and the USD 100 Billion Goal, OECD Publishing, Paris. ISBN 978-92-64-68312-9.
OECD, 2021: *Water Governance in African Cities*. OECD Studies on Water, OECD Publishing, Paris, 110 pp. ISBN 9789264715431.
OECD/SWAC, 2020: *Africa's Urbanisation Dynamics 2020: Africapolis, Mapping a New Urban Geography*. West African Studies, OECD Publishing, Paris. ISBN 9789264314306.
OGAR, J. N. and S. A. Bassey, 2019: African Environmental Ethics. *RAIS Journal for Social Sciences*, **3**(1), doi:10.5281/zenodo.3066462.
Ogden, N. H., 2017: Climate change and vector-borne diseases of public health significance. *FEMS Microbiol Lett*, **364**(19), doi:10.1093/femsle/fnx186.

Ogega, O. M. et al., 2020: Heavy precipitation events over East Africa in a changing climate: results from CORDEX RCMs. *Clim Dyn*, **55**(3), 993-1009, doi:10.1007/s00382-020-05309-z.
Oguntunde, P. G., B. J. Abiodun and G. Lischeid, 2017: Impacts of climate change on hydro-meteorological drought over the Volta Basin, West Africa. *Global and Planetary Change*, **155**, 121-132, doi:https://doi.org/10.1016/j.gloplacha.2017.07.003.
Ogutu-Ohwayo, R. et al., 2016: Implications of climate variability and change for African lake ecosystems, fisheries productivity, and livelihoods. *Journal of Great Lakes Research*, **42**(3), 498-510, doi:https://doi.org/10.1016/j.jglr.2016.03.004.
OKACOM, 2020: *Realising the Benefits of Transboundary Water Cooperation in the Cubango-Okavango River Basin*. The Permanent Okavango River Basin Water Commission (OKACOM), Gaborone, Botswana, 24 pp. Available at: https://unece.org/fileadmin/DAM/env/water/activities/Benefits_cooperation/OKACOM_Policy_Document_June_2020.pdf.
OKO Finance, 2021: OKO raises $1.2 million to bring innovative insurance to smallholder farmers across Africa, OKO Finance, Uganda. Available at: https://www.oko.finance/post/oko-raises-1-2-million-to-bring-innovative-insurance-to-smallholder-farmers-across-africa.
Okonya, J. S., O. C. Ajayi and P. L. Mafongoya, 2017: The role of indigenous knowledge in seasonal weather forecasting and planning of farm activities by rural crop farmers in Uganda. In: *Indigenous knowledge systems and climate change management in Africa* [Mafongoya, P. L. and O. C. Ajayi (eds.)]. The Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, The Netherlands, pp. 239.
Okoye, J. and K. Oni, 2017: Promotion of indigenous food preservation and processing knowledge and the challenge of food security in Africa. *Journal of Food Security*, **5**(3), 75-87, doi:https://doi.org/10.12691/jfs-5-3-3.
Okpara, J. N. et al., 2017a: The applicability of Standardized Precipitation Index: drought characterization for early warning system and weather index insurance in West Africa. *Natural Hazards*, **89**(2), 555-583, doi:10.1007/s11069-017-2980-6.
Okpara, U. T., L. C. Stringer and A. J. Dougill, 2017b: Using a novel climate-water conflict vulnerability index to capture double exposures in Lake Chad. *Reg Environ Change*, **17**(2), 351-366, doi:10.1007/s10113-016-1003-6.
Oladipo, J. A., 2015: Seeing through the opaque glass, darkly: farmers' perception of climate change. *Climate and Development*, **8**(2), 122-132, doi:10.1080/17565529.2015.1034227.
Olago, D. et al., 2007: Climatic, socio-economic, and health factors affecting human vulnerability to cholera in the Lake Victoria Basin, East Africa. *AMBIO: A Journal of the Human Environment*, **36**(4), 350-358, doi:10.1579/0044-7447(2007)36[350:CSAHFA]2.0.CO;2.
Olago, D. O. et al., 2021: Lentic-Lotic Water System Response to Anthropogenic and Climatic Factors in Kenya and Their Sustainable Management. In: *Climate Change and Water Resources in Africa*, pp. 193-218. ISBN 978-3-030-61224-5
978-3-030-61225-2.
Olaka, L. A., J. O. Ogutu, M. Y. Said and C. Oludhe, 2019: Projected Climatic and Hydrologic Changes to Lake Victoria Basin Rivers under Three RCP Emission Scenarios for 2015–2100 and Impacts on the Water Sector. *Water*, **11**(7), 1449, doi:10.3390/w11071449.
Olawuyi, D. S., 2018: From technology transfer to technology absorption: addressing climate technology gaps in Africa. *Journal of Energy & Natural Resources Law*, **36**(1), 61-84, doi:10.1080/02646811.2017.1379667.
Olazabal, M. et al., 2019: A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, **14**(12), 124056, doi:10.1088/1748-9326/ab5532.
Oliver, E. C. J. et al., 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9**(1), 1324, doi:10.1038/s41467-018-03732-9.
Olmstead, S. M., 2014: Climate change adaptation and water resource management: A review of the literature. *Energy Economics*, **46**, 500-509, doi:10.1016/j.eneco.2013.09.005.
Ologeh, I. O., J. B. Akarakiri and F. A. Adesina, 2018: Constraints and Limits to Climate Change Adaptation Efforts in Nigeria. In: *Limits to Climate Change Adaptation* [Leal Filho, W. and J. Nalau (eds.)]. Springer International Publishing, Cham, pp. 159-174. ISBN 978-3-319-64599-5.
Oluwatimilehin, I. A. and A. Ayanlade, 2021: Agricultural community-based impact assessment and farmers' perception of climate change in selected Ecological Zones in Nigeria. *Agriculture & Food Security*, **10**(1), 3, doi:10.1186/s40066-020-00275-5.
Omari-Motsumi, K., M. Barnett and L. Schalatek, 2019: *Broken Connections and Systemic Barriers: Overcoming the Challenge of the 'Missing Middle' in Adaptation Finance*. Global Commission on Adaptation, Africa Adaptation Initiative, Cape Town, 1-58 pp. Available at: https://gca.org/wp-content/uploads/2020/12/Missing_Middle_Adaptation_Finance_Background_Paper.pdf.
Omonijo, A. G., 2017: Assessing seasonal variations in urban thermal comfort and potential health risks using Physiologically Equivalent Temperature: A case of Ibadan, Nigeria. *Urban Climate*, **21**, 87-105, doi:https://doi.org/10.1016/j.uclim.2017.05.006.
Onwutuebe, C. J., 2019: Patriarchy and Women Vulnerability to Adverse Climate Change in Nigeria. *SAGE Open*, **9**(1), doi:10.1177/2158244019825914.

Onyango, E., O. Sahin, C. Chu and B. Mackey, 2016a: An Integrated Modelling Approach to Climate Change and Malaria Vulnerability Assessments. *International Congress on Environmental Modelling and Software*.
Onyango, E. A. et al., 2016b: An integrated risk and vulnerability assessment framework for climate change and malaria transmission in East Africa. *Malaria Journal*, **15**(1), 551, doi:10.1186/s12936-016-1600-3.
Onyekuru, A. N. and R. Marchant, 2014: Climate change impact and adaptation pathways for forest dependent livelihood systems in Nigeria. **9**(24), 1819-1832, doi:https://doi.org/DOI:10.5897/AJAR2013.8315.
Onyutha, C. et al., 2016: Analyses of rainfall trends in the Nile River Basin. *Journal of Hydro-environment Research*, **13**, 36-51, doi:10.1016/j.jher.2015.09.002.
Onywere, S. M. and I. S. John M. Mironga, 2012: Use of Remote Sensing Data in Evaluating the Extent of Anthropogenic
Activities and their Impact on Lake Naivasha, Kenya. *The Open Environmental Engineering Journal*, **5**, 9-18.
Oppenheimer, M. et al., 2019: *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, In press pp. Available at: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf.
Oppenheimer, M. et al., 2014: *Emergent risks and key vulnerabilities* [Field, C. B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (ed.)]. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1039-1099 pp. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap19_FINAL.pdf.
Ordway, E. M., G. P. Asner and E. F. Lambin, 2017: Deforestation risk due to commodity crop expansion in sub-Saharan Africa. *Environmental Research Letters*, **12**(4), 044015, doi:10.1088/1748-9326/aa6509.
Ortega-Cisneros, K. et al., 2018: Evaluating the effects of climate change in the southern Benguela upwelling system using the Atlantis modelling framework. *Fisheries Oceanography*, **27**(5), 489-503, doi:10.1111/fog.12268.
Ortiz-Bobea, A. et al., 2021: Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change*, **11**(4), 306-312, doi:10.1038/s41558-021-01000-1.
Oruonye, D. E., 2010: The impact of climate change on the Bade fishing festival of Yobe State, Nigeria. *International Journal of Sustainable Development*, **3**(3), 29-32.
Osima, S. et al., 2018: Projected climate over the Greater Horn of Africa under 1.5 °C and 2 °C global warming. *Environmental Research Letters*, **13**(6), 065004, doi:10.1088/1748-9326/aaba1b.
Oswald, K. N. et al., 2020: Increasing temperatures increase the risk of reproductive failure in a near threatened alpine ground-nesting bird, the Cape Rockjumper Chaetops frenatus. *Ibis*, **162**(4), 1363-1369, doi:https://doi.org/10.1111/ibi.12846.
Otieno, V. O. and R. O. Anyah, 2013: CMIP5 simulated climate conditions of the Greater Horn of Africa (GHA). Part II: projected climate. *Clim Dyn*, **41**(7-8), 2099-2113, doi:10.1007/s00382-013-1694-z.
Otto, F. E. et al., 2018: Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. *Environmental Research Letters*, **13**(12), 124010, doi:https://doi.org/10.1088/1748-9326/aae9f9.
Otto, F. E. L. et al., 2020: Challenges to Understanding Extreme Weather Changes in Lower Income Countries. *Bulletin of the American Meteorological Society*, **101**(10), E1851-E1860, doi:10.1175/bams-d-19-0317.1.
Otto, I. M. et al., 2017: Social vulnerability to climate change: a review of concepts and evidence. *Regional Environmental Change*, **17**(6), 1651-1662, doi:10.1007/s10113-017-1105-9.
Otzelberger, A., 2014: *Tackling the Double Injustice of Climate Change and Gender Inequality*. CARE Climate Change, CARE International. Available at: https://www.carefrance.org/ressources/themas/1/4442,CARE_COP20_Tackling-double-injustic.pdf.
Ouhamdouch, S. et al., 2019: Evaluation of climate change impact on groundwater from semi-arid environment (Essaouira Basin, Morocco) using integrated approaches. *Environmental Earth Sciences*, **78**(15), doi:10.1007/s12665-019-8470-2.
Ouweneel, B., K. Winter and K. Carden, 2020: How different Cape Town residential suburbs helped avert Day Zero. *H2Open Journal*, **3**(1), 118-134, doi:10.2166/h2oj.2020.018.
Ovalle-Rivera, O. et al., 2015: Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. *PLoS One*, **10**(4), e0124155, doi:10.1371/journal.pone.0124155.
Overland, I. et al., 2021: Financing for Research on Climate Change in Africa: A Review. *Climate and Development*, doi:https://doi.org/10.1080/17565529.2021.1976609.
Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071, doi:https://doi.org/10.1016/j.gloenvcha.2020.102071.
Oyero, O., 2007: Dynamics of indigenous language in environmental communication. *Lagos Papers in English Studies*, **1**(1), 228-235.
Ozaki, M., 2016: *Disaster Risk Financing in Bangladesh*. ADB South Asia Working Paper Series, **46**, Asian Development Bank. Available at: https://www.adb.org/sites/default/files/publication/198561/sawp-046.pdf.

Ozor, N. and A. Nyambane, 2020: *Nationally Determined Contributions Implementation Index and Tracking Tools for Africa*. The Pan Africa Climate Justice Alliance (PACJA). Available at: https://www.pacja.org/docs/publications/NDC%20Implementation%20Report%20-final.pdf.

Paalo, S. A. and A. K. Issifu, 2021: De-internationalizing Hybrid Peace: State-Traditional Authority Collaboration and Conflict Resolution in Northern Ghana. *Journal of Intervention and Statebuilding*, **15**(3), 406-424, doi:10.1080/17502977.2020.1856551.

Padowski, J. C., L. Carrera and J. W. Jawitz, 2016: Overcoming urban water insecurity with infrastructure and institutions. *Water Resources Management*, **30**(13), 4913-4926, doi:10.1007/s11269-016-1461-0.

Paige, S. B. et al., 2014: Beyond bushmeat: animal contact, injury, and zoonotic disease risk in Western Uganda. *Ecohealth*, **11**(4), 534-543, doi:10.1007/s10393-014-0942-y.

Palmer, M. A., J. G. Kramer, J. Boyd and D. Hawthorne, 2016: Practices for facilitating interdisciplinary synthetic research: the National Socio-Environmental Synthesis Center (SESYNC). *Current Opinion in Environmental Sustainability*, **19**, 111-122, doi:https://doi.org/10.1016/j.cosust.2016.01.002.

Pandit, R. et al., 2018: *Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. The Intergovernmental Platform on Biodiversity and Ecosystem Services, Bonn, Germany. Available at: https://www.ipbes.net/system/tdf/spm_3bi_ldr_digital.pdf?file=1&type=node&id=28335.

Panitz, H.-J. et al., 2013: COSMO-CLM (CCLM) climate simulations over CORDEX-Africa domain: analysis of the ERA-Interim driven simulations at 0.44° and 0.22° resolution. *Clim Dyn*, **42**(11-12), 3015-3038, doi:10.1007/s00382-013-1834-5.

Panthou, G. et al., 2018: Rainfall intensification in tropical semi-arid regions: the Sahelian case. *Environmental Research Letters*, **13**(6), 064013, doi:10.1088/1748-9326/aac334.

Panthou, G., T. Vischel and T. Lebel, 2014: Recent trends in the regime of extreme rainfall in the Central Sahel. *International Journal of Climatology*, **34**(15), 3998-4006, doi:https://doi.org/10.1002/joc.3984.

Park, S. et al., 2020: Recent ENSO influence on East African drought during rainy seasons through the synergistic use of satellite and reanalysis data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **162**, 17-26, doi:https://doi.org/10.1016/j.isprsjprs.2020.02.003.

Parkes, B., J. Cronin, O. Dessens and B. Sultan, 2019: Climate change in Africa: costs of mitigating heat stress. *Climatic Change*, **154**(3), 461-476, doi:10.1007/s10584-019-02405-w.

Parmar, A. et al., 2019: Exposure to air pollutants and heat stress among resource-poor women entrepreneurs in small-scale cassava processing. *Environmental Monitoring and Assessment*, doi:10.1007/s10661-019-7811-7.

Parrado, R. et al., 2020: Fiscal effects and the potential implications on economic growth of sea-level rise impacts and coastal zone protection. *Climatic Change*, **160**(2), 283-302, doi:10.1007/s10584-020-02664-y.

Partey, S. T., R. B. Zougmoré, M. Ouédraogo and B. M. Campbell, 2018: Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt. *Journal of Cleaner Production*, **187**, 285-295, doi:10.1016/j.jclepro.2018.03.199.

Pascale, S., S. B. Kapnick, T. L. Delworth and W. F. Cooke, 2020: Increasing risk of another Cape Town "Day Zero" drought in the 21st century. *Proceedings of the National Academy of Sciences*, **117**(47), 29495, doi:10.1073/pnas.2009144117.

Pasgaard, M. et al., 2015: Geographical imbalances and divides in the scientific production of climate change knowledge. *Global Environmental Change*, **35**, 279-288, doi:https://doi.org/10.1016/j.gloenvcha.2015.09.018.

Pasquini, L., 2020: The urban governance of climate change adaptation in least-developed African countries and in small cities: the engagement of local decision-makers in Dar es Salaam, Tanzania, and Karonga, Malawi. *Climate and Development*, **12**(5), 408-419, doi:10.1080/17565529.2019.1632166.

Pasquini, L. and R. M. Cowling, 2014: Opportunities and challenges for mainstreaming ecosystem-based adaptation in local government: evidence from the Western Cape, South Africa. *Environment, Development and Sustainability*, **17**(5), 1121-1140, doi:10.1007/s10668-014-9594-x.

Pasquini, L., G. Ziervogel, R. M. Cowling and C. Shearing, 2015: What enables local governments to mainstream climate change adaptation? Lessons learned from two municipal case studies in the Western Cape, South Africa. *Climate and Development*, **7**, 60-70, doi:10.1080/17565529.2014.886994.

Paterson, S. K. et al., 2017: Size does matter: City scale and the asymmetries of climate change adaptation in three coastal towns. *Geoforum*, **81**, 109-119, doi:https://doi.org/10.1016/j.geoforum.2017.02.014.

Patricola, C. M. and K. H. Cook, 2010: Northern African climate at the end of the twenty-first century: An integrated application of regional and global climate models. *Clim Dyn*, **35**, 193-212, doi:10.1007/s00382-009-0623-7.

Patrut, A. et al., 2018: The demise of the largest and oldest African baobabs. *Nature Plants*, **4**(7), 423-426, doi:10.1038/s41477-018-0170-5.

Paul, C. J., E. S. Weinthal, M. F. Bellemare and M. A. Jeuland, 2016: Social capital, trust, and adaptation to climate change: Evidence from rural Ethiopia. *Global Environmental Change*, **36**, 124-138, doi:https://doi.org/10.1016/j.gloenvcha.2015.12.003.

Paul, M. and M. wa Gĩthĩnji, 2017: Small farms, smaller plots: land size, fragmentation, and productivity in Ethiopia. *The Journal of Peasant Studies*, **45**(4), 757-775, doi:10.1080/03066150.2016.1278365.

Pauline, N. M., C. Vogel, S. Grab and E. T. Liwenga, 2017: Smallholder farmers in the Great Ruaha River sub-Basin of Tanzania: coping or adapting to rainfall variability? *Climate and Development*, **9**(3), 217-230, doi:10.1080/17565529.2016.1184607.
Payne, Benjamin L. and J. Bro-Jørgensen, 2016: Disproportionate Climate-Induced Range Loss Forecast for the Most Threatened African Antelopes. *Current Biology*, **26**(9), 1200-1205, doi:https://doi.org/10.1016/j.cub.2016.02.067.
Paz, M., A. Avendaño, A. Caballero and V. Gozalo, 2015: *Joining the dots of Informality and Climate Change: A Discussion Paper for Practitioners* [Konrad Adenauer Foundation (ed.)]. 40 pp. Available at: https://www.kas.de/c/document_library/get_file?uuid=6139364e-b294-8198-153f-1cdf2f91f034&groupId=252038.
Paz, S., 2009: Impact of temperature variability on cholera incidence in southeastern Africa, 1971-2006. *Ecohealth*, **6**(3), 340-345, doi:10.1007/s10393-009-0264-7.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science (New York, N.Y.)*, **355**(6332), doi:10.1126/science.aai9214.
Peer, N. et al., 2018: Latitudinal gradients and poleward expansion of mangrove ecosystems in South Africa: 50 years after Macnae's first assessment. *African Journal of Marine Science*, **40**(2), 101-120, doi:10.2989/1814232X.2018.1466728.
Peirson, A. E. and G. Ziervogel, 2021: Sanitation Upgrading as Climate Action: Lessons for Local Government from a Community Informal Settlement Project in Cape Town. *Sustainability*, **13**(15), doi:10.3390/su13158598.
Penney, R., G. Wilson and L. Rodwell, 2017: Managing sino-ghanaian fi shery relations : A political ecology approach. *Marine Policy*, **79**(December 2016), 46-53, doi:10.1016/j.marpol.2017.02.008.
Peprah, K., 2017: Sustainable production of afforestation and reforestation to salvage land degradation in Asunafo District, Ghana. *J. Degrade. Min. Land Manage.*, **5**(1), 955-964, doi:https://doi.org/10.15243/jdmlm.2017.051.955.
Perez, C. et al., 2015: How resilient are farming households and communities to a changing climate in Africa? A gender-based perspective. *Global Environmental Change*, **34**, 95-107, doi:10.1016/j.gloenvcha.2015.06.003.
Péron, G. and R. Altwegg, 2015: Twenty-five years of change in southern African passerine diversity: nonclimatic factors of change. *Global Change Biology*, **21**(9), 3347-3355, doi:https://doi.org/10.1111/gcb.12909.
Petesch, P. et al., 2018: Local normative climate shaping agency and agricultural livelihoods in sub-Saharan Africa. *Journal of Gender, Agriculture and Food Security*, **3**(1), 108-130, doi:https://doi.org/10.19268/JGAFS.312018.5.
Petrova, I. Y., C. C. van Heerwaarden, C. Hohenegger and F. Guichard, 2018: Regional co-variability of spatial and temporal soil moisture–precipitation coupling in North Africa: an observational perspective. *Hydrol. Earth Syst. Sci.*, **22**(6), 3275-3294, doi:10.5194/hess-22-3275-2018.
Peyre, M. a. C. V. a. A.-S. S. a. V. A. a. A.-M. N. a. T. E. a. R. F., 2015: A Systematic Scoping Study of the Socio-Economic Impact of Rift Valley Fever: Research Gaps and Needs. *Zoonoses and Public Health*, **62**(5), 309-325, doi:10.1111/zph.12153.
Pham-Duc, B. et al., 2020: The Lake Chad hydrology under current climate change. *Sci Rep*, **10**(1), 5498, doi:10.1038/s41598-020-62417-w.
Phillips, C. A. et al., 2020: Compound climate risks in the COVID-19 pandemic. *Nature Climate Change*, **10**(7), 586-588, doi:10.1038/s41558-020-0804-2.
Phillips, H., 2015: The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. *Environmental Science & Policy*, **47**, 118-125, doi:https://doi.org/10.1016/j.envsci.2014.11.003.
Phipps, W. L. et al., 2017: Due South: A first assessment of the potential impacts of climate change on Cape vulture occurrence. *Biological Conservation*, **210**, 16-25, doi:10.1016/j.biocon.2017.03.028.
Phiri, D., M. Simwanda and V. Nyirenda, 2021: Mapping the impacts of cyclone Idai in Mozambique using Sentinel-2 and OBIA approach. *South African Geographical Journal*, **103**(2), 237-258, doi:10.1080/03736245.2020.1740104.
Piao, S. et al., 2020: Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth & Environment*, **1**(1), 14-27, doi:10.1038/s43017-019-0001-x.
Pienaar, G. W. and D. A. Hughes, 2017: Linking hydrological uncertainty with equitable allocation for water resources decision-making. *Water Resources Management*, **31**(1), 269-282, doi:10.1007/s11269-016-1523-3.
Pigott, D. M. et al., 2017: Local, national, and regional viral haemorrhagic fever pandemic potential in Africa: a multistage analysis. *Lancet*, **390**(10113), 2662-2672, doi:10.1016/S0140-6736(17)32092-5.
Pinceel, T., B. Vanschoenwinkel, L. Brendonck and F. Buschke, 2016: Modelling the sensitivity of life history traits to climate change in a temporary pool crustacean. *Scientific Reports*, **6**(1), 29451, doi:10.1038/srep29451.
Pinto, I. et al., 2015: Evaluation and projections of extreme precipitation over southern Africa from two CORDEX models. *Climatic Change*, **135**(3-4), 655-668, doi:10.1007/s10584-015-1573-1.
Pittelkow, C. M. et al., 2015: Productivity limits and potentials of the principles of conservation agriculture. *Nature*, **517**(7534), 365-368, doi:10.1038/nature13809.
Plisnier, P.-D., M. Nshombo, H. Mgana and G. Ntakimazi, 2018: Monitoring climate change and anthropogenic pressure at Lake Tanganyika. *Journal of Great Lakes Research*, **44**(6), 1194-1208, doi:10.1016/j.jglr.2018.05.019.
Polley, H. W. et al., 2013: Climate Change and North American Rangelands: Trends, Projections, and Implications. *Rangeland Ecology & Management*, **66**(5), 493-511, doi:10.2111/REM-D-12-00068.1.

Popelka, S. J. and L. C. Smith, 2020: Rivers as political borders: a new subnational geospatial dataset. *Water Policy*, **22**(3), 293-312, doi:10.2166/wp.2020.041.
Potts, D., 2008: The urban informal sector in sub-Saharan Africa: from bad to good (and back again?). *Development Southern Africa*, **25**(2), 151-167, doi:10.1080/03768350802090527.
Poudel, S., S. Funakawa, H. Shinjo and B. Mishra, 2020: Understanding households' livelihood vulnerability to climate change in the Lamjung district of Nepal. *Environment, Development and Sustainability*, doi:10.1007/s10668-019-00566-3.
Pouramin, P., N. Nagabhatla and M. Miletto, 2020: A Systematic Review of Water and Gender Interlinkages: Assessing the Intersection With Health. *Frontiers in Water*, **2**, doi:10.3389/frwa.2020.00006.
Powell, B., P. Maundu, H. V. Kuhnlein and T. Johns, 2013: Wild Foods from Farm and Forest in the East Usambara Mountains, Tanzania. *Ecology of Food and Nutrition*, **52**(6), 451-478, doi:10.1080/03670244.2013.768122.
Pozniak, A. et al., 2020: HIV continuity of care after Cyclone Idai in Mozambique. *The Lancet HIV*, **7**(3), e159-e160, doi:10.1016/S2352-3018(20)30045-X.
Pragna, P. et al., 2018: Summer season induced rhythmic alterations in metabolic activities to adapt to heat stress in three indigenous (Osmanabadi, Malabari and Salem Black) goat breeds. *Biological Rhythm Research*, **49**(4), 551-565, doi:10.1080/09291016.2017.1386891.
Pratt, C. F., K. L. Constantine and S. T. Murphy, 2017: Economic impacts of invasive alien species on African smallholder livelihoods. *Global Food Security*, **14**, 31-37, doi:10.1016/j.gfs.2017.01.011.
Prinz, R. et al., 2018: Mapping the loss of Mt. Kenya's Glaciers: An example of the challenges of satellite monitoring of very small glaciers. *Geosciences*, **8**(5), doi:10.3390/geosciences8050174.
Prinz, R. et al., 2016: Climatic controls and climate proxy potential of Lewis Glacier, Mt. Kenya. *The Cryosphere*, **10**(1), 133-148, doi:10.5194/tc-10-133-2016.
Probert, J. R. et al., 2019: Anthropogenic modifications to fire regimes in the wider Serengeti-Mara ecosystem. *Global Change Biology*, **25**(10), 3406-3423, doi:10.1111/gcb.14711.
Protopopoff, N. et al., 2009: Ranking malaria risk factors to guide malaria control efforts in African highlands. *PLoS One*, **4**(11), e8022, doi:10.1371/journal.pone.0008022.
Pula, 2021: Pula Global Insuretech, Pula Global Insuretech, Nairobi, Kenya. Available at: https://www.pula-advisors.com/.
Quandt, A., H. Neufeldt and J. T. McCabe, 2017: The role of agroforestry in building livelihood resilience to floods and drought in semiarid Kenya. *Ecology and Society*, **22**(3), doi:10.5751/es-09461-220310.
Quesada, B., A. Arneth, E. Robertson and N. d. Noblet-Ducoudré, 2018: Potential strong contribution of future anthropogenic land-use and land-cover change to the terrestrial carbon cycle. *Environmental Research Letters*, **13**(6), 064023, doi:10.1088/1748-9326/aac4c3.
Ragavan, M. I., L. E. Marcil and A. Garg, 2020: Climate Change as a Social Determinant of Health. *Pediatrics*, **145**(5), e20193169, doi:10.1542/peds.2019-3169.
Rahimi, J. et al., 2021: Heat stress will detrimentally impact future livestock production in East Africa. *Nature Food*, **2**(2), 88-96, doi:10.1038/s43016-021-00226-8.
Rai, N., S. Best and M. Soanes, 2016: *Unlocking climate finance for decentralised energy access*. Working Paper, International Institute for Environment and Development (IIED), IIED, London, 48 pp. Available at: https://pubs.iied.org/sites/default/files/pdfs/migrate/16621IIED.pdf?
Raleigh, C. and D. Kniveton, 2012: Come rain or shine: An analysis of conflict and climate variability in East Africa. *Journal of Peace Research*, **49**(1), 51-64, doi:10.1177/0022343311427754.
Ralston, L., 2015: Conflict and Climate: a Micro-level Analysis. *CEGA Working Paper*.
Ramin, B., 2009: *Slums, climate change and human health in sub-Saharan Africa*. Bulletin of the World Health Organization, **86**, World Health Organization, 886 pp.
Ramutsindela, M. and B. Büscher, 2019: Environmental Governance and the (Re-)Making of the African State. In: *Oxford Research Encyclopedia of Politics*. ISBN 9780190228637.
Ranasinghe, R. et al., 2021: *Climate Change Information for Regional Impact and for Risk Assessment* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change **In Press**, Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_12.pdf.
Randell, H. and C. Gray, 2016: Climate variability and educational attainment: Evidence from rural Ethiopia. *Glob Environ Change*, **41**, 111-123, doi:10.1016/j.gloenvcha.2016.09.006.
Randell, H. and C. Gray, 2019: Climate change and educational attainment in the global tropics. *Proc Natl Acad Sci U S A*, **116**(18), 8840-8845, doi:10.1073/pnas.1817480116.
Rankoana, S., 2016a: Perceptions of Climate Change and the Potential for Adaptation in a Rural Community in Limpopo Province, South Africa. *Sustainability*, **8**(8), 672, doi:https://doi.org/10.3390/su8080672.
Rankoana, S. A., 2016b: Rainfall scarcity and its impacts on subsistence farming: the role of gender and religious rituals in adaptation to change. *Agenda*, **30**(3), 124-131, doi:https://doi.org/10.1080/10130950.2016.1259867.
Rannow, S. et al., 2014: Managing protected areas under climate change: challenges and priorities. *Environ Manage*, **54**(4), 732-743, doi:10.1007/s00267-014-0271-5.

Rao, N. et al., 2017: Gendered vulnerabilities to climate change: insights from the semi-arid regions of Africa and Asia. *Climate and Development*, **11**(1), 14-26, doi:10.1080/17565529.2017.1372266.
Rao, N. et al., 2019: A qualitative comparative analysis of women's agency and adaptive capacity in climate change hotspots in Asia and Africa. *Nature Climate Change*, **9**(12), 964-971, doi:10.1038/s41558-019-0638-y.
Rao, N. et al., 2020: Managing risk, changing aspirations and household dynamics: Implications for wellbeing and adaptation in semi-arid Africa and India. *World Development*, **125**, 104667, doi:https://doi.org/10.1016/j.worlddev.2019.104667.
Rao, S. et al., 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, **11**(12), 124013, doi:10.1088/1748-9326/11/12/124013.
Rapolaki, R. S. and C. J. C. Reason, 2018: Tropical storm Chedza and associated floods over south-eastern Africa. *Natural Hazards*, **93**(1), 189-217, doi:10.1007/s11069-018-3295-y.
Rauner, S. et al., 2020a: Coal-exit health and environmental damage reductions outweigh economic impacts. *Nature Climate Change*, doi:10.1038/s41558-020-0728-x.
Rauner, S. et al., 2020b: Air quality co-benefits of ratcheting up the NDCs. *Climatic Change*, doi:10.1007/s10584-020-02699-1.
Ravera, F. et al., 2016: Gender perspectives in resilience, vulnerability and adaptation to global environmental change. *Ambio*, **45**(Suppl 3), 235-247, doi:10.1007/s13280-016-0842-1.
Rawlins, J. M., W. J. De Lange and G. C. G. Fraser, 2018: An Ecosystem Service Value Chain Analysis Framework: A Conceptual Paper. *Ecological Economics*, **147**, 84-95, doi:https://doi.org/10.1016/j.ecolecon.2017.12.023.
Ray, D. K. et al., 2019: Climate change has likely already affected global food production. *PLoS One*, **14**(5), e0217148, doi:10.1371/journal.pone.0217148.
Ray, R. S. et al., 2011: Impaired respiratory and body temperature control upon acute serotonergic neuron inhibition. *Science (New York, N.Y.)*, **333**(6042), 637-642, doi:10.1126/science.1205295.
Reason, C. J. C. and M. Rouault, 2005: Links between the Antarctic Oscillation and winter rainfall over western South Africa. *Geophysical Research Letters*, **32**(7), doi:https://doi.org/10.1029/2005GL022419.
Record, S., N. D. Charney, R. M. Zakaria and A. M. Ellison, 2013: Projecting global mangrove species and community distributions under climate change. *Ecosphere*, **4**(3), art34, doi:https://doi.org/10.1890/ES12-00296.1.
Reed, M. S. et al., 2015: Reorienting land degradation towards sustainable land management: Linking sustainable livelihoods with ecosystem services in rangeland systems. *Journal of Environmental Management*, **151**, 472-485, doi:https://doi.org/10.1016/j.jenvman.2014.11.010.
Rehbein, J. A. et al., 2020: Renewable energy development threatens many globally important biodiversity areas. *Global Change Biology*, **26**(5), 3040-3051, doi:10.1111/gcb.15067.
Reid, H., 2014: *Ecosystem-and community-based adaptation: learning from natural resource management*. IIED Briefing Paper-International Institute for Environment and Development, 4 pp. Available at: http://pubs.iied.org/17243IIED.
Reid, H., 2016: Ecosystem- and community-based adaptation: learning from community-based natural resource management. *Climate and Development*, **8**(1), 4-9, doi:10.1080/17565529.2015.1034233.
Reid, H. et al., 2018: Chapter 16 - A Framework for Assessing the Effectiveness of Ecosystem-Based Approaches to Adaptation. In: *Resilience* [Zommers, Z. and K. Alverson (eds.)]. Elsevier, pp. 207-216. ISBN 978-0-12-811891-7.
Reid, H. et al., 2019: *Is ecosystem-based adaptation effective? Perceptions and lessons learned from 13 project sites*. IIED Research
Report, IIED, London. Available at: https://pubs.iied.org/17651IIED/ (accessed 2019/09/18/13:35:40).
Reimann, L. et al., 2018: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications*, **9**(1), doi:10.1038/s41467-018-06645-9.
Reinecke, R. et al., 2019: Spatially distributed sensitivity of simulated global groundwater heads and flows to hydraulic conductivity, groundwater recharge, and surface water body parameterization. *Hydrology and Earth System Sciences*, **23**(11), 4561-4582, doi:10.5194/hess-23-4561-2019.
Reizenberg, J.-L. et al., 2019: Variation in thermal tolerances of native freshwater fishes in South Africa's Cape Fold Ecoregion: examining the east-west gradient in species' sensitivity to climate warming. *J Fish Biol*, **94**(1), 103-112, doi:10.1111/jfb.13866.
Rennkamp, B. and A. Boyd, 2015: Technological capability and transfer for achieving South Africa's development goals. *Climate Policy*, **15**(1), 12-29, doi:10.1080/14693062.2013.831299.
Rentschler, J. and M. Salhab, 2020: *People in Harm's Way : Flood Exposure and Poverty in 189 Countries*. Policy Research Working Papers, World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/34655.
Revi, A. et al., 2020: Transformative Adaptation in Cities. *One Earth*, **3**(4), 384-387, doi:10.1016/j.oneear.2020.10.002.
Rhodes, C. J., 2017: The Imperative for Regenerative Agriculture. *Science Progress*, **100**(1), 80-129, doi:10.3184/003685017x14876775256165.
Rigaud, K. K. et al., 2018: *Groundswell: Preparing for Internal Climate Migration*. The World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/29461.
Rigden, A. J., V. Ongoma and P. Huybers, 2020: Kenyan tea is made with heat and water: how will climate change influence its yield? *Environmental Research Letters*, **15**(4), 044003, doi:10.1088/1748-9326/ab70be.

Rippke, U. et al., 2016: Timescales of transformational climate change adaptation in sub-Saharan African agriculture. *Nature Climate Change*, **6**(6), 605-609, doi:10.1038/nclimate2947.
Ritzema, R. S. et al., 2017: Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from East and West Africa. *Food Security*, **9**(1), 115-131, doi:10.1007/s12571-016-0638-y.
Roberts, C. M., B. C. O'Leary and J. P. Hawkins, 2020: Climate change mitigation and nature conservation both require higher protected area targets. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190121, doi:10.1098/rstb.2019.0121.
Roberts, C. M. et al., 2017: Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences*, **114**(24), 6167-6175, doi:10.1073/pnas.1701262114.
Roberts, D., 2010: Prioritizing climate change adaptation and local level resilience in Durban, South Africa. *Environment and Urbanization*, **22**(2), 397-413, doi:10.1177/0956247810379948.
Roberts, M. J. and W. Schlenker, 2013: Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate. *American Economic Review*, **103**(6), 2265-2295, doi:10.1257/aer.103.6.2265.
Robilliard, A.-S., 2020: *What's New About Income Inequality in Africa?* Issue Brief, World Inequality Lab, Lab, W. I., 9 pp. Available at: https://wid.world/document/whats-new-about-income-inequality-in-africa/.
Robinson, A. L. and J. Gottlieb, 2021: How to Close the Gender Gap in Political Participation: Lessons from Matrilineal Societies in Africa. *British Journal of Political Science*, **51**(1), 68-92, doi:10.1017/S0007123418000650.
Robinson, S.-a., 2020: Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. *WIREs Climate Change*, **11**(4), e653, doi:https://doi.org/10.1002/wcc.653.
Robledo, C., N. Clot, A. Hammill and B. Riché, 2012: The role of forest ecosystems in community-based coping strategies to climate hazards: Three examples from rural areas in Africa. *Forest Policy and Economics*, **24**, 20-28, doi:https://doi.org/10.1016/j.forpol.2011.04.006.
Rodina, L., 2019: Planning for water resilience: Competing agendas among Cape Town's planners and water managers. *Environmental Science & Policy*, **99**, 10-16, doi:10.1016/j.envsci.2019.05.016.
Rohat, G. et al., 2019: Projections of Human Exposure to Dangerous Heat in African Cities Under Multiple Socioeconomic and Climate Scenarios. *Earth's Future*, **7**(5), 528-546, doi:https://doi.org/10.1029/2018EF001020.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163, doi:https://doi.org/10.1016/j.crm.2017.02.001.
Roncoli, C., K. Ingram and P. Kirshen, 2002: Reading the Rains: Local Knowledge and Rainfall Forecasting in Burkina Faso. *Society & Natural Resources*, **15**(5), 409-427, doi:https://doi.org/10.1080/08941920252866774.
Rosenzweig, C. et al., 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, **111**(9), 3268, doi:10.1073/pnas.1222463110.
Rosenzweig, C. et al., 2020: Climate change responses benefit from a global food system approach. *Nature Food*, **1**(2), 94-97, doi:10.1038/s43016-020-0031-z.
Roson, R. and M. Sartori, 2016: *Estimation of Climate Change Damage Functions for 140 Regions in the GTAP9 Database*. Policy Research Working Paper, World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/24643.
Ross-Gillespie, V., M. D. Picker, H. F. Dallas and J. A. Day, 2018: The role of temperature in egg development of three aquatic insects Lestagella penicillata (Ephemeroptera), Aphanicercella scutata (Plecoptera), Chimarra ambulans (Trichoptera) from South Africa. *Journal of Thermal Biology*, **71**, 158-170, doi:10.1016/j.jtherbio.2017.11.008.
Rother, H.-A., 2020: Controlling and preventing climate-sensitive noncommunicable diseases in urban sub-Saharan Africa. *Science of The Total Environment*, **722**, 137772, doi:10.1016/j.scitotenv.2020.137772.
Rother, H.-A., C. E. Sabel and S. Vardoulakis, 2020: A Collaborative Framework Highlighting Climate-Sensitive Non-communicable Diseases in Urban Sub-Saharan Africa. In: *Africa and the Sustainable Development Goals* [Ramutsindela, M. and D. Mickler (eds.)]. Springer International Publishing, Cham, pp. 267-278.
Rouabhi, A., M. Hafsi and P. Monneveux, 2019: Climate change and farming systems in the region of Setif (Algeria). *Journal of Agriculture and Environment for International Development (JAEID)*, **113**(1), 79-95, doi:http://dx.doi.org/10.12895/jaeid.20191.928.
Roudier, P., A. Ducharne and L. Feyen, 2014: Climate change impacts on runoff in West Africa: a review. *Hydrology and Earth System Sciences*, **18**(7), 2789-2801, doi:10.5194/hess-18-2789-2014.
Rowell, D. P., B. B. B. Booth, S. E. Nicholson and P. Good, 2015: Reconciling Past and Future Rainfall Trends over East Africa. *Journal of Climate*, **28**(24), 9768-9788, doi:10.1175/jcli-d-15-0140.1.
Roxy, M. K. et al., 2016: A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean. *Geophysical Research Letters*, **43**(2), 826-833, doi:10.1002/2015gl066979.
Roy, J. et al., 2018a: *Sustainable development, poverty eradication and reducing inequalities* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C

above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, **In Press**. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter5_Low_Res.pdf.

Roy, M. et al., 2018b: Climate change and declining levels of green structures: Life in informal settlements of Dar es Salaam, Tanzania. *Landscape and Urban Planning*, **180**, 282-293, doi:10.1016/j.landurbplan.2017.11.011.

Rozenberg, J. et al., 2019: *From A Rocky Road to Smooth Sailing: Building Transport Resilience to Natural Disasters*. The World Bank, The World Bank, Washington, DC, 44 pp. Available at: https://openknowledge.worldbank.org/handle/10986/31913.

Rozenberg, J. and S. Hallegatte, 2015: *The impacts of climate change on poverty in 2030 and the potential from rapid, inclusive, and climate-informed development*. The World Bank, Washington DC. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=2ahUKEwib1sa_oYDlAhVimVwKHfwzDMgQFjABegQIAxAB&url=https%3A%2F%2Fwww.semanticscholar.org%2Fpaper%2FThe-impacts-of-climate-change-on-poverty-in-2030-Rozenberg-Hallegatte%2F9e9cbc9e3cf040fd749ce9d58c0b8c31fdae47be&usg=AOvVaw3SaJdptXEfBdMKTZj9-Xj1.

Ruhl, J. B., 2010: Climate Change Adaptation and the Structural Transformation of Environmental Law. *Environmental Law*, **40**(2), 363-436.

Rumble, O., 2019: Facilitating African Climate Change Adaptation through Framework Laws. *Carbon & Climate Law Review (CCLR)*, **2019**(4), 237-245.

Rurinda, J. et al., 2014: Sources of vulnerability to a variable and changing climate among smallholder households in Zimbabwe: A participatory analysis. *Climate Risk Management*, **3**, 65-78, doi:10.1016/j.crm.2014.05.004.

Russo, S., A. F. Marchese, J. Sillmann and G. Immé, 2016: When will unusual heat waves become normal in a warming Africa? *Environmental Research Letters*, **11**(5), 054016, doi:10.1088/1748-9326/11/5/054016.

Ryan, S. J., C. J. Carlson, E. A. Mordecai and L. R. Johnson, 2019: Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *PLOS Neglected Tropical Diseases*, **13**(3), e0007213, doi:10.1371/journal.pntd.0007213.

Ryan, S. J., C. A. Lippi and F. Zermoglio, 2020: Shifting transmission risk for malaria in Africa with climate change: a framework for planning and intervention. *Malaria Journal*, **19**(1), 170, doi:10.1186/s12936-020-03224-6.

Ryan, S. J. et al., 2015: Mapping Physiological Suitability Limits for Malaria in Africa Under Climate Change. *Vector-Borne and Zoonotic Diseases*, **15**(12), 718-725, doi:10.1089/vbz.2015.1822.

Saarinen, J., W. L. Hambira, J. Atlhopheng and H. Manwa, 2012: Tourism industry reaction to climate change in Kgalagadi South District, Botswana. *Development Southern Africa*, **29**(2), 273-285, doi:10.1080/0376835x.2012.675697.

Sadoine, M. L. et al., 2018: The associations between malaria, interventions, and the environment: a systematic review and meta-analysis. *Malar J*, **17**(1), 73, doi:10.1186/s12936-018-2220-x.

SAIA, 2018: *Accelerating our journey to Future-proofing our industry*. South African Insurance Association (SAIA), Pretoria, 68 pp. Available at: https://www.saia.co.za/index.php?id=2030.

Sala, E., S. Giakoumi and P. Linwood, 2018: No-take marine reserves are the most effective protected areas in the ocean. *ICES Journal of Marine Science*, **75**(3), 1166-1168, doi:10.1093/icesjms/fsx059.

Salack, S. et al., 2019: Designing Transnational Hydroclimatological Observation Networks and Data Sharing Policies in West Africa. *Data Science Journal (DSJ)*, **18**(1), doi:http://doi.org/10.5334/dsj-2019-033.

Salas, R. N., J. M. Shultz and C. G. Solomon, 2020: The Climate Crisis and Covid-19 — A Major Threat to the Pandemic Response. *New England Journal of Medicine*, **383**(11), e70, doi:10.1056/NEJMp2022011.

Salick, J. and N. Ross, 2009: Traditional peoples and climate change. *Global Environmental Change*, **19**(2), 137-190, doi:10.1016/j.gloenvcha.2009.01.004.

Salih, A. A. M., M. Baraibar, K. K. Mwangi and G. Artan, 2020: Climate change and locust outbreak in East Africa. *Nature Climate Change*, **10**(7), 584-585, doi:10.1038/s41558-020-0835-8.

Samy, A. M. and A. T. Peterson, 2016: Climate Change Influences on the Global Potential Distribution of Bluetongue Virus. *PLOS ONE*, **11**(3), e0150489, doi:10.1371/journal.pone.0150489.

Sango, I. and N. Godwell, 2015: Climate change trends and environmental impacts in the Makonde Communal Lands, Zimbabwe. *South African Journal of Science*, **111**(7/8), 1-6, doi:10.17159/sajs.2015/20140266.

Sanogo, K. et al., 2017: Farmers' perceptions of climate change impacts on ecosystem services delivery of parklands in southern Mali. *Agroforestry Systems*, **91**(2), 345-361, doi:10.1007/s10457-016-9933-z.

Sanogo, S. et al., 2015: Spatio-temporal characteristics of the recent rainfall recovery in West Africa. *International Journal of Climatology*, **35**(15), 4589-4605, doi:https://doi.org/10.1002/joc.4309.

Santam, 2018: *Santam integrated report 2018*. Santam Group, Cape Town. Available at: https://www.santam.co.za/media/2684712/santam_ir_-2018.pdf.

Sanya, T., 2012: Sustainable architecture evaluation method in an African context: transgressing discipline boundaries with a systems approach. *Sustainability Science*, **7**(1), 55-65, doi:10.1007/s11625-011-0137-1.

Sapiains, R. et al., 2021: Exploring the contours of climate governance: An interdisciplinary systematic literature review from a southern perspective. *Environmental Policy and Governance*, **31**(1), 46-59, doi:10.1002/eet.1912.

Saraswat, C. and P. Kumar, 2016: Climate justice in lieu of climate change: a sustainable approach to respond to the climate change injustice and an awakening of the environmental movement. *Energy, Ecology and Environment*, **1**(2), 67-74, doi:10.1007/s40974-015-0001-8.

Satterthwaite, D., 2017: The impact of urban development on risk in sub-Saharan Africa's cities with a focus on small and intermediate urban centres. *International Journal of Disaster Risk Reduction*, **26**, 16-23, doi:https://doi.org/10.1016/j.ijdrr.2017.09.025.
Satterthwaite, D. et al., 2020: Building Resilience to Climate Change in Informal Settlements. *One Earth*, **2**(2), 143-156, doi:https://doi.org/10.1016/j.oneear.2020.02.002.
Satterthwaite, D. and S. Bartlett, 2017: Editorial: The full spectrum of risk in urban centres: changing perceptions, changing priorities. *Environment and Urbanization*, **29**(1), 3-14, doi:10.1177/0956247817691921.
Saulnier-Talbot, E. et al., 2014: Small changes in climate can profoundly alter the dynamics and ecosystem services of tropical crater lakes. *PLoS One*, **9**(1), e86561, doi:10.1371/journal.pone.0086561.
Savary, S. et al., 2019: The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, **3**(3), 430-439, doi:10.1038/s41559-018-0793-y.
Savvidou, G. and A. Atteridge, 2021: Tracking adaptation finance in Africa. *Climate Policy*.
Scannell, H. A. et al., 2016: Frequency of marine heatwaves in the North Atlantic and North Pacific since 1950. *Geophysical Research Letters*, **43**(5), 2069-2076, doi:https://doi.org/10.1002/2015GL067308.
Schaeffer, M. et al., 2013: *Africa's Adaptation Gap Technical Report: Climate-change impacts, adaptation challenges and costs for Africa* [Schaeffer, M., R. Munang, J. Andrews, S. Adams and C. Baxter (eds.)]. UNEP, 58 pp. Available at: https://climateanalytics.org/media/schaeffer_et_al__2013__africao__s_a_daptation_gap_technical_report.pdf.
Schäfer, M. P., O. Dietrich and B. Mbilinyi, 2015: Streamflow and lake water level changes and their attributed causes in Eastern and Southern Africa: state of the art review. *International Journal of Water Resources Development*, **32**(6), 853-880, doi:10.1080/07900627.2015.1091289.
Schagerl, M. and R. W. Renaut, 2016: Dipping into the Soda Lakes of East Africa. In: *Soda Lakes of East Africa* [Schagerl, M. (ed.)]. Springer International Publishing, Switzerland, pp. 3-24. ISBN 978-3-319-28620-4.
Scheerens, C. et al., 2020: Tackling adverse health effects of climate change and migration through intersectoral capacity building in Sub-Saharan Africa. *BJGP Open*, **4**(2), bjgpopen20X101065, doi:10.3399/bjgpopen20X101065.
Scheff, J., R. Seager, H. Liu and S. Coats, 2017: Are Glacials Dry? Consequences for Paleoclimatology and for Greenhouse Warming. *Journal of Climate*, **30**(17), 6593-6609, doi:10.1175/JCLI-D-16-0854.1.
Scheffran, J., T. Ide and J. Schilling, 2014: Violent climate or climate of violence? Concepts and relations with focus on Kenya and Sudan. *The International Journal of Human Rights*, **18**(3), 369-390, doi:10.1080/13642987.2014.914722.
Scheiter, S. and P. Savadogo, 2016: Ecosystem management can mitigate vegetation shifts induced by climate change in West Africa. *Ecological Modelling*, **332**, 19-27, doi:https://doi.org/10.1016/j.ecolmodel.2016.03.022.
Schilling, J., K. P. Freier, E. Hertig and J. Scheffran, 2012: Climate change, vulnerability and adaptation in North Africa with focus on Morocco. *Agriculture, Ecosystems and Environment*, **156**, 12-26, doi:10.1016/j.agee.2012.04.021.
Schilling, J., E. Hertig, Y. Tramblay and J. Scheffran, 2020: Climate change vulnerability, water resources and social implications in North Africa. *Regional Environmental Change*, **20**(1), 15, doi:10.1007/s10113-020-01597-7.
Schlegel, R. W., E. C. J. Oliver, T. Wernberg and A. J. Smit, 2017: Nearshore and offshore co-occurrence of marine heatwaves and cold-spells. *Progress in Oceanography*, **151**, 189-205, doi:https://doi.org/10.1016/j.pocean.2017.01.004.
Schlenker, W. and D. B. Lobell, 2010: Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, **5**(1), 014010, doi:10.1088/1748-9326/5/1/014010.
Schleussner, C. F., J. F. Donges, R. V. Donner and H. J. Schellnhuber, 2016a: Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proc Natl Acad Sci U S A*, **113**(33), 9216-9221, doi:10.1073/pnas.1601611113.
Schleussner, C. F. et al., 2016b: Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, **6**, 827-835, doi:10.1038/nclimate3096.
Schmeier, S., 2017: Joint institutional arrangements for governing shared water resources: A comparative analysis of state practice. In: *Routledge Handbook of Water Law and Policy* [Rieu-Clarke, A., A. Allan and S. Hendry (eds.)]. Routledge, London, pp. 260-274. ISBN 1315651130.
Schmitt Olabisi, L. et al., 2018: Using participatory modeling processes to identify sources of climate risk in West Africa. *Environment Systems and Decisions*, **38**(1), 23-32, doi:10.1007/s10669-017-9653-6.
Schroth, G. et al., 2016: Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation. *Science of the Total Environment*, **556**, 231-241, doi:10.1016/j.scitotenv.2016.03.024.
Schroth, G. and F. Ruf, 2014: Farmer strategies for tree crop diversification in the humid tropics. A review. *Agronomy for Sustainable Development*, **34**(1), 139-154, doi:10.1007/s13593-013-0175-4.
Schulz, A. and M. Northridge, 2004: Social Determinants of Health: Implications for Environmental Health Promotion. *Health Education & Behavior*, **31**(4), 455 - 471, doi:https://doi.org/10.1177%2F1090198104265598.
Schuman, S., J. V. Dokken, D. van Niekerk and R. A. Loubser, 2018: Religious beliefs and climate change adaptation: A study of three rural South African communities. *Jamba*, **10**(1), 509, doi:10.4102/jamba.v10i1.509.
Schut, M. et al., 2016: Sustainable intensification of agricultural systems in the Central African Highlands: The need for institutional innovation. *Agricultural Systems*, **145**, 165-176, doi:https://doi.org/10.1016/j.agsy.2016.03.005.

Schweikert, A. et al., 2015: Road Infrastructure and Climate Change: Impacts and Adaptations for South Africa. *Journal of Infrastructure Systems*, **21**(3), 04014046, doi:10.1061/(ASCE)IS.1943-555X.0000235.
Scotford, E. and S. Minas, 2019: Probing the hidden depths of climate law: Analysing national climate change legislation. *Review of European, Comparative & International Environmental Law*, **28**(1), 67-81, doi:10.1111/reel.12259.
Scotford, E., S. Minas and A. Macintosh, 2017: Climate change and national laws across Commonwealth countries. *Commonwealth Law Bulletin*, **43**(3-4), 318-361, doi:10.1080/03050718.2017.1439361.
Scott, A. A. et al., 2017: Temperature and heat in informal settlements in Nairobi. *PLoS One*, **12**(11), e0187300, doi:10.1371/journal.pone.0187300.
Scovronick, N. and B. Armstrong, 2012: The impact of housing type on temperature-related mortality in South Africa, 1996-2015. *Environ Res*, **113**, 46-51, doi:10.1016/j.envres.2012.01.004.
Scovronick, N. et al., 2018: The association between ambient temperature and mortality in South Africa: A time-series analysis. *Environmental Research*, **161**, 229-235, doi:10.1016/j.envres.2017.11.001.
Seaman, J. A., G. E. Sawdon, J. Acidri and C. Petty, 2014: The Household Economy Approach. Managing the impact of climate change on poverty and food security in developing countries. *Climate Risk Management*, **4-5**, 59-68, doi:https://doi.org/10.1016/j.crm.2014.10.001.
Seif-Ennasr, M. et al., 2016: Climate change and adaptive water management measures in Chtouka Ait Baha region (Morocco). *Sci Total Environ*, **573**, 862-875, doi:10.1016/j.scitotenv.2016.08.170.
Selig, E. R. et al., 2018: Mapping global human dependence on marine ecosystems. *Conservation Letters*, **12**(2), doi:10.1111/conl.12617.
Selormey, E. E., M. Z. Dome, L. Osse and C. Logan, 2019: *Change ahead: Experience and awareness of climate change in Africa*. Pan African Profiles: Afrobarometer Policy Paper, **60**, Afrobarometer, Accra, Ghana, 1-30 pp. Available at: https://afrobarometer.org/sites/default/files/publications/Policy%20papers/ab_r7_policypaperno60_experience_and_awareness_of_climate_change_in_africa.pdf.
Semakula, H. M. et al., 2017a: Prediction of future malaria hotspots under climate change in sub-Saharan Africa. *Clim. Change*, **143**(3-4), 415-428.
Semakula, H. M. et al., 2017b: Prediction of future malaria hotspots under climate change in sub-Saharan Africa. *Climatic Change*, **143**(3-4), 415-428, doi:10.1007/s10584-017-1996-y.
Semenza, J. C. and J. E. Suk, 2018: Vector-borne diseases and climate change: a European perspective. *FEMS Microbiology Letters*, **365**(2), doi:10.1093/femsle/fnx244.
Seneviratne, S. I. et al., 2021: *Weather and Climate Extreme Events in a Changing Climate* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change **In Press**, Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_11.pdf.
Seo, D., C. J. Patrick and P. J. Kennealy, 2008: Role of Serotonin and Dopamine System Interactions in the Neurobiology of Impulsive Aggression and its Comorbidity with other Clinical Disorders. *Aggression and violent behavior*, **13**(5), 383-395, doi:10.1016/j.avb.2008.06.003.
Serdeczny, O. et al., 2017: Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, **17**(6), 1585-1600, doi:10.1007/s10113-015-0910-2.
Sesmero, J., J. Ricker-Gilbert and A. Cook, 2018: How Do African Farm Households Respond to Changes in Current and Past Weather Patterns? A Structural Panel Data Analysis from Malawi. *American Journal of Agricultural Economics*, **100**(1), 115-144, doi:10.1093/ajae/aax068.
Seti, V., E. Bornman and P. Alvarez-Mosquera, 2016: Opinions on indigenous languages as languages of learning and teaching in Africa. *International Journal of Communication and Linguistic Studies*, **14**(1), 17-31.
Sewe, M. et al., 2015: The association of weather variability and under five malaria mortality in KEMRI/CDC HDSS in Western Kenya 2003 to 2008: a time series analysis. *Int J Environ Res Public Health*, **12**(2), 1983-1997, doi:10.3390/ijerph120201983.
Shabani, F., L. Kumar and S. Taylor, 2012: Climate Change Impacts on the Future Distribution of Date Palms: A Modeling Exercise Using CLIMEX. *PLOS ONE*, **7**(10), e48021, doi:10.1371/journal.pone.0048021.
Shackleton, S. et al., 2015: Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(3), 321-344, doi:https://doi.org/10.1002/wcc.335.
Shaffer, L. J., 2014: Making sense of local climate change in rural Tanzania through knowledge co-production. *Journal of Ethnobiology*, **34**(3), 315-334, doi:http://dx.doi.org/10.2993/0278-0771-34.3.315.
Shao, Y., M. Klose and K.-H. Wyrwoll, 2013: Recent global dust trend and connections to climate forcing. *J Geophys Res-Atmos*, **118**(19), 11,107-111,118, doi:https://doi.org/10.1002/jgrd.50836.
Shelton, J. M. et al., 2018: Vulnerability of Cape Fold Ecoregion freshwater fishes to climate change and other human impacts. *Aquatic Conserv: Mar Freshw Ecosyst*, **28**(1), 68-77, doi:10.1002/aqc.2849.
Shepherd, 2019: Making Sense of "Day Zero": Slow Catastrophes, Anthropocene Futures, and the Story of Cape Town's Water Crisis. *Water*, **11**(9), 1744, doi:10.3390/w11091744.

Sherman, M. H. and J. Ford, 2014: Stakeholder engagement in adaptation interventions: an evaluation of projects in developing nations. *Climate Policy*, **14**(3), 417-441, doi:10.1080/14693062.2014.859501.
Shi, L. et al., 2016: Roadmap towards justice in urban climate adaptation research. *Nature Climate Change*, **6**(2), 131-137, doi:10.1038/nclimate2841.
Shiferaw, B. et al., 2014: Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and Climate Extremes*, **3**, 67-79, doi:https://doi.org/10.1016/j.wace.2014.04.004.
Shikuku, K. M. et al., 2017: Smallholder farmers' attitudes and determinants of adaptation to climate risks in East Africa. *Climate Risk Management*, **16**, 234-245, doi:https://doi.org/10.1016/j.crm.2017.03.001.
Shukla, P. R. et al., 2019: *Technical Summary* [P.R. Shukla, J. S., E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade,, R. v. D. S. Connors, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, and K. K. E. Huntley, M, Belkacemi, J. Malley, (eds.)]. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, In Press pp. Available at: https://www.ipcc.ch/site/assets/uploads/sites/4/2020/07/03_Technical-Summary-TS_V2.pdf.
Shukla, R. et al., 2021: Dynamic vulnerability of smallholder agricultural systems in the face of climate change for Ethiopia. *Environmental Research Letters*, **16**(4), 044007, doi:10.1088/1748-9326/abdb5c.
Shumsky, S. A., G. M. Hickey, B. Pelletier and T. Johns, 2014: Understanding the contribution of wild edible plants to rural social-ecological resilience in semi-arid Kenya. *Ecology and Society*, **19**(4), doi:http://dx.doi.org/10.5751/ES-06924-190434.
Siam, M. S. and E. A. B. Eltahir, 2017: Climate change enhances interannual variability of the Nile river flow. *Nature Climate Change*, **7**(5), 350-354, doi:10.1038/nclimate3273.
Siderius, C. et al., 2018: Hydrological response and complex impact pathways of the 2015/2016 El Niño in Eastern and Southern Africa. *Earth's Future*, **6**(1), 2-22, doi:10.1002/2017ef000680.
Siderius, C. et al., 2021: High Stakes Decisions Under Uncertainty: Dams, Development and Climate Change in the Rufji River Basin. In: *Climate Risk in Africa: Adaptation and Resilience* [D. Conway, K. V. (ed.)]. Springer International Publishing.
Siders, A. R., 2019: Adaptive capacity to climate change: A synthesis of concepts, methods, and findings in a fragmented field. *WIREs Climate Change*, **10**(3), e573, doi:https://doi.org/10.1002/wcc.573.
Sierra-Correa, P. C. and J. R. Cantera Kintz, 2015: Ecosystem-based adaptation for improving coastal planning for sea-level rise: A systematic review for mangrove coasts. *Marine Policy*, **51**, 385-393, doi:10.1016/j.marpol.2014.09.013.
Sietsma, A. J., J. D. Ford, M. W. Callaghan and J. C. Minx, 2021: Progress in climate change adaptation research. *Environmental Research Letters*, **16**(5), 054038, doi:10.1088/1748-9326/abf7f3.
Silva, R. A. et al., 2017: Future global mortality from changes in air pollution attributable to climate change. *Nature Climate Change*, **7**, 647, doi:10.1038/nclimate3354.
Silvestri, S. et al., 2012: Climate change perception and adaptation of agro-pastoral communities in Kenya. *Regional Environmental Change*, **12**(4), 791-802, doi:10.1007/s10113-012-0293-6.
Simon, D. and H. Leck, 2015: Editorial overview: Sustainability challenges: Assessing climate change adaptation in Africa. *Current Opinion in Environmental Sustainability*, **13**, iv-viii, doi:10.1016/j.cosust.2015.03.002.
Simple, O. et al., 2018: Influence of Climatic Factors on Malaria Epidemic in Gulu District, Northern Uganda: A 10-Year Retrospective Study. *Malar. Res. Treat.*, **2018**, 5482136, doi:10.1155/2018/5482136.
Simpson, N. P., 2020: Insurance in the Anthropocene: Exposure, Solvency and Manoeuvrability. In: *Criminology and Climate: Insurance, Finance and the Regulation of Harmscapes*, 1 ed. [Holley, C., L. Phelan and C. D. Shearing (eds.)]. Routledge, London, UK, pp. 135-152. ISBN 9780429201172.
Simpson, N. P. et al., 2021a: Climate Change Literacy in Africa. *Nature Climate Change*, doi:10.1038/s41558-021-01171-x.
Simpson, N. P. et al., 2021b: A framework for complex climate change risk assessment. *One Earth*, **4**(4), 489-501, doi:https://doi.org/10.1016/j.oneear.2021.03.005.
Simpson, N. P., C. Rabenold, M. Sowman and C. D. Shearing, 2021c: Adoption rationales and effects of off-grid renewable energy access for African youth: A case study from Tanzania. *Renewable and Sustainable Energy Reviews*, **141**(110793), 17, doi:https://doi.org/10.1016/j.rser.2021.110793.
Simpson, N. P., C. D. Shearing and B. Dupont, 2019a: Climate gating: A case study of emerging responses to Anthropocene Risks. *Climate Risk Management*, **26**, 100196, doi:10.1016/j.crm.2019.100196.
Simpson, N. P., C. D. Shearing and B. Dupont, 2020a: Gated Adaptation during the Cape Town Drought: Mentalities, Transitions and Pathways to Partial Nodes of Water Security. *Society & Natural Resources*, **33**(8), 1041-1049, doi:10.1080/08941920.2020.1712756.
Simpson, N. P., C. D. Shearing and B. Dupont, 2020b: 'Partial functional redundancy': An expression of household level resilience in response to climate risk. *Climate Risk Management*, **28**, 100216, doi:10.1016/j.crm.2020.100216.
Simpson, N. P., K. J. Simpson, C. D. Shearing and L. R. Cirolia, 2019b: Municipal finance and resilience lessons for urban infrastructure management: a case study from the Cape Town drought. *International Journal of Urban Sustainable Development*, **11**(3), 257-276, doi:10.1080/19463138.2019.1642203.

Singh, C. et al., 2018: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and Development*, **10**(5), 389-405, doi:10.1080/17565529.2017.1318744.
Sintayehu, D. W., A. Egeru, W. T. Ng and E. Cherenet, 2020: Regional dynamics in distribution of Prosopis juliflora under predicted climate change in Africa. *Tropical Ecology*, **61**(4), 437-445, doi:10.1007/s42965-020-00101-w.
Sitati, A. et al., 2021: Climate change adaptation in conflict-affected countries: A systematic assessment of evidence. *Discover Sustainability*.
Slim, H. et al., 2004: *Le littoral de la Tunisie. Étude géoarchéologique et historique*. vol. 1, Persée-Portail des revues scientifiques en SHS.
Slingsby, J. A. et al., 2017: Intensifying postfire weather and biological invasion drive species loss in a Mediterranean-type biodiversity hotspot. *Proceedings of the National Academy of Sciences*, **114**(18), 4697, doi:10.1073/pnas.1619014114.
Slingsby, J. A., G. R. Moncrieff, A. J. Rogers and E. C. February, 2020: Altered ignition catchments threaten a hyperdiverse fire-dependent ecosystem. *Global Change Biology*, **26**(2), 616-628, doi:https://doi.org/10.1111/gcb.14861.
Sloan, S., B. Bertzky and W. F. Laurance, 2017: African development corridors intersect key protected areas. *African Journal of Ecology*, **55**.
Sloat, L. L. et al., 2020: Climate adaptation by crop migration. *Nature Communications*, **11**(1), 1243, doi:10.1038/s41467-020-15076-4.
Sloat, L. L. et al., 2018: Increasing importance of precipitation variability on global livestock grazing lands. *Nature Climate Change*, **8**(3), 214-218, doi:10.1038/s41558-018-0081-5.
Smit, I. P. J. and H. H. T. Prins, 2015: Predicting the Effects of Woody Encroachment on Mammal Communities, Grazing Biomass and Fire Frequency in African Savannas. *PLOS ONE*, **10**(9), e0137857, doi:10.1371/journal.pone.0137857.
Smith, A. et al., 2016: Synergistic effects of climate and land-use change on representation of African bats in priority conservation areas. *Ecological Indicators*, **69**, 276-283, doi:10.1016/j.ecolind.2016.04.039.
Smith, K. R. et al., 2014: Human health: impacts, adaptation, and co-benefits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.
Snow, J. T. et al., 2016: *A New Vision for Weather and Climate Services in Africa*. UNDP, New York, USA. Available at: https://www.undp.org/sites/g/files/zskgke326/files/publications/WeatherAndClimateServicesAfrica.pdf.
Snowdon, R. J., B. Wittkop, T.-W. Chen and A. Stahl, 2021: Crop adaptation to climate change as a consequence of long-term breeding. *Theoretical and Applied Genetics*, **134**(6), 1613-1623, doi:10.1007/s00122-020-03729-3.
Soliev, I., K. Wegerich and J. Kazbekov, 2015: The Costs of Benefit Sharing: Historical and Institutional Analysis of Shared Water Development in the Ferghana Valley, the Syr Darya Basin. *Water*, **7**(6), 2728-2752, doi:https://doi.org/10.3390/w7062728.
Somanathan, E., R. Somanathan, A. Sudarshan and M. Tewari, 2015: *The Impact of Temperature on Productivity and Labor Supply: Evidence from Indian Manufacturing*. Indian Statistics Institute, Deli. Available at: https://www.isid.ac.in/~pu/dispapers/dp14-10.pdf.
Soneja, S. et al., 2016: Extreme precipitation events and increased risk of campylobacteriosis in Maryland, USA. *Environmental research*, **149**, 216-221.
Sonwa, D. J. et al., 2017: Drivers of climate risk in African agriculture. *Climate and Development*, **9**(5), 383-398, doi:10.1080/17565529.2016.1167659.
Sorensen, J. P. et al., 2015: Emerging contaminants in urban groundwater sources in Africa. *Water Res*, **72**, 51-63, doi:10.1016/j.watres.2014.08.002.
Soultan, A., M. Wikelski and K. Safi, 2019: Risk of biodiversity collapse under climate change in the Afro-Arabian region. *Sci Rep*, **9**(1), 955, doi:10.1038/s41598-018-37851-6.
Spalding-Fecher, R., B. Joyce and H. Winkler, 2017: Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wide impacts and policy implications. *Energy Policy*, **103**, 84-97, doi:10.1016/j.enpol.2016.12.009.
Spalding-Fecher, R. et al., 2014: *Water Supply and Demand Scenarios for the Zambezi River Basin. Climate Change and Upstream Development Impacts on New Hydropower Projects in the Zambezi Project*. Climate & Development Knowledge Network (CDKN), University of Cape Town, Cape Town, 92 pp. Available at: http://www.au.uct.ac.za/sites/default/files/image_tool/images/119/Hydro-Zambezi/HZ-Water_Supply_and_Demand_Scenarios_Report.pdf.
Spencer, D., 2015: *"TO PROTECT HER HONOUR" Child marriage in emergencies – the fatal confusion between protecting girls and sexual violence*. Gender and Protection in Humanitarian Contexts: Critical Issues Series, CARE International UK, United Kingdom. Available at: https://insights.careinternational.org.uk/media/k2/attachments/CARE_Child-marriage-in-emergencies_2015.pdf.

Speranza, I. C. et al., 2009: Indigenous knowledge related to climate variability and change: insights from droughts in semi-arid areas of former Makueni District, Kenya. *Climatic Change*, **100**(2), 295-315, doi:https://doi.org/10.1007/s10584-009-9713-0.
Spinoni, J. et al., 2021: Global exposure of population and land-use to meteorological droughts under different Warming Levels and Shared Socioeconomic Pathways: A Coordinated Regional Climate Downscaling Experiment-based study. *International Journal of Climatology*, doi:https://doi.org/10.1002/joc.7302.
Spinoni, J. et al., 2020: Future Global Meteorological Drought Hot Spots: A Study Based on CORDEX Data. *Journal of Climate*, **33**(9), 3635-3661, doi:10.1175/JCLI-D-19-0084.1.
Spinoni, J. et al., 2019: A new global database of meteorological drought events from 1951 to 2016. *Journal of Hydrology: Regional Studies*, **22**, 100593, doi:10.1016/j.ejrh.2019.100593.
Spinoni, J. et al., 2014: World drought frequency, duration, and severity for 1951–2010. *International Journal of Climatology*, **34**(8), 2792-2804, doi:https://doi.org/10.1002/joc.3875.
Squire, S. A. and U. Ryan, 2017: Cryptosporidium and Giardia in Africa: current and future challenges. *Parasites & vectors*, **10**(1), 195-195, doi:10.1186/s13071-017-2111-y.
Sridharan, V. et al., 2019: Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation. *Nat Commun*, **10**(1), 302, doi:10.1038/s41467-018-08275-7.
Sserumaga, J. P. et al., 2020: Aflatoxin-producing fungi associated with pre-harvest maize contamination in Uganda. *International Journal of Food Microbiology*, **313**, 108376, doi:https://doi.org/10.1016/j.ijfoodmicro.2019.108376.
St Louis, M. E. and J. J. Hess, 2008: Climate change: impacts on and implications for global health. *Am J Prev Med*, **35**(5), 527-538, doi:10.1016/j.amepre.2008.08.023.
Stafford, W. et al., 2017: The economics of landscape restoration: Benefits of controlling bush encroachment and invasive plant species in South Africa and Namibia. *Ecosystem Services*, **27**, 193-202, doi:https://doi.org/10.1016/j.ecoser.2016.11.021.
Stanimirova, R. et al., 2019: Sensitivity of Global Pasturelands to Climate Variation. *Earth's Future*, **7**(12), 1353-1366, doi:10.1029/2019EF001316.
Stark, L. and D. Landis, 2016: Violence against children in humanitarian settings: A literature review of population-based approaches. *Soc Sci Med*, **152**, 125-137, doi:10.1016/j.socscimed.2016.01.052.
Sterk, G. and J. J. Stoorvogel, 2020: Desertification–Scientific Versus Political Realities. *Land*, **9**(5), doi:10.3390/land9050156.
Stevens, N., B. F. N. Erasmus, S. Archibald and W. J. Bond, 2016: Woody encroachment over 70 years in South African savannahs: overgrazing, global change or extinction aftershock? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150437, doi:10.1098/rstb.2015.0437.
Stevens, N., C. E. R. Lehmann, B. P. Murphy and G. Durigan, 2017: Savanna woody encroachment is widespread across three continents. *Global Change Biology*, **23**(1), 235-244, doi:https://doi.org/10.1111/gcb.13409.
Stevenson, J. et al., 2012: Novel vectors of malaria parasites in the western highlands of Kenya. *Emerg. Infect. Dis.*, **18**(9), 1547-1549, doi:10.3201/eid1809.120283.
Steynor, A., J. Lee and A. Davison, 2020a: Transdisciplinary co-production of climate services: a focus on process. *Social Dynamics*, **46**(3), 414-433, doi:10.1080/02533952.2020.1853961.
Steynor, A. et al., 2020b: Learning from climate change perceptions in southern African cities. *Climate Risk Management*, **27**, 100202, doi:10.1016/j.crm.2019.100202.
Steynor, A. et al., 2016: Co-exploratory climate risk workshops: Experiences from urban Africa. *Climate Risk Management*, **13**, 95-102, doi:10.1016/j.crm.2016.03.001.
Steynor, A. and L. Pasquini, 2020: Using environmental psychology to increase the use of climate information.
Stokstad, E., 2019: After 20 years, Golden Rice nears approval. *Science (New York, N.Y.)*, **366**(6468), 934-934, doi:10.1126/science.366.6468.934.
Stratton, R. A. et al., 2018: A Pan-African convection-permitting regional climate simulation with the met office unified model: CP4-Africa. *Journal of Climate*, **31**(9), 3485-3508, doi:https://doi.org/10.1175/JCLI-D-17-0503.1.
Street, R. B., 2016: Towards a leading role on climate services in Europe: A research and innovation roadmap. *Climate Services*, **1**, 2-5, doi:10.1016/j.cliser.2015.12.001.
Stringer, L. C. et al., 2020: Adaptation and development pathways for different types of farmers. *Environmental Science and Policy*, **104**, 174-189, doi:10.1016/j.envsci.2019.10.007.
Stringer, L. C. et al., 2021: Climate change impacts on water security in global drylands. *One Earth*, **4**(6), 851-864, doi:10.1016/j.oneear.2021.05.010.
Strydom, S. and M. J. Savage, 2016: A spatio-temporal analysis of fires in South Africa. *South African Journal of Science*, **112**(11-12), 1-8, doi:10.17159/sajs.2016/20150489.
Suckall, N., E. Fraser, P. Forster and D. Mkwambisi, 2015: Using a migration systems approach to understand the link between climate change and urbanisation in Malawi. *Applied Geography*, **63**, 244-252, doi:https://doi.org/10.1016/j.apgeog.2015.07.004.
Sulieman, H. and H. Young, 2019: *Transforming pastoralist mobility in West Darfur: Understanding continuity and change*. Feinstein
International Center, University, T., Boston, 66 pp.
Sullivan, M. J. P. et al., 2020: Long-term thermal sensitivity of Earth's tropical forests. *Science (New York, N.Y.)*, **368**(6493), 869, doi:10.1126/science.aaw7578.

Sultan, B., D. Defrance and T. Iizumi, 2019: Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Scientific Reports*, **9**(1), 12834, doi:10.1038/s41598-019-49167-0.
Sultan, B. and M. Gaetani, 2016: Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation. *Frontiers in Plant Science*, **7**, 1262.
Sultan, B. et al., 2020: Current needs for climate services in West Africa: Results from two stakeholder surveys. *Climate Services*, **18**, 100166, doi:https://doi.org/10.1016/j.cliser.2020.100166.
Sun, Q. et al., 2019: Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. *Environment International*, **128**, 125-136, doi:https://doi.org/10.1016/j.envint.2019.04.025.
Sun, Q. et al., 2021: A Global, Continental, and Regional Analysis of Changes in Extreme Precipitation. *Journal of Climate*, **34**(1), 243-258, doi:10.1175/JCLI-D-19-0892.1.
Sunderland, T. et al., 2013: *Food security and nutrition*. Center for International Forestry Research,, Bogor, Indonesia.
Surminski, S., L. M. Bouwer and J. Linnerooth-Bayer, 2016: How insurance can support climate resilience. *Nature Climate Change*, **6**(4), 333-334, doi:10.1038/nclimate2979.
Sussman, F., A. Grambsch, J. Li and C. P. Weaver, 2014: Introduction to a special issue entitled Perspectives on Implementing Benefit-Cost Analysis in Climate Assessment. *Journal of Benefit-Cost Analysis*, **5**(3), 333-346, doi:10.1515/jbca-2014-9000.
Sutherland, C. et al., 2021: Socio-technical analysis of a sanitation innovation in a peri-urban household in Durban, South Africa. *Science of The Total Environment*, **755**, 143284, doi:https://doi.org/10.1016/j.scitotenv.2020.143284.
Swanepoel, E. and S. Sauka, 2019: *Ecosystem-based Adaptation in South African Coastal Cities: Challenges and Opportunities*. SAIIA Policy Briefing No 186, South African Institute of International Affairs (SAIIA), Cape Town, South Africa. Available at: https://saiia.org.za/research/ecosystem-based-adaptation-in-south-african-coastal-cities-challenges-and-opportunities/.
Swann, A. L. S., F. M. Hoffman, C. D. Koven and J. T. Randerson, 2016: Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences*, **113**(36), 10019-10024, doi:10.1073/pnas.1604581113.
SWECO, 2019: *Rwanda's pilot towards green urbanisation: mid term feasibility study*. SWECO GmbH, Frankfurt, Germany, 157 pp. Available at: https://greencitykigali.org/wp-content/uploads/Mid-Term-Feasibility-Study.pdf.
Swis Re, 2019: Natural Catastrophes: Tracking the protection gap, Swis Re, Online. Available at: http://files.swissre.com/natcat-protection-gap-map/index.html.
Sylla, M. B., N. Elguindi, F. Giorgi and D. Wisser, 2015a: Projected robust shift of climate zones over West Africa in response to anthropogenic climate change for the late 21st century. *Climatic Change*, **134**(1-2), 241-253, doi:10.1007/s10584-015-1522-z.
Sylla, M. B. et al., 2018: Projected Heat Stress Under 1.5 °C and 2 °C Global Warming Scenarios Creates Unprecedented Discomfort for Humans in West Africa. *Earth's Future*, **6**(7), 1029-1044, doi:10.1029/2018ef000873.
Sylla, M. B., F. Giorgi, E. Coppola and L. Mariotti, 2013: Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation. *International Journal of Climatology*, **33**(7), 1805-1817, doi:https://doi.org/10.1002/joc.3551.
Sylla, M. B. et al., 2015b: Projected Changes in the Annual Cycle of High-Intensity Precipitation Events over West Africa for the Late Twenty-First Century. *Journal of Climate*, **28**(16), 6475-6488, doi:10.1175/jcli-d-14-00854.1.
Sylla, M. B. et al., 2016: Climate Change over West Africa: Recent Trends and Future Projections. In: *Adaptation to Climate Change and Variability in Rural West Africa* [Yaro, J. A. and J. Hesselberg (eds.)]. Springer International Publishing, Cham, pp. 25-40. ISBN 978-3-319-31497-6.
Szopa, S. et al., 2021: *Short-Lived Climate Forcers* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (ed.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, In Press pp. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_06.pdf.
Tadesse, M. A., B. A. Shiferaw and O. Erenstein, 2015: Weather index insurance for managing drought risk in smallholder agriculture: lessons and policy implications for sub-Saharan Africa. *Agricultural and Food Economics*, **3**(1), 26, doi:10.1186/s40100-015-0044-3.
Takakura, J. y. et al., 2019: Dependence of economic impacts of climate change on anthropogenically directed pathways. *Nature Climate Change*, **9**(10), 737-741, doi:10.1038/s41558-019-0578-6.
Tamatamah, R. and T. Mwedzi, 2020: Environmental Flow Analysis of the Zambezi River Basin. In: *Ecological Changes in the Zambezi River Basin* [Ndebele-Murisa, M., I. A. Kimirei, C. P. Mubaya and T. Bere (eds.)]. CODESRIA, Dakar, pp. 183-210. ISBN 978-2-86978-713-1.
Tamoffo, A. T. et al., 2019: Daily characteristics of Central African rainfall in the REMO model. *Theoretical and Applied Climatology*, **137**(3-4), 2351-2368, doi:10.1007/s00704-018-2745-5.
Tanarhte, M., P. Hadjinicolaou and J. Lelieveld, 2012: Intercomparison of temperature and precipitation data sets based on observations in the Mediterranean and the Middle East. *J Geophys Res-Atmos*, **117**(D12), doi:10.1029/2011jd017293.

Tankari, M. R., 2017: Cash crops reduce the welfare of farm households in Senegal. *Food Security*, **9**(5), 1105-1115, doi:10.1007/s12571-017-0727-6.
Tariku, T. B. et al., 2021: Global warming impact to River Basin of Blue Nile and the optimum operation of its multi-reservoir system for hydropower production and irrigation. *Sci Total Environ*, **767**, 144863, doi:10.1016/j.scitotenv.2020.144863.
Tarusarira, J., 2017: African Religion, Climate Change, and Knowledge Systems. *The Ecumenical Review*, **69**(3), 398-410, doi:10.1111/erev.12302.
Tatem, A. J., 2017: WorldPop, open data for spatial demography. *Scientific Data*, **4**(1), 170004, doi:10.1038/sdata.2017.4.
Tatsumi, K. et al., 2011: Estimation of potential changes in cereals production under climate change scenarios. *Hydrological Processes*, **25**(17), 2715-2725, doi:https://doi.org/10.1002/hyp.8012.
Taye, M. T., P. Willems and P. Block, 2015: Implications of climate change on hydrological extremes in the Blue Nile basin: A review. *Journal of Hydrology: Regional Studies*, **4**, 280-293, doi:10.1016/j.ejrh.2015.07.001.
Taylor, A., 2016: Institutional inertia in a changing climate. *International Journal of Climate Change Strategies and Management*, **8**(2), 194-211, doi:10.1108/IJCCSM-03-2014-0033.
Taylor, A., H. Davies, G. Oelofse and S. Roux, 2016: *Urban Adaptation*. Climate Change: Law and Governance in South Africa, Juta, Cape Town, South Africa, 1-38 pp.
Taylor, A. et al., 2021a: Understanding and supporting climate-sensitive decision processes in southern African cities. *Current Opinion in Environmental Sustainability*, **51**, 77-84, doi:https://doi.org/10.1016/j.cosust.2021.03.006.
Taylor, A. and C. Peter, 2014: Strengthening climate resilience in African cities: A framework for working with informality. Available at: https://media.africaportal.org/documents/CDKN_ACC_WP_final_web-res.pdf.
Taylor, A., G. Siame and B. Mwalukanga, 2021b: Integrating Climate Risks into Strategic Urban Planning in Lusaka, Zambia. In: *Climate Risk in Africa: Adaptation and Resilience* [Conway, D. and K. Vincent (eds.)]. Springer International Publishing, Cham, pp. 115-129. ISBN 978-3-030-61160-6.
Taylor, C. M. et al., 2017: Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, **544**(7651), 475-478, doi:10.1038/nature22069.
Taylor, R. G., G. Favreau, B. R. Scanlon and K. G. Villholth, 2019: Topical Collection: Determining groundwater sustainability from long-term piezometry in Sub-Saharan Africa. *Hydrogeology Journal*, **27**(2), 443-446, doi:10.1007/s10040-019-01946-9.
Taylor, R. G. et al., 2006: Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature. *Geophysical Research Letters*, **33**(10), n/a-n/a, doi:10.1029/2006gl025962.
Taylor, R. G. et al., 2013: Ground water and climate change. *Nature Climate Change*, **3**(4), 322-329, doi:10.1038/nclimate1744.
Taylor, S., L. Kumar, N. Reid and D. J. Kriticos, 2012: Climate Change and the Potential Distribution of an Invasive Shrub, Lantana camara L. *PLOS ONE*, **7**(4), e35565, doi:10.1371/journal.pone.0035565.
Tebaldi, C. et al., 2021: Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth Syst. Dynam.*, **12**(1), 253-293, doi:10.5194/esd-12-253-2021.
Tellman, B. et al., 2021: Satellite imaging reveals increased proportion of population exposed to floods. *Nature*, **596**(7870), 80-86, doi:10.1038/s41586-021-03695-w.
Tendall, D. M. et al., 2015: Food system resilience: Defining the concept. *Global Food Security*, **6**, 17-23, doi:https://doi.org/10.1016/j.gfs.2015.08.001.
Tesfamariam, Y. and N. Zinyengere, 2017: Climate, Gender, and Ethnicity. In: *Beyond Agricultural Impacts*, pp. 169-191. ISBN 9780128126240.
Tesfaye, A. et al., 2019: Estimating the economic value of climate services for strengthening resilience of smallholder farmers to climate risks in Ethiopia: A choice experiment approach. *Ecological Economics*, **162**, 157-168, doi:https://doi.org/10.1016/j.ecolecon.2019.04.019.
Tesfaye, K. et al., 2016: Targeting drought-tolerant maize varieties in southern Africa: a geospatial crop modeling approach using big data. *International Food and Agribusiness Management Review*, **19**(A), 75-92.
The Global Commission on Adaptation, 2019: *Adapt Now: A Global Call for Leadership on Climate Resilience*. The Global Commission on Adaptation, Washington, DC. Available at: https://cdn.gca.org/assets/2019-09/GlobalCommission_Report_FINAL.pdf.
Theis, S., N. Lefore, R. Meinzen-Dick and E. Bryan, 2018: What happens after technology adoption? Gendered aspects of small-scale irrigation technologies in Ethiopia, Ghana, and Tanzania. *Agriculture and Human Values*, **35**(3), 671-684, doi:10.1007/s10460-018-9862-8.
Thiault, L. et al., 2019: Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. *Science Advances*, **5**(11), eaaw9976, doi:10.1126/sciadv.aaw9976.
Thierfelder, C. et al., 2017: How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. *Food Security*, **9**(3), 537-560, doi:10.1007/s12571-017-0665-3.
Thiery, W. et al., 2017: Early warnings of hazardous thunderstorms over Lake Victoria. *Environmental Research Letters*, **12**(7), 074012, doi:10.1088/1748-9326/aa7521.
Thiery, W. et al., 2021: Age-dependent extreme event exposure. *Science (New York, N.Y.)*.

Thivierge, M.-N. et al., 2016: Predicted Yield and Nutritive Value of an Alfalfa–Timothy Mixture under Climate Change and Elevated Atmospheric Carbon Dioxide. *Agronomy Journal*, **108**(2), 585-603, doi:10.2134/agronj2015.0484.
Thomas, A. et al., 2021: Global evidence of constraints and limits to human adaptation. *Regional Environmental Change*, **21**(3), 85, doi:10.1007/s10113-021-01808-9.
Thomas, N. and S. Nigam, 2018: Twentieth-Century Climate Change over Africa: Seasonal Hydroclimate Trends and Sahara Desert Expansion. *Journal of Climate*, **31**(9), 3349-3370, doi:10.1175/jcli-d-17-0187.1.
Thompson-Hall, M., E. R. Carr and U. Pascual, 2016: Enhancing and expanding intersectional research for climate change adaptation in agrarian settings. *Ambio*, **45**(3), 373-382, doi:10.1007/s13280-016-0827-0.
Thompson, J. R., A. Crawley and D. G. Kingston, 2017: Future river flows and flood extent in the Upper Niger and Inner Niger Delta: GCM-related uncertainty using the CMIP5 ensemble. *Hydrological Sciences Journal*, **62**(14), 2239-2265, doi:10.1080/02626667.2017.1383608.
Thomson, M. C. et al., 2006: Potential of environmental models to predict meningitis epidemics in Africa. *Tropical Medicine & International Health*, **11**(6), 781–788, doi:https://doi.org/10.1111/j.1365-3156.2006.01630.x.
Thorn, J., T. F. Thornton and A. Helfgott, 2015: Autonomous adaptation to global environmental change in peri-urban settlements: Evidence of a growing culture of innovation and revitalisation in Mathare Valley Slums, Nairobi. *Global Environmental Change*, **31**, 121-131, doi:10.1016/j.gloenvcha.2014.12.009.
Thorn, J. P. R. et al., 2020: A systematic review of participatory scenario planning to envision mountain social-ecological systems futures. *Ecology and Society*, **25**(3), 1-55, doi:10.5751/ES-11608-250306.
Thornton, P. K. and M. Herrero, 2014: Climate change adaptation in mixed crop–livestock systems in developing countries. *Global Food Security*, **3**(2), 99-107, doi:https://doi.org/10.1016/j.gfs.2014.02.002.
Thornton, P. K. and M. Herrero, 2015: Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nature Climate Change*, **5**(9), 830-836, doi:10.1038/nclimate2754.
Thornton, P. K. et al., 2018: A qualitative evaluation of CSA options in mixed crop-livestock systems in developing countries. In: *Climate Smart Agriculture* [Lipper, L., N. McCarthy, D. Zilberman, S. Asfaw and G. Branca (eds.)]. Springer, Cham, pp. 385-423.
Thwing, J. et al., 2017: Declines in Malaria Burden and All-Cause Child Mortality following Increases in Control Interventions in Senegal, 2005-2010. *Am J Trop Med Hyg*, **97**(3_Suppl), 89-98, doi:10.4269/ajtmh.16-0953.
Tiedemann, M. et al., 2017: Does upwelling intensity determine larval fish habitats in upwelling ecosystems? The case of Senegal and Mauritania. *Fisheries Oceanography*, **26**(6), 655-667, doi:https://doi.org/10.1111/fog.12224.
Tiepolo, M., 2014: Flood risk reduction and climate change in large cities south of the Sahara. In: *Climate change vulnerability in southern African cities* [Macchi, S. and M. Tiepolo (eds.)]. Springer, Cham, Switzerland, pp. 19-36.
Tierney, J. E., P. B. deMenocal and P. D. Zander, 2017: A climatic context for the out-of-Africa migration. *Geology*, **45**(11), 1023-1026, doi:10.1130/g39457.1.
Tiitmamer, N., 2020: South Sudan's devastating floods: why there is a need for urgent resilience measures. The Sudd Institute, Juba, South Sudan.
Timm Hoffman, M., R. F. Rohde and L. Gillson, 2019: Rethinking catastrophe? Historical trajectories and modelled future vegetation change in southern Africa. *Anthropocene*, **25**, 100189, doi:10.1016/j.ancene.2018.12.003.
Tompkins, A. M. and L. Caporaso, 2016: Assessment of malaria transmission changes in Africa, due to the climate impact of land use change using Coupled Model Intercomparison Project Phase 5 earth system models. *Geospat. Health*, **11**(1 Suppl), 380, doi:10.4081/gh.2016.380.
Tonnang, H. E. Z. et al., 2014: Zoom in at African country level: potential climate induced changes in areas of suitability for survival of malaria vectors. *Int. J. Health Geogr.*, **13**, 12, doi:10.1186/1476-072X-13-12.
Torabi, M. and S. M. Noori, 2019: Religious Leaders and the Environmental Crisis. *The Ecumenical Review*, **71**(3), 344-355, doi:10.1111/erev.12434.
Toreti, A. et al., 2020: Narrowing uncertainties in the effects of elevated CO2 on crops. *Nature Food*, **1**(12), 775-782, doi:10.1038/s43016-020-00195-4.
Totin, E. et al., 2018: Can scenario planning catalyse transformational change? Evaluating a climate change policy case study in Mali. *Futures*, **96**, 44-56, doi:https://doi.org/10.1016/j.futures.2017.11.005.
Toure, A., B. Diekkrüger, A. Mariko and A. Cissé, 2017: Assessment of Groundwater Resources in the Context of Climate Change and Population Growth: Case of the Klela Basin in Southern Mali. *Climate*, **5**(3), 45, doi:10.3390/cli5030045.
Tourre, Y. M. et al., 2019: Malaria in Burkina Faso (West Africa) during the twenty-first century. *Environmental Monitoring and Assessment*, **191**(2), 273, doi:10.1007/s10661-019-7410-7.
Tozer, L. et al., 2020: Whose city? Whose nature? Towards inclusive nature-based solution governance. *Cities*, **107**, 102892, doi:https://doi.org/10.1016/j.cities.2020.102892.
Trabacchi, C. and F. Mazza, 2015: *Emerging solutions to drive private investment in climate resilience*. Climate Policy Initiative, Australia. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2015/06/Finance-for-Climate-Resilience.pdf.
Trærup, S. L. M., R. A. Ortiz and A. Markandya, 2011: The costs of climate change: a study of cholera in Tanzania. *International journal of environmental research and public health*, **8**(12), 4386-4405, doi:10.3390/ijerph8124386.

Tramblay, Y., G. Villarini and W. Zhang, 2020: Observed changes in flood hazard in Africa. *Environmental Research Letters*, **15**(10), 1040b1045, doi:10.1088/1748-9326/abb90b.
Traore, B. et al., 2013: Effects of climate variability and climate change on crop production in southern Mali. *European Journal of Agronomy*, **49**, 115-125, doi:10.1016/j.eja.2013.04.004.
Trisos, C. H., J. Auerbach and M. Katti, 2021: Decoloniality and anti-oppressive practices for a more ethical ecology. *Nature Ecology & Evolution*, **5**(9), 1205-1212, doi:10.1038/s41559-021-01460-w.
Trisos, C. H., C. Merow and A. L. Pigot, 2020: The projected timing of abrupt ecological disruption from climate change. *Nature*, **580**(7804), 496-501, doi:10.1038/s41586-020-2189-9.
Troeger, C. et al., 2018: Rotavirus Vaccination and the Global Burden of Rotavirus Diarrhea Among Children Younger Than 5 Years. *JAMA Pediatr*, **172**(10), 958-965, doi:10.1001/jamapediatrics.2018.1960.
Trugman, A. T., D. Medvigy, J. S. Mankin and W. R. L. Anderegg, 2018: Soil Moisture Stress as a Major Driver of Carbon Cycle Uncertainty. *Geophysical Research Letters*, **45**(13), 6495-6503, doi:10.1029/2018GL078131.
Tsan, M., S. Totapally, M. Hailu and B. Addom, 2021: *The Digitalisation of African Agriculture Report, 2018-2019*. CTA, CTA, Wageningen, The Netherlands. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/101498/CTA-Digitalisation-report.pdf.
Tume, S. J. P., J. N. Kimengsi and Z. N. Fogwe, 2019: Indigenous Knowledge and Farmer Perceptions of Climate and Ecological Changes in the Bamenda Highlands of Cameroon: Insights from the Bui Plateau. *Climate*, **7**(12), 138, doi:https://doi.org/10.3390/cli7120138.
Turpie, J. K., C. Marais and J. N. Blignaut, 2008: The working for water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. *Ecological Economics*, **65**(4), 788-798, doi:https://doi.org/10.1016/j.ecolecon.2007.12.024.
Tusting, L. et al., 2020: Environmental temperature and growth faltering in African children: a cross-sectional study. *The Lancet Planetary Health*, **4**, e116-e123, doi:10.1016/S2542-5196(20)30037-1.
Tyukavina, A. et al., 2018: Congo Basin forest loss dominated by increasing smallholder clearing. *Science Advances*, **4**(11), eaat2993, doi:10.1126/sciadv.aat2993.
Uhe, P. et al., 2018: Attributing drivers of the 2016 Kenyan drought. *International Journal of Climatology*, **38**, e554-e568, doi:10.1002/joc.5389.
UK Space Agency, 2020: *Space for Finance in Developing Countries*. UK Space Agency International Partnership Programme UK Space Agency, Swindon, United Kingdom, 64 pp. Available at: https://www.spacefordevelopment.org/wp-content/uploads/2020/01/118601_UKSA_Finance-Report-2019_EL_v9.pdf.
Ukkola, A. M. et al., 2020: Robust Future Changes in Meteorological Drought in CMIP6 Projections Despite Uncertainty in Precipitation. *Geophysical Research Letters*, **47**(11), e2020GL087820, doi:https://doi.org/10.1029/2020GL087820.
Ulrichs, M., R. Slater and C. Costella, 2019: Building resilience to climate risks through social protection: from individualised models to systemic transformation. *Disasters*, **43**(Suppl 3), S368-s387, doi:10.1111/disa.12339.
UN-Habitat, 2014: *The State of African Cities 2014: Reimagining Sustainable Urban Transitions*. UN-Habitat, Nairobi, Kenya, 200 pp. Available at: https://unhabitat.org/state-of-african-cities-2014-re-imagining-sustainable-urban-transitions.
UN-Habitat, 2016: *World Cities Report 2016*. Urbanization and Development: Emerging Futures, UN-Habitat, Nairobi, Kenya, 49 pp. Available at: http://wcr.unhabitat.org/wp-content/uploads/2017/02/WCR-2016_-Abridged-version-1.pdf.
UN-Water, 2006: *Gender, Water and Sanitation: A Policy Brief*. Available at: https://www.unwater.org/publications/gender-water-sanitation-policy-brief/.
UN Environment, 2019: *Global Environment Outlook – GEO-6: Healthy Planet, Healthy People* [Ekins, P., J. Gupta and P. Boileau (eds.)]. UNEP, Cambridge University Press, Nairobi, 745 pp. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/27539/GEO6_2019.pdf?sequence=1&isAllowed=y.
UNAIDS, 2020: *UNAIDS data 2020*. Joint United Nations Programme on HIV/AIDS (UNAIDS), 436 pp. Available at: https://www.unaids.org/sites/default/files/media_asset/2020_aids-data-book_en.pdf.
UNCCD, 2020: Great Green Wall receives over $10b to regreen The Sahel - France, World Bank Listed Among Donors. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany, 13 pp.
UNCTAD, 2020: *Climate Change Impacts and Adaptation for Coastal Transport Infrastructure: A Compilation of Policies and Practices*. Transport and Trade Facilitation Series, **12**, United Nations, New York, USA. Available at: https://unctad.org/system/files/official-document/dtltlb2019d1_en.pdf.
UNDESA, 2019a: *Revision of World Urbanization Prospects*. United Nations Department of Economic and Social Affairs Population Dynamics, New York. Available at: https://population.un.org/wpp/Download/Standard/Population/.
UNDESA, 2019b: *World Urbanization Prospects: The 2018 Revision*. UN, New York. Available at: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf.
UNDP, 2016: *Climate Information & Early Warning Systems Communications Toolkit*. UNDP Programme on Climate Information for Resilient Development in Africa, UNDP. Available at: https://www.adaptation-undp.org/sites/default/files/resources/communications-toolkit-v3.docx.
UNDP, The 2019 Global Multidimensional Poverty Index (MPI). Available at: http://hdr.undp.org/en/2018-MPI.

UNECA, 2016: *Economic Report on Africa 2016: Greening Africa's Industrialization*. United Nations Economic Commission for Africa (UNECA), UNECA, Addis Ababa, Ethiopia, 254 pp. Available at: https://hdl.handle.net/10855/23017.
UNEP-FI, 2019a: *African insurance and UN leaders meet in Lagos to drive collaborative action for sustainable development*. UN Environment's Principles for Sustainable Insurance Initiative, Geneva, Switzerland, 4 pp. Available at: https://www.unepfi.org/psi/wp-content/uploads/2019/05/2nd-PSI-African-market-event-outcome-document.pdf.
UNEP-FI, 2019b: *African insurance industry leaders and UN Environment agree on key collaborative initiatives for sustainable development*. UNEP-FI, Nairobi, Kenya. Available at: https://www.unepfi.org/psi/wp-content/uploads/2019/05/2nd-PSI-African-market-event-outcome-document.pdf.
UNEP, 2010: *Africa Water Atlas*. UNEP, Nairobi, Kenya.
UNEP, 2015: *Africa's Adaptation Gap 2: Bridiging the gap – mobilising resources - technical report* [Schaeffer, M., F. Baarsch and R. Munang (eds.)]. United Nations Environment Programme, 67 pp. Available at: http://wedocs.unep.org/handle/20.500.11822/9092.
UNEP, 2016a: *The Adaptation Finance Gap Report* [Olhoff, A., B. Dickson, D. Puig, K. Alverson and S. Bee (eds.)]. United Nations Environment Programme (UNEP), Nairobi, Kenya. Available at: https://unepdtu.org/publications/the-adaptation-finance-gap-report/
UNEP, 2016b: *Options for Ecosystem-based Adaptation (EBA) in Coastal Environments: A Guide for Environmental Managers and Planners*. UNEP, Nairobi, Kenya, 103 pp. Available at: https://www.unep-wcmc.org/system/dataset_file_fields/files/000/000/380/original/Options_for_Ecosystem_based_Adaptation_in_Coastal_Environments_low-res.pdf?1462462607.
UNEP, 2019: *Tanzania: Ecosystem-based adaptation*. UNEP, Dodoma, Tanzania, 2 pp. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/28427/EbA_Tanzania.pdf?sequence=1&isAllowed=y.
UNEP, 2020: *Angola: Ecosystem-based Adaptation 2016-2020*. UNEP, Nairobi, Kenya, 2 pp. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/32051/AngolaEBA.pdf?sequence=1&isAllowed=y.
UNEP, 2021: *Adaptation Gap Report 2020*. United Nations Environment Programme, Nairobi, 120 pp. Available at: https://www.unep.org/adaptation-gap-report-2020.
UNEP PSI, 2021: The Nairobi Declaration on Sustainable Insurance. UN Environment Programme's Principles for Sustainable Insurance Initiative (PSI), Nairobi, Kenya, 1 pp.
UNESCO, 2003: *Convention for the safeguarding of the intangible cultural heritage*. UNESCO, Paris, 15 pp. Available at: https://ich.unesco.org/doc/src/15164-EN.pdf.
UNESCO, 2021: Sanké mon, collective fishing rite of the Sanké. Available at: https://ich.unesco.org/en/USL/sank-mon-collective-fishing-rite-of-the-sank-00289.
UNESCO, 2021: Enkipaata, Eunoto and Olng'esherr, three male rites of passage of the Maasai community. Available at: https://ich.unesco.org/en/USL/enkipaata-eunoto-and-olng-esherr-three-male-rites-of-passage-of-the-maasai-community-01390.
UNESCO, 2018b: *World Heritage for Sustainable Development in Africa* [Edmond, M. and O. Ishanlosen (eds.)]. United Nations Educational, Scientific and Cultural Organization, France, 274 pp.
UNESCO and UN-Water, 2020: *United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO, Paris 219 pp. ISBN 978-92-3-100371-4.
UNESCO Institute of Statistics, 2018: *One in five children, adolescents and youth is out of school. The United Nations Educational, Scientific and Cultural Organization*, Montreal, 13 pp. Available at: http://uis.unesco.org/sites/default/files/documents/fs48-one-five-children-adolescents-youth-out-school-2018-en.pdf.
UNFCCC, 2007: *Climate change: Impacts, vulnerabilities and adaptation in developing countries*. United Nations Climate Change Secretariat (UNFCCC), Bonn, Germany. Available at: http://unfccc.int/resource/docs/publications/impacts.pdf (accessed 2014/02/24/15:53:19).
UNFCCC, 2009: *Copenhagen Accord*. United Nations Framework Convention on Climate Change (UNFCCC), Copenhagen, Denmark, 43 pp. Available at: https://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf.
UNFCCC, 2018: *2018 Biennial Assessment and Overview of Climate Finance Flows*. United Nations Framework Convention on Climate Change Standing Committee on Finance, Benn, Germany, 172 pp. Available at: https://unfccc.int/sites/default/files/resource/2018%20BA%20Technical%20Report%20Final%20Feb%202019.pdf.
UNFCCC, Warsaw International Mechanism for Loss and Damage associated with Climate Change Impacts (WIM), United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany. Available at: https://unfccc.int/topics/adaptation-and-resilience/workstreams/loss-and-damage-ld/warsaw-international-mechanism-for-loss-and-damage-associated-with-climate-change-impacts-wim.
UNFCCC Adaptation Committee, 2019: *Various approaches to long-term adaptation planning*. United Nations Climate Change Secretariat, Bonn, Germany, 11 pp. Available at: https://unfccc.int/sites/default/files/resource/variousapproaches%20.pdf.
UNFCCC Paris Agreement, 2015: *Adoption of the Paris Agreement*. United Nations Climate Change Secretariat (UNFCCC), Bonn, Germany. Available at: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

UNICEF, WHO and WBG, 2019: *Levels and trends in child malnutrition: Key findings of the 2019 Edition Joint Child Malnutrition Estimates* [United Nations Children's Fund, World Health Organization and World Bank Group (eds.)]. World Health Organization, Geneva, 15 pp. Available at: https://apps.who.int/iris/rest/bitstreams/1269729/retrieve.

UNISDR Sendai Framework, 2015: Sendai Framework for Disaster Risk Reduction 2015–2030. United Nations Office for Disaster Risk Reduction, 24 pp.

United Nations General Assembly, 2015: *Transforming our world: the 2030 Agenda for Sustainable Development*, New York, USA. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld.

UNWTO, 2008: *Climate change and tourism: Resoponding to Global Challenges*. World Tourism Organization (UNWTO), Madrid, Spain.

Urban, M. C., 2015: Accelerating extinction risk from climate change. *Science (New York, N.Y.)*, **348**(6234), 571, doi:10.1126/science.aaa4984.

Valencia-Quintana, R. et al., 2020: Environment Changes, Aflatoxins, and Health Issues, a Review. *International Journal of Environmental Research and Public Health*, **17**(21), 7850, doi:10.3390/ijerph17217850.

van Baalen, S. and M. Mobjörk, 2018: Climate Change and Violent Conflict in East Africa: Integrating Qualitative and Quantitative Research to Probe the Mechanisms. *International Studies Review*, **20**(4), 547-575, doi:10.1093/isr/vix043.

van de Giesen, N., R. Hut and J. Selker, 2014: The trans-African hydro-meteorological observatory (TAHMO). *Wiley Interdisciplinary Reviews: Water*, **1**(4), 341-348, doi:https://doi.org/10.1002/wat2.1034.

van den Berg, H. et al., 2019: Linking water quality monitoring and climate-resilient water safety planning in two urban drinking water utilities in Ethiopia. *J Water Health*, **17**(6), 989-1001, doi:10.2166/wh.2019.059.

van der Linden, N. et al., 2019: The use of an 'acclimatisation' heatwave measure to compare temperature-related demand for emergency services in Australia, Botswana, Netherlands, Pakistan, and USA. *PLoS One*, **14**(3), e0214242, doi:10.1371/journal.pone.0214242.

van der Lingen, C. D. and I. Hampton, 2018: *Climate change impacts, vulnerabilities and adaptations: Southeast Atlantic and Southwest Indian Ocean marine fisheries* [Barange, M., T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options, FAO Fisheries and Aquaculture, Rome, Italy, 219-250 pp. Available at: http://www.fao.org/3/i9705en/I9705EN.pdf.

Van Der Ree, R., D. J. Smith and C. Grilo, 2015: *Handbook of road ecology*. John Wiley & Sons. ISBN 1118568168.

van der Zwaan, B. et al., 2018: An integrated assessment of pathways for low-carbon development in Africa. *Energy Policy*, **117**, 387-395, doi:10.1016/j.enpol.2018.03.017.

Van Hout, M. C. and R. Mhlanga-Gunda, 2019: Prison health situation and health rights of young people incarcerated in sub-Saharan African prisons and detention centres: a scoping review of extant literature. *BMC international health and human rights*, **19**(1), 17, doi:10.1186/s12914-019-0200-z.

van Oort, P. A. J. and S. J. Zwart, 2018: Impacts of climate change on rice production in Africa and causes of simulated yield changes. *Global Change Biology*, **24**(3), 1029-1045, doi:https://doi.org/10.1111/gcb.13967.

van Weezel, S., 2019: On climate and conflict: Precipitation decline and communal conflict in Ethiopia and Kenya. *Journal of Peace Research*, **56**(4), 514-528, doi:10.1177/0022343319826409.

van Wilgen, N. J. et al., 2016: Rising temperatures and changing rainfall patterns in South Africa's national parks. *International Journal of Climatology*, **36**(2), 706-721, doi:10.1002/joc.4377.

van Wyk, L., 2017: *Cultural and heritage sensitive adaptation measures and principles in climate change adaptation plans for South African metropolitan cities*. Council for Scientific and Industrial Research, South Africa, Stellenbosch, 9 pp. Available at: https://www.researchgate.net/publication/319136126_CULTURAL_AND_HERITAGE_SENSITIVE_ADAPTATION_MEASURES_AND_PRINCIPLES_IN_CLIMATE_CHANGE_ADAPTATION_PLANS_FOR_SOUTH_AFRICAN_METROPOLITAN_CITIES (accessed 2019/01/31/03:57:32).

van Wyk, L., L. C. Duncker and P. du Plessis, 2017: Harvesting Renewable Water: Part 1: Rainwater. In: *The Green Bulding Handbook South Africa: The Essential Guide* [Van Wyk, L. V. (ed.)]. Alive2green, Cape Town, South Africa, pp. 52-65.

Vaughan, C., S. Dessai and C. Hewitt, 2018: Surveying Climate Services: What Can We Learn from a Bird's-Eye View? *Weather, Climate, and Society*, **10**(2), 373-395, doi:10.1175/WCAS-D-17-0030.1.

Vaughan, C. et al., 2019: Evaluating agricultural weather and climate services in Africa: Evidence, methods, and a learning agenda. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(4), e586, doi:10.1002/wcc.586.

Veettil and Kamp, 2019: Global Disappearance of Tropical Mountain Glaciers: Observations, Causes, and Challenges. *Geosciences*, **9**(5), doi:10.3390/geosciences9050196.

Veldman, J. W. et al., 2015: Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *BioScience*, **65**(10), 1011-1018, doi:10.1093/biosci/biv118.

Vellinga, M. and S. F. Milton, 2018: Drivers of interannual variability of the East African "Long Rains". *Quarterly Journal of the Royal Meteorological Society*, **144**(712), 861-876, doi:https://doi.org/10.1002/qj.3263.

Venema, H. D. and J. Temmer, 2017: *Water supply and sanitation systems*. Building a Climate-Resilient City, Prairie Climate Centre, International Institute for Sustainable Development (IISD) and the University of Winnipeg, 10 pp. Available at: https://www.iisd.org/library/building-climate-resilient-city-water-supply-and-sanitation-systems.

Venter, Z. S., M. D. Cramer and H. J. Hawkins, 2018: Drivers of woody plant encroachment over Africa. *Nature Communications*, **9**(1), 2272, doi:10.1038/s41467-018-04616-8.
Verisk Maplecroft, Urbanisation and Climate Change Risk. Available at: https://www.maplecroft.com/insights/analysis/84-of-worlds-fastest-growing-cities-face-extreme-climate-change-risks/.
Verner, D. et al., 2018: *Climate Variability, Drought, and Drought Management in Tunisia's Agricultural Sector*. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/30603.
Vicedo-Cabrera, A. M. et al., 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11**(6), 492-500, doi:10.1038/s41558-021-01058-x.
Vidya, P. J. et al., 2020: Increased cyclone destruction potential in the Southern Indian Ocean. *Environmental Research Letters*, **16**(1), 014027, doi:10.1088/1748-9326/abceed.
Viles, H. A. and N. A. Cutler, 2012: Global environmental change and the biology of heritage structures. *Global Change Biology*, **18**(8), 2406-2418, doi:https://doi.org/10.1111/j.1365-2486.2012.02713.x.
Villamayor-Tomas, S. et al., 2015: The water-energy-food security nexus through the lenses of the value chain and the institutional analysis and development frameworks. *Water Alternatives*, **8**(1), 735-755.
Vincent, K. et al., 2020a: Addressing power imbalances in co-production. *Nature Climate Change*, **10**(10), 877-878, doi:10.1038/s41558-020-00910-w.
Vincent, K. and D. Conway, 2021: Key Issues and Progress in Understanding Climate Risk in Africa. In: *Climate Risk in Africa: Adaptation and Resilience* [Conway, D. and K. Vincent (eds.)]. Springer International Publishing, Cham, pp. 1-16. ISBN 978-3-030-61160-6.
Vincent, K. et al., 2020b: Re-balancing climate services to inform climate-resilient planning – A conceptual framework and illustrations from sub-Saharan Africa. *Climate Risk Management*, **29**, 100242, doi:https://doi.org/10.1016/j.crm.2020.100242.
Vincent, K. and G. Cundill, 2021: The evolution of empirical adaptation research in the global South from 2010 to 2020. *Climate and Development*, 1-14, doi:10.1080/17565529.2021.1877104.
Vincent, K., M. Daly, C. Scannell and B. Leathes, 2018: What can climate services learn from theory and practice of co-production? *Climate Services*, **12**, 48-58, doi:10.1016/j.cliser.2018.11.001.
Vizy, E. K. and K. H. Cook, 2012: Mid-twenty-first-century changes in extreme events over northern and tropical Africa. *Journal of Climate*, **25**, 5748-5767, doi:10.1175/JCLI-D-11-00693.1.
Vizy, E. K., K. H. Cook and X. Sun, 2018: Decadal change of the south Atlantic ocean Angola–Benguela frontal zone since 1980. *Clim Dyn*, **51**(9), 3251-3273, doi:10.1007/s00382-018-4077-7.
Vogel, C., A. Steynor and A. Manyuchi, 2019: Climate services in Africa: Re-imagining an inclusive, robust and sustainable service. *Climate Services*, **15**, 100107, doi:10.1016/j.cliser.2019.100107.
von Lossow, T., 2017: *The River Congo - Africa's sleeping giant: regional integration and intersectoral conflicts in the Congo Basin*. Stiftung Wissenschaft und Politik -SWP- Deutsches Institut für Internationale Politik und Sicherheit, Berlin. Available at: https://nbn-resolving.org/urn:nbn:de:0168-ssoar-55100-9.
von Uexkull, N., M. Croicu, H. Fjelde and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proceedings of the National Academy of Sciences*, **113**(44), 12391-12396, doi:10.1073/pnas.1607542113.
von Uexkull, N., M. d'Errico and J. Jackson, 2020: Drought, Resilience, and Support for Violence: Household Survey Evidence from DR Congo. *Journal of Conflict Resolution*, **64**(10), 1994-2021, doi:10.1177/0022002720923400.
Wada, Y., D. Wisser and M. F. P. Bierkens, 2014: Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth System Dynamics*, **5**(1), 15-40, doi:10.5194/esd-5-15-2014.
Waha, K. et al., 2017: Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. *Regional Environmental Change*, **17**(6), 1623-1638, doi:10.1007/s10113-017-1144-2.
Waha, K. et al., 2018: Agricultural diversification as an important strategy for achieving food security in Africa. *Global Change Biology*, **24**(8), 3390-3400, doi:https://doi.org/10.1111/gcb.14158.
Wainwright, C. M. et al., 2019: 'Eastern African Paradox'rainfall decline due to shorter not less intense Long Rains. *npj Climate and Atmospheric Science*, **2**(34), 1-9, doi:https://doi.org/10.1038/s41612-019-0091-7.
Wairore, J. N., S. M. Mureithi, O. V. Wasonga and G. Nyberg, 2016: Benefits Derived from Rehabilitating a Degraded Semi-Arid Rangeland in Private Enclosures in West Pokot County, Kenya. *Land Degradation & Development*, **27**(3), 532-541, doi:https://doi.org/10.1002/ldr.2420.
Walker, J. T., 2018: The influence of climate change on waterborne disease and Legionella: a review. *Perspectives in Public Health*, **138**(5), 282-286, doi:10.1177/1757913918791198.
Wanderi, H., 2019: Lamu Old Town: Balancing Economic Development with Heritage Conservation. *JOURNAL OF WORLD HERITAGE STUDIES*, **Special issue 2019**, 16-22, doi:http://doi.org/10.15068/00157681.
Wang, B., C. Jin and J. Liu, 2020a: Understanding Future Change of Global Monsoons Projected by CMIP6 Models. *Journal of Climate*, **33**(15), 6471-6489, doi:10.1175/JCLI-D-19-0993.1.
Wang, G. et al., 2020b: A Unique Feature of the 2019 Extreme Positive Indian Ocean Dipole Event. *Geophysical Research Letters*, **47**(18), e2020GL088615, doi:https://doi.org/10.1029/2020GL088615.
Wang, H. et al., 2016: Detecting cross-equatorial wind change as a fingerprint of climate response to anthropogenic aerosol forcing. *Geophysical Research Letters*, **43**(7), 3444-3450, doi:https://doi.org/10.1002/2016GL068521.

Wang, S.-J. and L.-Y. Zhou, 2019: Integrated impacts of climate change on glacier tourism. *Advances in Climate Change Research*, **10**(2), 71-79, doi:https://doi.org/10.1016/j.accre.2019.06.006.
Wangai, P. W., B. Burkhard and F. Müller, 2016: A review of studies on ecosystem services in Africa. *International Journal of Sustainable Built Environment*, **5**(2), 225-245, doi:https://doi.org/10.1016/j.ijsbe.2016.08.005.
Wangui, E., 2018: Adaptation to Current and Future Climate in Pastoral Communities Across Africa. Oxford University Press.
Ward, M. et al., 2020: Just ten percent of the global terrestrial protected area network is structurally connected via intact land. *Nature Communications*, **11**(1), 4563, doi:10.1038/s41467-020-18457-x.
Warren, M., 2019: Why Cyclone Idai is one of the Southern Hemisphere's most devastating storms. *Nature*, doi:10.1038/d41586-019-00981-6.
Warren, R. et al., 2018: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science (New York, N.Y.)*, **360**(6390), 791, doi:10.1126/science.aar3646.
WASH Alliance International, 2015: *Accelerating WASH in Ethiopia: Best practices from the 2011-2015 WASH Programme*. Available at: https://wash-alliance.org/wp-content/uploads/sites/36/2016/08/Best-Practice-Etiopia.pdf.
Watson, J. E. M. et al., 2018: The exceptional value of intact forest ecosystems. *Nature Ecology & Evolution*, **2**(4), 599-610, doi:10.1038/s41559-018-0490-x.
Watts, N. et al., 2015: Health and climate change: policy responses to protect public health. *Lancet*, **386**(10006), 1861-1914, doi:10.1016/S0140-6736(15)60854-6.
Watts, N. et al., 2018: The *Lancet* Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *Lancet*, **391**(10120), 581-630, doi:10.1016/S0140-6736(17)32464-9.
Weber, E. J., 2019: Weather Index Insurance in Sub-Saharan Africa. *SSRN 3396489*, 1-11, doi:https://dx.doi.org/10.2139/ssrn.3396489.
Weber, T. et al., 2020: Analysis of Compound Climate Extremes and Exposed Population in Africa Under Two Different Emission Scenarios. *Earth's Future*, **8**(9), e2019EF001473, doi:https://doi.org/10.1029/2019EF001473.
Weber, T. et al., 2018: Analyzing Regional Climate Change in Africa in a 1.5, 2, and 3°C Global Warming World. *Earth's Future*, **6**(4), 643-655, doi:10.1002/2017ef000714.
Weetman, D. et al., 2018: Aedes Mosquitoes and Aedes-Borne Arboviruses in Africa: Current and Future Threats. *Int J Environ Res Public Health*, **15**(2), doi:10.3390/ijerph15020220.
WEF, 2021: *Unlocking the potential of Earth Observation to address Africa's critical challenges*. World Economic Forum, Geneva, Switzerland, 31 pp. Available at: http://www3.weforum.org/docs/WEF_Digital_Earth_Africa_Unlocking_the_potential_of_Earth_Observation_to_address_Africa_2021.pdf.
Weiler, F. and F. A. Sanubi, 2019: Development and Climate Aid to Africa: Comparing Aid Allocation Models for Different Aid Flows. *Africa Spectrum*, **54**(3), 244-267, doi:10.1177/0002039720905598.
Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters*, **10**(9), 094021, doi:10.1088/1748-9326/10/9/094021.
Weinzierl, T. and J. Schilling, 2013: On demand, development and dependence: A review of current and future implications of socioeconomic changes for Integrated Water Resource Management in the Okavango Catchment of Southern Africa. *Land*, **2**(1), 60-80, doi:10.3390/land2010060.
Weiser, S. D. et al., 2010: Food insecurity as a barrier to sustained antiretroviral therapy adherence in Uganda. *PLoS One*, **5**(4), e10340, doi:10.1371/journal.pone.0010340.
Weiss, D. J. et al., 2020: Global maps of travel time to healthcare facilities. *Nature Medicine*, **26**(12), 1835-1838, doi:10.1038/s41591-020-1059-1.
Wekesa, C. et al. (eds.), Traditional knowledge-based innovations for adaptation and resilience to climate change: the case of coastal Kenya. XIV World Forestry Congress, Durban, South Africa, 7-11 September 2015.
Wenta, J., J. McDonald and J. S. McGee, 2019: Enhancing resilience and justice in climate adaptation laws. *Transnational Environmental Law*, **8**(1), 89-118, doi:10.1017/S2047102518000286.
Wenz, L. and A. Levermann, 2016: Enhanced economic connectivity to foster heat stress-related losses. *Sci Adv*, **2**(6), e1501026, doi:10.1126/sciadv.1501026.
Werners, S. E. et al., 2021: Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, **116**, 266-275, doi:https://doi.org/10.1016/j.envsci.2020.11.003.
Wessels, C., C. Merow and C. H. Trisos, 2021: Climate change risk to southern African wild food plants. *Regional Environmental Change*, **21**(2), 29, doi:10.1007/s10113-021-01755-5.
West, J. J. et al., 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3**(10), 885-889, doi:https://doi.org/10.1038/nclimate2009.
Westervelt, D. M. et al., 2016: Quantifying PM2.5-meteorology sensitivities in a global climate model. *Atmospheric Environment*, **142**, 43-56, doi:10.1016/j.atmosenv.2016.07.040.
Weston, P., R. Hong and Kabor, 2015: Farmer-Managed Natural Regeneration Enhances Rural Livelihoods in Dryland West Africa. *Environmental Management*, **55**(6), 1402-1417, doi:10.1007/s00267-015-0469-1.
Weyant, C. et al., 2018: Anticipated burden and mitigation of carbon-dioxide-induced nutritional deficiencies and related diseases: A simulation modeling study. *PLoS Med*, **15**(7), e1002586, doi:10.1371/journal.pmed.1002586.

WFP, 2020: *R4 Rural Resilience Initiative Annual Report*. World Food Programme, Rome, Italy, 124 pp. Available at: https://docs.wfp.org/api/documents/WFP-0000128425/download/?_ga=2.70893520.1511863330.1626445093-1538420741.1626445093.

White, R. and S. Wahba, 2019: Addressing constraints to private financing of urban (climate) infrastructure in developing countries. *International Journal of Urban Sustainable Development*, **11**(3), 245-256, doi:10.1080/19463138.2018.1559970.

Whitmee, S. et al., 2015: Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. *The Lancet*, **386**(10007), 1973-2028, doi:https://doi.org/10.1016/S0140-6736(15)60901-1.

WHO, 2014: *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s* [Hales, S., S. Kovats, S. Lloyd and D. Campbell-Lendrum (eds.)]. World Health Organization, Geneva, Switzerland. Available at: https://apps.who.int/iris/bitstream/handle/10665/134014/9789241507691_eng.pdf.

WHO, 2015: *Operational framework for building climate resilient health systems* [World Health Organization (ed.)]. World Health Organisation, 54 pp. Available at: https://apps.who.int/iris/bitstream/handle/10665/189951/9789241565073_eng.pdf.

WHO, 2016: *El Niño and health. Global Report*. World Health Organisation (WHO). Available at: https://www.who.int/hac/crises/el-nino/who_el_nino_and_health_global_report_21jan2016.pdf.

Wichmann, J., 2017: Heat effects of ambient apparent temperature on all-cause mortality in Cape Town, Durban and Johannesburg, South Africa: 2006-2010. *Sci Total Environ*, **587-588**, 266-272, doi:10.1016/j.scitotenv.2017.02.135.

Wiederkehr, C., M. Beckmann and K. Hermans, 2018: Environmental change, adaptation strategies and the relevance of migration in Sub-Saharan drylands. *Environmental Research Letters*, **13**(11), 113003, doi:https://doi.org/10.1088/1748-9326/aae6de.

Wigley, A. S. et al., 2020a: Measuring the availability and geographical accessibility of maternal health services across sub-Saharan Africa. *BMC Medicine*, **18**(1), 237, doi:10.1186/s12916-020-01707-6.

Wigley, B. J. et al., 2020b: Grasses continue to trump trees at soil carbon sequestration following herbivore exclusion in a semiarid African savanna. *Ecology*, **101**(5), e03008, doi:https://doi.org/10.1002/ecy.3008.

Wijesinghe, A. and J. P. R. Thorn, 2021: Governance of Urban Green Infrastructure in Informal Settlements of Windhoek, Namibia. *Sustainability*, **13**(16), doi:10.3390/su13168937.

Wilkinson, A., 2020: Local response in health emergencies: key considerations for addressing the COVID-19 pandemic in informal urban settlements. *Environment and Urbanization*, **32**(2), 503-522, doi:10.1177/0956247820922843.

Williams, D. S. et al., 2019a: Vulnerability of informal settlements in the context of rapid urbanization and climate change. *Environment and Urbanization*, **31**(1), 157-176, doi:10.1177/0956247818819694.

Williams, P. A., O. Crespo and M. Abu, 2019b: Adapting to changing climate through improving adaptive capacity at the local level – The case of smallholder horticultural producers in Ghana. *Climate Risk Management*, **23**, 124-135, doi:https://doi.org/10.1016/j.crm.2018.12.004.

Williams, P. A., L. Sikutshwa and S. Shackleton, 2020: Acknowledging Indigenous and Local Knowledge to Facilitate Collaboration in Landscape Approaches—Lessons from a Systematic Review. *Land*, **9**(9), doi:10.3390/land9090331.

Williams, P. A. et al., 2021: Feasibility assessment of climate change adaptation options across Africa: an evidence-based review. *Environmental Research Letters*, **16**(7), doi:10.1088/1748-9326/ac092d.

Wilson, J., 2014: The History of the Level of Lake Chilwa. *The Society of Malawi Journal*, **67**(2), 41-45.

Winrock, 2018: *Assessing Sustainability and Effectiveness of Climate Information Services in Africa Final Report*. Washington, DC, USA. Available at: https://www.climatelinks.org/resources/assessing-sustainability-and-effectiveness-climate-information-services-africa-final (accessed 21 June 2020).

Wiru, K. et al., 2019: The influence of apparent temperature on mortality in the middle belt of Ghana. *Environmental Epidemiology*, **3**(p 295), doi:10.1097/01.EE9.0000609192.22657.a7.

Wisner, B., 2016: Vulnerability as Concept, Model, Metric, and Tool. Oxford University Press.

Wisner, B. et al., 2015: Small Cities and Towns in Africa: Insights into Adaptation Challenges and Potentials. In: *Urban Vulnerability and Climate Change in Africa: A Multidisciplinary Approach* [Pauleit, S., A. Coly, S. Fohlmeister, P. Gasparini, G. Jørgensen, S. Kabisch, W. J. Kombe, S. Lindley, I. Simonis and K. Yeshitela (eds.)]. Springer International Publishing, pp. 153-196. ISBN 978-3-319-03982-4.

Witmer, F. D. et al., 2017: Subnational violent conflict forecasts for sub-Saharan Africa, 2015–65, using climate-sensitive models. *Journal of Peace Research*, **54**(2), 175-192, doi:10.1177/0022343316682064.

Witt, A., T. Beale and W. Van Wilgen Brian, 2018: An assessment of the distribution and potential ecological impacts of invasive alien plant species in eastern Africa. *Transactions of the Royal Society of South Africa*, **73**(3), 217-236, doi:10.1080/0035919X.2018.1529003.

WMO, 2021: *First Report of the WMO COVID-19 Task Team: Review on Meteorological and Air Quality Factors Affecting the COVID-19 Pandemic*. World Meteorological Organization (WMO), Geneva. Available at: https://library.wmo.int/index.php?lvl=notice_display&id=21857#.YNHse-gzaHs.

Wojewska, A. N., C. Singh and C. P. Hansen, 2021: A policy tool for monitoring and evaluation of participation in adaptation projects. *Climate Risk Management*, **33**, 100326, doi:https://doi.org/10.1016/j.crm.2021.100326.

Wolski, P. et al., 2014: Attribution of floods in the Okavango basin, Southern Africa. *Journal of Hydrology*, **511**, 350-358, doi:https://doi.org/10.1016/j.jhydrol.2014.01.055.
Wong, P. P. et al., 2014: Coastal Systems and Low-Lying Areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, United Kingdom and New York, NY, USA, pp. 361-409.
Woodhouse, P. et al., 2017: African farmer-led irrigation development: re-framing agricultural policy and investment? *The Journal of Peasant Studies*, **44**(1), 213-233, doi:10.1080/03066150.2016.1219719.
Woodroffe, R., R. Groom and J. W. McNutt, 2017: Hot dogs: High ambient temperatures impact reproductive success in a tropical carnivore. *Journal of Animal Ecology*, **86**(6), 1329-1338, doi:https://doi.org/10.1111/1365-2656.12719.
Woolway, R. I. et al., 2021: Lake heatwaves under climate change. *Nature*, **589**(7842), 402-407, doi:10.1038/s41586-020-03119-1.
Woolway, R. I. and S. C. Maberly, 2020: Climate velocity in inland standing waters. *Nature Climate Change*, **10**(12), 1124-1129, doi:10.1038/s41558-020-0889-7.
World Bank, 2015: *Promoting Green Urban Development in African Cities: Kampala, Uganda*. Urban Environmental Profile, International Bank for Reconstruction and Development / The World Bank, Bank, W., Washington, DC. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/22941/Promoting0gree0nvironmental0profile.pdf?sequence=5&isAllowed=y.
World Bank, 2017a: *Kariba Dam Rehabilitation Project (RI): Overview*. World Bank Group, Bank, W., Washington DC, 3 pp. Available at: https://projects.worldbank.org/en/projects-operations/project-detail/P146515?lang=en&tab=overview.
World Bank, 2017b: *Sierra Leone Rapid Damage and Loss Assessment of August 14th, 2017 Landslides and Floods in the Western Area*. Economic and Sector Work (ESW) Studies World Bank, Washington, DC, 118 pp. Available at: https://openknowledge.worldbank.org/handle/10986/28836.
World Bank, 2018: *World Bank Open Data*. World Bank Group, Washington, DC, USA. Available at: https://data.worldbank.org/.
World Bank, 2020a: *Covid-19 Crisis Through a Migration Lens*. World Bank, Washington, DC, 1-50 pp. Available at: https://www.knomad.org/publication/migration-and-development-brief-32-covid-19-crisis-through-migration-lens.
World Bank, 2020b: *Disability Inclusion in Nigeria: A Rapid Assessment*. Social Analysis, World Bank.
World Bank, 2020c: *Global Economic Prospects, June 2020*. World Bank Group, Washington DC, USA.
World Bank, 2020d: *The Next Generation Africa Climate Business Plan : Ramping Up Development-Centered Climate Action*. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/34098.
World Bank, 2020e: *Senegal River Basin Climate Change Resilience Development Project*. World Bank Group, World Bank, Washington DC, 8 pp. Available at: https://documents1.worldbank.org/curated/en/501211607382827776/pdf/Disclosable-Version-of-the-ISR-Senegal-River-Basin-Climate-Change-Resilience-Development-Project-P131323-Sequence-No-14.pdf.
World Bank, 2021: Debt Service Suspension and COVID-19, World Bank Group, Washington DC. Available at: https://www.worldbank.org/en/news/factsheet/2020/05/11/debt-relief-and-covid-19-coronavirus.
World Bank Group, 2016: *Climate information services providers in Kenya*. Agriculture global practice technical assistance paper, World Bank, Washington, DC, 1-46 pp. Available at: https://openknowledge.worldbank.org/handle/10986/23768.
World Travel and Tourism Council, Africa 2019 Annual Research: Key Highlights. Available at: https://www.wttc.org/economic-impact/country-analysis/country-data/.
World Travel and Tourism Council, 2019b: *The Economic Impact of Global Wildlife Tourism*. Available at: https://travesiasdigital.com/wp-content/uploads/2019/08/The-Economic-Impact-of-Global-Wildlife-Tourism-Final-19.pdf.
WorldPop, 2021: Population density, University of Southampton. Available at: https://www.worldpop.org/project/categories?id=18.
Wright, C. Y. et al., 2019: Socio-economic, infrastructural and health-related risk factors associated with adverse heat-health effects reportedly experienced during hot weather in South Africa. *Pan Afr Med J*, **34**, 40-40, doi:10.11604/pamj.2019.34.40.17569.
Wrigley-Asante, C., K. Owusu, I. S. Egyir and T. M. Owiyo, 2019: Gender dimensions of climate change adaptation practices: the experiences of smallholder crop farmers in the transition zone of Ghana. *African Geographical Review*, **38**(2), 126-139, doi:10.1080/19376812.2017.1340168.
Wu, M. et al., 2016: Vegetation–climate feedbacks modulate rainfall patterns in Africa under future climate change. *Earth System Dynamics*, **7**(3), 627-647, doi:10.5194/esd-7-627-2016.

Wuepper, D., H. Yesigat Ayenew and J. Sauer, 2018: Social Capital, Income Diversification and Climate Change Adaptation: Panel Data Evidence from Rural Ethiopia. *Journal of Agricultural Economics*, **69**(2), 458-475, doi:https://doi.org/10.1111/1477-9552.12237.
Wunder, S., J. Börner, G. Shively and M. Wyman, 2014: Safety Nets, Gap Filling and Forests: A Global-Comparative Perspective. *World Development*, **64**, S29-S42, doi:https://doi.org/10.1016/j.worlddev.2014.03.005.
WWF-SA, 2016: *Water: Facts & Futures Rethinking South Africa's Water Future*. WWF-SA, Cape Town, South Africa. Available at: https://www.wwf.org.za/our_research/publications/?25181/Water-Facts-and-Futures.
Xu, Y. et al., 2019: Preface: Groundwater in Sub-Saharan Africa. *Hydrogeology Journal*, **27**(3), 815-822, doi:10.1007/s10040-019-01977-2.
Yamana, T. K., A. Bomblies and E. A. B. Eltahir, 2016: Climate change unlikely to increase malaria burden in West Africa. *Nature Climate Change*, **6**(11), 1009-1013, doi:10.1038/nclimate3085.
Yang, Y., D. Tilman, G. Furey and C. Lehman, 2019: Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature Communications*, **10**(1), 718, doi:10.1038/s41467-019-08636-w.
Yang, Y. C. E. and S. Wi, 2018: Informing regional water-energy-food nexus with system analysis and interactive visualization – A case study in the Great Ruaha River of Tanzania. *Agricultural Water Management*, **196**, 75-86, doi:10.1016/j.agwat.2017.10.022.
Yehia, A. G., K. M. Fahmy, M. A. S. Mehany and G. G. Mohamed, 2017: Impact of extreme climate events on water supply sustainability in Egypt: case studies in Alexandria region and Upper Egypt. *Journal of Water and Climate Change*, **8**(3), 484-494, doi:10.2166/wcc.2017.111.
Yokohata, T. et al., 2019: Visualizing the Interconnections Among Climate Risks. *Earth's Future*, **7**, 85-100, doi:10.1029/2018EF000945.
Young, A. J., D. Guo, P. G. Desmet and G. F. Midgley, 2016: Biodiversity and climate change: Risks to dwarf succulents in Southern Africa. *Journal of Arid Environments*, **129**, 16-24, doi:https://doi.org/10.1016/j.jaridenv.2016.02.005.
Yu, W. et al., 2015: Projecting Future Transmission of Malaria Under Climate Change Scenarios: Challenges and Research Needs. *Critical Reviews in Environmental Science and Technology*, **45**(7), 777-811, doi:10.1080/10643389.2013.852392.
Yuan, X., L. Wang and E. F. Wood, 2018: Anthropogenic intensification of southern African flash droughts as exemplified by the 2015/16 season. *Bulletin of the American Meteorological Society*, **99**(1), S86-S90, doi:10.1175/BAMS-D-17-0077.1.
Zabel, F. et al., 2021: Large potential for crop production adaptation depends on available future varieties. *Global Change Biology*, **27**(16), 3870-3882, doi:https://doi.org/10.1111/gcb.15649.
Zacarias, D. A., 2020: Global bioclimatic suitability for the fall armyworm, Spodoptera frugiperda (Lepidoptera: Noctuidae), and potential co-occurrence with major host crops under climate change scenarios. *Climatic Change*, **161**(4), 555-566, doi:10.1007/s10584-020-02722-5.
Zahouli, J. B. Z. et al., 2017: Urbanization is a main driver for the larval ecology of Aedes mosquitoes in arbovirus-endemic settings in south-eastern Cote d'Ivoire. *PLoS Negl Trop Dis*, **11**(7), e0005751, doi:10.1371/journal.pntd.0005751.
Zambezi Watercourse Commission, 2021: *Pre-Feasibility Study for the Programme for Integrated Development and Adaptation to Climate Change in the Zambezi Watercourse (PIDACC Zambezi)*. United Nations Convention to Combat Desertification Secretariat, UNCCD, Bonn, Germany, 9 pp.
Zampaligré, N., L. H. Dossa and E. Schlecht, 2014: Climate change and variability: perception and adaptation strategies of pastoralists and agro-pastoralists across different zones of Burkina Faso. *Regional Environmental Change*, **14**(2), 769-783, doi:https://doi.org/10.1007/s10113-013-0532-5.
Zegeye, H., 2018: Climate change in Ethiopia: impacts, mitigation and adaptation. *International Journal of Research in Environmental Studies*, **5**(1), 18-35
Zengeya, T., 2017: South Africa should sort out the bad from the really bad on its invasive species list. *Water Wheel*, **16**(5), 38-39.
Zermoglio, F., S. J. Ryan and M. Swaim, 2019: *Shifting burdens: malaria risk in a hotter Africa*. Technical Report, United States Agency for International Development (USAID) and Adaptation Thought Leadership and Assessments (ATLAS). Available at: https://www.climatelinks.org/sites/default/files/asset/document/2019_USAID_ATLAS_Shifting%20Burdens.pdf.
Zevenbergen, C. et al., 2016: In the aftermath of the October 2015 Alexandria Flood Challenges of an Arab city to deal with extreme rainfall storms. *Natural Hazards*, **86**(2), 901-917, doi:10.1007/s11069-016-2724-z.
Zezza, A. and L. Tasciotti, 2010: Urban agriculture, poverty, and food security: Empirical evidence from a sample of developing countries. *Food Policy*, **35**(4), 265-273, doi:https://doi.org/10.1016/j.foodpol.2010.04.007.
Zhang, W. et al., 2019: From woody cover to woody canopies: How Sentinel-1 and Sentinel-2 data advance the mapping of woody plants in savannas. *Remote Sensing of Environment*, **234**, 111465, doi:https://doi.org/10.1016/j.rse.2019.111465.
Zhang, W. and X. Pan, 2016: Study on the demand of climate finance for developing countries based on submitted INDC. *Advances in Climate Change Research*, **7**(1-2), 99-104, doi:10.1016/j.accre.2016.05.002.

Zhao, Q. et al., 2021: Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *The Lancet Planetary Health*, **5**(7), e415-e425, doi:10.1016/S2542-5196(21)00081-4.
Zhao, T. and A. Dai, 2016: Uncertainties in historical changes and future projections of drought. Part II: model-simulated historical and future drought changes. *Climatic Change*, **144**(3), 535-548, doi:10.1007/s10584-016-1742-x.
Zheng, X. et al., 2019: A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. *Journal of Cleaner Production*, **234**, 1113-1133, doi:https://doi.org/10.1016/j.jclepro.2019.06.140.
Zhou, L. et al., 2014: Widespread decline of Congo rainforest greenness in the past decade. *Nature*, **509**(7498), 86-90, doi:10.1038/nature13265.
Zhou, X., W. Ma, A. Renwick and G. Li, 2020: Off-farm work decisions of farm couples and land transfer choices in rural China. *Applied Economics*, **52**(57), 6229-6247, doi:10.1080/00036846.2020.1788709.
Ziervogel, G., J. Enqvist, L. Metelerkamp and J. van Breda, 2021: Supporting transformative climate adaptation: community-level capacity building and knowledge co-creation in South Africa. *Climate Policy*, 1-16, doi:10.1080/14693062.2020.1863180.
Ziervogel, G. and S. Parnell, 2014: Tackling barriers to climate change adaptation in South African coastal cities. In: *Adapting to Climate Change* [Glavovic, B. C. and G. P. Smith (eds.)]. Springer, Dordrecht, pp. 57-73. ISBN 978-94-017-8630-0.
Zinngrebe, Y. et al., 2020: Agroforestry governance for operationalising the landscape approach: connecting conservation and farming actors. *Sustainability Science*, **15**(5), 1417-1434, doi:10.1007/s11625-020-00840-8.
Zinsstag, J., 2012: Convergence of EcoHealth and One Health. *Ecohealth*, **9**(4), 371-373, doi:10.1007/s10393-013-0812-z.
Zittis, G., 2018: Observed rainfall trends and precipitation uncertainty in the vicinity of the Mediterranean, Middle East and North Africa. *Theoretical and Applied Climatology*, **134**(3), 1207-1230, doi:10.1007/s00704-017-2333-0.
Zografos, C., M. C. Goulden and G. Kallis, 2014: Sources of human insecurity in the face of hydro-climatic change. *Global Environmental Change*, **29**, 327-336, doi:https://doi.org/10.1016/j.gloenvcha.2013.11.002.
Zougmoré, R. et al., 2016: Toward climate-smart agriculture in West Africa: a review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agriculture & Food Security*, **5**(1), 26, doi:10.1186/s40066-016-0075-3.
Zougmoré, R. B. et al., 2018: Facing climate variability in sub-Saharan Africa: analysis of climate-smart agriculture opportunities to manage climate-related risks. *Cahiers Agricultures (TSI)*, **27**(3), 1-9, doi:http://dx.doi.org/10.1051/cagri/2018019.
Zscheischler, J. et al., 2018: Future climate risk from compound events. *Nature Climate Change*, **8**(6), 469-477, doi:10.1038/s41558-018-0156-3.
Zubkova, M., L. Boschetti, J. T. Abatzoglou and L. Giglio, 2019: Changes in Fire Activity in Africa from 2002 to 2016 and Their Potential Drivers. *Geophysical Research Letters*, **46**(13), 7643-7653, doi:10.1029/2019GL083469.
Zuma-Netshiukhwi, G., K. Stigter and S. Walker, 2013: Use of traditional weather/climate knowledge by farmers in the South-western Free State of South Africa: Agrometeorological learning by scientists. *Atmosphere*, **4**(4), 383-410, doi:https://doi.org/10.3390/atmos4040383.
Zvobgo, L. and P. Do, 2020: COVID-19 and the call for 'Safe Hands': Challenges facing the under-resourced municipalities that lack potable water access - A case study of Chitungwiza municipality, Zimbabwe. *Water Research X*, **9**, 100074, doi:https://doi.org/10.1016/j.wroa.2020.100074.

Chapter 10: Asia

Coordinating Lead Authors: Rajib Shaw (Japan), Yong Luo (China), Tae Sung Cheong (Republic of Korea)

Lead Authors: Sharina Abdul Halim (Malaysia), Sanjay Chaturvedi (India), Masahiro Hashizume (Japan), Gregory E. Insarov (Russian Federation), Yoichi Ishikawa (Japan), Mostafa Jafari (Iran), Akio Kitoh (Japan), Juan Pulhin (Philippines), Chandni Singh (India), Kripa Vasant (India), Zhibin Zhang (China)

Contributing Authors: Rawshan Ara Begum (Bangladesh), Xi Chen (China), Rajarshi Dasgupta (India), Ronald C. Estoque (Philippines), Wanqin Guo (China), Garima Jain (India), Brian Johnson (USA), Tarek Katramiz (Syria), Pankaj Kumar (India), Xianbing Liu (China), Mythili Madhavan (India), Bijon Kumer Mitra (Bangladesh), Farah Mulyasari (Indonesia), Santosh Nepal (Nepal), Rekha Nianthi (Sri Lanka), Fereidoon Owfi (Iran), Gulsan Ara Parvin (Bangladesh), Shobha Poudel (Nepal), Atta-ur Rahman (Pakistan), Mihoko Sakurai (Japan), Amin Shaban (Lebanon), Dmitry Streletskiy (Russian Federation), Vibhas Sukhwani (India), Prabhakar S.V.R.K (India), Ai Tashiro (Japan), Tống Thị Mỹ Thi (Vietnam), Noralene Uy (Philippines) , Xinru Wan (China), Cunde Xiao (China)

Review Editors: Soojeong Myeong (Republic of Korea), Joy Jacqueline Pereira (Malaysia)

Chapter Scientist: Rajarshi Dasgupta (India), Yan Yang(China)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Observed surface air temperature has increased in the 20th century all over Asia *(high confidence[1])*. Significant warming has intensified the threat to social and economic sustainability in Asia (*medium confidence*). Rising temperature increases likelihood of the threat of heat waves across Asia, droughts in arid and semi-arid areas of West, Central and South Asia, delays and weakening of the monsoon circulation in South Asia, floods in monsoon regions in South, Southeast and East Asia, and glacier melting in the Hindu Kush Himalaya (HKH) region (*medium confidence*). {10.3.1; 10.3.3}

Asian countries are experiencing a hotter summer climate, resulting in increase of energy demand for cooling at a rapid rate, together with the population growth *(high confidence)*. Decrease in precipitation influences energy demand as well, as desalination, underground water pumping and other energy-intensive methods are increasingly used for water supply *(high confidence)*. More energy demands in summer seasons will exceed any energy savings from relatively lower heating demand due to warmer winter. Among thirteen developing countries with large energy consumption in Asia, eleven are exposed to high energy insecurity and industrial systems risk *(high confidence)*. {10.4.1}

Asian terrestrial ecosystems change is driven by global warming, precipitation and Asian monsoon alteration, permafrost thawing and extreme events like dust storms along with natural and human-related factors which are in interplay *(high confidence)*. Treeline position in North Asian mountains moves upward after 1990s, while in Himalaya treeline demonstrates a multidirectional shift, either moves upward, or does not show upslope advance or moves downward. This can be explained by site-specific complex interaction of positive effect of warming on tree growth, drought stress, change in snow precipitation, land use change, especially grazing, and other factors *(high confidence)*. The increased considerably changes in biomes in Asia are a response to warming *(medium confidence)*. Terrestrial and freshwater species, populations, and communities alter in line with climate change across Asia *(medium-to-high confidence)*. Climate change, human activity, and lightning determine the increase of wildfire severity and area burned in North Asia after 1990s *(medium confidence)*. Length of plant growth season increased in some parts of East and North Asia, while opposite trend or no change was observed in other parts *(high confidence)*. Observed biodiversity or habitat losses of animals or plants were linked to climate change in some parts of Asia *(high confidence)*. There are evidences that climate change can alter species interaction or spatial distribution of invasive species in Asia *(high confidence)*. Changes in ecosystems in Asia during the 21st century are expected to be driven by projected climatic, natural, and socioeconomic changes. Across Asia, under a range of RCPs and other scenarios rising temperature is expected to contribute to northward shift of biome boundaries and upward shift of mountain treeline *(medium confidence)*. {10.4.2}

Coastal habitats of Asia are diverse and the impacts of climate change including rising temperature, ocean acidification and sea level rise has brought negative effects to the services and the livelihood of people depending on it *(high confidence)*. The degree of bleaching of coral reefs was diverse among different presences of stress tolerant symbionts and higher thermal thresholds. The risk of irreversible loss of coral reefs, tidal marshes, seagrass meadows, plankton community and other marine and coastal ecosystems increases with global warming, especially at 2°C temperature rise or more *(high confidence)*. Mangroves in the region continue to face threats due to pollution, conversion for aquaculture, agriculture, in addition to climate based threats like SLR (Sea Level Rise) and coastal erosion. {10.4.3}

Both climatic and non-climatic drivers such as socio-economic changes have created water stress conditions in both water supply and demand in all sub-regions of Asia *(high confidence)*. These changes in space and time directly or indirectly affected water use sectors and services. By mid-21st Century, the international transboundary river basins of Amu Darya, Indus, Ganges and inter-state Sabarmati river basin in India could face severe water scarcity challenges with climate change acting as a stress multiplier *(high confidence)*. Due to global warming Asian countries could experience increase of drought conditions (5-20%) by the end of this century *(high confidence)*. {10.4.4}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

The Asia glaciers are in minor area shrinkage and mass loss during 2006-2016, resulting in the instability of water resource supply *(high confidence)*. Glaciers in Asia are the water resources of about 220 million people in the downstream areas. The glacier meltwater in southern Tibetan Plateau has increased during 1998-2007, and will further increase till 2050. The glacier is *likely*[2] to disappear by nearly 50% in High Mountain Asia and about 70% in Central and Western Asia by the end of the 21st century under the medium scenario, and more under the high scenario. The total amount and area of glacier lakes were found increased during last decade *(high confidence)*. More glacier collapses and surges were found in western Tibet. Glacier lake outburst flood (GLOF) will threaten the securities of the local and downstream communities *(high confidence)*. Snowmelt water contributed 19% of the increase change in runoff of arid region's rivers in Xinjiang, China and 10.6% of the upper Brahmaputra River during 2003-2014 *(medium confidence)*. {10.4.4; Box 10.5}

Since IPCC AR5, more studies reinforce the earlier findings on the spatial and temporal diversity of climate change impacts on food production in Asia depending on the geographic location, agro ecology, and crops grown, recognizing that there are winners and losers associated with the changing climate across scales *(high confidence)*. Most of these impacts have been associated with drought, monsoon rain, and oceanic oscillations, the frequency and severity of which have been linked with the changing climate. Climate-related risks to agriculture and food systems in Asia will progressively escalate with the changing climate, with differentiated impacts across the region *(medium confidence)*. Major projected impacts of climate change in the agriculture and food sector include decline in fisheries, aquaculture, and crop production particularly in South and Southeast Asia, reduction in livestock production in Mongolia, and changes in crop, farming systems and crop areas in almost all regions with negative implications to food security *(medium confidence)*. In India, rice production can decrease from 10% to 30% whereas maize production can decrease from 25% to 70% assuming a range of temperature increase from 1º to 4°C. Similarly, rice production in Cambodia can decrease by 45% by 2080 under high emission scenario. Occurrence of pests such as the golden apple snail (Pomacea canaliculate), associated with the predicted increase in climatically suitable habitats in 2080, threatens the top Asian rice-producing countries including China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Philippines and Japan. Increasing temperatures, changing precipitation levels, and extreme climate events like heat waves, droughts and typhoons will persist to be important vulnerability drivers that will shape agricultural productivity particularly in South Asia, Southeast Asia, and Central Asia. {10.4.5; Figure 10.6}

Asian urban areas are considered high risk locations from projected climate, extreme events, unplanned urbanisation, rapid land use change *(high confidence)* but also sites of ongoing adaptation *(medium confidence)*. Asia is home to the largest share of people living in informal settlements, with 332 million in Eastern and South-Eastern Asia, 197 million in Central and Southern Asia. By 2050, 64% of Asia's population will be urban. Coastal cities, especially in South and South East Asia are expected to see significant increase in average annual economic losses between 2005 and 2050 due to flooding, with very high losses in East Asian cities under high emission scenario *(high confidence)*. Climate change will amplify the urban heat island effect across Asian cities (especially South and East Asia) at 1.5°C and 2°C temperature rise, both substantially larger than under the present climate *(medium evidence, high agreement)*. Under high emission scenario, higher risks from extreme temperature and precipitation are projected for almost all cities *(medium confidence)*, with impacts on freshwater availability, regional food security, human health, and industrial outputs. By 2080, 940-1100 million urban dwellers in South and South East Asia could be affected by extreme heat lasting more than 30 days/year *(high confidence)*, with poorer populations affected the most. {10.4.6; Cross-Chapter Box URBAN in Chapter 6}

Climate change caused direct losses due to the damage in infrastructure, disruption in services and affected supply chains in Asia *(medium confidence)* and will increase risk to infrastructure as well as provide opportunities to invest in climate-resilient infrastructure and green jobs *(medium confidence)*.

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. This Report also uses the term 'likely range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

At higher warming, key infrastructures such as power lines, transport by roads, railways, and built infrastructure such as airports and harbours are more exposed to climate-induced extreme events, especially in coastal cities *(medium confidence)*. Evidence on urban adaptation across Asia is growing with examples on infrastructural adaptation (e.g. flood protection measures, and climate resilient highways and power infrastructure); institutional adaptation (e.g. sustainable land use planning, zoning plans); nature ecosystem-based solutions (e.g. mangrove restoration, restoring and managing urban green spaces, urban farming); technological solutions (e.g. smart cities, early warning systems); and behavioural adaptation (e.g. improved awareness and preparedness measures). However, adaptation actions tend to be in initial stages and more reactive (57% urban adaptations focus on preparatory interventions such as capacity building and 43% cities report implemented adaptation interventions) *(medium confidence)*. The degree of implementation of urban adaptation is uneven with large cities receiving more funding and priority and smaller cities and towns and peri-urban spaces seeing relatively lower adaptation action *(medium confidence)*. {10.4.6}

Climate change is increasing vector-borne and water-borne diseases, undernutrition, mental disorders and allergic diseases in Asia by increasing the hazards such as heatwaves, flooding and drought, air pollutants, in combination with more exposure and vulnerability *(high confidence)*. Sub-regional diversity in socioeconomic and demographic context (e.g., ageing, urban vs agrarian society, increasing population vs reduced birth rate, high income vs low to middle income) and geographical characteristics largely define the differential vulnerabilities and impacts within countries in Asia. Under the medium-high emissions scenario, rising temperature and extreme climate events will have an increasing impact on human health and wellbeing with varying types and magnitudes of impact across Asia *(high confidence)*. More frequent hot days and intense heat-waves will increase heat-related deaths in Asia. Increased floods and droughts will have adverse impact on food availability and prices of food resulting in increased undernourishment in South and Southeast Asia. Increases in heavy rain and temperature will increase the risk of diarrheal diseases, dengue fever and malaria in tropical and sub-tropical Asia. {10.4.7}

Increased climate variability and extreme events are already driving migration *(robust evidence, medium agreement)* and projecting longer-term climate change will increase migration flows across Asia *(medium confidence)*. One in three migrants comes from Asia and the highest ratio of outward migrants is seen from hazard-exposed Pacific countries. In 2019, Bangladesh, China, India and the Philippines each recorded more than 4 million disaster displacements. In South East and East Asia, cyclones, floods, and typhoons triggered internal displacement of 9.6 million people in 2019, almost 30% of total global displacements. {Box 10.2}

There is a small but growing literature highlighting the importance of behavioural aspects of adaptation in Asia *(high confidence)* but this is restricted primarily in agriculture and disaster risk reduction. Factors motivating adaptation actions include risk perception, perceived self-efficacy, socio-cultural norms and beliefs, previous experiences of impacts, levels of education and awareness *(high confidence)*. There is growing evidence on behavioural aspects of individual adaptation but lesser evidence on the socio-cognitive factors motivating governments and private sector actors to adapt. {10.5.3}

Climate change is already causing economic loss and damage across Asian regions and this will increase under higher warming *(medium confidence)*. Non-material losses and damages are reported to a lesser degree but this is due to underreporting and methodological issues with detection and attribution to climate change (*high confidence*). Loss and damage represents a key knowledge gap, especially in West, Central and North Asia. Insufficient literature differentiating loss and damage under future adaptation scenarios restricts a comprehensive assessment of residual damages and future loss and damage difficult. {Box 10.7}

Options such as climate smart agriculture, ecosystem-based disaster risk reduction, investing in urban blue-green infrastructure meet adaptation, mitigation, and sustainable development goals simultaneously, presenting opportunities for climate-resilient development (CRD) pathways in Asia *(high confidence)*. Climate risks, vulnerability and adaptation measures need to be factored into decision-making across all levels of governance (*high confidence*). To help achieve this, there is a need to advance the current understanding of climate impacts across sectors and spatiotemporal scales and improve on the current strategies in planning and budget allocation. More accurate forecasting of extreme events, risk awareness and prioritizing individual and collective decision choices are also need to be enhanced *(high confidence)*.

Options for Asian countries are transforming risks of climate change into opportunities for the advancement of projects in the energy sector – including promoting investment in non-fossil energies, securing local natural gas resources, enhancing water harvesting, adopting green building technologies, and encouraging multi-stakeholder partnerships. However, there are significant barriers to CRD such as fragmented, reactive governance; inadequate evidence on which actions to prioritise and how to sequence them; and finance deficits. Some Asia countries and regions offer solutions to overcome these barriers: Through use of advanced technologies (in-situ observation and remote sensing, a variety of new sensor technologies, citizen science, artificial intelligence, and machine learning tools); regional partnerships and learning; improved forecasting capabilities; and better risk awareness (*high confidence*). {10.5, 10.6}

10.1 Introduction

Asia is defined here as the land and territories of 51 countries/regions (**Figure 10.1**). It can be broadly divided into six sub-regions based on geographical position and coastal peripheries (IPCC, 2014b). These are, in alphabetical order, Central Asia (five countries), East Asia (seven countries/regions), North Asia (two countries), South Asia (eight countries), Southeast Asia (12 countries), and West Asia (17 countries). The population of Asia was reported to be about 4463 million in 2016, which is about 60% of the world population with an estimated density of 100 people per square kilometer (UNDESA, 2017). The highest life expectancy at birth is 84 (Japan) and the lowest is 52 (Afghanistan) (CIA, 2017). The gross domestic product (GDP) per capita ranged from US$587 (Afghanistan) to US$81,585 (Macao, PRC) (IMF, 2018).

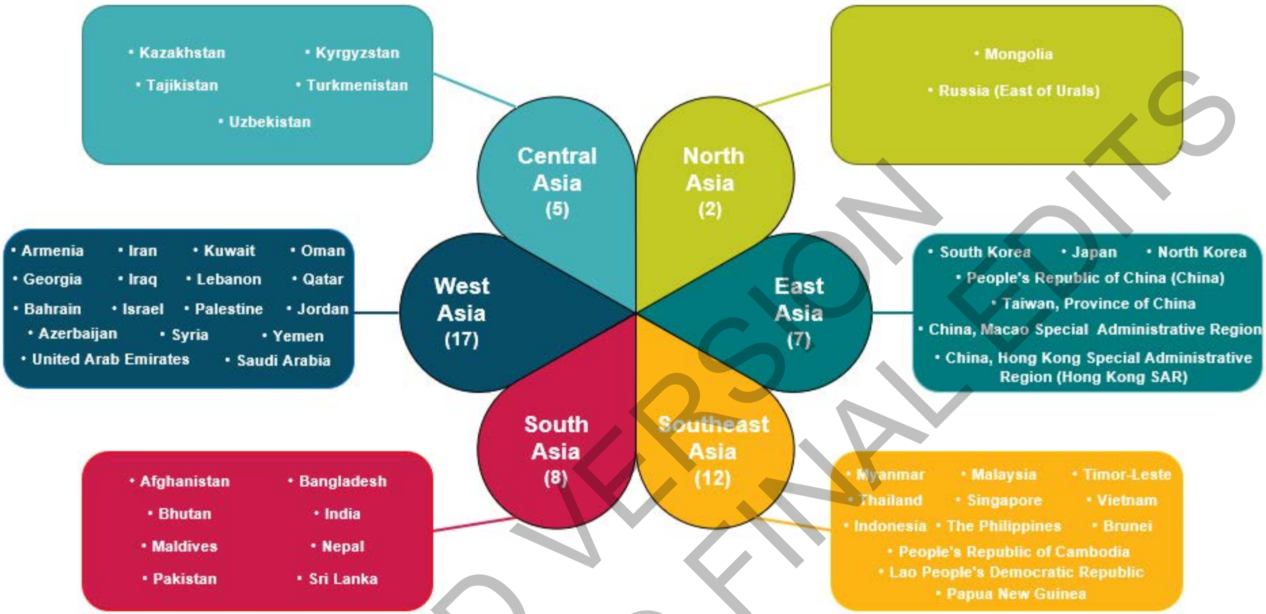


Figure 10.1: Countries and regions in Asia

[START BOX 10.1 HERE]

Box 10.1: What is New on Asia in AR6?

- Adaptation in energy sector is becoming increasingly crucial in the Asian region, which has been assessed in a new sub-section.
- Adaptation technology and innovations are also of high importance for the region. Classification of adaptation technology and its use in different systems are assessed.
- On the governance side, the nexus approach among several systems like food, energy, water is focused, and its importance is assessed.
- New concepts on decentralised and self-reliant society, such as the Circulating and Ecological Sphere (CES) are emerging for integrated adaptive governance.
- As a part of sustainable development pathway, interlinkages of climate change adaptation and disaster risk reduction is highlighted.

[END BOX 10.1 HERE]

10.2 Major Conclusions from Previous Assessments

As the most populous continent, Asia is faced with a unique set of challenges that vary across its climatic zones.

- The most perceptible change in climatic trends is observable in the increasing surface air temperature and rise in night time temperature, particularly during the season of winter. This is accompanied by monsoon rainfall variability, which is observable inter-seasonally, inter-annually and spatially.
- There is increasing evidence of an upward trend in the intensity and frequency of extreme weather events in Asia.
- The predictions for future climatic trends suggest an increase in warming along the higher latitudes of North Asia.
- Projections show that agricultural and food security will be impacted substantially, particularly in the area of cereal production by the end of the 21st century.
- Malnutrition among the poor and marginalised sections of the population in Asia remains a major concern that is further rendered complex by climate change.
- Projections of an increase in the incidence of pests and diseases impacts directly on the food security and health of vulnerable populations.
- Erosion will occur simultaneously with sea level rise; the projected rise could lead to large-scale flooding in low-lying areas, particularly South, Southeast and East Asia.
- The erosion of the major deltas of Asia may take place through a rise in sea levels, an increased frequency of extreme weather events, and the excessive withdrawal of groundwater.
- The priority areas for Asia include an enhancement of capabilities to collect social and biophysical data, information sharing, sectoral interactions, a mainstreaming of science and the identification of critical climate thresholds across regions and sectors.

Drawing upon a greater number of studies made possible by greater use of advanced research tools such as remote sensing as well as meticulous modelling of impacts, the Fifth Assessment Report could significantly expand its coverage of pertinent issues (IPCC, 2014c). For example, the discussion on the Himalayas was expanded to cover observed and projected impacts of climate change on tourism (see WGII AR5 Section 10.6.2); livelihood assets such as water and food (WGII AR5 Sections 9.3.3.1, 13.3.1.1, 18.5.3, 19.6.3); poverty (WGII AR5 Section 13.3.2.3); culture (WGII AR5 Section 12.3.2); flood risks (WGII AR5 Sections 18.3.1.1, 24.2.1); health risks (WGII AR5 Section 24.4.6.2); and ecosystems (WGII AR5 Section 24.4.2.2)(IPCC, 2014c).

- Over the past century, and across most of Asia, warming trends and increasing temperature extremes have been observed.
- Adequate supplies of freshwater resources are under considerable threat due to both the existing pattern of socio-economic growth and climate change.
- With a number of regions already close to the heat stress limits, most models, using a range of General Circulation Models (GCMs) and Special Report on Emission Scenarios (SRES) scenarios, suggest that higher temperatures will lead to shorter growing periods of rice cultivation resulting in lower rice yields.
- Climate change impacts have led to visible shifts on the terrestrial systems in many parts of Asia in the phenologies, growth rates, and the distributions of plant species.
- Coastal and marine systems in Asia are under increasing stress from both climatic and non-climatic drivers and mean sea level rise will contribute to upward trends in extreme coastal high water levels (WGI AR5 Section 3.7.6).(IPCC, 2014c) . Mangroves, salt marshes, and seagrass beds may decline unless they can move inland, while coastal freshwater swamps and marshes will be vulnerable to saltwater intrusion with rising sea levels. Damage to coral reefs will increase during the 21st century because of both warming and ocean acidification.
- Climate change will further compound multiple stresses caused due to rapid urbanisation, industrialisation, and economic growth. Development of sustainable cities in Asia with fewer fossil fuel-driven vehicles and with more trees and greenery would have a number of co-benefits, including improved public health.
- Extreme climate events will have an increasing impact on human health, security, livelihoods, and poverty, with the type and magnitude of impact varying across Asia.
- Local Knowledge and Indigenous Knowledge play an important role in the formulation of adaptation governance and related strategies (IPCC, 2007), and best quality, locality specific knowledge can help address serious lack of education on climate change and uncertainties surrounding quality, salience, credibility and legitimacy of available knowledge base.

Knowledge/research gaps identified in AR5 include, but are not limited to, an insufficient understanding of impacts, vulnerability and adaptation in urban settlements, under-researched linkages between local livelihoods, ecosystem functions, and land resources and a poor understanding of the impacts of projected climate changes on the vegetation of the lowland tropics.

10.3 Regional and Sub-regional Characteristics

10.3.1 Climatic Characteristics

Climate characteristics in Asia is diverse covering all climate zones from tropical to polar climate, including mountain climate. Monsoonal winds and associated precipitation are dominant in South, Southeast and East Asia. Annual mean surface air temperature averaged over the sub-region ranges from coldest North Asia (–3°C) to warmest Southeast Asia (25°C) based on JRA-55 (Kobayashi et al., 2015) climatology for 1981–2010. Most of North Asia and higher altitude is underlain by permafrost. West Asia is the driest and Southeast Asia is the wettest, with the annual precipitation averaged over the sub-region ranging about 10 times from 220 mm in West Asia to 2570 mm in Southeast Asia based on GPCC (Schamm et al., 2014) climatology for 1981–2010. Indonesia in Southeast Asia has the longest coastline in the world, causing this area (maritime continent) the wettest region (Yamanaka et al., 2018). The Hindu Kush-Himalaya (HKH) region is a biodiversity hotspot (Wester et al., 2019), and also has significant impacts on the Asian climate because of their orographic and thermodynamic effects (Wu et al., 2012).

Extreme precipitation events and related flooding occur frequently in monsoon Asia, i.e., Southeast, South and East Asia (Mori et al., 2021b). Tropical cyclones also affect East and South Asia with torrential rain, strong winds and storm surge. Floods and other weather-related hazards are causing thousands of casualty and millions of affected people each year (CRED/UNISDR, 2019). On the other hand, droughts have long-lasting effects on agriculture and livestock threatening water security in West Asia, Central Asia and northern China (Ranasinghe et al., 2021; Seneviratne et al., 2021). Adaptation to such extreme events was limited in Asia.

10.3.1.1 Observed climate change

Observations of past and current climate in Asia are assessed in IPCC WGI AR6 (IPCC, 2021a). Examples of observed impacts in Asia with attributed climatic impact-drivers (CIDs) are shown in **Figure 10.2.** Surface temperature has increased in the past century all over Asia (*very high confidence*). Elevation dependent warming, i.e. that the warming rate is different across elevation bands, is observed in high mountain Asia (*medium confidence*) (Krishnan et al., 2019) (Hock et al., 2019). While there is an overall trend of decreasing glacier mass in high mountain Asia, there are some regional differences and even areas with a positive mass balance due to increased precipitation (Wester et al., 2019). Rising temperature resulted in an increasing trend of growing season length. Number of hot days and warm nights continue to increase in the whole Asia (*high confidence*), while cold days and nights decrease except in the southern part of Siberia (Gutiérrez et al., 2021). Large increases in temperature extremes are observed in West and Central Asia (*high confidence*). Temperature increase is causing strong, more frequent, and longer heat waves in South and East Asia. East China 2013 heat waves case is such an example (Xia et al., 2016). Extreme warmth was observed in Asia in 2016 and 2018, for which event attribution study revealed that this would not have been possible without anthropogenic global warming (*medium confidence*) (Imada et al., 2018; Imada et al., 2019).

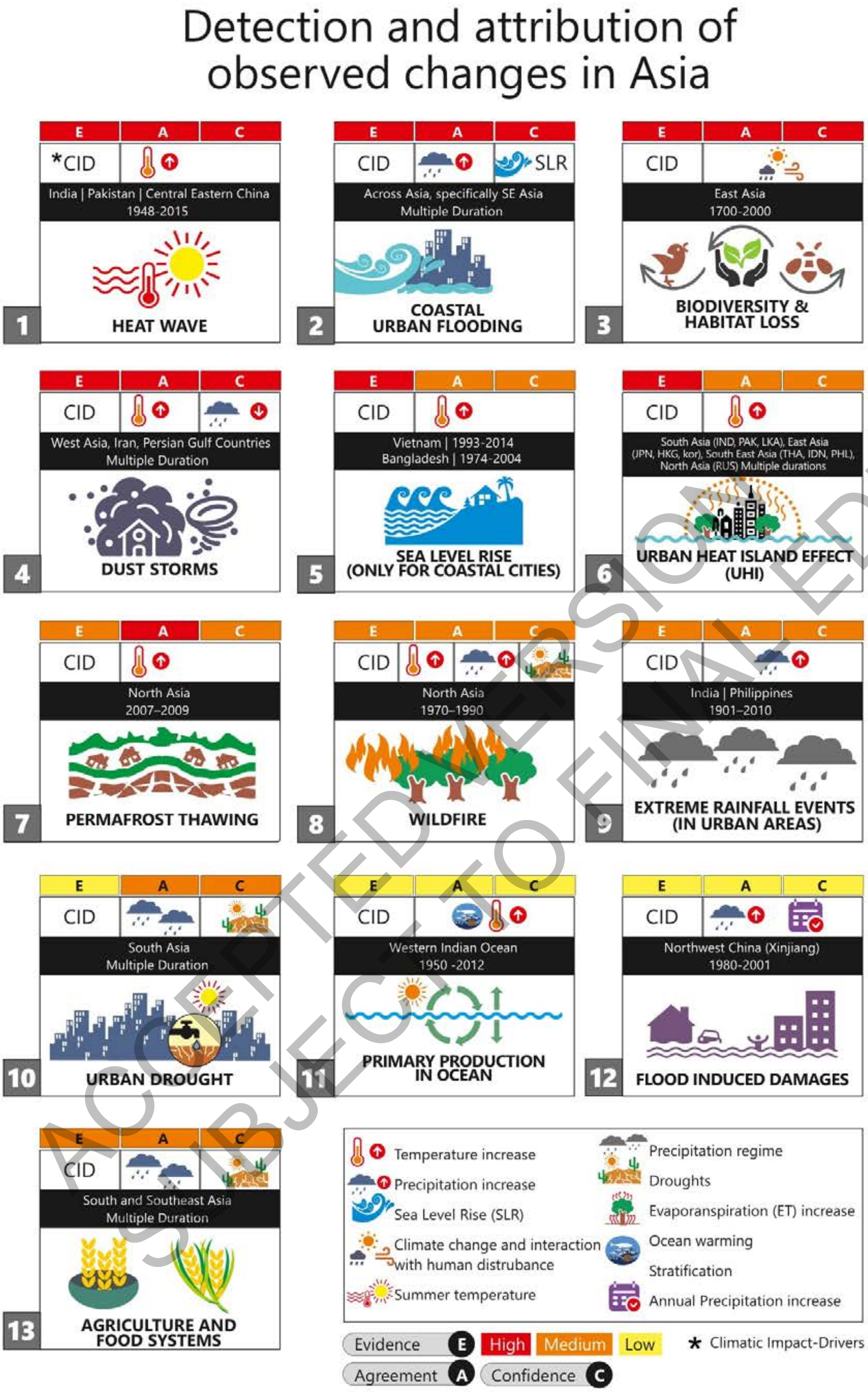


Figure 10.2: Detection and attribution of observed changes in Asia; Levels of Evidence (E), Agreement (A) and Confidence (C) are ranked by High (H), Medium (M) or Low (L). CID: Climatic Impact-Driver. References: (1) Heat waves, (Ross et al., 2018); (Mishra et al., 2015); (Rohini et al., 2016); (Panda et al., 2017); (Chen and Li, 2017). (2) Coastal urban flooding, (Dulal, 2019). (3) Biodiversity & habitat loss, (Wan et al., 2019). (4) Dust storms, (Alizadeh-Choobari et al., 2016); (Nabavi et al., 2016); (Yu et al., 2015); (Kelley et al., 2015). (5) Sea level rise (only for coastal cities),(Hens et al., 2018) (Brammer, 2014); (Shahid et al., 2016). (6) Urban heat island effect (UHI), (Kotharkar et al., 2018); (Choi et al.,

2014); (Estoque et al., 2017); (Santamouris, 2015); (Li et al., 2018a); (Ranagalage et al., 2017); (Hong et al., 2019c). (7) Permafrost thawing, (Biskaborn et al., 2019); (Shiklomanov et al., 2017a). (8) Wildfire, (Brazhnik et al., 2017); (Schaphoff et al., 2016). (9) Extreme rainfall events (in urban areas), (Ali et al., 2014). (10) Urban drought, (Pervin et al., 2020), (Gu et al., 2015). (11) Primary production in ocean, (Roxy et al., 2016). (12) Flood induced damages, (Fengqing et al., 2005). (13) Agriculture and food systems(Heino et al., 2018) (Prabnakorn et al., 2018)

There are considerable regional differences in observed annual precipitation trend (*medium confidence*). Observations show a decreasing trend of the South Asian summer monsoon precipitation during the second half of the 20th century (*high confidence*) (Douville et al., 2021). No clear trend in precipitation is observed in high mountain Asia (Nepal and Shrestha, 2015), while continuous shift toward a drier condition was observed since early 1980s in spring over the central Himalaya (Panthi et al., 2017). Increase in heavy precipitation occurred recently in South Asia (*high confidence*), and in Southeast and East Asia (*medium confidence*) (Seneviratne et al., 2021). In Japan, there is no significant long-term trend in the annual precipitation, while significant increasing trend is observed in the annual number of events of heavy precipitation (daily precipitation ≥ 400 mm) and intense precipitation (hourly precipitation ≥ 50 mm) (JMA, 2018). Decreased precipitation and increased evapotranspiration are observed in West and Central Asia, contributing to drought conditions and decreased surface runoff.

Annual surface wind speeds are decreasing in Asia since 1950s (*high confidence*) (Ranasinghe et al., 2021). The observed changes in the frequency of sand and dust storms vary from region to region in Asia (*medium confidence)*. The frequency and intensity of dust storms are increasing in some regions of Asia, such as West and Central Asia, due to land use and climate change (Mirzabaev et al., 2019). Significant decreasing trends of dust storms are observed in some part of Inner Mongolia and over the Tibetan Plateau (Ranasinghe et al., 2021). In contrast, West Asia has witnessed more frequent and intensified dust storms affecting Iran and Persian Gulf countries in the past decades (*medium confidence*) (Nabavi et al., 2016).

There is no significant long-term trend during 1951–2017 in the numbers of tropical cyclones (TCs) with maximum winds of 34 kt or higher forming in the western North Pacific and the South China Sea (*medium confidence*). There are substantial interdecadal variations in basin-wide TC frequency and intensity in the western North Pacific (Lee et al., 2020a). Numbers of strong TCs (maximum winds of 64 kt or higher) also show no discernible trend since 1977 when complete wind speed data near TC center becomes available (JMA, 2018). For TCs in the Philippines area, there are no significant trends in the annual number of TCs during 1951–2013 (Cinco et al., 2016). Their analysis showed that the Philippines have been affected by fewer TCs above 64 kt, but affected more by extreme TCs (above 81 kt). There is a significant northwestward shift in TC tracks since the 1980s, and a detectable poleward shift since the 1940s in the average latitude where TCs reach their peak intensity in the western North Pacific (Lee et al., 2020a) (*medium confidence*).

The oceans have warmed unabated since 2004, continuing the multi-decadal ocean warming trends (Bindoff et al., 2019). The report also summarised that there is increased agreement between coupled model simulations of anthropogenic climate change and observations of changes in ocean heat content (*high confidence*). Observed sea level rise around Asia over 1900–2018 is similar to the global mean sea level change of 1.7 mm/yr, but for the period 1993–2018, the sea level rise rate increased to 3.65 mm/yr in the Indo-Pacific region and 3.53 m/yr in the Northwest Pacific, compared to global value of 3.25 mm/yr (Ranasinghe et al., 2021). The extreme sea level has risen since 1980s along the coast of China (Feng et al., 2018b).

Ocean acidification continues with surface seawater pH values have shown a clear decrease by 0.01–0.09 from 1981–2011 along the Pacific coasts of Asia (*high confidence*) (Lauvset et al., 2015). For the western north Pacific along the 137°E line, the trend varies from –0.013 at 3°N to –0.021 at 30°N per decade during 1985–2017 (JMA, 2018). Ocean interior (about 150–800 m) pH also shows a decreasing trend with higher rates in the northern than the southern subtropics, which may be due to greater loading of atmospheric CO_2 in the former (JMA, 2018).

10.3.1.2 Projected climate change

Rising temperature increases likelihood of the threat of heat waves across Asia, droughts in arid and semi-arid areas of West, Central and South Asia, floods in monsoon regions in South, Southeast and East Asia, and glacier melting in the HKH region (*high confidence*) (Doblas-Reyes et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021). Confidence in direction of projected change in climatic impact-drivers in Asia are summarised in Table 12.4 of WGI AR6 Chapter 12 (Ranasinghe et al., 2021).

Projections of future annual mean surface air temperature change in Asia are qualitatively similar to those in the previous assessments with larger warming in higher latitudes, i.e. North Asia (*high confidence*) (Gutiérrez et al., 2021). Projected surface air temperature changes in the Tibetan Plateau, Central Asia and West Asia are also large (*high confidence*) (Gutiérrez et al., 2021). Highest levels of warming for extreme hot days are expected to occur in West and Central Asia with increased dryness of land (*high confidence*) (SR1.5). Over mountainous regions, elevation dependent warming will continue (*medium confidence*) (Hock et al., 2019). Glacier will generally shrink, but rates vary among region to region (*high confidence*) (Wester et al., 2019). Thawing permafrost presents a problem in northern areas of Asia, particularly Siberia (Parazoo et al., 2018). Temperature rise will be strongest in winter in most regions, while it will be strongest in summer in the northern part of West Asia and some parts of South Asia where desert climate prevails (*high confidence*) (Gutiérrez et al., 2021). The wet-bulb globe temperature (WBGT), which is a measure of heat stress, is *likely* to approach critical health thresholds in West and South Asia under the RCP4.5 scenario, and in some other regions such as East Asia under the RCP8.5 scenario (*high confidence*) (Lee et al., 2021a) (Seneviratne et al., 2021). Occurrence of extreme heat waves *very likely* increases in Asia. Projections show that a sizeable part of South Asia will experience heat stress conditions in the future (*high confidence*). It is *virtually certain* that cold days and nights become fewer (Ranasinghe et al., 2021).

Projections of future annual precipitation change are qualitatively similar to those in the previous SREX and AR5 assessments (IPCC, 2021a). *Very likely* large percent increase in annual precipitation is projected in South Asia and North Asia (*high confidence*) (Lee et al., 2021a) (Douville et al., 2021). Precipitation is projected to decrease over the north-western part of the Arabian Peninsula and increase over its southern part (*medium confidence*) (Gutiérrez et al., 2021). Both heavy precipitation and intense precipitation are projected to intensify and become more frequent in South, Southeast and East Asia (*high confidence*) (Seneviratne et al., 2021). There will be a large increase in flood frequency in these monsoon regions (Oppenheimer et al., 2019). This would lead to continuation to cause loss of lives and infrastructure without further mitigation efforts. SR1.5 assessed higher risk from heavy precipitation events at 2°C compared to 1.5°C of global warming in East Asia. A large ensemble modelling study shows that future warming is expected to further increase winter precipitation and extreme weather events such as rain-on-snow, result in the increase in extreme runoff in Japan (*low confidence*) (Ohba and Kawase, 2020). The earlier snowmelt will affect energy supply by hydropower.

Monsoon land precipitation *likely* increases in East, Southeast, and South Asia mainly due to increasing moisture convergence by elevated temperature (*high confidence*). However, there is *low confidence* in the magnitude and detailed spatial patterns of precipitation changes at sub-regional scale in East Asia (Doblas-Reyes et al., 2021). Increasing land-sea thermal contrast and resultant lower tropospheric circulation changes, together with increasing moisture, are considered to intensify the South Asian summer monsoon precipitation (*medium confidence*). Anthropogenic aerosols greatly modify sub-regional precipitation changes and their spatial and temporal changes are uncertain (Douville et al., 2021). Monsoonal winds will generally become weaker in future warming world with different magnitude across regions (*medium confidence*). Future changes in sand and dust storms are uncertain.

The global proportion of very intense TCs (category 4-5) will increase under higher levels of global warming (*medium-to-high confidence*). Mean global TC precipitation rate will increase (*medium-to-high confidence*). Models suggest a reduction of TC frequency, but an increase in the proportion of very intense TCs over the western North Pacific in the future. However, some individual studies project an increase in western North Pacific TC frequency (*medium confidence*) (Cha et al., 2020). In the western North Pacific, some models project a poleward expansion of the latitude of maximum TC intensity, leading to a future increase of intense TC frequency south of Japan (*medium confidence*) (Yoshida et al., 2017).

Relative sea level rise associated with climate change in Asia will range from 0.3 m–0.5 m in SSP1-2.6 to 0.7 m–0.8 m in SSP5-8.5 for 2081–2100 relative to 1995–2014 (Ranasinghe et al., 2021). In coastal region, evaluation of sea level rise is necessary in regional scale to assess the impacts on coastal sector. Liu et al. (2016c) investigates the regional scale sea level rise using dynamical downscaling from the three global climate models in western North Pacific. In their projection in the case following RCP 8.5 scenario, the regional sea level rises along Honshu Island in Japan during 2081–2100 relative to 1981–2000 are 6–25 cm higher than the global mean sea level rise due to the dynamical response of the ocean circulation. For the impact assessment of coastal hazard, the total sea level rise including extreme events due to the storm surge and high ocean wave, which are influenced by the changes of TCs (Seneviratne et al., 2021). Mori and Takemi (2016) summarised the characteristics of TCs in the western Pacific in the past and in the future, and the extreme value of significant wave height increase in several regions. There is considerable increase of the return levels along the China coast under 2.0°C warming compared with that under 1.5°C warming scenario (Feng et al., 2018b).

Ocean acidification will continue over the 21st century (*virtually certain*) (SROCC). Projected decrease in global surface ocean pH from 1986–2005 to 2081–2100 is about 0.145 under RCP4.5 (Lee et al., 2021a).

Diverse and complex climatic characteristics in Asia make the climate models' ability limited in reasonably simulating the current climate and projecting its future change (Gutiérrez et al., 2021).

10.3.2 Ecological Characteristics

Ecosystems in Asia are characterised by a variety of climate and topographic effects and can be divided into several distinct areas (Figure 10.3), and valuable ecosystem services provide vital support for human well-being and sustainable development (IPBES, 2018).

Boreal forests and tundra dominate in North Asia, deserts and xeric shrub-lands in Central and West Asia, and alpine ecosystems in the Hindu Kush-Himalaya, Tian Shan, Altai-Sayan, Ural and Caucasus mountain regions. Human-transformed landscapes occupies most parts of other sub-regions. Remained natural ecosystems in East Asia are temperate broadleaf and mixed forests and subtropical evergreen forests, and deserts and grasslands in the west. South Asia has tropical forests and semi-deserts in the northwest. Southeast Asia is covered mainly by tropical forests (Figure 10.3).

Ocean and coastal region in Asia have various ecological characteristics, such as high productivity in arctic/subpolar region, large biodiversity in tropical region, and unique system in marginal seas. In the atlas of WGI AR6, the ocean biomes in Asia is divided into 6 sub-regions (WGI AR6 Figure Atlas.4) (Gutiérrez et al., 2021). For the coastal region, the concept of the large marine ecosystem (e.g., (Sherman, 1994) provides the biological characteristics each marginal/semi-enclosed region and the regions characterised by boundary current system.

Biodiversity and ecosystem services play a critical role in socioeconomic development as well as the cultural and spiritual fulfilment of the population in the Asia (IPBES, 2018). For example, species richness reaches it maximum in the "coral triangle" of South-East Asia (central Philippines and central Indonesia) (IPCA, 2017) and the extent of mangrove forests in Asia is about 38.7% of the global total (Bunting et al., 2018). These coastal ecosystems provide multiple ecosystem services related to food production by fisheries/aquaculture, carbon sequestration, coastal protection, and tourism/Recreation (Ruckelshaus et al., 2013).

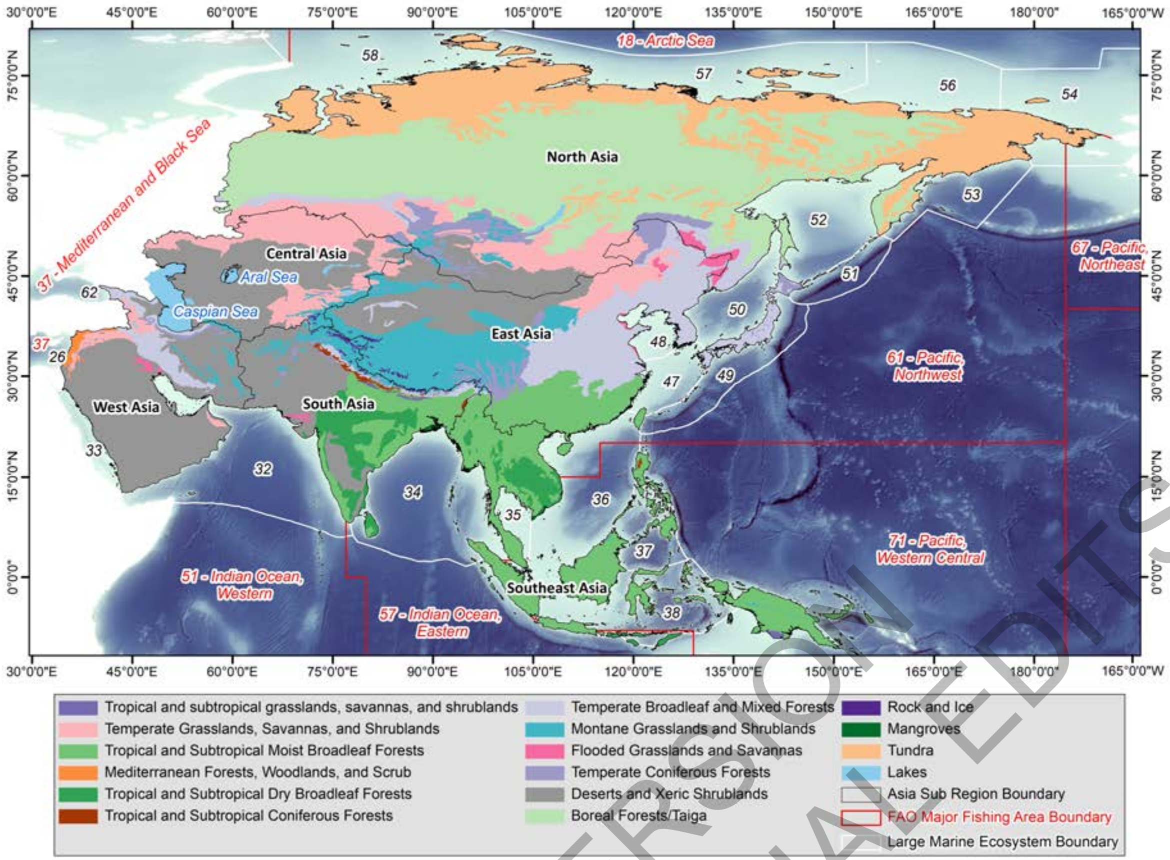


Figure 10.3: Terrestrial Ecoregions, Large Marine Ecosystems and Major Fishing areas of Asia. Large Marine Ecosystems (LMEs) of Asia: 26- Mediterranean Sea, 32- Arabian Sea, 33- Red Sea, 34- Bay of Bengal, 35- Gulf of Thailand, 36- South China Sea, 37- Sulu-Celebes Sea, 38- Indonesian Sea, 47- East China Sea, 48- Yellow Sea, 49- Kuroshio Current, 50- Sea of Japan, 51- Oyashio Current, 52- Sea of Okhotsk, 53- West Bering Sea, 54- Northern Bering - Chukchi Seas, 56- East Siberian Sea, 57- Laptev Sea, 58-Kara Sea, 62- Black Sea, developed after (Olson et al., 2001) (NOAA, 2010), (FAO, 2019)and made with Nature Earth. **Note**: The map is for illustrative purpose only. The boundaries and names shown and the designations used on this map are for the ecoregions and do not imply official endorsement or acceptance by the United Nations.

10.3.3 Demographics / Socio-economic Characteristics

In these six sub-regions of Asia, nature and biophysical impacts of climate change are observed in three climate change hot spots where strong climate signals and high concentrations of vulnerable people are present, namely in semi-arid, glacial fed river basins and mega deltas (Szabo et al., 2016b) (De Souza et al., 2015) (Kilroy, 2015). The impacts of global climate also have profound social implications, threatening human health and well-being, destabilising assets, coping capacities and response infrastructures and substantially increasing the number of socially, economically and psychologically vulnerable individuals and communities (Ford et al., 2015).

Vulnerability to climate change varies by geography and by the economic circumstances of the exposed population (Sovacool et al., 2017). The concentration of population growth in less developed regions means that an increasing number of people live in countries with the least ability to adapt to climate change (Auffhammer and Kahn, 2018). Bangladesh with 163 million people, an example, is one of the most vulnerable countries in the world to climate risks and natural hazards, faces severe floods, cyclones, droughts, heat waves and storm surges on a regular basis (Dastagir, 2015; Hossain et al., 2018; Roy and Haider, 2019).

Differential human vulnerability to environmental hazards results from a range of social, economic, historical, and political factors, all of which operate at multiple scales (Thomas, 2019) (De Souza et al., 2015). Climate change is expected to have serious impacts for people living within these hot spot areas, as observed from loss of food crop yields to disasters such as floods, fluctuations in seasonal water availability, or other systemic effects (De Souza et al., 2015). For instance in South Asia, extreme climatic conditions are threatening food security,thus agro-based economies like India and Pakistan are the most vulnerable to climate change in this regard (Mendelsohn, 2014; Ahmad, 2015; Kirby et al., 2016; Ali et al., 2017).

A broad-based understanding of gendered vulnerability as emerging from poverty and social discrimination as well social cultural practices in different political, geographical and historical settings, apart from climatic variability and environmental/natural risks is central to understanding people's capacities to cope with and adapt to change (Morchain et al., 2015; Yadav and Lal, 2018); (Rao et al., 2019). Studies highlight the fact that disasters do not affect people equally, mostly findings show that insufficient disaster education, inadequate protection measures, and powerful cultural issues, both pre- and post-disaster, increase women's vulnerability during and after disasters (Isik et al., 2015; Reyes and Lu, 2016; Hamidazada et al., 2019) . In particular, cultural issues play a role after disasters by affecting women's security, access to disaster aid, and health care (Raju, 2019). There must be more nuanced understanding and examination of gender, as well as poor, disadvantaged and vulnerable groups in vulnerability and risk assessments (Reyes and Lu, 2016; Reyer, 2017; Xenarios et al., 2019).

Based from the *World Economic Situation and Prospects as of mid-2019 Report*, the region has an estimated 400 million people living in extreme poverty below the threshold of $1.90 a day. At the higher international poverty line of $3.20 a day, the number of poor rises to 1.2 billion, accounting for more than a quarter of the region's total population (Holland, 2019). Beyond monetary measures, indicators of multidimensional aspects of poverty, most notably in Southern Asia indicate a large share of the population still lacks access to basic infrastructure and services (Bank, 2017b).

For instance, South Asia illustrates that on average it could lose nearly 2% of its GDP by 2050, rising to a loss of nearly 9% by 2100 under BAU (Business-as-Usual) scenario (Ahmed and Suphachalasai, 2014). The relationship between economic outcomes and cross-sectional climate variation is confounded by regional heterogeneity, including historical effects of settlement and colonisation (Dell et al., 2014; Newell et al., 2018). Climate change vulnerability may also depend on sufficient employment opportunities in the risk-prone areas, land holding size, gender, education level and family and community size, as observed in Nepal, Thailand, Vietnam (Baul and McDonald, 2015; Lebel L., 2015; Phuong et al., 2018a).

As poor households are constrained in their ability to receive nutrition, schooling and healthcare for their children, this is greatly dampening progress on human capital development and productivity growth, both of which are critical imperatives for sustainable development (Carleton and Hsiang, 2016; Schlenker and Auffhammer, 2018). Studies also have shown negative impacts of climate change on several essential components of people's livelihoods and well-being, such as water supply, food production, human health, availability of land and ecosystems (Roy and Haider, 2019) (Arnell et al., 2016);(Alauddin and Rahman, 2013).
Major population trends of urbanisation and urban area expansion are forecast to take place in Asia region has mentioned demographic change will make humanity more vulnerable to climate change particularly in places with high poverty rates and potentially prone to systemic disruptions in the food system (Puma et al., 2015; d'Amour et al., 2016; d'Amour et al., 2017).

The urban population of the world has grown rapidly from 751 million in 1950 to 4.2 billion in 2018. Asia, despite its relatively lower level of urbanisation, is home to 54% of the world's urban population (United Nations, 2019). Some cities have experienced population decline in recent years. Most of these are located in the low-fertility countries of Asia, where overall population sizes are stagnant or declining, as observed in a few cities in Japan and the Republic of Korea (for example, Nagasaki and Busan) have experienced population decline between 2000 and 2018 (United Nations, 2019). By 2030, the world is projected to have 43 megacities with more than 10 million inhabitants, most of them in developing regions. However, some of the fastest-growing urban agglomerations are cities with fewer than 1 million inhabitants, many of them located in Asia and Africa (United Nations, 2019). Challenges with water supply in many cases exist since decades (Dasgupta, 2015). Climate change increases these challenges (Hoque et al., 2016). As more people inhabit urban areas, the number of people vulnerable to heat stress is thus *likely* to rise, a problem that will be compounded by rising temperatures due to climate change (Acharya et al., 2018). Compared to rural areas, hot temperature risk is even higher in urban regions (Luo, 2018a; Ye, 2018; Setiawati Martiwi Diah, 2021).

The impact of heat in rural areas has been a blind spot so far, particularly for farmers and outdoor labourers who are increasingly exposed to high outdoor temperatures due to increase intensity in agriculture combined with changes in working hours (Tasgaonkar, 2018).

Farmers as a group have shown an increasing number of females over the years due to out-migration of male members in urban areas for employment, in which putting women at more severe risk in the context of climate variability (Singh, 2019). Women are required to acquire new capacities to manage new challenges, including risks from climate change, through capacity-building interventions to strengthen autonomous adaptation measures (Banerjee et al., 2019; James, 2019; Mishra, 2019). However, the overlapping crises of climate change and global public health crisis of COVID-19 represents a major challenge to gender equality and sustainable development (Katherine Brickell, 2020; Sultana, 2021).

For vulnerable populations, such as Indigenous Peoples, older and low-income groups, women, children, people with disabilities, and minorities, the health effects of climate change-related extreme weather events can be especially devastating (McGill, 2016). Such populations may be more susceptible to disease, have pre-existing health conditions or live in areas that do not promote good health or well-being, for instance loss of income and food supply shortages could lead children in rural households to nutritional deprivations that can have both immediate and lifelong impacts (Gleick, 2014; UNICEF, 2015). Children, already susceptible to age-related insecurities, face additional destabilising insecurities from questions about how they will cope with future climate change (Hansen et al., 2013).

[START BOX 10.2 HERE]

Box 10.2: Migration and Displacement in Asia

Migration and displacement in Asia: Migration is a key livelihood strategy across Asia and is driven by multiple factors such as socio-economic changes, increasing climate variability and disaster incidence, and changing aspirations. Displacement denotes a more involuntary movement in reaction to climatic or non-climatic factors. There is *robust evidence, medium agreement* that increased climate variability and extreme events are already driving migration (Gemenne et al., 2015; IDMC, 2020) (Rigaud et al., 2018; IDMC, 2019; Maharjan et al., 2020) (Jacobson et al., 2019; Siddiqui et al., 2019) and *medium evidence, medium agreement* projecting longer-term climate change will increase migration flows across Asia (Abubakar et al., 2018; Rigaud et al., 2018; Hauer et al., 2020; Bell et al., 2021).

Detection and attribution – does climate change drive migration? Ascertaining the role of climate change in migration is difficult and contested (see Cross-Chapter Box MIGRATE in Chapter 7 and RKR H in Chapter 16), with observation-based studies either linking extreme event incidence, weather anomalies, and environmental change with migration numbers or drivers (McLeman, 2014; Singh et al., 2019a; Kaczan and Orgill-Meyer, 2020) and projection studies looking at particular risks such as sea level rise or drought by linking increasing warming (often through RCPs) and population growth. Despite this methodological disagreement on detection and attribution of migration due to climate change, there is *medium evidence, medium agreement* that higher warming and associated changes in frequency and intensity of slow- and rapid-onset events are expected to increase forced migration in the future, especially under less optimistic development pathways (Dasgupta et al., 2014a; Davis et al., 2018; Rigaud et al., 2018; Hauer et al., 2020) but its role is smaller than non-climatic socio-economic drivers of migration (Wodon et al., 2014; Adger et al., 2021).

- *Current migration and displacement*: One in three migrants comes from Asia and the highest ratio of outward migrants is seen from hazard-exposed Pacific countries (Ober, 2019). In 2019, approximately 1,900 disasters triggered 24.9 million new displacements across 140 countries; in particular, Bangladesh, China, India and the Philippines each recorded more than 4 million disaster displacements (IDMC, 2019).Tajikistan, Kyrgyzstan and Russia see significant disaster-associated displacements: e.g. heavy rain-induced flooding in Khatlon (Tajikistan) triggered 5,400 new displacements; landslides in the Jalal-Abad (Kyrgyzstan) saw 4,700 new displacements, while floods in Altai, Tuva, and Khakassia (Russia) displaced 1,500 people. Iran reported highest sub-regional figures with > 520,000 new disaster-related displacements in 2019 (IDMC, 2019). In South East and East Asia, cyclones, floods, and typhoons triggered internal displacement of 9.6 million people in 2019, almost 30% of total global displacements (IDMC, 2019). With most migrants in the region being temporary migrant workers, loss of jobs and wages among them have been particularly severe due to adverse economic climate triggered by COVID-19 (ESCWA, 2020). It has also resulted in large-scale returns of migrant workers and remittances have declined drastically (Khanna, 2020; Li et al., 2021). Remittances to Eastern Europe and Central Asia are expected to decline 16.1 per cent from $57 billion in 2019 to $48 billion in 2020. Remittances in East Asia and the Pacific are estimated to fall 10.5 per cent over the same period, from $147 billion to $131 billion (United Nations, 2020). The COVID-19 pandemic has had significant impacts on migrants (Rajan, 2020) in the region and some countries have targeted migrants in economic stimulus packages or income support programmes; however, access to such support has been heterogenous.

- *Projected migration*: Regional variation is significant across Asia. By one estimate, in South Asia, internal climate migrants, i.e. those migrating due to climate change and associated impacts such as water scarcity, crop failure, sea-level rise, and storm surges, are projected to be 40 million by 2050 (1.8 percent of regional population) under high warming (Rigaud et al., 2018). While methodological critiques remain on projected migration estimates, what is certain is that some countries will be more affected that others; it is estimated that in south Bangladesh, sea level rise can displace 0.9-2.1 million people by direct inundation by 2050 (Jevrejeva et al.; Davis et al., 2018). In South Asia, migration hotspots include the Gangetic Plain and the Delhi–Lahore corridor, coastal cities such as Chennai, Chittagong, Dhaka, and Mumbai, which will be simultaneously exposed to climate change impacts and major migration destinations, and amplified rural–urban migration (Ober, 2019). Importantly, there is *low agreement* on projected numbers (see Boas et al. (2019)) with uncertainties around how local policies and individual behaviours will shape migration choices. Even in high-risk places, people might choose to stay or be unable to move, resulting 'trapped' populations (Zickgraf, 2019; Ayeb-Karlsson et al., 2020). There is currently inadequate evidence to ascertain the nature and numbers of trapped populations currently or in the future.

Implications of migration for adaptation: The evidence on migration and its impacts on adaptive capacity and risk reduction are mixed (Upadhyay, 2014; Banerjee et al., 2018; Szabo et al., 2018; Maharjan et al., 2020; Singh and Basu, 2020). Financial remittances help vulnerable households spread risk through better incomes, expanded networks, and improved assets such as housing, education, and communication technology (Jha et al., 2018; Szabo et al., 2018; Ober, 2019; Maharjan et al., 2020). Benefits from international remittances across the Asia Pacific region were approximately US$276 billion in 2017 (UN, 2018) and in countries such as Kyrgyzstan, Tajikistan, and Nepal remittances were ~25% of national GDP in 2015. However, migration requires a minimum level of resources and liquidity constraints impede internal migration by the poorest households often rendering them immobile (Ayeb-Karlsson et al., 2020; Maharjan et al., 2020). Further, migration does not necessarily mean people move out of risk and often might enter new risks. Notably, migrants in South and South East Asia were severely affected by the compounding crises of disasters and the COVID-19 pandemic and there is emerging evidence that inclusion of universal safety net provisions that embed adaptation planning can reduce vulnerabilities of migrants (Sengupta and Jha, 2020; Cundill et al., 2021; Sultana, 2021).

While there is *robust evidence (medium agreement)* that migration exacerbates gendered vulnerability and work burdens (Banerjee et al., 2019; Singh, 2019; Rao et al., 2020), it is well established that differential vulnerability of migrants intersects with ethnicity, age, and gender; political networks and social capital; and livelihoods in destination areas (Maharjan et al., 2020; Cundill et al., 2021). Across Asia, international and internal migration are changing social norms and household structures, with significant implications for local adaptive capacity (Singh, 2019; Evertsen and van der Geest, 2020; Porst and Sakdapolrak, 2020; Rao et al., 2020).

[END BOX 10.2 HERE]

10.4 Key Systems and Associated Impacts, Adaptation and Vulnerabilities

10.4.1 Energy Systems

10.4.1.1 Regional diversity

Energy consumption of Asia accounts for 36% of the global total at present. China, India and the ASEAN countries have largely contributed to the ever-growing global energy consumption. Asia is predicted to account for 80% of coal, 26% of natural gas and 52% of electricity consumption of the world by 2040 (IEA, 2018). The share of Asia in the global primary energy consumption will increase to 48% by 2050. China continues to be the world's largest energy consumer, and the combined consumption of India and ASEAN will be similar with that of China by that time (IEEJ, 2018).

The energy structure of Asia is dominated by fossil fuels so far. As the trend, the share of coal in China's primary energy consumption is forecasted to sharply decline from 60% in 2017 to around 35% in 2040 (BP, 2019). In contrast, India and ASEAN rely more on coal since coal may meet their soaring energy demand. Accordingly, more than 80% of the global coal will be consumed in Asia by 2050. China will surpass the U.S. in about 10 years to become the world's largest oil consumer. India will then replace the U.S. to be the second largest by late 2040s (IEEJ, 2018).

Around 60% of the incremental electricity demand globally, predicted to double in 2050, will occur in Asia. By that time, electrification rate in Asia will increase to 30% but 40% of electricity demand will be still covered by coal (IEEJ, 2018). Asia accounts for almost half of the growth in global renewable power generation. It is hardly for Japan and Korea to develop additional nuclear power plants as the planned. Whereas, nuclear generation continues to increase quickly in China and the scale will be similar to the entire of OECD by 2040 (BP, 2019). India and Russia's nuclear power sector is also growing fast, e.g., the recent launch of the Akademik Lomonosov offshore nuclear power in Russia.

The rapid growth of energy demand in Asia reinforces the region's position as the largest energy importer (BP, 2019). Around 80% of energy traded globally will be consumed in Asia and the rate of self-sufficiency will decrease from 72% to 63% by 2050. This tendency is especially remarkable for ASEAN, which will become a net importer in early 2020s. Self-sufficiency rate of coal will be maintained at a level of 80%, while that of oil and natural gas will decline significantly. The additional oil imports of the emerging Asian economies will be from North America, the Middle East and North Africa. The main players in Asia for the LNG imports will extend from Japan and Korea to China and India. ASEAN has been a net exporter of natural gas but starts to expand its import due to the increased consumption and resource depletion (IEEJ, 2018).

The increase in energy demand at a rapid rate in these countries cannot thus be attributed only to population growth and rising living standards, but also to increasingly extreme temperature variations. The decrease in precipitation influences energy demand as well, as countries are becoming more dependent on energy-intensive methods (e.g., desalination, underground water pumping) to supply water. Similarly, energy systems are influenced by the way the agriculture sector, mainly in Al Mashrek, relies increasingly on energy-intensive methods (e.g., more fertilisers, different irrigation and harvesting patterns) (Farajalla, 2013).

Climate change has direct and indirect impacts on energy and industrial systems. Climate change has a wide and profound impact on energy systems (energy development, transportation, supply, etc.). With global warming, the energy consumption for heating in winter decreases, while the energy consumption for cooling in summer significantly increases, but the overall energy demand shows an upward trend (Sailor, 2001; Szabo et al., 2018) (*High confidence*). Such demands in summer seasons will by far exceed any energy savings from the decrease in heating demand due to warmer winters. Higher demand for cooling due to hotter temperatures has become a major challenge in the energy sector in all countries. Furthermore, decreased water levels due to lower precipitation reduces hydroelectric output. This is particularly the case for countries such as Syria and Iraq with large hydroelectric capacity (Hamid and Raouf, 2009). Additionally, the decrease in water levels negatively affects low-carbon energy systems such as Concentrated Solar Power (SCP) and thermal generation plants that require regular cooling and cleaning.

Climate change adds extra pressure to current energy infrastructures in most countries where systems failures and blackouts are already common (Assaf, 2009). In the wake of extreme weather events (e.g., heat waves), energy infrastructures remain inadequate to cope. This is particularly the case for countries such as Lebanon, Syria, Jordan, and Palestine, with poor electricity infrastructures (Jordan, 2015). Extreme weather events could generate grave damage to power plants, most being located only a few meters above sea level, as well as power transmission towers and lines. In Lebanon, a small country where there are no Indigenous energy resources, the disruption of shipping of fuel supplies due to extreme weather events is a major risk. Other extreme weather events such as floods and sandstorms expose energy and industrial systems in the coastal areas due to a rise in sea level. Countries of the Arabian Peninsula are projected to experience significant inland flooding as sea levels rise (Hamid and Raouf, 2009). In East Asia wet snow accretion enhanced by global warming often cause damage to electric power lines (Sakamoto, 2000; Ohba and Sugimoto, 2020).

10.4.1.2 Key drivers to vulnerability, observed and projected impacts

The universal energy access is a big challenge for Asia (IEA, 2018). About 230 million Indian people lack access to electricity, and around 800 million still use the solid fuels for cooking (Sharma, 2019). The average electricity access rate in South Asia was 74%, an equivalent of 417 million people without electricity and accounting for more than a third of the global 1.2 billion lacking the access (Shukla et al., 2017). With a total population of nearly 640 million in ASEAN, an estimated 65 million people remain without electricity and 250 million rely on solid biomass as the cooking fuel (IEA, 2017). It is expected to achieve the universal access to electricity by 2030, while 1.6 billion people in Asia will still lack clean energy for cooking (UNESCAP, 2018b).

Asia faces energy security problem even with the rapid growth in production and trade (IEEJ, 2018). Among 13 developing countries with large energy consumption in Asia, 11 expose to high energy security risk (WEC, 2018). This will be a major challenge for the sustainable development of Asia due to the vulnerability to global energy supplies and price volatility (Nangia, 2019). Asia is lack of natural energy resources and has the smallest oil reserve, but largely relies on fossil fuels. The dependency of fossil fuels was as high as 88.3% in China, 72.3% in India, 89.6% in Japan and 82.8% in Korea in 2013 (BP, 2014). Many countries in south Asia rely on a single source to supply more than half of the electricity, i.e., 67.9% from coal for India, 99.9% from hydropower for Nepal, 91.5% from natural gas for Bangladesh and 50.2% from oil for Sri Lanka (Shukla et al., 2017). Additionally, it is still at a very preliminary stage for the cooperation in Asia to create the integrated energy systems for enhancing the overall security due to countries having different strategic plans and lack of cooperation among them on the common concern (Kimura and Phoumin, 2013).

Even energy efficiency is improving, the deployment of low carbon energy like renewables is not sufficient in Asia. To be consistent with the temperature goal of the Paris Agreement, the share of renewables in total energy consumption needs to reach 35% in Asia by 2030. The financing to deploy renewables presents another considerable challenge (UNESCAP, 2018b).

In order to cope with climate change, renewable energy has become the core of energy development and transformation. Since the 1960s, the total solar radiation on the ground in Asia has shown a downward trend as a whole, which is consistent with the change of global total solar radiation on the ground, and has experienced a phased change process of "first darkening and then brightening" (*high confidence*). This conclusion has been further confirmed by ground station observations, satellite remote sensing inversion data and model simulation research (Wang and Wild, 2016; Qin et al., 2018; Yang et al., 2018a).

However, wind speed over most Asian regions is obviously decreasing (*high confidence*). Based on meteorological observation records or reanalysis data, many studies have analysed the variation of near-surface average wind speed in Asia. It is generally found that the wind speed has declined since 1970s, although the declining trend is different (Yang et al., 2012c; Lin et al., 2013; Liu et al., 2014b; Zha et al., 2016; Guo et al., 2017a; Torralba et al., 2017; Wu et al., 2017a; Ohba, 2019). The decline of near-surface wind speed in Asia is consistent with the general decline of global land surface wind speed, among which the frequency of strong winds and the decline of wind speed are more prominent (McVicar et al., 2012; Jiang et al., 2013; Blunden and Arndt, 2017; Wu et al., 2018c). Since the early 2010' s, the average wind speed in the world and some parts of Asia has shown signs of increasing (Li et al., 2018d; Wu et al., 2018c; Zeng et al., 2019), which seems to be an interdecadal variability. Whether it means a change in its trend needs the support of longer observation data.

At the same time, with the increase of the proportion of renewable energy in the power system, the power system will be more vulnerable to climate change and extreme weather and climate events, and the vulnerability and risk of the power system will greatly increase (*medium confidence*).

10.4.1.3 Adaptation options

The overall solution would be to develop a resilient energy system and avoid the risk of unsustainable energy growth in developing Asia. This requires the strategic planning in consistent with the long term climate projection, impact and adaptation (EUEI-PDF, 2017). Although no single policy package would be applicable for all the countries across the region, several measures could be addressed as the common options, including to fortify energy infrastructure and diversify the sources by sufficient investment, to improve energy efficiency for the sector flexibility, and to promote regional cooperation and integration for increasing energy security (UNESCAP, 2018b). Adaptation also includes promoting renewable energy resources, securing local natural gas resources, enhancing water production, and adopting green building technologies. These adaptation measures may help increase the readiness for the anticipated impact of climate change.

The improvement of energy efficiency and demand side management can alleviate supply constraints and thus lower overall required energy capacity. Energy storage, smart grids for the electricity network as well as other flexibility management measures enable this energy demand shifting. Regional integration of energy markets drives productivity increase, cost reduction, new investment, human capability and diversity of energy sources (WEC, 2018). For example, better interconnection of natural gas supply networks among the ASEAN countries enhances gas security in the region. The development of the long planned regional power grid would make large scale renewable projects more viable, and aid the integration of rising shares of wind and solar power (IEA, 2017).

Providing enough investment in energy supply is a top priority to extend the connections to those without access to electricity and satisfy the soaring demand (IEA, 2017). The investment in non-fossil energies like renewables has been expanding to lever economic growth in China, India and Korea. According to the updated estimation of ADB, 14.7 trillion USD will be needed for the infrastructure development in power sector of developing Asia over the 15 years from 2016 to 2030 (ADB, 2017a). The cumulative investment needs of ASEAN for energy supply and efficiency up to 2040 is estimated at 2.7 to 2.9 trillion USD (IEA, 2017). Mobilising investment to such a scale requires significant participation from the private sector and international financial institutions.

Diversifying energy sources increases energy security and thus the resilience of the whole system. The deployment of renewable energy is widely recognised as a crucial measure enhancing energy access and diversity. There remains huge potential for renewable sources in Asia, i.e., India has the massive solar power potential (Shukla et al., 2017). Many renewable technologies, i.e., hydro, wind and solar PV, are becoming competitive and their lifecycle costs may fall below those of coal and natural gas in the near term. Great progresses have been made in Enhanced Geothermal Systems (EGS), and in conventional and unconventional fusion power that China is promoting. Conventional and underground pumped hydro level out supplies for intermittent renewable energy generation.

Substantial room may be fulfilled by increasing the share of renewable energy in overall energy consumption of this region (ADB, 2017a). Access to energy, particularly in rural areas, can reduce climate vulnerability of developing Asia. Due to the high cost of extending the electricity network to rural regions, an alternative way is to develop the off-grid renewable energy systems in these areas. The distributed instead of centralised energy systems can increase the energy access and resilience (EUEI-PDF, 2017).

Some countries in the Arabian Peninsula like the United Arab Emirates (UAE) are adopting an array of approaches to enhance the adaptive capacity of the energy infrastructure and diffuse the risk of climate change over a larger area (e.g., energy efficiency, demand management, storm planning for power plants). In Al Mashrek, building institutional capacity in the energy sector is a necessary first step to mainstream climate change adaptation. Countries such as Lebanon and Jordan have already made progress in mainstreaming climate change adaptation into electricity infrastructure. In the UAE, buildings account for more than 80% of the total electricity consumption. There are currently a set of measures and regulations on building conditions and specifications that are being applied to increase energy efficiency in buildings, but the rehabilitation and upgrading of old buildings still require further efforts (Environment, 2015). In Kuwait, one adaptation measure to dust storms is through the reduction of the proportion of open desert land from 75% to 51%, the increase of protected areas from 8% to 18%, and greenbelt projects in desert areas (Kuwait, 2015). Addressing climate change impact on energy systems in Lebanon, Jordan, Syria, Iraq, and Palestine needs to simultaneously consider other interlinked challenges of population growth, rapid urbanisation, refugee influx, conflict, and geopolitical location. To address these challenges and provide solutions for climate change adaptation, the promotion of multi-stakeholder partnerships is key to breaking the silo approach.

Climate change adaptation measures need to be broadened to fit the scope and depth of mitigation efforts by each country. Risk assessments and vulnerability assessments are in their early stages in the energy and industrial sectors and are not currently based on a comprehensive plan of action. The first step is to undertake comprehensive national assessments of the risks associated with climate change based on existing studies on climate impacts and risks and by making evidence-based decisions on adaptation actions.

10.4.2 Terrestrial and Freshwater Ecosystems

Sub-regional diversity of ecosystems is high in Asia, see 10.2.2. Climatic drivers of Asian terrestrial ecosystems (ATS) change are global warming, precipitation and Asian monsoon alteration, permafrost thawing and extreme events like dust storms. Observed and projected changes in ATS are affected by several interacting factors, which are in play. Non-climatic human-related drivers are change of land use, change of human use of natural resources including species and ecosystems overexploitation and other non-sustainable use, socioeconomic changes, direct impacts of rising GHGs. Ecosystem vulnerability resulted from complex interaction of climatic and non-climatic drivers, species interaction and natural variability of organisms, species and ecosystems is currently poorly understood, and much more work still needs to be done to unravel these multiple stressors (i.e. (Berner et al., 2013; Brazhnik and Shugart, 2015).

10.4.2.1 Observed Impacts

10.4.2.1.1 Biomes and mountain treeline

Changes in biomes in Asia are compatible with a response to regional SAT increase (Arias et al., 2021) (*medium agreement, medium evidence*). Expansion of the boreal forest and reduction of the tundra area is observed for about 60% of latitudinal and altitudinal sites in Siberia (Rees et al., 2020). In Central Siberia, the changes in climate and disturbance regimes are shifting the southern taiga ecotone northward (Brazhnik et al., 2017). In Taimyr, no significant changes in the forest boundary were observed during the last three decades (Pospelova et al., 2017). For the Japanese archipelago, it is suggested that tree community composition change along the temperature gradient is a response to past and/or current climate changes (Suzuki et al., 2015).

Alpine treeline position in Asian mountains in last decades either moves upward in North Asia, or demonstrate multidirectional shifts in Himalaya (*high confidence*). Since AR5, in North Asia new evidence appeared of trees expansion into mountain tundra and steppe, of intensive reproduction and increase of tree stands productivity in last 30-100 years at the upper treeline in Urals Mountains (Shiyatov and Mazepa, 2015; Zolotareva and Zolotarev, 2017; Moiseev et al., 2018; Sannikov et al., 2018; Fomin et al., 2020; Gaisin et al., 2020), in Russian Altai Mountains (Kharuk et al., 2017a; Cazzolla Gatti et al., 2019), in Putorana Mountains (Kirdyanov et al., 2012; Pospelova et al., 2017; Grigor'ev et al., 2019). Lower treelines in southernmost *Larix sibirica* forests in Saur Mountains, Eastern Kazakhstan, suffer from increased in last decades drought stress causing forest regeneration and tree growth decrease, and tree mortality increase (Dulamsuren et al., 2013). In Jeju Island, Korea, recent warming has enhanced *Quercus mongolica* growth at its higher distribution and has led to *Abies koreana* (ABKO) growth reduction at all elevations, except the highest locality. Thus, combination of warming, increasing competition, and frequent tropical cyclone disturbances can lead to population decline or even extinction of ABKO at Jeju Island (Altman et al., 2020). In Himalaya, treeline over recent decades either moves upward (Schickhoff et al., 2015; Suwal et al., 2016; Sigdel et al., 2018; Tiwari and Jha, 2018), or does not show upslope advance (Schickhoff et al., 2015; Gaire et al., 2017; Singh et al., 2018c), or moves downward (Bhatta et al., 2018). In Tibetan Plateau, treeline either shifted upwards or showed no significant upward shift (Wang et al., 2019c). This can be explained by site-specific complex interaction of positive effect of warming on tree growth, drought stress, change in snow precipitation, inter- and intraspecific interactions of trees and shrubs, land use change, especially grazing, and other factors (Liang et al., 2014; Lenoir and Svenning, 2015; Tiwari et al., 2017; Sigdel et al., 2018; Tiwari and Jha, 2018; Sigdel et al., 2020). It is largely unknown how broader scale climate inputs, as pre-monsoon droughts interact with local-scale factors to govern treeline response patterns (Schickhoff et al., 2015; Müller et al., 2016; Bhatta et al., 2018; Singh et al., 2019b).

10.4.2.1.2 Species ranges and biodiversity

Since AR5, new evidences appeared of terrestrial and freshwater species, populations and communities alterations in line with climate change (Arias et al., 2021) (*medium-to-high confidence*) across Asia. In North Asia, temperature increase and droughts promoted spread northward of the current silk moth outbreak (affected nearly 2.5 x 10^6 ha) in Central Siberia dark taiga since 2014 (Kharuk et al., 2017b; Kharuk et al., 2020). Climatic range of Colorado potato beetle, *Leptinotarsa decemlineata* in 1991–2010 expanded east- and northward in Siberia and Russian Far East compared with the 1951–1970 range (Popova, 2014). Climatic range of *Ixodes ricinus*, a vector of dangerous human diseases expanded into Central Asia and south of the Russian Far East (Semenov et al., 2020). A butterfly *Melanargia russiae* in the Middle Urals moved northward (Zakharova et al., 2017). Thrush birds in Western Siberia penetrated northward up to the limits of the sparse woodlands (Ryzhanovskiy, 2019a). Increase in the length of frost-free period observed in the Ilmen Nature Reserve, Middle Urals during the past decades is supposed to be interlinked with changes in the amplitude and frequency of population waves of bank vole (Kiseleva, 2020). In Katunskiy Biosphere Reserve, Russian Altai, in period 2005–2015, alpine plant species have shifted towards higher altitudes by 5.3 m on average (Artemov, 2018).Wild reindeer herds in Taimyr, north of the Central Siberia migrated northward up to the Arctic Sea coast in hot summers 1999–2003 and 2009–2016 because an earlier massive emergence of bloodsucking insects (Pospelova et al., 2017). In Yakutia, the ranges of red deer, elk and the northern pika are expanding, the winter survival of the mouse-like rodents has increased (Safronov, 2016). In the Chukchi Sea, in last decades the average duration polar bears spent onshore increased by 30 days (Rode et al., 2015b) in line with global warming and rapid declining of sea ice habitat (Derocher et al., 2013; Jenssen et al., 2015; Rode et al., 2015a).

In Central Kazakh Steppe, in line with warming, in 2018 there are more "southern" subarid species in the communities and fewer relatively "northern" boreal and polyzonal species of ground beetles (Carabidae) and black beetles (Tenebrionidae) than in 1976-78 (Mordkovich et al., 2020). Present distribution of Asian black birch, *Betula davurica* Pall. in East and North Asia was formed in result of northward expansion during post-Last Glacial Maximum global warming (Shitara et al., 2018). Both upper and low limits of avifauna of two New Guinean mountains, Mt. Karimui and Karkar Island shifted upslope over nearly a half-century since 1965 (Freeman and Freeman, 2014). In Korea, for the last 60 years, the northern boundary line of 63 southern butterfly species moved further north (Government, 2020). Change of butterflies' occurrence in this period was influenced mostly by large-scale reforestation, not by climate change (Kwon et al., 2021). Warming-driven geographical range shift was recorded in 87% of 124 endemic plant species studied in Sikkim Himalaya in period 1849-1850 to 2007-2010 (Telwala et al., 2013). In Darjeeling district, India, significant change in lichen community structure was shown in response to climate change and anthropogenic pollution (Bajpai et al., 2016).

Observed biodiversity or habitat loss of animals or plants was linked to climate change in some parts of Asia (*high confidence*). Climate change, together with human disturbances, caused local extinction of some large- and medium-sized mammals during past three centuries in China (Wan et al., 2019). Climate change showed significant impacts on subalpine plant species at low altitudes and latitudes in Republic of Korea and may impose a big threat to these plant species (Adhikari et al., 2018; Kim et al., 2019c). Climate change has caused habitat loss of amphibians (Surasinghe, 2011), and extinction of some endemic species in Sri Lanka (Kottawa-Arachchi and Wijeratne, 2017).

There are evidences that climate change can alter species interaction or spatial distribution of invasive species in Asia (*high confidence*). Climate warming enhanced the competition ability of the native species (*Sparganium angustifolium*) against the invasive species (*Egeria densa*) in China under a mesocosm experiment in a greenhouse (Yu et al., 2018e). Climate warming increased the non-target effect on a native plant (*Alternanthera sessilis*) by a biological control beetle (*Agasicles hygrophila*) in China due to range expansion of the beetle and change of phenology of the plant (Lu et al., 2015). Climate warming expanded the distribution of invasive bamboos (*Phyllostachys edulis* and *P. bambusoides*) northward and upslope in Japan (Takano et al., 2017), while soil dry-down rates were a key driver of invasion of dwarf bamboo, *Sasa kurilensis* in central Hokkaido above and below treeline (Winkler et al., 2016).

Climate change along with land-use and land cover change influences soil organic carbon content, microbial biomass C, microbial respiration and soil carbon cycle in the Hyrcanian forests, Iran (Soleimani et al., 2019; Francaviglia et al., 2020). In fir forest ecosystems of Tibetan Plateau, winter warming affects the ammonia oxidising bacteria and archaea, thus alters N cycle (Huang et al., 2016). Ecosystem carbon pool in spruce forests of the north-eastern Tibetan Plateau was reduced by ca 25% by deforestation due to recent decades climate warming and wood pasture and logging (Wagner et al., 2015). In Mongolia's forest-steppe, recent decades drought- and land use-induced deforestation reduces ecosystem carbon stock density by c. 40 % (Dulamsuren et al., 2016). In Inner Mongolia, China, the predicted decreases in precipitation and warming for most of the temperate grassland region could lead to pH change, which contributes to a soil C-N-P decoupling that may reduce plant growth and production in arid ecosystems (Jiao et al., 2016).

In Central Asia, in Vakhsh, Kafirnigan, and Kyzylsu river basins, Tajikistan it was shown that temperature stimulate algal species diversity, while precipitation and altitude suppress it (Barinova et al., 2015). In line with warming of Lake Baikal, Russia since the 1990s in the lake's south basin there are shifts in diatom community composition towards higher abundances of the cosmopolitan *Synedra acus* and a decline in endemic species, mainly *Cyclotella minuta* and *Stephanodiscus meyerii* and to a lesser extent *Aulacoseira baicalensis* and *A. skvortzowii* (Roberts et al., 2018). In Gonghai Lake, North China diatom biodiversity increased remarkably from 1966, but began to decline after 1990 presumably in response to rapid climatic warming (Yan et al., 2018).

10.4.2.1.3 Wildfires

Climate change, human activity and lightning determine increase of wildfire severity and area burned in North Asia (*high detection, medium-to-low attribution to climate change*). In North Asia, the extent of fire-affected areas in boreal forest can be millions hectares in a single extreme fire year (Duane et al., 2021) and has nearly doubled between 1970 and 1990 (Brazhnik et al., 2017). During recent decades, number, area and frequency of forest fires increased in Putorana Plateau, north of Central Siberia; in larch-dominated forests of Central Siberia; and in Siberian forests as a whole. This increase is in line with increase of the average annual air temperature, air temperature anomalies, droughts and the length of fire season (Ponomarev et al., 2016; Kharuk and Ponomarev, 2017; Pospelova et al., 2017). The number of forest fires and damaged areas in Gangwon Province and the Yeongdong area in the 2000s increased by factors of 1.7 and 5.6, respectively, compared with the 1990s (Government, 2020). Climate change is not the sole cause of increase of forest fire severity (Wu et al., 2014; Wu et al., 2018d). Ignition is often facilitated by lightning (Canadell et al., 2021), and over 80% of fires in Siberia are *likely* anthropogenic in origin (e.g., (Brazhnik et al., 2017). Gas field development and Indigenous tundra burning practices that may get out of control contribute to fire frequency in forest-tundra of west Siberia (Adaev, 2018; Moskovchenko et al., 2020). Climate change in combination with socioeconomic changes has resulted in an increase of fire severity and area burned in southern Siberia, illegal logging acts to increase fire danger in forest–steppe Scots pine stands (Ivanova et al., 2010; Schaphoff et al., 2016).

10.4.2.1.4 Phenology, growth rate and productivity

In East and North Asia, satellite measurements and ground-based observations in last decades demonstrate either increase of the length of plant growth season over sub-regions or in some territories in line with climate warming, or do not show any significant trend in other territories (*high confidence*). In last decades in China, it was increasing trend in annual mean grassland net primary production (NPP), average Leaf Area Index (LAI) and lengthening of the local growing season (Piao et al., 2015; Zhang et al., 2017b; Xia et al., 2019). Nevertheless, phenology pattern vary across different studies, species and parts of China. In most regions of Northeast China (NEC), start date and length of land surface phenology from 2000 to 2015 had advanced by approximately 1.0 days year^{-1} except for the needle-leaf and cropland areas (Zhang et al., 2017d). For Inner Mongolia, it was shown that neither start of growing season (SOS) nor end of growing season (EOS) presented detectable progressive pattern at the regional level in 1998 – 2012, except for the steppe desert (6% of the total area) (Sha et al., 2016). In the Tianshan Mountains (TM) in China, NPP of only two out of 12 types of vegetation increased in spring, and NPP of only one type increased in autumn from 2000-2003 to 2012-2016 (Hao et al., 2019). In Republic of Korea, from 1970 to 2013 the SOS has been advanced by 2.7 days/decade and the EOS has been delayed by 1.4 day/decade (Jung et al., 2015), during the last decade leaf unfolding was accelerating 1.37 days/year, and the timing of leaf fall was delaying 0.34 day/year (Kim et al., 2019d), cherry blossoms is predicted to flower 6.3 days and 11.2 days earlier after 2090 according to scenarios RCP 4.5 and RCP 8.5, respectively (Government, 2020). On Tibetan Plateau (TP), it was found that the SOS has advanced and EOS has been delayed over the last 30-40 years (Yang et al., 2017). Using NDVI data sets and ground-based budburst data, (Wang et al., 2017c) found no consistent evidence that SOS has been advancing or delaying over the TP during the last two to three decades. The discrepancies in the trends of spring phenology over the TP among different studies could be largely attributed to the use of different phenology retrieval methods. An uncertainty exists with the relationship between land surface phenology and climate change estimated by satellite-derived NDVI because these indices are usually composite products of a number of days (e.g., 16-days) that could fail to capture more details. Besides, due to lack of in situ observations, SOS and EOS at large areas cannot be easy defined (Zhang et al., 2017d).

In North Asia, in the Middle Siberia and south of Western Siberia, growth index of Siberian larch based on tree rings width increased with the onset of warming and changed in antiphase with aridity in 1980s (Kharuk et al., 2018). In Mongolia and Kazakhstan, the last decade's temperature increase promoted radial stem increment of Siberian larch. However, the simultaneous influence of increased temperature, decreased precipitation and increased anthropogenic pressure resulted in widespread declines in forest productivity and reduced forest regeneration, and increased tree mortality (Dulamsuren et al., 2013; Lkhagvadorj et al., 2013b; Lkhagvadorj et al., 2013a; Dulamsuren et al., 2014; Khansaritoreh et al., 2017). In Eastern Taimyr, growing season, the number of flowering shoots, annual increment, success of seed ripening and vegetation biomass have increased considerably in last decades (Pospelova et al., 2017). In Vishera Nature Reserve, Northern Urals Mountains, annual temperature increased in last decades in parallel with summer temperature drop and increase of summer frost numbers. As result, trends of vegetation change are mostly unreliable (Prokosheva, 2017).

Date of arrival of migrant birds to nesting areas, and date of departure from winter areas in Asia are changing consistently with climate change (*medium confidence*). Time of arrival of the gray crow to the Lower Ob river region, northwest Siberia, shifted to earlier dates in period 1970–2017 in consistent with increase of daily average temperatures on the day of arrival (Ryzhanovskiy, 2019b). In Ilmen Nature Reserve, Urals, an earlier arrival of the majority of nesting bird species is not observed last decades. It is explained by the fact that other factors as weather of each spring month of particular years, population density in the previous nesting period, the seed yield of the main feeding plants, and migration of wintering species from adjacent areas determinate long-term dynamics of bird arrival (Zakharov, 2016; Zakharov, 2018). In Yokohama, Japan observations since 1986 revealed that arrival of six winter bird species became later and departure earlier than in the past in line with warmer temperatures (Kobori et al., 2012; Cohen et al., 2018). Part of papers analysed corroborate that earlier start and late end of phenological events in Asia are associated with global warming, however another part of papers does not confirm such a connection. Comparison and synthesis of results is impeded by usage of different metrics, measurement methods and models (e.g., (Hao et al., 2019)). Relative contribution of climatic stress and other factors to phenology and plant growth trends are poorly understood (e.g., (Andreeva et al., 2019)).

10.4.2.2 Projected Impacts

10.4.2.2.1 Biomes and mountain treeline

Across Asia, under a range of RCPs and other scenarios rising temperature is expected to contribute to northward shift of biome boundaries and upward shift of mountain treeline (*medium confidence*). Northward shift and area change of bioclimatic zones in Siberia (Anisimov et al., 2017; Torzhkov et al., 2019) and NE Asia (Choi et al., 2019) are projected. Projected changes in vegetation in China at the end of the 21st century revealed that the area covered by cold-dry potential vegetation decreases as the area covered by warm-humid potential vegetation increases (Zhao et al., 2017a). Forest expansion into mountain tundra of the Northern Urals is expected (Sannikov et al., 2018). In Republic of Korea, projected under RCP 4.5 and RCP 8.5 in 2070s suitable area loss of six subalpine tree species, namely, Korean fir, Khingan fir, Sargent juniper, Yeddo spruce, Korean yew, and Korean arborvitae range from 17.7% ± 20.1% to 65.2% ± 34.7%, respectively (Lee et al., 2021b). Korean fir forests would be replaced by temperate forests at lower elevations, while would continuously persist at the highest elevations on Mt. Halla, Jeju Island, Republic of

Korea (Lim et al., 2018). Himalayan birch at its upper distribution boundary either projected to move upward (Schickhoff et al., 2015; Bobrowski et al., 2018), or considered to downslope as a response to global-change-type droughts (Liang et al., 2014). Upward shift in elevation of bioclimatic zones, decreases in area of the highest elevation zones, large expansion of the lower tropical and sub-tropical zones can be expected by the year 2050 throughout the transboundary Kailash Sacred Landscape of China, India and Nepal, and *likely* within the Himalayan region more generally (Zomer et al., 2014).

In North Asia, it is projected a shift in the dominant biomes from conifers to deciduous species across Russia after 20 years of altered climate conditions (Shuman et al., 2015). In Southern Siberia, Brazhnik and Shugart (2015) projected shift from the boreal forest to the steppe biome. Rumiantsev et al. (2013) also project positive northward shift of vegetation boundaries for greater part of Western Siberia (WS) in line with warming, however no shift for the north of WS, and negative shift for Southern Urals and North-western Kazakhstan are projected for 2046-2065. The replacement of forest-steppe with steppe at the lower treeline in Southern Siberia is projected (Brazhnik and Shugart, 2015), and retreat of larch forests from the southernmost strongholds of boreal forest in the Eastern Kazakhstan is expected as part of a global process of forest dieback in semiarid regions (Dulamsuren et al., 2013). In North Asia, tree growth is intertwined with permafrost, snowpack, insect outbreaks, wildfires, seed dispersal and climate (e.g. (Klinge et al., 2018)). It is challenging to isolate the affects of individual factors, particularly since they can feedback on one another in unanticipated ways because underlined mechanisms are not understood well (Berner et al., 2013; Brazhnik and Shugart, 2015). The accuracy of treeline shift projections is limited because projections are based on vegetation models which do not consider all the factors (Tishkov et al., 2020). Regional vegetation model structure and parameterisation can affect model performance, and correspondent projections can differ significantly (Shuman et al., 2015).

10.4.2.2.2 Species ranges and biodiversity

Considerable changes of plant and animal species distribution under warming stress until 2100 are expected in Asia (*high confidence*). In East Asia, *Cunninghamia lanceolate*, a fast growing and wide distributed in China coniferous timber species, is projected to increase distribution, to decrease the establishment probability and to reduce total NPP by 2050s (Liu et al., 2014c). In monsoon Asia, by the end of the 21st century, NPP is projected to increase by 9–45 % (Ito et al., 2016). Under climate change in the Korean Peninsula (KP), potential habitat for *Abies nephrolepis* is the northern part of KP, *A. koreana* disappear from Jeju Island and shrink significantly in the KP (Yun et al., 2018), while evergreen forest would expand to the northern part of KP (Koo et al., 2018; Lim et al., 2018). It is expected that under projected warming fig species in China will expand to higher latitudes and altitudes (Chen et al., 2018c). In Japan, under AIB scenario 89% of the area currently covered by *Fagus crenata*-dominant forest type to be replaced in the future by *Quercus spp*.-dominant forest types (Matsui et al., 2018). Current trends of climate change will reduce distribution of tall, 2-2.5 m height herb communities in Japan, and will increase suitable for them area in the Russian Far East (Korznikov et al., 2019). A range expansion of *Lobaria pindarensis*, an endemic in HKH region epiphytic lichen, is projected to the north-east and to higher altitudes in response to climate change, although the species' low dispersal abilities and the local availability of trees as a substratum will considerably limit latitudinal and altitudinal shifts (Devkota et al., 2019).

Climatic range of Italian locust (*Calliptamus italicus* L.) under the RCP4.5 will expand north- and eastward to Siberia, Russian Far East and Central Asia (Popova et al., 2016). In Krasnoyarsk Krai, Siberia it is projected that the needle cast disease caused by fungi from the genus *Lophodermium* Chevall. in the Scots pine nurseries would shift northwards up to 2080 under A2 and B1 scenarios (Tchebakova et al., 2016). All four RCP scenarios showed northward expansion of vulnerable regions to pine wilt disease in China, Korea, Russian Far East, and Japan under future climate conditions in 2070 (Hirata et al., 2017), and in 2026-2050 in Japan (Matsuhashi et al., 2020). It should be noted that disease expansion depends not only on climatic factors, but also on the dispersal capacity of insect vectors, the transportation of infected logs to non-infected regions, and susceptibility of host trees (e.g. (Gruffudd et al., 2016)). Suitable habitat area of snow leopard *Panthera uncia* is projected to increase for 20% under the IPCC Scenario A1B by 2080: for the seven northernmost snow leopard range states (Afghanistan, Tajikistan, Uzbekistan, Kyrgyzstan, Kazakhstan, Russia, and Mongolia) the suitable habitat area will increase, while habitat loss is expected on the south slope of the Himalaya and the south-eastern Tibetan Plateau (Farrington and Li, 2016). Climate change projected under four RCP scenarios will not affect the distribution patterns of Turkestan Rock Agama *Paralaudakia lehmanni* (Nikolsky 1896) (Sancholi, 2018). In Iran, among 37 studied species of plants and animals, ranges of 30 species are expected to shrink and range of seven species are expected to increase by 2030-2099 under climate change stress (Yousefi et al., 2019).

Future climate change would cause biodiversity and habitat loss in many parts of Asia using modelling approaches (*high confidence*). Warren et al. (2018) projected that extirpation risks terrestrial taxa (plants, amphibians, reptiles, birds and mammals) from 2°C to 4.5°C global warming in 12 priority Places of Asia under the assumptions of without adaptation (dispersal) by 2080s is from 12.2-26.4% to 29-56% (Table 10.1, Figure 10.4).Under different scenarios, future climate change could reduce the extent of a suitable habitat for giant pandas (Fan et al., 2014), the moose (*Alces alces*) (Huang et al., 2016), black muntjac (*Muntiacus crinifrons*) (Lei et al., 2016), the Sichuan snub-nosed monkey (*Rhinopithecus roxellana*) (Zhang et al., 2019d) in China; Persian leopard (*Panthera pardus saxicolor*) in Iran (Ashrafzadeh et al., 2019a), Bengal tiger (Mukul et al., 2019), and four tree snail species (*Amphidromus*) in Thailand (Klorvuttimontara et al., 2017). However, climate change would have little impact on the habitats of Asian elephant, but would cause extinction of Hoolock gibbon in Bangladesh by 2070 (Alamgir et al., 2015). Climate change would increase the distribution of Mesopotamian spiny-tailed lizard (*Saara loricate*) in Iran (Kafash et al., 2016). Future climate change would reduce suitable habitat of protected plants (Zhang et al., 2014), *Polygala tenuifolia* Wild (Lei et al., 2016), relict species in East Asia (Tang et al., 2018), and tree *Abies* (Ran et al., 2018) in China; two threatened medicinal plants (*Fritillaria cirrhosa* and *Lilium nepalense*) in Nepal (Rana et al., 2017); a medicinal and vulnerable plant species *Daphne mucronata* (Abolmaali et al., 2018) and *Bromus tomentellus* in Iran (Sangoony et al., 2016); a valuable threatened tree species *Dysoxylum binectariferum* in Bangladesh (Sohel et al., 2016); plant diversity in Korea (Lim et al., 2018).

Impact of future climate change on invasive species may be species- or region-specific (*medium confidence*). Climate change would promote invasion of a highly invasive aquatic plant *Eichhornia crassipes* (You et al., 2014), *Ambrosia artemisiifolia* (Qin et al., 2014), alligator weed (*Alternanthera philoxeroides*) (Wu et al., 2016), invasive alien plant *Solidago canadensis* (Xu et al., 2014), three invasive woody oil plant species (*Jatropha curcas, Ricinus communis,* and *Aleurites moluccana*) (Dai et al., 2018), 90 of ~150 poisonous plant species (Zhang et al., 2017a) in China; six mostly serious invasive species (*Ageratum houstonianum* Mill., *Chromolaena odorata* (L.) R.M. King & H. Rob., *Hyptis suaveolens* (L.) Poit*., Lantana camara* L*., Mikania micrantha* Kunth*,* and *Parthenium hysterophorus* L.) in Nepal (Shrestha et al. 2018), eleven invasive plant species in Western Himalaya (Thapa et al., 2018), alien plants in Georgia (Slodowicz et al., 2018), the invasive green anole (*Anolis carolinensis*) in Japan (Suzuki-Ohno et al., 2017), the Giant African Snail in India (Sarma et al., 2015), a major insect vector (*Monochamus alternatus*) of the pine wilt disease (Kim et al., 2016b) and melon thrips (*Thrips palmi* Karny) (Park et al., 2014) in Korea. In contrast, a few studies projected that the climate change would inhibit the invasion of one exotic species (*Spartina alterniflora*) (Ge et al., 2015), alien invasive weeds (Wan et al., 2017), invasive plant *Galinsoga parviflora* (Bi et al., 2019), an invasive species *Galinsoga quadriradiata* (Yang et al., 2018b) in China; two invasive plants (*Chromolaena odorata* and *Tridax procumben*s) in India (Panda and Behera, 2019).

Five of 15 endemic freshwater fish species in Iran will lose some parts of their current suitable range under climate change by 2070 (Yousefi et al., 2020). In line with projected large increases in mean water temperature, it is projected the strongest increase in exceeded frequency and magnitude of maximum temperature tolerance values for freshwater minnow (*Zacco platypus*) in East Asia for 2031 to 2100 (Van Vliet et al., 2013). Climate change under A1B scenario is projected to decrease diversity (-0.1%) along with increased local richness (+15%) and range size (+19%) of stream macroinvertebrates in the Changjiang River catchment, south-east China for the period 2021 to 2050, while land-use change was predicted to have the strongest negative impact (Kuemmerlen et al., 2015). Asian clam *Corbicula fluminea* (Müller, 1744), an invasive species native to southeast China, Korea, and south-eastern Russia, is projected to invade to South-east Asia under all four RCP scenarios for 2041–2060 and 2061–2080 periods (Gama et al., 2017). Projected sea level rise, related aquatic salinisation, and alteration in fish species composition may have a negative impact on poor households in Southwest Coastal Bangladesh (Dasgupta et al., 2017a).

10.4.2.2.3 Wildfires

Under regional projections for North Asia, warmer climate will increase forest fire severity by the late 21st century (*medium confidence*). For south taiga in Tuva Republic, central Siberia, in a warmer climate, both the annual area burned and fire intensity will increase by 2100. For middle taiga in Irkutsk Region, the annual area burned and the crown: ground fire fraction will increase by late 21st century against historical

(1960-1990) estimate. This moves forest composition toward greater contribution of hardwoods (*Betula* spp., *Populus* spp.) (Brazhnik et al., 2017). This shifting was also proved by observations in the Northern Mongolia, where boreal forest fires *likely* promote the relative dominance of *B. platyphylla* and threaten the existence of the evergreen conifers, *Picea obovata*, and *Pinus sibirica* (Otoda et al., 2013). For Tuva Republic, warming ambient temperatures increase the potential evapotranspiration demands on vegetation, but if no concurrent increase in precipitation occurs, vegetation becomes stressed and either dies from temperature-based drought stress or more easily succumbs to mortality from insects, fire, pathogens, or wind throw (Brazhnik et al., 2017). Although Torzhkov et al. (2019) also projected fire risk (FR) increase in Tuva Republic, they expect FR decrease in Irkutsk Region and Yakutia under RCP 8.5, and FR decrease in major part of central and eastern Siberia under RCP 4.5 for 2090-2099. This discrepancy is due to differences in models, climate projections, fire severity metrics and other assumptions. According to global projections, fire risk will increase in Central Asia, Russia, China and India under a range of scenarios (Sun et al., 2019).

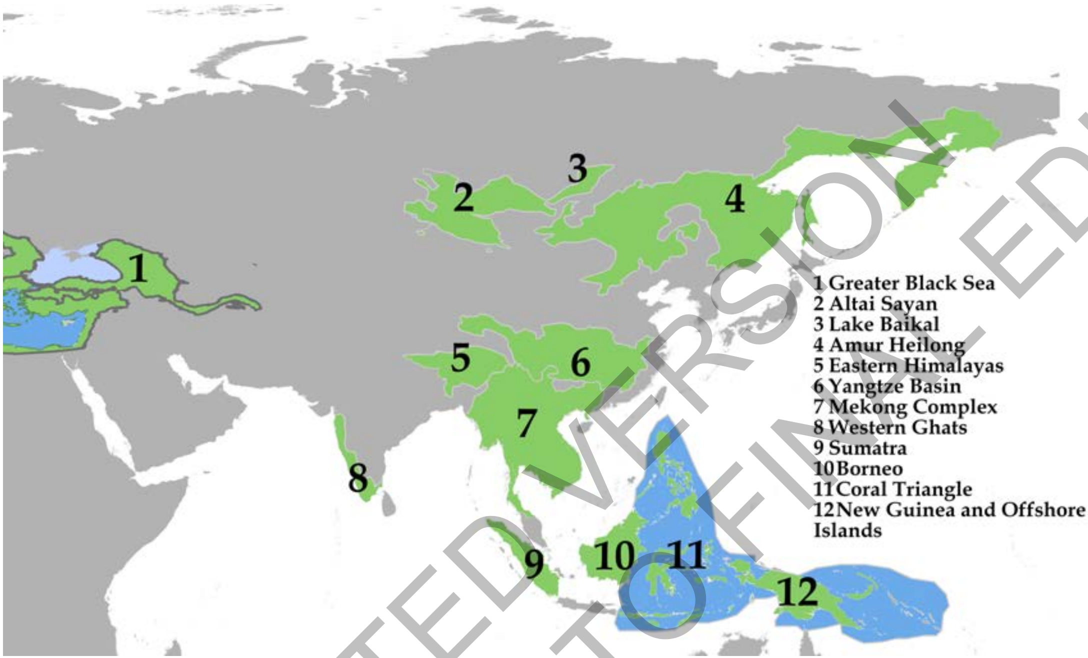


Figure 10.4. Location of Priority Places in Asia (modified from: Warren et al. (2018)

Table 10.1: Projected extirpation risks, % of taxa (plants, amphibians, reptiles, birds and mammals) for 2°C and 4.5°C global warming in Priority Places in Asia, without adaptation by 2080s (from: Warren et al. (2018))

Priority Places	**2°**	**4.5°**
Mekong	26.4	55.2
Baikal	22.8	49.5
Yangtze	20	42.6
Coral Triangle	19.2	41.8
W Ghats	18.8	41.67
New Guinea	19.8	41.2
Atlai-Syan	18.6	37
Sumatra	16.8	37
Borneo	17.6	36.8
Amur	14.2	35.6
Eastern Himalayas	12.2	29
Black sea	26.2	56

10.4.2.3 Vulnerabilities to Key Drivers

Both natural and managed ecosystems, ecosystem services and livelihoods in Asia will potentially be substantially impacted by changing climate (Wu et al., 2018d). There will be increased risk for biodiversity, particularly many endemic and threatened species of fauna and flora already under environmental pressure from land use change and other regional and global processes (Zomer et al., 2014; Rashid et al., 2015; Choi et al., 2019). Biomes shift not only serves as a signal of climate change but also provides important information for resources management and ecotone ecosystem conservation. A widespread upward encroachment of subalpine forests would displace regionally unique alpine tundra habitats and possibly cause the loss of alpine species (Schickhoff et al., 2015). In the North Asia, emissions from fires reduce forest ability to regulate climate. A warmer and longer growing season will increase vulnerability to fires, although fires can be attributed both to climate warming and to other human and natural influences. Recent field-based observations revealed that the forests in southern Siberia are losing their ability to regenerate post fire and other landscape disturbances under a warming climate (Brazhnik et al., 2017). Data support the hypothesis of climate-driven increase of fire frequency in boreal forests with the possible turning of boreal forests from carbon sink to a carbon source (Ponomarev et al., 2016; Schaphoff et al., 2016; Brazhnik et al., 2017; Ponomarev et al., 2018), however warming resulted from forest fire is partly compensated by cooling in response to increased surface albedo of burned areas in snow-on period (Chen and Loboda, 2018; Chen et al., 2018a; Jia et al., 2019; Lasslop et al., 2019).

10.4.2.4 Adaptation Options

Modelling of the interactions between climate-induced vegetation shifts, wildfire and human activities can provide keys to how people in Asia may be able to adapt to climate change (Kicklighter et al., 2014; Tian et al., 2020). Conservation and sustainable development would benefit from being tailored and modified considering the changing climatic conditions and shifting biomes, mountain belts and species ranges (Pörtner et al., 2021). Expanding the nature reserves would help species conservation; to facilitate species movements across climatic gradients, increase of landscape connectivity can be elaborated by setting up habitat corridors between nature reserves and along elevational and other climatic gradients (Brito-Morales et al., 2018; D'Aloia et al., 2019; United Nations Climate Change Secretariat, 2019). Assisted migration of species should be considered for isolated habitats as mountain summits or where movements are constrained by poor dispersal ability. Introducing seeds of the species to new regions will help to protect them from the extinction risk caused by climate change (Mazangi et al., 2016). In Asian boreal forest, a strategy and an integrated programmes should be developed for adaptation of forests to global climate change, including sustainable forest management, firefighting infrastructure and forest fuel management, afforestation, institutional, social, and other measures in line with SDG 15 'Life on Land' (Isaev and Korovin, 2013; Kattsov and Semenov, 2014; Government, 2020). Improvements in forest habitat quality can reduce the negative impacts of climate change on biodiversity and ecosystem services (Choi et al., 2021). Adaptation options for freshwater ecosystems in Asia include increasing connectivity in river networks, expanding protected areas, restoring hydrological processes of wetlands and rivers, creating shade to lower temperatures for vulnerable species, assisted translocation and migration of species (Hassan et al., 2020; IPCC, 2021b). Reducing of non-climate anthropogenic impacts can enhance the adaptive capacity of ecosystems (Tchebakova et al., 2016).

[START BOX 10.3 HERE]

Box 10.3: Case Study on Sand and Dust Storm, Climate Change, in West Asia, Iran

West Asia Region, especially Tigris-Euphrates alluvial plain, has been recognised as one of the most important dust source areas in the world (Cao et al., 2015). The inhabitants of each of these settlements have experienced a decline in dust storms in recent decades, since the late 1980s at Nouakchott, since 2004 at Zabol, and since the late 1970s at Minqin. Iran is mostly arid or semiarid, with deserts making up at least 25 million hectares of the country's area (NASA, 2018). Iran is experiencing unprecedented climate-related problems such as drying of lakes and rivers, dust storms, record-breaking temperatures, droughts, and floods (Vaghefi et al., 2019). There are three key factors responsible for the generation of sand and dust storms – strong wind, lack of vegetation and absence of rainfall (EcoMENA, 2020). It seems that it is closely related to the heating surface and the occurrence of local dry instabilities (Ghasem et al., 2012). According to

EcoMENA sand and dust storms cause significant negative impacts on society, economy and environment at local, regional and global scale (EcoMENA, 2020). The seasonality of the numbers of dusty days (NDD) in Iran shows the highest frequency for summer followed by the spring and autumn seasons (Modarres and Sadeghi, 2018). In the past decade, West Asia has witnessed more frequent and intensified dust storms affecting Iran and Persian Gulf countries (Nabavi et al., 2016). In terms of long-term frequency of dust events, observational analyses show an overall rising trend of the frequency of Iran's dust events in recent years (Alizadeh-Choobari et al., 2016). Results showed that there was a direct relationship between dust event and drought and years having intensive drought (Dastorani and Jafari, 2019). Compared to the period of 1980–2004, in the period of 2025–2049, Iran is *likely* to experience more extended periods of extreme maximum temperatures in the southern part of the country, more extended periods of dry (for ≥120 days: precipitation <2mm, Tmax ≥30°C) as well as wet (for ≤3 days: total precipitation ≥110mm) conditions, and higher frequency of floods (Vaghefi et al., 2019). The slope of precipitation, in West Asia region showed that during the period of 2016-2045 in January, February, July and August, precipitation would increase and decrease in other months of the year (Ahmadi et al., 2018). Temperatures in Central Asia have risen significantly within the last decades whereas mean precipitation remains almost unchanged (Haag et al., 2019). However, climatic trends can vary greatly between different sub-regions, across altitudinal levels, and within seasons (Haag et al., 2019).

[END BOX 10.3 HERE]

10.4.3 Ocean and Coastal Ecosystems

Coastal habitats of Asia are diverse and the impacts of climate change including rising temperature, ocean acidification and sea level rise has been known to affect the services and the livelihood of people depending on it. The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*) (IPCC, 2018b). In South China Sea coral growth and sea surface temperature (SST) showed regional long tern trends and inter-decadal variations while coral growth is predicted to decline by the end of this century (Yan et al., 2019). Increasing human impacts have also been found to reduce coral growth (Yan et al., 2019). In the SCS, nearly 571 coral species, have been severely impacted by global climate changes and anthropogenic activities (Huang et al., 2015a).

The 2014–2017 global-scale coral bleaching event (GCBE) resulted in very high coral mortality on many reefs, rapid deterioration of reef structures, and far-reaching environmental impacts (Eakin et al., 2019). The thermally tolerant Persian Gulf corals (Coles and Riegl, 2013) are facing an increasing frequency of mass bleaching (Riegl et al., 2018) and each event leaves a substantial long-term impact on coral communities (Burt, 2014) with low capacity for recovery indicating a bleak future for Persian Gulf reefs (Burt et al., 2019).

One of the probable results of global warming is rising high seas level. Scientists believe that increasing greenhouse gases (earth temperature controller) is the reason of this global warming and by using satellite measurements, have forecasted averagely 1-2 mm for rising high seas level (Jafari et al., 2016). The level of thermal stress (based on a degree heating month index, DHMI) at these locations during the 2015–2016 El Niño was unprecedented and stronger than previous ones (Lough et al., 2018) Persian Gulf the reef-bottom temperatures in 2017 were among the hottest on record, with mean daily maxima averaging 35.9 ± 0.10C across sites, with hourly temperatures reaching as high as 37.7o C (Riegl et al., 2018). About 94.3% of corals bleached, and two-thirds of corals suffered mortality in 2017 (Burt et al., 2019). In 2018 coral cover averaged just 7.5% across the southern basin of the Persian Gulf. This mass mortality did not cause dramatic shifts in community composition as earlier bleaching events had removed most sensitive taxa. An exception was the already rare Acropora which were locally extirpated in summer 2017 (Burt et al., 2019). During 2008-2011 also the coral communities of Musandam and Oman have shown changes depending on the stress tolerance levels of the species and the local environmental disturbance level (Bento et al., 2016).

Health and resilience of corals have been found to be associated with beneficial microorganisms of coral (BMC) which alter during environmental stress. Increased seawater temperature has been found to affect the functioning of symbiotic algae of corals (Lough et al., 2018) (Gong et al., 2019) and its bacterial consortia leading to coral bleaching and mortality (Bourne et al., 2016); (Peixoto et al., 2017); (Bernasconi et al., 2019); (Motone et al., 2020).

Coral reefs were found to be affected differentially during bleaching episodes and those species which survived had more stress tolerant symbionts and higher tolerance to thermal changes (Majumdar et al., 2018); (Thinesh et al., 2019) (van der Zande et al., 2020). Rare thermally tolerant algae and host species-specific algae may play important roles in coral bleaching (van der Zande et al., 2020). Along the Indian coast, coral reefs of Palk Bay (Bay of Bengal), varied bleaching and recovery pattern among coral genera was observed during the 2016 bleaching episode (Thinesh et al., 2019). Bleaching was high in Acropora (86.36%), followed by Porites (65.45%), while moderate to no bleaching was observed in Favites Symphyllia, Favia, Platygyra and Goniastrea.

Presence of stress-tolerant symbiont Durusdinium (Clade D) during the post bleach period indicated the high adaptive capacity of Acropora in tropical waters (Thinesh et al., 2019). Also Porites sp. were found to have higher thermal thresholds and showed good resilience to bleaching than species like Fungiid sp. (Majumdar et al., 2018). In Philippines, during the 2010 bleaching event, the size structure of the mushroom coral was found to be affected (Feliciano et al., 2018). In Indonesia , it was found that branching coral diversity may decrease relative to massive, more resilient corals (Hennige et al., 2010). This would have large-scale impacts upon reef bio-diversity and ecosystem services, and reef metabolism and net reef accretion rates, since massive species are typically slow growers (Hennige et al., 2010).

Macro-tidal coral reefs are particularly sensitive to medium to long-term changes in sea-level Andaman trenches (Simons et al., 2019). Data were compiled from 11 cities throughout East and Southeast Asia, with particular focus on Singapore, Jakarta, Hong Kong, and Naha (Okinawa) highlights several key characteristics of urban coral reefs, including "reef compression" (a decline in bathymetric range with increasing turbidity and decreasing water clarity over time and relative to shore), dominance by domed coral growth forms and low reef complexity, variable city-specific inshore-offshore gradients, early declines in coral cover with recent fluctuating periods of acute impacts and rapid recovery, and colonisation of urban infrastructure by hard corals (Heery et al., 2018).

In Taiwan, Province of China, calcification rate of the model reef coral *Pocillopora damicornis* was higher in coral reef mesocosms featuring seagrasses under ocean acidification conditions at 25 and 28°C. The presence of seagrass in the mesocosms helped to stabilise the metabolism of the system in response to simulated climate change (Liu et al., 2020a).

Increase in host susceptibility, pathogen abundance or virulence has led to higher prevalence and severity of coral diseases and lead to decline and changes in coral reef community composition (Maynard et al., 2015) . Relative risk has been found to be high in the province of Papua in Indonesia, Philippines, Japan, India, northern Maldives, the Persian Gulf and the Red Sea. For the combined disease risk metric, relative risk was considered lower for locations where anthropogenic stress was low or medium, condition found for some of these locations in Thailand (Maynard et al., 2015).

Degradation and loss of coral reefs can affect about 4.5 million people South East Asia and Indian Ocean (Lam et al., 2019). In the coral reef fisheries sector, there are about 3.35 million fishers in Southeast Asia and 1.5 million fishers in the Indian Ocean (Teh et al., 2013). The economic loss under different climate change scenarios and fishing effort were estimated to range from US$27.78 to US$31.72 million annually in Nha rang Bay, Vietnam. A survey conducted in Taiwan, Province of China, showed that the average annual personal willingness to pay was US$35.75 and total annual willingness to pay as US$0.43 billion. These high values indicate the need to preserve these coral reef ecosystems (Tseng et al., 2015). In Bangladesh the coral reef of St. Martin's Island contributes 33.6 million USD/year to the local economy climate change along with other anthropogenic activities has been identified as a threat these habitats (Rani et al., 2020a).

Mitigation of global warming has been identified to be essential to maintain healthy coral reef ecosystems of Asia (Comte and Pendleton, 2018); (Heery et al., 2018); (Yan et al., 2019); (Lam et al., 2019). Restoration of reefs (Nanajkar et al., 2019) and building resilience through multiple mechanisms, such as innovative policy combinations, complemented by environmental technology innovations and sustained investment (Hilmi et al., 2019); (McLeod et al., 2019) are suggested.

An ecosystem-based approach to managing coral reefs in the Gulf of Thailand is needed to identify appropriate marine protected area networks and to strengthen marine and coastal resource policies in order to build coral reef resilience (Sutthacheep et al., 2013). Scope to develop novel mitigation approaches toward coral protection through the use of symbiotic bacteria and their metabolites (Motone et al., 2018); (Motone et al., 2020) has been suggested. Coral culture and transplantation within the Gulf are feasible for helping maintain coral species populations and preserving genomes and adaptive capacities of Gulf corals that are endangered by future thermal stress events (Coles and Riegl, 2013). Greater focus on understanding the flexibility and adaptability of people associated with coral reefs, especially in a time of rapid global change (Hoegh-Guldberg et al., 2019) and a well-designed research program for developing a more targeted policy agenda (Lam et al., 2019). is also recommended. Cutting carbon emissions (Bruno and Valdivia, 2016) and limiting warming to below 1.5˚C is essential to preserving coral reefs worldwide and protecting millions of people (Frieler et al., 2013) (Hoegh-Guldberg et al., 2017). Many visitors to coral reefs have high environmental awareness and reef visitation can both help to fund and to encourage coral reef conservation (Spalding et al., 2017).

The largest mangrove forests are in Asia contributing to about 42% of the world's mangroves and this includes Sundarbans the world's largest remaining contiguous mangrove forest (Dasgupta et al., 2020.). Mangrove ecosystems are rich in biodiversity. The ecosystems are supported and maintained by both flora and a large array of living things, which include mammals, birds, fish, crustaceans, shrimps, insects and microbes (Tropical Coastal Ecosystems Portal. Available from http://www.nies.go.jp/TroCEP/index.html. Accessed 08-Oct. 2020). Contemporary rates of mangrove deforestation are lower than in the late twentieth century (Gandhi and Jones, 2019); (Friess et al., 2019). However, some areas in Asia continue the trend. Myanmar is the primary mangrove loss hotspot in Asia, exhibiting 35% loss from 1975–2005 and 28% between 2000–2014. Rates of loss in Myanmar were four times the global average from 2000–2012. The Philippines is additionally identified as a loss hotspot, with secondary hotspots including Malaysia, Cambodia and Indonesia (Gandhi and Jones, 2019).

Mangrove deforestation is expected to increase as many tropical nations utilise mangrove areas for economic security. Increased river damming would reduce fluvial sediment sources to the coast making mangroves more vulnerable SLR and uncertain climate with extreme oscillations can create unstable conditions for survival and propagation of mangrove (Friess et al., 2019).

Valuation of ecosystem services of mangroves indicated that they prevent more than 1.7 billion US$ in damages for extreme events (1-in-50-year) in Philippines (Menéndez et al., 2018). They reduce flooding to 613,500 people/year, 23% of whom live below the poverty line and avert damages to 1 billion US$/year in residential and industrial property. Mangroves have also become very popular as source of livelihood in Asia through tourism (Dehghani et al., 2010),(Kuenzer and Tuan, 2013), (Spalding and Parret, 2019) (Dasgupta et al., 2020.) and they support fisheries (Hutchison et al., 2014).

Mangroves, tidal marshes and seagrass meadows (collectively called coastal blue carbon ecosystems) sequester carbon dioxide from the atmosphere continuously over thousands of years, building stocks of carbon in biomass and organic rich soils. Carbon dynamics in mangrove-converted aquaculture in Indonesia indicated that the mean ecosystem carbon stocks in shrimp ponds were less than half of the relatively intact mangroves (Arifanti et al., 2019). Conversion of mangroves to shrimp ponds in the Mahakam Delta resulted in a carbon loss equivalent to 226 years of soil carbon accumulation in natural mangroves. In Philippines, abandoned fishpond reversion to former mangrove was found to be favourable for enhancing Climate Change Mitigation and Adaptation (Duncan et al., 2016). Integrated mangrove-shrimp farming, with deforested areas not exceeding 50% of the total farm area has been suggested to support both carbon sequestration as well as livelihood (Ahmed et al., 2018).

Globally the extent of blue carbon ecosystem has been estimated as 120380 km^{-2}, with highest spread by mangroves 114669 km^{-2}, (95.3%) followed by seagrass meadows 2201 km^{-2}, (1.8%) and salt marshes 3510 km^{-2}, (2.9%) (Himes-Cornell et al., 2018). In Asia, the total extent of these three ecosystems is 33224 km^{-2}, forming 27.6% of the global with highest spread of mangrove 32767 km^{-2}, which forms 28.6% of the global mangrove coverage. Area of seagrass meadows spread in Asia has been estimated as 236 km^{-2} and salt marsh 220 km^{-2},which forms 10.8% and 6.03% of the respective ecosystems globally (Himes-Cornell et al., 2018). Found at the interface between the land and the sea, seagrasses provide varied services apart from acting as ecosystem engineers providing shelter and habitat for several marine fauna which are fished in several Asian countries (Nordlund et al., 2018); (Jeyabaskaran et al., 2018); (Unsworth et al., 2019b) thereby providing livelihood to millions across the continent (UNEP, 2020).

The seagrass meadows are also good sinks of carbon (Fourqurean et al., 2012) capable of storing 19.9petagrams (Pg) organic carbon, but with very high regional and site and species variability (Ganguly et al., 2017);(Stankovic et al., 2018); (Gallagher et al., 2019); (Ricart et al., 2020). As highly efficient carbon sinks, these store up to 18 percent of the world's oceanic carbon and they also reduce the impacts of ocean acidification (UNEP, 2020).

The deterioration of this ecosystem is fast, 7% per year since 1990 (Waycott et al., 2009) which led to development of restoration protocols across Asia (Paling, 2009); (van Katwijk et al., 2016). In Vietnam, the loss of seagrass has been estimated as above 50% and in some regions complete loss has been observed (Van Luong et al., 2012). The seagrass meadows of Indonesia are fast deteriorating, and the need for increased local level autonomy for the management of marine resources and restoration have been highlighted (Unsworth et al., 2018). The need to develop science based policies for conservation including participatory methods (Fortes, 2018); (Ramesh et al., 2019) ;(Unsworth et al., 2019a), and large scale planting (van Katwijk et al., 2016) have been recommended to preserve the ecosystem services of these habitats.

Globally, the diversity of the plankton community has been predicted to be affected by warming and related changes (Ibarbalz et al., 2019) and these changes are expected in Asia also. Combined effects of high temperature, ocean acidification and high light exposure would affect important phytoplankton species in the SCS, *Thalassiosira pseudonana* (Yuan et al., 2018) and *Thalassiosira weissflogii.* (Gao et al., 2018b). Also in SCS the phytoplankton assemblage responses to rising temperature and CO2 levels were found to differ between coastal and offshore waters and the predicted increases in temperature and pCO2 may not boost surface phytoplankton primary productivity (Zhang et al., 2018).

Ocean warming and acidification can affect the functioning and ecological services of sedentary molluscs like the bivalves (Guo et al., 2016); (Zhao et al., 2017b); (Cao et al., 2018); (Zhang et al., 2019c); (Liu et al., 2020b) and gastropods(Leung et al., 2020) and also sea urchins (Zhan et al., 2020). The oyster *Crassostrea gigas* becomes more vulnerable to disease when exposed to acidification conditions and pathogen challenge indicating incapability for supporting long term viability of the population (Cao et al., 2018). More tolerance and benefits to rising pCO2 was observed in clam species like *Paphia undulate* which has been attributed to adaptation to its acidified sediment habitat (Guo et al., 2016). Warming boosted the energy budget of the marine calcifiers like the gastropod *Austrocochlea concamerata*, by faster shell growth and greater shell strength making them more mechanically resilient while acidification negatively affected the shell building thereby impacting the physiological adaptability (Leung et al., 2020). It is expected that there will be transgenerational acclimation to changes in ocean acidification in marine invertebrates (Lee et al., 2020b).

Assessment of the potential impacts and the vulnerability marine biodiversity in the Persian Gulf under climate change suggested a reduction of upto 35% of initial species richness and habitat loss for hawksbill turtles in south and southwestern parts of the Persian Gulf (Wabnitz et al., 2018).

Seaweeds are important biotic resource capable of capturing carbon and used widely as food, medicine and as raw material for industrial purposes. Warming and altered pH can affect seaweeds indifferent ways (Gao et al., 2016); (Gao et al., 2017); (Gao et al., 2018a), (Wu et al., 2019b). Outbreak of intense blooms of species like *Ulva rigida* (Gao et al., 2017) and *Ulva prolifera* (Zhang et al., 2019f) have increased due to varied factors including climate change. These have created huge economic losses in Yellow sea affecting local mariculture, tourism and the functioning of the coastal and marine ecosystems (Zhang et al., 2019f). Increased temperature was found to enhance the dark respiration (Rd) and light compensation point (EC) of *Ulva conglobate*, which thrives in the mid-intertidal to upper subtidal zones while the altered pH showed a limited effect (Li et al., 2020). Elevated temperature significantly enhanced growth, photosynthetic performances and carbon use efficiency of *Sargassum horneri* in both elevated and ambient CO2 levels suggesting that the present greenhouse effect would benefit the golden tide blooming macroalgae *Sargassum horneri*, which might enhance both the frequency and scale of golden tide (Wu et al., 2019b).

10.4.3.1 Key drivers to vulnerability

The vulnerabilities to disaster in coastal regions with high population densities are reported in several studies. (Sajjad et al., 2018) assessed the vulnerabilities of coastal community along the Chinese coast and showed that roughly 25% of the coastline and more than 5 million residents are in highly vulnerable coastal areas of mainland China, and these numbers are expected to double by 2100. Husnayaen et al. (2018) assessed along the Semarang coast in Indonesia and showed that 20% of the total coastline (48.7 km) is determined as a very high vulnerability. Mangroves continue to face threats due to pollution, conversion for aquaculture, agriculture, apart from Climate based threats like SLR and sea erosion (Richards and Friess, 2016; Romañach et al., 2018; Wang et al., 2018b) (Friess et al., 2019). Hypersalinity, storm effects sediment deposition, fishery development and land erosion are mainly responsible for most part of Sunderban mangrove degradations leading to loss of livelihood (Uddin, 2014); (Paul, 2017). In the Sunderbans of Asia, climate change is expected to increase river salinisation, which in turn could significantly negatively impact the valued timber species, *Heritiera fomes* (Dasgupta et al., 2017b). Augmented potential for honey production is also predicted which can increase man –wildlife conflict (Dasgupta et al., 2017b).

Destruction by natural hazards was found to remove the above ground C pool, but the sediment C pool was found to be maintained (Chen et al., 2018b). In Andaman & Nicobar islands the 2004 Indian Ocean Tsunami severely impacted the mangrove habitats at the Nicobar Islands (Nehru and Balasubramanian, 2018),while new inter-tidal habitats suitable for mangrove colonisation developed. Mangrove species with a wide distribution and larger propagules (showed high colonisation potential in the new habitats compared to other species (Nehru and Balasubramanian, 2018) Mangrove sites in Asia are predominantly minerogenic so continued sediment supply is essential for the long-term resilience of Asia's mangroves to SLR (Lovelock et al., 2015; Balke and Friess, 2016; Ward et al., 2016a; Ward et al., 2016b) .

10.4.3.2 Observed impacts

Primary production in Western Indian Ocean showed a reduction by 20% during the last six decades, attributed to rapid warming and ocean stratification which restricted nutrient mixing (Roxy et al., 2016) . Variation in secondary production- zooplankton densities and biomass in the East Asian Marginal Seas (EAMS) affected the recruitment of fishes due to mismatch in spawning period and larval feed availability during the last three Climate Regime Shifts (CRS) in the mid-1970s, late 1980s, and late 1990s, which were characterised by North Pacific Index (NPI) and Pacific Decadal Oscillation index (PDOI) (Kun Jung et al., 2017). In the western North Pacific Climate change has affected recruitment, and population dynamics of pelagic fishes like sardine and anchovy (Nakayama et al., 2018) and also shifts in the spawning ground and extension of spawning period in the chub mackerel *Scomber japonicas* (Kanamori et al., 2019).

Varied response to CRS Chinese Seas was observed for small pelagic (Ma et al., 2019) and Cephlalopods (Ichii et al., 2017). The winter and summer SSTs showed evidence of decadal variability with abrupt changes from cold to warm in substantial association with climate indices to which coastal cephalopods in China Seas responding differentially; some benefitting from warmer environment while others responded negatively (Pang et al., 2018). In the western and eastern North Pacific marine ecosystem it is indicated that groundfish may suffer more than pelagic fish (Yati et al., 2020) . Habitat Suitability Index models using SST, Chl-a, SSHA and SSS and fishing effort strongly indicated that Neon flying squid is affected by inter-annual environmental variations and it undertakes short term migrations to suitable habitat affecting the fisheries (Yu et al., 2015). The 2015-16 El Nino was found to impact coral reefs of shallower regions (depth of 5–15m) in South Andaman than those beyond 20 m (Majumdar et al., 2018). In the southeast coast of India, bleaching largely mediated by the SST anomaly and during the recovery period macro-algae outgrowth was observed (2.75%) indicating impacts on the benthic community (Ranith and Kripa, 2019). In South China Sea the increase in SST was found to be at a higher than the predicted in recent decade while the pH decreased at a rate of 0.012–0.014/year, more than the predicted due to high microbial respiratory processes releasing CO2 (Yuan et al., 2019). Simulation experiments showed differential adaption capacity of common species (Zheng, (2019).) (Yuan et al., 2019).

The Nations (2019) report on climate action and support trends have highlighted that the impacts of climate change on coastal ecosystems are mainly increased risks due to flooding, inundation due to extreme events, coastal erosions, ecosystem processes and on fisheries as variations in population or stock structures due to ocean circulation pattern, habitat loss degradation and ocean acidification. Analysis of data on occurrence of varied natural hazards from 1900 to 2019 (120 years) has shown that tropical cyclones, riverine floods and droughts have increased significantly and the impacts of these on coastal communities are also severe and destructive. The UNs average score for SDG Goal 14 (life under water) for Asia was estimated as 46 from scores of 40 nations and the Ocean Health Biodiversity index was comparatively high (average 87.9). However, the indices show that more region specific action plans are required to the achieve the UN 2030 goal for life under water.

Apart from the human community level impacts, the ecology and resource abundance of coastal waters have been found to be impacted by extreme events. During tropical cyclones ecological variations like lowering of SST, increase on chlorophyll a and decrease in oxygen (Chacko, 2019); (Girishkumar et al., 2019) have been observed. Global analysis on such events have indicated that these may have impact on the fishery directly by creating unfavourable ecological conditions and destruction of critical habitats indirectly by affecting the eggs and larvae and subsequent fishery recruitment (McKinnon et al., 2003); (Bailey and Secor, 2016). In South China Sea in July 2000, during a 3-day cyclone period, an estimated 30-fold increase in surface chlorophyll-a concentration was observed (Lin et al., 2003). The estimated carbon fixation resulting from this event alone is 0.8 Mt, or 2–4% of SCS's annual new production (Lin et al., 2003). Since an average of 14 cyclones pass over this region annually, the contribution of cyclones to annual new production has been estimated to be as high as 20-30% (Lin et al., 2003).

10.4.3.3 Projected impacts

Water pollution and climate stressors have been considered as major challenges to ecosystem sustainability and now it has been shown that the combined effect these two stressors would be more damaging (Buchanan et al., 2019). For seagrass beds the pollution stress was found to increase by 3.5% (from 39.7 % to 42.3%) when climate factors were added. Assuming the pollution levels to remain at 2014 levels different scenarios including RCP 2.6 and RCP 8.5 were worked out for Behoi Sea and the results indicated amplification of the impacts on ecosystem. Pollutants like Petroleum Hydrocarbons, Dissolved inorganic nitrogen and Soluble Reactive Phosphorus were the major pollution stressors (Lu et al., 2018) In the future, policies focused strictly on pollution control should be changed and should take into account the interactive effects of climate change for better forecast and management of potential ecological risks (Lu et al., 2018).

Projected changes in catch potential (%) by 2050 and 2100 relative to 2000 under RCP2.6 and RCP8.5 based on outputs from the dynamic bio-climate envelop model and the dynamic size-based food web models indicate that the marine and coastal resources of most Asian countries will be impacted with varying intensity (FAO, 2018b).

Better management of resources through projections of resource distribution, abundance and catch is required. However, lack of data (e.g., oceanographic surveys) and scientific knowledge is a constraint to this aim (Maung Saw Htoo et al., 2017). Effective forecasts of areas of resource abundance based on habitat preference have to be worked out for Asian region. Research Programs like EAF Nansen

Modelling and assessment of the vulnerability and habitat suitability of the Persian Gulf for 55 species to climate change indicated that there is a high rate of risk of local extinction in the southwestern part of the Persian Gulf, off the coast of Saudi Arabia, Qatar and the United Arab Emirates (UAE). Likelihood of reduced catch was observed and Bahrain and Iran were found to be more vulnerable to climate change(Wabnitz et al., 2018). Projected changes in fish catches can impact the supply of fish available for local consumption (i.e., food security) and exports (i.e., income generation) (Wabnitz et al., 2018). As per (UNESCAP, 2018a) Over 40 percent of coral reefs and 60 percent of coastal mangroves in the Asia-Pacific Region have already been lost, and approximately 80 percent of the region's coral reefs are currently at risk.

Regionally, the escalation in thermal stress estimated for the different global warming scenarios is greatest for Southeast Asia and least for the Pacific Ocean (Lough et al., 2018). For the 100 reef locations examined here and given current rates of warming, the 1.5 °C global warming target represents twice the thermal stress they experienced in 2016 (Lough et al., 2018).

In the southeast Asian region threats from both warming and acidification has indicated that by 2030, 99 percent of reefs will be affected and by 2050, 95 percent s are expected to be in the highest levels of threatened category (Burke et al., 2011), similar to global corals (Frieler et al., 2013), (Bruno and Valdivia, 2016) . Modelling results indicate that even under RCP scenarios the functional traits of coral reefs can be affected (van der Zande et al., 2020) and coral communities will mainly consist of small numbers of temperature-tolerant and fast-growing species (Kubicek et al., 2019). Increases in temperature (+3˚C) and pCO2 (+400 matm) projected for this century can reduce the sperm availability for fertilisation, which along with adult population decline either due to climate change or anthropogenic impacts (Hughes et al., 2017) can affect the coral reproductive success thereby reducing the recovery of populations and their adaption potential (Albright and Mason, 2013); (Hughes et al., 2018); (Jamodiong et al., 2018). In the southern Persian Gulf increased disturbance frequency and severity caused progressive reduction in coral size, cover, and population fecundity (Riegl et al., 2018), and this can lead to functional extinction. Connectivity required to avoid extinctions increased exponentially with disturbance frequency and correlation of disturbances across the metapopulation. In Philippines experiments have also proved that for Scleractinian corals like *A. tenuis, A. millepora* and *F. colemani* that spawn their gametes directly into the water column may experience limitations from sperm dilution and delays in initial sperm-egg encounters that can impact successful fertilisation (dela Cruz and Harrison, 2020).

Apart from these, threats, natural hazards have also been found to affect coral reefs of Asia. The extensive and diverse coral reefs of Muscat, Oman in the northeastern Arabian Peninsula were found to have long-term effects of Cyclone Gonu, which struck the Oman coast in June 2007 more than coastal development (Coles et al., 2015).

Sandy beaches are subject to highly dynamic hydrological and geomorphological processes, giving them more natural adaptive capacity to climate hazards (Bindoff et al., 2019). Progress is being made toward models that can reliably project beach erosion under future scenarios despite the presence of multiple confounding drivers in the coastal zone (AR6 WG2, Chap.3). Assuming minimal human intervention estimate impacts of SLR by 2100 under RCP8.5-like scenarios, 57–72% of Thai beaches (Ritphring, 2018), at least 50% loss of area on around a third of Japanese beaches (Mori, 2018) will disappear.

Marine heat waves (MHW) have been making changes in the structure and functioning of coastal and marine ecosystems (Kim and Han, 2017); (Oliver et al., 2017); (Oliver et al., 2019); (Frölicher and Laufkötter, 2018); (Smale et al., 2019) affecting resources like copepods (Doan et al., 2019) and coral reefs (Zhang et al., 2017c). in Asia. Coral reefs of Southeast Indian Ocean have been affected by marine MHW (Zhang et al., 2017c).

Simulation of RCP scenarios have shown that continued warming can drive a pole-ward shift in distribution of the seaweed Ecklonia cava of Japan and under the lowest emission scenario (RCP2.6), most population may not be impacted, but under highest emission scenario (RCP 8.5) the existing habitat may become unsuitable and it can also increase predation by herbivorous fishes (Takao et al., 2015).

10.4.3.4 Adaptation options

The Nations (2019) has identified establishment of protected areas, restoring ecosystems like mangroves / coral reefs, integrated coastal zone management practices, sand banks and structural technologies and implementing local monitoring networks for increasing adaptive capacity and protecting biodiversity of coastal ecosystem. In Asia, management of marine sites by earmarking protected areas (SDG 14) has been found to be low with only 27% area being protected. In India detailed climate change adaptation guideline coastal protection and management has been prepared considering various environmental and social aspects (Black et al., 2017). The Ocean Health Index for clean waters was also low, 54.6 and the threat to the ecosystem due to combined effect of pollution and climate change was high. Table 10.2 shows the ocean and Marine Protected Areas (MPA).

Table 10.2: Status of Ocean and MPA. Data Source: (Sachs et al., 2018)

	Ocean Health Index - Clean waters (0-100)	Fish stocks overexploited or collapsed (%)	Ocean Health Index - Fisheries (0-100)	Fish caught by trawling (%)	Ocean Health Index - Biodiversity (0-100)	Marine sites, mean protected area (%)
Eastern Asia	54.0	29.1	49.5	39.8	89.6	32.5
South-Eastern Asia	54.1	28.5	54.9	34.7	84.6	25.0
Western Asia	54.3	28.3	46.2	20.4	89.4	18.3
Southern Asia	50.3	17.4	51.0	15.1	88.3	41.2
Northern Asia	91.6	55.4	57.6	60.0	93.4	30.0
Asia	54.6	26.9	50.3	27.3	87.9	27.0

Conservation and Restoration of mangrove were found to be effective tools for enhancing ecosystem carbon storage and an important part of Reducing Emissions from Deforestation and forest Degradation plus (REDD+) schemes and climate change mitigation (Ahmed and Glaser, 2016). In East Asia restoration success has been attributed to right geomorphological locations (Van Cuong et al., 2015; Balke and Friess, 2016) and co-management models (Johnson and Iizuka, 2016; Veettil et al., 2019).

In South Asia, restoration programs have been largely successful (Jayanthi et al., 2018) but in some regions partly a failure due to inappropriate site selection, poor post planting care and other issues (Kodikara et al., 2017). Using remote sensing it was observed that there are high recovery rates of mangroves in a relatively short period of time (1.5 years) after a powerful typhoon indicating that natural recovery and regeneration would be a more economically and ecologically viable strategy. Better mangrove management through mapping is suggested (Castillo et al., 2018) (Gandhi and Jones, 2019). Statistical tools developed for modelling biomass and timber volume (Phan et al., 2019) and allometric models to estimate aboveground biomass and carbon stocks (Vinh et al., 2019) will be useful in estimating stocks in mangroves. Future mangrove loss may be offset by increasing national and international conservation initiatives that incorporate mangroves, such as the Sustainable Development Goals, Blue Carbon, and Payments for Ecosystem Services (Friess et al., 2019). Since seagrass meadows and marine macroalage are important habitats capable of combating impacts of climate change, the need for a global networking system with participation of stake holders has been suggested (Duffy et al., 2019).

10.4.4 Freshwater Resources

In Asia, freshwater resources, an important component of ecosystem services, are widely used for agriculture, domestic, irrigation, navigation, energy, industrial and ecosystem uses and services. Freshwater availability is changing at the global scale because of unsustainable use of surface and groundwater, pollution and other environmental changes. These changes in space and time, directly or indirectly, affect water use sectors and services (Wheater and Gober, 2015) (Rodell et al., 2018). About 82% of the global population served by freshwater provisions from upstream areas exposed to high threat (Green et al., 2015). Given that some of the fastest growing economies in the world today are in Asia, and the geographies of development are highly uneven, both climatic and non-climatic drivers such as socio-economic changes have contributed to water stress conditions in both water supply and demand in diverse sub-regions of Asia. In case of Asia therefore the entanglement between the non-climatic and climatic drivers makes it difficult to attribute environmental changes –both present and projected—neatly and exclusively to climatic drivers.

Immerzeel et al. (2020) has ranked all mountain-dependent water towers according to their water-supplying role and the downstream dependence of ecosystems, societies and economies. The resulting Global Water Tower Index (WTI) indicates that the upper Indus basin is both the most important and the most vulnerable Water Tower Unit (WTU) in the world. A WTU is defined as 'the intersection between major river basins and a topographic mountain classification based on elevation and surface roughness'. Whereas all important transboundary WTUs in Asia remain highly vulnerable, it is the Indus WTU (inhabited by approximately 235 million people in the basin in 2016, which is projected to increase by 50% by the middle of 21st century) where the average annual temperature is projected to increase by 1.9 °C between 2000 and 2050, with wide-ranging consequences and trans-sectoral spill overs. The Indus WTU faces a deep risk produced by a combination of factors including water stress, ineffective governance, hydro-political tensions, population growth and density, urbanisation and social transformations; with a significant bearing on SDG 6 on water, SDG 2 on food and SDG 7 on energy.

10.4.4.1 Key Drivers

Across Asia and its various sub-regions, the key drivers behind an increasingly inadequate supply of freshwater resources, affecting the livelihood security of millions, are varied, complex, and intersect with multiple social, cultural, economic and environmental stressors (Luo et al., 2017) (Tucker et al., 2015; Kongsager et al., 2016). Water stress' has been defined as the situation "when the demand for water exceeds its supply, during a certain period of time, or when poor quality restricts its use''(Felberg et al., 1999). See also Figure 4.32 in Lee et al. (2021a).

Freshwater resources in Asia, which include both surface water and groundwater, are considerably strained and changing climate is *likely* to act as a major stress multiplier (Fant et al., 2016) (Gao et al., 2018c) (Mack, 2018) (Dasgupta et al., 2015). In Southern and Eastern Asia (SEA) nearly 200 million people are at risk of serious water-stressed conditions. Effective mitigation might reduce the additional population-under-threat by 30% (60 million people), still there is a 1-in-2 chance that 100 million people across SEA might face a 50% increase in water stress and 1-in-10 chance that water stress would almost double in the absence of wide-ranging, multi-scalar adaptive measures (Gao et al., 2018c). In the absence of Millennium Development Goal 7c, that aimed to halve the population that had no sustainable access to water and basic sanitation before 2015, not been fully realised and sustainable development goals (SDG) 6 on water and sanitation not been effectively operationalised, the water-stress is *likely* to increase by the end of 2030 (Weststrate et al., 2019).

In Asia and elsewhere the interplay between the challenge of sustainability and climate change poses major policy challenges (von Stechow et al., 2016). The pursuit of SDG 6 —protection and restoration of water-related ecosystems, universal and equitable access to safe and affordable drinking water for all, improvement in water quality by reducing pollution, elimination of dumping and significant reduction in release of hazardous chemicals and materials, and treatment of wastewater through recycling and safe reuse globally—could be directly or indirectly challenged and undermined by climate change (Parkinson et al., 2019). Dissolved organic materials from sewage can enhance CO2 emission, especially in rapidly urbanising river systems which receives untreated wastewater/sewage across developing countries including Asia (Kim et al., 2019b). Conversely, policy interventions aimed at significant augmentation in water-use efficiency across all sectors, ensuring sustainable withdrawals and supply of freshwater to address water scarcity and a significant reduction in the number of victims of water scarcity, especially the poor and marginalised could mitigate vulnerabilities caused by climate change. More interdisciplinary research is needed on highly precarious future pathways and intersection between the climate and non-climate drivers in order to anticipate and mitigate diverging and uncertain outcomes.

10.4.4.2 Sub-regional Diversity

According to a quantitative scenario assessment for future water supply and demand in Asia to 2050, based on global climate change and socioeconomic scenarios (Satoh et al., 2017), water demand in sectors such as irrigation, industry, and households will increase by 30–40% around 2050 in comparison to 2010. Water stress is *likely* to be more pronounced in Pakistan, and northern parts of India and China. By mid-21st Century, the international transboundary river basins of Amu Darya, Indus, Ganges could face severe water scarcity challenges with climate change acting as a stress multiplier (*high confidence*). Within the country boundary as well, the water scarcity could be exacerbated, such as in India and China, due to various drivers like population and climate change. Research on the differentiated impact of climate change on freshwater sources across the Asian sub-regions remains inconclusive and requires assessment at sub-regional scale (IPCC, 2014b) (Wester et al., 2019).

10.4.4.3 Observed Impact

The climate change impact on different parts of freshwater ecosystems –as shown in section 10.4.2) of this chapter-- has affected water supply in various sub-regions of Asia. While headwater zones are susceptible to change in snow cover, permafrost and glaciers, the downstream plain areas of these river systems are vulnerable to increasing high demand of freshwater which will affect water availability in space and time. Observed impact of climate change has also been seen in direct physical losses such as precipitation (Mekong Delta), floods (Vietnam), salt-water intrusion leading to low agricultural productivity (Pervin et al., 2020) (Mora et al., 2018) (Almaden et al., 2019a).

The Hindu Kush-Himalaya (HKH) region extends 3500 km from Afghanistan in the west to Myanmar in the east is a source of major river systems originating in Asia, supports livelihoods, energy, agriculture and ecosystem for 240 million in the mountain and hills and 1.65 billion in the plains (Sharma et al., 2019). The HKH region stores about half of the ice mass in HMA, provisioning freshwater to almost 869 million population in the Indus, Tarim, Ganges and Brahmaputra river basins. While the warming climate increases the meltwater runoff enhancing water supply, it is indeed at the cost of glacier mass reduction that would eventually reduce meltwater and impact on the people's livelihood downstream in future (Nie et al., 2021). The melt runoff from the region play an important role in downstream agriculture such as in the case of Indus where two thirds of total irrigation withdrawal is from melt runoff in the pre-monsoon season (Biemans et al., 2019). Changes in cryosphere and other environmental changes have already impacted people living in high mountain areas and are *likely* to introduce new challenges for water, energy, and food security in the future (Rasul and Molden, 2019) (Borodavko et al., 2018; Adler et al., 2019; Bolch, 2019; Hoelzle et al., 2019; Shen et al., 2020).

With climate change impacts resulting in the shrinking and melting of snow, ice, glacier, and permafrost, and correspondingly causing increase in meltwater, the incidences of flash floods, debris flow, landslides, snow avalanches, livestock diseases, and other disasters in the HKH region have become more frequent and intense. Some of the key factors that come in the way of assigning confidence levels to climate change impacts include lack of sufficient observed data on factors such as river discharges, precipitation and glacier melt (You et al., 2017). Climate change impacts on cryospheric water sources in the Hindu Kush, Karakoram and Himalayan ranges which in turn carry consequences for the Indus, Ganges and Brahmaputra basins.

The combined impacts of climate change and non-climate drivers on hydrological processes and water resources in transboundary rivers in diverse regions of Asia were well noted in AR5. In Central Asia withdrawal is approximately equal to water availability, with Turkmenistan and Uzbekistan as most water stressed countries in the region (Karthe et al., 2017); (Russell, 2018). A study on water availability in mainland South Asia has pointed in the direction of decreasing precipitation trends in recent years, which have also contributed to the increasing incidence and severity of droughts (Liu et al., 2018b). There are reports of increase in occurrence and severity of different forms of droughts in the Koshi river basin (Central Himalaya) (Wu et al., 2019a; Hamal et al., 2020; Dahal et al., 2021; Nepal et al., 2021). Figure 10.5 shows the water stress in the HKH region. The water stress is relatively higher in western region compared to central and eastern region.

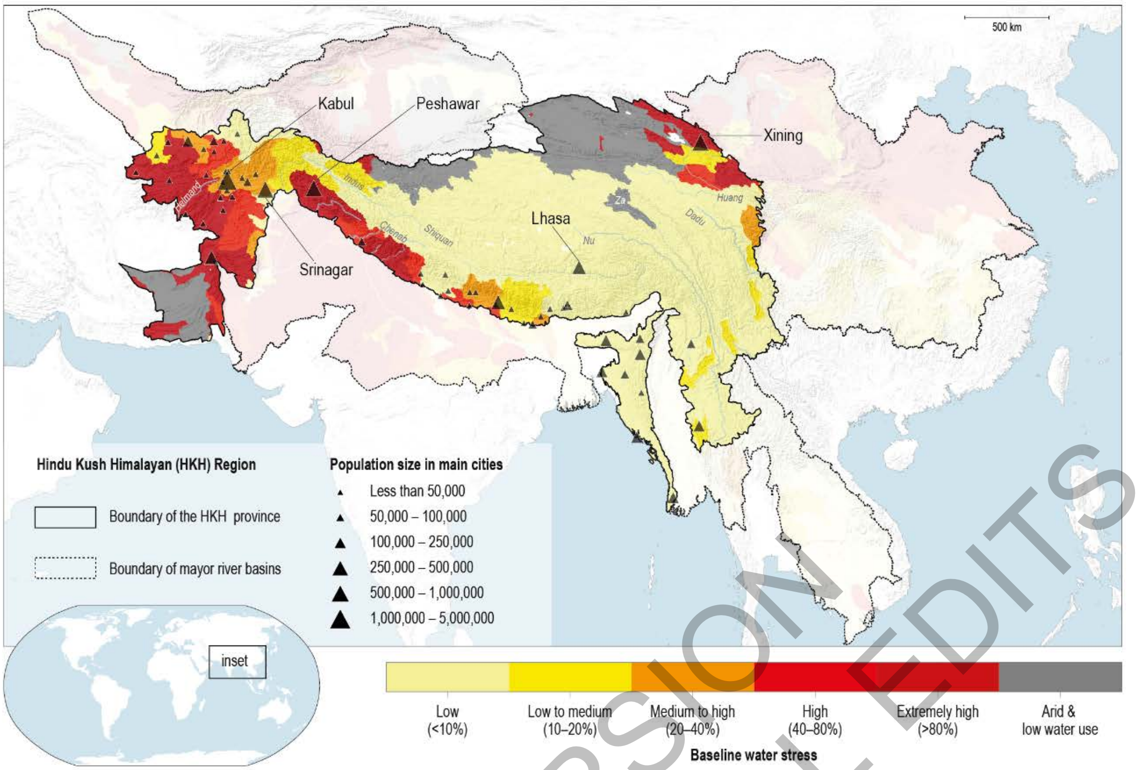


Figure 10.5: Water Stress in the Hindu Kush-Himalaya (HKH) region Source: (Wester et al., 2019). *The Hindu Kush Himalaya assessment: mountains, climate change, sustainability and people* (p. 627). Springer Nature; (Hu and Tan, 2018). No water, no growth – Does Asia have enough water to develop? China Water Risk. **Note:** The map is for illustrative purpose only. The boundaries and names shown and the designations used on this map are for river basins and do not imply official endorsement or acceptance by the United Nations.

Climate change is also having an impact on stream flows. A recent study (Chen et al., 2018f) has shown that with the average temperature after 1998 being 1.0°C higher than that during 1960–1998 in the Tienshan Mountains, the process of glacier shrinkage and decreases in snow cover and causing earlier runoff peak and aggravated extreme hydrological events, affecting regional water availability and adding to future water crisis in Central Asia. The magnitude and frequency of flooding have increased across Himalayan region in the past six decades such as Tarim basin in China (Zhang et al., 2016c) and higher Indus, Ganges and Brahmaputra (Elalem and Pal, 2015). The latter also reported the highest number of flood disaster and greater spatial coverage in the recent decades as compared to earlier decades. In the Middle Yellow River Basin, which has become much warmer and drier, climate variability accounts for 75.8% of streamflow decrease during 1980–2000. Whereas during 2001–2016, land use/cover change is the main factor in streamflow decrease, accounting for 75.5% of the decline (Bao et al., 2019). The changes in hydrological regime and extreme floods cause changes in the river morphology and river channel system which impact water availability.

In China, a quantitative assessment based on a multimodel dataset (6 global hydrological models driven by 3 observation-based global forcings) during the 1971-2010 period, suggested that climate variability dominated the changes in streamflow in more the 80% of river segment, while direct human impact dominated changes mostly in northern China (Liu et al., 2019b). In the Lancang-Mekong River basin, climate variability would have contributed 45% more flood occurrences in the middle of the basin while reservoir operation reduced it by 36% during 2008-2016 compared to the period 1985-2007 (Yun et al., 2020).

In western China, the total annual snow mass declines at a rate of 3.3 × 109 Pg per decade ($p < 0.05$), which accounts for approximately 0.46% of the mean of annual snow mass (7.2 × 1011 Pg). The loss could be valued in terms of replacement cost at CN¥0.1 billion (in the present value) every year ($1 = CN¥7) in the past 40 years. Compounded (Wu et al., 2021). In the Mekong River Delta in Vietnam, climate change impacts include a 30% annual increase in rainfall, shifting rainfall patterns, an average temperature increase of 0.5°C over the last 30 years, and an average sea level rise of 3mm per year over the last three decades, resulting in a greater flooding threat (Wang et al., 2021a).

A recent study (Wang et al., 2021b) has shown that during 1936–2019, due largely to intensified precipitation induced by a warming climate , the streamflow of Ob, Yenisei and Lena has increased by ~7.7%, 7.4% and 22.0%, respectively. Whilst rising temperature can reduce streamflow via evapotranspiration, it can enhance groundwater discharge to rivers due to permafrost thawing. In permafrost-developed basins, the thawing permafrost will continue to result in increased streamflow. However, with further permafrost degradation in future, the positive effect of permafrost thaw on streamflow would probably be offset by the negative effect of increase in basin evapotranspiration. This could result in a situation where runoff reaches threshold level and then declines. This is clearly marked in the Ob River basin, which is characterised by the highest precipitation. Whereas in case of Yenisei and Lena rivers, further research is needed.

The HKH region is susceptible to floods and related hazards caused by a cloud burst and other landscape-based processes such as glacial lake outburst floods which can seriously damage property, lives and infrastructure (Shrestha et al., 2010). Himalayan rivers are frequently hit by catastrophic floods caused by the failure of glacial lake (Cook et al., 2018) (Ahluwalia et al., 2016). In Kedarnath, India (western Himalaya), a flash flood was triggered by GLOF released from the Chorabari glacial lake in June 2013 which caused extensive flooding, erosion of riverbanks and damage to downstream villages and towns, as well as the loss of several thousand human lives in the state of Uttarakhand (Rafiq et al., 2019); (Das et al., 2015). Nepal has experienced 24 GLOF events which have caused considerable loss of life and damage to properties and infrastructure (Icimod, 2011). There is *high confidence* that current glacier shrinkages have caused more glacial lakes to form in most of the mountainous region including High mountain Asia but limited evidence that the frequency of GLOF has changed (Hock et al., 2019). (Veh et al., 2018) reported no clear trend of increasing GLOF events in the Himalayan region, although southern Himalaya was identified as a hotspot region compared to western Himalaya. Research has shown a decrease in glacier area of 24% in Nepal between 1980 and 2010 (Bajracharya et al., 2014).

Climate change impacts on both the quantity and quality of freshwater resources will hinder the attainment of SDG-6 (Water, 2020). Contamination of drinking water is caused by wildfires and drought that contribute to elevated levels of nutrients (nitrogen, phosphorus and sulphates), heavy metals (lead, mercury, cadmium and chromium), salts (chloride and fluorides), hydrocarbons, pesticides and even pharmaceuticals. Heavy rains and flooding also increase nutrients, heavy metals and pesticides as well as turbidity and fecal pathogens in water supplies - especially when sewage treatment plants are overwhelmed by runoff (Mora et al., 2018). Pharmaceuticals and personal care products (from source to disposal) are contributing to the vulnerability of urban waters. A study of vulnerability assessment of urban waters in highly populated cities in India and Sri Lanka, through analysing the concurrence of PPCPs, enteric viruses, antibiotic resistant bacteria, metals,
fecal contamination, and ARGs, also underlines the need for a resilience strategy and action plan (Rafiq et al., 2019).

Adequate water supply for various uses is crucial for millions of people living in the mountains of Asia. Particularly in the HKH region, mountain springs play an important role in generating stream flow for non-glaciated catchments and in maintaining dry-season flows across many watersheds (Scott et al., 2019) (Stott and Huq, 2014). There is a good deal of evidence that the springs are drying up or yielding less discharge (Tambe et al., 2012), (Tiwari and Joshi, 2014) (Sharma et al., 2016), threatening local communities who depend on spring water for their lives and livelihoods. Some of the main reasons for drying springs include anthropogenic impacts (deforestation, exploitative land use), infrastructure (road construction), socio-economic changes (increasing demand and modernisation of facilities) and climatic changes (changes in rainfall regime and higher temperature) (Stott and Huq, 2014; Tiwari and Joshi, 2014; Sharma et al., 2016).

The Ganges-Brahmaputra region also faces the threat increased frequency of flood events (Lutz et al., 2019). Floods and extreme events can impact river channel systems (Grainger and Conway, 2014). One of the challenges in South Asia is the shifting boundaries of river channels. For instance, the major floods on the

Indus in July 2010 altered the river's course in Pakistan, moving it closer to the Indian district of Kutch (Grainger and Conway, 2014). In the eastern tributary of Ganges system, the alluvial fan of the Koshi river basin has shifted to more than 113 km to the west in past two centuries (Chakraborty et al., 2010) which may be due to heavy sediment load from the Himalayan rivers in which about 50 million tons of sediment is deposited annually in the alluvial plains (Sinha et al., 2019) (Chakraborty et al., 2010).

Asia is no exception to the global trend of lake ecosystems providing drinking water to millions of people, being degraded (Jenny et al., 2020) and severely threatened at the same time by climate change (Mischke, 2020), with lake surface conditions, such as ice cover, surface temperature, evaporation and water level, responding dramatically to this threat, and carrying implications for water quantity and quality, food provisioning, recreational opportunities and transportation (Woolway et al., 2020). Due to substantial regional variability, the quantum of future changes in lake water storage remains uncertain. A recent study (Liu et al., 2019a) using Moderate Resolution Imaging Spectroradiometer (MODIS) 500m spatial resolution global water product data, and applying Least Squares Method (LSM) to analyse changes in the area of 14 lakes in Central Asia from 2001 to 2016, has shown that the shrinking of area changes for all plains lakes in the study region could be attributed to climate change and human activities.

10.4.4.4 Projections

Asian and global water demands for irrigation, despite geographical variation in terms of water availability, are *very likely* to be surpassing supply by 2050 (Chartres, 2014). A regional quantitative assessment (Lutz et al., 2019) of the impacts of a 1.5 versus a 2 °C global warming for a major global climate change hotspot: the Indus, Ganges, and Brahmaputra river basins (IGB) in South Asia, shows adverse impacts of climate change on agricultural production, hydropower production, and human health. A global temperature increase of 1.5 °C with respect to pre-industrial levels would imply a ≈ 2.1 °C temperature increase for IGB. Whereas under a 2.0 °C global temperature increase scenario, these river basins would warm up by ≈ 2.7 °C. Future warming is expected to further increase rain-on-snow (ROS) events that can cause the snowmelt flood during winter (Ohba and Kawase, 2020), affecting hydropower and resulting in river flooding, avalanches and landslides.

In the Mekong River Delta (in Vietnam) with an area of 40,500 km2 and the home to 17.8 million people in 2018, climate change is projected to increase the average temperature by 1.1-3.6 ◦C, and the maximum and minimum monthly flow are projected to increase and decrease, respectively, and *likely* to result in a high risk of food during the wet season and water shortages during the dry season (Wang et al., 2021a).

In High Mountain Asia, the glacier ice is projected to decrease by 49 ± 7 % and 64 ± 5% by the end of the century under RCP 4.5 and 8.5 scenarios (Kraaijenbrink et al., 2017). Local and regional-scale projections suggest that peak water will generally be reached around middle of the century, followed by steadily declining glacier runoff thereafter (Hock et al., 2019). A global-scale projection suggests that decline in glacier runoff by 2100 (RCP8.5) may reduce basin runoff by about 10% at least one month of the melt season in High Mountain Asia (Huss and Hock, 2018). Significantly, research on climate change and its impact across Asia remains inconclusive and requires an assessment at sub-regional scale (IPCC, 2014a); (Wester et al., 2019).

There is a projection of an increase in runoff until the 2050s mainly due to an increase in precipitation in the upper Ganges, Brahmaputra, Salween and Mekong basins, where it could be due to accelerated melting in the upper Indus basin. The runoff could increase in the range of 3-27% (7-12% in Indus, 10-27% in Ganges and 3-8% in Brahmaputra) by mid-century compared to the reference period (1998-2008) for Himalayan river basins depends on different RCP scenarios (Lutz et al., 2014a). Likewise, Khanal et al. (2021) suggested contrasting responses of climate change for HMAs rivers in which at the seasonal scale, the earlier onset of melting causes a shift in magnitude and peak of water availability whereas an annual scale, total water availability increases for the headwaters. The future flow would increase in the Central Himalaya region in Nepal (Ragettli et al., 2016); (Nepal, 2016); (Bajracharya et al., 2018). These changes in water availability in space and time will have serious consequences in downstream water availability for various sectoral uses and ecosystem functioning in Asia (Green et al., 2015) (Wijngaard et al., 2018); (Nepal et al., 2014); (Rasul and Molden, 2019) (Arfanuzzaman, 2018). However, future water availability has large uncertainty due to large variation in climate change projections among different global climate models (Nepal and Shrestha, 2015; Lutz et al., 2016; Li et al., 2019a).

A recent study (Didovets et al., 2021), covering eight river catchments having diverse natural conditions within Central Asia, where water availability/scarcity is also a major developmental concern, and using the eco-hydrological model SWIM (including scenarios from five bias-corrected GCMs under Representative Concentration Pathways 4.5 and 8.5) has show an increase of mean annual temperature in all catchments for both RCPs to the end of the 21st century. The projected changes in annual precipitation indicate a clear trend to increase in the Zhabay and to decrease in the Murghab catchments, and for other catchments, they were smaller. Both the projected trends for river discharge and precipitation show an increase in the northern and decrease in the southern parts of the study region. Whereas seasonal changes include a shift in the peak of river discharge up to one month, shortage of snow accumulation period, and reduction of discharge in summer months.

The intensity and frequency of extreme discharges are *very likely* to increase towards the end of the century. The future of the upper Indus basin water availability is highly uncertain in the long run due to uncertainty surrounding precipitation projections (Lutz et al., 2016). The future hydrological extremes of the Upper Indus, Ganges and Brahmaputra river basins suggest an increase in the magnitude of extremes towards the end of the 21st century by applying RCP4.5 and 8.5 scenarios, mainly due to increase in precipitation extremes (Wijngaard et al., 2017). In the Brahmaputra, Ganges and Meghna including the downstream component, the runoff is projected to increase by 16%, 33% and 40% respectively under the climate change scenarios by the end of the century in which the changes in runoff are larger in the wet seasons than the dry season (Masood et al., 2015). In the Mekong river basin also, extremely high flow events are *likely* to increase in both magnitude and frequency which can exacerbate flood risk in the basin (Hoang et al., 2016). However, the uncertainty is high in the future hydrological response due to large variation in precipitation projections, modelling approaches and bias corrections methods (Nepal and Shrestha, 2015; Lutz et al., 2016; Li et al., 2019a).

Current research on adverse relationship between climate change and river flows, research suggests that there is high possibility that some of the river basins affected by floods could be Brahmaputra, Congo, Ganges, Lena, Mekong, with a return period of 10 years (Best, 2018).

In most parts of the Upper Ganges and Brahmaputra rivers, the 50-year return level flood is *likely* to increase and to a lesser degree in Indus river. Similarly, the extreme precipitation events are also expected to increase to a higher degree in Indus than Ganges and Brahmaputra basins (Wijngaard et al., 2017). Increase in extreme precipitation events is *likely* to cause more flash flood events in the future (*medium confidence*). In case of Indus, increasing temperature trend in the future may lead to accelerated snow and ice melting which may increase the frequency and intensity of floods in the downstream areas (Hayat et al., 2019). The Ganges-Brahmaputra region also faces the threat of increased frequency of flood events (Lutz et al., 2019).Additionally, the Ganges basin also shows a higher sensitivity to changes in temperature and precipitation (Mishra and Lilhare, 2016).

Assessing the impact of climate change on water resources in nine alpine catchments in arid and semi-arid Xinjiang of China (Li et al., 2019a), it has been noted that even though the total discharge revealed an overall increasing trend in the near future, the impact of climate change on different hydrological components indicated significant spatiotemporal heterogeneity in terms of the area, elevation and slope of catchments, which could be usefully factored into climate adaptation strategies.

It was noted early on (Singh et al., 2011), that the main drivers that influence the provisioning of ecosystem services and human wellbeing in the HKH region are a mix of environmental change in general and climate change in particular, and much more data and knowledge a on the HKH region are needed in order to develop either a regional or global understanding of climate change processes.

Climate change impacts cryospheric water sources in the Hindu Kush, Karakoram and Himalayan ranges which in turn carry consequences for the Indus, Ganges and Brahmaputra basins. The impact of climate change on spring fed rivers in the Hindu Kush-Himalayas is under-researched and therefore make projections difficult. Further research is needed for understanding the impact of deforestation, urbanisation, development and introduction of water infrastructures such as tube-wells in the hill region (Aayog, 2017). This in turn call for greater investment in R&D for the Hindu Kush-Himalayas by both the national and regional organisations. There is *high confidence* that due to global warming Asian countries could experience increase of drought conditions (5-20%) by the end of this century (Prudhomme et al., 2014; Satoh et al., 2017).

Soil erosion in high mountains areas is particularly sensitive to climate change. A recent study (Wang et al., 2020) focused on the mid-Yarlung Tsangpo River, located in the southern part of the Tibetan Plateau, has revealed dramatic land surface environment changes due to climate change during the last decades. It has further shown that increasing precipitation and temperature would lead to increasing soil erosion risk in ~ 2050 based on the Coupled Model Intercomparison Project (CMIP5) and RUSLE models.

High-resolution climate change simulations suggest that due to deadly heat waves projected in some of the densely populated agricultural regions of South Asia (i.e. Ganges and Indus river basins), are *likely* to exceed the critical threshold of wet-bulb temperature of 35 °C under the business-as-usual scenario of future greenhouse gas emissions (Im et al., 2017).

[START BOX 10.4 HERE]

Box 10.4: Cryosphere

Asia's glaciers are in minor area shrinkage and mass loss among other world's glacierised regions during 2006-2016, resulting in near minimal contribution to sea level rise (1-7 Gt/a) (Zemp et al., 2019) (*high confidence*). However, Asia's glaciers are regarded as a reliable water source (Bolch, 2017). The melting water from Asia's glaciers protect ca. 220 million people in local and adjacent regions from drought, and the closer a region to river sources, the higher the fractions of melt water from glaciers (Pritchard, 2019). Researchers have found that the southern Tibetan Plateau has been consistently melting from 1998-2007 and is projected to continue melting until 2050 (Lutz et al., 2014b) (*high confidence*). The changes in snowmelt water can explain 19% of the variations in rivers of arid regions like Xinjiang, China (Bai et al., 2018) (*medium confidence*), and the 10.6% of the runoff of the upper Brahmaputra River was contributed by snow during 2003-2014 (Chen et al., 2017c) (*medium confidence*). The dominances of snow melt in spring were found in major river basins originating from southern Tibetan Plateau, compared to the glacier melt in summer (Lutz et al., 2014b).

On the other hand, the decreased stability of Asian glaciers, caused by warming climate (Ding et al., 2019) has posed a number of threats to regional security and water supplies (Gao et al., 2019). The *likely* increased frequency of hazards caused by abnormal glacier changes, such as the glacier collapses happened on two glaciers in western Tibet in 2016 (Kääb et al., 2018), and also surges which were frequently found in this vast region (e.g. Bhambri et al., 2017; Mukherjee et al., 2017; Ding et al., 2018), threatening the security of the local and down streaming societies (*high confidence*). However, the influence of climate change on natural hazards from glaciers needs further research.

The expansion of glacier lakes, following the shrinking glaciers, has also posed threat to social security downstream through glacier lake outburst flood (GLOF). The total amount and area of glacier lakes increased during last decade according to new studies (Zhang et al., 2015; Chen et al., 2017c) (*high confidence*). New GLOF events were continuously appearing all over Asia (e.g. Allen et al., 2016; Haeberli et al., 2016; Gurung et al., 2017). However, the frequency of GLOF has remained unchanged since later 1980s (Veh et al., 2019) (*high confidence*).

The impacts of permafrost changes on regional hydrology in Asia remains unclear. However, those changes may alter the soil carbon storage (e.g. Nie et al., 2019) and increase the riverine carbon exports (e.g. Song et al., 2019). But the fate of soil carbon within permafrost is more complicated and uncertain due to the influences of heterogeneous landforms, as pointed out in China's Second National Soil Survey (Jiang et al., 2019).

[END BOX 10.4 HERE]

10.4.4.5 Climate Vulnerability and Adaptation: Interfaces and Interventions

In Asia and its diverse sub-regions, the challenge of adaptation to climate change at diverse sectors, sites and scales of vulnerability in the domain of fresh water resources is compounded by the nexus between long-standing non-climatic vulnerabilities and climatic impacts, both observed and projected. Water insecurities in Asia are increasing due to excessive freshwater withdrawals (Satoh et al., 2017) economic and population growth (Gleick and Iceland, 2018), urbanisation and peri urbanisation (Roth et al., 2019) food insecurity (Demin, 2014) and lack of access to clean and safe drinking water (Cullet, 2016) which mostly affects the heath of most vulnerable sections of society.

Significantly, climate change will add to already existing vulnerabilities. In the case of Yellow River basin in China, underlining the interface between the future water scarcity and hydroclimatic and anthropogenic drivers, a recent study expects moderate to severe water scarcity over six Yellow River sub-catchments under the RCP4.5 scenario, and anticipates that human influences on water scarcity will be worse than that of climate change, with water availability in the downstream being impacted by concurrent changes in land-use and high temperature (Omer et al., 2020). Nearly 8% of internationally shared or transboundary aquifers (TBAs), ensuring livelihood security for millions of people through sustaining drinking water supply and food production, are currently overstressed due to human overexploitation (Wada and Heinrich, 2013). The Asia Pacific region has the highest annual water withdrawal due to its geographic size, growing population and irrigation practices, and water for agriculture continues to consume 80% of the region's resources (Taniguchi et al., 2017b; Visvanathan, 2018).

In South Asia, surface and groundwater resources are already under stress (both in terms of quality and quantity) due to population growth, economic development, poor governance/management and poor efficiency of use in economic production. In the last 40 years, there has been an increasing reliance on groundwater in South Asia for irrigation (Rodell et al., 2009; Surie and Prasai, 2015; Shah et al., 2018) (Tiwari et al., 2009) (Bhanja et al., 2016) (Shrestha et al., 2016; Mukherjee, 2018). It is significant to note that India, Bangladesh, Pakistan, and China together account for more than 50% of the world's groundwater withdrawals (Scott et al., 2019). A study conducted in Shahpur and Maner district of Bihar, India in which drinking water sourced from groundwater of 388 households was tested, shows that 70 to 90 percent of the sampled household's drinking water contained either arsenic or iron or both (Thakur and Gupta, 2019). Given the nexus between climatic and non-climatic drivers, an effective adaptation to the impacts of climate change would also demand sustainable development and management of shared aquifer resources, which in turn require reliable TBA inventories and improved knowledge production and knowledge sharing on the shared groundwater systems (Lee et al., 2018a).

In a study of peri-urban spaces, involving four South-Asian cities: Khulna (Bangladesh) (Pervin et al., 2020), Gurugram and Hyderabad (India), and Kathmandu (Nepal), shows nexus between intensifying use and deteriorating quality of water and the impact of climate change, resulting in peri-urban water insecurity and conflict (Roth et al., 2019). The challenge of ensuring access to water resources and their (re) allocation and prioritisation for marginalised communities remains on the agenda of policy-oriented interdisciplinary research and demands effective implementation of its findings at the grass root level by the administrative agencies. Taking water security as a key climate change adaptation goal at the urban-city-scale of Bangkok, a study (Babel et al., 2020) has shown the usefulness of a generic framework with 5 dimensions, 12 indicators, and a set of potential variables to support national level initiatives and plans in diverse climatic and socio-economic conditions across various sub-regions of Asia.

In the Kathmandu valley in Nepal, where groundwater resources are under immense pressure from multiple stresses, including over-extraction and climate change, mapping groundwater resilience to climate change has been demonstrated as a useful tool to understand the dynamics of groundwater systems, and thereby facilitating the development of strategies for sustainable groundwater management (Shrestha et al., 2020).

In Mekong Delta, the groundwater storage in Mekong Delta is projected to decline by more than 120 and 160 million cubic meter under RCP4.5 and RCP8.5 scenarios, respectively, by the end of the 21st century, in conjunction with land subsidence and sea level rise. This in turn calls for proactive planning and implementation of adaptation strategies that address multiple stresses in order to ensure sustainable utilisation of groundwater resources in the Mekong Delta in the context of future climatic conditions and associated uncertainties (Wang et al., 2021a). Proposed climate change adaptation strategies for the Mekong River Basin include a better understanding of the complex linkages between climate change, technological interventions, land use change, water use change, and socioeconomic developments both in the upstream and downstream riparian countries (Evers and Pathirana, 2018).

While South Asian countries have done well in attaining Goal 6 of Sustaining Development Goals, access to safe and clean drinking water remains a challenge. Taking Indian rivers as an example, it is suggested that participatory river protection and rehabilitation, based on comprehensive knowledge of the river-system dynamics, and local awareness at community level may act as a multiplier for river conservation measures (Nandi et al., 2016).

[START BOX 10.5 HERE]

Box 10.5: Case Study: Climate Vulnerability and Cross Boundary Adaptation in Central Asia

In Central Asia, water has been ranked in the top five global risks and water scarcity (Gleick, 1993; Zhupankhan et al., 2018). Cross boundary adaptation remains critically important in this region with abundant glaciers in Pamir Plateau of Tajikistan (Hu et al., 2017) and areas with severe glacier retreat in Tianshan Mountains (Liu and Liu, 2015). The spatial variations of glacier and other climate variables have added to uncertainty related to the dynamic of water cycle. The headwater regions, such as Pamir area, would be significantly affected by the climate parameters, such as the stronger rainfall intensity, more frequent rainfall and higher temperature (Luo et al., 2019). The water resources in Pamir plateau will range from-0.48% to 5.6% (Gulakhmadov et al., 2020), and the crop phenological period in Tajikistan and Kyrgyzstan will be about 1-2 weeks earlier. The threat of agricultural water stress is increasing as well. The oasis in downstream areas will face more complex water resource fluctuations, water crisis and desertification. In particular, rain fed agriculture in Northern Kazakhstan, Uzbekistan and Western Turkmenistan, is particularly dependent on water resources. Under RCP2.6 and RCP4.5 scenarios, considering CO_2 fertilisation effects and land use projections, the increase of CO_2 atmospheric concentration and accumulated temperature can contribute to 23% increase of cotton yield in Central Asia (Tian and Zhang, 2019), but extreme climate such as drought, heat waves and rainstorm will have 10% negative impact on agricultural production and ecological environment (Zhang and Ren, 2017). High efficiency water-saving technology will help the upstream and downstream water resources management in Central Asian countries to adapt to the variation in water resources quantity, frequency and spatial pattern.

[END BOX 10.5 HERE]

Hydro-climatic extreme in the HKH region could adversely impact the Ganga, Brahmaputra and Meghna Basins (Wijngaard et al., 2017; Acharya and Prakash, 2019). On adaptation, studies have recommended watershed or basin analysis to address the challenge of adaptation in urban spaces (Lele et al., 2018). A study of Northern Bangladesh, focused on encouraging traditional ways of cultivation, suggests that rural women have Indigenous Knowledge and their participation can play a useful role (Kanak Pervez et al., 2015). The knowledge pertains to agriculture, soil conservation, fish and animal production, irrigation and water conservation. There has also been a focus on gendered construction of local flood forecasting knowledge of rural communities in India living in the Gandak River basin (Acharya and Prakash, 2019). While designing the adaptation options, understanding Water-Energy-Food (WEF) nexus among different water use sectors are crucial (See **10.5.3.** for details). The understanding of WEF nexus could be beneficial for achieving water security in developing countries in Asia (Nepal et al., 2019).

AR5 had identified a number of adaptation challenges and options facing the stakeholders in the wake of climate change-induced vulnerabilities, uncertainties and risks in the freshwater sector, and underlined the importance of an integrated management approach, acknowledging diverse socio-economic contexts, differentiated capacities and uneven pace of impacts. Further validated by recent research in terms of their usefulness, these adaptation options include building and improving capital intensive physical water infrastructure such as irrigation channels, flood control dams and water storage (Nüsser and Schmidt, 2017). Drawing upon customary institutions and combining Indigenous Knowledge systems with scientific knowledge, innovative structures, including artificial glaciers, ice stupas and snow barrier bands, have been built by local communities in Ladakh and Zanskar and Himachal Pradesh in India (Hock et al., 2019). (Nüsser et al., 2019). Communities in Solukhumbu, Nepal, in response to depleting water flow in snow-fed rivers, have chosen adaptation through changing practices by collecting water from distance sources for domestic consumption (McDowell et al., 2013). Taking IPCC concept of climate risk as a basis for adaptation planning a pilot study of flood risk in Himachal Pradesh, India (Allen et al., 2018), integrating assessment of hazard, vulnerability and exposure in the complementary domains of climate change adaptation and disaster risk reduction, identifies stakeholder consultation, knowledge exchange and institutional capacity building as key steps in adaptation planning. Aquifer Storage and Recovery (ASR) has been proposed as an 'alternative climate-proof freshwater source' for deltaic regions in Asia, particularly those with a history of saline groundwater aquifers (Hoque et al., 2016). It is further argued (Hadwen et al., 2015) that water, sanitation and hygiene (WASH) objectives would need to be addressed as a component of a wider integrated water resource management (IWRM) framework.

Ensuring sustainability of the rivers and eco-systems requires coordinated and collaborative action on part of all countries with the long-term goal of synergising political, social, cultural and ecological facets associated with the riverine system. Daunting as this challenge is, evidence suggests that a long term view of transboundary basins, is not very optimistic as big rivers of Asia contribute heavily towards urban and agricultural activities, and are witnessing challenges of increasing sedimentation, large scale damming and pollution amongst others (Best, 2018). In case of China, Sun et al. (2016) show that the localised vulnerabilities within the Yangtze River Basin prompt an 'integrated basin-wide approach' that is able to account for the specific needs of each of its sub-basins.

In high mountain areas, factors that undermine effective adaptation to climate change include both the sudden-onset and slow-paced disasters and knowledge deficit about cryospheric change and its adverse impacts on water resources, agriculture, and hydropower sectors. Other key barriers include sectoral approach, overemphasis on structural approaches, the lack of context-sensitive, community-centric understanding of how these changes influence perceptions, options, and decisions about migration, relocation, and resettlement (Rasul et al., 2020) (Hock et al., 2019). More interdisciplinary research is needed on highly precarious future pathways and intersection between the climate and non-climate drivers in order to anticipate and mitigate diverging and uncertain outcomes.

10.4.5 Agriculture and Food

Asia accounts for 67% of the global agricultural production (Mendelsohn, 2014) and employs a large portion of the population in many developing member (Briones and Felipe, 2013; ADB, 2017b; ILO, 2017a). Since the release of IPCC AR5, more studies reinforce the earlier findings on the spatial and temporal diversity of climate change impacts on food production in Asia depending on the geographic location, agroecology, and crops grown (Hoegh-Guldberg et al., 2018; Ahmad et al., 2019), recognising that there are winners and losers associated with the changing climate across scales (Dasgupta et al., 2013a; Yong-Jian et al., 2013; Bobojonov and Aw-Hassan, 2014; Hijioka et al., 2014; Li et al., 2014a; Prabnakorn et al., 2018; Trisurat et al., 2018; Matsumoto, 2019). Despite the observed increase in total food production in terms of crops and food yields from 1990 to 2014 in Asia (FAO, 2015), there is *high confidence* that overall, at the regional level, the projected total negative impacts will far outweigh the expected benefits with India emerging as the most vulnerable nation in terms of crop production (Figure 10.6). Recent evidence also indicates that climate-related risks to agriculture and food security in Asia will progressively escalate as global warming reaches 1.5°C and higher above pre-industrial levels (IPCC, 2018b) with differentiated impacts across the Asian continent.

10.4.5.1 Observed Impacts

There remains a paucity of data for observed climate change impacts on Asian agriculture and food systems since the release of IPCC AR5. Most of these impacts have been associated with drought, monsoon rain, and oceanic oscillations, the frequency and severity of which have been linked with the changing climate (Heino et al., 2018; Heino et al., 2020). In general, major impacts to agricultural production such as those observed by the farmers in the Philippines and Indonesia include among others delays in crop harvesting, declining crop yields and quality of produce, increasing incidence of pests and diseases, stunted growth, livestock mortality, and low farm income (Stevenson et al., 2013). In South Asia, the series of monsoon floods from 2005 to 2015 contributed to high level of loss in agricultural production with peaks in 2008 and 2015 (FAO, 2018a). Similarly, in Pakistan, farmers are experiencing decline in crop yields and increasing incidence of crop diseases as a result of climate extremes particularly floods, droughts and heat waves (Fahad and Wang, 2018; Ahmad et al., 2019).

Limited studies have quantified the actual impacts of climate change on agricultural productivity and the economy. In a study in Mun River Basin, Northeast Thailand, yield losses of rice due to past climate trends covering the period of 1984–2013 was determined to be in the range of < 50kg/ha per decade or 3% of actual average yields with high possibility of more serious yield losses in the future (Prabnakorn et al., 2018). Likewise, in China, an economic loss of $595-858 million for the corn and soybean sectors was computed from 2000 to 2009 (Chen et al., 2016b). On the other hand, the intensive wheat-maize system in China seems to have benefited from climate change with the northward expansion of the northern limits of maize, and multi-cropping systems brought about by the rising temperature (Li and Li, 2014).

There is *high agreement* in more recent studies that linked the frequency and extent of El Niño phenomenon with global warming (Thirumalai et al., 2017; Wang et al., 2017a; Hoegh-Guldberg et al., 2018) that can trigger substantial loss in crop and fishery production. The 2004 El Niño caused the Philippines an 18% production loss during the dry season and 32% production loss during the wet season (Cruz et al., 2017). In the 2015 El Nino event, the Indian oil sardine fishery declined by more than 50% of the previous years (Kripa et al., 2018) severely impacting the coastal livelihood and economies (Shyam et al., 2017). The 2015-2016 El Niño also inflicted adverse impacts in agricultural productivity and food security, especially affecting the rural poor in middle- and lower-income countries in Southeast and South Asia (UNDP ESCAP OCHA RIMES APCC, 2017).

10.4.5.2 Projected Impacts

10.4.5.2.1 Fisheries and aquaculture

The fisheries and aquaculture production from Asia in 2019 was estimated at 159.67 mmt contributing to 74.7% of the global production (FAO, 2020). This sector provides employment to an estimated 50.46 million people where fishing and aquaculture are important socio-economic activities and fish products are a substantial source of animal protein (Bogard et al., 2015; Azad, 2017; FAO, 2018c). The economic contribution could be as high as 44 % of the coastal communities' GDP as in the case of Sri Lanka (Sarathchandra et al., 2018). Five Asian countries (i.e., China, Indonesia, India, Vietnam, Japan) are in the top 10 of the global fish producers, representing a cumulative share of 36% in 2018 (FAO, 2020). As a top producer with 15% global share, China also remains as a top exporter of fish and fish products with 14% global market share.

There is *high agreement* in the literature that Asian fisheries and aquaculture, including the local communities depending on them for livelihoods, are highly vulnerable to the impacts of climate change. Asia has been impacted by sea level rise (Panpeng and Ahmad, 2017), decrease in precipitation in some parts (Salik et al., 2015) and increase in temperature (Vivekanandan et al., 2016) which have drastic effects on fisheries and aquaculture (FAO, 2018c). Its coastal fishing communities is exposed to disasters, which are predicted to increase (Esham et al., 2018). Fisheries in most of South Asia and Southeast Asian countries involve small scale fishers who are more vulnerable to climate change impacts compared to commercial fishers (Sönke Kreft et al., 2016; Blasiak et al., 2017) though there is a general decreasing trend in number of small units (Fernandez-Llamazares et al., 2015; ILO, 2015). A regional study of South Asia forecast large decreases in potential catch of two key commercial fish species (hilsa shad and Bombay duck) in the Bay of Bengal (Fernandes et al., 2016) which forms a major fishery and food for coastal communities. About 69% of the commercially important species of the Indian marine fisheries were found to be impacted by climate change and other anthropogenic factors (Dineshbabu et al., 2020). Likewise, water salinisation brought about sea level rise is expected to impact on the availability of freshwater fish in Southwest coastal Bangladesh with adverse implications to poor communities (Dasgupta et al., 2017a). Analysis of fishery has indicated that there will be continued decrease in catch impacting the seafood sector in Philippines, Thailand, Malaysia and Indonesia (Nong, 2019). Climate change was predicted to decrease total productive fisheries potential in

South and Southeast Asia, driven by a temperature increase of approximately 2 °C by 2050 (Barange et al., 2014).

Like fisheries, Asian aquaculture is highly vulnerable to climate change. Shrimp farmers and fry catchers of Bangladesh are frequently affected by extreme climatic disruptions like cyclones and storm surges that severely damage the entire coastal aquaculture (Islam et al., 2016a; Kais and Islam, 2018). Majority of the shrimp farmers also observed that weather has changed abruptly during the last 5 years and that high temperature is most detrimental, lowers growth rate, increases susceptibility to diseases including deformation and affect production (Islam et al., 2016a). Low production in shrimp farming is also attributed to variation and intensity of rainfall perceived by majority of farmers as part of climate change impacts (Ahmed and Diana, 2015; Islam et al., 2016a; Henriksson et al., 2019). In Vietnam, small scale shrimp farmers are likewise vulnerable to climate change although those who practice extensive type of farming with low inputs are more vulnerable compared to those who practice more intensive type with more capital investment (Quach et al., 2015; Quach et al., 2017). Seaweed farming in Asia is very popular and the significance of seaweed aquaculture beds (SAB) in capturing carbon is recognised, but most of the farmed seaweeds are susceptible to climate change (Chung et al., 2017a; Duarte et al., 2017).

MHW are a new threat to fisheries and aquaculture (Froehlich et al., 2018; Frölicher and Laufkötter, 2018) including disease spread (Oliver et al., 2017), live feed culture (copepods) (Doan et al., 2018), and farming of finfishes like Cobia (Le et al., 2020). Predicting MHW is considered a pre-requisite for increasing the preparedness of farmers (Frölicher and Laufkötter, 2018). In Southeast Asian countries more than 30% of aquaculture areas are predicted to become unsuitable for production by 2050 - 2070 and aquaculture production is predicted to reduce 10% - 20% by 2050 - 2070 due to climate change (Froehlich et al., 2018).

10.4.5.2.2 Crop production

Since IPCC AR5, more studies have been done in different scales from local to global that focus on the differentiated projected impacts of climate change on the production and economics of various crops with rice, maize, and wheat among the major crops receiving more attention. New research findings affirm that climate change impacts on and will continue to significantly affect crop production in diverse ways in particular areas all over Asia (See Figure 10.6). Increasing number of sub-regional and regional studies using various modelling tools provide significant evidences on the overall projected impacts of climate change on crop production at the sub-regional and regional scales with clear indications of winners and losers among and within nations ((see for instance, (Mendelsohn, 2014; Cai et al., 2016; Chen et al., 2016b; Schleussner et al., 2016)).

Beyond the usual research interest on crop yields which has dominated current literature, recent studies such as those in Japan started to focus on the impacts of climate change on the quality of crops (see for instance, Sugiura et al. (2013) for apple, and Morita et al. (2016) and Masutomi et al. (2019) for rice). A large-scale evaluation by Ishigooka et al. (2017) shows that the increased risk in rice production brought about by temperature increase may be avoided by selecting an optimum transplanting date considering both yield and quality. More studies of this nature have to conducted for other crops in different locations to better understand and adapt to the negative impacts of the changing climate on the quality of crops (Ahmed and Stepp, 2016).

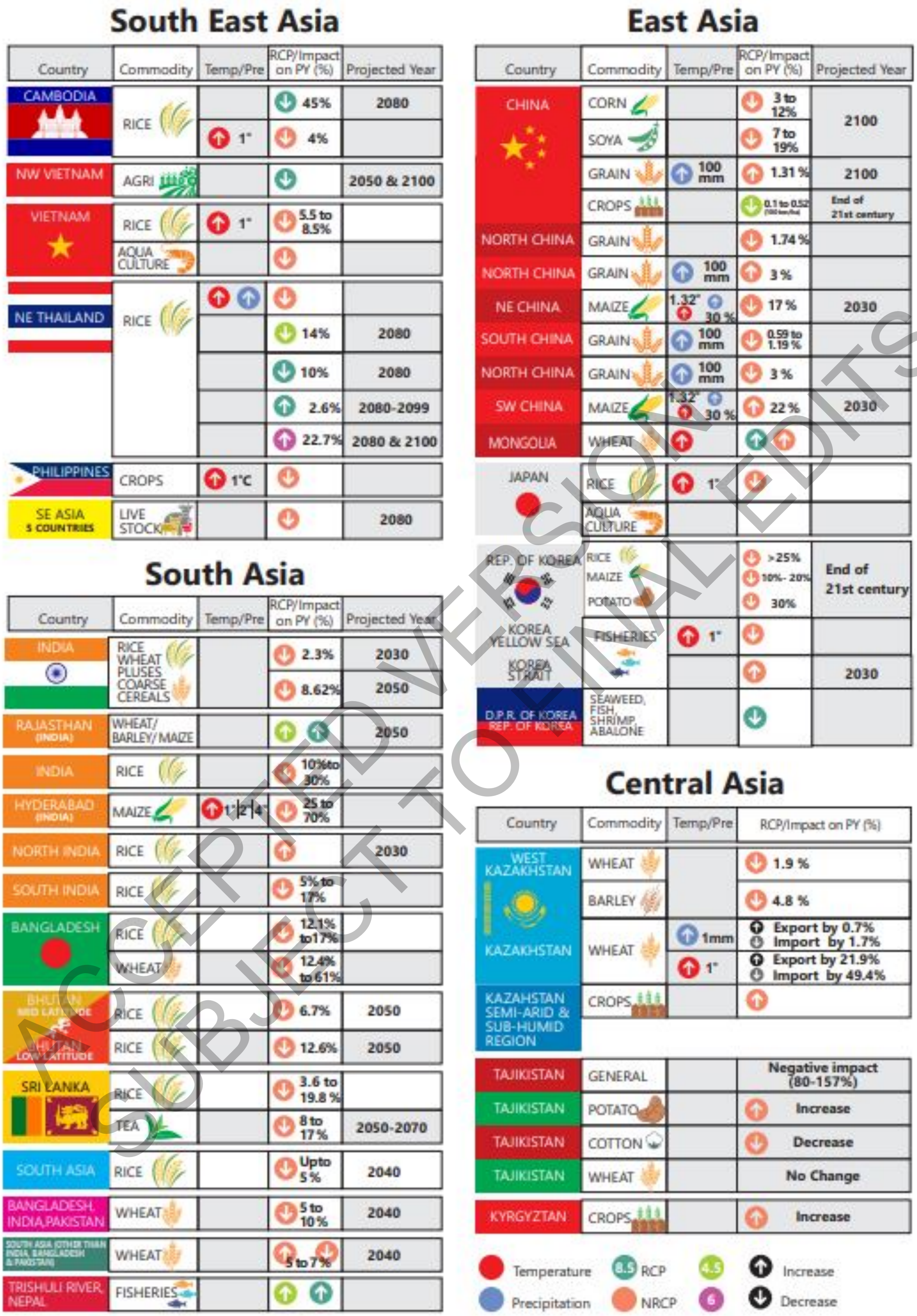


Figure 10.6: Projected impacts of climate change to agriculture and food systems in sub-regions of Asia based on post IPCC-AR5 studies. The figure illustrates the spatial and temporal diversity of projected future impacts on food production highlighting that there are winners and losers associated with the changing climate at different scales. (Abbreviations AGRI-Agriculture; E-East; N-North; NRCP-No RCP analysis; Pre-Precipitation; PY-Production Yield;

RCP-Representative Concentration Pathway; S-South; Temp-Temperature; W-West). (Please refer to Table SM10.2 for details and supporting references).

New studies have projected the *likely* negative impact of pests in Asian agriculture. The golden apple snail (*Pomacea canaliculate*), which is among the world's 100 most notorious invasive alien species, threatens the top Asian rice-producing countries including China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Philippines, and Japan with the predicted increase in climatically suitable habitats in 2080 (Lei et al., 2017). Similarly, a study by (Shabani et al., 2018) in Oman projected that pest of date palm trees, Dubas bug (*Ommatissus lybicus* Bergevin) could reduce the crop yield by 50% under future climate scenarios.

While there is general agreement that CO2 promotes growth and productivity of plants through enhanced photosynthesis, there remains uncertainty on the extent to which carbon fertilisation will influence agricultural production in Asia as it interacts with increasing temperatures, changing water availability, and the different adaptation measures employed (Ju et al., 2013; Jat et al., 2016; ADB, 2017b). As global warming compounds beyond 1.5 °C, however, the likelihood of adverse impacts to agricultural and food security in many parts of developing Asia increases (Mendelsohn, 2014; IPCC, 2018b). There is a growing trend towards more integrated studies and modelling that combines biophysical and socioeconomic variables (including management practices) in the context of changing climate to reduce uncertainty associated with future impacts of climate change to the agricultural sector ((see for instance (Mason-D'Croz et al., 2016; Smeets Kristkova et al., 2016; Gaydon et al., 2017)).

10.4.5.2.3 Livestock production

There is hardly any mention about the impacts of climate change on livestock production in the Asia chapter of AR5 due to limited studies on this area. This scarcity of information persists to the current assessment with very scanty information on the projected impacts and adaptation aspects of livestock production (Escarcha et al., 2018a). The use of scenarios/models to determine alternative futures with participatory engagement process has been recommended for informed policy and decision making with potential application in the livestock sector (Mason-D'Croz et al., 2016). Of the limited assessment available, a study on the smallholders' risk perceptions of climate change impacts on water buffalo production systems in Nueva Ecija, Philippines identified feed availability and animal health as the production aspects most severely affected by multiple weather extremes (Escarcha et al., 2018b). In the Mongolian Altai Mountains, early snowmelt and an extended growing season have resulted in reduced herder mobility and prolonged pasture use, which has in turn initiated grassland degradation (Lkhagvadorj et al., 2013a). Furthermore, reduced herder mobility has increased the pressure on forests resulting in increased logging for fuel and construction wood and reduced regeneration due to browsing damage by increasing goat populations (Khishigjargal et al., 2013; Dulamsuren et al., 2014).

In terms of direct impacts, climate change-induced heat stress and reduced water availability are *likely* to generally have negative effects on livestock (ADB, 2017b). In Hindu Kush-Himalaya (HKH) Region climate change has induced severe impacts on livestock through degradation of rangelands, pastures, and forests (Hussain et al., 2019). However, indirect effects maybe positive such as in Uzbekistan and South Asia where alfalfa and grassland productivity is expected to improve under warming conditions which have beneficial effects to livestock production (Sutton et al., 2013; Weindl et al., 2015).

At the global level, analysis involving 148 countries in terms of the potential vulnerability of their livestock sector to climate and population change shows that some Asian nations, particularly Mongolia, are *likely* to be the most vulnerable while South Asia is the most vulnerable region (Godber and Wall, 2014).

10.4.5.2.4 Farming systems and crop areas

There is new evidence since AR5 that farming systems and crop areas will change in many parts of Asia in response to climate change. In South Asia, a study in Nepal showed that farmers are inclined to change in cropland-use to reduce climate change risk (Chalise and Naranpanawa, 2016). In India, climate change is also predicted to lead to boundary changes in areas suitable for growing certain crops (Srinivasa Rao et al., 2016). A study in Bangladesh reveals a shift in crop choices among farmers implying changes in future rice cropping pattern. Specifically, temperature increase will compel farmers to choose irrigation based Boro, Aus and other crops in favor of rainfed Aman rice crop (Moniruzzaman, 2015).

In the coastal area of Odisha in India, adverse impact on the agriculture sector is anticipated considering the increasing temperature trends over the last 30 years for all the seasons (Mishra and Sahu, 2014). In a national study that groups Bangladesh into 16 sub-regions with similar farming areas, simulations of a 62 cm rise in mean sea level project damages to production because of area loss in excess of 31% in Sub-Region -15 and nearly 40% in Sub-Region -16 (Ruane et al., 2013). Also in Bangladesh, a study on predicting design water requirement of winter paddy rice under climate change condition shows that agricultural water resource management will help minimise drought risk and implement future agricultural water resources policies (Islam et al., 2018) that may have important implications to crop areas and production.

In East Asia, observed changes in agricultural flooding in different parts of China could influence farming systems and crop areas (Zhang et al., 2016b), as extreme events intensify in the context of changing climate. Agricultural management practice in China may also change to optimise soil organic carbon sequestration (Zhang et al., 2016a). A study on projected irrigation requirements under climate change using soil moisture model for 29 upland crops in Republic of Korea shows that water scarcity is a major limiting factor for sustainable agricultural production (Hong et al., 2016). In terms of drought, despite increasing future precipitation in most the scenario, crop-specific agricultural drought will be expected to risky significantly by rainfall variability (Lim et al., 2019a). On the other hand, a projected rise in water availability in the Korean Peninsula using multiple regional climate models and evapotranspiration methods indicates it will *likely* increase agricultural productivity for both rice and corn, but would decrease significantly in rainfed conditions (Lim et al., 2017b). Thus, irrigation and soil water management will be a major factor in determining future farming systems and crop areas in the country.

Global study on climate change-induced hot-spots of heat stress on agricultural crops shows that large suitable cropping areas in Central and Eastern Asia and the Northern part of the Indian subcontinent are under heat stress risk assuming the A1B emission scenario (Teixeira et al., 2013) and hence may reduce cropping areas in these regions. In Japan, the projected decline in rice yield in some areas, suggests that the current rice producing regions would be divided into suitable and unsuitable areas as temperatures increases (Ishigooka et al., 2017) with important implication on the possible shift in cropping area. Similarly, it has been shown that there will be change in the geographical distribution of the occurrence of poor skin color of table grape berries (Sugiura et al., 2019) and suitable areas for cultivation of subtropical citrus (Sugiura et al., 2014) in Japan by the middle of the 21st century.

There is emerging evidence from modelling and field experimentation that designing future farming systems and crop area that will promote sustainable development in Asia in the context of climate change would have to incorporate not only productivity and price considerations but also moderating temperature increase, enhancing water conservation, and optimising GHG mitigation potential (Sapkota et al., 2015; Zhang et al., 2016a; Ko et al., 2017; Lim et al., 2017b). Effects of agricultural landscape change on ecosystems services also need to be understood and taken into account in designing farming systems and allocating farm areas (Lee et al., 2015b; Zanzanaini et al., 2017).

10.4.5.3 Food Security

FAO (2001) defines food security as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". There is significant evidence that climate change significantly undermines both agricultural production and food security in Asia (ADB, 2017b). Increasing evidence from sub-regions and individual countries suggests that climate-related hazards such as increasing temperature, changing rainfall, sea level rise, drought, flooding, and the more frequent and intense occurrence of ENSO events, all impacts on agricultural production with significant effects on food security. All these hazards interact with non-climatic factors like competing demand for scarce water resources, rural-urban migration, food prices and increasing food demand in the long term, and poor governance, among others, that may worsen food insecurity in the region (Montesclaros and Teng, 2021).

In West Asia, particularly in Saudi Arabia and Yemen, increasing water scarcity brought about by temperature rise is anticipated to have severe impact on agriculture and food production that undermines food security (Al-Zahrani et al., 2019; Baig et al., 2019). Saudi Arabia, for instance, was forced to phase out its wheat production starting in 2016 and fully rely on import to conserve its drying fossil water resources (Al-Zahrani et al., 2019) which is also linked to water governance issue.

In Central Asia, a study using bioeconomic farm model shows very large differences in climate change impacts across farming systems at the sub-national level. Large-scale commercial farms in the northern regions of Kazakhstan will have positive income gains while small-scale farms in arid zones of Tajikistan will experience negative impact with *likely* effects to farm income security (Bobojonov and Aw-Hassan, 2014). Impacts on farmers' income in Western Uzbekistan will also significantly vary and could fall by as much as 25% depending on the extent of temperature increase and water use efficiency (Bobojonov et al., 2016).

In a regional study among South Asian countries using an integrated assessment modelling framework, changes in rice and wheat productions brought about by climate change are anticipated to engender wild price volatilities in the markets (Cai et al., 2016). Price spikes are projected for the period 2015 to 2040 in all South Asian regions with India, Pakistan and Sri Lanka predicted to witness increasingly much higher rice and wheat prices than under the baseline scenario creating major concerns over food affordability and food security. This will *likely* severely affect the overall economic growth of these countries since they are mainly agriculture driven economy.

A study on mapping global patterns of drought risk projected an increase of drought frequency and intensity in the populated areas of South to Central Asia extensively used for crop and livestock production with serious repercussion to food security and potential civil conflict in the medium- to long-term (Carrão et al., 2016). In Southeast Asia, a Philippine study on the relationship of seasonal rainfall, agricultural production, and civil conflict suggests that the projected change towards wetter rainy seasons and drier dry seasons in many parts of the country will lead to more civil conflict (Crost et al., 2018) with negative implications to food and human security. Similarly, floods and higher food prices are also associated with higher risks of social unrest in Asia that may undermine food security (Hendrix and Haggard, 2015; Ide et al., 2021).

Food insecurity will be localised across Asia where one part of the country or sub-region will be more food secured while the others, more insecure. This will require in-country or sub-regional trade and development cooperation to minimise the adverse impacts of food insecurity associated with the changing climate (Li et al., 2014a; Abid et al., 2016).

10.4.5.4 Key Drivers to vulnerability

There is *high confidence* that agriculture will continue to be among the most vulnerable sectors in Asia in the light of the changing climate (Mendelsohn, 2014; ADB, 2017b). Among the more vulnerable areas include mountain agriculture where fluctuation in crop production (Poudel and Shaw, 2016; Hussain et al., 2019) and food insufficiency is widespread than in lowland areas (Poudel and Shaw, 2015); (Kohler and Maselli, 2009). Also vulnerable are flood-prone areas like the Vietnam Mekong River Delta where 39% of the total rice area is exposed to sustained flood risks (Wassmann et al., 2019a). Increasing temperatures and changing precipitation levels will persist to be important vulnerability drivers that will shape agricultural productivity particularly in South Asia, Southeast Asia, and Central Asia as well as in selected areas of the region. With the increasing likelihood of extreme weather events like strong typhoons in the Philippines, the agricultural sector in the typhoon-prone areas of Southeast and East Asia as well as the Indus Delta, will be more vulnerable to crop destruction (Mallari and Ezra, 2016). Projections on increasing sea level rise and flooding such as those in Bangladesh and the Mekong Delta in Vietnam will submerge and decrease crop production areas and will severely affect agriculture and fishery sectors but will also trigger outmigration from these areas (ADB, 2017b).

Vulnerability of aquaculture-related livelihoods to climate change was assessed at the global scale using the MAGICC/SCENGEN climate modelling tools and Vietnam, Thailand were identified as most vulnerable in brackish water aquaculture production (Handisyde et al., 2017). Asian countries like China, Vietnam and the Philippines are also ranked highly vulnerable in marine production. Moreover, a recent vulnerability assessment of Korean aquaculture based on predicted changes in seawater temperature and salinity according to representative concentration pathways (RCP) scenario (RCP8.5) indicated that vulnerability was highest for seaweed, such as laver and sea mustard, while fish, shrimp, and abalone are relatively less vulnerable as they are less sensitive to high water temperature and their farming environments are controllable to a large extent (Kim et al., 2019a). In Indonesia, farming of white leg shrimp *Litopenaeus vannamei* has been found to be vulnerable to increased rainfall and temperature decrease (Puspa et al., 2018).

Climate change-induced vulnerability however is complicated by non-climatic drivers. In Thailand, for instance, a 38% reduction (from 21,486 to 13,328 million baht) in the export values of rice and products in the last quarter of 2011 has been attributed not only to impact of tropical cyclone Nock-Ten on Thai rice export but also with the economic slowdown in Thailand during 2011-2012 (Nara et al., 2014).

Considering the high vulnerability of Asia to climate change as a whole, there is a need to look at the drivers of vulnerability in an integrated and comprehensive manner. The increasing interest on nexus studies that links climate change impacts to agriculture with the other sectors like water, energy, land use change, urbanisation, poverty, economic liberalisation, and others ((see for example, (Takama et al., 2016; Aich et al., 2017; Eslamian et al., 2017; Duan et al., 2019b)) could contribute to a systemwide vulnerability reduction and an important initial step towards a more climate resilient future.

10.4.5.5 Adaptation Options

Since AR5, there is a surge in the volume of literature that documents and assesses the different adaptation practices already employed in Asian agriculture as well as those that provide future adaptation options. There is *robust evidence* that a variety of adaptation practices already employed in agriculture and fisheries are valuable in reducing negative effects of current climate anomalies but may not be sufficient to fully offset the adverse impacts of future climate scenarios. Recent literature, therefore focuses on how to build on current adaptation initiatives and processes to improve current and future outcomes (Iizumi, 2019).

Asian farmers and fisherfolks already employ a variety of adaptation practices to minimise the adverse impacts of climate change. A recent systematic and comprehensive review of farmers' adaptation practices in Asia, Shaffril et al. (2018) categorised these practices into different forms such as crop management, irrigation and water management, farm management, financial management, physical infrastructure management, and social activities. "Climate-smart agriculture" - an integrated approach for developing agricultural strategies that address the intertwined challenges of food security and climate change – is increasingly being promoted in many parts of the region, especially in Southeast and South Asia with potentially promising outcomes (Chandra et al., 2017; Khatri-Chhetri et al., 2017; Shirsath et al., 2017; Westermann et al., 2018; Wassmann et al., 2019b). Site specific adaptations such as those in Pakistan include the farmers' utilisation of several adaptation techniques which include changing crop type and variety and improving seed quality; fertiliser application and use of pesticides and plant shade trees; and water storage and farm diversification (Fahad and Wang, 2018), as well as the implementation of a comprehensive climate information services to farming communities (World Meteorological Organization, 2017).

Adaptation measures are also beneficial to small scale fishers and fish farmers (Miller et al., 2018) and through fisheries management plans (FMP) and early warning systems, the Asian region is reducing climate impact (FAO, 2018c). The most common FMPs adopted in different Asian countries are limits to fishing gear, licensing schemes and seasonal closures (ILO, 2015) protection of nursery grounds, providing alternative livelihoods (Azad, 2017), limiting fish aggregating devices (FADs) and introduction of monitoring and control tool (Department of Fisheries (Thailand), 2015). Fishers' strong sense of belonging to their place of residence and the sense of responsibility to protect the vulnerable fish stock has been advantageously used for developing cooperatives and starting community-based fisheries management (FAO, 2012; ILO, 2015; Shaffril et al., 2017) and these have yielded positive results.

In aquaculture, most households in shrimp communities rely on process-oriented multiple coping mechanisms such as consumption smoothing, income smoothing, and migration that enhance the farmers' resilience to climate anomalies (Kais and Islam, 2018). Diversification and integration of varied resources and interventions in feed and husbandry are seen help the aqua farmers increase their profit and overcome impacts of climate change (Henriksson et al., 2019). Strategies like polyculture, integrated multitrophic aquaculture (IMTA) and recirculating aquaculture systems (RAS), have been suggested to increase aquaculture productivity, environmental sustainability, and climate change adaptability (Ahmed et al., 2019c; Tran et al., 2020). In Bangladesh, several adaptation measures like integrated (Akber et al., 2017) community-based adaptation strategies and integrated coastal zone management (Ahmed and Diana, 2015) have been recommended to increase climate resilience among shrimp farmers.

More recently, Nature-based Solutions (NbS) have gained attention globally to enhance climate adaptation. In the context of agriculture, NbS is seen as cost-effective interventions that can increase resilience in food production, while advancing climate mitigation and improving the environment (Iseman and Miralles-Wilhelm, 2021). Experiences in implementing NbS in agricultural landscapes have been documented both in agriculture and fisheries sectors that promotes production while providing co-benefits such as environmental protection and sustainability (Miralles-Wilhelm, 2021).

Despite the numerous adaptation measures already employed, there is sufficient evidence that farmers' current adaptation practices are inadequate to offset the worsening climate change impacts. A more comprehensive approach that integrates economic and social strategies with other measures is seen to reduce climate vulnerability. For instance, agriculture insurance is viewed as a promising adaptation approach to reduce risks and increase the financial resilience of farmers and herders in many Asian countries (Prabhakar et al., 2018; Matheswaran et al., 2019; Nguyen et al., 2019; Stringer et al., 2020). Similarly, participation of multiple stakeholders from all relevant sectors at different levels in adaptation planning and decision-making is seen as important factor in improving outcomes (Arunrat et al., 2017; Hochman et al., 2017; Chandra and McNamara, 2018). Moreover, while adaptation is local and context-specific, the following general adaptation-related strategies are distilled from current literature based on Asian experience to enhance current and future adaptations: 1) create enabling policies (Chen et al., 2018d) and enhance institutional capacity (Wang et al., 2014; Hirota and Kobayashi, 2019); 2) improve adaptation planning and decision-making (Xu and Grumbine, 2014; Asmiwyati et al., 2015; Dissanayake et al., 2017; Hochman et al., 2017; Qiu et al., 2018; Shuaib et al., 2018; Aryal et al., 2020b; Ruzol et al., 2021; Ruzol and Pulhin, 2021); 3) promote science-based adaptation measures (Alauddin and Sarker, 2014; Sapkota et al., 2015; Lim et al., 2017b); 4) adopt an integrated approach to improve adaptation (Teixeira et al., 2013; Yamane, 2014; Abid et al., 2016; Sakamoto et al., 2017; Sawamura et al., 2017; Trinh et al., 2018); 5) invest on critical infrastructure (Cai et al., 2016; Rezaei and Lashkari, 2018); and 6) address farmers' adaptation barriers (Alauddin and Sarker, 2014; Pulhin et al., 2016; Fahad and Wang, 2018; Gunathilaka et al., 2018; Almaden et al., 2019b) (See Figure 10.7 for details or examples of each strategy).

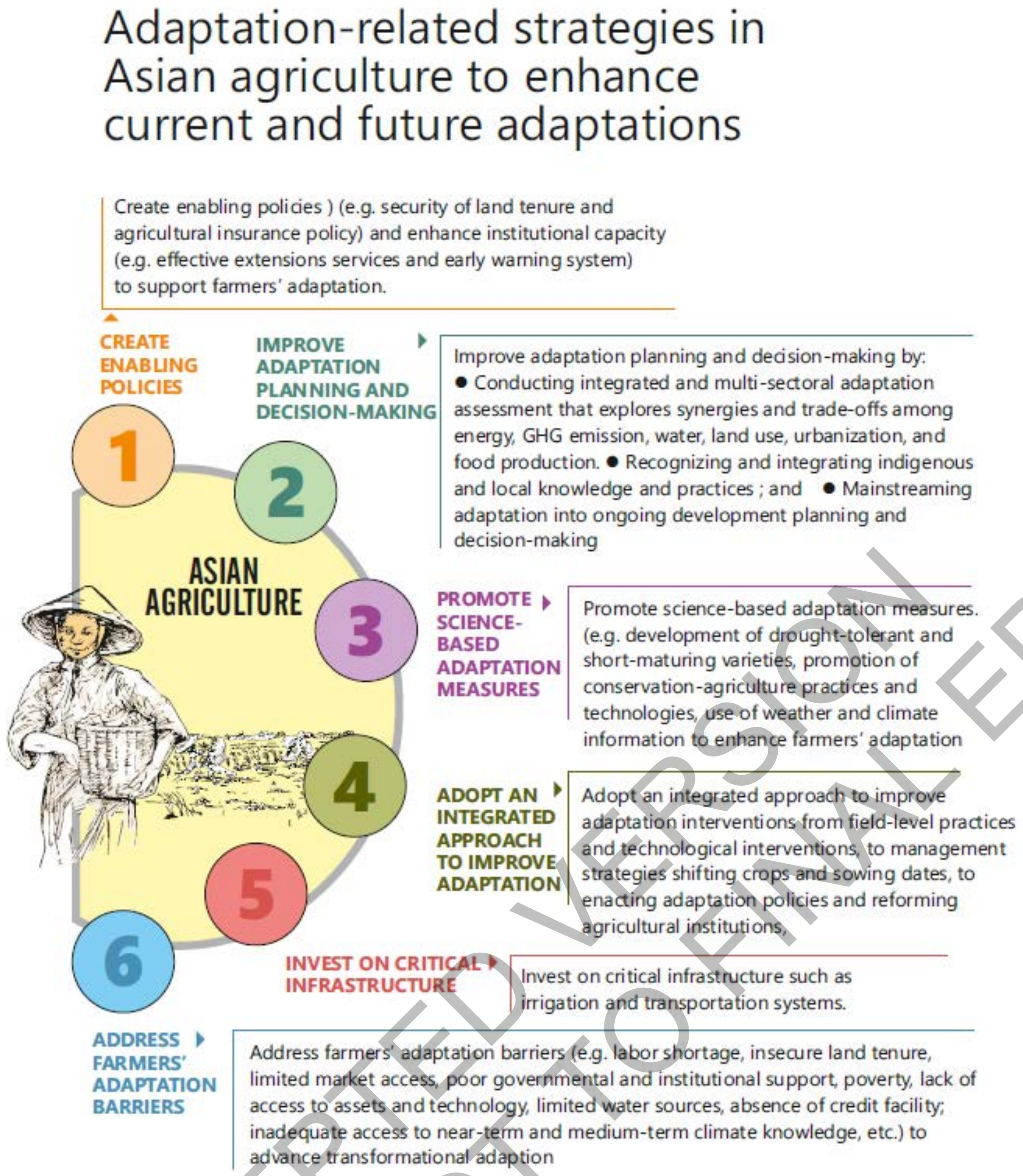


Figure 10.7: Adaptation related strategies in Asian agriculture to enhance current and future adaptations.

10.4.6 Cities, Settlements, and Key Infrastructures

Cities across Asia have large populations exposed to climatic risks but also present an opportunity for concerted climate action (Revi et al., 2014; Chu et al., 2017; Revi, 2017; Khosla and Bhardwaj, 2019) and report numerous examples of adaptation actions at various stages of planning and implementation (Dulal, 2019) (Singh et al., 2021b). However, challenges specific (though not exclusive) to Asian cities such as uneven economic development, rapid land use changes, increasing inequality, growing exposure to extreme events and environmental change such as land subsidence (with antecedent impacts on people and infrastructure), and large, socially differentiated vulnerable populations, remain key concerns as Asian cities simultaneously tackle challenges of sustainable development and equitable climate action.

10.4.6.1 Sub-regional diversity

By 2050, urban areas are expected to add 2.5 billion people, 90% of which will be in Asia and Africa (UNDESA, 2018). Critically, this urban population increase will be concentrated in India, China and Nigeria with India and China adding 416 million and 255 million urban dwellers respectively between 2018 and 2050 (UNDESA, 2018).

Asia is home to 54% of the world's urban population and by 2050, 64% of Asia's 3.3 billion people will be living in cities. Asia is also home to the world's largest urban agglomerations: Tokyo (37 million inhabitants), New Delhi (29 million), and Shanghai (26 million) are the top three with Cairo, Mumbai, Beijing and Dhaka home to nearly 20 million people each (UNDESA, 2018). By 2028, Delhi is projected to become the most populous city in the world. In certain parts of Asia (e.g. some cities in Japan and Republic of Korea), a steep decline in urban population is projected, mainly due to declining birth rates (Hori et al., 2020). Within Asia, rates of urbanisation differ sub-regionally. Eastern Asia has seen the most rapid urban growth with the percentage of urban population having more than tripled from 18 to 60 percent between 1950 and 2015, while rates of urbanisation have reduced in West Asia and remained steady in Central Asia (UNDESA, 2018).

Asian cities are seeing growing income inequality, with rural poverty being replaced by urban poverty (ADB, 2013). Regional studies show high and growing inequality within Indian and Chinese urban areas and reducing rural-urban income gaps in Thailand and Viet Nam (Baker and Gadgil, 2017; Imai and Malaeb, 2018). Critically, East Asia and the Pacific continues to house the world's largest population of slum dwellers at 250 million, with most numbers in China, Indonesia, and the Philippines and highest rates of urban poverty in Papua New Guinea, Vanuatu, Indonesia, and the Lao People's Democratic Republic (PDR) (McIlreavy, 2015; Baker and Gadgil, 2017). A lot of urbanisation, especially in South Asia, is also 'hidden' due to poor competing definitions of what is urban and limited data (Ellis and Roberts, 2016).

10.4.6.2 Key drivers of vulnerabilities

In Asian cities, exposure to climatic hazards such as changes in precipitation and in the Asian monsoon, sea level rise, cyclones, flooding, dust storms, heat waves, and permafrost thawing (Byers et al., 2018; Hoegh-Guldberg et al., 2018; Rogelj et al., 2018; Shiklomanov, 2019) and non-climatic vulnerabilities such as non-climatic hazards (e.g. seismic hazards), inadequate infrastructure and services, unplanned urbanisation, socio-economic inequalities, and existing adaptation deficits (Johnson et al., 2013; Araos et al., 2016; de Leon and Pittock, 2017; Meerow, 2017; Dulal, 2019) interact to shape overall urban risk (Shaw et al., 2016a; Rumbach and Shirgaokar, 2017; Dodman et al., 2019). Caught at the intersection of high exposure, socio-economic vulnerability, and low adaptive capacities, informal settlements in urban and peri-urban areas are particularly at risk (Meerow, 2017; Rumbach and Shirgaokar, 2017; Byers et al., 2018) (*robust evidence, high agreement*).

10.4.6.3 Observed and projected impacts

10.4.6.3.1 Multi-hazard risk

Of the multi-hazard global Average Annual Loss (AAL[3]) of US$293 billion, US$170 billion (58%) is in the Asia Pacific region (UNISDR, 2017). Of the top ten highest AALs associated with multi-hazards, six are in Asia (Japan, China, Korea, India, Philippines and Taiwan, Province of China) (UNISDR, 2017). As per Gu et al. (2015), 56% cities with population greater than 300,000 in 2014, are exposed to at least one of the six physical hazards (cyclones, floods, droughts, earthquakes, landslides, and volcanic eruptions). Cities in areas highly exposed and vulnerable to multiple hazards were also the ones that grew rapidly in population between 1950 and 2014, implying greater infrastructural investments in climate-sensitive areas. Among 27 cities highly exposed to multiple disasters, 13 cities had a population of 1 million or more in 2014. Among these were three megacities, Tokyo (Japan), Osaka (Japan) and Manila (Philippines), with more than 10 million inhabitants exposed to three or more hazards. Seven other cities with one million inhabitants or more in Asia were at high risk of three or more types of disaster. Manila is highly vulnerable to economic losses and disaster related mortality from all six types of disasters (Gu et al., 2015). Moscow (Russia) is the only megacity not exposed to the risk of any of the six types of physical hazards analysed (cyclones, floods, droughts, earthquakes, landslides, and volcano eruptions) (Gu et al., 2015). Of the eight megacities most vulnerable to disaster-related mortality, seven are in Asia, mainly Tokyo, Osaka, Karachi, Kolkata, Manila, Tianjin, and Jakarta, totalling 143 million people, and three of the four large cities with a population between

[3] Average Annual Loss (AAL) is the average amount that a country could expect to lose each year over the long-term due to hazard incidence. It corresponds to the expected average loss per year considering all the events that could occur over a long time-frame, including very intensive events. It is a probabilistic indication of the direct economic losses expected due to total or partial damage of physical assets existing in the affected area. (UNISDR, 2017).

5 million to 10 million: are in Asia: Chennai (India, 9.6 million), Nagoya (Japan, 9.4 million), and Tehran (Iran, 8.4 million) (Gu et al., 2015).

10.4.6.3.2 Extreme temperatures and heat waves

Urbanisation and climate change interact to drive urban heat island (UHI) effect across Asian cities (Chapman et al., 2017) (Hauck et al., 2016) [also see Fig 6.4 in Ch 6]. Three regions expected to see higher maximum wet bulb temperature than global averages are southwest Asia around the Persian Gulf and Red Sea, South Asia in the Indus and Ganges river valleys, and eastern China (Im et al., 2017) (Perkins-Kirkpatrick et al., 2020).

Impacts of heat waves in cities at 1.5°C and 2°C are substantially larger than under the present climate (Hoegh-Guldberg et al., 2018). In South Asia particularly, more intense heat waves of longer durations and occurring at a higher frequency are projected with *medium confidence* over India (Murari et al., 2015) and Pakistan (Nasim et al., 2018; Ali et al., 2020) (Ali et al., 2018) (IPCC AR6, WGI, Table 11.5)(IPCC, 2021a). At the city-level, these projections could translate into significant impacts: at 1.5°C, on average, Kolkata will experience, heat equivalent to the 2015 record heat waves every year; Karachi about once every 3.6 years and under 2°C warming, both regions could expect such heat annually (Matthews et al., 2017). In Pakistan, Hyderabad is *likely* to be the hottest city by 2100 with the highest average temperature reaching upto 29.9°C (RCP4.5) to 32°C (RCP8.5) followed by Jacobabad, Bahawalnagar, and Bahawalpur cities (Ali et al., 2020). The frequency of heat wave days (HWF) will increase by 22.8, 22.3, and 26.5 days/year in northern, eastern, and western Japan, respectively with megacities such as Tokyo, Osaka, and Nagoya seeing large increases in HWF and related deaths (Nakano et al., 2013).

In China's urban agglomerations, an increase in the global warming from 1.5 to 2°C is *likely* to exacerbate the intensity of extreme maximum temperature 4.1 times (Yu et al., 2018d). From 1995–2014 China's urban agglomerations (Beijing-Tianjin-Hebei, Yangtze River Delta, Middle Yangtze River, Chongqing-Chengdu, and Pearl River Delta (PRD)) experienced no more than three heat danger days/year, which is projected to increase to 3–13 days by 2041–2060 and 8-67 days by 2081–2100 under high-emission shared socioeconomic pathways SSP3-7.0 and SSP5-8.5, resulting in approximately 260 million people (19% of total Chinese population) and 310 million people (39% of the total China population) respectively facing more than three heat danger days annually (Zhang et al., 2021). This projected risk exposure is reduced under low-emission pathways (SSP1-2.6 and SSP2-4.5), where annual heat danger days will remain similar to current levels or increase slightly (Zhang et al., 2021).

Critically, these projections of higher temperatures will have significant impact on heat-related morbidity and mortality, labour productivity, mental health impacts and health and well-being outcomes across all sub-regions of Asia (*medium evidence, high confidence*) (Im et al., 2017) (Pal and Eltahir, 2016; Arifwidodo et al., 2019; Arshad et al., 2020). In West Asia and North China Plain especially, extreme wet-bulb temperatures are expected to approach and possibly exceed the physiologic threshold for human adaptability (35°C) (Pal and Eltahir, 2016; Kang and Eltahir, 2018). By end century, under higher projections (RCP 8.5) daily maximum wet-bulb temperature is expected to exceed survivability threshold across most of South Asia (Im et al., 2017). City-specific studies articulate what these regional projections will mean for urban populations. For example, at 1.5 °C warming, without adaptation, annual heat-related mortality in 27 major cities across China is projected to increase from 32.1 per million inhabitants annually in 1986–2005 to 48.8–67.1 per million. This number increases to 59.2–81.3 per million for 2°C warming (Wang et al., 2019a). In Korea, deaths from heat disorders are expected to increase approximately fivefold under the RCP4.5 and 7.2-fold under RCP 8.5 by 2060 compared to the current baseline value of ~23 people/summer (Kim et al., 2016a). Importantly, heat exposure is differentiated within cities: it disproportionally affects the poorest populations (Lohrey et al., 2021) and those with lower access to green spaces (Arifwidodo and Chandrasiri, 2020).

10.4.6.3.3 Precipitation extremes: excess rainfall and drought and water scarcity

Warming from 1.5°C to 2°C will increase extreme precipitation events across Asia especially over East and South Asia (*medium evidence, high agreement*) (Zhang et al. 2018); (Zhang et al., 2020b) (Supari et al., 2020). In East and Central Asia, under 1.5°C warming, extreme 1-day and 5-day precipitation will increase by 28% and 15%, relative to 1971–2000 (Zhang et al., 2020b). In China's urban agglomerations, an increase in the global warming from 1.5 to 2°C is *likely* to increase the intensity of total precipitation of very wet days

1.8 times and double maximum 5-day precipitation (Yu et al., 2018d). Extreme rainfall has direct and increasing consequences on urban flooding risk (Dasgupta et al., 2013b), which is further exacerbated by urbanisation trends that reduce permeability, divert water flow, and disrupt watersheds (Chen et al., 2015b; Duan et al., 2016).

Urban extent in drylands in expected to increase from 2000-2030 with large expansions in West Asia, Central Asia, South Asia, and China with antecedent impacts on exposure to drought and water scarcity (Güneralp et al., 2015). Urban dryland extent in West Asia will increase from 19,400km^2 to 67,400km^2 (Güneralp et al., 2015). In the Haihe River Basin in China, the proportion of people exposed to droughts at 1.5ºC (without accounting for population growth) is projected to reduce by 30.4%, but increase by 74.8% at 2°C relative to people exposed in 1986–2005 (339.65 million) (Sun et al., 2017). 411 million people living in 330 cities above 300,000 population are exposed to drought risk, which include three Asian megacities Delhi (India), Karachi (Abbas et al.), and Kolkata (India). Drought-related economic losses are also high in Dhaka (Pervin et al., 2020), Istanbul (Turkey), Manila (Philippines), and Shenzhen (China), while Manila is also highly vulnerable to drought-related mortality (Gu et al., 2015).

Increasing urban drought risk will also have cascading impacts on regions from where water is imported, exacerbating drought exposure beyond urban settlements and limiting water availability in certain regions (Chuah et al., 2018; Garrick et al., 2019; Zhang et al., 2020c; Zhao et al., 2020). There is *medium evidence (high agreement)* that urban water insecurity is experienced differentially based on income, risk exposure, and assets, and that urban drought and water scarcity is causing material and on-material losses and damage (Singh et al., 2021a). Importantly, in several Asian cities, flood and drought risk is expected to occur concurrently, especially in South Asia which is projected to see the largest increase in urban land exposed to both floods and droughts (25% to 32% increase in flood and drought risk between 2000-2030).

10.4.6.3.4 Sea-level rise and coastal flooding

Global assessments identify Asia as the most exposed to SLR [see CCP 2.2.1], in terms of number of people living in low-elevation coastal zones and the number of people exposed to flooding from 1-in-100 year storm surge events (Jevrejeva et al., 2016; Abadie et al., 2020) (Neumann et al., 2015; Kulp and Strauss, 2019) (Haasnoot, 2021). Twelve of the top 20 countries exposed to SLR and associated flood events are in Asia and of these, China, India, Bangladesh, Indonesia and Viet Nam are estimated to have the highest total coastal population exposure (Neumann et al., 2015) (Edmonds et al., 2020). Critically, regardless of emissions scenario, 70% of the global population exposed to SLR and land subsidence are in eight Asian countries: China, Bangladesh, India, Vietnam, Indonesia, Thailand, the Philippines, and Japan (Kulp and Strauss, 2019). This is particularly concerning since in highly populated low-lying coastal cities across Asia, it is estimated that land subsidence could be as influential as climate-induced SLR over the twenty-first century (Cao et al., 2021; Nicholls et al., 2021). In East Asia & the Pacific (expected to see 0.2-0.5m SLR), without adaptation, 1 million people (range of 0.3-2.2 million) are projected to be affected by submergence under RCP8.5 by 2095. Limiting warming reduces this risk and under RCP 4.5, these numbers of people at risk are reached by 2140. However, continuing on RCP8.5 increases risk exposure to 7 million (estimated range of 2-24 million people) (Haasnoot, 2021). Notably, assuming present-day population and adaptation (in the form of existing protection standards), East and South Asia already have a large number of people at risk of a 100-year flooding event (63 million) because of relatively lower flood protection (except in China and Malaysia).

These global scenarios will have significant impacts on national and sub-national populations. For example, in Bangladesh, under 0.44m and 2m mean SLR, direct inundation is estimated to drive migration of 0.73- 2.1 million people by 2100 (Davis et al., 2018). Such migration will have direct development implications: for example, destination locations could see additional demands on jobs (594 000), housing (197000), and food (783×109 calories) by mid-century as a result of those displaced by SLR (Davis et al., 2018).

Among the 20 largest coastal cities with highest flood losses by 2050, 13 are in Asia[4], with a regional concentration in South, South East and East Asia (Hallegatte et al., 2013). Further, 9 of these cities (Guangzhou, Kolkata, Tianjin, Ho Chi Minh, Jakarta, Zhanjiang, Bangkok, Xiamen, Nagoya) also have an

[4] Guangzhou, Mumbai, Kolkata, Shenzhen, Tianjin, Ho Chi Minh, Jakarta, Chennai, Surat, Zhanjiang, Bangkok, Xiamen and Nagoya

additional risk of subsidence due to sea-level rise and flooding (Hallegatte et al., 2013). Guangzhou, China is estimated to be the most economically vulnerable city in the world to SLR by 2050, with estimated losses of $254 million per year under 0.2m SLR (Jevrejeva et al., 2016). With a 2°C warming, Guangzhou is expected to see SLR of 0.34m; under 5°C warming, this number rises to 1.93m. A more recent estimate calculates expected damage in Guangzhou due to SLR under RCP8.5 to reach US$331 billion by 2050 and US$420 billion under the high-end scenario with figures doubling by 2070. By 2100, expected damage could reach US$1.4 trillion under RCP 8.5 and US$1.8 trillion the high-end scenario. Similarly, in Mumbai (India) SLR damages amount to US$49-50 billion by 2050 and could increase by a factor of 2.9 by 2070 (Abadie et al., 2020). In coastal cities such as Bangkok and Ho Chi Minh City, projected land subsidence rates, mainly due to excessive groundwater extraction, are comparable to, or exceed, expected rates of SLR, resulting in an additional 0.2 m sea level rise by 2025 (Jevrejeva et al., 2016). In Shanghai, current annual damage by coastal inundation is estimated at 0.03% of local GDP; under RCP4.5, this increases to 0.8% by 2100 (uncertainty range: 0.4%–1.4%), and further exacerbated by land subsidence and socioeconomic development (Du et al., 2020). It is important to note that these projections assume (1) no adaptation and (2) that damage repairs are undertaken and completed annually. Given these assumptions, while these estimates communicate the scale of projected impacts, they are indicators of possible damages in the absence of adaptation and not actual projections.

SLR affects economic growth, its drivers, and welfare outcomes (Hallegatte, 2012; Pycroft et al., 2016; Lee and Asuncion, 2020) through (1) permanent loss of land and natural capital, (2) loss of infrastructure and physical capital, (3) loss of social capital and migration, (4) temporary floods, food insecurity and loss of livelihoods, and (5) added expenditure for coastal protection. Without adaptation, direct damage to GDP by 2080 due to SLR would be highest in Asia (*robust evidence, medium agreement*), with China losing between $64.2 billion (at A1B of 2.4∘C by the 2050s and 3.8∘C by the 2090s/ 0.47 m), $95.8 billion (at RAHM scenario of 1.4 m SLR by 2100/1.12 m), and $118.4 billion (at High SLR of 2m by 2100/1.75 m) in direct damages, and an additional $5.7 billion, $4.5 billion, and $4.5 billion respectively due to migration (Pycroft et al., 2016). Closely after China, will be India, Korea, Japan, Indonesia, and Russia. Overall, Asia can experience direct losses of about $167.6 billion (at 0.47 m), $272.3 billion (at 1.12m), or $338.1 billion (at 1.75m) and an additional $8.5 billion, $24 billion or $ 15 billion at the respective SLR projections due to migration[5].

10.4.6.3.5 Tropical cyclones

Globally, there is *high confidence* that the proportion of intense tropical cyclones is expected to increase despite the total number of tropical cyclones expected to decrease or remain unchanged (Arias et al., 2021), especially in Southeast and East Asia (Knutson et al., 2015; Yamamoto et al., 2021). Historical trends from South Asia indicate that more lives are lost due to storm surge levels than the intensity of the cyclone (Niggol and Bakkensen, 2017). The number of people exposed to 1-in-100-year storm surge events, is highest in Asia. China, India, Bangladesh, Indonesia and Viet Nam have the highest numbers of coastal populations exposed (Neumann et al., 2015) with Guangzhou, Mumbai, Shenzen, Tianjin, Ho Chi Minh City, Kolkata, and Jakarta incurring losses of US$1520 million due to coastal flooding in 2005 alone (Dulal, 2019), although Jakarta is exposed to monsoonal storm surge. It is projected that by 2050, without adaptation, the annual losses incurred in these cities will increase to approximately US$32 billion (Dulal, 2019).

Globally, six of the top ten countries/places with the highest AAL associated with tropical cyclones are in Asia (Japan, Korea, Philippines, China, Taiwan, Province of China, and India) (Mori et al., 2021a). AAL associated with storm surge is primarily concentrated in Japan, China, Hong Kong SAR of China, and India. AAL associated with wind and storm surge relative to the existing capital stock in the country is highest in New Caledonia, Tonga, Vanuatu, Palau, Philippines, Fiji and Solomon Islands, indicating less resilience. For example, in Ise Bay, Japan, current storm surges are estimated to lead to property and business damage of approximately 100.04 billion JPY current adaptation (protective seawall) but this can more than double to 236.49 billion JPY under climate change-induced increases in storm surge intensity (Jiang et al., 2016).

[5] Cumulative migration in high SLR scenarios is always higher, but since much of the migration has already occurred in earlier decades, the additional migration is lower in the high SLR scenarios than the A1B scenario.

10.4.6.3.6 Riverine floods

Over on-third Asian cities and about 932 million urban dwellers live in areas with high risk of flooding (Gu et al., 2015). Of 437 cities at low risk of flood exposure but highly vulnerable to flood-related economic losses, approximately half are in Asia (Gu et al., 2015).

Globally, China and India have the highest AALs associated with riverine floods, with a magnitude of USD 13 billion and USD 6 billion respectively. Other countries from Asia among the top ten of absolute AALs are Japan, Bangladesh and Thailand. There is an increased flood risk for habitations on the deltas influenced by both riverine and coastal drivers of flooding (Szabo et al., 2016a), globally exposing 9.3% more people annually to riverine flooding than otherwise estimated without the compounded influence (Eilander et al., 2020). Simultaneously, SLR and subsidence are also expected to increase the risk due to frequent flood events for these delta regions than the longer-return periods otherwise associated with SLR (Yin et al., 2020).

10.4.6.3.7 Permafrost thawing and associated risks

In Northern Eurasia, observed and projected climate change impacts are especially pronounced. On land, the presence of permafrost, which occupies substantial areas of eastern Russia, Mongolia and mountain regions of China, creates specific challenges for economic development and human activities. By 2050, it is *likely* that 69% of fundamental human infrastructure in the Pan Arctic will be at risk (RCP 4.5 scenario), including more than 1200 settlements (Hjort et al., 2018). Majority of population and absolute majority (85%) of large settlements on permafrost are located in Russia and 44% of those are expected to be profoundly affected by permafrost thaw by 2050 (Streletskiy et al., 2019; Ramage et al., 2021). Under RCP8.5, climate-induced decrease of bearing capacity and, in regions with ice-rich permafrost, thaw subsidence, is projected to affect 54% of all residential buildings on permafrost with combined worth of $20.7 billion USD; 20% of commercial and industrial structures and 19% in critical infrastructure with a total worth of $84.4 billion USD (Streletskiy, 2019). Transport infrastructure in Russia and China are impacted by thaw subsidence and to lesser degree from frost heave, which add significant operational costs and limit accessibility of remote settlements (Ni et al, 2021; Porfiriev et al., 2019).

Especially in Russia, significant populations and fixed infrastructure assets are located in urban centers on permafrost that is degrading significantly. Two major risks associated with permafrost degradation are loss of permafrost bearing capacity and ground subsidence (Streletskiy et al., 2015). The former determines the ability to support foundations of buildings and structures and is a vital characteristic of sustainability of the economic centers, while the latter impacts the ability of critical infrastructure (roads, railroads) to provide transportation and support accessibility of remote populations and economic centers on permafrost. Proximity of some settlements to the coasts or areas with uneven topography may further increase risks associated with permafrost degradation as ice-rich coasts characterised by high rates of coastal erosion, while settlements located on slopes may experience higher rates of mass wasting processes.

Observed changes in climate resulted in permafrost warming and increased thaw depth in undisturbed locations (Biskaborn et al., 2019), but in built up areas these transformations were exacerbated by human activities (Grebenets et al., 2012). Norilsk, the largest city built on permafrost above the Arctic Circle (Shiklomanov et al., 2017b) was found to have one of the highest trends of near-surface permafrost warming (Streletskiy et al., 2012). Anomaly high temperatures and earlier snowmelt in 2020 may have contributed to oil storage collapse and resulting spill of 20 thousand tons of diesel fuel in Norilsk area (Rajendan et al., 2021). The ability of foundations to support structures have decreased by 10 to 40% relative to the 1960s in the majority of settlements on permafrost in Russia (Streletskiy et al., 2012) and further expected to decrease by 20 to 33% by 2050-59 relative to 2006-15 (Streletskiy et al., 2019).

10.4.6.3.8 Risks and impacts on infrastructure

South Asia and Africa bear the highest losses from unreliable infrastructure and climate change will increase these losses due to hazards, and necessitate additional infrastructure investments to address new risks (Hallegatte et al., 2019; Lu, 2019)[6]. Specifically, power generation and transport infrastructure incur losses

[6] While Hallegatte et al. (2019) estimate that in low- and middle-income countries, the cost of infrastructure disruptions range from $391-$647 billion, they highlight that "while these estimates are incomplete, they highlight the substantial costs that unreliable infrastructure impose on people in low- and middle- income countries".

of $30 billion a year on average from hazards (about $15 billion each), with low- and middle-income countries shouldering about $18 billion of the total amount (Koks et al., 2019; Nicholls et al., 2019).

Among the top 20 countries that are rapidly expanding their infrastructure stock while facing high disaster risk and low infrastructure quality, Laos, Philippines, Bangladesh, Cambodia, Kyrgyzstan, Bhutan, and Viet Nam are from Asia. (UNISDR, 2017; WEF, 2018). The losses are due to direct damage to infrastructure, disruption in services, and affected supply chains (Hallegatte et al., 2019). East Asia and the Pacific and South Asia have the highest adaptation deficits in coastal protection with USD 75 billion in the former and USD$49 billion in the latter (Nicholls et al., 2019). If overall damages are minimised, low- and middle-income countries may need to invest 0.1 to 0.5 percent of their GDP annually up to 2030 for protection against both coastal and river floods, varying based on level of acceptable risks, construction costs, urbanisation and climate uncertainties[7].

- **Power disruption:** Contrasting with high-income countries such as USA, where hazards, particularly storms, are responsible for 50% of power outages, this share is much lower in countries like Bangladesh or India, because system failures due to non-natural causes are very frequent. However, outages caused by hazards tend to be longer and geographically more widespread than other outages (Rentschler et al., 2019). Climate change induced sea-level is expected to impact power infrastructure even necessitating power plant relocation (Hallegatte et al., 2019). In Bangladesh, to avoid inundations caused by SLR (SSP2, RCP 8.5), approximately one-third of power plants may need to be relocated by 2030; an additional 30 percent power plants are *likely* to be affected by increased salinity of cooling water and increased frequency of flooding, while the northern region power plants will probably see a decrease in output because of droughts (Hallegatte et al., 2019). In 2013 in Chittagong (Pervin et al., 2020), users experienced about 16 power outages due to storms alone (Hallegatte et al., 2019). Further, low-carbon technology diffusion might make certain infrastructures redundant, leading to stranded assets.

  Across Asia, infrastructure impacts are mixed: net importers such as China and India will see GDP gains while extreme examples include Russia, a net exporter, which could see steep declines in fossil fuel production (Mercure et al., 2018). In low- and middle-income countries globally, disruption in power supply can impact firms directly (up to USD 120 billion per year), with coping costs (up to USD 65 billion a year), and other indirect impacts. Similarly, for households, the direct impact and cost of coping could be between USD 2.3 – 190 billion per year. Although all power outage is not due to natural hazards, there is a significant number that is attributed to disasters. Besides, outages caused by natural hazards tend to be longer and geographically larger than other causes (Hallegatte et al., 2019).

- **Transportation disruption:** Of the 20 countries in which the road and railway infrastructure is expected to be most affected in absolute terms due to multi-hazards, half are Asian (Koks et al., 2019). In low- and middle-income countries globally, the direct losses to firms on account of transportation disruption are about USD$107 billion per year, excluding the costs due to sales losses or delayed supplies and deliveries alone (Hallegatte et al., 2019). In the transport sector, floods and other hazards disrupt traffic and cause congestion, taking a toll on people and firms in rich and poor countries alike.

- **Water supply and disposal infrastructure disruption**: In low- and middle-income countries, disruption of water supply could lead to direct losses of about $6 billion per year to firms, and between $88 billion - $153 billion a year for households (willingness to pay to avoid disruption). Additionally, there are second order costs associated with finding alternate sources of water and health issues (of the order 6-9 billion USD per year accounting for medical bills and missed income) (Hallegatte et al., 2019). In China, climate models project that increasing number of wastewater treatment plant assets face climate-induced flood hazards in both the near and far future, potentially affecting as many as 208 million users by 2050 (Hu et al., 2019).

[7] Estimates based on the DIVA model that uses SSP 2, 3 and 5 and RCP 2.6, 4.5 and 8.5 in Nicholls et al. (2019) and investments from Ward et al. (2017). According to this study, uncertainty regarding socioeconomic changes and climate change is small compared with the uncertainty around construction costs and tolerance to risk.

Figure 10.8: Risks and key adaptation options in select cities across Asia. Cities were chosen to ensure coverage of different sub-regions of Asia, represent different risk profiles, different city sizes (based on current population and projected growth) and reported progress on different adaptation strategies (infrastructural, institutional, ecosystem-based, and behavioural). Full line of sight in SM10.4.

10.4.6.4 Adaptation in cities across Asia

A review of urban adaptation in South, East and Central Asia found examples of 180 adaptation activities across 74 cities (Dulal, 2019). Most adaptation actions in Asia are in initial stages (Araos et al., 2016) with more (57%) focus on preparatory actions such as capacity building and vulnerability assessment and 43% implemented adaptation (see also SM10.4). Most adaptation actions were focused on disaster risk management (Dulal, 2019) though proportion of climate finance spent on disaster preparedness is not very high (as (Georgeson et al., 2016) show in megacities of Beijing, Mumbai, and Jakarta). Although key port cities across Asia are at high risk from climate impacts, it is estimated that adaptation interventions constitute only a small proportion of cities' climate efforts (Blok and Tschötschel, 2015).

Critically, most urban adaptation in South, East and Central Asia were reactive in nature (Dulal, 2019) (Singh et al., 2021b), raising questions on preparedness, proactive building of adaptive capacities, and whether present actions can lock certain cities/sectors into maladaptive pathways (Friend et al., 2014; Gajjar et al., 2018) (Salim et al., 2019) (Chi et al., 2020). China, India, Thailand, and Republic of Korea record the most number of urban adaptation initiatives, driven mainly by supportive government policies (Lee and Painter, 2015; Dulal, 2019). The number of actors working on urban adaptation is growing: in addition to national governments and local municipalities, civil society, private sector actors (Shaw, 2019), and transnational municipal networks (Fünfgeld, 2015) are emerging as important for knowledge brokering, capacity building, and financing urban adaptation (Karanth and Archer, 2014; Chu et al., 2017; Bazaz et al., 2018).

Adaptation options include (1) infrastructural measures such as building flood protection measures and sea walls, and climate-resilient highways and power infrastructure (Shaw et al., 2016b; Ho et al., 2017); (2) sustainable land use planning through zoning, developing building codes (Knowlton et al., 2014; Nahiduzzaman et al., 2015; Rahman et al., 2016; Ahmed et al., 2019b); (3) ecosystem-based adaptation measures such as protecting urban green spaces, improving permeability, mangrove restoration in coastal cities etc. (Brink et al., 2016; Fink, 2016; Yu et al., 2018d), (4) relocation and migration out of risk-prone areas (McLeman, 2019; Hauer et al., 2020; Maharjan et al., 2020); and (5) disaster management and contingency planning such as through early warning systems, improved awareness and preparedness measures (Shaw et al., 2016a). Asian cities are also focusing on institutional adaptation measures which cut across the five categories mentioned above such as through building capacity and local networks (Anguelovski et al., 2014; Friend et al., 2014; Knowlton et al., 2014), improving awareness (Knowlton et al., 2014), and putting local research and monitoring mechanisms in place (Lee and Painter, 2015) to enable adaptation.

10.4.6.4.1 Infrastructural adaptation options

The challenge of adapting infrastructure to climate change is two-fold: there are significant infrastructure deficiencies, especially in low income countries across Asia, and key infrastructures are at high risk due to climate change (Hallegatte et al., 2019; Lu, 2019). Infrastructural adaptation options in cities attempt to enable networked energy, water, waste, and transportation systems to prepare for and deal with climate risks better (Meerow, 2017) through interventions such as improved highways and power plants, climate-resilient housing, and improved water infrastructure, etc. (ADB, 2014).

- **Power infrastructure**: Adaptations in electricity systems include climate resilient power infrastructure, particularly essential for coastal megacities such as Manila, Mumbai, Bangkok, Ho Chi Minh City (Meerow, 2017; Duy et al., 2019), which double as regional economic hubs and are home to tens of millions of people within Asia. In the Philippines, solar panels at water pumping stations are installed to operate and maintain a minimal capacity to pump water if the electricity grid were to break down (Stip et al., 2019).

- **Water infrastructure:** Sustainable water supply and resource management are key to urban adaptation through improved water service delivery, wastewater recycling, and storm water diversion (Deng and Zhao, 2015; Xie et al., 2017; Yu et al., 2018d). Infrastructure-based adaptation options in urban water management include building water storage facilities, storm water management, and enhancing water quality improving permeability, managing runoff, and enabling groundwater recharge. One example is of Shanghai (China), where infrastructural and policy incentives come to together to enable adaptation: the city has been divided into 14 water conservancy zones, including 348 polder areas with 2517 km of dykes, 1499 pump stations, and 2203 sluices (Yu et al., 2018d). It also depends on a regional inundation control system, flood early warning system, and emergency plan to deal with flood risk and mitigate waterlogging (Chen et al., 2018e; Yu et al., 2018d). Another example is Ho Chi Minh City (Viet Nam), where, given significant increases in area at risk of flooding under climate change, the city has invested in storm sewer upgradation, dike works, improving drainage, and increasing height of road embankments and minor bridges (Storch and Downes, 2011; ADB, 2014; Ho et al., 2017). These infrastructural interventions were complemented by designing an early warning system to initiate flood mitigation procedures, such as isolating critical electrical and mechanical operating systems from water.

- **Built infrastructure**: Current built infrastructure adaptation interventions are mostly reactive (e.g., strengthening housing units, using sandbags during flooding, storing of food, evacuation) rather than preventive (e.g., relocation, building multi-storey and stronger housing units), mainly due to limited resources within most vulnerable households for investing in proactive measures (Francisco and Zakaria, 2019). For cities in North Asia seeing permafrost thawing, adequate land-use practices, permafrost monitoring, maintenance of infrastructure and engineering solutions (e.g. using thermosiphons) may temporarily offset negative effects of permafrost degradation in small, economically vital areas, but are *unlikely* to have an effect beyond the immediate areas (Shiklomanov et al., 2017b; Streletskiy, 2019). Importantly, thawing permafrost and GHG emissions create feedbacks where emissions amplify warming and drive additional thaw. Reducing these impacts through mitigation will reduce the need for adaptation significantly (Schaefer et al., 2014).

- **Infrastructure and technology:** Several infrastructural options employ technology such as smart meters to monitor water usage, technology-based service delivery but these are differentially adopted across Asian sub-regions with higher adoption across East Asia. Examples include the Yokohama smart city project in Japan, which has been smart eco-urbanism interventions since 2011 (e.g. energy saving and storage infrastructure, wastewater management, behavioural change towards renewable energy and low-carbon transportation) (IUC, 2019); the Tianjin Eco-city mega-project in China, which is testing a range of measures to meet urban sustainability goals in partnership with Singapore (ICLEI, 2014b; Blok and Tschötschel, 2015), development in New Songdo (Republic of Korea) which is experimenting with interventions such as embedded smart waste management (Anthopoulos, 2017), and national policy initiatives such as the Smart Cities Mission covering 100 cities in India (e.g. technology-enabled water, energy, and land management for urban agriculture in Nashik city) (ICLEI, 2014a). However, the efficacy of such measures, especially for larger sustainability and climate change goals remain to be seen (ICLEI, 2014b; ICLEI, 2014a; Caprotti et al., 2015; Anthopoulos, 2017).

Infrastructural measures alone are seldom effective in building urban resilience as seen in the examples of 2011 floods in Bangkok and 2005 typhoon in Manila (Duy et al., 2019) or projected estimates by Pervin et al. (2020) who find that structural interventions in existing drainage systems reduce flooding risk by 7-19% in Sylhet (Bangladesh) and Bharatpur (Nepal) but without proper solid waste management, area under flood risk could increase to 18.5% in Sylhet and 7.6% in Bharatpur in five years, rendering the infrastructural interventions ineffective over time. While in some cities, it is estimated that infrastructural adaptation through 'hard' flood protection strategies (e.g. storm-surge barriers and floodwalls) is more effective than institutional or ecosystem-based adaptation by 2100 (e.g.Du et al.in Shanghai), a hybrid approach where hard strategies protect from flood risk and soft strategies reduce residual risk from hard strategies is suggested (Du et al., 2020). In Japan, without adaptation, estimated damage costs of floods (caused by tropical cyclones, altered precipitation), by 2081-2100 under RCP2.6 will be 28% higher (compared to 1981-2000), rising to 57% higher under RCP8.5 (Yamamoto et al., 2021). With a combination of adaptation measures (such as land use control, piloti building, flood control measures), estimated damage costs can be reduced even below 1981-2000 levels and with a combination of mitigation and these adaptation measures, an estimated 69% reduction in flood damage costs are expected; demonstrating the importance of concerted and immediate climate action in reducing damage.

Infrastructural interventions can sometimes be maladaptive when assessed over longer time periods; e.g. the Mumbai Coastal Road (MCR) project aimed at reducing flood risk and protecting against SLR will potentially cause damages to intertidal fauna and flora and local fishing livelihoods (Senapati and Gupta, 2017); Jakarta's Great Garuda project aimed at reducing flood risk is expected to *increase* flood risk for the poorest urban dwellers (Salim et al., 2019).

Figure 10.9: Effectiveness of select adaptation options in cities across Asia. Effectiveness is assessed based on the option's ability to reduce risk as reported in the literature.

10.4.6.4.2 Sustainable land use planning and regulation

Land use in cities impacts resource use (e.g. water, energy), risk (a function of population density, service provision, hazard exposure), and adaptive capacity, all of which influence efficacy of urban adaptation (de Coninck et al., 2018). Locally-suited land use planning and regulation (such as appropriate zoning or building codes, safeguarding land rights) can have adaptation co-benefits (Mitchell et al., 2015; Dhar and Khirfan, 2016), e.g. strict building regulations can protect urban wetlands and associated ecosystem services (Jiang et al., 2015); appropriate land zoning can safeguard green spaces, ensure improvements in permeability, and avoid new development in risk-prone locations (Duy et al., 2019); ensuring tenurial security or regularizing informal settlements can incentivise improvements to housing quality, thereby alleviating vulnerability of the most marginal (Mitchell et al., 2015).

Land tenure arrangements strongly shape urban dweller's vulnerability and their adaptive capacities (Roy et al., 2013; Michael et al., 2018). For example, in Khulna, Roy et al. (2013) find significant differences between the adaptive strategies of house owners and renters in low income settlements, a finding echoed in Bangalore (India) (Deshpande et al., 2018) and Phnom Penh (Cambodia) (Mitchell et al., 2015). In Riyadh (Saudi Arabia), land-based adaptation strategies include land zoning to control population and building density, demarcating environmental protection zones, and sub-urbanisation (Nahiduzzaman et al., 2015; Rahman et al., 2016). In many Asian cities, land subsidence control can serve as an adaptation strategy since it is estimated to significantly reduce relative sea-level rise (*high confidence*). This has an important implication in that subsidence control would be a good and a complementary measure to climate mitigation and climate adaptation in many coastal urban settings in Asia (Cao et al., 2021; Nicholls et al., 2021). Urban land use planning, if used proactively, can incentivise adaptation-mitigation synergies and avoid unintended negative consequences of urbanisation as Xu et al. (2019) show in Xiamen.

10.4.6.4.3 Ecosystem-based adaptation

The literature on urban Ecosystem-based Adaptation (EbA)[8], especially across Asia, has grown significantly since AR5 (Demuzere and al., 2014; Yao et al., 2015; Brink et al., 2016; Bazaz et al., 2018; de Coninck et

[8] Ecosystem-based Adaptation (EbA) is defined by IPBES as the conservation, sustainable management and restoration of natural ecosystems to help people adapt to climate change (Glossary, 2019). In urban areas, EbA includes improving ecological structures (e.g. maintaining watersheds, forests, green roofs), ecological functions and processes (e.g. wetland functioning for flood protection), valuation measures (including monetary or non-monetary values to ecosystem service benefits), and investing in ecosystem management practices (i.e. enabling adaption co-benefits through the maintenance, preservation, restoration or creation of ecological structures) (Liu et al., 2014a; Brink et al., 2016). Thus, EbA adaptation actions include protecting urban green spaces, improving permeability, fostering urban

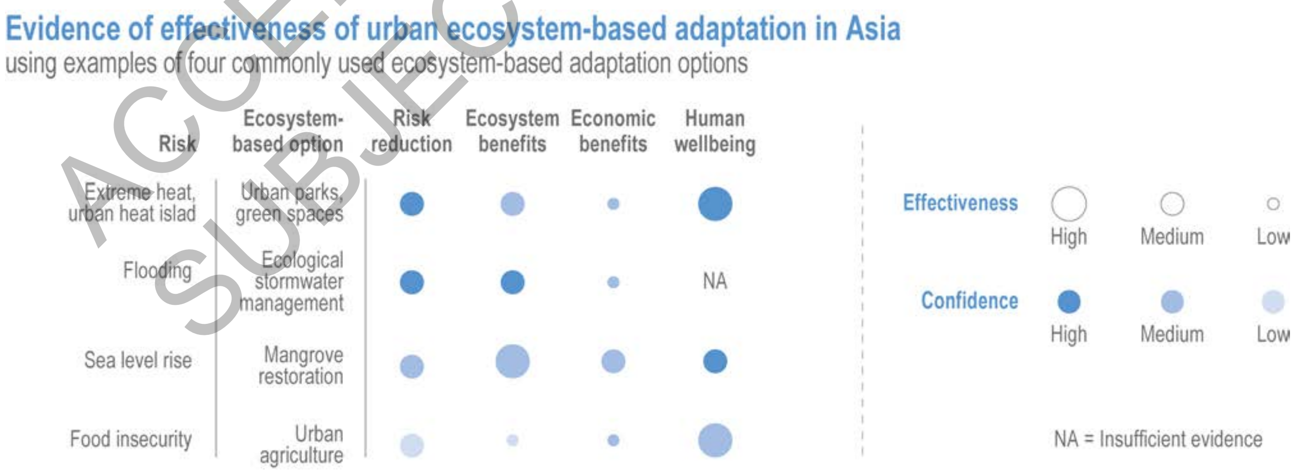
al., 2018; Ren, 2018). This growing literature reflects the wide recognition that infrastructural adaptation can often have ecological and social trade-offs (Palmer et al., 2015) and need to be complemented by ecosystem-based actions to manage risk more effectively (Du et al., 2020), build adaptive capacity, and in some cases, meet mitigation and sustainable development goals (Huang et al., 2020).

Illustrative examples of EbA in Asian cities include sponge cities in China for sustainable water management, flood mitigation, and minimising heat waves impact (Jiang et al., 2018; Yu et al., 2018d; Wang et al., 2019a; Zhanqiang et al., 2019), Singapore's Active, Beautiful, Clean Waters (ABC Waters) Programme, which uses bio-engineering approaches to protect river channels and prevent localised flooding, improve water quality, and create community spaces, and Dhaka's green roofs and urban agriculture (Zinia and McShane, 2018).

EbA approaches to manage floods, capture and store rainwater, restore urban lakes and rivers, and reduce surface run-off often blend infrastructural and ecosystem-based approaches. For example, in Tokyo (Japan), stormwater management is done by sophisticated underground infrastructure and an artificial infiltration stormwater system (Saraswat, 2016) (Mishra et al., 2019). China's Sponge City Program aims to reduce the impacts of flooding through low-impact development measures, urban greenery, and drainage infrastructure, such that 80 percent of urban areas reuse 70 percent of rainwater by 2020, which would help ensure the resilience of these cities to floods (Li et al., 2016b; Stip et al., 2019).

Case studies on urban EbA also raise equity concerns (*medium evidence, medium agreement*) such as interventions biased towards suburban areas in Guangzhou (China) (Zhanqiang et al., 2019); inadequate consideration of low-income, vulnerable populations (Blok and Tschötschel, 2015; Meerow, 2017) (Mabon and Shih, 2021); and low familiarity with interventions such as artificial wetlands, water retention ponds, green façade/walls can restrict inclusiveness (Zinia and McShane, 2018). Further, urban EbA is constrained by a range of factors such as inadequate institutional structures and processes for connecting different remits and knowledge systems and tradeoffs in landuse for different purposes (Mabon and Shih, 2021; Singh et al., 2021b).

EbA interventions are not uniform across Asian cities: in a global study on urban EbA, Brink et al. (2016) find Eastern Asia, India and Israel report most EbA interventions and there is variable and *limited evidence* on effectiveness and scalability (SM10.5). Using a risk framing (i.e. the extent to which an option reduces risk), urban EbA options in Asian cities score as being 'low to medium' effective (See SM10.5). However, when the assessment is expanded to assess the ecosystem benefits, economic impacts, and human wellbeing co-benefits of EbA, effectiveness increases. Figure 10.10 shows the evidence of effectiveness of EbA.



agriculture, mangrove restoration in coastal cities, improved wetland management, etc. (Doswald et al., 2014; Brink et al., 2016; de Coninck et al., 2018).

Figure 10.10: Evidence on effectiveness of ecosystem-based adaptation using examples of four commonly used EbA options[9]. Effectiveness is assessed qualitatively based on the evidence (for full line of sight see SM10.5) and is examined through four framings: potential to reduce risk (e.g. reduced exposure to hazard; reduced risk); benefits to ecosystems (through improved ecosystem health, high biodiversity); economic benefits (e.g. improved incomes, fewer man-days lost, better livelihoods); and human wellbeing outcomes (e.g. health, quality of living etc.). Darker shading signifies high effectiveness while lightest shade signifies low effectiveness of an EbA option (i.e. the option scores low on the indicator).

For example, urban agriculture is identified as offering multiple benefits such as mitigating emissions associated with food transportation from rural to urban areas, improving food and nutritional security, strengthening local livelihoods and economic development, improved microclimate, soil conservation, improved water and nutrient recycling, efficient water management (Padgham and Dietrich, 2015; Patil et al., 2019) but can potentially undermine ecosystem services through land use changes, water over-extraction or applying chemical fertilisers (Ackerman et al., 2014), expose smallholders to volatile markets and crops that are not consumed by farming households themselves, thus undermining food security, or increasing work burdens on women, and health externalities – e.g. through use of untreated wastewater, or rearing poultry and livestock in unsanitary conditions. There remain gaps on understanding the differential impacts of urban agriculture at different scales as well as its effectiveness in improving adaptive capacity at scale.

10.4.6.4.4 Migration and planned relocation

There is *medium evidence* with *high agreement* that climatic risks are exacerbating internal and international migration across Asia (IDMC, 2019) (Maharjan et al., 2020) **[Box 10.2].** In coastal cities, formal 'retreat' measures such as forced displacement and planned relocation (Oppenheimer et al., 2019) are commonly considered 'last resort' adaptation strategies once other infrastructural and ecosystem-based protect and accommodate strategies are exhausted (Haasnoot et al., 2019) (CCP 2.3). In contrast, migration (which can take various forms from seasonal, temporary mobility to circular or permanent movement), is a regular feature across Asian urban settlements (Maharjan et al., 2020)[Also see Box 10.2; MIGRATION CCB].

There is *robust evidence* (*medium agreement*) that across Asia, migration (and increasingly planned relocation) will continue to be a key risk management strategy, especially in low lying flood-prone cities (e.g. in SE and South Asia) and across drylands (e.g. in South and Central Asia) (Davis et al., 2018) (Ajibade, 2019) (Lincke and Hinkel, 2021). While there is insufficient evidence to project migration numbers under different warming levels, it is well established that migration as an adaptation strategy is not equally available to all (Ayeb-Karlsson, 2020) and climatic risks might reduce vulnerable populations' ability to move due to losses of assets, thus reinforcing existing inequalities and differential adaptive capacities (Singh and Basu, 2020);(Zickgraf, 2019) (Blondin, 2019; Cundill et al., 2021; Gavonel et al., 2021).

There is *medium evidence* (*low agreement*) about the effectiveness of migration and planned relocation in reducing risk exposure. Evidence on climate-driven internal migration shows that moving has mixed outcomes on risk reduction and adaptive capacity. On one hand, migration can improve adaptive capacity by increasing incomes and remittances as well as diversifying livelihoods (Maharjan et al., 2020). On the other, migration can expose migrants to new risks. For example, in Bangalore (India), migrants often face high exposure to localised flooding, insecure and unsafe livelihoods, and social exclusion, which collectively shape their vulnerability (Byers et al., 2018);(Singh and Basu, 2020). In Metro Manila (Philippines) and Chennai (India), planned relocations to reduce disaster risk have often exacerbated vulnerability, due to relocation sites being in environmentally sensitive areas, inadequate livelihood opportunities, and exposure to new risks (Ajibade, 2019; Jain et al., 2021) (Meerow, 2017).

10.4.6.4.5 Disaster management and contingency planning

There is rich case-based evidence across Asia on urban adaptation to extreme events with relatively more evidence on rapid-onset events such as cyclones and flooding than slow-onset disasters such as drought (Ray and Shaw, 2019; UNESCAP, 2019); (Singh et al., 2021a) see Box 10.7 on Loss and Damage). Overall, there

[9] Assessing effectiveness of adaptation actions is challenging because of the lack of a clear goal that signifies effective adaptation, varied conceptual framings and metrics used to assess effectiveness, and low empirical evidence on effectiveness of implemented adaptation actions, (Singh et al., 2021a);(Owen, 2020).

has been a growing emphasis on 'build back better' interventions (Mannakkara and Wilkinson, 2013); (Hallegatte et al., 2018) that approach disaster management holistically through infrastructural solutions such as climate-resilient housing or sea walls and soft approaches such as strengthening livelihoods, developing early warning systems (EWS)[10], increasing awareness about disaster risks and impacts, and building local capacities to deal with them (Bhowmik et al., 2021). Notably, urban disaster management is effective when land use planning processes including greenfield development, zoning and building codes, and urban redevelopment are leveraged to reduce and/or avoid risk, thereby averting potential maladaptation (Kuhl et al., 2021).

There is relatively lower empirical evidence on how microenterprises and businesses are adapting to increased risk but recent examples in Mumbai, India (Schaer and Pantakar, 2018) and Kratie, Cambodia (Ngin et al., 2020) suggest that businesses primarily adopt temporary and reactive responses rather than long-term, anticipatory adaptation measures.

A review of innovative disaster risk reduction (DRR) approaches notes the use of GIS and drone-based technologies for mapping risk exposure and impacts, mobile-based payments for post-disaster compensation, to transnational initiatives and learning networks on urban resilience (Izumi et al., 2019). Further, technology-based innovations such as using big data (Yu et al., 2018b), improved warnings through mobile phones, or mobilising relief through social media (Carley et al., 2016) are proving effective for disaster preparedness, relief and recovery. Community-based DRR is consistently ranked as most effective for its role in transforming DRR towards being more context-relevant and inclusive. Ecosystem-based disaster risk reduction (EbDRR) is also gaining prominence and includes strategies such as mangrove plantation and rejuvenation in vulnerable coastal areas. Nature-based solutions for flood protection and reducing drought incidence have emerged as an alternative to costlier 'hard' infrastructure (Rozenberg and Fay, 2019); (UN-Water, 2018); (Zevenbergen et al., 2018). Some cities are also reporting adaptation to heat risk. For example, Ahmedabad (India) has pioneered preparedness for extreme temperatures and heat waves by developing annual Heat Action Plans, building regulations to minimise trapping heat, advisories about managing heat stress, and instituting cool roofs policy (Ahmedabad Municipal, 2018).

Financing, regulations, and institutional processes have a significant role to play in incentivising disaster risk reduction and resilience in large-scale city-level built infrastructure by the private sector and other actors. Currently there are gaps in these mechanisms, leading to infrastructure development in disaster-prone areas, increasing exposure to people, property, economy and systems (Jain, 2013). Both firms and governments need to take disaster risks into consideration in supply-chain management to avoid disruptions and subsequent negative effects (Abe and Ye, 2013). There are several institutional challenges faced during DRR and CCA implementation including overlapping efforts and inefficient use of scarce resources due to inappropriate funding mechanisms, a lack of coordination and collaboration, a lack of implementation and mainstreaming, scale mismatches, poor governance, the socio-political-cultural structure, competing actors and institutions, lack of information, communication, knowledge sharing, and community involvement, and policy gaps (Seidler et al., 2018; Islam et al., 2020).

10.4.6.5 Enabling urban adaptation across Asia

There is growing empirical evidence of conditions enabling and constraining urban adaptation (Table 10.3) with relatively more literature from South, South East, and East Asia. Governance and capacity-related deficits are repeatedly identified as significant barriers to urban adaptation (*robust evidence, high agreement*) and interact with financial and informational constraints to mediate adaptation action.

[10] The set of technical, financial and institutional capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organisations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss. Dependent upon context, EWS may draw upon scientific and/or Indigenous knowledge. EWS are also considered for ecological applications e.g., conservation, where the organisation itself is not threatened by hazard but the ecosystem under conservation is (an example is coral bleaching alerts), in agriculture (for example, warnings of ground frost, hailstorms) and in fisheries (storm and tsunami warnings). (IPCC, 2018a)

Table 10.3: Barriers and enablers to adaptation across Asian cities.

Indicator	As an enabler	As a barrier
Governance and planning	**National policy directives** to adapt. e.g. strong national climate commitments in China, India, and Thailand (Dulal, 2019); and dedicated public-private councils on climate change in Seoul, Republic of Korea (Lee and Painter, 2015). Participatory planning, **co-producing solutions**, and engaging multiple stakeholders. E.g. Surat (Anguelovski et al., 2014; Karanth and Archer, 2014; Chu et al., 2017), Guwahati (Archer et al., 2014) in India; Bandar Lampung and Semarang in Indonesia (Archer et al., 2014); Seoul in Republic of Korea (Lee and Painter, 2015) **Devolving decision-making** to city governments (ADB, 2013) and strong **political leadership** helps institutionalising adaptation programs (Anguelovski et al., 2014; Friend et al., 2014; Lee and Painter, 2015), e.g. in Moscow (Russia) where the city mayor has spearheaded climate action (van der Heijden et al., 2019) **Mainstreaming climate adaptation** in city plans (UN-HABITAT and UNESCAP, 2018)	**Low accountability and transparency** in planning processes with inadequate spaces for public dialogue (Friend et al., 2014) and limited accountability to the most economically and politically marginalised people within cities (Garschagen and Marks, 2019). 65% of 180 urban adaptation interventions across Asia are **reactive** in nature (Dulal, 2019) thus missing opportunities for risk prevention and preparedness (Francisco and Zakaria, 2019). **Lack of forward-looking, learning-oriented processes** constrain adaptation with short-term development priorities often overshadowing long-term climate action needs (Friend et al., 2014; de Leon and Pittock, 2017; Gajjar et al., 2018; Khaling et al., 2018) (Garschagen and Marks, 2019; Jain et al., 2021). **Fragmented governance, lack of mainstreaming** between CCA and DRR (Fuhr et al., 2018; Khaling et al., 2018) E.g. in Vietnam, Thailand, Indonesia (Friend et al., 2014) and Metro Manila (Philippines) (Meerow, 2017)
Information	Knowledge sharing through **transnational municipal networks** such as C40, ACCRN, A-PLAT (Fünfgeld, 2015) City-level knowledge creation and knowledge transfer institutions (Lee and Painter, 2015)	**Data gaps** on projected climate risks and impacts in certain sub-regions and small settlements (Revi et al., 2014) **Numerous tools** for assessing vulnerability, adaptation planning (Nordgren et al., 2016)
Technology, infrastructure	Early warning systems, climate information, modelling studies inform adaptation decision-making (Reed et al., 2015; Singh et al., 2018a)	Inadequate **regional downscaled data** at city-scale (ADB, 2013; Khaling et al., 2018) Inadequate **cost benefit analyses** of different adaptation strategies (Khaling et al. 2018)
Capacity and awareness	A focus on **learning, experimentation, awareness and capacity building**, leads to more sustained, legitimate, and inclusive adaptation (ADB, 2013; Anguelovski et al., 2014); Reed et al. (2015)_	Limited access and capacity to use risk assessment tools (ADB, 2013; Shaw et al., 2016b)
Finance	**Dedicated adaptation financing**. E.g. in Beijing, adaptation spending is 0.33% of city's GDP (Georgeson et al., 2016); steering international and local funding to leverage adaptation benefits in urban development programs such as in Surat (India) (Cook and Chu, 2019); mainstreaming climate adaptation into development programming to leverage developmental finance for adaptation action (Cuevas et al., 2016; Narender and Sethi, 2018).	Inadequate **adaptation funding**, lack of **financial devolution** to city governments (Fuhr et al., 2018) (Garschagen and Marks, 2019).

10.4.7 Health and Wellbeing

Climate change is increasing risks to human health in Asia by increasing exposure and vulnerability to extreme weather events such as heat waves, flooding and drought, air pollutants, increasing vector-borne and water-borne diseases, undernutrition, mental disorders and allergic diseases (*high confidence*). Sub-regional diversity in socio-economic and demographic context (e.g., aging, urban vs agrarian society, increasing population vs reduced birth rate, high income vs low to middle income) and geographical characteristics largely define the differential vulnerabilities and impacts within countries in Asia (*high confidence*).

10.4.7.1 Observed Impacts

High temperatures affect mortality and morbidity in Asia (*high confidence*). In addition to all-cause mortality (Dang et al., 2016; Chen et al., 2018e), deaths related to circulatory, respiratory, diabetic (Li et al., 2014b) and infectious disease (Ingole et al., 2015), as well as infant mortality (Son et al., 2017) are increased with high temperature (*high confidence*). Increased hospital admissions (Giang et al., 2014; Lin et al., 2019) and ambulance transport (Onozuka and Hagihara, 2015) coincide with increased ambient temperature (*high confidence*). Heat waves are particularly detrimental to all-cause and cause-specific mortality (Chen et al., 2015a; Lee et al., 2016; Guo et al., 2017b; Yin et al., 2018). Both rural and urban populations are vulnerable to heat-related mortality (Ma et al., 2015; Chen et al., 2016a; Wang et al., 2018a). Individuals with lower degrees of education and socio-economic status, older individuals and individuals living in communities with less green space are more susceptible to heat-related mortality (*high confidence*) (Yang et al., 2012a; Huang et al., 2015b; Seposo et al., 2015; Son et al., 2016; Kim and Kim, 2017). These heat effects have been attenuating over recent decades in East Asian countries, although the driving force behind this remains unknown (*high confidence*) (Chung et al., 2017c; Chung et al., 2018).

Rising ambient temperatures accelerates pollutant formation reactions and may modify air-pollution related health effects (*medium confidence*). Higher temperatures are associated with increased effects of ozone on mortality (Shi et al., 2020). Climate change causes intensified droughts and greater wind erosion resulting in increased intensity and frequency of sand and dust storms (Akhtar et al., 2018). Mortality and hospital admissions for circulatory and respiratory diseases are increased after exposures to Asian dust events (*high confidence*) (Hashizume et al., 2020). El Niño has a major influence on weather patterns in various regions. For example, it causes dry conditions that sometimes result in forest fires and trans-boundary haze that increased all-cause mortality in children by 41% in Malaysia (Sahani et al., 2014).

Ambient temperature is associated with the risk of an outbreak of mosquito-borne disease in South and Southeast Asia (*high confidence*) (Servadio et al., 2018). Warmer climates are associated with a higher incidence of malaria (Xiang et al., 2018). Moderate rainfall also promotes malaria infection, while excessive rainfall decreases the risk of malaria (Wu et al., 2017b). El Niño intensity is positively associated with malaria incidence in a single year in India (Dhiman and Sarkar, 2017). The duration and survival rate of dengue mosquito development, mosquito density, mosquito biting activity, mosquito spatiotemporal range and distribution, and mosquito flying distance are all affected by temperature (*high confidence*) (Li et al., 2018b). Temperature, precipitation, humidity and air pressure are major weather factors associated with dengue fever transmission (*high confidence*) (Sang et al., 2014; Choi et al., 2016; Xu et al., 2017).

Climate change alters the hydrologic cycle by increasing the frequency of extreme weather events such as excess precipitation, storm surges, floods and droughts (*high confidence*). Water-borne diseases such as diarrhea, leptospirosis and typhoid fever can increase in incidence following heavy rainfall, tropical cyclones and flooding events (*high confidence*) (Deng et al., 2015; Levy et al., 2016; Li et al., 2018b; Matsushita et al., 2018; Zhang et al., 2019b). Droughts can cause increased concentrations of pathogens, which overwhelm water treatment plants and contaminate surface water. A positive association between ambient temperature and bacterial diarrhea has been reported, compared with a negative association with viral diarrhea (Carlton et al., 2016; Wang et al., 2018c).

Asia has the highest prevalence of undenourishment in the world, which was 11.4% in 2017, representing more than 515 million people. Southeast Asia has been affected by adverse climate conditions such as floods and cyclones, with impacts on food availability and prices (FAO, 2018d). Crop destruction due to tropical cyclones can include salt damage from tides blowing inland (*medium confidence*) (Iizumi and Ramankutty, 2015). Sea level rises result in intrusion of saline water into the coastal area of Bangladesh and people living in these areas face an increased risk of hypertension resulting from high salt consumption (Scheelbeek et al., 2016).

Weather conditions have been linked to mental health. High temperatures increase the risk of mental problems including mental disorders, depression, distress and anxiety in Vietnam (Trang et al., 2016), Hong Kong, China (Chan et al., 2018) and Republic of Korea (Lee et al., 2018d). In addition, high temperatures are reported to increase the risk of mortality from suicide in Japan, Republic of Korea, Taiwan, Province of China (Kim et al., 2016c), India (Carleton, 2017) and China (Luan et al., 2019). Extreme weather events such as storms, floods, hurricanes and cyclones increase injuries and mental disorders (post-traumatic stress disorder (PTSD) and depressive disorders) (Rataj et al., 2016), thereby negatively affecting well-being (*high confidence*).

Higher temperatures and increased CO2 elevate the level of allergens such as pollen, which can result in increased allergic diseases, such as asthma and allergic rhinosinusitis. The association between variations in ambient temperature and the occurrence of asthma has been reported in several Asian countries/regions such as Japan (Yamazaki et al., 2015), Republic of Korea (Kwon et al., 2016), China (Li et al., 2016a) and Hong Kong, China (*medium confidence*) (Lam et al., 2016).

10.4.7.2 Projected Impacts

Climate change is associated with significantly increased mortality (*high confidence*). Figure 10.11 shows projected health impacts due to climate change in Asia. The global estimates of excess deaths due to malnutrition, malaria, diarrhea and heat stress are approximately 250,000 deaths per year in 2030-2050 under the medium-high emissions scenario, assuming no adaptation (World Health Organization, 2014). The impacts are expected to be greatest in South, East and Southeast Asia. Another projection showed that the change in heat-related deaths is largest in Southeast Asia, which was 12.7% increase in the end of the century under a high-emission scenario (Gasparrini et al., 2017). As the proportion of older individuals in the population rises, the number of years lost due to disability increases more steeply (Chung et al., 2017b). In the 2080s, the number of annual temperature-related deaths is estimated to reach twice that in the 1980s in China (Li et al., 2018c). Over a 20-year period in the mid-21st century (2041–2060), the incidence of excess heat-related mortality in 51 cities in China was estimated to reach 37,800 (95% CI: 31,300–43,500) deaths per year under RCP8.5 (Bazaz et al., 2018).

Increased concentrations of fine particulate matter and ozone influenced by extreme events such as atmospheric stagnations and heat waves are projected to result in additional 12,100 and 8,900 deaths per year due to fine particulate matter and ozone exposure, respectively in China in the mid-century under RCP4.5 (Hong et al., 2019a). Excess ozone-related future premature deaths is noticeable in 2030 in East Asia and India for RCP8.5 (over 95% of global excess mortality) (Silva et al., 2016).

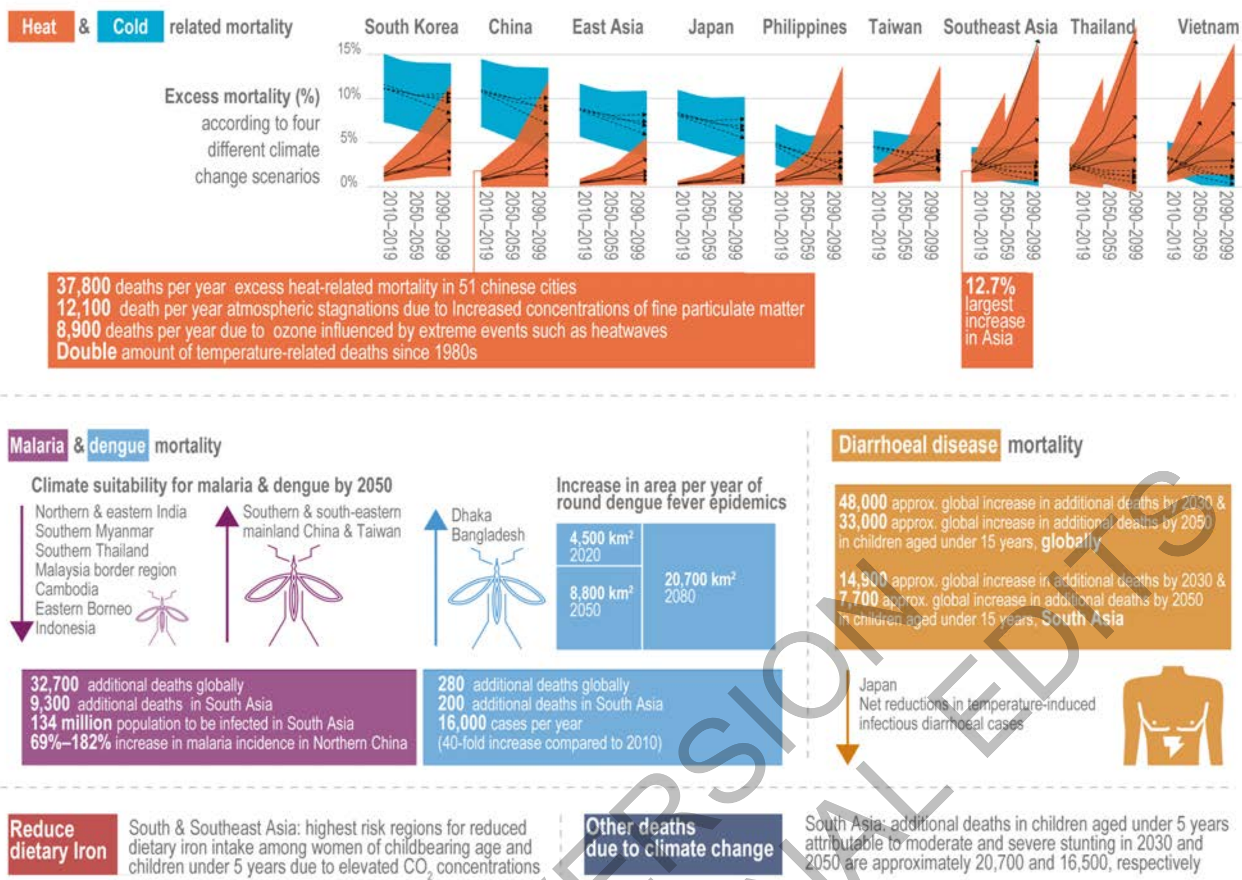


Figure 10.11: Projected health impacts due to climate change in Asia

The global estimates for increases in malaria and dengue deaths (annual estimates) are approximately 32,700 and 280 additional deaths, respectively, in 2050 under the medium-high emissions scenario (World Health Organization, 2014). Among these additional deaths, 9,300 and 200 deaths, respectively, are projected to occur in South Asia. The population at risk of malaria infection is estimated to increase by 134 million by 2030 in South Asia under the medium-high emissions scenario, considering socio-economic development. If no actions are taken, malaria incidence in northern China is projected to increase by 69%–182% by 2050 (Song et al., 2016). Another study suggested a decrease in climate suitability for malaria in northern and eastern India, southern Myanmar, southern Thailand, the Malaysia border region, Cambodia, eastern Borneo and Indonesia by 2050 (Khormi and Kumar, 2016). By contrast, climate suitability for malaria is projected to increase in the southern and south-eastern mainland of China and Taiwan, Province of China (Khormi and Kumar, 2016).

Dengue incidence is projected to increase to 16,000 cases per year by 2100 in Dhaka, Bangladesh, if ambient temperatures increase by 3.3°C without any adaptation measures or changes in socio-economic conditions (Banu et al., 2014). This would represent an increase in incidence of over 40-fold compared with 2010. Higher numbers of dengue fever cases are projected to occur under RCP 8.5 than RCP2.6 in China (Song et al., 2017). Compared with the average numbers in 1997–2012, the annual number of days suitable for dengue fever transmission in the 2020s, 2050s and 2080s will increase by 15, 25 and 40 days, respectively, in south China under RCP8.5. In addition, areas in which year-round dengue fever epidemics occur will *likely* increase by 4500, 8800 and 20,700 km^2 in the 2020s, 2050s and 2080s, respectively, under RCP8.5 (Nahiduzzaman et al., 2015).

The global estimates for increases in deaths due to diarrheal disease (annual estimates) in children aged under 15 years in 2030 and 2050 are approximately 48,000 and 33,000 additional deaths, respectively, under the medium-high emissions scenario (World Health Organization, 2014). Among these additional deaths, 14,900 and 7,700 deaths, respectively, are projected to occur in South Asia. An updated projection with pathogen-specific approach estimated 25,000 additional annual diarrheal deaths in Asia in 2080-2095 under the high emission scenario (Chua et al., 2021), while in some countries such as Japan, net reductions in temperature-induced infectious diarrheal cases were estimated, because viral infections are dominant in these countries during the cold season (Onozuka et al., 2019).

South and Southeast Asia are projected to be among the highest risk regions for reduced dietary iron intake among women of childbearing age and children under 5 years due to elevated CO_2 concentrations (*medium confidence*) (Smith and Myers, 2018). The estimated number of additional deaths due to climate change in children aged under 5 years attributable to moderate and severe stunting in 2030 and 2050 are approximately 20,700 and 16,500, respectively, in South Asia, under the medium-high emissions scenario (World Health Organization, 2014). In Bangladesh, due to climate change, river salinity is projected to be increased in coastal and freshwater fishery communities leading to significant shortages of drinking water in the coastal urban areas (Dasgupta et al., 2014c).

10.4.7.3 Adaptation Options/Co-benefits

The health co-benefits of greenhouse gas mitigation measures in energy generation have been reported to reduce disease burden. In China, the implementation of greenhouse gas policies would reduce the air pollution associated disease burden by 44% in 2020 under the Integrate Carbon Reduction scenario compared with the business as usual scenario (Liu et al., 2017b). Transition to a half-decarbonised power supply for the residential and transport sectors would avoid 55,000-69,000 deaths in 2030 compared with the business as usual scenario (Peng et al., 2018). A shift in travel modes from private motor vehicles to the use of mass rapid transit lines is estimated to reduce CO_2 equivalent emissions by 6% in Greater Kuala Lumpur and bring important health co-benefits to the population (Kwan et al., 2017). The 25 measures developed for reducing air pollution levels in Asia and the Pacific would reduce carbon dioxide emissions in 2030 by almost 20% relative to baseline projections and decrease warming by 0.3°C by 2050 which could eventually reduce heat-related excess deaths in the region (UNEP, 2019). The 25 measures include conventional emission controls focusing on emissions that lead to the formation of fine particulate matter ($PM_{2.5}$), next-stage air-quality measures for reducing emissions that lead to the formation of $PM_{2.5}$ and are not yet major components of clean air policies in many parts of the region, and measures contributing to development priority goals with benefits for air quality. Health co-benefits outweigh mitigation costs in Republic of Korea up to 2050 (Kim et al., 2020). Low-carbon pathways consistent with the 2 ◦C and 1.5 ◦C long-term climate targets defined in the Paris Agreement are associated with the largest health co-benefits when coordinated with stringent air pollution controls in Asia followed by Africa and Middle East (Rafaj et al., 2021).

Strategies to increase energy efficiency in urban built environment by compact urban design and circular economy policies can reduce greenhouse gas emissions and reap ancillary health benefits; compared to conventional single-sector strategies, national CO_2 emissions can be reduced by 15%–36%, and the annual deaths from 25,500 to 57,500 are avoidable from air pollution reduction in 637 Chinese cities (Ramaswami et al., 2017). In a city in China, the existing mitigation policies (e.g., promotion of tertiary and high-tech industry) and the one adaption policy (increasing resilience) increased co-benefits for wellbeing (Liu et al., 2016a).

Changing dietary patterns, particularly reducing red meat consumption and increasing fruit and vegetable consumption, contributes to the reduced greenhouse gas emissions, as well as premature deaths. The adoption of global dietary guidelines was estimated to avoid 5.1 million deaths per year relative to the reference scenario, in which the largest number of avoidable deaths occurred in East Asia and South Asia, and greenhouse gas emissions would be reduced most in East Asia (Springmann et al., 2016). In China, dietary shifts to meet the national dietary reference intakes reduced the daily carbon footprint by 5-28% depending on scenario (Song et al., 2017). In India, the optimised healthy diets (e.g., lower amounts of wheat, and increased amounts of legumes) could help reduce up to 30% water use per person for irrigation and reduce diet-related greenhouse gas emissions. This would result in 6,800 life-years gained per 100,000 population in 2050 (Milner et al., 2017).

10.5 Adaptation Implementation

10.5.1 Governance

10.5.1.1 Points of departure

Climate change governance is characterised by a scalar/stakeholder turn which includes (i) acknowledgement of the importance of both sub-national and transnational-regional scales along with the global scale; (ii) involvement of diverse stakeholders in decision-making systems; (iii) reliance on bottom-up architectures of governance that are supported by the framework given by the SDGs; (iv) emphasis on developmental and environmental co-benefits; (v) recognition of diverse experiences of marginalisation and social stratification, and their impacts on participation in governance-related activities; and (vi) greater decentralisation and strengthening of local institutions.

10.5.1.2 Findings

In order to facilitate local adaption, especially in a context characterised by regional diversity and spatial-temporal variation, climate adaptive governance invites greater policy attention to institution building (formal and informal) at multiple scales and across sectors, (Mubaya and Mafongoya, 2017). Ecosystem-based incremental adaptation (EbA) approach underlines the advantage of drawing upon ecosystem services for reducing vulnerabilities, increasing resilience of communities to adapt to climate change, and minimising threats to social systems and human security, provided climate change remains below 2°C or, better yet, below the 1.5°C of global warming (Barkdull and Harris, 2018).

Focus on multi-level governance, both below and beyond the state level, is steadily growing (Jogesh and Dubash, 2015; Jörgensen et al., 2015; Beermann et al., 2016). Discernible diversity across political systems and sectors in Asia notwithstanding, issues relevant to multilevel climate governance includes interplay between top-down national initiatives, which stem from supra-national, regional and sub-regional levels. In case of India, national climate governance has proliferated beyond the National Action Plan on Climate Change (NAPCC) to include State Action Plans on Climate Change (SAPCC) of over 28 states and union territories, demonstrating graphically the shared 'co-benefit' in terms of creating greater space for innovation and experimentation (Jörgensen et al., 2015).

In Japan's "Climate Change Adaptation Act", enacted by the Japanese Diet in June 2018, the national government shall formulate a National Action Plan (NAP) to promote adaptation in all sectors. Climate change adaptation act of Japan recommends prefectures and municipalities to designate "local climate change adaptation center (LCCAC)" as local climate change data collection and provision center, to provide more locally specific information and support for adaptation planning at the level of local municipalities. The Japanese government, in partnership with the private sector, has formulated a new comprehensive strategy, named Society 5.0, which aims at devising a number of technological innovative solutions (Mavrodieva and Shaw, 2020).

Significantly, the co-benefit concept for international city partnerships, comparative analysis of the challenges, capabilities and limitations of urban areas in Asia with regard to climate change adaptation governance remains under researched (Beermann et al., 2016).

In case of Vietnam, especially at district and commune levels, where the policy capacities in hierarchical governance systems to deal with climate change impacts are generally constrained, the value of clear legal institutions, provision of financing for implementing policies, and the training opportunities for governmental staff has been well demonstrated (Phuong et al., 2018b). A key finding is that any effort to support local actors (i.e. smallholder farmers) should ensure augmentation of policy capacity through necessary investments.

In case of China, a combination of market-based policies, emissions trading systems, growing number of environmental NGOs and international network appears to be serving as an important tool for climate governance, (Ramaswami et al., 2017; Wang et al., 2017b). Public private partnership (PPP) too is receiving increasing focus, especially with regard to climate related cost–effective and innovative infrastructure projects. In the absence of major investments in resilience, climate change may force up to 77 million people into poverty trap by 2030 (WorldBank, 2016). As seen in the case of Japan, most of the countries in Asia face the challenge of contractual allocation of risks associated with natural hazards and climate change between the public and private sectors and its long-term management in the face of uncertainty. Risk sharing, therefore could be addressed by clear definition and allocation (WorldBank, 2017). Given that in Asia, especially Singapore, China, Japan and Korea, water sector is a target of industrial and technology policy, PPPs could prove to be mutually beneficial. As a middle ground, key findings of a study on Indonesia (Yoseph-Paulus and Hindmarsh, 2016), underline the importance of building, sustaining and augmenting local capacity by addressing inadequacies with regard to resource endowment and capacity building, public awareness about climate change, government–community partnerships, vulnerability assessment, and providing inclusive decision making space to Indigenous Knowledge systems and communities.

In agriculture sector, farmers in Asia are adapting to climate change at the grass root level (Tripathi and Mishra, 2017). A recent, comprehensive and systematic review (Shaffril et al., 2018) shows how farmers in diverse sub-regions of Asia have adopted diverse adaptation strategies through management of crop, irrigation and water, farms, finances, physical infrastructure and social activities. Much more qualitative research on farmers' perceptions and decision-making about adaptation practices is needed in order to capture their location-specific priorities and diverse understanding of risks and threats. A study of Vietnamese smallholder farmer's perception of their current and future capacity to adapt to climate change (Phuong et al., 2018a) found considerable difference between farmers in crop production and livestock production in terms of their motives behind adopting particular planned adaptation options.

A study on farmers' awareness of and adaptation to climate change in the dry zones of Myanmar, critically dependent on agriculture, indicates how those in the frontline of the adverse effects of climate change are steadily abandoning the common sesame/groundnut cropping pattern, and trying to adapt to risks and uncertainties with the aid of conventional agricultural practices such as rainwater-collection, water-harvesting techniques, and resorting to the traditional weather forecasting techniques for weather prediction. Similarly, a case study of the Gandak Basin in Nepal shows that incorporation of local knowledge into agricultural practices and weather warning systems works best when coupled with multiple sources of information based on a method of triangulation. This also intersects with gender outcomes, where women frequently receive information from the men of their households, rather than directly from state institutional sources (Acharya and Prakash, 2019). Climate change adaptive governance is facilitated by improved cross-scalar and cross-sectoral cooperation, exchange of information and experiences and best practices (Smith et al., 2014; Watts et al., 2015; Gamble et al., 2016; Gilfillan et al., 2017).

An integrated approach informed by science, which examines multiple stressors along with Indigenous Knowledge, appears to be of immense value (Elum et al., 2017). A study on Pakistan concludes that poor agricultural communities are among the worst victims of climate change (Ali and Erenstein, 2017) and that farmers who are younger, better educated, belonging to joint families and possessing more landholdings are *likely* to adapt sooner and better. Correspondingly, this category achieved higher levels of income and food security. The climate-development nexus suggests that climate change adaptation practices at farm level can have significant development outcomes, besides reducing risk posed by changing weather patterns. Central to climate change adaptation (CCA) process is the growing recognition of the role that institutions play in both hierarchical setting and across different scales to influence implementation of CCA in diverse areas of governance across social and political domains. Cuevas (2018) highlights the usefulness of mainstreaming CCA into local land use planning in Albay, Philippines, by involving networks of interacting institutions and institutional arrangements for overcoming obstacles that are potentially counterproductive and conflictual.

As noted by AR5 (IPCC, 2014a), research on issues related to both climate change impacts on livestock production --demand for which is expected to double by 2050 in a world of 10 billion-- and policy choices with regard to adaptation, especially at the local scale, is still limited but in progress (Rojas-Downing et al., 2017). The promise of diversification of livestock animals (within species), crop diversification, and transition to mixed crop-livestock systems needs to be further explored. A study of livestock farmers in Pakistan shows that risk coping mechanisms such as purchasing livestock insurance and increasing land areas for fodder are far more rewarding policy options in comparison to selling livestock and migration. Relatedly, the association of migration with adaptation measure is context specific and involves a number of factors pertaining to the socio-economic circumstances of vulnerable agricultural groups in countries like India and Bangladesh (Ojha et al., 2014). In the 2010 United Nations Framework Convention on Climate Change's Cancun Adaptation Framework, migration was recognised as a form of adaptation that should be included in a country's long-term adaptation planning where appropriate (Paragraph 14f).

Also, agricultural climate adaptation policy targeting livestock farmers in rural areas is *very likely* to benefit from better education and awareness and increased access to extension services among livestock farmers on climate risk-coping choices and strategies (Rahut and Ali, 2018). In Myanmar, the lack of adequate agricultural extension strategies has had a negative impact on adaptation outcomes in what is labelled the central dry zone. Farmers' perceptions of climate change contribute to a comprehensive understanding of the context where they identify deforestation and related activities as the main culprits. Their adaptive methods include agricultural land preparation and crop rotation practices in addition to rainwater harvesting techniques (Swe et al., 2015). A study of vulnerable areas in Bangladesh (Alam et al., 2017), has shown that with policy support livestock rearing can prove to be a viable and substitute for crop production in areas prone to riverbank erosion. Carefully worked out partnerships between government organisations and NGOs can come to the rescue of poor farmers and their precarious households by providing information about best practices of local adaption strategies, including credit options with various institutions and creating an enabling environment for the promotion of agro-based industries. A study in community forestry in the Indian Himalayas (Gupta and Koontz, 2019) has shown how the synergies and successful partnerships could evolve between government and NGOs in local forest governance, with the former providing technical and financial support, and the latter directing the communities to those resources and in the making up for each other's limitations and thus enabling and augmenting community efforts in forest governance.

A study of Pakistan (Ali and Erenstein, 2017) shows that factors such as enhanced awareness about various climate risk coping strategies, better education and agricultural extension services, augmenting farm-household assets, lowering the cost of adaptation, improving access to services and alternative livelihoods, and providing support to poorer households appear to have paid rich dividends. Countries such as Bhutan and Sri Lanka have included provisions for 'climate-smart agriculture' in their NDCs (Amjath-Babu et al., 2019).

In the domain of forest adaptive governance, ever since the introduction of Reducing Emissions from Deforestation and forest Degradation plus (REDD+) at (COP 13) 2007 in Bali, the Indonesian experience suggests that some of the major challenges include curbing emissions, changes in cross-sectoral land-use as well as practice within forestry. and lack of effective, efficient and equitable implementation of diverse forest governance practices. The issue of how forest governance institutions are conceived and managed, both at national and sub-national levels, involving state, private sector and civil society, also needs serious attention (Agung et al., 2014).

In an example from Nepal, Clement (2018) shows that deliberative governance mechanisms can create the space for alternative framings of climate change to take a hold in ways that are cognisant of both the local and global contexts; this moves beyond a dependence on techno-managerialism in the construction of solutions, where local governance solutions can support institutional changes. The possibilities more incorporating deliberative methods into wider governance architecture are also expanded through an acknowledgment of the role of social learning; this is observable in the multi-stakeholder involvement that this approach fosters in regions of South Asia such as the Brahmaputra River Basin (Varma and Hazarika, 2018). Additionally, recent studies have reconfirmed the importance of linking Indigenous Knowledge with the scientific knowledge of climate change in diverse regions of the globe, including Asia and Africa (Hiwasaki et al., 2014; Etchart, 2017) (Taremwa et al., 2017) (Vadigi, 2017; Apraku et al., 2018; Inaotombi and Mahanta, 2018; Makondo and Thomas, 2018) for building farmers' resilience, enhancing climate change adaptation, ensuring cross cultural communication, promoting local skills, drawing upon Indigenous Peoples' intuitive thinking processes and geographical knowledge of remote areas.

A study of Sylhet Division in Bangladesh, deploying knowledge quality assessment' (KQA) tool found significant co-relation between a narrow technocratic problem framing, divorced from traditional knowledge strongly rooted in local socio-cultural histories and relatively low project success due to skewed risk-based calculation disconnected to the ground realities (Wani and Ariana, 2018) (Haque et al., 2017) while highlighting the vulnerability of the Bajo tribal communities, inhabiting the coastal areas of Indonesia, to climate change, share several examples of their Indigenous Knowledge and traditions of marine resource conservation, and show how this wisdom, a valuable asset for climate adaptation governance, has been passed from generation to generation through oral tradition.

10.5.1.3 Knowledge Gaps and Future directions

One of the major knowledge gaps in the domain of climate adaptation governance relates to implementation by various stakeholder at multiple scales and sharing of information and experiences in this regard. There is a need to assuage the perceptions of distrust in global information, through governance methods that engage multiple stakeholders in open and lucid channels of communication (Stott and Huq, 2014). This is observable in the structure of the New Urban Agenda which formed a part of the Sustainable Development Goal pertaining to cities and has been shaped by a bottom-up process marked by diverse participation including communities, experts and activists, rather than the top-down variant that is observable in the MDGs (Barnett and Parnell, 2016). This approach could also be evidenced in the Paris Agreement, which placed the onus of a successful global governance regime on the development of efficient systems of regional governance. However, these emerging systems of regional governance could equally pose a challenge to the global in way that can be witnessed through the development of such financial groups such as the BRICS and Asian Infrastructure Investment Bank (AIIB), which resulted from a perception of inadequate institutional transformation at the global level. From another perspective, a comprehensive approach would require simultaneous implementation of both Bottom-Up and Top-Down models of governance, retaining flexibility of scale.

Given the concerns surrounding food security, especially in the light of the principles of common but differentiated responsibility, under the Nationally Determined Contributions (NDCs) submitted by South Asian nations under the Paris agreement, emission reduction commitments are *less likely* to include agriculture sector. Prospects for enhancing both adaptive capacity and food security could be improved by strengthening resilience and profitability through the introduction of a basket of policy choices and actions including structural reforms, agriculture value chain interventions, and landscape-level efforts for climate resilience. Correspondingly, the substantial adaptation finance gap could be closed with the help of both private finance (autonomous adaptation) and international financial transfers (Amjath-Babu et al., 2019).

For nearly five decades, integrated coastal management (ICM), advocated by several international organisations (e.g., IMO, UNEP, WHO, FAO) and adopted by over 100 countries, has been acknowledged as a holistic coastal governance approach, aimed at achieving coastal sustainability and reducing the vulnerability of coastal communities in the face of multiple environmental impacts (*high confidence*). In view of threats posed to coastal ecological integrity by climate change induced tropical storm activity, accelerated sea level rise, and littoral erosion and socio-ecological impacts on the livelihood security of vulnerable coastal communities, the pressing need for approaches that innovatively combine coastal zone management and climate change adaptation measures, is widely acknowledged (Rosendo et al., 2018) yet under researched. A study focusing three coastal cities of Xiamen, Quanzhou and Dongying in China, a country with nearly 12% of national coastline already covered under the ICM governance framework, suggests that whereas ICM approach has been found to be effective in promoting the overall sustainability of China's coastal cities (Ye et al., 2015) using accurate and reliable data, as well as the developing unified standards could usefully reveal changing conditions and parameters related to ICM performance.

Steadily the regional scale of climate adaptive governance is acquiring salience in diverse sub-regions of Asia and more policy oriented empirical research is needed on how various regional forums, agencies and multilateral organisations could further contribute by way of in-house expertise and other resources, including financial. A study of climate adaptation in the health sector in South East Asia (Gilfillan, 2018) highlights the growing role of Asian Development Bank and the Asia-Pacific Regional Forum on Health and Environment, and shows that their mandates and goals could mutually benefit from the institutionalisation of coordination mechanism. An example from the Maldives shows that 2014 Tsunami, climate change and the risk of extreme weather events have led to the legitimisation of state-led population resettlement programmes; in China, this has occurred through the re-naming of previously existing resettlement initiative as climate adaption initiatives. However, the efficacy of resettlement as a CCA measure requires further scrutiny (Arnall, 2019). In India, the National Adaptation Fund on Climate Change (NAFCC) has been instituted in order to enable states to implement adaptation programmes. However, this does not address the question of mainstreaming CCA into designs for development (Prasad and Sud, 2019). This is closely related to the development of National Adaptation Programmes of Action (NAPAs) where the mainstreaming of adaptation within countries has been an important concern. Insights from developing countries indicate that there is still much ground to cover. The NAPA of the Maldives prioritises food security, coastal resources and public health, while Nepal has prioritised ecosystem management and public health, and food security, among other concerns (Saito, 2013). Importantly, Bangladesh's NAPA has shown that there is potential for 'reflexivity' in the integration of adaptation objectives with sectoral objectives (Vij et al., 2018). Conspicuous by its absence is the transboundary scale adaptation policies in South Asia (Vij et al., 2017).

A distinguishing feature of the case of Japanese apple growers is the co-existence of both top-down and bottom-up adaptation practices. The former pertains to farmers who rely on the support of the cooperative for agricultural support and follow institutional mechanisms. The latter pertains to non-co-op farmers who have been responsible for innovative practices of cultivation such as the shift to peaches and the sale in the market of apples without leaf-picking. Importantly, the non-co-op group also have access to sales channels that may not be accessible to the former owing to their direct interactions with customers, among other factors (Fujisawa and Kobayashi, 2011; Fujisawa et al., 2015) The significance of this combination of top-down and bottom-up approaches to agricultural adaptation practices may be further sharpened by formulating approaches for Asia and the Pacific region in ways that contribute to the fortification of food security objectives and the idea of co-benefits. This may be carried out by enhancing the ability of farmers to better manage cultivation practices in the context of climatic variability (FAO, 2018d).

There exist numerous barriers to the mainstreaming of climate change adaptation (CCA) measures across Asia. The integration of CCA into the dissemination of localised climatic information and its uptake and implementation through institutional policy arrangements remain areas of concern (Cuevas, 2018). Institutional incentives to agricultural production, for instance, are frequently compounded by the negative impacts these have on existing bases of natural resources. The disconnected operations of local governmental agencies coupled with inadequacies of cross-sectoral coordination further highlights the prevalent food-water-energy nexus (Rasul, 2016). One possible way of addressing these intersecting sources complexity is by locating emerging CCA measures in educational development. The introduction of CCA thinking into land use planning in the Philippines is an example of the successful role of enhancing public education and awareness through the dissemination of information by institutional channels. The linkages between the strength of local leadership and the inclusion of CCA in localised planning activities are also well illustrated by this case study (Cuevas, 2018).

As shown in the case of Pakistan, level of education shares a positive relationship with the implementation of adaptation measures (Ali and Erenstein, 2017). However, a closer examination of the educational imperatives that drive CCA in ways that improve the representational architecture of adaptation actions through a focus on gender is needed. Mainstreaming of gender into CCA would involve addressing a host of barriers to education and involvement that are often rooted in the differential structures of households, social norms and roles, and the domestic division of labour (Rao et al., 2019). A study from the Indian state of Bihar shows that gender plays a major role in determining intra-household decision making and also inhibits the ability of female-headed households to establish access to agricultural extension services (Mehar et al., 2016). Even within wider female farmer-operated federations such as the Bangladesh Kishani Sabha (BKS), the barriers to participation stem from social factors that include the limitation of female mobility through the gendered division of labour and a lack of recognition of female agency (Routledge, 2015). Gendered inequalities in educational attainment and outcomes viewed through the lens of social vulnerability thus intersect with environmental vulnerabilities in ways that affect the ability of women to participate in CCA, owing also to a lack of access to health and sanitation facilities. These factors have a direct impact on the ability of adaptation to be effective in the global South, and are especially important in the context of the commitments of CEDAW (UN Convention on the Elimination of All Forms of Discrimination Against Women) countries to the objective of gender equality (Roy, 2018).

[START BOX 10.6 HERE]

Box 10.6: Bangladesh Delta Plan 2100

"*The Bangladesh Delta Plan (BDP) 2100 is the plan moving Bangladesh forward for the next 100 years. We have formulated BDP 2100 in the way we want to build Bangladesh.*" (Commission, 2018).

Vision of BDP is revealed by this statement of Sheikh Hasina, the honourable Prime Minister of Bangladesh. Government approved BDP 2100 in 2018. Achievement of safe, climate resilient and prosperous delta is the aspiration of delta plan. Ensuring water and food security with economic growth, environmental sustainability, climate resilience, vulnerability reduction to natural hazards and minimising different challenges of delta through robust, adaptive and integrated strategies, and equitable water governance are the mission of this mega plan. Under this mission, three higher-level goals and six specific goals have been determined. Three higher-level goals include elimination of extreme poverty by 2030; achieve upper middle-income status by 2030 and being a prosperous country beyond 2041. Six specific goals of BDP 2100 are fully linked with SDG Goal 2, 6, 13 and 14 and partially linked with Goal 1, 5, 8, 9, 11 and 15. These specific goals comprise wide ranges of issues, including land and water resources, climate change, disaster, wetlands and ecosystems, river system and estuaries. Vision, mission and goals of BDP 2100 reveal that this mega plan is a holistic and integrated approach considering diversified themes and sectors for the whole country. The implementation of the BDP 2100 requires total spending of an amount of about 2.5% of GDP per annum. Series of strategies have been formulated for better implementation of the mega pan.

Water is the key and complicated resource of Bangladesh and therefore, BDP 2100 has kept water at the center of the plan. It aims to promote wise and integrated use of water and other resources through development of effective institutions and equitable governance for in-country and trans-boundary water resources management.

Along with water, for the first time in any development planning, BDP 2100 has taken the climate change issue as an exogenous variable in developing the macroeconomic framework of the plan. In a brief, it is said that the principle of BDP 2100 is "Living with Nature".

[END BOX 10.6 HERE]

10.5.2 Technology and Innovation

10.5.2.1 Point of Departure

Much like any other field, climate change adaptation is greatly facilitated by science, technology and continuous innovation. These ranges from the application of existing science, to the development of new scientific tools and methods, to the utilisation of Indigenous Knowledge and citizen sciences. Many of the pressing problems in Asia, including water scarcity, rapid urbanisation, loss of natural habitats, biodiversity, rising coastal and river basin hazards, and agricultural loss can be effectively minimised through the adoption of suitable science and technological methods. Despite the current challenges in the region, many significant advances in science and technology have been made, and the future prospects look bright. The following sections outline the present status and future prospects of science and technology in scaling up adaptation actions in four key sectors, namely disaster risk reduction, water and agriculture, urbanisation and forests and biodiversity.

10.5.2.2 Findings

10.5.2.2.1 Disaster Risk Reduction

Technological advances have enhanced the capabilities of Asian countries to monitor and prepare for climate-related hazards. Remote sensing technologies and GIS are widely used for disaster risk reduction (Kato et al., 2017), e.g., to assess and mitigate risks of an area to potential climate-related disasters (Wu et al., 2018b). The potential impacts of different types of hazards can be visualised using interactive maps (Lee, 2017), which helps local communities to understand risks and find appropriate evacuation areas (Cadiz, 2018). These provide situational overview and instant risk assessment (Yang et al., 2012b). As emerging technologies, artificial intelligence (AI) can identify conditioning factors of a landslide disaster (Hong et al., 2019b). Mobile virtual reality is used for disaster mitigation training, through a three-dimensional visualisation of a past disaster (Ghosh et al., 2018).

A community-based disaster risk reduction system provides risk investigation, training, and information analysis (Liu et al., 2016b). Sharing information enhances to establish such a system and contribute to disaster-prevention (Nakamura et al., 2017). One example is an online mapping tool, which has been developed by volunteers (Sakurai and Thapa, 2017). Social media enables population to reach real time information on a disaster (Ghosh et al., 2018), raises situation awareness (Yin et al., 2012), and empower communities towards appropriate emergency actions (Leong et al., 2015). Among various forms of social media, Twitter is widely used as social sensors to detect what is happening in a disaster event (Sakaki et al., 2013). Accuracy of information on Twitter has been proved in collecting local details about floods (Shi et al., 2019b), however it is noticed that Twitter generates rumors as well (Ogasahara et al., 2019). AI is expected to reduce human error when they operate a decision making system (Lin et al., 2018). Since technologies supporting disaster risk reduction completely depend on electricity, the loss of power supply and communication constrains the recovery work in disaster affected areas (Sakurai et al., 2014).

10.5.2.2.2 Urban sector

In the urban sector, a wide variety of sensor technologies are being used to monitor urban land-use and climate changes over time, and to better understand the potential impacts of future changes. These sensors range from large optical/thermal/radar satellite instruments with (near) global coverage (e.g., Landsat (US Geological Service), Sentinel (European Space Agency), ALOS (Japan Aerospace Exploration Agency), MethaneSAT to portable sensors embedded in mobile phones (e.g., phone cameras or temperature sensors) whose data are collected into centralised databases through crowdsourcing (Fenner et al., 2017; Meier et al., 2017). To combine and extract useful information from these heterogeneous sensor data – e.g., for conducting climate risk assessments (Perera and Emmanuel, 2018; Bechtel et al., 2019) and/or simulations of future land-use/climate changes in urban areas (Bateman et al., 2016), (Iizuka et al., 2017) (Liu et al., 2017c) – artificial intelligence technologies (e.g., machine-learning algorithms) are now being widely adopted (Johnson and Iizuka, 2016), (Joshi et al., 2016) (Mao et al., 2017). Thanks to advances in cloud computing technology, which allows for online processing of massive volumes of remote sensing data, high resolution (~30 meters) global urban area maps from the late 1990s to 2018 are now available from several different sources (Gong et al., 2020). Using these historical maps, researchers have been able to generate maps of future urban land-use changes at the global level to 2100 (Chen et al., 2020a), which can help to elucidate the potential impacts of this future urban expansion and identify adaptation needs. Technology also plays a major role in urban planning and design in the context of adaptation. To mitigate rising urban temperatures and reduce the impacts of climate-related hazards, many new "gray" infrastructure and "green" infrastructure technologies are being adopted in urban areas in Asia, e.g., cool (i.e. high solar reflectance) rooftops and pavements as well as green (i.e. vegetated) rooftops to mitigate high temperatures; and porous pavements to mitigate flooding (Akbari and Kolokotsa, 2016).

10.5.2.2.3 Water and agriculture

Majority of the Asian region is witnessing water stress in terms of both quantity and quality, due to poor management system and governance. This has dire consequences for national GDP as majority of the population belongs to agrarian community and their water dependent agriculture system. Despite a substantial investment and progress in research and development and capacity building in recent past, majority of the developing countries in Asian region are struggling to manage both water resources and agriculture sector heavily reliable on water resources, in lieu of rapid global changes. Considering the frequent extreme weather conditions, progress in management task become even more mammoth and hence need for advance science and technology viz. smart agriculture, robust early warning system using downscaled meteorological information, participatory approach, IWRM etc. for better climate change adaptation is critically important for these countries.

Having scientific knowledge relevant at local scale through placed knowledge is important to identify climate change risk and vulnerability. And once integrated with socio-economic attributes, it can be useful for natural resource management, agriculture etc. (Leith and Vanclay, 2017). Role of big data and data mining is undeniably very huge to get reliable climatic information and hence for designing appropriate adaptation measures for natural resource measurement. For example, use of big data in terms of early warning system and real time observation data provides more accurate information on hydro-meteorological extreme weather conditions or hazards like drought, flood, will help farmers and local government units to improve their perception and hence preparedness for better adaptation (Hou et al., 2017) (Ong and G.L.B.L., 2017). Using big data, different adaptation measures like new cultivar breeding, cropping region adjustment, irrigation pattern change, crop rotation and cropping practice optimisation are being designed in agriculture sector, which have greatly increased crop yield, leading to higher resource use efficiency as well as greatly increased soil organic carbon content with reduced greenhouse gas emissions. It results in win-win situation in terms of enhancing food security and mitigating climatic warming (Deng et al., 2017). However, usability and application of this technology are still not common especially in the data scarce regions. Integrated numerical simulations are efficient tools for estimating current status and predicting risk and efficiency of adaptive capabilities of different countermeasures for sustainable natural resource management like water (Kumar, 2019). Similarly, agent based model is commonly used to estimate risk of food borne diseases due to climate change, using tunable parameters such as hygiene level, microorganism's growth rate and number of consumers and hence has the potential to be a useful tool for optimising decision-making and urban planning strategies related to health and climate change (Gay Garcia et al., 2017). Integrated Assessment Model (IAM) under the Shared-Socioeconomic Pathway (SSP) framework is effectively used to estimate future energy development and possible mitigation strategies to reduce GHGs emission related to energy sector (Bauer et al., 2017). Sound understanding of different drivers, pressures and stress factors such as abnormal temperature, rainfall, insect pest/pathogen and their interaction pattern with genetic makeup of crops; is the key to produce high-yielding varieties of wheat with better nutritional quality and resistance to major diseases (Goel et al., 2017). Another critical point to address this water security is inclusive, polycentric and adaptive governance. Polycentric governance is a means that water management plans and policies should be framed and agreed by all relevant stakeholders. For adaptive governance, more emphasis will be on finding the best pathways to make robust water management plans amid rapid global changes. The benefit of such plans should reach the end users in terms of providing clean water, protection from hydrological hazards and maintaining the health of the ecosystem. In addition, there is urgent need for co-management, which includes the cycle of co-design, co-implementation and co-delivery throughout the whole water cycle. The best suitable example is using the Circulating and Ecological Sphere (CES) approach. CES is a concept that complements and supports regional resources by building broader networks, which is composed of natural connections (connections among forests; city and countryside; groundwater, rivers and the sea) and, economic connections (composed of human resources, funds, and others), thus complementing each other and generating synergy (Mavrodieva and Shaw, 2020). Another suitable example for managing water resources is Participatory Watershed Land-use Management (PWLM) approach. PWLM is another very innovative and successful approach for more robust water resource management explained by (Kumar et al., 2020). It helps to make land-use and climate change adaptation policies more effective at a local scale. This is an integrative method using both participating tactics and computer simulation modelling for water resource management at a regional scale.

10.5.2.2.4 Forests and Biodiversity

Technologies and its applications to identify habitat degradation, ecosystem functions and biodiversity conservation are increasing in Asia, with many countries looking up to new and improved means for forest and biodiversity monitoring and conservation. In particular, there has been an impressive use of temporal satellite data, particularly from the Landsat and the MODIS series for widespread monitoring of forests and ecological resources. These provided reliable information on forests and ecosystem services at country level, in difficult terrains, such as the mountains, cross-boundaries and otherwise inaccessible areas. For instance, Yin et al. (2017) estimated cross-boundary forest resources in Central Asia using remote sensing techniques, a region which traditionally suffered from lack of reliable forest data. In a separate study, Reddy et al. (2020) used long-term MODIS forest fire data from 2003–2017 to characterise fire frequency, density, and hotspots in South Asia. Archival of scientific data, particularly helped the provisioning of scientific research, backed by the state-of-the art modelling techniques, advance-computing methods and innovations in big data analysis. A number of studies simulated forest futures from local to continent scale under different socio-economic and climate scenarios. As for instance, at local scale, DasGupta et al. (2018) projected future extent of mangroves in the Sundarban delta under four local scenarios, while Estoque et al. (2019) modelled and developed spatial maps of regional forest futures in Southeast Asia using the five SSP scenarios. Science and technology also helped the monitoring of species diversity and abundance, pivotal for sustaining ecosystem and ecosystem based adaptation. Digital camera traps, radio-collaring methods have largely replaced old film cameras and labour-intensive methods of photo-screening to count target species (Pimm et al., 2015). This enhanced scientific capacities to monitor biodiversity and facilitate better conservation in difficult terrains, control poachers and maintain steady ecological balance. Umapathy et al. (2016), for example used VHF radio-collars and satellite-based tracking tools to monitor the movement of Bengal tigers in hostile island terrain. Photo recognition and other non-invasive techniques for individual identification have been rising in Asia. For example, a study by Gray et al. (2014) used fecal-DNA samples to estimate the population density of Asian elephant in Cambodia. The advancement of citizen science programs has greatly facilitated better monitoring of forest resources, including invasive floral and faunal species (Chandler et al., 2017; Johnson et al., 2020). In Asia, citizen science has been used effectively in India (Chandler et al., 2017), also in Malaysia for the monitoring the urban bird abundance (Puan et al., 2019).

10.5.2.3 Knowledge Gaps and Future Directions

With rapid advances of technologies, the use of appropriate technologies generates some degree of management problems. To resolve such problems, the enhancement of information science is essential to understanding design, implementation and adoption of digital tools under crisis (Xie et al., 2020). For example, social media research reveals a way of controlling malicious information (Tanaka et al., 2014) and its characteristics under Covid-19, showing a plain text message can be more powerful in the context of citizen engagement than media richness communications (Chen et al., 2020b). Information behaviour needs more investigation to understand how people survive and connect in the era of information overflow (Pan et al., 2020). Moreover, a new set of data e.g., travel history record and personal health data etc. becomes an important base of disaster risk reduction (Xie et al., 2020). Analysis of these personal data requires careful consideration, as it generates ethical issues (Sakurai and Chughtai, 2020). Indicators or measurements of technology enabled crisis response needs to be developed for further risk reduction (Wong et al., 2020). (Akbari and Kolokotsa, 2016). On the other hand, adopting infrastructure technologies requires investment, and due to the inherent uncertainties of climate projections, the future payoffs of these investments are also somewhat uncertain (Ginbo et al., 2020). In water and infrastructure sector for example, various options exist for conducting cost-benefit analysis considering future uncertainty, i.e. so-called robust approaches, which are able to identify adaptation projects/infrastructure that can achieve their intended purpose(s) across a wide range of climate scenarios (Dittrich et al., 2016). Despite a substantial investment and progress in research, development and capacity building in recent past, majority of the developing countries in Asian region are struggling to manage both water resources and agriculture sector. Considering the frequent extreme weather conditions, progress in management task has become even more mammoth and hence we need a holistic solution, which is currently missing in field implementation. These should be based on advance science and technology in association other attributes like social, economic, political dynamics, which play a pivotal role in sustainable management of water resources/agriculture, as a way forward.

10.5.3 Lifestyle Changes and Behavioural Factors

Point of departure: Understanding the motivations and processes underpinning decisions to adapt or not is key to enabling adaptation (Clayton et al., 2015; de Coninck et al., 2018; Taylor, 2019; van Valkengoed and Steg, 2019a; van Valkengoed and Steg, 2019b) (cross reference to Sec 17.2.2.1 in Chapter 17) because how and why certain people adapt is shaped by socio-cultural factors, ways of making sense of risks and uncertainty, and personal motivations to undertake action (Nguyen et al., 2016; Mortreux and Barnett, 2017; Singh et al., 2018b; van Valkengoed and Steg, 2019b). The IPCC's Assessment Report 5 was critiqued for silences on how perceptions shape climate action and the behavioural drivers of adaptation responses (Lorenzoni and Whitmarsh, 2014). Addressing this gap and assessing the growing literature from social sciences, notably psychology, behavioural economics, and risk perception studies, the IPCC Special Report on 1.5C (de Coninck et al., 2018) comprehensively assessed behavioural dimensions of climate change adaptation for the first time. However, compared to studies on mitigation behaviour, the literature on what motivates adaptation remains a gap (Lorenzoni and Whitmarsh, 2014; Clayton et al., 2015).

Findings: There are three key aspects of adaptation that psychology and behavioural science contribute to: understanding perceptions of climate risk, identifying the behavioural drivers of adaptation actions, and analysing the impacts of climate change on human well-being (Clayton et al., 2015). Overall, there is growing acknowledgement that individual adaptation is significantly shaped by perceptions of risk; perceived self-efficacy, i.e. beliefs about which options are effective and one's ability to implement specific adaptation interventions; socio-cultural norms and beliefs within which adaptation decisions are taken; past experiences of risk management; and the nature of the intervention itself (Grothmann and Patt, 2005; Werg et al., 2013; Clayton et al., 2015; Truelove et al., 2015; Pyhälä et al., 2016; Deng et al., 2017; Sullivan-Wiley and Short Gianotti, 2017; Taylor, 2019; van Valkengoed and Steg, 2019a). This is in addition to more commonly understood factors shaping adaptation behaviour such as technical know-how and cost and benefits associated with an option.

Across Asia, behavioural aspects of adaptation have been studied to a lesser extent: a global meta-analysis of 106 studies found most research focussed on North America and Europe with only 12% papers from Asia (van Valkengoed and Steg, 2019a). Within Asia, behavioural drivers of adaptation decision-making have been studied primarily in agriculture (in South, East, and SE Asia) and disaster risk management (from SE and East Asia) (Table 10.4) and tend to focus on technical adaptation interventions rather than how and why people adapt (Sun and Han, 2018).

Table 10.4: Table of sectors and sub-regions where behavioural aspects of adaptation have been assessed. NE= No Evidence

Sub-region	Sector	Adaptation interventions	Behavioural aspects affecting adaptation	Supporting references
West Asia	Agriculture	Soil and water conservation activities to mitigate drought impacts	Response efficacy and perceived severity shape water conservation	Iran (Keshavarz and Karami, 2016)
Central Asia	NE	NE	NE	NE
South Asia	Agriculture	Conservation agriculture, adjusting agricultural practices	Risk perceptions shape adoption of adaptation strategy (e.g. perceptions of decreasing rainfall motivate building water storage tanks)	Nepal (Piya et al., 2013; Halbrendt et al., 2014)
		Sustainable water management practices, adjusting agricultural practices	Risk perception is shaped by socio-cultural context, memories, experiences and expectations (of future change)	India (Singh et al., 2016)
		Alternate wetting and drying irrigation, alternative crop selection, using drought-resistant seeds	A combination of attitudes, self-efficacy, outcome efficacy, and community efficacy predict intent to adapt strongly	Sri Lanka (Truelove et al., 2015)
		Adjustment in farm management including growing short duration or drought-tolerant varieties, pest resistant varieties, changing planting distance, increasing weeding, soil conservation techniques, cultivation of direct seeded rice, switching to non-rice crops	Farmers' education, access to credit and extension services, experience with climate change impacts such as drought and flood, information on climate change issues, belief in climate change and the need to adapt all variously determine their decision-making	Nepal (Khanal et al., 2018)
	Disaster management	Flood and cyclone preparedness measures such as using durable building materials, raise plinth levels, storing food and water	Disaster management behaviour is intuitive: low evidence to suggest outcome-expectancy, self-efficacy, and preparedness intention follow linear patterns	India (Samaddar et al., 2014); Bangladesh (Dasgupta et al., 2014b)
		Use of emergency toolkits and evacuation plans	Risk perception and knowledge of adaptation options shape uptake and perceived benefits	Pakistan, Bangladesh (Alvi and Khayyam, 2020)
		Insurance to deal mitigate financial losses from floods, droughts	Frequency, severity of previous extreme events, socio-economic settings, ability to pay shape decisions to take crop insurance. Acceptability of flood insurance depends on perceived efficacy of the insurance (among other factors such as age of household head, landownership, off-farm income sources)	Pakistan (Arshad et al. 2016) (Abbas et al., 2015)

		Embankments/dikes for flood risk mitigation	Willingness to contribute manual labour to flood protection measures is positively influenced by the number of adult family members, livestock damage, compensation received and expected effectiveness of the intervention, but is negatively influenced by age and education of the household head, farm income and the distance of the farm from the river.	Pakistan (Abbas et al., 2019)
Southeast Asia	Agriculture	Changing agricultural practices, diversifying livelihoods	Values, personal and social beliefs of risk shape adaptation	Vietnam (Le Dang et al., 2014; Cullen and Anderson, 2016; Nguyen et al., 2016; Arunrat et al., 2017)
	Disaster management	Raising floor height to avoid flooding, retrofitting houses	Perceived probabilities and perceived consequences of flood shape preparedness	Vietnam (Reynaud et al., 2013; Ling et al., 2015)
		Flood insurance	Likelihood of purchasing flood insurance increased with higher physical exposure and subjective perceptions of vulnerability	Malaysia (Aliagha, 2013; Aliagha et al., 2014)
		Evacuation	Individual risk perceptions lead to learning, but only where previous disaster experiences are traumatic	Philippines, India (Walch, 2018)
		Disaster preparedness measures such as having kits, undertaking precautionary measures	Perceived self-efficacy was the most significant measure affecting reactive adaptation; education had the highest effect size on anticipatory adaptation.	Cambodia (Ung et al., 2015)
East Asia	Agriculture	Changing agricultural practices, diversifying incomes, adopting water saving technology, purchasing weather insurance	Perceived self-efficacy strongly predicts adaptive intent	China (Jianjun et al., 2015; Zhang et al., 2016a; Burnham and Ma, 2017; Feng et al., 2017)
	Disaster management	General	Higher education, being in environments where climate is discussed leads to stronger risk perceptions	Taiwan, Province of China (Sun and Han, 2018)
		Drought management through early warnings, prevention information	Policies can positively shape adaptation decision-making depending on how information is given, what support is provided	China (Wang et al., 2015).

In agriculture, studies demonstrate how perceptions of risk (e.g. climate variability) (Singh et al., 2016; Zheng and Dallimer, 2016; Burnham and Ma, 2017; Feng et al., 2017), socio-cultural norms and personal experiences (Masud, 2016; Nguyen et al., 2016; Singh et al., 2016), and perceived efficacy of adaptation interventions in having a positive/desirable impact (Halbrendt et al., 2014; Truelove et al., 2015; Feng et al., 2017) affect adaptation decisions. Policies on providing early warnings of drought or information on prevention techniques shape farmer decisions to undertake adaptation interventions (Wang et al., 2015).

In disaster risk management, risk appraisal (Samaddar et al., 2014; Rauf et al., 2017; Hung et al., 2018), previous experience and losses (Said et al., 2015; Hung et al., 2018; Walch, 2018)[11], perceived probabilities and consequences (Reynaud et al., 2013), perceived self-efficacy (Ung et al., 2015; Hung et al., 2018), and awareness (Hung et al., 2018; Wu et al., 2018a; Alvi and Khayyam, 2020) shape preparedness. Individual risk management is nested within public policies such as those on flood management which shape individual flood risk perception and protective behaviours (Reynaud et al., 2013) as well as personal factors such as religious beliefs (Alshehri et al., 2013). For example, communities often perceive disasters as 'acts of God' (Birkmann et al., 2019) or punishment for wrongdoings (Alshehri et al., 2013; Iqbal et al., 2018), which might constrain adaptive action. However, religious faith can also motivate people to prepare for extreme events, as Alshehri et al. (2013) show in Saudi Arabia demonstrating how "Islam urges that it is most important to prepare the people to escape from disaster" (p.1825).

Trust in public action as a mediator of risk management had conflicting evidence: some studies discussed trust being critical to effective preparedness (Kittipongvises and Mino, 2015; Walch, 2018) while others found that trust in public actions such as structural interventions to mitigate flood impacts can lower individual motivations to act since they feel protected (Hung et al., 2018).

Belief in climate variability and change significantly shapes adaptation decision-making (Le Dang et al., 2014; Singh et al., 2016; Khanal et al., 2018; Liu et al., 2018a) with those believing in climate change and associated impacts tending to engage in adaptation. Crucially, those who do not believe in climate change, can be influenced by social norms (Arunrat et al., 2017) thereby incentivising adaptation behaviour. While risk perception is a critical step in adaptation decision-making, higher risk perception does not necessarily signal better capacity to cope: in Taiwan, Province of China, Sun and Han (2018) highlight how perceptions of climate risk as a global problem tends reduce its urgency as an individual issue. Providing information on climate risks, impacts, and possible adaptation options enables adaptation behaviour (Piya et al., 2013; Zheng and Dallimer, 2016; Rauf et al., 2017) but information alone is not sufficient to motivate adaptive behaviour. Specifically, awareness building on concrete measures and outcomes such as amount of water saved or number of deaths averted rather than abstract notions of climate change motivate adaptation (Deng et al., 2017; Rauf et al., 2017).
Lifestyle changes: Changes in current lifestyles and consumption patterns are acknowledged as critical to climate action (de Coninck et al., 2018; IGES, 2019). With rapidly changing diets and increasing purchasing power, lifestyle changes in countries across Asia, especially those with large populations such as China and India will be critical to contributing to global climate solutions (IGES, 2019). Lifestyle shifts that can contribute towards adaptation include:

- Engaging in urban agriculture through rooftop gardening, community gardens in urban and peri-urban areas etc. (with implications for food associated footprints but also nutritional, livelihood, and wellbeing benefits) (Mohanty et al., 2012; Ackerman et al., 2014; Padgham and Dietrich, 2015)
- Shifts towards organic farming and creating demand for organically sourced food and other materials
- Shifts towards water-saving behaviour such as rainwater harvesting, water conservation, reducing water usage etc.

Knowledge gaps: Overall, understanding behavioural factors shaping adaptation implementation and uptake is important (*medium evidence, high agreement*). While there is a growing literature on behavioural drivers of adaptation at individual and household levels, gaps remain in understanding how socio-cognitive factors affect adaptation behaviour at higher scales (e.g. at local or sub-national government, in the private sector etc.)[12]. More empirical evidence is needed in sectors beyond agriculture and disaster risk management (e.g.

[11] Two exceptions to this were found. One is a survey in Saudi Arabia which tested public perceptions of disaster risk and found that direct experience with such disasters does not directly influence risk perception (Alshehri et al., 2013). Second, a study on flood experience and ensuing adaptation behaviour in Pakistan found that those with prior flood experience do not make significantly different choices than those who have no experience of flooding; what is more significant is repeated exposure to flooding events (Said et al., 2015)

[12] Some studies compare nationally representative surveys on climate perceptions and their impacts on climate action to demonstrate that higher risk perception leads to higher motivations to undertake climate action (Corner, Markowitz, and Pidgeon 2014; Smith and Mayer 2018). Others, however, highlight that higher risk perception can lead to a normalization

factors motivating urban adaptation) and better coverage across Asia's sub-regions. Importantly, there are no studies on behavioural aspects of adaptation from Central Asia.

10.5.4 Costs and Finance

10.5.4.1 Point of departure

Estimates of adaptation costs and financial needs have evolved significantly from the previous IPCC assessments. These developments are based on the improvements in the understanding on how the hazard interacts with the physical and socio-economic elements and how to capture these interactions in systematic modelling frameworks. The developments are also clearly reported especially in the area of addressing the underestimates in adaptation costs that the previous studies suffered from as the previous studies tend to rely on data from wealthy economies (Carleton et al., 2020);(Hochrainer-Stigler et al., 2014). The adaptation cost estimates also improved from the previous IPCC reports due to constant improvements in capturing the loss and damages of disaster events (Hochrainer-Stigler et al., 2014). The reliance of earlier studies on correlations to derive adaptation costs was addressed to some extent by addressing the endogeneity of disaster measures (Kousky, 2014), especially by relying upon the physical measures of disaster such as wind speed, though more work is needed in this area.

10.5.4.2 Findings

Climate change can cause significant impacts and as a result can impose considerable adaptation costs to countries and people. Despite the importance, the research on adaptation costs is limited in Asia, especially on the economy wide costs, while fragmented literature is available on sector level adaptation costs. Most of the available literature on adaptation costs at the regional level originate from the work carried out by the development finance institutions such as ADB.

Estimates suggest that climate change impacts could result in a loss of 2% of GDP of South Asian countries by 2050 and 9% by 2100 (Ahmed and Suphachalasai, 2014). These impacts will be felt in major vulnerable sectors, including agriculture, water, coastal, marine, health and energy, and will have significant impact on the economic growth and poverty reduction in the region. Countries could differ widely in terms of economic costs they face. In South Asia, the economic costs were projected to be 12.6% of GDP for the Maldives, which is the highest among the South Asian countries, and 6.6% for Sri Lanka, the least among the South Asian countries. The resultant adaptation costs for countries were projected to range from 0.36% (Copenhagen Cancun Scenario for 2050) to 1.32% (BAU scenario) of GDP in various scenarios during 2010-2050 (ibid) (*Medium agreement*, *limited evidence*).

Arto et al. (2019) have reported the adaptation costs of Mahanadi delta in India for agriculture, fisheries and infrastructure sectors (Arto et al., 2019). The cumulative adaptation costs for 2015-2016 were reported to be 276 million USD for agriculture and 0.163 million USD for fisheries. In comparison, the modelled cumulative agricultural GDP loss due to climate change impacts was reported to be 5% up to 2050, and 8% for infrastructure. Adaptation interventions such as embankments were found to provide an avoided losses (adaptation benefits) to the tune of 2.2% of the delta GDP by 2050. Similarly, input subsidies in seeds, fertilisers and biofertilisers were found to buffer the shocks in agriculture by 10%, and buffers the GDP per capita by 3% (ibid).

Markandya and González-Eguino (2019) have estimated the adaptation cots and residual adaptation costs accrued due to insufficient adaptation using integrated assessment models. Using the residual damages as a measure of loss and damage, the authors have estimated adaptation costs and residual costs under high damages-low discount rate and low damages-high discount rate scenarios. The estimates suggested adaptation costs of 182, 193 billion USD by 2050, 737, and 783 by 2100 for South Asia and East Asia respectively under high damages-low discount rate scenario. The residual costs for the same scenario were 289% and 76% for 2050 and 238% and 62% for 2100 for South Asia and East Asia respectively. Estimates

of risks, leading to lower climate action (Luís, Vauclair, and Lima 2018). In all of these papers, there is a recognition that the literature on perceptual drivers of climate action is US-centric and is negligible in Asia (Capstick et al. 2015).

for low damages-high discount rate were significantly lower adaptation costs and residual costs for both the sub-regions of Asia.

Climate change adaptation efforts can be characterised as fragmented, incoherent, and lacking a perspective (Ahmed et al., 2019a), and the picture on adaptation financing can be stated as similarly fragmented with very limited literature published in peer reviewed journals. Adaptation financing is crucial for supporting vulnerable countries enhance adaptation as it is evident that the enhanced adaptation finance support has positively affected the pace of adaptation in low-income countries (Ford et al., 2015). At the organisational level, adaptation financing provided multiple functions that include risk assessment functions, valuation functions, and risk disclosure functions (Linnenluecke et al., 2016).

Of the total global public adaptation finance of 28 billion USD, East Asia and Pacific attracted 46% of the total funding, while south Asian countries attracted only 9% of the total funding (UNEP, 2016). These differences reflect the capacity of countries to attract adaptation finance. Some of the important adaptation-targeted climate funds are Pilot Program for Climate Resilience, Green Climate Fund, and Least-Developed Countries Fund, and South Asian countries have significantly benefited from these dedicated climate funds. Due to disaster implications of climate change, there is a need to allocate adaptation finances for disaster risk reduction (DRR). Estimates suggest that East Asia and Pacific allocated 27% of the total adaptation funds to DRR while South Asia allocated 25% (Caravani, 2016). Low-income economies tend to allocate more adaptation funds to DRR (46%) while lower-middle income economies allocated 22%.

Least developed countries lack the capacity to adapt to climate change and the Least Developed Country Fund (LDCF) has been found to make significant contribution to adaptation in these countries (*High agreement, limited evidence*). Based on the interview-based field research in four least developed countries, Sovacool et al. (2017) opined that the LDCF projects are contributing to the adaptive capacity of these countries (Sovacool et al., 2017). They also found that these projects are taking a marginal approach to adaptation rather than radical or transformational one.

Kissinger et al. (2019) have estimated the climate financing needs in the land sector under Paris Agreement. The estimates suggested adaptation needs of 2.5 billion USD for Bangladesh, 40.5 million USD for Lao PDR, 31 million USD for Mongolia, for the forest sector alone (*Low agreement, limited evidence*).

Financing green growth and low-carbon development can provide resilience benefits (*High agreement, limited evidence*). Kameyama et al. (2016) have estimated the cost of low carbon investments that can provide resilience benefits in Asia and reported that such low-carbon development will cost in the range of USD125-149 billion annually. A combination of public, private, bilateral and multilateral funding sources, and carbon market offsets, were suggested to achieve this level of funding. In terms of the total resources available, a combination of public, private and bi-, and multilateral funding could help the region to raise as much as 222.3-412.5 billion USD annually, with a possibility to reach higher amounts depending on the future economic growth of countries in the region. Soil carbon sequestration in agricultural soils was found to be a win-win solution for both mitigation and adaptation as it can help improve soils while increasing farm yields and income of smallholders (Aryal et al., 2020a).

New adaptation financing sources have been emerging which could provide country-specific adaptation financing suiting local level adaptation needs in Asia. The newly established Asia Infrastructure Investment Bank (AIDB), and newly emerging developing country development finance institutions are known to provide an additional adaptation finance (Neufeldt et al., 2018). However, despite these emerging financial sources, the region will fall short of the adaptation target in the Paris Agreement (ibid).

10.5.4.3 Knowledge Gaps

Adaptation cost estimates can vary between various studies due to the differences in methodologies they adopt. Some studies have conducted cost assessments using a combination of stakeholder consultations and quantitative modelling of climate change impacts and adaptation (Ahmed and Suphachalasai, 2014), while others depended solely on the quantitative modelling. Studies also differ in the coverage of sectors too, they either focused on the multiple vulnerable sectors (Ahmed and Suphachalasai, 2014) or on a single sector (Hossain et al., 2019). Studies differed in their estimates depending on their ability to take into consideration the transition costs of sudden adaptation (Hossain et al., 2019), nature of social cost/damage functions employed (Arto et al., 2019), discount rates applied (Markandya and González-Eguino, 2019), and consideration for the effects of GHG mitigation on adaptation needs (Duan et al., 2019a). In addition, the assumptions made on the pace of adaptation in estimating adaptation costs can make a difference in adaptation cost estimates. Adaptation at a slow or normal pace could require more adaptation finance, as large amount of damage remain not eliminated, than when adaptation is implemented at a faster rate (Markandya and González-Eguino, 2019). Though there have been improvements in adaption cost estimates, there is a need to address the issue of endogeneity ((Kousky, 2014); (Samuel et al., 2019)). The vast majority of studies that rely on databases such as EM-DAT tend to suffer from such endogeneity problems due to their inability to control the causality between GDP and damages (Kousky, 2014). Costs attributable to non-economic loss and damages are the least reported and least quantified in the adaptation costs literature due to lack of sufficient, robust and accessible methodologies (Chiba et al., 2017); (Chiba et al., 2019); (Serdeczny, 2019)). This is a major limitation in assessing adaptation costs and financial needs and it can lead to gross underestimation of adaptation costs. A detailed description of issues related to non-economic loss and damages and its importance in strengthening adaptation is provided in Box 10.7 (Loss and damage across Asia: mapping the evidence and knowledge gaps), and Table 10.5.

[START BOX 10.7 HERE]

Box 10.7: Loss and Damage Across Asia: Mapping the Evidence and Knowledge Gaps

Losses and damages are climate impacts after implementing adaptation and mitigation actions, signifying the presence of residual risks (Kugler and Sariego, 2016; Mechler et al., 2019) (Chapter 1). These residual risks indicate that despite adaptation, there are soft and hard adaptation limits (Mechler et al., 2019). This box reviews the adaptation literature across 51 countries in Asia on L&D, and adaptation barriers and limits and identifies knowledge/regional gaps. The key messages are (1) climate-induced L&D is already occurring across Asia (*medium evidence, high agreement*), (2) these L&Ds are *very likely* to increase at higher warming levels (*medium evidence, high agreement*), and (3) measuring and attributing non-economic/intangible L&D remains a challenge (*low evidence, high agreement*).

Findings on losses and damages in Asia: Evidence on climate-related L&D highlights tangible or material losses and damages such as loss to life, property, infrastructure and livelihoods (*medium evidence, high agreement*); and intangible or non-material losses and damages such as increasing conflict and civil unrest, erosion of sociocultural practices, and decreased wellbeing (*low evidence, high agreement*). The main constraint in assessing past and future L&D is that this terminology is not used prominently or consistently in the disaster management and climate risk literature in Asia, which potentially leads to underreporting. In contrast, there is *robust evidence (high agreement*) on adaptation constraints, notably on governance, informational, and physical constraints to adapting but regional evidence is very uneven with gaps in Central, North and West Asia. Table 10.5 presents a summary of L&D but draws on national/sub-national studies.

Knowledge gaps

- Attribution studies linking anthropogenic climate change and L&D remain focused on rapid-onset extreme events and evidence on L&D from slow-onset events such as drought and water scarcity is low (Singh et al., 2021a) (Pereira et al., 2019).
- Regional evidence gaps in Central, North and West Asia. Further, *low evidence* of national-level projected loss and damages (Uchiyama et al., 2020; Singh et al., 2021a).
- Disproportionate emphasis on economic L&D while intangible, non-economic L&D are relatively less measured and reported (Chiba et al., 2017); (Bahinipati, 2020). Economic loss estimates are largely approximations and therefore suffer from various methodological, assumption, and data-related uncertainties.
- Insufficient literature differentiating L&D under future adaptation scenarios, which makes assessment of residual damages and future L&D difficult. L&D projections are constrained by limited understanding on how vulnerabilities will evolve with economic and demographic changes. Most projected L&D are based on the population and GDP projections. More future projections are based

on the RCP scenarios and least number of studies were conducted on the combination of RCP and shared socio-economic pathways.

- Mitigation will have L&D and adaptation co-benefits (Kugler and Sariego, 2016; Toussaint, 2020), especially at the lower temperature stabilisation 1.5ºC (Nishiura et al., 2020), but the literature is currently insufficient to assess these L&D co-benefits of mitigation efforts.
- Negligible regional evidence on limits to adaptation.

Way forward: Developing robust metrics and institutions for measuring and reporting L&D at national and regional scales, especially non-economic damages and L&D due to slow-onset events is critical. In addition to vulnerability assessments, assessing L&D and limits to adaptation can inform adaptation prioritisation and enhance adaptation effectiveness (e.g.(Craft and Fisher, 2016) (Leiter et al., 2019)). Lessons are available from biodiversity and ecosystem services monitoring frameworks that have well-developed metrics and processes (e.g., (Díaz et al., 2020)).

[END BOX 10.7 HERE]

Table 10.5: Tangible and intangible losses and damages across Asia. For definitions on losses and damages and limits, see Cross-Chapter Box LOSS in Chapter 1.

Magnitude of losses and damages	
(dark orange)	High (>50% sector/population affected relative to reported baseline)
(light orange)	Medium (25-50% sector/population affected)
(pale orange)	Low (<25% sector/population affected)
(grey)	Not assessed due to inadequate evidence

Evidence	
***	High (≥ 10 papers)
**	Medium (5-9 papers)
*	Low (≤ 4 papers)
NE	No evidence

Adaptation constraints	
E	Economic
S	Socio-cultural
H	Human capacity
G	Governance
F	Financial
I	Informational/Technology
P	Physical
B	Biological

Sub-region (no. of papers)	Key risks reported in L&D papers	Losses and damages					Adaptation constraints (bold ticks denote strong barrier)								Adaptation limits	
		Tangible				Intangible	E	S	H	G	F	I	P	B	Soft	Hard
		Past	RCP 2.5	RCP 4.5	RCP 8.5											
East Asia (32)	Coastal flooding, Heat waves, SLR	***	*	**	**	*	✓			✓	✓	**✓**	✓		NE	NE
South East Asia (4)	Coastal flooding, SLR	*				*			✓	✓		✓			NE	NE
South Asia (18)	Coastal flooding, Drought, SLR, Heat waves	***	*	**	**	**	✓			**✓**	✓	✓			*	**
Central Asia (3)	Snowmelt, Heat waves, Drought	*			*	*						✓	✓		NE	NE
North Asia (2)	Permafrost thaw			*	*	*							✓		NE	NE
West Asia (9)	Heat waves, Drought	**		*	*	*							✓		*	**

Table Notes:

East Asia: (Yu et al., 2018c); (Tezuka et al., 2014); (Udo and Takeda, 2018); (Udo and Takeda, 2018); (Chen et al., 2017b); (Li et al., 2015a); (Lee et al., 2017); (Abadie et al., 2017); (Liu et al., 2019d); (Liu, 2020); (Liu and Chen, 2020); (Chung et al., 2017b); (Lee et al., 2018c); (Lee et al., 2019); (Kim and Lee, 2020); (Lee and Kim, 2016); (Lee et al., 2018b); (Kim et al., 2016a); (Yu, 2016); (Lei et al., 2015); (Wang et al., 2019b); (Liu et al., 2019c); (Elliott et al., 2015); (Wu et al., 2019d); (Yu et al., 2018a); (Feng et al., 2018a); (Yu et al., 2020); (Li et al., 2015b; Chen et al., 2017a); (Zhao et al., 2016b); **South East Asia:** (Dau et al., 2017); (Giuliani et al., 2016); (Mehvar et al., 2018); (Vu and Ranzi, 2017); **South Asia:** (Abadie et al., 2017); (Ahmed et al., 2016b); (Aslam et al., 2017); (Bahinipati, 2020); (Bahinipati and Patnaik, 2020); (Bhowmik et al., 2021); (Chhogyel and Kumar, 2018); (Chiba et al., 2017); (van der Geest, 2017); (Jevrejeva et al., 2016; Jevrejeva et al., 2018; Khan et al., 2020); (Leng and Hall, 2019); (Mehvar et al., 2019); (Mishra et al., 2017); (Patankar and Patwardhan, 2016); (Jevrejeva et al., 2016); (Wijetunge, 2014); **Central Asia:** (Babagaliyeva et al., 2017); (Groll et al., 2015); (Otto et al., 2017); **North Asia:** (Hjort et al., 2018); (Tschakert et al., 2019); **West Asia:** (Ashrafzadeh et al., 2019b); (Bierkens and Wada, 2019); (Gleick, 2014); (Gohari et al., 2017); (Houmsi et al., 2019); (Mantyka-Pringle et al., 2015); (Mosavi et al., 2020); (Pal and Eltahir, 2016); (Ghomian and Yousefian, 2017).

10.5.5 Risk Insurance

10.5.4.1 Point of departure:

Risk insurance approaches and tools have significantly evolved during recent years. The emphasis has been mainly on mitigating the adverse selection and moral hazard that has been the limitations of traditional area-based crop insurance approaches (He et al., 2019). This has been achieved by shifting the indemnity calculations on to the specific weather parameters and developing a weather index (Greatrex et al., 2015); (Fischer, 2019). Technological applications in the development of insurance products have seen a significant progress, including that of the blockchain and smart contracts (Gatteschi et al., 2018). There are technological developments in loss estimation, which has been a major limitation in the traditional insurance approaches in the past that either delayed the indemnity payment or have misjudged the losses. Application of multi-model and multi-stage decision support systems has begun to make crop loss assessments for insurance more efficient (Aggarwal et al., 2020). Technological applications also include remote sensing (Di et al., 2017) and mobile phone app technologies (Meena et al., 2018) to provide accurate and quick damage assessments, and application of internet-based indemnity approvals have enabled quick payment of indemnities (OECD, 2017b).

10.5.4.2 Findings

As against financing post-disaster relief and reconstruction, which has been the norm of disaster management for decades in Asia, the evolution of ex-ante risk financing in the form of risk insurance has seen a steady rise globally and in Asia. The rise in popularity for risk financing in general and insurance in specific stem from the observation that governments have recognised the burden of mainly financing the post-disaster relief and reconstruction only (Juswanto and Nugroho, 2017; UNESCAP, 2018c; ADB, 2019), and from the realisation of cost savings and efficiency that risk financing for risk mitigation brings to the overall risk reduction (*High agreement*, *medium evidence*). As a result, a gamut of risk financing instruments have been introduced to finance disaster risk reduction and climate change adaptation initiatives in Asia among which risk insurance has gained prominence for it provides a low cost and easy option for individuals, provides an opportunity for the governments to effectively engage the private sector in implementation, and has ability to inculcate risk-aware decision making at various levels (Hazell and Hess, 2017; UNESCAP, 2018c) (*High agreement*, *medium evidence*).

Several Asian countries including India, The Philippines, China have a significant experience of offering agricultural insurance against typhoons, droughts and floods (Yang, 2018). For the most part, these insurance systems followed a traditional indemnity based insurance which faced several challenges in implementation including moral hazard and adverse selection, disagreements and delays in crop damage assessments that relied upon crop cutting experiments, often leading to delay in processing indemnity payments, costly insurance premiums, and poor insurance expansion (Patnaik and Swain, 2017; Ghosh et al., 2019) (*High agreement*, *robust evidence*). Other factors contributing to poor penetration of insurance include limited awareness on the importance of insurance, and poor access.

To tackle the problem of costly insurance premiums, governments have subsidised the premiums (Ghosh et al., 2019). Premium subsidies have been reported to undermine the ability to convey the real cost of risks by the insured (price distortion), and encouraged adverse selection and moral hazard (Nguyen and Jolly, 2019). On the contrary, subsidies have been suggested to address the issue of adverse selection associated with the insurance (Zhao et al., 2017c).

Despite the fact that the insurance programs are able to obtain high participation rates due to subsidised premiums, their impact on farmers' income seems to be insignificant especially under the conditions of low indemnities, low guarantee, and wide coverage (Zhao et al., 2016a). The subsidy burden of insurance on national governments is found to be significant with an estimated 6 billion dollars spent by China alone on insurance (Hazell et al., 2017). In addition, the insurance programs in the Asian countries are reporting higher producer claim ratios, and often governments have to spend more than the money being transferred to the insured through the insurance programs (ibid).

To address the issues associated with the traditional indemnity insurance, efforts have been made to develop weather index insurance in Asia that bases the payouts on the rainfall or temperature index rather than on the direct damage measurements. The parametric insurance products help avoid the delays in insurance payouts as they are based on modelled risks rather than actual damage measurements, and control the adverse selection and moral hazard though basis risks could be increased due to improper matching of payouts with the index (De Leeuw et al., 2014). Index insurance is known to promote public-private partnerships that in turn will enhance the efficiency of overall program delivery (Hazell and Hess, 2017). Several countries including India, Bangladesh, Thailand, Indonesia, Myanmar, and The Philippines either are currently piloting or are expanding the weather index insurance (Surminski and Oramas-Dorta, 2014; Tyagi and Joshi, 2019). Index insurance is constantly expanding with an estimated 194 million farmers already enrolled in China and India, which is much lower than the potential number of farmers it can reach (Hazell et al., 2017).

Few significant bottlenecks that are limiting the scaling up of weather index insurance include lack of reliable weather data, low density of weather stations leading to high basis risk, and limited data on damage and hazard for parametric modelling of the insurance (Shirsath et al., 2019). Several innovations are being tried and tested to overcome the limitations associated with the index insurance which include developing multiscale index insurance, application of remote sensing, smartphone based near-surface remote sensing, and building insurance based on vegetation indices instead of relying on weather data alone (Hufkens et al., 2019). Alternative indices such as using Normalised Difference Vegetation Index (NDVI) are being tested for their applications in designing index-based insurance in India (IFAD, 2017). Agro-meteorology-based statistical analysis and crop growth modelling have been suggested to calibrate and to rectify faulty weather indices (Shirsath et al., 2019; Zhu et al., 2019). Establishing automatic weather stations can improve the data accuracy while avoiding the delay in acquiring the weather data (Sinha and Tripathi, 2016). These technological applications have already started finding space within insurance programs designed by national governments in Asia. For example, the government of India has released new operational guidelines for the application of new technologies such as drones, remote sensing, and mobile phone apps in implementation of the national agricultural insurance which is the third largest insurance in the world (Department of Agriculture, 2019).

10.5.4.3 Knowledge Gaps

Despite these developments, several issues still seem to hinder the penetration of insurance in Asia. Issues such as lack of sufficient choices, lack of clear model, lack of legal support, limited or absence of proper monitoring and evaluation, and limited data for underwriters to properly evaluate claims have been suggested (Nguyen and Jolly, 2019). Low interest among the potential buyers due to unaffordable insurance premiums, lack of provision for partial loss claim settlement, high hassles in claim settlement process, and lack of timely settlement of claims are reported (Parappurathu et al., 2017). In addition, insurance has been reported to have expanded the coverage of cash crops at the expense of drought resistant subsistence crops with effects on natural capital and potential increase in farmer's vulnerability to market price fluctuations (Müller et al., 2017).

Regional catastrophic insurance pools have also received attention in Asia. With the formation of Southeast Asia Disaster Risk Insurance Facility (SEADRIF) (Haraguchi and Lall, 2019), the regional insurance pool has been introduced in the Southeast Asia region initially being piloted in Lao PDR and Myanmar and to be expanded to the rest of the ASEAN region. Regional catastrophic insurance provides vulnerable countries to buffer climatic shocks by diversifying the risks beyond country boundaries.

10.5.6 Social protection

10.5.6.1 Point of departure

Social protection (SP) encompasses of initiatives that involve transfer income or assets to the poor, protect the vulnerable against risks to their livelihood, and enhance the social status and rights of the marginalised (Béné et al., 2014; Kothari, 2014). Social protection offers a wide range of instruments (e.g., cash transfers, insurance products, pension schemes and employment guarantee schemes) that can be used to support households that are exposed to climate changes (Bank, 2015). It also presents an opportunity to develop inclusive comprehensive risk management strategies to address loss and damage from climate change as well as means to climate change adaptation (CCA) (Aleksandrova, 2019).

Social protection programmes assist individuals and families, especially the poor and vulnerable, cope with crises and shocks, finds jobs, improve productivity, invest in the health and education of their children, and protect the aging population (Bank, 2018b). Social protection that is well-designed and implemented in a more long-term approach can enhance human capital and productivity, reduce inequalities, build resilience, empowerment and end inter-generational cycle of poverty (*medium evidence, medium agreement*) as indicated from various experiences in the region such as cash transfer programmes in Indonesia (Kwon and Kim, 2015); Benazir Income Support Programme in Pakistan (Watson et al., 2017); Chars Livelihoods Programme in Bangladesh (Pritchard et al., 2015); Minsei-in designated volunteer social workers in Japan (Boeckmann, 2016). Key consideration in strengthening resilience through social protection programmes is to design with climate and disaster risk considerations in mind and implemented in close synergy with existing programs, such as on sustainable livelihoods, early warning systems, and financial inclusion (Bank, 2018a) (Coirolo et al., 2013).

10.5.6.2 Findings

The Asia region is already the most disaster prone in the world, with over 200,000 lives lost and almost a billion-people affected by storms and floods alone between 2005 and 2014, while a heat wave in North and Central Asia in 2010 killed 56,000 people (United Nations, 2015). Climate change is increasing the frequency and intensity of these sudden and slow-onset disasters, amongst them, hydrological changes in major river basins where 1.5 billion people live (such as the Indus, Ganges, Brahmaputra, Mekong, Yellow, Yangtze, Tarim, Amu and Syr Darya rivers) (Bank, 2017a). According to the latest estimates of the International Labour Organisation (ILO), 55% of the global population (around four billion people) remains without any SP benefits, whereas the SP coverage gap is the highest in Africa (82.2%) and Asia and the Pacific (61%) (ILO, 2017b).

Risks are generally amplified for people without social protection or essential infrastructure and services, and for people with limited access to land and quality housing, especially those in exposed areas and informal settlements without secure tenure (ESCAP, 2017). Stateless people are disproportionately affected by climate change and disasters as they tend to reside in hazard-prone areas and their statues as non-citizens often limits access to assistance (Connell, 2015). The three main types of social protection, namely (i) social safety nets (also known as social assistance), which include conditional and unconditional cash transfers, public work programs, subsidies, and food stamps; (ii) social insurance, which consists of contributory pensions and contributory health insurance; and (iii) labour market measures, which include instruments such as unemployment compensation (Bank, 2018b). The potential for an integrated adaptive social protection is not yet harnessed by policymakers in tackling the structural causes of vulnerability to climate change (Tenzing, 2019). Public works program, i.e. India's MGNREGA should take into account climate risk in planning and support development of community assets to increase collective resilience.

Aligning social protection with climate change interventions are attempts to develop more durable pathways out of poverty and climate vulnerability, examples from the Mahatma Gandhi National Rural Employment Guarantee Act in Andhra Pradesh (MGNREGA) depicts the attempt to align through mainstreaming approach has helped women and their households (Steinbach et al., 2016) (Adam, 2015). On another note, Catastrophe Insurance Framework, first model introduced in Shenzen, China, provides timely relief for citizens and operates as a safety net particularly for the poorest residents who do not have disposable income to cover the costs associated with bodily injuries arising from disasters (Telesetsky and He, 2016). The DOLE (Department of Labour and Employment) Integrated Livelihood and Emergency Employment Program (DILEEP) in Philippines, is part of the recovery efforts after Typhoon Haiyan, provide short-term wage employment and facilitates entrepreneurship for people affected by natural calamities and economic shocks (Bank, 2018b).

In each of these instances, governments are using social protection to protect populations suffering from climate change or adversely affected by structural, pro-climate economic reforms (Hallegatte et al., 2015) However, additional research is still needed and new tools developed to inform policy design and support the implementation of "green" social protection, as well as to measure the net welfare impacts of such policies

(Canonge, 2016). In order to enhance social protection programmes, one of the cross-cutting issues is to discuss the linkages between gender roles and responsibilities, food security, agricultural productivity and the mediating role that social protection programmes can have (Jones et al., 2017). Social protection has a potentially important role to play in contributing to food security and agricultural productivity in a gender-responsive way (Holmes and Jones, 2013). As such experience from Challenging the Frontiers of Poverty Reduction: Targeting the Ultra Poor (CFPR/TUP) programme in Bangladesh, promoted social innovation by creating social and economic values, fostering microenterprises, food security, fostering inclusive growth and whilst empowering ultra-poor women (Emran et al., 2014; Mahmuda et al., 2014). Although there is increasing evidence that social protection programmes are having positive impacts to reduce vulnerability in women's everyday lives (Jones et al., 2017). However, transformative impact of these programmes is rare due to limitation in recognising women's access to productive inputs and resources (Tanjeela and Rutherford, 2018; Cameron, 2019).

On the other hand, poor governance practices affect delivery of social protection programmes, and the ability of beneficiary households to reap benefits from such support (Sijapati, 2017). In Nepal, closer look at public expenditure, about 60% of social protection budget is used by social insurance programmes that predominantly consists of public sector pensions (Babken Babajanian, 2014; Koehler, 2014). Towards this end, more efforts needed to improve its existing programmes so that there is an equality of opportunities, along with secured human rights, citing example from Nepal's Child Grant is indicative of an incremental approach to social policy (Garde et al., 2017). Meanwhile, in Philippines despite the existence of flagship national interventions that cover a significant number of people in need and have clear and robust implementation rules, there are still many programs with overlapping mandates and target population, and several gaps in their monitoring systems (Bank, 2018b).

Thus, having an integrated social protection information system would allow policymakers to better monitor inputs, outputs and outcomes (e.g., who are beneficiaries, what are they receiving, at what frequency, what are the existing gaps) (OECD, 2017a; Samad and Shahid, 2018). Evidence-based from three countries' assessment (Mongolia, Nepal and Vietnam), the political and institutional arrangements (the software) is as important as the technical fixes (the hardware) in the success of using ICT for delivering social protection programs (ADB, 2016). By 2050, climate-induced migration will *likely* be a major policy aspect of the rural-urban nexus as slow onset impacts of climate change in Sub-Saharan Africa, South Asia, and Latin America will *likely* force over 143 million people to migrate within their national borders (Kumari Rigaud, 2018). This will have major implications for SP systems and therefore national SP strategies should be designed to anticipate and address climate-induced internal mobility (Schwan and Yu, 2017). For instance, it does not offer a solution for maintaining Indigenous culture often strongly affected or even disrupted by climate change (Olsson, 2014). Hence, an effective approach needs to combine different policy instruments to support protection, adaptation and migration (O'Brien et al., 2018).

Evidently, social protection has been typically financed through the combination of government tax revenues and Official Development Assistance (ODA) challenges of the increasing frequency and intensity of natural and economic crises, are putting strains on these traditional financial sources (Durán-Valverde, 2020).In this context, innovative financing schemes are seen as critical to achieve the sustainable financing of social protection (Asher, 2015; UNICEF, 2019) via social and solidarity economy, as seen in women's autonomous adaptation measures in precautionary savings and flood preparedness in Nepal (Banerjee et al., 2019), and self-help groups as development intermediaries (Anderson, 2019). Still, there are constraints of SP to reach those who are most vulnerable to climate change and other hazards due to their legal status, such as attention to forcibly displaced populations within the social protection field has been limited (Sabates-Wheeler, 2019).

10.5.6.3 Knowledge gaps

Government social protection can attenuate negative impacts in facing disasters, depending on difference in political systems and focus on socio-political measures (*medium evidence, medium agreement*) not only in restoring livelihoods but also easing mental burdens faced by rural households in developing countries (Kosec and Mo, 2017) (Dalton et al., 2016) (Liebenehm, 2018). However, limited government capacities and fiscal feasibility may impede the expansion and effective implementation of social protection as developing countries need further support to design, adjust and implement social protection schemes effectively

(Klonner, 2014; Schwan and Yu, 2017). Most countries have comprehensive strategies for both SP and CC, few have attempted to align them, as in practice, they remain in separate institutional homes, governed by their own intra-sector coordination groups and funding channels (Bank, 2018b) (Steinbach et al., 2016). Thus, significant knowledge gaps remain in terms of understanding the potential of SP to build long-term resilience to climate change (Ulrichs et al., 2019). Future efforts should be geared to develop climate-responsive social protection policies that consider a broad range of issues including urbanisation and migration, impact of green policies on the poor, access to essential health care and risks to socially marginalised groups (Aleksandrova, 2019). Along with strengthening links to climate information and early warning systems, finance for enabling social protection systems to address climate-related shocks and stresses dynamically needs to be scaled up (Ulrichs et al., 2019) (Kuriakose et al., 2013).

10.5.7 Education and Capacity Development

10.5.7.1 Point of departure

Countries with the least capacity are hit first and hardest by impacts, such as the Himalayan region and densely-populated deltas in Asia (De Souza et al., 2015); (Khan, 2017). Acknowledging the limitation in terms of capacity and coping mechanisms towards climate change, education, training and awareness-building is central to sustaining long-term capacity-building (Clemens et al., 2016). Education has lot more to offer and room for improvements in addressing climate change, particularly in the climate hotspots of the Asia region where mostly poor, disadvantaged and vulnerable communities to CC are residing (Mani et al., 2018). In particular, dissemination of climate change awareness and information need more explanation (Wi and Chang, 2018); (Steg et al., 2014),(Cho, 2020) international and national support through institutions and financing is critical for successful capacity-building (Hemachandra, 2019); capacity building must be designed for long-term and self-sustaining (Gustafson et al., 2018); national ownership by recipient countries and members of communities of capacity building efforts is key to ensuring their success (Mikulewicz, 2017); (Roberts and Pelling, 2016).

10.5.7.2 Findings

The need to develop tailored climate communication and education strategies for individual nations as public awareness and risk perceptions towards climate change vary greatly (Lee et al., 2015a) (*medium evidence, high agreement*). Improving and investing on basic education, climate literacy and place-based strategies of climate change are vital to enhance public engagement, societies adaptive capacity and support for climate action (Lutz et al., 2014c); (Hu and Chen, 2016). As stated in IPCC Special Report 1.5C sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (Roy et al., 2018). Hence, various concepts are introduced to foster awareness, understanding, knowledge, participation as well as commitment towards managing climate change in a sustainable manner, such as Education for Sustainable Development (ESD) aimed at integrating principles and practices of sustainable development in all aspects of education and learning to foster individuals who will contribute to the realisation of a more sustainable society (Kitamura, 2017).

Climate Change Education (CCE) is also now addressed in the context of Education for Sustainable Development (ESD) that allows for learners to understand the causes and consequences of climate change and their readiness to take actions (Mochizuki and Bryan, 2015). ESD and CCE are gaining broader attention, for instance in China (Han, 2015) and Korea (Sung, 2015), however development of policies and implementation of initiatives regarding ESD and CCE still face a handful of challenges, in which requires a strong political will and consensus of key stakeholders (Læssøe and Mochizuki, 2015). Effective communication on climate change education particularly for younger generation engagement is also essential as they are our future leaders as climate change is an inter-generational equity issue (Corner et al., 2015). Action for Climate Empowerment (ACE) of Article 6 UNFCCC, target youth as a major group for effective engagement in the formulation and implementation of decisions on climate change (UNFCCC, 2015). Increasing attention from countries in Asia, such as Thailand, India, to encourage innovative ways to provide adequately in educating and engaging youth in climate change issues (Dür and Keller, 2018); (Narksompong and Limjirakan, 2015).

Integrated approach of knowledge about climate change, embraces both the importance in bridging knowledge of climate science and respecting Local Knowledge and Indigenous Knowledge, should be at the heart of any effort to educate citizens to have a deeper understanding of the causes and consequence of climate change in a holistic manner (Aswani et al., 2018). Indigenous Peoples—comprising about six percent of the global population—play a crucial role in the fight against CC for two interlinked reasons, first, they have a particular physical and spiritual relationship with land, water and associated ecosystems and tend to be among the most vulnerable to CC (Magni, 2017). Second, they have a specialised ecological and traditional knowledge relevant to finding the best solutions to CC (Rautela and Karki, 2015). Indigenous knowledge systems and resource management practices are important tools for both mitigating and adapting to CC (Fernandez-Llamazares et al., 2015). Indigenous knowledge is increasingly recognised as a powerful tool for compiling evidence of CC over time (Ahmed et al., 2016a). Knowledge of Climate Change Adaptation (CCA) and Disaster Risk Reduction (DRR) provide a range of complementary approaches in building resilience and reducing the vulnerability of natural and human systems to the impacts of CC and environmental hazards (Mall et al., 2019). The adaptation dimension involves developing knowledge and utilising existing Local Knowledge and Indigenous Knowledge, skills and dispositions to better cope with already evident and looming climate impacts (Aghaei et al., 2018). It is also important to ensure inclusive efforts in DRR across different nations and communities as well as increasing skills and capacities of women towards DRR efforts (Hemachandra et al., 2018); (Reyes and Lu, 2016); (Drolet et al., 2015); (Alam and Rahman, 2014); (Islam et al., 2016b). More effective and efficient teaching and learning strategies as well as collaborative networks are needed to increase preparedness and DRR activities across various levels of community (Gampell et al., 2017); (Shiwaku et al., 2016); (Takahashi et al., 2015); (Oktari et al., 2015); (Tuladhar et al., 2015b).

As shown in Table 10.6, education and capacity-building aspects affecting adaptation by sub-regions examples.

Table 10.6: Education and capacity-building aspects affecting adaptation by sub-regions examples.

Sub-region		Adaptation interventions	Education and Capacity-building aspects affecting adaptation	Supporting references
North Asia	Human well-being	PEEX (Pan-Eurasian Experiment) originated from a bottom-up approach by the science communities aiming at resolving major uncertainties in Earth system science and global sustainability issues concerning the Arctic and boreal pan-Eurasian regions, as well as China	Educating next generation of multidisciplinary experts and scientists capable of finding tools in solving future environmental, socioeconomic and demographic development of the Arctic and boreal regions as well as China	Pan Eurasian regions, as well as China (Kulmala et al., 2015)
West Asia	Agriculture	Smallholders farmers' vulnerability assessment	Level of education high more human capacity, adaptive capacity, less vulnerability	Iran (Jamshidi et al., 2019)
Central Asia	Agriculture, Water Resources, and Energy	Carrying out the selection and cultivation of drought-tolerant salt tolerant crops, preservation of the upper watershed of the rivers, improve climate resilience of hydro-facilities	Focal point for the preparation and implementation of programs for CC at the regional level, increased capacity of professionals in targeted areas and networking between them, and strengthen institutional, technical and human resources to promote adaptation and research in fields of climate and hydrological investigations, geographical information systems (GIS), environmental impact assessment, and protection and re-cultivation of lands,	Kazakhstan, Tajikistan, and Kyrzigstan Mountain societies in Central Asia (Schmidt-Vogt et al., 2016) (Xenarios et al., 2019)

South Asia	Agriculture	Productivity, net crop income, improvement in livelihoods and food security	Farmers' education, easy access to farm advisory services, weather forecasting and marketing information affect adaptation decisions.	Pakistan (Abid et al., 2016)
		Passive adaptation in agricultural and farming practices implicitly to cope with climate change	Increasing knowledge on climate change crucial to take concrete steps dealing with perceived climatic changes	India (Tripathi and Mishra, 2017)
		Farmers' perceptions shape knowledge vice versa on climate change	Age, education, occupation, farming experience, knowledge about coping strategies, significantly related with farmers' perception about climate change.	India (Aslam Ansari, 2018)
	Disaster Risk Reduction	Local institutions preparedness and capacity managing disaster at local scale	Capacity-building, technical support and financial capacity as well as adopt proactive approach to achieve higher level of disaster preparedness.	Pakistan (Shah et al., 2019)
Southeast Asia	Agriculture	Farm cultural practices adopt to minimise production losses due to extreme weather	Small scale farmers' attendance in climate change training enhance adaptive capacity.	Vietnam (Trinh et al., 2018)
		Farmers' barriers to adopt adaptation measures lack of fund and timely information	Knowledge of crop variety, increase educational outreach and communicating CC related information likelihood employ adaptive strategies.	China (Zhai et al., 2018)
		In Lower Mekong Basin, farmers in rural, under-resourced communities are unaware of how climate change will affect them.	Scientific findings can be merged with local knowledge at a community level to help raise awareness; knowledge gaps on both can be filled for better understanding and adaptation planning.	Cambodia, Laos, Vietnam, Thailand (USAID, 2015); (Gustafson et al., 2018)
	Coastal areas	Households' vulnerability due to variation in socio-economic and livelihoods assets.	Increase resilience by establishing effective communication system, improve knowledge on climate.	Vietnam; Indonesia ((Huynh and Stringer, 2018); (Nanlohy et al., 2015)
	Disaster Risk Reduction	Capacity-building through learning lab on disaster risk management for sustainable development (DRM-SD).	Transfer learning initiative to provide approach guidelines and innovative mechanisms for DRM practitioners who will have the know-how and potential for leadership in DRM-SD.	Four ASEAN countries; Malaysia, Vietnam, Lao PDR, Cambodia (Ahmad Shabudin et al., 2017)
East Asia	Disaster Risk Reduction	Community participation and disaster education need to be conducted so that people can take actions in disaster management.	Educational resilience system tested and revised through experiences from past disasters. Also recognising gender perspectives into mainstream disaster management. 'School-based recovery concept' facilitates short-term recovery and the longer-term community building needs. It can also help communities in building new networks and solving chronic social problems.	Japan (Matsuura and Shaw, 2014; Saito, 2014; Shiwaku et al., 2016)
	Bridging Indigenous Knowledge and scientific knowledge	Effort to solve real-world problems should first engage with those local communities that are most affected, beginning	Paying attention to the Indigenous perception of a hazard and risk can increase the effectiveness of projects implemented by practitioners who might need to communicate risks in the future.	(Mistry and Berardi, 2016; Roder et al., 2016)

		from the perspective of Indigenous Knowledge and then seeking relevant scientific knowledge	Empowering younger generation to ensure continuity of Indigenous cultures and theirlinked ecosystems.	

Knowledge gaps: Capacity-building at national and local levels still need to address gaps in research and practice, such as impacts and results of different preparedness measures (Alcayna et al., 2016). Ad-hoc and localised documentations and monitoring of efforts to build adaptive capacities has rendered it difficult to assess success (Cinner et al., 2018). Recommendations for strengthened capacity building are sometimes made or understood in isolation from the underlying structural issues shaping vulnerability, or without adequately recognising the political relationships that mediate the ways in which particular technical interventions result in differentiated outcomes for different groups (Archer and Dodman, 2015). Thus, design and decision-based tools such as rapid assessment for community resilience to climate change as well as rapid approach to monitor the effectiveness of aid projects support community- based adaptation to climate change is analysed using multidimensional approach, procedural, distributional, rights and responsibilities (Nkoana et al., 2018); (Jacobson et al., 2019). As a model of communication and engagement, citizen science has the potential to promote individual and collective climate change action (Groulx et al., 2017). More than information provision is needed to mobilise public action on climate change (Kyburz-Graber, 2013). Citizen science links communication and engagement in a manner that hold important lessons on ways to promote collective responses to climate (Bonney et al., 2016); (Wals et al., 2014). The power of science-based citizen engagement lies in citizen group contribution in drawing upon their local knowledge to enrich the knowledge base required for management decisions (Sayer et al., 2015). Scientific evidence may be less attuned to the complexity of local realities in managing climate change, thus citizen science has the potential in bridging this gap and has many advantages for climate mitigation and adaptation practice and policy (Ford et al., 2016). While citizen science uses citizens as policy passive objects for research in conducting measurements for big data sets, citizen social science (CSS) is gaining its momentum where it repositions citizens as central co-learners that can widen the climate science evidence-base to a more holistic understanding for the benefit of all (Kythreotis et al., 2019).

10.6 Climate Resilient Development Pathways

10.6.1 Climate-resilient Development Pathways in Asia

Climate-resilient development pathways (CRDPs) are 'trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation to and resilience in a changing climate' (Roy et al., 2018). Moving beyond a business-as-usual scenario, CRDPs involve not only adaptation and mitigation choices but also sustainable development implications and societal transformation (Roy et al., 2018). This basic understanding of CRDPs explicitly reflects that climate action (mitigation and adaptation) and sustainable development are fundamentally integrated and interdependent.

There is *high confidence* that currently implemented climate action in Asia (such as climate smart agriculture, ecosystem-based disaster risk reduction, investing in urban blue-green infrastructure) can meet adaptation, mitigation, and sustainable development goals simultaneously, presenting opportunities for climate-resilient development (CRD). However, there also exist significant barriers to CRD such as fragmented, reactive governance; inadequate evidence on which actions to prioritise and how to sequence them; and finance deficits. Some Asia countries and regions offer solutions to overcome these barriers: Through use of advanced technologies (in-situ observation and remote sensing, a variety of new sensor technologies, citizen science, artificial intelligence, and machine learning tools); regional partnerships and learning; improved forecasting capabilities; and better risk awareness (*high confidence*).

Asian countries are repeatedly identified as the most vulnerable to climatic risks with key sectors such as agriculture, cities and infrastructure, and terrestrial ecosystems expected to see high exposure to multiple hazards (Section 10.3). Owing to rapid development and large populations, Asian countries have large and growing GHG emissions: in 2018, five of the top 10 emitters in the world were Asian : China (1), India (3), Japan (5) Republic of Korea (8), and Indonesia (10) (Friedlingstein et al., 2019) although it is critical to note that per capita emissions and cumulative emissions are relatively lower than developed economies (Raupach et al., 2014). However, in the 2020 Sustainability Index and Dashboard, only two Asian countries made it to the top 30 countries in the world: Japan (17) and Republic of Korea (20) (Sachs et al., 2020). Finally, Asia has varied capacities to adapt with high heterogeneity in adaptation progress across the region.

Given this context of high risks, growing emissions, and varied adaptive capacities in Asia, CRDPs can enable (1) reducing existing vulnerability and inequality, (2) sustainable development and meeting the SDGs, and (3) managing multiple and often concurrent risks, including climate change and disaster risks Potentially, combinations of adaptation and mitigation options will be required to lead to climate-resilient development (see Fig on CRDPs in Ch 18) and some of these are outlined in Table 10.7. For example, climate-smart agriculture strengthens food security (SDG 2, Zero Hunger) (Aggarwal et al., 2019); urban disaster management such as Jakarta Disaster Risk Reduction Education Initiative contributes to SDG 11 (Sustainable Cities) (Ajibade et al., 2019).

Table 10.7: Adaptation options that can have mitigation and SDG synergies and trade-offs, providing opportunities for triple wins necessary for CRDPs.

Adaptation option	**Mitigation impacts (H/M/L/NA)[a]**	**Implications on SDGs**		**References**
		Positive	**Negative**	
Wetland protection, restoration	*Medium synergy* Carbon sequestration through mangroves	SDGs 8, 14, 15		(Griscom et al., 2020) in SE Asia
Solar drip irrigation	*High synergy* Shift to cleaner energy	SDGs 2, 7, 12	SDG 10	(Alam et al., 2020) in South Asia
Climate-smart agriculture	*High synergy [b]* No till practices and improved residue management can reduce soil carbon emissions	SDGs 2, 12		(Aggarwal et al., 2019), (Aryal et al., 2020b), (Aryal et al., 2020a), and (Tankha et al., 2020) in South Asia; (Chandra and McNamara, 2018) in SE Asia
Integrated smart water grids	*High synergy* Reduced energy needs for supplying water	SDGs 6, 9, 11, 13		(Kim, 2017) in Asia
Disaster risk management (including early warning systems)[c]	Not applicable	SDGs 9, 11	SDGs 5, 10	(Ajibade et al., 2019), (Herbeck and Flitner, 2019), (Aryal et al., 2020b) and (Mishra, 2020) in South and SE Asia; (Iturrizaga, 2019) in Asia; (Sovacool et al., 2012) in Bhutan; Grefalda et al. (2020) in Philippines
Carefully planned resettlement and migration (including decongestion of urban areas)	Inadequate evidence to make an assessment	SDGs 8, 10, 11	SDGs 6, 10, 11	(Arnall, 2019) in Asia; (Maharjan et al., 2020) in South Asia; (Estoque et al., 2020) in the Philippines; Banerjee et al. (2019) in Nepal
Aquifer storage and recovery	*Low synergy*	SDGs 6, 12		(Lopez et al., 2014) in Saudi Arabia; (Hoque et al., 2016) in South and SE Asia
Nature-based solutions in urban areas: green infrastructure (including urban green space, blue-green infrastructure)	*High synergy* Blue-green infrastructure act as carbon sinks	SDGs 3, 9, 11		(Mabon et al., 2019) in Japan; (Estoque et al., 2020) in the Philippines; (Byrne et al., 2015) and (Zhang et al., 2020a) in China; (Mabon and Shih, 2018) in Taiwan, Province of China; (Liao, 2019) and (Radhakrishnan et al., 2019) in Singapore
Coastal green infrastructure	*High synergy*	SDGs 9, 11, 13, 14, 15		(Sovacool et al., 2012), (Chow, 2018) and (Zinia and McShane, 2018) in Bangladesh; (Koh and

				Teh, 2019) and (Herbeck and Flitner, 2019) in SE Asia; (Giffin et al., 2020) in Asia

Table Notes:
[a] Expert judgement
[b] Climate change adaptation options in the agricultural sector include soil management, crop diversification, cropping system optimisation, and management, water management, sustainable land management, crop pest and disease management, and direct seeding of rice (Aryal et al., 2020b). Other specific agricultural practices that have adaptation and mitigation synergies include between tillage and residue management, alternate wetting and drying, site-specific nutrient management, crop diversification to less water-intensive crops such as maize, and improved livestock management (Aryal et al., 2020a).
[c] Risk management strategies in agriculture include crop insurance, index insurance, social networking and community-based adaptation, collective international action, and integrated agro-meteorological advisory services (Aryal et al., 2020b).

The following sub-sections examine CRDPs through three approaches that are particularly important in Asia and have a large body of evidence to assess implications for adaptation, mitigation, and sustainable development. The three illustrative approaches are: (1) Disaster risk management and adaptation synergies; (2) Food Water Energy Nexus; (3) Poverty alleviation and meeting equity goals.

10.6.2 Disaster Risk Reduction and Climate Change Adaptation Linkages

10.6.2.1 Point of Departure

There is growing evidence on the interconnectedness of extreme weather, climate change and disaster impacts (Asia, 2017; Reyer, 2017). In the Asian region, climate-related disasters have become more recurrent and destructive in terms of both economic and social impacts (Bhatt et al., 2015); (Aich et al., 2017); (Vij et al., 2017). Projections of increasing frequency, intensity, and severity of climate-related disasters call for better integration of climate change adaptation and disaster risk reduction (Sapountzaki, 2018) in policy development to address risks efficiently (Rahman et al., 2018) and to promote sustainable development pathways for reduced vulnerability and increased resilience(Seidler et al., 2018). Connecting climate change adaptation and disaster risk reduction efforts in both policy and practice continue to be a challenge, however, because the convergence of national policy and planning processes on CCA and DRR within Asia is in its early stages (Cousins, 2014) and structural barriers persist (Mall et al., 2019). CCA and DRR have developed as separate policy domains because of the different temporal and spatial scales considered, the diversity of actors involved, the policies and institutional frameworks adopted, and differences in tools and methodological approaches used. This has resulted to the CCA and DRR communities, and the knowledge and research they produce to support planning and decision making not always being well connected (Street et al., 2019).

10.6.2.2 Findings

Climate risk management in Asia is approached by focusing on hazards that are associated with extremes, i.e., extreme weather events with increased frequency and severity, and climate-and weather-related events. For example, farming has been affected by climatic variability and change in a wide variety of ways that include an increase in drought periods and intensity, a shortage of irrigation water availability, an increase in flooding and landslides, pest infestation of crops, a rising number of crop diseases, the introduction of invasive species and crop weeds, land degradation and an overall reduction in crop yields (Khanal et al., 2019). Estimation of the number of daily patients of heat-related illness based on the weather data and newly introduced metrics shows that the effects of age, successive days, and heat adaptation are key variables (Kodera et al., 2019).

Because most developing countries in Asia are highly vulnerable to the impacts of climate change due to a number of factors, many studies have focused on understanding vulnerability, for instance, gendered vulnerability at micro scale, which limits capacity to respond to both climatic and socioeconomic stressors (Ferdous and Mallick, 2019); vulnerability of urban poor communities due to the interaction of environmental and social factors (e.g., low incomes, gender, migrant status) and heightens the impacts of climate change on the poor (Porio, 2014); socio-ecological vulnerability where a degraded environment influences hazard patterns and vulnerability of people (Depietri, 2020); and livelihood vulnerability due to perceived climate risks and adaptation constraints (Fahad and Wang, 2018); (Hossain et al., 2020).

Risk assessments have been undertaken for different hazards such as floods (Al Saud, 2015; Al-Amin et al., 2019; Jha and Gundimeda, 2019; Mahmood et al., 2019; Zhang et al., 2019e); drought (Guo et al., 2019; Mainali et al., 2019); rainfall-induced landslide (Li et al., 2019b), sea level rise (Imaduddina and Subagyo, 2014; Suroso and Firman, 2018) and heat stress (Onosuka et al., 2019), among others, as well as environmental assessment, for example, in coastal zones (Islam and Zhang, 2019). Different types of strategies for climate risk management have also been studied including in-situ adaptation through ecosystem-based and community-based adaptation (Jamero et al., 2017); managed retreat or relocation (Buchori et al., 2018; Doberstein et al., 2020); planned sheltering in flood zones (Wu et al., 2019c); sustainable livelihoods that consider long term CCA measures of farmers and fishermen (Nizami et al., 2019; Shaffril et al., 2019); coastal afforestation through mangrove plantation (Rahman et al., 2018); management of ecosystem services to mitigate the effects of droughts (Tran and Brown, 2019); pre-investments, including holistic assessment of the basin (Inaoka et al., 2019); institutionalisation, where entry points are identified in efforts to build resilience (Lassa, 2019) and adaptive governance (Walch, 2019); and linking science and local knowledge (Mehta et al., 2019; van Gevelt et al., 2019).

The sectors that CCA and DRR have been linked are varied: (Filho et al., 2019) assessed adaptive capacity and resilience to climate change based on urban poverty, infrastructure and community facilities; (Mabon et al., 2019) looked at adaptation via the built environment, green roofs, and citizen and private sector involvement in smaller-scale greening actions; (Lama and Becker, 2019) focused on adaptation to reduce risk in conflicts; (Banwell et al., 2018) studied the link between health, CCA and DRR; and (Izumi et al., 2019) surveyed science, technology and innovation for DRR, {Banwell, 2018, Towards Improved Linkage of Disaster Risk Reduction and Climate Change Adaptation in Health: A Review} to name a few. Vulnerable groups have been given much attention such as farmers (Afroz, 2017; Gupta et al., 2019; Jawid and Khadjavi, 2019; Khanal et al., 2019; Shi et al., 2019a), women (Goodrich et al., 2019; Udas et al., 2019); (Hossain et al., 2019); and children, elderly and refugees (Asia, 2017). Finally, issues identified include water resources management (Bhatta et al., 2019; Sen et al., 2019; Zhang et al., 2019a); food security (Aleksandrova et al., 2016; Le, 2016); disaster governance (Blanco, 2015); climate boundary shifting wherein impacts of climate change are significant for crop production, soil management, and DRR (Talchabhadel and Karki, 2019); and institutional dimensions of CCA (Cuevas, 2018); (Islam et al., 2020).

Case studies on climate risk management and integrated CCA and DRR actions highlight some key lessons including an integrated and transformative approach to CCA, which focuses on long term changes in addressing climate impacts (Filho et al., 2019); adoption of an adaptive flood risk management framework incorporating both risk observation and public perceptions (Al-Amin et al., 2019); holistic approach and non-structural and technological measures in flood control management (Chan, 2014); monitoring of changes in urban surface water in relation to changes in seasons, land covers, anthropogenic activities, and topographical characteristics for managing watersheds and urban planning (Faridatul et al., 2019); removing 'gender blindness' in agrobiodiversity conservation and adaptation policies (Ravera et al., 2019); understanding uncertainties in CCA and DRR at the local level (van der Keur et al., 2016; Djalante and Lassa, 2019); promoting the use of Local Knowledge and Indigenous Knowledge alongside scientific knowledge (Hiwasaki et al., 2014); and increasing information, education and communication activities, and capacity development on DRR at the local level (Tuladhar et al., 2015a).

Several studies also identify enabling conditions to effectively implement CCA and DRR actions. In the Arab region in Asia (ARA), the following are critical: capacity building to develop knowledge and awareness, mainstreaming CCA and DRR in the national strategies and policies (e.g., water and environmental strategies), empowering the role of CCA and DRR actors notably women and rural societies, adopting lessons learned from regions with similar physical characteristics to ARA, establishing forecasting and prediction platforms that is supported by advanced monitoring technologies (e.g., remote sensing), and encouraging universities and research centers to develop studies on CCA and DRR. In Southeast Asia, laws and policies, institutional and financial arrangements, risk assessment, capacity building, and planning and implementation are entry points in integrating CCA and DRR (Lassa and Sembiring, 2017; Agency, 2018). According to (Cutter et al., 2015), holistic solutions and integrated approaches, rigorous risk research that shows coherent science-based assessment and knowledge transfer from research to practice, and aligned targets on disaster risk management, climate change and sustainable development targets are critical. Social capital and social protection measures could promote pro-poor and gender responsive adaptation and socially inclusive policy (Dilshad et al., 2019; Yari et al., 2019). Community-based approaches could allow local perceptions of climate change and experience of place to be included in planning (Dujardin et al., 2018; Dwirahmadi et al., 2019; Widiati and Irianto, 2019) and multi-stakeholder participation could engage various actors like the private sector in CCA and DRR. Further, multi-level climate governance could benefit from vertical and horizontal interactions at different levels and layers in the city (Zen et al., 2019). To mainstream and secure funding commitment, CCA and DRR could be integrated into national development plans and sectoral long-term plans (Ishiwatari and Surjan, 2020; Rahayu et al., 2020; Rani et al., 2020b).

10.6.2.3 Knowledge Gaps

Adaptation follows knowledge on risks, and literature exists that systematically identifies and characterises exposure and vulnerability, but gaps still exist. Decision making under uncertainty is challenged by the lack of data for adapting to current and uncertain future climate, the different perceptions of risk, and the potential solutions across different cultures and languages (van der Keur et al., 2016). Lack of downscaled climatic data, diverse institutional structures, and missing links in policies, are among the challenges in South Asia (Mall et al., 2019). In agriculture, there are gaps in the use of advanced farming techniques such as drought-resistant crops, and information on climate change to support farming households in making adaptation decisions (Akhtar et al., 2019; Khanal et al., 2019; Ullah et al., 2019). Better understanding of effective water management is crucial due to conflicts for shared water in ARA (Shaban and Hamze, 2017; UNDP, 2018). For delta regions, gaps identified are methodologies and approaches appropriate for understanding social vulnerability at various scales, pathways required for adaptation policy and response in the deltas that transcend development, and the lessons from implemented policy and how practice can build on these lessons in the deltas, among others (Lwasa, 2015). Approaches in tackling the challenges of climate change and disasters in the cities of developing countries could be better understood, and shared between cities so they can learn from one another (Filho et al., 2019).

10.6.3 Food Water Energy Nexus

Point of Departure: Food, energy, water, and land are vital elements for sustainable development as well as enhancing resilience to both climatic and non-climatic shocks. All these resources are highly vulnerable to climate change (10.3.1; 10.3.4; 10.3.4). Poor people are most affected due to changes in resources availability and accessibility. Food, water, and energy security are interconnected (Bizikova et al., 2013; Ringler et al., 2013; Rasul, 2014; Chang et al., 2016; Ringler et al., 2016). Although adapting to the climate change is one of the core component of global, regional, national and sub-national agenda, the focus of adaptation action has remained sectoral. Undermining the interlinkages of food energy and water security may increase trade-offs between sectors or places, which may lead to maladaptation (Barnett and O'Neill, 2010; Howells et al., 2013; Lele et al., 2013). Therefore, focusing on the nature of trade-offs and synergies across food water and energy nexus for integrated management of resources is a potential strategy for adaption to both climatic and non-climatic challenges (Bhaduri et al., 2015; Zaman et al., 2017). Due to its importance to the Paris Agreement and Sustainable Development Goals (SDGs), food water energy nexus approach got increasing attentions to capture synergies and minimise trade-offs in this interconnected system, which is also critical for enhancing adaptation together (Bazilian et al., 2011; Lawford et al., 2013; UNESCAP, 2013; FAO, 2014; Rasul and Sharma, 2014; Taniguchi et al., 2017a; Sukhwani et al., 2019; Sukhwani et al., 2020).

Findings: The FEW nexus can be evaluated in the two-way interactions between water-food, water-energy and food energy (Taniguchi et al., 2017a). The water energy nexus includes water for energy and energy for water (Rothausen and Conway, 2011; Hussey and Pittock, 2012; Byers et al., 2014), water food nexus, which includes water for food and impact of food production on water (Hoekstra and Mekonnen, 2012) and energy consumption for food production and food crops for biofuel production (Tilman et al., 2009). Food water energy land nexus has diversified implications at the sub-regional level in Asia. The increase in water supply-gap raises questions about sustainability of main mode of electricity generation in South Asia-thermal power generation and hydropower generation- are both threatened by water shortage in South Asia (Luo, 2018b; Mitra et al., 2021). Furthermore, policy mismatch driven anthropogenic cause lead unsustainable water use for food production in India. For example, subsidised electricity supply for watering agriculture plays key role in losing groundwater's buffer capacity against the various changes including climate variabilities (Badiani et al., 2012; Mitra, 2017). In the Mekong River basin of Southeast Asia, massive and rapid export oriented hydropower development will have direct implication on regional food security and livelihoods through major negative effect on the aquatic ecosystem (Baran and Myschowoda, 2009; Dugan et al., 2010; Arias et al., 2014). Similarly, in Central Asia, shifting of water storage for irrigation to power development has increased risks on reliable quality and quality of water (Granit et al., 2012). Deforestation lead agro-environmental changes led to decrease forest water supply, increase irrigation water demand and negatively effect on cropland stability and productivity (Lim et al., 2017a; Lim et al., 2019b).

Knowledge gaps: Despite getting attention at the global, regional, national and sub-national agenda, there are many challenges remain in both scientific research and policy actions. The scientific challenges include data, information and knowledge gaps in understanding food energy water and land interlinkages, and lack of systematic tools to address trade-offs (Liu et al., 2017a). Until very recently, implementation of food energy water nexus focused primarily on technical solutions, whereas governance, i.e. the institutions and processes governing the WEF nexus, has not received much consideration (Scheyvens and Shivakoti, 2019). At the policy end, the common challenges for implementation of water energy food land nexus are absence of sectoral coordination (Pahl-Wostl, 2019); the influence of political priorities on decisions and lack of processes for scientific knowledge to shape decisions; lack of capacity to understand interlinkages between sectors; lack of multistakeholder engagement in planning and decision-making processes; and lack of incentive mechanisms and adequate finance to support the approach (Bao et al., 2018; Scheyvens and Shivakoti, 2019).

10.6.4 Social Justice and Equity

Social justice focuses on justice-related implications of social and economic institutions, examined in different ways such as distributional justice (distribution of benefits and burdens across different societal groups; procedural justice (the design of just institutions and processes for decision-making); inter-generational justice (duties of justice to future generations); and recognitional justice (recognition of historical inequality) (Thaler et al., 2017). Climate change is affecting every aspect of our society and economy, thus it is pertinent to understand the interactions between social justice and climate change impacts (Tol, 2018). In particular focusing on how vulnerability to various impacts is created, maintained and distributed across geographical, social, demographic and economic dimensions (Bulkeley et al., 2014; Schlosberg and Collins, 2014; Van de Vliert, 2014; Burke et al., 2016). For instance, environmental and health consequences of climate change, which disproportionately affect low-income countries and poor people in high-income countries, profoundly affect human rights and social justice (Levy and Patz, 2015). Furthermore, great concern is expressed about the plight of the poor, disadvantaged and vulnerable populations when it comes to climate but not in other policy domains (Winters, 2014).

Evidence is increasing on the importance of focusing on environmental sustainability and relieving poverty and social injustice are not conflicting aims, in fact there is a further need for mainstreaming such approaches in order to respond to the climate change challenge in a socially just manner (Mayrhofer and Gupta, 2016). These not conflicting aims are described as co-benefits as reiterated in the IPCC reports as a central concept that refers to 'the positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare' (IPCC, 2014b). Better understanding of how social justice affects and is affected by efforts to build adaptive capacity will be crucial to avoiding unintended and even perverse outcomes. For example, in Andaman coast of Thailand, responses to climate change trends and events tended to be reactive rather than proactive, making already vulnerable people even more vulnerable and undermining their capacity to adapt in the future (Bennett et al., 2014). Different forms of inequality, moreover, render some groups of people more vulnerable than others to damage from climate hazards. In Mumbai, India, for example, the houses of poorer families required repeated repairs to secure them against flood damage, and the cumulative cost of those repairs consumed a greater proportion of their income than for richer populations (UN, 2016). Building the resilience of vulnerable groups requires strong community and government institutions that can support efforts to cope with devastating events, offering social protection and social development initiatives to support at-risk or vulnerable groups (Drolet et al., 2015). In addition, agencies need to consider how they can best work in ways which potentially support longer-term positive change to gender roles and relations, such as post-disaster activities must build and resource women's resilience and adaptive capacity in practice and challenge the constraints that impinge on their lives (Alam and Rahman, 2019) (Hadiyanto et al., 2018) (Yumarni and Amaratunga, 2018) (Sohrabizadeh et al., 2016) (Sadia et al., 2016).

Insights from the environmental justice literature show that an over-emphasis on emission reductions at national levels obscures negative impacts on disadvantaged communities, including low-income communities (Burch and Harris, 2014). The issue of social justice and adaptation is particularly relevant because of the politics that drive how adaptation and recovery efforts and investments are targeted towards specific populations, places, and capacities (Klinsky et al., 2017). Hence, climate justice and equity need to be highlighted more explicitly in integrative approaches to mitigation and adaptation (Moellendorf, 2015; Henrique KP, 2020) (*medium evidence, high agreement*).

The term climate justice is used to problematise global warming in ethical and political contexts. It does so by employing the concepts of environmental justice and social justice to examine inequalities and violation of human/collective rights in relation to climate change impacts (Ghimire, 2016)

At the heart of climate justice concerns lies the asymmetry that those who have contributed least to the problem of climate change i.e. greenhouse gas (GHG) emissions are the ones who will be affected by its adverse impacts the most. It is about sharing the burden and benefits equitably – i) among developed and developing countries in the context of historical responsibility, and ii) within nations to uplift the marginalised and affected populations who have contributed the least to the problem in the contexts of per-capita equity and local vulnerability (Joshi, 2014; Chaudhuri, 2020; Shawoo, 2020).

An ethical analysis of the climate regime reveals an abiding strong interconnection between economic circumstances, geopolitical power and the justice claims that nations can assert in negotiations (Okereke, 2016). Events within the climate regime highlight the importance of questioning the extent to which claims of justice can ever be truly realised in the context of international regimes of environmental governance as well as how much concerns for justice are motivated by other con- cerns such as relative economic gains or geopolitical objectives (Sikor T, 2014) .

The global land rush and mainstream climate change narratives have broadened the ranks of state and social actors concerned about land issues, while strengthening those opposed to social justice-oriented land policies (Borras, 2018).The five deep social reforms (redistribution, recognition, restitution, regeneration and resistance) of socially just land policy are necessarily intertwined. But the global land rush amidst deepening climate change calls attention to the linkages, especially between the pursuit of agrarian justice on the one hand and climate justice on the other. Here, the relationship is not without contradictions, and warrants increased attention as both unit of analysis and object of political action. Understanding and deepening agrarian justice imperatives in climate politics, and understanding and deepening climate justice imperatives in agrarian politics, is needed more than ever in the ongoing pursuit of alternatives. For example, the intersection between land grabs and climate change mitigation politics in Myanmar has created new political opportunities for scaling up, expanding and deepening struggles toward ‘agrarian climate justice’(Sekine, 2021).

[START FAQ10.1 HERE]

FAQ 10.1: What are the current and projected key risks related to climate change in each sub-region of Asia?

Climate change related risks are projected to increase progressively at 1.5°C, 2°C and 3°C of global warming in many parts of Asia. Heat stress and water deficit are affecting human health and food security. Risks due to extreme rainfall and sea level rise are exacerbating in vulnerable Asia.

Climatologically, the summertime surface air temperature in South, Southeast and Southwest Asia is high, and its coastal area is very humid. In these regions, heat stress is already a medium risk for humans. Large cities are warmer more than 2°C compared to the surroundings due to heat island effects, exacerbating heat stress conditions. Future warmings will cause more frequent temperature extremes and heat waves especially in densely populated South Asian cities, where working conditions will be exacerbated and day-time outdoor work becomes danger. For example, incidence of excess heat-related mortality in 51 cities in China is estimated to reach 37,800 deaths per year over a 20-year period in the mid-21st century (2041–2060) under the RCP 8.5 scenario.

Asian glaciers are the water resources for local and adjacent regions. Glaciers are decreasing in Central, Southwest, Southeast and North Asia, but are stable or increased in some parts of Hindu Kush-Himalaya. The glacier melt water in southern Tibetan Plateau has increased during 1998-2007, and the total amount and area of glacier lakes increased during last decades. In the future, maximum glacial runoff is projected in High Mountain Asia. Glacier collapses and surges, together with glacier lake outburst flood (GLOF) due to the expansion of glacier lakes, will threaten the securities of the local and down streaming societies. The glacier is *likely* to disappear by nearly 50% in High Mountain Asia and about 70% in Central and Western Asia by the end of the 21st century under the RCP4.5 scenario, and more under the RCP8.5 scenario.

As a large number of populations is living in the drought-prone areas, water scarcity is a prevailing risk across Asia through water and food shortage leading to malnutrition. Population vulnerable to impacts related to water is going to increase progressively at 1.5°C, 2°C and 3°C of global warming. Aggravating drought condition is projected in Central Asia. Water quality degradation also has profound impact on human health.

Extreme rainfall causes floods in vulnerable rivers. Observed changes in extreme rainfall vary considerably region by region in Asia. Extreme rainfall events (such as heavy rainfall > 100 mm day^{-1}) have been increasing in South and East Asia. In the future, most of East and Southeast Asia are projected to experience more intense rainfall events as soon as by the middle of the 21st century. In those regions, the flood risk will become more frequent and severe. It is estimated that over 1/3rd Asian cities and about 932 million urban dwellers are living in areas with high risk of flooding.

Sea level rise is continuing. Higher than the global mean sea level rise is projected in Asian coasts. Storm surge and high wave by tropical cyclones of higher intensity are high risk for a large number of Asian mega-cities facing the ocean; China, India, Bangladesh, Indonesia and Viet Nam have the highest numbers of coastal populations exposed, thus most vulnerable disaster-related mortality.

Changes in terrestrial biome are observed that are consistent with warming, such as an upward move of treeline position in mountains. Climate change, human activity, lightning and quality of forest governance and management determine increase of wildfire severity and area burned in North Asia last decades. Changes in marine primary production are also observed. Up to 20% decrease over the past six decades in the Western Indian Ocean due to ocean warming and stratification restricts nutrient mixing. The risk of irreversible loss of many ecosystems will increase with global warming.

The likelihood of adverse impacts to agricultural and food security in many parts of developing Asia will progressively escalate with the changing climate. Potential of total fisheries production in South and Southeast Asia is also projected to decrease.

Figure FAQ10.1 Key risks related climate change in Asia.

[END FAQ10.1 HERE]

[START FAQ10.2 HERE]

FAQ 10.2: What are current and emerging adaptation options across Asia?

Mirroring the heterogeneity across Asia, different countries and communities are undertaking a range of reactive and proactive strategies to manage risk in various sectors. Several of these adaptation actions show promise; reducing vulnerability and improving societal wellbeing. However, challenges remain around scaling up adaptation actions in a manner that is effective and inclusive while simultaneously meeting national development goals.

Asia exhibits tremendous variation in terms of ecosystems, economic development, cultures, and climate risk exposure. Mirroring this variation, households, communities, and governments have a wide range of coping and adaptation strategies to deal with changing climatic conditions, with co-benefits for various non-climatic issues such as poverty, conflict, and livelihood dynamics.

Currently, Asian countries have rich evidence on managing risk, drawing on long histories of dealing with change. For example, to deal with erratic rainfall and shifting monsoons, farmers make incremental shifts such as changing what and when they grow or adjusting their irrigation practices. Communities living in coastal settlements are using early warning systems to prepare for cyclones or raising the height of their houses to minimize flood impacts. These types of strategies, seen across all Asian sub-regions, based on local social and ecological contexts, are termed *autonomous adaptations* that occur incrementally and help people manage current impacts.

Currently and in the future, Asia is identified as one of regions most vulnerable to climate change, especially on extreme heat, flooding, sea level rise, and erratic rainfall. All these climatic risks, when overlaid on existing development deficits show us that incremental adaptation will not be enough, transformational change is required. Recognizing this, at sub-national and national levels, government and non-governmental actors are also prioritizing *planned adaptation strategies* which include interventions like 'climate-smart agriculture' as seen in South and South East Asian countries or changing labour laws to reduce exposure to heat as seen in West Asia. These are often sectoral priorities governments lay out through national or subnational policies and projects, drawing on various sources of funding: domestic, bilateral, and international. Apart from these planned adaptation strategies in social systems, Asian countries also report and invest in adaptation measures in natural systems such as expanding nature reserves to enable species conservation; or setting up habitat corridors to facilitate landscape connectivity and species movements across climatic gradients.

Overall, the fundamental challenges that Asia will see exacerbate under climate change are around water and food insecurity, poverty and inequality, and increased frequency and severity of extreme events. In some places and for some people, climate change, even at 1.5°C and more so at 2°C, will significantly constrain the functioning and wellbeing of human and ecological systems. Asian cities, villages, and countries are rising to this current and projected challenge, albeit somewhat unevenly.

Some examples of innovative adaptation actions are China's Sponge Cities which are trying to protect ecosystems while reduce risk for people, now and in the future. Another example is India's Heat Action Plans that are using 'cool roofs' technologies and awareness building campaigns to reduce impacts of extreme heat. Across South and Southeast Asia, climate-smart agriculture programmes are reducing greenhouse gas emissions associated with farming while helping farmers adapt to changing risks. Each country is experimenting with infrastructural, nature-based, technological, institutional, and behavioral strategies to adapt to current and future climate change with local contexts shaping both the possibility of undertaking such actions as well as the effectiveness of these actions to reduce risk. What works for aging cities in Japan exposed to heatwaves and floods may not work for pastoral communities in the highlands of Central Asia but there is progress on understanding what actions work and for whom. The challenge is to scale current adaptation action, especially in most exposed areas and for most vulnerable populations, as well as move beyond adapting to single risks alone (i.e. adapt to multiple coinciding risks such as flooding and water scarcity in coastal cities across South Asia or extreme heat and flash floods in West Asia). In this context, funding and implementing adaptation is essential and while Asian countries are experimenting with a range of autonomous and planned adaptation actions to deal with these multiple and often concurrent challenges, making current development pathways climate-resilient is necessary and, some might argue, unavoidable.

Table FAQ10.2.1: System transitions, sectors, and illustrative adaptation options.

System transitions	Sectors	Illustrative adaptation options
Energy and industrial systems	Energy and industries	• Diversifying energy sources • Improving energy access, especially in rural areas • Improving resilience of power infrastructure • Rehabilitation and upgrading of old buildings
Land and ecosystems	Terrestrial and freshwater ecosystems	• Expanding nature reserves • Assisted species migration • Introducing species to new regions to protect from climate-induced extinction risk • Sustainable forest management including afforestation, forest fuel management, fire management
	Ocean and coastal ecosystems	• Marine protected areas • Mangrove and coral reef restoration • Integrated coastal zone management • Sand banks and structural technologies
	Freshwater	• Integrated watershed management • Transboundary water management • Changing water access and use practices to reduce/manage water demand • High efficiency water-saving technology • Aquifer storage and recovery
	Agriculture, fisheries, and food	• Changing crop type and variety, improving seed quality • Water storage, irrigation and water management • Climate-smart agriculture • Early warning systems and use of climate information services • Fisheries management plans (e.g., seasonal closures, limited fishing licenses, livelihood diversification)

Urban systems	Cities, settlements and	• Flood protection measures and sea walls • sustainable land use planning and regulation • Protecting urban green spaces, improving permeability, mangrove restoration in coastal cities • Planned relocation and migration • Disaster management and contingency planning
	Key infrastructures	• climate-resilient highways and power infrastructure • relocating key infrastructure
Health systems		• Reducing air pollution • Changing dietary patterns

[END FAQ10.2 HERE]

[START FAQ10.3 HERE]

FAQ 10.3: How is Local Knowledge and Indigenous Knowledge being incorporated in the design and implementation of adaptation projects and policies in Asia?

Indigenous People, comprising about six percent of the global population, play a crucial role in managing climate change for two important reasons, first, they have a physical and spiritual connection with land, water and associated ecosystems, thus making them most vulnerable to any environmental and climatic changes. Second, their ecological and local knowledge are relevant to finding solutions to climate changes.

Local Knowledge and Indigenous Knowledge (LIK) play an important role in the formulation of adaptation governance and related strategies (IPCC 2007), and best quality, locality specific knowledge can help address serious lack of education on climate change and uncertainties surrounding quality, salience, credibility and legitimacy of available knowledge base.

Key findings across Asia, underline the importance of building, sustaining and augmenting local capacity through addressing inadequacies in terms of resource base, climate change awareness, government-community partnerships, and vulnerability assessment. Furthermore, inclusion of Local Knowledge and Indigenous Knowledge as well as practices will improve adaptation planning and decision-making process to climate change.

In climate sensitive livelihoods, integrated approach informed by science that examines multiple stressors along with LIK appears to be of immense value. For instance in building farmers' resilience, enhancing climate change adaptation, ensuring cross cultural communication, and promoting local skills are drawing upon Indigenous People's intuitive thinking processes and geographical knowledge of remote areas.

There is also a widespread recognition that Local Knowledge and Indigenous Knowledge are important in ensuring successful ecosystem-based adaptation (EbA). However, this recognition requires more practical and translation into LIK driven EbA projects. For instance, in the Coral Triangle region, creating historical timelines and mapping seasonal calendars can help to capture LIK while also feeding this information into climate science and climate adaptation planning. Identifying indigenous crop species for agriculture by using LIK is already identified as an important way to localise climate adaptation, an example observed from Bali's vital contribution of moral economies to food systems have long build resilience among groups of communities in terms of food security and sovereignty even with challenges faced due to modernizing of local food systems.

Many of the pressing problems of Asia, including water scarcity, rapid urbanisation, deforestation, loss of species, rising coastal hazards, agricultural loss can be effectively negated, or at least minimised through proper adoption of suitable science and technological method. Climate change adaptation is greatly facilitated by science, technology and innovation. This ranges from application of existing science, new development on scientific tools and methods, application of LIK and citizen sciences. Deploying Knowledge Quality Assessment Tool found significant co-relation between science-based and LIK framing would help to address, acknowledge, and utilise integrated approach in showing how the respect to this wisdom of LIK, a valuable asset for climate adaptation governance. LIK based environmental indicators need to be seen as part of a separate system of knowledge that coexists with, but is not submerged into, another conventional knowledge system.

In the context of education and capacity development of climate change, integrated approach of embracing both the importance of climate science and LIK is acknowledged. The LIK is increasingly recognised as a powerful tool for compiling evidence of climate change over time. Such as knowledge of climate change adaptation (CCA) and disaster risk reduction (DRR) provide a range of complementary approaches in building resilience and reducing vulnerability of natural and human systems. Developing knowledge and utilising existing Local Knowledge and Indigenous Knowledge, skills, and dispositions to better cope with already evident and looming climate impacts. Engaging communities in the process of documenting and understanding long-term trends and practices will enable both Local Knowledge and Indigenous Knowledge as well as Western scientific assessments of change in designing appropriate climate adaptation measures.

[END FAQ10.3 HERE]

[START FAQ10.4 HERE]

FAQ 10.4: How can Asia meet multiple goals of climate change adaptation and sustainable development within the coming decades?

Asian countries are testing ways to develop in a climate resilient manner to meet goals of climate change and sustainable development simultaneously. Some promising examples exist but the window of opportunity to put some of these plans in place is small and reducing, highlighting the need for urgent action across and within countries.

In order to achieve multiple goals of climate change adaptation, mitigation, and sustainable development; rapid, system transitions across energy systems; land and ecosystems; urban and infrastructural systems; are critical. This is especially important across Asia, which has the largest population exposed to current climate risks, high sub-regional diversity, and where risks are expected to rise significantly and unevenly under higher levels of global warming. However, such transformational change is deeply challenging because of variable national development imperatives; differing capacities and requirements of large, highly unequal, and vulnerable populations; and socio-economic and ecological diversity that requires very contextual solutions. Further, issues such as growing transboundary risks, inadequate data for long-term adaptation planning, finance barriers, uneven institutional capacity, and non-climatic issues such as increasing conflict, political instability, and polarization, constrain rapid, transformational action across systems.

Despite these challenges, there are increasing examples of action across Asia that are meeting climate adaptation and sustainable development goals simultaneously such as through climate smart agriculture, disaster risk management, and nature-based solutions. To enable these system transitions, vertical and horizontal policy linkages; active communication and cooperation between multiple stakeholders; and attention to the root causes of vulnerability are essential Further, rapid systemic transformation can be enabled by policies and finances to incentivize capacity building, new technological innovation and diffusion. The effectiveness of such technology-centric approaches can be maximized by combining with attention to behavioral shifts such as by improving education and awareness, building local capacities and institutions, and leveraging Indigenous and local knowledge.

The window of opportunity to act is small and reducing; if system transitions are delayed, there is high confidence that climatic risks will increase human and natural system vulnerability as well as increase inequality and erode achievement of multiple SDGs. Thus, urgent, systemic change that is suited to national and sub-national socio-ecological contexts across Asia is imperative.

Adaptation option	Mitigation impacts	Implications on SDGs	
		Positive	Negative
Wetland protection, restoration	Medium synergy (carbon sequestration through mangroves)	8, 14, 15	
Solar drip irrigation	High synergy (shift to cleaner energy)	2, 7, 12	10
Climate-smart agriculture	High synergy (no till practices and improved residue management can reduce soil carbon emissions)	2, 12	
Integrated smart water grids	High synergy (reduced energy needs for supplying water)	6, 9, 11	
Disaster risk management (including early warning systems)	Not applicable	9, 11	5, 10
Aquifer storage and recovery	Low synergy	6, 12	
Nature-based solutions in urban areas: green infrastructure	High synergy (blue-green infrastructure act as carbon sinks)	3, 9, 11	
Coastal green infrastructure	High synergy	9, 11, 14, 15	

Figure FAQ10.4.1: Adaptation options, mitigations impacts and implications on SDGs.

[END FAQ10.4 HERE]

References

Aayog, N., 2017: Inventory and Revival of Springs in the Himalayas for Water Security. *Dept. of Science and Technology, Government of India, New Delhi*.

Abadie, L. M., I. Galarraga and E. S. de Murieta, 2017: Understanding risks in the light of uncertainty: low-probability, high-impact coastal events in cities. *Environmental Research Letters*, **12**(1), doi:https://doi.org/10.1088/1748-9326/aa5254.

Abadie, L. M. et al., 2020: Comparing urban coastal flood risk in 136 cities under two alternative sea-level projections: RCP 8.5 and an expert opinion-based high-end scenario. *Ocean Coastal Manage.*, **193**, 105249, doi:https://doi.org/10.1016/j.ocecoaman.2020.105249.

Abbas, A., T. S. Amjath-Babu, H. Kächele and K. Müller, 2015: Non-structural flood risk mitigation under developing country conditions: an analysis on the determinants of willingness to pay for flood insurance in rural Pakistan | SpringerLink. *Natural Hazards*, **75**(3), 2119-2135, doi:10.1007/s11069-014-1415-x.

Abbas, A. et al., 2019: Participatory adaptation to climate extremes: an assessment of households' willingness to contribute labor for flood risk mitigation in Pakistan. *Journal of Water and Climate Change*, **7**(3), 621-636, doi:10.2166/wcc.2016.002.

Abe, M. and L. Ye, 2013: Building resilient supply chains against natural disasters: The cases of Japan and Thailand. *Global Business Review*, **14**(4), 567-586.

Abid, M., U. A. Schneider and J. Scheffran, 2016: Adaptation to climate change and its impacts on food productivity and crop income: Perspectives of farmers in rural Pakistan. *Journal of Rural Studies*, **47**, 254-266, doi:10.1016/j.jrurstud.2016.08.005.

Abolmaali, S. M.-R., M. Tarkesh and H. Bashari, 2018: MaxEnt modeling for predicting suitable habitats and identifying the effects of climate change on a threatened species, Daphne mucronata, in central Iran. *Ecological Informatics*, **43**, 116-123, doi:10.1016/j.ecoinf.2017.10.002.

Abubakar, I. et al., 2018: The UCL–Lancet Commission on Migration and Health: the health of a world on the move. *The Lancet*, **392**(10164), 2606-2654.

Acharya, A. and A. Prakash, 2019: When the river talks to its people: Local knowledge-based flood forecasting in Gandak River basin, India. *Environmental Development, Elsevier*, **31**, 55-67, doi:10.1016/j.envdev.2018.12.003.

Acharya, P., B. Boggess and K. Zhang, 2018: Assessing heat stress and health among construction workers in a changing climate: A review. *International journal of environmental research and public health*, **15**(2), 247.

Ackerman, K. et al., 2014: Sustainable Food Systems for Future Cities: The Potential of Urban Agriculture. *The Economic and Social Review*, **45**(2), doi:https://www.esr.ie/article/view/136.

Adaev, V., 2018: Smoke over taiga and tundra: fire in the culture of Northern peoples of Western Siberia as a means of environmental management. *VESTNIK ARHEOLOGII, ANTROPOLOGII I ETNOGRAFII*, 138-147, doi:10.20874/2071-0437-2018-41-2-138-147.

Adam, H. N., 2015: Mainstreaming adaptation in India – the Mahatma Gandhi National Rural Employment Guarantee Act and climate change. *Climate and Development*, **7**(2), 142-152, doi:10.1080/17565529.2014.934772.

ADB, 2013: *Investing in Resilience: Ensuring a Disaster-Resistant Future*. 188 pp. ISBN 9789290929499.

ADB, 2014: *Climate proofing ADB investment in the transport sector: initial experience*.

ADB, 2016: *Integrating Information and Communication Technology in Social Protection Programs*. ADB Briefs, ADB, Manila.

ADB, 2017a: Meeting Asia's Infrastructure Needs.

ADB, 2017b: *A region at risk: The human dimensions of climate change in Asia and the Pacific* Asian Development Bank, Mandalyong City, Metro Manila. Available at: https://www.adb.org/sites/default/files/publication/325251/region-risk-climate-change.pdf.

ADB, 2019: The Enabling Environment for Disaster Risk Financing in Sri Lanka: Country Diagnostics Assessment. 56.

Adger, W. N. et al., 2021: Perceived environmental risks and insecurity reduce future migration intentions in hazardous migration source areas. *One Earth*, **4**(1), 146-157.

Adhikari, P. et al., 2018: Potential impact of climate change on the species richness of subalpine plant species in the mountain national parks of South Korea. *Journal of Ecology and Environment*, **42**(4), 298-307, doi:10.1186/s41610-018-0095-y.

Adler, C., C. Huggel, B. Orlove and A. Nolin, 2019: Climate change in the mountain cryosphere: impacts and responses. Springer.

Afroz, R., 2017: Determinants of Malaysian farmers' choice of adaptation strategies for adapting to climate change in Kedah Malaysia. *Asian Journal of Agricultural Research* **11**, 120-127, doi:10.3923/ajar.2017.120.127.

Agency, J. I. C., 2018: Project for Strengthening Institutional and Policy Framework on Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) Integration (ASEAN). JICA.

Aggarwal, P. et al., 2020: Application note: Crop-loss assessment monitor–A multi-model and multi-stage decision support system. *Computers and Electronics in Agriculture*, **175**, 105619.

Aggarwal, P., S. Vyas, P. Thornton and B. M. Campbell, 2019: How much does climate change add to the challenge of feeding the planet this century? *Environmental Research Letters*, **14**(4), 043001, doi:10.1088/1748-9326/aafa3e.

Aghaei, N., H. Seyedin and H. Sanaeinasab, 2018: Strategies for disaster risk reduction education: A systematic review. *J Educ Health Promot*, **7**, 98, doi:10.4103/jehp.jehp_31_18.

Agung, P., G. Galudra, M. Van Noordwijk and R. Maryani, 2014: Reform or reversal: the impact of REDD+ readiness on forest governance in Indonesia. *Climate Policy*, **14**(6), 748-768, doi:10.1080/14693062.2014.941317.
Ahluwalia, R. S. et al., 2016: Towards the understanding of the flash flood through isotope approach in Kedarnath valley in June 2013, Central Himalaya, India. *Natural Hazards*, **82**(1), 321-332, doi:10.1007/s11069-016-2203-6.
Ahmad, A. A., Muhammad & Rasul, Ghulam & Wajid, Syed & Khaliq, Tasneem & Rasul, Fahd & Saeed, Umer & Rahman, Muhammad & Hussain, Jamshad & Baig, Irfan & Naqvi, Syed & Syed, Ahsan & Ahmad, Shakeel & Jatoi, Wajid & Valdivia, Roberto, 2015: *Chapter 7: Impact of Climate Change on the Rice–Wheat Cropping System of Pakistan* [Cynthia Rosenzweig, D. H. (ed.)]. 219-258 pp.
Ahmad, I. et al., 2019: Climate change impacts and adaptation strategies for agronomic crops. IntechOpen. ISBN 978-1-78985-667-5.
Ahmad Shabudin, A. F., S. N. F. Syed Azhar and T. F. Ng, 2017: Learning lab on disaster risk management for sustainable development (DRM-SD). *International Journal of Climate Change Strategies and Management*, **9**(5), 600-625, doi:10.1108/ijccsm-08-2016-0114.
Ahmadi, M., P. Chatrchi and A. A. Dadashi Rodbari, 2018: Modeling the precipitation trend in the West Asia region under climate change. *RESEARCHES IN EARTH SCIENCES*, **9**(35 #P00479), -.
Ahmed, A. U., A. N. Appadurai and S. Neelormi, 2019a: Status of climate change adaptation in South Asia region. In: *Status of Climate Change Adaptation in Asia and the Pacific*. Springer, pp. 125-152.
Ahmed, C. I., W. B. Hu and S. Kumar, 2016a: Indigenous knowledge about prediction in climate change. *International Journal of Humanities and Social Science*, **5**(1), 45-62.
Ahmed, I. et al., 2019b: Opportunities and challenges of compliance to safe building codes: Bangladesh and Nepal. *APN Science Bulletin*, **9**(1), doi:https://doi.org/10.30852/sb.2019.834.
Ahmed, M. and S. Suphachalasai, 2014: *Assessing the costs of climate change and adaptation in South Asia*. Asian Development Bank.
Ahmed, N. and J. S. Diana, 2015: Threatening "white gold": Impacts of climate change on shrimp farming in coastal Bangladesh. *Ocean Coastal Manage.*, **114**, 42-52, doi:10.1016/j.ocecoaman.2015.06.008.
Ahmed, N. and M. Glaser, 2016: Coastal aquaculture, mangrove deforestation and blue carbon emissions: Is REDD+ a solution? *Marine Policy*, **66**, 58 - 66, doi:https://doi.org/10.1016/j.marpol.2016.01.011.
Ahmed, N., S. Thompson and M. Glaser, 2018: Integrated mangrove-shrimp cultivation: Potential for blue carbon sequestration. *Ambio*, **47**(4), 441-452, doi:10.1007/s13280-017-0946-2.
Ahmed, N., S. Thompson and M. Glaser, 2019c: Global aquaculture productivity, environmental sustainability, and climate change adaptability. *Environmental Management*, **63**(2), 159-172, doi:10.1007/s00267-018-1117-3.
Ahmed, S. et al., 2016b: A comparative review of China, India and Pakistan renewable energy sectors and sharing opportunities. *Renewable and Sustainable Energy Reviews*, **57**, 216-225, doi:https://doi.org/10.1016/j.rser.2015.12.191.
Ahmed, S. and J. Stepp, 2016: Beyond yields: Climate change effects on specialty crop quality and agroecological management. *Elementa: Science of the Anthropocene*, **4**, 000092, doi:10.12952/journal.elementa.000092.
Ahmedabad Municipal, C., 2018: Ahmedabad heat action plan 2018. guide to extreme heat planning in Ahmedabad, India.
Aich, V. et al., 2017: Climate Change in Afghanistan Deduced from Reanalysis and Coordinated Regional Climate Downscaling Experiment (CORDEX)—South Asia Simulations. *Climate*, **5**(2), doi:10.3390/cli5020038.
Ajibade, I. and E. Michael, 2019: SDGs and climate change adaptation in Asia megacities: Synergies and opportunities for transformation. In: *Achieving the Sustainable Development Goals: Global Governance Challenges* [Dalby, A., S. Horton, R. Mahon and D. Thomaz (eds.)]. Routledge, London, pp. 100-116.
Ajibade, I., 2019: Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. *Climatic Change*, **157**(2), 299-317.
Akbari, H. and D. Kolokotsa, 2016: Three decades of urban heat islands and mitigation technologies research. *Energy and Buildings*, **133**, 834-842, doi:10.1016/j.enbuild.2016.09.067.
Akber, M. A. et al., 2017: Changes of shrimp farming in southwest coastal Bangladesh. *Aquaculture International*, **25**(5), 1883-1899, doi:10.1007/s10499-017-0159-5.
Akhtar, R., M. M. Masud and R. Afroz, 2019: Perception of Climate Change and the Adaptation Strategies and Capacities of the Rice Farmers in Kedah, Malaysia. *Environment and Urbanization ASIA*, **10**(1), 99-115, doi:10.1177/0975425318822338.
Akhtar, S., K. Zahedi and T. Bonapace, 2018: *Sand and dust storms in Asia and the Pacific: opportunities for regional cooperation and action.*, United Nations Economic and Social Commission for Asia and the Pacific, Bangkok. Available at: https://www.unescap.org/sites/default/files/UNESCAP%20SDS%20Report_1.pdf (accessed 12 June 2021).
Al-Amin, A. Q. et al., 2019: Evaluating the impacts of climate disasters and the integration of adaptive flood risk management. *International Journal of Disaster Risk Reduction*, **39**, doi:https://doi.org/10.1016/j.ijdrr.2019.101241.
Al-Zahrani, K. H., M. B. Baig and G. S. Straquadine, 2019: Food Waste in the Kingdom of Saudi Arabia: Implications for Extension Education. In: *Climate Change, Food Security and Natural Resource Management : Regional Case Studies from Three Continents* [Behnassi, M., O. Pollmann and H. Gupta (eds.)]. Springer International Publishing, Cham, pp. 73-101. ISBN 978-3-319-97091-2.

Al Saud, M., 2015: *Flood Control Management for the City and Surroundings of Jeddah, Saudi Arabia*, 1 ed. Springer Natural Hazards, Springer Netherlands, XIII, 169 pp.
Alam, G. M. M., K. Alam and S. Mushtaq, 2017: Climate change perceptions and local adaptation strategies of hazard-prone rural households in Bangladesh. *Climate Risk Management*, **17**, 52-63, doi:10.1016/j.crm.2017.06.006.
Alam, K. and M. H. Rahman, 2014: Women in natural disasters: A case study from southern coastal region of Bangladesh. *International Journal of Disaster Risk Reduction*, **8**, 68-82, doi:10.1016/j.ijdrr.2014.01.003.
Alam, K. and M. H. Rahman, 2019: Post-disaster recovery in the cyclone Aila affected coastline of Bangladesh: women's role, challenges and opportunities. *Natural Hazards*, doi:10.1007/s11069-019-03591-7.
Alam, M. F. et al., 2020: *Convergence and co-financing opportunities for climate-resilient water management*. Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH; Water Security and Climate Adaptation in Rural India (WASCA), Bonn, Germany and New Delhi, India, 109 pp.
Alamgir, M., S. A. Mukul and S. M. Turton, 2015: Modelling spatial distribution of critically endangered Asian elephant and Hoolock gibbon in Bangladesh forest ecosystems under a changing climate. *Applied Geography*, **60**, 10-19.
Alauddin, M. and M. A. R. Sarker, 2014: Climate change and farm-level adaptation decisions and strategies in drought-prone and groundwater-depleted areas of Bangladesh: an empirical investigation. *Ecological Economics*, **106**, 204-213, doi:https://doi.org/10.1016/j.ecolecon.2014.07.025.
Alauddin, S. and K. F. Rahman, 2013: Vulnerability to climate change and adaptation practices in Bangladesh. *Journal of SUB*, **4**(2), 25-42.
Albright, R. and B. Mason, 2013: Projected Near-Future Levels of Temperature and pCO(2) Reduce Coral Fertilization Success. *Plos One*, **8**(2), 8, doi:10.1371/journal.pone.0056468.
Alcayna, T., V. Bollettino, P. Dy and P. Vinck, 2016: Resilience and Disaster Trends in the Philippines: Opportunities for National and Local Capacity Building. *PLoS Curr*, **8**, doi:10.1371/currents.dis.4a0bc960866e53bd6357ac135d740846.
Aleksandrova, M., 2019: Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries. *Climate and Development*, 1-10, doi:10.1080/17565529.2019.1642180.
Aleksandrova, M., A. K. Gain and C. Giupponi, 2016: Assessing agricultural systems vulnerability to climate change to inform adaptation planning: an application in Khorezm, Uzbekistan. *Mitigation and adaptation strategies for global change*, **21**(8), 1263-1287.
Ali, A. and O. Erenstein, 2017: Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management*, **16**, 183-194, doi:10.1016/j.crm.2016.12.001.
Ali, H., V. Mishra and D. S. Pai, 2014: Observed and projected urban extreme rainfall events in India. *Journal of Geophysical Research: Atmospheres*, **119**(22), 12,621-612,641, doi:10.1002/2014JD022264.
Ali, J. et al., 2018: Centennial heat wave projections over Pakistan using ensemble NEX GDDP data set. *Earth Systems and Environment*, **2**(3), 437-454.
Ali, S. et al., 2020: Identifying hotspots cities vulnerable to climate change in Pakistan under CMIP5 climate projections. *International Journal of Climatology*, doi:https://doi.org/10.1002/joc.6638.
Ali, S. et al., 2017: Climate Change and Its Impact on the Yield of Major Food Crops: Evidence from Pakistan. *Foods*, **6**(6), doi:10.3390/foods6060039.
Aliagha, U. G. et al., 2014: Factors affecting flood insurance purchase in residential properties in Johor, Malaysia. *Natural Hazards and Earth System Sciences*, **14**(12), 3297-3310, doi:https://doi.org/10.5194/nhess-14-3297-2014.
Aliagha, U. G., Mar Iman, A. H., Ali, H. M., Kamaruddin, N., & Ali, K. N., 2013: Discriminant factors of flood insurance demand for flood-hit residential properties: a case for Malaysia - Aliagha - 2015 - Journal of Flood Risk Management - Wiley Online Library. *Journal of Flood Risk Management*, **8**, 39–51, doi:10.1111/jfr3.12065.
Alizadeh-Choobari, O., P. Ghafarian and E. Owlad, 2016: Temporal variations in the frequency and concentration of dust events over Iran based on surface observations. *International Journal of Climatology*, **36**(4), 2050-2062, doi:10.1002/joc.4479.
Allen, S. K. et al., 2018: Translating the concept of climate risk into an assessment framework to inform adaptation planning: Insights from a pilot study of flood risk in Himachal Pradesh, Northern India. *Environmental science & policy*, **87**, 1-10.
Allen, S. K. et al., 2016: Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. *Landslides*, **13**(6), 1479-1491, doi:10.1007/s10346-015-0584-3.
Almaden, C. R. C. et al., 2019a: Meso-Level Analysis on Rice-Farmers' Adaptive Measures for Slow Onset Hazard: The Case of Saltwater Intrusion in the Philippines and Vietnam.
Almaden, C. R. C. et al., 2019b: Determinants of Adaptation for Slow-Onset Hazards: The Case of Rice-Farming Households Affected by Seawater Intrusion in Northern Mindanao, Philippines. *Asian Journal of Agriculture and Development, Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA)*, **16(1)**, 117-132, doi:10.22004/ag.econ.289833.
Alshehri, S. A., Y. Rezgui and H. Li, 2013: Public perception of the risk of disasters in a developing economy: the case of Saudi Arabia. *Natural Hazards*, **65**(3), 1813-1830, doi:10.1007/s11069-012-0445-5.
Altman, J. et al., 2020: Tree growth response to recent warming of two endemic species in Northeast Asia. *Climatic Change*, **162**(3), 1345-1364, doi:10.1007/s10584-020-02718-1.

Alvi, S. and U. Khayyam, 2020: Mitigating and adapting to climate change: attitudinal and behavioural challenges in South Asia. *International Journal of Climate Change Strategies and Management*, **12**(4), 477-493, doi:10.1108/ijccsm-08-2019-0054.
Amjath-Babu, T., P. K. Aggarwal and S. Vermeulen, 2019: Climate action for food security in South Asia? Analyzing the role of agriculture in nationally determined contributions to the Paris agreement. *Climate policy*, **19**(13), 283-298.
Anderson, M. K. G. P. B. C. L., 2019: Delivering development? Evidence on self-help groups as development intermediaries in South Asia and Africa. *Development Policy Review*, **37**(1), 129-151.
Andreeva, M. V., Y. N. Kurochkin, M. V. Syromyatina and K. V. Chistyakov, 2019: Factors of Spatial and Temporal Variability of Siberian Larch Growth in the Mountain Regions of Altai, Tuva, and Mongolia. *Russian Journal of Ecology*, **50**(5), 453-459, doi:10.1134/S1067413619040040.
Anguelovski, I., E. Chu and J. Carmin, 2014: Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South. *Global Environmental Change*, **27**, 156-167, doi:10.1016/j.gloenvcha.2014.05.010.
Anisimov, O., V. Kokorev and Y. Zhiltcova, 2017: Arctic Ecosystems and their Services Under Changing Climate: Predictive-Modeling Assessment. *Geographical Review*, **107**(1), 108-124, doi:10.1111/j.1931-0846.2016.12199.x.
Anthopoulos, L., 2017: Smart utopia VS smart reality: Learning by experience from 10 smart city cases. *Cities*, **63**, 128-148.
Apraku, A., W. Akpan and P. Moyo, 2018: Indigenous knowledge, global ignorance? Insights from an Eastern Cape climate change study. *South African Review of Sociology*, **49**(2), 1-21.
Araos, M. et al., 2016: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science and Policy*, **66**, 375-382, doi:10.1016/j.envsci.2016.06.009.
Archer, D. et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Climate and Development*, **6**(4), 345-356, doi:10.1080/17565529.2014.918868.
Archer, D. and D. Dodman, 2015: Making capacity building critical: Power and justice in building urban climate resilience in Indonesia and Thailand. *Urban Climate*, **14**, 68-78, doi:https://doi.org/10.1016/j.uclim.2015.06.007.
Arfanuzzaman, M., 2018: Economics of transboundary water: an evaluation of a glacier and snowpack-dependent river basin of the Hindu Kush Himalayan region. *Water Policy*, **20**(1), 90-108.
Arias, M. E. et al., 2014: Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. *Ecol Model*, **272**, 252-263.
Arias, P. A. et al., 2021: Technical Summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Arifanti, V. B. et al., 2019: Carbon dynamics and land use carbon footprints in mangrove-converted aquaculture: The case of the Mahakam Delta, Indonesia. *Forest Ecology and Management*, **432**, 17-29, doi:10.1016/j.foreco.2018.08.047.
Arifwidodo, S. D. and O. Chandrasiri, 2020: Urban heat stress and human health in Bangkok, Thailand. *Environmental research*, **185**, 109398.
Arifwidodo, S. D., O. Chandrasiri, R. Abdulharis and T. Kubota, 2019: Exploring the effects of urban heat island: A case study of two cities in Thailand and Indonesia. *APN Science Bulletin*.
Arnall, A., 2019: Resettlement as climate change adaptation: what can be learned from state-led relocation in rural Africa and Asia? *Climate and Development*, **11**(3), 253-263.
Arnell, N. W. et al., 2016: The impacts of climate change across the globe: a multi-sectoral assessment. *Climatic Change*, **134**(3), 457-474.
Arshad, A. et al., 2020: Vulnerability assessment of urban expansion and modelling green spaces to build heat waves risk resiliency in Karachi. *International journal of disaster risk reduction*, **46**, 101468.
Artemov, I. A., 2018: Changes in the Altitudinal Distribution of Alpine Plants in Katunskiy Biosphere Reserve (Central Altai) Revealed on the Basis of Multiyear Monitoring Data. *Contemporary Problems of Ecology*, **11**(1), 1-12, doi:10.1134/S1995425518010018.
Arto, I. et al., 2019: The socioeconomic future of deltas in a changing environment. *Science of the Total Environment*, **648**, 1284-1296.
Arunrat, N. et al., 2017: Farmers' intention and decision to adapt to climate change: A case study in the Yom and Nan basins, Phichit province of Thailand. *Journal of Cleaner Production*, **143**, 672-685, doi:10.1016/j.jclepro.2016.12.058.
Aryal, J. P. et al., 2020a: Climate change mitigation options among farmers in South Asia. *Environment, Development and Sustainability*, **22**(4), 3267-3289, doi:10.1007/s10668-019-00345-0.
Aryal, J. P. et al., 2020b: Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environment, Development and Sustainability*, **22**(6), 5045-5075, doi:10.1007/s10668-019-00414-4.
Asher, M. B., Azad. , 2015: Public Pension Programs in Southeast Asia: An Assessment. . *Asian Economic Policy Review*, doi:10. 10.1111/aepr.12100.

Ashrafzadeh, M. R., A. A. Naghipour, M. Haidarian and I. Khorozyan, 2019a: Modeling the response of an endangered flagship predator to climate change in Iran. *Mammal Res*, **64**(1), 39-51, doi:10.1007/s13364-018-0384-y.
Ashrafzadeh, M. R. et al., 2019b: Effects of climate change on habitat and connectivity for populations of a vulnerable, endemic salamander in Iran. *Global Ecology and Conservation*, **19**, doi:https://doi.org/10.1016/j.gecco.2019.e00637.
Asia, E. a. S. C. f. W., 2017: ESCWA Water Development Report 7 ; Climate Change andDisaster Risk Reduction in the Arab Region, 64 pp.
Aslam Ansari, M., 2018: Understanding farmers perceptions about climate change: a study in a North Indian State. *Advances in Agriculture and Environmental Science: Open Access (AAEOA)*, **1**(2), doi:10.30881/aaeoa.00015.
Aslam, A. Q. et al., 2017: Vulnerability and impact assessment of extreme climatic event: A case study of southern Punjab, Pakistan. *Science of The Total Environment* **580**, 468-481, doi:https://doi.org/10.1016/j.scitotenv.2016.11.155.
Asmiwyati, I. G. A. A. R., M. S. Mahendra, N. H. S. Arifin and T. Ichinose, 2015: Recognizing Indigenous Knowledge on Agricultural Landscape in Bali for Micro Climate and Environment Control. *Procedia Environmental Sciences*, **28**, 623-629, doi:10.1016/j.proenv.2015.07.073.
Assaf, H., 2009: *Infrastructure*. Arab Environment: Impact of Climate Change on Arab Countries, AFED Report, 113–120 pp.
Aswani, S., A. Lemahieu and W. H. H. Sauer, 2018: Global trends of local ecological knowledge and future implications. *PLoS One*, **13**(4), e0195440, doi:10.1371/journal.pone.0195440.
Auffhammer, M. and M. E. Kahn, 2018: Chapter 5 - The farmer's climate change adaptation challenge in least developed countries✶✶We thank the editors and several reviewers for useful comments. We thank Brian Casey and Nolan Jones for valuable research assistance. All errors are ours. In: *Handbook of Environmental Economics* [Dasgupta, P., S. K. Pattanayak and V. K. Smith (eds.)]. Elsevier, pp. 193-229. ISBN 1574-0099.
Ayeb-Karlsson, S., 2020: 'I do not like her going to the shelter': Stories on gendered disaster (im)mobility and wellbeing loss in coastal Bangladesh. *International Journal of Disaster Risk Reduction*, **50**, 101904.
Ayeb-Karlsson, S., D. Kniveton and T. Cannon, 2020: Trapped in the prison of the mind: Notions of climate-induced (im) mobility decision-making and wellbeing from an urban informal settlement in Bangladesh. *Palgrave Communications*, **6**(1), 1-15.
Azad, S. A., 2017: *Yearbook of Fisheries Statistics of Bangladesh (July 2015 - June 2016)*. Available at: https://drive.google.com/file/d/0B6XjGVIRbmt0bHhjcVl2UWNCbmM/view.
Babagaliyeva, Z., A. Kayumov, N. Mahmadullozoda and N. Mustaeva, 2017: *Migration, remittances and climate resilience in Tajikistan*. (CAREC), R. E. C. f. C. A. Available at: https://carececo.org/eng_P2%20WP1%20Migration,%20remittances_FIN.pdf.
Babel, M. S., V. R. Shinde, D. Sharma and N. M. Dang, 2020: Measuring water security: A vital step for climate change adaptation. *Environmental research*, **185**, 109400.
Babken Babajanian, J. H.-Z. a. R. H., 2014: *How do social protection and labour programmes contribute to social inclusion?*, ODI.
Badiani, R., K. K. Jessoe and S. Plant, 2012: Development and the environment: the implications of agricultural electricity subsidies in India. *The Journal of Environment & Development*, **21**(2), 244-262.
Bahinipati, C. S., 2020: Assessing the costs of droughts in rural India: a comparison of economic and non-economic loss and damage. *Current Science*, **118**, 1832-1841, doi:https://doi.org/10.18520/cs/v118/i11/1832-1841.
Bahinipati, C. S. and U. Patnaik, 2020: Does development reduce damage risk from climate extremes? Empirical evidence for floods in India. *Water Policy*, **22**(5), 748–767, doi:https://doi.org/10.2166/wp.2020.059.
Bai, J. et al., 2018: Snowmelt Water Alters the Regime of Runoff in the Arid Region of Northwest China. *Water*, **10**(7), doi:10.3390/w10070902.
Baig, M. B., A. M. Qureshi, G. S. Straquadine and A. Hajiyev, 2019: Realizing Food Security Through Sustainable Agriculture in the Republic of Yemen: Implications for Rural Extension. In: *Climate Change, Food Security and Natural Resource Management : Regional Case Studies from Three Continents* [Behnassi, M., O. Pollmann and H. Gupta (eds.)]. Springer International Publishing, Cham, pp. 19-60. ISBN 978-3-319-97091-2.
Bailey, H. and D. H. Secor, 2016: Coastal evacuations by fish during extreme weather events. *Sci Rep*, **6**, 9, doi:10.1038/srep30280.
Bajpai, R., S. Mishra, S. Dwivedi and D. K. Upreti, 2016: Change in atmospheric deposition during last half century and its impact on lichen community structure in Eastern Himalaya. *Sci Rep*, **6**, doi:10.1038/srep30838.
Bajracharya, A. R., S. R. Bajracharya, A. B. Shrestha and S. B. Maharjan, 2018: Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Science of the Total Environment*, **625**, 837-848.
Bajracharya, S. R. et al., 2014: *Glacier status in Nepal and decadal change from 1980 to 2010 based on Landsat data*. International Centre for Integrated Mountain Development. ISBN 9291153117.
Baker, J. L. and G. U. Gadgil, 2017: *East Asia and Pacific Cities: Expanding Opportunities for the Urban Poor*. ISBN 9781464810930.
Balke, T. and D. A. Friess, 2016: Geomorphic knowledge for mangrove restoration: a pan-tropical categorization. *Earth Surface Processes and Landforms*, **41**(2), 231-239, doi:10.1002/esp.3841.

Banerjee, S., R. Black, A. Mishra and D. Kniveton, 2018: Assessing vulnerability of remittance-recipient and non-recipient households in rural communities affected by extreme weather events: Case studies from south-west China and northeast India. *Popul. Space Place*, **25**(2), e2157, doi:10.1002/psp.2157.
Banerjee, S., A. Hussain, S. Tuladhar and A. Mishra, 2019: Building capacities of women for climate change adaptation: Insights from migrant-sending households in Nepal. *Climatic Change*, **157**(3), 587-609, doi:10.1007/s10584-019-02572-w.
Bank, A. D., 2017a: *A region at risk: The human dimension of climate change in Asia and the Pacific*. ADB, Philppines.
Bank, A. D., 2018a: *Strengthening resilience through social protection programs : guidance note*. Manila. Available at: https://www.adb.org/documents/strengthening-resilience-social-protection-guidance-note.
Bank, W., 2015: The state of social safety nets 2015. The World Bank Washington, DC.
Bank, W., 2017b: *Tracking universal health coverage : 2017 global monitoring report (English)*. World Bank, Washington, D.C. Available at: http://documents.worldbank.org/curated/en/640121513095868125/Tracking-universal-health-coverage-2017-global-monitoring-report.
Bank, W., 2018b: *Philippines: Social Protection Review and Assessment*. Bank, W., Philippines.
Banu, S. et al., 2014: Projecting the impact of climate change on dengue transmission in Dhaka, Bangladesh. *Environ Int*, **63**, 137-142, doi:https://doi.org/10.1016/j.envint.2013.11.002.
Banwell, N., S. Rutherford, B. Mackey and C. Chu, 2018: Towards Improved Linkage of Disaster Risk Reduction and Climate Change Adaptation in Health: A Review. *International Journal of Environmental Research and Public Health*.
Bao, P. N. et al., 2018: *Governing the Water-Energy-Food Nexus Approach for Creating Synergies and Managing Trade-offs*. Institute for Global Environmental Strategies.
Bao, Z. et al., 2019: The impact of climate variability and land use/cover change on the water balance in the Middle Yellow River Basin, China. *Journal of Hydrology*, **577**, 123942.
Baran, E. and C. Myschowoda, 2009: Dams and fisheries in the Mekong Basin. *Aquatic Ecosystem Health & Management*, **12**(3), 227-234.
Barange, M. et al., 2014: Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nature Climate Change*, **4**, 211, doi:10.1038/nclimate2119
https://www.nature.com/articles/nclimate2119#supplementary-information.
Barinova, S., M. Boboev and H. Hisoriev, 2015: Freshwater algal diversity of the South-Tajik Depression in a high-mountainous extreme environment, Tajikistan. *Turkish Journal of Botany*, **39**, 535-546, doi:10.3906/bot-1406-45.
Barkdull, J. and P. G. Harris, 2018: Emerging responses to global climate change: ecosystem-based adaptation. *Global Change, Peace & Security*, **31**(1), 19-37, doi:10.1080/14781158.2018.1475349.
Barnett, C. and S. Parnell, 2016: Ideas, implementation and indicators: epistemologies of the post-2015 urban agenda. *Environment and Urbanization*, **28**(1), 87-98.
Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20**(2), 211-213, doi:10.1016/j.gloenvcha.2009.11.004.
Bateman, I. et al., 2016: Spatially explicit integrated modeling and economic valuation of climate driven land use change and its indirect effects. *J Environ Manage*, **181**, 172-184, doi:10.1016/j.jenvman.2016.06.020.
Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.
Baul, T. K. and M. McDonald, 2015: Integration of Indigenous knowledge in addressing climate change. *Integration of Indigenous knowledge in addressing climate change*, **1**(1), 20-27.
Bazaz, A. et al., 2018: *Summary for Urban Policymakers – What the IPCC Special Report on 1.5C Means for Cities*. Bengaluru.
Bazilian, M. et al., 2011: Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, **39**(12), 7896-7906, doi:10.1016/j.enpol.2011.09.039.
Bechtel, B. et al., 2019: SUHI analysis using Local Climate Zones—A comparison of 50 cities. *Urban Climate*, **28**, doi:10.1016/j.uclim.2019.01.005.
Beermann, J., A. Damodaran, K. Jörgensen and M. A. Schreurs, 2016: Climate action in Indian cities: an emerging new research area. *Journal of Integrative Environmental Sciences*, **13**(1), 55-66, doi:10.1080/1943815x.2015.1130723.
Bell, A. R. et al., 2021: Migration towards Bangladesh coastlines projected to increase with sea-level rise through 2100. *Environmental Research Letters*, **16**(2), 024045, doi:10.1088/1748-9326/abdc5b.
Béné, C. et al., 2014: Social Protection and Climate Change. doi:doi:https://doi.org/10.1787/5jz2qc8wc1s5-en.
Bennett, N. J., P. Dearden, G. Murray and A. Kadfak, 2014: The capacity to adapt?: communities in a changing climate, environment, and economy on the northern Andaman coast of Thailand. *Ecology and Society*, **19**(2), doi:10.5751/es-06315-190205.
Bento, R. et al., 2016: The implications of recurrent disturbances within the world's hottest coral reef. *Mar. Pollut. Bull.*, **105**(2), 466-472, doi:10.1016/j.marpolbul.2015.10.006.
Bernasconi, R., M. Stat, A. Koenders and M. J. Huggett, 2019: Global Networks of Symbiodinium-Bacteria Within the Coral Holobiont. *Microb. Ecol.*, **77**(3), 794-807, doi:10.1007/s00248-018-1255-4.
Berner, L. T., P. S. Beck, A. G. Bunn and S. J. Goetz, 2013: Plant response to climate change along the forest-tundra ecotone in northeastern Siberia. *Glob Chang Biol*, **19**(11), 3449-3462, doi:10.1111/gcb.12304.

Best, J., 2018: Anthropogenic stresses on the world's big rivers. *Nat. Geosci.*, 1.

Bhaduri, A. et al., 2015: Sustainability in the water–energy–food nexus. *Water International*, **40**(5-6), 723-732, doi:10.1080/02508060.2015.1096110.

Bhambri, R., K. Hewitt, P. Kawishwar and B. Pratap, 2017: Surge-type and surge-modified glaciers in the Karakoram. *Sci Rep*, **7**, doi:10.1038/s41598-017-15473-8.

Bhanja, S. N. et al., 2016: Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurements in India. *Journal of hydrology*, **543**, 729-738.

Bhatt, R. K., Mall, T. and Banerjee, 2015: Climate change, climate extremes and disaster risk reduction. *Natural Hazards* **78**, 775–778, doi:10.1007/s11069-015-1874-8.

Bhatta, B. et al., 2019: Evaluation and application of a SWAT model to assess the climate change impact on the hydrology of the Himalayan River Basin. *Catena*, **181**, doi:https://doi.org/10.1016/j.catena.2019.104082.

Bhatta, K. P., J.-A. Grytnes and O. R. Vetaas, 2018: Downhill shift of alpine plant assemblages under contemporary climate and land-use changes. *Ecosphere*, **9**(1), doi:10.1002/ecs2.2084.

Bhowmik, J., H. M. Irfanullah and S. A. Selim, 2021: Empirical evidence from Bangladesh of assessing climate hazard-related loss and damage and state of adaptive capacity to address them. *Climate Risk Management*, **31**, 100273, doi:https://doi.org/10.1016/j.crm.2021.100273.

Bi, X. et al., 2019: The potential suitable area of Galinsoga Parviflora in China in response to climate change. *Journal of Shaanxi Normal University. Natural Science Edition*, **47**(2), 70-75.

Biemans, H. et al., 2019: Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, **2**(7), 594.

Bierkens, M. F. P. and Y. Wada, 2019: Non-renewable groundwater use and groundwater depletion: a review. *Environmental Research Letters*, **14**, doi:https://doi.org/https://doi.org/10.1088/1748-9326/ab1a5f.

Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press %& 5 %! Changing Ocean, Marine Ecosystems, and Dependent Communities %U https://www.ipcc.ch/site/assets/uploads/sites/3/2019/2012/SROCC_FullReport_FINAL.pdf.

Birkmann, J., N. Setiadi and G. Fiedler, 2019: A culture of resilience and preparedness: The 'last mile' case study of tsunami rise in Padang, Indonesia. In: *Cultures and Disasters: Understanding Cultural Framings in Disaster Risk Reduction* [Kruger, F., G. Bankoff, T. Cannon, B. Orlowski and L. F. Schipper (eds.)]. Routledge, Londona nd New York.

Biskaborn, B. K. et al., 2019: Permafrost is warming at a global scale. *Nature Communications*, **10**(1), 264, doi:10.1038/s41467-018-08240-4.

Bizikova, L. et al., 2013: *The water-energy-food security nexus: Towards a practical planning and decision-support framework for landscape investment and risk management*. International Institute for Sustainable Development Winnipeg.

Black, K. P. et al., 2017: *Climate change adaptation guidelines for coastal protection and management in India*. Bank, A. D.

Blanco, D. V., 2015: Disaster Governance in the Philippines: Issues, Lessons Learned, and Future Directions in the Post-Yolanda Super Typhoon Aftermath. *International Journal of Public Administration* **38**(10), 743-756, doi:https://doi.org/10.1080/01900692.2014.979198.

Blasiak, R. et al., 2017: Climate change and marine fisheries: Least developed countries top global index of vulnerability. *PLoS One*, **12**(6), e0179632, doi:10.1371/journal.pone.0179632.

Blok, A. and R. Tschötschel, 2015: World port cities as cosmopolitan risk community: Mapping urban climate policy experiments in Europe and East Asia:. *Environment and Planning C: Politics*, doi:10.1177_0263774X15614673.

Blondin, S., 2019: Environmental migrations in Central Asia: A multifaceted approach to the issue. *Central Asian Survey*, **38**(2), 275-292.

Blunden, J. and D. S. Arndt, 2017: State of the Climate in 2016. *Bulletin of the American Meteorological Society*, **98**(8), Si-S280, doi:10.1175/2017BAMSStateoftheClimate.1.

Boas, I. et al., 2019: Climate migration myths. *Nature Climate Change*, **9**(12), 901-903.

Bobojonov, I. and A. Aw-Hassan, 2014: Impacts of climate change on farm income security in Central Asia: An integrated modeling approach. *Agriculture, Ecosystems & Environment*, **188**, 245-255, doi:10.1016/j.agee.2014.02.033.

Bobojonov, I. et al., 2016: Income and irrigation water use efficiency under climate change: An application of spatial stochastic crop and water allocation model to Western Uzbekistan. *Climate Risk Management*, **13**, 19-30, doi:https://doi.org/10.1016/j.crm.2016.05.004.

Bobrowski, M. et al., 2018: Application of Thermal and Phenological Land Surface Parameters for Improving Ecological Niche Models of Betula utilis in the Himalayan Region. *Remote Sensing*, **10**(6), doi:10.3390/Rs10060814.

Boeckmann, M., 2016: Exploring the health context: A qualitative study of local heat and climate change adaptation in Japan. *Geoforum*, **73**, 1-5, doi:10.1016/j.geoforum.2016.04.006.

Bogard, J. R. et al., 2015: Nutrient composition of important fish species in Bangladesh and potential contribution to recommended nutrient intakes. *Journal of Food Composition and Analysis*, **42**, 120-133, doi:10.1016/j.jfca.2015.03.002.
Bolch, T., 2017: HYDROLOGY: Asian glaciers are a reliable water source. *Nature*, **545**(7653), 161-162, doi:10.1038/545161a.
Bolch, T., 2019: Past and future glacier changes in the Indus River Basin. *Indus River Basin*, 85-97.
Bonney, R., T. B. Phillips, H. L. Ballard and J. W. Enck, 2016: Can citizen science enhance public understanding of science? *Public Understanding of Science*, **25**(1), 2-16.
Borodavko, P. S. et al. (eds.), Climate change impact on high-altitude geomorphological systems. IOP Conference Series: Earth and Environmental Science, IOP Publishing, 012004 pp. ISBN 1755-1315.
Borras, S. M. F., Jennifer C, 2018: The challenge of locating land-based climate change mitigation and adaptation politics within a social justice perspective: towards an idea of agrarian climate justice. *Third World Quarterly*, doi:10.1080/01436597.2018.1460592.
Bourne, D. G., K. M. Morrow and N. S. Webster, 2016: Insights into the Coral Microbiome: Underpinning the Health and Resilience of Reef Ecosystems. In: *Annual Review of Microbiology, Vol 70* [Gottesman, S. (ed.)]. Annual Reviews, Palo Alto, pp. 317-+. ISBN 978-0-8243-1170-4.
BP, Statistical Review of World Energy. Available at: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html.
BP, 2019: BP Energy Outlook: 2019 edition.
Brammer, H., 2014: Bangladesh's dynamic coastal regions and sea-level rise. *Climate Risk Management*, **1**, 51-62, doi:https://doi.org/10.1016/j.crm.2013.10.001.
Brazhnik, K., C. Hanley and H. H. Shugart, 2017: Simulating changes in fires and ecology of the 21st century Eurasian boreal forests of Siberia. *Forests*, **8**(2), doi:10.3390/f8020049.
Brazhnik, K. and H. H. Shugart, 2015: 3D simulation of boreal forests: structure and dynamics in complex terrain and in a changing climate. *Environmental Research Letters*, **10**(10), doi:10.1088/1748-9326/10/10/105006.
Brink, E. et al., 2016: Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, **36**, 111-123, doi:10.1016/j.gloenvcha.2015.11.003.
Briones, R. and J. Felipe, 2013: *Agriculture and structural transformation in developing asia: Review and utlook*. Asian Development Bank, Manduluyong City. Available at: https://www.adb.org/sites/default/files/publication/30380/ewp-363.pdf.
Brito-Morales, I. et al., 2018: Climate Velocity Can Inform Conservation in a Warming World. *Trends Ecol Evol*, **33**(6), 441-457, doi:10.1016/j.tree.2018.03.009.
Bruno, J. F. and A. Valdivia, 2016: Coral reef degradation is not correlated with local human population density. *Sci Rep*, **6**, 8, doi:10.1038/srep29778.
Buchanan, J. R. et al., 2019: Regional extinction risks for marine bony fishes occurring in the Persian/Arabian Gulf. *Biol. Conserv.*, **230**, 10-19, doi:10.1016/j.biocon.2018.11.027.
Buchori, I. et al., 2018: Adaptation to coastal flooding and inundation: Mitigations and migration pattern in Semarang City, Indonesia. *Ocean and Coastal Management* **163**, 445-455, doi:https://doi.org/10.1016/j.ocecoaman.2018.07.017.
Bulkeley, H., G. A. S. Edwards and S. Fuller, 2014: Contesting climate justice in the city: Examining politics and practice in urban climate change experiments. *Global Environmental Change*, **25**, 31-40, doi:10.1016/j.gloenvcha.2014.01.009.
Bunting, P. et al., 2018: The global mangrove watch—a new 2010 global baseline of mangrove extent. *Remote Sensing*, **10**(10), 1669.
Burch, S. L. and S. E. Harris, 2014: A Massive Open Online Course on climate change: the social construction of a global problem using new tools for connectedness. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(5), 577-585, doi:10.1002/wcc.300.
Burke, L., K. Reytar, M. Spalding and A. Perry, 2011: Reefs at risk revisited. World Resources Institute.
Burke, M. et al., 2016: CLIMATE ECONOMICS. Opportunities for advances in climate change economics. *Science*, **352**(6283), 292-293, doi:10.1126/science.aad9634.
Burnham, M. and Z. Ma, 2017: Climate change adaptation: factors influencing Chinese smallholder farmers' perceived self-efficacy and adaptation intent. *Regional Environmental Change*, **17**(1), 171-186, doi:10.1007/s10113-016-0975-6.
Burt, J. A. et al., 2019: Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. *Coral Reefs*, **38**(4), 567-589, doi:10.1007/s00338-019-01767-y.
Burt, J. V. L., Hanneke & Feary, David., 2014: *Persian Gulf Reefs: An Important Asset for Climate Science in Urgent Need of Protection.* Ocean Challenge., vol. 20.
Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, **13**(5), 055012, doi:10.1088/1748-9326/aabf45.
Byers, E. A., J. W. Hall and J. M. Amezaga, 2014: Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, **25**, 16-30, doi:10.1016/j.gloenvcha.2014.01.005.

Byrne, J. A., A. Y. Lo and Y. Jianjun, 2015: Residents' understanding of the role of green infrastructure for climate change adaptation in Hangzhou, China. *Landscape and Urban Planning*, **138**, 132-143, doi:https://doi.org/10.1016/j.landurbplan.2015.02.013.
Cadiz, N. R., 2018: UP NOAH in Building Resilient Philippines; Multi-hazard and Risk Mapping for the Future. *Procedia Engineering*, **212**, 1018-1025, doi:https://doi.org/10.1016/j.proeng.2018.01.131.
Cai, Y., J. S. Bandara and D. Newth, 2016: A framework for integrated assessment of food production economics in South Asia under climate change. *Environmental Modelling & Software*, **75**, 459-497, doi:10.1016/j.envsoft.2015.10.024.
Cameron, L., Social protection programs for women in developing countries, IZA World of Labor.
Canadell, J. G. et al., 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Canonge, J., Social protection and climate change: Greener economies and just societies, ILO. Available at: social-protection.org.
Cao, A. et al., 2021: Future of Asian Deltaic Megacities under sea level rise and land subsidence: current adaptation pathways for Tokyo, Jakarta, Manila, and Ho Chi Minh City. *Current Opinion in Environmental Sustainability*, **50**, 87-97.
Cao, H., F. Amiraslani, J. Liu and N. Zhou, 2015: Identification of dust storm source areas in West Asia using multiple environmental datasets. *Science of the Total Environment*, **502**, 224-235.
Cao, R. W. et al., 2018: Seawater Acidification Reduced the Resistance of Crassostrea gigas to Vibrio splendidus Challenge: An Energy Metabolism Perspective. *Front. Physiol.*, **9**, 14, doi:10.3389/fphys.2018.00880.
Caprotti, F., F. Springer and N. Harmer, 2015: 'Eco' For Whom? Envisioning Eco-urbanism in the Sino-Singapore Tianjin Eco-city, China. *International Journal of Urban and Regional Research*, doi:10.1111/1468-2427.12233.
Caravani, A., 2016: Does adaptation finance invest in disaster risk reduction?, 21.
Carleton, T. A., 2017: Crop-damaging temperatures increase suicide rates in India. *Proc Natl Acad Sci USA*, **114**(33), 8746-8751, doi:10.1073/pnas.1701354114.
Carleton, T. A. and S. M. Hsiang, 2016: Social and economic impacts of climate. *Science*, **353**(6304), aad9837.
Carleton, T. A. et al., 2020: *Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits*. National Bureau of Economic Research.
Carley, K. M. et al., 2016: Crowd sourcing disaster management: The complex nature of Twitter usage in Padang Indonesia. *Safety science*, **90**, 48-61.
Carlton, E. J. et al., 2016: A systematic review and meta-analysis of ambient temperature and diarrhoeal diseases. *International journal of epidemiology*, **45**(1), 117-130, doi:10.1093/ije/dyv296.
Carrão, H., G. Naumann and P. Barbosa, 2016: Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change*, **39**, 108-124, doi:10.1016/j.gloenvcha.2016.04.012.
Castillo, J. A. A., A. A. Apan, T. N. Maraseni and S. G. Salmo, 2018: Tree biomass quantity, carbon stock and canopy correlates in mangrove forest and land uses that replaced mangroves in Honda Bay, Philippines. *Reg. Stud. Mar. Sci.*, **24**, 174-183, doi:10.1016/j.rsma.2018.08.006.
Cazzolla Gatti, R. et al., 2019: Accelerating upward treeline shift in the Altai Mountains under last-century climate change. *Sci Rep*, **9**(1), 7678, doi:10.1038/s41598-019-44188-1.
Cha, E. J. et al., 2020: Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region – Part II: Future projections. *Tropical Cyclone Research and Review*, **9**(2), 75-86, doi:https://doi.org/10.1016/j.tcrr.2020.04.005.
Chacko, N., 2019: Differential chlorophyll blooms induced by tropical cyclones and their relation to cyclone characteristics and ocean pre-conditions in the Indian Ocean. *J. Earth Syst. Sci.*, **128**(7), 11, doi:10.1007/s12040-019-1207-5.
Chakraborty, T., R. Kar, P. Ghosh and S. Basu, 2010: Kosi megafan: Historical records, geomorphology and the recent avulsion of the Kosi River. *Quaternary International*, **227**(2), 143-160.
Chalise, S. and A. Naranpanawa, 2016: Climate change adaptation in agriculture: A computable general equilibrium analysis of land-use change in Nepal. *Land Use Policy*, **59**, 241-250, doi:10.1016/j.landusepol.2016.09.007.
Chan, E. Y. Y. et al., 2018: Association between Ambient Temperatures and Mental Disorder Hospitalizations in a Subtropical City: A Time-Series Study of Hong Kong Special Administrative Region. *Int J Environ Res Public Health*, **15**(4), doi:10.3390/ijerph15040754.
Chan, N. W., 2014: Impacts of Disasters and Disaster Risk Management in Malaysia: The Case of Floods. *Resilience and Recovery in Asian Disasters*, 239-265, doi:https://link.springer.com/chapter/10.1007/978-4-431-55022-8_12.
Chandler, M. et al., 2017: Contribution of citizen science towards international biodiversity monitoring. *Biol. Conserv.*, **213**, 280-294, doi:10.1016/j.biocon.2016.09.004.
Chandra, A. et al., 2017: A study of climate-smart farming practices and climate-resiliency field schools in Mindanao, the Philippines. *World Development*, **98**, 214-230.

Chandra, A. and K. E. McNamara, 2018: Chapter 13 - Climate-Smart Agriculture in Southeast Asia: Lessons from Community-Based Adaptation Programs in the Philippines and Timor-Leste. In: *Resilience* [Zommers, Z. and K. Alverson (eds.)]. Elsevier, pp. 165-179. ISBN 978-0-12-811891-7.
Chang, Y. et al., 2016: Quantifying the Water-Energy-Food Nexus: Current Status and Trends. *Energies*, **9**(2), doi:10.3390/en9020065.
Chapman, S. et al., 2017: The impact of urbanization and climate change on urban temperatures: a systematic review. *Landscape Ecology*, **32**(10), 1921-1935.
Chartres, C., 2014: Is water scarcity a constraint to feeding Asia's growing population? *International Journal of Water Resources Development*, **30**(1), 28-36, doi:10.1080/07900627.2013.846713.
Chaudhuri, N. R., 2020: Social movements and grassroots discourse of climate justice in the context of droughts in semi-arid regions: A case study in India. *OÑATI SOCIO-LEGAL SERIES FORTHCOMING: CLIMATE JUSTICE IN THE ANTHROPOCENE*, doi:https://doi.org/10.35295/osls.iisl/0000-0000-0000-1157.
Chen, D. and T. V. Loboda, 2018: Surface forcing of non-stand-replacing fires in Siberian larch forests. *Environmental Research Letters*, **13**(4), doi:10.1088/1748-9326/aab443.
Chen, D. et al., 2018a: Strong cooling induced by stand-replacing fires through albedo in Siberian larch forests. *Sci Rep*, **8**, doi:10.1038/s41598-018-23253-1.
Chen, G. et al., 2018b: Top-meter soil organic carbon stocks and sources in restored mangrove forests of different ages. *Forest Ecology and Management*, **422**, 87-94, doi:10.1016/j.foreco.2018.03.044.
Chen, G. et al., 2020a: Global projections of future urban land expansion under shared socioeconomic pathways. *Nat Commun*, **11**(1), 537, doi:10.1038/s41467-020-14386-x.
Chen, H., Y. Zhang, Y. Peng and R. T. Corlett, 2018c: Latitudinal effects on phenology near the northern limit of figs in China. *Sci Rep*, **8**, doi:10.1038/s41598-018-22548-7.
Chen, J., S. Yin, H. Gebhardt and X. Yang, 2018d: Farmers' livelihood adaptation to environmental change in an arid region: A case study of the Minqin Oasis, northwestern China. *Ecol Indic*, **93**, 411-423, doi:https://doi.org/10.1016/j.ecolind.2018.05.017.
Chen, K. et al., 2015a: Influence of heat wave definitions to the added effect of heat waves on daily mortality in Nanjing, China. *Sci Total Environ*, **506-507**, 18-25, doi:10.1016/j.scitotenv.2014.10.092.
Chen, K. et al., 2017a: Impact of climate change on heat-related mortality in Jiangsu Province, China. *Environmental Pollution*, **224**, 317-325, doi:https://doi.org/10.1016/j.envpol.2017.02.011.
Chen, K. et al., 2016a: Urbanization Level and Vulnerability to Heat-Related Mortality in Jiangsu Province, China. *Environmental health perspectives*, **124**(12), 1863-1869, doi:10.1289/ehp204.
Chen, L.-L., C.-H. Tseng and Y.-H. Shih, 2017b: Climate-related economic losses in Taiwan. *International Journal of Global Warming*, **11**(4), doi:https://doi.org/10.1504/IJGW.2017.083670.
Chen, Q. et al., 2020b: Unpacking the black box: How to promote citizen engagement through government social media during the COVID-19 crisis. *Computers in Human Behavior*, 106380.
Chen, R. et al., 2018e: Association between ambient temperature and mortality risk and burden: time series study in 272 main Chinese cities. *BMJ (Clinical research ed.)*, **363**, k4306, doi:10.1136/bmj.k4306.
Chen, S., X. Chen and J. Xu, 2016b: Impacts of climate change on agriculture: Evidence from China. *Journal of Environmental Economics and Management*, **76**, 105-124, doi:10.1016/j.jeem.2015.01.005.
Chen, X. et al., 2017c: Improved modeling of snow and glacier melting by a progressive two-stage calibration strategy with GRACE and multisource data: How snow and glacier meltwater contributes to the runoff of the Upper Brahmaputra River basin? *Water Resources Research*, **53**(3), 2431-2466, doi:10.1002/2016wr019656.
Chen, Y. and Y. Li, 2017: An Inter-comparison of Three Heat Wave Types in China during 1961–2010: Observed Basic Features and Linear Trends. *Sci Rep*, **7**(1), 45619, doi:10.1038/srep45619.
Chen, Y., Z. Li, G. Fang and W. Li, 2018f: Large Hydrological Processes Changes in the Transboundary Rivers of Central Asia. *Journal of Geophysical Research: Atmospheres*, doi:10.1029/2017JD028184.
Chen, Y. et al., 2015b: Urban flood risk warning under rapid urbanization. *Environmental Research*, **139**, 3-10.
Chhogyel, N. and L. Kumar, 2018: Climate change and potential impacts on agriculture in Bhutan: a discussion of pertinent issues. *Agriculture & Food Security*, **7**(79), doi:https://doi.org/10.1186/s40066-018-0229-6.
Chi, C.-F., S.-Y. Lu and J.-D. Lee, 2020: Ostensibly Effective Adaptive Measures Could Potentially Be Maladaptations: A Case Study of the Jiadung Coastal Area, Pingtung County, Taiwan. *Coastal Management*, **48**(6), 643-676.
Chiba, Y., S. V. R. K. Prabhakar and M. A. Islam, 2019: Addressing non-economic loss and damage associated with climatic events: Cases of Japan and Bangladesh. *APN Science Bulletin*.
Chiba, Y., R. Shaw and S. Prabhakar, 2017: Climate change-related non-economic loss and damage in Bangladesh and Japan. *International Journal of Climate Change Strategies and Management*, **9**(2), 166-183, doi:https://doi.org/10.1108/IJCCSM-05-2016-0065.
Cho, H., 2020: Climate Change Risk Assessment for Kurunegala, Sri Lanka: Water and Heat Waves. *Climate*, **8**, 140, doi: https://doi.org/10.3390/cli8120140.
Choi, Y.-Y., M.-S. Suh and K.-H. Park, 2014: Assessment of Surface Urban Heat Islands over Three Megacities in East Asia Using Land Surface Temperature Data Retrieved from COMS. *Remote Sensing*, **6**(6), doi:10.3390/rs6065852.

Choi, Y. et al., 2021: Forest management can mitigate negative impacts of climate and land-use change on plant biodiversity: Insights from the Republic of Korea. *J Environ Manage*, **288**, 112400, doi:10.1016/j.jenvman.2021.112400.
Choi, Y. et al., 2019: Novel Index for bioclimatic zone-based biodiversity conservation strategies under climate change in Northeast Asia. *Environmental Research Letters*, **14**(12), doi:https://doi.org/10.1088/1748-9326/ab5237.
Choi, Y. et al., 2016: Effects of weather factors on dengue fever incidence and implications for interventions in Cambodia. *BMC public health*, **16**, 241, doi:10.1186/s12889-016-2923-2.
Chow, J., 2018: Mangrove management for climate change adaptation and sustainable development in coastal zones. *Journal of Sustainable Forestry*, **37**(2), 139-156, doi:10.1080/10549811.2017.1339615.
Chu, E., I. Anguelovski and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**, 378-387, doi:10.1016/j.cities.2016.10.016.
Chua, P. L. et al., 2021: Global projections of temperature-attributable mortality due to enteric infections: a modelling study. *The Lancet Planetary Health*, **5**(7), e436-e445.
Chuah, C. J., B. H. Ho and W. T. L. Chow, 2018: Trans-boundary variations of urban drought vulnerability and its impact on water resource management in Singapore and Johor, Malaysia. *Environmental Research Letters*, **13**(7), 074011.
Chung, I. K., C. F. A. Sondak and J. Beardall, 2017a: The future of seaweed aquaculture in a rapidly changing world. *Eur. J. Phycol.*, **52**(4), 495-505, doi:10.1080/09670262.2017.1359678.
Chung, S. E. et al., 2017b: Current and projected burden of disease from high ambient temperature in Korea. *Epidemiology*, 98-105, doi:https://doi.org/10.1097/EDE.0000000000000731.
Chung, Y. et al., 2017c: Temporal Changes in Mortality Related to Extreme Temperatures for 15 Cities in Northeast Asia: Adaptation to Heat and Maladaptation to Cold. *American journal of epidemiology*, **185**(10), 907-913, doi:10.1093/aje/kww199.
Chung, Y. et al., 2018: Changing Susceptibility to Non-Optimum Temperatures in Japan, 1972-2012: The Role of Climate, Demographic, and Socioeconomic Factors. *Environmental health perspectives*, **126**(5), 057002, doi:10.1289/ehp2546.
CIA, The World Factbook 2017, Central Intelligence Agency. Available at: https://www.cia.gov/library/publications/download/download-2017/index.html.
Cinco, T. A. et al., 2016: Observed trends and impacts of tropical cyclones in the Philippines. *International Journal of Climatology*, **36**(14), 4638-4650, doi:10.1002/joc.4659.
Cinner, J. E. et al., 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, **8**(2), 117-123, doi:10.1038/s41558-017-0065-x.
Clayton, S. et al., 2015: Psychological research and global climate change. *Nature Climate Change*, **5**(7), 640-646, doi:10.1038/nclimate2622.
Clemens, M. et al., 2016: Social learning for adaptation to climate change in developing countries: insights from Vietnam. *Journal of Water and Climate Change*, **7**(2), 365-378.
Clement, F., 2018: Climate Change Governance and Adaptation. In: *Climate Change Governance and Adaptation*. CRC Press, pp. 29-50.
Cohen, J. M., M. J. Lajeunesse and J. R. Rohr, 2018: A global synthesis of animal phenological responses to climate change. *Nature Climate Change*, **8**(3), 224-228, doi:10.1038/s41558-018-0067-3.
Coirolo, C., S. Commins, I. Haque and G. Pierce, 2013: Climate change and social protection in Bangladesh: are existing programmes able to address the impacts of climate change? *Development Policy Review*, **31**, o74-o90.
Coles, S. L., E. Looker and J. A. Burt, 2015: Twenty-year changes in coral near Muscat, Oman estimated from manta board tow observations. *Mar. Environ. Res.*, **103**, 66-73, doi:10.1016/j.marenvres.2014.11.006.
Coles, S. L. and B. M. Riegl, 2013: Thermal tolerances of reef corals in the Gulf: A review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. *Mar. Pollut. Bull.*, **72**(2), 323-332, doi:10.1016/j.marpolbul.2012.09.006.
Commission, B. P., 2018: *Bangladesh Delta Plan 2100- Abridged Version*
Comte, A. and L. H. Pendleton, 2018: Management strategies for coral reefs and people under global environmental change: 25 years of scientific research. *J. Environ. Manage.*, **209**, 462-474, doi:10.1016/j.jenvman.2017.12.051.
Connell, J., 2015: Statelessness and environmental displacement. *Forced Migration Review*, 49.
Cook, K. L. et al., 2018: Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science*, **362**(6410), 53-57.
Cook, M. and E. Chu, 2019: Between Policies, Programs, and Projects: How Local Actors Steer Domestic Urban Climate Adaptation Finance in India | SpringerLink. doi:10.1007/978-3-319-65003-6_13.
Corner, A. et al., 2015: How do young people engage with climate change? The role of knowledge, values, message framing, and trusted communicators. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(5), 523-534, doi:10.1002/wcc.353.
Cousins, S., 2014: Can't Afford to Wait: Why Disaster Risk Reduction and Climate Change Adaptation plans in Asia are still failing millions of people. Oxfam GB, Oxford, UK.
Craft, B. and S. Fisher, 2016: *Measuring effective and adequate adaptation*. JSTOR.
CRED/UNISDR, 2019: 2018 Review of Disaster Events: Centre for Research on the Epidemiology of Disasters.

Crost, B., C. Duquennois, J. H. Felter and D. I. Rees, 2018: Climate change, agricultural production and civil conflict: Evidence from the Philippines. *Journal of Environmental Economics and Management*, **88**, 379-395, doi:10.1016/j.jeem.2018.01.005.
Cruz, R. V. O. et al., 2017: *2017 Philippine Climate Change Assessment: Impacts, Vulnerabilities and Adaptation*. The Oscar M. Lopez Center for Climate Change Adaptation and Disaster Risk Management Foundation, Inc. and Climate Change Commission, Pasig City, Metro Manila. Available at: https://climate.gov.ph/files/PhilCCA-WG2.pdf.
Cuevas, S. C., 2018: Institutional dimensions of climate change adaptation: insights from the Philippines. **18**(4), 499-511, doi:https://doi.org/10.1080/14693062.2017.1314245.
Cuevas, S. C., A. Peterson, C. Robinson and T. H. Morrison, 2016: Institutional capacity for long-term climate change adaptation: evidence from land use planning in Albay, Philippines. *Regional Environmental Change*, **16**(7), 2045-2058, doi:10.1007/s10113-015-0909-8.
Cullen, A. C. and C. L. Anderson, 2016: Perception of Climate Risk among Rural Farmers in Vietnam: Consistency within Households and with the Empirical Record. *Risk Analysis*, doi:10.1111/risa.12631.
Cullet, P., 2016: Governing Water to Foster Equity and Conservation: Need for New Legal Instruments. *Economic & Political Weekly*, **51**(53).
Cundill, G. et al., 2021: Toward a climate mobilities research agenda: intersectionality, immobility, and policy responses. *Global Environmental Change*, **69**, doi:https://doi.org/10.1016/j.gloenvcha.2021.102315.
Cutter, S. L. et al., 2015: Pool knowledge to stem losses from disasters. *Nature*, **522**, 277-279.
D'Aloia, C. C. et al., 2019: Coupled Networks of Permanent Protected Areas and Dynamic Conservation Areas for Biodiversity Conservation Under Climate Change. *Frontiers in Ecology and Evolution*, **7**, doi:10.3389/Fevo.2019.00027.
d'Amour, C. B. et al., 2017: Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences*, **114**(34), 8939-8944.
d'Amour, C. B. et al., 2016: Teleconnected food supply shocks. *Environ. Res. Lett*, **11**(035007), 10.1088.
Dahal, N. M. et al., 2021: Spatiotemporal analysis of drought variability based on the standardized precipitation evapotranspiration index in the Koshi River Basin, Nepal. *Journal of Arid Land*, 1-22.
Dai, G. H. et al., 2018: The potential impact of invasive woody oil plants on protected areas in China under future climate conditions. *Sci Rep*, **8**, doi:10.1038/S41598-018-19477-W.
Dalton, P. S., S. Ghosal and A. Mani, 2016: Poverty and Aspirations Failure. *The Economic Journal*, **126**(590), 165-188, doi:10.1111/ecoj.12210.
Dang, T. N. et al., 2016: Characterizing the relationship between temperature and mortality in tropical and subtropical cities: a distributed lag non-linear model analysis in Hue, Viet Nam, 2009-2013. *Global health action*, **9**, 28738, doi:10.3402/gha.v9.28738.
Das, S., N. S. Kar and S. Bandyopadhyay, 2015: Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images. *Natural Hazards*, **77**(2), 769-786.
Dasgupta, P., D. Bhattacharjee and A. Kumari, 2013a: Socio-economic analysis of climate change impacts on foodgrain production in Indian states. *Environmental Development*, **8**, 5-21, doi:https://doi.org/10.1016/j.envdev.2013.06.002.
DasGupta, R., S. Hashimoto, T. Okuro and M. Basu, 2018: Scenario-based land change modelling in the Indian Sundarban delta: an exploratory analysis of plausible alternative regional futures. *Sustainability Science*, **14**(1), 221-240, doi:10.1007/s11625-018-0642-6.
Dasgupta, S. et al., 2015: River salinity and climate change: evidence from coastal Bangladesh. In: *World Scientific Reference on Asia and the World Economy*. World Scientific, pp. 205-242.
Dasgupta, S. et al., 2013b: A megacity in a changing climate: the case of Kolkata. *Climatic Change*, **116**(3), 747-766.
Dasgupta, S., M. M. Hossain, M. Huq and D. Wheeler, 2014a: *Facing the Hungry Tide: Climate Change, Livelihood Threats, and Household Responses in Coastal Bangladesh*. Policy Research Working Papers, The World Bank, 30 pp.
Dasgupta, S. et al., 2014b: Cyclones in a changing climate: the case of Bangladesh. *Climate and Development*, **6**(2), 96-110, doi:10.1080/17565529.2013.868335.
Dasgupta, S. et al., 2017a: The impact of aquatic salinization on fish babitats and poor communities in a changing climate: Evidence from Southwest coastal Bangladesh. *Ecological Economics*, **139**, 128-139, doi:https://doi.org/10.1016/j.ecolecon.2017.04.009.
Dasgupta, S. et al., 2014c: *River Salinity and Climate Change : Evidence from Coastal Bangladesh.* Policy Research Working Paper No. 6817., World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/17735
Dasgupta, S., Kamal, F.A., Khan, Z.H., Choudhury, S., Nishat, A. , 2015: River Salinity and Climate Change: Evidence from Coastal Bangladesh. In: *Asia and the World Economy - Actions on Climate Change by Asian Countries* [Pan, J. W. a. J. (ed.)]. World Scientific Press, pp. 205-242.
Dasgupta, S., I. Sobhan and D. Wheeler, 2017b: The impact of climate change and aquatic salinization on mangrove species in the Bangladesh Sundarbans. *Ambio*, **46**(6), 680-694, doi:10.1007/s13280-017-0911-0.
Dasgupta, S. et al., 2020. : Coping with Climate Change in the Sundarbans : Lessons from Multidisciplinary Studies . International Development in Focus;. World Bank. , Washington, DC:.

Dastagir, M. R., 2015: Modeling recent climate change induced extreme events in Bangladesh: A review. *Weather and Climate Extremes*, **7**, 49-60, doi:10.1016/j.wace.2014.10.003.
Dastorani, M. and M. Jafari, 2019: Analysis of the Trend of Dust Changes in Ardestan Region, Iran. *Desert Ecosystem Engineering Journal*, **2**(1), 45-54, doi:10.22052/jdee.2019.173755.1049.
Dau, Q. V., K. Kuntiyawichai and V. Plermkamon, 2017: Quantification of flood damage under potential climate change impacts in Central Vietnam. *Irrigation and Drainage*, **66**(5), 842-853, doi:https://doi.org/10.1002/IRD.2160.
Davis, K. F., A. Bhattachan, P. D'Odorico and S. Suweis, 2018: A universal model for predicting human migration under climate change: examining future sea level rise in Bangladesh. *Environmental Research Letters*, doi:doi:10.1088/1748-9326/aac4d4.
de Coninck, H. et al., 2018: Strengthening and implementing the global response. In: *Global Warming of 1.5 C an IPCC special report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.
De Leeuw, J. et al., 2014: The potential and uptake of remote sensing in insurance: A review. *Remote Sensing*, **6**(11), 10888-10912.
de Leon, E. G. and J. Pittock, 2017: Integrating climate change adaptation and climate-related disaster risk-reduction policy in developing countries: A case study in the Philippines. *Climate and Development*, **9**(5), 471-478, doi:10.1080/17565529.2016.1174659.
De Souza, K. et al., 2015: Vulnerability to climate change in three hot spots in Africa and Asia: key issues for policy-relevant adaptation and resilience-building research. *Regional Environmental Change*, **15**(5), 747-753, doi:10.1007/s10113-015-0755-8.
Dehghani, M. et al., 2010: Recreation Value of Hara Biosphere Reserve using Willingness-to-pay method. *Int J Environ Res*, **4**(2), 271-280.
dela Cruz, D. W. and P. L. Harrison, 2020: Optimising conditions for in vitro fertilization success of Acropora tenuis, A. millepora and Favites colemani corals in northwestern Philippines. *J. Exp. Mar. Biol. Ecol.*, **524**, 8, doi:10.1016/j.jembe.2019.151286.
Dell, M., B. F. Jones and B. A. Olken, 2014: What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature*, **52**(3), 740-798.
Demin, A., 2014: Water resources and food program. *Water Resources*, **41**(3), 232-241.
Demuzere, M. and e. al., 2014: Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *J. Environ. Manage.*
Deng, X. and C. Zhao, 2015: Identification of Water Scarcity and Providing Solutions for Adapting to Climate Changes in the Heihe River Basin of China. *Advances in Meteorology*, **13**.
Deng, Y., M. Wang and R. Yousefpour, 2017: How do people's perceptions and climatic disaster experiences influence their daily behaviors regarding adaptation to climate change? — A case study among young generations. *Science of the Total Environment*, **581-582**, 840-847, doi:10.1016/j.scitotenv.2017.01.022.
Deng, Z. et al., 2015: Impacts of tropical cyclones and accompanying precipitation on infectious diarrhea in cyclone landing areas of Zhejiang Province, China. *Int J Environ Res Public Health*, **12**(2), 1054-1068, doi:10.3390/ijerph120201054.
Department of Agriculture, 2019: *Operational Guidelines: Pradhan Mantri Fasal Bima Yojana*. Department of Agriculture, Cooperation and Farmers Welfare. Ministry of Agriculture and Farmers Welfare, New Delhi, India.
Department of Fisheries (Thailand), 2015: *Marine Fisheries Management Plan of Thailand*. Department of Fisheries, Ministry of Agriculture and Cooperatives (Thailand), Bangkok. Available at: http://extwprlegs1.fao.org/docs/pdf/tha165156.pdf.
Depietri, Y., 2020: The Social-Ecological Dimension of Vulnerability and Risk to Natural Hazards. *Sustainability Science*, **15**, 587-604.
Derocher, A. E. et al., 2013: Rapid ecosystem change and polar bear conservation. *Conservation Letters*, **6**(5), 368-375, doi:10.1111/conl.12009.
Deshpande, T., K. Michael and K. Bhaskara, 2018: Barriers and enablers of local adaptive measures: a case study of Bengaluru's informal settlement dwellers. *Local Environment*, **24**(3), 167-179, doi:10.1080/13549839.2018.1555578.
Devkota, S. et al., 2019: Climate change-induced range shift of the endemic epiphytic lichen *Lobaria pindarensis* in the Hindu Kush Himalayan region. *Lichenologist*, **51**(2), 157-173, doi:10.1017/S002428291900001x.
Dhar, T. K. and L. Khirfan, 2016: Climate change adaptation in the urban planning and design research: missing links and research agenda. *https://doi.org/10.1080/09640568.2016.1178107*, doi:10.1080/09640568.2016.1178107.
Dhiman, R. C. and S. Sarkar, 2017: El Nino Southern Oscillation as an early warning tool for malaria outbreaks in India. *Malaria journal*, **16**(1), 122, doi:10.1186/s12936-017-1779-y.
Di, L. et al., 2017: RF-CLASS: A remote-sensing-based flood crop loss assessment cyber-service system for supporting crop statistics and insurance decision-making. *Journal of integrative agriculture*, **16**(2), 408-423.
Díaz, S. et al., 2020: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

Didovets, I. et al., 2021: Central Asian rivers under climate change: Impacts assessment in eight representative catchments. *Journal of Hydrology: Regional Studies*, **34**, 100779, doi:https://doi.org/10.1016/j.ejrh.2021.100779.
Dilshad, T. et al., 2019: Growing social vulnerability in the river basins: Evidence from the Hindu Kush Himalaya (HKH) Region. *Environmental Development* **31**, 19–33, doi:https://doi.org/10.1016/j.envdev.2018.12.004.
Dineshbabu, A. P. et al., 2020: Assessment of stock vulnerability of Indian marine fishes to past changes in climate and options for adaptation. *Climate Research*, **79**, 175-192, doi:10.3354/cr01586.
Ding, M. et al., 2018: Surge-type glaciers in Karakoram Mountain and possible catastrophes alongside a portion of the Karakoram Highway. *Natural Hazards*, **90**(2), 1017-1020, doi:10.1007/s11069-017-3063-4.
Ding, Y. et al., 2019: Global warming weakening the inherent stability of glaciers and permafrost. *Science Bulletin*, **64**(4), 245-253, doi:10.1016/j.scib.2018.12.028.
Dissanayake, S., J. Asafu-Adjaye and R. Mahadeva, 2017: Addressing climate change cause and effect on land cover and land use in South Asia. *Land Use Policy*, **67**, 352-366, doi:https://doi.org/10.1016/j.landusepol.2017.06.003.
Dittrich, R., A. Wreford and D. Moran, 2016: A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics*, **122**, 79-89.
Djalante, R. and S. Lassa, 2019: Governing Complexities and Its Implication on the SFDRR Priority 2 on Governance.
Doan, N. X. et al., 2018: Temperature-and sex-specific grazing rate of a tropical copepod Pseudodiaptomus annandalei to food availability: Implications for live feed in aquaculture. *Aquaculture Research*, **49**(12), 3864-3873, doi:10.1111/are.13854.
Doan, N. X. et al., 2019: Extreme temperature impairs growth and productivity in a common tropical marine copepod. *Sci Rep*, **9**, 9, doi:10.1038/s41598-019-40996-7.
Doberstein, B., A. Tadgell and A. Rutledge, 2020: Managed Retreat for Climate Change Adaptation in Coastal Megacities: A Comparison of Policy and Practice in Manila and Vancouver. *J. Environ. Manage.*, **253**.
Doblas-Reyes, F. J. et al., 2021: Linking Global to Regional Climate Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Chang* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Dodman, D., D. Archer and D. Satterthwaite, 2019: Editorial: Responding to climate change in contexts of urban poverty and informality. *Environment and Urbanization*, 095624781983000, doi:10.1177/0956247819830004.
Doswald, N. et al., 2014: Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *http://dx.doi.org/10.1080/17565529.2013.867247*, doi:10.1080/17565529.2013.867247.
Douville, H. et al., 2021: Water Cycle Changes. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Drolet, J. et al., 2015: Women rebuilding lives post-disaster: innovative community practices for building resilience and promoting sustainable development. *Gender & Development*, **23**(3), 433-448, doi:10.1080/13552074.2015.1096040.
Du, S. et al., 2020: Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. *Global Environmental Change*, **61**, 102037.
Duan, H., G. Zhang, S. Wang and Y. Fan, 2019a: Integrated benefit-cost analysis of China's optimal adaptation and targeted mitigation. *Ecological Economics*, **160**, 76-86.
Duan, H., G. Zhang, S. Wang and Y. Fan, 2019b: Robust climate change research: a review on multi-model analysis. *Environmental Research Letters*, **14**(3), doi:10.1088/1748-9326/aaf8f9.
Duan, W. et al., 2016: Floods and associated socioeconomic damages in China over the last century. *Natural Hazards*, **82**(1), 401-413.
Duane, A., M. Castellnou and L. Brotons, 2021: Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change*, **165**(3), 43, doi:10.1007/s10584-021-03066-4.
Duarte, C. M. et al., 2017: Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, **4**(100), doi:10.3389/fmars.2017.00100.
Duffy, J. E. et al., 2019: Toward a Coordinated Global Observing System for Seagrasses and Marine Macroalgae. *Frontiers in Marine Science*, **6**(317), doi:10.3389/fmars.2019.00317.
Dugan, P. J. et al., 2010: Fish migration, dams, and loss of ecosystem services in the Mekong basin. *Ambio*, **39**(4), 344-348.
Dujardin, S., J., Hermesse and N. Dendoncker, 2018: Making space for experiential knowledge in climate change adaptation? Insights from municipal planning officers in Bohol, Philippines. *Jàmbá: Journal of Disaster Risk Studies* **10**(1), 433, doi:https://doi.org/10.4102/jamba.v10i1.433.
Dulal, H. B., 2019: Cities in Asia: how are they adapting to climate change? *Journal of Environmental Studies and Sciences*, **9**(1), 13-24, doi:10.1007/s13412-018-0534-1.
Dulamsuren, C., M. Khishigjargal, C. Leuschner and M. Hauck, 2014: Response of tree-ring width to climate warming and selective logging in larch forests of the Mongolian Altai. *Journal of Plant Ecology*, **7**(1), 24-38, doi:10.1093/jpe/rtt019.

Dulamsuren, C. et al., 2016: Carbon pool densities and a first estimate of the total carbon pool in the Mongolian forest-steppe. *Global Change Biology*, **22**(2), 830-844, doi:https://doi.org/10.1111/gcb.13127.
Dulamsuren, C. et al., 2013: Increased Summer Temperatures Reduce the Growth and Regeneration of *Larix sibirica* in Southern Boreal Forests of Eastern Kazakhstan. *Ecosystems*, **16**(8), 1536-1549, doi:10.1007/s10021-013-9700-1.
Duncan, C. et al., 2016: Rehabilitating mangrove ecosystem services: A case study on the relative benefits of abandoned pond reversion from Panay Island, Philippines. *Mar Pollut Bull*, **109**(2), 772-782, doi:10.1016/j.marpolbul.2016.05.049.
Dür, M. and L. Keller, 2018: Education for Sustainable Development through International Collaboration. A Case Study on Concepts and Conceptual Change of School-Students from India and Austria on Gender Equality and Sustainable Growth. *Education Sciences*, **8**(4), doi:10.3390/educsci8040187.
Durán-Valverde, F., Pacheco-Jiménez, J., Muzaffar, T., Elizondo-Barboza, H., 2020: *Financing gaps in social protection: Global estimates and strategies for developing countries in light of the COVID-19 crisis and beyond*, International Labour Organization.
Duy, P. N., L. Chapman, M. Tight and L. V. Thuong, 2019: Urban Resilience to Floods in Coastal Cities: Challenges and Opportunities for Ho Chi Minh City and Other Emerging Cities in Southeast Asia | Journal of Urban Planning and Development | Vol 144, No 1. *Journal of Urban Planning and Development*.
Dwirahmadi, F., S. Rutherford, D. Phung and C. Chu, 2019: Understanding the Operational Concept of a Flood-Resilient Urban Community in Jakarta, Indonesia, from the Perspectives of Disaster Risk Reduction, Climate Change Adaptation, and Development Agencies. *International Journal of Environmental Research and Public Health*, **16**.
Eakin, C. M., H. P. A. Sweatman and R. E. Brainard, 2019: The 2014-2017 global-scale coral bleaching event: insights and impacts. *Coral Reefs*, **38**(4), 539-545, doi:10.1007/s00338-019-01844-2.
EcoMENA. Available at: https://www.ecomena.org/ecomena/.
Edmonds, D. A., R. L. Caldwell, E. S. Brondizio and S. M. O. Siani, 2020: Coastal flooding will disproportionately impact people on river deltas. *Nature communications*, **11**(1), 1-8.
Eilander, D. et al., 2020: The effect of surge on riverine flood hazard and impact in deltas globally. *Environmental Research Letters*.
Elalem, S. and I. Pal, 2015: Mapping the vulnerability hotspots over Hindu-Kush Himalaya region to flooding disasters. *Weather and Climate Extremes*, **8**, 46-58, doi:https://doi.org/10.1016/j.wace.2014.12.001.
Elliott, R. J. R., E. Strobl and P. Sun, 2015: The local impact of typhoons on economic activity in China: A view from outer space. *Journal of Urban Economics*, **88**, 50-66, doi:https://doi.org/10.1016/j.jue.2015.05.001.
Ellis, P. and M. Roberts, 2016: *Leveraging urbanization in South Asia: managing spatial transformation for prosperity and livability*. ISBN 9781464806629.
Elum, Z. A., D. M. Modise and A. Marr, 2017: Farmer's perception of climate change and responsive strategies in three selected provinces of South Africa. *Climate Risk Management*, **16**, 246-257, doi:10.1016/j.crm.2016.11.001.
Emran, M. S., V. Robano and S. C. Smith, 2014: Assessing the frontiers of ultrapoverty reduction: evidence from challenging the frontiers of poverty reduction/targeting the ultra-poor, an innovative program in Bangladesh. *Economic Development and Cultural Change*, **62**(2), 339-380.
Environment, U. A. E. M. o. C. C., 2015: National Climate Change Plan of the United Arab Emirates 2017-2050.
ESCAP, U., 2017: *Migration and climate change in Asia and the Pacific*. ESCAP, U., Bangkok.
Escarcha, J., J. Lassa and K. Zander, 2018a: Livestock Under Climate Change: A Systematic Review of Impacts and Adaptation. *Climate*, **6**(3), doi:10.3390/cli6030054.
Escarcha, J. F., J. A. Lassa, E. P. Palacpac and K. K. Zander, 2018b: Understanding climate change impacts on water buffalo production through farmers' perceptions. *Climate Risk Management*, **20**, 50-63, doi:https://doi.org/10.1016/j.crm.2018.03.003.
ESCWA, 2020: *Impact of COVID-19 on Migrants and Refugees in the Arab Region, Technical Paper*. United Nations Economic and Social Commission for Western Asia (ESCWA), Beirut, Lebanon.
Esham, M., B. Jacobs, H. S. R. Rosairo and B. B. Siddighi, 2018: Climate change and food security: a Sri Lankan perspective. *Environment, Development and Sustainability*, **20**(3), 1017-1036, doi:10.1007/s10668-017-9945-5.
Eslamian, S. et al., 2017: A Review of Drought Indices. *International Journal of Constructive Research in Civil Engineering*, **3**(4), doi:10.20431/2454-8693.0304005.
Estoque, R. C., Y. Murayama and S. W. Myint, 2017: Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia. *Science of the Total Environment*, **577**, 349-359.
Estoque, R. C. et al., 2019: The future of Southeast Asia's forests. *Nat Commun*, **10**(1), 1829, doi:10.1038/s41467-019-09646-4.
Estoque, R. C. et al., 2020: Heat health risk assessment in Philippine cities using remotely sensed data and social-ecological indicators. *Nature Communications*, **11**(1), 1581, doi:10.1038/s41467-020-15218-8.
Etchart, L., 2017: The role of indigenous peoples in combating climate change. *Palgrave Communications*, **3**, doi:10.1057/palcomms.2017.85.
EUEI-PDF, 2017: Energy and Climate Change Adaptation in Developing Countries.
Evers, J. and A. Pathirana, 2018: Adaptation to climate change in the Mekong River Basin: introduction to the special issue. *Climatic Change*, **149**(1), 1-11, doi:10.1007/s10584-018-2242-y.

Evertsen, K. F. and K. van der Geest, 2020: Gender, environment and migration in Bangladesh. *Climate and Development*, **12**(1), 12-22.
Fahad, S. and J. Wang, 2018: Farmers' risk perception, vulnerability, and adaptation to climate change in rural Pakistan. *Land Use Policy*, **79**, 301-309, doi:https://doi.org/10.1016/j.landusepol.2018.08.018.
Fan, J. T. et al., 2014: Assessing the impact of climate change on the habitat distribution of the giant panda in the Qinling Mountains of China. *Ecol Model*, **274**, 12-20, doi:10.1016/j.ecolmodel.2013.11.023.
Fant, C. et al., 2016: Projections of water stress based on an ensemble of socioeconomic growth and climate change scenarios: a case study in Asia. *PLoS One*, **11**(3), e0150633.
FAO, 2001: *The state of food insecurity in the world* Food and Agriculuture Organization of the United Nations, Rome. Available at: http://www.fao.org/3/y1500e/y1500e00.htm.
FAO (ed.), Actions to Adapt to and Mitigate Climate Change Impacts on Natural Resources: the Case of Fisheries and Aquaculture, Forestry, and Livestock in the Near East. Rome, Food and Agriculture Organization of the United Nations.
FAO, 2014: *The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture*. Food and Agriculture Orgnization, Organization, F. a. A., Rome (accessed 6 October 2019).
FAO, 2015: *FAO Statistical Pocketbook*. Food and Agricultural Organization (FAO) Rome, Italy. Available at: http://www.fao.org/3/a-i4691e.pdf.
FAO, 2018a: *The impact of disasters and crises on agriculture and food security 2017* Food and Agriculture Organization of the United Nations, Rome. Available at: http://www.fao.org/3/I8656EN/i8656en.pdf.
FAO, 2018b: *Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options*. Available at: http://www.fao.org/3/i9705en/i9705en.pdf.
FAO, 2018c: *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals.* Available at: http://www.fao.org/3/i9540en/i9540en.pdf.
FAO, 2019: FAO Fisheries & Aquaculture - Statistics - Introduction.
FAO, 2020: *The state of world fisheries and aquaculture 2020 - sustainability in action*. Food and Agriculture Organization, Rome. Available at: http://www.fao.org/3/ca9229en/ca9229en.pdf.
FAO, I., UNICEF, WFP and WHO., 2018d: *The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition.* . Rome.
Farajalla, N., 2013: Impact of Climate Change on the Arab World.
Faridatul, M. I., B., Wu and X. Zhu, 2019: Assessing long-term urban surface water changes using multi-year satellite images: A tale of two cities, Dhaka and Hong Kong. *J. Environ. Manage.*, **243**, 287–298, doi:https://doi.org/10.1016/j.jenvman.2019.05.019.
Farrington, J. and J. Li, 2016: Climate Change Impacts on Snow Leopard Range. In: *Snow Leopards: Biodiversity of the World: Conservation from Genes to Landscapes* [Nyhus, P., T. McCarthy and D. Mallon (eds.)]. Elsevier, London, pp. 85-95. ISBN 9780128022139.
Felberg, K., P. Mellen and D. Puig, 1999: Environment in the European Union at the Turn of the Century: Co-author of 3.12. Urban areas. In: *Environment in the European Union at the Turn of the Century*. European Environment Agency.
Feliciano, G. N. R., L. M. F. Gagalac, A. Nava and W. Y. Licuanan, 2018: Size structure and possible bleaching susceptibility of mushroom corals in the Philippines following a bleaching event. *Reg. Stud. Mar. Sci.*, **24**, 288-295, doi:10.1016/j.rsma.2018.09.003.
Feng, A. et al., 2018a: Assessing the inundation risk resulting from extreme water levels under sea-level rise: a case study of Rongcheng, China. *Geomatics, Natural Hazards and Risk*, **9**(1), 456-470, doi:https://doi.org/10.1080/19475705.2018.1447026.
Feng, J. et al., 2018b: Changes of Extreme Sea Level in 1.5 and 2.0°C Warmer Climate Along the Coast of China. *Frontiers in Earth Science*, **6**, doi:10.3389/feart.2018.00216.
Feng, X., M. Liu, X. Huo and W. Ma, 2017: What Motivates Farmers' Adaptation to Climate Change? The Case of Apple Farmers of Shaanxi in China. *Sustainability*, **9**(4), 519, doi:10.3390/su9040519.
Fengqing, J. et al., 2005: Magnification of Flood Disasters and its Relation to Regional Precipitation and Local Human Activities since the 1980s in Xinjiang, Northwestern China. *Natural Hazards*, **36**(3), 307-330, doi:10.1007/s11069-005-0977-z.
Fenner, D. et al., 2017: Intra and inter 'local climate zone' variability of air temperature as observed by crowdsourced citizen weather stations in Berlin, Germany. *Meteorologische Zeitschrift*, **26**(5), 525-547, doi:10.1127/metz/2017/0861.
Ferdous, J. and D. Mallick, 2019: Norms, practices, and gendered vulnerabilities in the lower Teesta T basin, Bangladesh. *Environmental Development* **31**, 88–96, doi:https://doi.org/10.1016/j.envdev.2018.10.003.
Fernandes, J. A. et al., 2016: Projecting marine fish production and catch potential in Bangladesh in the 21st century under long-term environmental change and management scenarios. *ICES Journal of Marine Science: Journal du Conseil*, **73**(5), 1357-1369, doi:10.1093/icesjms/fsv217.
Fernandez-Llamazares, A. et al., 2015: Rapid ecosystem change challenges the adaptive capacity of Local Environmental Knowledge. *Glob Environ Change*, **31**, 272-284, doi:10.1016/j.gloenvcha.2015.02.001.
Filho, W. L. et al., 2019: Assessing the impacts of climate change in cities and their adaptive capacity: Towards transformative approaches to climate change adaptation and poverty reduction in urban areas in a set of

developing countries. *Science of the Total Environment*, **692**, 1175-1190, doi:https://doi.org/10.1016/j.scitotenv.2019.07.227.
Fink, H. S., 2016: Human-nature for climate action: Nature-based solutions for urban sustainability. *Sustainability (Switzerland)*, **8**(3), doi:10.3390/su8030254.
Fischer, E., J. Hellin, H. Greatrex, N. Gensen, 2019: Index insurance and climate risk management: Addressing social equity. *Development Policy Review*, **37**(5), 581-602.
Fomin, V. V., A. P. Mikhailovich and S. G. Shiyatov, 2020: Trees in the Upper Treeline Ecotone in the Polar Urals: Centuries-Old Change and Spatial Patterns. *Mountain Research and Development*, **40**(2), R32.
Ford, J. D. et al., 2015: The status of climate change adaptation in Africa and Asia. *Regional Environmental Change*, **15**(5), 801-814.
Ford, J. D. et al., 2016: Opinion: Big data has big potential for applications to climate change adaptation. *Proc Natl Acad Sci U S A*, **113**(39), 10729-10732, doi:10.1073/pnas.1614023113.
Fortes, M. D., 2018: Seagrass ecosystem conservation in Southeast Asia needs to link science to policy and practice. *Ocean Coastal Manage.*, **159**, 51-56, doi:10.1016/j.ocecoaman.2018.01.028.
Fourqurean, J. W. et al., 2012: Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.*, **5**(7), 505-509, doi:10.1038/ngeo1477.
Francaviglia, R. et al., 2020: Probability assessment of climate change impacts on soil organic carbon stocks in future periods: a case study in Hyrcanian forests (Northern Iran). *Eur J Forest Res*, **139**(1), 1-16, doi:10.1007/s10342-019-01228-9.
Francisco, H. A. and N. A. Zakaria, 2019: Understanding Climate Change Adaptation Needs and Practices of Households in Southeast Asia: Lessons from Five Years of Research | SpringerLink. In: *Handbook of Climate Mitigation and Adaptation*. SpringerLink. Available at: https://link.springer.com/referenceworkentry/10.1007%2F978-3-319-14409-2_67.
Freeman, B. G. and A. M. C. Freeman, 2014: Rapid upslope shifts in New Guinean birds illustrate strong distributional responses of tropical montane species to global warming. *P Natl Acad Sci USA*, **111**(12), 4490-4494, doi:10.1073/pnas.1318190111.
Friedlingstein, P. et al., 2019: Global Carbon Budget 2019. *Earth Syst. Sci. Data*, **11**(4), 1783-1838, doi:10.5194/essd-11-1783-2019.
Frieler, K. et al., 2013: Limiting global warming to 2 degrees C is unlikely to save most coral reefs. *Nature Climate Change*, **3**(2), 165-170, doi:10.1038/nclimate1674.
Friend, R. et al., 2014: Mainstreaming urban climate resilience into policy and planning; reflections from Asia. *Urban Climate*, **7**, 6-19.
Friess, D. A. et al., 2019: The State of the World's Mangrove Forests: Past, Present, and Future. In: *Annual Review of Environment and Resources, Vol 44* [Gadgil, A. and T. P. Tomich (eds.)]. Annual Reviews, Palo Alto, pp. 89-115. ISBN 978-0-8243-2344-8.
Froehlich, H. E., R. R. Gentry and B. S. Halpern, 2018: Global change in marine aquaculture production potential under climate change. *Nature Ecology & Evolution*, **2**(11), 1745-1750, doi:10.1038/s41559-018-0669-1.
Frölicher, T. L. and C. Laufkötter, 2018: Emerging risks from marine heat waves. *Nature Communications*, **9**(1), 650, doi:10.1038/s41467-018-03163-6.
Fuhr, H., T. Hickmann and K. Kern, 2018: The role of cities in multi-level climate governance: local climate policies and the 1.5 °C target. *Current Opinion in Environmental Sustainability*, **30**, 1-6, doi:10.1016/j.cosust.2017.10.006.
Fujisawa, M. and K. Kobayashi, 2011: Climate change adaptation practices of apple growers in Nagano, Japan. *Mitigation and adaptation strategies for global change*, **16**(8), 865-877.
Fujisawa, M., K. Kobayashi, P. Johnston and M. New, 2015: What drives farmers to make top-down or bottom-up adaptation to climate change and fluctuations? A comparative study on 3 cases of apple farming in Japan and South Africa. *PloS one*, **10**(3), e0120563.
Fünfgeld, H., 2015: Facilitating local climate change adaptation through transnational municipal networks. *Current Opinion in Environmental Sustainability*, **12**, 67-73, doi:10.1016/j.cosust.2014.10.011.
Gaire, N. P., M. Koirala, D. R. Bhuju and M. Carrer, 2017: Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. *Dendrochronologia*, **41**, 44-56, doi:https://doi.org/10.1016/j.dendro.2016.03.001.
Gaisin, I. K. et al., 2020: Expansion of Tree Vegetation in the Forest-Mountain Steppe Ecotone on the Southern Urals in Relation to Changes in Climate and Habitat Moisture. *Russian Journal of Ecology*, **51**(4), 306-318, doi:10.1134/S1067413620040074.
Gajjar, S. P., C. Singh and T. Deshpande, 2018: Tracing back to move ahead: a review of development pathways that constrain adaptation futures. *Climate and Development*, 1-15, doi:10.1080/17565529.2018.1442793.
Gallagher, J. B., C. H. Chuan, T. K. Yap and W. F. F. Dona, 2019: Carbon stocks of coastal seagrass in Southeast Asia may be far lower than anticipated when accounting for black carbon. *Biol. Lett.*, **15**(5), 5, doi:10.1098/rsbl.2018.0745.
Gama, M., D. Crespo, M. Dolbeth and P. M. Anastacio, 2017: Ensemble forecasting of *Corbicula fluminea* worldwide distribution: Projections of the impact of climate change. *Aquat Conserv*, **27**(3), 675-684, doi:10.1002/aqc.2767.
Gamble, J. L. et al., 2016: *The Impacts of Climate Change on Human Health in The United States A Scientific Assessment*.

Gampell, A. V., J. C. Gaillard, M. Parsons and K. Fisher, 2017: Beyond stop disasters 2.0: an agenda for exploring the contribution of video games to learning about disasters. *Environmental Hazards*, **16**(2), 180-191, doi:10.1080/17477891.2016.1275502.
Gandhi, S. and T. G. Jones, 2019: Identifying Mangrove Deforestation Hotspots in South Asia, Southeast Asia and Asia-Pacific. *Remote Sensing*, **11**(6), 27, doi:10.3390/rs11060728.
Ganguly, D. et al., 2017: Seagrass metabolism and carbon dynamics in a tropical coastal embayment. *Ambio*, **46**(6), 667-679, doi:10.1007/s13280-017-0916-8.
Gao, G., A. S. Clare, C. Rose and G. S. Caldwell, 2017: Eutrophication and warming-driven green tides (Ulva rigida) are predicted to increase under future climate change scenarios. *Mar. Pollut. Bull.*, **114**(1), 439-447, doi:10.1016/j.marpolbul.2016.10.003.
Gao, G., A. S. Clare, C. Rose and G. S. Caldwell, 2018a: Ulva rigida in the future ocean: potential for carbon capture, bioremediation and biomethane production. *GCB Bioenergy*, **10**(1), 39-51, doi:10.1111/gcbb.12465.
Gao, G. et al., 2018b: Global warming interacts with ocean acidification to alter PSII function and protection in the diatom Thalassiosira weissflogii. *Environ. Exp. Bot.*, **147**, 95-103, doi:10.1016/j.envexpbot.2017.11.014.
Gao, G., Z. H. Zhong, X. H. Zhou and J. T. Xu, 2016: Changes in morphological plasticity of Ulva prolifera under different environmental conditions: A laboratory experiment. *Harmful Algae*, **59**, 51-58, doi:10.1016/j.hal.2016.09.004.
Gao, J. et al., 2019: Collapsing glaciers threaten Asia's water supplies. *Nature*, **565**(7737), 19-21, doi:10.1038/d41586-018-07838-4.
Gao, X., C. A. Schlosser, C. Fant and K. Strzepek, 2018c: The impact of climate change policy on the risk of water stress in southern and eastern Asia. *Environmental Research Letters*, **13**(6), 064039.
Garde, M., N. Mathers and T. Dhakal, 2017: The evolution of Nepal's child grant: From humble beginnings to a real driver of change for children? *Global Social Policy*, **17**(3), 359-364, doi:10.1177/1468018117729911.
Garrick, D. et al., 2019: Rural water for thirsty cities: A systematic review of water reallocation from rural to urban regions. *Environmental Research Letters*, **14**(4), 043003.
Garschagen, M. and D. Marks, 2019: Towards an Agenda for Profound Urban Climate Resilience in Southeast Asia. In: *Urban Climate Resilience in Southeast Asia*. Springer, pp. 223-228.
Gasparrini, A. et al., 2017: Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet Health*, **1**(9), e360-e367, doi:10.1016/S2542-5196(17)30156-0.
Gatteschi, V. et al., 2018: Blockchain and smart contracts for insurance: Is the technology mature enough? *Future Internet*, **10**(2), 20.
Gavonel, M. F. et al., 2021: The migration-sustainability paradox: transformations in mobile worlds. *Current Opinion in Environmental Sustainability*, **49**, 98-109.
Gay Garcia, C., E. Bautista Gonzalez and B. Bastien-Olvera, 2017: An Agent-based Model of Food-borne Diseases Under Climate Change Scenarios in Mexico City - The Risk of Street-food in a Warming City. In: *Proceedings of the 7th International Conference on Simulation and Modeling Methodologies, Technologies and Applications*, pp. 474-479, doi:10.5220/0006484404740479.
Gaydon, D. S. et al., 2017: Evaluation of the APSIM model in cropping systems of Asia. *Field Crops Research*, **204**, 52-75, doi:https://doi.org/10.1016/j.fcr.2016.12.015.
Ge, Z. M. et al., 2015: Future vegetation patterns and primary production in the coastal wetlands of East China under sea level rise, sediment reduction, and saltwater intrusion. *Journal of Geophysical Research-Biogeosciences*, **120**(10), 1923-1940, doi:10.1002/2015JG003014.
Gemenne, F. et al., 2015: How climate extremes are affecting the movement of populations in the Asia Pacific region. *Global Implications of Development, Disasters and Climate Change: Responses to Displacement from Asia Pacific*, 21-40.
Georgeson, L., M. Maslin, M. Poessinouw and S. Howard, 2016: Adaptation responses to climate change differ between global megacities. *Nature Climate Change*, **6**(6), 584-588, doi:10.1038/nclimate2944.
Ghasem, A., A. Shamsipour, M. Miri and T. Safarrad, 2012: Synoptic and remote sensing analysis of dust events in southwestern Iran. *Natural hazards*, **64**(2), 1625-1638.
Ghimire, D. P., D., 2016: Interconnection of climate change, agriculture and climate justice: Complexities for feeding the world under changing climate. *Development*, **59**(4), 270, doi:https://doi.org/10.1057/s41301-017-0118-5.
Ghomian, Z. and S. Yousefian, 2017: Natural disasters in the Middle-East and North Africa with a focus on Iran: 1900 to 2015. *Health in Emergencies and Disasters Quarterly*, **2**(2), 53-62, doi:https://doi.org/10.18869/nrip.hdq.2.2.53.
Ghosh, R. K., S. Gupta, V. Singh and P. S. Ward, 2019: *Is there a market for multi-peril crop insurance in developing countries moving beyond subsidies? Evidence from India*. vol. 1820, Intl Food Policy Res Inst.
Ghosh, S. et al., 2018: Exploitation of social media for emergency relief and preparedness: Recent research and trends. *Information Systems Frontiers*, 1-7, doi:10.1007/s10796-018-9878-z.
Giang, P. N. et al., 2014: The effect of temperature on cardiovascular disease hospital admissions among elderly people in Thai Nguyen Province, Vietnam. *Global health action*, **7**, 23649, doi:10.3402/gha.v7.23649.
Giffin, A. L. et al., 2020: Marine and coastal ecosystem-based adaptation in Asia and Oceania: review of approaches and integration with marine spatial planning. *Pacific Conservation Biology*.

Gilfillan, D., 2018: Regional organisations supporting health sector responses to climate change in Southeast Asia. *Global Health*, **14**(1), 80, doi:10.1186/s12992-018-0388-z.
Gilfillan, D., T. T. Nguyen and H. T. Pham, 2017: Coordination and health sector adaptation to climate change in the Vietnamese Mekong Delta. *Ecology and Society*, **22**(3), doi:10.5751/es-09235-220314.
Ginbo, T., L. Di Corato and R. Hoffmann, 2020: Investing in climate change adaptation and mitigation: A methodological review of real-options studies. *Ambio*.
Girishkumar, M. S. et al., 2019: Quantifying Tropical Cyclone's Effect on the Biogeochemical Processes Using Profiling Float Observations in the Bay of Bengal. *J. Geophys. Res.-Oceans*, **124**(3), 1945-1963, doi:10.1029/2017jc013629.
Giuliani, M. et al., 2016: Large storage operations under climate change: expanding uncertainties and evolving tradeoffs. *Environmental Research Letters*, **11**(3), doi:https://doi.org/10.1088/1748-9326/11/3/035009.
Gleick, P. and C. Iceland, 2018: Water, Security, and Conflict. World Resource Institute.
Gleick, P. H., 1993: Water and conflict: Fresh water resources and international security. *International security*, **18**(1), 79-112.
Gleick, P. H., 2014: Water, Drought, Climate Change, and Conflict in Syria. *Weather, Climate, and Society*, **6**(3), 331-340, doi:10.1175/wcas-d-13-00059.1.
Glossary, IPBES., 2019: *Glossary*. Available at: https://www.ipbes.net/sites/default/files/ipbes_global_assessment_glossary_unedited_31may.pdf.
Godber, O. F. and R. Wall, 2014: Livestock and food security: vulnerability to population growth and climate change. *Glob Chang Biol*, **20**(10), 3092-3102, doi:10.1111/gcb.12589.
Goel, S., K. Singh and N. K. Singh, 2017: Wheat Improvement in India: Present and Future. In: *Wheat Biotechnology: Methods and Protocols* [Bhalla, P. L. and M. B. Singh (eds.)]. Springer New York, New York, NY, pp. 61-82. ISBN 978-1-4939-7337-8.
Gohari, A., A. Mirchi and K. Madani, 2017: System dynamics evaluation of climate change adaptation strategies for water resources management in Central Iran. *Water Resources Management*, **31**, 1413–1434, doi:https://doi.org/10.1007/s11269-017-1575-z.
Gong, S. Q. et al., 2019: Differences in Symbiodiniaceae communities and photosynthesis following thermal bleaching of massive corals in the northern part of the South China Sea. *Mar. Pollut. Bull.*, **144**, 196-204, doi:10.1016/j.marpolbul.2019.04.069.
Gong, Y., J. Yang and X. Shi, 2020: Towards a comprehensive understanding of digital transformation in government: Analysis of flexibility and enterprise architecture. *Government Information Quarterly*, **37**(3), 101487.
Goodrich, C. G., A., Prakash and P. B. Udas, 2019: Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. *Environmental Development* **31**, 1-8, doi:https://doi.org/10.1016/j.envdev.2019.01.001.
Government, K., 2020: *Climate Change Impact and Adaptation. Korean Climage Change Assessment Report 2020. Summary for Policymakers* [Bae, Y. J., H. J. Lee, B. W. Jung and H.-C. Jung (eds.)]. Ministry of Environment of Republic of Korea, 43 pp.
Grainger, S. and D. Conway, 2014: Climate change and International River Boundaries: fixed points in shifting sands. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(6), 835-848, doi:10.1002/wcc.306.
Granit, J. et al., 2012: Regional options for addressing the water, energy and food nexus in Central Asia and the Aral Sea Basin. *International Journal of Water Resources Development*, **28**(3), 419-432.
Gray, T. N. E. et al., 2014: Population size estimation of an Asian elephant population in eastern Cambodia through non-invasive mark-recapture sampling. *Conservation Genetics*, **15**(4), 803-810, doi:10.1007/s10592-014-0579-y.
Greatrex, H. et al., 2015: Scaling up index insurance for smallholder farmers: Recent evidence and insights.
Grebenets, V., D. Streletskiy and N. Shiklomanov, 2012: Geotechnical safety issues in the cities of Polar Regions. *Geography, Environment, Sustainability*, **5**(3), 104-119.
Green, P. A. et al., 2015: Freshwater ecosystem services supporting humans: Pivoting from water crisis to water solutions. *Global Environmental Change*, **34**, 108-118, doi:10.1016/j.gloenvcha.2015.06.007.
Grefalda, L. B. et al., 2020: Building institutional resilience in the context of climate change in Aurora, Philippines. *Environmental Research*, **186**, 109584, doi:https://doi.org/10.1016/j.envres.2020.109584.
Grigor'ev, A. A. et al., 2019: Structure and dynamics of tree stands at the upper timberline in the western part of the Putorana Plateau. *Russian Journal of Ecology*, **50**(4), 311-322, doi:10.1134/s1067413619040076.
Griscom, B. W. et al., 2020: National mitigation potential from natural climate solutions in the tropics. *Philos Trans R Soc Lond B Biol Sci*, **375**(1794), 20190126, doi:10.1098/rstb.2019.0126.
Groll, M. et al., 2015: Water quality, potential conflicts and solutions—an upstream–downstream analysis of the transnational Zarafshan River (Tajikistan, Uzbekistan). *Environmental Earth Sciences*, **73**, 743–763, doi:https://doi.org/10.1007/S12665-013-2988-5.
Grothmann, T. and A. Patt, 2005: Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Global Environmental Change*, **15**(3), 199-213, doi:10.1016/j.gloenvcha.2005.01.002.
Groulx, M. et al., 2017: A Role for Nature-Based Citizen Science in Promoting Individual and Collective Climate Change Action? A Systematic Review of Learning Outcomes. *Science Communication*, **39**(1), 45-76, doi:10.1177/1075547016688324.

Gruffudd, H. R., T. A. R. Jenkins and H. F. Evans, 2016: Using an evapo-transpiration model (ETpN) to predict the risk and expression of symptoms of pine wilt disease (PWD) across Europe. *Biological Invasions*, **18**(10), 2823-2840, doi:10.1007/s10530-016-1173-7.
Gu, D., P. Gerland, F. Pelletier and B. Cohen, 2015: *Risks of Exposure and Vulnerability to Natural Disasters at the City Level: A Global Overview*. UN Population Division, Technical Paper, No. 2015/2, New York, USA. Available at: https://population.un.org/wup/Publications/Files/WUP2014-TechnicalPaper-NaturalDisaster.pdf.
Gulakhmadov, A. et al., 2020: Long-Term Hydro-Climatic Trends in the Mountainous Kofarnihon River Basin in Central Asia. *Water*, **12**, doi:10.3390/w12082140.
Gunathilaka, R. P. D., J. C. R. Smart and C. M. Fleming, 2018: Adaptation to climate change in perennial cropping systems: Options, barriers and policy implications. *Environmental Science & Policy*, **82**, 108-116, doi:https://doi.org/10.1016/j.envsci.2018.01.011.
Güneralp, B., I. Güneralp and Y. Liu, 2015: Changing global patterns of urban exposure to flood and drought hazards. *Glob. Environ. Change*, **31**, 217–225, doi:doi:10.1016/j.gloenvcha.2015.01.002.
Guo, X., L. Wang, L. Tian and X. Li, 2017a: Elevation-dependent reductions in wind speed over and around the Tibetan Plateau. *International Journal of Climatology*, **37**(2), 1117-1126, doi:10.1002/joc.4727.
Guo, X. Y. et al., 2016: Early development of undulated surf clam, Paphia undulate under elevated pCO(2). *J. Exp. Mar. Biol. Ecol.*, **484**, 23-30, doi:10.1016/j.jembe.2016.08.002.
Guo, Y. et al., 2017b: Heat Wave and Mortality: A Multicountry, Multicommunity Study. *Environmental health perspectives*, **125**(8), 087006, doi:10.1289/ehp1026.
Guo, Y. et al., 2019: Dynamic Evaluation and Regionalization of Maize Drought Vulnerability in the Midwest of Jilin Province. *Sustainability*, **11**, 4234, doi:doi:10.3390/su11154234.
Gupta, A. K. et al., 2019: Assessing the vulnerability of socio-environmental systems to climate change along an altitude gradient in the Indian Himalayas. *Ecological Indicators* **106**, doi:https://doi.org/10.1016/j.ecolind.2019.105512.
Gupta, D. and T. M. Koontz, 2019: Working together? Synergies in government and NGO roles for community forestry in the Indian Himalayas. *World Development*, **114**, 326-340.
Gurung, D. R. et al., 2017: Lemthang Tsho glacial Lake outburst flood (GLOF) in Bhutan: cause and impact. *Geoenvironmental Disasters*, **4**(1), 17, doi:10.1186/s40677-017-0080-2.
Gustafson, S., A. J. Cadena and P. Hartman, 2018: Adaptation planning in the Lower Mekong Basin: Merging scientific data with local perspective to improve community resilience to climate change. *Climate and Development*, **10**(2), 152-166.
Gutiérrez, J. M. et al., 2021: Atlas. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Haag, I., P. D. Jones and C. Samimi, 2019: Central Asia's changing climate: How temperature and precipitation have changed across time, space, and altitude. *Climate*, **7**(10), 123.
Haasnoot, M. et al., 2019: Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. *Environmental Research Communications*, **1**(7), 071006.
Haasnoot, M. e. a., 2021: Long-term sea-level rise necessitates a commitment to adaptation: a first order assessment. *Climate Risk Management (in press)*.
Hadiyanto et al., 2018: Relation of social capital to women's proactive participation in the community for sustainability of river in urban areas. *E3S Web of Conferences*, **73**, doi:10.1051/e3sconf/20187303003.
Hadwen, W. L. et al., 2015: Putting WASH in the water cycle: Climate change, water resources and the future of water, sanitation and hygiene challenges in Pacific Island Countries. *Journal of Water, Sanitation and Hygiene for Development*, **5**(2), 183-191.
Haeberli, W. et al., 2016: New lakes in deglaciating high-mountain regions - opportunities and risks. *Climatic Change*, **139**(2), 201-214, doi:10.1007/s10584-016-1771-5.
Halbrendt, J. et al., 2014: Differences in farmer and expert beliefs and the perceived impacts of conservation agriculture. *Global Environmental Change*, **28**(1), 50-62, doi:10.1016/j.gloenvcha.2014.05.001.
Hallegatte, S., 2012: A Framework to Investigate the Economic Growth Impact of Sea Level Rise *Environmental Research Letters*, **7**(1), doi:https://doi.org/10.1088/1748-9326/7/1/015604.
Hallegatte, S. et al., 2015: *Shock waves: managing the impacts of climate change on poverty*. The World Bank. ISBN 146480673X.
Hallegatte, S., C. Green, R. J. Nicholls and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature climate change*, **3**(9), 802-806.
Hallegatte, S., J. Rentschler and J. Rozenberg, 2019: *Lifelines : The Resilient Infrastructure Opportunity: Sustainable Infrastructure Series*. Available at: https://elibrary.worldbank.org/doi/abs/10.1596/978-1-4648-1430-3.
Hallegatte, S., J. Rentschler and B. Walsh, 2018: *Building back better: achieving resilience through stronger, faster, and more inclusive post-disaster reconstruction*. World Bank.
Hamal, K. et al., 2020: Assessment of drought impacts on crop yields across Nepal during 1987–2017. *Meteorological Applications*, **27**(5), e1950.

Hamid, A. and M. A. Raouf, 2009: Climate change in the Arab world: Threats and responses. *Troubled Waters; Climate Change, Hydro politics, and Transboundary Resources David Michel and Amit Pandya Editors: The Henry L. Stimson Center*.
Hamidazada, M., A. M. Cruz and M. Yokomatsu, 2019: Vulnerability Factors of Afghan Rural Women to Disasters. *International Journal of Disaster Risk Science*, **10**(4), 573-590, doi:10.1007/s13753-019-00227-z.
Han, Q., 2015: Education for Sustainable Development and Climate Change Education in China: A Status Report. *Journal of Education for Sustainable Development*, **9**(1), 62-77, doi:10.1177/0973408215569114.
Handisyde, N., T. C. Telfer and L. G. Ross, 2017: Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish. Fish.*, **18**(3), 466-488, doi:10.1111/faf.12186.
Hansen, J. et al., 2013: Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. *PloS one*, **8**(12), e81648.
Hao, X. M. et al., 2019: Response of ecosystem water use efficiency to climate change in the Tianshan Mountains, Central Asia. *Environmental Monitoring and Assessment*, **191**(9), doi:10.1007/S10661-019-7673-Z.
Haque, M. M., S. Bremer, S. B. Aziz and J. P. van der Sluijs, 2017: A critical assessment of knowledge quality for climate adaptation in Sylhet Division, Bangladesh. *Climate Risk Management*, **16**, 43-58, doi:10.1016/j.crm.2016.12.002.
Haraguchi, M. and U. Lall, 2019: Concepts, Frameworks, and Policy Tools for Disaster Risk Management: Linking with Climate Change and Sustainable Development. *Sustainable Development in Africa: Concepts and Methodological Approaches*, **5**, 57.
Hashizume, M. et al., 2020: Health Effects of Asian Dust: A Systematic Review and Meta-Analysis. *Environmental health perspectives*, **128**(6), 66001, doi:10.1289/EHP5312.
Hassan, B. et al., 2020: Impact of Climate Change on Freshwater Ecosystem and Its Sustainable Management. In: *Fresh Water Pollution Dynamics and Remediation* [Qadri, H., R. A. Bhat, M. A. Mehmood and G. H. Dar (eds.)]. Springer Singapore, Singapore, pp. 105-121. ISBN 978-981-13-8277-2.
Hauck, M., C. Dulamsuren and C. Leuschner, 2016: Anomalous increase in winter temperature and decline in forest growth associated with severe winter smog in the Ulan Bator basin. *Water, Air, & Soil Pollution*, **227**(8), 1-10.
Hauer, M. E., E. Fussell and V. Mueller, 2020: Sea-level rise and human migration. *Nat Rev Earth Environ*, **1**, 28–39, doi:https://doi.org/10.1038/s43017-019-0002-9.
Hayat, H. et al., 2019: Simulating Current and Future River-Flows in the Karakoram and Himalayan Regions of Pakistan Using Snowmelt-Runoff Model and RCP Scenarios. *Water*, **11**(4), 761.
Hazell, P. and U. Hess, 2017: Beyond hype: Another look at index-based agricultural insurance. In: *Agriculture and Rural Development in a Globalizing World*. Routledge, pp. 211-226.
Hazell, P., R. Sberro-Kessler and P. Varangis, 2017: *When and how should agricultural insurance be subsidized? Issues and good practices*. World Bank.
He, J., X. Zheng, R. M. Rejesus and J. M. Yorobe Jr, 2019: Moral hazard and adverse selection effects of cost-of-production crop insurance: evidence from the Philippines. *Australian Journal of Agricultural and Resource Economics*, **63**(1), 166-197.
Heery, E. C. et al., 2018: Urban coral reefs: Degradation and resilience of hard coral assemblages in coastal cities of East and Southeast Asia. *Mar. Pollut. Bull.*, **135**, 654-681, doi:10.1016/j.marpolbul.2018.07.041.
Heino, M. et al., 2020: A multi-model analysis of teleconnected crop yield variability in a range of cropping systems. *Earth Syst. Dynam.*, **11**(1), 113-128, doi:10.5194/esd-11-113-2020.
Heino, M. et al., 2018: Two-thirds of global cropland area impacted by climate oscillations. *Nature Communications*, **9**(1), 1257, doi:10.1038/s41467-017-02071-5.
Hemachandra, K., 2019: Regional cooperation multihazards early warning systems in Asia. *International journal on advanced science engineering information technology*, **9**(1), 287-292.
Hemachandra, K., D. Amaratunga and R. Haigh, 2018: Role of women in disaster risk governance. *Procedia Engineering*, **212**, 1187-1194, doi:10.1016/j.proeng.2018.01.153.
Hendrix, C. S. and S. Haggard, 2015: Global food prices, regime type, and urban unrest in the developing world. *Journal of Peace Research*, **52**(2), 143-157, doi:10.1177/0022343314561599.
Hennige, S. J. et al., 2010: Acclimation and adaptation of scleractinian coral communities along environmental gradients within an Indonesian reef system. *J. Exp. Mar. Biol. Ecol.*, **391**(1-2), 143-152, doi:10.1016/j.jembe.2010.06.019.
Henriksson, P. et al., 2019: Indonesian aquaculture futures — identifying interventions for reducing environmental impacts. *Environmental Research Letters*, **14**, doi:10.1088/1748-9326/ab4b79.
Henrique KP, T. P., 2020: Pathways to urban transformation: From dispossession to climate justice. *Progress in Human Geography.*, doi: doi:10.1177/0309132520962856.
Hens, L. et al., 2018: Sea-level rise and resilience in Vietnam and the Asia-Pacific: A synthesis. *Vietnam Journal Of Earth Sciences*, **40**(2), 126-152.
Herbeck, J. and M. Flitner, 2019: Infrastructuring coastal futures: Key trajectories in Southeast Asian megacities. *DIE ERDE – Journal of the Geographical Society of Berlin*, **150**(3), doi:10.12854/erde-2019-451.
Hijioka, Y. et al., 2014: Asia. In: *Climate Change 2014: Impacts, Adaptation and Vulnerability [IPCC Working Group II]*. Cambridge University Press, London.

Hilmi, N. et al., 2019: Socio-economic tools to mitigate the impacts of ocean acidification on economies and communities reliant on coral reefs - a framework for prioritization. *Reg. Stud. Mar. Sci.*, **28**, 10, doi:10.1016/j.rsma.2019.100559.
Himes-Cornell, A., L. Pendleton and P. Atiyah, 2018: Valuing ecosystem services from blue forests: A systematic review of the valuation of salt marshes, sea grass beds and mangrove forests. *Ecosystem Services*, **30**, 36-48, doi:10.1016/j.ecoser.2018.01.006.
Hirata, A. et al., 2017: Potential distribution of pine wilt disease under future climate change scenarios. *PLOS ONE*, **12**(8), e0182837, doi:10.1371/journal.pone.0182837.
Hirota, T. and K. Kobayashi, 2019: The Roles of Farmers, Scientists, and Extension Staff in Technology Development for Soil Frost Control as an Adaptation to Climate Change in Tokachi, Hokkaido, Japan. In: *Adaptation to Climate Change in Agriculture: Research and Practices* [Iizumi, T., R. Hirata and R. Matsuda (eds.)]. Springer Singapore, Singapore, pp. 211-228. ISBN 978-981-13-9235-1.
Hiwasaki, L., E. Luna, Syamsidik and R. Shaw, 2014: Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. *International Journal of Disaster Risk Reduction*, **10**, 15-27, doi:10.1016/j.ijdrr.2014.07.007.
Hjort, J. et al., 2018: Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications*, **91**(9), 1-9, doi:https://doi.org/10.1038/s41467-018-07557-4.
Ho, P. L. et al., 2017: Adaptation to Sea Level Rise: A Multidisciplinary Analysis for Ho Chi Minh City, Vietnam. *Water Resources Research*, **53**(12), 10841-10857, doi:10.1002/2017wr021344.
Hoang, L. P. et al., 2016: Mekong River flow and hydrological extremes under climate change. *Hydrology and Earth System Sciences*, **20**(7), 3027-3041.
Hochman, Z. et al., 2017: Smallholder farmers managing climate risk in India: 2. Is it climate-smart? *Agricultural Systems*, **151**, 61-72, doi:10.1016/j.agsy.2016.11.007.
Hochrainer-Stigler, S., R. Mechler, G. Pflug and K. Williges, 2014: Funding public adaptation to climate-related disasters. Estimates for a global fund. *Global Environmental Change*, **25**, 87-96.
Hock, R. et al., 2019: High Mountain Areas. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press %& 2 %! High Mountain Areas %U https://www.ipcc.ch/site/assets/uploads/sites/3/2019/2012/SROCC_FullReport_FINAL.pdf.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5ºC global warming on natural and human systems. In: *Global Warming of 1.5 C an IPCC special report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.
Hoegh-Guldberg, O., L. Pendleton and A. Kaup, 2019: People and the changing nature of coral reefs. *Reg. Stud. Mar. Sci.*, **30**, 20, doi:10.1016/j.rsma.2019.100699.
Hoegh-Guldberg, O., E. S. Poloczanska, W. Skirving and S. Dove, 2017: Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science*, **4**, doi:10.3389/fmars.2017.00158.
Hoekstra, A. Y. and M. M. Mekonnen, 2012: The water footprint of humanity. *Proc Natl Acad Sci U S A*, **109**(9), 3232-3237, doi:10.1073/pnas.1109936109.
Hoelzle, M. et al., 2019: The status and role of the alpine cryosphere in Central Asia. In: *The Aral Sea Basin*. Taylor & Francis.
Holland, D. S., Gabe & Grozdanic, Andrea & Cox, Ian & Kennedy, Leah & Agabekian, Grigor & Vergara, Sebastián & Pitterle, Ingo & Ng, Poh & Podolski, Michal., 2019: *World Economic Situation and Prospects as of mid-2019.* . United Nations, New York.
Holmes, R. and N. Jones, 2013: *Gender and social protection in the developing world: Beyond mothers and safety nets*. Zed Books, London.
Hong, C. et al., 2019a: Impacts of climate change on future air quality and human health in China. *Proceedings of the National Academy of Sciences*, **116**(35), 17193-17200.
Hong, E.-M., W.-H. Nam, J.-Y. Choi and Y. A. Pachepsky, 2016: Projected irrigation requirements for upland crops using soil moisture model under climate change in South Korea. *Agricultural Water Management*, **165**, 163-180, doi:https://doi.org/10.1016/j.agwat.2015.12.003.
Hong, H., J. Liu and A.-X. Zhu, 2019b: Landslide susceptibility evaluating using artificial intelligence method in the Youfang district (China). *Environmental Earth Sciences*, **78**(15), 488, doi:10.1007/s12665-019-8415-9.
Hong, J.-W., J. Hong, E. E. Kwon and D. K. Yoon, 2019c: Temporal dynamics of urban heat island correlated with the socio-economic development over the past half-century in Seoul, Korea. *Environmental Pollution*, **254**, 112934, doi:https://doi.org/10.1016/j.envpol.2019.07.102.
Hoque, M. A. et al., 2016: Drinking water vulnerability to climate change and alternatives for adaptation in coastal South and South East Asia. *Climatic Change*, **136**(2), 247-263, doi:10.1007/s10584-016-1617-1.
Hori, K. et al., 2020: Projecting population distribution under depopulation conditions in Japan: scenario analysis for future socio-ecological systems. *Sustainability Science*, doi:10.1007/s11625-020-00835-5.
Hossain, B., M. S. Sohel and C. M. Ryakitimbo, 2020: Climate Change Induced Extreme Flood Disaster in Bangladesh: Implications on People's Livelihoods in the Char Village and Their Coping Mechanisms. *Progress in Disaster Science*, **6**.

Hossain, M. S. et al., 2019: Economic impact of climate change on crop farming in Bangladesh: An application of Ricardian method. *Ecological Economics*, **164**, 106354.
Hossain, M. S. et al., 2018: Climate change and crop farming in Bangladesh: an analysis of economic impacts. *International Journal of Climate Change Strategies and Management*.
Hou, L., J. Huang and J. Wang, 2017: Early warning information, farmers' perceptions of, and adaptations to drought in China. *Climatic Change*, **141**(2), 197-212, doi:10.1007/s10584-017-1900-9.
Houmsi, M. R. et al., 2019: Spatial shift of aridity and its impact on land use of Syria. *Sustainability*, **11**(24), doi:https://doi.org/doi:10.3390/su11247047.
Howells, M. et al., 2013: Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, **3**(7), 621-626.
Hu, F. and D. Tan, 2018: No water, no growth: Does Asia have enough water to develop. Hong Kong: China Water Risk.
Hu, S. and J. Chen, 2016: Place-based inter-generational communication on local climate improves adolescents' perceptions and willingness to mitigate climate change. *Climatic change*, **138**(3-4), 425-438.
Hu, X. et al., 2019: Methodology and Findings for the Exposure Analysis of the Chinese Wastewater Sector to Flooding and Earthquakes Hazards.
Hu, Z. et al., 2017: Variations and changes of annual precipitation in Central Asia over the last century. *International Journal of Climatology*, **37**(S1), 157-170, doi:10.1002/joc.4988.
Huang, C. et al., 2016: Effects of snow thickness on the abundance of archaeal and bacterial amoA genes and gene transcripts during dwarf bamboo litter decomposition in an alpine forest on the eastern Tibetan Plateau. *Russian Journal of Ecology*, **47**(4), 419-429, doi:10.1134/s106741361604010x.
Huang, D. W. et al., 2015a: Extraordinary diversity of reef corals in the South China Sea. *Mar. Biodivers.*, **45**(2), 157-168, doi:10.1007/s12526-014-0236-1.
Huang, Y. et al., 2020: Nature-based solutions for urban pluvial flood risk management. *Wiley Interdisciplinary Reviews: Water*, **7**(3), e1421.
Huang, Z. et al., 2015b: Individual-level and community-level effect modifiers of the temperature-mortality relationship in 66 Chinese communities. *BMJ open*, **5**(9), e009172, doi:10.1136/bmjopen-2015-009172.
Hufkens, K. et al., 2019: Monitoring crop phenology using a smartphone based near-surface remote sensing approach. *Agricultural and forest meteorology*, **265**, 327-337.
Hughes, T. P. et al., 2017: Global warming and recurrent mass bleaching of corals. *Nature*, **543**(7645), 373-+, doi:10.1038/nature21707.
Hughes, T. P. et al., 2018: Global warming transforms coral reef assemblages. *Nature*, **556**(7702), 492-+, doi:10.1038/s41586-018-0041-2.
Hung, H.-C., Y.-T. Lu and C.-H. Hung, 2018: The determinants of integrating policy-based and community-based adaptation into coastal hazard risk management: a resilience approach. *Journal of Risk Research*, 1-19, doi:10.1080/13669877.2018.1454496.
Husnayaen et al., 2018: Physical assessment of coastal vulnerability under enhanced land subsidence in Semarang, Indonesia, using multi-sensor satellite data. *Advances in Space Research*, **61**(8), 2159-2179, doi:10.1016/j.asr.2018.01.026.
Huss, M. and R. Hock, 2018: Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, **8**(2), 135-140.
Hussain, A., B. Mahapatra and G. Rasul, 2019: Adaptation in Mountain Agriculture: Food Security in the Hindu-Kush Himalayan (HKH) Region. In: *Status of Climate Change Adaptation in Asia and the Pacific*, pp. 211-236.
Hussey, K. and J. Pittock, 2012: The Energy–Water Nexus: Managing the Links between Energy and Water for a Sustainable Future. *Ecology and Society*, **17**(1), doi:10.5751/es-04641-170131.
Hutchison, J. et al., 2014: Predicting Global Patterns in Mangrove Forest Biomass. *Conservation Letters*, **7**(3), 233-240, doi:10.1111/conl.12060.
Huynh, L. T. M. and L. C. Stringer, 2018: Multi-scale assessment of social vulnerability to climate change: An empirical study in coastal Vietnam. *Climate Risk Management*, **20**, 165-180, doi:https://doi.org/10.1016/j.crm.2018.02.003.
Ibarbalz, F. M. et al., 2019: Global Trends in Marine Plankton Diversity across Kingdoms of Life. *Cell*, **179**(5), 1084-+, doi:10.1016/j.cell.2019.10.008.
Ichii, T. et al., 2017: Impacts of extensive driftnet fishery and late 1990s climate regime shift on dominant epipelagic nekton in the Transition Region and Subtropical Frontal Zone: Implications for fishery management. *Progress in Oceanography*, **150**, 35-47, doi:10.1016/j.pocean.2015.03.007.
Icimod, 2011: *Glacial Lakes and Glacial Lake Outburst Floods in Nepal*. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, 99 pp. Available at: http://lib.icimod.org/record/27755 (accessed 22/09/2020).
ICLEI, 2014a: *Urban NEXUS Case Study 2014 - 02, Nashik, India*. Available at: http://old.iclei.org/fileadmin/PUBLICATIONS/Case_Studies/Urban_NEXUS_cs02_Nashik_ICLEI-GIZ_2014.pdf.

ICLEI, 2014b: *Urban NEXUS Case Study 2014 - 05, Tianjin Eco-City, China*. Available at: http://old.iclei.org/fileadmin/PUBLICATIONS/Case_Studies/Urban_NEXUS_cs05_Tianjin_ICLEI-GIZ_2014.pdf.
Ide, T., A. Kristensen and H. Bartusevičius, 2021: First comes the river, then comes the conflict? A qualitative comparative analysis of flood-related political unrest. *Journal of Peace Research*, **58**(1), 83-97, doi:10.1177/0022343320966783.
IDMC, 2019: *GRID Report*.
IDMC, 2020: *Global Report on Internal Displacement 2020*. IDMC. Available at: https://www.internal-displacement.org/global-report/grid2020/.
IEA, 2017: *Southeast Asia Energy Outlook 2017*. World Energy Outlook Special Report. Available at: https://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_SoutheastAsiaEnergyOutlook.pdf.
IEA, 2018: *World Energy Outlook 2018 Paris*.
IEEJ, 2018: *IEEJ Outlook 2019: Energy transition and a thorny path for 3E challenges*.
IFAD, 2017: Remote sensing for index insurance: Findings and lessons learned for smallholder agriculture. 174.
IGES (ed.), 1.5 Degree Lifestyles: Targets and options for reducing lifestyle carbon footprints. ISBN 9784887882201.
Iizuka, K. et al., 2017: Modeling Future Urban Sprawl and Landscape Change in the Laguna de Bay Area, Philippines. *Land*, **6**(2), doi:10.3390/land6020026.
Iizumi, T., 2019: Emerging Adaptation to Climate Change in Agriculture. In: *Adaptation to Climate Change in Agriculture: Research and Practices* [Iizumi, T., R. Hirata and R. Matsuda (eds.)]. Springer Singapore, Singapore, pp. 3-16. ISBN 978-981-13-9235-1.
Iizumi, T. and N. Ramankutty, 2015: How do weather and climate influence cropping area and intensity? *Global Food Security*, **4**, 46-50, doi:https://doi.org/10.1016/j.gfs.2014.11.003.
ILO, 2015: *Value chain analysis and competitiveness strategy: Marine capture fisheries*. International Labour Organization, Myeik and Yangon. Available at: https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---emp_ent/documents/publication/wcms_446510.pdf.
ILO, 2017a: *World of work report 2014: Developing with jobs*. International Labour Organization, Geneva, Switzerland. Available at: https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/documents/publication/wcms_243961.pdf.
ILO, 2017b: *World Social Protection Report 2017-19: Universal social protection to achieve the Sustainable Development Goals*. International Labour Office, Geneva.
Im, E.-S., J. S. Pal and E. A. Eltahir, 2017: Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science advances*, **3**(8), e1603322.
Imada, Y. et al., 2018: Climate Change Increased the Likelihood of the 2016 Heat Extremes in Asia. *Bulletin of the American Meteorological Society*, **99**(1), S97-S101, doi:10.1175/bams-d-17-0109.1.
Imada, Y. et al., 2019: The July 2018 high temperature event in Japan could not have happened without human-induced global warming. *SOLA*, 15A-002.
Imaduddina, A. H. and W. W. H. Subagyo, 2014: Sea Level Rise Flood Zones: Mitigating Floods in Surabaya Coastal Area. *Procedia-Social and Behavioral Sciences* **135**, 123-129, doi:10.1016/j.sbspro.2014.07.335.
Imai, K. S. and B. Malaeb, 2018: Asia's rural-urban disparity in the context of growing inequality. IFAD Research Series, 30-30 pp.
IMF, 2018: IMF Annual Report 2018.
Immerzeel, W. W. et al., 2020: Importance and vulnerability of the world's water towers. *Nature*, doi:10.1038/s41586-019-1822-y.
Inaoka, M., K. Takeya and S. Akiyama, 2019: JICA's policies, experiences and lessons learned on impacts of urban floods in Asia. *International Journal of Water Resources Development*, **35**(2), 343-363, doi:10.1080/07900627.2018.1444980.
Inaotombi, S. and P. C. Mahanta, 2018: Pathways of socio-ecological resilience to climate change for fisheries through indigenous knowledge. *Human and Ecological Risk Assessment: An International Journal*, 1-13, doi:10.1080/10807039.2018.1482197.
Ingole, V., J. Rocklov, S. Juvekar and B. Schumann, 2015: Impact of Heat and Cold on Total and Cause-Specific Mortality in Vadu HDSS--A Rural Setting in Western India. *Int J Environ Res Public Health*, **12**(12), 15298-15308, doi:10.3390/ijerph121214980.
IPBES, 2018: The IPBES regional assessment report on biodiversity and ecosystem services for Asia and the Pacific.
IPCC, 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L. (ed.)]. Cambridge University Press, Cambridge, United Kingdom, 976 pp. ISBN 9780521880107.
IPCC, 2014a: *Climate change 2014: Impacts, adaptation, and vulnerability*. IPCC, Geneva.
IPCC, 2014b: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
IPCC, 2014c: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.

R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

IPCC, 2018a: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., Zhai, P., H.-O. Portner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, Moufouma-Okia, W., C. Pean, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, Gomis, M.I., E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.

IPCC, 2018b: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [V. Masson-Delmotte, P. Z., H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (ed.)]. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_version_stand_alone_LR.pdf.

IPCC, 2021a: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

IPCC, 2021b: *Working Group 2, Chapter 2: Terrestrial and Freshwater Ecosystems and their Services, 6th assessment report*.

Iqbal, M. W., S. Donjadee, B. Kwanyuen and S. Liu, 2018: Farmers' perceptions of and adaptations to drought in Herat Province, Afghanistan. *Journal of Mountain Science*, **15**(8), 1741-1756, doi:10.1007/s11629-017-4750-z.

Isaev, A. S. and G. N. Korovin, 2013: Forests as a national treasure of Russia. *Contemporary Problems of Ecology*, **6**(7), 677-682, doi:10.1134/S1995425513070056.

Iseman, T. and F. Miralles-Wilhelm, 2021: *Nature-based solutions in agriculture – The case and pathway for adoption*. FAO and The Nature Conservancy, Virginia. Available at: http://www.fao.org/3/cb3141en/cb3141en.pdf.

Ishigooka, Y. et al., 2017: Large-scale evaluation of the effects of adaptation to climate change by shifting transplanting date on rice production and quality in Japan. *農業気象*, **73**(4), 156-173, doi:10.2480/agrmet.D-16-00024.

Ishiwatari, M. and A. Surjan, 2020: Good Enough Today is Not Enough Tomorrow: Challenges of Increasing Investments in Disaster Risk Reduction and Climate Change Adaptation. *Progress in Disaster Science*.

Isik, O. et al., 2015: Are women in Turkey both risks and resources in disaster management? *Int J Environ Res Public Health*, **12**(6), 5758-5774, doi:10.3390/ijerph120605758.

Islam, A., S. Islam and A. Wahab, 2016a: Impacts of climate change on shrimp farming in the South-West coastal region of Bangladesh. *Research in Agriculture, Likestock and fisheries*, **3**(1), 227-239.

Islam, A. R. M. T., S.-H. Shen and S.-B. Yang, 2018: Predicting design water requirement of winter paddy under climate change condition using frequency analysis in Bangladesh. *Agricultural Water Management*, **195**, 58-70, doi:10.1016/j.agwat.2017.10.003.

Islam, M. R., V. Ingham, J. Hicks and I. Manock, 2016b: The changing role of women in resilience, recovery and economic development at the intersection of recurrent disaster: A case study from Sirajgang, Bangladesh. *Journal of Asian and African Studies*, **52**(1), 50-67, doi:10.1177/0021909614560244.

Islam, M. S. and Y. Zhang, 2019: The Potential of Strategic Environmental Assessment to Reduce Disaster Risks Through Climate Change Adaptation in the Coastal Zone of Bangladesh. *International Journal of Climate Change Strategies and Management*, **11**(1), 137-153.

Islam, S., C. Chu and J. Smart, 2020: Challenges in integrating disaster risk reduction and climate change adaptation: exploring the Bangladesh case. *International journal of disaster risk reduction*, 101540.

Ito, A., K. Nishina and H. M. Noda, 2016: Evaluation of global warming impacts on the carbon budget of terrestrial ecosystems in monsoon Asia: a multi-model analysis. *Ecological Research*, **31**(3), 459-474, doi:10.1007/s11284-016-1354-y.

Iturrizaga, L., 2019: Historical beacon fire lines as early warning systems for glacier lake outbursts in the Hindu Kush–Karakoram Mountains. *Natural Hazards*, **99**(1), 39-70.

IUC, FutureCity Yokohama - Yokohama Smart City Project. Available at: http://www.iuc.eu/japan-en/bestpractice/yokohama/.

Ivanova, G. A., V. A. Ivanov, E. A. Kukavskaya and A. J. Soja, 2010: The frequency of forest fires in Scots pine stands of Tuva, Russia. *Environmental Research Letters*, **5**(1), doi:10.1088/1748-9326/5/1/015002.

Izumi, T. et al., 2019: Disaster Risk Reduction and Innovations. *Progress in Disaster Science*, **2**.

Jacobson, C., S. Crevello, C. Chea and B. Jarihani, 2019: When is migration a maladaptive response to climate change? *Regional Environmental Change*, **19**(1), 101-112, doi:10.1007/s10113-018-1387-6.

Jafari, A., M. Torabi Azad and S. Sohrabi, 2016: The study of temperature increases effects due to global climate change on the Mean Sea Level (MSL) in the north coasts of Persian Gulf (Hormozgan province). *Journal of Environmental Science and Technology*, **18**(3), 81-97.

Jain, G., 2013: The Role of Private Sector for Disaster Risk Reduction in Large Scale Infrastructure and Real Estate Development - The Case of Delhi. Indian Institute for Human Settlements, Bangalore.
Jain, G., C. Singh and T. Malladi, 2021: (Re)creating disasters – A case of post-disaster resettlements in Chennai (forthcoming). In: *Rethinking Urban Risk and Relocation* [Johnson, C., G. Jain and A. Lavell (eds.)]. UCL Press, London.
Jamero, M. L. et al., 2017: Small-Island Communities in the Philippines Prefer Local Measures to Relocation in Response to Sea-Level Rise. *Nature Climate Change*, **7**, 581-586.
James, H., 2019: *Women, Water and 'Wicked Problems': Community Resilience and Adaptation to Climate Change in Northern Pakkoku, Myanmar*. Population, Development, and the Environment, Palgrave Macmillan, Singapore.
Jamodiong, E. A. et al., 2018: Coral spawning and spawn-slick observation in the Philippines. *Mar. Biodivers.*, **48**(4), 2187-2192, doi:10.1007/s12526-017-0680-9.
Jamshidi, O. et al., 2019: Vulnerability to climate change of smallholder farmers in the Hamadan province, Iran. *Climate Risk Management*, **23**, 146-159, doi:10.1016/j.crm.2018.06.002.
Jat, M. L. et al., 2016: Chapter Three - Climate Change and Agriculture: Adaptation Strategies and Mitigation Opportunities for Food Security in South Asia and Latin America. In: *Advances in Agronomy* [Sparks, D. L. (ed.)]. Academic Press, pp. 127-235. ISBN 0065-2113.
Jawid, A. and M. Khadjavi, 2019: Adaptation to climate change in Afghanistan: Evidence on the impact of external interventions. *Economic Analysis and Policy* **64**, 64–82, doi:https://doi.org/10.1016/j.eap.2019.07.010.
Jayanthi, M. et al., 2018: Spatial and temporal changes in mangrove cover across the protected and unprotected forests of India. *Estuarine, Coastal and Shelf Science*, **213**, 81-91, doi:10.1016/j.ecss.2018.08.016.
Jenny, J.-P. et al., 2020: Scientists' warning to humanity: rapid degradation of the world's large lakes. *Journal of Great Lakes Research*, **46**(4), 686-702.
Jenssen, B. M. et al., 2015: Anthropogenic flank attack on polar bears: interacting consequences of climate warming and pollutant exposure. *Frontiers in Ecology and Evolution*, **3**(16), doi:10.3389/fevo.2015.00016.
Jevrejeva, S. et al., 2018: Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C. *Environmental Research Letters*, **17**(7), doi:https://doi.org/10.1088/1748-9326/aacc76.
Jevrejeva, S. et al., 2016: Coastal sea level rise with warming above 2 °C. *Proceedings of the National Academy of Sciences*, **113**(47), 13342-13347, doi:https://doi.org/10.1073/pnas.1605312113.
Jeyabaskaran, R. et al., 2018: Conservation of seagrass beds with special reference to associated species and fishery resources, Journal of the Marine Biological Association of India, 62-70 pp.
Jha, C. K., V. Gupta, U. Chattopadhyay and B. A. Sreeraman, 2018: Migration as adaptation strategy to cope with climate change. *International Journal of Climate Change Strategies and Management*.
Jha, R. K. and H. Gundimeda, 2019: An integrated assessment of vulnerability to floods using composite index – A district level analysis for Bihar, India. *International Journal of Disaster Risk Reduction*, **35**, doi:https://doi.org/10.1016/j.ijdrr.2019.101074.
Jia, G. et al., 2019: *IPCC Special Report on Climate Change and Land (SRCCL) final government distribution, chapter 2: land-climate interactions*. Available at: https://www.ipcc.ch/site/assets/uploads/2019/08/2c.-Chapter-2_FINAL.pdf (Downloaded 2019-08-16).
Jiang, L. et al., 2019: Assessment of frozen ground organic carbon pool on the Qinghai-Tibet Plateau. *Journal of Soils and Sediments*, **19**(1), 128-139, doi:10.1007/s11368-018-2006-3.
Jiang, T.-t. et al., 2015: Current status of coastal wetlands in China: degradation, restoration, and future management. *Estuarine, Coastal and Shelf Science*, **164**, 265-275.
Jiang, X. et al., 2016: Estimation of property loss and business interruption loss caused by storm surge inundation due to climate change: a case of Typhoon Vera revisit. *Natural Hazards*, **84**(1), 35-49.
Jiang, Y., Y. Luo and Z. Zhao, 2013: Maximum wind speed changes over China. *Acta Meteorologica Sinica*, **27**(1), 63-74, doi:10.1007/s13351-013-0107-x.
Jiang, Y., C. Zevenbergen and Y. Ma, 2018: Urban pluvial flooding and stormwater management: A contemporary review of China's challenges and "sponge cities" strategy. *Environmental Science and Policy*, **80**(September 2017), 132-143, doi:10.1016/j.envsci.2017.11.016.
Jianjun, J., G. Yiwei, W. Xiaomin and P. K. Nam, 2015: Farmers' risk preferences and their climate change adaptation strategies in the Yongqiao District, China. *Land Use Policy*, **47**, 365-372, doi:10.1016/j.landusepol.2015.04.028.
Jiao, F., X. R. Shi, F. P. Han and Z. Y. Yuan, 2016: Increasing aridity, temperature and soil pH induce soil C-N-P imbalance in grasslands. *Sci Rep*, **6**, doi:10.1038/Srep19601.
JMA, 2018: *Climate Change Monitoring Report*. Japan Meteorological Agency.
Jogesh, A. and N. K. Dubash, 2015: State-led experimentation or centrally-motivated replication? A study of state action plans on climate change in India. *Journal of Integrative Environmental Sciences*, **12**(4), 247-266, doi:10.1080/1943815x.2015.1077869.
Johnson, B. A. and K. Iizuka, 2016: Integrating OpenStreetMap crowdsourced data and Landsat time-series imagery for rapid land use/land cover (LULC) mapping: Case study of the Laguna de Bay area of the Philippines. *Applied Geography*, **67**, 140-149, doi:10.1016/j.apgeog.2015.12.006.
Johnson, B. A., A. D. Mader, R. Dasgupta and P. Kumar, 2020: Citizen science and invasive alien species: An analysis of citizen science initiatives using information and communications technology (ICT) to collect invasive alien species observations. *Global Ecology and Conservation*, **21**, doi:10.1016/j.gecco.2019.e00812.

Johnson, C. et al., 2013: *Understanding the nature and scale of urban risk in low- and middle- income countries and its implications for humanitarian preparedness , planning and response*. ISBN 9781843699156.
Jones, N., R. Holmes, E. Presler-Marshall and M. Stavropoulou, 2017: Transforming gender constraints in the agricultural sector: The potential of social protection programmes. *Global Food Security*, **12**, 89-95, doi:https://doi.org/10.1016/j.gfs.2016.09.004.
Jordan, K. o., Hashemite Kingdom of Jordan Intended Nationally Determined Contribution (INDC) (Arabic & English). Available at: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Jordan%20First/Jordan%20INDCs%20Final.pdf.
Jörgensen, K., A. Jogesh and A. Mishra, 2015: Multi-level climate governance and the role of the subnational level. *Journal of Integrative Environmental Sciences*, **12**(4), 235-245, doi:10.1080/1943815x.2015.1096797.
Joshi, N. et al., 2016: A Review of the Application of Optical and Radar Remote Sensing Data Fusion to Land Use Mapping and Monitoring. *Remote Sensing*, **8**(1), doi:10.3390/rs8010070.
Joshi, S., 2014: Environmental justice discourses in Indian climate politics. *GeoJournal*, doi:https://doi.org/10.1007/s10708-014-9545-y.
Ju, H. et al., 2013: Climate Change Modelling and Its Roles to Chinese Crops Yield. *Journal of Integrative Agriculture*, **12**(5), 892-902, doi:https://doi.org/10.1016/S2095-3119(13)60307-X.
Jung, M.-P., K.-M. Shim, Y. Kim and I.-T. Choi, 2015: Change of Climatic Growing Season in Korea. *Korean Journal of Environmental Agriculture*, **34**(3), 192-195, doi:KJEA-34-192.
Juswanto, W. and S. A. Nugroho, 2017: Promoting Disaster Risk Financing in Asia and the Pacific.
Kääb, A. et al., 2018: Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nat. Geosci.*, **11**(2), 114-+, doi:10.1038/s41561-017-0039-7.
Kaczan, D. J. and J. Orgill-Meyer, 2020: The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change*, **158**(3), 281-300.
Kafash, A. et al., 2016: Ensemble distribution modeling of the Mesopotamian spiny-tailed lizard, Saara loricata (Blanford, 1874), in Iran: an insight into the impact of climate change. *Turk J Zool*, **40**(2), 262-271, doi:10.3906/zoo-1504-10.
Kais, S. M. and M. S. Islam, 2018: Impacts of and resilience to climate change at the bottom of the shrimp commodity chain in Bangladesh: A preliminary investigation. *Aquaculture*, **493**, 406-415, doi:10.1016/j.aquaculture.2017.05.024.
Kameyama, Y., K. Morita and I. Kubota, 2016: Finance for achieving low-carbon development in Asia: the past, present, and prospects for the future. *Journal of cleaner production*, **128**, 201-208.
Kanak Pervez, A., Q. Gao and M. E. Uddin, 2015: Rural women's awareness on indigenous technical knowledge: case of northern Bangladesh. *The Anthropologist*, **21**(3), 415-426.
Kanamori, Y., A. Takasuka, S. Nishijima and H. Okamura, 2019: Climate change shifts the spawning ground northward and extends the spawning period of chub mackerel in the western North Pacific. *Mar. Ecol.-Prog. Ser.*, **624**, doi:10.3354/meps13037.
Kang, S. and E. A. B. Eltahir, 2018: North China Plain threatened by deadly heatwaves due to climate change and irrigation. *Nature communications*, **9**(1), 1-9.
Karanth, A. and D. Archer, 2014: Institutionalising mechanisms for building urban climate resilience: experiences from India. *Development in Practice*, **24**(4), 514-526, doi:10.1080/09614524.2014.911246.
Karthe, D. et al., 2017: Water in Central Asia: an integrated assessment for science-based management. Springer.
Katherine Brickell, F. P., Nithya Natarajan, Vincent Guermond, Laurie Parsons, Giacomo Zanello, Milford Bateman, 2020: Compounding crises of social reproduction: Microfinance, over-indebtedness and the COVID-19 pandemic. *World Development*, **136**, doi:https://doi.org/10.1016/j.worlddev.2020.105087.
Kato, A. et al. (eds.), Tropical forest disaster monitoring with multi-scale sensors from terrestrial laser, UAV, to satellite radar. 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 23-28 July 2017, 2883-2886 pp. ISBN 2153-7003.
Kattsov, V. M. and S. M. Semenov, 2014: *Second Roshydromet assessment report on climate change and its consequences in Russian Federation. General Summary.*, Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet), Moscow, Russia.
Kelley, C. P. et al., 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences*, **112**(11), 3241, doi:10.1073/pnas.1421533112.
Keshavarz, M. and E. Karami, 2016: Farmers' pro-environmental behavior under drought: Application of protection motivation theory. *Journal of Arid Environments*, **127**, 128-136, doi:10.1016/j.jaridenv.2015.11.010.
Khaling, S. et al., 2018: Progress on integrating climate change adaptation and disaster risk reduction for sustainable development pathways in South Asia: Evidence from six research projects. *International Journal of Disaster Risk Reduction*, **31**(May), 92-101, doi:10.1016/j.ijdrr.2018.04.023.
Khan, A. M. et al., 2020: Economic Effects of Climate Change-Induced Loss of Agricultural Production by 2050: A Case Study of Pakistan. *Sustainability*, **12**(3), doi:https://doi.org/10.3390/su12031216.
Khan, M. R., 2017: Capacity building for climate change. (accessed 18 April 2019).
Khanal, S. et al., 2021: Variable 21st century climate change response for rivers in High Mountain Asia at seasonal to decadal time scales. *Water Resources Research*, e2020WR029266.

Khanal, U., C. and Wilson, 2019: Derivation of a climate change adaptation index and assessing determinants and barriers to adaptation among farming households in Nepal. *Environmental Science and Policy*, **101**, 156-165, doi:https://doi.org/10.1016/j.envsci.2019.08.006.
Khanal, U., C. Wilson, V.-N. Hoang and B. Lee, 2018: Farmers' adaptation to climate change, its determinants and impacts on rice yield in Nepal. *Ecological Economics*, **144**, 139-147.
Khanna, A., 2020: Impact of Migration of Labour Force due to Global COVID-19 Pandemic with Reference to India. *Journal of Health Management*, **22**(2), 181-191, doi:doi:10.1177/0972063420935542

Khansaritoreh, E. et al., 2017: Higher climate warming sensitivity of Siberian larch in small than large forest islands in the fragmented Mongolian forest steppe. *Global Change Biology*, **23**(9), 3675-3689, doi:https://doi.org/10.1111/gcb.13750.
Kharuk, V. I. et al., 2017a: Tree wave migration across an elevation gradient in the Altai Mountains, Siberia. *Journal of Mountain Science*, **14**(3), 442-452, doi:10.1007/s11629-016-4286-7.
Kharuk, V. I., S. T. Im, K. J. Ranson and M. N. Yagunov, 2017b: Climate-Induced Northerly Expansion of Siberian Silkmoth Range. *Forests*, **8**(8), doi:10.3390/f8080301.
Kharuk, V. I., S. T. Im and V. V. Soldatov, 2020: Siberian silkmoth outbreaks surpassed geoclimatic barrier in Siberian Mountains. *Journal of Mountain Science*, **17**(8), 1891-1900, doi:10.1007/s11629-020-5989-3.
Kharuk, V. I. et al., 2018: Comparative Reaction of Larch (*Larix sibirica Ledeb.*) Radial Increment on Climate Change in the Forest Steppe and Highlands of Southern Siberia. *Contemporary Problems of Ecology*, **11**(4), 388-395, doi:10.1134/S1995425518040042.
Kharuk, V. I. and E. I. Ponomarev, 2017: Spatiotemporal characteristics of wildfire frequency and relative area burned in larch-dominated forests of Central Siberia. *Russian Journal of Ecology*, **48**(6), 507-512, doi:10.1134/s1067413617060042.
Khatri-Chhetri, A., P. K. Aggarwal, P. K. Joshi and S. Vyas, 2017: Farmers' prioritization of climate-smart agriculture (CSA) technologies. *Agricultural Systems*, **151**, 184-191, doi:https://doi.org/10.1016/j.agsy.2016.10.005.
Khishigjargal, M. et al., 2013: Contrasting responses of seedling and sapling densities to livestock density in the Mongolian forest-steppe. *Plant Ecology*, **214**(11), 1391-1403, doi:10.1007/s11258-013-0259-x.
Khormi, H. and L. Kumar, 2016: Future malaria spatial pattern based on the potential global warming impact in South and Southeast Asia. *Geospatial Health*, **11**(3), 416, doi:doi: 10.4081/gh.2016.416.
Khosla, R. and A. Bhardwaj, 2019: Urbanization in the time of climate change: Examining the response of Indian cities. *Wiley Interdiscip. Rev. Clim. Change* **10**(e560), doi:doi:10.1002/wcc.560.
Kicklighter, D. W. et al., 2014: Potential influence of climate-induced vegetation shifts on future land use and associated land carbon fluxes in Northern Eurasia. *Environmental Research Letters*, **9**(3), doi:10.1088/1748-9326/9/3/035004.
Kilroy, G., 2015: A review of the biophysical impacts of climate change in three hotspot regions in Africa and Asia. *Regional Environmental Change*, **15**(5), 771-782, doi:10.1007/s10113-014-0709-6.
Kim, B.-T., C. L. Brown and D.-H. Kim, 2019a: Assessment on the vulnerability of Korean aquaculture to climate change. *Marine Policy*, **99**, 111-122, doi:10.1016/j.marpol.2018.10.009.
Kim, D.-W., R. C. Deo, J.-H. Chung and J.-S. Lee, 2016a: Projection of heat wave mortality related to climate change in Korea. *Natural Hazards*, **80**(1), 623-637.
Kim, D. et al., 2019b: Comparing effects of untreated and treated wastewater on riverine greenhouse gas emissions. *APN Science Bulletin*, doi:10.30852/sb.2019.872.
Kim, D. and J. Lee, 2020: Spatial changes in work capacity for occupations vulnerable to heat stress: Potential regional impacts from global climate change. *Safety and Health at Work*, **11**(1), 1-9, doi:https://doi.org/10.1016/j.shaw.2019.10.004.
Kim, E.-S., J.-S. Lee, G.-E. Park and J.-H. Lim, 2019c: Change of Subalpine Coniferous Forest Area over the Last 20 Years. *Journal of Korean Society of Forest Science*, **108**(1), 10-20, doi:10.14578/JKFS.2019.108.1.10.
Kim, E. J. and H. Kim, 2017: Effect modification of individual- and regional-scale characteristics on heat wave-related mortality rates between 2009 and 2012 in Seoul, South Korea. *Sci Total Environ*, **595**, 141-148, doi:10.1016/j.scitotenv.2017.03.248.
Kim, J.-Y. and I.-S. Han, 2017: Sea Surface Temperature Time Lag Due to the Extreme Heat Wave of August 2016, Journal of the Korean Society of Marine Environment & Safety, 677-683 pp.
Kim, J., S. Jeong and S. Son, 2019d: A National-level Study on Plant Phenology across Forest Region of South Korea during the last decade. December 01, 2019, **2019**, pp. B33K-2628.
Kim, J., H. Jung and Y. H. Park, 2016b: Predicting Potential Distribution of Monochamus alternatus Hope responding to Climate Change in Korea. *Korean Journal of Applied Entomology*, 501-511, doi:10.5656/KSAE.2016.11.0.053.
Kim, K.-G., 2017: Development of an integrated smart water grid model as a portfolio of climate smart cities. *Journal of Smart Cities*, **3**, 23-34.
Kim, S. E. et al., 2020: Air quality co-benefits from climate mitigation for human health in South Korea. *Environ Int*, **136**, 105507, doi:10.1016/j.envint.2020.105507.
Kim, Y. et al., 2016c: Suicide and Ambient Temperature in East Asian Countries: A Time-Stratified Case-Crossover Analysis. *Environmental health perspectives*, **124**(1), 75-80, doi:10.1289/ehp.1409392.

Kimura, F. and H. Phoumin, 2013: Energy Market Integration in EAST Asia: Energy Trade, Cross Border Electricity, and Price Mechanism. *Books*.
Kirby, J. et al., 2016: The impact of climate change on regional water balances in Bangladesh. *Climatic change*, **135**(3-4), 481-491.
Kirdyanov, A. V. et al., 2012: 20th century tree-line advance and vegetation changes along an altitudinal transect in the Putorana Mountains, northern Siberia. *Boreas*, **41**(1), 56-67, doi:10.1111/j.1502-3885.2011.00214.x.
Kiseleva, N. V., 2020: Long-term Population Dynamics of the Bank Vole in the Ilmen Nature Reserve. *Russian Journal of Ecology*, **51**(2), 188-194, doi:10.1134/S1067413620020071.
Kissinger, G., A. Gupta, I. Mulder and N. Unterstell, 2019: Climate financing needs in the land sector under the Paris Agreement: An assessment of developing country perspectives. *Land Use Policy*, **83**, 256-269.
Kitamura, Y., 2017: *Education for Sustainable Development (ESD) in Asia*.
Kittipongvises, S. and T. Mino, 2015: Perception and Communication of Flood Risk: Lessons Learned about Thailand's Flood Crisis of 2011. *https://www.tci-thaijo.org/index.php/aer*, **37**(1), doi:https://www.tci-thaijo.org/index.php/aer/article/view/30895.
Klinge, M. et al., 2018: Climate effects on vegetation vitality at the treeline of boreal forests of Mongolia. *Biogeosciences*, **15**(5), 1319-1333, doi:10.5194/bg-15-1319-2018.
Klinsky, S. et al., 2017: Why equity is fundamental in climate change policy research. *Global Environmental Change*, **44**, 170-173, doi:https://doi.org/10.1016/j.gloenvcha.2016.08.002.
Klonner, S. a. O., C, 2014: Safety Net for India's Poor or Waste of Public Funds? Poverty and Welfare in the Wake of the World's Largest Job Guarantee Program.
Klorvuttimontara, S., C. Tumpeesuwan and S. Tumpeesuwan, 2017: Distribution range and extinction risk of tree snail subgenus Amphidromus (Pulmonata: Camaenidae) in Thailand. *Raffles B Zool*, **65**, 189-197.
Knowlton, K. et al., 2014: Development and implementation of South Asia's first heat-health action plan in Ahmedabad (Gujarat, India). *International journal of environmental research and public health*, **11**(4), 3473-3492, doi:10.3390/ijerph110403473.
Knutson, T. R. et al., 2015: Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate*, **28**(18), 7203-7224, doi:10.1175/jcli-d-15-0129.1.
Ko, C.-H. et al., 2017: Carbon sequestration potential via energy harvesting from agricultural biomass residues in Mekong River basin, Southeast Asia. *Renewable and Sustainable Energy Reviews*, **68**, 1051-1062, doi:10.1016/j.rser.2016.03.040.
Kobayashi, S. et al., 2015: The JRA-55 Reanalysis: General Specifications and Basic Characteristics. *Journal of the Meteorological Society of Japan. Ser. II*, **93**(1), 5-48, doi:10.2151/jmsj.2015-001.
Kobori, H. et al., 2012: The effects of climate change on the phenology of winter birds in Yokohama, Japan. *Ecological Research*, **27**(1), 173-180, doi:10.1007/s11284-011-0891-7.
Kodera, S. et al., 2019: Estimation of heat-related morbidity from weather data: A computational study in three prefectures of Japan over 2013–2018. *Environment International* **130**, doi:https://doi.org/10.1016/j.envint.2019.104907.
Kodikara, K. A. S. et al., 2017: Have mangrove restoration projects worked? An in-depth study in Sri Lanka. *Restoration Ecology*, **25**(5), 705-716, doi:10.1111/rec.12492.
Koehler, G., 2014: Introduction: Preliminary Reflections on Development and Welfare Policy. In: *Development and Welfare Policy in South Asia*. Routledge, Abingdon.
Koh, H. L. and S. Y. Teh, 2019: Climate Change Mitigation and Adaptation: Role of Mangroves in Southeast Asia. In: *Climate Action* [Leal Filho, W., A. M. Azul, L. Brandli, P. G. Özuyar and T. Wall (eds.)]. Springer International Publishing, Cham, pp. 1-13. ISBN 978-3-319-71063-1.
Kohler, T. and D. Maselli, 2009: *Mountains and climate change. From understanding to action*. Geographica Bernensia. ISBN 3905835169.
Koks, E. E. et al., 2019: A global multi-hazard risk analysis of road and railway infrastructure assets. *Nature communications*, **10**(1), 1-11.
Kongsager, R., B. Locatelli and F. Chazarin, 2016: Addressing climate change mitigation and adaptation together: A global assessment of agriculture and forestry projects. *Environmental management*, **57**(2), 271-282.
Koo, K. A. et al., 2018: Future distributions of warm-adapted evergreen trees, Neolitsea sericea and *Camellia japonica* under climate change: ensemble forecasts and predictive uncertainty. *Ecological Research*, **33**(2), 313-325, doi:10.1007/s11284-017-1535-3.
Korznikov, K. A., D. E. Kislov and P. V. Krestov, 2019: Modeling the bioclimatic range of tall herb communities in northeastern Asia. *Russian Journal of Ecology*, **50**(3), 241-248, doi:10.1134/s1067413619030093.
Kosec, K. and C. H. Mo, 2017: Aspirations and the role of social protection: Evidence from a natural disaster in rural Pakistan. *World Development*, **97**, 49-66, doi:10.1016/j.worlddev.2017.03.039.
Kothari, J., 2014: A Social Rights Model for Social Security: Learnings from India. *Verfassung und Recht in Übersee / Law and Politics in Africa, Asia and Latin America*, **47**(1), 5-21.
Kotharkar, R., A. Ramesh and A. Bagade, 2018: Urban Heat Island studies in South Asia: A critical review. *Urban Climate*, **24**, 1011-1026, doi:https://doi.org/10.1016/j.uclim.2017.12.006.

Kottawa-Arachchi, J. and M. Wijeratne, 2017: Climate climate change impacts on biodiversity and ecosystems in Sri Lanka: A REVIEW. *Nature Conservation Research*, **2**, 2-22, doi:10.24189/ncr.2017.042.
Kousky, C., 2014: Informing climate adaptation: A review of the economic costs of natural disasters. *Energy economics*, **46**, 576-592.
Kraaijenbrink, P., M. Bierkens, A. Lutz and W. Immerzeel, 2017: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, **549**(7671), 257.
Kripa, V. et al., 2018: Overfishing and Climate Drives Changes in Biology and Recruitment of the Indian Oil Sardine Sardinella longiceps in Southeastern Arabian Sea. *Frontiers in Marine Science*, **5**, doi:10.3389/fmars.2018.00443.
Krishnan, R. et al., 2019: Unravelling Climate Change in the Hindu Kush Himalaya: Rapid Warming in the Mountains and Increasing Extremes. In: *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People* [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer International Publishing, Cham, pp. 57-97. ISBN 978-3-319-92288-1.
Kubicek, A., B. Breckling, O. Hoegh-Guldberg and H. Reuter, 2019: Climate change drives trait-shifts in coral reef communities. *Sci Rep*, **9**, 10, doi:10.1038/s41598-019-38962-4.
Kuemmerlen, M. et al., 2015: An attack on two fronts: predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. *Freshwater Biol*, **60**(7), 1443-1458, doi:10.1111/fwb.12580.
Kuenzer, C. and V. Q. Tuan, 2013: Assessing the ecosystem services value of Can Gio Mangrove Biosphere Reserve: Combining earth-observation- and household-survey-based analyses, Applied Geography, 167-184 pp.
Kugler, N. R. and P. M. Sariego, 2016: "Climate change damages", conceptualization of a legal notion with regard to reparation under international law. *Climate Risk Management*, **13**, 103-111.
Kuhl, L. et al., 2021: Transformational Adaptation in the Context of Coastal Cities. *Annual Review of Environment and Resources*, **46**.
Kulmala, M. et al., 2015: Introduction: The Pan-Eurasian Experiment (PEEX) – multidisciplinary, multiscale and multicomponent research and capacity-building initiative. *Atmospheric Chemistry and Physics*, **15**(22), 13085-13096, doi:10.5194/acp-15-13085-2015.
Kulp, S. A. and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature communications*, **10**(1), 1-12.
Kumar, P., 2019: Numerical quantification of current status quo and future prediction of water quality in eight Asian megacities: challenges and opportunities for sustainable water management. *Environ Monit Assess*, **191**(6), 319, doi:10.1007/s10661-019-7497-x.
Kumar, P. et al., 2020: Participatory Approach for More Robust Water Resource Management: Case Study of the Santa Rosa Sub-Watershed of the Philippines. *Water*, **12**(4), doi:10.3390/w12041172.
Kumari Rigaud, K., Alex de Sherbinin, Bryan Jones, Jonas Bergmann, Viviane Clement, Kayly Ober, Jacob Schewe, Susana Adamo, Brent McCusker, Silke Heuser, and Amelia Midgley, 2018: *Groundswell: Preparing for Internal Climate Migration*. The World Bank, Bank, T. W., Washington DC.
Kun Jung, H. et al., 2017: The influence of climate regime shifts on the marine environment and ecosystems in the East Asian Marginal Seas and their mechanisms. *Deep Sea Research Part II: Topical Studies in Oceanography*, **143**, 110-120, doi:10.1016/j.dsr2.2017.06.010.
Kuriakose, A. T. et al., 2013: Climate-responsive social protection. *Development Policy Review*, **31**, o19-o34.
Kuwait, G. o., 2015: Kuwait's Intended Nationally Determined Contribution (INDC).
Kwan, S. C. et al., 2017: The carbon savings and health co-benefits from the introduction of mass rapid transit system in Greater Kuala Lumpur, Malaysia. *Journal of Transport & Health*, **6**, 187-200, doi:https://doi.org/10.1016/j.jth.2017.06.006.
Kwon, H.-j. and W.-r. Kim, 2015: The evolution of cash transfers in Indonesia: policy transfer and national adaptation. *Asia & the Pacific Policy Studies*, **2**(2), 425-440, doi:10.1002/app5.83.
Kwon, J.-W. et al., 2016: Emergency Department Visits for Asthma Exacerbation due to Weather Conditions and Air Pollution in Chuncheon, Korea: A Case-Crossover Analysis. *Allergy Asthma Immunol Res*, **8**(6), 512-521.
Kwon, T.-S. et al., 2021: Habitat change has greater effects than climate change on butterfly occurrence in South Korea. *Global Ecology and Conservation*, **26**, e01464, doi:https://doi.org/10.1016/j.gecco.2021.e01464.
Kyburz-Graber, R. S. a. t. e. e. a. r. I. S., R. B., Brody, M., Dillon, J., Wals, A. (Eds.), International handbook of research on environmental education (pp. 310-330). New York, NY: Routledge. , 2013: Socio-ecological approaches to environmental education and research. In: *International handbook of research on environmental education*. Routledge, New York, pp. 310-330.
Kythreotis, A. P. et al., 2019: Citizen Social Science for More Integrative and Effective Climate Action: A Science-Policy Perspective. *Frontiers in Environmental Science*, **7**, doi:10.3389/fenvs.2019.00010.
Læssøe, J. and Y. Mochizuki, 2015: Recent Trends in National Policy on Education for Sustainable Development and Climate Change Education. *Journal of Education for Sustainable Development*, **9**(1), 27-43, doi:10.1177/0973408215569112.
Lam, H. C.-y., A. M. Li, E. Y.-y. Chan and W. B. Goggins, 2016: The short-term association between asthma hospitalisations, ambient temperature, other meteorological factors and air pollutants in Hong Kong: a time-series study. *Thorax*, **71**(12), 1097, doi:10.1136/thoraxjnl-2015-208054.
Lam, V. W. Y. et al., 2019: Dealing with the effects of ocean acidification on coral reefs in the Indian Ocean and Asia. *Reg. Stud. Mar. Sci.*, **28**, 10, doi:10.1016/j.rsma.2019.100560.

Lama, P. D. and P. Becker, 2019: Conflicts in adaptation: case studies from Nepal and the Maldives. *Disaster Prevention and Management* **28**(3), 304-318, doi:10.1108/DPM-12-2018-0393.
Lassa, J. A., 2019: Negotiating Institutional Pathways for Sustaining Climate Change Resilience and Risk Governance in Indonesia. *Climate*, **7**(95), doi:10.3390 / cli7080095.
Lassa, J. A. and M. Sembiring, 2017: Towards Policy Integration of Disaster Risk, Climate Adaptation, and Development in ASEAN: A Baseline Assessment.
Lasslop, G. et al., 2019: Influence of fire on the carbon cycle and climate. *Current Climate Change Reports*, **5**(2), 112-123, doi:10.1007/s40641-019-00128-9.
Lauvset, S. K. et al., 2015: Trends and drivers in global surface ocean pH over the past 3 decades. *Biogeosciences*, **12**(5), 1285-1298, doi:10.5194/bg-12-1285-2015.
Lawford, R. et al., 2013: Basin perspectives on the water–energy–food security nexus. *Current Opinion in Environmental Sustainability*, **5**(6), 607-616.
Le Dang, H., E. Li, I. Nuberg and J. Bruwer, 2014: Farmers' perceived risks of climate change and influencing factors: A study in the Mekong Delta, Vietnam. *Environmental Management*, **54**(2), 331-345, doi:10.1007/s00267-014-0299-6.
Le, M.-H., K. V. Dinh, M. V. Nguyen and I. Rønnestad, 2020: Combined effects of a simulated marine heatwave and an algal toxin on a tropical marine aquaculture fish cobia (Rachycentron canadum). *Aquaculture Research*, **51**(6), 2535-2544, doi:10.1111/are.14596.
Le, T. T. H., 2016: Effects of climate change on rice yield and rice market in Vietnam. *Journal of Agricultural and Applied Economics*, **48**(4), 366–382, doi:10.1017/aae.2016.21.
Lebel L., W. S., Talerngsri P. , 2015: Assessments of ecosystem services and human well-being in Thailand build and create demand for coproductive capacity. *Ecology and Society*, **20**.
Lee, E., R. Jayakumar, S. Shrestha and Z. Han, 2018a: Assessment of transboundary aquifer resources in Asia: Status and progress towards sustainable groundwater management. *Journal of Hydrology: Regional Studies*, **20**, 103-115.
Lee, J. Y. et al., 2018b: Projection of future mortality due to temperature and population changes under representative concentration pathways and shared socioeconomic pathways. *International Journal of Environmental Research and Public Health*, **15**(4), doi:https://doi.org/10.3390/ijerph15040822.
Lee, J. Y. and H. Kim, 2016: Projection of future temperature-related mortality due to climate and demographic changes. *Environ Int*, **94**, 489-494, doi:https://doi:10.1016/j.envint.2016.06.007.
Lee, J. Y., H. S. Lee, S.-C. Hong and H. Kim, 2017: Projecting future summer mortality due to ambient ozone concentration and temperature changes. *Atmospheric Environment*, **156**, 88-94, doi:https://doi.org/10.1016/j.atmosenv.2017.02.034.
Lee, J. Y., W.-S. Lee, K. L. Ebi and H. Kim, 2019: Temperature-related summer mortality under multiple climate, population, and adaptation scenarios. *International Journal of Environmental Research and Public Health*, **16**(6), doi:https://doi.org/10.3390/ijerph16061026.
Lee, J. Y. et al., 2021a: Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Lee, M. and R. C. Asuncion, 2020: Impacts of Sea Level Rise on Economic Growth in Developing Asia. *Resources and Environmental Economics* **2**(1), 102–111, doi:https://doi.org/10.25082/ree.2020.01.002.
Lee, S.-W., K. Lee and B. Lim, 2018c: Effects of climate change-related heat stress on labor productivity in South Korea. *International journal of biometeorology*, **62**, 2119-2129, doi:https://doi.org/10.1007/s00484-018-1611-6.
Lee, S., H. Jung and J. Choi, 2021b: Projecting the Impact of Climate Change on the Spatial Distribution of Six Subalpine Tree Species in South Korea Using a Multi-Model Ensemble Approach. *Forests*, **12**, 37, doi:10.3390/f12010037.
Lee, S. et al., 2018d: Mental disease-related emergency admissions attributable to hot temperatures. *Science of The Total Environment*, **616-617**, 688-694, doi:https://doi.org/10.1016/j.scitotenv.2017.10.260.
Lee, T.-C. et al., 2020a: Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region – Part I: Observed changes, detection and attribution. *Tropical Cyclone Research and Review*, **9**(1), 1-22, doi:https://doi.org/10.1016/j.tcrr.2020.03.001.
Lee, T. and M. Painter, 2015: Comprehensive local climate policy: The role of urban governance. *Urban Climate*, **14**, 566-577, doi:10.1016/j.uclim.2015.09.003.
Lee, T. M. et al., 2015a: Predictors of public climate change awareness and risk perception around the world. *Nature climate change*, **5**(11), 1014.
Lee, W. K., H. A. Lee, Y. H. Lim and H. Park, 2016: Added effect of heat wave on mortality in Seoul, Korea. *International journal of biometeorology*, **60**(5), 719-726, doi:10.1007/s00484-015-1067-x.
Lee, Y.-C., J. Ahern and C.-T. Yeh, 2015b: Ecosystem services in peri-urban landscapes: The effects of agricultural landscape change on ecosystem services in Taiwan's western coastal plain. *Landscape and Urban Planning*, **139**, 137-148, doi:10.1016/j.landurbplan.2015.02.023.

Lee, Y.-J., 2017: A synthesized biophysical and social vulnerability assessment for Taiwan. *IOP Conference Series: Earth and Environmental Science*, **94**, 012161, doi:10.1088/1755-1315/94/1/012161.
Lee, Y. H. et al., 2020b: Transgenerational acclimation to changes in ocean acidification in marine invertebrates. *Mar. Pollut. Bull.*, **153**, 18, doi:10.1016/j.marpolbul.2020.111006.
Lei, J., L. Chen and H. Li, 2017: Using ensemble forecasting to examine how climate change promotes worldwide invasion of the golden apple snail (Pomacea canaliculata). *Environ Monit Assess*, **189**(8), 404, doi:10.1007/s10661-017-6124-y.
Lei, J., S. Wang, J. Wang and J. Wu, 2016: Potential effects of future climate change on suitable habitat of Muntiacus crinifrons, an endangered and endemic species in China. *Biodiversity Science*, **24**, 1390-1399, doi:10.17520/biods.2016152.
Lei, Y. et al., 2015: Adaptive governance to typhoon disasters for coastal sustainability: A case study in Guangdong, China. *Environmental Science & Policy*, **54**, 281–286, doi:https://doi.org/10.1016/j.envsci.2015.07.016.
Leiter, T. et al., 2019: Adaptation Metrics. Current Landscape and Evolving Practices.
Leith, P. and F. Vanclay, 2017: Placing Science for Natural Resource Management and Climate Variability: Lessons from Narratives of Risk, Place and Identity. *Sociologia Ruralis*, **57**(2), 155-170, doi:10.1111/soru.12124.
Lele, S., V. Srinivasan, B. K. Thomas and P. Jamwal, 2018: Adapting to climate change in rapidly urbanizing river basins: insights from a multiple-concerns, multiple-stressors, and multi-level approach. *Water international*, **43**(2), 281-304.
Lele, U., M. Klousia-Marquis and S. Goswami, 2013: Good Governance for Food, Water and Energy Security. *Aquatic Procedia*, **1**, 44-63, doi:10.1016/j.aqpro.2013.07.005.
Leng, G. and J. Hall, 2019: Crop yield sensitivity of global major agricultural countries to droughts and the projected changes in the future. *Science of The Total Environment*, **654**(1), 811-821, doi:https://doi.org/10.1016/j.scitotenv.2018.10.434.
Lenoir, J. and J.-C. Svenning, 2015: Climate-related range shifts – a global multidimensional synthesis and new research directions. *Ecography*, doi:10.1111/ecog.00967.
Leong, C. M. L., S. L. Pan, P. Ractham and L. Kaewkitipong, 2015: ICT-enabled community empowerment in crisis response: social media in Thailand Flooding 2011. *Journal of the Association for Information Systems*, **16**(3), 1-39.
Leung, J. Y. S., B. D. Russell and S. D. Connell, 2020: Linking energy budget to physiological adaptation: How a calcifying gastropod adjusts or succumbs to ocean acidification and warming. *Science of the Total Environment*, **715**, 8, doi:10.1016/j.scitotenv.2020.136939.
Levy, B. S. and J. A. Patz, 2015: Climate Change, Human Rights, and Social Justice. *Ann Glob Health*, **81**(3), 310-322, doi:10.1016/j.aogh.2015.08.008.
Levy, K., A. P. Woster, R. S. Goldstein and E. J. Carlton, 2016: Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. *Environ Sci Technol*, **50**(10), 4905-4922, doi:10.1021/acs.est.5b06186.
Li, B. et al., 2018a: Comparative Analysis of Urban Heat Island Intensities in Chinese, Russian, and DPRK Regions across the Transnational Urban Agglomeration of the Tumen River in Northeast Asia. *Sustainability*, **10**(8), doi:10.3390/su10082637.
Li, C., Y. Lu, J. Liu and X. Wu, 2018b: Climate change and dengue fever transmission in China: Evidences and challenges. *Sci Total Environ*, **622-623**, 493-501, doi:10.1016/j.scitotenv.2017.11.326.
Li, G. et al., 2020: Algal density mediates the photosynthetic responses of a marine macroalga Ulva conglobata (Chlorophyta) to temperature and pH changes. *Algal Res.*, **46**, 7, doi:10.1016/j.algal.2020.101797.
Li, H.-C. et al., 2015a: Applying risk analysis to the disaster impact of extreme typhoon events under climate change. *Journal of Disaster Research*, **10**(3), 513-526, doi:https://doi.org/10.20965/jdr.2015.p0513.
Li, J. et al., 2021: Work Resumption Rate and Migrant Workers' Income During the COVID-19 Pandemic. *Frontiers in Public Health*, **9**(464), doi:10.3389/fpubh.2021.678934.
Li, J. M. and Z. H. Li, 2014: Physical limitations and challenges to Grain Security in China. *Food Secur.*, **6**(2), 159-167, doi:10.1007/s12571-013-0326-0.
Li, K. et al., 2016a: Effects of temperature variation between neighbouring days on daily hospital visits for childhood asthma: a time-series analysis. *Public Health*, **136**, 133-140, doi:https://doi.org/10.1016/j.puhe.2016.04.002.
Li, L. et al., 2019a: Twenty-first-century glacio-hydrological changes in the Himalayan headwater Beas River basin. *Hydrology and Earth System Sciences*, **23**(3), 1483-1503.
Li, Q. et al., 2019b: Debris Flow Risk Assessment Based on a Water–Soil Process Model at the Watershed Scale Under Climate Change: A Case Study in a Debris-Flow-Prone Area of Southwest China. *Sustainability* **11**, 3199, doi:10.3390/su11113199.
Li, T. et al., 2015b: Heat-related mortality projections for cardiovascular and respiratory disease under the changing climate in Beijing, China. *Sci Rep*, **5**, doi:https://doi.org/10.1038/srep11441.
Li, T. et al., 2018c: Long-term projections of temperature-related mortality risks for ischemic stroke, hemorrhagic stroke, and acute ischemic heart disease under changing climate in Beijing, China. *Environ Int*, **112**, 1-9, doi:10.1016/j.envint.2017.12.006.

Li, X., Y. Gao, Y. Pan and Y. Xu, 2018d: Evaluation of near-surface wind speed simulations over the Tibetan Plateau from three dynamical downscalings based on WRF model. *Theoretical and Applied Climatology*, **134**(3), 1399-1411, doi:10.1007/s00704-017-2353-9.

Li, X. et al., 2016b: *Case Studies of the Sponge City Program in China*. 295-308 pp.

Li, X., T. Takahashi, N. Suzuki and H. M. Kaiser, 2014a: Impact of Climate Change on Maize Production in Northeast and Southwest China and Risk Mitigation Strategies. *APCBEE Procedia*, **8**, 11-20, doi:10.1016/j.apcbee.2014.01.073.

Li, Y. et al., 2014b: Extremely cold and hot temperatures increase the risk of diabetes mortality in metropolitan areas of two Chinese cities. *Environ Res*, **134**, 91-97, doi:10.1016/j.envres.2014.06.022.

Liang, E., B. Dawadi, N. Pederson and D. Eckstein, 2014: Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature? *Ecology*, **95**, 2453–2465, doi:10.1890/13-1904.1.

Liao, K.-H., 2019: The socio-ecological practice of building blue-green infrastructure in high-density cities: what does the ABC Waters Program in Singapore tell us? *Socio-Ecological Practice Research*, **1**(1), 67-81, doi:10.1007/s42532-019-00009-3.

Liebenehm, S., 2018: Temporal Stability of Risk Attitudes and the Impact of Adverse Shocks—A Panel Data Analysis from Thailand and Vietnam. *World Development*, **102**, 262-274, doi:10.1016/j.worlddev.2017.07.020.

Lim, C.-H. et al., 2017a: Impact of Deforestation on Agro-Environmental Variables in Cropland, North Korea. *Sustainability*, **9**(8), doi:10.3390/su9081354.

Lim, C.-H. et al., 2017b: Estimation of the Virtual Water Content of Main Crops on the Korean Peninsula Using Multiple Regional Climate Models and Evapotranspiration Methods. *Sustainability*, **9**, 1172, doi:10.3390/su9071172.

Lim, C.-H. et al., 2019a: Assessment of Agricultural Drought Considering the Hydrological Cycle and Crop Phenology in the Korean Peninsula. *Water*, **11**(5), 1105.

Lim, C. H., J. H. An, S. H. Jung and C. S. Lee, 2018: Allogenic succession of Korean fir (*Abies koreana* Wils.) forests in different climate condition. *Ecological Research*, **33**(2), 327-340, doi:10.1007/s11284-018-1592-2.

Lim, C. H. et al., 2019b: Decoupling of forest water supply and agricultural water demand attributable to deforestation in North Korea. *J Environ Manage*, **248**, 109256, doi:10.1016/j.jenvman.2019.07.027.

Lin, C., K. Yang, J. Qin and R. Fu, 2013: Observed Coherent Trends of Surface and Upper-Air Wind Speed over China since 1960. *Journal of Climate*, **26**, 2891–2903, doi:10.1175/JCLI-D-12-00093.1.

Lin, I. et al., 2003: New evidence for enhanced ocean primary production triggered by tropical cyclone. *Geophysical Research Letters*, **30**(13), 4, doi:10.1029/2003gl017141.

Lin, W.-Y. et al., 2018: Filtering disaster responses using crowdsourcing. *Automation in Construction*, **91**, 182-192, doi:10.1016/j.autcon.2018.03.016.

Lin, Y. K., A. T. Maharani, F. T. Chang and Y. C. Wang, 2019: Mortality and morbidity associated with ambient temperatures in Taiwan. *Sci Total Environ*, **651**(Pt 1), 210-217, doi:10.1016/j.scitotenv.2018.09.161.

Lincke, D. and J. Hinkel, 2021: Coastal Migration due to 21st Century Sea-Level Rise. *Earth's Future*, **9**(5), e2020EF001965.

Ling, F. H. et al., 2015: Reducing flood risks in rural households: survey of perception and adaptation in the Mekong delta. *Climatic change*, **132**(2), 209-222.

Linnenluecke, M. K. et al., 2016: Emerging trends in Asia-Pacific finance research: A review of recent influential publications and a research agenda. *Pacific-Basin Finance Journal*, **36**, 66-76.

Liu, D. et al., 2018a: Flood risk perception of rural households in western mountainous regions of Henan Province, China. *International Journal of Disaster Risk Reduction*, **27**, 155-160.

Liu, H. et al., 2019a: Recent lake area changes in Central Asia. *Sci Rep*, **9**(1), 1-11.

Liu, J. et al., 2018b: Large observational bias on discharge in the Indus River since 1970s. *Sci Rep*, **8**(1), 1-10.

Liu, J. et al., 2017a: Challenges in operationalizing the water–energy–food nexus. *Hydrological Sciences Journal*, **62**(11), 1714-1720, doi:10.1080/02626667.2017.1353695.

Liu, M. et al., 2016a: Do Climate Change Policies Promote or Conflict with Subjective Wellbeing: A Case Study of Suzhou, China. *International Journal of Environmental Research and Public Health*, **13**(3), 344.

Liu, M. et al., 2017b: Estimating health co-benefits of greenhouse gas reduction strategies with a simplified energy balance based model: The Suzhou City case. *Journal of Cleaner Production*, **142**, 3332-3342, doi:https://doi.org/10.1016/j.jclepro.2016.10.137.

Liu, P. J., S. J. Ang, A. B. Mayfield and H. J. Lin, 2020a: Influence of the seagrass Thalassia hemprichii on coral reef mesocosms exposed to ocean acidification and experimentally elevated temperatures. *Science of the Total Environment*, **700**, 11, doi:10.1016/j.scitotenv.2019.134464.

Liu, Q. and S. Liu, 2015: Response of glacier mass balance to climate change in the Tianshan Mountains during the second half of the twentieth century. *Climate Dynamics*, **46**, 301-316, doi:10.1007/s00382-015-2585-2.

Liu, W., W. Chen and C. Peng, 2014a: Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study. *Ecol Model*, **291**.

Liu, X., 2020: Reductions in labor capacity from intensified heat stress in China under future climate change. *International Journal of Environmental Research and Public Health*, **17**(4), doi:https://doi.org/10.3390/ijerph17041278.

Liu, X. et al., 2017c: A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. *Landscape and Urban Planning*, **168**, 94-116, doi:10.1016/j.landurbplan.2017.09.019.
Liu, X. et al., 2019b: Multimodel assessments of human and climate impacts on mean annual streamflow in China. *Hydrology and Earth System Sciences*, **23**(3), 1245-1261.
Liu, X. et al., 2019c: The value of China's coastal wetlands and seawalls for storm protection. *Ecosystem Services*, **36**, doi:https://doi.org/10.1016/j.ecoser.2019.100905.
Liu, X. et al., 2019d: The value of China's coastal wetlands and seawalls for storm protection. *Ecosystem Services*, **36**, doi:https://doi.org/10.1016/j.ecoser.2019.100905.
Liu, X., X. Zhang, Q. Tang and X. Zhang, 2014b: Effects of surface wind speed decline on modeled hydrological conditions in China. *Hydrology and Earth System Sciences*, **18**, 2803-2813, doi:10.5194/hess-18-2803-2014.
Liu, Y. and J. Chen, 2020: Socioeconomic risk of droughts under a 2.0°C warmer climate: Assessment of population and GDP exposures to droughts in China. *International Journal of Climatology*, doi:https://doi.org/10.1002/joc.6691.
Liu, Y. et al., 2016b: A community-based disaster risk reduction system in Wanzhou, China. *International Journal of Disaster Risk Reduction*, **19**, 379-389, doi:10.1016/j.ijdrr.2016.09.009.
Liu, Y. P. et al., 2014c: The potential effects of climate change on the distribution and productivity of *Cunninghamia lanceolata* in China. *Environmental Monitoring and Assessment*, **186**(1), 135-149, doi:10.1007/s10661-013-3361-6.
Liu, Z.-J., S. Minobe, Y. N. Sasaki and M. Terada, 2016c: Dynamical downscaling of future sea level change in the western North Pacific using ROMS. *Journal of Oceanography*, **72**(6), 905-922, doi:10.1007/s10872-016-0390-0.
Liu, Z. Q. et al., 2020b: Ocean acidification inhibits initial shell formation of oyster larvae by suppressing the biosynthesis of serotonin and dopamine. *Science of the Total Environment*, **735**, 12, doi:10.1016/j.scitotenv.2020.139469.
Lkhagvadorj, D., M. Hauck, C. Dulamsuren and J. Tsogtbaatar, 2013a: Pastoral nomadism in the forest-steppe of the Mongolian Altai under a changing economy and a warming climate. *Journal of Arid Environments*, **88**, 82-89.
Lkhagvadorj, D., M. Hauck, C. Dulamsuren and J. Tsogtbaatar, 2013b: Twenty Years After Decollectivization: Mobile Livestock Husbandry and Its Ecological Impact in the Mongolian Forest-Steppe. *Human Ecology*, **41**(5), 725-735, doi:10.1007/s10745-013-9599-3.
Lopez, O., G. Stenchikov and T. M. Missimer, 2014: Water management during climate change using aquifer storage and recovery of stormwater in a dunefield in western Saudi Arabia. *Environmental Research Letters*, **9**(7), 075008, doi:10.1088/1748-9326/9/7/075008.
Lorenzoni, I. and L. Whitmarsh, 2014: Climate change and perceptions, behaviors, and communication research after the IPCC 5th Assessment Report - a WIREs Editorial. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(6), 703-708, doi:10.1002/wcc.319.
Lough, J. M., K. D. Anderson and T. P. Hughes, 2018: Increasing thermal stress for tropical coral reefs: 1871-2017. *Sci Rep*, **8**, 8, doi:10.1038/s41598-018-24530-9.
Lovelock, C. E. et al., 2015: The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, **526**(7574), 559-563, doi:10.1038/nature15538.
Lu, X., 2019: *Building Resilient Infrastructure for the Future: Background paper for the G20 Climate Sustainability Working Group*. Asian Development Bank Bank, A. D., Metro Manila, Philippines. Available at: https://www.adb.org/sites/default/files/publication/519821/sdwp-061-building-resilient-infrastructure-future.pdf.
Lu, X. M. et al., 2015: Climate warming increases biological control agent impact on a non-target species. *Ecol Lett*, **18**(1), 48-56, doi:10.1111/ele.12391.
Lu, Y. et al., 2018: Interaction between pollution and climate change augments ecological risk to a coastal ecosystem. *Ecosystem Health and Sustainability*, **4**(7), 161-168.
Luan, G., P. Yin, L. Wang and M. Zhou, 2019: Associations between ambient high temperatures and suicide mortality: a multi-city time-series study in China. *Environmental Science and Pollution Research*, doi:10.1007/s11356-019-05252-5.
Luo, M., & Lau, N.-C. , 2018a: Increasing heat stress in urban areas of eastern China: Acceleration by urbanization. *Geophysical Research Letters*, **45**(13), doi:https://doi.org/10.1029/2018GL080306.
Luo, M. et al., 2019: Identifying climate change impacts on water resources in Xinjiang, China. *Science of The Total Environment*, **676**, doi:10.1016/j.scitotenv.2019.04.297.
Luo, T., Deepak Krishnan, and Shreyan Sen, 2018b: *Parched Power: Water Demands, Risks, and Opportunities for India's Power Sector*. World Resources Institute, Washington, DC (accessed 6 October 2019).
Luo, X.-S. et al., 2017: Inclusive development and agricultural adaptation to climate change. *Current opinion in environmental sustainability*, **24**, 78-83.
Lutz, A., W. Immerzeel, A. Shrestha and M. Bierkens, 2014a: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, **4**(7), 587.
Lutz, A. F. et al., 2016: Climate change impacts on the upper indus hydrology: Sources, shifts and extremes. *PloS one*, **11**(11), e0165630.
Lutz, A. F., W. W. Immerzeel, A. B. Shrestha and M. F. P. Bierkens, 2014b: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, **4**(7), 587-592, doi:10.1038/nclimate2237.

Lutz, A. F. et al., 2019: South Asian river basins in a 1.5 C warmer world. *Regional Environmental Change*, **19**(3), 833-847.
Lutz, W., R. Muttarak and E. Striessnig, 2014c: Universal education is key to enhanced climate adaptation. *Science*, **346**(6213), 1061-1062.
Lwasa, S., 2015: A systematic review of research on climate change adaptation policy and practice in Africa and South Asia deltas. *Regional Environmental Change* **15**, 815–824, doi:10.1007/s10113-014-0715-8.
Ma, S. et al., 2019: Interannual to decadal variability in the catches of small pelagic fishes from China Seas and its responses to climatic regime shifts. *Deep Sea Research Part II: Topical Studies in Oceanography*, **159**, 112-129, doi:10.1016/j.dsr2.2018.10.005.
Ma, W. et al., 2015: The short-term effect of heat waves on mortality and its modifiers in China: an analysis from 66 communities. *Environ Int*, **75**, 103-109, doi:10.1016/j.envint.2014.11.004.
Mabon, L. et al., 2019: Fukuoka: Adapting to climate change through urban green space and the built environment? *Cities*, **93**, 273-285, doi:https://doi.org/10.1016/j.cities.2019.05.007.
Mabon, L. and W.-Y. Shih, 2018: What might 'just green enough' urban development mean in the context of climate change adaptation? The case of urban greenspace planning in Taipei Metropolis, Taiwan. *World Development*, **107**, 224-238, doi:https://doi.org/10.1016/j.worlddev.2018.02.035.
Mabon, L. and W.-Y. Shih, 2021: Urban greenspace as a climate change adaptation strategy for subtropical Asian cities: A comparative study across cities in three countries. *Global Environmental Change*, **68**, 102248.
Mack, T. J., 2018: Groundwater Availability in the Kabul Basin, Afghanistan. In: *Groundwater of South Asia*. Springer, pp. 23-35.
Magni, G., 2017: Indigenous knowledge and implications for the sustainable development agenda. *European Journal of Education*, **52**(4), 437-447, doi:10.1111/ejed.12238.
Maharjan, A., R. Safra de Caompos, C. Singh and e. al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, **6**, doi:doi:10.1007/s40641-020-00153-z.
Mahmood, S., A.U., Rahman and R. Shaw, 2019: Spatial appraisal of flood risk assessment and evaluation using integrated hydro-probabilistic approach in Panjkora River Basin, Pakistan. *Environmental Monitoring and Assessment* **191**, 573, doi:https://doi.org/10.1007/s10661-019-7746-z.
Mahmuda, I., A. Baskaran and J. Pancholi, 2014: Financing social innovation for poverty reduction: A case study of microfinancing and microenterprise development in Bangladesh. *Science, Technology and Society*, **19**(2), 249-273.
Mainali, J., N. G. and Pricope, 2019: Mapping the need for adaptation: assessing drought vulnerability using the livelihood vulnerability index approach in a mid-hill region of Nepal. *Climate and Development*, **11**(7), 607-622, doi:10.1080/17565529.2018.1521329.
Majumdar, S. D. et al., 2018: Threats to coral reef diversity of Andaman Islands, India: A review. *Reg. Stud. Mar. Sci.*, **24**, 237-250, doi:10.1016/j.rsma.2018.08.011.
Makondo, C. C. and D. S. G. Thomas, 2018: Climate change adaptation: Linking indigenous knowledge with western science for effective adaptation. *Environmental Science & Policy*, **88**, 83-91, doi:10.1016/j.envsci.2018.06.014.
Mall, R. K. et al., 2019: Disaster Risk Reduction Including Climate Change Adaptation Over South Asia: Challenges and Ways Forward. *International Journal of Disaster Risk Science* **10**, 14-27, doi:https://doi.org/10.1007/s13753-018-0210-9
Mallari and C. A. Ezra, 2016: Climate Change Vulnerability Assessment in the Agriculture Sector: Typhoon Santi Experience. *Procedia - Social and Behavioral Sciences*, **216**, 440-451, doi:10.1016/j.sbspro.2015.12.058.
Mani, M. et al., 2018: *South Asia hotspots*. World Bank Group, Washington.
Mannakkara, S. and S. Wilkinson, 2013: Build Back Better principles for post-disaster structural improvements. *Structural Survey*, **31**(4), 314-327, doi:10.1108/SS-12-2012-0044.
Mantyka-Pringle, C. S. et al., 2015: Climate change modifies risk of global biodiversity loss due to land-cover change. *Biol. Conserv.*, **187**, 103-111, doi:https://doi.org/10.1016/j.biocon.2015.04.016.
Mao, H., Y.-Y. Ahn, B. Bhaduri and G. Thakur, 2017: Improving land use inference by factorizing mobile phone call activity matrix. *Journal of Land Use Science*, **12**(2-3), 138-153, doi:10.1080/1747423x.2017.1303546.
Markandya, A. and M. González-Eguino, 2019: Integrated Assessment for Identifying Climate Finance Needs for Loss and Damage: A Critical Review. In: *Loss and Damage from Climate Change*. Springer, pp. 343-362.
Mason-D'Croz, D. et al., 2016: Multi-factor, multi-state, multi-model scenarios: Exploring food and climate futures for Southeast Asia. *Environmental Modelling & Software*, **83**, 255-270, doi:https://doi.org/10.1016/j.envsoft.2016.05.008.
Masood, M., P.-F. Yeh, N. Hanasaki and K. Takeuchi, 2015: Model study of the impacts of future climate change on the hydrology of Ganges–Brahmaputra–Meghna basin. *Hydrology and Earth System Sciences*, **19**(2), 747-770.
Masud, M. M., Al-Amin, A.Q., Junsheng, H., Ahmed, F., Yahaya, S.R., Akhtar, R. and Banna, H., 2016: Climate change issue and theory of planned behaviour: relationship by empirical evidence. *Journal of Cleaner Production*, **113**(1), 613-623.
Masutomi, Y. et al., 2019: Rice grain quality degradation and economic loss due to global warming in Japan. *Environmental Research Communications*, **1**(12), 121003, doi:10.1088/2515-7620/ab52e7.

Matheswaran, K., N. Alahacoon, R. Pandey and G. Amarnath, 2019: Flood risk assessment in South Asia to prioritize flood index insurance applications in Bihar, India. *Geomatics, Natural Hazards and Risk*, **10**(1), 26-48, doi:10.1080/19475705.2018.1500495.

Matsuhashi, S. et al., 2020: Developing a point process model for ecological risk assessment of pine wilt disease at multiple scales. *Forest Ecology and Management*, **463**, 118010, doi:https://doi.org/10.1016/j.foreco.2020.118010.

Matsui, T. et al., 2018: Potential impact of climate change on canopy tree species composition of cool-temperate forests in Japan using a multivariate classification tree model. *Ecological Research*, **33**(2), 289-302, doi:10.1007/s11284-018-1576-2.

Matsumoto, K. i., 2019: Climate change impacts on socioeconomic activities through labor productivity changes considering interactions between socioeconomic and climate systems. *Journal of Cleaner Production*, **216**, 528-541, doi:https://doi.org/10.1016/j.jclepro.2018.12.127.

Matsushita, N. et al., 2018: The non-linear and lagged short-term relationship between rainfall and leptospirosis and the intermediate role of floods in the Philippines. *PLoS neglected tropical diseases*, **12**(4), e0006331, doi:10.1371/journal.pntd.0006331.

Matsuura, S. and R. Shaw, 2014: Exploring the possibilities of school-based recovery and community building in Toni District, Kamaishi. *Natural Hazards*, **75**(1), 613-633, doi:10.1007/s11069-014-1344-8.

Matthews, T. K. R., R. L. Wilby and C. Murphy, 2017: Communicating the deadly consequences of global warming for human heat stress. doi:10.1073/pnas.1617526114.

Maung Saw Htoo, T. et al., 2017: Seasonal dynamics influencing coastal primary production and phytoplankton communities along the southern Myanmar coast. *Journal of Oceanography*, **73**(3), 345-364, doi:10.1007/s10872-016-0408-7.

Mavrodieva, A. V. and R. Shaw, 2020: Disaster and Climate Change Issues in Japan's Society 5.0—A Discussion. *Sustainability*, **12**(5), doi:10.3390/su12051893.

Maynard, J. et al., 2015: Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nature Climate Change*, **5**(7), 688-+, doi:10.1038/nclimate2625.

Mayrhofer, J. P. and J. Gupta, 2016: The science and politics of co-benefits in climate policy. *Environmental Science & Policy*, **57**, 22-30, doi:10.1016/j.envsci.2015.11.005.

Mazangi, A. et al., 2016: Effects of climate change on the distribution of endemic Ferula xylorhachis Rech.f. (Apiaceae: Scandiceae) in Iran: Predictions from ecological niche models. *Russian Journal of Ecology*, **47**(4), 349-354, doi:10.1134/s1067413616040123.

McDowell, G. et al., 2013: Climate-related hydrological change and human vulnerability in remote mountain regions: a case study from Khumbu, Nepal. *Regional Environmental Change*, **13**(2), 299-310.

McGill, N., 2016: Vulnerable populations at risks from effects of climate change: Public health working to find solutions. *The Nation's Health* **46**(9), 1-14.

McIlreavy, C., 2015: *East Asia's Changing Urban Landscape: Measuring a Decade of Spatial Growth*. The World Bank, 1-26 pp. ISBN 978-1-4648-0363-5.

McKinnon, A. D. et al., 2003: Rapid changes in shelf waters and pelagic communities on the southern Northwest Shelf, Australia, following a tropical cyclone. *Cont. Shelf Res.*, **23**(1), 93-111, doi:10.1016/s0278-4343(02)00148-6.

McLeman, R., 2019: International migration and climate adaptation in an era of hardening borders. *Nature Climate Change*, **9**, 911–918, doi:https://doi.org/10.1038/s41558-019-0634-2.

McLeman, R. A., 2014: *Climate and human migration: Past experiences, future challenges*. Cambridge University Press. ISBN 1107022657.

McLeod, E. et al., 2019: The future of resilience-based management in coral reef ecosystems. *J. Environ. Manage.*, **233**, 291-301, doi:10.1016/j.jenvman.2018.11.034.

McVicar, T. R. et al., 2012: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology*, **416-417**, 182-205, doi:https://doi.org/10.1016/j.jhydrol.2011.10.024.

Mechler, R. et al., 2019: Science for loss and damage. Findings and propositions. In: *Loss and damage from climate change*. Springer, pp. 3-37.

Meena, R., B. Jirli, M. Kanwat and N. Meena, 2018: Mobile applications for agriculture and allied sector. *International Journal of Current Microbiology and Applied Sciences*, **7**(2), 2317-2326.

Meerow, S., 2017: Double exposure, infrastructure planning, and urban climate resilience in coastal megacities: A case study of Manila. *Environment and Planning A: Economy and Space*, **49**(11), 2649-2672, doi:10.1177/0308518X17723630.

Mehar, M., S. Mittal and N. Prasad, 2016: Farmers coping strategies for climate shock: Is it differentiated by gender? *Journal of Rural Studies*, **44**, 123-131.

Mehta, J. et al., 2019: Climate change and uncertainty from 'above' and 'below': perspectives from India. *Regional Environmental Change*, **19**, 1533–1547 doi:https://doi.org/10.1007/s10113-019-01479-7.

Mehvar, S. et al., 2019: Quantitative assessment of the environmental risk due to climate change-driven coastline recession: A case study in Trincomalee coastal area, Sri Lanka. *Climate Risk Management*, **25**, doi:https://doi.org/10.1016/j.crm.2019.100192.

Mehvar, S. et al., 2018: Developing a framework to quantify potential Sea level rise-driven environmental losses: A case study in Semarang coastal area, Indonesia. *Environmental Science & Policy*, **89**, 216-230, doi:https://doi.org/10.1016/J.ENVSCI.2018.06.019.

Meier, F. et al., 2017: Crowdsourcing air temperature from citizen weather stations for urban climate research. *Urban Climate*, **19**, 170-191, doi:10.1016/j.uclim.2017.01.006.

Mendelsohn, R., 2014: The Impact of Climate Change on Agriculture in Asia. *Journal of Integrative Agriculture*, **13**(4), 660-665, doi:10.1016/s2095-3119(13)60701-7.

Menéndez, P. et al., 2018: Valuing the protection services of mangroves at national scale: The Philippines. *Ecosystem Services*, **34**, 24-36, doi:10.1016/j.ecoser.2018.09.005.

Mercure, J.-F. et al., 2018: Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, **8**(7), 588-593, doi:doi:10.1038/s41558-018-0182-1.

Michael, K., T. Deshpande and G. Ziervogel, 2018: Examining vulnerability in a dynamic urban setting: the case of Bangalore's interstate migrant waste pickers. *Climate and Development*, 1-12, doi:10.1080/17565529.2018.1531745.

Mikulewicz, M., 2017: Politicizing vulnerability and adaptation: on the need to democratize local responses to climate impacts in developing countries. *Climate and Development*, **10**(1), 18-34, doi:10.1080/17565529.2017.1304887.

Miller, D. D. et al., 2018: Adaptation strategies to climate change in marine systems. *Global Change Biology*, **24**(1), e1-e14, doi:10.1111/gcb.13829.

Milner, J. et al., 2017: Projected health effects of realistic dietary changes to address freshwater constraints in India: a modelling study. *Lancet Planet Health*, **1**(1), e26-e32, doi:10.1016/S2542-5196(17)30001-3.

Miralles-Wilhelm, F., 2021: *Nature-based solutions in agriculture – Sustainable management and conservation of land, water, and biodiversity*. FAO and The Nature Conservancy, Virginia.

Mirzabaev, A. et al., 2019: Desertification. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press %& 3 %! Desertification %U https://www.ipcc.ch/srccl-report-download-page/.

Mischke, S., 2020: *Large Asian Lakes in a Changing World: Natural State and Human Impact*. Springer Nature. ISBN 3030422542.

Mishra, A., Appadurai, A.N., Choudhury, D., Regmi, B.R., Kelkar, U., Alam, M., Chaudhary, P., Mu, S.S., Ahmed, A.U., Lotia, H. and Fu, C., , 2019: Adaptation to climate change in the Hindu Kush Himalaya: Stronger action urgently needed. In: *The Hindu Kush Himalaya Assessment* Springer, Cham, pp. 457-490.

Mishra, B., A. Mansoor, C. Saraswat and A. Gautam, 2019: Climate change adaptation through optimal stormwater capture measures. APN Sci Bull 9 (1).

Mishra, D. and N. C. Sahu, 2014: Economic Impact of Climate Change on Agriculture Sector of Coastal Odisha. *APCBEE Procedia*, **10**, 241-245, doi:10.1016/j.apcbee.2014.10.046.

Mishra, H. S., 2020: Sustainable Development Goals and Disaster Risk Reduction, Targets and Challenges for India. In: *Disaster Management for 2030 Agenda of the SDG* [Malhotra, V. K., R. L. S. Fernando and N. P. Haran (eds.)]. Springer Singapore, Singapore, pp. 59-76. ISBN 978-981-15-4324-1.

Mishra, V., A. R. Ganguly, B. Nijssen and D. P. Lettenmaier, 2015: Changes in observed climate extremes in global urban areas. *Environmental Research Letters*, **10**(2), 024005, doi:10.1088/1748-9326/10/2/024005.

Mishra, V. and R. Lilhare, 2016: Hydrologic sensitivity of Indian sub-continental river basins to climate change. *Global and Planetary Change*, **139**, 78-96.

Mishra, V., S. Mukherjee, R. Kumar and D. A. Stone, 2017: Heat wave exposure in India in current, 1.5 °C, and 2.0 °C worlds. *Environmental Research Letters*, **12**(12), doi:https://doi.org/10.1088/1748-9326/aa9388.

Mistry, J. and A. Berardi, 2016: Bridging indigenous and scientific knowledge. *Science*, **352**(6291), 1274, doi:10.1126/science.aaf1160.

Mitchell, D., S. Enemark and P. van der Molen, 2015: Climate resilient urban development: Why responsible land governance is important.

Mitra, B. K., D. Sharma, X. Zhou and R. Dasgupta, 2021: Assessment of the Impacts of Spatial Water Resource Variability on Energy Planning in the Ganges River Basin under Climate Change Scenarios. *Sustainability*, **13**(13), 7273.

Mitra, B. K. S., Sebnem; Markandya, Anil; Pham Ngoc Bao, 2017: Improving Irrigation Water Use Efficiency Holds the Key to Tackling Water Scarcity in South Asia: Technical Potential and Financing Options. Institute for Global Environmental Strategies, Hayama.

Mochizuki, Y. and A. Bryan, 2015: Climate Change Education in the Context of Education for Sustainable Development: Rationale and Principles. *Journal of Education for Sustainable Development*, **9**(1), 4-26, doi:10.1177/0973408215569109.

Modarres, R. and S. Sadeghi, 2018: Spatial and temporal trends of dust storms across desert regions of Iran. *Natural Hazards*, **90**(1), 101-114, doi:10.1007/s11069-017-3035-8.

Moellendorf, D., 2015: Climate change justice. *Philosophy Compass*, 173-186.

Mohanty, B., M. Scherfler and V. Devatha, 2012: *Lifestyle Choices and Societal Behavior Changes as Local Climate Strategy*. ADBI Working Paper Series 398. Available at: https://www.adb.org/sites/default/files/publication/156253/adbi-wp398.pdf.
Moiseev, P. A., I. K. Gaisin, M. O. Bubnov and O. O. Moiseeva, 2018: Dynamics of Tree Vegetation in Steppificated Areas on the Slopes of the Southern Kraka Massif during the Past 80 Years. *Russian Journal of Ecology*, **49**(2), 190-195, doi:10.1134/S1067413618020108.
Moniruzzaman, S., 2015: Crop choice as climate change adaptation: Evidence from Bangladesh. *Ecological Economics*, **118**, 90-98, doi:10.1016/j.ecolecon.2015.07.012.
Montesclaros, J. M. L. and P. S. Teng, 2021: Agriculture and Food Security in Asia. In: *Climate Change, Disaster Risks, and Human Security: Asian Experience and Perspectives* [Pulhin, J. M., M. Inoue and R. Shaw (eds.)]. Springer Singapore, Singapore, pp. 137-168. ISBN 978-981-15-8852-5.
Mora, C. et al., 2018: Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change*, **8**(12), 1062.
Morchain, D., G. Prati, F. Kelsey and L. Ravon, 2015: What if gender became an essential, standard element of Vulnerability Assessments? *Gender & Development*, **23**(3), 481-496, doi:10.1080/13552074.2015.1096620.
Mordkovich, V. G., S. Khudyaev, I. Lyubechanskii and D. R.Yu, 2020: Zoological Indication of Climate Change in the Central Kazakh Steppe Compared to the Middle of the 20th Century Using the Example of Carabid and Tenebrionid Beetles. *Contemporary Problems of Ecology*, **13**, 443–468, doi:10.1134/S1995425520050078.
Mori, N. et al., 2021a: Future projection of maximum potential storm surge height at three major bays in Japan using the maximum potential intensity of a tropical cyclone. *Climatic Change*, **164**(3), 1-18.
Mori, N., S. Nakajo, S. Iwamura and Y. Shibutani, 2018: Projection of decrease in Japanese beaches due to climate change using a geographic database. , Coastal Engineering Journal ,, 239-246, pp.
Mori, N. and T. Takemi, 2016: Impact assessment of coastal hazards due to future changes of tropical cyclones in the North Pacific Ocean. *Weather and Climate Extremes*, **11**, 53-69, doi:10.1016/j.wace.2015.09.002.
Mori, N. et al., 2021b: Recent nationwide climate change impact assessments of natural hazards in Japan and East Asia. *Weather and Climate Extremes*, **32**, 100309, doi:https://doi.org/10.1016/j.wace.2021.100309.
Morita, S., H. Wada and Y. Matsue, 2016: Countermeasures for heat damage in rice grain quality under climate change. *Plant Production Science*, **19**(1), 1-11, doi:10.1080/1343943x.2015.1128114.
Mortreux, C. and J. Barnett, 2017: Adaptive capacity: exploring the research frontier. *WIREs Clim Change*, 1-12, doi:10.1002/wcc.467.
Mosavi, S. H., S. Soltani and S. Khalilian, 2020: Coping with climate change in agriculture: Evidence from Hamadan-Bahar plain in Iran. *Agricultural Water Management*, **241**, doi:https://doi.org/10.1016/j.agwat.2020.106332.
Moskovchenko, D. V., S. P. Aref'ev, M. D. Moskovchenko and A. A. Yurtaev, 2020: Spatiotemporal Analysis of Wildfires in the Forest Tundra of Western Siberia. *Contemporary Problems of Ecology*, **13**(2), 193-203, doi:10.1134/S1995425520020092.
Motone, K. et al., 2018: Protection of Coral Larvae from Thermally Induced Oxidative Stress by Redox Nanoparticles. *Mar. Biotechnol.*, **20**(4), 542-548, doi:10.1007/s10126-018-9825-5.
Motone, K. et al., 2020: A Zeaxanthin-Producing Bacterium Isolated from the Algal Phycosphere Protects Coral Endosymbionts from Environmental Stress. *mBio*, **11**(1), 13, doi:10.1128/mBio.01019-19.
Mubaya, C. P. and P. Mafongoya, 2017: The role of institutions in managing local level climate change adaptation in semi-arid Zimbabwe. *Climate Risk Management*, **16**, 93-105, doi:10.1016/j.crm.2017.03.003.
Mukherjee, A., 2018: Overview of the groundwater of South Asia. In: *Groundwater of South Asia*. Springer, pp. 3-20.
Mukherjee, K. et al., 2017: Surge-type glaciers in the Tien Shan (Central Asia). *Arctic Antarctic and Alpine Research*, **49**(1), 147-171, doi:10.1657/aaar0016-021.
Mukul, S. A. et al., 2019: Combined effects of climate change and sea-level rise project dramatic habitat loss of the globally endangered Bengal tiger in the Bangladesh Sundarbans. *Science of the Total Environment*, **663**, 830-840, doi:10.1016/j.scitotenv.2019.01.383.
Müller, B., L. Johnson and D. Kreuer, 2017: Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change*, **46**, 23-33.
Müller, M. et al., 2016: How do soil properties affect alpine treelines? General principles in a global perspective and novel findings from Rolwaling Himal, Nepal. *Progress in Physical Geography-Earth and Environment*, **40**(1), 135-160, doi:10.1177/0309133315615802.
Murari, K. K. et al., 2015: Intensification of future severe heat waves in India and their effect on heat stress and mortality. *Reg. Environ. Change*, **15**(4), 569– 579.
Nabavi, S. O., L. Haimberger and C. Samimi, 2016: Climatology of dust distribution over West Asia from homogenized remote sensing data. *Aeolian Research*, **21**, 93-107.
Nahiduzzaman, K. M., A. S. Aldosary and M. T. Rahman, 2015: Flood induced vulnerability in strategic plan making process of Riyadh city. *Habitat International*, **49**, 375-385, doi:10.1016/j.habitatint.2015.05.034.
Nakamura, H., H. Umeki and T. Kato, 2017: Importance of communication and knowledge of disasters in community-based disaster-prevention meetings. *Safety Science*, **99**, 235-243, doi:10.1016/j.ssci.2016.08.024.
Nakano, M., M. Matsueda and M. Sugi, 2013: Future projections of heat waves around Japan simulated by CMIP3 and high-resolution Meteorological Research Institute atmospheric climate models. *Journal of Geophysical Research: Atmospheres*, **118**(8), 3097-3109.

Nakayama, S.-I., A. Takasuka, M. Ichinokawa and H. Okamura, 2018: Climate change and interspecific interactions drive species alternations between anchovy and sardine in the western North Pacific: Detection of causality by convergent cross mapping. *Fisheries Oceanography*, **27**(4), 312-322, doi:https://doi.org/10.1111/fog.12254.
Nanajkar, M., K. De and B. Ingole, 2019: Coral reef restoration - A way forward to offset the coastal development impacts on Indian coral reefs. *Mar. Pollut. Bull.*, **149**, 110504, doi:https://doi.org/10.1016/j.marpolbul.2019.110504.
Nandi, I., A. Tewari and K. Shah, 2016: Evolving human dimensions and the need for continuous health assessment of Indian rivers. *Curr Sci*, **111**, 263-271.
Nangia, R., 2019: Securing Asia's energy future with regional integration. *Energy Policy*, **132**, 1262-1273.
Nanlohy, H., A. N. Bambang, Ambariyanto and S. Hutabarat, 2015: Coastal Communities Knowledge Level on Climate Change as a Consideration in Mangrove Ecosystems Management in the Kotania Bay, West Seram Regency. *Procedia Environmental Sciences*, **23**, 157-163, doi:10.1016/j.proenv.2015.01.024.
Nara, P., G.-G. Mao and T.-B. Yen, 2014: Climate Change Impacts on Agricultural Products in Thailand: A Case Study of Thai Rice at the Chao Phraya River Basin. *APCBEE Procedia*, **8**, 136-140, doi:10.1016/j.apcbee.2014.03.015.
Narender, A. and M. Sethi, 2018: Mainstreaming co-benefits in urban policy, governance and finance. In: *Mainstreaming Climate Co-Benefits in Indian Cities*. Springer, pp. 341-373.
Narksompong, J. and S. Limjirakan, 2015: Youth Participation in Climate Change for Sustainable Engagement. *Review of European, Comparative & International Environmental Law*, **24**(2), 171-181, doi:10.1111/reel.12121.
NASA, Powerful Dust Storms in Western Asia, NASA earth observatory. Available at: https://earthobservatory.nasa.gov/images/92212/powerful-dust-storms-in-western-asia.
Nasim, W. et al., 2018: Future risk assessment by estimating historical heat wave trends with projected heat accumulation using SimCLIM climate model in Pakistan. *Atmospheric Research*, **205**, 118-133.
Nations, U., 2019: Climate action and support trends, 40 pp.
Nehru, P. and P. Balasubramanian, 2018: Mangrove species diversity and composition in the successional habitats of Nicobar Islands, India: A post-tsunami and subsidence scenario. *Forest Ecology and Management*, **427**, 70-77, doi:10.1016/j.foreco.2018.05.063.
Nepal, S., 2016: Impacts of climate change on the hydrological regime of the Koshi river basin in the Himalayan region. *Journal of Hydro-Environment Research*, **10**, 76-89.
Nepal, S., W.-A. Flügel and A. B. Shrestha, 2014: Upstream-downstream linkages of hydrological processes in the Himalayan region. *Ecological Processes*, **3**(1), 19.
Nepal, S. et al., 2019: Achieving water security in Nepal through unravelling the water-energy-agriculture nexus. *International Journal of Water Resources Development*, 1-27.
Nepal, S. et al., 2021: Space–time variability in soil moisture droughts in the Himalayan region. *Hydrology and Earth System Sciences*, **25**(4), 1761-1783.
Nepal, S. and A. B. Shrestha, 2015: Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature. *International Journal of Water Resources Development*, **31**(2), 201-218, doi:10.1080/07900627.2015.1030494.
Neufeldt, H. et al., 2018: The Adaptation Gap Report 2018.
Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. *PloS one*, **10**(3), e0118571.
Newell, R., B. Prest and S. Sexton, 2018: *The GDP-Temperature Relationship: Implications for Climate Change Damages*. RFF Working Paper. Available at: http://www. rff. org/research/publications ….
Ngin, C., C. Chhom and A. Neef, 2020: Climate change impacts and disaster resilience among micro businesses in the tourism and hospitality sector: The case of Kratie, Cambodia. *Environmental research*, **186**, 109557.
Nguyen, K. A. T. and C. M. Jolly, 2019: Steps Toward the Establishment of a Commercial Aquaculture Insurance Program: Lessons from an Assessment of the Vietnamese Pilot Insurance Program. *Reviews in Fisheries Science & Aquaculture*, **27**(1), 72-87.
Nguyen, T. P. L. et al., 2016: Perceiving to learn or learning to perceive? Understanding farmers' perceptions and adaptation to climate uncertainties. *Agricultural Systems*, **143**, 205-216, doi:10.1016/j.agsy.2016.01.001.
Nguyen, T. Q., A. K. Das and L. T. Tran, 2019: *NEO Smart Contract for Drought-Based Insurance*. 1-4 pp.
Nicholls, R. J., J. Hinkel, D. Lincke and T. van der Pol, 2019: *Global investment costs for coastal defense through the 21st century*. The World Bank. ISBN 1813-9450.
Nicholls, R. J. et al., 2021: A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, **11**(4), 338-342.
Nie, X. Q. et al., 2019: Storage, patterns and controls of soil organic carbon in the alpine shrubland in the Three Rivers Source Region on the Qinghai-Tibetan Plateau. *Catena*, **178**, 154-162, doi:10.1016/j.catena.2019.03.019.
Nie, Y. et al., 2021: Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment*, **2**(2), 91-106.
Niggol, S., S., and L. A. Bakkensen, 2017: Is Tropical Cyclone Surge, Not Intensity, What Kills so Many People in South Asia? . *Weather, Climate, and Society* **9**(2), 171–181, doi:https://doi.org/10.1175/WCAS-D-16-0059.1.
Nishiura, O. et al., 2020: An Assessment of Global Macroeconomic Impacts Caused by Sea Level Rise Using the Framework of Shared Socioeconomic Pathways and Representative Concentration Pathways. *Sustainability*, **12**(9), 3737.

Nizami, A., J. Ali and M. Zulfiqar, 2019: Climate Change, Hydro-Meteorological Hazards and Adaptation for Sustainable Livelihood in Chitral Pakistan. *Sarhad Journal of Agriculture* **35**(2), 432-441, doi:http://dx.doi.org/10.17582/journal.sja/2019/35.2.432.441.
Nkoana, E., A. Verbruggen and J. Hugé, 2018: Climate change adaptation tools at the community level: An integrated literature review. *Sustainability*, **10**(3), 796.
NOAA, 2010: *NOAA Large Marine Ecosystem Program Report*.
Nong, D., 2019: Potential economic impacts of global wild catch fishery decline in Southeast Asia and South America. *Economic Analysis and Policy*, **62**, doi:10.1016/j.eap.2019.04.004.
Nordgren, J., M. Stults and S. Meerow, 2016: Supporting local climate change adaptation: Where we are and where we need to go. *Environmental Science & Policy*, **66**(December), 344-352, doi:10.1016/j.envsci.2016.05.006.
Nordlund, L. M., R. K. F. Unsworth, M. Gullstrom and L. C. Cullen-Unsworth, 2018: Global significance of seagrass fishery activity. *Fish. Fish.*, **19**(3), 399-412, doi:10.1111/faf.12259.
Nüsser, M. et al., 2019: Socio-hydrology of "artificial glaciers" in Ladakh, India: assessing adaptive strategies in a changing cryosphere. *Regional Environmental Change*, **19**(5), 1327-1337.
Nüsser, M. and S. Schmidt, 2017: Nanga Parbat revisited: Evolution and dynamics of sociohydrological interactions in the Northwestern Himalaya. *Annals of the American Association of Geographers*, **107**(2), 403-415.
O'Brien, C. et al., 2018: Shock-Responsive Social Protection Systems Research Synthesis Report. Oxford Policy Management: Oxford, UK.
Ober, K., 2019: The links between climate change, disasters, migration, and social resilience in Asia: A literature review. *Asian Development Bank Economics Working Paper Series*,(586).
OECD, 2017a: *Social Protection System Review of Cambodia*. OECD Development Pathways.
OECD, 2017b: *Technology and innovation in the insurance sector*. OECD, Paris, France.
Ogasahara, M., H. Kawashima and H. Fujishiro, 2019: How Did Rumors on Twitter Diffuse and Change in Expression? An Investigation of the Process of Spreading Rumors on Twitter during the 2011 Great East Japan Earthquake. *Advances in Human-Computer Interaction*, **2019**, 8, doi:10.1155/2019/5103840.
Ohba, M., 2019: The Impact of Global Warming on Wind Energy Resources and Ramp Events in Japan. *Atmosphere*, **10**, 265, doi:10.3390/atmos10050265.
Ohba, M. and H. Kawase, 2020: Rain-on-Snow events in Japan as projected by a large ensemble of regional climate simulations. *Climate Dynamics*, **55**(9), 2785-2800, doi:10.1007/s00382-020-05419-8.
Ohba, M. and S. Sugimoto, 2020: Impacts of climate change on heavy wet snowfall in Japan. *Climate Dynamics*, **54**(5), 3151-3164, doi:10.1007/s00382-020-05163-z.
Ojha, H. R. et al., 2014: Is South Asian agriculture adapting to climate change? Evidence from the Indo-Gangetic Plains. *Agroecology and sustainable food systems*, **38**(5), 505-531.
Okereke, C. C., Philip, 2016: Climate justice and the international regime: before, during and after Paris. *Wiley Interdisciplinary Reviews: Climate Change*, doi:10.1002/wcc.419

Oktari, R. S. et al., 2015: A conceptual model of a school–community collaborative network in enhancing coastal community resilience in Banda Aceh, Indonesia. *International Journal of Disaster Risk Reduction*, **12**, 300-310, doi:10.1016/j.ijdrr.2015.02.006.
Oliver, E. C. J. et al., 2017: The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature Communications*, **8**, 12, doi:10.1038/ncomms16101.
Oliver, E. C. J. et al., 2019: Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Frontiers in Marine Science*, **6**, 12, doi:10.3389/fmars.2019.00734.
Olson, D. M. et al., 2001: Terrestrial Ecoregions of the World: A New Map of Life on EarthA new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience*, **51**(11), 933-938.
Olsson, L., Opondo, M., Tschakert, P., Agrawal, A., Eriksen, S.H., Ma, S., Perch, L.N. and Zakieldeen, S.A., 2014: *Livelihoods and poverty* Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York, NY, 793-832. pp.
Omer, A. et al., 2020: Water scarcity in the Yellow River Basin under future climate change and human activities. *Science of The Total Environment*, **749**, 141446.
Ong, R. T., Rodriguez, M.S., Epino, E.V., Aying, J.A.G., Lamparas, and B. G.L.B.L., R. (eds.), Automated waterlevel monitoring using real-time observation (AleRTO).
Onosuka, D. et al., 2019: Future projections of temperature-related excess out-of-hospital cardiac arrest under climate change scenarios in Japan. *Science of the Total Environment* **682**, 333–339 doi:https://doi.org/10.1016/j.scitotenv.2019.05.196.
Onozuka, D. et al., 2019: Modeling Future Projections of Temperature-Related Excess Morbidity due to Infectious Gastroenteritis under Climate Change Conditions in Japan. *Environmental health perspectives*, **127**(7), 77006, doi:10.1289/EHP4731.
Onozuka, D. and A. Hagihara, 2015: All-Cause and Cause-Specific Risk of Emergency Transport Attributable to Temperature: A Nationwide Study. *Medicine*, **94**(51), e2259, doi:10.1097/md.0000000000002259.
Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V.

Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press %& 4 %! Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities %U https://www.ipcc.ch/site/assets/uploads/sites/3/2019/2012/SROCC_FullReport_FINAL.pdf.
Otoda, T. et al., 2013: Frequent fires may alter the future composition of the boreal forest in northern Mongolia. *Journal of Forest Research*, **18**(3), 246-255, doi:10.1007/s10310-012-0345-2.
Otto, I. M. et al., 2017: Social vulnerability to climate change: a review of concepts and evidence. *Regional Environmental Change*, **17**, 1651–1662, doi:https://doi.org/10.1007/S10113-017-1105-9.
Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071.
Padgham, J., Jason and K. Dietrich, 2015: Managing change and building resilience: A multi-stressor analysis of urban and peri-urban agriculture in Africa and Asia. *Urban Climate*, **12**, 183-204.
Pahl-Wostl, C., 2019: Governance of the water-energy-food security nexus: A multi-level coordination challenge. *Environmental Science & Policy*, **92**, 356-367, doi:10.1016/j.envsci.2017.07.017.
Pal, J. S. and E. A. B. Eltahir, 2016: Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change*, **6**(2), 197.
Paling, a. F. M. a. K. M. a. v. K. M., 2009: Seagrass restoration. *Coastal wetlands: an integrated ecosystems approach.*, 687-713.
Palmer, M. A. et al., 2015: Water security: Gray or green? *Science*, **349**(6248), 584-585.
Pan, S. L., M. Cui and J. Qian, 2020: Information resource orchestration during the COVID-19 pandemic: A study of community lockdowns in China. *International Journal of Information Management*, 102143.
Panda, D. K., A. AghaKouchak and S. K. Ambast, 2017: Increasing heat waves and warm spells in India, observed from a multiaspect framework. *Journal of Geophysical Research: Atmospheres*, **122**(7), 3837-3858, doi:10.1002/2016JD026292.
Panda, R. M. and M. D. Behera, 2019: Assessing harmony in distribution patterns of plant invasions: a case study of two invasive alien species in India. *Biodiversity and Conservation*, **28**(8-9), 2245-2258, doi:10.1007/s10531-018-1640-9.
Pang, Y. et al., 2018: Variability of coastal cephalopods in overexploited China Seas under climate change with implications on fisheries management. *Fisheries Research*, **208**, 22-33, doi:10.1016/j.fishres.2018.07.004.
Panpeng, J. and M. Ahmad, 2017: Vulnerability of Fishing Communities from Sea-Level Change: A Study of Laemsing District in Chanthaburi Province, Thailand. *Sustainability*, **9**(8), doi:10.3390/su9081388.
Panthi, S., A. Bräuning, Z.-K. Zhou and Z.-X. Fan, 2017: Tree rings reveal recent intensified spring drought in the central Himalaya, Nepal. *Global and Planetary Change*, **157**, 26-34.
Parappurathu, S. et al., 2017: What ails fisheries insurance in India? An assessment of issues, challenges and future potential. *Marine Policy*, **86**, 144-155.
Parazoo, N. C. et al., 2018: Detecting the permafrost carbon feedback: talik formation and increased cold-season respiration as precursors to sink-to-source transitions. *The Cryosphere*, **12**(1), 123-144.
Park, J. J. et al., 2014: Predicting the potential geographic distribution of Thrips palmi in Korea, using the CLIMEX model. *Entomol Res*, **44**(2), 47-57, doi:10.1111/1748-5967.12049.
Parkinson, S. et al., 2019: Balancing clean water-climate change mitigation trade-offs. *Environmental Research Letters*, **14**(1), 014009.
Patankar, A. and A. Patwardhan, 2016: Estimating the uninsured losses due to extreme weather events and implications for informal sector vulnerability: a case study of Mumbai, India. *Natural Hazards*, **80**, 285–310, doi:https://doi.org/10.1007/s11069-015-1968-3.
Patil, S., B. Dhanya, R. S. Vanjari and S. Purushothaman, 2019: Urbanisation and new agroecologies: The story of Bengaluru's peripheries. *Economic and Political Weekly*, **53**(41), 71-77.
Patnaik, S. and M. Swain, 2017: Agrarian Distress and Crop Insurance in Odisha: Some Empirical Findings from Kalahandi District of Odisha. *Journal of Rural Development*, **36**(3), 353-378.
Paul, A. a. R. R. a. K. A. a. J. S., 2017: Mangrove Degradation in the Sundarbans. 357-392, doi:10.1007/978-3-319-56179-0_11.
Peixoto, R. S. et al., 2017: Beneficial Microorganisms for Corals (BMC): Proposed Mechanisms for Coral Health and Resilience. *Front. Microbiol.*, **8**, 16, doi:10.3389/fmicb.2017.00341.
Peng, W., J. N. Yang, X. Lu and D. L. Mauzerall, 2018: Potential co-benefits of electrification for air quality, health, and CO2 mitigation in 2030 China. *Appl Energ*, **218**, 511-519, doi:10.1016/j.apenergy.2018.02.048.
Pereira, J. J. et al., 2019: Appraising slow onset hazards for loss and damage: Case studies in Southeast Asia. *APN*, **9**(1), 45-51.
Perera, N. G. R. and R. Emmanuel, 2018: A "Local Climate Zone" based approach to urban planning in Colombo, Sri Lanka. *Urban Climate*, **23**, 188-203, doi:10.1016/j.uclim.2016.11.006.
Perkins-Kirkpatrick, S.E. and S. C. Lewis, 2020: Increasing trends in regional heatwaves. *Nature Communications*, **11**(3357), doi:https://doi.org/10.1038/s41467-020-16970-7.
Pervin, I. A. et al., 2020: Adapting to urban flooding: a case of two cities in South Asia. *Water Policy*, **22**(S1), 162–188, doi:10.2166/wp.2019.174.

Phan, S. M., H. T. T. Nguyen, T. K. Nguyen and C. Lovelock, 2019: Modelling above ground biomass accumulation of mangrove plantations in Vietnam. *Forest Ecology and Management*, **432**, 376-386, doi:10.1016/j.foreco.2018.09.028.

Phuong, L. T. H., G. R. Biesbroek, L. T. H. Sen and A. E. Wals, 2018a: Understanding smallholder farmers' capacity to respond to climate change in a coastal community in Central Vietnam. *Climate and Development*, **10**(8), 701-716.

Phuong, L. T. H., G. R. Biesbroek and A. E. Wals, 2018b: Barriers and enablers to climate change adaptation in hierarchical governance systems: the case of Vietnam. *Journal of environmental policy & planning*, **20**(4), 518-532.

Piao, S. L. et al., 2015: Detection and attribution of vegetation greening trend in China over the last 30 years. *Global Change Biology*, **21**(4), 1601-1609, doi:10.1111/gcb.12795.

Pimm, S. L. et al., 2015: Emerging Technologies to Conserve Biodiversity. *Trends Ecol Evol*, **30**(11), 685-696, doi:10.1016/j.tree.2015.08.008.

Piya, L., K. L. Maharjan and N. P. Joshi, 2013: Determinants of adaptation practices to climate change by Chepang households in the rural Mid-Hills of Nepal. *Regional Environmental Change*, **13**(2), 437-447, doi:10.1007/s10113-012-0359-5.

Ponomarev, E. I., V. I. Kharuk and K. J. Ranson, 2016: Wildfires dynamics in Siberian larch forests. *Forests*, **7**(6), doi:10.3390/f7060125.

Ponomarev, E. I., E. G. Shvetsov and V. I. Kharuk, 2018: The intensity of wildfires in fire emissions estimates. *Russian Journal of Ecology*, **49**(6), 492-499, doi:10.1134/s1067413618060097.

Popova, E. N., 2014: The Influence of Climatic Changes on Range Expansion and Phenology of the Colorado Potato Beetle (Leptinotarsa Decemlineata, Coleoptera, Chrysomelidae) in the Territory of Russia. *Zool Zh*, **93**(4), 537-548, doi:10.7868/S0044513414020093.

Popova, E. N., S. M. Semenov and I. O. Popov, 2016: Assessment of possible expansion of the climatic range of Italian locust (*Calliptamus italicus* L.) in Russia in the 21st century at simulated climate changes. *Russ Meteorol Hydro+*, **41**(3), 213-217, doi:10.3103/S1068373916030079.

Porio, E., 2014: Climate Change Vulnerability and Adaptation in Metro Manila: Challenging Governance and Human Security Needs of Urban Poor Communities. *Asian Journal of Social Science*, **42**, 75-102, doi:10.1163/15685314-04201006.

Porst, L. and P. Sakdapolrak, 2020: Gendered translocal connectedness: Rural–urban migration, remittances, and social resilience in Thailand. *Popul. Space Place*, **26**(4), e2314.

Pörtner, H. O. et al., 2021: *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change*. IPBES secretariat, Bonn, Germany. Available at: DOI: 10.5281/zenodo.4659158.

Pospelova, E. B., I. N. Pospelov and M. V. Orlov, 2017: Climate change in Eastern Taimyr over the last 80 years and the warming impact on biodiversity and ecosystem processes in its territory. *Nature Conservation Research*, **2**(3), 48-60.

Poudel, S. and R. Shaw, 2015: Demographic changes, economic changes and livelihood changes in the HKH Region. In: *Mountain hazards and disaster risk reduction*. Springer, pp. 105-123.

Poudel, S. and R. Shaw, 2016: The Relationships between Climate Variability and Crop Yield in a Mountainous Environment: A Case Study in Lamjung District, Nepal. *Climate*, **4**(1), doi:10.3390/cli4010013.

Prabhakar, S. et al., 2018: *Benefits and costs of risk insurance in selected countries of Asia*. APN Science Bulletin, 8(1), Asia-Pacific Network for Global Change Research.

Prabnakorn, S., S. Maskey, F. X. Suryadi and C. de Fraiture, 2018: Rice yield in response to climate trends and drought index in the Mun River Basin, Thailand. *Science of The Total Environment*, **621**, 108-119, doi:https://doi.org/10.1016/j.scitotenv.2017.11.136.

Prasad, R. S. and R. Sud, 2019: Implementing climate change adaptation: lessons from India's national adaptation fund on climate change (NAFCC). *Climate policy*, **19**(3), 354-366.

Pritchard, H. D., 2019: Asia's shrinking glaciers protect large populations from drought stress. *Nature*, **569**(7758), 649-654, doi:10.1038/s41586-019-1240-1.

Pritchard, M., A. Rahman and M. Alam, 2015: Empowering Women on the Chars: Increasing Resilience to Disasters and Building Sustainable Livelihoods. *Journal of Agricultural Science and Technology A*, **5**(4), doi:10.17265/2161-6256/2015.04.003.

Prokosheva, I. V., 2017: Dynamics of phenology process in mountain taiga zone of Vishera nature reserve (Northern Urals) under the influence of climatic changes. *Problems of Ecological Monitoring and Ecosystem Modelling*, **28**, 40-55, doi:10.21513/0207-2564-2017-2-40-55.

Prudhomme, C. et al., 2014: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences*, **111**(9), 3262-3267.

Puan, C. L. et al., 2019: Influence of landscape matrix on urban bird abundance: evidence from Malaysian citizen science data. *Journal of Asia-Pacific Biodiversity*, **12**(3), 369-375, doi:10.1016/j.japb.2019.03.008.

Pulhin, J., R. J. Peras, F. Pulhin and D. Gevaña, 2016: Farmers' Adaptation to Climate Variability: Assessment of Effectiveness and Barriers Based on Local Experience in Southern Philippines. *Journal of Environmental Science and Management*, **2016**(1).

Puma, M. J., S. Bose, S. Y. Chon and B. I. Cook, 2015: Assessing the evolving fragility of the global food system. *Environmental Research Letters*, **10**(2), 024007.

Puspa, A., T. Osawa and I. W. Arthana, 2018: Quantitative assessment of vulnerability in aquaculture: climate change impacts on whiteleg shrimp (Litopenaeus vannamei) farming in East Java Province. *IOP Conference Series: Earth and Environmental Science*, **162**, 012027, doi:10.1088/1755-1315/162/1/012027.
Pycroft, J., J. Abrell and J. C. Ciscar, 2016: The Global Impacts of Extreme Sea-Level Rise: A Comprehensive Economic Assessment. *Environmental and Resource Economics* **64**(2), 225–253, doi:https://doi.org/10.1007/s10640-014-9866-9.
Pyhälä, A. et al., 2016: Global environmental change: local perceptions, understandings, and explanations. *Ecology and Society*, **21**(3), art25, doi:10.5751/ES-08482-210325.
Qin, W. et al., 2018: Comparison of deterministic and data-driven models for solar radiation estimation in China. *Renewable and Sustainable Energy Reviews*, **81**, 579-594, doi:https://doi.org/10.1016/j.rser.2017.08.037.
Qin, Z., A. DiTommaso, R. S. Wu and H. Y. Huang, 2014: Potential distribution of two Ambrosia species in China under projected climate change. *Weed Res*, **54**(5), 520-531, doi:10.1111/wre.12100.
Qiu, G. Y., X. Zhang, X. Yu and Z. Zou, 2018: The increasing effects in energy and GHG emission caused by groundwater level declines in North China's main food production plain. *Agricultural Water Management*, **203**, 138-150, doi:https://doi.org/10.1016/j.agwat.2018.03.003.
Quach, A. V., F. Murray and A. Morrison-Saunders, 2015: Perspectives of Farmers and Experts in Ca Mau, Vietnam on the Effects of Climate Change on Shrimp Production. *International Journal of Environmental Science and Development*, **6**(10), 718-726, doi:10.7763/ijesd.2015.V6.687.
Quach, A. V., F. Murray and A. Morrison-Saunders, 2017: The vulnerability of shrimp farming income to climate change events. *International Journal of Climate Change Strategies and Management*, **9**(2), 261-280, doi:10.1108/ijccsm-05-2015-0062.
Radhakrishnan, M. et al., 2019: Development of context specific sustainability criteria for selection of plant species for green urban infrastructure: The case of Singapore. *Sustainable Production and Consumption*, **20**, 316-325, doi:https://doi.org/10.1016/j.spc.2019.08.004.
Rafaj, P. et al., 2021: Air quality and health implications of 1.5 °C–2 °C climate pathways under considerations of ageing population: a multi-model scenario analysis. *Environmental Research Letters*, **16**(4), 045005, doi:10.1088/1748-9326/abdf0b.
Rafiq, M., S. A. Romshoo, A. K. Mishra and F. Jalal, 2019: Modelling Chorabari Lake outburst flood, Kedarnath, India. *Journal of Mountain Science*, **16**(1), 64-76.
Ragettli, S., W. W. Immerzeel and F. Pellicciotti, 2016: Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proceedings of the National Academy of Sciences*, **113**(33), 9222-9227.
Rahayu, H. P. et al., 2020: A Micro Scale Study of Climate Change Adaptation and Disaster Risk Reduction in Coastal Urban Strategic Planning for the Jakarta. *International Journal of Disaster Resilience in the Built Environment*, **11**(1), 119-133.
Rahman, M. T., A. S. Aldosary, K. M. Nahiduzzaman and I. Reza, 2016: Vulnerability of flash flooding in Riyadh, Saudi Arabia. *Natural Hazards*, **84**(3), 1807-1830, doi:10.1007/s11069-016-2521-8.
Rahman, S. et al., 2018: Climate change adaptation and disaster risk reduction (DRR) through coastal afforestation in South-Central Coast of Bangladesh. *Management of Environmental Quality: An International Journal* **30**(3), 498-517, doi:10.1108/MEQ-01-2018-0021.
Rahut, D. B. and A. Ali, 2018: Impact of climate-change risk-coping strategies on livestock productivity and household welfare: empirical evidence from Pakistan. *Heliyon*, **4**(10), e00797, doi:10.1016/j.heliyon.2018.e00797.
Rajan, S. I., 2020: Migrants at a crossroads: COVID-19 and challenges to migration. *Migration and Development*, **9**(3), 323-330, doi:10.1080/21632324.2020.1826201.
Raju, E., 2019: Gender as Fundamental to Climate Change Adaptation and Disaster Risk Reduction: Experiences from South Asia'. In: *Climate Hazards, Disasters, and Gender Ramifications* [Kinvall, C. a. R., H. (eds) (ed.)]. Routledge, London, pp. 122-137. ISBN 9781138354364.
Ramaswami, A. et al., 2017: Urban cross-sector actions for carbon mitigation with local health co-benefits in China. *Nature Climate Change*, **7**(10), 736-+, doi:10.1038/Nclimate3373.
Ramesh, R. et al., 2019: Chapter 14 - Importance of Seagrass Management for Effective Mitigation of Climate Change. 283 - 299, doi:https://doi.org/10.1016/B978-0-12-810473-6.00015-7.
Ran, L., W. Chun-Jing, H. E. Jian and Z. Zhi-Xiang, 2018: Analysis of geographical distribution of Abies in China under climate change. *Bulletin of Botanical Research*, **38**(1), 37-46.
Rana, S. K. et al., 2017: Predicting the impact of climate change on the distribution of two threatened Himalayan medicinal plants of Liliaceae in Nepal. *Journal of Mountain Science*, **14**(3), 558-570, doi:10.1007/s11629-015-3822-1.
Ranagalage, M., R. C. Estoque and Y. Murayama, 2017: An Urban Heat Island Study of the Colombo Metropolitan Area, Sri Lanka, Based on Landsat Data (1997–2017). *ISPRS International Journal of Geo-Information*, **6**(7), doi:10.3390/ijgi6070189.
Ranasinghe, R. et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S.

Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Rani, S. et al., 2020a: Economic valuation and conservation, restoration & management strategies of Saint Martin's coral island, Bangladesh. *Ocean Coastal Manage.*, **183**, 17, doi:10.1016/j.ocecoaman.2019.105024.

Rani, W. N. M. W. M., K. H. Kamarudin, K. A. Razak and Z. M. Asmawi (eds.), 2020: Climate Change Adaptation and Disaster Risk Reduction in Urban Development Plans for Resilient Cities. The First International Conference on Urban Design and Planning, IOP Publishing.

Ranith, R. and V. Kripa, 2019: Post-bleaching benthic status on reef sites of Mandapam group of islands and Palk Bay, Indian Ocean following the 2016 bleaching events. *Reg. Stud. Mar. Sci.*, **27**, doi:10.1016/j.rsma.2019.100525.

Rao, N. et al., 2019: Gendered vulnerabilities to climate change: insights from the semi-arid regions of Africa and Asia. *Climate and Development*, **11**(1), 14-26.

Rao, N. et al., 2020: Managing risk, changing aspirations and household dynamics: Implications for wellbeing and adaptation in semi-arid Africa and India. *World Development*, **125**, 104667.

Rashid, I. et al., 2015: Projected climate change impacts on vegetation distribution over Kashmir Himalayas. *Climatic Change*, **132**(4), 601-613, doi:10.1007/s10584-015-1456-5.

Rasul, G., 2014: Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. *Environmental Science & Policy*, **39**, 35-48, doi:10.1016/j.envsci.2014.01.010.

Rasul, G., 2016: Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environmental Development*, **18**, 14-25.

Rasul, G. and D. Molden, 2019: The Global Social and Economic Consequences of Mountain Cryospheric Change. *Frontiers in Environmental Science*.

Rasul, G., B. Pasakhala, A. Mishra and S. Pant, 2020: Adaptation to mountain cryosphere change: issues and challenges. *Climate and Development*, **12**(4), 297-309.

Rasul, G. and B. Sharma, 2014: Water, Food, and Energy Nexus in South Asia: Implications for Adaption to Climate Change. In: *Handbook of Climate Change Adaptation*, pp. 1-18. ISBN 978-3-642-40455-9.

Rataj, E., K. Kunzweiler and S. Garthus-Niegel, 2016: Extreme weather events in developing countries and related injuries and mental health disorders - a systematic review. *BMC public health*, **16**(1), 1020, doi:10.1186/s12889-016-3692-7.

Rauf, S. et al., 2017: How hard they hit? Perception, adaptation and public health implications of heat waves in urban and peri-urban Pakistan. *Environ Sci Pollut Res Int*, **24**(11), 10630-10639, doi:10.1007/s11356-017-8756-4.

Raupach, M. R. et al., 2014: Sharing a quota on cumulative carbon emissions. *Nature Climate Change*, **4**(10), 873-879, doi:10.1038/nclimate2384.

Rautela, P. and B. Karki, 2015: Weather Forecasting: Traditional Knowledge of the People of Uttarakhand Himalaya. *Journal of Geography, Environment and Earth Science International*, **3**(3), 1-14, doi:10.9734/jgeesi/2015/19016.

Ravera, F. et al., 2019: Gendered agrobiodiversity management and adaptation to climate change: differentiated strategies in two marginal rural areas of India. *Agriculture and Human Values* **36**, 455–474 doi:https://doi.org/10.1007/s10460-018-09907-w.

Ray, B. and R. Shaw, 2019: *Urban Drought - Emerging Water Challenges in Asia*. Springer.

Reddy, C. S. et al., 2020: Identification and characterization of spatio-temporal hotspots of forest fires in South Asia. *Environmental Monitoring and Assessment*, **191**(S3), doi:10.1007/s10661-019-7695-6.

Reed, S. O. et al., 2015: Resilience projects as experiments: implementing climate change resilience in Asian cities. *Climate and Development*, **7**(5), 469-480.

Rees, W. G. et al., 2020: Is subarctic forest advance able to keep pace with climate change? *Global Change Biology*, **26**(7), 3965-3977, doi:https://doi.org/10.1111/gcb.15113.

Ren, C., Yang, R., Cheng, C., Xing, P., Fang, X., Zhang, S., Wang, H., Shi, Y., Zhang, X., Kwok, Y.T. and Ng, E., 2018: Creating breathing cities by adopting urban ventilation assessment and wind corridor plan – The implementation in Chinese cities. *Journal of Wind Engineering and Industrial Aerodynamics*, **182**, 170-188.

Rentschler, J., M. Obolensky and M. Kornejew, 2019: *Candle in the wind? Energy system resilience to natural shocks*. The World Bank. ISBN 1813-9450.

Revi, A., 2017: Re-imagining the United Nations' Response to a Twenty-first-century Urban World. *Urbanisation*.

Revi, A. et al., 2014: Towards transformative adaptation in cities: the IPCC's Fifth Assessment. *Environment and Urbanization*, **26**(1), 11-28.

Reyer, C., Otto, I.M., Adams, S. et al. , 2017: Climate change impacts in Central Asia and their implications for development. *Reg Environ Change* **17**, 1639-1650, doi:https://doi.org/10.1007/s10113-015-0893-z

Reyes, D. D. and J. L. Lu, 2016: Gender dimension in disaster situations: A case study of flood prone women in Malabon City, Metro Manila. *International Journal of Disaster Risk Reduction*, **15**, 162-168, doi:10.1016/j.ijdrr.2015.11.001.

Reynaud, A., C. Aubert and M. H. Nguyen, 2013: Living with floods: Protective behaviours and risk perception of vietnamese households. *Geneva Papers on Risk and Insurance: Issues and Practice*, **38**(3), 547-579, doi:10.1057/gpp.2013.16.

Rezaei, E. E. and A. Lashkari, 2018: The consequences of change in management practices on maize yield under climate warming in Iran. *Theoretical and Applied Climatology*, doi:10.1007/s00704-018-2637-8.

Ricart, A. M. et al., 2020: High variability of Blue Carbon storage in seagrass meadows at the estuary scale. *Sci Rep*, **10**(1), 12, doi:10.1038/s41598-020-62639-y.
Richards, D. R. and D. A. Friess, 2016: Rates and drivers of mangrove deforestation in Southeast Asia, 2000-2012. *Proc Natl Acad Sci U S A*, **113**(2), 344-349, doi:10.1073/pnas.1510272113.
Riegl, B. et al., 2018: Population collapse dynamics in Acropora downingi, an Arabian/Persian Gulf ecosystem-engineering coral, linked to rising temperature. *Global Change Biology*, **24**(6), 2447-2462, doi:10.1111/gcb.14114.
Rigaud, K. K. et al., 2018: Groundswell.
Ringler, C., A. Bhaduri and R. Lawford, 2013: The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? *Current Opinion in Environmental Sustainability*, **5**(6), 617-624, doi:10.1016/j.cosust.2013.11.002.
Ringler, C. et al., 2016: Global linkages among energy, food and water: an economic assessment. *Journal of Environmental Studies and Sciences*, **6**(1), 161-171, doi:10.1007/s13412-016-0386-5.
Ritphring, S., C. Somphong, K. Udo and S. Kazama, 2018: Projections of future beach loss due to sea level rise for sandy beaches along Thailand's coastlines. . Journal of Coastal Research, 541-545 pp.
Roberts, E. and M. Pelling, 2016: Climate change-related loss and damage: translating the global policy agenda for national policy processes. *Climate and Development*, **10**(1), 4-17, doi:10.1080/17565529.2016.1184608.
Roberts, S. L. et al., 2018: Diatom evidence of 20th century ecosystem change in Lake Baikal, Siberia. *Plos One*, **13**(12), doi:10.1371/journal.pone.0208765.
Rode, K. D., C. T. Robbins, L. Nelson and S. C. Amstrup, 2015a: Can polar bears use terrestrial foods to offset lost ice-based hunting opportunities? *Frontiers in Ecology and the Environment*, **13**(3), 138-145, doi:10.1890/140202.
Rode, K. D. et al., 2015b: Increased land use by Chukchi Sea polar bears in relation to changing sea ice conditions. *Plos One*, **10**(11), doi:10.1371/journal.pone.0142213.
Rodell, M. et al., 2018: Emerging trends in global freshwater availability. *Nature*, **557**, 651-659, doi:10.1038/s41586-018-0123-1.
Rodell, M., I. Velicogna and J. S. Famiglietti, 2009: Satellite-based estimates of groundwater depletion in India. *Nature*, **460**(7258), 999.
Roder, G., T. Ruljigaljig, C.-W. Lin and P. Tarolli, 2016: Natural hazards knowledge and risk perception of Wujie indigenous community in Taiwan. *Natural Hazards*, **81**(1), 641-662, doi:10.1007/s11069-015-2100-4.
Rogelj, J. et al., 2018: The many possible climates from the Paris Agreement's aim of 1.5 °C warming. *Nature*, **558**(7708), 41-49, doi:10.1038/s41586-018-0181-4.
Rohini, P., M. Rajeevan and A. K. Srivastava, 2016: On the Variability and Increasing Trends of Heat Waves over India. *Sci Rep*, **6**(1), 26153, doi:10.1038/srep26153.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163.
Romañach, S. S. et al., 2018: Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean Coastal Manage.*, **154**, 72-82, doi:10.1016/j.ocecoaman.2018.01.009.
Rosendo, S., L. Celliers and M. Mechisso, 2018: Doing more with the same: A reality-check on the ability of local government to implement Integrated Coastal Management for climate change adaptation. *Marine Policy*, **87**, 29-39.
Ross, R. S., T. N. Krishnamurti, S. Pattnaik and D. S. Pai, 2018: Decadal surface temperature trends in India based on a new high-resolution data set. *Sci Rep*, **8**(1), 7452-7452, doi:10.1038/s41598-018-25347-2.
Roth, D. et al., 2019: Climates of urbanization: local experiences of water security, conflict and cooperation in peri-urban South-Asia. *Climate Policy*, **19**(sup1), S78-S93.
Rothausen, S. G. and D. Conway, 2011: Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, **1**(4), 210.
Routledge, P., 2015: Engendering Gramsci: Gender, the philosophy of praxis, and spaces of encounter in the climate caravan, Bangladesh. *Antipode*, **47**(5), 1321-1345.
Roxy, M. K. et al., 2016: A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean. *Geophysical Research Letters*, **43**(2), 826-833, doi:10.1002/2015gl066979.
Roy, A. and M. Z. Haider, 2019: Stern review on the economics of climate change: implications for Bangladesh. *International Journal of Climate Change Strategies and Management*, **11**(1), 100-117.
Roy, J. et al., 2018: Sustainable Development, Poverty Eradication and Reducing Inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., Zhai, P., H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, Moufouma-Okia, W., C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, Gomis, M.I., E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.
Roy, M., D. Hulme and F. Jahan, 2013: Contrasting adaptation responses by squatters and low-income tenants in Khulna, Bangladesh:. *http://dx.doi.org/10.1177/0956247813477362*, doi:10.1177_0956247813477362.
Roy, S. S., 2018: *Linking Gender to Climate Change Impacts in the Global South*. Springer. ISBN 3319757768.

Rozenberg, J. and M. Fay, 2019: *Beyond the gap: How countries can afford the infrastructure they need while protecting the planet*. The World Bank. ISBN 1464813639.
Ruane, A. C. et al., 2013: Multi-factor impact analysis of agricultural production in Bangladesh with climate change. *Global Environmental Change*, **23**(1), 338-350, doi:10.1016/j.gloenvcha.2012.09.001.
Ruckelshaus, M. et al., 2013: Securing ocean benefits for society in the face of climate change. *Marine Policy*, **40**, 154 - 159, doi:https://doi.org/10.1016/j.marpol.2013.01.009.
Rumbach, A. and M. Shirgaokar, 2017: Predictors of household exposure to monsoon rain hazards in informal settlements. *Natural Hazards*, **85**(2), 709-728, doi:10.1007/s11069-016-2599-z.
Rumiantsev, V. Y., S. M. Malkhazova, N. B. Leonova and M. S. Soldatov, 2013: Forecasting possible changes in zonal vegetation boundaries in European Russia and Western Siberia in connection with global warming. *Contemporary Problems of Ecology*, **6**(4), 343-349, doi:10.1134/S1995425513040094.
Russell, M., Water in Central Asia An increasingly scarce resource, European Parliamentary Research Service. Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2018/625181/EPRS_BRI(2018)625181_EN.pdf.
Ruzol, C., L. L. Lomente and J. Pulhin, 2021: Cultural consensus knowledge of rice farmers for climate risk management in the Philippines. *Climate Risk Management*, **32**, 100298, doi:https://doi.org/10.1016/j.crm.2021.100298.
Ruzol, C. D. and J. M. Pulhin, 2021: Cultural Dimensions of Human Security. In: *Climate Change, Disaster Risks, and Human Security: Asian Experience and Perspectives* [Pulhin, J. M., M. Inoue and R. Shaw (eds.)]. Springer Singapore, Singapore, pp. 169-192. ISBN 978-981-15-8852-5.
Ryzhanovskiy, V. N., 2019a: Ecology of thrush birds (Passeriformes, Turdidae) in northwestern Siberia under effects of climate and landscape changes. *Contemporary Problems of Ecology*, **12**(3), 220-230, doi:10.1134/s1995425519030107.
Ryzhanovskiy, V. N., 2019b: The phenology of seasonal phenomena and the territorial distribution of gray crow (*Corvus cornix*) from the Lower Ob region. *Russian Journal of Ecology*, **50**(1), 88-92, doi:10.1134/s1067413618060103.
Sabates-Wheeler, 2019: Mapping differential vulnerabilities and rights: 'opening' access to social protection for forcibly displaced populations. *Comparative Migration Studies* **7**, 38, doi:https://doi.org/10.1186/s40878-019-0142-6".
Sachs, J. et al., 2018: SDG Index and Dashboards Report 2018. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).
Sachs, J. et al., 2020: *The Sustainable Development Goals and COVID-19. Sustainable Development Report 2020*. Cambridge University Press, Cambridge, 508 pp.
Sadia, H. et al., 2016: Gender-sensitive public health risks and vulnerabilities' assessment with reference to floods in Pakistan. *International Journal of Disaster Risk Reduction*, **19**, 47-56, doi:10.1016/j.ijdrr.2016.08.024.
Safronov, V. M., 2016: Climate change and mammals of Yakutia. *Biology Bulletin*, **43**(9), 1256-1270, doi:10.1134/s1062359016110121.
Sahani, M. et al., 2014: A case-crossover analysis of forest fire haze events and mortality in Malaysia. *Atmospheric Environment*, **96**, 257-265, doi:https://doi.org/10.1016/j.atmosenv.2014.07.043.
Said, F., U. Afzal and G. Turner, 2015: Risk taking and risk learning after a rare event: Evidence from a field experiment in Pakistan. *Journal of Economic Behaviour & Organization*, **118**, 167-183.
Sailor, D., 2001: Relating residential and commercial sector electricity loads to climate - Evaluating state level sensitivities and vulnerabilities. *Energy*, **26**, 645-657, doi:10.1016/S0360-5442(01)00023-8.
Saito, N., 2013: Mainstreaming climate change adaptation in least developed countries in South and Southeast Asia. *Mitigation and Adaptation Strategies for Global Change*, **18**(6), 825-849.
Saito, Y., 2014: Progress or repetition? Gender perspectives in disaster management in Japan. *Disaster Prevention and Management: An International Journal*, **23**(2), 98-111, doi:10.1108/dpm-08-2013-0134.
Sajjad, M. et al., 2018: Assessing Hazard Vulnerability, Habitat Conservation, and Restoration for the Enhancement of Mainland China's Coastal Resilience. *Earth's Future*, **6**(3), 326-338, doi:10.1002/2017ef000676.
Sakaki, T., M. Okazaki and Y. Matsuo, 2013: Tweet Analysis for Real-Time Event Detection and Earthquake Reporting System Development. *IEEE Transactions on Knowledge and Data Engineering*, **25**(4), 919-931, doi:10.1109/TKDE.2012.29.
Sakamoto, D. et al., 2017: Application of Livestock Waste Compost as a Source of Nitrogen Supplementation during the Fall-winter Season Causes Dead Flower Buds in Japanese Pear 'Kosui'. *The Horticulture Journal*, doi:10.2503/hortj.MI-134.
Sakamoto, Y., 2000: Snow accretion on overhead wires. *Philosophical Transactions of The Royal Society A: Mathematical, Physical and Engineering Sciences*, **358**, 2941-2970, doi:10.1098/rsta.2000.0691.
Sakurai, M. and H. Chughtai, 2020: Resilience against crises: COVID-19 and lessons from natural disasters. *European Journal of Information Systems*, 1-10.
Sakurai, M. and D. Thapa, 2017: Building resilience through effective disaster management: An information ecology perspective. *International Journal of Information Systems for Crisis Response and Management (IJISCRAM)*, **9**(1), 11-26, doi:10.4018/IJISCRAM.2017010102.

Sakurai, M., R. Watson, C. Abraham and J. Kokuryo, 2014: Sustaining life during the early stages of disaster relief with a frugal information system: learning from the great east Japan earthquake. *Communications Magazine, IEEE*, **52**(1), 176-185, doi:10.1109/MCOM.2014.6710081.

Salik, K. M., S. Jahangir, W. u. Z. Zahdi and S. u. Hasson, 2015: Climate change vulnerability and adaptation options for the coastal communities of Pakistan. *Ocean Coastal Manage.*, **112**, 61-73, doi:10.1016/j.ocecoaman.2015.05.006.

Salim, W., K. Bettinger and M. Fisher, 2019: Maladaptation on the waterfront: Jakarta's growth coalition and the Great Garuda. *Environment and Urbanization Asia*, **10**(1), 63-80.

Samad, S. A. and K. M. Shahid, 2018: Social protection programme in Malaysia. *International Journal for Studies on Children, Women, Elderly and Disabled*, **5**.

Samaddar, S., R. Chatterjee, B. Misra and H. Tatano, 2014: Outcome-expectancy and self-efficacy: Reasons or results of flood preparedness intention? *International Journal of Disaster Risk Reduction*, **8**, 91-99, doi:10.1016/j.ijdrr.2014.02.002.

Samuel, O. O., T. S. Sylvia and S. R. Casadevall, 2019: Establishing the nexus between climate change adaptation strategy and smallholder farmers' food security status in South Africa: A bi-casual effect using instrumental variable approach. *Cogent Social Sciences*, **5**(1), 1656402.

Sancholi, N., 2018: Effects of Climate Change on *Paralaudakia lehmanni* (Nicolsky, 1896) (Reptilia: Agamidae) in Central Asia. *Contemporary Problems of Ecology*, **11**(6), 682-686, doi:10.1134/s199542551806015x.

Sang, S. et al., 2014: Predicting local dengue transmission in Guangzhou, China, through the influence of imported cases, mosquito density and climate variability. *PLoS One*, **9**(7), e102755, doi:10.1371/journal.pone.0102755.

Sangoony, H., M. Vahabi, M. Tarkesh and S. Soltani, 2016: Range Shift of Bromus Tomentellus Boiss. As a Reaction to Climate Change in Central Zagros, Iran. *Appl Ecol Env Res*, **14**(4), 85-100, doi:10.15666/aeer/1404_085100.

Sannikov, S. N., N. V. Tantsyrev and I. V. Petrova, 2018: Invasion of Siberian Pine populations in mountain tundra in the Northern Urals. *Contemporary Problems of Ecology*, **11**(4), 396-405, doi:10.1134/s1995425518040078.

Santamouris, M., 2015: Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *The Science of the total environment*, **512-513C**, 582-598, doi:10.1016/j.scitotenv.2015.01.060.

Sapkota, T. B. et al., 2015: Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains. *Journal of Integrative Agriculture*, **14**(8), 1524-1533, doi:https://doi.org/10.1016/S2095-3119(15)61093-0.

Sapountzaki, K., 2018: Boundaries, Overlaps and Conflicts between Disaster Risk Reduction and Adaptation to Climate Change: Are There Prospects of Integration? In: *Smart, Reslient and Transition Cities*, pp. 237-.

Saraswat, C., 2016: Assessment of stormwater runoff management practices and governance under climate change and urbanization: An analysis of Bangkok, Hanoi and Tokyo. *Environmental Science and Policy*.

Sarathchandra, C. et al., 2018: Significance of Mangrove Biodiversity Conservation in Fishery Production and Living Conditions of Coastal Communities in Sri Lanka. *Diversity*, **10**(2), doi:10.3390/d10020020.

Sarma, R. R., M. Munsi and A. N. Ananthram, 2015: Effect of Climate Change on Invasion Risk of Giant African Snail (Achatina fulica Ferussac, 1821: Achatinidae) in India. *Plos One*, **10**(11), doi:10.1371/journal.pone.0143724.

Satoh, Y. et al., 2017: Multi-model and multi-scenario assessments of Asian water futures: The Water Futures and Solutions (WFaS) initiative. *Earth's Future*, **5**(7), 823-852.

Sawamura, Y., Y. Suesada, T. Sugiura and H. Yaegaki, 2017: Chilling Requirements and Blooming Dates of Leading Peach Cultivars and a Promising Early Maturing Peach Selection, Momo Tsukuba 127. *The Horticulture Journal*, **86**(4), 426-436, doi:10.2503/hortj.OKD-052.

Sayer, J. et al., 2015: The Role of Citizen Science in Landscape and Seascape Approaches to Integrating Conservation and Development. *Land*, **4**(4), doi:10.3390/land4041200.

Schaefer, K. et al., 2014: The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters*, **9**(8), 085003.

Schaer, C. and A. Pantakar, 2018: Promoting private sector engagement in climate change adaptation and flood resilience—a case study of innovative approaches applied by MSMEs in Mumbai, India. In: *Theory and Practice of Climate Adaptation*. Springer, pp. 175-191.

Schamm, K. et al., 2014: Global gridded precipitation over land: a description of the new GPCC First Guess Daily product. *Earth Syst. Sci. Data*, **6**(1), 49-60, doi:10.5194/essd-6-49-2014.

Schaphoff, S. et al., 2016: Tamm review: observed and projected climate change impacts on Russia's forests and its carbon balance. *Forest Ecology and Management*, **361**, 432-444, doi:10.1016/j.foreco.2015.11.043.

Scheelbeek, P. F. D. et al., 2016: Drinking Water Sodium and Elevated Blood Pressure of Healthy Pregnant Women in Salinity-Affected Coastal Areas. *Hypertension*, **68**(2), 464-470, doi:doi:10.1161/HYPERTENSIONAHA.116.07743.

Scheyvens, H. and B. R. Shivakoti, 2019: *Asia-Pacific Landscape Transformations, Solutions for Sustainability*. (IGES), I. f. G. E. S., Hayama, Japan.

Schickhoff, U. et al., 2015: Do Himalayan treelines respond to recent climate change? An evaluation of sensitivity indicators. *Earth System Dynamics*, **6**(1), 245-265, doi:10.5194/esd-6-245-2015.

Schlenker, W. and M. Auffhammer, 2018: The cost of a warming climate. Nature Publishing Group.

Schleussner, C.-F. et al., 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth System Dynamics*, **7**(2), 327-351, doi:10.5194/esd-7-327-2016.

Schlosberg, D. and L. B. Collins, 2014: From environmental to climate justice: climate change and the discourse of environmental justice. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(3), 359-374, doi:10.1002/wcc.275.
Schmidt-Vogt, D., M. Foggin and C. Hergarten, 2016: Strengthening Mountain Societies in Central Asia in a Context of Multidimensional Change. *Mountain Research and Development*, **36**(3), 380-383, doi:10.1659/mrd-journal-d-16-00101.1.
Schwan, S. and X. Yu, 2017: Social protection as a strategy to address climate-induced migration. *International Journal of Climate Change Strategies and Management*, doi:10.1108/ijccsm-01-2017-0019.
Scott, C. A. et al., 2019: Water in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment*. Springer, pp. 257-299.
Seidler, R. et al., 2018: Progress on integrating climate change adaptation and disaster risk reduction for sustainable development pathways in South Asia: Evidence from six research projects. *International journal of disaster risk reduction*, **31**, 92-101.
Sekine, Y., 2021: Emerging 'agrarian climate justice' struggles in Myanmar. *The Journal of Peasant Studies*, **48** (3), 517-540, doi:https://doi.org/10.1080/03066150.2020.1839054.
Semenov, S. M., I. O. Popov and V. V. Yasyukevich, 2020: Statistical Model for Assessing the Formation of Climate-related Hazards Based on Climate Monitoring Data. *Russ Meteorol Hydro+*, **45**(5), 339-344, doi:10.3103/S1068373920050040.
Sen, S. M., A. and Kansal, 2019: Achieving water security in rural Indian Himalayas: A participatory account T of challenges and potential solutions. *Journal of Environmental Management* **245**, 398–408, doi:https://doi.org/10.1016/j.jenvman.2019.05.132.
Senapati, S. and V. Gupta, 2017: Socio-economic vulnerability due to climate change: Deriving indicators for fishing communities in Mumbai. *Marine Policy*, **76**, 90-97, doi:10.1016/j.marpol.2016.11.023.
Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Sengupta, S. and M. K. Jha, 2020: Social policy, COVID-19 and impoverished migrants: challenges and prospects in locked down India. *The International Journal of Community and Social Development*, **2**(2), 152-172.
Seposo, X. T., T. N. Dang and Y. Honda, 2015: Evaluating the Effects of Temperature on Mortality in Manila City (Philippines) from 2006-2010 Using a Distributed Lag Nonlinear Model. *Int J Environ Res Public Health*, **12**(6), 6842-6857, doi:10.3390/ijerph120606842.
Serdeczny, O., 2019: Non-economic loss and damage and the Warsaw international mechanism. In: *Loss and damage from climate change*. Springer, pp. 205-220.
Servadio, J. L., S. R. Rosenthal, L. Carlson and C. Bauer, 2018: Climate patterns and mosquito-borne disease outbreaks in South and Southeast Asia. *Journal of infection and public health*, **11**(4), 566-571, doi:10.1016/j.jiph.2017.12.006.
Setiawati Martiwi Diah, J. M. P., Gomez-Garcia Martin, Fukushi Kensuke, 2021: Accelerating Urban Heating Under Land-Cover and Climate Change Scenarios in Indonesia: Application of the Universal Thermal Climate Index *Frontiers in Built Environment* 7, 65, doi:10.3389/fbuil.2021.622382
Sha, Z. et al., 2016: Spatio-temporal patterns of satellite-derived grassland vegetation phenology from 1998 to 2012 in Inner Mongolia, China. *Journal of Arid Land*, **8**(3), 462-477, doi:10.1007/s40333-016-0121-9.
Shaban, A. and M. Hamze, 2017: *Shared Water Resources of Lebanon*. Water Resource Planning, Development and Management, 174 pp.
Shabani, F., L. Kumar and R. Hamdan Saif Al Shidi, 2018: Impacts of climate change on infestations of Dubas bug (Ommatissus lybicus Bergevin) on date palms in Oman. *PeerJ*, **6**, e5545, doi:10.7717/peerj.5545.
Shaffril, H. A. M., A.A. Samah, S.F. Samsuddin and Z. Ali, 2019: Mirror-mirror on the wall, what climate change adaptation strategies are practiced by the Asian's fishermen of all? . *Journal of Cleaner Production* **232**, doi:https://doi.org/10.1016/j.jclepro.2019.05.262.
Shaffril, H. A. M., A. Abu Samah and J. L. D'Silva, 2017: Adapting towards climate change impacts: Strategies for small-scale fishermen in Malaysia. *Marine Policy*, **81**, 196-201, doi:10.1016/j.marpol.2017.03.032.
Shaffril, H. A. M., S. E. Krauss and S. F. Samsuddin, 2018: A systematic review on Asian's farmers' adaptation practices towards climate change. *Sci Total Environ*, **644**, 683-695, doi:10.1016/j.scitotenv.2018.06.349.
Shah, A. A. et al., 2019: Current capacities, preparedness and needs of local institutions in dealing with disaster risk reduction in Khyber Pakhtunkhwa, Pakistan. *International Journal of Disaster Risk Reduction*, **34**, 165-172, doi:10.1016/j.ijdrr.2018.11.014.
Shah, T. et al., 2018: Solar pumps and South Asia's energy-groundwater nexus: exploring implications and reimagining its future. *Environmental Research Letters*, **13**(11), 115003.
Shahid, S. et al., 2016: Climate variability and changes in the major cities of Bangladesh: observations, possible impacts and adaptation. *Regional Environmental Change*, **16**(2), 459-471.
Sharma, B. et al., 2016: *Springs, storage towers, and water conservation in the midhills of Nepal*. International Centre for Integrated Mountain Development. ISBN 9291153958.

Sharma, E. et al., 2019: Introduction to the hindu kush himalaya assessment. In: *The Hindu Kush Himalaya Assessment*. Springer, pp. 1-16.
Sharma, V., 2019: Access for adaptation? Reviewing the linkages between energy, disasters, and development in India. *Energy Research & Social Science*, **52**, 10-19.
Shaw, R., 2019: Role of private sectors in disaster risk reduction: Potential and challenges. *Journal of Disaster Research*, **13**(7), 1207-1212, doi:10.20965/jdr.2018.p1207.
Shaw, R., Atta-ur-Rahman, A. Surjan and G. A. Parvin, 2016a: *Urban Disasters and Resilience in Asia*.
Shaw, R., T. Izumi and P. Shi, 2016b: Perspectives of Science and Technology in Disaster Risk Reduction of Asia. *International Journal of Disaster Risk Science*, **7**(4), 329-342, doi:10.1007/s13753-016-0104-7.
Shawoo, Z., & McDermott, C.L., 2020: Justice through polycentricity? A critical examination of climate justice framings in Pakistani climate policymaking. *Climate Policy*, **20**(2), 199-216, doi:https://doi.org/10.1080/14693062.2019.1707640.
Shen, Y.-J. et al., 2020: Review of historical and projected future climatic and hydrological changes in mountainous semiarid Xinjiang (northwestern China), central Asia. *Catena*, **187**, 104343.
Sherman, K., 1994: Sustainability, Biomass Yields, and Health of Coastal Ecosystems - An Ecological Perspective. *Mar. Ecol.-Prog. Ser.*, **112**(3), 277-301, doi:10.3354/meps112277.
Shi, W. et al., 2020: Modification Effects of Temperature on the Ozone–Mortality Relationship: A Nationwide Multicounty Study in China. *Environmental Science & Technology*, **54**(5), 2859-2868, doi:10.1021/acs.est.9b05978.
Shi, X. et al., 2019a: Farmers' perceived efficacy of adaptive behaviors to climate change in the Loess Plateau, China. *Science of the Total Environment* **697**, doi:https://doi.org/10.1016/j.scitotenv.2019.134217.
Shi, Y., T. Sayama, K. Takara and K. Ohtake, 2019b: Detecting flood inundation information through Twitter: The 2015 Kinu River flood disaster in Japan. *Journal of Natural Disaster Science*, **40**(1), 1-13.
Shiklomanov, 2019: Climate Change and Stability of Urban Infrastructure in Russian Permafrost Regions: Prognostic Assessment based on GCM Climate Projections - Shiklomanov - 2017 - Geographical Review - Wiley Online Library. doi:10.1111/gere.12214.
Shiklomanov, N. I., D. A. Streletskiy, V. I. Grebenets and L. Suter, 2017a: Conquering the permafrost: urban infrastructure development in Norilsk, Russia. *Polar Geography*, **40**(4), 273-290, doi:10.1080/1088937X.2017.1329237.
Shiklomanov, N. I., D. A. Streletskiy, T. B. Swales and V. A. Kokorev, 2017b: Climate Change and Stability of Urban Infrastructure in Russian Permafrost Regions: Prognostic Assessment based on GCM Climate Projections. *Geographical Review*, **107**(1), 125-142, doi:10.1111/gere.12214.
Shirsath, P., S. Vyas, P. Aggarwal and K. N. Rao, 2019: Designing weather index insurance of crops for the increased satisfaction of farmers, industry and the government. *Climate Risk Management*, **25**, 100189.
Shirsath, P. B., P. K. Aggarwal, P. K. Thornton and A. Dunnett, 2017: Prioritizing climate-smart agricultural land use options at a regional scale. *Agricultural Systems*, **151**, 174-183, doi:10.1016/j.agsy.2016.09.018.
Shitara, T. et al., 2018: Formation of disjunct plant distributions in Northeast Asia: a case study of Betula davurica using a species distribution model. *Plant Ecology*, **219**(9), 1105-1115, doi:10.1007/s11258-018-0862-y.
Shiwaku, K., A. Sakurai and R. Shaw (eds.), 2016: *Disaster resilience of education system : experiences from Japan*, Springer, Japan.
Shiyatov, S. G. and V. S. Mazepa, 2015: Contemporary expansion of Siberian larch into the mountain tundra of the Polar Urals. *Russian Journal of Ecology*, **46**(6), 495-502, doi:10.1134/s1067413615060168.
Shrestha, A. et al., 2010: Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. *Geomatics, Natural Hazards and Risk*, **1**(2), 157-169.
Shrestha, S., S. Neupane, S. Mohanasundaram and V. P. Pandey, 2020: Mapping groundwater resiliency under climate change scenarios: A case study of Kathmandu Valley, Nepal. *Environmental research*, **183**, 109149.
Shrestha, S., V. P. Pandey, S. Thatikonda and B. R. Shivakoti, 2016: *Groundwater environment in Asian cities: concepts, methods and case studies*. Butterworth-Heinemann. ISBN 0128031670.
Shuaib, M. et al., 2018: Impact of rapid urbanization on the floral diversity and agriculture land of district Dir, Pakistan. *Acta Ecologica Sinica*, **38**(6), 394-400, doi:https://doi.org/10.1016/j.chnaes.2018.04.002.
Shukla, A. K., K. Sudhakar and P. Baredar, 2017: Renewable energy resources in South Asian countries: Challenges, policy and recommendations. *Resource-Efficient Technologies*, **3**(3), 342-346.
Shuman, J. K. et al., 2015: Forest forecasting with vegetation models across Russia. *Canadian Journal of Forest Research*, **45**(2), 175-184, doi:10.1139/cjfr-2014-0138.
Shyam, S. S., K. S. Mohamed, P. K. Safeena and R. Remya, 2017: Effect of declining oil sardine landings on the livelihoods of traditional fishers in Kerala. *Journal of Indian Fisheries Association*, **44 (2)**, 7.
Siddiqui, T. et al., 2019: Migration in the Hindu Kush Himalaya: Drivers, Consequences, and Governance. In: *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People* [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer International Publishing, Cham, pp. 517-544. ISBN 978-3-319-92288-1.
Sigdel, S. R. et al., 2020: Tree-to-tree interactions slow down Himalayan treeline shifts as inferred from tree spatial patterns. *Journal of Biogeography*, **47**(8), 1816-1826, doi:https://doi.org/10.1111/jbi.13840.

Sigdel, S. R. et al., 2018: Moisture-mediated responsiveness of treeline shifts to global warming in the Himalayas. *Global Change Biology*, **24**(11), 5549-5559, doi:https://doi.org/10.1111/gcb.14428.
Sijapati, B., 2017: The quest for achieving universal social protection in Nepal: Challenges and opportunities. *Indian Journal of Human Development*, **11**(1), 17-36.
Sikor T, N. P., 2014: Globalizing environmental justice? *Geoforum*, **54**, 151-157.
Silva, R. A. et al., 2016: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmos. Chem. Phys.*, **16**(15), 9847-9862, doi:10.5194/acp-16-9847-2016.
Simons, W. J. F. et al., 2019: Vertical motion of Phuket Island (1994-2018) due to the Sumatra-Andaman mega-thrust earthquake cycle: impact on sea-level and consequences for coral reefs. *Mar. Geol.*, **414**, 92-102, doi:10.1016/j.margeo.2019.05.008.
Singh, C., 2019: Migration as a driver of changing household structures: Implications for local livelihoods and adaptation. *Migration and Development*, **8**(3), 301-319.
Singh, C. and R. Basu, 2020: Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural–urban continuum in India. *The Geographical Journal*, **186**(1), 87-102.
Singh, C. et al., 2018a: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and Development*, **10**(5), 389-405, doi:10.1080/17565529.2017.1318744.
Singh, C., P. Dorward and H. Osbahr, 2016: Developing a holistic approach to the analysis of farmer decision-making: Implications for adaptation policy and practice in developing countries. *Land Use Policy*, **59**, 329-343, doi:10.1016/j.landusepol.2016.06.041.
Singh, C., G. Jain, V. Sukhwani and R. Shaw, 2021a: Losses and damages associated with slow-onset events: urban drought and water insecurity in Asia. *Current Opinion in Environmental Sustainability*, **50**, 72-86.
Singh, C., M. Madhavan, J. Arvind and A. Bazaz, 2021b: Climate change adaptation in Indian cities: A review of existing actions and spaces for triple wins. *Urban Climate*, **36**, 100783, doi:https://doi.org/10.1016/j.uclim.2021.100783.
Singh, C., H. Osbahr and P. Dorward, 2018b: The implications of rural perceptions of water scarcity on differential adaptation behaviour in Rajasthan, India. *Regional Environmental Change*, **18**(8), 2417–2432, doi:10.1007/s10113-018-1358-y.
Singh, C. et al., 2019a: Exploring methodological approaches to assess climate change vulnerability and adaptation: reflections from using life history approaches. *Regional Environmental Change*, **19**(8), 2667-2682.
Singh, S. P., I. Bassignana-Khadka, B. Singh Karky and E. Sharma, 2011: *Climate change in the Hindu Kush-Himalayas: the state of current knowledge*. International Centre for Integrated Mountain Development (ICIMOD).
Singh, S. P., S. Sharma and P. P. Dhyani, 2019b: Himalayan arc and treeline: distribution, climate change responses and ecosystem properties. *Biodiversity and Conservation*, **28**(8-9), 1997-2016, doi:10.1007/s10531-019-01777-w.
Singh, U. et al., 2018c: Static tree line of Himalayan silver fir since last several decades at Tungnath, western Himalaya. *Trop Ecol*, **59**(2), 351-363.
Sinha, R. et al., 2019: Basin-scale hydrology and sediment dynamics of the Kosi river in the Himalayan foreland. *Journal of hydrology*, **570**, 156-166.
Sinha, S. and N. Tripathi, 2016: Assessing the challenges in successful implementation and adoption of crop insurance in Thailand. *Sustainability*, **8**(12), 1306.
Slodowicz, D. et al., 2018: Areas of high conservation value at risk by plant invaders in Georgia under climate change. *Ecol Evol*, **8**(9), 4431-4442, doi:10.1002/ece3.4005.
Smale, D. A. et al., 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9**(4), 306-+, doi:10.1038/s41558-019-0412-1.
Smeets Kristkova, Z., M. Van Dijk and H. Van Meijl, 2016: Projections of long-term food security with R&D driven technical change—A CGE analysis. *NJAS - Wageningen Journal of Life Sciences*, **77**, 39-51, doi:https://doi.org/10.1016/j.njas.2016.03.001.
Smith, K. R. et al., 2014: *Human Health: Impacts, Adaptation, and Co-Benefits*.
Smith, M. R. and S. S. Myers, 2018: Impact of anthropogenic CO2 emissions on global human nutrition. *Nature Climate Change*, **8**(9), 834-839, doi:10.1038/s41558-018-0253-3.
Sohel, S. I. et al., 2016: Predicting impacts of climate change on forest tree species of Bangladesh: evidence from threatened Dysoxylum binectariferum (Roxb.) Hook. f. ex Bedd. (Meliaceae). *Iforest*, **10**, 154-160, doi:10.3832/ifor1608-009.
Sohrabizadeh, S., D. S. Tourani Ph and H. R. Khankeh, 2016: Women and health consequences of natural disasters: Challenge or opportunity? *Women Health*, **56**(8), 977-993, doi:10.1080/03630242.2016.1176101.
Soleimani, A. et al., 2019: Influence of land use and land cover change on soil organic carbon and microbial activity in the forests of northern Iran. *Catena*, **177**, 227-237, doi:10.1016/j.catena.2019.02.018.
Son, J. Y., K. J. Lane, J. T. Lee and M. L. Bell, 2016: Urban vegetation and heat-related mortality in Seoul, Korea. *Environ Res*, **151**, 728-733, doi:10.1016/j.envres.2016.09.001.
Son, J. Y., J. T. Lee and M. L. Bell, 2017: Is ambient temperature associated with risk of infant mortality? A multi-city study in Korea. *Environ Res*, **158**, 748-752, doi:10.1016/j.envres.2017.07.034.
Song, C. L. et al., 2019: Importance of active layer freeze-thaw cycles on the riverine dissolved carbon export on the Qinghai-Tibet Plateau permafrost region. *Peerj*, **7**, doi:10.7717/peerj.7146.

Song, G. et al., 2017: Dietary changes to mitigate climate change and benefit public health in China. *Science of The Total Environment*, **577**, 289-298, doi:https://doi.org/10.1016/j.scitotenv.2016.10.184.
Song, Y. et al., 2016: Spatial distribution estimation of malaria in northern China and its scenarios in 2020, 2030, 2040 and 2050. *Malaria journal*, **15**(1), 345, doi:10.1186/s12936-016-1395-2.
Sönke Kreft, D. Eckstein and I. Melchior, 2016: GLOBAL CLIMATE RISK INDEX 2017: Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2015.
Sovacool, B. K., A. L. D'Agostino, A. Rawlani and H. Meenawat, 2012: Improving climate change adaptation in least developed Asia. *Environmental Science & Policy*, **21**, 112-125, doi:https://doi.org/10.1016/j.envsci.2012.04.009.
Sovacool, B. K., B.-O. Linnér and R. J. Klein, 2017: Climate change adaptation and the Least Developed Countries Fund (LDCF): Qualitative insights from policy implementation in the Asia-Pacific. *Climatic Change*, **140**(2), 209-226.
Spalding, M. et al., 2017: Mapping the global value and distribution of coral reef tourism, Marine Policy, 104-113 pp.
Spalding, M. and C. L. Parret, 2019: Global patterns in mangrove recreation and tourism, Marine Policy.
Springmann, M., H. C. J. Godfray, M. Rayner and P. Scarborough, 2016: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, **113**(15), 4146-4151, doi:10.1073/pnas.1523119113.
Srinivasa Rao, C. et al., 2016: Chapter Four - Climate Resilient Villages for Sustainable Food Security in Tropical India: Concept, Process, Technologies, Institutions, and Impacts. In: *Advances in Agronomy* [Sparks, D. L. (ed.)]. Academic Press, pp. 101-214. ISBN 0065-2113.
Stankovic, M., N. Tantipisanuh and A. Prathep, 2018: Carbon storage in seagrass ecosystems along the Andaman coast of Thailand. *Bot. Marina*, **61**(5), 429-440, doi:10.1515/bot-2017-0101.
Steg, L., J. W. Bolderdijk, K. Keizer and G. Perlaviciute, 2014: An Integrated Framework for Encouraging Pro-environmental Behaviour: The role of values, situational factors and goals. *Journal of Environmental Psychology*, **38**, 104-115, doi:10.1016/j.jenvp.2014.01.002.
Steinbach, D. et al., 2016: Aligning social protection and climate resilience. *IIED: London, UK*.
Stevenson, L. A., M. L. Shrestha and A. Sterin, 2013: *Climate Change Adaptation Strategies of Selected Smallholder Upland Farmers in Southeast Asia: Philippines and Indonesia*.
Stip, C. et al., 2019: Water Infrastructure Resilience.
Storch, H. and N. K. Downes, 2011: A scenario-based approach to assess Ho Chi Minh City's urban development strategies against the impact of climate change. *Cities*, **28**(6), 517-526, doi:10.1016/j.cities.2011.07.002.
Stott, C. and S. Huq, 2014: Knowledge flows in climate change adaptation: exploring friction between scales. *Climate and Development*, **6**(4), 382-387.
Street, R. B. et al., 2019: How could climate services support disaster risk reduction in the 21st century. *International Journal of Disaster Risk Reduction*, **34**, 28–33, doi:https://doi.org/10.1016/j.ijdrr.2018.12.001.
Streletskiy, D. A., A. B. Sherstiukov, O. W. Frauenfeld and F. E. Nelson, 2015: Changes in the 1963–2013 shallow ground thermal regime in Russian permafrost regions. *Environmental Research Letters*, **10**(12), 125005.
Streletskiy, D. A., N. I. Shiklomanov and F. E. Nelson, 2012: Permafrost, infrastructure, and climate change: a GIS-based landscape approach to geotechnical modeling. *Arctic, antarctic, and alpine research*, **44**(3), 368-380.
Streletskiy, D. A., Suter, L.J., Shiklomanov, N.I., Porfiriev, B.N. and Eliseev, D.O., 2019: Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. *Environmental Research Letters*, doi:doi:10.1088/1748-9326/aaf5e6.
Stringer, L. C. et al., 2020: Adaptation and development pathways for different types of farmers. *Environmental Science & Policy*, **104**, 174-189, doi:https://doi.org/10.1016/j.envsci.2019.10.007.
Sugiura, T., H. Ogawa, N. Fukuda and T. Moriguchi, 2013: Changes in the taste and textural attributes of apples in response to climate change. *Sci Rep*, **3**, 2418, doi:10.1038/srep02418.
Sugiura, T. et al., 2014: Predicted Changes in Locations Suitable for Tankan Cultivation Due to Global Warming in Japan. *Journal of the Japanese Society for Horticultural Science*, **83**(2), 117-121, doi:10.2503/jjshs1.CH-094.
Sugiura, T., M. Shiraishi, S. Konno and A. Sato, 2019: Assessment of deterioration in skin color of table grape berries due to climate change and effects of two adaptation measures. *Journal of Agricultural Meteorology*, doi:10.2480/agrmet.D-18-00032.
Sukhwani, V., R. Shaw, B. K. Mitra and W. Yan, 2019: Optimizing Food-Energy-Water (FEW) nexus to foster collective resilience in urban-rural systems. *Progress in Disaster Science*, **1**, 100005, doi:https://doi.org/10.1016/j.pdisas.2019.100005.
Sukhwani, V. et al., 2020: Addressing Urban–Rural Water Conflicts in Nagpur through Benefit Sharing. *Water*, **12**(11), 2979, doi:https://doi.org/10.3390/w12112979.
Sullivan-Wiley, K. A. and A. G. Short Gianotti, 2017: Risk Perception in a Multi-Hazard Environment. *World Development*, **97**, 138-152, doi:10.1016/j.worlddev.2017.04.002.
Sultana, F., 2021: Climate change, COVID-19, and the co-production of injustices: a feminist reading of overlapping crises. *Soc. Cult. Geogr.*, **22**(4), 447-460.
Sun, F., W. Kuang, W. Xiang and Y. Che, 2016: Mapping water vulnerability of the Yangtze River Basin: 1994–2013. *Environmental management*, **58**(5), 857-872.
Sun, H. et al., 2017: Exposure of population to droughts in the Haihe River Basin under global warming of 1.5 and 2.0 C scenarios. *Quaternary International*, **453**, 74-84.

Sun, Q. H. et al., 2019: Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. *Environ Int*, **128**, 125-136, doi:10.1016/j.envint.2019.04.025.
Sun, Y. and Z. Han, 2018: Climate change risk perception in Taiwan: Correlation with individual and societal factors. *International Journal of Environmental Research and Public Health*, **15**(1), doi:10.3390/ijerph15010091.
Sung, J., 2015: Climate change education and education for sustainable development in the Republic of Korea : a status report. *Journal of Education for Sustainable Development*, **9**(1), 78-89, doi:10.1177/0973408215569116.
Supari et al., 2020: Multi-model projections of precipitation extremes in Southeast Asia based on CORDEX-Southeast Asia simulations. *Environmental Research*, **184**, 109350, doi:https://doi.org/10.1016/j.envres.2020.109350.
Surasinghe, T., 2011: Conservation and distribution status of amphibian fauna in Sri Lanka. *Biodiversity*, **10**, doi:10.1080/14888386.2009.9712632.
Surie, M. and S. Prasai, 2015: Strengthening transparency and access to information on transboundary rivers in South Asia. *The Asia Foundation, New Delhi*.
Surminski, S. and D. Oramas-Dorta, 2014: Flood insurance schemes and climate adaptation in developing countries. *International Journal of Disaster Risk Reduction*, **7**, 154-164.
Suroso, D. S. A. and T. Firman, 2018: The role of spatial planning in reducing exposure towards impacts of global sea level rise case study: Northern coast of Java, Indonesia. *Ocean and Coastal Management* **153**, 84-97, doi:https://doi.org/10.1016/j.ocecoaman.2017.12.007.
Sutthacheep, M. et al., 2013: Impacts of the 1998 and 2010 mass coral bleaching events on the Western Gulf of Thailand. *Deep-Sea Res. Part II-Top. Stud. Oceanogr.*, **96**, 25-31, doi:10.1016/j.dsr2.2013.04.018.
Sutton, W. R., J. P. Srivastava and J. E. Neumann, 2013: *Looking Beyond the Horizon How Climate Change Impacts and Adaptation Responses Will Reshape Agriculture in Eastern Europe and Central Asia*. Bank, W. Available at: http://documents.worldbank.org/curated/en/676601468249642651/pdf/Looking-beyond-the-horizon-how-climate-change-impacts-and-adaptation-responses-will-reshape-agriculture-in-Eastern-Europe-and-Central-Asia.pdf.
Suwal, M. K. et al., 2016: Land-use change under a warming climate facilitated upslope expansion of Himalayan silver fir (*Abies spectabilis* (D. Don) Spach). *Plant Ecology*, **217**(8), 993-1002, doi:10.1007/s11258-016-0624-7.
Suzuki-Ohno, Y. et al., 2017: Factors restricting the range expansion of the invasive green anole Anolis carolinensis on Okinawa Island, Japan. *Ecol Evol*, **7**(12), 4357-4366, doi:10.1002/ece3.3002.
Suzuki, S. N., M. I. Ishihara and A. Hidaka, 2015: Regional-scale directional changes in abundance of tree species along a temperature gradient in Japan. *Global Change Biology*, **21**(9), 3436-3444, doi:10.1111/gcb.12911.
Swe, L. M. M., R. P. Shrestha, T. Ebbers and D. Jourdain, 2015: Farmers' perception of and adaptation to climate-change impacts in the Dry Zone of Myanmar. *Climate and Development*, **7**(5), 437-453.
Szabo, S., W. N. Adger and Z. Matthews, 2018: Home is where the money goes: migration-related urban-rural integration in delta regions. *Migration and Development*, **7**(2), 163-179.
Szabo, S. et al., 2016a: Population Dynamics, Delta Vulnerability and Environmental Change: Comparison of the Mekong, Ganges–Brahmaputra and Amazon Delta Regions. *Sustainability Science* **11**(4), 539–554, doi:https://doi.org/10.1007/s11625-016-0372-6.
Szabo, S. et al., 2016b: Making SDGs work for climate change hotspots. *Environment: Science and Policy for Sustainable Development*, **58**(6), 24-33, doi:10.1080/00139157.2016.1209016.
Takahashi, K. et al., 2015: School Health: an essential strategy in promoting community resilience and preparedness for natural disasters. *Glob Health Action*, **8**, 29106, doi:10.3402/gha.v8.29106.
Takama, T., E. Aldrian, S. D. A. Kusumaningtyas and W. Sulistya, 2016: Identified vulnerability contexts for a paddy production assessment with climate change in Bali, Indonesia. *Climate and Development*, **9**(2), 110-123, doi:10.1080/17565529.2016.1167658.
Takano, K. T. et al., 2017: Detecting latitudinal and altitudinal expansion of invasive bamboo Phyllostachys edulis and Phyllostachys bambusoides (Poaceae) in Japan to project potential habitats under 1.5 degrees C-4.0 degrees C global warming. *Ecol Evol*, **7**(23), 9848-9859, doi:10.1002/ece3.3471.
Takao, S. et al., 2015: Projecting the impacts of rising seawater temperatures on the distribution of seaweeds around Japan under multiple climate change scenarios. *Ecol Evol*, **5**(1), 213-223, doi:10.1002/ece3.1358.
Talchabhadel, R. and R. Karki, 2019: Assessing climate boundary shifting under climate change scenarios across Nepal. *Environmental Monitoring and Assessment* **191**, 520, doi:https://doi.org/10.1007/s10661-019-7644-4.
Tambe, S. et al., 2012: Reviving dying springs: climate change adaptation experiments from the Sikkim Himalaya. *Mountain Research and Development*, **32**(1), 62-73.
Tanaka, Y., Y. Sakamoto and H. Honda (eds.), The impact of posting URLs in disaster-related tweets on rumor spreading behavior. 2014 47th Hawaii International Conference on System Sciences, IEEE, 520-529 pp. ISBN 1479925047.
Tang, C. Q. et al., 2018: Identifying long-term stable refugia for relict plant species in East Asia. *Nature Communications*, **9**(1), 4488, doi:10.1038/s41467-018-06837-3.
Taniguchi, M., A. Endo, J. J. Gurdak and P. Swarzenski, 2017a: Water-Energy-Food Nexus in the Asia-Pacific Region. *Journal of Hydrology: Regional Studies*, **11**, 1-8, doi:10.1016/j.ejrh.2017.06.004.
Taniguchi, M., N. Masuhara and K. Burnett, 2017b: Water, energy, and food security in the Asia Pacific region. *Journal of Hydrology: Regional Studies*.
Tanjeela, M. and S. Rutherford, 2018: The Influence of Gender Relations on Women's Involvement and Experience in Climate Change Adaptation Programs in Bangladesh. *SAGE Open*, **8**(4), doi:10.1177/2158244018812620.

Tankha, S., D. Fernandes and N. C. Narayanan, 2020: Overcoming barriers to climate smart agriculture in India. *International Journal of Climate Change Strategies and Management*, **12**(1), 108-127, doi:10.1108/IJCCSM-10-2018-0072.

Taremwa, N. K., D. Gashumba, A. Butera and T. Ranganathan, 2017: Climate Change Adaptation in Rwanda through Indigenous Knowledge Practice. *Kamla Raj Enterprises*, doi:10.1080/09718923.2016.11893524.

Tasgaonkar, P., D'Souza, M., Bendapudi, R. & Jacobs, C. , 2018: *Vulnerability to heat stress: A case study of Yavatmal, Maharashtra, India.*, ASSAR (Adaptation at Scale in Semi-Arid Regions).

Taylor, A. L., 2019: General and specific motivations. *Nature Climate Change*, **9**(2), 89-90, doi:10.1038/s41558-018-0395-3.

Tchebakova, N. M. et al., 2016: Assessment of climatic limits of needle cast-affected area under climate change in Central Siberia. *Contemporary Problems of Ecology*, **9**(6), 721-729, doi:10.1134/s1995425516060135.

Teh, L. S. L., L. C. L. Teh and U. R. Sumaila, 2013: A Global Estimate of the Number of Coral Reef Fishers. *Plos One*, **8**(6), 10, doi:10.1371/journal.pone.0065397.

Teixeira, E. I. et al., 2013: Global hot-spots of heat stress on agricultural crops due to climate change. *Agricultural and Forest Meteorology*, **170**, 206-215, doi:10.1016/j.agrformet.2011.09.002.

Telesetsky, A. and Q. He, 2016: Climate Change Insurance and Disasters: Is the Shenzhen Social Insurance Program a Model for Adaptation. *BC Envtl. Aff. L. Rev.*, **43**, 485.

Telwala, Y., B. W. Brook, K. Manish and M. K. Pandit, 2013: Climate-Induced Elevational Range Shifts and Increase in Plant Species Richness in a Himalayan Biodiversity Epicentre. *Plos One*, **8**(2), doi:10.1371/journal.pone.0057103.

Tenzing, J. D., 2019: Integrating social protection and climate change adaptation: A review. *WIREs Climate Change*, **11**(2), doi:10.1002/wcc.626.

Tezuka, S. et al., 2014: Estimation of the effects of climate change on flood-triggered economic losses in Japan. *International Journal of Disaster Risk Reduction*, **9**, 58-67, doi:https://doi.org/10.1016/J.IJDRR.2014.03.004.

Thakur, B. K. and V. Gupta, 2019: Valuing health damages due to groundwater arsenic contamination in Bihar, India. *Economics & Human Biology*, **35**, 123-132.

Thaler, T., S. Fuchs, S. Priest and N. Doorn, 2017: Social justice in the context of adaptation to climate change—reflecting on different policy approaches to distribute and allocate flood risk management. *Regional Environmental Change*, **18**(2), 305-309, doi:10.1007/s10113-017-1272-8.

Thapa, S. et al., 2018: Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. *Plos One*, **13**(4), doi:10.1371/journal.pone.0195752.

Thinesh, T. et al., 2019: Differential bleaching and recovery pattern of southeast Indian coral reef to 2016 global mass bleaching event: Occurrence of stress-tolerant symbiont Durusdinium (Clade D) in corals of Palk Bay. *Mar. Pollut. Bull.*, **145**, 287-294, doi:10.1016/j.marpolbul.2019.05.033.

Thirumalai, K., P. N. DiNezio, Y. Okumura and C. Deser, 2017: Extreme temperatures in Southeast Asia caused by El Nino and worsened by global warming. *Nat Commun*, **8**, 15531, doi:10.1038/ncomms15531.

Thomas, K., Hardy, R.D., Lazrus, H., Mendez, M., Orlove, B., Rivera-Collazo, I., Roberts, J.T., Rockman, M., Warner, B.P. and Winthrop, R., , 2019: Explaining differential vulnerability to climate change: A social science review. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(2).

Tian, J. and Y. Zhang, 2019: Detecting changes in irrigation water requirement in Central Asia under CO2 fertilization and land use changes. *Journal of Hydrology*, **583**, 124315, doi:10.1016/j.jhydrol.2019.124315.

Tian, X. R., W. B. Cui and L. F. Shu, 2020: Evaluating fire management effectiveness with a burn probability model in Daxing'anling, China. *Canadian Journal of Forest Research*, **50**(7), 670-679, doi:10.1139/cjfr-2019-0413.

Tilman, D. et al., 2009: Beneficial biofuels—the food, energy, and environment trilemma. *Science*, **325**(5938), 270-271.

Tishkov, A. et al., 2020: Regional biogeographic effects of "fast" climate changes in the Russian Arctic in the 21st century. *Arctic: Ecology and Economy*, 31-44, doi:10.25283/2223-4594-2020-2-31-44.

Tiwari, A., Z. X. Fan, A. S. Jump and Z. K. Zhou, 2017: Warming induced growth decline of Himalayan birch at its lower range edge in a semi-arid region of Trans-Himalaya, central Nepal. *Plant Ecology*, **218**(5), 621-633, doi:10.1007/s11258-017-0716-z.

Tiwari, A. and P. K. Jha, 2018: An overview of treeline response to environmental changes in Nepal Himalaya. *Trop Ecol*, **59**(2), 273-285.

Tiwari, P. C. and B. Joshi, 2014: Environmental changes and their impact on rural water, food, livelihood, and health security in Kumaon Himalaya. *International Journal of Urban and Regional Studies on Contemporary India*, **1**, 1-12.

Tiwari, V., J. Wahr and S. Swenson, 2009: Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophysical Research Letters*, **36**(18).

Tol, R. S. J., 2018: The Economic Impacts of Climate Change. *Review of Environmental Economics and Policy*, **12**(1), 4-25, doi:10.1093/reep/rex027.

Torralba, V., F. J. Doblas-Reyes and N. Gonzalez-Reviriego, 2017: Uncertainty in recent near-surface wind speed trends: a global reanalysis intercomparison. *Environmental Research Letters*, **12**(11), 114019, doi:10.1088/1748-9326/aa8a58.

Torzhkov, I. et al., 2019: The economic consequences of future climate change in the forest sector of Russia. *IOP Conference Series: Earth and Environmental Science*, **226**, 012032, doi:10.1088/1755-1315/226/1/012032.

Toussaint, P., 2020: Loss and damage and climate litigation: The case for greater interlinkage. *Review of European, Comparative & International Environmental Law*.
Tran, L. and K. Brown, 2019: The importance of ecosystem services to smallholder farmers in climate change adaptation: learning from an ecosystem-based adaptation pilot in Vietnam. *Agroforest Systems* **93**, 1949–1960, doi:https://doi.org/10.1007/s10457-018-0302-y (0123456789.
Tran, N. et al., 2020: Profitability and perceived resilience benefits of integrated shrimp-tilapia-seaweed aquaculture in North Central Coast, Vietnam. *Marine Policy*, **120**, 104153, doi:https://doi.org/10.1016/j.marpol.2020.104153.
Trang, P. M. et al., 2016: Heatwaves and Hospital Admissions for Mental Disorders in Northern Vietnam. *PLOS ONE*, **11**(5), e0155609, doi:10.1371/journal.pone.0155609.
Trinh, T. Q., R. F. Rañola, L. D. Camacho and E. Simelton, 2018: Determinants of farmers' adaptation to climate change in agricultural production in the central region of Vietnam. *Land Use Policy*, **70**, 224-231, doi:10.1016/j.landusepol.2017.10.023.
Tripathi, A. and A. K. Mishra, 2017: Knowledge and passive adaptation to climate change: An example from Indian farmers. *Climate Risk Management*, **16**, 195-207, doi:10.1016/j.crm.2016.11.002.
Trisurat, Y., A. Aekakkararungroj, H. O. Ma and J. M. Johnston, 2018: Basin-wide Impacts of Climate Change on Ecosystem Services in the Lower Mekong Basin. *Ecol Res*, **33**(1), 73-86, doi:10.1007/s11284-017-1510-z.
Truelove, H. B., A. R. Carrico and L. Thabrew, 2015: A socio-psychological model for analyzing climate change adaptation: A case study of Sri Lankan paddy farmers. *Global Environmental Change*, **31**, 85-97, doi:10.1016/j.gloenvcha.2014.12.010.
Tschakert, P. et al., 2019: One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change*, **55**, 58-72, doi:https://doi.org/10.1016/j.gloenvcha.2018.11.006.
Tseng, W. W., S. H. Hsu and C. C. Chen, 2015: Estimating the willingness to pay to protect coral reefs from potential damage caused by climate change--The evidence from Taiwan. *Mar Pollut Bull*, **101**(2), 556-565, doi:10.1016/j.marpolbul.2015.10.058.
Tucker, J. et al., 2015: Social vulnerability in three high-poverty climate change hot spots: What does the climate change literature tell us? *Regional Environmental Change*, **15**(5), 783-800.
Tuladhar, G. et al., 2015a: Disaster risk reduction knowledge of local people in Nepal. *Geoenvironmental Disasters* **2**(5), doi:10.1186/s40677-014-0011-4.
Tuladhar, G., R. Yatabe, N. Bhandary and R. Dahal, 2015b: Assessment of disaster risk reduction knowledge of school teachers in Nepal. *International Journal of Health System and Disaster Management*, **3**(1), doi:10.4103/2347-9019.147142.
Tyagi, N. K. and P. K. Joshi, 2019: Index-Based Insurance for Mitigating Flood Risks in Agriculture: Status, Challenges and Way Forward. In: *Climate Smart Agriculture in South Asia*. Springer, pp. 183-204.
Uchiyama, C., L. A. Stevenson and E. Tandoko, 2020: Climate change research in Asia: A knowledge synthesis of Asia-Pacific Network for Global Change Research (2013–2018). *Environmental Research*, **188**, 109635.
Udas, P. B. et al., 2019: Basin level gendered vulnerabilities and adaptation: A case of Gandaki River Basin. *Environmental Development* **31**, 43–54, doi:https://doi.org/10.1016/j.envdev.2019.05.002.
Uddin, M. a. S. M. A. R. a. K. S. a. N. M. K., 2014: Climate change impacts on the Sundarbans mangrove ecosystem services and dependent livelihoods in Bangladesh. *Asian Journal of Conservation Biology*, **2**, 152-156.
Udo, K. and Y. Takeda, 2018: Projections of future beach loss in Japan due to sea-level rise and uncertainties in projected beach loss. *Coastal Engineering Journal*, **59**(2), doi:DOI: 10.1142/S057856341740006X.
Ullah, W., M. Nafees, M. Khurshid and T. Nihei, 2019: Assessing farmers' perspectives on climate change for effective farm-level adaptation measures in Khyber Pakhtunkhwa, Pakistan. *Environmental Monitoring and Assessment* **191**, 547, doi:https://doi.org/10.1007/s10661-019-7651-5.
Ulrichs, M., R. Slater and C. Costella, 2019: Building resilience to climate risks through social protection: from individualised models to systemic transformation. *Disasters*, **43**, S368-S387.
Umapathy, G. et al., 2016: Ranging, Activity and Habitat Use by Tigers in the Mangrove Forests of the Sundarban. *Plos One*, **11**(4), doi:10.1371/journal.pone.0152119.
UN-HABITAT and UNESCAP, 2018: *Climate Change and National Urban Policies in Asia and The Pacific: A regional guide for integrating climate change concerns into urban-related policy, legislative, financial and institutional frameworks*. Available at: https://www.fukuoka.unhabitat.org/projects/asian_subregion/pdf/RegionalGuide_Print_NEWVersion.pdf.
UN-Water, 2018: *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. UNESCO, Paris.
UN, 2016: *World Economic and Social Survey 2016*. **(E/2016/50/Rev.1).** Nations, U., New York.
UN, 2018: Towards Safe, Orderly and Regular Migration in the Asia-Pacific Region Challenges and Opportunities.
UNDESA, 2017: *World Population Prospects: Key findings & advance tables*. New York. Available at: https://reliefweb.int/organization/un-desa.
UNDESA, 2018: *World Urbanization Prospects: The 2018 Revision*. Available at: https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf.

UNDP ESCAP OCHA RIMES APCC, 2017: *Enhancing Resilience to Extreme Climate Events: Lessons from the 2015-2016 El Niño Event in Asia and the Pacific*. Available at: https://www.unescap.org/sites/default/files/El%20Nino%20report-%20finalized%20ESCAP07082017.pdf.

UNDP, G., 2018: Climate Change Adaptation in the Arab States: Best practices and lessons learned, Bangkok, 90 pp.

UNEP, 2016: The Adaptation Finance Gap Report 2016.

UNEP, 2019: *Air Pollution in Asia and the Pacific: Science-based solutions*. Available at: https://www.ccacoalition.org/en/resources/air-pollution-asia-and-pacific-science-based-solutions-summary-full-report.

UNEP, 2020: *Out of the Blue: The Value of Seagrasses to the Environment and to People*. Available at: https://www.unenvironment.org/resources/report/out-blue-value-seagrasses-environment-and-people.

UNESCAP, 2013: *The status of the water-energy-food nexus in Asia and the Pacific*. UNESCAP, B., Thailand (accessed 6 October 2019).

UNESCAP, 2018a: Economic and Social Commission for Asia and the Pacific Committee on Environment and Development. Fifth session Bangkok, 21–23 November 2018. Item 2 of the provisional agenda* Environmental challenges in the context of the implementation of the 2030 Agenda for Sustainable Development, 21pp pp.

UNESCAP, 2018b: *Energy Transition Pathways for the 2030 Agenda in Asia and the Pacific: Regional Trends Report on Energy for Sustainable Development 2018*.

UNESCAP, 2018c: Opportunities for Regional Cooperation in Disaster Risk Financing. 70.

UNESCAP, 2019: *Asia-Pacific Disaster Report 2019. The Disaster Riskscape Across Asia-Pacific*. (ESCAP), E. a. S. C. f. A. a. t. P., Bangkok, Thailand. Available at: https://www.unescap.org/sites/default/files/publications/Asia-Pacific%20Disaster%20Report%202019_full%20version.pdf.

UNFCCC, 2015: Article 6 Climate education and training.

Ung, M., I. Luginaah, R. Chuenpagdee and G. Campbell, 2015: Perceived Self-Efficacy and Adaptation to Climate Change in Coastal Cambodia. *Climate*, **4**(1), 1, doi:10.3390/cli4010001.

UNICEF, 2015: *The impact of climate change on children*. UNICEF, New York: USA.

UNICEF, I.-I., 2019: *Social Protection in Asia and the Pacific: Inventory of non-contributory programmes.*, International Policy Centre for Inclusive Growth., Brasilia.

UNISDR, 2017: GAR Atlas: Unveiling Global Disaster Risk.

United Nations, 2015: *Transforming our world : 2030 Agenda for Sustainable Development*. General Assembly on 25 September 2015 ed., n, United Nation ,New York. Available at: https://www.preventionweb.net/publications/view/45418.

United Nations Climate Change Secretariat, 2019: *Climate action and support trends*. Bonn, Germany, 33 pp.

United Nations, D. o. E. a. S. A., Population Division (UNDESA), 2019: *World Urbanization Prospects: The 2018 Revision*. United Nations
New York.

United Nations, E. a. S. C. f. A. a. t. P. E., 2020: *Asia-Pacific Migration Report 2020: Assessing Implementation of the Global Compact for Migration*. United Nations, Bangkok.

Unsworth, R. K. F. et al., 2018: Indonesia's globally significant seagrass meadows are under widespread threat. *Science of the Total Environment*, **634**, 279-286, doi:10.1016/j.scitotenv.2018.03.315.

Unsworth, R. K. F. et al., 2019a: Global challenges for seagrass conservation. *Ambio*, **48**(8), 801-815, doi:10.1007/s13280-018-1115-y.

Unsworth, R. K. F., L. M. Nordlund and L. C. Cullen-Unsworth, 2019b: Seagrass meadows support global fisheries production. *Conservation Letters*, **12**(1), 8, doi:10.1111/conl.12566.

Upadhyay, H., 2014: Migrating to adapt?: contesting dominant narratives of migration and climate change; case of Maldives and Lakshadweep.

USAID, 2015: *USAID Mekong Adaptation and Resilience to Climate Change (USAID Mekong ARCC) : Lessons on Integrating Scientific and Community Knowledge of Climate Change to Develop Adaptation Plans in Lower Mekong Basin*. Available at: https://www.weadapt.org/.

Vadigi, S., 2017: Indigenous Knowledge Systems and Formal Scientific Research for Climate Change. *Kamla Raj Enterprises*, doi:10.1080/09709274.2016.11906967.

Vaghefi, S. A. et al., 2019: Author Correction: The future of extreme climate in Iran. *Sci Rep*, **9**(1), 17420, doi:10.1038/s41598-019-53784-0.

Van Cuong, C., M. Russell, S. Brown and P. Dart, 2015: Using Shoreline Video Assessment for coastal planning and restoration in the context of climate change in Kien Giang, Vietnam. *Ocean Science Journal*, **50**(2), 413-432, doi:10.1007/s12601-015-0038-9.

Van de Vliert, E. T., RSJ, 2014: Harsh climate promotes harsh governance (except in cold-dry-weathy environments. *Climate Research*, **61**(1), 19-28, doi:10.3354/cr01246.

van der Geest, K., 2017: Landslide Loss and Damage in Sindhupalchok District, Nepal: Comparing Income Groups with Implications for Compensation and Relief. *International Journal of Disaster Risk Science*, **9**, 157–166, doi:https://doi.org/10.1007/s13753-018-0178-5.

van der Heijden, J., A. Cherkasheva and O. Luckman, 2019: Urban climate governance in Russia: Critical insights from Moscow and St Petersburg. *Journal of Urban Affairs*, doi:10.1080/07352166.2019.1617036.

van der Keur, P. et al., 2016: Identification and Analysis of Uncertainty in Disaster Risk Reduction and Climate Change Adaptation in South and Southeast Asia. *International Journal of Disaster Risk Reduction*, **16**, 208-214.

van der Zande, R. M. et al., 2020: Paradise lost: End-of-century warming and acidification under business-as-usual emissions have severe consequences for symbiotic corals. *Global Change Biology*, **26**(4), 2203-2219, doi:10.1111/gcb.14998.

van Gevelt, T. et al., 2019: Indigenous perceptions of climate anomalies in Malaysian Borneo. *Global Environmental Change* **58**, doi:https://doi.org/10.1016/j.gloenvcha.2019.101974.

van Katwijk, M. M. et al., 2016: Global analysis of seagrass restoration: the importance of large-scale planting. *J. Appl. Ecol.*, **53**(2), 567-578, doi:10.1111/1365-2664.12562.

Van Luong, C. et al., 2012: Status and threats on seagrass beds using GIS in Vietnam. **8525**, 214 -- 226, doi:10.1117/12.977277.

van Valkengoed, A. and L. Steg, 2019a: The Psychology of Climate Change Adaptation. In: *Elements in Applied Social Psychology* [Clayton, S. (ed.)]. Cambridge University Press. ISBN 9781108724456.

van Valkengoed, A. M. and L. Steg, 2019b: Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, **9**(2), 158-163, doi:10.1038/s41558-018-0371-y.

Van Vliet, M. T. H., F. Ludwig and P. Kabat, 2013: Global streamflow and thermal habitats of freshwater fishes under climate change. *Climatic Change*, **121**(4), 739-754, doi:10.1007/s10584-013-0976-0.

Varma, N. and S. Hazarika, 2018: Bridges and Barriers for Governance of Water Resources in South Asia—Insights from Brahmaputra Basin in India. In: *Climate Change Governance and Adaptation*. CRC Press, pp. 161-182.

Veettil, B. K. et al., 2019: Mangroves of Vietnam: Historical development, current state of research and future threats. *Estuarine, Coastal and Shelf Science*, **218**, 212-236, doi:10.1016/j.ecss.2018.12.021.

Veh, G., O. Korup, S. Roessner and A. Walz, 2018: Detecting Himalayan glacial lake outburst floods from Landsat time series. *Remote sensing of environment*, **207**, 84-97.

Veh, G. et al., 2019: Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. *Nature Climate Change*, **9**(5), 379-+, doi:10.1038/s41558-019-0437-5.

Vij, S., R. Biesbroek, A. Groot and K. Termeer, 2018: Changing climate policy paradigms in Bangladesh and Nepal. *Environmental science & policy*, **81**, 77-85.

Vij, S. et al., 2017: Climate adaptation approaches and key policy characteristics: Cases from South Asia. *Environmental Science & Policy*, **78**, 58-65.

Vinh, T. V. et al., 2019: Allometric models to estimate above-ground biomass and carbon stocks in Rhizophora apiculata tropical managed mangrove forests (Southern Viet Nam). *Forest Ecology and Management*, **434**, 131-141, doi:10.1016/j.foreco.2018.12.017.

Visvanathan, C., 2018: *Water Quality and Security in Asia and the Pacific ~What 3R and Circular Economy can Offer?*, United Nations Centre for Regional Development, Indore, Madhya Pradesh, India.

Vivekanandan, E., R. Hermes and C. O'Brien, 2016: Climate change effects in the Bay of Bengal Large Marine Ecosystem. *Environmental Development*, **17**, 46-56, doi:10.1016/j.envdev.2015.09.005.

von Stechow, C. et al., 2016: 2 C and SDGs: united they stand, divided they fall? *Environmental Research Letters*, **11**(3), 034022.

Vu, T. T. and R. Ranzi, 2017: Flood risk assessment and coping capacity of floods in central Vietnam. *Journal of Hydro-environment Research*, **14**, 44-60, doi:https://doi.org/10.1016/J.JHER.2016.06.001.

Wabnitz, C. C. C. et al., 2018: Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. *Plos One*, **13**(5), 26, doi:10.1371/journal.pone.0194537.

Wada, Y. and L. Heinrich, 2013: Assessment of transboundary aquifers of the world—vulnerability arising from human water use. *Environmental Research Letters*, **8**(2), 024003.

Wagner, B. et al., 2015: Carbon pools of semi-arid *Picea crassifolia* forests in the Qilian Mountains (north-eastern Tibetan Plateau). *Forest Ecology and Management*, **343**, 136-143, doi:https://doi.org/10.1016/j.foreco.2015.02.001.

Walch, C., 2018: Evacuation ahead of natural disasters: Evidence from cyclone Phailin in India and typhoon Haiyan in the Philippines. *Geo: Geography and Environment*, **5**(1), 1-16, doi:10.1002/geo2.51.

Walch, C., 2019: Adaptive Governance in the Developing World: Disaster Risk Reduction in the State of Odisha, India. *Climate and Development*, **11**(3), 238-252.

Wals, A. E., M. Brody, J. Dillon and R. B. Stevenson, 2014: Convergence between science and environmental education. *Science*, **344**(6184), 583-584.

Wan, J. Z., C. J. Wang, J. F. Tan and F. H. Yu, 2017: Climatic niche divergence and habitat suitability of eight alien invasive weeds in China under climate change. *Ecol Evol*, **7**(5), 1541-1552, doi:10.1002/ece3.2684.

Wan, X. et al., 2019: Historical records reveal the distinctive associations of human disturbance and extreme climate change with local extinction of mammals. *Proceedings of the National Academy of Sciences*, **116**(38), 19001, doi:10.1073/pnas.1818019116.

Wang, C. et al., 2018a: Different response of human mortality to extreme temperatures (MoET) between rural and urban areas: A multi-scale study across China. *Health & place*, **50**, 119-129, doi:10.1016/j.healthplace.2018.01.011.

Wang, G., P. Yang and X. Zhou, 2017a: Identification of the driving forces of climate change using the longest instrumental temperature record. *Sci Rep*, **7**, 46091, doi:10.1038/srep46091.

Wang, H., C. Mei, J. Liu and W. Shao, 2019a: A new strategy for integrated urban water management in China: Sponge city | SpringerLink. doi:10.1007/s11431-017-9170-5.
Wang, H. et al., 2019b: Tropical cyclone damages in Mainland China over 2005–2016: Losses analysis and implications. *Environment, Development and Sustainability*, **21**, 3077–3092, doi:https://doi.org/10.1007/s10668-019-00481-7.
Wang, J.-x., J.-k. Huang and J. Yang, 2014: Overview of Impacts of Climate Change and Adaptation in China's Agriculture. *Journal of Integrative Agriculture*, **13**(1), 1-17, doi:https://doi.org/10.1016/S2095-3119(13)60588-2.
Wang, J., Y. Yang, J. Huang and K. Chen, 2015: Information provision, policy support, and farmers' adaptive responses against drought: An empirical study in the North China Plain. *Ecol Model*, **318**, 275-282, doi:10.1016/j.ecolmodel.2014.12.013.
Wang, K. et al., 2021a: Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of mekong river delta. *Resources, Conservation and Recycling*, **167**, 105390, doi:https://doi.org/10.1016/j.resconrec.2020.105390.
Wang, L. et al., 2020: Assessment of soil erosion risk and its response to climate change in the mid-Yarlung Tsangpo River region. *Environmental Science and Pollution Research*, **27**(1), 607-621.
Wang, M. et al., 2018b: Assessing changes of mangrove forest in a coastal region of southeast China using multi-temporal satellite images. *Estuarine, Coastal and Shelf Science*, **207**, 283-292, doi:10.1016/j.ecss.2018.04.021.
Wang, P., W. B. Goggins and E. Y. Y. Chan, 2018c: A time-series study of the association of rainfall, relative humidity and ambient temperature with hospitalizations for rotavirus and norovirus infection among children in Hong Kong. *Sci Total Environ*, **643**, 414-422, doi:10.1016/j.scitotenv.2018.06.189.
Wang, P. et al., 2021b: Potential role of permafrost thaw on increasing Siberian river discharge. *Environmental Research Letters*, **16**(3), 034046.
Wang, P., L. Liu and T. Wu, 2017b: A review of China's climate governance: state, market and civil society. *Climate Policy*, **18**(5), 664-679, doi:10.1080/14693062.2017.1331903.
Wang, X. et al., 2017c: No consistent evidence for advancing or delaying trends in spring phenology on the Tibetan Plateau. *Journal of Geophysical Research-Biogeosciences*, **122**(12), 3288-3305, doi:10.1002/2017jg003949.
Wang, Y. et al., 2019c: The stability of spruce treelines on the eastern Tibetan Plateau over the last century is explained by pastoral disturbance. *Forest Ecology and Management*, **442**, 34-45, doi:https://doi.org/10.1016/j.foreco.2019.03.058.
Wang, Y. and M. Wild, 2016: A new look at solar dimming and brightening in China. *Geophysical Research Letters*, **43**(22), 11,777-711,785, doi:10.1002/2016GL071009.
Wani, K. A. and L. Ariana, 2018: Impact of Climate Change on Indigenous People and Adaptive Capacity of Bajo Tribe, Indonesia. *https://doi.org/10.1080/10406026.2018.1504380*, doi:1504380.
Ward, P. J. et al., 2017: A global framework for future costs and benefits of river-flood protection in urban areas. *Nature climate change*, **7**(9), 642-646.
Ward, R. et al., 2016a: Improved modelling of the impacts of sea level rise on coastal wetland plant communities. *Hydrobiologia*, **774**(1), 203-216.
Ward, R. D., D. A. Friess, R. H. Day and R. A. Mackenzie, 2016b: Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and Sustainability*, **2**(4), doi:10.1002/ehs2.1211.
Warren, R. et al., 2018: The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Climatic Change*, **147**(3-4), 395-409, doi:10.1007/s10584-018-2158-6.
Wassmann, R. et al., 2019a: High-resolution mapping of flood and salinity risks for rice production in the Vietnamese Mekong Delta. *Field Crops Research*, **236**, 111-120, doi:10.1016/j.fcr.2019.03.007.
Wassmann, R. et al., 2019b: Adaptation, mitigation and food security: Multi-criteria ranking system for climate-smart agriculture technologies illustrated for rainfed rice in Laos. *Global Food Security*, **23**, 33-40, doi:10.1016/j.gfs.2019.02.003.
Water, U., 2020: UN world water development report 2020: Water and climate change. *Retrieved March*, **22**, 2020.
Watson, C. et al., 2017: *Shock responsive and social protection Pakistan*, Management, O. P., Pakistan.
Watts, N. et al., 2015: *Strengthening Health Resilience to Climate Change*.
Waycott, M. et al., 2009: Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *P Natl Acad Sci USA*, **106**(30), 12377-12381, doi:10.1073/pnas.0905620106.
WEC, 2018: *World Energy Trilemma Index 2018*. Available at: https://www.worldenergy.org/assets/downloads/World-Energy-Trilemma-Index-2018.pdf.
WEF, 2018: *The Global Competitiveness Report 2017–2018: 2.01 Quality of overall infrastructure*. World Economic Forum.
Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters*, **10**(9), doi:10.1088/1748-9326/10/9/094021.
Werg, J., T. Grothmann and P. Schmidt, 2013: Assessing social capacity and vulnerability of private households to natural hazards - Integrating psychological and governance factors. *Natural Hazards and Earth System Sciences*, **13**(6), 1613-1628, doi:10.5194/nhess-13-1613-2013.
Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.), 2019: *The Hindu Kush Himalaya Assessment – Mountains, Climate Change, Sustainability and People*, Springer, Cham, Switzerland, 627 pp. ISBN 9783319922874.

Westermann, O. et al., 2018: Scaling up agricultural interventions: Case studies of climate-smart agriculture. *Agricultural Systems*, **165**, 283-293, doi:https://doi.org/10.1016/j.agsy.2018.07.007.
Weststrate, J. et al., 2019: The sustainable development goal on water and sanitation: learning from the millennium development goals. *Social Indicators Research*, **143**(2), 795-810.
Wheater, H. S. and P. Gober, 2015: Water security and the science agenda. *Water Resources Research*, **51**, 5406-5424, doi:10.1002/2015WR016892@10.1002/(ISSN)1944-7973.WRR50.
Wi, A. and C.-H. Chang, 2018: Promoting pro-environmental behaviour in a community in Singapore – from raising awareness to behavioural change. *Environmental Education Research*, 1-19, doi:10.1080/13504622.2018.1528496.
Widiati, I. R. and Irianto, 2019: Mitigation and adaptation to climate change on among stakeholder for sustainability: Evaluation a regional multistakeholder for an approach of the role of disaster risk management. *IOP Conf. Series: Earth and Environmental Science* **235**, doi:10.1088/1755-1315/235/1/012103.
Wijetunge, J. J. (ed.), Disaster risk assessment and mitigation strategy for tropical cyclone induced storm surge hazard and coastal impacts of climate change in Sri Lanka. International Conference on Hydroinformatics, New York, City University of New York.
Wijngaard, R. R. et al., 2018: Climate change vs. socio-economic development: understanding the future South Asian water gap. *Hydrology and Earth System Sciences*, **22**(12), 6297-6321.
Wijngaard, R. R. et al., 2017: Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. *PloS one*, **12**(12), e0190224.
Winkler, D. E. et al., 2016: Seasonal dry-down rates and high stress tolerance promote bamboo invasion above and below treeline. *Plant Ecology*, **217**(10), 1219-1234, doi:10.1007/s11258-016-0649-y.
Winters, L. A. A. a. M., Antonio, 2014: Trade Liberalization and Poverty: What Have We Learned in a Decade? *Annual Review of Resource Economics*, **6**(1), 493-512.
Wodon, Q., A. Liverani, G. Joseph and N. Bougnoux, 2014: *Climate change and migration: evidence from the Middle East and North Africa*. The World Bank. ISBN 0821399713.
Wong, J. et al., 2020: Preparing for a COVID-19 pandemic: a review of operating room outbreak response measures in a large tertiary hospital in Singapore. *Canadian Journal of Anesthesia/Journal canadien d'anesthésie*, 1-14.
Woolway, R. I. et al., 2020: Global lake responses to climate change. *Nature Reviews Earth & Environment*, 1-16.
World Health Organization, 2014: *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s.* [Simon Hales, Sari Kovats, Simon Lloyd and D. Campbell-Lendrum (eds.)].
World Meteorological Organization, 2017: TAHAK, A meteorological application services initiated by IRIMO to support end users.
WorldBank, 2016: *Emerging Trends in Mainstreaming Climate Resilience in Large Scale, Multi-sector Infrastructure PPPs*. Available at: file:///C:/Users/dasgupta/Downloads/Mainstreaming_Climate_Resilience.pdf.
WorldBank, 2017: *Resilient Infrastructure Public-Private Partnerships (PPPs): Contracts and Procurement Resilient - The Case of Japan*. https://www.globalinfrafacility.org/sites/gif/files/Resilient%20Infrastrcuture%20PPP%20Japan%20Case%20Study%20FINAL_web.pdf.
Wu, G., Z. Han, W. Xu and Y. Gong, 2018a: Mapping individuals' earthquake preparedness in China. *Natural Hazards and Earth System Sciences*, **18**(5), 1315-1325, doi:10.5194/nhess-18-1315-2018.
Wu, G. et al., 2012: Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: I. Formation. *Climate Dynamics*, **39**(5), 1169-1181, doi:10.1007/s00382-012-1334-z.
Wu, H., J. Carrillo and J. Q. Ding, 2016: Invasion by alligator weed, Alternanthera philoxeroides, is associated with decreased species diversity across the latitudinal gradient in China. *Journal of Plant Ecology*, **9**(3), 311-319, doi:10.1093/jpe/rtv060.
Wu, H. et al., 2019a: Spatio-temporal analysis of drought variability using CWSI in the Koshi River Basin (KRB). *International journal of environmental research and public health*, **16**(17), 3100.
Wu, H. L. et al., 2019b: Effects of increased CO2 and temperature on the physiological characteristics of the golden tide blooming macroalgae Sargassum horneri in the Yellow Sea, China. *Mar. Pollut. Bull.*, **146**, 639-644, doi:10.1016/j.marpolbul.2019.07.025.
Wu, J. et al., 2018b: Disaster Monitoring and Emergency Response Services in CHINA. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, **XLII-3**, 1879-1881, doi:10.5194/isprs-archives-XLII-3-1879-2018.
Wu, J. et al., 2019c: Planned Sheltering as an Adaptation Strategy to Climate Change: Lessons Learned from the Severe Flooding in Anhui Province of China in 2016. *Science of the Total Environment*, **694**.
Wu, J., J. Zha and D. Zhao, 2017a: Evaluating the effects of land use and cover change on the decrease of surface wind speed over China in recent 30 years using a statistical downscaling method. *Climate Dynamics*, **48**(1), 131-149, doi:10.1007/s00382-016-3065-z.
Wu, J., J. Zha, D. Zhao and Q. Yang, 2018c: Changes in terrestrial near-surface wind speed and their possible causes: an overview. *Climate Dynamics*, **51**(5), 2039-2078, doi:10.1007/s00382-017-3997-y.
Wu, N. et al., 2018d: Chapter 4: Direct and indirect drivers of change in biodiversity and nature's contributions to people. In: *IPBES (2018): The IPBES regional assessment report on biodiversity and ecosystem services for Asia and the Pacific* [Karki, M., S. Senaratna Sellamuttu, S. Okayasu and W. Suzuki (eds.)]. Secretariat of the

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, pp. 265-370.

Wu, S., L. Liu, J. Gao and W. Wang, 2019d: Integrate risk from climate change in China under global warming of 1.5°C and 2.0°C. *Earths Future*, **7**(12), 1307-1322, doi:https://doi.org/10.1029/2019EF001194.

Wu, X. et al., 2021: Snow cover loss compounding the future economic vulnerability of western China. *Science of The Total Environment*, **755**, 143025.

Wu, Y. et al., 2017b: Describing interaction effect between lagged rainfalls on malaria: an epidemiological study in south-west China. *Malaria journal*, **16**(1), 53, doi:10.1186/s12936-017-1706-2.

Wu, Z. W. et al., 2014: Relative effects of climatic and local factors on fire occurrence in boreal forest landscapes of northeastern China. *Science of the Total Environment*, **493**, 472-480, doi:10.1016/j.scitotenv.2014.06.011.

Xenarios, S. et al., 2019: Climate change and adaptation of mountain societies in Central Asia: uncertainties, knowledge gaps, and data constraints. *Regional Environmental Change*, **19**(5), 1339-1352, doi:10.1007/s10113-018-1384-9.

Xia, J. et al., 2019: Shifts in timing of local growing season in China during 1961-2012. *Theoretical and Applied Climatology*, **137**(3-4), 1637-1642, doi:10.1007/s00704-018-2698-8.

Xia, J., K. Tu, Z. Yan and Y. Qi, 2016: The super-heat wave in eastern China during July–August 2013: a perspective of climate change. *International Journal of Climatology*, **36**(3), 1291-1298, doi:https://doi.org/10.1002/joc.4424.

Xiang, J. et al., 2018: Association between malaria incidence and meteorological factors: a multi-location study in China, 2005-2012. *Epidemiology and infection*, **146**(1), 89-99, doi:10.1017/s0950268817002254.

Xie, B. et al., 2020: Global health crises are also information crises: A call to action. *Journal of the Association for Information Science and Technology*.

Xie, J. et al., 2017: An integrated assessment of urban flooding mitigation strategies for robust decision making. *Environmental Modelling and Software*, **95**, 143-155.

Xu, J. and R. E. Grumbine, 2014: Integrating local hybrid knowledge and state support for climate change adaptation in the Asian Highlands. *Climatic Change*, **124**(1-2), 93-104, doi:10.1007/s10584-014-1090-7.

Xu, L. et al., 2017: Climate variation drives dengue dynamics. *Proc Natl Acad Sci U S A*, **114**(1), 113-118, doi:10.1073/pnas.1618558114.

Xu, L. et al., 2019: Identifying the trade-offs between climate change mitigation and adaptation in urban land use planning: An empirical study in a coastal city. *Environ Int*, **133**, 105162.

Xu, Z. L., H. H. Peng, Z. D. Feng and N. Abdulsalih, 2014: Predicting Current and Future Invasion of Solidago Canadensis: A Study from China. *Pol J Ecol*, **62**(2), 263-271, doi:Doi 10.3161/104.062.0207.

Yadav, S. S. and R. Lal, 2018: Vulnerability of women to climate change in arid and semi-arid regions: The case of India and South Asia. *Journal of Arid Environments*, **149**, 4-17, doi:https://doi.org/10.1016/j.jaridenv.2017.08.001.

Yamamoto, T. et al., 2021: Evaluation of flood damage reduction throughout Japan from adaptation measures taken under a range of emissions mitigation scenarios. *Climatic Change*, **165**(3), 60, doi:10.1007/s10584-021-03081-5.

Yamanaka, M. D. et al., 2018: Maritime continent coastlines controlling Earth's climate. *Progress in Earth and Planetary Science*, **5**(1), doi:10.1186/s40645-018-0174-9.

Yamane, T., 2014: Foliar Calcium Applications for Controlling Fruit Disorders and Storage Life in Deciduous Fruit Trees. *Japan Agricultural Research Quarterly: JARQ*, **48**, 29-33, doi:10.6090/jarq.48.29.

Yamazaki, S. et al., 2015: Exposure to air pollution and meteorological factors associated with children's primary care visits at night due to asthma attack: case-crossover design for 3-year pooled patients. *BMJ open*, **5**(4), e005736, doi:10.1136/bmjopen-2014-005736.

Yan, H. Q. et al., 2019: Regional coral growth responses to seawater warming in the South China Sea. *Science of the Total Environment*, **670**, 595-605, doi:10.1016/j.scitotenv.2019.03.135.

Yan, Y. et al., 2018: Diatom response to climatic warming over the last 200 years: A record from Gonghai Lake, North China. *Palaeogeogr Palaeocl*, **495**, 48-59, doi:10.1016/j.palaeo.2017.12.023.

Yang, B. et al., 2017: New perspective on spring vegetation phenology and global climate change based on Tibetan Plateau tree-ring data. *P Natl Acad Sci USA*, **114**(27), 6966-6971, doi:10.1073/pnas.1616608114.

Yang, J. et al., 2012a: Daily temperature and mortality: a study of distributed lag non-linear effect and effect modification in Guangzhou. *Environmental health : a global access science source*, **11**, 63, doi:10.1186/1476-069x-11-63.

Yang, L., G. Su and H. Yuan, 2012b: Design principles of integrated information platform for emergency responses: The case of 2008 Beijing Olympic Games. *Information Systems Research*, **23**(3-part-1), 761-786, doi:10.1287/isre.1110.0387.

Yang, R., 2018: Agricultural Insurance: Theory, Empirical Research and Experience–Based on Farmers Household Data. *China Agricultural Economic Review*, **10**(1), 173-175.

Yang, S., X. Wang and M. Wild, 2018a: Homogenization and trend analysis of the 1958-2016 in-situ surface solar radiation records in China. *Journal of Climate*, **31**, doi:10.1175/JCLI-D-17-0891.1.

Yang, X. et al., 2012c: The decreasing wind speed in southwestern China during 1969–2009, and possible causes. *Quaternary International*, **263**, 71–84, doi:10.1016/j.quaint.2012.02.020.

Yang, Y. B. et al., 2018b: Where will Invasive Plants Colonize in Response to Climate Change: Predicting the Invasion of Galinsoga quadriradiata in China. *Int J Environ Res*, **12**(6), 929-938, doi:10.1007/s41742-018-0146-3.

Yao, L., L. Chen, W. Wei and R. Sun, 2015: Potential reduction in urban runoff by green spaces in Beijing: A scenario analysis. doi:10.1016/j.ufug.2015.02.014.
Yari, A. et al., 2019: Underlying factors affecting death due to flood in Iran: A qualitative content analysis. *International Journal of Disaster Risk Reduction* **40**, doi:https://doi.org/10.1016/j.ijdrr.2019.101258.
Yati, E. et al., 2020: Marine Ecosystem Variations Over the North Pacific and Their Linkage to Large-Scale Climate Variability and Change. *Frontiers in Marine Science*, **7**(925), doi:10.3389/fmars.2020.578165.
Ye, G. et al., 2015: Is integrated coastal management an effective framework for promoting coastal sustainability in China's coastal cities? *Marine Policy*, **56**, 48-55, doi:10.1016/j.marpol.2015.02.009.
Ye, H., Huang, Z., Huang, L., Lin, L., & Luo, M., 2018: Effects of urbanization on increasing heat risks in South China. *International Journal of Climatology.*, doi:https://doi.org/10.1002/joc.5747

Yin, H., A. Khamzina, D. Pflugmacher and C. Martius, 2017: Forest cover mapping in post-Soviet Central Asia using multi-resolution remote sensing imagery. *Sci Rep*, **7**(1), doi:10.1038/s41598-017-01582-x.
Yin, J. et al., 2020: Flood Risks in Sinking Delta Cities: Time for a Reevaluation? *Earth's Future*, **8**(8), e2020EF001614, doi:10.1029/2020ef001614.
Yin, J. et al., 2012: Using Social Media to Enhance Emergency Situation Awareness. *IEEE Intelligent Systems*, **27**(6), 52-59, doi:10.1109/MIS.2012.6.
Yin, P. et al., 2018: The added effects of heatwaves on cause-specific mortality: A nationwide analysis in 272 Chinese cities. *Environ Int*, **121**(Pt 1), 898-905, doi:10.1016/j.envint.2018.10.016.
Yong-Jian, R. et al., 2013: Climate Change Impacts on Central China and Adaptation Measures. *Advances in Climate Change Research*, **4**(4), 215-222, doi:10.3724/sp.J.1248.2013.215.
Yoseph-Paulus, R. and R. Hindmarsh, 2016: Addressing inadequacies of sectoral coordination and local capacity building in Indonesia for effective climate change adaptation. *Climate and Development*, **10**(1), 35-48, doi:10.1080/17565529.2016.1184609.
Yoshida, K. et al., 2017: Future Changes in Tropical Cyclone Activity in High-Resolution Large-Ensemble Simulations. *Geophysical Research Letters*, **44**(19), 9910-9917, doi:10.1002/2017gl075058.
You, Q.-L. et al., 2017: An overview of studies of observed climate change in the Hindu Kush Himalayan (HKH) region. *Advances in Climate Change Research*, **8**(3), 141-147.
You, W. H. et al., 2014: Responses of the invasive aquatic plant water hyacinth to altered nutrient levels under experimental warming in China. *Aquat Bot*, **119**, 51-56, doi:10.1016/j.aquabot.2014.06.004.
Yousefi, M., A. Jouladeh-Roudbar and A. Kafash, 2020: Using endemic freshwater fishes as proxies of their ecosystems to identify high priority rivers for conservation under climate change. *Ecol Indic*, **112**, doi:10.1016/j.ecolind.2020.106137.
Yousefi, M. et al., 2019: Climate Change is a Major Problem for Biodiversity Conservation: A Systematic Review of Recent Studies in Iran. *Contemporary Problems of Ecology*, **12**(4), 394-403, doi:10.1134/S1995425519040127.
Yu, C. et al., 2018a: Assessing the impacts of extreme agricultural droughts in China under climate and socioeconomic changes. *Earths Future*, **6**(5), 689-703, doi:https://doi.org/10.1002/2017EF000768.
Yu, L., 2016: Agro-pastoralism under climate change: Institutions and local climate adaptations in northern China. *Land Use Policy*, **58**, 173-182, doi:https://doi.org/10.1016/j.landusepol.2016.07.022.
Yu, L. et al., 2020: Impacts of 1.5°C and 2°C global warming on net primary productivity and carbon balance in China's terrestrial ecosystems. *Sustainability*, **12**(7), doi:doi:10.3390/su12072849.
Yu, M., C. Yang and Y. Li, 2018b: Big data in natural disaster management: a review. *Geosciences*, **8**(5), 165.
Yu, Q., A. K. H. Lau, K. T. Tsang and J. C. H. Fung, 2018c: Human damage assessments of coastal flooding for Hong Kong and the Pearl River Delta due to climate change-related sea level rise in the twenty-first century. *Natural Hazards*, **92**, 1011–1038, doi:https://doi.org/10.1007/S11069-018-3236-9.
Yu, R., P. Zhai and Y. Chen, 2018d: Facing climate change-related extreme events in megacities of China in the context of 1.5 °C global warming. *Current Opinion in Environmental Sustainability*, **30**, 75-81, doi:10.1016/j.cosust.2018.03.008.
Yu, R., P. Zhai and Y. Lu, 2018e: Implications of differential effects between 1.5 and 2 °C global warming on temperature and precipitation extremes in China's urban agglomerations. *International Journal of Climatology*, **38**(5), 2374-2385, doi:10.1002/joc.5340.
Yu, W. et al., 2015: Variability of Suitable Habitat of Western Winter-Spring Cohort for Neon Flying Squid in the Northwest Pacific under Anomalous Environments. *PLoS One*, **10**(4), e0122997, doi:10.1371/journal.pone.0122997.
Yuan, W. B. et al., 2018: Combined effects of ocean acidification and warming on physiological response of the diatom Thalassiosira pseudonana to light challenges. *Mar. Environ. Res.*, **135**, 63-69, doi:10.1016/j.marenvres.2018.01.016.
Yuan, X. et al., 2019: Coral responses to ocean warming and acidification: Implications for future distribution of coral reefs in the South China Sea. *Mar Pollut Bull*, **138**, 241-248, doi:10.1016/j.marpolbul.2018.11.053.
Yumarni, T. and D. Amaratunga, 2018: Gender mainstreaming as a strategy to achieve sustainable post-disaster reconstruction. *Built Environment Project and Asset Management*, **8**(5), 544-556, doi:10.1108/bepam-10-2017-0086.

Yun, J. H. et al., 2018: Vulnerability of subalpine fir species to climate change: using species distribution modeling to assess the future efficiency of current protected areas in the Korean Peninsula. *Ecological Research*, **33**(2), 341-350, doi:10.1007/s11284-018-1581-5.
Yun, X. et al., 2020: Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin. *Journal of Hydrology*, **590**, 125472.
Zakharov, V. D., 2016: The influence of climate change on the dates of bird arrival to the Ilmen State Reserve (Southern Urals). *Russian Journal of Ecology*, **47**(6), 546-551, doi:10.1134/s1067413616060138.
Zakharov, V. D., 2018: Long-Term Dynamics of Winter Communities of Forest Birds in the Ilmen Nature Reserve. *Russian Journal of Ecology*, **49**(4), 332-337, doi:10.1134/s106741361803013x.
Zakharova, E. Y., A. O. Shkurikhin and T. S. Oslina, 2017: Morphological variation of *Melanargia russiae* (Esper, 1783) (Lepidoptera, Satyridae) from the main part of the range and in case of its expansion to the north under climate change conditions. *Contemporary Problems of Ecology*, **10**(5), 488-501, doi:10.1134/S1995425517050146.
Zaman, K., S. Shamsuddin and M. Ahmad, 2017: Energy-water-food nexus under financial constraint environment: good, the bad, and the ugly sustainability reforms in sub-Saharan African countries. *Environmental Science and Pollution Research*, **24**(15), 13358-13372, doi:10.1007/s11356-017-8961-1.
Zanzanaini, C. et al., 2017: Integrated landscape initiatives for agriculture, livelihoods and ecosystem conservation: An assessment of experiences from South and Southeast Asia. *Landscape and Urban Planning*, **165**, 11–21, doi:http://dx.doi.org/10.1016/j.landurbplan.2017.03.010.
Zemp, M. et al., 2019: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, **568**(7752), 382-+, doi:10.1038/s41586-019-1071-0.
Zen, I. S., A.Q., Al-amin and B. Doberstein, 2019: Mainstreaming climate adaptation and mitigation policy: Towards multi-level climate governance in Melaka, Malaysia. *Urban Climate* **30**, doi:https://doi.org/10.1016/j.uclim.2019.100501.
Zeng, Z. et al., 2019: A reversal in global terrestrial stilling and its implications for wind energy production. *Nature Climate Change*, **9**(12), 979-985, doi:10.1038/s41558-019-0622-6.
Zevenbergen, C., D. Fu and A. Pathirana, 2018: Transitioning to sponge cities: challenges and opportunities to address urban water problems in China. Multidisciplinary Digital Publishing Institute.
Zha, J., J. Wu and D. Zhao, 2016: Changes of probabilities in different wind grades induced by land use and cover change in Eastern China Plain during 1980-2011. *Atmospheric Science Letters*, **17**, n/a-n/a, doi:10.1002/asl.653.
Zhai, S.-y. et al., 2018: Climate change and Chinese farmers : perceptions and determinants of adaptive strategies. *Journal of Integrative Agriculture*, **17**(4), 949-963, doi:10.1016/s2095-3119(17)61753-2.
Zhan, Y. Y. et al., 2020: CO2-driven ocean acidification repressed the growth of adult sea urchin Strongylocentrotus intermedius by impairing intestine function. *Mar. Pollut. Bull.*, **153**, 9, doi:10.1016/j.marpolbul.2020.110944.
Zhang, C. and W. Ren, 2017: Complex climatic and CO2 controls on net primary productivity of temperate dryland ecosystems over central Asia during 1980–2014. *Journal of Geophysical Research: Biogeosciences*, **122**(9), 2356-2374, doi:10.1002/2017JG003781.
Zhang, C., Y. Huang, A. Javed and G. B. Arhonditsis, 2019a: An ensemble modeling framework to study the effects of climate change on the trophic state of shallow reservoirs. *Science of the Total Environment*, **697**, doi:https://doi.org/10.1016/j.scitotenv.2019.134078.
Zhang, F., C. K. L. Chung and Z. Yin, 2020a: Green infrastructure for China's new urbanisation: A case study of greenway development in Maanshan. *Urban Studies*, **57**(3), 508-524, doi:10.1177/0042098018822965.
Zhang, G. et al., 2015: An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global and Planetary Change*, **131**, 148-157, doi:10.1016/j.gloplacha.2015.05.013.
Zhang, G., G. Zeng, X.-Z. Liang and C. Huang, 2021: Increasing heat risk in China's urban agglomerations. *Environmental Research Letters*.
Zhang, H. X., M. L. Zhang and Y. Wang, 2017a: Distribution pattern of poisonous plant species in arid grasslands: a case from Xinjiang, Northwestern China. *Rangeland J*, **39**(3), 279-287, doi:10.1071/RJ16018.
Zhang, L. et al., 2016a: Toward optimal soil organic carbon sequestration with effects of agricultural management practices and climate change in Tai-Lake paddy soils of China. *Geoderma*, **275**, 28-39, doi:10.1016/j.geoderma.2016.04.001.
Zhang, M., H. Yu, A. D. King and *e. al.*, 2020b: Greater probability of extreme precipitation under 1.5 °C and 2 °C warming limits over East-Central Asia. *Climatic Change*, doi:https://doi.org/10.1007/s10584-020-02725-2.
Zhang, M. L. et al., 2017b: Spatial and temporal variability in the net primary production of grassland in China and its relation to climate factors. *Plant Ecology*, **218**(9), 1117-1133, doi:10.1007/s11258-017-0756-4.
Zhang, N. et al., 2019b: The impact of the 2016 flood event in Anhui Province, China on infectious diarrhea disease: An interrupted time-series study. *Environ Int*, **127**, 801-809, doi:10.1016/j.envint.2019.03.063.
Zhang, N. N. et al., 2017c: Opposite polarities of ENSO drive distinct patterns of coral bleaching potentials in the southeast Indian Ocean. *Sci Rep*, **7**, 10, doi:10.1038/s41598-017-02688-y.
Zhang, P. et al., 2019c: Thermal tolerance traits of the undulated surf clam Paphia undulata based on heart rate and physiological energetics. *Aquaculture*, **498**, 343-350, doi:https://doi.org/10.1016/j.aquaculture.2018.08.037.
Zhang, Q. et al., 2016b: Flood-induced agricultural loss across China and impacts from climate indices. *Global and Planetary Change*, **139**, 31-43, doi:10.1016/j.gloplacha.2015.10.006.

Zhang, Q. et al., 2016c: Magnitude, frequency and timing of floods in the Tarim River basin, China: Changes, causes and implications. *Global and Planetary Change*, **139**, 44-55.
Zhang, X. et al., 2020c: Evaluating the vulnerability of physical and virtual water resource networks in China's megacities. *Resources, Conservation and Recycling*, **161**, 104972.
Zhang, Y. et al., 2019d: Identifying refugia and corridors under climate change conditions for the Sichuan snub-nosed monkey (Rhinopithecus roxellana) in Hubei Province, China. *Ecol Evol*, **9**(4), 1680-1690, doi:10.1002/ece3.4815.
Zhang, Y. et al., 2017d: Land surface phenology of Northeast China during 2000-2015: temporal changes and relationships with climate changes. *Environmental Monitoring and Assessment*, **189**(11), doi:10.1007/s10661-017-6247-1.
Zhang, Y. et al., 2018: Rising levels of temperature and CO2 antagonistically affect phytoplankton primary productivity in the South China Sea. *Mar. Environ. Res.*, **141**, 159-166, doi:10.1016/j.marenvres.2018.08.011.
Zhang, Y. et al., 2019e: Assessment of future flash flood inundations in coastal regions under climate change scenarios—A case study of Hadahe River basin in northeastern China. *Science of the Total Environment* **693**, doi:https://doi.org/10.1016/j.scitotenv.2019.07.356.
Zhang, Y. B., Y. Z. Wang, M. G. Zhang and K. P. Ma, 2014: Climate change threats to protected plants of China: an evaluation based on species distribution modeling. *Chinese Sci Bull*, **59**(34), 4652-4659, doi:10.1007/s11434-014-0642-6.
Zhang, Y. Y. et al., 2019f: Ulva prolifera green-tide outbreaks and their environmental impact in the Yellow Sea, China. *Natl. Sci. Rev.*, **6**(4), 825-838, doi:10.1093/nsr/nwz026.
Zhanqiang, Z., J. Ren and L. Xuan, 2019: Green Infrastructure Provision for Environmental Justice: Application of the Equity Index in Guangzhou, China. *Urban Forestry & Urban Greening*.
Zhao, H. et al., 2020: Virtual water scarcity risk in China. *Resources, Conservation and Recycling*, **160**, 104886.
Zhao, J., H. Y. Du, Y. F. Shi and Y. J. Che, 2017a: A GIS simulation of potential vegetation in China under different climate scenarios at the end of the 21st century. *Contemporary Problems of Ecology*, **10**(3), 315-325, doi:10.1134/s1995425517030131.
Zhao, X. G. et al., 2017b: Ocean acidification adversely influences metabolism, extracellular pH and calcification of an economically important marine bivalve, Tegillarca granosa. *Mar. Environ. Res.*, **125**, 82-89, doi:10.1016/j.marenvres.2017.01.007.
Zhao, Y.-f., Z.-h. CHAI, M. S. Delgado and P. V. Preckel, 2017c: A test on adverse selection of farmers in crop insurance: Results from Inner Mongolia, China. *Journal of integrative agriculture*, **16**(2), 478-485.
Zhao, Y., Z. Chai, M. S. Delgado and P. V. Preckel, 2016a: An empirical analysis of the effect of crop insurance on farmers' income: results from inner Mongolia in China. *China Agricultural Economic Review*, **8**(2), 299-313.
Zhao, Y. et al., 2016b: Potential escalation of heat-related working costs with climate and socioeconomic changes in China. *Proceedings of the National Academy of Sciences*, **113**(17), 4640-4645, doi:https://doi.org/10.1073/pnas.1521828113.
Zheng, X., Kuo, F., Pan, K., Huang, H., & Lin, R., (2019). : Different calcification responses of two hermatypic corals to CO 2 -driven ocean acidification. .
Zheng, Y. and M. Dallimer, 2016: What motivates rural households to adapt to climate change ? *Climate and Development*, **8**(2), 110-121, doi:10.1080/17565529.2015.1005037.
Zhu, W., L. Porth and K. S. Tan, 2019: A credibility-based yield forecasting model for crop reinsurance pricing and weather risk management. *Agricultural Finance Review*, **79**(1), 2-26.
Zhupankhan, A., K. Tussupova and R. Berndtsson, 2018: Water in Kazakhstan, a key in Central Asian water management. *Hydrological Sciences Journal*, **63**(5), 752-762, doi:10.1080/02626667.2018.1447111.
Zickgraf, C., 2019: Keeping People in Place: Political Factors of (Im) mobility and Climate Change. *Social Sciences*, **8**(8), 228.
Zinia, N. J. and P. McShane, 2018: Ecosystem services management: An evaluation of green adaptations for urban development in Dhaka, Bangladesh. *Landscape and urban planning*, **173**, 23-32.
Zolotareva, N. V. and M. P. Zolotarev, 2017: The phenomenon of forest invasion to steppe areas in the Middle Urals and its probable causes. *Russian Journal of Ecology*, **48**(1), 21-31, doi:10.1134/s106741361606014x.
Zomer, R. J. et al., 2014: Projected climate change impacts on spatial distribution of bioclimatic zones and ecoregions within the Kailash Sacred Landscape of China, India, Nepal. *Climatic Change*, **125**(3-4), 445-460, doi:10.1007/s10584-014-1176-2.

Chapter 11: Australasia

Coordinating Lead Authors: Judy Lawrence (New Zealand) and Brendan Mackey (Australia)

Lead Authors: Francis Chiew (Australia), Mark J. Costello (New Zealand/Norway/Ireland), Kevin Hennessy (Australia), Nina Lansbury (Australia), Uday Bhaskar Nidumolu (Australia), Gretta Pecl (Australia), Lauren Rickards (Australia), Nigel Tapper (Australia), Alistair Woodward (New Zealand), Anita Wreford (New Zealand)

Contributing Authors: Jason Alexandra (Australia), Anne-Gaelle Ausseil (New Zealand), Shaun Awatere (New Zealand), Douglas Bardsley (Australia), Rob Bell (New Zealand), Paula Blackett (New Zealand), Sarah Boulter (Australia), Nicholas Cradock-Henry (New Zealand), Sandra Creamer (Australia), Rebecca Darbyshire (Australia), Sam Dean (New Zealand), Alejandro Di Luca (Australia/Canada), Andrew Dowdy (Australia), Joanna Fountain (New Zealand), Michael Grose (Australia), Stefan Hajkowicz (Australia), David Hall (New Zealand), Sarah Harris (Australia), Peter Hayman (Australia), Jane Hodgkinson (Australia), Karen Hussey (Australia), Rhys Jones (New Zealand), Darren King (New Zealand), Martina Linnenluecke (Australia), Erich Livengood (New Zealand), Mary Livingston (New Zealand), Cate MacInnis-Ng (New Zealand), Belinda McFadgen (New Zealand), Celia McMichael (Australia), Bradley Moggridge (Australia), Sandy Morrison (New Zealand), Vinnitta Mosby (Australia), Esther Onyango (Australia/Kenya), Sharanjit Paddam (Australia), Grant Pearce (New Zealand), Petra Pearce (New Zealand), Rosh Ranasinghe (Netherlands), David Schoeman (Australia), Rodger Tomlinson (Australia), Michael Watt (New Zealand), Seth Westra (Australia), Russell Wise (Australia).

Review Editors: Ove Hoegh-Guldberg (Australia), David Wratt (New Zealand)

Chapter Scientists: Belinda McFadgen (New Zealand), Esther Onyango (Australia/Kenya)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Observed changes and impacts

Ongoing climate trends have exacerbated many extreme events (*very high confidence*). The Australian trends include further warming and sea-level rise, with more hot days and heatwaves, less snow, more rainfall in the north, less April-October rainfall in the south-west and south-east, more extreme fire weather days in the south and east. The New Zealand trends include further warming and sea-level rise, more hot days and heatwaves, less snow, more rainfall in the south, less rainfall in the north, and more extreme fire weather in the east. There have been fewer tropical cyclones and cold days in the region. Extreme events include Australia's hottest and driest year in 2019 with a record-breaking number of days over 39ºC, New Zealand's hottest year in 2016, three widespread marine heatwaves during 2016-2020, Category 4 cyclone Debbie in 2017, seven major hailstorms over eastern Australia and two over New Zealand from 2014-2020, three major floods in eastern Australia and three over New Zealand during 2019-2021, and major fires in southern and eastern Australia during 2019-2020. {11.2.1, Table 11.2, 11.3.8}

Climate trends and extreme events have combined with exposure and vulnerabilities to cause major impacts for many natural systems, with some experiencing or at risk of irreversible change in Australia (*very high confidence)* and in New Zealand *(high confidence).* For example, warmer conditions with more heatwaves, droughts and catastrophic wildfires have negatively impacted terrestrial and freshwater ecosystems. The Bramble Cay melomys, an endemic mammal species, became extinct due to loss of habitat associated with sea-level rise and storm surges in the Torres Strait. Marine species abundance and distributions have shifted polewards, and extensive coral bleaching events and loss of temperate kelp forests have occurred, due to ocean warming and marine heatwaves across the region. In New Zealand's Southern Alps, from 1978-2016, the area of 14 glaciers declined 21%, and extreme glacier mass loss was at least six times more likely in 2011, and ten times more likely in 2018, due to climate change. The end-of-summer snowline elevation for 50 glaciers rose 300 m from 1949-2019. {11.3.1.1, 11.3.2.1, Table 11.2b, Table 11.4, Table 11.6, Table 11.9}

Climate trends and extreme events have combined with exposure and vulnerabilities to cause major impacts for some human systems (*high confidence*). Socio-economic costs arising from climate variability and change have increased. Extreme heat has led to excess deaths and increased rates of many illnesses. Nuisance and extreme coastal flooding have increased due to sea-level rise superimposed upon high tides and storm surges in low-lying coastal and estuarine locations, including impacts on cultural sites, traditions and lifestyles of Aboriginal and Torres Strait Islander Peoples in Australia and Tangata Whenua Māori in New Zealand. Droughts have caused financial and emotional stress in farm households and rural communities. Tourism has been negatively affected by coral bleaching, fires, poor ski seasons and receding glaciers. Governments, business and communities have experienced major costs associated with extreme weather, droughts and sea-level rise. {11.3, 11.4, 11.5.2, Table 11.2, Boxes 11.1-11.6}

Climate impacts are cascading and compounding across sectors and socio-economic and natural systems *(high confidence)*. Complex connections are generating new types of risks, exacerbating existing stressors and constraining adaptation options. An example is the impacts that cascade between interdependent systems and infrastructure in cities and settlements. Another example is the 2019-2020 south-eastern Australian wildfires which burned 5.8 to 8.1 million hectares, with 114 listed threatened species losing at least half of their habitat and 49 losing over 80%, over 3,000 houses destroyed, 33 people killed, a further 429 deaths and 3230 hospitalizations due to cardiovascular or respiratory conditions, $1.95 billion in health costs, $2.3 billion in insured losses, and $3.6 billion in losses for tourism, hospitality, agriculture and forestry. {11.5.1, Box 11.1}

Increasing climate risks are projected to exacerbate existing vulnerabilities and social inequalities and inequities *(high confidence)*. These include inequalities between Indigenous and non-Indigenous Peoples, and between generations, rural and urban areas, incomes and health status, increasing the climate risks and adaptation challenges faced by some groups and places. Resultant climate change impacts include the displacement of some people and businesses, and threaten social cohesion and community wellbeing. {11.3.5, 11.3.6, 11.3.10, 11.4}

Projected impacts and key risks

Further climate change is inevitable, with the rate and magnitude largely dependent on the emission pathway (*very high confidence*[1]). Ongoing warming is projected, with more hot days and fewer cold days (*very high confidence*). Further sea-level rise, ocean warming and ocean acidification are projected (*very high confidence*). Less winter and spring rainfall is projected in southern Australia, with more winter rainfall in Tasmania, less autumn rainfall in south-western Victoria and less summer rainfall in western Tasmania (*medium confidence*), with uncertain rainfall changes in northern Australia. In New Zealand, more winter and spring rainfall is projected in the west and less in the east and north, with more summer rainfall in the east and less in the west and central North Island (*medium confidence*). In New Zealand, ongoing significant clean ice glacier retreat is projected (*very high confidenc*e). More droughts and extreme fire weather are projected in southern and eastern Australia (*high confidence*) and over most of New Zealand (*medium confidence*). Increased rainfall intensity is projected, with fewer tropical cyclones and a greater proportion of severe cyclones *(medium confidence*). {11.2.2, Table 11.3, Box 11.6}

Climate risks are projected to increase for a wide range of systems, sectors and communities, which are exacerbated by underlying vulnerabilities and exposures (*high confidence*) {11.3; 11.4}. Nine key risks were identified, based on magnitude, likelihood, timing and adaptive capacity {11.6, Table 11.14}:

Ecosystems at critical thresholds, where recent climate change has caused significant damage and further climate change may cause irreversible damage, with limited scope for adaptation

Loss and degradation of coral reefs and associated biodiversity and ecosystem service values in Australia due to ocean warming and marine heatwaves, e.g. three marine heatwaves on the Great Barrier Reef during 2016-2020 caused significant bleaching and loss. {11.3.2.1, 11.3.2.2, Box 11.2}

Loss of alpine biodiversity in Australia due to less snow, e.g. loss of alpine vegetation communities (snow patch Feldmark and short alpine herb-fields) and increased stress on snow-dependent plant and animal species, {11.3.1.1, 11.3.1.2}

Key risks that have potential to be severe but can be reduced substantially by rapid, large-scale and effective mitigation and adaptation

Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires, e.g. declining rainfall in southern Australia over the past 30 years has led to drought-induced canopy dieback across a range of forest and woodland types, and death of fire-sensitive tree species due to unprecedented wildfires. {11.3.1.1, 11.3.1.2}

Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins, e.g. less than 10% of giant kelp in Tasmania was remaining by 2011 due to ocean warming. {11.3.2.1, 11.3.2.2}

Loss of natural and human systems in low-lying coastal areas due to sea-level rise, e.g. for 0.5 m sea-level rise, the value of buildings in New Zealand exposed to 1-in-100 year coastal inundation could increase by NZ$12.75 billion and the current 1-in-100 year flood in Australia could occur several times a year. {11.3.5; Box 11.6}

Disruption and decline in agricultural production and increased stress in rural communities in south-western, southern and eastern mainland Australia due to hotter and drier conditions, e.g. by 2050, a decline in median wheat yields of up to 30% in south-west Australia and up to 15% in South Australia, and increased heat stress in livestock by 31–42 days per year. {11.3.4; 11.3.5; Box 11.3}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Increase in heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves, e.g. heat-related excess deaths in Melbourne, Sydney and Brisbane are projected to increase by about 300/year (low emission pathway) to 600/year (high emission pathway) during 2031-2080 relative to 142/year during 1971-2020. {11.3.1, 11.3.5.1, 11.3.5.2, 11.3.6.1, 11.3.6.2}

Key cross-sectoral and system-wide risk

Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply-chains and services due to wildfires, floods, droughts, heatwaves, storms and sea-level rise, e.g. in New Zealand, extreme snow, heavy rainfall and wind events have combined to impact road networks, power and water supply, interdependent wastewater and stormwater services and business activities {11.3.3, 11.5.1, 11.8.1}.

Key implementation risk

Inability of institutions and governance systems to manage climate risks, e.g. the scale and scope of projected climate impacts overwhelm the capacity of institutions, organisations and systems to provide necessary policies, services, resources and coordination to address the socio-economic impacts {11.5.1.2, 11.5.1.3, 11.5.2.3, 11.6, 11.7.1, 11.7.2, 11.7.3}.

There are important interactions between mitigation and adaptation policies and their implementation *(high confidence)*. Integrated policies in interdependent systems across biodiversity, water quality, water availability, energy, transport, land use and forestry for mitigation, can support synergies between adaptation and mitigation. These have co-benefits for the management of land use, water and associated conflicts, and for the functioning of cities and settlements. For example, projected increases in fire, drought, pest incursions, storms and wind place forests at risk and affect their ongoing role in meeting New Zealand's emissions reduction goals. {11.3.4.3, 11.3.10.2, 11.3.5.3, Box 11.5}

Challenges and solutions

The ambition, scope and progress of the adaptation process has increased across governments, non-government organisations, businesses and communities (*high confidence*). This process includes vulnerability and risk assessments, identification of strategies and options, planning, implementation, monitoring, evaluation and review. Initiatives include institutional frameworks in statute for risk assessment and national adaptation planning and monitoring in New Zealand, a National Recovery and Resilience Agency and National Disaster Risk Reduction Framework in Australia, deployment of new national guidance, decision tools, collaborative governance approaches, and the introduction of climate risk and disclosure regimes for the private sector. The focus however has been on adaptation planning, rather than on implementation. {11.5.1, 11.7.1.1, Box 11.6, Table 11.15a, Table 11.15b, Table 11.17}

Adaptation progress is uneven, due to gaps, barriers and limits to adaptation, and adaptive capacity deficits (*very high confidence*). Progress in adaptation planning, implementation, monitoring and evaluation is lagging. Barriers include lack of consistent policy direction, competing objectives, divergent risk perceptions and values, knowledge constraints, inconsistent information, fear of litigation, up-front costs, and lack of engagement, trust and resources. Adaptation limits are being approached for some species and ecosystems. Adaptive capacity to address the barriers and limits can be built through greater engagement with groups and communities to build trust and social legitimacy through inclusion of diverse values, including those of Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori. {11.4, 11.5, 11.6, 11.7, 11.8, Table 11.4, Table 11.5, Table 11.6, Table 11.16, Box 11.2}

A range of incremental and transformative adaptation options and pathways is available as long as enablers are in place to implement them (*high confidence*). Key enablers for effective adaptation include shifting from reactive to anticipatory planning, integration and coordination across levels of government and sectors, inclusive and collaborative institutional arrangements, government leadership, policy alignment, nationally consistent and accessible information, decision-support tools, along with adaptation funding and finance and robust consistent and strategic policy commitment. Over three-quarters of people in Australia and New Zealand agree that climate change is occurring and over 60% believe climate change is caused by humans, giving climate adaptation and mitigation action further social legitimacy. {11.7.3, Table 11.17}

New knowledge on system complexity, managing uncertainty and how to shift from reactive to adaptive implementation is critical for accelerating adaptation (*high confidence*). Priorities include: greater understanding of impacts on natural system dynamics; the exposure and vulnerability of different groups within society, including Indigenous Peoples; the relationship between mitigation and adaptation; the effectiveness and feasibility of different adaptation options; the social transitions needed for transformative adaptation; and the enablers for new knowledge to better inform decision making, e.g. monitoring data repositories, risk and vulnerability assessments, robust planning approaches, sharing adaptation knowledge and practice. {11.7.3.3}

Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori can enhance effective adaptation through the passing down of knowledge about climate change planning that promotes collective action and mutual support across the region (*high confidence*). Supporting Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori institutions, knowledge and values, enables self-determination and creates opportunities to develop adaptation responses to climate change. Actively upholding the UN Declaration on the Rights of Indigenous Peoples and Māori interests under the Treaty of Waitangi at all levels of government enables intergenerational approaches for effective adaptation. {11.3, 11.4, 11.6, 11.7.3; Cross-Chapter Box INDIG in Chapter 18}

A step change in adaptation is needed to match the rising risks and to support climate resilient development *(very high confidence*). Current adaptation is largely incremental and reactive. A shift to transformative and proactive adaptation can contribute to climate resilient development. The scale and scope of cascading, compounding and aggregate impacts require new, larger-scale and timely adaptation. Monitoring and evaluation of the effectiveness of adaptation progress and continual adjustment is critical. The transition to climate-resilient development pathways can generate major co-benefits, but complex interactions between objectives can create trade-offs. {11.7, 11.8.1, 11.8.2}

Delay in implementing adaptation and emission reductions will impede climate resilient development, resulting in more costly climate impacts and greater scale of adjustments (*very high confidence*). The region faces an extremely challenging future. Reducing the risks would require significant and rapid emission reductions to keep global warming to 1.5-2.0ºC, as well as robust and timely adaptation. The projected warming under current global emissions reduction policies would leave many of the region's human and natural systems at very high risk and beyond adaptation limits. {11.8, Table 11.1, Table 11.14, Figure 11.6}

11.1 Introduction

This chapter assesses observed impacts, projected risks, vulnerability and adaptation, and the implications for climate resilient development for the Australasia region, based on literature published up to 1 September 2021. It should be read in conjunction with other Working Group 2 chapters, the climate science assessment in the Working Group 1 Report and the greenhouse gas emissions and mitigation assessment in the Working Group 3 Report.

11.1.1 Context

The Australasia region is defined as the Exclusive Economic Zones (EEZ) and territories of Australia and New Zealand. In both countries, climate adaptation is largely implemented at a sub-national level through devolution of functions constitutionally or by statute, alongside disaster risk reduction (COAG, 2011; Lawrence et al., 2015; Macintosh et al., 2015).

Australia's economy is dominated by financial and insurance services, education, mining, construction, tourism, health care and social assistance (ABS, 2018) with Australian exports accruing mostly from mining (ABS, 2018; ABS, 2019). In New Zealand, service industries, including tourism, collectively account for around two thirds of GDP (NZ Treasury, 2016). The primary sector contributes 6% of New Zealand's GDP and over half of the country's export earnings (NZ Treasury, 2016).

Existing vulnerabilities expose and exacerbate inequalities between rural, regional and urban areas, Indigenous and non-Indigenous Peoples, those with health and disability needs, and between generations, incomes and health status, increasing the relative climate change risk faced by some groups and places (Jones et al., 2014; Bertram, 2015; Perry, 2017; Hazledine and Rashbrooke, 2018) (*high confidence*).

Previous IPCC reports (Table 11.1) have documented observed climate impacts, projected risks, adaptation challenges and opportunities. In this chapter, there is more evidence of observed climate impacts and adaptation, better quantification of socio-economic risks, new information about cascading and compounding risks, greater emphasis on adaptation enablers and barriers, and links to climate-resilient development.

Table 11.1: Summary of key conclusions from the IPCC 5th Assessment Report (AR5) Australasia chapter (Reisinger et al., 2014) and relevant conclusions from the IPCC Special Reports on Global Warming of 1.5°C (IPCC, 2018), Climate Change and Land (IPCC, 2019a) and Oceans and Cryosphere (IPCC, 2019b)

Conclusions	Report
Our regional climate is changing (*very high confidence*) and warming will continue through the 21st century (*virtually certain*) with more hot days, fewer cold days, less snow, less rainfall in southern Australia and the northeast of both of New Zealand's islands, more rainfall in western New Zealand, more extreme rainfall, sea-level rise, increased fire weather in southern Australia and across New Zealand, and fewer cyclones but a greater proportion of intense cyclones. Key risks include changes in the structure and composition of Australian coral reefs, loss of montane ecosystems, increased flood damage, reduced water resources in southern Australia, more deaths and infrastructure damage during heatwaves, more fire-related impacts on ecosystems and settlements in southern Australia and across New Zealand, greater risk to coastal infrastructure and ecosystems, and reduced water availability in the Murray-Darling Basin and southern Australia (*high confidence*). Benefits are projected for some sectors and locations *(high confidence)*, including reduced winter mortality and energy demand for heating, increased forest growth, and enhanced pasture productivity. Adaptation is occurring and adaptation is becoming mainstreamed in some planning processes (*high confidence*). Adaptive capacity is considered generally high in many human systems, but adaptation implementation faces major barriers, especially for transformational responses (*high confidence*). Some synergies and trade-offs exist between different adaptation responses, and between mitigation and adaptation, with interactions occurring both within and outside the region (*very high confidence*).	(Reisinger et al., 2014)

Vulnerability remains uncertain due to incomplete consideration of socio-economic dimensions *(very high confidence),* including governance, institutions, patterns of wealth and aging, access to technology and information, labour force participation, and societal values.	
Emissions reductions under Nationally Determined Contributions from signatories to the Paris Agreement are consistent with a global warming of 2.5-3.0°C above pre-industrial temperatures by 2100. Much deeper emission reductions are needed prior to 2030 to limit warming to 1.5°C. There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses. Climate impacts will disproportionately affect the welfare of impoverished and vulnerable people because they lack adaptation resources. Strengthening the climate-action capacities of national and sub-national authorities, civil society, the private sector, Indigenous people and local communities can support implementation of actions.	(IPCC, 2018)
Land-related responses that contribute to climate change adaptation and mitigation can also combat desertification, land degradation, and enhance food security. Appropriate design of policies, institutions and governance systems at all scales can contribute to land-related adaptation and mitigation while facilitating the pursuit of climate-adaptive development pathways. Mutually supportive climate and land policies have the potential to save resources, amplify social resilience, support ecological restoration, and foster collaboration between stakeholders. Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits. Delaying action (both mitigation and adaptation) will be more costly.	(IPCC, 2019a)
The rate of global mean sea-level rise of 3.6 mm per year for 2006–2015 is unprecedented over the last century. Extreme wave heights, coastal erosion and flooding, have increased in the Southern Ocean by around 1.0 cm per year over the period 1985–2018. Some species of plants and animals have increased in abundance, shifted their range, and established in new areas as glaciers receded and the snow-free season lengthened. Some cold-adapted or snow-dependent species have declined in abundance, increasing their risk of extinction, notably on mountain summits. Many marine species have shifted their range and seasonal activities. Altered interactions between species have caused cascading impacts on ecosystem structure and functioning. Mean sea-level rise projections are higher by 0.1 m compared to AR5 under RCP8.5 in 2100. Extreme sea-level events that are historically rare (once per century) are projected to occur frequently (at least once per year) at many locations by 2050. Projected ecosystem responses include losses of species habitat and diversity, and degradation of ecosystem functions. Warm water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C. Governance arrangements (e.g., marine protected areas, spatial plans and water management systems) are too fragmented across administrative boundaries and sectors to provide integrated responses to the increasing and cascading risks. Financial, technological, institutional and other barriers exist for implementing responses. Enabling climate resilience and sustainable development depends critically on urgent and ambitious emissions reductions coupled with coordinated, sustained and increasingly ambitious adaptation actions. This includes better cooperation and coordination among governing authorities, education and climate literacy, sharing of information and knowledge, finance, addressing social vulnerability and equity, and institutional support.	(IPCC, 2019b)

11.1.2 Economic, Demographic and Social Trends

Economic, demographic and socio-cultural trends influence the exposure, vulnerability and adaptive capacity of individuals and communities (*high confidence*) (Elrick-Barr et al., 2016; Smith et al., 2016; Hayward, 2017; B. Frame et al., 2018; Plummer et al., 2018; Smith et al., 2018; Gartin et al., 2020). In the absence of proactive adaptation, climate change, impacts are projected to worsen inequalities between Indigenous and non-Indigenous people and other vulnerable groups (Green et al., 2009; Manning et al., 2014; Ambrey et al., 2017) (*high confidence*). Socio-economic inequality, low incomes and high levels of debt, poor health and disabilities increase vulnerability and limit adaptation (Hayward, 2012) (11.7.2). Lack of services, such as schools and medical services, in poorer and rural areas, and decision-making processes that privilege some voices over others, exacerbate inequalities (Kearns et al., 2009; Hinkson and Vincent, 2018).

Changes to the composition and location of different demographic groups in the region contributes to increased exposure or vulnerability to climate change (*medium confidence*). Australia's population reached 25 million in 2018 and is projected to grow to 37.4–49.2 million by 2066, with most growth in major cities (accounting for 81% of Australia's population growth from 2016–17) (ABS, 2018), although COVID-19 is expected to slow the growth rate (CoA, 2020c). Highest growth rates outside of major cities occurred mostly in coastal regions (ABS, 2017) which have built assets exposed to sea-level rise. New Zealand's population was 5.1 million at the end of 2020 and is projected to increase to 6.0–6.5 million by 2068 assuming no marked changes in migration patterns (Stats NZ, 2016; Stats NZ, 2021). Although the population densities of both countries are much lower than other OECD countries, they are highly urbanized with over 86% living in urban areas in both countries (Productivity Commission, 2017; World Bank, 2018). This proportion is projected to increase to over 90% by 2050 (UN DESA, 2019) mostly in coastal areas (Rouse et al., 2017). Consideration of climate change impacts when planning and managing such growth and associated infrastructure could help avoid new vulnerabilities being created, particularly from wildfires, sea-level rise, heat stress and flooding.

The region has an increasingly diverse population through the arrival of migrants, including those from the Pacific, whose innovations, skills and transnational networks enhance their and others' adaptive capacity (De et al., 2016; Fatorić et al., 2017; Barnett and McMichael, 2018), although language barriers and socio-economic disadvantage can create vulnerabilities for some (11.7.2).

Climate change inaction exacerbates intergenerational inequity including prospects for the current younger population (Hayward, 2012). Increasing transient worker populations (ABS, 2018) may diminish social networks and adaptive capacity (Jiang et al., 2017). The region has an aging population and increasing numbers of people living on their own who are highly vulnerable to extreme events, including heat stress and flooding (Zhang et al., 2013).

Socio-economic trends are affected by global mega trends (KPMG, 2021), which are expected to influence the region's ability to implement climate change adaptation strategies (World Economic Forum, 2014). Digital technological advances have potential benefits for building adaptive capacity (Deloitte, 2017a).

11.2 Observed and Projected Climate Change

11.2.1 Observed Climate Change

Regional climate change has continued since the Fifth Assessment Report (AR5) in 2014, with trends exacerbating many extreme events (*very high confidence*). The following changes are quantified with references in Tables 11.2a and 11.2b. The region has continued to warm (Figure 11.1), with more extremely high temperatures and fewer extremely low temperatures. Snow depths and glacier volumes have declined. Sea-level rise and ocean acidification have continued. Northern Australia has become wetter, while April-October rainfall has decreased in south-western and south-eastern Australia. In New Zealand, most of the south has become wetter while most of the north has become drier (Figure 11.2). The frequency, severity and duration of extreme fire weather conditions have increased in southern and eastern Australia and eastern New Zealand. Changes in extreme rainfall are mixed. There has been a decline in tropical cyclone frequency near Australia.

Reliable measurements are limited for some types of storms, particularly thunderstorms, lightning, tornadoes and hail (Walsh et al., 2016). Many high impact events are a combination of interacting physical processes across multiple spatial and temporal scales (e.g. fires, heatwaves and droughts), and better understanding of these extreme and compound events is needed (Zscheischler et al., 2018).

Some of the observed trends and events can be partly attributed to anthropogenic climate change, as documented in Chapter 16. Examples include regional warming trends and sea-level rise, terrestrial and marine heatwaves, declining rainfall and increasing fire weather in southern Australia, and extreme rainfall and severe droughts in New Zealand.

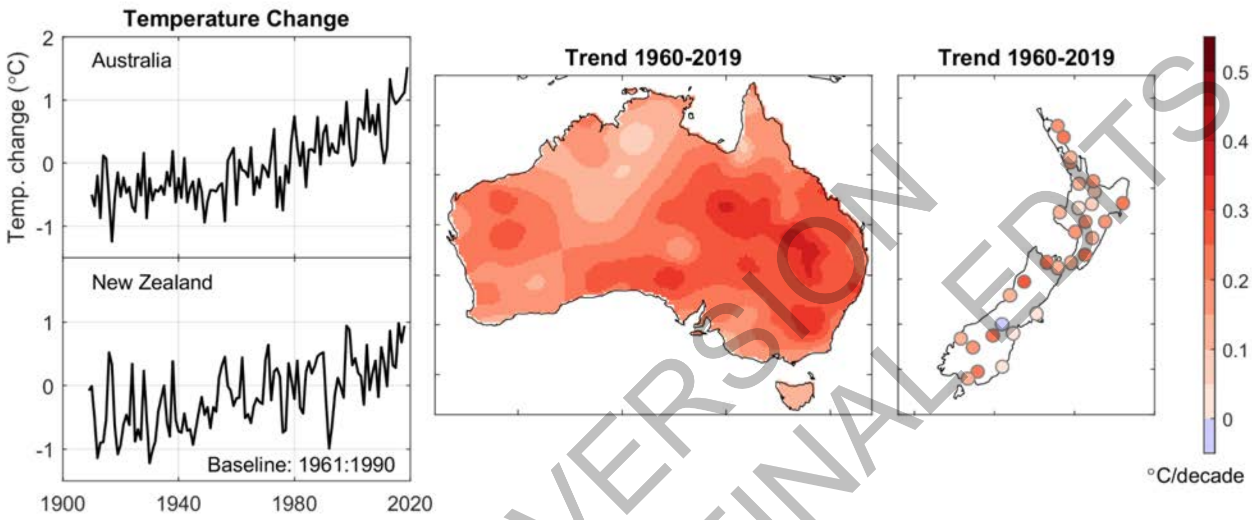


Figure 11.1: Observed temperature changes in Australia and New Zealand. Annual temperature change time-series are shown for 1910–2019. Mean annual temperature trend maps are shown for 1960–2019 using contours for Australia and individual sites for New Zealand. Data courtesy of BoM and NIWA.

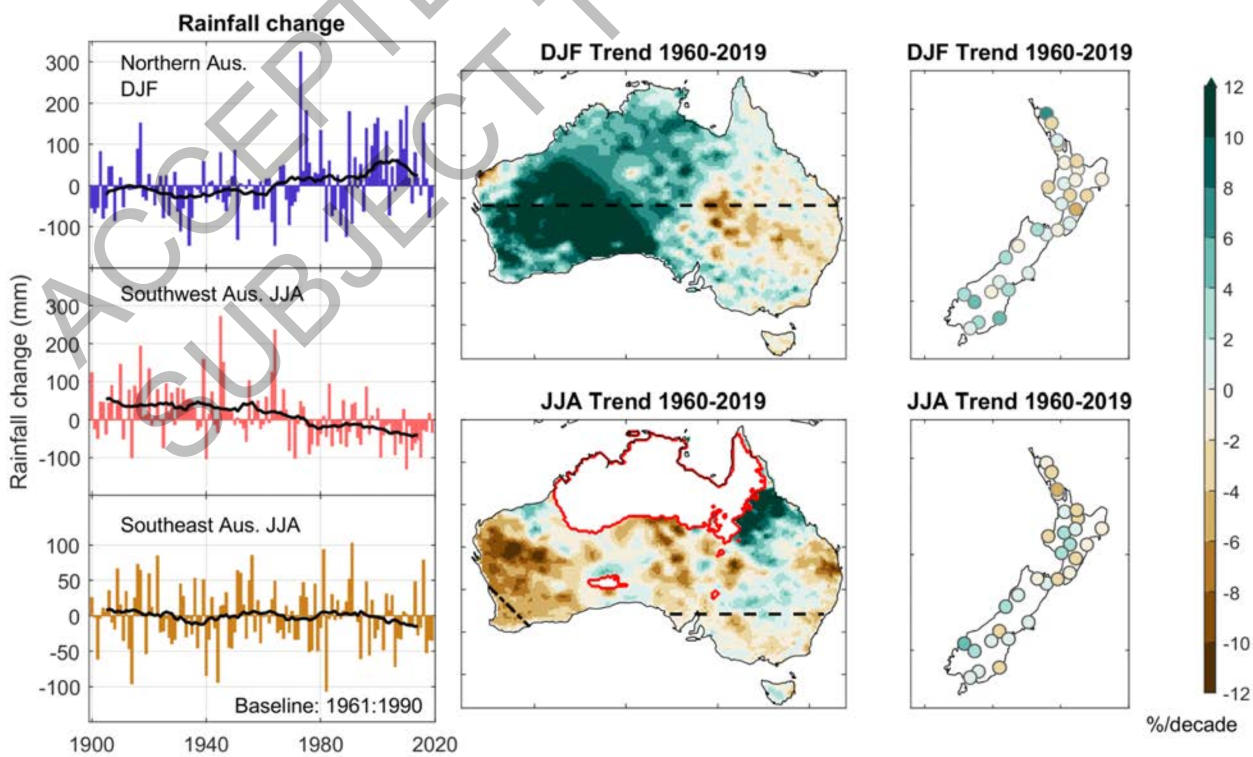


Figure 11.2: Observed rainfall changes in Australia and New Zealand. Rainfall change time-series for 1900–2019 are shown for northern Australia (December-February: DJF), southwest Australia (June-August: JJA) and southeast

Australia (JJA). Dashed lines on the maps for Australia show regions used for the time-series. Rainfall trend maps are shown for 1960–2019 (DJF and JJA) using contours for Australia and individual sites for New Zealand. Areas of low Australian rainfall (less than 0.25 mm/day) are shaded white in JJA. Data courtesy of BoM and NIWA.

Table 11.2a: Observed climate change for Australia**.**

Climate variable	Observed change	References
Air temperature over land	Increased by 1.4°C from 1910–2019. 2019 was the warmest year, and nine of the ten warmest on record occurred since 2005. Clear anthropogenic attribution.	(BoM, 2020b; BoM and CSIRO, 2020; Trewin et al., 2020; Gutiérrez et al., 2021)
Sea surface temperature	Increased by 1.0°C from 1900-2019 (0.09ºC/decade), with an increase of 0.16-0.20ºC/decade since 1950 in the south-east. Eight of the ten warmest years on record occurred since 2010.	(BoM and CSIRO, 2020)
Air temperature extremes over land	More extremely hot days and fewer extremely cold days in most regions. Weaker warming trends in minimum temperatures in southeast Australia compared to elsewhere during 1960-2016. Frost frequency in south-east and south-west Australia has been relatively unchanged since the 1980s. Very high monthly maximum or minimum temperatures that occurred around 2% of the time in the past (1960–1989) now occur 11-12% of the time (2005–2019). Multi-day heatwave events have increased in frequency and duration across many regions since 1950. In 2019, the national average maximum temperature exceeded the 99th percentile on 43 days (more than triple the number in any of the years prior to 2000) and exceeded 39°C on 33 days (more than the number observed from 1960 to 2018 combined).	(Perkins-Kirkpatrick et al., 2016; Alexander and Arblaster, 2017; Pepler et al., 2018; BoM and CSIRO, 2020; Perkins-Kirkpatrick and Lewis, 2020; Trancoso et al., 2020)
Sea temperature extremes	Intense marine heatwave in 2011 near Western Australia (peak intensity 4°C, duration 100 days) - likelihood of an event of this duration estimated to be about 5 times higher than under pre-industrial conditions. Marine heatwave over northern Australia in 2016 (peak intensity 1.5°C, duration 200 days). Marine heatwave in the Tasman Sea and around southeast mainland Australia and Tasmania from September 2015 to May 2016 (peak intensity 2.5°C, duration 250 days) - likelihood of an event of this intensity and duration has increased about 50-fold. Marine heatwave in the Tasman Sea from November 2017 to March 2018 (peak intensity 3°C, duration 100 days). Marine heatwave on the Great Barrier Reef in 2020 (peak intensity 1.2°C, duration 90 days) (BoM, 2020).	(BoM and CSIRO, 2018; BoM, 2020a; Laufkötter et al., 2020; Oliver et al., 2021)
Rainfall	Northern Australian rainfall has increased since the 1970s, with an attributable human influence. April to October rainfall has decreased 16% since the 1970s in south-western Australia (partly due to human influence) and 12% from 2000-2019 in south-eastern Australia. Australian-average rainfall was lowest on record in 2019.	(Delworth and Zeng, 2014; Knutson and Zeng, 2018; Dey et al., 2019; BoM, 2020c; BoM and CSIRO, 2020)
Rainfall extremes	Hourly extreme rainfall intensities increased by 10–20% in many locations between 1966–1989 and 1990–2013. Daily rainfall associated with thunderstorms increased 13-24% from 1979-2016, particularly in northern Australia. Daily rainfall intensity increased in the northwest from 1950–2005 and in the east from 1911–2014, and decreased in the south-west and Tasmania from 1911–2010.	(Donat et al., 2016; Alexander and Arblaster, 2017; Evans et al., 2017; Guerreiro et al., 2018; Dey et al., 2019; BoM and CSIRO, 2020; Bruyère et al., 2020; Dowdy, 2020; Dunn et al., 2020; Gutiérrez et al., 2021)

Drought	Major Australian droughts occurred in 1895-1902, 1914-1915, 1937-1945, 1965-1968, 1982-1983, 1997-2009 and 2017-2019. Fewer droughts have occurred across most of northern and central Australia since the 1970s, more droughts in the south-west since the 1970s, and mixed drought trends in the south-east since the late 1990s.	(Gallant et al., 2013; Delworth and Zeng, 2014; Alexander and Arblaster, 2017; Dai and Zhao, 2017; Knutson and Zeng, 2018; Dey et al., 2019; Spinoni et al., 2019; BoM, 2020b; Dunn et al., 2020; Rauniyar and Power, 2020; BoM, 2021; Seneviratne et al., 2021)
Windspeed	Windspeed decreased 0.067 m/s per decade over land from 1941-2016, with a decrease of 0.062 m/s per decade over land from 1979–2015, and a decrease of 0.05-0.10 m/s per decade over land from 1988-2019. Windspeed increased 0.02 m/s per year across the Southern Ocean from 1985-2018.	(Troccoli et al., 2012; Young and Ribal, 2019; Blunden and Arndt, 2020; Azorin-Molina et al., 2021)
Sea-level rise	Relative sea level rise was 3.4 mm/year from 1993-2019, which includes the influence of internal variability (e.g. ENSO) and anthropogenic greenhouse gases.	(Watson, 2020)
Fire	An increase in the number of extreme fire weather days from July 1950 to June 1985 compared to July 1985 to June 2020, especially in the south and east, partly attributed to climate change. More dangerous conditions for extreme pyro convection events since 1979, particularly in south-eastern Australia. Extreme fire weather in 2019-2020 was at least 30% more likely due to climate change.	(Dowdy and Pepler, 2018; BoM and CSIRO, 2020; van Oldenborgh et al., 2021)
Tropical cyclones and other storms	Fewer tropical cyclones since 1982, with a 22% reduction in translation speed over Australian land areas from 1949-2016. No significant trend in the number of East Coast Lows. From 1979–2016, thunderstorms and dry lightning decreased in spring and summer in northern and central Australia, decreased in the north in autumn, and increased in the south-east in all seasons. Convective rainfall intensity per thunderstorm increased by about 20% in the north and 10% in the south. An increase in the frequency of large to giant hail events across south-eastern Queensland and north-eastern and eastern New South Wales in the most recent decade. Seven major hail storms over eastern Australia from 2014-2020 and three major floods over eastern Australia from 2019-2021.	(Pepler et al., 2015b; Ji et al., 2018; Kossin, 2018; BoM and CSIRO, 2020; Dowdy, 2020; ICA, 2021) (Bruyère et al., 2020)
Snow	At Spencers Creek (1830 m elevation) in NSW, annual maximum snow depth decreased 10% and length of snow season decreased 5% during 2000–2013 relative to 1954–1999. At Rocky Valley Dam (1650 m elevation) in Victoria, annual maximum snow depth decreased 5.7 cm/decade from 1954-2011. At Mt Hotham, Mt Buller and Falls Creek (1638-1760 m elevation), annual maximum snow depth decreased 15%/decade from 1988-2013.	(Bhend et al., 2012; Fiddes et al., 2015; Pepler et al., 2015a; BoM and CSIRO, 2020)
Ocean acidification	Average pH of surface waters has decreased since the 1880s by about 0.1 (over 30% increase in acidity).	(BoM and CSIRO, 2020)

Table 11.2b: Observed climate change for New Zealand.

Climate variable	Observed change	References
Air temperature	Increased by 1.1°C from 1909–2019. Warmest year on record was 2016, followed by 2018 and 1998 as equal 2nd warmest.	(MfE, 2020a; NIWA, 2020)

	Six years between 2013 and 2020 were among New Zealand's warmest on record.	
Sea surface temperature	Increased by 0.2°C/decade from 1981–2018.	(MfE, 2020a)
Air temperature extremes	Number of frost days (below 0 degrees Celsius) decreased at 12 of 30 sites, the number of warm days (over 25°C) increased at 19 of 30 sites, and the number of heatwave days increased at 18 of 30 sites during 1972–2019. Increase in the frequency of hot February days exceeding the 90th percentile between 1980–1989 and 2010–2019, with some regions showing more than a five-fold increase.	(Harrington, 2020; MfE, 2020a)
Sea temperature extremes	The eastern Tasman Sea experienced a marine heatwave in 2017/18 lasting 138 days with a maximum intensity of 4.1°C, and another marine heatwave in 2018/19 lasting 137 days with a maximum intensity of 2.8°C.	(NIWA, 2019; Salinger et al., 2019b; Salinger et al., 2020; Oliver et al., 2021)
Rainfall	From 1960–2019, almost half of the 30 sites had an increase in annual rainfall (mostly in the south) and 10 sites (mostly in the north) had a decrease, but few of the trends are statistically significant. Rainfall increased by 2.8% per decade in Whanganui, 2.1% per decade in Milford Sound and 1.3% per decade in Hokitika. Rainfall decreased by 4.3% per decade in Whangarei and 3.2% per decade in Tauranga.	(MfE, 2020a)
Rainfall extremes	The number of days with extreme rainfall increased at 14 of 30 sites and decreased at 11 sites from 1960–2019. Most sites with increasing annual rainfall had more extreme rainfall and most sites with decreasing annual rainfall had less extreme rainfall.	(MfE, 2020a)
Drought	Drought frequency increased at 13 of 30 sites from 1972–2019 and decreased at 9 sites. Drought intensity increased at 14 sites, 11 of which are in the north, and decreased at 9 sites, 7 of which are in the south.	(MfE, 2020a)
Windspeed	Since 1970, the wind belt has often been shifted to the south of New Zealand, bringing an overall decrease in wind-speed over the country. For 1980–2019, the annual maximum wind gust decreased at 11 of the 14 sites that had enough data to calculate a trend, and increased at 2 of the 14 sites	(MfE, 2020a)
Sea-level rise	Increased 1.8 mm/year from 1900–2018 and 2.4 mm/year from 1961–2018, mostly due to climate change.	(Bell and Hannah, 2019)
Fire	Six of 28 sites (Napier, Lake Tekapo, Queenstown, Gisborne, Masterton, and Gore) had an increase in days with very high or extreme fire danger from 1997–2019 and 6 sites (Blenheim, Christchurch, Nelson, Tara Hills, Timaru, and Wellington) had a decrease. An increase in fire impacts from 1988–2018 included homes lost, damaged, threatened and evacuated.	(Pearce, 2018; MfE, 2020a)
Tropical cyclones and other storms	No significant change in storminess. Three major floods and two major hail-storms during 2019-2021.	(MfE, 2020a; ICNZ, 2021)

Snow and ice	From 1978-2019, the snowline rose 3.7 m/year. From 1977 to 2018, glacier ice volume decreased from 26.6 km^3 to 17.9 km^3 (a loss of 33%). From 1978-2016, the area of 14 glaciers in the Southern Alps declined 21%. The end-of-summer snowline elevation for 50 glaciers rose 300 m from 1949-2019. In the Southern Alps, extreme glacier mass loss was at least six times more likely in 2011, and ten times more likely in 2018, due to climate change.	(Baumann et al.; Salinger et al., 2019a; Chinn and Chinn, 2020; MfE, 2020a; Salinger et al., 2021) (Vargo et al., 2020)
Ocean acidification	Sub-Antarctic ocean off the Otago coast became 7% more acidic from 1998–2017.	(MfE, 2020a)

11.2.2 Projected Climate Change

There are three main sources of uncertainty in climate projections: emission scenarios, regional climate responses, and internal climate variability (CSIRO and BOM, 2015). Emission scenario uncertainty is captured in four Representative Concentration Pathways (RCPs) for greenhouse gases and aerosols. RCP2.6 represents low emissions, RCP4.5 medium emissions and RCP8.5 high emissions. Regional climate response uncertainty and internal climate variability uncertainty are captured in climate model simulations driven by the RCPs.

Further climate change is inevitable, with the rate and magnitude largely dependent on the emission pathway (IPCC, 2021) (*very high confidence*). Preliminary projections based on CMIP6 models are described in the IPCC Working Group I Atlas. For Australia, the CMIP6 projections broadly agree with CMIP5 projections except for a group of CMIP6 models with greater warming and a narrower range of summer rainfall change in the north and winter rainfall change in the south (Grose et al., 2020). For New Zealand, the CMIP6 projections are similar to CMIP5, but the CMIP6 models indicate greater warming, a smaller increase in summer precipitation and a larger increase in winter precipitation (Gutiérrez et al., 2021).

Dynamical and/or statistical downscaling offers the prospect of improved representation of regional climate features and extreme weather events (IPCC 2021: Working Group I Chapter 10), but the added value of downscaling is complex to evaluate (Ekström et al., 2015; Rummukainen, 2015; Virgilio et al., 2020). Downscaled simulations are available for New Zealand (MfE, 2018) and various Australian regions (Evans et al., 2020) (IPCC 2021: Working Group I Atlas). Further downscaling was recommended by the Royal Commission into National Natural Disaster Arrangements (CoA, 2020e). Projections for rainfall, thunderstorms, hail, lightning and tornadoes have large uncertainties (Walsh et al., 2016; MfE, 2018).

Future changes in climate variability are affected by the El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM), Indian Ocean Dipole (IOD) and Interdecadal Pacific Oscillation (IPO). An increase in strong El Niño and La Niña events is projected (Cai, 2015), along with more extreme positive phases of the IOD (Cai et al., 2018) and a positive trend in SAM (Lim et al., 2016), but potential changes in the IPO are unknown (NESP ESCC, 2020). There is uncertainty about regional climate responses to projected changes in ENSO (King et al., 2015; Perry et al., 2020; Virgilio et al., 2020).

Australian climate projections are quantified with references in Table 11.3a. Further warming is projected, with more hot days, fewer cold days, reduced snow cover, ongoing sea-level rise and ocean acidification (*very high confidence*). Winter and spring rainfall and soil moisture are projected to decrease with more droughts in southern Australia, increased extreme rainfall intensity, higher evaporation rates, decreased wind over southern mainland Australia, increased wind over Tasmania, and more extreme fire weather in southern and eastern Australia (*high confidence*). Increased winter rainfall is projected over Tasmania, with decreased rainfall in south-western Victoria in autumn and in western Tasmania in summer, fewer tropical cyclones with a greater proportion of severe cyclones and decreased soil moisture in the north (*medium confidence*). Hailstorm frequency may increase (*low confidence*).

New Zealand climate projections are quantified with references in Table 11.3b. Further warming is projected, with more hot days, fewer cold days, less snow and glacial ice, ongoing sea-level rise and ocean acidification (*very high confidence*). Increases in winter and spring rainfall are projected in the west of the North and South Islands, with drier conditions in the east and north, caused by stronger westerly winds (*medium confidence*). In summer, wetter conditions are projected in the east of both islands, with drier conditions in the west and central North Island (*medium confidence*). Fire weather is projected to increase in most areas, except for Taranaki-Manawatū, West Coast and Southland (*medium confidence*). Extreme rainfall is projected to increase over most regions, with increased extreme wind-speeds in eastern regions, especially in Marlborough and Canterbury, and reduced relative humidity almost everywhere, except for the West Coast in winter (*medium confidence*). Drought frequency may increase in the north (*medium confidence*).

Table 11.3a: Projected climate change for Australia. Projections are given for different Representative Concentration Pathways (RCP2.6 is low, RCP4.5 is medium, RCP8.5 is high) and years (e.g. 20–year period centered on 2090). Uncertainty ranges are generally 10–90th percentile, and median projections are given in square brackets where possible. The four Australian regions are shown in Chapter 2 of (CSIRO and BOM, 2015). Preliminary projections based on CMIP6 models are included for some climate variables from the IPCC (2021) Working Group 1 report.

Climate variable	Projected change (year, RCP) relative to 1986-2005	References
Air temperature	Annual mean temperature • +0.5–1.5°C (2050, RCP2.6), +1.5–2.5°C (2050, RCP8.5), +0.5–1.5°C (2090, RCP2.6), +2.5–5.0°C (2090, RCP8.5) • Weaker increase in the south, stronger increase in the centre. • Preliminary CMIP6 projections: +0.6-1.3ºC (2050, SSP1-RCP2.6), +1.2-2.0ºC (2050, SSP5-RCP8.5), +0.6-1.5ºC (2090, SSP1-RCP2.6), +2.8-4.9ºC (2090, SSP5-RCP8.5) relative to 1995-2014	(NESP ESCC, 2020; IPCC, 2021)
Sea surface temperature	• + 0.4–1.0°C (2030, RCP8.5), • +2–4°C (2090, RCP8.5).	(CSIRO and BOM, 2015)
Air temperature extremes	• Annual frequency of days over 35°C may increase 20–70% by 2030 (RCP4.5), and 25–85% (RCP2.6) to 80–350% (RCP8.5) by 2090 • Heatwaves may be 85% more frequent if global warming increases from 1.5 to 2.0°C, and four times more frequent for a 3°C warming • Annual frequency of frost days may decrease by 10–40% (2030, RCP4.5), 10–40% (2090, RCP2.6) and 50–100% (2090, RCP8.5).	(CSIRO and BOM, 2015; Trancoso et al., 2020)
Rainfall	Annual mean rainfall • South: –15 to +2% (2050, RCP2.6), –14 to +3% (2050, RCP8.5), –15 to +3% (2090, RCP2.6), –26 to +4% (2090, RCP8.5) • East: –13 to +7% (2050, RCP2.6), –17 to +8% (2050, RCP8.5), –19 to +6% (2090, RCP2.6), –25 to +12% (2090, RCP8.5) • North: –12 to +5% (2050, RCP2.6), -8 to +11% (2050, RCP8.5), -12 to +3% (2090, RCP2.6), -26 to +23% (2090, RCP8.5) • Rangelands: -18 to +3% (2050, RCP2.6), -15 to +8% (2050, RCP8.5), -21 to +3% (2090, RCP2.6), -32 to +18% (2090, RCP8.5).	(Liu et al., 2018; NESP ESCC, 2020)
Rainfall extremes	Intensity of daily-total rain with 20-year recurrence interval • +4 to +10% (2050, RCP2.6), • +8 to +20% (2050, RCP8.5), • +4 to +10% (2090, RCP2.6), • +15 to +35% (2090, RCP8.5).	(NESP ESCC, 2020)
Drought	Time in drought (Standardized Precipitation Index below -1) • Southern Australia: 32-46% [39%] (1995), 38-68% [54%] (2050, RCP8.5), 41-81% [60%] (2090, RCP8.5) • Eastern Australia: 25-46% [37%] (1995), 24-67% [47%] (2050, RCP8.5), 19-76% [56%] (2090, RCP8.5) • Northern Australia: 26-44% [34%] (1995), 18-54% [40%] (2050, RCP8.5), 9-81% [39%] (2090, RCP8.5)	(Kirono et al., 2020)

	• Australian Rangelands: 29-43% [34%] (1995), 26-58% [42%] (2050, RCP8.5), 23-70% [46%] (2090, RCP8.5).	
Windspeed	0-5% decrease over southern mainland Australia and 0-5% increase over Tasmania (2090, RCP8.5)	(CSIRO and BOM, 2015)
Sea-level rise	• South (Port Adelaide): 13-29 cm [21 cm] (2050, RCP2.6), 16-33 cm [25 cm] (2050, RCP8.5), 23-55 cm [39 cm] (2090, RCP2.6), 40-84 cm [61 cm] (2090, RCP8.5) • East (Newcastle): 14-30 cm [22 cm] (2050, RCP2.6), 19-36 cm [27 cm] (2050, RCP8.5), 22-54 cm [38 cm] (2090, RCP2.6), 46-88 cm [66 cm] (2090, RCP8.5) • North (Darwin City Council, 2011): 13-28 cm [21 cm] (2050, RCP2.6), 17-33 cm [25 cm] (2050, RCP8.5), 22-55 cm [38 cm] (2090, RCP2.6), 41-85 cm [62 cm] (2090, RCP8.5) • West (Port Hedland): 13-28 cm [20 cm] (2050, RCP2.6), 16-33 cm [24 cm] (2050, RCP8.5), 22-55 cm [38 cm] (2090, RCP2.6), 40-84 cm [61 cm] (2090, RCP8.5). These projections have not been updated to include an Antarctic dynamic ice sheet factor which increased global sea level projections for RCP8.5 by ~10 cm. Preliminary CMIP6 projections indicate +40-50 cm (2090, SSP1-RCP2.6) and +70-90 cm (2090, SSP5-RCP8.5).	(McInnes et al., 2015; Zhang et al., 2017; IPCC, 2019b) (IPCC, 2021)
Sea-level extremes	Increase in the allowance for a storm tide event with 1% annual exceedance probability (100-year return period) • South (Port Adelaide): 21 cm (2050, RCP2.6), 25 cm (2050, RCP8.5), 41 cm (2090, RCP2.6), 66 cm (2090, RCP8.5) • East (Newcastle): 24 cm (2050, RCP2.6), 30 cm (2050, RCP8.5), 49 cm (2090, RCP2.6), 86 cm (2090, RCP8.5) • North (Darwin): 21 cm (2050, RCP2.6), 26 cm (2050, RCP8.5), 43 cm (2090, RCP2.6), 71 cm (2090, RCP8.5) • West (Port Hedland): 21 cm (2050, RCP2.6), 26 cm (2050, RCP8.5), 43 cm (2090, RCP2.6), 70 cm (2090, RCP8.5).	(McInnes et al., 2015)
Fire	• East: annual number of severe fire weather days 0 to +30% (2050, RCP2.6), 0 to +60% (2050, RCP8.5), 0 to +30% (2090, RCP2.6), 0 to +110% (2090, RCP8.5) • Elsewhere: number of severe fire weather days +5 to +35% (2050, RCP2.6), +10 to +70% (2050, RCP8.5), +5 to +35% (2090, RCP2.6) +20 to +130% (2090, RCP8.5).	(Clarke and Evans, 2019; Dowdy et al., 2019, {Clark, 2021 #2658; Virgilio et al., 2019; NESP ESCC, 2020)
Tropical cyclones and other storms	• Eastern region tropical cyclones: -8 to +1% (2050, RCP2.6), -15 to +2% (2050, RCP8.5), -8 to +1% (2090, RCP2.6), -25 to +5% (2090, RCP8.5) • Western region tropical cyclones: -10 to -2% (2050, RCP2.6), -20 to -4% (2050, RCP8.5), -10 to -2% (2090, RCP2.6), -30 to -10% (2090, RCP8.5) • East coast lows: -15 to -5% (2050, RCP2.6), -30 to -10% (2050, RCP8.5), -15 to -5% (2090, RCP2.6), -50 to -20% (2090, RCP8.5). • Hailstorm frequency may increase, but there are large uncertainties.	(NESP ESCC, 2020; Raupach et al., 2021)

Snow and ice	• Maximum snow depth at Falls Creek and Mt Hotham may decline 30–70% (2050, B1) and 45–90% (2050, A1FI) relative to 1990. • Maximum snow depth at Mt Buller and Mt Buffalo may decline 40–80% (2050, B1) and 50–100% (2050, A1FI) relative to 1990. • Length of Victorian ski-season may contract 65–90% and mean annual snowfall may decline 60–85% (2070–2099, RCP8.5) relative to 2000–2010. • The snowpack may decrease by about 15% (2030, A2) to 60% (2070, A2).	(Bhend et al., 2012; Harris et al., 2016; Di Luca et al., 2018)
Ocean acidification	pH is projected to drop by about 0.1 (2090, RCP2.6) to 0.3 (2090, RCP8.5).	(CSIRO and BOM, 2015; Hurd et al., 2018)

Table 11.3b: Projected climate change for New Zealand. Projections are given for different Representative Concentration Pathways (RCP2.6 is low, RCP4.5 is medium, RCP8.5 is high) and years (e.g. 20–year period centered on 2090). Uncertainty ranges are 5–95th percentile, and median projections are given in square brackets where possible. Preliminary projections (10-90th percentile) based on CMIP6 models are included for some climate variables from the IPCC (2021) Working Group 1 report.

Climate variable	Projected change (year, RCP) relative to 1986-2005	References
Air temperature	Annual mean temperature • +0.2–1.3°C [0.7°C] (2040, RCP2.6), +0.5–1.7°C [1.0°C] (2040, RCP8.5), +0.1–1.4°C [0.7°C] (2090, RCP2.6), +2.0–4.6°C [3.0°C] (2090, RCP8.5) • More warming in summer and autumn, less in winter and spring. • More warming in the north than the south. • Preliminary CMIP6 projections: +0.4-1.1°C (2050, SSP1-RCP2.6), +0.9-1.7°C (2050, SSP5-RCP8.5), +0.5-1.5°C (2090, SSP1-RCP2.6), +2.2-4.1°C (2090, SSP5-RCP8.5) relative to 1995-2014	(MfE, 2018) (IPCC, 2021)
Sea surface temperature	• +1.0°C (2045, RCP8.5), • +2.5°C (2090, RCP8.5).	(Law et al., 2018b)
Air temperature extremes	• Annual frequency of days over 25°C may increase 20–60% (2040, RCP2.6) to 50–100% (2040, RCP8.5), and 20–60% (2090, RCP2.6) to 130–350% (2090, RCP8.5) • Annual frost frequency may decrease 20–60% (2040, RCP2.6) to 30–70% (2040, RCP8.5), and 20–60% (2090, RCP2.6) to 70–95% (2090, RCP8.5).	(MfE, 2018)

Rainfall	Annual mean rainfall • Waikato, Auckland and Northland: -7 to +7% (2040, RCP2.6), -8 to +5% (2040, RCP8.5), -5 to +11% [+2%] (2090, RCP2.6), -15 to +12% [-2%] (2090, RCP8.5) • Hawke's Bay and Gisborne: -8 to +8% [-1%] (2040, RCP2.6), -12 to +7% [-2%] (2040, RCP8.5), -9 to +4% [-2%] (2090, RCP2.6), -15 to +15% [-3%] (2090, RCP8.5) • Taranaki, Manawatū and Wellington: -4 to +9% [+1%] (2040, RCP2.6), -6 to +10% [+1%] (2040, RCP8.5), -6 to +15% [+3%] (2090, RCP2.6), -14 to +14% [+2%] (2090, RCP8.5) • Tasman-Nelson and Marlborough: -3 to +5% [+1%] (2040, RCP2.6), -3 to +8% [+1%] (2040, RCP8.5), -4 to +8% [+2%] (2090, RCP2.6), -3 to +15% [+5%] (2090, RCP8.5) • West Coast and Southland: -4 to +12% [+3%] (2040, RCP2.6), -4 to +12% [+4%] (2040, RCP8.5), -2 to +18% [+5%] (2090, RCP2.6), -8 to +23% (2090, RCP8.5) • Canterbury and Otago: -7 to +15% [+3%] (2040, RCP2.6), -7 to +19% [+3%] (2040, RCP8.5), -6 to +18% (2090, RCP2.6), -9 to +28% [+8%] (2090, RCP8.5).	(Liu et al., 2018; MfE, 2018)
Rainfall extremes	Intensity of daily rain with 20-year recurrence interval • +2.8 to 7.2% [5%] (2040, RCP2.6) • +4.2 to 10.4% [7%] (2040, RCP8.5) • +2.8 to 7.2% [5%] (2090, RCP2.6) • +12.6 to 31.5% [2%] (2090, RCP8.5).	(MfE, 2018)
Drought	Increase in potential evapotranspiration deficit • Northern and eastern North Island: 100-200 mm (2090, RCP8.5) • Western North Island: 50-100 mm (2090, RCP8.5) • Eastern South Island: 50-200 mm (2090, RCP8.5) • Western South Island: 0-50 mm (2090, RCP8.5).	(MfE, 2018)
Windspeed	99th percentile of daily mean wind speed • Northern North Island: 0 to -5% (2090, RCP8.5) • Southern North Island: 0 to +5% (2090, RCP8.5) • South Island: 0 to +10% (2090, RCP8.5).	(MfE, 2018)
Sea-level rise	• 23 cm (2050, RCP2.6) • 28 cm (2050, RCP8.5) • 42 cm (2090 RCP2.6) • 67 cm (2090 RCP8.5). These projections have not been updated to include an Antarctic dynamic ice sheet factor which increased global sea-level projections for RCP 8.5 by ~10 cm. Preliminary CMIP6 projections indicate 40-50 cm (2090, SSP1-RCP2.6) and 70-90 cm (2090, SSP5-RCP8.5).	(MfE, 2017a; IPCC, 2019b)
Sea-level extremes	For a rise in sea level of 30 cm, the 1-in-100-year high water levels may occur about: • Every 4 years at the port of Auckland • Every 2 years at the port of Dunedin • Once a year at the port of Wellington • Once a year at the port of Christchurch.	(PCE, 2015)

Fire	• Seasonal Severity Rating (SSR) increases 50-100% in coastal Marlborough and Otago, 40-50% in Wellington and 30-40% in Taranaki and Whanganui, 0-30% elsewhere (2050, A1B). • Number of days with very high or extreme fire weather increase >100% in coastal Otago, Marlborough and the lower North Island, 50-100% in Taupō and Rotorua, 20-50% in the rest of the North Island, and little change in the rest of the South Island (2050, A1B).	(Pearce et al., 2011)
Tropical cyclones and other storms	Poleward shift of mid-latitude cyclones and potential for a small reduction in frequency.	(MfE, 2018)
Snow and ice	• Maximum snow depth on 31 August may decline by 0-10% (2040, A1B) and 26-54% (2090, A1B). • Annual snow days may be reduced by 5-15 days (2040, RCP2.6), 10-25 days (2040, RCP8.5), 5-15 days (2090, RCP2.6) and 15-45 days (2090 RCP8.5). • Relative to 2015, New Zealand glaciers are projected to lose 36%, 53% and 77 % of their mass by the end of the century under RCP2.6, RCP4.5 and RCP8.5, respectively. • Over the period 2006-2099, New Zealand glaciers are projected to lose 50 to 92% of their ice volume for RCP2.6 to RCP8.5.	(Hendrikx et al., 2013; MfE, 2018; Marzeion et al., 2020) (Anderson et al. 2021)
Ocean acidification	pH is projected to drop by about 0.1 (2090, RCP2.6) to 0.3 (2090 RCP8.5).	(CSIRO and BOM, 2015; Hurd et al., 2018; Law et al., 2018b)

11.3 Observed Impacts, Projected Impacts and Adaptation

This section assesses observed impacts, projected risks, and adaptation for 10 sectors and systems. Boxes provide more detail on specific issues. Risk is considered in terms of vulnerability, hazards (impact driver), exposure, reasons for concern, complex and cascading risks (Chapter 1 Figure 1.2).

11.3.1 Terrestrial and Freshwater Ecosystems

11.3.1.1 Observed Impacts

Widespread and severe impacts on ecosystems and species are now evident across the region (*very high confidence*) (Table 11.4). Climate impacts reflect both on-going change and discrete extreme weather events (Harris et al., 2018) and the climatic change signal is emerging despite confounding influences (Hoffmann et al., 2019). Fundamental shifts are observed in the structure and composition of some ecosystems and associated services (Table 11.4). Impacts documented for species include global and local extinctions, severe regional population declines, and phenotypic responses (Table 11.4). In terrestrial and freshwater ecosystems, land use impacts are interacting with climate, resulting in significant changes to ecosystem structure, composition and function (Bergstrom et al., 2021) with some landscapes experiencing catastrophic impacts (Table 11.4). Some of observed changes may be irreversible where projected impacts on ecosystems and species persist (Table 11.5). Of note is the global extinction of an endemic mammal species, the Bramble Cay melomys (*Melomys rubicola*), from the loss of habitat attributable in part to sea-level rise and storm surges in the Torres Strait (Table 11.4).

Natural forest and woodland ecosystem processes are experiencing differing impacts and responses depending on the climate zone (*high confidence*). In Australia, an overall increase in the forest fire danger index, associated with warming and drying trends (Table 11.2a), has been observed particularly for southern and eastern Australia in recent decades (Box 11.1). The 2019-2020 mega wildfires of south eastern Australia burnt between 5.8 - 8.1 million hectares of mainly temperate broadleaf forest and woodland, but with substantial areas of rainforest also impacted, and were unprecedented in their geographic location, spatial extent, and forest types burnt (Boer et al., 2020; Nolan et al., 2020; Abram et al., 2021; Collins et al., 2021; Godfree et al., 2021). The human influence on these events is evident (Abram et al., 2021; van Oldenborgh et al., 2021) (Box 11.1). The fires had significant consequences for wildlife (Hyman et al., 2020; Nolan et al., 2020; Ward et al., 2020) (Box 11.1) and flow-on impacts for aquatic fauna (Silva et al., 2020). In southern Australia, deeply rooted native tree species can access soil and ground-water resources during drought, providing a level of natural resilience (Bell and Nikolaus Callow, 2020; Liu et al., 2020). However, the Northern Jarrah forests of south western Australia have experienced tree mortality and dieback from long term precipitation decline and acute heatwave-compounded drought (Wardell-Johnson et al., 2015; Matusick et al., 2018). While there is limited information on observed impacts for New Zealand, increased mast seeding events in beech forest ecosystems that stimulate invasive population irruptions have been recorded (Schauber et al., 2002; Tompkins et al., 2013).

Table 11.4: Observed impacts on terrestrial and freshwater ecosystems and species in the region where there is documented evidence that these are directly (e.g. a species thermal tolerances are exceeded) or indirectly (e.g. through changed fire regimes) the result of climate change pressures.

Ecosystem	Climate-related Pressure	Impact	Source
Australia			
Forest and woodlands of southern and southwestern Australia	30-year declining rainfall	Drought-induced canopy dieback across a range of forest and woodland types (e.g. northern jarrah)	(Matusick et al., 2018; Hoffmann et al., 2019)
	Multiple wildfires in short succession resulting from increased fire risk conditions including declining winter rainfall and increasing hot days	Local extirpations and replacement of dominant canopy tree species and replacement by woody shrubs due to seeders having insufficient time to reach reproductive age (Alpine Ash) or vegetative regeneration capacity is exhausted (Snow Gum woodlands)	(Slatyer, 2010; Bowman et al., 2014; Fairman et al., 2016; Harris et al., 2018; Zylstra, 2018)
	Background warming and drying created soil and vegetation conditions that are conducive to fires being ignited by lightning storms in regions that have rarely experienced fire over the last few millennia	Death of fire sensitive trees species from unprecedented fire events (Palaeo-endemic pencil pine forest growing in sphagnum, Tasmania, killed by lightning-ignited fires in 2016)	(Hoffmann et al., 2019)
Australia Alps Bioregion and Tasmanian alpine zones	Severe winter drought; warming and climate-induced biotic interactions	Shifts in dominant vegetation with a decline in grasses and other graminoids and an increase in forb and shrub cover in Bogong High Plains, Victoria, Australia	(Bhend et al., 2012; Hoffmann et al., 2019)

	Snow loss, fire, drought and temperature changes	Changing interactions within and among three key alpine taxa related to food supply and vegetation habitat resources: The mountain pygmy-possum (Burramys parvus), the mountain plum pine (Podocarpus lawrencei) and the bogong moth (Agrostis infusia)	(Hoffmann et al., 2019)
	Retreat of snow line	Increased species diversity in alpine zone	(Slatyer, 2010)
	Reduced snow cover	Loss of snow-related habitat for alpine zone endemic and obligate species	(ACE CRC, 2010; Pepler et al., 2015a; Thompson, 2016; Mitchell et al., 2019)
Wet Tropics World Heritage Area	Warming and increasing length of dry season	Some vertebrate species have already declined in both distribution area and population size, both earlier and more severely than originally predicted	(Moran et al., 2014; Hoffmann et al., 2019)
Sub-Antarctic Macquarie island	Reduced summer water availability for 17 consecutive summers, and increases in mean wind speed, sunshine hours and evapotranspiration over four decades	Dieback in the critically endangered habitat-forming cushion plant Azorella macquariensis in the fellfield and herb field communities	(Bergstrom et al., 2015; Hoffmann et al., 2019)
Mass mortality of wildlife species (flying foxes, freshwater fish)	Extreme heat events; rising water temperatures, temperature fluctuations, altered rainfall regimes including droughts and reduced in-flows	flying foxes - thermal tolerances of species exceeded; fish - amplified extreme temperature fluctuations, increasing annual water basin temperatures, extreme droughts and reduced runoff after rainfall	(AAS, 2019; Ratnayake et al., 2019; Vertessy et al., 2019)
Bramble Cay melomys (mammal) *Melomys rubicola*	Sea-level rise and storm surges in Torres Strait	Loss of habitat and global extinction	(Lunney et al., 2014; Gynther et al., 2016; Waller et al., 2017; CSIRO, 2018)
Koala, *Phascolarctos cinereus*	Increasing drought and rising temperatures, compounding impacts of habitat loss, fire and increasing human population	Population declines and enhanced risk of local extinctions	(Lunney et al., 2014)
Tawny dragon lizard, *Ctenophorus decresii*	Desiccation stress driven by higher body temperatures and declining rainfall	Population decline and potential local extinction in Flinders Ranges, South Australia	(Walker et al., 2015)

Birds	Changing thermal regimes including increasing thermal stress and changes in plant productivity are identified causal	Changes in body size, mass and condition and other traits linked to heat exchange	(Gardner et al., 2014a; Gardner et al., 2014b; Campbell-Tennant et al., 2015; Gardner et al., 2018; Hoffmann et al., 2019)
New Zealand			
Forest Birds	Warming	Increasing invasive predation pressure on endemic forest birds surviving in cool forest refugia, particularly larger-bodied bird species that nest in tree cavities and are poor dispersers	(Walker et al., 2019)
Coastal ecosystems	More severe storms and rising sea levels	Erosion of coastal habitats including dunes and cliffs is reducing habitat	(Rouse et al., 2017)
Beech forest ecosystems	Increasing mean temperatures and indirectly through effects of events like El Niño–Southern Oscillation (ENSO)	Increased beech mast seeding events that stimulate population irruptions for invasive rodents and mustelids which then prey on native species	(Schauber et al., 2002; Tompkins et al., 2013)

11.3.1.2 Projected Impacts

In the near-term (2030-2060), climate change is projected to become an increasingly dominant stress on the region's biodiversity, with some ecosystems experiencing irreversible changes in composition and structure and some threatened species becoming extinct (*high confidence*). Climate change will interact with current ecological conditions, threats and pressures, with cascading ecological impacts, including population declines, heat-related mortalities, extinctions and disruptions for many species and ecosystems (*high confidence*) (Table 11.5)**.** These include inadequate allocation of environmental flows for freshwater fish (Vertessy et al., 2019), native forest logging for old-growth forest-dependent fauna (Lindenmayer et al., 2015; Lindenmayer and Taylor, 2020a; Lindenmayer and Taylor, 2020b), and invasive species (Scott et al., 2018). Climate change has synergistic and compounding impacts particularly in bioregions already experiencing ecosystem degradation, threatened endemics, collapse of keystone species, including those of value to Indigenous Peoples, and high extinction rates as a consequence of human activities (Table 11.4) (Gordon, 2009; Australia SoE, 2016; Weeks et al., 2016; Cresswell and Murphy, 2017; Hare et al., 2019; MfE, 2019; Lindenmayer and Taylor, 2020a; Lindenmayer and Taylor, 2020b; Bergstrom et al., 2021). Some native species are projected to have potentially greater geographic range if they can colonise new areas, while other species may be resilient to projected climate change impacts (Bulgarella et al., 2014; K. Lawrence et al., 2017; Conroy et al., 2019; Rizvanovic et al., 2019).

In southern Australia, some forest ecosystems (alpine ash, snowgum woodland, pencil pine, northern jarrah) are projected to transition to a new state or collapse due to hotter and drier conditions with more fires (Table 11.5) (*high confidence*). In Australia, most native Eucalyptus forest plants have a range of traits that enable them to persist with recurrent fire through recovery buds (sprouters) or regenerate through seeding (Collins, 2020), affording them a high level of resilience. For high end projected 2060-2080 fire weather conditions in south east Australia (Clarke and Evans, 2019), stand-killing wildfires could occur at a severity and frequency greater than the regenerative capacity of seeders (Enright et al., 2015; Clarke and Evans, 2019). Most New

Zealand native plants are not fire resistant and are projected to be replaced by fire-resistant introduced species following climate-change related fires (Perry et al., 2014).

A loss of alpine biodiversity in the south-east Australian Alps Bioregion is projected in the near-term due to less snow on snow patch Feldmark and short alpine herb-fields as well as increased stress on snow-dependent plant and animal species (*high confidence*) (Table 11.3, Table 11.5). In Australia, invasive plants and weeds response rates are expected to be faster than for native species, and climate change could foster the appearance of a new set of weed species, with many bioregions facing increased impacts from non-native plants (*medium confidence)* (Gallagher et al., 2013; Scott et al., 2014; March-Salas and Pertierra, 2020) (Table 11.5), along with declines in some listed weeds (Duursma et al., 2013; Gallagher et al., 2013). In New Zealand, climate change is projected to enable invasive species to expand to higher elevations and southwards (Giejsztowt et al., 2020; MfE, 2020a) (Table 11.5) (*medium confidence*).

Projected responses of ecosystem processes are uncertain in part due to complex interactions of climate change with soil respiration, plant nutrient availability (Hasegawa et al., 2015; Orwin et al., 2015; Ochoa-Hueso et al., 2017) and changing fire regimes (Scheiter et al., 2015; Dowdy et al., 2019) (Table 11.5). For aquatic biota, responses will reflect seasonal differences in water temperature (Wallace et al., 2015), and changes in rainfall intensity, productivity and biodiversity (Jardine et al., 2015). Extreme floods may impact negatively on New Zealand river biota by mobilising nutrients, sediments and toxic chemicals, and aiding dispersal of invasive species. These effects are compounded by homogenisation of rivers through channelization (Death et al., 2015).

Improved coastal modelling, experiments and *in situ* studies are reducing uncertainties at a local scale about the impact of future sea-level rise on coastal freshwater terrestrial wetlands *(medium confidence)* (Shoo et al., 2014; Bayliss et al., 2018; Grieger et al., 2019). Low-lying coastal wetlands are susceptible to saltwater intrusion from sea-level rise (Shoo et al., 2014; Kettles and Bell, 2015; Finlayson et al., 2017) with consequences for species dependent on freshwater habitats (Houston et al., 2020). Saline habitat conditions will move inland and new coastal ecosystem states may emerge, including the World Heritage listed Kakadu's freshwater wetland (Bayliss et al., 2018) (Table 11.5). Increasingly, sea-level rise will shrink the intertidal zone, having implications for wading birds which use this zone (Tait and Pearce, 2019) (Box 11.6). The ecology of freshwater wetlands in New Zealand are projected to be impacted by the intersection of warming, drought and heavy rainfall (Pingram et al., 2021) (Table 11.5).

The impacts on species from projected global warming depend on their physiological and ecological responses for which knowledge is limited (Table 11.5) (Bulgarella et al., 2014; Carter et al., 2018; Green et al., 2021). Knowledge of projected impacts is constrained by uncertainties about the influence of physiological limits, barriers to dispersal, competition, the availability of habitat resources (Worth et al., 2014) and disruptions to ecological interactions (Lakeman-Fraser and Ewers, 2013; Parida et al., 2015; Porfirio et al., 2016). Gaps in ecological modelling of future climate impacts include consideration of long term rainfall and temperature changes (Grimm-Seyfarth et al., 2017; Grimm-Seyfarth et al., 2018), species dispersal rates, evolutionary capacity and phenotypic plasticity and the thresholds at which they are considered adequate to counter the impacts of climate change (Ofori et al., 2017b), as well as indirect effects including sea-level rise and altered fire regimes (Shoo et al., 2014; Cadenhead et al., 2016; He et al., 2016).

Table 11.5: An indicative selection of projected climate-change impacts on terrestrial and freshwater ecosystems and species in Australia and New Zealand respectively.

Ecosystem, species	Climate-related pressure	Projected Impact	Source
Australia			

Floristic composition of vegetation communities	Increases in temperature and reductions in annual precipitation by 2070. Many plant species based on median projection from five global climate models (ACCESS1.0, CNRM-CM5, HADGEM2-CC, MIROC5, NorESM1-M) centred on the decade 2070 under RCP8.5.	47% of vegetation types have characteristic plant species at risk of their climatic tolerances being exceeded from increasing mean annual temperature by 2070 with only 2% at risk from reductions in annual precipitation by 2070	(Gallagher et al., 2019)
Some south east Australian temperate forests	Reduction in winter rainfall and rising spring temperatures resulting in an increase in the frequency of very high fire weather conditions and increased risk of catastrophic wildfires; based on output from 15 CMIP5 GCMs using RCP 8.5 for years for 2060–2079 as compared to 1990–2009	Increase in fire frequency prevents recruitment of obligate seeder resulting in changing dominant species and vegetation structure including long lasting or irreversible shift in formation from tall wet temperate eucalypt forests dominated by obligate seeder trees (e.g. Alpine Ash) to open forest or in worst case to shrubland.	(Doherty et al., 2017; Zylstra, 2018; Bowman et al., 2019; Dowdy et al., 2019; Naccarella et al., 2020)
		Declining rainfall and regolith drying, more unplanned, intense fires and declining productivity places stress on tree growth and compromises biodiversity in northern jarrah forest.	(Wardell-Johnson et al., 2015)
		Tree line stasis or regression (Snow Gum)	(Doherty et al., 2017) (Bowman et al., 2019; Naccarella et al., 2020)
	Increase in lightning-ignited landscape fires along with contracting palaeoendemic refugia due to warmer and drier climates	Population collapse and severe range contraction of slow-growing, fire-sensitive palaeoendemic temperate rainforest species (e.g. Pencil Pine)	(Doherty et al., 2017) (Bowman et al., 2019)
	Rhizosphere responses or accelerated rates of soil organic matter decomposition	Plant nutrient availability may be enhanced	(Hasegawa et al., 2015; Ochoa-Hueso et al., 2017)
Alpine ecosystems	Increasing global warming and rising temperatures ongoing reduction in snow cover and winter rain, and increasing frequency and magnitude of wildfires	Loss of alpine vegetation communities (snow patch Feldmark and short alpine herb-fields) and increased stress on snow-dependent plant and animal species; changing suitability for invasive species	(Slatyer, 2010; Morrison and Pickering, 2013; Pepler et al., 2015a; Williams et al., 2015; Harris et al., 2017)
Northern tropical savannahs	Rainfall and CO_2 effects	Potentially resulting in an in increase in ecosystem carbon storage	(Scheiter et al., 2015)
Murray-Darling River Basin	Drought	Reduced river flow; mass fish kills	(Grafton et al., 2014; AAS, 2019)
Unimpaired river basins	Elevated CO_2 levels	Increase plant water use reduces stream flow	(Ukkola et al., 2016)

Bearded dragons (lizards), *Pogona spp.*	Changes in precipitation	P. henrylawsoni and P. microlepidota to gain suitable habitat, P. nullarbor and P. vitticeps showing the most potential loss	(Wilson and Swan, 2017; Silva et al., 2018)
Xeric bees	Broad temperate tolerances, arid climate adapted	Climate resilient, only small response	(Silva et al., 2018)
Great desert skink Liopholis kintorei	Buffering capacity of underground microclimates, for nocturnal and crepuscular ectotherms	Warming impacts projected to be indirect	(Moore et al., 2018)
22 narrow range fish species in imminent risk of extinction	Projected changes in rainfall, run-off, air temperatures and the frequency of extreme events (drought, fire, flood) compound risk from other key threats especially invasive species	Extinction likely within next 20 years	(Lintermans et al., 2020)
Freshwater taxa (freshwater fish, crayfish, turtles and frogs)	Changed hydrological regimes	Substantial changes to the composition of faunal assemblages in Australian rivers well before the end of this century, with gains/losses balanced for fish but suitable habitat area predicted to decrease for many crayfish and turtle species and nearly all frog species	(James et al., 2017)
New Zealand			
Modified lowland wetlands	Intersection of warming, drought and heavy rainfall (ex-tropical cyclones)	Prolonged anoxic conditions in waterways (blackwater events) leading to mortality of fish (e.g. shortfin eels) and invertebrates, while botulism outbreaks can lead to impacts on waterfowl	(Pingram et al., 2021)
Native forests and lands	Elevated CO_2 levels, warming, increased precipitation.	Short-term beneficial effects on carbon storage. Droughts in eastern areas would decrease productivity and rates of carbon storage in the medium term	(Ausseil et al., 2019b)
	Increased fire intensity and frequency in hot and dry parts of New Zealand	Much of the native vegetation has no fire adaptations causing vulnerability to local extinction due to 'interval squeeze'	(Perry et al., 2014)
Freshwater rivers	Rainfall variation	Cascading effects of warming, drought, floods, and algal blooms compounded by water abstraction	(Macinnis-Ng et al., 2021)
Three species of naturalized woody weeds	Warming and increased CO_2 levels	Increased geographic range	(Sheppard and Stanley, 2014)

Kauri tree, *Agathis australis*	Lower than average rainfall stimulates a drought-deciduous response in this evergreen species	Increased litter fall	(Macinnis-Ng and Schwendenmann, 2015)
Windmill palm	Warming	Increased geographic range	(Aguilar et al., 2017)
New Zealand tussock grasslands	Warming	Enhanced respiration	(Graham et al., 2014)
Invasive species	Warming	Increased invasive species abundance & increased predation on native species	(Tompkins et al., 2013; Macinnis-Ng et al., 2021)
	Warming	Expanded ranges of invasive species in higher/cooler areas	(Sheppard and Stanley, 2014; Walker et al., 2019)
	Warming	Change in flowering phenology and pollination competition	(Giejsztowt et al., 2020)
	Warming	Increase in invasive plants, insects, and pathogens from subtropical/tropical climates	(Macinnis-Ng et al., 2021)
Tuatara (reptile), *Sphenodon punctatus*	Warming	Temperature-dependent sex determination with more males hatch threatening small isolated populations	(Grayson et al., 2014)
	Warming	Increased geographic range	(Carter et al., 2018)
Cattle tick	Warming	Increased geographic range and risk of tick-spread anaemia in cattle	(K. Lawrence et al., 2017)
Brown mudfish, *Neochanna apoda*	Drought	Reduced flow regimes associated with drought interact with reduced habitat due to land use change, leading to population declines and potential local extinction	(White et al., 2016b; White et al., 2017)
Suter's skink (lizard) *Oligosoma suteri*	Warming	Increased suitable range but unclear if dispersal is possible because habitats are isolated	(Stenhouse et al., 2018)
Threatened endemic passerine bird, *Notiomystis cincta*	Fluctuations in total precipitation, particularly increased and more variable rainfall	Heavy rainfall can flood nests and kill fledglings while droughts can cause population-wide reproductive failure	(Correia et al., 2015)
Feral cats	Warming	Increased geographic range	(Aguilar et al., 2015b)

11.3.1.3 Adaptation

Managing climate change risks to ecosystems is primarily based on reducing the impact of other anthropogenic pressures, including invasive species, and facilitating natural adaptation (*high confidence*). This approach is most feasible within protected areas on public, private and Indigenous land and sea (Bellard et al., 2014; Liu et al., 2020) but is also applicable elsewhere (Barnes et al., 2015). Effective strategies promote ecosystem resilience through changing unsustainable land uses and management practices, increasing habitat connectivity, controlling introduced species, restoring habitats, implementing appropriate fire management, integrated risk assessment and adaptation planning (B. Frame et al., 2018; Lindenmayer et al., 2020; Macinnis-Ng et al., 2021). Complementary approaches include *ex situ* seed banks (Morrison and Pickering, 2013; Christie et al., 2020).

Best practice conservation adaptation planning is informed by data on key habitats, including refugia, and restoration that facilitates species movements and employs adaptive pathways (*very high confidence*) (Guerin and Lowe, 2013; Reside et al., 2014; Shoo et al., 2014; Keppel et al., 2015; Andrew and Warrener, 2017; Baumgartner et al., 2018; Harris et al., 2018; Jacobs et al., 2018a; Das et al., 2019; Walker et al., 2019; Molloy et al., 2020). Landscape planning (Bond et al., 2014; McCormack, 2018) helps reduce habitat loss and facilitates species dispersal and gene flow (McLean et al., 2014; Shoo et al., 2014; Lowe et al., 2015; Harris et al., 2018; McCormack, 2018) and allows for new ecological opportunities (Norman and Christidis, 2016). Coastal squeeze is a threat to freshwater wetlands and requires planning for the potential inland shift (Grieger et al., 2019). Adaptations that maintain critical volumes and periodicity of environmental flows will help protect freshwater biodiversity (Yen et al., 2013; Barnett et al., 2015; Wang et al., 2018b) (Box 11.3).

Adaptation planning for ecosystems and species requires monitoring and evaluation to identify trigger points and thresholds for new actions to be implemented *(high confidence)* (Tanner-McAllister et al., 2017; Williams et al., 2020). Best planning practice includes keeping options open (Barnett et al., 2015; Dunlop et al., 2016; Finlayson et al., 2017) and updating management plans in light of new information. New insights are emerging into how species' natural adaptive capacities can inform adaptation planning (Llewelyn et al., 2016; Steane et al., 2017; Hoeppner and Hughes, 2019). Physiological limits to adaptation in some species are being identified (Barnett et al., 2015; Sorensen et al., 2016) and where natural responses are not feasible, human-assisted translocations may be warranted (Becker et al., 2013; Chauvenet et al., 2013; Innes et al., 2019) for some species (Ofori et al., 2017a; Ofori et al., 2017b). Legal reform may be needed to better enable climate adaptation for biodiversity conservation that recognises species' natural adjustments to their distributions, and the difficulties in predicting the consequences for ecological interactions and ecosystem services (McCormack, 2018; McDonald et al., 2019).

Adaptation research priorities include understanding of the interactions and cumulative impacts of existing stressors and climate change, and the implications for managing ecosystems and natural resources (Williams et al., 2020). For Australia, research on implementation strategies for conservation and managing threats, stress and natural assets is a priority (Williams et al., 2020). For New Zealand, understanding how terrestrial ecosystems and species respond to climate change is a priority and where existing stressors are affecting freshwater quantity and quality, in-situ monitoring to detect and evaluate projections of climate change impacts on biodiversity, and a national data repository are lacking (MfE, 2020a). The projected increase in invasive species indicates the importance of a step up in pest management effort to ensure native species persistence as invasive species spread from climate change (Firn et al., 2015). There remains a gap between the knowledge generated, potential adaptation strategies, and their incorporation into conservation instruments (*medium confidence*) (Graham et al., 2019; Hoeppner and Hughes, 2019), though there is increasing recognition of the need to improve governance and management structures for their implementation (Christie et al., 2020).

[START BOX 11.1 HERE]

Box 11.1: Escalating Impacts and Risks of Wildfire

Fire activity depends on weather, ignition sources, land management practices, and fuel flammability, availability and continuity (Bradstock et al., 2014). Increased fire activity in southeast Australia associated with climate change has been observed since 1950 (Abram et al., 2021) but trends vary regionally (Bradstock et al., 2014) (*medium confidence*). In New Zealand, there has been an increased frequency of major wildfires in plantations (FENZ, 2018) and at the rural-urban interface (Pearce, 2018) (*medium confidence*). In northern Australia, increased wet season rainfall (Gallego et al., 2017) has increased dry season fuel loads (Harris et al., 2008).

In Australia, the frequency and severity of dangerous fire weather conditions is increasing, with partial attribution to climate change (*very high confidence*) (Dowdy and Pepler, 2018; Abram et al., 2021) (11.2.1,

Figure Box 11.1.1), especially in southern and eastern Australia during spring and summer (Harris and Lucas, 2019). Although Australia's eucalypt forests and woodlands are fire adapted (Collins, 2020), increasing intensity and frequency of fires may exceed their resilience due to shorter intervals between high-severity fires (Bowman et al., 2014; Etchells et al., 2020; Lindenmayer and Taylor, 2020a). Recent fires have severely impacted eastern rainforests, including significant Gondwana refugia (Abram et al., 2021). In New Zealand, the trends in very high and extreme fire weather (1997–2019) have not yet been attributed to climate change (MfE, 2020a).

Fire weather is projected to increase in frequency, severity and duration for southern and eastern Australia (*high confidence*) and most of New Zealand (*medium confidence*) (11.2.2), with projected increases in pyro-convection risk for parts of southern Australia (Dowdy et al., 2019) and increased dry-lightning and fire ignition for southeast Australia (Mariani et al., 2019; Dowdy, 2020). Increased fire risk in spring may reduce opportunities for prescribed fuel-reduction burning in some regions (Harris and Lucas, 2019; Di Virgilio et al., 2020). Fuel dryness is a key constraint on wildfire occurrence (Ruthrof et al., 2016). Vegetation change will affect fuel load and fire risk in different areas in complex ways (Watt et al., 2019; Alexandra and Max Finlayson, 2020; Clarke et al., 2020; Sanderson and Fisher, 2020).

Direct effects of wildfire include death and injury to people and animals, and damage to ecosystems, property, agriculture, water supplies and other infrastructure (Brodison, 2013; Pearce, 2018; de Jesus et al., 2020; Johnston et al., 2020; Maybery et al., 2020). Indirect effects include electricity and communication blackouts leading to cascading impacts on services, infrastructure and communities (Bowman, 2012; Schavemaker and van der Sluis, 2017).

For New Zealand, there has been recent increased frequency and magnitude of property losses due to wildfire (Pearce, 2018). The 1660ha Port Hills fire in 2017 resulted in the greatest house losses (9) in almost 100 years (Langer et al., 2018), but the subsequent 5540ha Lake Ohau fire destroyed 53 houses in 2020 (Waitaki District Council, 2020).

In Australia, between 1987 and 2016, there were 218 deaths, 1,000 injuries, 2,600 people left homeless and 69,000 people affected by wildfire (Deloitte, 2017b). Wildfires cost about $1.1 billion per year on average (11.5.2).

The Australian wildfires of 2019–2020 resulted in 33 deaths, over 3,000 houses destroyed, $2.3 billion in insured losses, and $3.6 billion in losses for tourism, hospitality, agriculture and forestry (CoA, 2020e; Filkov et al., 2020) (Figure Box 11.1.2). Smoke caused a further 429 deaths and 3230 hospitalizations as a result of respiratory distress and illness, with health costs totalling $1.95 billion (Johnston et al., 2020). These fires burnt about 5.8 to 8.1 million hectares of forest in eastern Australia (Ward et al., 2020; Godfree et al., 2021) resulting in the loss or displacement of nearly 3 billion vertebrate animals (CoA, 2020e; Wintle et al., 2020). 114 listed threatened species lost at least 50% of their habitat, and 49 lost 80% (Wintle et al., 2020) among other severe ecological impacts (Hyman et al., 2020). Smoke carried over 4,000 km to New Zealand where it increased snow/glacier melt through darkening surfaces and produced detectable odour (Pu et al. 2021)(Filkov et al., 2020). The fire season of 2019–20 was at least 30% more likely than a century ago due to the influence of climate change (van Oldenborgh et al., 2021). Following the fires, a Royal Commission into National Natural Disaster Arrangements made 80 recommendations, most of which were accepted by government, including establishing a disaster advisory body and a resilience and recovery agency (11.5.2.3) (CoA, 2020e).

In the face of climate change and the increased cost of fire damage and suppression, there has been considerable investment in fire risk reduction (Table Box 11.1.1). Recent analysis of 8,800 fires in Australia shows resource constraints in response capacity are a barrier to effectively containing fires (Collins et al., 2018b), compounded by lengthened and more extreme fire seasons.

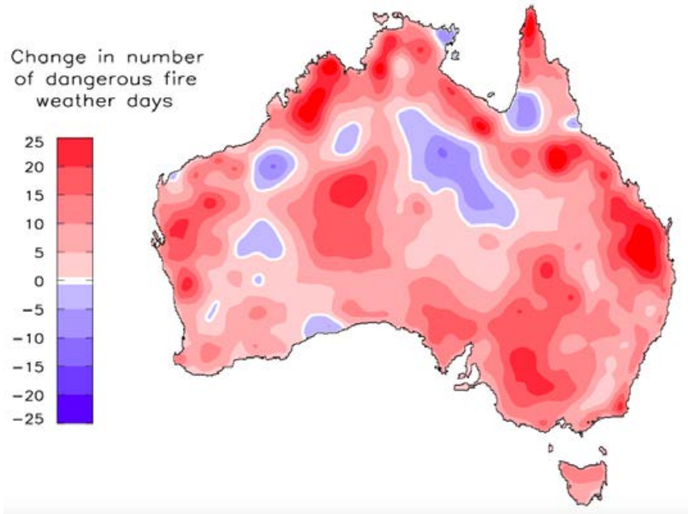


Figure Box 11.1.1: Change in the annual (July to June) number of days that the Forest Fire Danger Index (FFDI) exceeds its 90th percentile from July 1985 to June 2020 relative to July 1950 to June 1985 (BoM and CSIRO, 2020; Abram et al., 2021).

Fires in southern and eastern Australia from Sep 2019 to Feb 2020

KEY

A. Extreme air pollution

B. 5.8 to 8.1 million hectares burned with net emissions of up to 830 million tonnes of CO_2-eq

C. Respiratory illness and disruption of outdoor activities and transport

D. Massive fire-fighting effort, saving many lives and at least 16,000 buildings

E. Building and facility closures, sporting events cancelled, holidays cancelled, workplace closures

F. Degraded and destroyed:
- Wineries
- Fruit
- Livestock
- Dairy
- Plantations

G. Loss of or displacement of 3 billion animals, with possible extinctions

H. Change in framework vegetation species and depletion of vegetation habitat resources

I. Smoke and ash transported to New Zealand, affecting air quality and glaciers

J. Destroyed and damaged utilities and infrastructure, e.g. roads closed for weeks, power and communication outages, fuel shortages, back-up generators without diesel, phone batteries run flat

K. Emergency evacuations of thousands of people by road, sea and air involving State Emergency Services and National Defence Force

L. Contamination of rivers and water supply with ash and sediment

M. **Economic impacts:** Estimates of the national financial impacts are over $8 billion

N. **Social impacts:** 33 people killed by fires, 429 killed by smoke, 3,103 houses destroyed, social disruption, injuries, exhaustion and mental health issues

O. **Environmental impacts:** Loss of ecosystem service benefits

Figure Box 11.1.2: Cascading impacts on people, economic activity, built assets, ecosystems and species arising from the Black Summer fires of 2019–2020 in eastern and southern Australia (Boer et al., 2020; CoA, 2020e; CoA, 2020b; CoA, 2020a; CSIRO, 2020; Filkov et al., 2020; Johnston et al., 2020; Ward et al., 2020; Wintle et al., 2020; Abram et al., 2021; Godfree et al., 2021).

Table Box 11.1.1: Examples of adaptation options and enablers to reduce wildfire risk (Hart and Langer, 2011; Mitchell, 2013; Price et al., 2015; Tolhurst and McCarthy, 2016; Deloitte, 2017b; Miller et al., 2017; Steffen et al., 2017; Kornakova and Glavovic, 2018; Newton et al., 2018; Pearce, 2018; CoA, 2020e; McKemey et al., 2020).

Land management
Prescribed burning to reduce fuel load close to built assets.
Engagement with Australia's Aboriginal and Torres Strait Islander Peoples to utilise and learn from their fire management knowledge and skills to assist in management of the landscape and greenhouse gas mitigation.
Locating power lines appropriately or underground and decentralizing power supply to reduce ignitions.
Preventative, community-based interventions to reduce ignitions from arson and accidental fires.
Reduced exposure of new assets through statutory spatial planning and land use regulations, building codes and building design standards.
Communications
Clearer communication of existing exposure and vulnerability to enable informed decisions about risk tolerance and management. This should include sites of key biodiversity that are sensitive or susceptible to fire.
Increased research to understand interactions between fire, fuel, weather, climate and human factors to enhance projections of fire occurrence and behaviour.
Community education and engagement, encouraging house and property maintenance, improving early warning systems, more targeted messaging, and increased emergency evacuation planning and sheltering options.
Infrastructure
Enhanced training and support for fire-fighters and aerial fire-fighting assets, including sharing of resources nationally and internationally to address the increasing overlap of fire seasons which are lengthening across the world.
Nationally consistent response to exceedance of air quality standards.
Improved governance arrangements to ensure greater accountability and coordination between agencies, sharing of data and resources for emergency planning, and greater understanding of risks to critical infrastructure and supply chains.
Development of new systems to augment capability of fire services and technological advances to detect and respond to fires.

[END BOX 11.1 HERE]

11.3.2 Coastal and Ocean Ecosystems

Australia's EEZ covers over 8.1 million km^2 of marine territory, including 50,000 km of coastline (Dhanjal-Adams et al., 2016), spanning sub-Antarctic islands in the south to tropical waters in the north. New Zealand's marine territory extends from the sub-tropics to sub-Antarctic waters, encompassing an EEZ of 4 million km^2, 18,000 km of coastline and 700 smaller islands and islets, in addition to the two main islands (Costello et al., 2010a; MfE, 2016).

The marine environment is important to the culture, health and well-being of the region's diverse Indigenous Peoples, including those who had sovereign ownership, governance, resource rights, and stewardship over 'Sea Country' for many thousands of years before the current sea level stabilised approximately 6000 years ago and before current coastal ecosystems were established (Rist et al., 2019). Marine environments contribute A$69 billion per year to Australia's economy (Eadie et al., 2011), and NZ$4 billion per year to New Zealand's economy (MfE, 2016). They have a high proportion of rare and endemic species (Croxall et al., 2012) and provide ecosystem services including food production, coastal protection, tourism and carbon sequestration (Croxall et al., 2012; Kelleway et al., 2017). Half of the species within New Zealand's seas are endemic (Costello et al., 2010b).

11.3.2.1 Observed Impacts

Climate change is having major impacts on the region's oceans (*very high confidence*) (Table 11.6) (Law et al., 2016; Sutton and Bowen, 2019). Rising sea surface temperatures have exacerbated marine heatwaves, notably near Western Australia in 2011, the Great Barrier Reef in 2016, 2017 and 2020, and the Tasman Sea in 2015/2016, 2017/2018 and 2018/19 (Table 11.2) (BoM and CSIRO, 2018; AMS, 2019; NIWA, 2019; Salinger et al., 2019b; Sutton and Bowen, 2019; BoM, 2020a; Salinger et al., 2020; Oliver et al., 2021). Temperature anomalies ranged from 1.2-4.0˚C and durations ranged from 90-250 days (Table 11.2).

Ocean carbon storage and acidification has led to decreased surface pH in the region (Table 11.2) including the sub-Antarctic waters off the East Coast of New Zealand's South Island (*very high confidence*) (Law et al., 2016). The depth of the Aragonite Saturation Horizon has shallowed by 50–100 m over much of New Zealand, which may limit and/or increase the energetic costs of growth of calcifying species (Anderson et al., 2015; Bostock et al., 2015; Mikaloff-Fletcher et al., 2017) (*low confidence*).

In the estuaries of south-western Australia, sustained warming and drying trends have caused dramatic declines in freshwater flows of up to 70% since the 1970s, and increased frequency and severity of hypersaline conditions; enhanced water column stratification and hypoxia; and reduced flushing and greater retention of nutrients (Hallett et al., 2017).

Extensive changes in the life history and distribution of species have been observed in Australia's (*very high confidence*) (Gervais et al., 2021) and New Zealand's marine systems (*medium confidence*) (Table 11.6) (Cross-Chapter box MOVING SPECIES in Chapter 5). New occurrences or increased prevalence of disease, toxins and viruses are evident (de Kantzow et al., 2017; Condie et al., 2019), along with heat stress mortalities and changes in community composition (Wernberg et al., 2016; Zarco-Perello et al., 2017; Thomsen et al., 2019). Extreme climatic events in Australia from 2011 to 2017 led to abrupt and extensive mortality of key habitat-forming organisms – corals, kelps, seagrasses, and mangroves – along over 45% of the continental coastline of Australia (*high confidence*) (Babcock et al., 2019).

In 2016 and 2017, the Great Barrier Reef (GBR) experienced consecutive occurrences of the most severe coral bleaching in recorded history (*very high confidence*) (Box 11.2), with shallow-water reef in the top two thirds of the GBR affected and the severity of bleaching on individual reefs tightly correlated with the level of local heat exposure (Hughes et al., 2018b; Hughes et al., 2019c). Mass mortality of corals from these two unprecedented events resulted in larval recruitment in 2018 declining by 89% compared to historical levels (Hughes et al., 2019b). Southern reefs were also affected by warming, although significantly less than in the north (Kennedy et al., 2018). Coral reefs in Australia are at very high risk of continued negative effects on ecosystem structure and function (Hughes et al., 2019b) (*very high confidence*), cultural well-being (Goldberg et al., 2016; Lyons et al., 2019) (*very high confidence*), food provision (Hoegh-Guldberg et al., 2017) (*medium confidence*), coastal protection (Ferrario et al., 2014) (*high confidence*) and tourism (Deloitte Access Economics, 2017; Prideaux and Pabel, 2018; GBRMPA, 2019) (*high confidence*). If bleaching persists, an estimated 10,000 jobs and A$1 billion in revenue would be lost per year from declines in tourism alone (Swann and Campbell, 2016).

11.3.2.2 Projected Impacts

Future ocean warming, coupled with periodic extreme heat events, is projected to lead to the continued loss of ecosystem services and ecological functions (*high confidence*) (Smale et al., 2019), as species further shift their distributions and/or decline in abundance (Day et al., 2018). Compounding climate-driven changes in the distribution of habitat forming species, invasive macroalgae are predicted to exhibit higher growth under all higher pCO_2 and lower pH conditions (Roth-Schulze et al., 2018). Corals and mangroves around northern Australia and kelp and seagrass around southern Australia are of critical importance for ecosystem structure and function, fisheries productivity, coastal protection and carbon sequestration; these ecosystem services are therefore *extremely likely*[2] to decline with continued warming. Equally, many species provide important ecosystem structure and function in New Zealand's seas including in the deep sea (Tracey and Hjorvarsdottir, 2019). The future level of sustainable exploitation of fisheries is dependent on how climate change impacts these ecosystems. Native kelp is projected to further decline in south-eastern New Zealand with warming seas (Table 11.6). Climate change could affect New Zealand fisheries' productivity (Cummings et al., 2021), and both ocean warming and acidification may directly affect shellfish culture (Cunningham et al., 2016; Cummings et al., 2019), and indirectly through changes in phytoplankton production (Pinkerton, 2017).

Climate change related temperature and acidification may affect species sex ratios and thus population viability (*medium confidence*) (Table 11.3) (Law et al., 2016; Tait et al., 2016; Mikaloff-Fletcher et al., 2017). Acidification may alter sex determination (e.g., in the oyster *Saccostrea glomerate*), resulting in changes in sex ratios (Parker et al., 2018), and may thus affect reproductive success (*low confidence*). Decreasing river flows (Chiew et al., 2017) are projected to cause periodically open estuaries across south-west Australia to remain closed for longer periods, inhibiting the extent to which marine taxa can access these systems (Hallett et al., 2017) and with warming predicted to constrain activity in some large fish (Scott et al., 2019b). Major knowledge gaps include environmental tolerances of key life stages, sources of recruitment, population linkages, critical ecological (e.g., predator–prey interactions) or phenological relationships, and projected responses to lowered pH (Fleming et al., 2014; Fogarty et al., 2019).

Black-browed albatrosses breeding on Macquarie Island may be more vulnerable to future climate-driven changes to weather patterns in the Southern Ocean, and potential latitudinal shifts in the sub-Antarctic Front (Cleeland et al., 2019). New Zealand coastal ecosystems face risks from sea-level rise and extreme weather events (MfE, 2020a).

Nutrient availability and productivity in sub-tropical waters of New Zealand are projected to decline due to increased sea surface temperature and strengthening of the thermocline, but may increase in sub-Antarctic waters, potentially bringing some benefit to fish and other species (*low confidence*) (Law et al., 2018b). For New Zealand waters as a whole, declines in net primary productivity of 1.2% and 4.5% are projected under RCP4.5 and RCP8.5 respectively by 2100, and declines in primary production of surface waters by an average 6% from the present day under RCP8.5, with sub-tropical waters experiencing the largest decline (Tait et al., 2016).

The pH of surface waters around New Zealand is projected to decline by 0.33 under RCP 8.5 by 2090 (Tait et al., 2016), and the depth at which carbonate dissolves is projected to be significantly shallower (Mikaloff-Fletcher et al., 2017) affecting the distribution of some species of calcifying cold water corals (Law et al., 2016) (*medium confidence*). However, model projections suggest that the top of the Chatham Rise may provide temporary refugia for scleractinian stony corals from ocean acidification because the Chatham Rise sits above the aragonite saturation horizon (Anderson et al., 2015; Bostock et al., 2015). For sub-tropical corals, skeletal formation will be vulnerable to the changes in ocean pH with implications for their longer-term growth and resilience (Foster et al., 2015).

11.3.2.3 Adaptation

Climate change adaptation opportunities and pathways have been identified across aquaculture, fisheries, conservation and tourism sectors in the region (MacDiarmid et al., 2013; Fleming et al., 2014; MPI, 2015; Jennings et al., 2016; MfE, 2016; Royal Society Te Apārangi, 2017; Ling and Hobday, 2019) and some stakeholders are already autonomously adapting (Pecl et al., 2019). Some fishing and aquaculture industries use seasonal forecasts of environmental conditions, to improve decision making, risk management, and business planning (Hobday et al., 2016) with potential to use 5-yearly forecasts similarly (Champion et al., 2019). Shifts in the distribution, and availability of target species (e.g., oceanic tuna) would impact the

[2] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

ability of domestic fishing vessels to continue current fishing practices, with potential social and economic adjustment costs (Dell et al., 2015), including disruption to supply chains (Fleming et al., 2014; Plagányi et al., 2014) (Cross-Chapter Box MOVING SPECIES in Chapter 5). Species abundance data are insufficient to enable projections of climate impacts on fishery productivity. However, fishery and aquaculture industries are considering adaptation strategies, such as changing harvests and relocating farms (Pinkerton, 2017). Thus, while climate change is *extremely likely* to affect the abundance and distribution of marine species around New Zealand, insufficient monitoring means there is limited evidence of ecosystem level change in biodiversity to date, and no quantitative projections of which species may win and lose to climate change (Table 11.6) (Law et al., 2018a; Law et al., 2018b).

Table 11.6: Observed climate-change related changes in the marine ecosystems of Australia and New Zealand. Climate-related impacts have been documented at a range of scales from single species or region-specific studies, to multi-species or community-level changes.

Type of change	Examples	Climate-related Pressure	Source
Australia			
Reduced activity and increased energetic demands	Coral trout (*Plectropomus leopardus*) one of Australia's most important commercial and recreational tropical finfish species	Increased temperature (experimental laboratory study) and ocean warming	(Johansen et al., 2014; Scott et al., 2017)
Estuaries warming and freshening	Australian lagoons and rivers warming and decreasing pH at a faster rate than predicted by climate models	Warming and reduction in rainfall (leading to reduced flows and therefore being less frequently open to the sea)	(Scanes et al., 2020)
Changes in life-history traits, behaviour or recruitment	Reduced size of Sydney rock oysters (for commercial sale)	Limited capacity to bio mineralize under acidification conditions	(Fitzer et al., 2018)
	Reduced growth in tiger flathead fish in equatorward range	Ocean warming	(Morrongiello and Thresher, 2015)
	55% of 335 fish species became smaller and 45% became larger as seas warmed around Australia	Ocean warming (over three decades)	(Audzijonyte et al., 2020)
	Rock lobster display reduced avoidance of predators at 23°C compared to 20°C	Increased temperature (experimental laboratory study)	(Briceño et al., 2020)
	Analysis of stress rings in cores of corals from the Great Barrier Reef dating back to 1815, found that following bleaching events, the coral was less affected by subsequent marine heatwaves.	Heat events	(DeCarlo et al., 2019)
	Mortality and reductions in spawning stocks of fishery important abalone, prawns, rock lobsters	2011 marine heatwave	(Caputi et al., 2019)

	Recruitment of coral on GBR reduced to 11% of long-term average	Warming-driven back-to-back global bleaching events	(Hughes et al., 2019b)
	Green turtle hatchlings from southern GBR 65-69% female and hatchlings from northern GBR 100% female for last two decades	Increased sand temperatures	(Jensen et al., 2018)
New diseases, toxins	First occurrence of the virulent virus causing Pacific Oyster Mortality Syndrome (POMS), up to 90% of all farmed oysters died in impacted areas	Detected during heatwave	(de Kantzow et al., 2017)
	Mussels, scallops, oysters, clams, abalone and rock lobsters on the east coast of Tasmania found to have high levels of Paralytic Shellfish Toxins, originating from a bloom of the harmful *Alexandrium tamarense*	Warming and extension of the East Australian Current	(Hallegraeff and Bolch, 2016)
	Range expansion of phytoplankton *Noctiluca* which can be toxic	Warming and extension of the East Australian Current	(Hallegraeff et al., 2020)
	Mortality fish following algal blooms in South Australia	2013 marine heatwave	(Roberts et al., 2019)
Changes in species distributions	Range extensions at the poleward range limit have been detected in: Fish, Cephalopods, Crustaceans, Nudibranchs, Urchins, Corals.	Ocean warming	(Baird et al., 2012; Robinson et al., 2015; Sunday et al., 2015; Ling et al., 2018; Nimbs and Smith, 2018; Ramos et al., 2018; Smith et al., 2019; Caswell et al., 2020)
	Contractions in range at the equatorward range edge have been detected in: Anemones, Asteroids, Gastropods, Mussels, Algae.	Ocean warming	(Pitt et al., 2010; Poloczanska et al., 2011; Smale et al., 2019)
	Australia's most southern dominant reef building coral, *Plesiastrea versipora* in eastern Bass Strait, increasing in abundance at the poleward edge of the species' range, and also in Western Australia	Ocean warming	(Tuckett et al., 2017; Ling et al., 2018)
	South-west Australia fish assemblages- warm water fish increasing in density at poleward edge of distributions and cool-water species decrease in density at equatorward edge of distributions; increase in warm-water habitat forming species leading to reduced habitat for invertebrate assemblages	Combination of increased temperatures and changes in habitat-forming algal species	(Shalders et al., 2018; Teagle et al., 2018)
	Predicted reduction range of rare W*ilsonia humilis* herb in Tasmanian saltmarsh but no change in rest of community	Wetter and drier climate	(Prahalad and Kirkpatrick, 2019)

Changes in abundance	Shift towards a zooplankton community dominated by warm-water small copepods in south-east Australia	Ocean warming	(Kelly et al., 2016)
	Diebacks of tidal wetland mangroves	2015–2016 heatwaves combined with moisture stress	(Duke et al., 2017)
	Decline in giant kelp in Tasmania, Australia. Less than 10% remaining. Loss of kelp Australia-wide totalling at least 140,187 ha	Ocean warming & change in East Australian Current (lower nutrients)	(Wahl et al., 2015; Butler et al., 2020; Filbee-Dexter and Wernberg, 2020)
	Regional loss of seagrass in Shark Bay World Heritage Area, Western Australia	High air and water temperatures during 2011 heatwave	(Strydom et al., 2020)
	Increased annual dugong and inshore dolphin mortality across Queensland	Sustained low air temperature and increased freshwater discharge during high SOI (ENSO) index	(Meager and Limpus, 2014)
	Predict equatorward decline and poleward shift of sea urchin in eastern Australia	Ocean warming	(Castro et al., 2020)
	Increasing mortality of Australian fur seal pups in low-lying colonies	Storm surges and high tides amplified by ongoing sea-level rise	(McLean et al., 2018) (Box 11.6)
Rapid shifts in community composition, structure and integrity	Community-wide tropicalization in Australian temperate reef communities. Temperate species replaced by seaweeds, invertebrates, corals, and fishes characteristic of subtropical and tropical waters	Extreme marine heatwaves led to a 100-km range contraction of extensive kelp forests	(Vergés et al., 2016; Wernberg et al., 2016)
	On-going declines in habitat-forming seaweeds	Climate-driven shift of tropical herbivores	(Thomson et al., 2015; Nowicki et al., 2017; Zarco-Perello et al., 2017) (Wernberg et al., 2016)
	Dieback of temperate seagrass in Shark Bay, Australia, subsequently replaced by a tropical early successional seagrass with seagrass-associated megafauna (sea turtles) declining in health status	2011 Marine heatwave	(Strydom et al., 2020)
	Increased herbivory by fish on tropicalized reefs of Western Australia	Change in species composition due to ocean warming	(Zarco-Perello et al., 2019)
	No recovery two years after coral bleaching and macro alga mortality in western Australia	2011 marine heatwave	(Bridge et al., 2014)

	Mass mortality of particular coral species on affected reefs during heatwaves on the Great Barrier Reef (eastern Australia) led to altered coral reef structure and species composition 8 months later.	2016 marine heatwave	(Hughes et al., 2018c)
	Community-wide restructuring along the Great Barrier Reef, one year after the 2016 mass bleaching event.	2016 Marine heatwave	(Stuart-Smith et al., 2018)
New Zealand			
Changes in life-history	Alteration of the shell of pāua (black footed abalone, *Haliotis iris*) under lowered pH (calcite layer thinner, greater etching of external shell surface)	Lowered pH (experimental laboratory study)	(Cummings et al., 2019)
	Decline in maximum swimming performance of kingfish and snapper	Elevated CO_2 (experimental laboratory study)	(Watson et al., 2018; McMahon et al., 2020)
	Increased mortality and faster growth in juvenile kingfish	Increased temperature	(Watson et al., 2018)
	Earlier spawning of snapper in South Island	2017–2018 heatwave	(Salinger et al., 2019b)
Increase in mortality	Heat stress mortality in salmon farms off Marlborough, New Zealand, where 20 % of the salmon stocks died	2017–18 marine heatwave	(Salinger et al., 2019b)
Changes in species distributions	Species increasingly caught further south, e.g. snapper and kingfish	Ocean warming and 2017–2018 marine heatwave	(Salinger et al., 2019b)
	Non-breeding distribution of New Zealand nesting seabird (Antarctic Prion) shifting south with long term climate inferred from stable isotopes	Climate warming	(Grecian et al., 2016)
	Less phytoplankton production in Tasman Sea but more on subtropical front	Ocean warming	(Chiswell and Sutton, 2020)
	Loss of bull kelp (*Durvillaea*) populations in southern New Zealand subsequently replaced by the introduced kelp *Undaria*	2017-18 heatwave when sea and air temperatures exceeded 23 and 30 °C respectively	(Salinger et al., 2019b; Thomsen et al., 2019; Salinger et al., 2020)

[START BOX 11.2 HERE]

Box 11.2: The Great Barrier Reef in Crisis

The Great Barrier Reef (“GBR”) is the world’s largest coral reef system, comprising 3,863 reefs over an area of 348,700 km^2, stretching for 2,300 km. The GBR is a central cornerstone of the beliefs, knowledges, Lores, languages and ways of living for over 70 geographically and culturally diverse Traditional Owner groups spanning the length of the GBR (Dale et al., 2018), and contributes an estimated A$6.4 billion per year (pre COVID) to the Australian economy, mainly via tourism. As the world's most extensive coral reef ecosystem, GBR is a globally outstanding and significant entity, with practically the entire ecosystem inscribed as World Heritage in 1981 (UNESCO, 2021).

The GBR is already severely impacted by climate change, particularly ocean warming, through more frequent and severe coral bleaching (Hughes et al., 2018b; Hughes et al., 2019c) (*very high confidence*). The worst coral bleaching event on record affected over 90% of reefs in 2016 (Hughes et al., 2018b). In the most northern 700-km-long section of the GBR in which the heat exposure was the most extreme, 50% of the coral cover on reef crests was lost within eight months (Hughes et al., 2018c). Throughout the entire GBR, including the southern third where heat exposure was minimal, the cover of corals declined by 30% between March and November 2016 (Hughes et al., 2018b). In 2017, the central third of the reef was the most severely affected and the back-to-back regional-scale bleaching events has led to an unprecedented shift in the composition of GBR coral assemblages, transforming the northern and middle sections of the reef system (Hughes et al., 2018c) to a highly degraded state *(very high confidence)*. Coral recruitment to the GBR in 2018 was reduced to only 11% of the long-term average (Hughes et al., 2019b). A mass bleaching event also occurred in 2020, making it the third event in five years (BoM, 2020a) (Figure Boxes 11.2.1 and 11.2.2).

Increased heat exposure also affects the abundance and distribution of associated fish, invertebrates and algae *(high confidence)* (Stuart-Smith et al., 2018). Thus, coral bleaching is an indicator of thermal effects on coral habitat, fauna and flora. Bleaching is expected to continue for the GBR, and Australia's other coral reef systems (*virtually certain*). Bleaching conditions are projected to occur twice each decade from 2035 and annually after 2044 under RCP8.5, and annually after 2051 under RCP4.5 (Heron et al., 2017). Three degrees of global warming would result in over six times the 2016 level of thermal stress (Lough et al., 2018).

Increases in cyclone intensity projected for this century, and other extreme weather events, will greatly accelerate coral reef degradation (Osborne et al., 2017). Additionally, through interactions between elevated ocean temperature and coastal runoff (nutrient and sediment), extreme weather events may contribute to an increased frequency and/or amplitude of crown of thorn starfish outbreaks (Uthicke et al., 2015), further reducing the spatial distribution of coral.

Recovery of coral reefs following repeated disturbance events is slow (Hughes et al., 2019b; IPCC, 2019b), and it takes at least a decade after each bleaching event for the very fastest growing corals to recover (*high confidence*) (Gilmour et al., 2013; Osborne et al., 2017). Estimates of future levels of thermal stress, measured as 'degree heating months' which incorporates both the magnitude and duration of warm season sea surface temperatures (SST) anomalies, suggest that achieving the 1.5°C Paris Agreement target would be insufficient to prevent more frequent mass bleaching events (*very high confidence*) (Lough et al., 2018), although it may reduce their occurrence (Heron et al., 2017), and occurrences of warming events similar to 2016 bleaching could be reduced by 25% (King et al., 2017).

Tourist motivations for visiting the GBR are changing, with a recent survey finding that two-thirds of tourists were visiting 'before it was gone' and a similar number were reporting damage to the reef – an example of 'last chance tourism' (Piggott-McKellar and McNamara, 2016). The Australian Government is investing A$1.9 billion to support the Great Barrier Reef through science and practical environmental outcomes including reducing other anthropogenic pressures which can suppress natural adaptive capacity (CoA, 2019b; GBRMPA, 2019). However, adaptation efforts on the Great Barrier Reef aimed specifically at climate impacts, for example, coral restoration following marine heatwave impacts (Boström-Einarsson et al., 2020) may slow the impacts of climate change in small discrete regions of the reef, or reduce short-term socio-economic ramifications, but will not prevent widespread bleaching (Condie et al. 2021).

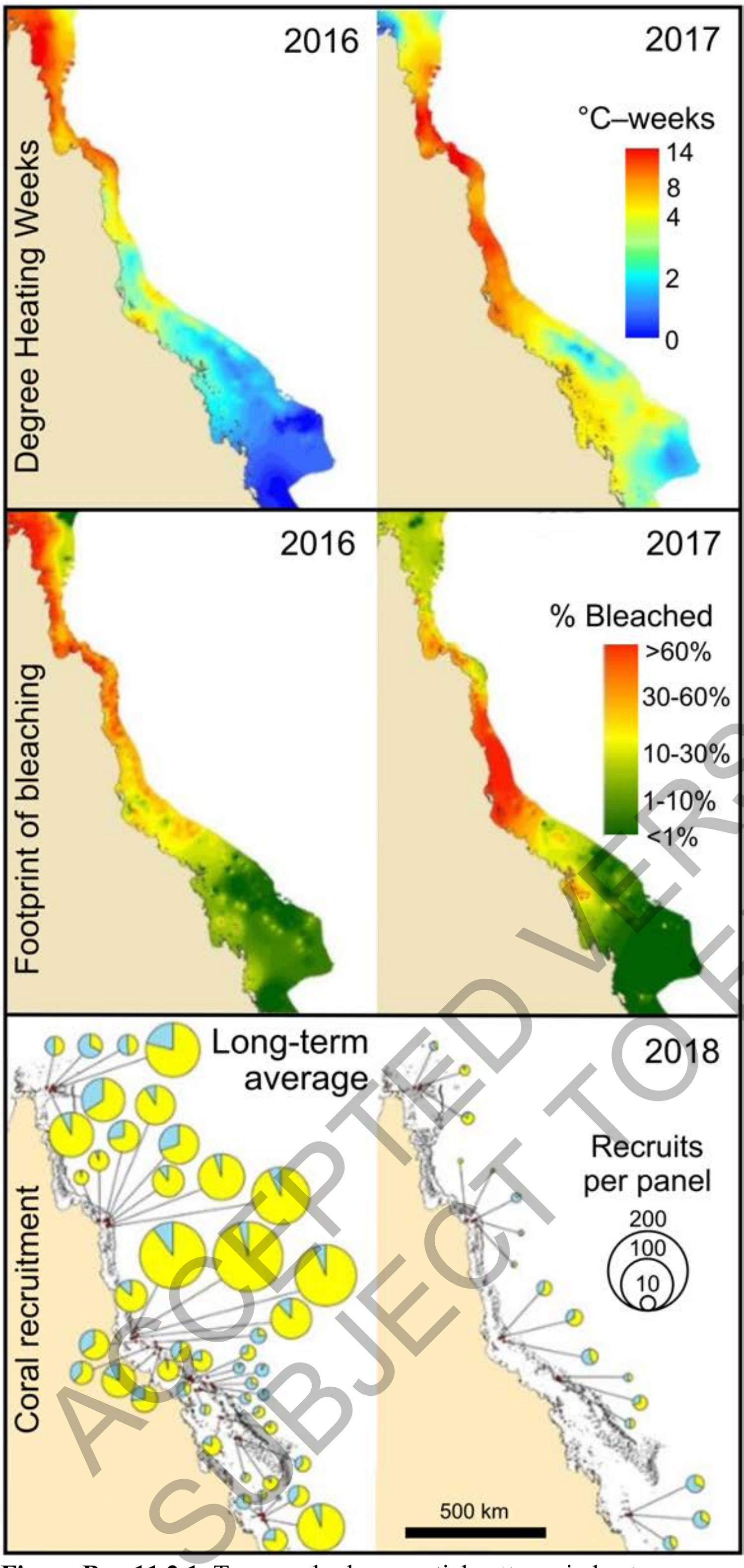


Figure Box 11.2.1: Top panels show spatial patterns in heat exposure along the Great Barrier Reef in 2016 (left) and 2017 (right), measured from satellites as Degree Heating Weeks (DHW, ºC-weeks). Middle panels show the geographic footprint of recurrent coral bleaching in 2016 (left) and again in 2017 (right), measured by aerial assessments of individual reefs (adapted from (Hughes et al., 2019c)). Bottom panels display the density of coral recruits (mean per recruitment panel on each reef), measured over three decades, from 1996 to 2016 (*n* = 47 reefs, 1,784 panels) (left), compared to the density of coral recruits in 2018 after the mass mortality of corals in 2016 and 2017 due to the back-to-back bleaching events (*n* = 17 reefs, 977 panels) (right). The area of each circle is scaled to the overall recruit density of spawners and brooders combined. Yellow and blue indicate the proportion of spawners and brooders, respectively (from (Hughes et al., 2019b)).

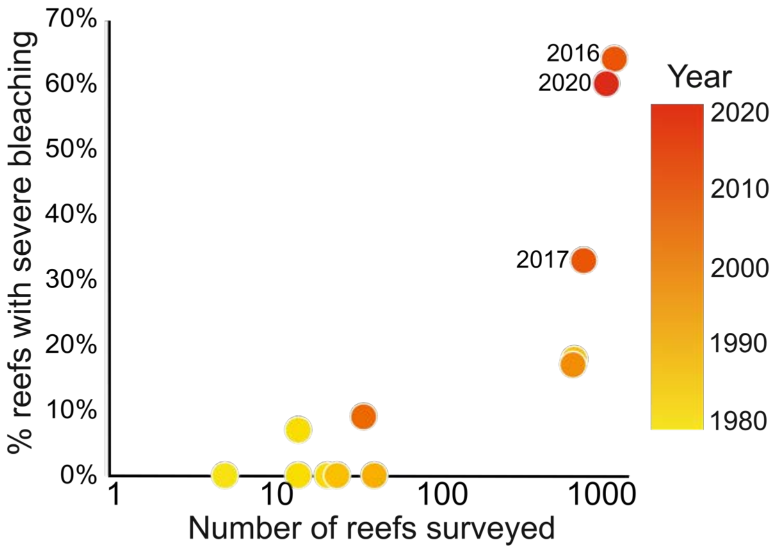


Figure Box 11.2.2: Variation in the severity of mass-bleaching episodes recorded on Australia's Great Barrier Reef over the last four decades (1980–2020). The overall number of reefs surveyed was substantially higher in 1998, 2002, 2016, 2017 and 2020 when aerial surveys were undertaken, whereas the severity of other more localised bleaching episodes was documented with in-water surveys (adapted from (Pratchett et al., 2021). Extent of bleaching in 2020 was similar in severity to 2016, but more geographically widespread and included southern reefs.

[END BOX 11.2 HERE]

11.3.3 Freshwater Resources

Climate change impacts on freshwater resources cascade across people, agriculture, industries and ecosystems (Boxes 11.3 and 11.5). The challenge of satisfying multiple demands with a finite resource is exacerbated by high inter-annual and inter-decadal variability of river flows, particularly in Australia (Chiew and McMahon, 2002; Peel et al., 2004; McKerchar et al., 2010).

11.3.3.1 Observed Impacts

Streamflow has generally increased in northern Australia and decreased in southern Australia since the mid-1970s (Zhang et al., 2016) (*high confidence*). Declining river flows since the mid-1970s in southwest Australia have led to changed water management (WA Government, 2012; WA Government, 2016). The large decline in river flows during the 1997–2009 'Millennium' drought in south-east Australia resulted in low irrigation water allocations, severe water restrictions and major environmental impacts (Potter et al., 2010; Chiew and Prosser, 2011; Leblanc et al., 2012; van Dijk et al., 2013). The drying in southern Australia highlighted the need for hydrological models that adequately account for climate change (Vaze et al., 2010; Chiew et al., 2014; Saft et al., 2016; Fowler et al., 2018). The decline in streamflow was largely due to the decline in cool season rainfall (which has been partly attributed to climate change) (Figure 11.2) (Timbal and Hendon, 2011; Post et al., 2014; Hope et al., 2017; DELWP, 2020) when most of the runoff in southern Australia occurs.

In New Zealand, precipitation has generally decreased in the north and increased in the southwest (Figure 11.2) (Harrington et al., 2014), but it is difficult to ascertain trends in the relatively short streamflow records. Glaciers in New Zealand's southern alps have lost one third of their mass since 1977 (Mackintosh et al., 2017; Salinger et al., 2019b), and glacier mass loss in 2018 was at least ten times more likely to occur with anthropogenic forcing than without (Vargo et al., 2020).

11.3.3.2 Projected Impacts

Projections indicate that future runoff in south-east and south-west Australia are *likely* to decline (median estimate of 20% and 50% respectively, under 2.2°C global average warming) (Figure 11.3) (Chiew et al., 2017; Zheng et al., 2019). These projections are broadly similar to those reported previously and in AR5 (Teng et al., 2012; Reisinger et al., 2014). The range of estimates arises mainly from the uncertainty in projected future precipitation (Table 11.2a).

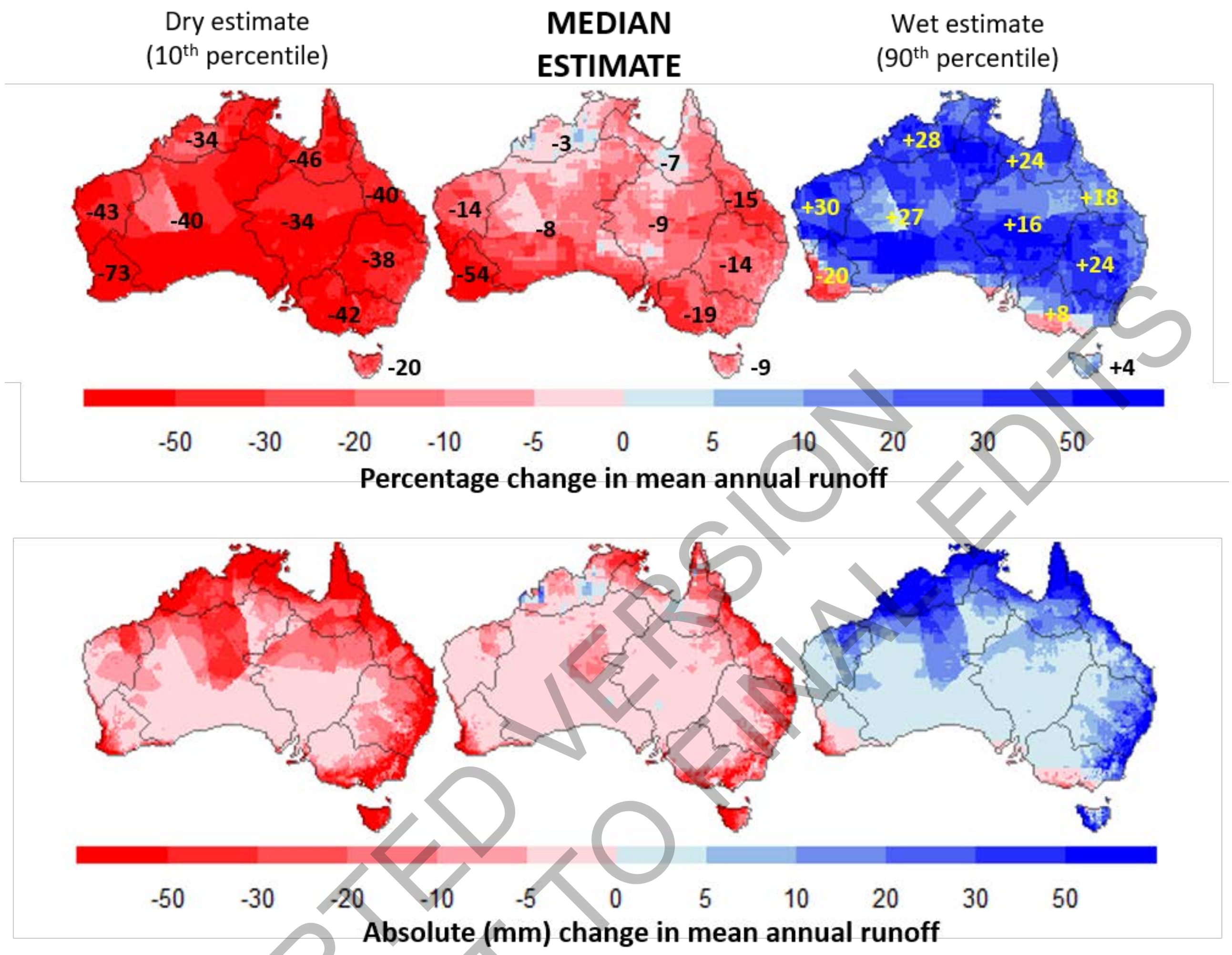


Figure 11.3: Projected changes in mean annual runoff for 2046–2075 relative to 1976–2005 for RCP8.5 from hydrological modelling with future climate projections informed by 42 CMIP5 GCMs. Projections for RCP4.5 are about three quarters of the above projections. Plots show median projection, and the 10th and 90th percentile range of estimates. The boundaries are based on hydroclimate regions and major drainage basins. Source: (Zheng et al., 2019).

The runoff decline in southern Australia is projected to be further accentuated by higher temperature and potential evapotranspiration (Potter and Chiew, 2011; Chiew et al., 2014), transpiration from tree regrowth following more frequent and severe wildfires (Brookhouse et al., 2013) (Box 11.1), interceptions from farm dams (Fowler et al., 2015), and reduced surface-groundwater connectivity (limiting groundwater discharge to rivers) in long dry spells (Petrone et al., 2010; Hughes et al., 2012; Chiew et al., 2014) (*high confidence*). In the longer-term, runoff will also be affected by changes in vegetation and surface-atmosphere feedback in a warmer and higher CO_2 environment, but the impact is uncertain because of the complex interactions including changes in climate inputs, fire patterns (Box 11.1) and nutrient availability (Raupach et al., 2013; Ukkola et al., 2016; Cheng et al., 2017).

Climate change is projected to affect groundwater recharge and the relationship between surface waters and aquifers, and through rising sea-levels where groundwater has a tidal signature (PCE, 2015; MfE, 2017a). Groundwater recharge across southern Australia has decreased in recent decades (Fu et al., 2019) and this trend is expected to continue (Barron et al., 2011; Crosbie et al., 2013) (*high confidence*). Climate change is also projected to impact water quality in rivers and water bodies, particularly through higher temperature and low flows (Jöhnk et al., 2008) (Box 11.5) and increased sediment and nutrient load following wildfires (Biswas et al., 2021) (Box 11.1) and floods (Box 11.4) (*high confidence*).

The projected changes in river flows in New Zealand are consistent with the precipitation projections (Table 11.2), with increases in the west and south of the South Island and decreases in the east and north of the North Island (Figure 11.4). In the South Island, the runoff increase occurs mainly in winter due to increasing moisture-bearing westerly airflow, with more precipitation falling as rain and snow melting earlier. In the North Island, the runoff decrease occurs in spring and summer (Caruso et al., 2017; Collins et al., 2018a; Jobst et al., 2018; D. Collins, 2020).

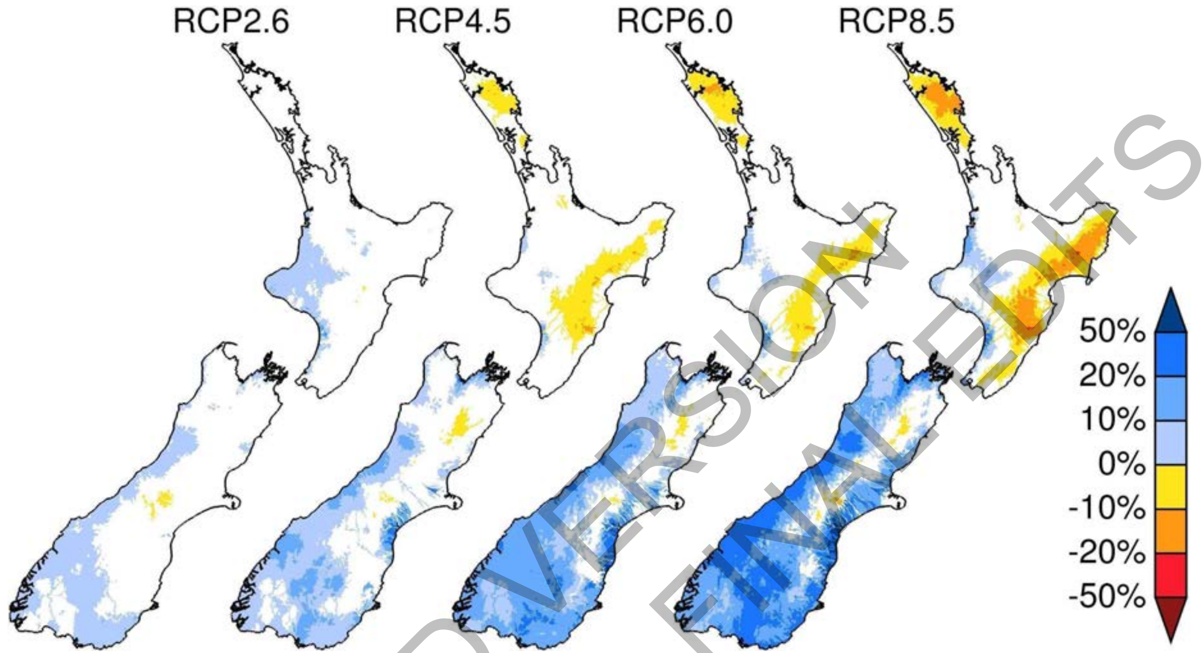


Figure 11.4: Projected percentage change in mean annual runoff for 2086–2099 relative to 1986–2005 from hydrological modelling informed by six CMIP5 GCMs for four RCPs. Maps show median projection from the six modelling runs. White indicates that the change is not statistically significant. Source: (D. Collins, 2020).

11.3.3.3 Adaptation

In Australia, prolonged droughts and projections of a drier future have accelerated policy and management change in urban and rural water systems. Adaptation initiatives and mechanisms, like significant government investment to enhance the Bureau of Meteorology online water information (Vertessy, 2013; BoM, 2016), funding to improve agriculture water use and irrigation efficiency (Koech and Langat, 2018), enhanced supply through inter-basin transfers and upgrading water infrastructure, and an active water trading market (Wheeler et al., 2013; Kirby et al., 2014; Grafton et al., 2016) are helping to buffer regional systems against droughts, and facilitating some adaptation to climate change (*medium confidence*). However, these measures could also be maladaptive as they may perpetuate unsustainable water and land uses under ongoing climate change (Boxes 11.3 and 11.5).

The widespread 2017-2019 drought across eastern Australia (BoM, 2019) has led to the Australian Government establishing a Future Drought Fund (Australian Government, 2019) to enhance drought resilience, and a National Water Grid Authority to develop regional water infrastructure to support agriculture. Nevertheless, the ability to adapt to climate change is compounded by uncertainties in future water projections, complex interactions between science, policy, community values and political voice, and competition between different sectors dependent on water (Boxes 11.3 and 11.5). The impact of declining water resource on agricultural, ecosystems and communities in south-eastern Australia would escalate with ongoing climate change (Hart, 2016; Moyle et al., 2017) (*medium confidence*), highlighting the importance of more ambitious, anticipatory, participatory and integrated adaptation responses (Bettini et al., 2015; Abel et al., 2016; Marshall and Lobry de Bruyn, 2021).

Altered water regimes resulting from the combined effects of climatic conditions and water policies carry uneven and far-reaching implications for communities (*high confidence*). Acting on Indigenous Peoples' claims to cultural flows (to maintain connection to Country) is increasingly recognised as an important water management and social justice issue (Taylor et al., 2017; Hartwig et al., 2018; Jackson, 2018; Jackson and Moggridge, 2019; Moggridge et al., 2019). Compounding stressors such as coal and coal seam gas developments can also severely impact local communities, water catchments and water-dependent ecosystems and assets, exacerbating their vulnerability to climate change (Navi et al., 2015; Tan et al., 2015; Chiew et al., 2018).

In Australian capital cities and regional centres, water planning has focused on securing new supplies that are resilient to climate change. This includes increasing use of stormwater and sewage recycling and managed aquifer recharge (Bekele et al., 2018; Page et al., 2018; Gonzalez et al., 2020). All major coastal Australian cities have desalination plants. Household scale adaptation like rainwater harvesting, water smart gardens, dual flush toilets, water-efficient showerheads and voluntary residential use targets can help reduce water demand by up to 40% (Shearer, 2011; Rhodes et al., 2012; Moglia et al., 2018). Water utilities across Australia have established climate change adaptation guidelines (WSAA, 2016). Coordinated efforts to reduce demand, design and retrofit infrastructure to reduce flood risk and harvest water, and water sensitive urban design, are evident (WSAA, 2016; Kunapo et al., 2018; Rogers et al., 2020b). Transitioning centralised water systems to a more sustainable basis represents adaptation progress but is complex and faces many barriers and limits (Morgan et al., 2020) (*medium confidence*). Developing multiple redundant or decentralised systems can enhance community resilience and promote autonomous adaptations that may be more sustainable and cost effective in the longer term (Mankad and Tapsuwan, 2011; WSAA, 2016; Iwanaga et al., 2020).

In New Zealand, many water supplies are at risk from drought, extreme rainfall events and sea-level rise, exacerbated by underinvestment in existing water infrastructure (in part due to funding constraints), and urban densification (CCATWG, 2017; MfE and StatsNz, 2021) (*high confidence*). Lessons can be learned from global experience (e.g. Cape Town, South Africa; Chapter 4.3.4). Water quality has diminished, with hotter conditions and drought causing algal blooms, combined with intensification of agricultural land uses in some areas, and heavy rainfall and sea-level rise causing flooding and sedimentation of water sources and health impacts (11.3.6; Box 11.5). Some towns are only partially metered or not metered at all, which exacerbates the adaptation challenge (Hendy et al., 2018; WaterNz, 2018; Paulik et al., 2019b). Unregulated or absent water supplies accentuate risks to vulnerable groups of people (MfE, 2020b). Māori view water as the essence of all life, which makes any impacts on water, of governance and stewardship concern, and increasingly, the subject of legal claims (MfE, 2020a; MfE, 2020b; MfE, 2020c) (11.4.2). Māori understanding of time can also open up new spaces for rethinking freshwater management in a climate change context that does not reinforce or rearticulate multiple environmental injustices (Parsons et al., 2021).

Water resource adaptation in New Zealand is variable across local government and water authorities but they all actively monitor water availability, demand and quality, and most have drought management plans. The 2019/20 drought led to water shortages in the most populated areas of Waikato, Auckland and Northland, resulting in water reduction advisories and five to eight weeks waiting time for water tank refills and water rationing. The Havelock North water supply contamination that arose after an extreme rainfall event (DIA, 2017a; DIA, 2017b) was exacerbated by fragmented governance, and led to the Taumata Arawai-Water Services Regulator Act 2020 and the Water Services Bill 2020 to protect source water. The 2017 update to the National Policy Statement for Freshwater Management with guidelines for implementation at the regional level (MfE, 2017b), including consideration of climate change which creates opportunities for adaptation. However, there remain tensions between land, water and people which are exacerbated by climate changes and yet to be addressed (Box 11.5). The first National Adaptation Plan and the Resource Management law reform have potential for helping to resolve these tensions (11.7.1) (CCATWG, 2017; MfE, 2020a).

[START BOX 11.3 HERE]

Box 11.3: Drought, Climate Change, and Water Reform in the Murray-Darling Basin

The Murray-Darling Basin (MDB) is Australia's largest, most economically important and politically complex river system (Figure Box 11.3.1). The MDB supports agriculture worth A$24 billion/year, 2.6 million people in diverse rural communities, and important environmental assets including 16 Ramsar listed wetlands (DAWE, 2021). Climate change is projected to substantially reduce water resources in the MDB (*high confidence*), with the median projection indicating a 20% decline in average annual runoff under 2.2°C average global warming (Figure 11.3) (Whetton and Chiew, 2020). This reduction, plus increased demand for water in hot and dry conditions, would increase the already intense competition for water (*high confidence*) (CSIRO, 2008; Hart, 2016).

The economic, environmental and social impacts of the 1997–2009 'Millennium Drought' in the MDB (Chiew and Prosser, 2011; Leblanc et al., 2012; van Dijk et al., 2013), and projections of a drier future under climate change, have accelerated significant water policy reforms, costing more than A$12 billion (Bark et al., 2014; Docker and Robinson, 2014; Hart, 2016). These reforms included the development of a Basin Plan (MDBA, 2011; MDBA, 2012) requiring consistent regional water resource plans (MDBA, 2011; MDBA, 2012; MDBA, 2013) and environmental watering strategies (MDBA, 2014) across the MDB. Despite contestation, the reforms have resulted in some substantive achievements, including returning an equivalent of about one fifth of consumptive water to the environment through the purchase of irrigation water entitlements and infrastructure projects (Hart, 2016; Gawne et al., 2020; MDBA, 2020) (*medium confidence*). However, the overall impacts of these water management initiatives are difficult to measure due to hydroclimatic variability, time lags and environmental, social and institutional complexity (Crase, 2011; Bark et al., 2014; Docker and Robinson, 2014; MDBA, 2020).

Reform initiatives such as water markets, improving agriculture water use efficiency (Koech and Langat, 2018), and increasing environmental water are helping buffer the system against droughts (Moyle et al., 2017) (*medium confidence*) but they can also be maladaptive by perpetuating unsustainable water and land use under ongoing climate change. While water markets can allow users to adapt and shift water to higher value uses, they can also have adverse impacts unless supported by wider policy goals and planning processes (Wheeler et al., 2013; Kirby et al., 2014; Grafton et al., 2016; Qureshi et al., 2018).

Adapting MDB management to climate risks is an escalating challenge, with the projected decline in runoff being potentially greater than the water recovered for the environment (Chiew et al., 2017). While the Basin Plan includes mechanisms for climate risks management (Neave et al., 2015), it does not require altering pre-existing rules that distribute the impacts of anticipated reductions in water resource between users (Hart, 2016; Capon and Capon, 2017; Alexandra, 2020). The intense drought conditions in 2017-2019 (BoM, 2019), the South Australian Royal Commission into the MDB reforms (SA Government, 2019b), and major fish kills in the lower Darling River in the summer of 2018/2019 (AAS, 2019; Vertessy et al., 2019) have increased concerns about the Basin Plan's climate adaptation deficit (*medium confidence*). The Murray Darling Basin Authority (MDBA) consequently is undertaking an assessment of climate change risks and developing adaptation mechanisms (MDBA, 2019) that can feed into the revisions to the Basin Plan scheduled for 2026. The MDB reforms to date illustrate the difficulties in integrating climate change science and projections into management (Alexandra, 2018; Alexandra, 2020). Anticipatory and participatory governance and adaptive management approaches supported by structural and institutional reforms would support the effectiveness of the reforms (Abel et al., 2016; Alexandra, 2019; Hassenforder and Barone, 2019; Marshall and Lobry de Bruyn, 2021).

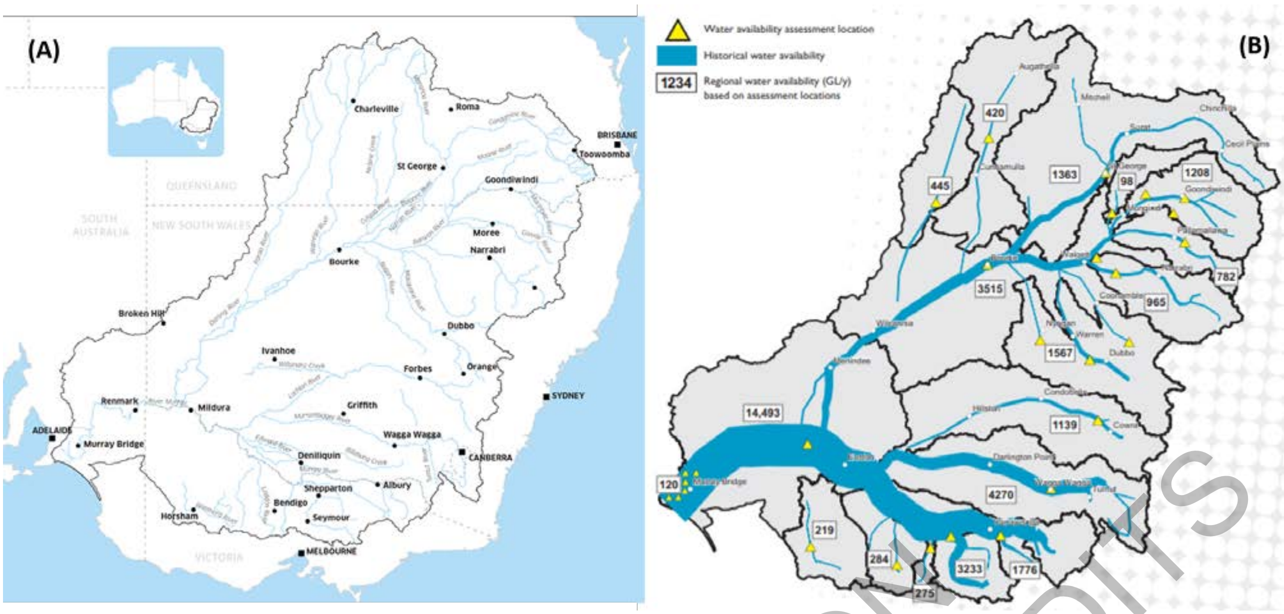


Figure Box 11.3.1: (A) The Murray-Darling Basin, and (B) average annual river flows in the Basin under pre-development conditions (from (CSIRO, 2008) showing that most of the runoff comes from the south-eastern highlands. The borders show key drainage basins.

[END BOX 11.3 HERE]

[START BOX 11.4 HERE]

Box 11.4: Changing Flood Risk

Pluvial (flash flood from high intensity rainfall) and fluvial (river) flooding are the most costly natural disasters in Australia, averaging A$8.8 billion per year (Deloitte, 2017b). In New Zealand, insured damages for the 12 costliest flood events from 2007-2017 exceeded NZ$472 million of which NZ$140 million has been attributed to anthropogenic climate change (Frame et al., 2020). Extreme rainfall intensity in northern Australia and New Zealand has been increasing, particularly for shorter (sub-daily) duration and more extreme high rainfall (*high confidence*) (Westra and Sisson, 2011; Griffiths, 2013; Laz et al., 2014; Rosier et al., 2015). Changes are also occurring in spatial and temporal patterns and seasonality (Wasko and Sharma, 2015; Zheng et al., 2015; Wasko et al., 2016).

Extreme rainfall is projected to become more intense (*high confidence*) but the magnitude of change is uncertain (Evans and McCabe, 2013; Bao et al., 2017) (Table 11.3). The insured damage in New Zealand from more intense extreme rainfall under RCP8.5 is projected to increase 25% by 2080–2100 (Pastor-Paz et al., 2020). In urban areas, extreme rainfall intensity is projected to increase pluvial flood risk (*high confidence*). In New Zealand, 20,000km^2 of land, 675,000 people, and 411,000 buildings with a NZ$135 billion replacement value are exposed to 1-in-100 year flood risk (Paulik et al., 2019a).

In non-urban areas, where the flood response is also dependent on antecedent catchment conditions (Johnson et al., 2016; Sharma et al., 2018), there is no evidence of increasing flood magnitudes in Australia (Ishak et al., 2013; Zhang et al., 2016; Bennett et al., 2018) except for the most extreme events (Sharma et al., 2018; Wasko and Nathan, 2019). Modelling studies project increases in flood magnitudes in northern and eastern Australia, and in western and northern New Zealand (*high confidence*) (Hirabayashi et al., 2013; Collins et al., 2018a; Do et al., 2020). The change in flood magnitude in southern Australia is uncertain because of the compensating effect of more intense extreme rainfall, versus projected drier antecedent conditions (Johnson et al., 2016; Pedruco et al., 2018; Wasko and Nathan, 2019). Higher rainfall intensity and peak flows also increase erosion, sediment and nutrient loads in waterways (Lough et al., 2015) and exacerbate problems from aging stormwater and wastewater infrastructure (Jollands et al., 2007; WSAA, 2016; Hughes et al., 2021).

There is some recognition of the need for flood management and planning to adapt to climate change (COAG, 2011; CCATWG, 2018; CoA, 2020d) (*medium confidence*). Australian flood estimation guidelines recommend a 5% increase in design rainfall intensity per degree global average warming (Bates et al., 2015). In New Zealand, the recommended increase ranges from 5% to more than 10% for shorter duration and longer return period storms (MfE, 2010; Carey-Smith et al., 2018). Both guidelines also indicate the potential for higher increases in extreme rainfall intensity.

Adaptation to reduce flooding and its impacts have included: improved flood forecasting (Vertessy, 2013; BoM, 2016) and risk management (AIDR, 2017); accommodating risk through raising floor levels and sealing external doors (Queensland Government, 2011; Wang et al., 2015), deployment of temporary levee structures; and risk reduction through spatial planning and relocation. Adaptation options in urban areas include improved stormwater management (Hettiarachchi et al., 2019; Matteo et al., 2019), ecosystem-based approaches such as maintaining floodplains, restoring wetlands and retrofitting existing flood control systems to attenuate flows, and water sensitive urban design (WSAA, 2016; Radcliffe et al., 2017; Radhakrishnan et al., 2017; Rogers et al., 2020b).

Adaptation to changing flood risks is currently mostly reactive and incremental in response to flood and heavy rainfall events (*high confidence*). For example, the 2010-2011 flooding in eastern Australia resulted in changes to reservoir operations to mitigate floods (QFCI, 2012) and insurance practice to cover flood damages (Phelan, 2011; Phelan et al., 2011; QFCI, 2012; Schuster, 2013). Nevertheless, adaptation planning that is pre-emptive and incorporates uncertainties into flood projections is emerging (Schumacher, 2020) (*medium confidence*). Examples from New Zealand include the use of Dynamic Adaptive Pathways Planning (Lawrence and Haasnoot, 2017) with Real Options assessment (Infometrics and PSConsulting, 2015) and design of decision signals and triggers to monitor changes before physical and coping thresholds are reached (Stephens et al., 2018). Implementing adaptive flood risk management relies upon an understanding of how such risks change in uncertain and ambiguous ways necessitating adaptive and robust decision making processes. These can enable learning through participatory adaptive pathways approaches (Lawrence and Haasnoot, 2017; Bosomworth and Gaillard, 2019) and through coordination across different levels of government and statutory mandates, adaptation funding, and individual and community adaptations (Glavovic et al., 2010; Boston and Lawrence, 2018; McNicol, 2021).

[END BOX 11.4 HERE]

11.3.4 Food, Fibre, Ecosystem Products

The food, fibre and ecosystem products sectors are economically important in the region. Agriculture contributes around 4% of New Zealand GDP and 2% of Australian GDP, and over 50% of New Zealand's and 11% of Australia's exports (NZ Treasury, 2016; Jackson et al., 2020). Forestry contributes 1% of New Zealand GDP and 0.5% Australian GDP (NZ Treasury, 2016; Whittle, 2019). With the processing and indirect effects, the primary sector of New Zealand contributes 25% of GDP (Saunders et al., 2016). The region has the lowest level of agricultural subsidies across the OECD (OECD, 2017), and highly responsive producers to market drivers but limited strategic, longer-term approaches to environmental challenges and adaptation (Wreford et al., 2019). Both countries receive government financial drought assistance (Pomeroy, 2015; Downing et al., 2016).

Impacts resulting from climate change are observed across sectors and the region (*high confidence*). While more intense changes are observed in Australia, New Zealand is also experiencing impacts, including the economic impacts of drought attributable to climate change (Frame et al. 2020). Overall, modelling indicates that negative impacts will intensify with increased levels of warming in both countries, with declining crop yield and quality, and negative effects on livestock production and forestry. Although benefits are identified, particularly in the short term for New Zealand (MfE, 2020a), an absence of studies that consider the totality of climatic variables, including extremes, moderate the benefits identified from considering only selected variables and systems in isolation.

Incremental adaptation is occurring (Hochman et al., 2017; Hughes and Lawson, 2017; Hughes and Gooday, 2021). In the longer term, transformative adaptation, including land-use change, will be required (Cradock-Henry et al., 2020a), both as a result of sectoral adaptations and mitigation (Grundy et al., 2016) (*medium confidence*). Specific changes are context specific and challenging to project (Bryan et al., 2016). Future adaptive capacity may be limited by declining institutional and community capacity resulting from high debt, unavailability of insurance, increasing regulatory requirements, and funding mechanisms that lock-in ongoing exposure to climate risk, creating mental health impacts (Rickards et al., 2014; Wiseman and Bardsley, 2016; McNamara and Buggy, 2017; McNamara et al., 2017; Moyle et al., 2017; Robinson et al., 2018; Ma et al., 2020; Yazd et al., 2020).

11.3.4.1 Field Crops and Horticulture

11.3.4.1.1 Observed impacts

Drought, heat and frost in recent decades have shown the vulnerability of Australian field crops and horticulture to climate change (Cai et al., 2014; Howden et al., 2014; CSIRO and BOM, 2015; Lobell et al., 2015; Hughes and Lawson, 2017; King et al., 2017; Webb et al., 2017; Harris et al., 2020) as recognised by policy makers (CoA, 2019a) (*high confidence*). Drought has caused economic losses attributable to climate change of at least NZ$800M in New Zealand (Frame et al., 2020). Northern Australia's agricultural output losses are on average 19% each year due to drought (Thi Tran et al., 2016). In southern Australia, the frequency of frost has been relatively unchanged since the 1980s (Dittus et al., 2014; Pepler et al., 2018; BoM and CSIRO, 2020). Drier winters have increased the irrigation requirement for wine grapes (Bonada et al., 2020) while smoke from the 2019/20 fires, which occurred early in the season, caused significant taint damage (Jiang et al., 2021). In New Zealand, reduced winter chill has a compounded impact on the kiwifruit industry, resulting in early harvest and increased energy demand for refrigeration and port access problems (Cradock-Henry et al., 2019) (11.5).

Across all types of agriculture, drought and its physical flow-on effects have caused financial and emotional disruption and stress in farm households and communities (Austin et al., 2018; Bryant and Garnham, 2018; Yazd et al., 2019) (11.3.6). Severe and uncertain climate conditions are statistically associated with increases in farmer suicide (Crnek-Georgeson et al., 2017; Perceval et al., 2019). Rural women often carry extra stress and responsibilities, including increased unpaid and paid work and emotional load (Whittenbury, 2013; Hanigan et al., 2018; Rich et al., 2018).

11.3.4.1.2 Projected impacts

Australian crop yields are projected to decline due to hotter and drier conditions, including intense heat spikes (Anwar et al., 2015; Lobell et al., 2015; Prokopy et al., 2015; Dreccer et al., 2018; Nuttall et al., 2018; Wang et al., 2018a) (*high confidence*). Interactions of heat and drought could lead to even greater losses than heat alone (Sadras and Dreccer, 2015; Hunt et al., 2018). Australian wheat yields are projected to decline by 2050, with a median yield decline of up to 30% in south-west Australia and up to 15% in South Australia, with possible increases and decreases in the east (Taylor et al., 2018, Wang, #1599; Wang et al., 2018a). In temperate fruit, accumulated winter chill for horticulture is projected to further decline (Darbyshire et al., 2016). Winegrape maturity is projected to occur earlier due to warmer temperatures (Webb et al., 2014; van Leeuwen and Darriet, 2016; Jarvis et al., 2018; Ausseil et al., 2019b) (*high confidence*) leading to potential changes in wine style (Bonada et al., 2015). Rice is susceptible to heat stress and average grain yield losses across rice varieties range from 83% to 53% in experimental trials when heat stress was applied during plant emergence and grain fill stages (Ali et al., 2019). In Tasmania, wheat yields are projected to increase, particularly at sites presently temperature-limited (Phelan et al., 2014).

New Zealand evidence on impacts across crops is very limited. Considering precipitation and temperature changes alone show minor effects on crop yield, and winter yields of some crops may increase (e.g. wheat, maize) (Ausseil et al., 2019b). For temperate fruit, loss of winter chill may reduce yields in some regions and trigger impacts across supply chains (Cradock-Henry et al., 2019) (11.5.1). Increased pathogens could damage the cut flower, guava and feijoa fruit growing, and the honey industries (Lawrence et al., 2016). The combined effects of changes in seasonality, temperature, precipitation, water availability and extremes, such as drought, have the potential to escalate impacts, but understanding of these effects is limited.

Other climate-change related factors complicate crop climate responses. When CO_2 was elevated from present-day levels of 400 ppm to 550 ppm in trials, yields of rainfed wheat, field pea and lentil increased approximately 25% (0-70%). However, there was a 6% reduction in wheat protein that could not be offset by additional nitrogen fertilizer (O'Leary et al., 2015; Fitzgerald et al., 2016; Tausz et al., 2017). Elevated CO2 will worsen some pest and disease pressures, e.g. Barley Yellow Dwarf Virus impacts on wheat (Trębicki et al., 2015). Warmer temperatures are also expanding the potential range of the Queensland fruit fly, including into New Zealand (Aguilar et al., 2015a) threatening the horticulture industry (Sultana et al., 2017; Sultana et al., 2020). Some crop pests (e.g. the oat aphid) are projected to be negatively affected by climate change (Macfadyen et al., 2018), but so too are beneficial insects. There is large uncertainty in rainfall and crop projections for northern Australia (Table 11.3). For sugarcane, impact assessment for CO_2 at 734ppm using the A2 emission scenario at Ayr in Queensland projected modest yield increases (Singels et al., 2014). Climate change are projected to adversely impact tropical fruit crops such as mangoes through higher minimum and maximum temperatures reducing the number of inductive days for flowering (Clonan et al., 2020).

Climate change is projected to shift agro-ecological zones (Lenoir and Svenning, 2015; Scheffers et al., 2016) (*high confidence*). This includes the climatically determined cropping strip bounded by the inner arid rangelands and the wetter coast or mountain ranges in mainland Australia (Nidumolu et al., 2012; Eagles et al., 2014; Tozer et al., 2014). A narrowing of grain growing regions is projected with a shift of the inner margin towards the coast under drier and warmer conditions (Nidumolu et al., 2012; Fletcher et al., 2020). The economic impact of the shift depends on adaptation (Sanderson et al., 2015; Hunt et al., 2019) and how resources, support industries, infrastructure and settlements adapt. Shifts in agro-ecological zones present some opportunities, for example, warming is projected to be beneficial for wine production in Tasmania (Harris et al., 2020).

11.3.4.1.3 Adaptation

Some farmers are adapting to drier and warmer conditions through more effective capture of non-growing season rainfall (e.g. stubble retention to store soil water), improved water use efficiency, and matching sowing times and cultivars to the environment (Kirkegaard and Hunt, 2011; Fitzer et al., 2019; Haensch et al., 2021) (*high confidence*). Observed adaptations include new technologies that improve resource efficiencies, professional knowledge and skills development, new farmer and community networks, and diversification of business and household income (Ghahramani et al., 2015; De et al., 2016). For Australian wheat, earlier sowing and longer season cultivars may increase yield by 2-4% by 2050, with a range of -7 to +2% by 2090 (Wang et al., 2018a). In the wheat industry, breeding for improved reproductive frost tolerance remains a priority (Lobell et al., 2015). Modelling suggests that, since 1990, farm management has held Australian wheat yields constant, but declining rainfall and increasing temperature may have contributed to a 27% decline in simulated potential Australian wheat yield (Hochman et al., 2017).

Other observed incremental adaptations include later pruning in the grape industry to spread harvest period and partially restore wine balance, with neutral effects on yield and cost (Moran et al., 2019; Ausseil et al., 2021). The cotton sector increasingly requires shifts in sowing dates to avoid financial impacts (Luo et al., 2017). During years of low water availability, rice growers have been trading water and/or shifting to dry land farming (Mushtaq, 2016).

Growers in New Zealand are changing the timing of their operations, growing crops within covered enclosures, and purchasing insurance (Cradock-Henry and McKusker, 2015)(Teixeira et al. 2018). Investment of capital in irrigation infrastructure has increased (Cradock-Henry et al., 2018a), although its effectiveness as an adaptation depends on water availability (Box 11.5). In industries based on long-lived plants, such as the kiwifruit and grape industries, many of the adaptations (e.g. breeding and growing heat-adapted and disease-resistant varieties) have long-lead times and require greater investment than in the cropping sector (Cradock-Henry et al., 2020a). While breeding programmes for traits with enhanced resilience to future climates are beginning, there is little evidence of strategic industry planning (Cradock-Henry et al., 2018a).

For drought management, balancing near-term needs with long-term adaptation to increasing aridity is essential (Downing et al., 2016). Insufficient and maladaptive decisions can have far-reaching effects, including changes to resources, infrastructure, services and supply chains to which others have to adapt

(Fleming et al., 2015; Graham et al., 2018). While there is potential for greater proportion of agriculture to be located to northern Australia, there are significant and complex agronomic, environmental, institutional, financial and social challenges for successful transformation including the risk of disruption (Jakku et al., 2016) (*medium confidence*).

11.3.4.2 Livestock

11.3.4.2.1 Observed impacts

Both the seasonality and annual production of pasture is changing (*high confidence*). In many regions, warming is increasing winter pasture growth (Lieffering, 2016); effects on spring growth are more mixed with some regions experiencing increased growth {(Newton et al. 2014)} and others experiencing reduced spring growth (Perera et al., 2020). Droughts are causing economic damage to livestock enterprises with drought and market prices significantly affecting profit (Hughes et al., 2019a), in addition to the impacts on animal health and the livelihoods of pastoralists, periods of drought contribute to land degradation, particularly in the cattle regions of northern Australia (Marshall, 2015). Heat load in cattle leads to reduced growth rates and reproduction, and extreme heat waves can lead to death (Lees et al., 2019; Harrington, 2020). Temperatures over 32ºC reduce ewe and ram fertility along with the birth weight of lambs (van Wettere et al., 2021).

11.3.4.2.2 Projected impacts

Some areas may experience increased pasture growth, but others may experience a decrease that cannot be fully offset by adaptation (Moore and Ghahramani, 2013; Lieffering, 2016; Kalaugher et al., 2017) (*high confidence*). Climate change may modify the seasonality of pasture growth rates more than annual yields in New Zealand (Lieffering, 2016). In eastern parts of Queensland, climate change impacts on pasture growth are equivocal, with simple empirical models suggesting a decrease in net primary productivity (Liu et al., 2017), whilst mechanistic models that include increases in length of the growing season and the beneficial effects of CO_2 fertilisation indicate increases in pasture growth (Cobon et al., 2020). In Tasmania, annual pasture production is projected to increase by 13–16%, even with summer growth projected to reduce with increased inter-annual variability, resulting in projected increase of milk yields by 3–16% per annum (Phelan et al., 2015).

Extreme climatic events (droughts, floods and heatwaves) are projected to adversely impact productivity for livestock systems (*medium confidence*). This includes reduced pasture growth rates between 3-23% by 2070 from late spring to autumn, and elevated growth in winter and early spring (Cullen et al., 2009; Hennessy et al., 2016; Chang-Fung-Martel et al., 2017). Heavy rainfall and storms are projected to lead to increased erosion, particularly in extensively grazed systems on steeper land, reducing productivity for decades, reducing soil carbon (Orwin et al., 2015), and increasing sedimentation. Increased heat stress in livestock is projected to decrease milk production and livestock reproduction rates (high confidence) (Nidumolu et al., 2014; Ausseil et al., 2019b; Lees et al., 2019). In Australia, the average number of moderate to severe heat stress days for livestock is projected to increase 12-15 days by 2025 and 31–42 days by 2050 compared to 1970-2000 (Nidumolu et al., 2014). In New Zealand, an extra 5 (RCP2.6) to 7 (RCP8.5) moderate heat stress days per year are projected for 2046-2060 (Ausseil et al., 2019b) (*high confidence*) especially affecting animals transported long distances (Zhang and Phillips, 2019) and strain the cold chains needed to deliver meat and dairy products safely. The distribution of existing and new pests and diseases are projected to increase, for example, new tick and mosquito-borne diseases such as Bovine ephemeral fever (Kean et al., 2015).

11.3.4.2.3 Adaptation

Adaptations in both grazing and confined beef cattle systems require enhanced decision-making skills capable of integrating biophysical, social and economic considerations (*high confidence*). Social learning networks that support integration of lessons learned from early adopters and involvement with science-based organizations can help enhance decision-making and climate adaptation planning (Derner et al., 2018). Pasture management adaptations for livestock production include deeper rooted pasture species in higher rainfall regions (Cullen et al., 2014) and drought tolerant species (Mathew et al., 2018). Soil and land management practices are important in ensuring soils maintain their supporting and regulating services (Orwin et al., 2015). Adaptations in the primary sector in New Zealand are now positioned within the requirements of the National Policy Statement on Freshwater (MfE, 2020b). Adaptations to manage heat stress in livestock include altering the breeding calendar, providing shade and sprinklers, altering nutrition and feeding times, and more heat-tolerant animal breeds (Chang-Fung-Martel et al., 2017; Lees et al., 2019; van Wettere et al., 2021).

Beef rangeland systems in Queensland are projected to have benefits in the south-east through higher CO_2 and temperatures extending the growing season and reducing frost, but a warmer and drier climate in the south-west may reduce pasture and livestock production (Cobon et al., 2020). Northern Queensland is most resilient to temperature and rainfall changes (production limited by soil fertility) while western/central west Queensland is most sensitive to rainfall changes. i.e. low rainfall associated with lower productivity (Cobon et al., 2020). The social context of climate change impacts and the processes shaping vulnerability and adaptation, especially at the scale of the individual, are critical to successful adaptation efforts.(Marshall and Stokes, 2014)

11.3.4.3 Forestry

11.3.4.3.1 Observed impacts

Climate change may have increased tree mortality in Australia's commercial *Eucalyptus globulus* and *Pinus radiata* plantation forests (Crous et al., 2013; Pinkard et al., 2014). Climate warming decreased fine root biomass of *E. globulus* (Quentin et al., 2015) and enhanced tree water use and vulnerability to heat (Crous et al., 2013). Increases in fire frequency and intensity in forests of southern Australia are leading to diminishing resources available for timber production (Pinkard et al., 2014) [Box 11.1].

11.3.4.3.2 Projected impacts

The projected declines in rainfall in far southwest and far southeast mainland Australia are projected to reduce plantation forest yields (*high confidence*). Warmer temperatures are projected to reduce forest growth in hotter regions (between 7-25%), especially where species are grown at the upper range of their temperature tolerances, and increase plantation forest growth (>15%) in cooler margins like Tasmania and the Victorian highlands (2030, A2); emission scenario A2 creates a warming trajectory slightly higher than the RCP6.0 warming scenario, but less than RCP8.5 (Rogelj et al., 2012; Battaglia and Bruce, 2017). Elevated CO_2 is projected to increase forest growth if other biophysical factors are not limiting (*medium confidence*) (Quentin et al., 2015; Duan et al., 2018).

Forestry plantations are projected to be negatively impacted from increases in fire weather (Box 11.1), particularly in southern Australia (Pinkard et al., 2014) (*high confidence*). Increased pest damage due to temperature increases may reduce eucalypt and pine plantation growth by as much as 40% in some Australian environments by 2050) (Pinkard et al., 2014). Increased heat and water stress may enhance insect pest defoliation for *P. radiata* in Australia (e.g. *Sirex noctilio, Ips grandicollis and Essigella californica*) (Mead, 2013; Pinkard et al., 2014).

Combined impacts from heavy rainfall, soil erosion, drought, fire and pest incursions are projected to increase risks to the permanence of carbon offset and removal strategies in New Zealand for meeting its climate change targets (PCE, 2019; Watt et al., 2019; Anderegg et al., 2020; Schenuit et al., 2021). Effective management of the interactions between mitigation and adaptation policies can be achieved through governance and institutions, including Māori tribal organisations and sectoral adaptation, to ensure effective and continued carbon sequestration and storage as the climate changes (Lawrence et al., 2020b) (11.4.2) (Box 11.5) (*medium confidence*). The productivity of radiata pine (*P. radiata D. Don*) in New Zealand due to higher CO_2 is projected to increase by 19% by 2040 and 37% by 2090, but greater wind damage to trees is expected (Watt et al., 2019). Changes in the distribution of existing weeds, pests and diseases with potential establishment of new subtropical pests and seasonal invasions are projected (Kean et al., 2015; Watt et al., 2019; MfE, 2020a). Increased pathogens such as pitch canker, red needle cast and North American bark beetles could damage plantations (Hauraki Gulf Forum, 2017; Lantschner, 2017; Watt et al., 2019).

11.3.4.3.3 Adaptation

Adaptation options include: increased investment in monitoring forest condition and functioning; early detection and management of insect pests, diseases and invasive species; improved selection of land with appropriate growing conditions for plantation timber production under current and future conditions; trialling new species and genetic varieties; changing timing and frequency of planned fuel reduction fires, introducing more fire-tolerant tree species where appropriate, reducing ignition sources and maintaining access and emergency response capacity (Boulter, 2012; Pinkard et al., 2014; Keenan, 2017).

11.3.4.4 Marine Food

11.3.4.4.1 Observed impacts

Ecological impacts of climate change on fisheries species have already emerged (Morrongiello and Thresher, 2015; Gervais et al., 2021)(*high confidence*). This includes loss of habitats for fisheries species (Vergés et al., 2016; Babcock et al., 2019), and poleward shifts in distribution of barrens-forming urchins (Ling and Keane, 2018) impacting abalone and rock lobster fisheries. The percentage of reef as barrens across eastern Tasmania grew from 3.4% to 15.2% from 2001/02 to 2016/17, a ~10.5% increase per annum over the 15-year period (Ling and Keane, 2018). Oysters farmed from wild spat (Sydney rock oysters *Saccostrea glomerata*) are most at risk from climate change, primarily due to observed increases in summer temperatures and heat wave-related mortalities (Doubleday et al., 2013). The exceptional 2017/18 summer heatwave caused significant losses of farmed salmon in New Zealand, with farm owners seeking consent to move operations to cooler water (Salinger et al., 2019b).

11.3.4.4.2 Projected impacts

Aquaculture is projected to be more easily adapted than wild fisheries to avoid excessive exposure to the physio-chemical stresses from acidification, warming and extreme events (Richards et al., 2015). In New Zealand, wild and cultured shellfish are identified as most at risk from climate change (Capson and Guinotte, 2014). Changes in ocean temperature and acidification, and the downstream impacts on species distribution, productivity and catch are projected concerns (Law et al., 2016) (*medium confidence*) that impact Māori harvesting of traditional seafood, and the social, cultural and educational elements of food gathering (mahinga kai) (MfE, 2016). Warm temperate hatchery-based finfish species (yellowtail kingfish *Seriola lalandi*) are projected to be the least at risk, because of well controlled environmental conditions in hatcheries, and temperature increases which are expected to increase growth rates and productivity during the grow-out stage (Doubleday et al., 2013). For wild fisheries, multi-model projections suggest temperate and demersal systems, especially invertebrate shallow water species, would be more strongly affected by climate change than tropical and pelagic systems (Pecl et al., 2014; Fulton et al., 2018; Pethybridge et al., 2020) (*medium confidence*). In New Zealand waters, available habitat for both albacore tuna and oceanic tuna (Cummings et al., 2021) is expected to widen and shift.

11.3.4.4.3 Adaptation

Selective breeding in oysters is projected to be an important global adaptation strategy for sustainable shellfish aquaculture which can withstand future climate-driven change to habitat acidification (Fitzer et al., 2019). Less than a quarter of fisheries management plans for 99 of Australia's most important fisheries considered climate change, and only to a limited degree (Fogarty et al., 2019; Fogarty et al., 2021). Implementation of management and policy responses to climate change have lagged in part because climate change has not been considered as the most pressing issue (Hobday and Cvitanovic, 2017; Fogarty et al., 2019; Fogarty et al., 2021) (Cross-Chapter Box MOVING SPECIES in Chapter 5).

[START BOX 11.5 HERE]

Box 11.5: New Zealand's Land, Water and People Nexus under a changing climate

New Zealand's economy, dominated by the primary sector and the tourist industry (pre-COVID), relies upon a "clean green" image of water, natural ecosystems and pristine landscapes (Foote et al., 2015; Roche and Argent, 2015; Hayes and Lovelock, 2017). Water is highly valued by Māori for its mauri or life force and for its intrinsic values and multiple uses (Harmsworth et al., 2016). Increasingly, these diverse values are in conflict (Hopkins et al., 2015) due to increasing pressures from how land is used and managed and the effects on water availability and quality. Such tensions will be further challenged as temperatures rise and extreme events intensify beyond what has been experienced, thus stressing current adaptive capacities (Hughey and Becken, 2014; Cradock-Henry and McKusker, 2015; Hopkins et al., 2015; MfE and StatsNz, 2021) (11.2.2; 11.3.4) (*high confidence*).

Irrigation has increasingly been used to enhance primary sector productivity and regional economic development (Srinivasan et al., 2017; Fielke and Srinivasan, 2018; MfE and StatsNz, 2021). Pressure for long-term access to groundwater or large-scale water storage is increasing to ensure the ongoing viability of the primary sector as the climate changes. While investment in irrigation infrastructure may reduce climate change impacts in the short-term, maladaptive outcomes cannot be ruled out longer-term which means that focusing attention now on adaptive and transformational measures can help increase climate resilience in areas exposed to increasing drought and climate extremes that disrupt production (Abel et al., 2016; Cradock-Henry et al., 2019) (Yletyinen et al., 2019) (*medium confidence*).

Furthermore, over-allocation raises further tensions from competing uses of water such as for horticulture and urban water supplies, as well as for ecological requirements. The deterioration of water quality and loss of places of social, economic, cultural, and spiritual significance creates increasing tension for Māori especially (Harmsworth et al., 2016; Salmon, 2019; MfE and StatsNz, 2021). Public concern has increased about the deterioration of New Zealand's waterways and the profiting of some land uses at the expense of environmental quality and human health - tensions that make adaptation to climate change more challenging (Duncan, 2014; Foote et al., 2015; Scarsbrook and Melland, 2015; McDowell et al., 2016; McKergow et al., 2016; Greenhalgh and Samarasinghe, 2018). A lack of precautionary governance of water resources linked to unsustainable land use practices degrading water quality (Scarsbrook and Melland, 2015; Salmon, 2019) highlights the role that foresight could play in managing the nexus between land, water and people in a changing climate (11.3.3). Adaptive planning has potential for navigating these multi-dimensional challenges (Sharma-Wallace et al., 2018; Cradock-Henry and Fountain, 2019; Hurlbert et al., 2019) (11.7).

Furthermore, land and particularly plantation and native forests play a critical role in meeting New Zealand's emissions reduction goals. However, the persistence of land and forests as a carbon sink is uncertain and the sequestered carbon is at risk from future loss resulting from climate change impacts, including from increased fire, drought and pest incursions, storms and wind (IPCC, 2019a; PCE, 2019; Watt et al., 2019; Anderegg et al., 2020) (11.3.4.3), emphasising the importance of interactions between mitigation and adaptation policy and implementation. Integrated climate change policies across biodiversity, water quality, water availability, land use and forestry for mitigation can support the management of land use, water and people conflicts, but there is little evidence of such coordinated policies (Cradock-Henry et al., 2018b; Wreford et al., 2019). Implementation of the National Policy Statement for Freshwater Management 2020 (MfE, 2020b) and the National Adaptation Plan (due August 2022) present opportunities for such interconnections and diverse values to be addressed, as well as enabling sector and community benefits to be realised across New Zealand (Awatere et al., 2018; Lawrence et al., 2020b).

[END BOX 11.5 HERE]

11.3.5 Cities, Settlements and Infrastructure

Almost 90% of the population of Australia and New Zealand is urban (World Bank, 2019). Each country has vibrant and diverse urban, rural and remote settlements, with some highly disadvantaged areas isolated by distance and limited infrastructure and services (Argent et al., 2014; Charles-Edwards et al., 2018; Spector et al., 2019). Some areas in northern Australia and New Zealand, especially those with higher proportions of Indigenous inhabitants, face severe housing, health, education, employment and services issues (Kotey, 2015) which increases their vulnerability to climate change.

Infrastructure within and between cities and settlements is critical for activity across all sectors, with interdependencies increasing exposure to climate hazards (11.5.1). Previous planning horizons for existing infrastructure are compromised by now having to accommodate ongoing sea-level rise, warming, and increasing frequency of extreme rainfall and storm events (Climate Institute, 2012; MfE, 2017a). There is almost no information on the costs and benefits of adapting vulnerable and exposed infrastructure in Australia or New Zealand. Given the value of the infrastructure and the rising damage costs, this represents a large knowledge gap leading to an adaptation investment deficit.

11.3.5.1 Observed Impacts

Critical infrastructure, cities and settlements are being increasingly affected by chronic and acute climate hazards including heat, drought, fire, pluvial and fluvial flooding and sea-level rise, with consequent effects for many sectors (Instone et al., 2014; Loughnan et al., 2015; Zografos et al., 2016; Hughes et al., 2021) (*high confidence*). Risks and impacts vary with physical characteristics, location, connectivity and socio-economic status of settlements because of the ways these influence exposure and vulnerability (Loughnan et al., 2013; MfE, 2020a) (*high confidence*).

Weather-related disasters are causing significant disruption and damage (Paulik et al., 2019a; CSIRO, 2020; Paulik et al., 2020). In Australia, during 1987-2016, natural disasters caused an estimated 971 deaths and 4,370 injuries, 24,120 people were made homeless and about 9 million people were affected (Deloitte, 2017a). More than 50% of these deaths and injuries came from heatwaves in cities and 22% from fires. During 2007-2016, Australia natural disaster costs averaged A$18.2 billion per year with largest contributions from floods (A$8.8 billion), followed by cyclones (A$3.1 billion), hail (A$2.9 billion), storms (A$2.3 billion) and fires (A$1.1 billion) (Deloitte, 2017a). The Australian fires in 2019-2020 cost over A$8 billion, with devastating impacts on settlements and infrastructure (Box 11.1)

Sea-level rise affects many interdependent systems in cities and settlements which increase the potential for compounding and cascading impacts (11.5.1). Seaports, airports, water treatment plants, desalination plants, roads and railways are increasingly exposed to sea-level rise (*very high confidence*), impacting their longevity, levels of service and maintenance (*high confidence*) (McEvoy and Mullett, 2014; Woodroffe et al., 2014; PCE, 2015; Ranasinghe, 2016; Newton et al., 2018; Paulik et al., 2020) (Box 11.6). Compounding coastal hazards in New Zealand, such as elevated water tables associated with rising sea-level and intense rainfall (Morgan and Werner, 2015; McBride et al., 2016; White et al., 2017; Hughes et al., 2021) are exerting pressure on stormwater and wastewater infrastructure and drinking water supply and quality (MfE, 2020a).

Extreme heat events exacerbate problems for vulnerable people and infrastructure in urban Australia where urban heat is superimposed upon regional warming, and there are adverse impacts for population and vegetation health, particularly for socio-economically disadvantaged groups (Tapper et al., 2014; Heaviside et al., 2017; Filho et al., 2018; Gebert et al., 2018; Rogers et al., 2018; Longden, 2019; Marchionni et al., 2019; Tapper, In Press) (11.3.6), energy demand, energy supply and infrastructure (Newton et al., 2018) (11.3.10) (*very high confidence*). Extreme heat is increasingly threatening liveability in some rural areas in Australia (Turton, 2017), particularly given their reliance on outside physical work and older populations. Settlement design and the level of greening interact with climate change to influence local heating levels (Tapper et al., 2014; Wong et al., 2020; Tapper, In Press).

Floods cause major damage. The floods of early 2019 in north Queensland cost A$5.68 billion (Deloitte, 2019), while Cyclone Yasi and the Queensland floods of 2011 cost A$6.9 billion (Deloitte, 2016). Floodplains in New Zealand have considerably higher overall national exposure of buildings and population than coasts (Paulik et al., 2019a) (Box 11.4). The insured loss from the 12 costliest floods in New Zealand from 2007-2017 totalled NZ$471.56 million, of which NZ$140.48 million could be attributed to climate change (Frame et al., 2020).

Climatic extremes are exacerbating existing vulnerabilities *(high confidence)*. Long supply chains, poorly maintained infrastructure, social disadvantage and poor health, and lack of skilled workers (Eldridge and Beecham, 2018; Mathew et al., 2018; Rolfe et al., 2020) are contributing to serious stress and disruption (Smith and Lawrence, 2014; Kiem et al., 2016). In many rural settlements, population ageing and reliance on an over-stretched volunteer base for recovery from extreme events are increasing vulnerability to climate change (Astill and Miller, 2018; Davies et al., 2018). Recovery from long, intense, more frequent and compounding climatic events in rural areas has been disrupted by the erosion of natural, financial, built, human and social capital (De et al., 2016; Sheng and Xu, 2019). Delayed recovery from extreme climatic events has been compounded by long-term displacement which in turn prolongs the impacts (Matthews et al., 2019). Severe droughts have contributed to poor health outcomes for rural communities, including extreme stress and suicide (Beautrais, 2018; Perceval et al., 2019). In Australia, competition between water users has left some rural communities experiencing extreme water shortage and insecurity with associated health impacts (Wheeler et al., 2018; Judd, 2019) (Box 11.3).

11.3.5.2 Projected Impacts

Changes in heat waves, droughts, fire weather, heavy rainfall, storms and sea-level rise are projected to increase negative impacts for cities, settlements and infrastructure (Tables 11.3a and 11.3b; Boxes 11.1, 11.3, 11.4) (*high confidence*).

Increased floods, coastal inundation (assuming a sea-level rise of 1.6 m by 2100), wildfires, windstorms and heatwaves may cause property damage in Australia estimated at A$91 billion per year by 2050 and A$117 billion per year by 2100 for RCP8.5, while damage-related loss of property value is estimated at A$611 billion by 2050 and A$770 billion by 2100 for RCP8.5 (Steffen et al., 2019). For 1.0 m sea-level rise, the value of exposed assets in New Zealand would be NZ$25.5 billion (Box 11.6). For 1.1 m sea-level rise, the value of exposed assets in Australia would be A$164-226 billion (Box 11.6). These cost estimates exclude impacts on personal livelihood, well-being or lifestyle.

Extreme heat risks are projected to exacerbate existing heat-related impacts on human health, vegetation and infrastructure (Tapper et al., 2014; Tapper, In Press) (11.3.6). In Australia, the annual frequency of days over 35ºC is projected to increase 20-70% by 2030 (RCP4.5), and 25–85% (RCP2.6) to 80–350% (RCP8.5) by 2090 (Table 11.3a). For example, Perth may average 36 days over 35ºC by 2030 (RCP4.5). In New Zealand, the annual frequency of days over 25ºC may increase 20-60% (RCP2.6) to 50-100% (RCP8.5) by 2040, and 20–60% (RCP2.6) to 130-350% (RCP8.5) by 2090 (Table 11.3b). For example, Auckland may average 39 days over 25ºC by 2040 (RCP8.5). Unprecedented extreme temperatures, as high as 50ºC in Sydney or Melbourne, could occur with global warming of 2.0ºC (Lewis et al., 2017). Heat-related costs for Melbourne during 2012-2051 are estimated at A$1.9 billion, of which A$1.6 billion is human health/mortality costs (AECOM, 2012). Extreme heat is threatening liveability in some rural areas in Australia (Turton, 2017), particularly given their reliance on outside physical work and older populations.

Key infrastructure and services face major challenges. Structural metal corrosion rates are projected to increase significantly at coastal locations but decrease inland (Trivedi et al., 2014). A drier climate may decrease the rate of deterioration of road pavements but extreme rainfall events and heat pose a significant risk (Taylor and Philp, 2015), especially to unsealed roads in northern Australia (CoA, 2015). Critical infrastructure on coasts is at risk from sea-level rise and storm surges (Box 11.6). Facilities such as hospitals face weather-related hazards exacerbated by climate change and not originally anticipated in building and infrastructure design (Loosemore et al., 2011; Loosemore et al., 2014). By 2050, increased risks are projected for the availability and quality of potable water supplies, delivery of wastewater and stormwater services to communities, transport systems, electricity infrastructure, operating municipal landfills, and contaminated sites located near rivers and the coast (Gilpin et al., 2020; MfE, 2020a; Hughes et al., 2021). These then create risks to social cohesion and community wellbeing from displacement of individuals, families and communities, with inequitable outcomes for vulnerable groups (Boston and Lawrence, 2018).

11.3.5.3 Adaptation

In cities and settlements, climate adaptation is underway and is being led and facilitated by state and local government leadership and facilitation, particularly in Australia (Hintz et al., 2018; Newton et al., 2018) (Table 11.7, Supplementary Material Table SM11.1a) (*high confidence*).

Effective adaptations to urban heat include spatial planning, expanding tree canopy and greenery, shading, sprays and heat-resistant and energy-efficient building design, including cool materials and reflective or green roofs (*very high confidence*) (Broadbent et al., 2018; Jacobs et al., 2018b; Haddad et al., 2019; Haddad et al., 2020a; Yenneti et al., 2020; Bartesaghi-Koc et al., 2021; Tapper, In Press). Reducing urban heat not only benefits human health but reduces demand for, and cost of, air conditioning (Haddad et al., 2020b) and the risk of electricity blackouts (11.3.10).

Adaptation progress is being hampered by current urban redevelopment practice and statutory planning guidelines that are leading to removal of critical urban green space (Newton and Rogers, 2020). Reform of approaches to urban redevelopment would facilitate adaptation (Newton and Rogers, 2020). Several cities in Australia and New Zealand are part of the 100 Resilient Cities global network which helped facilitate the metropolitan Melbourne Urban Forest Strategy across councils (Fastenrath et al., 2019; Coenen et al., 2020) and in New Zealand, restoration of the urban forest in Hamilton is reducing heat stressors (Wallace and Clarkson, 2019). In peri-urban zones, adapting to fire risk is a contested issue, raising difficult trade-offs between heat management, ecological values and fuel reduction in treed landscapes (Robinson et al., 2018).

The resilience of Australia's major cities to flooding and drought has been advanced through a range of economic and physical interventions. Water sensitive urban design irrigates vegetation with harvested storm water that improves water security, flood risk, carbon sequestration, biodiversity, air and water quality, and delivers cooling that can save human lives in heatwaves (Wong et al., 2020). Storm water harvesting is supported by some councils in New Zealand and can deliver recycled water for households (Attwater and Derry, 2017), improving climate resilience and reducing water demand (White et al., 2017). Addressing infrastructure vulnerability is essential given the long lifetime of the assets, criticality of services and high costs of maintenance (Chester et al., 2020; Hughes et al., 2021).

Climate risk management is developing, but adaptive capacity, implementation, monitoring and evaluation are uneven across all scales of cities, settlements and infrastructure (*very high confidence*) (Tables 11.15a and 11.15b; Supplementary Material Tables SM11.1a, and SM11.1b). There is increasing awareness of the need to move from incremental coping and defensive coastal strategies (Jongejan et al., 2016) to transformational adaptation, for example, managed retreat (Torabi et al., 2018; Hanna, 2019), and to consider the flow-on effects (e.g. for housing and employment) (Fatorić et al., 2017; Torabi et al., 2018). Strategies limited to building household and community self-reliance (Astill and Miller, 2018) are increasingly inadequate given systemic and interconnected stressors and cascading impacts across interdependent systems (Lawrence et al., 2020b). Integrated approaches to climate change adaptation and emissions reduction have potential for addressing interdependent systems (e.g. nature-based approaches, climate-sensitive urban design, energy and transport systems) (Norman et al., 2021). Climate risk assessment and adaptation guidelines have been prepared for transport infrastructure authorities and organisations (Finlayson et al., 2017; Byett et al., 2019; Yenneti et al., 2020).

Table 11.7: Cities, settlements and infrastructure: key risks and adaptation options.

Sector	Key Risks	Adaptation Options	Inter-Sector Dependencies	Sources
Road	Heat; sea-level rise; coastal surges; floods and high intensity rainfall impacts on road foundations	Re-routing; coastal protection; improved drainage	Ports (fuel supply); rail (fuel supply); electricity	(NCCARF, 2013; CoA, 2018a; MfE, 2020a)
Rail	Extreme temperatures; flooding; sea-level rise; high intensity rainfall impacts on track foundations	Drainage and ventilation improvements; systematic risk assessments; overhead wire and rail/sleeper upgrades; rerouting	Electricity; telecommunications; fuel supply (transport, ports)	(CoA, 2018a; MfE, 2020a)
Urban and Rural Built Environment[1]	Extreme temperatures; floods; extreme weather events; wildfire (at urban-rural interface); sea-level rise	Multiple options from the building-to-city scale to reduce heat impacts and improve climate resilience; behavioural change; coastal defences and managed retreat	Road; rail; electricity; air and seaports; telecommunications; water and wastewater	(CoA, 2018a; Newton et al., 2018; Haddad et al., 2019; MfE, 2020a; Paulik et al., 2020; Tapper, In Press) (Box 11.4) (Box 11.4)

Electricity	High wind/ temperature events; wildfire; lightning; dust storms; drought (hydro)	Demand management; re-engineering and new technology; network intelligence; smart metering; improved planning for outages	Road; rail; water	(CoA, 2017; MfE, 2020a) (11.3.10.)
Ports: Air and Sea	Sea-level rise; coastal surges; wind; heat; extreme weather events	Air; improved coastal, pluvial and fluvial flood protection, on-site services. Sea; widening operational limits, raising wharfs, roads and breakwaters.	Electricity; road; rail, water	(McEvoy and Mullett, 2014; MfE, 2020a)
Telecommunications	Floods; wildfires; extreme wind	Protect; place underground; wireless systems	Electricity; digital connectivity; all sectors serviced; rural communities	(NCCARF, 2013)
Stormwater Wastewater and Water supply[1.]	High intensity rainfall; increased and extreme temperatures; flooding; drought; sea-level rise	Large investments in upgrading centralized infrastructure and capacity; increasing investment in decentralized infrastructure and capacity (e.g. Water Sensitive Urban Design); demand management; fewer options in smaller communities; governance at scale	Electricity; telecommunications; urban and rural built environment	(White et al., 2017; CoA, 2018a; Gilpin et al., 2020; MfE, 2020a; Wong et al., 2020; Hughes et al., 2021) (Box 11.4)

Table Notes:
[1.] Water supply safety and security and exposure of buildings have been identified as the most significant risks for New Zealand in terms of urgency and consequence (MfE, 2020a). No such ranking of risk has been done for Australia.

Infrastructure service vulnerability in New Zealand is supported by new institutional adaptations including the Infrastructure Commission to develop a 30-year national infrastructure strategy. The Climate Change Commission (Climate Change Commission, 2020) has issued six principles for climate-relevant infrastructure investments and is mandated to monitor the National Climate Change Adaptation Plan based on the first National Climate Change Risk Assessment (MfE, 2020a). A National Disaster Resilience Strategy addresses integrated planning for risk reduction and awareness-raising in New Zealand (Department of the Prime Minister and Cabinet, 2019).

Successive inquiries and reviews highlight potential synergies between disaster risk management and climate resilience (11.5.1) (Smith and Lawrence, 2018; Ruane, 2020). In Australia, there is a National Disaster Risk Reduction Framework (CoA, 2018b) and a National Recovery and Resilience Agency (CoA, 2021) that help underpin the development of national support systems for rural and regional emergency management and associated volunteer sectors (McLennan et al., 2016) and wildfire smoke impacts (CoA, 2020e). The National Heatwave Framework Working Group uses a Heatwave Forecast Service, and heatwave early warning and adaptation systems that operate in Adelaide, Melbourne, Sydney and Brisbane have reduced potential death rates (Nitschke et al., 2016).

Infrastructure planning is lagging behind international standards for climate resilience evaluation and guidance for adaptation to climate risk (CSIRO, 2020; Kool et al., 2020; Hughes et al., 2021) *(high* *confidence)*. Some companies have examined their exposure to climate risk and developed strategies to minimise their vulnerability (Climate Institute, 2012) (11.3.8). Climate risk assessments have been conducted for the electricity sector in both Australia and New Zealand (11.3.10). Climate change is considered in Australian infrastructure plans for national and regional water supply security, water for irrigated agriculture, a coastal hazards adaptation strategy, and the Tanami Road upgrade (Infrastructure Australia, 2016; Infrastructure Australia, 2019; Infrastructure Australia, 2021).

Industry associations are beginning to facilitate climate adaptation for infrastructure, including the Australian Green Infrastructure Council (CoA, 2015), the Green Building Council of Australia, Green Star Programme (GBCA, 2020), the Water Services Association of Australia, Climate Change Adaptation Guidelines (WSAA, 2016) and the Australian Sustainable Built Environment Council, Built Environment Adaptation Framework (ASBEC, 2012). The Infrastructure Sustainability Rating Scheme measures the social, environmental, governance and cultural outcomes delivered by more than $160 billion worth of infrastructure, and it is projected to deliver a cost-benefit ratio of 1:1.6 to 1:2.4 during 2020-2040 (RPS, 2020). There is scope for engagement of industry in transitioning to a low carbon green economy that is adapted to climate change, but less certainty on how to develop appropriate business cases (Newton and Newman, 2015).

There are tensions between settlement-scale adaptation options such as managed retreat that focus on the long term, and people's values, place attachments, needs and capacities (Gorddard et al., 2016; Fatorić et al., 2017; Graham et al., 2018; O'Donnell, 2019; Norman et al., 2021). Tensions also exist between climate change adaptation and mitigation goals (e.g. current energy efficiency standards in Australian buildings can worsen their heat resistance and increase dependence on air-conditioning) (Hatvani-Kovacs et al., 2018). Where there is a lack of coordination between jurisdictions, there can be flow-on effects from failure to adapt, for example in coastal local government areas (Dedekorkut-Howes et al., 2020) (Box 11.6). There is limited information across the region on climate change impacts and adaptation options for telecommunications (NCCARF, 2013) (Table 11.7). There is an emerging recognition that implementing and evaluating the adaptation process (vulnerability and risk assessments, identification of options, planning, implementation, monitoring, evaluation and review) in local contexts can advance more effective adaptation (Moloney and McClaren, 2018). For example, the Victorian State Government has built monitoring, evaluation and adaptation components into its adaptation plan (Table 11.15a).

[START BOX 11.6 HERE]

Box 11.6: Rising to the Sea-Level Challenge

Many of the region's cities and settlements, cultural sites and place attachments are situated around harbours, estuaries and lowland rivers (Black, 2010; PCE, 2015; Australia SoE, 2016; Rouse et al., 2017; Hanslow et al., 2018; Birkett-Rees et al., 2020) exposed to ongoing relative sea-level rise (RSLR). RSLR includes regional variability in oceanic conditions (Zhang et al., 2017) and vertical land movement along New Zealand's tectonically dynamic coasts (Levy et al., 2020) and some Australian hotspots for subsidence (Denys et al., 2020; King et al., 2020; Watson, 2020).

Table Box 11.6.1: Observed and projected impacts from higher mean sea level

Impacts from increase in mean sea level	References
Nuisance and extreme coastal flooding have increased from higher mean sea level in New Zealand. Projected sea level rise will cause more frequent flooding in Australia and New Zealand before mid-century (*very high confidence*)	(Hunter, 2012; McInnes et al., 2016; Stephens et al., 2017; Stephens et al., 2020) (Steffen et al., 2014; PCE, 2015; MfE, 2017a; Hague et al., 2019; Paulik et al., 2020)
Squeeze in intertidal habitats (*high confidence)*	(Steffen et al., 2014; Peirson et al., 2015; Mills et al., 2016a; Mills et al., 2016b; Pettit et al., 2016; Rouse et al., 2017; Rayner et al., 2021)

Significant property and infrastructure damage (*high confidence*)	(Steffen et al., 2014; PCE, 2015; Harvey, 2019; LGNZ, 2019; Paulik et al., 2020) (Table Box 11.5.2) (Table Box 11.6.2)
Loss of significant cultural and archaeological sites and projected to compound with several hazards over this century (*medium confidence*)	(Bickler et al., 2013; Birkett-Rees et al., 2020; NZ Archaeological Association, 2020)
Increasing flood risk and water insecurity with health and well-being impacts on Torres Strait Islanders (*high confidence*)	(Steffen et al., 2014; McInnes et al., 2016; McNamara et al., 2017)
Degradation and loss of freshwater wetlands (*high confidence*)	(Pettit et al., 2016; Bayliss and Ligtermoet, 2018; Tait and Pearce, 2019; Grieger et al., 2020; Swales et al., 2020)

Coastal shoreline position is driven by a complex combination of natural drivers, past and present human interventions, climate variability (Bryan et al., 2008; Helman and Tomlinson, 2018; Allis and Murray Hicks, 2019) and variation in sediment flux (Blue and Kench, 2017; Ford and Dickson, 2018). RSLR, to date, is a secondary factor influencing shoreline stability (*medium confidence*), and in Australia no definitive sea-level rise signature is yet observed in shoreline recession, nor documented in New Zealand, due to variability in shoreline position responding to storms and seasonal, annual and decadal climate drivers (Australian Government, 2009; McInnes et al., 2016; Sharples et al., 2020).

The primary impacts of rising mean sea level (Table Box 11.6.1) are being compounded by climate-related changes in waves, storm surge, rising water tables, river flows and alterations in sediment delivery to the coast (*medium confidence*). The net effect is projected to increase erosion on sedimentary coastlines and flooding in low-lying coastal areas(McInnes et al., 2016; MfE, 2017a; Hanslow et al., 2018; Wu et al., 2018). Waves are projected to be higher in southern Australasia and lower elsewhere (Morim et al., 2019) and storm surge slightly higher in the south, slightly lower further north in New Zealand (Cagigal et al., 2019) and small robust declines along southern Australia, with potentially larger changes in the Gulf of Carpentaria (Colberg et al., 2019).

The cumulative direct and residual risk from RSLR and associated impacts are projected to continue for centuries, necessitating on-going adaptive decisions for exposed coastal communities and assets (MfE, 2017c; Oppenheimer et al., 2019; Tonmoy et al., 2019) (*high confidence*).

Table Box 11.6.2: Observed relative sea-level rise (variance-weighted average) with uncertainty range (standard deviation) and projected impacts on infrastructure and population of 1.1 m in Australia and 1 m in New Zealand. Sea-level rise projections for 2050 and 2090 are given in Table 11.3a and Table 11.3b.

Country	Observed relative sea-level rise	Projected impacts of sea-level rise (1.1m Australia; 1.0m New Zealand)			
		Value of coastal urban infrastructure	Number of buildings exposed	Number of residents exposed	Public council assets exposed

Australia	2.2±1.8 mm/year to 2018 for four >75-year records (or an average of 0.17 m over 75 years). 3.4 mm/year from 1993-2019 (Watson, 2020)	A$164 to >226 billion (DCCEE, 2011; Steffen et al., 2019) 111% rise in inundation cost from 2020-2100 (Mallon et al., 2019)	187,000 to 274,000 residential buildings, 5,800 to 8,600 commercial buildings, 3,700 to 6,200 light industrial buildings (DCCEE, 2011)	N/A	27,000 to 35,000 km of roads, and 1,200 to 1,500 km of rail lines and tramways (DCCEE, 2011)
New Zealand	1.8 mm/year from 1900-2018, 1.2 mm/year from 1900-1960 and 2.4 mm/year from 1961-2018 (Bell and Hannah, 2019)	NZ$25.5 billion (Paulik et al., 2020)	75,890 (Paulik et al., 2020)	105,580 (Paulik et al., 2020)	4000 km pipelines, 1440 km roads, 101 km rail, 72 km electricity transmission lines (Paulik et al., 2020) NZ$5 billion (2018) (reserves, buildings, utility networks, roads) (LGNZ, 2019)

Prevailing decision-making assumes shorelines can continue to be maintained and protected from extreme storms, flooding and erosion, even with RSLR (Lawrence et al., 2019a). Rapid coastal development has increased exposure of coastal communities and infrastructure (*high confidence*) (Helman and Tomlinson, 2018; Paulik et al., 2020) reinforcing perceptions of safety (Gibbs, 2015; Lawrence et al., 2015) and creating barriers to retreat and nature-based adaptations (Schumacher, 2020) (*very high confidence*). The efficacy and increasing costs of protection and accommodation risk reduction approaches, and rebuilding after extreme events have been questioned and have limits (PCE, 2015; MfE, 2017a; Harvey, 2019; LGNZ, 2019; Paulik et al., 2020; Haasnoot et al., 2021). Future shoreline erosion is often signalled by using defined coastal setback lines(s) and using probabilistic approaches to signal uncertainty (Ramsay et al., 2012; Ranasinghe, 2016).

Flooding from high spring ("king") tides or storm tides during extreme weather events are raising public awareness of sea-level rise (Green Cross Australia, 2012) including through media coverage (Priestley et al., 2021). The use of adaptive decision tools (11.7.3.1; Table 11.17) is increasing the understanding of changing coastal risk (Bendall, 2018; Lawrence et al., 2019b; Palutikof et al., 2019b) and how dynamic adaptive pathways and monitoring of them can aid implementation (Stephens et al., 2018; Lawrence et al., 2020b). Collaborative governance between local governments and their communities, including with Māori tribal organisations, is emerging in New Zealand (OECD, 2019b) assisted by national direction (DoC NZ, 2010) and guidance on adaptive planning (Table 11.15b). This shift from reactive to pre-emptive planning is better suited to ongoing RSLR (Lawrence et al., 2020b).

In Australia, adaptation to sea-level rise remains uneven across jurisdictions in the absence of clear Federal or State guidance, rendering Australia unprepared for flooding from sea-level rise (Dedekorkut-Howes et al., 2020). Risk-averse coastal governance at the local level has led to shifts in liabilities to other actors and to future generations (Jozaei et al., 2020). Managed retreat has emerged as an adaptation option in New Zealand (Rouse et al., 2017; Hanna, 2019; Kool et al., 2020; Lawrence et al., 2020c) where protective measures are transitional (DoC NZ, 2010) and where managed retreat has arisen from collaborative governance (Owen et al., 2018). Remaining adaptation barriers are social or cultural (the absence of licence and legitimacy) and institutional (the absence of regulations, policies and processes that support changes to existing property rights and the funding of retreat) (O'Donnell and Gates, 2013; Tombs et al., 2018; Grace et al., 2019; O'Donnell et al., 2019) (*high confidence*).

Legacy development, competing public and private interests, trade-offs among development and conservation objectives, policy inconsistencies, short and long-term objectives, and the timing and scale of impacts, compound to create contestation over implementation of coastal adaptation (Mills et al., 2016b; McClure and Baker, 2018; Dedekorkut-Howes et al., 2020; McDonald, 2020; Schneider et al., 2020) (*high confidence*). Legal barriers to coastal adaptation remain (Schumacher, 2020) with a risk that the courts become decision makers (Iorns Magallanes et al., 2018) due to legislative fragmentation, status quo leadership, lack of coordination between governance levels and agreement about who pays for what adaptation (Waters et al., 2014; Boston and Lawrence, 2018; Palutikof et al., 2019a; Noy, 2020) (*very high confidence*). The nexus of climate, law, place and property rights continues to expose people and assets to ongoing sea-level rise (Johnston and France-Hudson, 2019; O'Donnell, 2019), especially where the risks of sea-level rise are not being reflected in property valuations (Cradduck et al., 2020). Risk signalling through land use planning, flooding events, and changes in insurance availability and costs, are projected to increase recognition of coastal risks (Storey and Noy, 2017; CCATWG, 2018; Lawrence et al., 2018a; Harvey and Clarke, 2019; Steffen et al., 2019; Cradduck et al., 2020; ICNZ, 2021) (*medium confidence*). Proactive local-led engagement and strategy are key to effective adaptation and incentivising and supporting communities to act(Gibbs, 2020; Schneider et al., 2020). Adopting 'fit for purpose' decision tools that are flexible as sea levels rise (11.7.3) can build adaptive capacity in communities and institutions (*high confidence*).

[END BOX 11.6 HERE]

11.3.6 Health and Wellbeing

11.3.6.1 Observed Impacts

There is ample evidence of health loss due to extreme weather in Australia and New Zealand, and rising temperatures, changing rainfall patterns and increasing fire weather have been attributed to anthropogenic climate change (11.2.1). Extreme heat leads to excess deaths and increased rates of many illnesses (Hales et al., 2000; Nitschke et al., 2011; Lu et al., 2020). Between 1991 and 2011 it is estimated that 35-36% of heat-related mortality in Brisbane, Sydney and Melbourne was attributable to climate change, amounting to about 106 deaths a year on average over the study period (Vicedo-Cabrera et al., 2021). Exposure to high temperatures at work is common in Australia, and the health consequences may include more accidents, acute heat stroke and chronic disease (Kjellstrom et al., 2016). Long-term rise in temperatures is changing the balance of summer and winter mortality in Australia (Hanigan et al., 2021). The Black Summer wildfires in Australia in 2019/2020 (Box 11.1) caused 33 deaths directly (Davey and Sarre, 2020) and exposed millions of people to heavy particulate pollution (Vardoulakis et al., 2020). In the Australian States most heavily affected by the fires, 417 deaths, 3151 hospital admissions for cardiovascular or respiratory conditions, and about 1300 emergency department presentations for asthma are attributed to wildfire smoke exposure (Borchers Arriagada et al., 2020). Immediate smoke-related health costs from the 2019-20 fires are estimated at A$1.95 billion (Johnston et al., 2020).

Extreme heat is associated with decreased mental well-being, more marked in women than men (Ding et al., 2016). Changing climatic patterns in Western Australia have undermined farmers' sense of identity and place, heightened anxiety and increased self-perceived risks of depression and suicide (Ellis and Albrecht, 2017). Following the Black Saturday wildfires in Victoria in 2009, 10-15% of the population in the most severely affected areas reported persistent fire-related post-traumatic stress disorder, depression and psychological distress (Bryant et al., 2014). Repeated exposure to the threat of wildfires in Australia, either directly (Box 11.1) or through media coverage (Looi et al., 2020) may compound effects on mental health. In March 2017, 31,000 people in New South Wales and Queensland were displaced by Tropical Cyclone Debbie. Six months post-cyclone, adverse mental health outcomes were more common among those whose access to health and social care was disrupted (King et al., 2020).

Dengue fever remains a threat in northern Australia and variations in rainfall and temperature are related to disease outbreaks and patterns of spread, although most outbreaks are sparked by travellers bringing the virus into the country (Bannister-Tyrrell et al., 2013; Hall et al., 2021). Cases of dengue fever and other arboviral diseases have been increasing amongst recent arrivals to New Zealand from overseas, but to date there have been no reports of local transmission (Ammar et al., 2021).

In 2016 in New Zealand, it is estimated 6-8,000 people became ill due to contamination of the Havelock North water supply with the bacteria *Campylobacter* (Gilpin et al., 2020). The infection was traced to sheep faeces washed into the underground aquifer that feeds the town's (untreated) water supply after an extraordinarily heavy rainfall event. This is not an isolated finding: increases in pediatric hospital admissions are seen across New Zealand two days after heavy rainfall events (Lai et al., 2020).

11.3.6.2 Projected impacts

Climate change is projected to have detrimental effects on human health due to heat stress, changing rainfall patterns including floods and drought, and climate-sensitive air pollution (including that caused by wildfires) (*high confidence*). Vulnerability to detrimental effects of climate change will vary with socio-economic conditions (*high confidence*).

The greatest number of people affected by compounding effects of heat, wildfires and poor air quality will be in urban and peri-urban areas of Australia. By 2100 the proportion of all deaths attributable to heat in Melbourne, Sydney and Brisbane may rise from about 0.5% to 0.8% (under RCP 2.6), or 3.2% (under RCP 8.5) (Gasparrini et al., 2017). Heat-wave related excess deaths in Melbourne, Sydney and Brisbane are projected to increase to 300/year (RCP2.6) or 600/year (RCP8.5) during 2031-2080 relative to 142/year during 1971-2020, assuming no adaptation and high population growth (Guo et al., 2018). High temperatures amplify the risks due to local air pollution: without adaptation, ozone-related deaths in Sydney may increase by 50-60 per year by 2070 (Physick et al., 2014).

Unless there is more effective control of nutrient run-off, bacterial contamination of drinking water supplies is projected to increase due to more intense rainfall events, exacerbating risks to human health (Gilpin et al., 2020, Lai, 2020 #2680), and higher temperatures will increase freshwater toxic blooms (Hamilton et al., 2016).

Less certain climate change impacts include: surges in vector-borne diseases (*medium confidence*); threats to mental health (*medium confidence*); reduction in winter mortality (*medium confidence*); emergence of new or poorly understood weather-related threats (such as thunderstorm asthma or interactions between rising heat and air pollution) (*low confidence*); and spill-over effects on health from global impacts of climate change (e.g., on trade, conflict, migration) (*low confidence*).

In general, the area of Australia suitable for transmission of dengue is projected to increase (Zhang and Beggs, 2018; Messina et al., 2019) but estimates of local disease risk vary considerably according to climate change scenario and socio-economic pathways (Williams et al., 2016). The spread of *Wolbachia* amongst *Aedes* mosquitoes in northern Australia has already reduced dengue transmission and may decrease the influence of climate in the future (Ryan et al., 2019). In New Zealand, the risk of dengue remains low for the remainder of this century (Messina et al., 2019). Higher temperatures and more intense rainfall may also increase pollen production and the risk of allergic illness throughout the region (Haberle et al., 2014).

11.3.6.3 Adaptation

Strengthening basic public health services can rapidly reduce vulnerability to death and ill-health caused by climate change, however this opportunity is often missed (*very high confidence*). The 2020 New Zealand Health and Disability System Review pointed to short-comings in leadership and governance, structures that embed health inequity, lack of transparency in planning and reporting, and under-investment in public health personnel and systems (HDSR, 2020). An Australian study found that without deliberate planning the health system 'would only be able to deal with climate change in an expensive, *ad hoc* crisis management manner' (Burton, 2014). In both Australia and New Zealand the COVID-19 epidemic has highlighted weaknesses in information systems, primary care for marginalized groups and inter-sectoral planning (Salvador-Carulla et al., 2020; Skegg and Hill, 2021): all these deficiencies are relevant to climate adaptation.

Underlying health and economic trends affect the vulnerability of the population to extreme weather (*high confidence*). Poor housing quality is a risk factor for climate-related health threats (Alam et al., 2016). Homeless people lack access to temperature-controlled or structurally safe housing, and often are excluded from disaster preparation and responses (Every, 2016). These inequalities are reversible. For example, a government partnership with social housing providers in Australia improved the thermal performance of housing for low-income tenants (Barnett et al., 2014a). A postcode-level analysis of the vulnerability of urban populations to extreme heat in Australian capital cities (Loughnan et al., 2013) led to the development of an interactive website for purposes of planning and emergency preparedness (Figure 11.5) as well as subsequent work on green urban design for cooler, more liveable cities (Tapper, In Press).

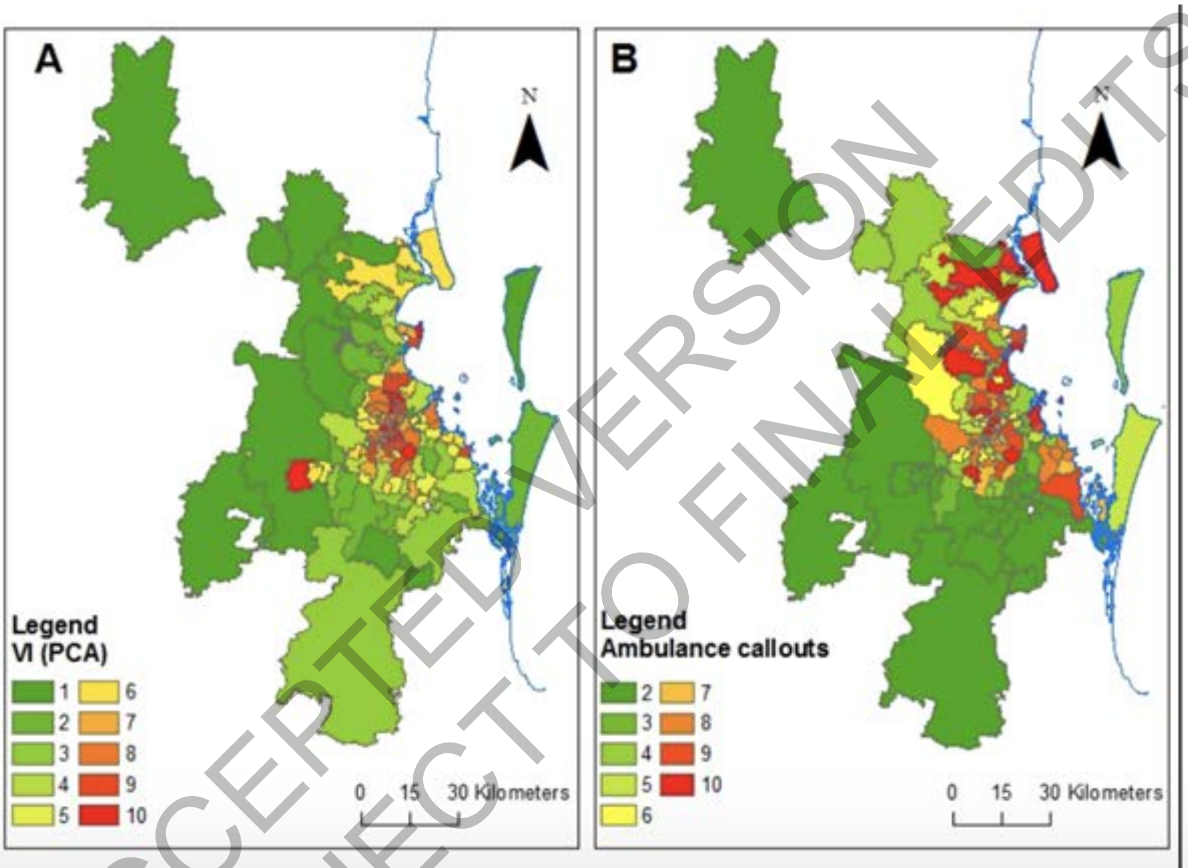


Figure 11.5: Housing and socio-economic disadvantage is correlated with the use of emergency services on hot days (rho = 0.55, $p<0.01$). The spatial distribution of (A) a community vulnerability index (VI (PCA) by deciles and (B) ambulance call-outs on days above daily mean of 34ºC, in Brisbane, Australia. Ambulance call-out data are expressed as deciles based on per-capita calls during 2003-2011 (Loughnan et al., 2013).

Heat-wave responses, from public education to formal heat-warning systems, are the best-developed element of adaptation planning for health in Australia, but many metropolitan centres are still not covered (Nicholls et al., 2016; Nitschke et al., 2016) (*high confidence*). Air conditioning (AC) in Australian homes reduces mortality in heat-waves by up to 80% (Broome and Smith, 2012) but heavy reliance on AC carries risks. It is estimated that a power outage on the third day of extreme heat-waves would result in an additional 10–21 deaths in Adelaide, 24–47 in Melbourne and 7–13 in Brisbane (Nairn and Williams, 2019). Multiple interventions at the landscape, building and individual scale are available to reduce the negative health effects of extreme heat (Jay et al., 2021)

Heat extremes receive most policy attention, but the numbers of deaths are less than those resulting from more frequent exposures to moderately high temperatures (Longden, 2019). Melbourne provides a case study in long-term planning for cooler cities, with its Urban Forest Strategy (Gulsrud et al., 2018). Australian workers' perceptions of heat and responses to high temperatures show that heat policies on their own are insufficient for full protection; workers also require knowledge and agency to slow down or take breaks on their own initiative (Singh et al., 2015; Lao et al., 2016).

The first national climate change risk assessment in New Zealand (MfE, 2020a) highlighted the risk to potable water supplies. An inquiry into the Havelock North outbreak recommended that all registered drinking water supplies (which supply about 80% of the national population) in New Zealand should be disinfected and have stronger oversight by a national regulatory body (Government Inquiry into Havelock North Drinking Water, 2017). The use of local and Indigenous knowledge strengthens interventions to protect water supplies to remote settlements that may be affected by climatic changes (Henwood, 2019).

Adaptation requires better protection of health facilities and supply chains, but hospital managers seldom have capacity to invest in long-term improvements in infrastructure (Loosemore et al., 2014). However, health services in the region are required to prepare disaster plans: these could be expanded to explicitly cover health adaptation and local threats from climate change, including flooding events (Rychetnik et al., 2019).

11.3.7 Tourism

11.3.7.1 Observed Impacts

Tourism is a major economic driver in the region, accounting for 3% (Australia) and 6% (New Zealand) of GDP pre-COVID-19 (WTTC, 2018). Climate change is having significant impacts on tourism due to the heavy reliance of the sector on natural heritage and outdoor attractions (11.3.1; Box 11.2). Furthermore, as Australia and New Zealand are both long-haul destinations, a global increase in 'flygskam' (flight shame) will to impact travel patterns (Becken et al., 2021).

Impacts of climate change are being observed across the tourism system (Scott et al., 2019a) (*high confidence*), most notably the Great Barrier Reef (Box 11.2) (Ma and Kirilenko, 2019). Australia's ski industry is very sensitive to climatic change, due to reduction in snow depth and the length of the snow season (Table 11.2) (Steiger et al., 2019; Knowles and Scott, 2020). The 2019-2020 summer wildfires (Box 11.1), impacted tourism and travel infrastructure, affecting air quality, vineyards and wineries (CoA, 2020e; Filkov et al., 2020). Global media coverage of the wildfires, alongside Australia's climate change policy response, profoundly and negatively, affected Australia's destination image (Schweinsberg et al., 2020; Wen et al., 2020). In New Zealand's South Island, Fox and Franz Josef Glaciers have retreated approximately 700m since 2008, with ice melt and retreat resulting in increased rock fall risks and negatively affecting the tourist experience (Purdie, 2013; Stewart et al., 2016; Wang and Zhou, 2019). The West Coast of New Zealand is extremely prone to flooding events impacting amenity values and access (Paulik et al., 2019b). Damage to tracks, huts and bridges have closed popular destinations, including the Hooker Glacier and the popular Routeburn and Heaphy Tracks during heavy rainfall events (Christie et al., 2020). Climate-driven damage is motivating 'last chance' tourism to see key natural heritage and outdoor attractions, e.g. Great Barrier Reef (Piggott-McKellar and McNamara, 2016) and Franz and Fox Glaciers (Stewart et al., 2016).

11.3.7.2 Projected Impacts

Widespread impacts from projected climate change are *very likely* across the tourism sector. The World Heritage listed Kakadu National Park in Australia is projected to experience increasing severity of cyclones (Turton, 2014) and sea-level rise is projected to affect freshwater wetlands (11.3.1.2; Table 11.5) (McInnes et al., 2015) and Indigenous rock art (Higham et al., 2016; Hughes et al., 2018a). The projected increase in the number of hot days in northern and inland Australia may impact the attractiveness of the region for tourists (Amelung and Nicholls, 2014; Webb and Hennessy, 2015). Coastal erosion and flooding of Australasian beaches due to sea-level rise and intensifying storm activity is estimated to increase by 60% on the Sunshine Coast by 2030 causing significant damage to tourist-related infrastructure (Hughes et al., 2018a). Urgent 'hard' and 'soft' adaptation strategies are projected to help reduce sea-level rise impacts (Becken and Wilson, 2016).

Glacier tourism, a multimillion-dollar industry in New Zealand, is potentially under threat because glacier volumes are projected to decrease (Purdie, 2013) (*very high confidence).* Glacier volume reductions of 50–92% by 2099 relative to present reflect the large range of temperature projections between RCP2.6 and RCP8.5. Under RCP2.6 at 2099, the glaciers retain a similar configuration to present, although clean-ice glaciers will retreat significantly. For RCP4.5, RCP6.0 and RCP8.5, the clean-ice glaciers will retreat to become small remnants in the high mountains (Anderson et al. 2021).

Snow skiing faces significant challenges from climate change (*high confidence*). In Australia, the annual maximum snow depth is estimated to decrease from current levels by 15% (2030) and 60% by 2070 (SRES A2) (Di Luca et al., 2018). By 2070-2099, relative to 2000-2010, the length of the Victorian ski-season is projected to contract by 65-90% under RCP8.5 (Harris et al., 2016). The New Zealand tourism destination of Queenstown is expected to experience declining snowfall, increased wind and more severe weather events (Becken and Wilson, 2016). Ski tourism stakeholders have been responding to longer-term climate risks with an increase in snow-making machines in New Zealand since 2013 (Hopkins, 2015) and in Australia (Harris et al., 2016).

11.3.7.3 Adaptation

Current snow-making technologies are expected to sustain the ski industry until mid-century. However, with warmer winter temperatures and declining water availability, snow-making is projected to decrease to half at most resorts by 2030 (Harris et al., 2016). New Zealand's ski industry may benefit from Australian skiers visiting New Zealand, due to lower relative vulnerability (Hopkins, 2015). However, tourists may substitute destinations or ski less in the absence of snow (*medium agreement, limited evidence*) (Cocolas et al., 2015; Walters and Ruhanen, 2015).

With the exception of the ski industry (Becken, 2013; Hopkins, 2015), tourism stakeholders generally focus on coping with short-term weather events, rather than longer-term climate risks, but do exhibit high adaptive capacity by diversifying their activities (Stewart et al., 2016). Post Covid-19 pandemic economics and recovery policies challenge this sector's prospects, and the combination of COVID-19 and climate change (e.g. fires, floods) has also highlighted the need for the tourism sector to be able to respond to multiple, overlapping crises.

There is limited evidence that research into the impact of climate change on tourism in Australia and New Zealand is translating into policy or action (Moyle et al., 2017). New Zealand government tourism sector strategies acknowledge this and the need for greater understanding of climate change for the sector, (TIA, 2019), but do not offer solutions (MBIE, 2019b; MfE, 2020a). The COVID-19 pandemic and the global pause of international travel offers an opportunity to potentially 'reset' tourism to account for the impacts of climate change (Prideaux et al., 2020).

11.3.8 Finance

11.3.8.1 Observed Impacts

The finance sector has significant exposure to climate variability and extreme events (*high confidence*). Aggregated insured losses from weather-related hazard events from 2013-2020 were almost A$15 billion for Australia (1.2% of GDP) and almost NZ$1 billion for New Zealand (0.4% of GDP) (ICA, 2020a; NIWA, 2020). However, there is no trend in normalised losses because the rising insurance costs are being driven by more people living in vulnerable locations with more to lose (McAneney et al., 2019). In New Zealand, two major hailstorms during 2014-2020 and three major floods during 2019-2021 caused significant insurance losses (ICNZ, 2021). Insured losses exceeded NZ$472 million for the 12 costliest floods from 2007-2017, of which NZ$140 million could be attributed to anthropogenic climate change (Frame et al., 2020). In Australia, insured damage was almost A$1.0 billion for the Queensland hailstorm in 2020, A$1.7 billion for east coast flooding in 2020, A$2.3 billion for the 2019-2020 fires, A$2.3 billion for the Queensland hailstorm in 2019, A$1.2 billion for the north Queensland floods in 2019, A$1.4 billion for the NSW hailstorm in 2018, A$1.8 billion for Cyclone Debbie in 2017 and A$1.5 billion for the Brisbane hailstorm in 2014 (ICA, 2020b). The insured loss from the seven costliest hailstorms in Australia from 2014-2021 totalled A$7.6 billion (ICA, 2021).

Some homes in the highest risk areas tend to be in lower socio-economic groups that may not buy insurance (Actuaries Institute, 2020). For example, one quarter of residents that experienced loss or damage in the 2019 Townsville floods did not have insurance (ACCC, 2020). Under-insurance reduces people's capacity to recover from adverse events, while over-reliance on private insurance undermines collective disaster recovery efforts (Lucas and Booth, 2020). In Australia, those in high-risk areas minimise house and contents insurance for financial reasons (Booth and Harwood, 2016; Osbaldison et al., 2019; Actuaries Institute, 2020). Insurance premiums in northern Australia are almost double those in the rest of Australia, and rising, mainly due to cyclone damage (ACCC, 2020).

11.3.8.2 Projected Impacts

Risks for the finance sector are projected to increase (*medium confidence*). The potential impact of increased coastal and inland flooding, soil desiccation and contraction, fire and wind could lead to higher insurance costs, reduced property values and difficulty for some customers to service loans (CBA, 2018). Under a high emission scenario (RCP8.5), estimated annual losses to home-lending customers may increase 27% by 2060, and the proportion of properties with high credit risk may rise from 0.01% in 2020 to 1% in 2060, assuming no change in the portfolio (CBA, 2018). In New Zealand, weather-related insurance claims between 2000–2017 totaled NZ$450 million, 40% of which were due to extreme rainfall. Using six climate model projections of extreme rainfall, the insured damage is projected to increase by 7% (RCP2.6) to 8% (RCP8.5) by 2020–2040 and 9% (RCP2.6) to 25% (RCP8.5) by 2080–2100, relative to 2000–2017 (Pastor-Paz et al., 2020). By 2050–2070, tropical cyclone risk for properties not in flood plains or storm surge zones in south-east Queensland may increase by 33% under a 2°C scenario, and by 317% under a 3°C scenario for properties in flood plains and storm surge zones (IAG, 2019).

11.3.8.3 Adaptation

Banks, insurers and investors increasingly recognise the risks posed by climate change to their businesses (Paddam and Wong, 2017) (*high confidence*). Collaborations between banks, insurers and superannuation funds in Australia and New Zealand are driving efforts aimed at achieving the Paris Agreement goals, including the New Zealand Centre for Sustainable Finance and Australian Sustainable Finance Initiative (AFSI, 2020; TAO, 2020; NZCFSF, 2021). Company directors including superannuation fund directors have legal obligations to disclose and appropriately manage material financial risks (Barker et al., 2016; Hutley and Davis, 2019). Financial regulators are aware of climate risks for financial stability and financial institutions (RBNZ, 2018; RBA, 2019) and are closely supervising climate risk disclosure practices (TCFD, 2017; RBNZ, 2018; APRA, 2019; CMSI, 2020; IGCC, 2021b). In Australia, regulatory action (APRA, 2021) includes issuing prudential guidelines for financial institutions on managing climate risk, aligned with guidelines developed by the Climate Measurement Standards Initiative (NESP ESCC, 2020). In New Zealand, the Financial Sector (Climate-related Disclosure and Other Matters) Amendment Bill aims to ensure that the effects of climate change are routinely considered in business, investment, lending, and insurance underwriting decisions (NZ Government, 2021).

Banks and insurers are beginning to undertake climate risk analyses (CRO Forum, 2019; Bruyère et al., 2020) and disclose their risks (Paddam and Wong, 2017; ANZ, 2018; CBA, 2018). For example, the agricultural banking sector has analysed climate risk and embedded climate adaptation financing into its risk scoring and lending practices (CBA, 2019). However, the overall number of disclosures continues to lag expectations, suggesting the need for mandatory climate risk disclosure in Australia (IGCC, 2021a).

Climate adaptation finance is not evident (*medium confidence*). There is an adaptation finance gap (Mortimer et al. 2020). Private sector initiatives are beginning to emerge through large scale projects or public-private partnerships, such as the Queensland Betterment Fund (Banhalmi-Zakar et al., 2016; Ware and Banhalmi-Zakar, 2020). Addressing investor pressure (IGCC, 2017) could increase investment in adaptation. However, ongoing policy uncertainty in Australia continues to be the key barrier to allocating further capital to invest in climate solutions for 70% of investors (IGCC, 2021a).

Current and future insurance affordability pressures could be addressed by increased mitigation, revisions to building codes and standards, and better land-use planning (ACCC, 2020; Actuaries Institute, 2020). In New Zealand, insurance signals are motivating the government to address adaptation funding mechanisms (Boston and Lawrence, 2018; CCATWG, 2018). Some insurers offer premium discounts to customers with reduced risk (Drill et al., 2016) with increasing premiums reflecting known risk and no cover for some hazards in risky locations (CCATWG, 2017). Special excess payments are available for flood hazard so customers take responsibility for part of the claim, with increasing premiums to reflect known and foreseeable risk, and downgrading cover from replacement value to market value (Bruyère et al., 2020). Retreat by private insurers from risky locations could increase the unfunded fiscal risk to the government (Storey and Noy, 2017) creating moral hazard (Boston and Lawrence, 2018). The litigation risk from failing to take adaptation action (Hodder, 2019) could affect financial markets and government policy settings, creating cascading impacts across society (Lawrence et al., 2020b)(CRO Forum, 2019). For some climate risks, national governments act as "last resort" insurers (CCATWG, 2017), but this could become unsustainable (CRO Forum, 2019).

11.3.9 Mining

Many mines are exposed and sensitive to climate extremes (*high confidence*), but there is little available research on climate change impacts (Odell et al., 2018). Most Australian mines face higher temperatures, cyclones, erosion and landslides, and hazards such as sea-level rise and storms across their supply chains, including ports (Cahoon et al., 2016). Impacts include operational disruptions such as acute drainage problems (Loechel and Hodgkinson, 2014) and heat-induced illness, irritation and absenteeism among workers (McTernan et al., 2016), lost revenue and increased costs (Pizarro et al., 2017).

Damage and disruption from climate impacts can cost operators billions of dollars (Cahoon et al., 2016). Climatic extremes increase the risk and impact of spillages along transportation routes (Grech et al., 2016) exacerbate mining's effects on hydrology, ecosystems, and air quality (Phillips, 2016; Ali et al., 2018); increase contamination risks (Metcalfe and Bui, 2016); and disrupt and slow mine site rehabilitation (Wardell-Johnson et al., 2015; Hancock et al., 2017). Adaptations such as improved water management are emerging slowly (Gasbarro et al., 2016; Becker et al., 2018). Some companies are spatially diversifying and relocating (Hodgkinson et al., 2014). Others are replacing workers with automation and remote operations (Halteh et al., 2018; Keenan et al., 2019).

11.3.10 Energy

Australia's energy generation is a mix of coal (56%), gas (23%) and renewables (21%) (DISER, 2020), with ageing coal-fired infrastructure being replaced with a growing proportion of renewable and distributed energy resources (AEMO, 2018). In New Zealand, 60% of energy generation comes from hydro-electricity and 15% from geothermal (MBIE, 2021), with coal (2%) and gas (13%) generation capacity to be retired, and total renewable energy to increase from 82% in 2017 to around 95% by 2050, mostly through wind generation (MBIE, 2019a).

11.3.10.1 Observed Impacts

The energy sector is highly vulnerable to climate change (*high confidence*). Oil and gas systems are vulnerable to storms, fires, drought, floods, sea-level rise, extreme heat and fires which can damage infrastructure, slow production, and add to operational costs (Smith, 2013). The electricity system is vulnerable to high temperatures reducing generator and network capacity and increasing failure rates and maintenance costs(AEMO, 2020a). Fires (including those sparked by electrical distribution lines) pose risks to assets, smoke can cause electricity transmission to trip, high winds reduce wind-energy capacity and threaten the integrity of transmission lines, low rainfall reduces hydro-energy capacity and increases the demand for desalination energy, higher sea-level may affect some low-lying generation, distribution and transmission assets, and compound extreme weather events can cause outages (Vose and Applequist, 2014; Lawrence et al., 2016; AEMO, 2020b; AEMO, 2020a; ESCI, 2021). For example, in September 2016, a major windstorm in South Australia damaged 23 transmission towers and cut power to over 900,000 households. In February 2017, the South Australian energy system failed to cope with a heatwave-related jump in demand, causing power cuts to 40,000 homes (Steffen et al., 2017). In April 2018, a storm over

Auckland New Zealand left 182,000 properties without power (Bell, 2018). The 2019/20 Australian heatwaves and fires caused widespread blackouts that disrupted communications, transport, and emergency response capacity (Box 11.1).

11.3.10.2 Projected Impacts

Risks for the energy sector are projected to increase with climate change (*medium confidence*). Projected increases in the frequency and intensity of heatwaves, fires, droughts and wind-storms would increase risks for energy supply and demand (AEMO, 2020b; ESCI, 2021). Households are unevenly vulnerable to energy sector risks due to varying housing quality and health dependencies (11.3.6). In New Zealand, a warmer climate and increasing energy efficiency is projected to marginally reduce annual average peak electricity heating demand (Stroombergen et al., 2006; MBIE, 2019a). Winter and spring inflows to main hydro lakes are projected to increase 5-10% and may reduce hydroelectric energy vulnerability (McKerchar and Mullan, 2004; Poyck et al., 2011; Stevenson et al., 2018). However, major electricity supply disruptions are projected to increase as dependence on electricity grows from 25% of total energy in 2016 to 58% in 2050 (Transpower, 2020).

In Australia, the total heating and cooling energy demand of 5-star energy-rated houses is projected to change by 2100 (Wang et al., 2010). At 2°C global warming, the estimated change in demand is –27% in Hobart, –21% in Melbourne, +61% in Darwin, +67% in Alice Springs and +112% in Sydney. For a 4°C global warming, the changes are –48%, –14%, +135%, +213% and +350% respectively.

11.3.10.3 Adaptation

Options to manage risks include adaptation of energy markets, integrated planning, improved asset design standards, smart-grid technologies, energy generation diversification, distributed generation (e.g. roof-top solar, micro-grids), energy efficiency, demand management, pumped hydro storage, battery storage, and improved capacity to respond to supply deficits and balance variable energy resources across the network (Table 11.8) (*high confidence*). With increasing electrification, diversification and resilience can contribute to security of supply as fossil fuels are retired from the energy mix (AEMO, 2020b). In Australia, the AEMO (2020) Integrated System Plan has evaluated various options, costs and benefits. Risks associated with an increasing reliance on weather-dependent renewable energy (e.g. solar, wind, hydro) (ESCI, 2021) can be managed through strong long-distance interconnection via high voltage powerlines and storage (Blakers et al., 2017; Blakers et al., 2021; Lu et al., 2021). However, implementation of adaptation options remains inadequate (Gasbarro et al., 2016).

Table 11.8: Adaptation options for the energy sector.

Adaptation options	References
Diversification of electricity supplies geographically and technically, including distributed energy resources and variable renewable energy	(AEMO, 2020b)
Integrated planning, improved asset design and management, and disaster recovery to build resilience to more extreme weather	(AEMO, 2020b; Transpower, 2020)
Augmentation of transmission grid to support change in generation mix using interconnectors and renewable energy zones, coupled with energy storage, adds capacity and helps balance variable resources across the network	(Blakers et al., 2017; ICCC, 2019; AEMO, 2020b)
Climate change risks included in the design, location, and rating of future infrastructure and consideration of the implications for future transmission developments	(Bridge et al., 2018; AEMO, 2020b)
Increased design and construction standards, flood defence measures, insurance, improved water efficiency, improved insulation of super-cooled LNG processes, more efficient air conditioning and creating fire breaks for the oil and gas sector	(Smith, 2013; Gasbarro et al., 2016)

Technological developments to strengthen existing resilience under climate change that reinforces the relative advantage of Western Australia and Tasmania for new wind energy installations	(Evans et al., 2018)
Energy generation diversity, demand management, pumped hydro storage and battery storage	(Keck et al., 2019; Transpower, 2020)
Tools and strategies to manage winter energy deficits and dry years alongside renewable electricity generation deployment	(Transpower, 2020)
Improved insulation and heating of buildings, and flexible electricity consumption to reduce the significance of winter electricity demand peak	(Stroombergen et al., 2006; MBIE, 2019a; Transpower, 2020)

11.3.11 Detection and Attribution of Observed Climate Impacts

Detection and attribution of observed climate trends and events is called 'climate attribution'. This has been assessed by IPCC Working Group I (Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021) and summarised in IPCC Working Group 2 Chapter 16. Trends that have been formally attributed in part to anthropogenic climate change include regional warming trends and sea-level rise, decreasing rainfall and increasing fire risk in southern Australia. Events include extreme rainfall in New Zealand during 2007-2017, the 2007/8 and 2012/13 droughts in New Zealand, high temperatures in Australia during 2013-2020, the 2016 northern Australian marine heatwave, the 2016/2017 and 2017/18 Tasman Sea marine heatwaves, and 2019/2020 fires in Australia.

Detection and attribution of climate impacts on natural and human systems is called 'impact attribution'. This often involves a two-step approach (joint attribution) that links climate attribution to observed impacts. Impact attribution is complicated by confounding factors, e.g. changes in exposure arising from population growth, urban development and underlying vulnerabilities.

Impact attribution has been considered in Sections 11.3.1 to 11.3.10 and summarised in Table 11.9. More literature is available for natural systems than human systems, which represents a knowledge gap rather than an absence of impacts that are attributable to anthropogenic climate change. Fundamental shifts in the structure and composition of some ecosystems are partly due to anthropogenic climate change (*high confidence*). In human systems, the costs of droughts and floods in New Zealand, and heat-related mortality and fire damage in Australia, are partly attributed to anthropogenic climate change (*medium confidence*).

Table 11.9: Examples of observed impacts that can be partly attributed to climate change.

Impact	Source
Mass bleaching of the Great Barrier Reef in 2016/2017 due to a marine heatwave	Box 11.2
In the New Zealand Southern Alps, extreme glacier mass loss was at least six times more likely in 2011, and ten times more likely in 2018, due to warming	11.2.1, 11.3.3
In the Australian Alps bioregion, loss of habitat for endemic and obligate species due to snow loss and increases in fire, drought and temperature	Table 11.4
In the Australian wet tropics world heritage area, some vertebrate species have declined in distribution area and population size due to increasing temperatures and length of dry season	Table 11.4
Extinction of Bramble Cay melomys due to loss of habitat caused by storm surges and sea-level rise in Torres Strait	Table 11.4
In New Zealand, increasing invasive predation pressure on endemic forest birds surviving in cool forest refugia due to anthropogenic warming	Table 11.4
In New Zealand, erosion of coastal habitats due to more severe storms and sea-level rise	Table 11.4, Box 11.6

In Australia, estuaries warming and freshening with decreasing pH	Table 11.6
Changes in life-history traits, behaviour or recruitment of fish and invertebrates due to ocean acidification or warming, severe decline in recruitment of coral on the Great Barrier Reef due to ocean warming, aquaculture stock deaths due to heat stress	Table 11.6
New diseases and toxins due to warming and extension of East Australian Current	Table 11.6
Changes in almost 200 marine species distributions and abundance due to ocean warming	Table 11.6
Temperate marine species replaced by seaweeds, invertebrates, corals and fishes characteristic of subtropical and tropical waters	Table 11.6
River flow decline in southern Australia is largely due to the decline in cool season rainfall partly attributed to anthropogenic climate change	11.3.3
In New Zealand, the 2007/08 drought and the 2012/13 drought were 20% attributed to anthropogenic climate change	11.3.3
In New Zealand, about 30% of the insured damage for the 12 costliest flood events from 2007-2017 can be attributed to anthropogenic climate change	11.3.8
In Australia, 35-36% of heat-related excess mortality in Melbourne, Sydney and Brisbane from 1991-2018 can be attributed to anthropogenic climate change	11.3.6

11.4 Indigenous Peoples

Indigenous perspectives of well-being embrace physical, social, emotional and cultural domains, collectiveness and reciprocity, and more fundamentally connections between all elements across the past, present and future generations (Australia. NAHS Working Party, 1989; MfE, 2020a). Changing climate conditions are expected to exacerbate many of the social, economic and health inequalities faced by Aboriginal and Torres Strait Islander Peoples in Australia and Māori in New Zealand (Bennett et al., 2014; Hopkins et al., 2015; AIHW, 2016; Lyons et al., 2019) (*high confidence*). As a consequence, effective policy responses are those that take advantage of the interlinkages and dependencies between mitigation, adaptation and Indigenous Peoples' wellbeing (Jones, 2019) and those that address the transformative change needed from colonial legacies (Hill et al., 2020) (*high confidence)*. There is a central role for Indigenous Peoples in climate change decision making that helps address the enduring legacy of colonisation through building opportunities based on Indigenous governance regimes, cultural practices to care for land and water, and intergenerational perspectives (Nursey-Bray et al., 2019; Petzold et al., 2020) (Cross-Chapter Box INDIG in Chapter 18) (*very high confidence*).

11.4.1 Aboriginal and Torres Strait Islander Peoples of Australia

The highly diverse Aboriginal and Torres Strait Islander Peoples of Australia have survived and adapted to climate changes such as sea-level rise and extreme rainfall variability during the late Pleistocene era, through intimate place-based Indigenous Knowledge in practice and while losing traditional land and sea Country ownership (Liedloff et al., 2013) (Cross-Chapter-Box INDIG in Chapter 18) including during the Late Pleistocene era (Golding and Campbell, 2009; Nunn and Reid, 2016). They belong to the world's oldest living cultures, continually resident in their own ancestral lands, or 'country', for over 65,000 years (Kingsley et al., 2013; Marmion et al., 2014; Nagle et al., 2017; Tobler et al., 2017; Nursey-Bray and Palmer, 2018). The majority of the Australian Indigenous Peoples live in urban areas in southern and eastern Australia, but are the predominant population in remote areas.

Climate-related impacts on Aboriginal and Torres Strait Islander Peoples, Countries (traditional estates) and cultures have been observed across Australia and are pervasive, complex and compounding(Green et al., 2009) (11.5.1) (*high confidence*). For example, loss of bio-cultural diversity, nutritional changes through availability of traditional foods and forced diet change, water security, and loss of land and cultural resources through erosion and sea-level rise (Table 11.10)](TSRA, 2018). Moreover, these impacts are being experienced now particularly in low-lying geographical areas- especially in the Torres Strait Islands (Mosby, 2012; Kelly, 2014; Murphy, 2019; Hall et al., 2021). Estimates of the loss from fire impacts on ecosystem services that contribute to the wellbeing of remotely-located Indigenous Australians were found to be higher than the financial impacts from the same fires on pastoral and conservation lands (Sangha et al., 2020) and could increase with both financial and non-financial impacts (Box 11.1).

Table 11.10: Climate-related impacts on Aboriginal and Torres Strait Islander Peoples, country and cultures.

Impacts	Implications
Loss of bio-cultural diversity (land, water and sky) (*medium confidence*)	Healthy country is critical to Indigenous Australians' livelihoods, caring for country responsibilities, health and wellbeing. Damage to land can magnify the loss of spiritual connection to land from dispossession from traditional Country and leads to disruption of cultural structures. Climate change impacts can exacerbate and/or accelerate existing threats of habitat degradation and biodiversity loss, and create challenges for traditional stewardship of landscapes (Mackey and Claudie, 2015)
Climate-driven loss of native title and other customary lands (*medium confidence*)	Traditional coastal lands lost through erosion and rising sea level, with associated mental health implications from loss of cultural and traditional artefacts and landscapes, including the destruction and exhumation of ancestral graves and burial grounds. This is also occurring and predicted to intensify in the low-lying islands of the Torres Strait (TSRA, 2018; Hall et al., 2021) and was also noted during the extreme bushfires in Eastern Australia in late 2019 and early 2020.
Changing availability of traditional foods and forced diet change (*medium confidence*)	Human health impacts can be exacerbated by climate change through changing availability of traditional foods and medicines, while outages and high costs of electricity can limit storage of fresh food and medication (Kingsley et al., 2013; Spurway and Soldatic, 2016; Hall and Crosby, 2020)
Changing climatic conditions for subsistence food harvesting (*medium confidence*)	Climate change-induced sea-level rise and saltwater intrusion can limit the capacity for traditional Indigenous floodplain pastoralism, and also affect food security, access and affordability to healthy, nutritional food (Ligtermoet, 2016; Spurway and Soldatic, 2016)
Extreme weather events triggering disasters (*high confidence*)	Increasing frequency or intensity of extreme weather events (floods, droughts, cyclones, heatwaves) can cause disaster responses in remote communities, including infrastructure damage of essential water and energy systems and health facilities (TSRA, 2018; Hall and Crosby, 2020)
Heatwave impacts on human health (*high confidence*)	Heatwaves can occur in many regions. Tropical regions can experience prolonged seasons of high temperatures and humidity levels, resulting in extreme heat stress risks. For example, the Torres Strait Island are already categorised under the U.S. National Oceanic and Atmospheric Administration (NOAA) Heat Index as a danger zone for extreme human health risk during Summer (TSRA, 2018)
Health impacts from changing conditions for vector-borne diseases (*high confidence*)	Climate change can change exposure and increase risk for remote Indigenous Peoples to infection from waterborne and insect-borne diseases, especially if medical services are limited or damaged by extreme weather events. For example, in the Torres Strait Islands the changing climate is affecting the range and extension of the Aedes albopictus and Aedes aegypti mosquitoes that can carry and transmit dengue and other viruses (Horwood et al., 2018; TSRA, 2018)
Unadaptable infrastructure for changing environmental conditions (*high confidence*)	Poorly-designed, inferior quality and unmaintained housing can create health challenges for tenants in extreme heat (Race et al., 2016). Essential community-scale water and energy service infrastructure, unpaved roads, sea walls and storm water drains can fail in extreme weather events (McNamara et al., 2017)

Drinking water security (*medium confidence*)	Predicted continued increases in arid conditions in Australia are expected to reduce the recharge rate of finite groundwater supplies (Barron et al., 2011). For remote communities reliant on groundwater for drinking supplies, this water insecurity creates vulnerabilities from over-extraction and lack of access (Jackson et al., 2019; Hall and Crosby, 2020). This groundwater can also have microbial contamination from sewage and chemicals supporting bacterial growth, such as high iron levels supporting the growth of *Burkholderia pseudomallei* that causes melioidosis in humans and animals (Kaestli et al., 2019). In the Torres Strait, increasing reliance on desalination for drinking water raises costs for fuel and its associated transport (Beal et al., 2018)

Due to ongoing impacts of colonisation, Aboriginal and Torres Strait Islander Peoples have, on average, lower income, poorer nutrition, lower school outcomes and employment opportunities, and higher incarceration and removal of children than non-Indigenous Australians, represented in high comorbidities of chronic diseases and mental health impacts (Marmot, 2011; Green and Minchin, 2014; AIHW, 2015). This relative poverty can reduce climate-adaptive capacities while exacerbating climate change vulnerabilities (Nursey-Bray and Palmer, 2018). In remote Country, this can combine with lack of security for food and water, non-resilient housing and extreme weather events, contributing to migration off traditional Country and into towns and cities- with flow-on social impacts such as homelessness, dislocation from community and family, and disconnection from country and spirituality (Mosby, 2012; Brand et al., 2016).

Recognition of the role Aboriginal and Torres Strait Islander Peoples in identifying solutions to the impacts of climate change is slowly emerging (UN, 2018) having been largely excluded from meaningful representation from the conception of climate change dialogue, through to debate and decision-making (Nursey-Bray et al., 2019). Honouring the United Nations' Declaration on the Rights of Indigenous Peoples and social justice values would support self-determination and the associated opportunity for Indigenous Australians to develop adaptation responses to climate change (Langton et al., 2012; Nursey-Bray and Palmer, 2018; Nursey-Bray et al., 2019), including the adaptive capacity opportunities available through Indigenous Knowledge (Liedloff et al., 2013; Petheram et al., 2015; Stewart et al., 2019) (Cross-Chapter Box INDIG in Chapter 18). The Uluru Statement from the Heart proposes a pathway and roadmap forward for enhanced representation of Aboriginal and Torres Strait Islander Peoples in decision-making in Australia (Ululru Statement, 2017). Table 11.11 provides examples of traditional Indigenous practices of adaptation to a changing climate. However, due to Indigenous methods of knowledge sharing and knowledge holding, such knowledge relies disproportionately on elders and seniors, who form a very small portion of the total Aboriginal and Torres Strait Islander Peoples of Australia, and is limited in the formal literature (ABS, 2016).

Table 11.11: Examples of Aboriginal and Torres Strait Islander Peoples' practices of adaptation to a changing climate

'Caring for Country': Traditional Practices for Holistic Land and Cultural Protection and Adaptation in a Changing Climate	Source
Indigenous Protected Area (IPA) management plans enable culturally and ecologically compatible development that contribute to local Indigenous economies	(Mackey and Claudie, 2015).
IPAs can avoid the potential for 'nature–cultures dualism' that locks out Indigenous access in some protected area legislation, as they are based on relational values informed by local Indigenous Knowledge	(Lee, 2016)
Fire management using cultural practices can achieve greenhouse gas emission targets while also maintaining Indigenous cultural heritage.	(Robinson et al., 2016)
Indigenous Ranger programmes provide a means for Indigenous-guided land management, including for fire management and carbon abatement, fauna studies, medicinal plant products, weed management and recovery of threatened species	(Mackey and Claudie, 2015)

Faunal field surveys can engage local, bounded and fine-scale intuitive species location by Indigenous knowledge holders and their knowledge used for conservation planning	(Wohling, 2009; Ziembicki et al., 2013)
Cultural flows in waterways are a demonstration of cultural knowledge, values and practice in action as they are informed by Indigenous knowledge, bound by water-dependent values, and define when and where water is to be delivered - particularly in a changing climate.	(Bark et al., 2015; Taylor et al., 2017)

11.4.2 Tangata Whenua – New Zealand Māori

Māori society faces diverse impacts, risks and opportunities from climate change (Table 11.12). Studies exploring climate change impacts, scenarios, policy implications, adaptation options and tools for Māori society have increased substantially e.g. (King et al., 2012; Bargh et al., 2014; Jones et al., 2014; Bryant et al., 2017; Awatere et al., 2018; Colliar and Blackett, 2018). Māori priorities surrounding climate change risks and natural resource management have been articulated in planning documents by many Māori kin-groups e.g. (Ngāti Tahu- Ngāti Whaoa Rūnanga Trust, 2013; Raukawa Settlement Trust, 2015; Ngai-Tahu, 2018; Te Urunga Kea - Te Arawa Climate Change Working Group, 2021) reflecting the importance of reducing vulnerability and enhancing resilience to climate impacts and risks through adaptation and mitigation.

Māori have long-term interests in land and water and are heavily invested in climate sensitive sectors (agriculture, forestry, fishing, tourism and renewable energy) (King et al., 2010). Large proportions of collectively owned land already suffer from high rates of erosion (Warmenhoven et al., 2014; Awatere et al., 2018) which are projected to be exacerbated by climate change induced extreme rainfalls (RSNZ, 2016; Awatere et al., 2018) (*high confidence*). Changing drought occurrence, particularly across eastern and northern New Zealand, is also projected to affect primary sector operations and production (King et al., 2010; Smith et al., 2017; Awatere et al., 2018) (*medium confidence*). Further, many Māori-owned lands and cultural assets such as marae and urupa are located on coastal lowlands vulnerable to sea-level rise impacts (Manning et al., 2014; Hardy et al., 2019) (*high confidence*). Māori tribal investment in fisheries and aquaculture faces substantial risks from changes in ocean temperature and acidification, and the downstream impacts for species distribution, productivity and yields (Law et al., 2016) (*medium confidence*). A clearer understanding of climate change risks and the implications for sustainable outcomes can enable more informed decisions by tribal organisations and governance groups.

Changing climate conditions are projected to exacerbate health inequities faced by Māori (Bennett et al., 2014; Jones et al., 2014; Hopkins, 2015) (*medium confidence*). The production and ecology of some keystone cultural flora and fauna may be impacted by projected warming temperatures and reductions in rainfall (RSNZ, 2016; Bond et al., 2019; Egan et al., 2020) (*medium confidence*). Obstruction of access to keystone species is expected to adversely impact customary practice, cultural identity and well-being (Jones et al., 2014; Bond et al., 2019)(*medium confidence*). Social-cultural networks and conventions that promote collective action and mutual support are central features of many Māori communities, and these practices are invaluable for initiating responses to, and facilitating recovery from, climate stresses and extreme events (King et al., 2011; Hopkins et al., 2015). Māori tribal organisations have a critical role in defining climate risks and policy responses (Bargh et al., 2014; Parsons et al., 2019) as well as entering into strategic partnerships with business, science, research and government to address these risks (Manning et al., 2014; Beall and Brocklesby, 2017; CCATWG, 2017) (*high confidence*).

More integrated assessments of climate change impacts, adaptation and socio-economic risk for different Māori groups and communities, in the context of multiple stresses, inequities and different ways of knowing and being (King et al., 2013; Schneider et al., 2017; Henwood, 2019) would assist those striving to evaluate impacts and risks, and how to integrate these assessments into adaptation plans (*high confidence*). Better understanding of the social, cultural and fiscal implications of sea-level rise is urgent (PCE, 2015; Rouse et al., 2017; Colliar and Blackett, 2018), including what duties local and central Government might have with respect to actively upholding Māori interests under the Treaty of Waitangi (Iorns Magallanes, 2019) (*high confidence*). Intergenerational approaches to climate change planning will become increasingly important, elevating political discussions about conceptions of rationality, diversity and the rights of non-human entities (Ritchie, 2013; Carter et al., 2018; Ruru, 2018; Munshi et al., 2020) (*high confidence*).

Table 11.12: Climate-related impacts and risks for Tangata Whenua New Zealand Māori

Impact	Risks
Changes in drought occurrence and extreme weather events	Risks to Māori tribal investment in forestry, agriculture and horticulture sector operations and production, particularly across eastern and northern New Zealand (King et al., 2010; Awatere et al., 2018; Hardy et al., 2019)(*medium confidence*)
Changes in rainfall, temperature, drought, extreme weather events and ongoing sea-level rise	Risks to potable water supplies (availability and quality) for remote Māori populations (RSNZ, 2016; Henwood, 2019)(*medium confidence*)
Changes in rainfall, temperature, drought, extreme weather events and ongoing sea-level rise	Risks of exacerbating existing inequities (e.g. health, economic, education and social services), social cohesion and well-being (Bennett et al., 2014; Jones et al., 2014)(*medium confidence*)
Changes in rainfall regimes and more intense drought combined with degradation of lands and water	Risks to the distribution and survival of cultural keystone flora and fauna, as well as cascading risks for Māori customary practice, cultural identity and well-being (King et al., 2010; RSNZ, 2016; Bond et al., 2019)(*high confidence*)
Changes in ocean temperature and acidification	Risks to nearshore and ocean species productivity and distribution, as well as cascading risks for Māori tribal investment in the fisheries and aquaculture sectors (King et al., 2010; Law et al., 2016)(*medium confidence*)
Sea-level rise induced erosion, flooding and saltwater intrusion	Risks to Māori-owned coastal lands and economic investment as well as risks to community wellbeing from displacement of individuals, families and communities (Manning et al., 2014; Smith et al., 2017; Hardy et al., 2019)(*high confidence*)
Sea-level rise induced erosion, inundation and saltwater intrusion	Risks to Māori cultural heritage as well as cascading risks for tribal identity and spiritual well-being (King et al., 2010; Manning et al., 2014; RSNZ, 2016)(*medium confidence*)
Impacts of climate change, adaptation and mitigation actions	Risks that governments are unable to uphold Māori interests, values and practices under the Treaty of Waitangi, creating new, modern-day breaches of the Treaty of Waitangi (Iorns Magallanes, 2019; MfE, 2020a)(*high confidence*)

11.5 Cross-Sectoral and Cross-Regional Implications

The impacts and adaptation processes described in sections 11.3 and 11.4 are focused on specific sectors, systems and Indigenous Peoples. Added complexity, risk and adaptation potential stem from cross-sectoral and cross-regional inter-dependencies.

11.5.1 Cascading, compounding and aggregate impacts

11.5.1.1 Observed Impacts

Climate impacts are cascading, compounding and aggregating across sectors and systems due to complex interactions (*high confidence*) (Pescaroli and Alexander, 2016; Challinor et al., 2018; Zscheischler et al., 2018; Steffen et al., 2019; AghaKouchak et al., 2020; CoA, 2020e; Lawrence et al., 2020b; Simpson et al., 2021) (Box 11.1; Box 11.3; Box 11.4; Box 11.5; Box 11.6). Cascading impacts propagate via interconnections and systemic factors, including supply chains, shared reliance on connected biophysical systems (e.g. water catchments and ecosystems), infrastructure and essential goods and services, and the exercise of governance, leadership, regulation, resources and standard practices (e.g. in planning and building codes), including lock-in of past decisions and experience (CSIRO, 2018; Lawrence et al., 2020b). The capacity of critical systems such as Information, Communication and Technology, water infrastructure, health care, electricity and transport networks are being stretched, with impacts cascading to other systems and places, exacerbating existing hazards and generating new risks (Cradock-Henry, 2017) (11.3.6;11.3.10; Box 11.1). Temporal or spatial overlap of hazards (e.g. drought, extreme heat and fire; drought followed by extreme rainfall) are compounding impacts (Zscheischler et al., 2018) and affecting multiple sectors.

In Australia, extreme events such as heatwaves, droughts, floods, storms and fires have caused deaths and injuries (Deloitte, 2017a) (11.3.5.1), and affected many households, communities and businesses via impacts on ecosystems, critical infrastructure, essential services, food production, the national economy, valued places and employment. This has created long-lasting impacts (e.g. mental health, homelessness, health incidents and reduced health services) (Brown et al., 2017; Brookfield and Fitzgerald, 2018; Rychetnik et al., 2019) and reduced adaptive capacity (Friel et al., 2014; O'Brien et al., 2014; Ding et al., 2015; CoA, 2020e) (Box 11.1, Box 11.3, 11.3.1-11.3.10).

In New Zealand, extreme snow, rainfall and wind events have combined to impact road networks, power and water supply, and have impeded interdependent wastewater and stormwater services and business activities (Deloitte, 2019; Lawrence et al., 2020b; MfE, 2020a) (Box 11.4). Community and infrastructure services are periodically disrupted during extreme weather events, triggering impacts from the interdependencies across enterprises and individuals (Glavovic, 2014; Paulik et al., 2021).

Slow onset climate change impacts have also had cascading and compounding effects. For example, degradation of the Great Barrier Reef by ocean heating, acidification and non-climatic pressures (Marshall et al., 2019), repeated pluvial, fluvial and coastal flooding of some settlements (Paulik et al., 2019a; Paulik et al., 2020), long droughts and water insecurity in rural communities (Tschakert et al., 2017), and the gradual loss of species and ecological communities, have caused substantial ecological, social and economic losses. Indigenous peoples have especially been impacted by multiple and complex losses (Johnson et al., 2021) (11.4).

11.5.1.2 Projected Impacts

Cascading, compounding and aggregate impacts are projected to grow due to a concurrent increase in heatwaves, droughts, fires, storms, floods and sea level (*high confidence*) (CSIRO, 2020; Lawrence et al., 2020b). Urban wastewater, stormwater and water supply systems are particularly vulnerable in New Zealand (Paulik et al., 2019a; Hughes et al., 2021) to pluvial flooding (Box 11.4) and to sea-level rise (Box 11.6), with flow-on effects to settlements, insurance and finance sectors, and governments (Lawrence et al., 2020b). Furthermore, consecutive heavy rainfall events in late summer and autumn, following drought conditions in low-lying modified wetland areas, have implications for the operation of flood control infrastructure as increased rainfall intensity, land subsidence, and sea-level rise compound and result in the retention of floodwaters (Pingram et al., 2021).

In Australia, the aggregate loss of wealth due to climate-induced reductions in productivity across agriculture, manufacturing and service sectors is projected to exceed A$19 billion by 2030, A$211 billion by 2050 and A$4 trillion by 2100 for RCP8.5 (Steffen et al., 2019) (Table 11.13). Projected impacts also cascade across national boundaries via value chains, markets, movement of humans and other organisms, and geopolitics (e.g. migration from near-neighbours as a pathway for adaptation, mobile climate-sensitive diseases and changes in production and trade patterns) (Lee et al., 2018; Nalau and Handmer, 2018; Schwerdtle et al., 2018; Dellink et al., 2019). The scale of impacts is projected to challenge the adaptive capacity of sectors, governments and institutions (Steffen et al., 2019), including the insurability of assets and risks to lenders (Storey and Noy, 2017).

11.5.1.3 Adaptation

Coordinating adaptation strategies and addressing underlying exposure and vulnerability can increase resilience to cascading, compounding and aggregate impacts (Table 11.17; 11.7.3) (*high confidence*). Systems understanding, network analysis, stress testing, spatial mapping, collaboration, information sharing and interoperability across states, sectors, agencies and value chains, as well as national scale facilitation, can increase adaptive capacity (Espada et al., 2015; CoA, 2020e; Cradock-Henry et al., 2020b; Jozaei et al., 2020). Greater system diversity, modularity, redundancy, adaptability and decentralised control can reduce the risk of cascading failures and system breakdown (Sinclair et al., 2017; Sellberg et al., 2018). Addressing existing vulnerabilities in systems can reduce susceptibility and improve the resilience of interdependent systems (11.7.3). Multi-level leadership, including national and sub-national policies, laws and finance can reduce and manage aggregate risks supported by the enablers in Table 11.17.

Anticipatory governance and agile decision making can build resilience to cascading, compounding and aggregate impacts (Boston, 2016; Deloitte, 2016; Steffen et al., 2019; CoA, 2020e; CSIRO, 2020; Lawrence et al., 2020b; MfE, 2020c) (*high confidence*). There is uncertainty about whether standard integrated assessment models can estimate cascading and compounding impacts across systems and sectors, but systems methodologies and social network analysis hold promise (Stoerk et al., 2018; Cradock-Henry et al., 2020b). Interventions at the landscape, building and individual scale can reduce the negative health effects of current and future extreme heat, if integrated in well-communicated heat action plans with robust surveillance and monitoring (Jay et al., 2021).

In Australia, the National Disaster Risk Reduction Framework (CoA, 2018b), National Recovery and Resilience Agency, and Australian Climate Service (CoA, 2021) can provide some support for adaptation across multiple sectors. New Zealand has effective partnerships across critical infrastructure through lifelines groups, but organisational silos and lack of stress testing of plans hamper coordinated decision making during crises and for adaptation (Brown et al., 2017; Lawrence et al., 2020b). The New Zealand national risk assessment, national adaptation plan, forthcoming Climate Change Adaptation Act, and monitoring of adaptation progress by the Climate Change Commission, provide a framework for anticipating climate change risks (MfE, 2020a).

11.5.2 Implications for National Economies

The implications of climate change for national economies are significant (*high confidence*). The costs associated with lost productivity, disaster relief expenditure and unfunded contingent liabilities represent a major risk to financial system stability (MfE, 2020a). Costs include significant and often long-term social impacts, temporary dislocation, business disruption, and impacts on employment, education, community networks, health and wellbeing (Deloitte, 2017a). Climate change disrupts international patterns of agricultural production and trade in ways that may be negative, but may also lead to new opportunities for agriculture (Mosnier et al., 2014; Nelson et al., 2014; Lee et al., 2018). Net exports may increase following global climate shocks (Lee et al., 2018), but the longer term effects on GDP are *likely* to be negative (Dellink et al., 2019).

11.5.2.1 Observed Impacts

In Australia, during 2007-2016, total economic costs from natural disasters averaged A$18.2 billion per year (Deloitte, 2017a). Individual weather-related disaster costs across multiple sectors have exceeded A$4 billion, such as the 2009 fires in Victoria (Parliament of Victoria, 2010), the 2010-2011 floods in south-east Queensland (Deloitte, 2017b), the 2019 floods in northern Queensland (Deloitte, 2019) and the 2019-2020 fires in southern and eastern Australia (Box 11.1).

In New Zealand, the annual cost of rural fire to the economy has been estimated at NZ$67 million, with indirect 'costs' potentially 2–3 times direct costs (Scion, 2018). Insured losses from weather-related disasters cost almost NZ$1 billion during 2015-2021 (ICNZ, 2021). Floods cost the New Zealand economy at least NZ$120 million for privately insured damages between 2007 and 2017 (D. Frame et al., 2018). The 2007/08 drought cost NZ$3.2 billion and the 2012/13 drought cost NZ$1.6 billion, of which about 20% could be attributed to anthropogenic climate change (Frame et al., 2020) (11.5.3.1).

The intangible costs of climate impacts - including death and injury, impacts on health and wellbeing, education and employment, community connectedness, and the loss of ancestral lands, cultural sites and ecosystems (Barnett et al., 2016; Warner et al., 2019) - affect multiple sectors and systems and exacerbate existing vulnerabilities. While often incommensurable, intangible costs may be far higher than the tangible costs. For example, following the Victorian fires in 2009, the tangible costs were A$3.1 billion while the intangible costs were A$3.4 billion; following the Queensland floods in 2010/11, the tangible costs were A$6.7 billion while the intangible costs were A$7.4 billion (Deloitte, 2016).

11.5.2.2 Projected Impacts

The economic impact increases with higher levels of warming (*high confidence*) but there is a wide range in projections. Conservative estimates for the impacts of a 1, 2 or 3°C global warming (relative to 1986-2005) on Australian GDP growth are -0.3%/year, -0.6%/year and -1.1%/year, respectively, while for New Zealand the estimates are -0.1%, -0.4%/year and -0.8%/year, respectively (Kompas et al., 2018). More detailed modelling indicates a loss in Australia's GDP of 6% by 2070 for 3°C global warming, while a 2.6% GDP rise by 2070 is possible for 1.5°C global warming (Deloitte, 2020). The potential for much more severe effects on GDP is shown in recent estimates which attempt to account for the increased severity of uncertain effects (e.g. up to 18.5% reduction in Australia's GDP by mid-Century) (Swiss Re, 2021).

In Australia, the total annual cost of damage due to floods, coastal inundation, forest fires, subsidence and wind (excluding cyclones) is estimated to increase 55% between 2020 and 2100 for RCP8.5 (Mallon et al., 2019). National damage costs and impacts on asset values could be significant (Table 11.13). The macro-economic shocks induced from climate change, including reduced agricultural yields, damage to property and infrastructure and commodity price increases, could lead to significant market corrections and potential financial instability (Steffen et al., 2019). Under a 'slow decline' scenario by 2060 where Australia fails to adequately address climate change and sustainability challenges, GDP is projected to grow at 0.7% less per year and real wages would be 50% lower than under an 'outlook scenario' where Australia meets climate change and sustainability challenges (CSIRO, 2019).

In New Zealand, the value of buildings exposed to coastal inundation could increase by NZ$2.55 billion for every 0.1 m increment in sea level, i.e. $25.5 billion for a 1.0 m sea-level rise (Paulik et al., 2020). Greater understanding is required of the distributional impacts, the rate of change of costs over time and the economic implications of delayed action (Warner et al., 2020).

Table 11.13: Economy-wide projected costs (A$) of climate change in Australia. (Estimates are not comparable across studies because different methods have been used. Estimates for later in the century are speculative as both impacts and adaptation are uncertain).

Impact	2030	2050	2090	Reference
Damage-related loss of property value in Australia	$571 billion	$611 billion	$770 billion	(Steffen et al., 2019)
Property damage in Australia		$91 billion per year	$117 billion per year	(Steffen et al., 2019)
Loss of asset value of road infrastructure (including freeways, main roads and unsealed roads) in Australia at risk of a sea-level rise of 1.1 metres by 2100			$46-60 billion	(DCCEE, 2011)
Loss of asset value of rail and tramway infrastructure in Australia at risk of a sea-level rise of 1.1 metres by 2100			$4.9-6.4 billion	(DCCEE, 2011)
Loss of asset value of residential buildings in Australia at risk of a sea-level rise of 1.1 metres by 2100 (2008 replacement value)			$51-72 billion	(DCCEE, 2011)
Loss of asset value of light industrial buildings (used for warehousing, manufacturing, and assembly activities and services) in Australia at risk of a sea-level rise of 1.1 metres by 2100			$4.2-6.7 billion	(DCCEE, 2011)

Loss of asset value of commercial buildings (used for wholesale, retail, office and transport activities) in Australia at risk of a sea-level rise of 1.1 metres by 2100 (2008 replacement value)			$58-81 billion	(DCCEE, 2011)
Accumulated loss of wealth due to reduced agricultural productivity and labour productivity	$19 billion	$211 billion	$4.2 trillion	(Steffen et al., 2019)
Wind damage to dwellings in Cairns, Townsville, Rockhampton and south-east Queensland (assuming a 4 per cent discount rate)	$3.8 billion	$9.7 billion	$20 billion	(Stewart and Wang, 2011)
Damage to Australian coastal residential buildings due to sea-level rise (A1B scenario, 3.5°C global warming)			$8 billion	(Wang et al., 2016)

11.5.2.3 Adaptation

Investments in mitigation and adaptation can help reduce or prevent economic losses now and in the coming decades (IPCC, 2018; Steffen et al., 2019), however the costs and the benefits of mitigation and adaptation are not well understood in the region (CSIRO, 2019; MfE, 2020a) (*high confidence*).

In New Zealand, the emphasis has been on rebuilding after climate disasters, rather than anticipatory adaptation (Boston and Lawrence, 2018). Australia is similarly focused on disaster response and recovery, even though investment in disaster resilience can provide a cost:benefit ratio of 1:2 to 1:11 through reduced post-disaster recovery and reconstruction (GCA, 2019). Recent Australian and state government spending on direct recovery from disasters was around A$2.75 billion per year, compared to funding for natural disaster resilience of approximately A$0.1 billion per year (Deloitte, 2017b). The Australian Government is supporting most of the 80 recommendations from the Royal Commission into National Natural Disaster Arrangements, including establishing a disaster advisory body and a resilience and recovery agency (CoA, 2020e; CoA, 2020b). Australia and New Zealand provide humanitarian and disaster assistance across the Pacific, which is increasingly focused on climate adaptation and the Sustainable Development Goals (Brolan et al., 2019) as cyclones and floods become amplified by climate change (Fletcher et al., 2013) (Table 11.3). Climate change may increase current migration flows to and impacts on diaspora in Australia and New Zealand from near neighbour island nations, as they become increasingly stressed by rising seas, higher temperatures, more droughts and stronger storms (Nalau and Handmer, 2018).

Delaying adaptation to climate risks may result in higher overall costs in future when adaptation is more urgent and impacts more extreme (Boston and Lawrence, 2018; IPCC, 2018) (*medium confidence*). Estimates of the magnitude of adaptation costs and benefits in the region are localised and sectoral, e.g. (Thamo et al., 2017) or regionally aggregated (Joshi et al., 2016). Adaptation costs are expected to increase markedly for higher RCPs, e.g. a tripling of expected costs between RCP2.6 and RCP8.5 for sea-level rise protection in Australia (Ware et al., 2020). Existing governance arrangements for funding adaptation are inadequate for the scope and scale of climate change impacts anticipated; dedicated funding mechanisms that can be sustained over generations can enable more timely adaptation (Boston and Lawrence, 2018).

11.6 Key Risks and Benefits

Nine key risks have been identified (Table 11.14) based on four criteria: magnitude, likelihood, timing and adaptive capacity (Chapter 16). Most of the key risks are similar to those in the IPCC AR5 Australasia chapter (Reisinger et al., 2014), but the emphasis here is on specific systems affected by multiple hazards rather than specific hazards affecting multiple systems. The selection of key risks reflects what has been observed, projected and documented, noting that there are gaps in knowledge, and a lack of knowledge does not imply a lack of risk (11.7.3.3). Key risks are grouped into four categories:

Ecosystems at critical thresholds where recent climate change has caused significant damage and further climate change may cause irreversible damage, with limited scope for adaptation

1. Loss and degradation of coral reefs in Australia and associated biodiversity and ecosystem service values due to ocean warming and marine heatwaves (11.3.2.1, 11.3.2.2, Box 11.2).
2. Loss of alpine biodiversity in Australia due to less snow (11.3.1.1, 11.3.1.2).

Key risks that have potential to be severe but can be reduced substantially by rapid, large-scale and effective mitigation and adaptation

3. Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires (11.3.1.1, 11.3.1.2)
4. Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins (11.3.2.1, 11.3.2.2).
5. Loss of natural and human systems in low-lying coastal areas due to sea level rise (11.3.5, Box 11.6).
6. Disruption and decline in agricultural production and increased stress in rural communities in south-western, southern and eastern mainland Australia due to hotter and drier conditions (11.3.4, 11.3.5, Box 11.3).
7. Increase in heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves (11.3.5.1, 11.3.5.2, 11.3.6.1, 11.3.6.2).

Key cross-sectoral and system-wide risk

8. Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply-chains and services due to wildfires, floods, droughts, heatwaves, storms and sea-level rise (11.5.1.1, 11.5.1.2, Box 11.1, Box 11.4, Box 11.6).

Key implementation risk

9. Inability of institutions and governance systems to manage climate risks. (11.5; 11.7.1, 11.7.2, 11.7.3).

At higher levels of global warming, adaptation costs increase, options become limited and risks grow. The 'burning embers' diagram in Figure 11.6 has four IPCC risk categories: "undetectable", "moderate", "high" and "very high", with transition points defined by different global warming ranges. The embers are indicative, based on an assessment of available literature and expert judgement (Supplementary Material SM 11.2). Outcomes for low and moderate adaptation have been compared, with the latter including both incremental and transformative options. Illustrative examples of adaptation pathways are shown in Figure 11.7 for low-lying coastal areas and Figure 11.8 for heat-related mortality. These figures highlight thresholds at which adaptation options become ineffective, and possible combinations of strategies and options implemented at different times to manage emerging risks and changing risk profiles.

Caveats: (a) key risks are assessed at regional scales, so they do not include other risks for finer scales or specific groups; (b) non-climatic vulnerabilities are held constant for simplicity; (c) the assessment of risk ratings at different levels of global warming is limited by available literature; (d) risks increase with global warming, despite the lack of an IPCC risk rating beyond "very high"; and (e) the feasibility and effectiveness of adaptations options were not assessed due to limited literature (11.7.3.3).

The New Zealand National Climate Change Risk Assessment (MfE, 2020a) identified the priority risks from climate change for New Zealand based on a literature review and expert elicitation. The top two risks in each of five domains are: *Natural environment* (1) risks to coastal ecosystems due to ongoing sea-level rise and extreme weather events, (2) risks to indigenous ecosystems and species from invasive species; *Human environment* (1) risks to social cohesion and community well-being from displacement of people, (2) risks of exacerbating existing inequities and creating new and additional inequities from distribution impacts; *Economy* (1) risks to governments from economic costs associated with lost productivity, disaster relief expenditure and unfunded contingent liabilities, (2) risks to the financial system from instability; *Built environment* (1) risk to potable water supplies due to changes in rainfall, temperature, drought, extreme weather events and ongoing sea-level rise,(2) risks to buildings due to extreme weather events, drought, increased fire weather and ongoing sea-level rise; *Governance* (1) risk of maladaptation due to practices, processes and tools that do not account for uncertainty and change over long timeframes, and (2) risk that climate change impacts across all domains will be exacerbated, because current institutional arrangements are not fit for adaptation. Not all of these risks feature as key risks for the wider Australasia region; nonetheless they are reflected across Chapter 11 and remain priorities for New Zealand to address through the National Adaptation Plan, its implementation and monitoring.

Short-term benefits from climate change may include reduced winter mortality, reduced energy demand for winter heating, increased agriculture productivity and forest growth in south and west New Zealand, and increased forest and pasture growth in southern Australia except where rainfall and soil nutrients are limiting (11.3.4; 11.3.6; 11.3.10) (*medium confidence*).

Table 11.14: Key risks from climate change based on assessment of the literature and expert judgement (Supplementary Material SM 11.2**)**. Assessment criteria are magnitude, timing, likelihood and adaptive capacity. Risk drivers are hazards, exposure and vulnerability. Adaptation options describe ways in which risks can be reduced. Confidence ratings are based on the amount of evidence and agreement between lines of evidence**.**

Key risk (*confidence rating*) (Chapter reference)	Consequences influenced by hazards, exposure, vulnerability and adaptation options
1. Loss and degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values in Australia due to ocean warming and marine heatwaves (*very high confidence*) (11.3.2, Box 11.2)	Consequences: Widespread destruction of coral reef ecosystems and dependent socio-ecological systems. Three mass bleaching events from 2016-2020 have already caused significant loss of corals in shallow-water habitats across the Great Barrier Reef. Globally, bleaching is projected to occur twice each decade from 2035 and annually after 2044 under RCP 8.5 and annually after 2051 under RCP4.5. A 3ºC global warming could cause over six times the 2016 level of thermal stress. Hazards: Increase in background warming and marine heatwave events degrade reef-building corals by triggering coral bleaching events at a frequency greater than the recovery time. Fish populations also decline during and following heat wave events. Exposure: Increasing geographic area affected by rate and severity of ocean warming Vulnerability: Vulnerability to increases in sea temperature is already very high because of other stressors on the ecosystem, including sediment, pollutants, and overfishing. Adaptation options: Minimising other stressors. Efforts on the Great Barrier Reef may slow the impacts of climate change in small sections or reduce short-term socio-economic ramifications, but will not prevent widespread bleaching.
2. Loss of alpine biodiversity in Australia due to less snow (*high confidence*) (11.3.1, Tables 11.2, 11.3, 11.4, 11.5)	Consequences: Loss of endemic and obligate alpine wildlife species and plant communities (feldmark and short alpine herb-fields) as well as increased stress on snow-dependent plant and animal species. Hazards: Projected decline in annual maximum snow depth by 2050 is 30-70% (low emissions) and 45-90% (high emissions); projected increases in temperature and decreases in precipitation. Exposure: Alpine species face elevation squeeze due to lack of nival zone and alpine environments have restricted geographic extent. Vulnerability: Narrow ecological niche of species including snow-related habitat requirements; encroachment from sub-Alpine woody shrubs; vulnerability generated by non-climatic stressors including weeds and feral animals, especially horses Adaptation options: Reducing pressure on alpine biodiversity from land uses that degrade vegetation and ecological condition, along with weed and pest management.

3. Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires (*high confidence*) (11.2, 11.3.1, 11.3.2, Box 11.1)	Consequences: If regenerative capacities of the dominant (framework) canopy tree species are exceeded, a long lasting or irreversible transition to a new ecosystem state is projected with loss of characteristic and framework species including loss of some narrow range endemics. Hazards: Hotter and drier conditions have increased extreme fire weather risk since 1950, especially in southern and eastern Australia. The number of severe fire weather days is projected to increase 5-35% (RCP2.6) and 10-70% (RCP8.5) by 2050 Exposure: Shift in landscape fire regimes to larger, more intense and frequent wildfires over extensive areas (~10 million hectares) of forests and woodlands from longer fire seasons and more hazardous fire conditions and increasing human-sourced ignitions from urbanisation and projected increase in frequency of lightning strikes Vulnerability: The resilience and adaptive capacity of the forests is being reduced by ongoing land clearing and degrading land management practices Adaptation options: Increased capacity to extinguish wildfires during extreme fire weather conditions; avoiding and reducing forest degradation from inappropriate forest management practices and land use.
4. Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins (*high confidence*) (11.3.2)	Consequences: Observed decline in giant kelp in Tasmania since 1990, with less than 10% remaining by 2011 due to ocean warming. Extensive loss of kelp -140,187 hectares across Australia. Loss of bull kelp in southern New Zealand, replaced by the introduced kelp following the 2017/18 marine heatwave. Further loss of native kelp is projected with warming oceans. Hazards: Ocean warming and marine heatwave events Exposure: Coastal waters around Australia and New Zealand Vulnerability: Giant kelp are already Federally listed in Australia as an endangered marine community type. In Australia, kelp forests are vulnerable to nutrient poor East Australian Current waters pushing further south, warming waters and increased herbivory from range-extending species. Adaptation options: Minimizing other stressors, local restoration, and transplantation of heat-tolerant phenotypes.
5. Loss of human and natural systems in low-lying coastal areas from ongoing sea-level rise (*high confidence*) (11.2, 11.3.2, 11.3.5, 11.3.10, 11.4, Table 11.3; Box 11.6)	Consequences: Nuisance and extreme coastal flooding are already occurring due to sea-level rise (SLR). For 0.2-0.3 m SLR, coastal flooding is projected to become more frequent, e.g. current 1-in-100 year flood would occur every year in Wellington and Christchurch. For 0.5 m SLR, the value of buildings in New Zealand exposed to coastal inundation could increase by NZ$12.75 billion and the current 1-in-100 year flood in Australia could occur several times a year. For 1.0 m SLR, the value of exposed assets in New Zealand would be NZ$25.5 billion. For 1.1 m SLR, the value of exposed assets in Australia would be A$164-226 billion. This would be associated with displacement of people, disruption and reduced social cohesion, degraded ecosystems, loss of cultural heritage and livelihoods, and loss of traditional lands and sacred sites. Hazards: Rising sea level (0.2-0.3 m by 2050, 0.4-0.7 m by 2090), storm surges, rising ground water tables. Exposure: Population growth, new and infill urbanization, tourism developments in low-lying coastal areas. Buildings, roads, railways, electricity and water infrastructure. Torres Strait Island and remote Māori communities are particularly exposed and sensitive. Vulnerability: Ineffective planning regulations, reduced availability and increased cost of insurance, and costs to governments as insurers of last resort. Inadequate investment in avoidance and preparedness exacerbating underlying social vulnerabilities. Financial and physical capacities to cope and adapt are uneven across populations, creating equity issues. Adaptation options: Risk reduction coordinated across all levels of government with communities. Statutory planning frameworks, decision tools and funding mechanisms that can address the changing risk. Planning and land use decisions, including managed retreat where it is inevitable. Improved capacity of emergency services, early warning systems,

	improved planning and regulatory practice and building and infrastructure design standards. Options that anticipate risk and adjust as conditions change.
6. Disruption and decline in agricultural production and increased stress in rural communities across south western, southern and eastern mainland Australia due to hotter and drier conditions. (*high confidence*) (11.2, 11.3.4, 11.3.6.3, 11.4.1, Table 11.11, Boxes 11.1, 11.3)	Consequences: Projected decline in crop, horticulture and dairy production. e.g. decline in median wheat yields by 2050 of up to 30% in south-west Australia and up to 15% in South Australia. Increased heat stress in livestock by 31–42 days per year by 2050. Reduced winter chilling for horticulture. Increased smoke impacts for viticulture. Flow-on effects for agricultural supply chains, farming families and rural communities across south-western, southern and south-eastern Australia, including the Murray-Darling Basin (MDB). Hazards: Hotter and drier conditions with constraints on water resources and more frequent and severe droughts in south-western, southern and eastern Australia. Exposure: Across south western, southern and eastern Australia, many production regions are exposed including the MDB which supports agriculture worth A$24 billion/year, 2.6 million people in diverse rural communities, and important environmental assets containing 16 Ramsar listed wetlands. Vulnerability: Existing financial, social, health and environmental pressures on rural, regional and remote communities. Existing competition for water resources among communities, industries and environment, and uncertainty about sharing of water under a drying climate. Adaptation options: Improved governance and collaboration to build rural resilience, including regional and basin-scale initiatives. Improved water policies and initiatives (e.g. MDB Plan) and changes in management and technologies. Resilience-focused planning for rural settlements, land-use, industry, infrastructure and value chains. Adoption of information, tools and methods to better manage uncertainty, variability and change. Incremental changes in farm management practices (e.g. stubble retention, weed control, water-use efficiency, sowing dates, cultivars). In some regions, major changes may be necessary, e.g. diversification in agricultural enterprises, transition to different land-uses (e.g. carbon sequestration, renewable energy production, biodiversity conservation) or migration to another area. Flows in waterways based on Indigenous knowledge to protect cultural assets.
7. Increase in heat-related mortality and morbidity for people and wildlife in Australia (*high confidence*) (11.2, 11.3.1, 11.3.5, 11.3.6, 11.4)	Consequences: During 1987-2016, natural disasters caused 971 deaths and 4,370 injuries, with more than 50% due to heatwaves. Annual increases are projected for excess deaths, additional hospitalisations and ambulance callouts. Heatwave related excess deaths in Melbourne, Sydney and Brisbane are projected to increase by about 300/year (RCP2.6) to 600/year (RCP8.5) during 2031-2080 relative to 142/year during 1971-2020, assuming no adaptation. Significant heat-related mortality of wildlife species (flying foxes, freshwater fish) has been observed and is projected to increase. Hazards: Increased frequency, intensity and duration of extreme heat events Exposure: Pervasive, but differentially affecting some wildlife species depending on their thermal tolerances and occupational groups (e.g. outdoor workers) and those living in high exposure areas (e.g. urban heat islands). Health risks multiply with other harmful exposures, e.g. to wildfire smoke. Vulnerability: Lower adaptive capacity for young/old/sick people, those in low quality housing and lower socio-economic status, and areas served by fragile utilities (power, water). Remote locations with extreme heat and inadequate cooling in housing infrastructure (such as remote indigenous communities). For wildlife, impacts of extreme heat events are being amplified by habitat loss and degradation. Adaptation options: Urban cooling interventions including irrigated green infrastructure and increased albedo, education to reduce heat stress, heatwave/fire early-warning systems, battery/generator systems for energy system security, building standards that improve insulation/cooling, accessible / well-resourced primary health care. For wildlife, removing human stressors, reducing pressures from ferals and weeds, and ensuring there is suitable habitat.
8. Cascading, compounding and	Consequences: Widespread and pervasive damage and disruption to human activities generated by interdependencies and interconnectedness of physical, social and natural

aggregate impacts on cities, settlements, infrastructure, supply-chains and services due to extreme events (*high confidence*) (11.2, 11.3.4, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.9, 11.3.10, 11.4, 11.5.1, Boxes 11.1, 11.4, 11.6)	systems. Examples include: Failure of transport, energy and communication infrastructure and services, heat-stress, injuries and deaths, air pollution, stress on hospital services, damage to agriculture and tourism, insurance loss from heatwaves and fires; failure of transport, stormwater and flood-control infrastructure and services from floods and storms; water restrictions, reduced agricultural production, stress for rural communities, mental health issues, lack of potable water from droughts; damage to buildings, roads, railways, electricity and water infrastructure, loss of assets and lives, displacement of people, reduced social cohesion, and degraded ecosystems from extreme sea-level rise. Large aggregate costs due to lost productivity and major disaster relief expenditure, creating unfunded liabilities and supply chain disruption, e.g., the 2019-2020 Australian fires cost A$8 billion. The impact of a 1, 2 or 3°C global warming (relative to 1986-2005) on Australian GDP growth is estimated at -0.3%/year, -0.6%/year and -1.1%/year, respectively, while for New Zealand estimates are -0.1%/year, -0.4%/year and -0.8%/year, respectively. Impacts on Māori tribal investments in forestry, agriculture, horticulture, fisheries and aquaculture. Hazards: Heatwaves, droughts, fires, floods, storms and sea-level rise. This includes cascading and compound events such as heatwaves with fires, storms with floods, or droughts followed by heavy rainfall and extreme sea levels. Exposure: Highly populated areas, rural and remote settlements, traditional lands and sacred sites. Greater urban density and population growth increases exposure in high-risk areas. Different exposure for different hazards, e.g. heatwaves: urban and peri-urban areas; fire: peri-urban areas and settlements near forests; floods: people, property and infrastructure from pluvial floods in cities and settlements and fluvial floods on floodplains; storms: buildings and infrastructure in cities and settlements. Vulnerability: Existing social and economic challenges (e.g. those caused by COVID-19) and socio-economic and cultural inequalities; competing resource and land use demands across sectors; inadequate planning, policy, governance, decision making and disaster resilience capacity; and non-climatic stresses on ecosystems. Vulnerabilities generated by interdependencies and interconnectedness of physical, social and natural systems. Adaptation options: Flexible and timely adaptation strategies that prepare socio-economic and natural systems for surprises and unexpected threats. Multi-sector coordinated actions that address widespread impacts, redress existing vulnerabilities and building adaptive capacity and systemic resilience. Improved coordination between and within levels of governments, communities and private sector. Greater use of dynamic decision frameworks and suitable economic and social assessment tools. Improved emergency services and early warning systems; use of climate resilient standards for buildings and infrastructure. Transformational adaptations e.g. managed retreat, that can be planned in stages.
9. Inability of institutions and governance systems to manage climate risks (*high confidence*) (11.2, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.10, 11.4, 11.5.1, 11.7.2, Boxes 11.1-11.6)	Consequences: Climate hazards overwhelm the capacity of institutions, organisations, systems and leaders to provide necessary policies, services, resources, coordination and leadership. Failed adaptation at the institutional and governance level has widespread, pervasive impacts for all areas of society. This includes a reliance on reactive, short-term decision making that locks in existing exposures, leaves perverse incentives and interconnected and systemic impacts unaddressed, and generates high costs, fiscal impacts. This worsens vulnerability and leads to maladaptation, inequities and injustices within and across generations, as well as actions that do not uphold the rights, interests, values and practices of Indigenous Peoples. Resultant failure to take adaptation action generates litigation risk. Hazards: The increasing frequency, duration, severity and complexity of extreme weather events, droughts and sea-level rise Exposure: All sectors, communities, organisations, and governments Vulnerability: Fragmented institutional and legal arrangements, under-resourcing of services, lack of dedicated adaptation funding instruments and resources to support communities and local government, uneven capability to manage uncertainty, and conflicting values and competing policy and political interests. Adaptation options: Pre-emptive options that avoid and reduce risks. Redesign of policy and statutory frameworks, and funding instruments for addressing changing risks and uncertainties that enable just and collaborative governance across scales and domains. Addressing existing vulnerabilities, and capacity, capability and leadership deficits within

	and across all levels of government, all sectors, Indigenous peoples and communities. Risk and vulnerability assessment methodologies and decision-making tools that build resilience and address changing risks and vulnerabilities. Co-designed adaptation approaches implemented with communities, including Māori tribal organisations and Australian Aboriginal and Torres Strait Island peoples.

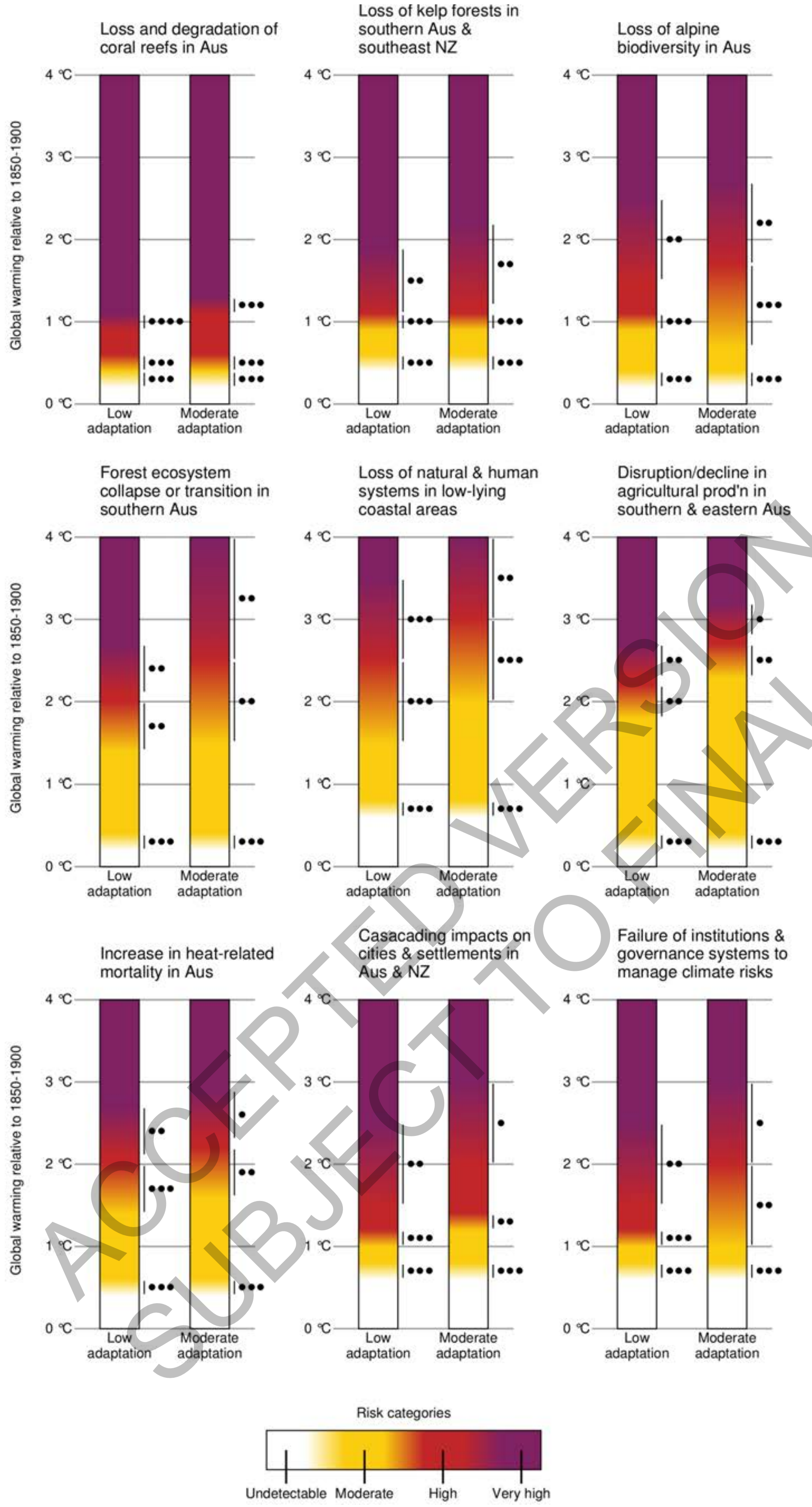


Figure 11.6: Burning embers diagram for each of the nine key risks for low and moderate adaptation. The risk categories are undetectable, moderate, high and very high. While there is no risk category beyond very high, risks obviously get worse with further global warming, and the risk for coral reefs is already very high. The assessment is based on available literature and expert judgement, summarised in Table 11.14 and described in Supplementary Material SM 11.2. The global warming range associated with each risk transition has a confidence rating (**** *very high,* *** *high,* ** *moderate,* * *low*) based on the amount of evidence and level of agreement between lines of evidence.

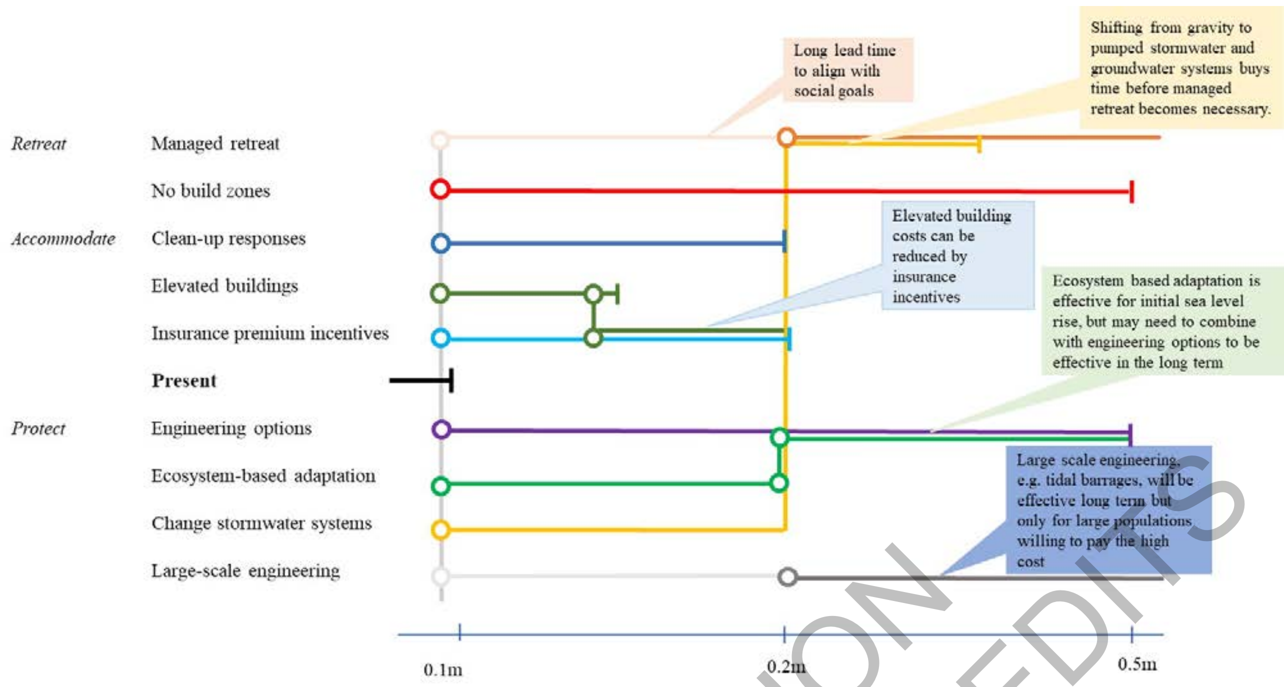


Figure 11.7: Illustrative adaptation pathway for risk to natural and human systems in low-lying coastal areas due to sea-level rise.

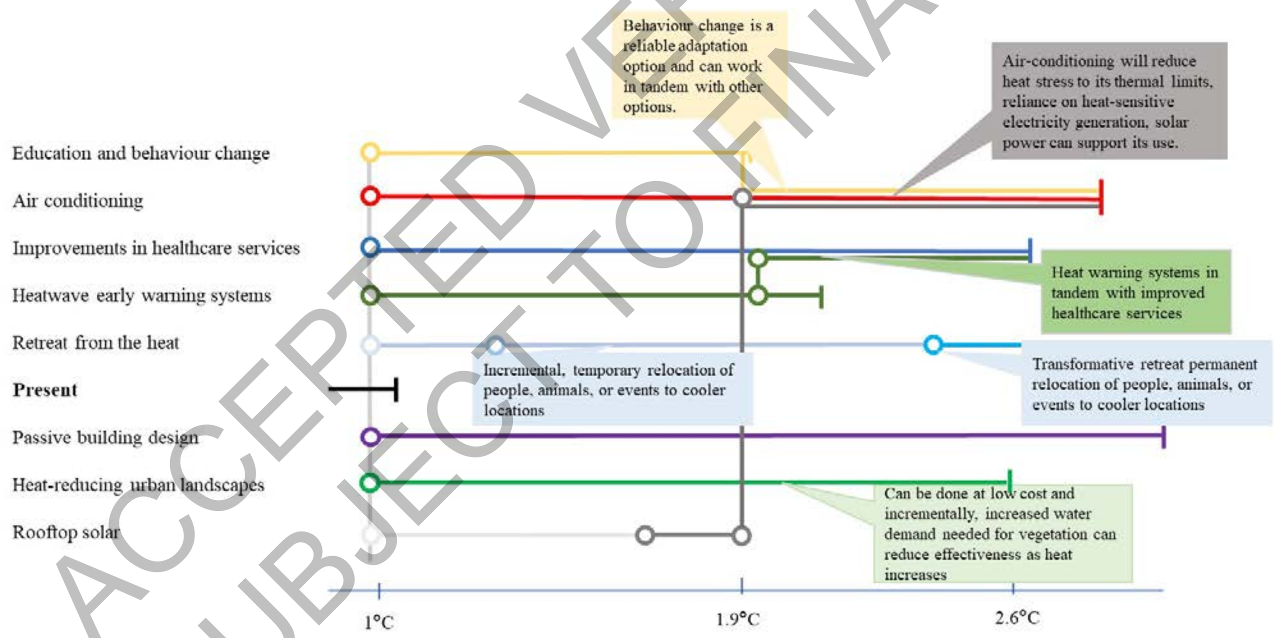


Figure 11.8: Illustrative adaptation pathway for risk of heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves.

11.7 Enabling Adaptation Decision-making

11.7.1 Observed Adaptation Decision-Making

The ambition, scope and progress on adaptation by governments has risen, but is uneven with a focus on high level strategies at national level adaptation planning at sub-national levels and new enabling legislation (Tables 11.15a and 11.15b; (Lawrence et al., 2015; Macintosh et al., 2015; MfE, 2020a) (*very high confidence*). The adaptation process comprises vulnerability and risk assessments, identification of options, planning, implementation, monitoring, evaluation and review. Large gaps remain, especially in effective implementation, monitoring and evaluation (Supplementary Material SM 11.1) (CCATWG, 2017; Warnken and Mosadeghi, 2018) and current adaptation is largely incremental and reactive (Box 11.4, Box 11.6, Table 11.14) (*very high confidence*).

Australia has a National Climate Resilience and Adaptation Strategy, and a National Recovery and Resilience Agency (11.5.2.3), the first National Action Plan to implement the Disaster Risk Reduction Framework acknowledges climate change as a disaster risk driver (Home Affairs, 2020). States and territories have climate change adaptation strategies with plans to address them (Table 11.15a).with some adaptation implementation at state level and increasingly at local government level (Jacobs et al., 2016; Warnken and Mosadeghi, 2018) (Table 11.15a). In coastal zones, however, few local government planning instruments are being applied (Warnken and Mosadeghi, 2018; Harvey, 2019; Robb et al., 2019; Elrick-Barr and Smith, 2021). Some businesses and industry sectors are recognizing climate-related risks and adaptation planning (11.3.4; 11.3.7; 11.3.10) (Harris et al., 2016; Hennessy et al., 2016; CBA, 2019). There is an opportunity for Australia to undertake a national risk assessment and to develop a national climate adaptation implementation plan that is aligned with Paris Agreement expectations of a national level system for adaptation planning, monitoring and reporting (Morgan et al., 2019).

New Zealand's Climate Change Response Act in 2019 creates a legal mandate for National Climate Change Risk Assessments (first one completed) (MfE, 2020a) and National Adaptation Plans (first in preparation) and a Climate Change Commission to monitor and report on adaptation implementation. Preparation of Natural and Built Environment, Strategic Planning and Climate Change Adaptation Acts is underway, including provision for funding and managed retreat (MfE, 2020c). National coastal guidance is available for adaptation planning to address changing climate risks (MfE, 2017a) (Table 11.15b). Meanwhile, several local authorities have developed integrated climate change strategies and plans and revised policies and rules to enable adaptation (Table 11.15b). Different adaptation approaches continue to create confusion and inertia while development pressures continue (Schneider et al., 2017). Opportunities for integrated adaptation and mitigation planning in regional policies and plans have arisen through the Resource Management Amendment Act 2020 (Dickie, 2020), the National Policy Statement on Freshwater Management (MfE, 2020b), and the revised national coastal guidance (MfE, 2017a), but rely on funding instruments to be in place and statutes are aligned for their effectiveness (Boston and Lawrence, 2018; CCATWG, 2018) (*very high confidence*).

There is a growing awareness of the need for more proactive adaptation planning at multiple scales and across sectors, and a better understanding of future risks and limits to adaptation is emerging (Evans et al., 2014; Archie et al., 2018; Christie et al., 2020; MfE, 2020a) (*medium confidence*). Disaster risk reduction is being positioned as part of climate change adaptation (Forino et al., 2017; CDEM, 2019; Forino et al., 2019; CoA, 2020e; CSIRO, 2020). Public and private climate adaptation services are informing climate risk assessments, but are characterized by fragmentation, duplication, inconsistencies, poor governance and inadequate funding - addressing these gaps presents adaptation opportunities (CCATWG, 2018; Webb et al., 2019; NESP ESCC, 2020) (Tables 11.15a; 11.15b). Large infrastructure asset planning is starting to factor in climate risks, but implementation is variable (Gibbs, 2020). Local governments in Australia are increasingly implementing adaptation plans but few monitor or evaluate actual outcomes or know how to (Scott and Moloney, 2021).

Observed and projected rates of sea-level rise (Box 11.6) and increased flood frequency (11.3.3) are challenging established uses of modelling, risk assessment, and cost benefit analysis, where climate change damage functions cannot be projected or are unknown (deep uncertainty), or impacts on communities are ambiguous (Infometrics and PSConsulting, 2015; Lawrence et al., 2019a; MfE, 2020a). New tools are available in the region (Table 11.17) but uptake cannot be assumed (Lawrence and Haasnoot, 2017; Palutikof et al., 2019c) (*high confidence*).

Resilience and adaptation approaches are beginning to converge (White and O'Hare, 2014; Aldunce et al., 2015) (Supplementary Material SM 11.1) but widespread "bounce back" resilience-driven responses that lock in risk by discounting ongoing and changing climate risk (Leitch and Bohensky, 2014; O'Hare et al., 2016; Wenger, 2017; Torabi et al., 2018) can create maladaptation and impede long-term adaptation goals (Glavovic and Smith, 2014; Dudney et al., 2018) (*high confidence*).

Local government engagement with communities on adaptation is starting to motivate a change towards more collaborative engagement practices (Archie et al., 2018; Bendall, 2018; MfE, 2019; Schneider et al., 2020). Nature-based adaptations (Colloff et al., 2016; Lavorel et al., 2019; Della Bosca and Gillespie, 2020) and 'green infrastructure' (Lin et al., 2016; Alexandra and Norman, 2020) are increasingly being adopted (Rogers et al., 2020a) (*medium confidence*).

Some businesses have initiated active adaptation (Aldum et al., 2014; Linnenluecke et al., 2015; Bremer and Linnenluecke, 2017; CCATWG, 2017; MfE, 2018) with most focused on identifying climate risks (Aldum et al., 2014; Gasbarro et al., 2016; Cradock-Henry, 2017). Businesses are more likely to engage in anticipatory adaptation when the frequency of climate events is known (McKnight and Linnenluecke, 2019). Effective cooperation and a positive innovation culture can contribute to the collaborative development of climate change adaptation pathways (Bardsley et al., 2018) (*medium confidence*).

Some areas in northern Australia and New Zealand, especially those with higher proportions of Indigenous populations, face severe housing, health, education, employment and services deficits that exacerbate the impacts of climate change (Kotey, 2015) (11.3.5; 11.4; 11.6). Where adaptation relies upon an aging population and an over-stretched volunteer base, vulnerability to climate change impacts is being exacerbated (Astill and Miller, 2018; Davies et al., 2018). Adaptation options that succeed within remote Indigenous communities are founded on connections to traditional lands, alignment with cultural values and contribute to social, cultural and economic goals (Nursey-Bray and Palmer, 2018). Knowledge co-production for Indigenous adaptation pathways can enable transformative change from colonial legacies (Hill et al., 2020). Learning and experimentation across governance boundaries and between agencies and local communities enables adaptation to be better aligned with changing climate risks and community (Fünfgeld, 2015; Howes et al., 2015; Bardsley and Wiseman, 2016; Lawrence et al., 2019b) (*high confidence*).

There is increasing focus on improving adaptive capacity for transitional and transformational responses, but reactive responses dominate (Smith et al., 2015; Schlosberg et al., 2017; Boston and Lawrence, 2018) (*very high confidence*). While extreme events can provide opportunities for positive transitions within communities (Cradock-Henry et al., 2018b) (for example the Queensland Reconstruction Authority Building Back Better scheme), often rebuilding occurs in at-risk places to aid quick recovery (Lawrence and Saunders, 2017). Community-based adaptation innovations (Kench et al., 2018; Forino et al., 2019){Bendall, 2018 #413} include: relationship building; use of new decision tools, pathways planning with communities, visualisation and serious games (Lawrence and Haasnoot, 2017; Schlosberg et al., 2017; Flood et al., 2018; Reiter et al., 2018; Serrao-Neumann and Choy, 2018); communities of practice; and climate information sharing (Astill et al., 2019; Stone et al., 2019).

Table 11.15a: Examples of Australian adaptation strategies, plans and initiatives by government agencies at the (a) national level, (b) sub-national, and (c) regional or local level. These examples have not been assessed for their effectiveness (see Supplementary Material Table SM11.1a).

Jurisdiction	Strategies /Plans /Actions
National Level	
Australia	National Climate Resilience and Adaptation Strategy 2015 (CoA, 2015) National Disaster Risk Reduction Framework (2018) (CoA, 2018b) National Recovery and Resilience Agency and Australian Climate Service (CoA, 2021)
Sub-national	
Australian Capital Territory (ACT)	ACT Climate Change Strategy 2019-2025 (ACT Government, 2019) Canberra's Living Infrastructure Plan: Cooling the City (ACT Government, 2020b); ACT Wellbeing Framework (ACT Government, 2020a)

New South Wales	NSW Climate Change Policy Framework (NSW Government, 2016)
	Coastal Management Framework (OEH, 2018b) including: Coastal Management Act 2016; State Environmental Planning Policy (Coastal Management) 2018; NSW Coastal Management Manual (OEH, 2018c; OEH, 2018a)
Northern Territory	Northern Territory Climate Change Response: Towards 2050 (DENR, 2020b); Three-year action plan (DENR, 2020a)
Queensland	Pathways to climate resilient Queensland: Queensland Climate Adaptation Strategy 2017-2030 (DEHP, 2013) Sector adaptation plans https://www.qld.gov.au/environment/climate/climate-change/adapting/sectors-systems State heatwave risk assessment 2019 (QFES, 2019) Planning Act 2016 (Queensland Government, 2020) and the Coastal Protection and Management Act 1995 (Queensland Government, 1995) plus supporting initiatives: Coastal Management Plan (DEHP, 2013); Shoreline Erosion Management Plans (DES, 2018) Queensland's QCoast2100 program
South Australia	Directions for a Climate Smart South Australia (SA Government, 2019a)
Tasmania	Climate Action 21: Tasmania's Climate Change Action Plan 2017–2021 (State of Tasmania, 2017a) Tasmania's 2016 State Natural Disaster Risk Assessment (White et al., 2016a) Tasmanian Planning Scheme – State Planning Provisions 2017, Coastal Inundation Hazard Code and a Coastal Erosion Hazard Code (Government of Tasmania, 2017).
Victoria	In accordance with the Climate Change Act 2017, Victoria has a Climate Change Adaptation Plan 2017-2020 (Victoria State Government DELWP, 2016) including a Monitoring, Evaluation, Reporting and Improvement (MERI) framework for Climate Change Adaptation in Victoria (DELWP, 2018), Victorian Climate Projections (2019) and multiple resources for regions and local government (Victoria DELWP 2020). Heatwaves in Victoria. A 2018 vulnerability assessment of the state to heatwaves using a Damage and Loss Assessment methodology (Natural Capital Economics, 2018)
Western Australia	Western Australian Government Adapting to our changing climate 2012 (WA Government, 2016) State Planning Policy 2.6 – Coastal Planning (SPP2.6)
Regional and local (examples only)	
104 have declared Climate Emergencies to leverage climate action as of September 2021 covering 36.6% of the Australian population (Climate Emergency Declaration, 2020)	
Tasmania	2017: Tasmanian Planning Scheme – State Planning Provisions. State of Tasmania, 514. (State of Tasmania 2017) (State of Tasmania, 2017b)
South Australia	Regional integrated vulnerability assessments (IVAs) and adaptation plans (SA Government, 2019a)
NSW	Enabling Regional Adaptation (Jacobs et al., 2016)

Victoria	Every region and catchment Management Authority in Victoria has an adaptation plan, as does virtually every local government. There are also three alliances of multiple local governments working on climate change and new initiatives such as the Climate Change Exchange. https://www.parliament.vic.gov.au/967-epc-la/inquiry-into-tackling-climate-change-in-victorian-communities
NSW	Coastal Zone Management Plan for Bilgola Beach (Bilgola) and Basin Beach (Mona Vale) (Haskoning Australia, 2016)
Queensland	Torres Strait Climate Change Strategy (TSRA, 2014); Torres Strait Regional Adaptation and Resilience Plan 2016-2021 (TSRA, 2016) Climate Risk Management Framework for Queensland Local Government (Erhart et al., 2020)
Northern Territory	Climate Change Action Plan (2011-2020) (Darwin City Council, 2011)

Table 11.15b: Examples of New Zealand's adaptation strategies, plans and initiatives by government agencies at the (a) national level, (b) sub-national, and (c) regional or local level. NB These examples have not been assessed for their effectiveness (see Supplementary Material Table SM11.1b)

Jurisdiction	Strategies/Plans/Actions
New Zealand central Government	The New Zealand Government's adaptation policy framework is based on the following legislation: Resource Management Act 1991; Local Government Act 2002; National Disaster Resilience Strategy 2019 (CDEM, 2019), and the Climate Change Response (Zero Carbon Amendment) Act 2002 (CCRA 2002). Adaptation preparedness report 2020/21 baseline is the reporting organisation responses from the First Information request under the CCRA 2002 (MfE, 2021) to assist the monitoring of progress and effectiveness of adaptation, by the Climate Change Commission The Department of Conservation's Climate Change Adaptation Action plan sets out a long-term strategy for climate research, monitoring, and action. DOC climate adaptation plan
Local Government	In July 2017, a group of 39 Local Government Mayors and Council Chairs (of 78 in total) endorsed a 2015 local government declaration calling for urgent responsive leadership and a holistic approach on climate change, with the government needing to play a vital enabling leadership role (LGNZ, 2017; Schneider et al., 2017). Seventeen councils have declared Climate Emergencies to leverage climate action plans as of September 2021, covering 75.3% of the New Zealand population. The MFE adaptation preparedness report states that 18% of councils (11 of 61 surveyed in 2021) have some sort of plan or strategy to increase resilience to climate impacts (MfE, 2021). Out of New Zealand's 15 regional and unitary councils, two councils have climate adaptation strategies in place. One council has conducted a climate risk assessment. and four have one in development. Five councils have climate action plans and three are in development.
Regional Councils (examples only)	
Bay of Plenty Regional Council	Climate Action Plan July 2019 (non-statutory) Climate Action Plan
Waikato Regional Council	Long Term Plan 2018-2028 (LTP)

Greater Wellington Regional Council	GWRC's Climate Change Strategy (October 2015) Climate change strategy implementation Hutt River Flood Risk Management Plan
Unitary Authorities (examples only)	
Auckland Council	Auckland Unitary Plan AUP RPS B10 Table B11.9- (bottom of doc) E36. Natural hazards and flooding
Marlborough District Council	Marlborough Environment Plan First to integrate Dynamic Adaptive Pathways Planning (DAPP) into Plan policies.
Gisborne District Council	Tairāwhiti Resource Management Plan (District Plan) March 2020
District Council (example only)	
Waimakariri District Council	Infrastructure Strategy in the Long Term Plan 2017. Long-Term-Plan-Further-Information-Document-WEB.pdf Page 113/31

11.7.2 Barriers and Limits to Adaptation

Major gaps in the adaptation process remain across all sectors and at all levels of decision-making (11.3; Table 11.115a Table 15b) (*very high confidence*). Efforts to build, resource and deploy adaptive capacity are slow compared to escalating impacts and risks (Stephenson et al., 2018; CoA, 2020e). Barriers to effective adaptation include governance inertia at all levels, hindering the development of careful and comprehensive adaptation plans and their implementation (Boston and Lawrence, 2018; MfE and Hawke's Bay Regional Council, 2020; White and Lawrence, 2020). Lack of clarity about mandate, roles and leadership, and inadequate funding for adaptation by national and State governments and sectors, are slowing adaptation (Lukasiewicz et al., 2017; Waters and Barnett, 2018; LGNZ, 2019; MfE, 2020c) (11.3; 11.7.1). Established planning tools and measures were designed for static risk profiles, and practitioners are slow to take up tools better suited to changing climate risks (CoA, 2020e; Schneider et al., 2020) (11.5; Box 11.5). The communication of relevant climate change information remains ad hoc (Stevens and O'Connor, 2015; CCATWG, 2017; Palutikof et al., 2019c; Salmon, 2019). In Australia, the lack of national guidance or adaptation laws create barriers to adaptation, reflected in uneven coastal adaptation based on a "wait and see" approach (Dedekorkut-Howes et al., 2020).

Table 11.16: Examples of barriers to adaptation action in the region

Barrier	Source
Governments Lack of consistent policy direction from higher levels and frequent policy reversals	(Dedekorkut-Howes et al., 2020)
Conflicts between community-based initiatives, City Councils and business interests	(Forino et al., 2019)
Different framings of adaptation between local governments (risk) and community groups (vulnerability, transformation)	(Smith et al., 2015; Schlosberg et al., 2017; McClure and Baker, 2018)
Competing planning objectives	(McClure and Baker, 2018)
Divergent perceptions of risk concepts	(Button and Harvey, 2015; Mills et al., 2016b; Tonmoy et al., 2018)
Focus on climate variability rather than climate change	(Dedekorkut-Howes and Vickers, 2017)

Low prioritization of climate change adaptation among competing institutional objectives	(Glavovic and Smith, 2014; Lawrence et al., 2015; McClure and Baker, 2018)
Constraints in using new knowledge	(Temby et al., 2016)
Lack of institutional and professional capabilities and capacity e.g. to monitor and evaluate adaptation outcomes	(Lawrence et al., 2015; Scott and Moloney, 2021)
Lack of understanding of Indigenous knowledge and practices	(Parsons et al., 2019)
Lack of authority and political legitimacy	(Hayward, 2008; Boston and Lawrence, 2018; CCATWG, 2018; Parsons et al., 2019)
Fear of litigation	(Tombs et al., 2018; Iorns Magallanes and Watts, 2019; O'Donnell et al., 2019)
The upfront costs of adaptation relative to competing demands on government expenditure	(Gawith et al., 2020; Warren-Myers et al., 2020b)
Private sector	
Governance and policy uncertainty, lack of cross sector coordination, lack of capital investment in climate solutions	(CCATWG, 2017; Forino et al., 2017; IGCC, 2021a)
Inconsistent hazard information and incomplete understanding of adaptation	(CCATWG, 2017; Harvey, 2019)
Mismatch in duration of insurance cover (annual) lending (decades) and infrastructure and housing investment (50-100ys)	(Storey and Noy, 2017; O'Donnell, 2020)
Perceived unaffordability of adaptation, lack of client demand and awareness of climate change risks and limited and inconsistent climate risk regulation in the construction industry	(Hurlimann, 2008; Hurlimann et al., 2018)
Translating information into organisations to address disinterest amongst clients in the property industry	(Warren-Myers et al., 2020b; Warren-Myers et al., 2020a)
Erosion of adaptive capacity and challenges of transformational adaptation in agriculture and rural communities	(Jakku et al., 2016)
Communities	
Nature of government engagement with communities	(Public Participation, 2014; MfE, 2017a; Archie et al., 2018; OECD, 2019b)
Lack of clarity regarding roles and responsibilities	(Gorddard et al., 2016; Elrick-Barr et al., 2017; Goode et al., 2017; Waters and Barnett, 2018)
Lack of resourcing of adaptation	(Singh-Peterson et al., 2015; Lukasiewicz et al., 2017; Brookfield and Fitzgerald, 2018)
Lack of deep engagement with climate change	(Kench et al., 2018; Pearce, 2018)
Diverging perceptions, values and goals within communities	(Austin et al., 2018; Fitzgerald et al., 2019; Marshall et al., 2019)
Inequities within and between communities	(Eriksen, 2014; Parkinson, 2019)
Lack of sustained engagement, learning and trust between community, scientists and policy makers	(Serrao-Neumann et al., 2020)

There are many barriers to starting adaptation pre-emptively (CCATWG, 2018) (Table 11.16) (*very high confidence*). Recent institutional changes in New Zealand indicate that this is changing (11.7.1; Table 15b). Many groups are yet to engage deeply with climate change adaptation (Kench et al., 2018) and some adaptation processes are being blocked (Pearce et al., 2018; Garmestani et al., 2019; Alexandra, 2020) or exploited to deflect from mitigation responsibilities (Smith and Lawrence, 2018; Nyberg and Wright, 2020). Some actors are resistant to using climate change information (Tangney and Howes, 2016; Alexandra, 2020). Fear of litigation and demands for compensation can contribute to this reluctance (Tombs et al., 2018; O'Donnell et al., 2019)and is increasingly inviting litigation and other costs (Hodder, 2019; Bell-James and Collins, 2020). Jurisprudence is evolving from cases on projects, to cases about decision making accountability in the public and private sectors (Bell-James and Collins, 2020; Peel et al., 2020) and rights based cases (Peel and Osofsky, 2018). National and sub-national governments may become exposed to unsustainable fiscal risk as insurers of "last resort", which can lead to inequitable outcomes for vulnerable groups and future generations (11.3.8), path dependencies and negative effects on physical, social, economic and cultural systems (Hamin and Gurran, 2015; Boston and Lawrence, 2018). Cross-scale governance tensions can prevent local adaptation initiatives from performing as intended (Tschakert et al., 2016; Piggott-McKellar et al., 2019). Adaptation that draws on Māori cultural understanding in partnership with local government in New Zealand can lead to more effective and equitable adaptation outcomes (MfE, 2020a).

Communities' vulnerabilities are dynamic and uneven (*high confidence*). In Australia, 435,000 people in remote areas face particular challenges (CoA, 2020e). Some groups do not have the time, resources or opportunity to participate in formal adaptation planning as it is currently organised (Victorian Council of Social Service, 2016; Tschakert et al., 2017; Mathew et al., 2018). Linguistically diverse groups can be disadvantaged by social isolation, language barriers, and others' ignorance of the knowledge and skills they can bring to adaptation (Shepherd and van Vuuren, 2014; Dun et al., 2018) (11.1.2). Social, cultural and economic vulnerabilities, biases and injustices, such as those faced by many women (Eriksen, 2014; Parkinson, 2019) and non-heterosexual groups and gender minorities (Dominey-Howes et al., 2016; Gorman-Murray et al., 2017), can deepen impacts and impede adaptation; (Fitzgerald et al., 2019; Marshall et al., 2019) (Cross-Chapter Box GENDER in Chapter 18).

Potential biophysical limits to adaptation for non-human species and ecosystems where impacts are projected to be irreversible, with limited scope for adaptation, are signalled in key risks 1-4 (11.6). In some human systems, fundamental limits to adaptation include thermal thresholds and safe freshwater (Alston et al., 2018) (Table 11.14) and the inability of some low-lying coastal communities to adapt in-place (Box 11.6) (*very high confidence*). Some individuals and communities are already reaching their psycho-social adaptation limits (Evans et al., 2016). A lack of robust and timely adaptation means key risks will increasingly manifest as impacts, and numerous systems, communities and institutions are projected to reach limits (Table 11.14, Figure 11.6), compounding current adaptation deficits and undermining society's capacity to adapt to future impacts (*very high confidence*).

11.7.3 Adaptation enablers

Adaptation enablers include understanding relevant knowledge, diverse values and governance, institutions and resources (Gorddard et al., 2016) (*very high confidence*). Skills and learning, community networks, people-place connections, trust-building, community resources and support and engaged governance build social resilience that support adaptation (Maclean et al., 2014; Eriksen, 2019; Phelps and Kelly, 2019). A multi-faceted focus on the role societal inequalities and environmental degradation play in generating climate change vulnerability can enable fairer adaptation outcomes (McManus et al., 2014; Ambrey et al., 2017; Schlosberg et al., 2017; Graham et al., 2018).

The feasibility and effectiveness of adaptation options will change over time depending on place, values, cultural appropriateness, social acceptability, ongoing cost-effectiveness, leadership and the ability to implement them through the prevailing governance regime (Singh et al., 2020). The capacity and commitment of the political system can drive early action that can reduce risks (Boston, 2017).

Decision makers face the challenge of how to adapt when there are ongoing knowledge gaps, and uncertainties about when some climate change impacts will occur and their scale, e.g. coastal flooding (Box

11.6), or extreme rainfall events and their cascading effects (Box 11.4) (*very high confidence*). No-regrets decisions are *likely* to be insufficient (Hallegatte et al., 2012). A perception exists in some sectors that all climate risks are manageable based on past experience (CCATWG, 2017). Projected impacts, however, are outside the range experienced, meaning that decisions have to be made now for long-lived assets, land uses and communities exposed to the key risks (Paulik et al., 2019a; Paulik et al., 2020) often under contested conditions where adaptation competes with other public expenditure (Kwakkel et al., 2016). New planning approaches being used across the region, can enable more effective adaptation, e.g. continual iterative adaptation (Khan et al., 2015) rapid deployment of decision tools appropriate for addressing uncertainties (Marchau et al., 2019, and transformation of governance and institutional arrangements {Boston, 2018 #444) (Table 11.17). Recognising co-benefits for mitigation and sustainable development can help incentivise adaptation (11.3.5.3, 11.8.2).

Table 11.17: Key enablers for adaptation

Enabler	Example
Governance frameworks	Clear climate change adaptation mandate Measures that inform a shift from reactive to anticipatory decision making, e.g. decision tools that have long timeframes Institutional frameworks integrated across all levels of government for better coordination Revised design standards for buildings, infrastructure, landscape such as common land use planning guidance and codes of practice that integrate consideration of climate risks to address existing and future exposures and vulnerability of people, physical and cultural assets (11.3.1, 11.3.2, 11.3.3, 11.3.4.3, 11.3.5, 1.3.6, 11.4.1, 11.4.2, 11.5.1, 11.5.2, 11.6, 11.7.1, 11.7.2, 11.8.1, 11.8.2, Table 11.7, Table 11.14, Box 11.1, Box 11.3, Box 11.5, Box 11.6)
Building capacity for adaptation	Provision of nationally consistent risk information through agreed methodologies for risk assessment that address non-stationarity Targeted research including understanding the projected scope and scale of cascading and compounding risks Education, training and professional development for adaptation under changing risk conditions Accessible adaptation tools and information (11.1.2, 11.3.4, 11.3.5, 11.4.1, 11.5.1, 11.6, 11.7.1, 11.7.2, Table 11.14, Table 11.16, Table 11.18, Box 11.6)
Community partnership and collaborative engagement	Community engagement based on principles that consider social and cultural and Indigenous Peoples' contexts and an understanding of what people value and wish to protect, e.g. International Association of Public Participation (Public Participation, 2014). Use of collaborative and learning-oriented engagement approaches tailored for the social and informed by the cultural context Community awareness and network building Building on Indigenous Australian and Māori communities' social-cultural networks and conventions that promote collective action and mutual support (11.3.5, 11.4, 11.7.1, 11.7.3.2, Table Box 11.1.1, Table 11.14, Box 11.6)
Dynamic adaptive decision-making	Increased understanding and use of decision-making tools to address uncertainties and changing risks, such as scenario planning and dynamic adaptive pathways planning to enable effective adaptation as climate risk profiles worsen (11.7.3.1, 11.7.3.2, Table 11.14, Table 15b, Table 11.18, Box 11.4, Box 11.6)
Funding mechanisms	Adaptation funding framework to increase investment in adaptation actions New private sector financial instruments to support adaptation (11.7.1, 11.7.2, Table 11.16)
Reducing systemic vulnerabilities	Economic and social policies that reduce income and wealth inequalities Strengthening social capital and cohesion Identifying and redressing rigid or fragmented administrative and service delivery systems Review of land use and spatial planning to reduce exposure to climate risks Restoring degraded ecosystems and avoiding further environmental degradation and loss. (11.1.1,11.1.2,11.3.5, 11.3.11, 11.4.1, 11.5.1.3, 11.7.2, 11.8.1, Table 11.10, Table 11.13)

11.7.3.1 Planning and Tools

Adaptation decision support tools enable a shift from reactive to anticipatory planning for changing climate risks (*high confidence)*. The available tools are diversifying with futures and systems methodologies and dynamic adaptive policy pathways being increasingly used (Bosomworth et al., 2017; Prober et al., 2017; Lawrence et al., 2018a; CoA, 2020e; Rogers et al., 2020a; Schneider et al., 2020) (11.5; Box 11.6) to help shift from static to dynamic adaptation by highlighting path dependencies and potential lock in of decisions, system dependencies and the potential for cascading impacts (Table 11.17) (Wilson et al., 2013; Clarvis et al., 2015; Pearson et al., 2018; Cradock-Henry et al., 2020b; Lawrence et al., 2020b). Modelling and tools to test the robustness and cost-effectiveness of options (Infometrics and PSConsulting, 2015; Qin and Stewart, 2020) can be used alongside adaptation strategies with decision-relevant and usable information (Smith et al., 2016; Tangney, 2019; Serrao-Neumann et al., 2020), particularly when supported by effective governance and national and sub-national guidance (Box 11.6).

More inclusive, collaborative and learning-oriented community engagement processes are fundamental to effective adaptation outcomes (11.7.3.2) (Boston, 2016; Lawrence and Haasnoot, 2017; Sellberg et al., 2018; Serrao-Neumann et al., 2019a; Simon et al., 2020) (*very high confidence*). More participatory vulnerability and risk assessments can better reflect different knowledge systems, values, perspectives, trade-offs, dilemmas, synergies, costs and risks (Jacobs et al., 2019; Ogier et al., 2020; Tonmoy et al., 2020). A shift from hierarchical to more cooperative governance modalities can assist effective adaptation (Vermeulen et al., 2018; Steffen et al., 2019; CoA, 2020e; Lawrence et al., 2020b; MfE, 2020a; Hanna et al., 2021).

Regular monitoring, evaluation, communication and coordination of adaptation are essential for accelerating learning and adjusting to dynamic climate impacts and socio-economic and cultural conditions change (Moloney and McClaren, 2018; Palutikof et al., 2019a; Cradock-Henry et al., 2020a) (*high confidence*). Training to improve decision-makers' 'evaluative capacity' can play a role (Scott and Moloney, 2021). Climate action benchmarking, diagnostic tools and networking can enhance the adaptation process across diverse decision settings e.g. water, coasts, protected areas and Indigenous Peoples (Ayre and Nettle, 2017; Davidson and Gleeson, 2018; Coenen et al., 2019; Gibbs, 2020). Effective adaptation requires cross-jurisdictional and cross-sectoral policy coherence and national coordination (Delany-Crowe et al., 2019; Rychetnik et al., 2019; MfE, 2020c).

Table 11.18: Examples of adaptation decision tools

Tools	Application	Source
Scenario analysis, modelling, futures narratives	For futures planning in coastal, urban, agriculture and health sectors	(Randall et al., 2012; Jones et al., 2013; CSIRO, 2014; Bosomworth et al., 2015; Infometrics and PSConsulting, 2015; Knight-Lenihan, 2016; Maier et al., 2016; Stephens et al., 2017; B. Frame et al., 2018; Stephens et al., 2018; Ausseil et al., 2019a; Coulter et al., 2019; Serrao-Neumann et al., 2019b)
Dynamic Adaptive Pathways Planning (DAPP)	For conditions of deep uncertainty for short-term and long-term options and flexibility, and with communities	(Cradock-Henry et al., 2018b; Cradock-Henry et al., 2020a) (agriculture); (Lawrence et al., 2019b) (flood risk management) (Lawrence and Haasnoot, 2017; Colliar and Blackett, 2018) (coastal communities) (Tasmanian Climate Change Office, 2012; Lin et al., 2017; Ramm et al., 2018) (capacity building) (Moran et al., 2014; Colloff et al., 2016; Dunlop et al., 2016; Bosomworth et al., 2017) (natural resource, management) (Hadwen et al., 2012; Barnett et al., 2014b; Fazey et al., 2015; Lazarow, 2017; Ramm et al., 2018) (coastal) (Siebentritt et al., 2014; Zografos et al., 2016) (regional development)

		(Maru et al., 2014) (disadvantaged communities) (Hertzler et al., 2013; Sanderson et al., 2015) (agriculture) (Ren et al., 2011) (infrastructure and resilient cities) (Cunningham et al., 2017) (social network analysis with communities)
Serious Games	To catalyse learning, raise awareness and explore attitudes and values	(Lawrence and Haasnoot, 2017; Colliar and Blackett, 2018; Flood et al., 2018; Edwards et al., 2019)
Signals and Triggers for monitoring DAPP	For where there is near-term certainty and longer-term deep uncertainty e.g. sea-level rise	(Stephens et al., 2017; Stephens et al., 2018)
Shared Socio-economic Pathways	For where there is deep uncertainty and scenarios are used	(B. Frame et al., 2018)
Hybrid Multi-criteria analysis and DAPP (deep uncertainty)	For conditions of deep uncertainty for short-term and long-term options and flexibility desired	(D. Frame et al., 2018; Lawrence et al., 2019a)
Real Options Analysis (ROA)	For conditions of deep uncertainty	(Infometrics and PSConsulting, 2015; Infometrics, 2017; Lawrence et al., 2019a; Wreford et al., 2020)
Scenario-based cost-benefit analysis	For conditions of deep uncertainty	(Guthrie, 2019)
Portfolio analysis	For uncertainties in the land use sector	(Monge et al., 2016; Awatere et al., 2018)(West et al. 2021)
Cost Benefit Analysis	Where decisions can be easily reversed	(Hadwen et al., 2012; Little and Lin, 2015; Stewart, 2015; Luo et al., 2017; Thamo et al., 2017)
Vulnerability assessment	For assessing and prioritising physical and social place-based risks, using indices, modelling and participatory approaches	(Ramm et al., 2017; Moglia et al., 2018; Pearce et al., 2018; Tonmoy and El-Zein, 2018)
Statutory tools	For planning direction	(DoC NZ, 2010; DoC NZ, 2017a; DoC NZ, 2017b; NSW Government, 2018)
	For planning and design of adaptation	(MfE, 2017a)
Standards	For adaptation best practice	(ISO, 2019)
Jurisprudence	For adaptation implementation and legal interpretation	(O'Donnell and Gates, 2013; McAdam, 2015; Iorns Magallanes and Watts, 2019; Peel et al., 2020)
Guidance	For adaptation and use of uncertainty tools	(CSIRO and BOM, 2015; MfE, 2017a; Lawrence et al., 2018b; Palutikof et al., 2019b)
Information delivery and decision support portal	For adaptation decision making	https://coastadapt.com.au/

Monitoring, evaluation and reporting on adaptation progress (incl. adaptation indices and web-based tools)	For local government, private sector and finance sector to benchmark, track progress	(Goodhue et al., 2012; Little et al., 2015; IGCC, 2017; Lawrence et al., 2020a; LGAQ and DES, 2020; Rogers et al., 2020b; WAGA, 2020) (Moloney and McClaren, 2018)

11.7.3.2 Attitudes, Engagement and Accessible Information as Enablers

Concern for climate change has become widespread (Hopkins, 2015; Borchers Arriagada et al., 2020), giving climate adaptation social legitimacy (*high confidence*). Over three quarters of Australians (77%) agree that climate change is occurring and 61% believe climate change is caused by humans (Merzian et al., 2019). A growing proportion of Australians perceive links between climate change and high temperatures experienced during heatwaves and extremely hot days (2018/2019 Summer) (48%), droughts and flooding (42%), and urban water shortages (30%) (Merzian et al., 2019). Rural populations in NSW perceive climate change impacts as stressing their wellbeing and mental health and requiring leadership and action (Austin et al., 2020). In New Zealand, between 2009 and 2018, the proportion of New Zealanders who agreed or strongly agreed that climate change is real increased from 58% to 78% (a 34.5% increase), while those agreeing or strongly agreeing with human causation increased from 41% to 64% (a 56.1% increase) (Milfont et al., 2021). Nevertheless, New Zealanders have a tendency to overestimate the amount of sea-level rise, especially amongst those most concerned about climate change, and incorrectly associate it with melting sea ice, which has implications for engagement and communication strategies (Priestley et al., 2021).

Use of more systemic, collaborative and future-oriented engagement approaches is facilitating adaptation in local contexts (Rouse et al., 2013; MfE, 2017a; Leitch et al., 2019) (*high confidence*). Local 'adaptation champions' and experimental and tailored engagement processes can enhance learning (McFadgen and Huitema, 2017; Lindsay et al., 2019). Dynamic adaptive pathways planning (Lawrence et al., 2019a) and inclusive community governance (Schneider et al., 2020)can help progress difficult decisions such as the relocation of cultural assets and managed retreat, and contestation about which public goods to prioritise and how adaptation should be implemented (Kwakkel et al., 2016) (Colliar and Blackett, 2018). Participatory climate change scenario planning can test assumptions about the present and the future (Mitchell et al., 2017; Serrao-Neumann and Choy, 2018; Chambers et al., 2019; Serrao-Neumann et al., 2019c) and help envision people-centred, place-based adaptation (Barnett et al., 2014b; Lindsay et al., 2019). Social network analysis can inform engagement and communication of adaptation (Cunningham et al., 2017). Knowledge brokers, information portals and alliances can help communities, governments and sector groups to better access and use climate change information (Shaw et al., 2013; Fünfgeld, 2015; Lawrence and Haasnoot, 2017). Novel approaches to building climate change literacy and adaptation capability go hand in hand with dedicated expert organisational support (Stevens and O'Connor, 2015; CCATWG, 2018; Palutikof et al., 2019c; Salmon, 2019). All of these approaches depend on adequate resourcing (*very high confidence*).

11.7.3.3 Knowledge Gaps and Implementation Enablers

There are two priority areas where new knowledge is critical for accelerating adaptation implementation.

1) *System complexity and uncertainty in observed and projected impacts*
- Regionally relevant projections of rainfall, runoff, compound and extreme weather (11.2.1; 11.3.3; Box 11.4).
- Inclusion of cascading and compounding impacts in integrated assessments (11.5.1) including for infrastructure (11.3.5), tourism (11.3.7) and health (11.3.6) and for different groups, including Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori communities (11.4).
- Impacts on terrestrial and freshwater ecosystems, including in-situ monitoring to detect ongoing changes especially in New Zealand (11.3.1), and marine biodiversity including environmental tolerances of key life stages (11.3.2).
- Repository of indigenous species distribution data for monitoring responses to climate change and climate advisory services for New Zealand (11.3.1.3).

- National risk assessment for Australia (11.7.1).
- The interactions between adaptation and mitigation, particularly where land carbon mitigation is impacted by climate change (11.3.4.3; Box 11.5).

2) *Supporting adaptation decision making*

- Better understanding of who and what is exposed and where, and their vulnerability to climate hazards (11.3, 11.4).
- National assessments of the costs and benefits of climate change, with and without different levels and timings of adaptation and mitigation (11.5.2.3) (11.7.1).
- Understanding available adaptation strategies and options, their feasibility and effectiveness as the climate changes, including their intended and unintended outcomes (11.7, 11.8).
- Understanding how to embed robust planning approaches into decision making that retain flexibility to change course in the future (11.7.1).
- Mechanisms for sharing knowledge and practice of adaptation (11.7).
- The role of development paradigms, values and political economy in adaptation framing and effective implementation (11.8).
- Understanding social transitions and social licence, for timely, robust and transformational adaptation (11.8.2).

11.8 Climate Resilient Development Pathways

Adaptation to climate risks and global mitigation of greenhouse emissions determine whether development pathways are climate resilient (Chapter 18). In the near-term, progress towards climate resilient development can be monitored by progress on the Sustainable Development Goals (SDGs). According to government reports (OECD, 2019a) (Figure 11.6) current and projected trajectories fall short of meeting all targets (Allen et al., 2019). Key climate risks for the region (11.6, Table 11.14) affect all of the SDGs, and pre-existing societal inequalities exacerbate climate risks (11.3.5). Projected climate risks combined with underlying SDG indicators will increasingly impede the region's capacity to achieve and maintain a number of SDGs, including sustainable agriculture, affordable and clean energy, sustainable cities and communities, life below water and life on land (OECD, 2019a). Reducing these risks would require significant and rapid emission reductions to keep global warming to 1.5-2.0°C, and robust and timely adaptation (IPCC, 2018).

11.8.1 System Adaptations and Transitions

A step-change in adaptation action is needed to address climate risks and to be consistent with climate resilient development *(very high confidence).* Current adaptation falls short on assessment of complex risks, implementation, monitoring, and evaluation. It is largely incremental and temporary given the scale of projected impacts, it has limits and is mainly reactive rather than anticipatory. Furthermore, risks are projected to cascade and compound, with impacts and costs that challenge adaptive capacities (11.5) and call for transformational responses (11.6, Table 11.15a; Table 11.15b; Supplementary Tables SM11.1a; SM11.1b).

Current global emissions reduction policies are projected to lead to a global warming of 2.1-3.9 °C by 2100 (Liu and Raftery, 2021), leaving many of the region's human and natural systems at very high risk and beyond adaptation limits (*high confidence*). With higher levels of warming, adaptation costs increase, loss and damages grow, and governance and institutional responses have reduced adaptive capacity. Underlying social and economic vulnerabilities and injustices further reduce adaptive capacity, exacerbating disadvantage in particular groups in society. Sustainable development across and beyond the region will help reduce shared adaptation challenges (11.5.1.2). Effective adaptation avoids lock-in and path dependency, reduces vulnerabilities, increases flexibility to change, builds adaptive capacity and progresses SDGs, thus improving intra- and inter-generational justice (11.5, 11.6, 11.7). Reducing greenhouse gas emissions and structural inequalities is key to achieving the SDGs and contributing to climate resilient development.

Integrated and inclusive adaptation decision making can contribute to climate resilient development by better mediating competing values, interests and priorities and helping to reconcile short-and long-term objectives, as well as public and private costs and benefits, in the face of rapidly and continuously changing risk profiles

(Gorddard et al., 2016; MfE, 2017a; Schlosberg et al., 2017) (11.5.2) *(very high confidence).* Use of new tools and approaches (Table 11.18) to address system interactions that match the scale and scope of the problem can result in more effective adaptation, including proactive and anticipatory governance and institutional enablers (11.7, Table 11.17) (Schlosberg et al., 2017; Boston and Lawrence, 2018). Building cities and settlements that are resilient to the impacts of climate change requires the simultaneous consideration of infrastructural, ecological, social, economic, institutional, and political dimensions of resilience including political will, leadership, commitment, community support, multilevel governance, and policy continuity (Torabi et al., 2021).

11.8.2 Challenges for Climate Resilient Development Pathways

Implementing enablers can help drive adaptation ambition and action consistent with climate resilient development (11.7.3, Table 11.17) (*very high confidence*). However, the scale and scope of cascading, compounding and aggregate impacts (11.5.1) calls for new and timely adaptation, including more effective ongoing monitoring, evaluation, review and continual adjustment (11.7.3) towards the transformations that can break through the 'path dependencies' that define the way things are done now (Cradock-Henry et al., 2018b; UN et al., 2018; Head, 2020). However, complex interactions between objectives can create social and economic trade-offs (Table 11.1, 11.3.5.3, 11.7.3.1, Box 11.6).

Delay in implementing climate change adaptation and emissions reductions will impede climate resilient development, resulting in more costly climate impacts and greater scale of adjustments in the future (IPCC, 2018) (11.5.1; 11.5.2) (Box 11.6) and legal risks for those with adaptation mandates and for financial institutions (11.5.1) (*very high confidence*). The scale and scope of societal change needed for the region to transition to more climate resilient development pathways requires close attention to governance, ethical questions, the role of civil society, the place of Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori in the co-production of ongoing adaptation at multiple scales (Koehler et al., 2017; Loorbach et al., 2017; Hill et al., 2020).

The region faces an extremely challenging future that will be highly disruptive for many human and natural systems (IPCC, 2018) (UNEP, 2020; AAS, 2021; IPCC, 2021) (11.5.1; 11.6; 11.7) (Box 11.1-11.6) (Table 11.14). The extent to which the limits to adaptation are reached depends on whether global warming peaks this century at 1.5, 2 or 3+°C above pre-industrial levels. Whatever the outcome, adaptation and mitigation are essential and urgent. (*very high confidence*)

[START FAQ11.1 HERE]

FAQ 11.1: How is climate change affecting Australia and New Zealand?

Climate change is affecting Australia and New Zealand significantly. Some natural systems of cultural, environmental, social and economic significance are at risk of irreversible change. The socio-economic costs of climate change are substantial, with impacts that cascade and compound across sectors and regions, as demonstrated by heatwaves, wildfire, cyclone, drought and flood events.

Temperature has increased by 1.4°C in Australia and 1.1°C in New Zealand over the last 110 years, with more extreme hot days. The oceans in the region have warmed significantly, resulting in longer and more frequent marine heatwaves. Sea levels have risen and the oceans have become more acidic. Snow depths have declined and glaciers have receded. North-western Australia and most of southern New Zealand have become wetter, while southern Australia and most of northern New Zealand have become drier. The frequency, severity and duration of extreme wildfire weather conditions has increased in southern and eastern Australia and north-eastern New Zealand.

The impacts of climate change on marine, terrestrial and freshwater ecosystems and species are evident. The mass mortality of corals throughout the Great Barrier Reef during marine heatwaves in 2016–2020 is a striking example. Climate change has contributed to the unprecedented south-eastern Australia wildfires in the spring-summer of 2019–2020, loss of alpine habitats in Australia, extensive loss of kelp forests, shifts further south in the distribution of almost 200 marine species, decline and extinction in some vertebrate species in the Australian wet tropics, expansion of invasive plants, animals and pathogens in New Zealand, erosion and flooding of coastal habitats in New Zealand, river flow decline in southern Australia, increased stress in rural communities, insurance losses for floods in New Zealand, increase in heat wave mortalities in Australian capital cities, and the fish deaths in Murray-Darling River in the summer of 2018–2019.

[END FAQ11.1 HERE]

[START FAQ11.2 HERE]

FAQ 11.2: What systems in Australia and New Zealand are most at risk from ongoing climate change?

The nine key risks to human systems and ecosystems in Australia and New Zealand from ongoing climate change are shown in Figure FAQ 11.2.1. Some risks, especially on ecosystems, are now difficult to avoid. Other risks can be reduced by adaptation, if global mitigation is effective.

Risk is the combination of hazard, exposure and vulnerability. For a given hazard (e.g. fire), the risk will be greater in areas with high exposure (e.g. many houses) and/or high vulnerability (e.g. remote communities with limited escape routes). The severity and type of climate risk varies geographically (Figure FAQ 11.2.1). Everyone will be affected by climate change, with disadvantaged and remote people and communities the most vulnerable.

The risks to natural and human systems are often compounded by impacts across multiple spatial and temporal scales. For example, fires damage property, farms, forests and nature with short- and long-term effects on biodiversity, natural resources, human health, communities and the economy. Major impacts across multiple sectors can disrupt supply chains to industries and communities and constrain delivery of health, energy, water and food services. These impacts create challenges for adaptation and governance of climate risks. When combined, these have far-reaching socio-economic and environmental impacts.

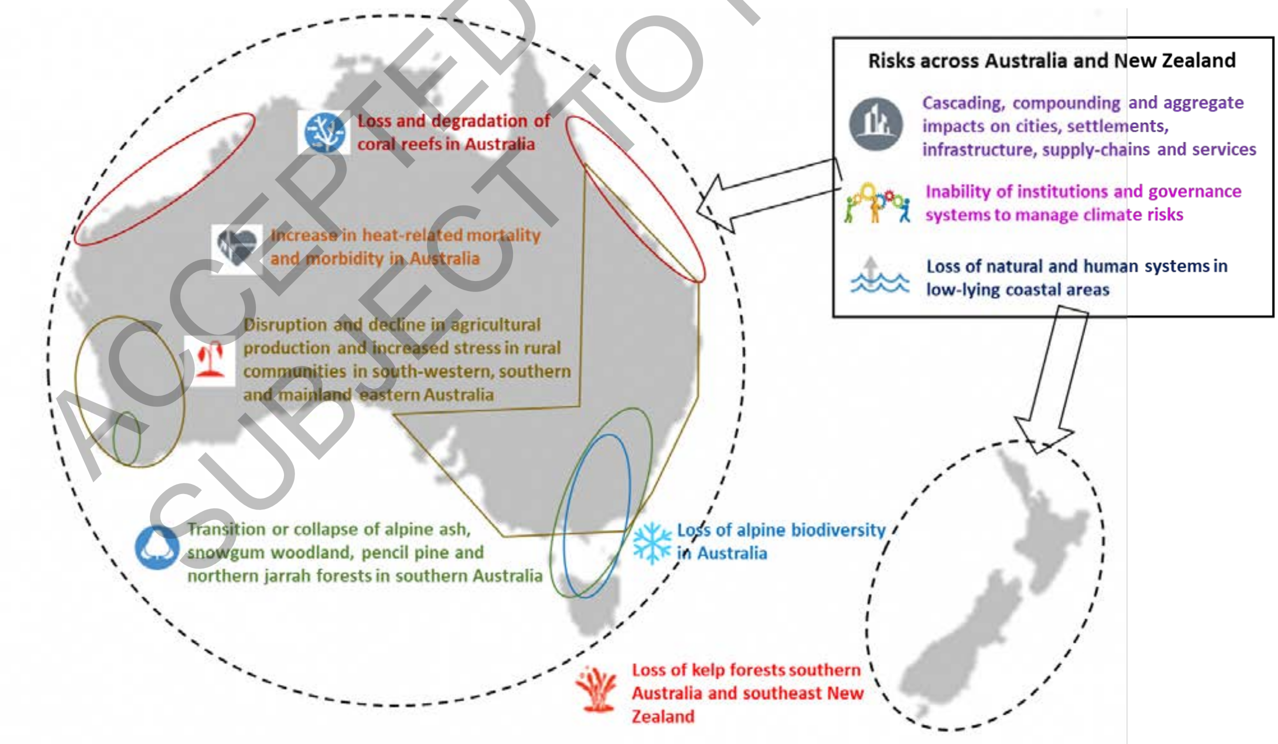


Figure FAQ 11.2.1: Key risks from climate change

[END FAQ11.2 HERE]

[START FAQ11.3 HERE]

FAQ 11.3: How can Indigenous Peoples' knowledge and practice help us understand contemporary climate impacts and inform adaptation in Australia and New Zealand?

In Australia and New Zealand, as with many places around the world, Indigenous Peoples with connections to their traditional country and extensive histories, hold deep knowledge from observing and living in a changing climate. This provides insights that inform adaptation to climate change.

Indigenous Australians - Aboriginal and Torres Strait Islanders - maintain knowledge regarding previous sea-level rise, climate patterns, and shifts in seasonal change associated with flowering of trees and emergence of food sources, developed over thousands of generations of observation of their traditional country. Knowledge of localised contemporary adaptation is also held by many Indigenous Australians with connections to traditional lands. With assured Free and Prior-Informed Consent, this provides a means for Indigenous-guided land management, including for fire management and carbon abatement, fauna studies, medicinal plant products, threatened species recovery, water management, and weed management.

Tangata Whenua Māori in New Zealand are grounded in Mātauranga Māori knowledge which is based on human-nature relationships and ecological integrity and incorporates practices used to detect and anticipate changes taking place in the environment. Social-cultural networks and conventions that promote collective action and mutual support are central features of many Māori communities and these customary approaches are critical to responding to, and recovering from, adverse environmental conditions. Intergenerational approaches to planning for the future are also intrinsic to Māori social-cultural organisation and are expected to become increasingly important, elevating political discussions about conceptions of rationality, diversity and the rights of non-human entities in climate change policy and adaptation.

[END FAQ11.3 HERE]

[START FAQ11.4 HERE]

FAQ 11.4: How can Australia and New Zealand adapt to climate change?

There is already work underway by governments, businesses, communities and Indigenous Peoples to help us adapt to climate change. However, much more adaptation is needed for the ongoing and intensifying climate risks. This includes coordinated laws, plans, guidance and funding that enable society to adapt, and the information, education and training that can support it. Everyone has a role to play, working together.

We currently mainly react to climate events such as wildfires, heatwaves, floods and droughts, and generally rebuild in the same places. However, climate change is making these events more frequent and intense, and ongoing sea-level rise and changes in natural ecosystems are advancing. Better coordination and collaboration between government agencies, communities, Aboriginal and Torres Strait Islanders and Tangata Whenua Indigenous Peoples, not-for-profit organisations and businesses will help prepare for these climate impacts more proactively, in combination with future climate risks integrated into their decisions and planning. This will reduce the impacts we experience now and the risks that will affect future generations.

Some of the risks for natural systems are close to critical thresholds and adaptation may be unable to prevent ecosystem collapse. Other risks will be severe, but we can reduce their impact by acting now, for example coastal flooding from sea-level rise, heat-related mortality and managing water stresses. Many of the risks have potential to cascade across social and economic sectors with widespread societal impacts. In such cases, really significant system-wide changes will be needed to the way we live and govern currently. To facilitate such change, new governance frameworks, nationally consistent and accessible information, collaborative engagement and partnerships with all sectors, communities and Indigenous Peoples and the resources to address the risks, are needed (Figure FAQ 11.4.1).

However, our ability to adapt to climate change impacts also rests on every region in the world playing its part in reducing greenhouse gas emissions. If mitigation is ineffective, global warming will be rapid, adaptation costs will increase, with worsening losses and damages.

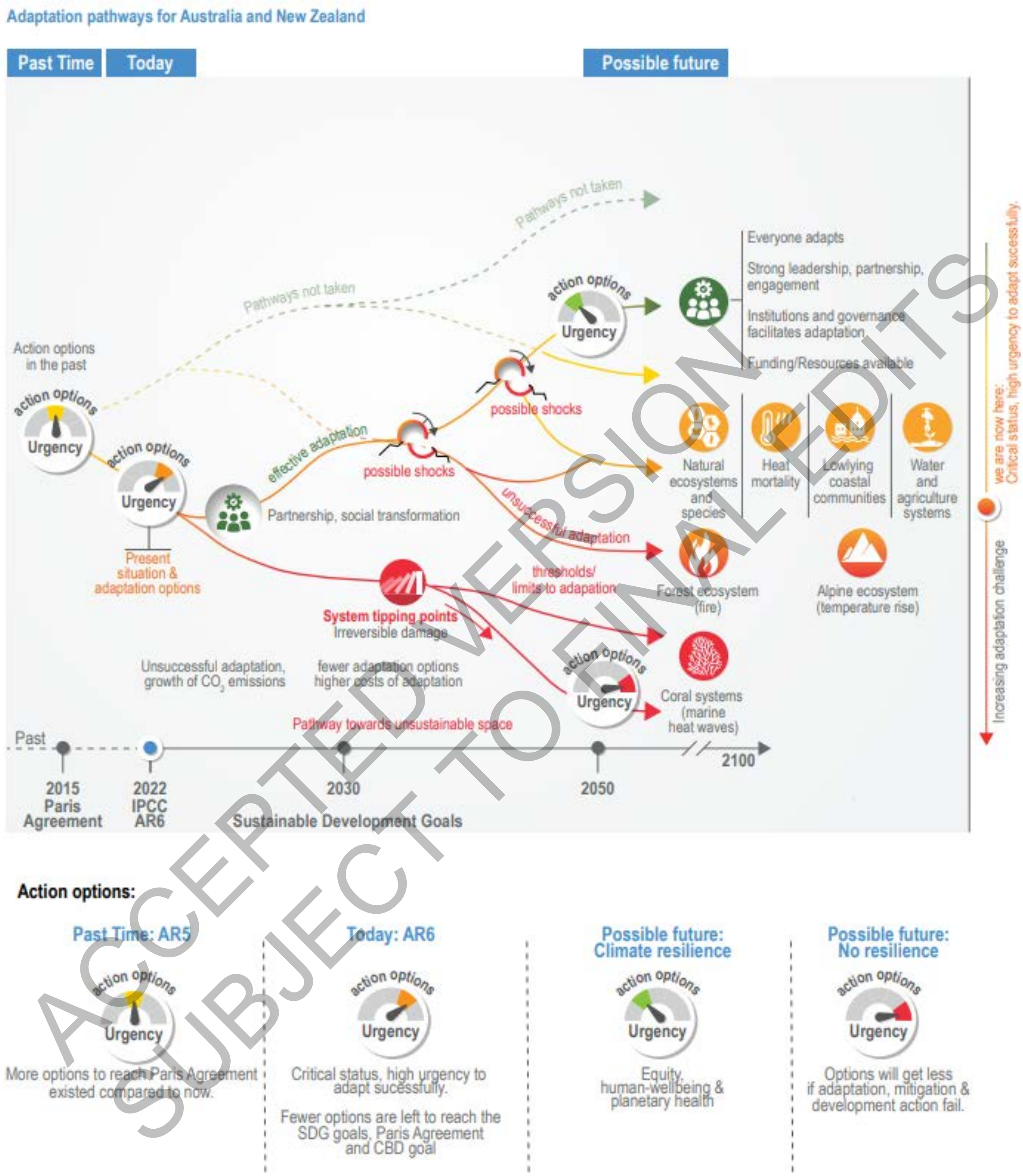


Figure FAQ 11.4.1: Developing adaptation plans in the solutions space showing system tipping points, thresholds and limits to adaptation, unsustainable pathways, critical systems and enablers to climate resilient development

[END FAQ11.4 HERE]

References

AAS, 2019: *Investigation into the Causes of Mass Fish Kills in the Menindee Region NSW over Summer of 2018-2019*. Australian Academy of Science Secretariat, 162 [Available at: https://www.science.org.au/files/userfiles/support/reports-and-plans/2019/academy-science-report-mass-fish-kills-digital.pdf].

AAS, 2021: *The risks to Australia of a 3°C warmer world*. Australian Academy of Science, 97 [Available at: https://www.science.org.au/files/userfiles/support/reports-and-plans/2021/risks-australia-three-deg-warmer-world-report.pdf].

Abel, N. et al., 2016: Building resilient pathways to transformation when "no one is in charge": insights from Australia's Murray-Darling Basin. *Ecology and Society*, **21** (2), doi:10.5751/es-08422-210223.

Abram, N. J. et al., 2021: Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment*, **2** (1), doi:10.1038/s43247-020-00065-8.

ABS, 2016: National Aboriginal and Torres Strait Islander Social Survey, 2014--15.

ABS, 2017: *Regional Population Growth, Australia, 2016*. Australian Bureau of Statistics, Canberra, ACT, Australia [Available at: http://www.abs.gov.au/ausstats/abs@.nsf/mf/3218.0].

ABS. 8155.0 Australian Industry, 2016-17, Mining - Key Points. [Available at: http://www.abs.gov.au/ausstats/abs@.nsf/mf/8155.0]

ABS. 8155.0 - Australian Industry, 2017-18, Mining - Key Points. [Available at: https://www.abs.gov.au/ausstats/abs@.nsf/mf/8155.0]

ACCC, 2020: *Northern Australia Insurance Inquiry*. Australian Competition and Consumer Commission, 592 [Available at: https://www.accc.gov.au/focus-areas/inquiries-finalised/northern-australia-insurance-inquiry].

ACE CRC, 2010: *Climate Futures for Tasmania. Climate Modelling - the Summary*. 9 [Available at: https://web.archive.org/web/20150406013036if_/http://www.dpac.tas.gov.au/__data/assets/pdf_file/0016/151126/CFT_-_Climate_Modelling_Summary.pdf].

ACT Government, 2019: *ACT Climate Change Strategy 2019-25*. Australian Capital Territory, Canberra, 100 [Available at: https://www.environment.act.gov.au/__data/assets/pdf_file/0003/1414641/ACT-Climate-Change-Strategy-2019-2025.pdf/_recache].

ACT Government, 2020a: *ACT Wellbeing Framework*. Australian Capital Territory, Canberra, 32 [Available at: https://www.act.gov.au/__data/assets/pdf_file/0004/1498198/ACT-wellbeing-framework.pdf].

ACT Government, 2020b: *Canberra's Living Infrastructure Plan: Cooling the City*. Australian Capital Territory, Canberra,34 pp.

Actuaries Institute, 2020: *Property insurance affordability. Challenges and solutions*. Actuaries Institute, 52 [Available at: https://actuaries.asn.au/Library/Miscellaneous/2020/GIRESEARCHPAPER.pdf].

AECOM, 2012: *Economic assessment of the urban heat island effect*. City of Melbourne, 71.

AEMO, 2018: *Integrated System Plan 2018*. Australian Energy Market Operator [Available at: http://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Integrated-System-Plan].

AEMO, 2020a: *2019-20 NEM summer operations review report*. Operator, A. E. M. [Available at: https://www.aemo.com.au/-/media/files/electricity/nem/system-operations/summer-operations/2019-20/summer-2019-20-nem-operations-review.pdf].

AEMO, 2020b: *2020 ISP Appendix 8. Resilience and Climate Change*. Australian Energy Market Operator, 35 [Available at: https://aemo.com.au/-/media/files/major-publications/isp/2020/appendix--8.pdf?la=en].

AFSI, 2020: *Australian Sustainable Finance Roadmap*. Australian Sustainable Finance Initiative, 95 [Available at: https://static1.squarespace.com/static/5c982bfaa5682794a1f08aa3/t/5fcdb70bfe657040d5b08594/1607317288512/Australian+Sustainable+Finance+Roadmap.pdf].

AghaKouchak, A. et al., 2020: Climate Extremes and Compound Hazards in a Warming World. *Annual Review of Earth and Planetary Sciences*, **48** (1), 519-548, doi:10.1146/annurev-earth-071719-055228.

Aguilar, G. et al., 2015a: Queensland fruit fly invasion of New Zealand : predicting area suitability under future climate change scenarios. *Unitec ePress Perspectives in Biosecurity Research Series*, **2015/2**.

Aguilar, G. D. et al., 2017: A performance based consensus approach for predicting spatial extent of the Chinese windmill palm (Trachycarpus fortunei) in New Zealand under climate change. *Ecological informatics*, **39**, 130-139.

Aguilar, G. D., M. J. Farnworth and L. Winder, 2015b: Mapping the stray domestic cat (Felis catus) population in New Zealand: Species distribution modelling with a climate change scenario and implications for protected areas. *Applied Geography*, **63**, 146-154, doi:10.1016/j.apgeog.2015.06.019.

AIDR, 2017: *Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia (Handbook 7)*. Commonwealth of Australia, Australia, C. o., 92 [Available at: file:///C:/Users/chi163/Desktop/adr-handbook-7.pdf].

AIHW, 2015: *The health and welfare of Australia's Aboriginal and Torres Strait Islander peoples*. Australian Institute of Health and Welfare, Canberra.

AIHW, 2016: *Australian Burden of Disease Study: Impact and causes of illness and death in Aboriginal and Torres Strait Islander people 2011*. Australian Burden of Disease Study series no. 6. Cat. no. BOD 7, Australian Institute of Health and Welfare, Canberra.

Alam, M. et al., 2016: Modelling the correlation between building energy ratings and heat-related mortality and morbidity. *Sustainable Cities and Society*, **22**, 29-39, doi:10.1016/j.scs.2016.01.006.
Aldum, N., J. Duggie and B. J. Robson, 2014: Climate change adaptation support tools in Australia. *Regional Environmental Change*, **14**, 401-411.
Aldunce, P., R. Beilin, M. Howden and J. Handmer, 2015: Resilience for disaster risk management in a changing climate: Practitioners' frames and practices. *Global Environmental Change*, **30**, 1-11.
Alexander, L. V. and J. M. Arblaster, 2017: Historical and projected trends in temperature and precipitation extremes in Australia in observations and CMIP5. *Weather and Climate Extremes*, **15**, 34-56, doi:10.1016/j.wace.2017.02.001.
Alexandra, J., 2018: Evolving Governance and Contested Water Reforms in Australia's Murray Darling Basin. *Water*, **10** (2), 18, doi:10.3390/w10020113.
Alexandra, J., 2019: Losing the authority – what institutional architecture for cooperative governance in the Murray Darling Basin? *Australasian Journal of Water Resources*, **23** (2), 99-115, doi:10.1080/13241583.2019.1586066.
Alexandra, J., 2020: The science and politics of climate risk assessment in Australia's Murray Darling Basin. *Environmental Science & Policy*, **112**, 17-27, doi:10.1016/j.envsci.2020.05.022.
Alexandra, J. and C. Max Finlayson, 2020: Floods after bushfires: rapid responses for reducing impacts of sediment, ash, and nutrient slugs. *Australasian Journal of Water Resources*, 1-3, doi:10.1080/13241583.2020.1717694.
Alexandra, J. and B. Norman, 2020: The city as forest - integrating living infrastructure, climate conditioning and urban forestry in Canberra, Australia. *Sustainable Earth*, **3** (1), doi:10.1186/s42055-020-00032-3.
Ali, A., V. Strezov, P. J. Davies and I. Wright, 2018: River sediment quality assessment using sediment quality indices for the Sydney basin, Australia affected by coal and coal seam gas mining. *Science of The Total Environment*, **616-617**, 695-702.
Ali, F. et al., 2019: Australian rice varieties vary in grain yield response to heat stress during reproductive and grain filling stages. *Journal of Agronomy and Crop Science*, **205** (2), 179-187, doi:10.1111/jac.12312.
Allen, C., G. Metternicht, T. Wiedmann and M. Pedercini, 2019: Greater gains for Australia by tackling all SDGs but the last steps will be the most challenging. *Nature Sustainability*, **2** (11), 1041-1050, doi:10.1038/s41893-019-0409-9.
Allis, M. J. and D. Murray Hicks, 2019: Adaptating to Coastal Change at Carters Beach, New Zealand. *Coastal Sediments 2019*, doi:10.1142/9789811204487_0134.
Alston, M., J. Clarke and K. Whittenbury, 2018: Limits to adaptation: Reducing irrigation water in the Murray-Darling Basin dairy communities. *Journal of Rural Studies*, **58**, 93-102, doi:10.1016/j.jrurstud.2017.12.026.
Ambrey, C. et al., 2017: Cultivating climate justice: Green infrastructure and suburban disadvantage in Australia. *Appl. Geogr.*, **89**, 52-60.
Amelung, B. and S. Nicholls, 2014: Implications of climate change for tourism in Australia. *Tourism Manage.*, **41**, 228-244, doi:10.1016/j.tourman.2013.10.002.
Ammar, S. E., M. McLntyre, M. G. Baker and S. Hales, 2021: Imported arboviral infections in New Zealand, 2001 to 2017: A risk factor for local transmission. *Travel Med. Infect. Dis.*, **41**, 102047, doi:10.1016/j.tmaid.2021.102047.
AMS, 2019: *Explaining extreme events of 2017 from a climate perspective* [Herring, S. C., N. Christidis, A. Hoell, M. P. Hoerling and P. A. Stott (eds.)]. **100**, Bulletin of the American Meteorological Society, S1-S117 [Available at: http://dx.doi.org/10.1175/BAMS-ExplainingExtremeEvents2017.1.].
Anderegg, W. R. L. et al., 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368** (6497), doi:10.1126/science.aaz7005.
Anderson, O., S. Mikaloff Fletcher and H. Bostock, 2015: Development of models for predicting future distributions of protected coral species in the New Zealand Region. *Prepared for Marine Species and Threats, Department of Conservation*.
Andrew, M. E. and H. Warrener, 2017: Detecting microrefugia in semi-arid landscapes from remotely sensed vegetation dynamics. *Remote Sens. Environ.*, **200**, 114-124, doi:10.1016/j.rse.2017.08.005.
Anwar, M. R. et al., 2015: Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia. *Agricultural Systems*, **132**, 133-144, doi:10.1016/j.agsy.2014.09.010.
ANZ, 2018: *2018 Annual Review*. ANZ Bank, 32-34.
APRA, 2019: *Climate Change: Awareness to Action*. Australian Prudential Regulation Authority, 29 [Available at: https://www.apra.gov.au/sites/default/files/climate_change_awareness_to_action_march_2019.pdf].
APRA, 2021: *Prudential Practice Guide on Climate Change Financial Risks*. Australian Prudential Regulation Authority, 2 [Available at: https://www.apra.gov.au/sites/default/files/2021-04/Consultation%20on%20draft%20Prudential%20Practice%20Guide%20on%20Climate%20Change%20Financial%20Risks_1.pdf].
Archie, K. M., R. Chapman and S. Flood, 2018: Climate change response in New Zealand communities: Local scale adaptation and mitigation planning. *Environmental Development*, **28**, 19-31, doi:10.1016/j.envdev.2018.09.003.
Argent, N., M. Tonts, R. Jones and J. Holmes, 2014: The Amenity Principle, Internal Migration, and Rural Development in Australia. *Ann. Assoc. Am. Geogr.*, **104** (2), 305-318.
ASBEC, 2012: *Built Environment Adaptation Framework*. Council, A. S. B. E., 2 [Available at: https://www.asbec.asn.au/research-items/a-climate-change-adaptation-framework-for-the-built-environment/].

Astill, S. et al., 2019: Reconceptualising'community'to identify place-based disaster management needs in Tasmania. *Australian Journal of Emergency Management, The*, **34** (1), 48.
Astill, S. and E. Miller, 2018: 'The trauma of the cyclone has changed us forever': self-reliance, vulnerability and resilience among older Australians in cyclone-prone areas. *Ageing and Society*, **38** (2), 403-429, doi:10.1017/s0144686x1600115x.
Attwater, R. and C. Derry, 2017: Achieving Resilience through Water Recycling in Peri-Urban Agriculture. *Water*, **9** (3), 223, doi:10.3390/w9030223.
Audzijonyte, A. et al., 2020: Fish body sizes change with temperature but not all species shrink with warming. *Nat Ecol Evol*, **4** (6), 809-814, doi:10.1038/s41559-020-1171-0.
Ausseil, A.-G. E. et al., 2021: Projected Wine Grape Cultivar Shifts Due to Climate Change in New Zealand. *Front. Plant Sci.*, **12**, 618039, doi:10.3389/fpls.2021.618039.
Ausseil, A. G. E., A. J. Daigneault, B. Frame and E. I. Teixeira, 2019a: Towards an integrated assessment of climate and socio-economic change impacts and implications in New Zealand. *Environmental Modelling & Software*, **119**, 1-20, doi:10.1016/j.envsoft.2019.05.009.
Ausseil, A. G. E. et al., 2019b: *Climate impacts on land use suitability* [LC3573, R. p. f. D. S. N. S. C. C. R. (ed.)]. Manaaki Whenua - Landcare Research.
Austin, E. K. et al., 2018: Drought-related stress among farmers: findings from the Australian Rural Mental Health Study. *Med. J. Aust.*, **209** (4), 159-165.
Austin, E. K. et al., 2020: Concerns about climate change among rural residents in Australia. *Journal of Rural Studies*, **75**, 98-109, doi:10.1016/j.jrurstud.2020.01.010.
Australia SoE, 2016: *Marine environment*. Australia State of the Environment Report [Available at: https://soe.environment.gov.au/theme/marine-environment].
Australia. NAHS Working Party, 1989: *A national Aboriginal health strategy / prepared by the National Aboriginal Health Strategy Working Party*. [National Aboriginal Health Strategy Working Party], [Canberra].
Australian Government, 2009: *Climate Change Risks to Australia's Coast. A First Pass National Assessment*.
Australian Government, 2019: *Future Drought Fund (Drought Resilience Funding Plan 2020 to 2024) Determination 2020*. Department of Agriculture, Water and the Environment, 14 [Available at: https://haveyoursay.awe.gov.au/48071/widgets/284939/documents/144176].
Awatere, S. et al., 2018: *Climate Resilient Māori Land*.
Ayre, M. L. and R. A. Nettle, 2017: Enacting resilience for adaptive water governance: a case study of irrigation modernization in an Australian catchment. *Ecology and Society*, **22** (3), doi:10.5751/es-09256-220301.
Azorin-Molina, C. et al., 2021: A decline of observed daily peak wind gusts with distinct seasonality in Australia, 1941-2016. *Journal of Climate*, 1-63, doi:10.1175/jcli-d-20-0590.1.
B. Frame et al., 2018: Adapting global shared socio-economic pathways for national and local scenarios. *Climate Risk Management*, **21**, 39-51, doi:10.1016/j.crm.2018.05.001.
Babcock, R. C. et al., 2019: Severe Continental-Scale Impacts of Climate Change Are Happening Now: Extreme Climate Events Impact Marine Habitat Forming Communities Along 45% of Australia's Coast. *Frontiers in Marine Science*, **6**, 411, doi:10.3389/fmars.2019.00411.
Baird, A. H., B. Sommer and J. S. Madin, 2012: Pole-ward range expansion of Acropora spp. along the east coast of Australia. *Coral Reefs*, **31** (4), 1063-1063, doi:10.1007/s00338-012-0928-6.
Banhalmi-Zakar, Z. et al., 2016: Mechanisms to finance climate change adaptation in Australia.
Bannister-Tyrrell, M. et al., 2013: Weather-driven variation in dengue activity in Australia examined using a process-based modeling approach. *Am. J. Trop. Med. Hyg.*, **88** (1), 65-72, doi:10.4269/ajtmh.2012.11-0451.
Bao, J., S. C. Sherwood, L. V. Alexander and J. P. Evans, 2017: Future increases in extreme precipitation exceed observed scaling rates. *Nature Climate Change*, **7** (2), 128-132, doi:10.1038/nclimate3201.
Bardsley, D. K., E. Palazzo and M. Pütz, 2018: Regional path dependence and climate change adaptation: A case study from the McLaren Vale, South Australia. *Journal of Rural Studies*, **63**, 24-33, doi:10.1016/j.jrurstud.2018.08.015.
Bardsley, D. K. and N. D. Wiseman, 2016: Socio-ecological lessons for the Anthropocene: Learning from the remote Indigenous communities of Central Australia. *Anthropocene*, **14**, 58-70.
Bargh, M., S.-L. Douglas and A. Te One, 2014: Fostering sustainable tribal economies in a time of climate change. *New Zealand Geographer*, **70** (2), 103-115, doi:10.1111/nzg.12042.
Bark, R., M. Kirby, J. D. Connor and N. D. Crossman, 2014: Water allocation reform to meet environmental uses while sustaining irrigation: a case study of the Murray–Darling Basin, Australia. *Water Policy*, **16** (4), 739-754, doi:10.2166/wp.2014.128.
Bark, R. H. et al., 2015: Operationalising the ecosystem services approach in water planning: a case study of indigenous cultural values from the Murray–Darling Basin, Australia. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **11** (3), 239-249, doi:10.1080/21513732.2014.983549.
Barker, S., M. Baker-Jones, E. Barton and E. Fagan, 2016: Climate change and the fiduciary duties of pension fund trustees – lessons from the Australian law. *Journal of Sustainable Finance & Investment*, **6** (3), 211-244, doi:10.1080/20430795.2016.1204687.
Barnes, M., J. K. Szabo, W. K. Morris and H. Possingham, 2015: Evaluating protected area effectiveness using bird lists in the Australian Wet Tropics. *Diversity and Distributions*, **21** (4), 368-378, doi:10.1111/ddi.12274.

Barnett, G. et al., 2014a: Pathways for adaptation of low-income housing to extreme heat. In: Applied Studies in Climate Adaptation, **9781118845011**, 364-371.

Barnett, J. et al., 2015: From barriers to limits to climate change adaptation: path dependency and the speed of change. *Ecol. Soc.*, **20** (3), 1-11, doi:10.5751/es-07698-200305.

Barnett, J. et al., 2014b: A local coastal adaptation pathway. *Nature Climate Change*, **4** (12), 1103-1108, doi:10.1038/nclimate2383.

Barnett, J. and C. McMichael, 2018: The effects of climate change on the geography and timing of human mobility. *Population and Environment*, **39** (4), 339-356, doi:10.1007/s11111-018-0295-5.

Barnett, J., P. Tschakert, L. Head and W. N. Adger, 2016: A science of loss. *Nat. Clim. Chang.*, **6** (11), 976-978, doi:10.1038/nclimate3140.

Barron, O. V. et al., 2011: *Climate Change Impact on Groundwater Resources in Australia*. Commonwealth Scientific and Industrial Research Organisation, 25 [Available at: https://publications.csiro.au/rpr/download?pid=csiro:EP121194&dsid=DS1].

Bartesaghi-Koc, C. et al., 2021: Can urban heat be mitigated in a single urban street? Monitoring, strategies, and performance results from a real scale redevelopment project. *Solar Energy*, **216**, 564-588, doi:10.1016/j.solener.2020.12.043.

Bates, B. C. et al., 2015: Revision of Australian Rainfall and Runoff - the interim climate change guideline. In: *Floodplain Management Association National Conference*, 2015, 14.

Battaglia, M. and J. Bruce, 2017: Direct climate change impacts on growth and drought risk in blue gum (eucalyptus globulus) plantations in Australia. *Australian Forestry*, **80**, 216-227.

Baumann, S. et al., Updated inventory of glacier ice in New Zealand based on 2016 satellite imagery. doi:10.26686/wgtn.13821809.

Baumgartner, J. B., M. Esperón-Rodríguez and L. J. Beaumont, 2018: Identifying in situ climate refugia for plant species. *Ecography*, **41** (11), 1850-1863, doi:10.1111/ecog.03431.

Bayliss, P. et al., 2018: An integrated risk-assessment framework for multiple threats to floodplain values in the Kakadu Region, Australia, under a changing climate. *Mar. Freshwater Res.*, **69** (7), 1159-1185, doi:10.1071/mf17043.

Bayliss, P. and E. Ligtermoet, 2018: Seasonal habitats, decadal trends in abundance and cultural values of magpie geese (Anseranus semipalmata) on coastal floodplains in the Kakadu Region, northern Australia. *Marine and Freshwater Research*, **69** (7), 1079, doi:10.1071/mf16118.

Beal, C. D. et al., 2018: Identifying and understanding the drivers of high water consumption in remote Australian Aboriginal and Torres Strait Island communities. *J. Clean. Prod.*, **172**, 2425-2434, doi:10.1016/j.jclepro.2017.11.168.

Beall, E. and J. Brocklesby, 2017: Exploring with Māori organizations comparative advantage in the context of climate change. *Journal of Management & Organization*, **23** (6), 821-838, doi:10.1017/jmo.2017.65.

Beautrais, A. L., 2018: Farm suicides in New Zealand, 2007-2015: A review of coroners' records. *Aust N Z J Psychiatry*, **52** (1), 78-86, doi:10.1177/0004867417704058.

Becken, S., 2013: Developing a Framework for Assessing Resilience of Tourism Sub-Systems to Climatic Factors. *Ann. Touris. Res.*, **43**, 506-528, doi:10.1016/j.annals.2013.06.002.

Becken, S. et al., 2021: Climate crisis and flying: social media analysis traces the rise of "flightshame". *Journal of Sustainable Tourism*, **29** (9), 1450-1469, doi:10.1080/09669582.2020.1851699.

Becken, S. and J. Wilson, 2016: Are tourism businesses' responses to weather variability a suitable precursor to climate change adaptation? *Worldwide Hospitality and Tourism Themes*, **8** (5), 578-592, doi:10.1108/whatt-06-2016-0033.

Becker, A., A. K. Y. Ng, D. McEvoy and J. Mullett, 2018: Implications of climate change for shipping: Ports and supply chains. *Wiley Interdisciplinary Reviews: Climate Change*, **9** (2), e508.

Becker, M. et al., 2013: Hybridization may facilitate in situ survival of endemic species through periods of climate change. *Nat. Clim. Chang.*, **3** (12), 1039-1043, doi:10.1038/nclimate2027.

Bekele, E. et al., 2018: Water Recycling via Aquifers for Sustainable Urban Water Quality Management: Current Status, Challenges and Opportunities. *Water*, **10** (4), 457, doi:10.3390/w10040457.

Bell-James, J. and B. Collins, 2020: Queensland's Human Rights Act: A New Frontier for Australian Climate Change Litigation? *UNSW Law Journal*.

Bell, R.-A. and J. Nikolaus Callow, 2020: Investigating Banksia Coastal Woodland Decline Using Multi-Temporal Remote Sensing and Field-Based Monitoring Techniques. *Remote Sensing*, **12** (4), 669, doi:10.3390/rs12040669.

Bell, R., 2018: *Impacts of severe weather: Chasing resilience for New Zealand*. New Zealand Parliament [Available at: http://library.niwa.co.nz/cgi-bin/koha/opac-detail.pl?biblionumber=281114].

Bell, R. G. and J. Hannah, 2019: *Update to 2018 of the annual MSL series and trends around New Zealand*. National Institute of Water & Atmospheric Research Ltd, 20 [Available at: https://www.mfe.govt.nz/sites/default/files/media/Marine/update-to-2018-of-the-annual-MSL-series-and-trends-around-nz.pdf].

Bellard, C. et al., 2014: Vulnerability of biodiversity hotspots to global change. *Glob. Ecol. Biogeogr.*, **23** (12), 1376-1386.

Bendall, S., 2018: *Clifton to Tangoio Coastal Hazards Strategy 2120*. Northern and Southern Cell Assessment Panels [Available at: https://www.hbcoast.co.nz/assets/Document-Library/Assessment-Panel-Report-FINAL-28.2.18-reduced-size.pdf].
Bennett, B., M. Leonard, Y. Deng and S. Westra, 2018: An empirical investigation into the effect of antecedent precipitation on flood volume. *Journal of Hydrology*, **567**, 435-445, doi:10.1016/j.jhydrol.2018.10.025.
Bennett, H. et al., 2014: Health and equity impacts of climate change in Aotearoa-New Zealand, and health gains from climate action. *N. Z. Med. J.*, **127** (1406), 16-31.
Bergstrom, D. M. et al., 2015: Rapid collapse of a sub-Antarctic alpine ecosystem: the role of climate and pathogens. *Journal of Applied Ecology*, **52** (3), 774-783, doi:10.1111/1365-2664.12436.
Bergstrom, D. M. et al., 2021: Combating ecosystem collapse from the tropics to the Antarctic. *Glob. Chang. Biol.*, **27** (9), 1692-1703, doi:10.1111/gcb.15539.
Bertram, G., 2015: Research Note: a revised set of New Zealand wealth estimates. *Policy Quarterly*, **11** (3), 73-75.
Bettini, Y., R. R. Brown and F. J. de Haan, 2015: Exploring institutional adaptive capacity in practice: examining water governance adaptation in Australia. *Ecology and Society*, **20** (1), doi:10.5751/es-07291-200147.
Bhend, J., J. Bathols and K. Hennessy, 2012: *Climate change impacts on snow in Victoria*. CSIRO and BoM, 42 [Available at: https://publications.csiro.au/rpr/pub?list=SEA&pid=csiro:EP117309&sb=RECENT&expert=false&n=12&rpp=25&page=1&tr=425&q=Hennessy&dr=all].
Bickler, S., R. Clough and S. Macready, 2013: *The impact of climate change on the archaeology of New Zealand's coastline: a case study from the Whangarei District*. New Zealand Department of Conservation (DOC). 58 [Available at: https://dcon01mstr0c21wprod.azurewebsites.net/globalassets/documents/science-and-technical/sfc322entire.pdf].
Birkett-Rees, J., D. Bruno and B. Suttie, 2020: *Buchan valley and gippsland lakes cultural mapping project*. Gunaikurnai Land and Waters Aboriginal Corporation, 73 [Available at: https://bridges.monash.edu/articles/report/Gippsland_Lakes_region_predictive_modelling/15094260].
Biswas, T. K. et al., 2021: 2019-2020 Bushfire impacts on sediment and contaminant transport following rainfall in the Upper Murray River catchment. *Integr. Environ. Assess. Manag.*, doi:10.1002/ieam.4492.
Black, C. F., 2010: *The Land is the Source of the Law: A Dialogic Encounter with Indigenous Jurisprudence*. Routledge, 224 pp.
Blakers, A., B. Lu and M. Stocks, 2017: 100% renewable electricity in Australia. *Energy*, **133**, 471-482, doi:10.1016/j.energy.2017.05.168.
Blakers, A., M. Stocks, B. Lu and C. Cheng, 2021: A review of pumped hydro energy storage. *Progress in Energy*, **3** (2), 022003, doi:10.1088/2516-1083/abeb5b.
Blue, B. and P. S. Kench, 2017: Multi-decadal shoreline change and beach connectivity in a high-energy sand system. *New Zealand Journal of Marine and Freshwater Research*, **51** (3), 406-426, doi:10.1080/00288330.2016.1259643.
Blunden, J. and D. S. Arndt, 2020: State of the Climate in 2019. *Bulletin of the American Meteorological Society*, **101** (8), S1-S429, doi:10.1175/2020bamsstateoftheclimate.1.
Boer, M. M., V. R. de Dios and R. A. Bradstock, 2020: Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, **10**, 170-172, doi:https://doi.org/10.1038/s41558-020-0716-1.
BoM, 2016: *Improving Water Information Programme Progress Report*. Bureau of Meteorology, Meteorology, B. o., 33.
BoM, 2019: *Annual climate statement 2018*. Australian Bureau of Meteorology [Available at: http://www.bom.gov.au/climate/current/annual/aus/].
BoM, 2020a: *2020 marine heatwave on the Great Barrier Reef*. Bureau of Meteorology, 4 [Available at: http://www.bom.gov.au/environment/doc/2020-GBR-marine-heatwave-factsheet.pdf].
BoM. Annual climate statement 2019. [Available at: http://www.bom.gov.au/climate/current/annual/aus/]
BoM. Annual Climate Statement 2020. [Available at: http://www.bom.gov.au/]
BoM. Previous droughts. [Available at: http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml]
BoM and CSIRO, 2018: *State of the Climate 2018*. Bureau of Meteorology and Commonwealth Scientific Industrial and Research Organisation, Organisation, B. o. M., I. Commonwealth Scientific and Research, 24.
BoM and CSIRO, 2020: *State of the Climate 2020*. Bureau of Meteorology and Commonwealth Scientific Industrial and Research Organisation, Organisation, B. o. M., I. Commonwealth Scientific and Research.
Bonada, M. et al., 2020: Impact of low rainfall during dormancy on vine productivity and development. *Australian Journal of Grape and Wine Research*, doi:10.1111/ajgw.12445.
Bonada, M. et al., 2015: Impact of elevated temperature and water deficit on the chemical and sensory profiles of Barossa Shiraz grapes and wines. *Australian Journal of Grape and Wine Research*, **21** (2), 240-253, doi:10.1111/ajgw.12142.
Bond, M. O., B. J. Anderson, T. H. A. Henare and P. M. Wehi, 2019: Effects of climatically shifting species distributions on biocultural relationships. *People and Nature*, **1** (1), 87-102, doi:10.1002/pan3.15.
Bond, N. R., J. R. Thomson and P. Reich, 2014: Incorporating climate change in conservation planning for freshwater fishes. *Diversity and Distributions*, **20** (8), 931-942, doi:10.1111/ddi.12213.

Booth, K. and A. Harwood, 2016: Insurance as catastrophe: A geography of house and contents insurance in bushfire-prone places. *Geoforum*, **69**, 44-52.
Borchers Arriagada, N. et al., 2020: Unprecedented smoke-related health burden associated with the 2019-20 bushfires in eastern Australia. *Med. J. Aust.*, doi:10.5694/mja2.50545.
Bosomworth, K. and E. Gaillard, 2019: Engaging with uncertainty and ambiguity through participatory 'Adaptive Pathways' approaches: scoping the literature. *Environmental Research Letters*, **14** (9), 093007, doi:10.1088/1748-9326/ab3095.
Bosomworth, K., A. Harwood, P. Leith and P. Wallis, 2015: Adaptation Pathways: a playbook for developing robust options for climate change adaptation in Natural Resource Management. *https://www.terranova.org.au/repository/southern-slopes-nrm-collection/adaptation-pathways-a-playbook-for-developing-options-for-climate-change-adaptation-in-natural-resource-management*.
Bosomworth, K., P. Leith, A. Harwood and P. J. Wallis, 2017: What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. *Environmental Science & Policy*, **76**, 23-28, doi:10.1016/j.envsci.2017.06.007.
Bostock, H. C. et al., 2015: The carbonate mineralogy and distribution of habitat-forming deep-sea corals in the southwest pacific region. *Deep Sea Research Part I: Oceanographic Research Papers*, **100**, 88-104, doi:10.1016/j.dsr.2015.02.008.
Boston, J., 2016: Anticipatory governance: how well is New Zealand safeguarding the future? *Policy Quarterly*, **12** (3), doi:10.26686/pq.v12i3.4614.
Boston, J., 2017: *Governing for the Future: Designing Democratic Institutions for a Better Tomorrow*. Emerald Group Publishing, 576 pp.
Boston, J. and J. Lawrence, 2018: Funding climate change adaptation: the case for a new policy framework. *Policy Quarterly*, **14** (2), 40-49.
Boström-Einarsson, L. et al., 2020: Coral restoration – A systematic review of current methods, successes, failures and future directions. *PLOS ONE*, **15** (1), e0226631, doi:10.1371/journal.pone.0226631.
Boulter, S., 2012: *A Preliminary Assessment of the Vulnerability of Austra-lian Forests to the Impacts of Climate Change – Synthesis. NationalClimate Chan ge Adaptation Research Facility, Gold Coast, Qld, Australia*. 254.
Bowman, D., 2012: Hot issue – bushfires, powerlines and climate change.
Bowman, D. M. J. S. et al., 2019: Fire caused demographic attrition of the Tasmanian palaeoendemic conifer Athrotaxis cupressoides. *Austral Ecology*, **44** (8), 1322-1339, doi:10.1111/aec.12789.
Bowman, D. M. J. S. et al., 2014: Abrupt fire regime change may cause landscape-wide loss of mature obligate seeder forests. *Glob. Chang. Biol.*, **20** (3), 1008-1015, doi:10.1111/gcb.12433.
Bradstock, R. et al., 2014: Divergent responses of fire to recent warming and drying across south-eastern Australia. *Glob. Chang. Biol.*, **20** (5), 1412-1428, doi:10.1111/gcb.12449.
Brand, E., C. Bond and C. Shannon, 2016: *Indigenous in the City: Urban Indigenous populations in local and global contexts*. The University of Queensland [Available at: https://poche.centre.uq.edu.au/files/609/Indigenous-in-the-city%281%29.pdf].
Bremer, J. and M. Linnenluecke, 2017: Determinants of the perceived importance of organisational adaptation to climate change in the Australian energy industry. *Australian Journal of Management*, **42** (3), 502-521.
Briceño, F. A. et al., 2020: Temperature alters the physiological response of spiny lobsters under predation risk. *Conserv Physiol*, **8** (1), coaa065, doi:10.1093/conphys/coaa065.
Bridge, G. et al., 2018: *Energy and society: a critical perspective*. Routledge.
Bridge, T. C. L. et al., 2014: Variable Responses of Benthic Communities to Anomalously Warm Sea Temperatures on a High-Latitude Coral Reef. *PLOS ONE*, **9** (11), e113079, doi:10.1371/journal.pone.0113079.
Broadbent, A., A. Coutts, N. Tapper and M. Demuzere, 2018: The cooling effect of irrigation on urban microclimate during heatwave conditions. *Urban Climate*, **23**, 20, doi:10.1016/j.uclim.2017.05.002.
Brodison, K., 2013: *Effect of smoke in grape and wine production*. Perth, Western Australia
Brolan, C. E., C. A. McEwan and P. S. Hill, 2019: Australia's overseas development aid commitment to health through the sustainable development goals: a multi-stakeholder perspective. *Globalization and Health*, **15** (1), doi:10.1186/s12992-019-0507-5.
Brookfield, S. and L. Fitzgerald, 2018: Homelessness and natural disasters: the role of community service organisations. *Australian Journal of Emergency Management*, **33** (4), 62-68.
Brookhouse, M. T., G. D. Farquhar and M. L. Roderick, 2013: The impact of bushfires on water yield from south-east Australia's ash forests. *Water Resources Research*, **49** (7), 4493-4505, doi:10.1002/wrcr.20351.
Broome, R. A. and W. T. Smith, 2012: The definite health risks from cutting power outweigh possible bushfire prevention benefits. *Med. J. Aust.*, **197** (8), 440-441, doi:10.5694/mja12.10218.
Brown, C., E. Seville and J. Vargo, 2017: Measuring the organizational resilience of critical infrastructure providers: A New Zealand case study. *International Journal of Critical Infrastructure Prevention*, **18**, 37-49.
Bruyère, C. et al., 2020: *Severe weather in a changing climate, 2nd Ed*. IAG and NCAR, 132 [Available at: https://www.iag.com.au/sites/default/files/Documents/Climate%20action/Severe-weather-in-a-changing-climate-2nd-Edition.pdf].

Bryan, B. A. et al., 2016: Land-use and sustainability under intersecting global change and domestic policy scenarios: Trajectories for Australia to 2050. *Global Environmental Change*, **38**, 130-152, doi:10.1016/j.gloenvcha.2016.03.002.
Bryan, K. R., P. S. Kench and D. E. Hart, 2008: Multi-decadal coastal change in New Zealand: Evidence, mechanisms and implications. *New Zealand Geographer*, **64** (2), 117-128, doi:10.1111/j.1745-7939.2008.00135.x.
Bryant, L. and B. Garnham, 2018: Farming exit and ascriptions of blame: The ordinary ethics of farming communities. *Journal of Rural Studies*, **62**, 62-67, doi:10.1016/j.jrurstud.2018.07.004.
Bryant, M., P. Allan and H. Smith, 2017: Climate Change Adaptations for Coastal Farms: Bridging Science and Mātauranga Māori with Art and Design. *The Plan Journal*, **2** (2), doi:10.15274/tpj.2017.02.02.25.
Bryant, R. A. et al., 2014: Psychological outcomes following the Victorian Black Saturday bushfires. *Aust. N. Z. J. Psychiatry*, **48** (7), 634-643, doi:10.1177/0004867414534476.
Bulgarella, M. et al., 2014: Shifting ranges of two tree weta species (Hemideina spp.): Competitive exclusion and changing climate. *J. Biogeogr.*, **41** (3), 524-535, doi:10.1111/jbi.12224.
Burton, P., 2014: *Responding to climate change : lessons from an Australian hotspot*. Collingwood, Vic : CSIRO Publishing.
Butler, C. L., V. L. Lucieer, S. J. Wotherspoon and C. R. Johnson, 2020: Multi-decadal decline in cover of giant kelp Macrocystis pyrifera at the southern limit of its Australian range. *Mar. Ecol. Prog. Ser.*, **653**, 1-18, doi:10.3354/meps13510.
Button, C. and N. Harvey, 2015: Vulnerability and adaptation to climate change on the South Australian coast: a coastal community perspective. *Transactions of the Royal Society of South Australia*, **139** (1), 38-56, doi:10.1080/03721426.2015.1035216.
Byett, A. et al., 2019: *Climate change adaptation within New Zealand's transport system*. Ministry of Transport, unknown, 11 [Available at: https://deepsouthchallenge.co.nz/wp-content/uploads/2021/01/Climate-Change-Adaptation-within-New-Zealands-Transport-System.pdf].
Cadenhead, N. C. R. et al., 2016: Climate and Fire Scenario Uncertainty Dominate the Evaluation of Options for Conserving the Great Desert Skink. *Conservation Letters*, **9** (3), 181-190, doi:10.1111/conl.12202.
Cagigal, L. et al., 2019: Historical and future storm surge around New Zealand: From the 19th century to the end of the 21st century. *Int. J. Climatol.*, **19**, 77, doi:10.1002/joc.6283.
Cahoon, S., S. L. Chen and B. Brooks, 2016: The impact of climate change on Australian ports and supply chains: the emergence of adaptation strategies. In: Climate Change and Adaptation Planning for Ports [Ng, A., A. Becker and S. Cahoon (eds.)]. Routledge, London, 194-214.
Cai, W., 2015: ENSO and greenhouse warming. *Nature Climate Change*, doi: DOI: 10.1038/NCLIMATE2743.
Cai, W. et al., 2014: Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, **4** (2), 111-116, doi:10.1038/nclimate2100.
Cai, W. et al., 2018: Stabilised frequency of extreme positive Indian Ocean Dipole under 1.5 °C warming. *Nat. Commun.*, **9** (1), 1419, doi:10.1038/s41467-018-03789-6.
Campbell-Tennant, D. J. E., J. L. Gardner, M. R. Kearney and M. R. E. Symonds, 2015: Climate-related spatial and temporal variation in bill morphology over the past century in Australian parrots. *J. Biogeogr.*, **42** (6), 1163-1175, doi:10.1111/jbi.12499.
Capon, S. J. and T. R. Capon, 2017: An Impossible Prescription: Why Science Cannot Determine Environmental Water Requirements for a Healthy Murray-Darling Basin. *Water Economics and Policy*, **03** (03), 1650037, doi:10.1142/s2382624x16500375.
Capson, T. L. and J. Guinotte, 2014: *Future proofing New Zealand's shellfish aquaculture: monitoring and adaptation to ocean acidification*. New Zealand Aquatic Environment and Biodiversity Report, Zealand, M. f. P. I. N.
Caputi, N. et al., 2019: Factors Affecting the Recovery of Invertebrate Stocks From the 2011 Western Australian Extreme Marine Heatwave. *Frontiers in Marine Science*, **6**, 484, doi:10.3389/fmars.2019.00484.
Carey-Smith, T., R. Henderson and S. Singh, 2018: *High Intensity System Design Rainfall Version 4*. National Institute for Water and Atmospheric Research, Research, N. I. f. W. and Atmospheric, Wellington, 73 [Available at: https://www.niwa.co.nz/information-services/hirds].
Carter, A. L. et al., 2018: Geostatistical interpolation can reliably extend coverage of a very high-resolution model of temperature-dependent sex determination. *J. Biogeogr.*, **45** (3), 652-663, doi:10.1111/jbi.13152.
Caruso, B., S. Newton, R. King and C. Zammit, 2017: Modelling climate change impacts on hydropower lake inflows and braided rivers in a mountain basin. *Hydrological Sciences Journal*, **62** (6), 928-946, doi:10.1080/02626667.2016.1267860.
Castro, L. C. et al., 2020: Combined mechanistic modelling predicts changes in species distribution and increased co-occurrence of a tropical urchin herbivore and a habitat-forming temperate kelp. *Diversity and Distributions*, **26** (9), 1211-1226, doi:10.1111/ddi.13073.
Caswell, B. A., N. G. Dissanayake and C. L. J. Frid, 2020: Influence of climate-induced biogeographic range shifts on mudflat ecological functioning in the subtropics. *Estuar. Coast. Shelf Sci.*, **237**, 106692, doi:10.1016/j.ecss.2020.106692.
CBA, 2018: *Annual Report 2018*. Commonwealth Bank of Australia, 50-60.

CBA, 2019: *CBA Annual Report 2019*. Commonwealth Bank of Australia, 322 [Available at: https://www.commbank.com.au/content/dam/commbank/about-us/shareholders/pdfs/annual-reports/CBA-2019-Annual-Report.pdf].
CCATWG, 2017: *Adapting to Climate Change in New Zealand: Stocktake Report from the Climate Change Adaptation Technical Working Group*. Group, C. C. A. T. W. [Available at: www.mfe.govt.nz].
CCATWG, 2018: *Adapting to Climate Change in New Zealand: Recommendations from the Climate Change Adaptation Technical Working Group*. Group, C. C. A. T. W. [Available at: https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/ccatwg-report-web.pdf].
CDEM, 2019: *National-Disaster-Resilience-Strategy - Rautaki ā-Motu Manawaroa Aituā*. Ministry of Civil Defence & Emergency Management, 52 [Available at: https://www.civildefence.govt.nz/assets/Uploads/publications/National-Disaster-Resilience-Strategy/National-Disaster-Resilience-Strategy-10-April-2019.pdf].
Challinor, A. J. et al., 2018: Transmission of climate risks across sectors and borders. *Philos. Trans. A Math. Phys. Eng. Sci.*, **376** (2121), doi:10.1098/rsta.2017.0301.
Chambers, I. et al., 2019: A public opinion survey of four future scenarios for Australia in 2050. *Futures*, **107**, 119-132, doi:10.1016/j.futures.2018.12.002.
Champion, C. et al., 2019: Changing windows of opportunity: past and future climate-driven shifts in temporal persistence of kingfish (Seriola lalandi) oceanographic habitat within south-eastern Australian bioregions. *Mar. Freshwater Res.*, **70** (1), doi:10.1071/mf17387.
Chang-Fung-Martel, J. et al., 2017: The impact of extreme climatic events on pasture-based dairy systems: a review. *Crop & Pasture Science*, **68** (12), 1158-1169, doi:10.1071/cp16394.
Charles-Edwards, E., M. Bell, J. Cooper and A. Bernard, 2018: Population shift: Understanding internal migration in Australia.
Chauvenet, A. L. M., J. G. Ewen, D. Armstrong and N. Pettorelli, 2013: Saving the hihi under climate change: a case for assisted colonization. *J. Appl. Ecol.*, **50** (6), 1330-1340, doi:10.1111/1365-2664.12150.
Cheng, L. et al., 2017: Recent increases in terrestrial carbon uptake at little cost to the water cycle. *Nat. Commun.*, **8** (1), 110, doi:10.1038/s41467-017-00114-5.
Chester, M. V., B. Shane Underwood and C. Samaras, 2020: Keeping infrastructure reliable under climate uncertainty. *Nature Climate Change*, **10** (6), 488-490, doi:10.1038/s41558-020-0741-0.
Chiew, F. et al., 2018: Impact of Coal Resource Development on Streamflow Characteristics: Influence of Climate Variability and Climate Change. *Water*, **10** (9), 1161, doi:10.3390/w10091161.
Chiew, F. and I. Prosser, 2011: Water and Climate. In: Water: Science and Solutions for Australia [Prosser, I. (ed.)]. CSIRO Publishing, 150 Oxford Street (PO Box 1139) Collingwood VIC 3066 Australia, 29-46.
Chiew, F. H. S. and T. A. McMahon, 2002: Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. *Hydrological Sciences Journal*, **47** (3), 505-522, doi:10.1080/02626660209492950.
Chiew, F. H. S. et al., 2014: Observed hydrologic non-stationarity in far south-eastern Australia: implications for modelling and prediction. *Stochastic Environmental Research and Risk Assessment*, **28** (1), 3-15, doi:10.1007/s00477-013-0755-5.
Chiew, F. H. S. et al., 2017: Future runoff projections for Australia and science challenges in producing next generation projections. In: *22nd International Congress on Modelling and Simulation (MODSIM 2017)*, 2017/12, 1745-1751.
Chinn, W. G. H. and T. J. H. Chinn, 2020: Tracking the snow line: Responses to climate change by New Zealand alpine invertebrates. *Arctic, Antarctic, and Alpine Research*, **52** (1), 361-389, doi:10.1080/15230430.2020.1773033.
Chiswell, S. M. and P. J. H. Sutton, 2020: Relationships between long-term ocean warming, marine heat waves and primary production in the New Zealand region. *null*, **54** (4), 614-635, doi:10.1080/00288330.2020.1713181.
Christie, J. et al., 2020: *Department of Conservation climate change adaptation action plan*. Department of Conservation, New Zealand, 80.
Clarke, H. and J. P. Evans, 2019: Exploring the future change space for fire weather in southeast Australia. *Theoretical and Applied Climatology*, **136** (1-2), 513-527, doi:10.1007/s00704-018-2507-4.
Clarke, H. et al., 2020: The Proximal Drivers of Large Fires: A Pyrogeographic Study. *Front Earth Sci. Chin.*, **8**, 90, doi:10.3389/feart.2020.00090.
Clarvis, M. H., E. Bohensky and M. Yarime, 2015: Can Resilience Thinking Inform Resilience Investments? Learning from Resilience Principles for Disaster Risk Reduction. *Sustain. Sci. Pract. Policy*, **7** (7), 9048-9066, doi:10.3390/su7079048.
Cleeland, J. B. et al., 2019: Factors influencing the habitat use of sympatric albatrosses from Macquarie Island, Australia. *Mar. Ecol. Prog. Ser.*, **609**, 221-237, doi:10.3354/meps12811.
Climate Change Commission, 2020.
Climate Emergency Declaration, 2020: Climate emergency declarations in 1,769 jurisdictions and local governments cover 820 million citizens.
Climate Institute, 2012: *Coming Ready or Not: Managing climate risks to Australia's infrastructure*. The Climate Institute, Sydney, 31.
Clonan, M. et al., 2020: *Impact of climate change on flowering induction in mangoes in the Northern Territory*. Earth Systems and Climate Change Hub, 66 [Available at: https://nespclimate.com.au/wp-content/uploads/2019/05/CC-NT-mango-flowering-TR-final.pdf].

CMSI, 2020: *Scenario analysis of climate-related physical risk for buildings and infrastructure: Climate science guidance*. Climate Measurement Standards Initiative, 12 [Available at: https://uploads-ssl.webflow.com/5f1bdaf710347301b0c01fd4/5f5c2f4cb000cab9c03025d8_CMSI%20-%20Climate%20Science%20Technical%20Summary.pdf].
CoA, 2015: *National Climate Resilience and Adaptation Strategy*. Commonwealth of Australia, 80 [Available at: https://www.environment.gov.au/system/files/resources/3b44e21e-2a78-4809-87c7-a1386e350c29/files/national-climate-resilience-and-adaptation-strategy.pdf].
CoA, 2017: *Stability and Affordability: Forging a path to Australia's renewable energy future*. Senate Select Committee into the Resilience of Electricity Infrastructure in a Warming World, 176.
CoA, 2018a: *Current and future impacts of climate change on housing, buildings and infrastructure*. Environment and Communications References Committee,222 pp.
CoA, 2018b: *National disaster risk reduction framework*. Commonwealth of Australia, 23 [Available at: https://www.homeaffairs.gov.au/emergency/files/national-disaster-risk-reduction-framework.pdf].
CoA, 2019a: *Joint Agency Drought Taskforce. Developing a Commonwealth Strategy for Drought Preparedness and Resilience. Consultations*. Department of the Prime Minister and Cabinet, Canberra
CoA, 2019b: *State party report on the state of conservation of the great barrier reef world heritage area (Australia)*. Department of the Environment and Energy, 68 [Available at: https://www.environment.gov.au/system/files/resources/bfcd4506-2d94-4dc4-9eab-2cc97b931fac/files/gbr-state-party-report-2019.pdf].
CoA, 2020a: *Estimating greenhouse gas emissions from bushfires in Australia's temperate forests: focus on 2019-20*. Australian Government, 17 [Available at: https://apo.org.au/node/308455].
CoA, 2020b: A national approach to national disasters.
CoA, 2020c: *Population Statement*. Commonwealth of Australia, 21 [Available at: https://population.gov.au/docs/population_statement_2020_overview.pdf].
CoA, 2020d: *Royal Commission into National Natural Disaster Arrangements*. Commonwealth of Australia,594 pp.
CoA, 2020e: *Royal Commission Into National Natural Disaster Arrangements Report October 2020 Appendices: Volumes 1-2 - Volume 2*. Australian Government - Attorney General's Department, 594 pp.
CoA. National Recovery and Resilience Agency. [Available at: https://recovery.gov.au/]
COAG, 2011: *National Strategy for Disaster Resilience*. Council of Australian Governments [Available at: https://knowledge.aidr.org.au/media/2153/nationalstrategyfordisasterresilience.pdf].
Cobon, D. H. et al., 2020: Native pastures and beef cattle show a spatially variable response to a changing climate in Queensland, Australia. *European Journal of Agronomy*, **114**, 126002, doi:10.1016/j.eja.2020.126002.
Cocolas, N., G. Walters and L. Ruhanen, 2015: Behavioural adaptation to climate change among winter alpine tourists: an analysis of tourist motivations and leisure substitutability. *J. Sustainable Tour.*, **24** (6), 846-865, doi:10.1080/09669582.2015.1088860.
Coenen, L. et al., 2020: Metropolitan governance in action? Learning from metropolitan Melbourne's urban forest strategy. *Australian Planner*, 1-5, doi:10.1080/07293682.2020.1740286.
Coenen, L., K. Davidson and B. Gleeson, 2019: Situating C40 in the Evolution of Networked Urban Climate Governance. *Global Policy*, **10** (4), 723-725, doi:10.1111/1758-5899.12759.
Colberg, F., K. L. McInnes, J. O'Grady and R. Hoeke, 2019: Atmospheric circulation changes and their impact on extreme sea levels around Australia. *Natural Hazards and Earth System Sciences*, **19** (5), 1067-1086, doi:10.5194/nhess-19-1067-2019.
Colliar, J. and P. E. Blackett, 2018: *Tangoio Climate Change Adaptation Decision Model: A process for exploring adaptation pathways for Tangoio Marae*.
Collins, D., K. Montgomery and C. Zammit, 2018a: *Hydrological projections for New Zealand rivers under climate change*. Ministry for the Environment, Wellington, N.Z. [Available at: http://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/Hydrological%20projections%20report-final.pdf].
Collins, K. M., O. F. Price and T. D. Penman, 2018b: Suppression resource decisions are the dominant influence on containment of Australian forest and grass fires. *J. Environ. Manage.*, **228**, 373-382, doi:10.1016/j.jenvman.2018.09.031.
Collins, L., 2020: Eucalypt forests dominated by epicormic resprouters are resilient to repeated canopy fires. *Journal of Ecology*, **108** (1), 310-324, doi:10.1111/1365-2745.13227.
Collins, L. et al., 2021: The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. *Environmental Research Letters*, **16** (4), 044029, doi:10.1088/1748-9326/abeb9e.
Colloff, M. J. et al., 2016: Adaptation services of floodplains and wetlands under transformational climate change. *Ecological Applications*, **26** (4), 1003-1017, doi:10.1890/15-0848.
Condie, S. A., E. C. J. Oliver and G. M. Hallegraeff, 2019: Environmental drivers of unprecedented Alexandrium catenella dinoflagellate blooms off eastern Tasmania, 2012–2018. *Harmful Algae*, **87**, 101628, doi:10.1016/j.hal.2019.101628.
Conroy, G. C., Y. Shimizu-Kimura, R. W. Lamont and S. M. Ogbourne, 2019: A multidisciplinary approach to inform assisted migration of the restricted rainforest tree, Fontainea rostrata. *PLOS ONE*, **14** (1), doi:10.1371/journal.pone.0210560.

Correia, D. L. P., A. L. M. Chauvenet, J. M. Rowcliffe and J. G. Ewen, 2015: Targeted management buffers negative impacts of climate change on the hihi, a threatened New Zealand passerine. *Biol. Conserv.*, **192**, 145-153, doi:10.1016/j.biocon.2015.09.010.
Costello, M. J., A. Cheung and N. De Hauwere, 2010a: Surface area and the seabed area, volume, depth, slope, and topographic variation for the world's seas, oceans, and countries. *Environ. Sci. Technol.*, **44** (23), 8821-8828, doi:10.1021/es1012752.
Costello, M. J. et al., 2010b: A census of marine biodiversity knowledge, resources, and future challenges. *PLOS ONE*, **5** (8), e12110, doi:10.1371/journal.pone.0012110.
Coulter, L., S. Serrao-Neumann and E. Coiacetto, 2019: Climate change adaptation narratives: Linking climate knowledge and future thinking. *Futures*, **111**, 57-70, doi:10.1016/j.futures.2019.05.004.
Cradduck, L., G. Warren-Myers and B. Stringer, 2020: Courts' views on climate change inundation risks for developments: Australian perspectives and considerations for valuers. *Journal of European Real Estate Research*, **13** (3), 435-453, doi:10.1108/jerer-03-2020-0019.
Cradock-Henry, N., J. Fountain and F. Buelow, 2018a: Transformations for Resilient Rural Futures: The Case of Kaikōura, Aotearoa-New Zealand. *Sustainability*, **10** (6), 1952.
Cradock-Henry, N. A., 2017: New Zealand kiwifruit growers' vulnerability to climate and other stressors. *Regional Environmental Change*, **17** (1), 245-259, doi:10.1007/s10113-016-1000-9.
Cradock-Henry, N. A. et al., 2020a: Climate adaptation pathways for agriculture: Insights from a participatory process. *Environmental Science & Policy*, **107**, 66-79, doi:10.1016/j.envsci.2020.02.020.
Cradock-Henry, N. A., J. Connolly, P. Blackett and J. Lawrence, 2020b: Elaborating a systems methodology for cascading climate change impacts and implications. *MethodsX*, **7**, 100893, doi:10.1016/j.mex.2020.100893.
Cradock-Henry, N. A. et al., 2019: Adaptation knowledge for New Zealand's primary industries: Known, not known and needed. *Climate Risk Management*, **25**, 100190, doi:10.1016/j.crm.2019.100190.
Cradock-Henry, N. A. and J. Fountain, 2019: Characterising resilience in the wine industry: Insights and evidence from Marlborough, New Zealand. *Environmental Science & Policy*, **94**, 182-190, doi:10.1016/j.envsci.2019.01.015.
Cradock-Henry, N. A. et al., 2018b: Dynamic adaptive pathways in downscaled climate change scenarios. *Climatic Change*, **150** (3-4), 333-341, doi:10.1007/s10584-018-2270-7.
Cradock-Henry, N. A. and K. McKusker, 2015: *Impacts, indicators and thresholds in sheep and beef land management systems*. Ministry for Primary Industries, Wellington, N.Z.
Crase, L., 2011: The Fallout to the Guide to the Proposed Basin Plan. *Australian Journal of Public Administration*, **70** (1), 84-93, doi:10.1111/j.1467-8500.2011.00714.x.
Cresswell, I. D. and H. T. Murphy, 2017: *Australia state of the environment 2016: biodiversity, independent report to the Australian Government Minister for the Environment and Energy*. State of environment report, Australian Government Department of the Environment and Energy, Australua, C. o., Canberra.
Crnek-Georgeson, K., L. Wilson and A. Page, 2017: Factors influencing suicide in older rural males: a review of Australian studies. *Rural and Remote Health*, **17** (4), doi:10.22605/rrh4020.
CRO Forum, 2019: *The heat is on: Insurability and Resilience in a Changing Climate Emerging Risk Initiative - Position Paper*. 52 [Available at: www.thecroforum.org].
Crosbie, R. S. et al., 2013: An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. *Climatic Change*, **117** (1-2), 41-53, doi:10.1007/s10584-012-0558-6.
Crous, K. Y. et al., 2013: Photosynthesis of temperate Eucalyptus globulus trees outside their native range has limited adjustment to elevated CO2 and climate warming. *Glob. Chang. Biol.*, **19** (12), 3790-3807, doi:10.1111/gcb.12314.
Croxall, J. P. et al., 2012: Seabird conservation status, threats and priority actions: a global assessment. *Bird Conserv. Int.*, **22** (01), 1-34, doi:10.1017/s0959270912000020.
CSIRO, 2008: *Water Availability in the Murray-Darling Basin A report from CSIRO to the Australian Government*. Commonwealth Scientific Industrial and Research Organisation, 67 [Available at: https://publications.csiro.au/rpr/download?pid=legacy:530&dsid=DS1].
CSIRO, 2014: *Climate change adaptation tools and resources for NRM. https://adaptnrm.csiro.au*.
CSIRO, 2018: Climate change in the Torres Strait: Implications for fisheries and marine ecosystems. *Earth Systems and Climate Change*, **4**, 40.
CSIRO, 2019: Australian National Outlook 2019 - CSIRO.
CSIRO, 2020: *Climate and Disaster Resilience: Technical Reports*. CSIRO, Australia., Csiro, 60 [Available at: https://www.csiro.au/en/Research/Environment/Extreme-Events/Bushfire/frontline-support/report-climate-disaste-resilience].
CSIRO and BOM, 2015: *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report*. CSIRO and Bureau of Meteorology, Australia.
Cullen, B. R. et al., 2009: Climate change effects on pasture systems in south-eastern Australia. *Crop and Pasture Science*, **60** (10), doi:10.1071/cp09019.
Cullen, B. R. et al., 2014: Use of modelling to identify perennial ryegrass plant traits for future warmer and drier climates %J Crop and Pasture Science. **65** (8), 758-766, doi:https://doi.org/10.1071/CP13408.

Cummings, V. J. et al., 2021: *Assessment of potential effects of climate-related changes in coastal and offshore waters on New Zealand's seafood sector*. New Zealand Aquatic Environment and Biodiversity, 153.

Cummings, V. J. et al., 2019: Effect of reduced pH on physiology and shell integrity of juvenile (pāua) from New Zealand. *PeerJ*, **7**, e7670, doi:10.7717/peerj.7670.

Cunningham, R. et al., 2017: *Social network analysis: a primer on engaging communities on climate adaptation in New South Wales, Australia*. Institute for Sustainable Futures, New South Wales, Australia.

Cunningham, S. C., A. M. Smith and M. D. Lamare, 2016: The effects of elevated CO2 on growth, shell production and metabolism of cultured juvenile abalone, Haliotis iris. *Aquaculture Research*, **47** (8), 2375-2392, doi:10.1111/are.12684.

D. Collins, B., 2020: New Zealand River Hydrology under Late 21st Century Climate Change. *Water*, **12** (8), 2175, doi:10.3390/w12082175.

D. Frame et al., 2018: *Estimating financial costs of climate change in New Zealand: An estimate of climate change-related weather event costs*. New Zealand Climate Change Research Institute and NIWA, 18.

Dai, A. and T. Zhao, 2017: Uncertainties in historical changes and future projections of drought. Part I: estimates of historical drought changes. *Climatic Change*, **144** (3), 519-533, doi:10.1007/s10584-016-1705-2.

Dale, A. et al., 2018: *Traditional Owners of the Great Barrier Reef: The Next Generation of Reef 2050 Actions*. [Available at: https://www.environment.gov.au/system/files/resources/7b495328-8097-4aab-84aa-67b2a9e789fb/files/reef-2050-traditional-owner-aspirations-report.pdf].

Darbyshire, R., P. Measham and I. Goodwin, 2016: A crop and cultivar-specific approach to assess future winter chill risk for fruit and nut trees. *Climatic Change*, **137** (3-4), 541-556, doi:10.1007/s10584-016-1692-3.

Darwin City Council, 2011: *Climate Change Action Plan 2011-2020*. Climate Change & Environment, Darwin City Council, 47 [Available at: https://www.darwin.nt.gov.au/sites/default/files/publications/attachments/cod_climatechangeactionplan_web.pdf].

Das, S. et al., 2019: Identifying climate refugia for 30 Australian rainforest plant species, from the last glacial maximum to 2070. *Landscape Ecology*, **34** (12), 2883-2896, doi:10.1007/s10980-019-00924-6.

Davey, S. M. and A. Sarre, 2020: Editorial: the 2019/20 Black Summer bushfires. *Australian Forestry*, **83** (2), 47-51, doi:10.1080/00049158.2020.1769899.

Davidson, K. and B. Gleeson, 2018: New Socio-ecological Imperatives for Cities: Possibilities and Dilemmas for Australian Metropolitan Governance. *Urban Policy and Research*, **36** (2), 230-241, doi:10.1080/08111146.2017.1354848.

Davies, A., L. Lockstone-Binney and K. Holmes, 2018: Who are the future volunteers in rural places? Understanding the demographic and background characteristics of non-retired rural volunteers, why they volunteer and their future migration intentions. *Journal of Rural Studies*, **60**, 167-175, doi:10.1016/j.jrurstud.2018.04.003.

DAWE. Murray Darling Basin. [Available at: https://www.agriculture.gov.au/water/mdb, accessed 9th September 2021]

Day, P. B., R. D. Stuart-Smith, G. J. Edgar and A. E. Bates, 2018: Species' thermal ranges predict changes in reef fish community structure during 8 years of extreme temperature variation. *Diversity and Distributions*, **24** (8), 1036-1046, doi:10.1111/ddi.12753.

DCCEE, 2011: *Climate Change Risks to Coastal Buildings and Infrastructure: A supplement to the first pass national assessment*. Australian Government Department of Climate Change, Energy and Efficiency,20 pp.

de Jesus, A. L. et al., 2020: Two decades of trends in urban particulate matter concentrations across Australia. *Environ. Res.*, **190**, 110021, doi:10.1016/j.envres.2020.110021.

de Kantzow, M. C., P. M. Hick, N. K. Dhand and R. J. Whittington, 2017: Risk factors for mortality during the first occurrence of Pacific Oyster Mortality Syndrome due to Ostreid herpesvirus – 1 in Tasmania, 2016. *Aquaculture*, **468**, 328-336, doi:10.1016/j.aquaculture.2016.10.025.

De, L. L. et al., 2016: Our family comes first: migrants' perspectives on remittances in disaster. *Migration and Development*, **5** (1), 130-148, doi:10.1080/21632324.2015.1017971.

Death, R. G., I. C. Fuller and M. G. Macklin, 2015: Resetting the river template: the potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshw. Biol.*, **60** (12), 2477-2496, doi:10.1111/fwb.12639.

DeCarlo, T. M. et al., 2019: Acclimatization of massive reef-building corals to consecutive heatwaves. *Proc. Biol. Sci.*, **286** (1898), 20190235, doi:10.1098/rspb.2019.0235.

Dedekorkut-Howes, A., E. Torabi and M. Howes, 2020: Planning for a different kind of sea change: lessons from Australia for sea level rise and coastal flooding. *Climate Policy*, 1-19, doi:10.1080/14693062.2020.1819766.

Dedekorkut-Howes, A. and J. Vickers, 2017: Coastal Climate Adaptation at the Local Level: A Policy Analysis of the Gold Coast. *Climate Change Adaptation in Pacific Countries*, 401-415, doi:10.1007/978-3-319-50094-2_25.

DEHP, 2013: *Coastal Management Plan*. Coastal Planning, Department of Environment and Heritage Protection,16 pp.

Delany-Crowe, T. et al., 2019: Australian policies on water management and climate change: are they supporting the sustainable development goals and improved health and well-being? *Global. Health*, **15** (1), 68, doi:10.1186/s12992-019-0509-3.

Dell, J. T. et al., 2015: Potential impacts of climate change on the distribution of longline catches of yellowfin tuna (Thunnus albacares) in the Tasman sea. *Deep Sea Res. Part 2 Top. Stud. Oceanogr.*, **113**, 235-245, doi:10.1016/j.dsr2.2014.07.002.

Della Bosca, H. and J. Gillespie, 2020: Bringing the swamp in from the periphery: Australian wetlands as sites of climate resilience and political agency. *null*, **63** (9), 1616-1632, doi:10.1080/09640568.2019.1679100.
Dellink, R., E. Lanzi and J. Chateau, 2019: The Sectoral and Regional Economic Consequences of Climate Change to 2060. *Environmental and Resource Economics*, **72** (2), 309-363, doi:10.1007/s10640-017-0197-5.
Deloitte, 2016: *The economic cost of the social impact of natural disasters*. Deloitte Access Economics, 116 [Available at: http://australianbusinessroundtable.com.au/assets/documents/Report%20-%20Social%20costs/Report%20-%20The%20economic%20cost%20of%20the%20social%20impact%20of%20natural%20disasters.pdf].
Deloitte, 2017a: *Beyond the noise: The megatrends of tomorrow's world*. Consulting, D., München [Available at: https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/public-sector/deloitte-nl-ps-megatrends-2ndedition.pdf].
Deloitte, 2017b: *Building resilience to natural disasters in our states and territories*. 120.
Deloitte, 2019: *The social and economic cost of the North and Far North Queensland Monsoon Trough*. Queensland Reconstruction Authority, 36 [Available at: https://www2.deloitte.com/content/dam/Deloitte/au/Documents/Economics/deloitte-au-dae-monsoon-trough-social-economic-cost-report-160719.pdf].
Deloitte, 2020: *A new choice Australia's climate for growth*. Deloitte Access Economics, Brisbane, 74 [Available at: https://www2.deloitte.com/content/dam/Deloitte/au/Documents/Economics/deloitte-au-dae-new-choice-climate-growth.pdf?nc=1].
Deloitte Access Economics, 2017: *At what price? The economic, social and icon value of the Great Barrier Reef*. [Available at: https://www2.deloitte.com/au/en/pages/economics/articles/great-barrier-reef.html#].
Delworth, T. L. and F. Zeng, 2014: Regional rainfall decline in Australia attributed to anthropogenic greenhouse gases and ozone levels. *Nature Geoscience*, **7** (8), 583-587, doi:10.1038/ngeo2201.
DELWP, 2018: *Monitoring, Evaluation, Reporting & Improvement Framework for Climate Change Adaptation in Victoria*. State of Victoria Department of Environment, Land, Water and Planning,24 pp.
DELWP, 2020: *Victoria's water in a changing climate*. The State of Victoria Department of Environment, Land, Water and Planning, 97 [Available at: https://www.water.vic.gov.au/__data/assets/pdf_file/0024/503718/VICWACI_VictoriasWaterInAChangingClimate_FINAL.pdf].
DENR, 2020a: *Delivering the Climate Change Response: Towards 2050 A Three-Year Action Plan for the Northern Territory Government*. Office of Climate Change, Department of Environment and Natural Resources, Northern Territory Government,6 pp.
DENR, 2020b: *Northern Territory Climate Change Response: Towards 2050*. Office of Climate Change, Department of Environment and Natural Resources, Northern Territory Government,11 pp.
Denys, P. H. et al., 2020: Sea Level Rise in New Zealand: The Effect of Vertical Land Motion on Century-Long Tide Gauge Records in a Tectonically Active Region. *Journal of Geophysical Research: Solid Earth*, **125** (1), doi:10.1029/2019jb018055.
Department of the Prime Minister and Cabinet, 2019: *National Disaster Resilience Strategy. Rautaki ā-Motu Manawaroa Aituā*. NZ Ministry of Civil Defence & Emergency Management,50 pp.
Derner, J. et al., 2018: Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. *Climatic Change*, **146** (1), 19-32, doi:10.1007/s10584-017-2029-6.
DES, 2018: *Preparing a shoreline erosion management plan - Guideline for coastal development*. Queensland Government, 5 [Available at: https://www.qld.gov.au/__data/assets/pdf_file/0011/107300/gl-cd-preparing-a-shoreline-erosion-management-plan.pdf].
Dey, R., S. C. Lewis and N. J. Abram, 2019: Investigating observed northwest Australian rainfall trends in Coupled Model Intercomparison Project phase 5 detection and attribution experiments. *International Journal of Climatology*, **39** (1), 112-127, doi:10.1002/joc.5788.
Dhanjal-Adams, K. L. et al., 2016: The distribution and protection of intertidal habitats in Australia. *Emu - Austral Ornithology*, **116** (2), 208-214, doi:10.1071/mu15046.
Di Luca, A., J. P. Evans and F. Ji, 2018: Australian snowpack in the NARCliM ensemble: evaluation, bias correction and future projections. *Clim. Dyn.*, **51** (1), 639-666, doi:10.1007/s00382-017-3946-9.
Di Virgilio, G. et al., 2020: Climate Change Significantly Alters Future Wildfire Mitigation Opportunities in Southeastern Australia. *Geophys. Res. Lett.*, **47** (15), e2020GL088893, doi:10.1029/2020GL088893.
DIA, 2017a: *Report of the Havelock North Drinking Water Inquiry, Stage 1*. Government Inquiry into Havelock North Drinking Water [Available at: https://www.dia.govt.nz/vwluResources/Report-Havelock-North-Water-Inquiry-Stage-1/$file/Report-Havelock-North-Water-Inquiry-Stage-1.pdf].
DIA, 2017b: *Report of the Havelock North Drinking Water Inquiry: Stage 2*. Government Inquiry into Havelock North Drinking Water,296 pp.
Dickie, B., 2020: Climate Change Implications for Local Government of the Resource Management Amendment Act 2020. *Resource Management*.
Ding, N., H. Berry and L. O'Brien, 2015: The Effect of Extreme Heat on Mental Health – Evidence from Australia. *Int. J. Epidemiol.*, **44** (suppl_1), i64-i64, doi:10.1093/ije/dyv097.238.

Ding, N., H. L. Berry and C. M. Bennett, 2016: The Importance of Humidity in the Relationship between Heat and Population Mental Health: Evidence from Australia. *PLOS ONE*, **11** (10), e0164190, doi:10.1371/journal.pone.0164190.
DISER, 2020: *Australian energy update 2020*. Australian Energy Statistics, 38 [Available at: https://www.energy.gov.au/government-priorities/energy-data/australian-energystatistics].
Dittus, A. J., D. J. Karoly, S. C. Lewis and L. V. Alexander, 2014: An investigation of some unexpected frost day increases in Southern Australia. *Australian Meteorological and Oceanographic Journal*, **64**, 261–271, doi:10.22499/2.6404.002.
Do, H. X. et al., 2020: Historical and future changes in global flood magnitude – evidence from a model–observation investigation. *Hydrology and Earth System Sciences*, **24** (3), 1543-1564, doi:10.5194/hess-24-1543-2020.
DoC NZ, 2010: *New Zealand Coastal Policy Statement 2010*. New Zealand Department of Conservation,30 pp.
DoC NZ, 2017a: *NZCPS 2010 Guidance Note: Coastal Hazards. Objective 5 and Policies 24, 25, 26 & 27*. Department of Conservation, New Zealand Government,102 pp.
DoC NZ, 2017b: *NZCPS 2010 implementation guidance introductory note*. Department of Conservation, New Zealand Government,8 pp.
Docker, B. and I. Robinson, 2014: Environmental water management in Australia: experience from the Murray-Darling Basin. *International Journal of Water Resources Development*, **30** (1), 164-177, doi:10.1080/07900627.2013.792039.
Doherty, M. D., A. Malcolm Gill, G. J. Cary and M. P. Austin, 2017: Seed viability of early maturing alpine ash (Eucalyptus delegatensis subsp. delegatensis) in the Australian Alps, south-eastern Australia, and its implications for management under changing fire regimes. *Australian Journal of Botany*, **65** (7), 517, doi:10.1071/bt17068.
Dominey-Howes, D., A. Gorman-Murray and S. McKinnon, 2016: Emergency management response and recovery plans in relation to sexual and gender minorities in New South Wales, Australia. *International Journal of Disaster Risk Reduction*, **16**, 1-11.
Donat, M. G. et al., 2016: More extreme precipitation in the world's dry and wet regions. *Nature Climate Change*, **6** (5), 508-513, doi:10.1038/nclimate2941.
Doubleday, Z. A. et al., 2013: Assessing the risk of climate change to aquaculture: a case study from south-east Australia. *Aquaculture Environment Interactions*, **3** (2), 163-175, doi:10.3354/aei00058.
Dowdy, A. and A. Pepler, 2018: Pyroconvection risk in Australia: Climatological changes in atmospheric stability and surface fire weather conditions. *Geophys. Res. Lett.*, **45(4)**, 2005-2013.
Dowdy, A. J., 2020: Climatology of thunderstorms, convective rainfall and dry lightning environments in Australia. *Climate Dynamics*, **54** (5-6), 3041-3052, doi:10.1007/s00382-020-05167-9.
Dowdy, A. J. et al., 2019: Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Sci. Rep.*, **9** (1), 10073, doi:10.1038/s41598-019-46362-x.
Downing, K., R. Jones and B. Singley, 2016: Handout or Hand-up: Ongoing Tensions in the Long History of Government Response to Drought in Australia. *Australian Journal of Politics & History*, **62**, 186-202.
Dreccer, M. F. et al., 2018: Comparison of sensitive stages of wheat, barley, canola, chickpea and field pea to temperature and water stress across Australia. **248**, 275-294.
Drill, A., S. Paddam and S. Wong, 2016: *Climate Risk Management for Financial Institutions*. Climate Change Working Group, Actuaries Institute Australia.
Duan, H., G. Huang, S. Zhou and D. Tissue, 2018: Dry mass production, allocation patterns and water use efficiency of two conifers with different water use strategies under elevated [CO2], warming and drought conditions. *Eurpoean Journal of Forest Research*, **137**, 605-618.
Dudney, J. et al., 2018: Navigating Novelty and Risk in Resilience Management. *Trends in Ecology & Evolution*, **33** (11), 863-873, doi:10.1016/j.tree.2018.08.012.
Duke, N. C. et al., 2017: Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. *Mar. Freshwater Res.*, **68** (10), 1816-1829.
Dun et al., 2018: Recognising knowledge transfers in 'unskilled'and 'low-skilled'international migration: insights from Pacific Island seasonal workers in rural Australia. *Asia Pac. Viewp.*, **59**, 276-292.
Duncan, R., 2014: Regulating agricultural land use to manage water quality: The challenges for science and policy in enforcing limits on non-point source pollution in New Zealand. *Land use policy*, **41**, 378-387, doi:10.1016/j.landusepol.2014.06.003.
Dunlop, M. et al., 2016: *Exploring Adaptation Pathways in the Murray Basin*. CSIRO, Australia.
Dunn, R. J. H. et al., 2020: Development of an updated global land in situ-based data set of temperature and precipitation extremes: HadEX3. *J. Geophys. Res.*, **125** (16), e2019JD032263, doi:10.1029/2019jd032263.
Duursma, D. E. et al., 2013: Next-generation invaders? Hotspots for naturalised sleeper weeds in Australia under future climates. *PLOS ONE*, **8** (12), e84222, doi:10.1371/journal.pone.0084222.
Eadie, Laura and C. Hoisington, 2011: *Stocking Up: Securing our marine economy*. Centre for Policy Development, 72 [Available at: https://cpd.org.au/wp-content/uploads/2011/09/stocking-up_final_for-web.pdf].
Eagles, H. A. et al., 2014: Ppd1, Vrn1, ALMT1 and Rht genes and their effects on grain yield in lower rainfall environments in southern Australia. *Crop and Pasture Science*, **65** (2), doi:10.1071/cp13374.

Edwards, P. et al., 2019: Tools for adaptive governance for complex social-ecological systems: a review of role-playing-games as serious games at the community-policy interface. *Environ. Res. Lett.*, **14** (11), 113002, doi:10.1088/1748-9326/ab4036.
Egan, E., J.-M. Woolley and E. Williams, 2020: *Climate Change Vulnerability Assessment of Selected Taonga Species*. NIWA, 90 [Available at: https://waimaori.maori.nz/wp-content/uploads/2020/09/2020073CH_Report_FINAL_15April-Technical-Report.pdf].
Ekström, M., M. R. Grose and P. H. Whetton, 2015: An appraisal of downscaling methods used in climate change research. *Wiley Interdiscip. Rev. Clim. Change*, **6** (3), 301-319, doi:10.1002/wcc.339.
Eldridge, D. J. and G. Beecham, 2018: The Impact of Climate Variability on Land Use and Livelihoods in Australia's Rangelands. *Climate Variability Impacts on Land Use and Livelihoods in Drylands*, 293-315, doi:10.1007/978-3-319-56681-8_14.
Ellis, N. R. and G. A. Albrecht, 2017: Climate change threats to family farmers' sense of place and mental wellbeing: A case study from the Western Australian Wheatbelt. *Soc. Sci. Med.*, **175**, 161-168, doi:10.1016/j.socscimed.2017.01.009.
Elrick-Barr, C., D. Thomsen, B. Preston and T. Smith, 2017: Perceptions matter: household adaptive capacity and capability in two Australian coastal communities. *Regional Environ. Change*, **17**, 1141-1151.
Elrick-Barr, C. E. and T. F. Smith, 2021: Policy is rarely intentional or substantial for coastal issues in Australia. *Ocean & Coastal Management*, **207**, 105609, doi:10.1016/j.ocecoaman.2021.105609.
Elrick-Barr, C. E. et al., 2016: How are coastal households responding to climate change? *Environ. Sci. Policy*, **63**, 177-186, doi:10.1016/j.envsci.2016.05.013.
Enright, N. J. et al., 2015: Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, **13** (5), 265-272, doi:10.1890/140231.
Erhart, D. et al., 2020: *Climate Risk Management Framework for Queensland Local Government*. Local Government Association Queensland [Available at: https://qcrc.lgaq.asn.au/climate-risk-management-framework1].
Eriksen, C., 2014: Gendered Risk Engagement: Challenging the Embedded Vulnerability, Social Norms and Power Relations in Conventional Australian Bushfire Education. *Geographical Research*, **52** (1), 23-33, doi:10.1111/1745-5871.12046.
Eriksen, C., 2019: Negotiating adversity with humour: A case study of wildland firefighter women. *Political Geography*, **68**, 139-145, doi:10.1016/j.polgeo.2018.08.001.
ESCI, 2021: *Electricity Sector Climate Information Project Final Report*. 58 [Available at: https://www.climatechangeinaustralia.gov.au/en/projects/esci/esci-publications/esci-project-reports/].
Espada, R., Jr., A. Apan and K. McDougall, 2015: Vulnerability assessment and interdependency analysis of critical infrastructures for climate adaptation and flood mitigation. *International Journal of Disaster Resilience in the Built Environment*, **6** (3), 313-346, doi:10.1108/ijdrbe-02-2014-0019.
Etchells, H., A. J. O'Donnell, W. Lachlan McCaw and P. F. Grierson, 2020: Fire severity impacts on tree mortality and post-fire recruitment in tall eucalypt forests of southwest Australia. *For. Ecol. Manage.*, **459**, 117850, doi:10.1016/j.foreco.2019.117850.
Evans, J., M. Kay, A. Prasad and A. Pitman, 2018: The resilience of Australian wind energy to climate change. *Environ. Res. Lett.*, **13**.
Evans, J. P., D. Argueso, R. Olson and A. Di Luca, 2017: Bias-corrected regional climate projections of extreme rainfall in south-east Australia. *Theoretical and Applied Climatology*, **130** (3-4), 1085-1098, doi:10.1007/s00704-016-1949-9.
Evans, J. P. et al., 2020: The CORDEX-Australasia ensemble: evaluation and future projections. *Climate Dynamics*, doi:10.1007/s00382-020-05459-0.
Evans, J. P. and M. F. McCabe, 2013: Effect of model resolution on a regional climate model simulation over southeast Australia. *Climate Research*, **56** (2), 131-145, doi:10.3354/cr01151.
Evans, L., T. L. Milfont and J. Lawrence, 2014: Considering local adaptation increases willingness to mitigate. *Global Environmental Change*, **25**, 69-75, doi:10.1016/j.gloenvcha.2013.12.013.
Evans, L. S. et al., 2016: Structural and psycho-social limits to climate change adaptation in the Great Barrier Reef Region. *PLOS ONE*, **11** (3), e0150575.
Every, D., 2016: *Disaster Risk Education Community Connections and Emergency Communication with People who are Homeless*. Prepared!for!Emergency Management Planning Communications, Victoria State Emergency Service, 29.
Fairman, T. A., C. R. Nitschke and L. T. Bennett, 2016: Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. *International Journal of Wildland Fire*, **25** (8), 831, doi:10.1071/wf15010.
Fastenrath, S., L. Coenen and K. Davidson, 2019: Urban Resilience in Action: the Resilient Melbourne Strategy as Transformative Urban Innovation Policy? *Sustain. Sci. Pract. Policy*, **11** (3), 693, doi:10.3390/su11030693.
Fatorić, S., R. Morén-Alegret, R. J. Niven and G. Tan, 2017: Living with climate change risks: stakeholders' employment and coastal relocation in mediterranean climate regions of Australia and Spain. *Environment Systems and Decisions*, **37** (3), 276-288, doi:10.1007/s10669-017-9629-6.

Fazey, I. et al., 2015: Past and future adaptation pathways. *Climate and Development*, 1-19, doi:10.1080/17565529.2014.989192.
FENZ, 2018: Annual return of fires database, 1991/92 - 2017/18. Fire and Emergency New Zealand, Wellington.
Ferrario, F. et al., 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat. Commun.*, **5**, 3794, doi:10.1038/ncomms4794.
Fiddes, S. L., A. B. Pezza and V. Barras, 2015: A new perspective on Australian snow. *Atmospheric Science Letters*, **16** (3), 246-252, doi:10.1002/asl2.549.
Fielke, S. J. and M. S. Srinivasan, 2018: Co-innovation to increase community resilience: influencing irrigation efficiency in the Waimakariri Irrigation Scheme. *Sustainability Science*, **13** (1), 255-267, doi:10.1007/s11625-017-0432-6.
Filbee-Dexter, K. and T. Wernberg, 2020: Author Correction: Substantial blue carbon in overlooked Australian kelp forests. *Sci. Rep.*, **10** (1), 17253, doi:10.1038/s41598-020-74313-4.
Filho, W. et al., 2018: Coping with the impacts of urban heat islands. A literature based study on understanding urban heat vulnerability and the need for resilience in cities in a global climate change context. *J. Clean. Prod.*, **171**, 1140-1149, doi:10.1016/j.jclepro.2017.10.086.
Filkov, A. I. et al., 2020: Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science and Resilience*, **1** (1), 44-56, doi:10.1016/j.jnlssr.2020.06.009.
Finlayson, C. M. et al., 2017: Policy considerations for managing wetlands under a changing climate. *Mar. Freshwater Res.*, **68** (10), 1803-1815, doi:10.1071/mf16244.
Firn, J. et al., 2015: Priority threat management of invasive animals to protect biodiversity under climate change. *Glob. Chang. Biol.*, **21** (11), 3917-3930, doi:10.1111/gcb.13034.
Fitzer, S. C. et al., 2019: Selectively bred oysters can alter their biomineralization pathways, promoting resilience to environmental acidification. *Glob. Chang. Biol.*, doi:10.1111/gcb.14818.
Fitzer, S. C. et al., 2018: Coastal acidification impacts on shell mineral structure of bivalve mollusks. *Ecol. Evol.*, **8** (17), 8973-8984, doi:10.1002/ece3.4416
10.1002/ece3.4416. eCollection 2018 Sep.
Fitzgerald, G. et al., 2019: Long-term consequences of flooding: A case study of the 2011 Queensland floods. *Aust. J. Emerg. Manage.*, **34** (1), 35.
Fitzgerald, G. J. et al., 2016: Elevated atmospheric [CO2] can dramatically increase wheat yields in semi-arid environments and buffer against heat waves. *Global Change Biology*, **22** (6), 2269-2284, doi:10.1111/gcb.13263.
Fleming, A. et al., 2015: Climate change is the least of my worries": stress limitations on adaptive capacity. *Rural Society*, **24** (1), 24-41.
Fleming, A. et al., 2014: Climate change risks and adaptation options across Australian seafood supply chains – A preliminary assessment. *Climate Risk Management*, **1**, 39-50.
Fletcher, A. L. et al., 2020: Has historic climate change affected the spatial distribution of water-limited wheat yield across Western Australia? *Climatic Change*, doi:10.1007/s10584-020-02666-w.
Fletcher, S. M. et al., 2013: Traditional coping strategies and disaster response: examples from the South Pacific region. *J. Environ. Public Health*, **2013**, 264503-264503, doi:10.1155/2013/264503.
Flood, S., N. A. Cradock-Henry, P. Blackett and P. Edwards, 2018: Adaptive and interactive climate futures: systematic review of 'serious games' for engagement and decision-making. *Environ. Res. Lett.*, **13** (6), 063005.
Fogarty, H. E., C. Cvitanovic, A. J. Hobday and G. T. Pecl, 2019: Prepared for change? An assessment of the current state of knowledge to support climate adaptation for Australian fisheries. *Rev. Fish Biol. Fish.*, **29** (4), 877-894, doi:10.1007/s11160-019-09579-7.
Fogarty, H. E., C. Cvitanovic, A. J. Hobday and G. T. Pecl, 2021: Stakeholder perceptions on actions for marine fisheries adaptation to climate change. *Mar. Freshwater Res.*, doi:10.1071/MF21055.
Foote, K. J., M. K. Joy and R. G. Death, 2015: New Zealand Dairy Farming: Milking Our Environment for All Its Worth. *Environ. Manage.*, **56** (3), 709-720, doi:10.1007/s00267-015-0517-x.
Ford, M. R. and M. E. Dickson, 2018: Detecting ebb-tidal delta migration using Landsat imagery. *Marine Geology*, **405**, 38-46, doi:10.1016/j.margeo.2018.08.002.
Forino, G., J. von Meding and G. Brewer, 2019: Community based initiatives to mainstream climate change adaptation into disaster risk reduction: evidence from the Hunter Valley (Australia). *Local Environment*, **24** (1), 52-67, doi:10.1080/13549839.2018.1548010.
Forino, G., J. von Meding and G. J. Brewer, 2017: Climate Change Adaptation and Disaster Risk Reduction Integration in Australia: Challenges and Opportunities. *Handbook of Disaster Risk Reduction & Management*, 273-294, doi:10.1142/9789813207950_0011.
Foster, T. et al., 2015: Effect of ocean warming and acidification on the early life stages of subtropical Acropora spicifera. *Coral Reefs*, **34** (4), 1217-1226, doi:10.1007/s00338-015-1342-7.
Fowler, K. et al., 2018: Simulating Runoff Under Changing Climatic Conditions: A Framework for Model Improvement. *Water Resources Research*, **54** (12), 9812-9832, doi:10.1029/2018wr023989.
Fowler, K., R. Morden, L. Lowe and R. Nathan, 2015: Advances in assessing the impact of hillside farm dams on streamflow. *Australasian Journal of Water Resources*, **19** (2), 96-108, doi:10.1080/13241583.2015.1116182.

Frame, D. J. et al., 2020: Climate change attribution and the economic costs of extreme weather events: a study on damages from extreme rainfall and drought. *Climatic Change*, doi:10.1007/s10584-020-02729-y.
Friel, S. et al., 2014: The impact of drought on the association between food security and mental health in a nationally representative Australian sample. *BMC public health*, **14** (1102).
Fu, G. et al., 2019: Attributing variations of temporal and spatial groundwater recharge: A statistical analysis of climatic and non-climatic factors. *Journal of Hydrology*, **568**, 816-834, doi:10.1016/j.jhydrol.2018.11.022.
Fulton, E. A., C. M. Bulman, H. Pethybridge and S. D. Goldsworthy, 2018: Modelling the Great Australian Bight Ecosystem. *Deep Sea Research Part II: Topical Studies in Oceanography*, **157-158**, 211-235, doi:10.1016/j.dsr2.2018.11.002.
Fünfgeld, H., 2015: Facilitating local climate change adaptation through transnational municipal networks. *Current Opinion in Environmental Sustainability*, **12**, 67-73, doi:10.1016/j.cosust.2014.10.011.
Gallagher, R. V., S. Allen and I. J. Wright, 2019: Safety margins and adaptive capacity of vegetation to climate change. *Sci. Rep.*, **9** (1), 8241, doi:10.1038/s41598-019-44483-x.
Gallagher, R. V. et al., 2013: The grass may not always be greener: projected reductions in climatic suitability for exotic grasses under future climates in Australia. *Biological Invasions*, **15** (5), 961-975, doi:10.1007/s10530-012-0342-6.
Gallant, A. J. E., M. J. Reeder, J. S. Risbey and K. J. Hennessy, 2013: The characteristics of seasonal-scale droughts in Australia, 1911-2009. *International Journal of Climatology*, **33** (7), 1658-1672, doi:10.1002/joc.3540.
Gallego, D., R. García-Herrera, C. Peña-Ortiz and P. Ribera, 2017: The steady enhancement of the Australian Summer Monsoon in the last 200 years. *Sci. Rep.*, **7** (1), 16166-16166, doi:10.1038/s41598-017-16414-1.
Gardner, J. L. et al., 2014a: Temporal patterns of avian body size reflect linear size responses to broadscale environmental change over the last 50 years. *J. Avian Biol.*, **45**, 529–35.
Gardner, J. L. et al., 2014b: Dynamic size responses to climate change: prevailing effects of rising temperature drive long-term body size increases in a semi-arid passerine. *Glob. Chang. Biol.*, **20**, 2062–2075.
Gardner, J. L. et al., 2018: Associations between changing climate and body condition over decades in two southern hemisphere passerine birds. *Clim. Change Res.*, **5**, 2(1-14).
Garmestani, A. et al., 2019: The Role of Social-Ecological Resilience in Coastal Zone Management: A Comparative Law Approach to Three Coastal Nations. *Frontiers in Ecology and Evolution*, **7**, 410, doi:10.3389/fevo.2019.00410.
Gartin, M. et al., 2020: Climate Change as an Involuntary Exposure: A Comparative Risk Perception Study from Six Countries across the Global Development Gradient. *Int. J. Environ. Res. Public Health*, **17** (6), doi:10.3390/ijerph17061894.
Gasbarro, F., F. Rizzi and M. Frey, 2016: Adaptation measures of energy and utility companies to cope with water scarcity induced by climate change. *Business Strategy and the Environment*, **25**, 54-72.
Gasparrini, A. et al., 2017: Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet Health*, **1** (9), e360-e367, doi:10.1016/S2542-5196(17)30156-0.
Gawith, D., I. Hodge, F. Morgan and A. Daigneault, 2020: Climate change costs more than we think because people adapt less than we assume. *Ecol. Econ.*, **173**, 106636, doi:10.1016/j.ecolecon.2020.106636.
Gawne, B. et al., 2020: Monitoring, evaluation, and adaptive management in the Murray–Darling Basin. In: Murray-Darling Basin, Australia - Its Future Management [Barry, H., B. Neil, B. Nick, P. Carmel and S. Michael (eds.)]. Elsevier, 227-249.
GBCA. Green Star Programme. [Available at, accessed 3rd September 2021]
GBRMPA, 2019: *Great Barrier Reef Outlook Report 2019*. Great Barrier Reef Marine Park Authority [Available at: http://hdl.handle.net/11017/3474].
GCA, 2019: *Adapt now: A global call for leadership on climate resilience*. Global Center on Adaptation and World Resources Institute, 90 [Available at: https://cdn.gca.org/assets/2019-09/GlobalCommission_Report_FINAL.pdf].
Gebert, L. L., A. M. Coutts and N. J. Tapper, 2018: The influence of urban canyon microclimate and contrasting photoperiod on the physiological response of street trees and the potential benefits of water sensitive urban design. *Urban For. Urban Greening*, doi:10.1016/j.ufug.2018.07.017.
Gervais, C. R., C. Champion and G. T. Pecl, 2021: Species on the move around the Australian coastline: A continental-scale review of climate-driven species redistribution in marine systems. *Glob. Chang. Biol.*, **27** (14), 3200-3217, doi:10.1111/gcb.15634.
Ghahramani, A. et al., 2015: The value of adapting to climate change in Australian wheat farm systems: farm to cross-regional scale. *Agriculture, Ecosystems & Environment*, **211**, 112-125, doi:10.1016/j.agee.2015.05.011.
Gibbs, M. T., 2015: Pitfalls in developing coastal climate adaptation responses. *Climate Risk Management*, **8** (C), 1-8, doi:10.1016/j.crm.2015.05.001.
Gibbs, M. T., 2020: The two-speed coastal climate adaptation economy in Australia. *Ocean & Coastal Management*, **190**, 105150, doi:10.1016/j.ocecoaman.2020.105150.
Giejsztowt, J., A. T. Classen and J. R. Deslippe, 2020: Climate change and invasion may synergistically affect native plant reproduction. *Ecology*, **101** (1), e02913, doi:10.1002/ecy.2913.
Gilmour, J. P. et al., 2013: Recovery of an isolated coral reef system following severe disturbance. *Science*, **340** (6128), 69-71, doi:10.1126/science.1232310.
Gilpin, B. J. et al., 2020: A large scale waterborne Campylobacteriosis outbreak, Havelock North, New Zealand. *J. Infect.*, **81** (3), 390-395, doi:10.1016/j.jinf.2020.06.065.

Glavovic, B. C., 2014: The 2004 Manawatu Floods, New Zealand: Integrating Flood Risk Reduction and Climate Change Adaptation. *Adapting to Climate Change*, 231-268, doi:10.1007/978-94-017-8631-7_10.

Glavovic, B. C., W. S. A. Saunders and J. S. Becker, 2010: Land-use planning for natural hazards in New Zealand: the setting, barriers, 'burning issues' and priority actions. *Natural Hazards*, **54** (3), 679-706, doi:10.1007/s11069-009-9494-9.

Glavovic, B. C. and G. P. Smith, 2014: Introduction: Learning from Natural Hazards Experience to Adapt to Climate Change. In: Adapting to Climate Change Lessons from natural Hazards planning [Glavovic, B. C. and G. P. Smith (eds.)]. Springer, 1-38.

Godfree, R. C. et al., 2021: Implications of the 2019–2020 megafires for the biogeography and conservation of Australian vegetation. *Nature Communications*, **12** (1), doi:10.1038/s41467-021-21266-5.

Goldberg, J. et al., 2016: Climate change, the Great Barrier Reef and the response of Australians. *Palgrave Communications*, **2** (1), doi:10.1057/palcomms.2015.46.

Golding, B. and C. Campbell, 2009: Learning to be drier in the southern Murray-Darling Basin: Setting the scene for this research volume. *Australian Journal of Adult Learning*, **49** (3), 423-450.

Gonzalez, D., P. Dillon, D. Page and J. Vanderzalm, 2020: The Potential for Water Banking in Australia's Murray–Darling Basin to Increase Drought Resilience. *Water*, **12** (10), 2936, doi:10.3390/w12102936.

Goode, N. et al., 2017: Defining disaster resilience: comparisons from key stakeholders involved in emergency management in Victoria, Australia. *Disasters*, **41** (1), 171-193.

Goodhue, N. et al., 2012: *Coastal Adaptation to Climate Change: Mapping a New Zealand Coastal Sensitivity Index*. [Available at: https://niwa.co.nz/sites/niwa.co.nz/files/HAM2013-011%20-%20NZ%20Coastal%20Sensitivity%20Index.pdf].

Gorddard, R. et al., 2016: Values, rules and knowledge: Adaptation as change in the decision context. *Environmental Science & Policy*, **57**, 60-69, doi:10.1016/j.envsci.2015.12.004.

Gordon, D. P., 2009: New Zealand inventory of biodiversity. Canterbury University Press.

Gorman-Murray, A. et al., 2017: Problems and possibilities on the margins: LGBT experiences in the 2011 Queensland floods. *Gender, Place & Culture*, **24** (1), 37-51, doi:10.1080/0966369x.2015.1136806.

Government Inquiry into Havelock North Drinking Water, 2017: *Havelock North drinking water inquiry: Stage 2*. Auckland, New Zealand.

Government of Tasmania, 2017: *Tasmanian Planning Scheme – State Planning Provisions*. State of Tasmania, Australia,514 pp.

Grace, E., B. Kilvington and M. France-Hudson, 2019: *Reducing risk through the management of existing uses: tensions under the RMA*. Institute of Geological and Nuclear Sciences, 144 [Available at: https://www.gns.cri.nz/static/download/existinguses/SR2019-55-AD-Reducing-risk-through-the-management-of-existing-uses-tensions_FINAL.pdf].

Grafton, R. Q. et al., 2014: Water planning and hydro-climatic change in the Murray-Darling Basin, Australia. *Ambio*, **43** (8), 1082-1092.

Grafton, R. Q., R. Quentin Grafton, J. Horne and S. A. Wheeler, 2016: On the Marketisation of Water: Evidence from the Murray-Darling Basin, Australia. *Water Resources Management*, **30** (3), 913-926, doi:10.1007/s11269-015-1199-0.

Graham, E. M. et al., 2019: Climate change and biodiversity in Australia: a systematic modelling approach to nationwide species distributions. *Australasian Journal of Environmental Management*, **26** (2), 112-123, doi:10.1080/14486563.2019.1599742.

Graham, S. et al., 2018: Local values and fairness in climate change adaptation: Insights from marginal rural Australian communities. *World Development*, **108**, 332-343.

Graham, S. L. et al., 2014: Effects of soil warming and nitrogen addition on soil respiration in a New Zealand tussock grassland. *PLOS ONE*, **9** (3), e91204.

Grayson, K. L. et al., 2014: Sex ratio bias and extinction risk in an isolated population of Tuatara (Sphenodon punctatus). *PLOS ONE*, **9** (4), e94214, doi:10.1371/journal.pone.0094214.

Grech, A., R. Pressey and J. Day, 2016: Coal, cumulative impacts, and the Great Barrier Reef. *Conservation Letters*, **9** (3), 200-207.

Grecian, W. J. et al., 2016: Contrasting migratory responses of two closely related seabirds to long-term climate change. *Marine Ecology Progress Series*, **559**, 231-242.

Green Cross Australia, 2012: Witness King Tides. A snapshot of future sea levels: photographing Queensland's king tide 19 January – 9 February 2012.

Green, D., U. King and J. Morrison, 2009: Disproportionate burdens: the multidimensional impacts of climate change on the health of Indigenous Australians. *Med. J. Aust.*, **190** (1), 4-5.

Green, D. and L. Minchin, 2014: Living on Climate-Changed Country: Indigenous Health,Well-Being and Climate Change in Remote Australian Communities. *EcoHealth, 10.1007/s10393-013-0892-9*, doi:10.1007/s10393-013-0892-9.

Green, K. et al., 2021: Australian Bogong moths Agrotis infusa (Lepidoptera: Noctuidae), 1951–2020: decline and crash. *Austral Entomology*, **60** (1), 66-81, doi:10.1111/aen.12517.

Greenhalgh, S. and O. Samarasinghe, 2018: Sustainably managing freshwater resources. *Ecology and Society*, **23** (2), doi:10.5751/es-10233-230244.

Grieger, R., S. Capon and W. Hadwen, 2019: Resilience of coastal freshwater wetland vegetation of subtropical Australia to rising sea levels and altered hydrology. *Regional Environmental Change*, **19** (1), 279-292, doi:10.1007/s10113-018-1399-2.
Grieger, R., S. J. Capon, W. L. Hadwen and B. Mackey, 2020: Between a bog and a hard place: a global review of climate change effects on coastal freshwater wetlands. *Climatic Change*, **163** (1), 161-179, doi:10.1007/s10584-020-02815-1.
Griffiths, 2013: New Zealand six main centre extreme rainfall trends 1962-2011. *Weather and Climate*, **33**, 76, doi:10.2307/26169738.
Grimm-Seyfarth, A., J. B. Mihoub, B. Gruber and K. Henle, 2018: Some like it hot: from individual to population responses of an arboreal arid-zone gecko to local and distant climate. *Ecol. Monogr.*, **88** (3), 336-352, doi:10.1002/ecm.1301.
Grimm-Seyfarth, A., J. B. Mihoub and K. Henle, 2017: Too hot to die? The effects of vegetation shading on past, present, and future activity budgets of two diurnal skinks from arid Australia. *Ecol. Evol.*, **7** (17), 6803-6813, doi:10.1002/ece3.3238.
Grose, M. R. et al., 2020: Insights From CMIP6 for Australia's Future Climate. *Earth's Future*, **8** (5), 147, doi:10.1029/2019EF001469.
Grundy, M. J. et al., 2016: Scenarios for Australian agricultural production and land use to 2050. *Agricultural Systems*, **142**, 70-83, doi:10.1016/j.agsy.2015.11.008.
Guerin, G. R. and A. J. Lowe, 2013: Multi-species distribution modelling highlights the Adelaide Geosyncline, South Australia, as an important continental-scale arid-zone refugium. *Austral Ecol.*, **38** (4), 427-435, doi:10.1111/j.1442-9993.2012.02425.x.
Guerreiro, S. B. et al., 2018: Detection of continental-scale intensification of hourly rainfall extremes. *Nature Climate Change*, **8(9)**, 803-807.
Gulsrud, N. M., K. Hertzog and I. Shears, 2018: Innovative urban forestry governance in Melbourne?: Investigating “green placemaking” as a nature-based solution. *Environ. Res.*, **161**, 158-167, doi:10.1016/j.envres.2017.11.005.
Guo, Y. et al., 2018: Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLoS Med.*, **15** (7), e1002629, doi:10.1371/journal.pmed.1002629.
Guthrie, G., 2019: *Real Options Analysis of Climate-Change Adaptation: A Simplified Approach*. Victoria University Wellington [Available at: https://ssrn.com/abstract=3323549].
Gutiérrez, J. M. et al., 2021: Interactive Atlas. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Gynther, I., N. Waller and L. K. P. Leung, 2016: *Confirmation of the Extinction of the Bramble Cay Melomys Melomys Rubicola on Bramble Cay, Torres Strait: Results and Conclusions from a Comprehensive Survey in August-September 2014*. Queensland Government, 59 pp.
Haasnoot, M., J. Lawrence and A. K. Magnan, 2021: Pathways to coastal retreat. *Science*, **372** (6548), 1287-1290, doi:10.1126/science.abi6594.
Haberle, S. G. et al., 2014: The Macroecology of Airborne Pollen in Australian and New Zealand Urban Areas. *PLOS ONE*, **9** (5), 13, doi:10.1371/journal.pone.0097925.
Haddad, S. et al., 2020a: On the potential of building adaptation measures to counterbalance the impact of climatic change in the tropics. *Energy and Buildings*, **229**, 110494, doi:10.1016/j.enbuild.2020.110494.
Haddad, S. et al., 2020b: Holistic approach to assess co-benefits of local climate mitigation in a hot humid region of Australia. *Scientific Reports*, **10** (1), doi:10.1038/s41598-020-71148-x.
Haddad, S. et al., 2019: Experimental and Theoretical analysis of the urban overheating and its mitigation potential in a hot arid city – Alice Springs. *Architectural Science Review*, 1-16, doi:10.1080/00038628.2019.1674128.
Hadwen, W. L. et al., 2012: *Climate change responses and adaptation pathways in Australian coastal ecosystems: Synthesis report*. National Climate Change Adaptation Research Facility (NCCARF), Gold Coast, 359 pp.
Haensch, J., S. A. Wheeler and A. Zuo, 2021: Explaining permanent and temporary water market trade patterns within local areas in the southern Murray–Darling Basin. *Aust. J. Agric. Resour. Econ.*, **65** (2), 318-348, doi:10.1111/1467-8489.12420.
Hague, B. S., B. F. Murphy, D. A. Jones and A. J. Taylor, 2019: Developing impact-based thresholds for coastal inundation from tide gauge observations. *Journal of Southern Hemisphere Earth Systems Science*, **69** (1), 252, doi:10.1071/es19024.
Hales, S. et al., 2000: Daily mortality in relation to weather and air pollution in Christchurch, New Zealand. *Aust. N. Z. J. Public Health*, **24** (1), 89-91, doi:10.1111/j.1467-842x.2000.tb00731.x.
Hall, N. L. et al., 2021: Climate change and infectious diseases in Australia's Torres Strait Islands. *Aust. N. Z. J. Public Health*, **45** (2), 122-128, doi:10.1111/1753-6405.13073.
Hall, N. L. and L. Crosby, 2020: Climate Change Impacts on Health in Remote Indigenous Communities in Australia. *International Journal of Environmental Health Research*, 1-16, doi:10.1080/09603123.2020.1777948.
Hallegatte, S. et al., 2012: Investment Decision Making under Deep Uncertainty - Application to Climate Change. *Policy Research Working Papers*, doi:10.1596/1813-9450-6193.

Hallegraeff, G. and C. Bolch, 2016: Unprecedented toxic algal blooms impact on Tasmanian seafood industry. *Microbiol. Aust.*, **37** (3), 143-144, doi:10.1071/MA16049.
Hallegraeff, G. M. et al., 2020: Overview of Australian and New Zealand harmful algal species occurrences and their societal impacts in the period 1985 to 2018, including a compilation of historic records. *Harmful Algae*, 101848, doi:10.1016/j.hal.2020.101848.
Hallett, C. S. et al., 2017: Observed and predicted impacts of climate change on the estuaries of south-western Australia, a Mediterranean climate region. *Regional Environ. Change*, **18** (5), 1357-1373, doi:10.1007/s10113-017-1264-8.
Halteh, J. et al., 2018: The impact of technology on employment: a research agenda for New Zealand and beyond. *Labour & Industry: a journal of the social and economic relations of work*, **28** (3), 203-216, doi:10.1080/10301763.2018.1519774.
Hamilton, D. P., N. Salmaso and H. W. Paerl, 2016: Mitigating harmful cyanobacterial blooms: strategies for control of nitrogen and phosphorus loads. *Aquat. Ecol.*, **50** (3), 351-366, doi:10.1007/s10452-016-9594-z.
Hamin, E. and N. Gurran, 2015: Climbing the Adaptation Planning Ladder: Barriers and Enablers in Municipal Planning. *Handbook of Climate Change Adaptation*, 839-860, doi:10.1007/978-3-642-38670-1_25.
Hancock, G. R., D. Verdon-Kidd and J. B. C. Lowry, 2017: Soil erosion predictions from a landscape evolution model – An assessment of a post-mining landform using spatial climate change analogues. *Science of The Total Environment*, **601-602**, 109-121, doi:10.1016/j.scitotenv.2017.04.038.
Hanigan, I. C., K. B. G. Dear and A. Woodward, 2021: Increased ratio of summer to winter deaths due to climate warming in Australia, 1968-2018. *Aust. N. Z. J. Public Health*, doi:10.1111/1753-6405.13107.
Hanigan, I. C., J. Schirmer and T. Niyonsenga, 2018: Drought and Distress in Southeastern Australia. *Ecohealth*, **15** (3), 642-655, doi:10.1007/s10393-018-1339-0.
Hanna, C., I. White and B. C. Glavovic, 2021: Managed retreats by whom and how? Identifying and delineating governance modalities. *Climate Risk Management*, **31**, 100278, doi:10.1016/j.crm.2021.100278.
Hanna, C. J., 2019: Restraints of change: Limits to 'managed retreats' in Aotearoa New Zealand. Ph.D. Thesis. University of Waikato
Hanslow, D. J., B. D. Morris, E. Foulsham and M. A. Kinsela, 2018: A Regional Scale Approach to Assessing Current and Potential Future Exposure to Tidal Inundation in Different Types of Estuaries. *Sci. Rep.*, **8** (1), 7065, doi:10.1038/s41598-018-25410-y.
Hardy, D. et al., 2019: *Planning for Climate Change Impacts on Māori Coastal Ecosystems and Economies: A Case Study of 5 Māori-owned land blocks in the Horowhenua Coastal Zone*. Massey University, 116 [Available at: https://www.deepsouthchallenge.co.nz/sites/default/files/2020-03/Hardy%20et%20al.%20CC%20Impacts%20on%20Maori%20FINAL%20LOW%20RES%20Sections%201%20to%204_2.pdf].
Hare, K. M. et al., 2019: Intractable: species in New Zealand that continue to decline despite conservation effort. *J. R. Soc. N. Z.*, doi:10.1080/03036758.2019.1599967.
Harmsworth, G., S. Awatere and M. Robb, 2016: Indigenous Māori values and perspectives to inform freshwater management in Aotearoa-New Zealand. *Ecology and Society*, **21** (4), doi:10.5751/es-08804-210409.
Harrington, Harrington and Renwick, 2014: Secular changes in New Zealand rainfall characteristics 1950-2009. *Weather and Climate*, **34**, 50, doi:10.2307/26169744.
Harrington, L. J., 2020: Rethinking extreme heat in a cool climate: a New Zealand case study. *Environ. Res. Lett.*, doi:10.1088/1748-9326/abbd61.
Harris, R. et al., 2020: Climate change: Australia's wine future-climate information for adaptation to change. *Wine & Viticulture*.
Harris, R. M. B. et al., 2018: Biological responses to the press and pulse of climate trends and extreme events. *Nat. Clim. Chang.*, **8** (7), 579-587, doi:10.1038/s41558-018-0187-9.
Harris, R. M. B., D. J. Kriticos, T. Remenyi and N. Bindoff, 2017: Unusual suspects in the usual places: a phylo-climatic framework to identify potential future invasive species. *Biological Invasions*, **19** (2), 577-596, doi:10.1007/s10530-016-1334-8.
Harris, R. M. B., T. Remenyi and N. L. Bindoff, 2016: *The Potential Impacts of Climate Change on Victorian Alpine Resorts. A Report for the Alpine Resorts Co-ordinating Council*. The Antarctic Climate & Ecosystems Cooperative Research Centre, 203 [Available at: https://www.arcc.vic.gov.au/uploads/publications-and-research/The%20Potential%20Impact%20of%20Climate%20Change%20on%20Victorian%20Alpine%20Resorts%20Study_FINAL.pdf].
Harris, S. and C. Lucas, 2019: Understanding the variability of Australian fire weather between 1973 and 2017. *PLOS ONE*.
Harris, S. et al., 2008: The relationship between the monsoonal summer rain and dry-season fire activity of northern Australia. *Int. J. Wildland Fire*, **17** (5), 674-684, doi:10.1071/WF06160.
Hart, B. T., 2016: The Australian Murray–Darling Basin Plan: challenges in its implementation (part 1). *International Journal of Water Resources Development*, **32** (6), 819-834, doi:10.1080/07900627.2015.1083847.
Hart, M. and E. R. Langer, 2011: *Mitigating the risk of human caused wildfires: Literature review and stakeholder study*. New Zealand Forest Research Institute.

Hartwig, L., S. Jackson and N. Osborne, 2018: Recognition of Barkandji Water Rights in Australian Settler-Colonial Water Regimes. *Resources*, **7** (1), 16, doi:10.3390/resources7010016.
Harvey, N., 2019: Protecting private properties from the sea: Australian policies and practice. *Mar. Policy*, **107**, 103566, doi:10.1016/j.marpol.2019.103566.
Harvey, N. and B. Clarke, 2019: 21st Century reform in Australian coastal policy and legislation. *Marine Policy*, **103**, 27-32, doi:10.1016/j.marpol.2019.02.016.
Hasegawa, S., C. A. Macdonald and S. A. Power, 2015: Elevated carbon dioxide increases soil nitrogen and phosphorus availability in a phosphorus-limited Eucalyptus woodland. *Glob. Chang. Biol.*, **22** (4), 1628-1643.
Haskoning Australia, 2016: *Coastal Zone Management Plan for Bilgola Beach (Bilgola) and Basin Beach (Mona Vale)*. Haskoning Australia Pty Ltd, 80 [Available at: https://files.northernbeaches.nsw.gov.au/sites/default/files/2017224002_201707-bilgolabasinczmp-ecertified.pdf].
Hassenforder, E. and S. Barone, 2019: Institutional arrangements for water governance. *International Journal of Water Resources Development*, **35** (5), 783-807, doi:10.1080/07900627.2018.1431526.
Hatvani-Kovacs, G., M. Belusko, J. Pockett and J. Boland, 2018: Heat stress-resistant building design in the Australian context. *Energy and Buildings*, **158**, 290-299, doi:10.1016/j.enbuild.2017.10.025.
Hauraki Gulf Forum, 2017: *State of our Gulf - Hauraki State of the Environment Report 2017*. Hauraki Gulf Forum, Auckland,127 pp.
Hayes, S. and B. Lovelock, 2017: 'Demystifying' worldmaking: exploring New Zealand's clean and green imaginary through the lens of angling tourists. *Tourism Recreation Research*, **42** (3), 380-391, doi:10.1080/02508281.2016.1265235.
Hayward, B., 2008: 'Nowhere Far From the Sea': Political Challenges of Coastal Adaptation To Climate Change in New Zealand. *Polit. Sci.*, **60** (1), 47-59, doi:10.1177/003231870806000105.
Hayward, B., 2012: Children, Citizenship and Environment. doi:10.4324/9780203106839.
Hayward, B., 2017: *Sea Change: Climate Politics and New Zealand*. Bridget Williams Books, 112 pp.
Hazledine, T. and M. Rashbrooke, 2018: The New Zealand rich list twenty years on. *New Zealand Economic Papers*, **52** (3), 289-303, doi:10.1080/00779954.2017.1354907.
HDSR, 2020: *Health and Disability System Review – Final Report – Pūrongo Whakamutunga*. Health and Disability System Review, Wellington, 266 [Available at: https://www.systemreview.health.govt.nz/assets/Uploads/hdsr/health-disability-system-review-final-report.pdf].
He, T. H. et al., 2016: Evolutionary potential and adaptation of Banksia attenuata (Proteaceae) to climate and fire regime in southwestern Australia, a global biodiversity hotspot. *Sci. Rep.*, **6**, doi:10.1038/srep26315.
Head, L., 2020: Transformative change requires resisting a new normal. *Nature Climate Change*, **10** (3), 173-174, doi:10.1038/s41558-020-0712-5.
Heaviside, C., H. Macintyre and S. Vardoulakis, 2017: The Urban Heat Island: Implications for Health in a Changing Environment. *Current Environmental Health Reports*, **4** (3), 296-305, doi:10.1007/s40572-017-0150-3.
Helman, P. and R. Tomlinson, 2018: Two Centuries of Climate Change and Climate Variability, East Coast Australia. *J. Mar. Sci. Eng.*, **6** (1), 3, doi:10.3390/jmse6010003.
Hendrikx, J., C. Zammit, E. Ö. Hreinsson and S. Becken, 2013: A comparative assessment of the potential impact of climate change on the ski industry in New Zealand and Australia. *Climatic Change*, **119** (3-4), 965-978, doi:10.1007/s10584-013-0741-4.
Hendy, J. et al., 2018: *Drought and climate change adaptation - impacts and projections*. Motu Economic and Public Policy Research, 16.
Hennessy, K. et al., 2016: *Climate change impacts on Australia's dairy regions.*, CSIRO Oceans and Atmosphere, Melbourne, Australia., 64.
Henwood, W. B. T. M.-B. H. M. E. Z. C. M. T., 2019: Enhancing drinking water quality in remote Māori communities. *MAI Journal: A New Zealand Journal of Indigenous Scholarship*, **8** (2), doi:10.20507/maijournal.2019.8.2.1.
Heron, S. F. et al., 2017: *Impacts of Climate Change on World Heritage Coral Reefs: A First Global Scientific Assessment*. Center, U. W. H., Paris.
Hertzler, G. et al., 2013: *Will primary producers continue to adjust practices and technologies, change production systems or transform their industry? An application of real options*. National Climate Change Adaptation Research Facility, Gold Coast, 93 pp.
Hettiarachchi, S., C. Wasko and A. Sharma, 2019: Can antecedent moisture conditions modulate the increase in flood risk due to climate change in urban catchments? *Journal of Hydrology*, **571**, 11-20, doi:10.1016/j.jhydrol.2019.01.039.
Higham, J. et al., 2016: Climate change, tourist air travel and radical emissions reduction. *J. Clean. Prod.*, **111**, 336-347, doi:10.1016/j.jclepro.2014.10.100.
Hill, R. et al., 2020: Knowledge co-production for Indigenous adaptation pathways: Transform post-colonial articulation complexes to empower local decision-making. *Global Environmental Change*, **65**, 102161, doi:10.1016/j.gloenvcha.2020.102161.
Hinkson, M. and E. Vincent, 2018: Shifting Indigenous Australian Realities: Dispersal, Damage, and Resurgence: Introduction. *Oceania*, **88** (3), 240-253.

Hintz, M. J., C. Luederitz, D. J. Lang and H. von Wehrden, 2018: Facing the heat: A systematic literature review exploring the transferability of solutions to cope with urban heat waves. *Urban Climate*, **24**, 714-727, doi:10.1016/j.uclim.2017.08.011.
Hirabayashi, Y. et al., 2013: Global flood risk under climate change. *Nature Climate Change*, **3** (9), 816-821, doi:10.1038/nclimate1911.
Hobday, A. J. and C. Cvitanovic, 2017: Preparing Australian fisheries for the critical decade: insights from the past 25 years. *Marine and Freshwater Research*, **68** (10), doi:10.1071/mf16393.
Hobday, A. J., C. M. Spillman, J. Paige Eveson and J. R. Hartog, 2016: Seasonal forecasting for decision support in marine fisheries and aquaculture. *Fish. Oceanogr.*, **25**, 45-56, doi:10.1111/fog.12083.
Hochman, Z., D. L. Gobbett and H. Horan, 2017: Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology*, **23** (5), 2071-2081, doi:10.1111/gcb.13604.
Hodder, J., 2019: *Climate change litigation- who's afraid of creative judges? A paper for presentation to the "Climate Change Adaptation" session of the Local Government New Zealand Rural and Provincial Sector Meeting*. Jack Hodder QC, Wellington.
Hodgkinson, J., A. Hobday and E. Pinkard, 2014: Climate adaptation in Australia's resource-extraction industries: ready or not? *Regional Environ. Change*, **14**, 1663–1678.
Hoegh-Guldberg, O., E. S. Poloczanska, W. Skirving and S. Dove, 2017: Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science*, **4**, doi:10.3389/fmars.2017.00158.
Hoeppner, J. M. and L. Hughes, 2019: Climate readiness of recovery plans for threatened Australian species. *Conserv. Biol.*, **33** (3), 534-542, doi:10.1111/cobi.13270.
Hoffmann, A. A. et al., 2019: Impacts of recent climate change on terrestrial flora and fauna: Some emerging Australian examples. *Austral Ecol.*, **44** (1), 3-27, doi:10.1111/aec.12674.
Home Affairs, 2020: *The first national action plan to implement the national disaster risk reduction framework*. Australian Department of Home Affairs, 85 [Available at: https://www.homeaffairs.gov.au/emergency/files/first-national-action-plan.pdf].
Hope, P. et al., 2017: *A Synthesis of Findings from the Victorian Climate Initiative (VicCI)*. Bureau of Meteorology Australia, 56 [Available at: https://www.water.vic.gov.au/__data/assets/pdf_file/0030/76197/VicCI-25-07-17-MR.pdf].
Hopkins, D., 2015: Applying a Comprehensive Contextual Climate Change Vulnerability Framework to New Zealand's Tourism Industry. *Ambio*, **44** (2), 110-120, doi:10.1007/s13280-014-0525-8.
Hopkins, D. et al., 2015: Climate change and Aotearoa New Zealand. *Wiley Interdisciplinary Reviews: Climate Change*, **6** (6), 559-583, doi:10.1002/wcc.355.
Horwood, P., E. McBryde, D. Peniyamina and S. Ritchie, 2018: The Indo-Papuan conduit: a biosecurity challenge for Northern Australia. *Aust. N. Z. J. Public Health*, **42** (5), 434-436, doi:10.1111/1753-6405.12808.
Houston, W. A. et al., 2020: Climate change, mean sea levels, wetland decline and the survival of the critically endangered Capricorn Yellow Chat. *Austral Ecology*, doi:10.1111/aec.12886.
Howden, M., S. Schroeter, S. Crimp and I. Hanigan, 2014: The changing roles of science in managing Australian droughts: An agricultural perspective. *Weather and Climate Extremes*, **3**, 80-89, doi:10.1016/j.wace.2014.04.006.
Howes, M. et al., 2015: Towards networked governance: improving interagency communication and collaboration for disaster risk management and climate change adaptation in Australia. *J. Environ. Planning Manage.*, **58** (5), 757-776.
Hughes, J. et al., 2021: Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Climate Risk Management*, **31**, 100262, doi:10.1016/j.crm.2020.100262.
Hughes, J. D., K. C. Petrone and R. P. Silberstein, 2012: Drought, groundwater storage and stream flow decline in southwestern Australia. *Geophysical Research Letters*, **39** (3), doi:10.1029/2011gl050797.
Hughes, L., P. Stock, L. Brailsford and D. Alexander, 2018a: *Icons at risk: Climate change threatening Australia's tourism*. Council, C.
Hughes, N., D. Galeano and S. Hatfield-Dodds, 2019a: *The effects of drought and climate variability on Australian farms*. Sciences, A. B. o. A. a. R. E. a., Canberra.
Hughes, N. and P. Gooday, 2021: *Climate change impacts and adaptation on Australian farms*. Department of Agriculture Water and the Environment, 15 [Available at: https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1032401/0].
Hughes, N. and K. Lawson, 2017: Climate adjusted productivity on Australian cropping farms. In: New Directions in Productivity Measurement and Efficiency Analysis: Counting the Environment and Natural Resources [Ancev, T., M. Samad Azad and F. Hernandez-Sancho (eds.)]. Edward Elgar, Cheltenham, 173.
Hughes, T. P. et al., 2018b: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, **359** (6371), 80-83, doi:10.1126/science.aan8048.
Hughes, T. P. et al., 2019b: Global warming impairs stock–recruitment dynamics of corals. *Nature*, **568** (7752), 387-390, doi:10.1038/s41586-019-1081-y.
Hughes, T. P. et al., 2018c: Global warming transforms coral reef assemblages. *Nature*, **556** (7702), 492-496, doi:10.1038/s41586-018-0041-2.
Hughes, T. P. et al., 2019c: Ecological memory modifies the cumulative impact of recurrent climate extremes. *Nat. Clim. Chang.*, **9** (1), 40-43, doi:10.1038/s41558-018-0351-2.

Hughey, K. F. D. and S. Becken, 2014: Understanding climate coping as a basis for strategic climate change adaptation – The case of Queenstown-Lake Wanaka, New Zealand. *Global Environmental Change*, **27**, 168-179, doi:10.1016/j.gloenvcha.2014.03.004.
Hunt, J. R., P. T. Hayman, R. A. Richards and J. B. Passioura, 2018: Opportunities to reduce heat damage in rain-fed wheat crops based on plant breeding and agronomic management. *Field Crops Research*, **224**, 126-138, doi:10.1016/j.fcr.2018.05.012.
Hunt, J. R. et al., 2019: Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change*, **9** (3), 244-247, doi:10.1038/s41558-019-0417-9.
Hunter, J., 2012: A simple technique for estimating an allowance for uncertain sea-level rise. *Climatic Change*, **113** (2), 239-252, doi:10.1007/s10584-011-0332-1.
Hurd, C. L., A. Lenton, B. Tilbrook and P. W. Boyd, 2018: Current understanding and challenges for oceans in a higher-CO2 world. *Nat. Clim. Chang.*, **8**, 686–694.
Hurlbert, M. et al., 2019: Risk management and decision making in relation to sustainable development. In: Special Report on Climate Change and Land.
Hurlimann, A. C., 2008: Barriers to implementing water efficiency practices in the built environment:The case of Melbourne and Bendigo, Australia. *Australian Planner*, **45** (3), 34-42, doi:10.1080/07293682.2008.9982676.
Hurlimann, A. C., G. R. Browne, G. Warren-Myers and V. Francis, 2018: Barriers to climate change adaptation in the Australian construction industry–Impetus for regulatory reform. *Build. Environ.*, **137**, 235-245.
Hutley and S. H. Davis, 2019: *Climate change and directors' duties: supplementary memorandum of opinion*. The Centre for Policy Development [Available at: https://apo.org.au/node/74091].
Hyman, I. T. et al., 2020: Impacts of the 2019–2020 bushfires on New South Wales biodiversity: a rapid assessment of distribution data for selected invertebrate taxa. *Technical Reports of the Australian Museum online*, **32**, 1-17, doi:10.3853/j.1835-4211.32.2020.1768.
IAG, 2019: Climate-related disclosure 2019.
ICA, 2020a: Catastrophe Data.
ICA, 2020b: Top five insured loss events normalised in 2017 dollars.
ICA, 2021: Insurance Council of Australia Data Hub.
ICCC, 2019: *Accelerated Electrification*. Interim Climate Change Committee NZ, 120 [Available at: https://www.iccc.mfe.govt.nz/assets/PDF_Library/daed426432/FINAL-ICCC-Electricity-report.pdf].
ICNZ, 2021: Cost of natural disasters. Insurance Council of New Zealand.
IGCC, 2017: *From Risk to Return: Investing in Climate Change Adaptation*. Investor Group on Climate Change, Investor Group on Climate Change . https://igcc.org.au/wp-content/uploads//03/Adaptation, F. p.
IGCC, 2021a: *Aspiration to Action: Insights into investor progress towards net zero*. Investor Group on Climate Change, 28 [Available at: https://igcc.org.au/wp-content/uploads/2021/08/ASPIRATION-TO-ACTION_FINAL_17AUG2021.pdf].
IGCC, 2021b: *Confusion to clarity: a plan for mandatory TCFD-aligned disclosure in Australia*. Investor Group on Climate Change, CDP and PRI, 65 [Available at: https://igcc.org.au/wp-content/uploads/2021/06/ConfusiontoClarity_APlanforMandatoryTCFDalignedDisclosureinAus.pdf].
Infometrics, 2017: *Real Options Analysis of Strategies to Manage Coastal Hazard Risks-Southern-Units-J-L.pdf*. Hawke's Bay Regional Council, 33 [Available at: https://hbcoast.co.nz/assets/Document-Library/Other-documents/Real-Options-Analysis-of-Strategies-to-Manage-Coastal-Hazard-Risks-Southern-Units-J-L.pdf].
Infometrics and PSConsulting, 2015: *Flood Protection: Option Flexibility and its Value for Greater Wellington Regional Council*. Infometrics and PS Consulting,27 pp.
Infrastructure Australia, 2016: *Infrastructure Priority List 2021: Project and Initiative Summaries*. Infrastructure Australia.
Infrastructure Australia, 2019: *Australian Infrastructure Audit 2019: Report*. Infrastructure Australia.
Infrastructure Australia, 2021: *Australian Infrastructure Plan: The Infrastructure Priority List*. Infrastructure Australia.
Innes, J. et al., 2019: New Zealand ecosanctuaries: types, attributes and outcomes. *J. R. Soc. N. Z.*, **49** (3), 370-393, doi:10.1080/03036758.2019.1620297.
Instone, L. et al., 2014: Climate change adaptation in the rental sector. In: Applied Studies in Climate Adaptation [Palutikof, J. P., S. Boulter, J. Barnett and D. Rissik (eds.)]. John Wiley & Sons, 372-379.
Iorns Magallanes, C., 2019: *Treaty of Waitangi duties relevant to adaptation to coastal hazards from sea-level rise*. Research Report for the Deep South National Science Challenge, 190 [Available at: https://www.deepsouthchallenge.co.nz/sites/default/files/2019-08/Treaty%20%26%20Adaptation%20Final%20Report%20August%202019.pdf].
Iorns Magallanes, C., V. James and T. Stuart, 2018: Courts as Decision-Makers on Sea Level Rise Adaptation Measures: Lessons from New Zealand. *Climate Change Management*, 315-335, doi:10.1007/978-3-319-70703-7_17.
Iorns Magallanes, C. and J. Watts, 2019: *Adaptation to Sea-level Rise: Local Government Liability Issues : Research Report for the Deep South National Science Challenge*. Deep South National Science Challenge.
IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global*

response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V. (ed.)]. In press pp.
IPCC, 2019a: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R. (ed.)]. In press pp.
IPCC, 2019b: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O. (ed.)]. In press pp.
IPCC, 2021: *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Ishak, E. H. et al., 2013: Evaluating the non-stationarity of Australian annual maximum flood. *Journal of Hydrology*, **494**, 134-145, doi:10.1016/j.jhydrol.2013.04.021.
ISO, 2019: Standard ISO 14190 Adaptation to Climate Change. Principles, requirements and guidelines 2019.
Iwanaga, T. et al., 2020: A socio-environmental model for exploring sustainable water management futures: Participatory and collaborative modelling in the Lower Campaspe catchment. *Journal of Hydrology: Regional Studies*, **28**, 100669, doi:10.1016/j.ejrh.2020.100669.
Jackson, M. et al., 2019: Collaborating for Sustainable Water and Energy Management: Assessment and Categorisation of Indigenous Involvement in Remote Australian Communities. *Sustainability*, **11** (2), doi:10.3390/su11020427.
Jackson, S., 2018: Water and Indigenous rights: Mechanisms and pathways of recognition, representation, and redistribution. *Wiley Interdisciplinary Reviews: Water*, **5** (6), e1314, doi:10.1002/wat2.1314.
Jackson, S. and B. Moggridge, 2019: Indigenous water management. *Australasian Journal of Environmental Management*, **26** (3), 193-196, doi:10.1080/14486563.2019.1661645.
Jackson, T., K. Zammit and S. Hatfield-Dodds, 2020: *Snapshot of Australian Agriculture 2020*. Department of Agriculture, Water and the Environment, Canberra, 8.
Jacobs, B., L. Boronyak and P. Mitchell, 2019: Application of Risk-Based, Adaptive Pathways to Climate Adaptation Planning for Public Conservation Areas in NSW, Australia. *Climate*, **7** (4), 58, doi:10.3390/cli7040058.
Jacobs, B. et al., 2018a: Towards a climate change adaptation strategy for national parks: Adaptive management pathways under dynamic risk. *Environmental Science & Policy*, **89**, 206-215, doi:10.1016/j.envsci.2018.08.001.
Jacobs, B. et al., 2016: Adaptation Planning Process and Government Adaptation Architecture Support Regional Action on Climate Change in New South Wales, Australia. In: Innovation in Climate Change Adaptation [Filho, W. L. (ed.)]. Springer International Publishing, Switzerland, 17-29.
Jacobs, S., A. Gallant, N. Tapper and D. Li, 2018b: Use of Cool Roofs and Vegetation to Mitigate Urban Heat and Improve Human Thermal Stress in Melbourne, Australia. *J. Appl. Meteorol. Climatol.*, **57** (8), 1747-1764, doi:10.1175/JAMC-D-17-0243.1.
Jakku, E. et al., 2016: Learning the hard way: a case study of an attempt at agricultural transformation in response to climate change. *Climatic Change*, **137** (3), 557-574, doi:10.1007/s10584-016-1698-x.
James, C. S. et al., 2017: Sink or swim? Potential for high faunal turnover in Australian rivers under climate change. *J. Biogeogr.*, **44** (3), 489-501, doi:10.1111/jbi.12926.
Jardine, T. D. et al., 2015: Does flood rhythm drive ecosystem responses in tropical riverscapes? *Ecology*, **96** (3), 684-692, doi:10.1890/14-0991.1.
Jarvis, C. et al., 2018: Advancement of winegrape maturity continuing for winegrowing regions in Australia with variable evidence of compression of the harvest period. *Australian Journal of Grape and Wine Research*, doi:10.1111/ajgw.12373.
Jay, O. et al., 2021: Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *The Lancet*, **398** (10301), 709-724, doi:https://doi.org/10.1016/S0140-6736(21)01209-5.
Jennings, S. et al., 2016: Setting objectives for evaluating management adaptation actions to address climate change impacts in south-eastern Australian fisheries. *Fisheries Oceanography*, **25**, 29-44, doi:10.1111/fog.12137.
Jensen, M. P. et al., 2018: Environmental Warming and Feminization of One of the Largest Sea Turtle Populations in the World. *Curr. Biol.*, **28** (1), 154-159.e4, doi:10.1016/j.cub.2017.11.057.
Ji, F. et al., 2018: Trends and low frequency variability of East Coast Lows in the twentieth century. *Journal of Southern Hemisphere Earth System Science*, **68** (1), 1-15, doi:10.22499/3.6801.001.
Jiang, N., G. Pacheco and K. Dasgupta, 2017: *Residential movement within New Zealand: Quantifying and characterising the transient population*. Social Policy Evaluation and Research Unit.
Jiang, W. et al., 2021: Compositional Changes in Grapes and Leaves as a Consequence of Smoke Exposure of Vineyards from Multiple Bushfires across a Ripening Season. *Molecules*, **26** (11), doi:10.3390/molecules26113187.
Jobst, A. M., D. G. Kingston, N. J. Cullen and J. Schmid, 2018: Intercomparison of different uncertainty sources in hydrological climate change projections for an alpine catchment (upper Clutha River, New Zealand). *Hydrology and Earth System Sciences*, **22** (6), 3125-3142, doi:10.5194/hess-22-3125-2018.
Johansen, J. L. et al., 2014: Increasing ocean temperatures reduce activity patterns of a large commercially important coral reef fish. *Glob. Chang. Biol.*, **20** (4), 1067-1074, doi:10.1111/gcb.12452.

Jöhnk, K. D. et al., 2008: Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology*, **14** (3), 495-512, doi:10.1111/j.1365-2486.2007.01510.x.
Johnson, D., M. Parsons and K. Fisher, 2021: Engaging Indigenous perspectives on health, wellbeing and climate change. A new research agenda for holistic climate action in Aotearoa and beyond. *Local Environ.*, **26** (4), 477-503, doi:10.1080/13549839.2021.1901266.
Johnson, F. et al., 2016: Natural hazards in Australia: floods. *Clim. Change*, **139** (1), 21-35, doi:10.1007/s10584-016-1689-y.
Johnston, F. H. et al., 2020: Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires. *Nature Sustainability*, doi:10.1038/s41893-020-00610-5.
Johnston, V. and B. France-Hudson, 2019: Implications of Climate Change for Western Concepts of Ownership: Australian Case Study.
Jollands, N., M. Ruth, C. Bernier and N. Golubiewski, 2007: The climate's long-term impact on New Zealand infrastructure (CLINZI) project—A case study of Hamilton City, New Zealand. *Journal of Environmental Management*, **83** (4), 460-477, doi:10.1016/j.jenvman.2006.09.022.
Jones, R., 2019: Climate change and Indigenous Health Promotion. *Glob. Health Promot.*, **26** (3_suppl), 73-81, doi:10.1177/1757975919829713.
Jones, R., H. Bennett, G. Keating and A. Blaiklock, 2014: Climate change and the right to health for Māori in Aotearoa/New Zealand. *Health Hum. Rights*, **16** (1), 54-68.
Jones, R. N. et al., 2013: *Valuing adaptation under rapid change*. National Climate Change Adaptation Research Facility, Gold Coast, pp. 182. http://www.nccarf.edu.au/publications/valuing-adaptation-under-rapid-change.
Jongejan, R. et al., 2016: Drawing the line on coastline recession risk. *Ocean Coast. Manag.*, **122**, 87-94, doi:10.1016/j.ocecoaman.2016.01.006.
Joshi, S. R. et al., 2016: Physical and Economic Consequences of Sea-Level Rise: A Coupled GIS and CGE Analysis Under Uncertainties. *Environ. Resour. Econ.*, **65** (4), 813-839, doi:10.1007/s10640-015-9927-8.
Jozaei, J., M. Mitchell and S. Clement, 2020: Using a resilience thinking approach to improve coastal governance responses to complexity and uncertainty: a Tasmanian case study, Australia. *J. Environ. Manage.*, **253**, 109662, doi:10.1016/j.jenvman.2019.109662.
Judd, B., 2019: Kapi Wiya: Water insecurity and aqua-nullius in remote inland Aboriginal Australia. *Thesis Eleven*, **150** (1), 102-118, doi:10.1177/0725513618821969.
K. Lawrence, E. et al., 2017: Using a rule-based envelope model to predict the expansion of habitat suitability within New Zealand for the tick Haemaphysalis longicornis, with future projections based on two climate change scenarios. *Veterinary Parasitology*, **243**, 226-234, doi:10.1016/j.vetpar.2017.07.001.
Kaestli, M. et al., 2019: Opportunistic pathogens and large microbial diversity detected in source-to-distribution drinking water of three remote communities in Northern Australia. *PLoS Negl. Trop. Dis.*, **13** (9), e0007672, doi:10.1371/journal.pntd.0007672.
Kalaugher, E. et al., 2017: Modelling farm-level adaptation of temperate, pasture-based dairy farms to climate change. *Agricultural Systems*, **153**, 53-68, doi:10.1016/j.agsy.2017.01.008.
Kean, J. et al., 2015: *Effects of climate change on current and potential biosecurity pests and diseases in New Zealand*.
Kearns, R. A., N. Lewis, T. McCreanor and K. Witten, 2009: 'The status quo is not an option': Community impacts of school closure in South Taranaki, New Zealand. *Journal of Rural Studies*, **25** (1), 131-140, doi:10.1016/j.jrurstud.2008.08.002.
Keck, F., M. Lenzen, A. Vassallo and M. Li, 2019: The impact of battery energy storage for renewable energy power grids in Australia. *Energy*, **173**, 647-657, doi:10.1016/j.energy.2019.02.053.
Keenan, J., D. Kemp and J. Owen, 2019: Corporate responsibility and the social risk of new mining technologies. *Corporate Social Responsibility and Environmental Management*, **26** (4), 752-760, doi:10.1002/csr.1717.
Keenan, R. J., 2017: Climate change and Australian production forests: impacts and adaptation. *Australian Forestry*, **80** (4), 197-207, doi:10.1080/00049158.2017.1360170.
Kelleway, J. et al., 2017: *Technical review of opportunities for including blue carbon in the Australian Government's Emissions Reduction Fund*. Commonwealth Scientific and Industrial Research Organisation (CSIRO) Australia.
Kelly, E. 2020: Rising seas pose a cultural threat to Australia's 'forgotten people'. [Available at: https://theconversation.com/rising-seas-pose-a-cultural-threat-to-australias-forgotten-people-34359 accessed 4 November]
Kelly, P. et al., 2016: Zooplankton responses to increasing sea surface temperatures in the southeastern Australia global marine hotspot. *Estuar. Coast. Shelf Sci.*, **180**, 242-257, doi:10.1016/j.ecss.2016.07.019.
Kench, P. S. et al., 2018: Co-creating Resilience Solutions to Coastal Hazards Through an Interdisciplinary Research Project in New Zealand. *Journal of Coastal Research*, **85**, 1496-1500, doi:10.2112/si85-300.1.
Kennedy, E. V., A. Ordoñez and G. Diaz-Pulido, 2018: Coral bleaching in the southern inshore Great Barrier Reef: a case study from the Keppel Islands. *Mar. Freshwater Res.*, **69** (1), doi:10.1071/mf16317.
Keppel, G. et al., 2015: The capacity of refugia for conservation planning under climate change. *Front. Ecol. Environ.*, **13** (2), 106-112, doi:10.1890/140055.
Kettles, H. and R. G. Bell, 2015: Estuarine ecosystem. In: *Freshwater conservation under a changing climate*, 2015 [Robertson, H., S. Bowie, R. White, R. Death and D. Collins (eds.)], Dept of Conservation publication, Christchurch, 24–30.

Khan, S. J. et al., 2015: Extreme weather events: Should drinking water quality management systems adapt to changing risk profiles? *Water Research*, **85**, 124-136, doi:http://dx.doi.org/10.1016/j.watres.2015.08.018.
Kiem, A. S. et al., 2016: Natural hazards in Australia: droughts. *Climatic Change*, **139** (1), 37-54, doi:10.1007/s10584-016-1798-7.
King, A. D., M. G. Donat, L. V. Alexander and D. J. Karoly, 2015: The ENSO-Australian rainfall teleconnection in reanalysis and CMIP5. *Climate Dynamics*, **44** (9-10), 2623-2635, doi:10.1007/s00382-014-2159-8.
King, A. D., D. J. Karoly and B. J. Henley, 2017: Australian climate extremes at 1.5 °C and 2 °C of global warming. *Nature Climate Change*, **7** (6), 412-416, doi:10.1038/nclimate3296.
King, D. et al., 2012: *Maori Community Adaptation to Climate Variability and Change*. National Institute of Atmospheric and Water Research, 131 [Available at: https://niwa.co.nz/sites/niwa.co.nz/files/niwa_report_akl2011-015_0.pdf].
King, D. J., R. M. Newnham, W. Roland Gehrels and K. J. Clark, 2020: Late Holocene sea-level changes and vertical land movements in New Zealand. *New Zealand Journal of Geology and Geophysics*, 1-16, doi:10.1080/00288306.2020.1761839.
King, D. N. et al., 2013: *Coastal adaptation to climate variability and change: Examining community risk, vulnerability and endurance at Mitimiti, Hokianga, Aotearoa-New Zealand*. NIWA, 140 [Available at: https://niwa.co.nz/sites/niwa.co.nz/files/NIWA%20Report%20AKL2013-022_smaller.pdf].
King, D. N., G. Penny and C. Severne, 2010: The climate change matrix facing Māori society. In: Climate change adaptation in New Zealand: Future scenarios and some sectoral perspectives [Jones, N. W. B. (ed.)]. New Zealand Climate Change Centre,Wellington, 100-111.
King, K. J., R. M. de Ligt and G. J. Cary, 2011: Fire and carbon dynamics under climate change in south-eastern Australia: insights from FullCAM and FIRESCAPE modelling. *Int. J. Wildland Fire*, **20** (4), 563-577, doi:10.1071/WF09073.
Kingsley, J., M. Townsend, C. Henderson-Wilson and B. Bolam, 2013: Developing an Exploratory Framework Linking Australian Aboriginal Peoples' Connection to Country and Concepts of Wellbeing. **10** (2), 678-698.
Kirby, J. M. et al., 2014: Climate change and environmental water reallocation in the Murray–Darling Basin: Impacts on flows, diversions and economic returns to irrigation. *Journal of Hydrology*, **518**, 120-129, doi:10.1016/j.jhydrol.2014.01.024.
Kirkegaard, J. A. and J. R. Hunt, 2011: Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany*, **61**, 4129-4143, doi:doi:10.1093/jxb/erq245.
Kirono, D. G. C. et al., 2020: Drought projections for Australia: Updated results and analysis of model simulations. *Weather and Climate Extremes*, **30**, 100280, doi:10.1016/j.wace.2020.100280.
Kjellstrom, T. et al., 2016: Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. *Annu. Rev. Public Health*, **37**, 97-112, doi:10.1146/annurev-publhealth-032315-021740.
Knight-Lenihan, S., 2016: Benefit cost analysis, resilience and climate change. *Clim. Policy*, **16** (7), 909-923, doi:10.1080/14693062.2015.1052957.
Knowles, N. L. B. and D. Scott, 2020: Media representations of climate change risk to ski tourism: a barrier to climate action? *null*, 1-8, doi:10.1080/13683500.2020.1722077.
Knutson, T. R. and F. Zeng, 2018: Model Assessment of Observed Precipitation Trends over Land Regions: Detectable Human Influences and Possible Low Bias in Model Trends. *Journal of Climate*, **31** (12), 4617-4637, doi:10.1175/jcli-d-17-0672.1.
Koech, R. and P. Langat, 2018: Improving Irrigation Water Use Efficiency: A Review of Advances, Challenges and Opportunities in the Australian Context. *Water*, **10** (12), 1771, doi:10.3390/w10121771.
Koehler, J. et al., 2017: A research agenda for the Sustainability Transitions Research Network, STRN Working Group.
Kompas, T., V. H. Pham and T. N. Che, 2018: The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord. *Earth's Future*, **6** (8), 1153-1173, doi:10.1029/2018ef000922.
Kool, R., J. Lawrence, M. Drews and R. Bell, 2020: Preparing for Sea-Level Rise through Adaptive Managed Retreat of a New Zealand Stormwater and Wastewater Network. *Infrastructures*, **5** (11), 92, doi:10.3390/infrastructures5110092.
Kornakova, M. and B. Glavovic, 2018: Institutionalising wildfire planning in New Zealand: Lessons learnt from the 2009 Victorian bushfire experience. *Australas. J. Disaster Trauma Stud.*, **22** (2), 12.
Kossin, J. P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558** (7708), 104-107, doi:10.1038/s41586-018-0158-3.
Kotey, B., 2015: Demographic and economic changes in remote Australia. *Australian Geographer*, **46** (2), 183-201.
KPMG, 2021: *Anticipate, prepare, respond - Geopolitical megatrends and business resilience*. Australian Geopolitics Hub, KPMG Australia, 12 [Available at: https://assets.kpmg/content/dam/kpmg/au/pdf/2021/geopolitical-megatrends-business-resilience.pdf].
Kunapo, J. et al., 2018: A spatially explicit framework for climate adaptation. *Urban Water Journal,*, **15** (2), 159-166, doi:10.1080/1573062X.2018.1424216.

Kwakkel, J. H., W. E. Walker and M. Haasnoot, 2016: Coping with the Wickedness of Public Policy Problems: Approaches for Decision Making under Deep Uncertainty. *Journal of Water Resources Planning and Management*, **142** (3), 01816001, doi:10.1061/(asce)wr.1943-5452.0000626.
Lai, H. et al., 2020: Effects of heavy rainfall on waterborne disease hospitalizations among young children in wet and dry areas of New Zealand. *Environ. Int.*, **145**, 106136, doi:10.1016/j.envint.2020.106136.
Lakeman-Fraser, P. and R. M. Ewers, 2013: Enemy release promotes range expansion in a host plant. *Oecologia*, **172** (4), 1203-1212, doi:10.1007/s00442-012-2555-x.
Langer, E. R., J. McLennan and D. M. Johnston, 2018: Editorial: Special issue on the Port Hills wildfires. *Australas. J. Disaster Trauma Stud.*, **22** (2), 29-34.
Langton, M. et al., 2012: *National Climate Change Adaptation Research Plan for Indigenous Communities*. National Climate Change Adaptation Research Facility, Gold Coast.
Lantschner, M., et al., 2017: Predicting North American Scolytinae invasions in the Southern Hemisphere. *Ecological Applications*, **27**, 66-77.
Lao, J. et al., 2016: Working smart: An exploration of council workers' experiences and perceptions of heat in Adelaide, South Australia. *Saf. Sci.*, **82**, 228-235, doi:10.1016/j.ssci.2015.09.026.
Laufkötter, C., J. Zscheischler and T. L. Frölicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science*, **369** (6511), 1621-1625, doi:10.1126/science.aba0690.
Lavorel, S. et al., 2019: Mustering the power of ecosystems for adaptation to climate change. *Environ. Sci. Policy*, **92**, 87-97, doi:10.1016/j.envsci.2018.11.010.
Law, C. S. et al., 2018a: Ocean acidification in New Zealand waters: trends and impacts. *New Zealand Journal of Marine and Freshwater Research*, **52** (2), 155-195, doi:10.1080/00288330.2017.1374983.
Law, C. S. et al., 2018b: Climate change projections for the surface ocean around New Zealand. *New Zealand Journal of Marine and Freshwater Research*, **52** (3), 309-335, doi:10.1080/00288330.2017.1390772.
Law, C. S. et al., 2016: *Climate Changes, Impacts and Implications for New Zealand to 2100. Synthesis Report: RA2 Marine Case Study*. The New Zealand EEZ and South West Pacific, 41 [Available at: https://ccii.org.nz/app/uploads/2017/04/RA2-MarineCaseStudySynthesisReport.pdf].
Lawrence, J. et al., 2018a: National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. *Environmental Science & Policy*, **82**, 100-107, doi:10.1016/j.envsci.2018.01.012.
Lawrence, J. et al., 2020a: *Supporting decision making through adaptive tools in a changing climate: Practice guidance on signals and triggers*. Victoria University of Wellington, 67 [Available at: https://www.deepsouthchallenge.co.nz/sites/default/files/2020-03/Supporting%20decision%20making%20through%20adaptive%20tools%20in%20a%20changing%20climate%20Practice%20guidance%20on%20signals%20and%20triggers.pdf].
Lawrence, J., R. Bell and A. Stroombergen, 2019a: A Hybrid Process to Address Uncertainty and Changing Climate Risk in Coastal Areas Using Dynamic Adaptive Pathways Planning, Multi-Criteria Decision Analysis & Real Options Analysis: A New Zealand Application. *Sustainability*, **11** (2), 406, doi:10.3390/su11020406.
Lawrence, J., P. Blackett, N. A. Craddock-Henry and B. J. Nistor, 2018b: *Climate Change: The Cascade Effect. Cascading impacts and implications for Aotearoa New Zealand*. Deep South National Science Challenge, Victoria University of Wellington Wellington, New Zealand.
Lawrence, J. et al., 2016: *Synthesis Report RA4: Enhancing capacity and increasing coordination to support decision making. Climate Change Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225.* NZCCRI, Victoria University of Wellington; NIWA; Landcare Research, Wellington, 74.
Lawrence, J., P. Blackett and N. A. Cradock-Henry, 2020b: Cascading climate change impacts and implications. *Climate Risk Management*, **29**, 100234, doi:10.1016/j.crm.2020.100234.
Lawrence, J. et al., 2020c: Implementing Pre-Emptive Managed Retreat: Constraints and Novel Insights. *Current Climate Change Reports*, **6**, 66-80, doi:https://doi.org/10.1007/s40641-020-00161-z.
Lawrence, J. and M. Haasnoot, 2017: What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environmental Science & Policy*, **68**, 47-57, doi:10.1016/j.envsci.2016.12.003.
Lawrence, J. et al., 2019b: Dynamic Adaptive Policy Pathways (DAPP): From Theory to Practice. In: Decision making under Deep Uncertainty. From theory to Practice. [Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen and S. W. Popper (eds.)]. Springer, 187-199.
Lawrence, J. and W. Saunders, 2017: The Planning Nexus Between Disaster Risk Reduction and Climate Change Adaptation. *The Routledge Handbook of Disaster Risk Reduction Including Climate Change Adaptation*, 418-428, doi:10.4324/9781315684260-39.
Lawrence, J. et al., 2015: Adapting to changing climate risk by local government in New Zealand: institutional practice barriers and enablers. *Local Environment*, **20** (3), 298-320, doi:10.1080/13549839.2013.839643.
Laz, O. U., A. Rahman, A. Yilmaz and K. Haddad, 2014: Trends in sub-hourly, sub-daily and daily extreme rainfall events in eastern Australia. *Journal of Water and Climate Change*, **5** (4), 667-675, doi:10.2166/wcc.2014.035.
Lazarow, N., 2017: *Real options for coastal adaptation*. CoastAdapt, National Climate Change Adaptation Research Facility. https://coastadapt.com.au/sites/default/files/factsheets/T4W5_Real_options.pdf.
Leblanc, M., S. Tweed, A. Van Dijk and B. Timbal, 2012: A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and Planetary Change*, **80-81**, 226-246, doi:10.1016/j.gloplacha.2011.10.012.

Lee, E., 2016: Protected areas, country and value: The Nature–Culture Tyranny of the IUCN's protected area guidelines for Indigenous Australians. *Antipode*, **48** (2), 355-374.
Lee, H.-L., Y.-P. Lin and J. R. Petway, 2018: Global Agricultural Trade Pattern in A Warming World: Regional Realities. *Sustain. Sci. Pract. Policy*, **10** (8), 2763, doi:10.3390/su10082763.
Lees, A. M. et al., 2019: The Impact of Heat Load on Cattle. *Animals (Basel)*, **9** (6), doi:10.3390/ani9060322.
Leitch, A. M. and E. L. Bohensky, 2014: Return to 'a new normal': Discourses of resilience to natural disasters in Australian newspapers 2006–2010. *Global Environmental Change*, **26**, 14-26, doi:10.1016/j.gloenvcha.2014.03.006.
Leitch, A. M. et al., 2019: Co-development of a climate change decision support framework through engagement with stakeholders. *Climatic Change*, **153** (4), 587-605, doi:10.1007/s10584-019-02401-0.
Lenoir, J. and J. C. Svenning, 2015: Climate-related range shifts–a global multidimensional synthesis and new research directions. *Ecography*, **38** (1), 15-28.
Levy, R. et al., 2020: *Te tai pari o Aotearoa – Future sea level rise around New Zealand's dynamic coastline*. New Zealand Coastal Society, 10 [Available at: https://www.coastalsociety.org.nz/assets/Publications/Special-Issues/SP4-Low-res-version.pdf?].
Lewis, S. C., A. D. King and D. M. Mitchell, 2017: Australia's Unprecedented Future Temperature Extremes Under Paris Limits to Warming. *Geophysical Research Letters*, **44** (19), 9947-9956, doi:10.1002/2017gl074612.
LGAQ and DES, 2020: QCoast 2100: Councils leading coastal adaptation.
LGNZ, 2017: *New Zealand Local Government Leaders' Climate Change Declaration*. Local Government New Zealand, 8 [Available at: https://www.lgnz.co.nz/assets/Uploads/0827d40e5d/Climate-Change-Declaration.pdf].
LGNZ, 2019: *Vulnerable: The quantum of local government instrastructure exposed to sea level rise* [Simonson, T. and G. Hall (eds.)]. Local Government New Zealand, 51 [Available at: http://www.lgnz.co.nz/our-work/publications/vulnerable-the-quantum-of-local-government-infrastructure-exposed-to-sea-level-rise].
Liedloff, A. C., E. L. Woodward, G. A. Harrington and S. Jackson, 2013: Integrating indigenous ecological and scientific hydro-geological knowledge using a Bayesian Network in the context of water resource development. *Journal of Hydrology*, **499**, 177-187, doi:10.1016/j.jhydrol.2013.06.051.
Lieffering, M. e. a., 2016: Exploring climate change impacts and adaptations of extensive pastoral agriculture systems by combining biophysical simulation and farm system models. *Agricultural Systems*, **144**, 77-86.
Ligtermoet, E., 2016: Maintaining customary harvesting of freshwater resources: sustainable Indigenous livelihoods in the floodplains of northern Australia. *Rev Fish Biol Fisheries*, **26**, 649–678.
Lim, E. P., H. H. Hendon, J. M. Arblaster and others, 2016: The impact of the Southern Annular Mode on future changes in Southern Hemisphere rainfall. *Geophysical*.
Lin, B. B. et al., 2017: Adaptation Pathways in Coastal Case Studies: Lessons Learned and Future Directions. *Coast. Manage.*, **45** (5), 384-405, doi:10.1080/08920753.2017.1349564.
Lin, B. B., J. Meyers, R. M. Beaty and G. B. Barnett, 2016: Urban Green Infrastructure Impacts on Climate Regulation Services in Sydney, Australia. *Sustain. Sci. Pract. Policy*, **8** (8), 788, doi:10.3390/su8080788.
Lindenmayer, D., D. Blair, L. McBurney and S. Banks, 2015: *Mountain Ash: Fire, Logging and the Future of Victoria's Giant Forests*. CSIRO PUBLISHING, 200 pp.
Lindenmayer, D. and C. Taylor, 2020a: Extensive recent wildfires demand more stringent protection of critical old growth forest. *Pacific Conservation Biology*, **26** (4), 384, doi:10.1071/pc20037.
Lindenmayer, D. B. et al., 2020: Managing interacting disturbances: Lessons from a case study in Australian forests. *Journal of Applied Ecology*, **57** (9), 1711-1716, doi:10.1111/1365-2664.13696.
Lindenmayer, D. B. and C. Taylor, 2020b: New spatial analyses of Australian wildfires highlight the need for new fire, resource, and conservation policies. *Proc. Natl. Acad. Sci. U. S. A.*, **117** (22), 12481-12485, doi:10.1073/pnas.2002269117.
Lindsay, J. et al., 2019: The Role of Community Champions in Long-Term Sustainable Urban Water Planning. *Water*, **11** (3), 476, doi:10.3390/w11030476.
Ling, S. D., N. S. Barrett and G. J. Edgar, 2018: Facilitation of Australia's southernmost reef-building coral by sea urchin herbivory. *Coral Reefs*, **37** (4), 1053-1073, doi:10.1007/s00338-018-1728-4.
Ling, S. D. and A. J. Hobday, 2019: National research planning accelerates relevance and immediacy of climate-adaptation science. *Mar. Freshwater Res.*, **70** (1), doi:10.1071/mf17330.
Ling, S. D. and J. P. Keane, 2018: *Resurvey of the longspined sea urchin (Centrostephanus rodgersii) and associated barren reef in Tasmania*. Institute for Marine and Antarctic Studies, University of Tasmania [Available at: https://eprints.utas.edu.au/28761/].
Linnenluecke, M. K., A. Griffiths and P. J. Mumby, 2015: Executives' engagement with climate science and perceived need for business adaptation to climate change. *Clim. Change*, **131** (2), 321–333.
Lintermans, M. et al., 2020: Big trouble for little fish: identifying Australian freshwater fishes in imminent risk of extinction. *Pacific Conservation Biology*, **26** (4), 365, doi:10.1071/pc19053.
Little, L. R. et al., 2015: Funding climate adaptation strategies with climate derivatives. *Climate Risk Management*, **8**, 9-15, doi:10.1016/j.crm.2015.02.002.
Little, L. R. and B. B. Lin, 2015: A decision analysis approach to climate adaptation: a structured method to consider multiple options. *Mitigation and Adaptation Strategies for Global Change*, 1-14, doi:10.1007/s11027-015-9658-8.

Liu, N. et al., 2020: Drought can offset potential water use efficiency of forest ecosystems from rising atmospheric CO2. *Journal of Environmental Sciences*, **90**, 262-274, doi:10.1016/j.jes.2019.11.020.
Liu, P. R. and A. E. Raftery, 2021: Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 °C target. *Commun Earth Environ*, **2**, doi:10.1038/s43247-021-00097-8.
Liu, W. et al., 2018: Global Freshwater Availability Below Normal Conditions and Population Impact Under 1.5 and 2 °C Stabilization Scenarios. *Geophysical Research Letters*, **45** (18), 9803-9813, doi:10.1029/2018gl078789.
Liu, X. et al., 2017: Assessing the impact of historical and future climate change on potential natural vegetation types and net primary productivity in Australian grazing lands. *The Rangeland Journal*, **39** (4), 387, doi:10.1071/rj17081.
Llewelyn, J. et al., 2016: Intraspecific variation in climate-relevant traits in a tropical rainforest lizard. *Diversity and Distributions*, **22** (10), 1000-1012, doi:10.1111/ddi.12466.
Lobell, D. B. et al., 2015: The shifting influence of drought and heat stress for crops in northeast Australia. *Global Change Biology*, **21** (11), 4115-4127, doi:10.1111/gcb.13022.
Loechel, B. and J. Hodgkinson, 2014: Climate Impacts and Adaptation in Australian Mining Communities: Industry and Local Government Views and Activities—2013 Follow-up Survey.
Longden, T., 2019: The impact of temperature on mortality across different climate zones. *Clim. Change*, doi:10.1007/s10584-019-02519-1.
Looi, J. C. L., S. Allison, T. Bastiampillai and P. Maguire, 2020: Commentary. Fire, disease and fear: Effects of the media coverage of 2019–2020 Australian bushfires and novel coronavirus 2019 on population mental health. *Australian & New Zealand Journal of Psychiatry*, **54** (9), 938-940, doi:10.1177/0004867420931163.
Loorbach, D., N. Frantzeskaki and F. Avelino, 2017: Sustainability Transitions Research: Transforming Science and Practice for Societal Change. *Annu. Rev. Environ. Resour.*, **42** (1), 599-626, doi:10.1146/annurev-environ-102014-021340.
Loosemore, M., J. Carthey, V. Chandra and A. Mirti Chand, 2011: Climate change risks and opportunities in hospital adaptation. *International Journal of Disaster Resilience in the Built Environment*, **2** (3), 210-221, doi:10.1108/17595901111167097.
Loosemore, M., V. Chow and D. McGeorge, 2014: Managing the health risks of extreme weather events by managing hospital infrastructure. *Eng. Constr. Archit. Manage.*, **21** (1), 4-32, doi:10.1108/ECAM-10-2012-0060.
Lough, J. M., K. D. Anderson and T. P. Hughes, 2018: Increasing thermal stress for tropical coral reefs: 1871-2017. *Sci. Rep.*, **8** (1), 6079, doi:10.1038/s41598-018-24530-9
10.1038/s41598-018-24530-9.
Lough, J. M., S. E. Lewis and N. E. Cantin, 2015: Freshwater impacts in the central Great Barrier Reef: 1648–2011. *Coral Reefs*, **34** (3), 739-751, doi:10.1007/s00338-015-1297-8.
Loughnan, M., M. Carroll and N. Tapper, 2015: The relationship between housing and heat wave resilience in older people. *Int. J. Biometeorol.*, **59** (9), 1291-1298, doi:10.1007/s00484-014-0939-9.
Loughnan, M. E. et al., 2013: *A spatial vulnerability analysis of urban populations during extreme heat events in Australian capital cities*. National Climate Change Adaptation Research Facility.
Lowe, K., J. G. Castley and J. M. Hero, 2015: Resilience to climate change: complex relationships among wetland hydroperiod, larval amphibians and aquatic predators in temporary wetlands. *Mar. Freshwater Res.*, **66** (10), 886-899, doi:10.1071/mf14128.
Lu, B. et al., 2021: A zero-carbon, reliable and affordable energy future in Australia. *Energy*, **220**, 119678, doi:10.1016/j.energy.2020.119678.
Lu, P. et al., 2020: Temporal trends of the association between ambient temperature and hospitalisations for cardiovascular diseases in Queensland, Australia from 1995 to 2016: A time-stratified case-crossover study. *PLoS Med.*, **17** (7), e1003176, doi:10.1371/journal.pmed.1003176.
Lucas, C. H. and K. I. Booth, 2020: Privatizing climate adaptation: How insurance weakens solidaristic and collective disaster recovery. *WIREs Climate Change*, doi:10.1002/wcc.676.
Lukasiewicz, A., S. Dovers and M. Eburn, 2017: Shared responsibility: the who, what and how. *Environmental Hazards*, **16** (4), 291-313, doi:10.1080/17477891.2017.1298510.
Lunney, D., E. Stalenberg, T. Santika and J. R. Rhodes, 2014: Extinction in Eden: identifying the role of climate change in the decline of the koala in south-eastern NSW. *Wildl. Res.*, **41** (1), 22-34.
Luo, Q., K. Behrendt and M. Bange, 2017: Economics and Risk of Adaptation Options in the Australian Cotton Industry. *Agric. Syst.*, **150**, 46–53, doi:10.1016/j.agsy.2016.09.014.
Lyons, I. et al., 2019: Putting uncertainty under the cultural lens of Traditional Owners from the Great Barrier Reef Catchments. *Regional Environmental Change*, **19** (6), 1597–1610.
Ma, S. and A. P. Kirilenko, 2019: Climate Change and Tourism in English-Language Newspaper Publications. *Journal of Travel Research*, 004728751983915, doi:10.1177/0047287519839157.
Ma, W., A. Renwick and X. Zhou, 2020: Short communication: The relationship between farm debt and dairy productivity and profitability in New Zealand. *J. Dairy Sci.*, **103** (9), 8251-8256, doi:10.3168/jds.2019-17506.
MacDiarmid, A. B., C. S. Law, M. Pinkerton and J. Zeldis, 2013: New Zealand marine ecosystem services. *Ecosystem services in New Zealand--Conditions and trends*, 238-253.

Macfadyen, S., G. McDonald and M. P. Hill, 2018: From species distributions to climate change adaptation: Knowledge gaps in managing invertebrate pests in broad-acre grain crops. *Agriculture, Ecosystems & Environment*, **253**, 208-219, doi:10.1016/j.agee.2016.08.029.
Macinnis-Ng, C. et al., 2021: Climate change impacts exacerbate conservation threats in island systems: New Zealand as a case study. *Frontiers in Ecology and the Environment*, **19** (4), 216-224, doi:10.1002/fee.2285.
Macinnis-Ng, C. and L. Schwendenmann, 2015: Litterfall, carbon and nitrogen cycling in a southern hemisphere conifer forest dominated by kauri (Agathis australis) during drought. *Plant Ecology*, **216** (2), 247-262, doi:10.1007/s11258-014-0432-x.
Macintosh, A., A. Foerster and J. McDonald, 2015: Policy design, spatial planning and climate change adaptation: a case study from Australia. *J. Environ. Planning Manage.*, **58** (8), 1432-1453.
Mackey, B. and D. Claudie, 2015: Points of Contact: Integrating Traditional and Scientific Knowledge for Biocultural Conservation. *Environmental Ethics*, **Fall**, 341-357.
Mackintosh, A. N. et al., 2017: Regional cooling caused recent New Zealand glacier advances in a period of global warming. *Nat. Commun.*, **8**, 14202, doi:10.1038/ncomms14202.
Maclean, K., M. Cuthill and H. Ross, 2014: Six attributes of social resilience. *Journal of Environmental Planning and Management*, **57** (1), 144-156, doi:10.1080/09640568.2013.763774.
Maier, H. R. et al., 2016: An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software*, **81**, 154-164, doi:10.1016/j.envsoft.2016.03.014.
Mallon, K. et al., 2019: *Change Risk to Australia's Built Environment: A Second Pass National Assessment*. 82 [Available at: https://xdi.systems/wp-content/uploads/2019/10/Climate-Change-Risk-to-Australia%E2%80%99s-Built-Environment-V4-final-reduced-2.pdf].
Mankad, A. and S. Tapsuwan, 2011: Review of socio-economic drivers of community acceptance and adoption of decentralised water systems. *J. Environ. Manage.*, **92** (3), 380-391, doi:10.1016/j.jenvman.2010.10.037.
Manning, M., J. Lawrence, D. N. King and R. Chapman, 2014: Dealing with changing risks: a New Zealand perspective on climate change adaptation. *Regional Environ. Change*, **15**, 581-594, doi:DOI.10.1007/s10113-014-0673-1.
March-Salas, M. and L. R. Pertierra, 2020: Warmer and less variable temperatures favour an accelerated plant phenology of two invasive weeds across sub-Antarctic Macquarie Island. *Austral Ecology*, **45** (5), 572-585, doi:10.1111/aec.12872.
Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen and S. W. Popper, 2019: Introduction. *Decision Making under Deep Uncertainty*, 1-20, doi:10.1007/978-3-030-05252-2_1.
Marchionni, V. et al., 2019: Water balance and tree water use dynamics in remnant urban reserves. *J. Hydrol.*, **575**, 343-353, doi:10.1016/j.jhydrol.2019.05.022.
Mariani, M. et al., 2019: Climate change reduces resilience to fire in subalpine rainforests. *Glob. Chang. Biol.*, **0** (0).
Marmion, D., K. Obata and J. Troy, 2014: *Community, identity, wellbeing: the report of the Second National Indigenous Languages Survey*. Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS), 62.
Marmot, M., 2011: Social determinants and the health of Indigenous Australians. *Medical Journal of Australia*, **194**, 16 May.
Marshall, G. R. and L. A. Lobry de Bruyn, 2021: Water Policy Reform for Sustainable Development in the Murray-Darling Basin, Australia: Insights from Resilience Thinking. In: Water Resilience: Management and Governance in Times of Change [Baird, J. and R. Plummer (eds.)]. Springer International Publishing, Cham, 65-89.
Marshall, N. et al., 2019: Reef Grief: investigating the relationship between place meanings and place change on the Great Barrier Reef, Australia. *Sustainability Science*, **14** (3), 579-587, doi:10.1007/s11625-019-00666-z.
Marshall, N. A., 2015: Adaptive capacity on the northern Australian rangelands. *The Rangeland Journal*, **37** (6), doi:10.1071/rj15054.
Marshall, N. A. and C. J. Stokes, 2014: Influencing adaptation processes on the Australian rangelands for social and ecological resilience. *Ecology and Society*, **19** (2), doi:10.5751/es-06440-190214.
Maru, Y. T. et al., 2014: A linked vulnerability and resilience framework for adaptation pathways in remote disadvantaged communities. *Glob. Environ. Change*, **28** (0), 337-350, doi:10.1016/j.gloenvcha.2013.12.007.
Marzeion, B. et al., 2020: Partitioning the Uncertainty of Ensemble Projections of Global Glacier Mass Change. *Earth's Future*, **8** (7), doi:10.1029/2019ef001470.
Mathew, S., B. Zeng, K. K. Zander and R. K. Singh, 2018: Exploring agricultural development and climate adaptation in northern Australia under climatic risks. *The Rangeland Journal*, **40** (4), 353, doi:10.1071/rj18011.
Matteo, M. D. et al., 2019: Controlling rainwater storage as a system: An opportunity to reduce urban flood peaks for rare, long duration storms. *Environmental Modelling & Software*, **111**, 34-41, doi:10.1016/j.envsoft.2018.09.020.
Matthews, V. et al., 2019: Differential Mental Health Impact Six Months After Extensive River Flooding in Rural Australia: A Cross-Sectional Analysis Through an Equity Lens. *Frontiers in Public Health*, **7**, doi:10.3389/fpubh.2019.00367.
Matusick, G. et al., 2018: Chronic historical drought legacy exacerbates tree mortality and crown dieback during acute heatwave-compounded drought. *Environmental Research Letters*, **13** (9), 095002, doi:10.1088/1748-9326/aad8cb.
Maybery, D. et al., 2020: A mixed-methods study of psychological distress following an environmental catastrophe: the case of the Hazelwood open-cut coalmine fire in Australia. *Anxiety Stress Coping*, **33** (2), 216-230, doi:10.1080/10615806.2019.1695523.

MBIE, 2019a: *Electricity demand and generation scenarios: Scenario and results summary*. Ministry of Business, Innovation and Employment, 40 [Available at: https://www.mbie.govt.nz/dmsdocument/5977-electricity-demand-and-generation-scenarios].
MBIE, 2019b: *New Zealand-Aotearoa Government Tourism Strategy*. Ministry of Business, Innovation and Employment and Department of Conservation, 22 [Available at: https://www.mbie.govt.nz/dmsdocument/5482-2019-new-zealand-aotearoa-government-tourism-strategy-pdf].
MBIE, 2021: Electricity statistics.
McAdam, J., 2015: The emerging New Zealand jurisprudence on climate change, disasters and displacement. *Migration Studies*, **3**, 131-142.
McAneney, J. et al., 2019: Normalised insurance losses from Australian natural disasters: 1966–2017. *Environmental Hazards*, **18** (5), 414-433, doi:10.1080/17477891.2019.1609406.
McBride, G. et al., 2016: *The Firth of Thames and Lower Waihou River. Synthesis Report RA2, Coastal Case Study. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100*. 50 [Available at: https://researchspace.auckland.ac.nz/handle/2292/39671].
McClure, L. and D. Baker, 2018: How do planners deal with barriers to climate change adaptation? A case study in Queensland, Australia. *Landsc. Urban Plan.*, **173**, 81-88, doi:10.1016/j.landurbplan.2018.01.012.
McCormack, P. C., 2018: The Legislative Challenge of Facilitating Climate Change Adaptation for Biodiversity. *Aust. Law J.*, **92** (7), 546-562.
McDonald, J., 2020: Girt by Sea: Antipodean Lessons in Coastal Adaptation Law. *Sea Grant L. & Pol'y J.*, **10**, 29.
McDonald, J. et al., 2019: Adaptation pathways for conservation law and policy. *Wiley Interdisciplinary Reviews-Climate Change*, **10** (1), doi:10.1002/wcc.555.
McDowell, R. W. et al., 2016: A review of the policies and implementation of practices to decrease water quality impairment by phosphorus in New Zealand, the UK, and the US. *Nutr. Cycling Agroecosyst.*, **104** (3), 289-305, doi:10.1007/s10705-015-9727-0.
McEvoy, D. and J. Mullett, 2014: Enhancing the resilience of seaports to a changing climate. *Applied Studies in Climate Adaptation*, 200-207, doi:10.1002/9781118845028.ch22.
McFadgen, B. and D. Huitema, 2017: Stimulating Learning through Policy Experimentation: A Multi-Case Analysis of How Design Influences Policy Learning Outcomes in Experiments for Climate Adaptation. *Water*, **9** (9), 648, doi:10.3390/w9090648.
McInnes, K. et al., 2015: Information for Australian impact and adaptation planning in response to sea-level rise. *Australian Meteorological and Oceanographic Journal*, **65** (1), 127-149, doi:10.22499/2.6501.009.
McInnes, K. L. et al., 2016: Natural hazards in Australia: sea level and coastal extremes. *Clim. Change*, **139** (1), 69-83.
McKemey, M. et al., 2020: Indigenous Knowledge and Seasonal Calendar Inform Adaptive Savanna Burning in Northern Australia. *Sustainability*, **12** (3), 995, doi:10.3390/su12030995.
McKerchar, A. and B. Mullan, 2004: *Seasonal Inflow Distributions for New Zealand Hydroelectric Power Stations*. NIWA Client Report: CHC2004-131, Prepared for the Ministry of Economic Development (MED) by the National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand, 12.
McKerchar, A. I., J. A. Renwick and J. Schmidt, 2010: Diminishing streamflows on the east coast of the South Island New Zealand and linkage to climate variability and change. *J. Hydrol.*, **49** (1).
McKergow, L. A., F. E. Matheson and J. M. Quinn, 2016: Riparian management: A restoration tool for New Zealand streams. *Ecological Management & Restoration*, **17** (3), 218-227, doi:10.1111/emr.12232.
McKnight, B. and M. K. Linnenluecke, 2019: Patterns of Firm Responses to Different Types of Natural Disasters. *Business & Society*, **58** (4), 813-840, doi:10.1177/0007650317698946.
McLean, E. H. et al., 2014: Plasticity of functional traits varies clinally along a rainfall gradient in Eucalyptus tricarpa. *Plant Cell Environ.*, **37** (6), 1440-1451, doi:10.1111/pce.12251.
McLean, L. J. et al., 2018: Impact of rising sea levels on Australian fur seals. *PeerJ*, **6**, e5786, doi:10.7717/peerj.5786 10.7717/peerj.5786. eCollection 2018.
McLennan, B., J. Whittaker and J. Handmer, 2016: The changing landscape of disaster volunteering: opportunities, responses and gaps in Australia. *Natural Hazards*, **84** (3), 2031-2048, doi:10.1007/s11069-016-2532-5.
McMahon, S. J. et al., 2020: Elevated CO2 and heatwave conditions affect the aerobic and swimming performance of juvenile Australasian snapper. *Marine Biology*, **167** (1), doi:10.1007/s00227-019-3614-1.
McManus, P., K. K. Shrestha and D. Yoo, 2014: Equity and climate change: Local adaptation issues and responses in the City of Lake Macquarie, Australia. *Urban Climate*, **10**, 1-18, doi:10.1016/j.uclim.2014.08.003.
McNamara, K. E. and L. Buggy, 2017: Community-based climate change adaptation: a review of academic literature. *Local Environ.*, **22** (4), 443-460.
McNamara, K. E., R. Westoby and S. G. Smithers, 2017: Identification of limits and barriers to climate change adaptation: case study of two islands in Torres Strait, Australia. *Geographical Research*, **55** (4), 438-455, doi:10.1111/1745-5871.12242.
McNicol, I., 2021: Increasing the Adaptation Pathways Capacity of Land Use Planning – Insights from New South Wales, Australia. *Urban Policy and Research*, **39** (2), 143-156, doi:10.1080/08111146.2020.1788530.
McTernan, W. P., M. F. Dollard, M. R. Tuckey and R. J. Vandenberg, 2016: Beneath the Surface: An Exploration of Remoteness and Work Stress in the Mines. *Psychosocial Factors at Work in the Asia Pacific*, 341-358, doi:10.1007/978-3-319-44400-0_19.

MDBA, 2011: *Plain English summary of the proposed Basin Plan*. Murray–Darling Basin Authority, 138 [Available at: https://www.mdba.gov.au/sites/default/files/archived/proposed/plain_english_summary.pdf].
MDBA, 2012: *Proposed Basin Plan — A revised draft*. Murray Darling Basin Authority, 215 [Available at: https://www.mdba.gov.au/sites/default/files/archived/revised-BP/PBP_reviseddraft.pdf].
MDBA, 2013: *Handbook for Practitioners: Water Plan Requirements*. Murray–Darling Basin Authority, 120 [Available at: https://www.mdba.gov.au/sites/default/files/pubs/WRP-Handbook-for-Practitioners_0.pdf].
MDBA, 2014: *Basin-wide environmental watering strategy*. 125 [Available at: https://www.mdba.gov.au/sites/default/files/pubs/Final-BWS-Nov14.pdf].
MDBA, 2019: *Climate Change and the Murray-Darling Basin - MDBA Discussion Paper*. Murray-Darling Basin Authority, Authority, M.-D. B., 29.
MDBA, 2020: *The 2020 Basin Plan Evaluation*. Murray-Darling Basin Authority, 140 [Available at: https://www.mdba.gov.au/sites/default/files/pubs/bp-eval-2020-full-report.pdf].
Mead, D., 2013: *Sustainable management of Pinus radiata plantations.* Forestry Paper No. 170, Food and Agriculture Organization of the United Nations. FAO, Rome: .
Meager, J. J. and C. Limpus, 2014: Mortality of inshore marine mammals in eastern Australia is predicted by freshwater discharge and air temperature. *PLOS ONE*, **9** (4), e94849, doi:10.1371/journal.pone.0094849.
Merzian, R. et al., 2019: *Climate of the Nation 2019: Tracking Australia's attitudes towards climate change and energy*. The Australia Institute, Canberra.
Messina, J. P. et al., 2019: The current and future global distribution and population at risk of dengue. *Nat Microbiol*, **4** (9), 1508-1515, doi:10.1038/s41564-019-0476-8.
Metcalfe, D. and E. Bui, 2016: *Land: Contemporary land-use pressures*. Australia State of the Environment, Australian Government Department of the Environment and Energy, Canberra [Available at: https://soe.environment.gov.au/theme/land/topic/2016/contemporary-land-use-pressures].
MfE, 2010: *Tools for Estimating the Effects of Climate Change on Flood Flows - A Guidance Manual for Local Government in New Zealand*. Ministry for Environment, New Zealand, Ministry for Environment, N. Z., 63 [Available at: https://www.mfe.govt.nz/sites/default/files/tools-estimating-effects-climate-change.pdf].
MfE, 2016: *New Zealand's Environmental Reporting Series: Our marine environment 2016*. **ME**, New Zealand, Ministry for the Environment & Statistics [Available at: http://www.mfe.govt.nz].
MfE, 2017a: *Coastal Hazards and Climate Change: Guidance for Local Government* [Bell, R. G., J. Lawrence, S. Allan, P. Blackett and S. A. Stephens (eds.)]. Ministry for the Environment, 284 p + Appendices [Available at: http://www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government].
MfE, 2017b: *National Policy Statement for Freshwater Management 2014 - updated in 2017*. New Zealand, Ministry for the Environment,47 pp.
MfE, 2017c: *New Zealand's Environmental Reporting Series: Our atmosphere and climate 2017*. 58 [Available at: https://www.mfe.govt.nz/sites/default/files/media/Environmental%20reporting/our-atmosphere-and-climate-2017.pdf].
MfE, 2018: *Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Ffith Assessment, 2nd Edition*. Ministry for the Environment, Wellington, 131 [Available at: http://www.mfe.govt.nz/publications/climate-change/climate-change-projections-new-zealand].
MfE, 2019: Environment Aotearoa 2019 | Ministry for the Environment.
MfE, 2020a: *National Climate Change Risk Assessment for Aotearoa New Zealand: Main report – Arotakenga Tūraru mō te Huringa Āhuarangi o Āotearoa: Pūrongo whakatōpū*. Ministry for the Environment, 133 [Available at: chrome-extension://bomfdkbfpdhijjbeoicnfhjbdhncfhig/view-file.html].
MfE, 2020b: *National Policy Statement for Freshwater Management*. Ministry for the Environment, 70 [Available at: https://www.mfe.govt.nz/sites/default/files/media/Fresh%20water/national-policy-statement-for-freshwater-management-2020.pdf].
MfE, 2020c: *New directions for resource management in New Zealand*. Resource Management Review Panel, 531 [Available at: https://www.mfe.govt.nz/sites/default/files/media/RMA/rm-panel-review-report-web.pdf].
MfE, 2021: *Adaptation preparedness: 2020/21 baseline A summary of reporting organisation responses to the first information request under the Climate Change Response Act 2002*. Ministry for the Environment, 39 [Available at: https://environment.govt.nz/publications/adaptation-preparedness-202021-baseline/].
MfE and Hawke's Bay Regional Council, 2020: *Challenges with implementing the Clifton to Tangoio Coastal Hazards Strategy 2120 case study*. Ministry for the environment, 33 [Available at: https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/challenges-with-implementing-the-Clifton-to-Tangoio-coastal-hazards-strategy-2120-case-study.pdf].
MfE and StatsNz, 2021: *Our Land 2021*. New Zealand's Environmental Reporting Series, 61 [Available at: https://environment.govt.nz/assets/Publications/our-land-2021.pdf].
Mikaloff-Fletcher, S. E., H. C. Bostock, M. J. Williams and A. Forcen, 2017: *Modelling the Effects of Ocean Acidification in New Zealand*. New Zealand Aquatic Environment and Biodiversity [Available at: https://fs.fish.govt.nz/Doc/24502/AEBR-187-Modelling-Effects-of-Ocean-Acidification.pdf.ashx].

Milfont, T. L., E. Zubielevitch, P. Milojev and C. G. Sibley, 2021: Ten-year panel data confirm generation gap but climate beliefs increase at similar rates across ages. *Nat. Commun.*, **12** (1), 4038, doi:10.1038/s41467-021-24245-y.
Miller, C. et al., 2017: Electrically caused wildfires in Victoria, Australia are over-represented when fire danger is elevated. *Landsc. Urban Plan.*, **167**, 267-274, doi:10.1016/j.landurbplan.2017.06.016.
Mills, M. et al., 2016a: Reconciling development and conservation under coastal squeeze from rising sea level. *Conservation Letters*, **9** (5), 361-368.
Mills, M. et al., 2016b: Perceived and projected flood risk and adaptation in coastal Southeast Queensland, Australia. *Climatic Change*, **136** (3-4), 523-537, doi:10.1007/s10584-016-1644-y.
Mitchell, J. W., 2013: Power line failures and catastrophic wildfires under extreme weather conditions. *Eng. Fail. Anal.*, **35**, 726.
Mitchell, M. et al., 2017: Mapping Scenario Narratives: A Technique to Enhance Landscape-scale Biodiversity Planning. *Conservation and Society*, **15** (2), 179, doi:10.4103/cs.cs_15_121.
Mitchell, N. et al., 2019: *The Action Plan for Australian Lizards and Snakes 2017*. CSIRO PUBLISHING, 680 pp.
Moggridge, B. J., L. Betterridge and R. M. Thompson, 2019: Integrating Aboriginal cultural values into water planning: a case study from New South Wales, Australia. *Australasian Journal of Environmental Management*, **26** (3), 273-286, doi:10.1080/14486563.2019.1650837.
Moglia, M., S. Cook and S. Tapsuwan, 2018: Promoting Water Conservation: Where to from here? *Water*, **10** (11), 1510, doi:10.3390/w10111510.
Molloy, S. W., A. H. Burbidge, S. Comer and R. A. Davis, 2020: Using climate change models to inform the recovery of the western ground parrot Pezoporus flaviventris. *Oryx*, **54** (1), 52-61, doi:10.1017/s0030605318000923.
Moloney, S. and H. McClaren, 2018: Designing a 'Fit-for-Purpose' Approach to Tracking Progress on Climate Change Adaptation and Resilience: Learning from Local Governments in Australia. In: Resilience-Oriented Urban Planning. Springer, Cham, 67-90.
Monge, J. J., W. J. Parker and J. W. Richardson, 2016: Integrating forest ecosystem services into the farming landscape: A stochastic economic assessment. *J Environ Manage*, **174**, 87-99, doi:10.1016/j.jenvman.2016.01.030.
Moore, A. D. and A. Ghahramani, 2013: Climate change and broadacre livestock production across southern Australia. 1. Impacts of climate change on pasture and livestock productivity, and on sustainable levels of profitability. *Glob Chang Biol*, **19** (5), 1440-55, doi:10.1111/gcb.12150.
Moore, D., A. Stow and M. R. Kearney, 2018: Under the weather?-The direct effects of climate warming on a threatened desert lizard are mediated by their activity phase and burrow system. *J. Anim. Ecol.*, **87** (3), 660-671, doi:10.1111/1365-2656.12812.
Moran, C., T. S. M and R. Hill, 2014: *Adaptation Pathways and Opportunities for the Wet Tropics NRM Cluster region. Volume 2. Infrastructure, Industry, Indigenous peoples, Social adaptation, Emerging planning frameworks, Evolving methodologies and Climate adaptation planning in practice*. James Cook University, Cairns. ISBN: 978-0-9941500-2-8. http://eprints.qut.edu.au/78942/1/Moran_et_al_2014__Adaptation_Pathways_Opportunities_WTC_Volume_2-1.pdf.
Moran, M., P. Petrie and V. Sadras, 2019: Effects of late pruning and elevated temperature on phenology, yield components, and berry traits in Shiraz. *American Journal of Enology and Viticulture*, **70** (1), 9-18, doi:10.5344/ajev.2018.18031.
Morgan, E. A., J. Nalau and B. Mackey, 2019: Assessing the alignment of national-level adaptation plans to the Paris Agreement. *Environmental Science & Policy*, **93**, 208-220, doi:10.1016/j.envsci.2018.10.012.
Morgan, E. A., E. Torabi and A. Dedekorkut-Howes, 2020: Responding to change: lessons from water management for metropolitan governance. *Australian Planner*, **56** (2), 125-133, doi:10.1080/07293682.2020.1742171.
Morgan, L. K. and A. D. Werner, 2015: A national inventory of seawater intrusion vulnerability for Australia. *Journal of Hydrology: Regional Studies*, **4**, 686-698, doi:10.1016/j.ejrh.2015.10.005.
Morim, J. et al., 2019: Robustness and uncertainties in global multivariate wind-wave climate projections. *Nat. Clim. Chang.*, **9** (9), 711-718, doi:10.1038/s41558-019-0542-5.
Morrison, C. and C. Pickering, 2013: Limits to Climate Change Adaptation: Case Study of the Australian Alps. *Geographical Research*, **51** (1), 11-25, doi:10.1111/j.1745-5871.2012.00758.x.
Morrongiello, J. R. and R. E. Thresher, 2015: A statistical framework to explore ontogenetic growth variation among individuals and populations: a marine fish example. doi:10.1890/13-2355.1.
Mosby, V., 2012: Using metasynthesis to develop sensitising concepts to understand Torres Strait Islander migration. *Cosmopolitan Civil Societies: an interdisciplinary journal*, **5** (1), 1-18.
Mosnier, A. et al., 2014: Global food markets, trade and the cost of climate change adaptation. *Food Security*, **6** (1), 29-44, doi:10.1007/s12571-013-0319-z.
Moyle, C.-L. J. et al., 2017: Have Australia's tourism strategies incorporated climate change? *J. Sustainable Tour.*, **26** (5), 703-721, doi:10.1080/09669582.2017.1387121.
MPI, 2015: *Situation and Outlook for Primary Industries*. Ministry for Primary Industries, Zealand, M. f. P. I. N., 72 [Available at: https://www.mpi.govt.nz/dmsdocument/7878-situation-and-outlook-for-primary-industries-sopi-2015].

Munshi, D. et al., 2020: *Centring Culture in Public Engagement on Climate Change Adaptation: Re-shaping the Future of the NZ Tourism Sector - A report to the Deep South National Science Challenge*. University of Waikato, Deep South National Science Challenge, 48 [Available at: https://www.deepsouthchallenge.co.nz/sites/default/files/2020-02/Centring%20Culture%20Compressed%20Report.pdf].
Murphy, K. 2020: Torres Strait Islanders take climate change complaint to the United Nations: Morrison government accused of failing to take action to reduce emissions or pursue adaptation measures. [Available at: https://www.theguardian.com/australia-news/2019/may/13/torres-strait-islanders-take-climate-change-complaint-to-the-united-nations accessed 4 November]
Mushtaq, S., 2016: Economic and policy implications of relocation of agricultural production systems under changing climate: Example of Australian rice industry. *Land use policy*, **52**, 277-286, doi:10.1016/j.landusepol.2015.12.029.
Naccarella, A., J. W. Morgan, S. C. Cutler and S. E. Venn, 2020: Alpine treeline ecotone stasis in the face of recent climate change and disturbance by fire. *PLOS ONE*, **15** (4), e0231339, doi:10.1371/journal.pone.0231339.
Nagle, N. et al., 2017: Aboriginal Australian mitochondrial genome variation – An increased understanding of population antiquity and diversity. *Sci. Rep.*, **7**, 1-12.
Nairn, J. and S. Williams, 2019: *Power outages during heatwaves: Predicting mortality burden in Australian cities*. Australian Energy Market Operator (AEMO), 37 [Available at: https://aemo.com.au/-/media/files/initiatives/strategic-partnerships/2020/power-outages-and-mortality-burden-australian-cities.pdf].
Nalau, J. and J. Handmer, 2018: Improving Development Outcomes and Reducing Disaster Risk through Planned Community Relocation. *Sustain. Sci. Pract. Policy*, **10** (10), 3545, doi:10.3390/su10103545.
Natural Capital Economics, 2018: *Heatwaves in Victoria: A Vulnerability Assessment*. Department of Environment, Land, Water and Planning, Victoria, 102 [Available at: https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0029/399440/Heatwaves_VulnerabilityAssessment_2018.pdf].
Navi, M., C. Skelly, M. Taulis and S. Nasiri, 2015: Coal seam gas water: potential hazards and exposure pathways in Queensland. *Int. J. Environ. Health Res.*, **25** (2), 162-183, doi:10.1080/09603123.2014.915018.
NCCARF, 2013: *Ensuring Australia's Urban Water Supplies Under Climate Change*. National Climate Change Adaptation Research Facility, Facility, N. C. C. A. R., 6.
Neave, I., A. McLeod, G. Raisin and J. Swirepik, 2015: *Managing water in the Murray-Darling basin under a variable and changing climate*. Water, Australian Water Association, 6 [Available at: https://www.mdba.gov.au/sites/default/files/pubs/Managing%20water%20in%20the%20murray-darling%20basin%20under%20a%20variable%20and%20changing%20climate.pdf].
Nelson, G. C., H. Valin, R. D. Sands and others, 2014: Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the*.
NESP ESCC, 2020: *Scenario analysis of climate-related physical risk for buildings and infrastructure: financial disclosure guidelines.* . Initiative, C. M. S. [Available at: https://www.cmsi.org.au/reports].
Newton, P. et al., 2018: Australian cities and the governance of climate change. *Australia's Metropolitan Imperative: An Agenda for Governance Reform*, 193.
Newton, P. and P. Newman, 2015: Critical Connections: The Role of the Built Environment Sector in Delivering Green Cities and a Green Economy. *Sustainability*, **7** (7), 9417-9443, doi:10.3390/su7079417.
Newton, P. W. and B. C. Rogers, 2020: Transforming Built Environments: Towards Carbon Neutral and Blue-Green Cities. *Sustain. Sci. Pract. Policy*, **12** (11), 4745, doi:10.3390/su12114745.
Ngai-Tahu, 2018: *He Rautaki Mo Te Huringa O Te Ahuarangi Climate Change Strategy*. Te Runanga O Ngai Tahu, 32 [Available at: filesystem:chrome-extension://bomfdkbfpdhijjbeoicnfhjbdhncfhig/persistent/6F4CC382A83D11E9BC5EA282DE8EC746/pp_attachments/7a8ee170-bca8-07d0-bda7-40d68212f8ca].
Ngāti Tahu- Ngāti Whaoa Rūnanga Trust, 2013: *Rising above the mist - te aranga ake i te taimahatanga*. Iwi Environmental Management Plan, 116.
Nicholls et al., 2016: Building evidence that effective heat alert systems save lives in southeast Australia. In: Climate Services for Health: Improving public health decision-making in a new climate. WHO/WMO, 188-190.
Nidumolu, U. et al., 2014: Spatio-temporal modelling of heat stress and climate change implications for the Murray dairy region, Australia. *Int J Biometeorol*, **58** (6), 1095-108, doi:10.1007/s00484-013-0703-6.
Nidumolu, U. B., P. T. Hayman, S. M. Howden and B. M. Alexander, 2012: Re-evaluating the margin of the South Australian grain belt in a changing climate. *Climate Research*, **51**, 249-260, doi:10.3354/cr01075.
Nimbs, M. and S. Smith, 2018: Beyond Capricornia: Tropical Sea Slugs (Gastropoda, Heterobranchia) Extend Their Distributions into the Tasman Sea. *Diversity*, **10** (3), doi:10.3390/d10030099.
Nitschke, M. et al., 2016: Evaluation of a heat warning system in Adelaide, South Australia, using case-series analysis. *BMJ Open*, **6** (7), e012125, doi:10.1136/bmjopen-2016-012125.
Nitschke, M. et al., 2011: Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. *Environ. Health*, **10**, 42, doi:10.1186/1476-069X-10-42.
NIWA, 2019: *Annual climate summary 2018*. New Zealand National Institute of Water and Air.
NIWA, 2020: NZ Historic Weather Events Catalogue.

Nolan, R. H. et al., 2020: Causes and consequences of eastern Australia's 2019-20 season of mega-fires. *Glob. Chang. Biol.*, **26** (3), 1039-1041, doi:10.1111/gcb.14987.
Norman, B., P. Newman and W. Steffen, 2021: Apocalypse now: Australian bushfires and the future of urban settlements. *npj Urban Sustainability*, **1** (1), doi:10.1038/s42949-020-00013-7.
Norman, J. A. and L. Christidis, 2016: Ecological opportunity and the evolution of habitat preferences in an arid-zone bird: implications for speciation in a climate-modified landscape. *Sci. Rep.*, **6**, doi:10.1038/srep19613.
Nowicki, R. J. et al., 2017: Predicting seagrass recovery times and their implications following an extreme climate event. *Mar. Ecol. Prog. Ser.*, **567**, 79-93, doi:10.3354/meps12029.
Noy, I., 2020: Paying a Price of Climate Change: Who Pays for Managed Retreats? *Current Climate Change Reports*, **6** (1), 17-23, doi:10.1007/s40641-020-00155-x.
NSW Government, 2016: *NSW Climate Change Policy Framework*. Office of Environment and Heritage,12 pp.
NSW Government, 2018: *State Environmental Planning Policy (Coastal Management)*. Government of New South Wales,22 pp.
Nunn, P. and N. Reid, 2016: Aboriginal Memories of Inundation of the Australian Coast Dating from More than 7000 Years Ago. *Australian Geographer*, **47** (1), 11-47, doi:10.1080/00049182.2015.1077539.
Nursey-Bray, M. and R. Palmer, 2018: Country, climate change adaptation and colonisation: insights from an Indigenous adaptation planning process, Australia. *Heliyon*, **4** (3), doi:10.1016/j.heliyon.2018.e00565.
Nursey-Bray, M., R. Palmer, T. F. Smith and P. Rist, 2019: Old ways for new days: Australian Indigenous peoples and climate change. *Local Environment*, **24** (5), 473-486, doi:10.1080/13549839.2019.1590325.
Nuttall, J. G. et al., 2018: Acute High Temperature Response in Wheat.
Nyberg, D. and C. Wright, 2020: Climate-proofing management research. *Academy of Management Perspectives*, doi:10.5465/amp.2018.0183.
NZ Archaeological Association, 2020: Archaeological site recording scheme.
NZ Government, 2021: NZ becomes first in world for climate reporting.
NZ Treasury, 2016: *New Zealand Economic and Financial Overview 2016* [Treasury, N. Z. (ed.)]. New Zealand Treasury, Wellington.
NZCFSF, 2021: Centre for Sustainable Finance.
O'Brien, L. V., H. L. Berry, C. Coleman and I. C. Hanigan, 2014: Drought as a mental health exposure. *Environ. Res.*, **131**, 181-187, doi:10.1016/j.envres.2014.03.014.
O'Donnell, T., 2019: Coastal management and the political-legal geographies of climate change adaptation in Australia. *Ocean & Coastal Management*, **175**, 127-135, doi:10.1016/j.ocecoaman.2019.03.022.
O'Donnell, T., 2020: Don't get too attached: Property–place relations on contested coastlines. *Transactions of the Institute of British Geographers*, **45** (3), 559-574, doi:10.1111/tran.12368.
O'Hare, P., I. White and A. Connelly, 2016: Insurance as maladaptation: Resilience and the 'business as usual' paradox. *Environment and Planning C: Government and Policy*, **34** (6), 1175-1193, doi:10.1177/0263774x15602022.
O'Leary, G. J. et al., 2015: Response of wheat growth, grain yield and water use to elevated CO 2 under a free-air CO 2 enrichment (FACE) experiment and modelling in a semi-arid environment. *Global Change Biology*, **21** (7), 2670-2686.
O'Donnell, T. and L. Gates, 2013: Getting the balance right: a renewed need for the public interest test in addressing coastal climate change and sea level rise. *Environ. Plann. Law J.*, **30** (3), 220-235.
O'Donnell, T., T. F. Smith and S. Connor, 2019: Property rights and land use planning on the Australian coast. In: Research Handbook on Climate Change Adaptation Policy: Update on Progress [Keskitalo, E. C. and B. P (eds.)]. Edward Elgar, UK & USA.
Ochoa-Hueso, R. et al., 2017: Rhizosphere-driven increase in nitrogen and phosphorus availability under elevated atmospheric CO2 in a mature Eucalyptus woodland. *Plant Soil*, **416** (1-2), 283-295, doi:10.1007/s11104-017-3212-2.
Odell, S. D., A. Bebbington and K. E. Frey, 2018: Mining and climate change: A review and framework for analysis. *The Extractive Industries and Society*, **5**, 201-214.
OECD, 2017: *OECD Environmental Performance Reviews: New Zealand 2017*. OECD Environmental Performance Reviews, OECD Publishing, Paris.
OECD, 2019a: *Measuring Distance to the SDG Targets 2019 An Assessment of Where OECD Countries Stand: An Assessment of Where OECD Countries Stand*. OECD Publishing, 144 pp.
OECD, 2019b: *Responding to Rising Seas: OECD Country approaches to tackling coastal risks*. OECd Publishing, 168 [Available at: https://www.oecd-ilibrary.org/docserver/9789264312487-en.pdf?expires=1600345024&id=id&accname=guest&checksum=6B3F33F96053916FBCE1939FCFC15666].
OEH, 2018a: *Our future on the coast. NSW Coastal Management Manual Part B: Stage 1 – Identify the scope of a coastal management program*. State of NSW and Office of Environment and Heritage, 39 [Available at: https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Water/Coasts/coastal-management-manual-part-b-stage-1-170672.pdf].
OEH, 2018b: *Our future on the coast: An overview of coastal management in NSW*. Office of Environment and Heritage, 16 [Available at: https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Water/Coasts/coastal-management-overview-170648.pdf].

OEH, 2018c: *Our Future on the Coast: NSW Coastal Management Manual Part A - Introduction and mandatory requirements for a coastal management program*. State of NSW and Office of Environment and Heritage, 29 [Available at: https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Water/Coasts/coastal-management-manual-part-a-170671.pdf].
Ofori, B. Y., L. J. Beaumont and A. J. Stow, 2017a: Cunningham's skinks show low genetic connectivity and signatures of divergent selection across its distribution. *Ecol. Evol.*, **7** (1), 48-57, doi:10.1002/ece3.2627.
Ofori, B. Y., A. J. Stow, J. B. Baumgartner and L. J. Beaumont, 2017b: Combining dispersal, landscape connectivity and habitat suitability to assess climate-induced changes in the distribution of Cunningham's skink, Egernia cunninghami. *PLOS ONE*, **12** (9), doi:10.1371/journal.pone.0184193.
Ogier, E. et al., 2020: Responding to Climate Change: Participatory Evaluation of Adaptation Options for Key Marine Fisheries in Australia's South East. *Frontiers in Marine Science*, **7**, doi:10.3389/fmars.2020.00097.
Oliver, E. C. J. et al., 2021: Marine Heatwaves. *Annual Review of Marine Science*, **13**, 313-42, doi:https://doi.org/10.1146/annurev-marine-032720-095144.
Oppenheimer, M. et al., 2019: Sea level rise and implications for low lying islands, coasts and communities.
Orwin, K. H. et al., 2015: Effects of climate change on the delivery of soil-mediated ecosystem services within the primary sector in temperate ecosystems: a review and New Zealand case study. *Glob Chang Biol*, **21** (8), 2844-60, doi:10.1111/gcb.12949.
Osbaldison, N., C. McShane, R. Oleszek and Others, 2019: Underinsurance in cyclone and flood environments: A case study in Cairns, Queensland. *Australian Journal of Emergency Management, The*, **34** (1), 41.
Osborne, K. et al., 2017: Delayed coral recovery in a warming ocean. *Glob. Chang. Biol.*, **23** (9), 3869-3881, doi:10.1111/gcb.13707
10.1111/gcb.13707. Epub 2017 May 9.
Owen, S. et al., 2018: *Anticipating staged managed retreat at the coastal margins*. New Zealand Planning Institute, 5 [Available at: http://resiliencechallenge.nz/wp-content/uploads/2018/08/Owen-et-al-2018_planning-quarterly.pdf].
Paddam, S. and S. Wong, 2017: *Climate risk disclosure – financial institutions feel the heat*. Actuaries Institute Australia.
Page, D., E. Bekele, J. Vanderzalm and J. Sidhu, 2018: Managed Aquifer Recharge (MAR) in Sustainable Urban Water Management. *Water*, **10** (3), 239, doi:10.3390/w10030239.
Palutikof, J. P. et al., 2019a: Overcoming knowledge barriers to adaptation using a decision support framework. *Climatic Change*, **153** (4), 607-624, doi:10.1007/s10584-018-2177-3.
Palutikof, J. P. et al., 2019b: CoastAdapt: an adaptation decision support framework for Australia's coastal managers. *Climatic Change*, **153** (4), 491-507, doi:10.1007/s10584-018-2200-8.
Palutikof, J. P., R. B. Street and E. P. Gardiner, 2019c: Decision support platforms for climate change adaptation: an overview and introduction. *Climatic Change*, **153** (4), 459-476, doi:10.1007/s10584-019-02445-2.
Parida, M., A. A. Hoffmann and M. P. Hill, 2015: Climate change expected to drive habitat loss for two key herbivore species in an alpine environment. *J. Biogeogr.*, **42** (7), 1210-1221, doi:10.1111/jbi.12490.
Parker, L. M. et al., 2018: Ocean acidification but not warming alters sex determination in the Sydney rock oyster, Saccostrea glomerata. *Proc. Biol. Sci.*, **285** (1872), doi:10.1098/rspb.2017.2869
10.1098/rspb.2017.2869.
Parkinson, D., 2019: Investigating the Increase in Domestic Violence Post Disaster: An Australian Case Study. *J. Interpers. Violence*, **34** (11), 2333-2362, doi:10.1177/0886260517696876.
Parliament of Victoria, 2010: *2009 Victorian Bushfires Royal Commission*. Victorian Bushfire Royal Commission, 42 [Available at: http://royalcommission.vic.gov.au/Commission-Reports/Final-Report.html].
Parsons, M., K. Fisher and R. P. Crease, 2021: Rethinking freshwater management in the context of climate change: Planning for different times, climates and generations. In: Decolonising Blue Spaces in the Anthropocene: Freshwater management in Aotearoa New Zealand [Parsons, M., K. Fisher and R. P. Crease (eds.)]. Springer Nature, 419-462.
Parsons, M., J. Nalau, K. Fisher and C. Brown, 2019: Disrupting path dependency: Making room for Indigenous knowledge in river management. *Global Environmental Change*, **56**, 95-113, doi:10.1016/j.gloenvcha.2019.03.008.
Pastor-Paz, J. et al., 2020: *Projecting the effect of climate change-induced increases in extreme rainfall on residential property damages: A case study from New Zealand*. Motu Economic and Public Policy Research, 32 [Available at: http://motu-www.motu.org.nz/wpapers/20_02.pdf].
Paulik, R. et al., 2021: Flood Impacts on Dairy Farms in the Bay of Plenty Region, New Zealand. *Climate*, **9** (2), 30, doi:10.3390/cli9020030.
Paulik, R., C. Heather and D. Collins, 2019a: *New Zealand Fluvial and Pluvial Flood Exposure*. National Institute of Water and Atmospheric Research, New Zealand (NIWA),58 pp.
Paulik, R. et al., 2019b: *Coastal Flooding Exposure Under Future Sea-level Rise for New Zealand*. NIWA, 76 [Available at: https://www.deepsouthchallenge.co.nz/sites/default/files/2019-08/2019119WN_DEPSI18301_Coast_Flood_Exp_under_Fut_Sealevel_rise_FINAL%20(1)_0.pdf].
Paulik, R. et al., 2020: National-Scale Built-Environment Exposure to 100-Year Extreme Sea Levels and Sea-Level Rise. *Sustainability*, **12** (4), 1513, doi:10.3390/su12041513.

PCE, 2015: *Preparing New Zealand for rising seas: Certainty and Uncertainty*. Parliamentary Commissioner for the Environment, 93 [Available at: https://www.pce.parliament.nz/media/1390/preparing-nz-for-rising-seas-web-small.pdf].
PCE, 2019: *Farms, Forests and Fossil Fuels: The Next Great Landscape Transformation?* Office of the Parliamentary Commissioner for the Environment, 184 pp.
Pearce, H. G., 2018: The 2017 Port Hills wildfires – a window into New Zealand's fire. *Australasian Journal of Disaster and Trauma Studies*, **22**.
Pearce, H. G. et al., 2011: Improved estimates of the effect of climate change on NZ fire danger. *Scion Client Report*, (18087).
Pearce, T., E. H. Rodríguez, D. Fawcett and J. D. Ford, 2018: *How is Australia Adapting to Climate Change Based on a Systematic Review?* [Available at: http://dx.doi.org/10.20944/preprints201808.0226.v1].
Pearson, J. et al., 2018: Flood resilience: consolidating knowledge between and within critical infrastructure sectors. *Environment Systems and Decisions*, **38** (3), 318-329, doi:10.1007/s10669-018-9709-2.
Pecl, G. T. et al., 2019: Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot. *Ambio*, doi:10.1007/s13280-019-01186-x.
Pecl, G. T. et al., 2014: Rapid assessment of fisheries species sensitivity to climate change. *Climatic Change*, **127** (3-4), 505-520, doi:10.1007/s10584-014-1284-z.
Pedruco, P. et al., 2018: Assessing climate change impacts on rural flooding in Victoria. In: *Hydrology and Water Resources Symposium (HWRS 2018): Water and Communities*, 2018, 645.
Peel, J. and H. M. Osofsky, 2018: A Rights Turn in Climate Change Litigation? *Transnational Environmental Law*, **7** (1), 37-67, doi:10.1017/s2047102517000292.
Peel, J., H. M. Osofsky and A. Foerster, 2020: Shaping the Next Generation of Climate Change Litigation in Australia. *Climate Change Litigation in the Asia Pacific*, 175-206, doi:10.1017/9781108777810.009.
Peel, M. C., T. A. McMahon and B. L. Finlayson, 2004: Continental differences in the variability of annual runoff-update and reassessment. *Journal of Hydrology*, **295** (1-4), 185-197, doi:10.1016/j.jhydrol.2004.03.004.
Peirson, W. et al., 2015: Opportunistic management of estuaries under climate change: A new adaptive decision-making framework and its practical application. *Journal of Environmental Management*, **163**, 214-223, doi:10.1016/j.jenvman.2015.08.021.
Pepler, A., L. Ashcroft and B. Trewin, 2018: The relationship between the subtropical ridge and Australian temperatures. *Journal of Southern Hemisphere Earth System Science*, **68** (1), 201-214, doi:10.22499/3.6801.011.
Pepler, A., B. Trewin and C. Ganter, 2015a: The influence of climate drivers on the Australian snow season. *Australian Meteorological and Oceanographic Journal*, **65** (2), 195-205, doi:10.22499/2.6502.002.
Pepler, A. S. et al., 2015b: Impact of Identification Method on the Inferred Characteristics and Variability of Australian East Coast Lows. *Monthly Weather Review*, **143** (3), 864-877, doi:10.1175/mwr-d-14-00188.1.
Perceval, M. et al., 2019: Environmental factors and suicide in Australian farmers: A qualitative study. *Arch. Environ. Occup. Health*, **74** (5), 279-286, doi:10.1080/19338244.2018.1453774.
Perera, R. S., B. R. Cullen and R. J. Eckard, 2020: Changing patterns of pasture production in south-eastern Australia from 1960 to 2015. *Crop and Pasture Science*, **71** (1), doi:10.1071/cp19112.
Perkins-Kirkpatrick, S. E. and S. C. Lewis, 2020: Increasing trends in regional heatwaves. *Nat. Commun.*, **11** (1), 3357, doi:10.1038/s41467-020-16970-7.
Perkins-Kirkpatrick, S. E. et al., 2016: Natural hazards in Australia: heatwaves. *Clim. Change*, **139** (1), 101-114, doi:10.1007/s10584-016-1650-0.
Perry, B., 2017: Household incomes in New Zealand: Trends in indicators of inequality and hardship 1982 to 2016. *Ministry of Social Development: Wellington, New Zealand*.
Perry, G. L. W., J. M. Wilmshurst and M. S. McGlone, 2014: Ecology and long-term history of fire in New Zealand. *N. Z. J. Ecol.*, **38** (2), 1.
Perry, S. J. et al., 2020: Projected late 21st century changes to the regional impacts of the El Niño-Southern Oscillation. *Climate Dynamics*, **54** (1-2), 395-412, doi:10.1007/s00382-019-05006-6.
Pescaroli, G. and D. Alexander, 2016: Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Natural Hazards*, **82** (1), 175-192, doi:10.1007/s11069-016-2186-3.
Petheram, L., N. Stacey and A. Fleming, 2015: Future sea changes: Indigenous women's preferences for adaptation to climate change on South Goulburn Island, Northern Territory (Australia). *Climate and Development*, **7** (4), 339-352.
Pethybridge, H. R. et al., 2020: Contrasting Futures for Australia’s Fisheries Stocks Under IPCC RCP8.5 Emissions – A Multi-Ecosystem Model Approach. *Frontiers in Marine Science*, **7**, doi:10.3389/fmars.2020.577964.
Petrone, K. C., J. D. Hughes, T. G. Van Niel and R. P. Silberstein, 2010: Streamflow decline in southwestern Australia, 1950-2008. *Geophysical Research Letters*, **37** (11), doi:10.1029/2010gl043102.
Pettit, N. E., P. Bayliss and R. Bartolo, 2016: Dynamics of plant communities and the impact of saltwater intrusion on the floodplains of Kakadu National Park. *Mar. Freshwater Res.*, **69** (7), 1124-1133, doi:10.1071/MF16148.
Petzold, J. et al., 2020: Indigenous knowledge on climate change adaptation: a global evidence map of academic literature. *Environmental Research Letters*, **15** (11), 113007, doi:10.1088/1748-9326/abb330.

Phelan, D. C., M. T. Harrison, E. P. Kemmerer and D. Parsons, 2015: Management opportunities for boosting productivity of cool-temperate dairy farms under climate change. *Agric. Syst.*, **138**, 46-54, doi:10.1016/j.agsy.2015.05.005.
Phelan, D. C. et al., 2014: Beneficial impacts of climate change on pastoral and broadacre agriculture in cool-temperate Tasmania. *Crop Pasture Sci.*, **65** (2), 194-205, doi:10.1071/CP12425.
Phelan, L., 2011: Managing climate risk: extreme weather events and the future of insurance in a climate-changed world. *Australasian Journal of Environmental Management*, **18** (4), 223-232, doi:10.1080/14486563.2011.611486.
Phelan, L., R. Taplin, A. Henderson-Sellers and G. Albrecht, 2011: Ecological Viability or Liability? Insurance System Responses to Climate Risk. *Environmental Policy and Governance*, **21** (2), 112-130, doi:10.1002/eet.565.
Phelps, D. and D. Kelly, 2019: Overcoming drought vulnerability in rangeland communities: lessons from central-western Queensland. *The Rangeland Journal*, **41** (3), 251, doi:10.1071/rj18052.
Phillips, J., 2016: Climate change and surface mining: A review of environment-human interactions & their spatial dynamics. *Appl. Geogr.*, **74**, 95-108, doi:10.1016/j.apgeog.2016.07.001.
Physick, W., M. Cope and S. Lee, 2014: The impact of climate change on ozone-related mortality in Sydney. *Int. J. Environ. Res. Public Health*, **11** (1), 1034-1048, doi:10.3390/ijerph110101034.
Piggott-McKellar, A. E. and K. E. McNamara, 2016: Last chance tourism and the Great Barrier Reef. *J. Sustainable Tour.*, **25** (3), 397-415, doi:10.1080/09669582.2016.1213849.
Piggott-McKellar, A. E., K. E. McNamara, P. D. Nunn and J. E. M. Watson, 2019: What are the barriers to successful community-based climate change adaptation? A review of grey literature. *Local Environ.*, **24** (4), 374-390.
Pingram, M. A. et al., 2021: Surviving invasion: Regaining native fish resilience following fish invasions in a modified floodplain landscape. *Water Resources Research*, doi:10.1029/2020wr029513.
Pinkard, E., K. Paul, M. Battaglia and J. Bruce, 2014: Vulnerability of Plantation Carbon Stocks to Defoliation under Current and Future Climates. *Forests*, **5** (6), 1224-1242, doi:10.3390/f5061224.
Pinkerton, M. H., 2017: Impacts of Climate Change on New Zealand Fisheries and Aquaculture. *Climate Change Impacts on Fisheries and Aquaculture*, 91-119, doi:10.1002/9781119154051.ch5.
Pitt, N. R., E. S. Poloczanska and A. J. Hobday, 2010: Climate-driven range changes in Tasmanian intertidal fauna. *Mar. Freshwater Res.*, **61**, 963-970.
Pizarro, J., B. Sainsbury, J. Hodgkinson and B. Loechel, 2017: Australian uranium industry climate change vulnerability assessment. *Environmental Development*, **24**, 109-123, doi:10.1016/j.envdev.2017.06.002.
Plagányi, É. E. et al., 2014: A quantitative metric to identify critical elements within seafood supply networks. *PLOS ONE*, **9** (3), e91833, doi:10.1371/journal.pone.0091833.
Plummer, R., J. Baird, R. Bullock and others, 2018: Flood Governance: A multiple country comparison of stakeholder perceptions and aspirations. *Environ. Policy Law*.
Poloczanska, E. S. et al., 2011: Little change in the distribution of rocky shore faunal communities on the Australian east coast after 50years of rapid warming. *J. Exp. Mar. Bio. Ecol.*, **400** (1-2), 145-154, doi:10.1016/j.jembe.2011.02.018.
Pomeroy, A., 2015: Resilience of family farming 1984-2014: Case studies from two sheep/beef hill country districts of New Zealand. *New Zealand Geographer*, **71** (3), 146-158, doi:10.1111/nzg.12106.
Porfirio, L. L. et al., 2016: Projected direct and indirect effects of climate change on the Swift Parrot, an endangered migratory species. *Emu*, **116** (3), 273-283, doi:10.1071/MU15094.
Post, D. A. et al., 2014: Decrease in southeastern Australian water availability linked to ongoing Hadley cell expansion. *Earth's Future*, **2** (4), 231-238, doi:10.1002/2013ef000194.
Potter, N. J. and F. H. S. Chiew, 2011: An investigation into changes in climate characteristics causing the recent very low runoff in the southern Murray-Darling Basin using rainfall-runoff models. *Water Resources Research*, **47** (12), doi:10.1029/2010wr010333.
Potter, N. J., F. H. S. Chiew and A. J. Frost, 2010: An assessment of the severity of recent reductions in rainfall and runoff in the Murray–Darling Basin. *Journal of Hydrology*, **381** (1-2), 52-64, doi:10.1016/j.jhydrol.2009.11.025.
Poyck, S. et al., 2011: Combined snow and streamflow modelling to estimate impacts of climate change on water resources in the Clutha River, New Zealand. *J. Hydrol.*, **50(2)**, 293-312.
Prahalad, V. and J. B. Kirkpatrick, 2019: Saltmarsh conservation through inventory, biogeographic analysis and predictions of change: Case of Tasmania, south-eastern Australia. *Aquat. Conserv.*, **29** (5), 717-731, doi:10.1002/aqc.3085.
Pratchett, M. S., S. F. Heron, C. Mellin and G. S. Cumming, 2021: Recurrent Mass-Bleaching and the Potential for Ecosystem Collapse on Australia's Great Barrier Reef. In: Ecosystem Collapse and Climate Change [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, 265-289.
Price, O. F., T. D. Penman, R. A. Bradstock and others, 2015: Biogeographical variation in the potential effectiveness of prescribed fire in south-eastern Australia. *Journal of*.
Prideaux, B. and A. Pabel, 2018: Australia's Great Barrier Reef – protection, threats, value and tourism use. *Coral Reefs: Tourism, Conservation and Management*, 44-60, doi:10.4324/9781315537320-4.
Prideaux, B., M. Thompson and A. Pabel, 2020: Lessons from COVID-19 can prepare global tourism for the economic transformation needed to combat climate change. *Tourism Geographies*, **22** (3), 667-678, doi:10.1080/14616688.2020.1762117.

Priestley, R. K., Z. Heine and T. L. Milfont, 2021: Public understanding of climate change-related sea-level rise. *PLOS ONE*, **16** (7), e0254348, doi:10.1371/journal.pone.0254348.
Prober, S. M. et al., 2017: Informing climate adaptation pathways in multi-use woodland landscapes using the values-rules-knowledge framework. *Agriculture, Ecosystems & Environment*, **241**, 39-53, doi:10.1016/j.agee.2017.02.021.
Productivity Commission, 2017: *Better Urban Planning: Final Report*.
Prokopy, L. S. et al., 2015: Farmers and Climate Change: A Cross-National Comparison of Beliefs and Risk Perceptions in High-Income Countries. *Environmental Management*, **56** (2), 492-504, doi:10.1007/s00267-015-0504-2.
Public Participation, 2014: IAP2 Spectrum of Participation.
Purdie, H., 2013: Glacier Retreat and Tourism: Insights from New Zealand. *Mt. Res. Dev.*, **33** (4), 463-472, doi:10.1659/MRD-JOURNAL-D-12-00073.1.
QFCI, 2012: *Queensland Floods Commission of Inquiry*. Queensland Government, Government, Q., 654.
QFES, 2019: *State Heatwave Risk Assessment 2019*. The State of Queensland (Queensland Fire and Emergency Services),108 pp.
Qin, H. and M. G. Stewart, 2020: Risk-based cost-benefit analysis of climate adaptation measures for Australian contemporary houses under extreme winds. *Journal of Infrastructure Preservation and Resilience*, **1** (1), 3, doi:10.1186/s43065-020-00002-1.
Queensland Government, 1995: *Coastal Protection and Management Act (1995)*.
Queensland Government, 2011: *Understanding Floods: Questions and Answers*. Queensland Government,36 pp.
Queensland Government, 2020: *Planning Act 2016*.366 pp.
Quentin, A., K. Crous, C. Barton and D. Ellsworth, 2015: Photosynthetic enhancement by elevated CO2 depends on seasonal temperatures for warmed and non-warmed Eucalyptus globulus trees. *Tree Physiology*, **35**, 1249-1263.
Qureshi, M. E. et al., 2018: Impact of Climate Variability Including Drought on the Residual Value of Irrigation Water Across the Murray–Darling Basin, Australia. *Water Econs. Policy*, **04** (01), 1550020, doi:10.1142/S2382624X15500204.
Race, D., S. Mathew, M. Campbell and K. Hampton, 2016: Are Australian Aboriginal Communities Adapting to a Warmer Climate? A Study of Communities Living in Semi-Arid Australia. *J. Sustainable Dev. Afr.*, **9** (3), 208-223.
Radcliffe, J. C., D. Page, B. Naumann and P. Dillon, 2017: Fifty years of water sensitive urban design, Salisbury, South Australia. *Frontiers of Environmental Science & Engineering*, **11** (4), doi:10.1007/s11783-017-0937-3.
Radhakrishnan, M., A. Pathirana, R. Ashley and C. Zevenbergen, 2017: Structuring Climate Adaptation through Multiple Perspectives: Framework and Case Study on Flood Risk Management. *Water*, **9** (2), 129, doi:10.3390/w9020129.
Ramm, T. D., S. Graham, C. J. White and C. S. Watson, 2017: Advancing values-based approaches to climate change adaptation: A case study from Australia. *Environmental Science & Policy*, **76**, 113-123, doi:10.1016/j.envsci.2017.06.014.
Ramm, T. D., C. S. Watson and C. J. White, 2018: Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. *Environ. Sci. Policy*, **87**, 92-101, doi:10.1016/j.envsci.2018.06.001.
Ramos, J. E. et al., 2018: Population genetic signatures of a climate change driven marine range extension. *Sci. Rep.*, **8** (1), 9558, doi:10.1038/s41598-018-27351-y
10.1038/s41598-018-27351-y.
Ramsay, D., B. Gibberd, J. Dahm and R. Bell, 2012: *Defining coastal hazard zones for setback lines. A Guide for Good Practice*. NIWA report for Envirolink [Available at: https://envirolink.govt.nz/assets/Envirolink/Defining20coastal-hazard20zones20for20setbacks20lines.pdf].
Ranasinghe, R., 2016: Assessing climate change impacts on open sandy coasts: A review. *Earth-Sci. Rev.*, **160**, 320-332, doi:10.1016/j.earscirev.2016.07.011.
Ranasinghe, R. et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Randall, A. et al., 2012: *Choosing a decision-making framework to manage uncertainty in climate adaptation decision-making: a practitioner's handbook*. Report for the National Climate Change Adaptation Research Facility (NCCARF), Griffith University. https://www.nccarf.edu.au/publications/Handbook-decision-making-framework-climate-adaptation.
Ratnayake, H. U. et al., 2019: Forecasting wildlife die-offs from extreme heat events. *Animal Conservation*, **22** (4), 386-395, doi:10.1111/acv.12476.
Raukawa Settlement Trust, 2015: *Te Rautaki Taio A Raukawa: Raukawa Environmental Management Plan 2015*. Raukawa Settlement Trust, 245.
Rauniyar, S. P. and S. B. Power, 2020: The Impact of Anthropogenic Forcing and Natural Processes on Past, Present, and Future Rainfall over Victoria, Australia. *Journal of Climate*, **33** (18), 8087-8106, doi:10.1175/jcli-d-19-0759.1.

Raupach, M. R., V. Haverd and P. R. Briggs, 2013: Sensitivities of the Australian terrestrial water and carbon balances to climate change and variability. *Agricultural and Forest Meteorology*, **182-183**, 277-291, doi:10.1016/j.agrformet.2013.06.017.
Raupach, T. H. et al., 2021: The effects of climate change on hailstorms. *Nature Reviews Earth & Environment*, **2** (3), 213-226, doi:10.1038/s43017-020-00133-9.
Rayner, D. et al., 2021: Intertidal wetland vegetation dynamics under rising sea levels. *Sci. Total Environ.*, **766**, 144237, doi:10.1016/j.scitotenv.2020.144237.
RBA, 2019: Climate Change and the Economy | Speeches.
RBNZ, 2018: *Financial Stability Report*. Reserve Bank of New Zealand, 50 [Available at: https://www.rbnz.govt.nz/-/media/ReserveBank/Files/Publications/Financial%20stability%20reports/2018/fsr-nov-2018.pdf].
Reisinger, A. et al., 2014: Australasia. In: Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, 1371-1438.
Reiter, D. et al., 2018: Increasing the effectiveness of environmental decision support systems: lessons from climate change adaptation projects in Canada and Australia. *Regional Environ. Change*, **18** (4), 1173-1184, doi:10.1007/s10113-017-1255-9.
Ren, Z., Z. Chen and X. Wang, 2011: Climate change adaptation pathways for Australian residential buildings. *Build. Environ.*, **46** (11), 2398-2412, doi:10.1016/j.buildenv.2011.05.022.
Reside, A. E. et al., 2014: Characteristics of climate change refugia for A ustralian biodiversity. *Austral Ecol.*, **39** (8), 887-897.
Rhodes, B. G., J. E. Fagan and K. S. Tan, 2012: Responding to a rapid climate shift - Experiences from Melbourne Australia. In: *Proceedings of the World Congress on Water, Climate and Energy*, 2012.
Rich, J. L., S. L. Wright and D. Loxton, 2018: Older rural women living with drought. *Local Environment*, **23** (12), 1141-1155, doi:10.1080/13549839.2018.1532986.
Richards, R. G. et al., 2015: Effects and mitigations of ocean acidification on wild and aquaculture scallop and prawn fisheries in Queensland, Australia. *Fisheries Research*, **161**, 42-56, doi:10.1016/j.fishres.2014.06.013.
Rickards, L., R. Ison, H. Fünfgeld and J. Wiseman, 2014: Opening and closing the future: climate change, adaptation, and scenario planning. *Environ. Plann. C Gov. Policy*, **32**, 587-602.
Rist, P. et al., 2019: Indigenous protected areas in Sea Country: Indigenous-driven collaborative marine protected areas in Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **29** (S2), 138-151, doi:10.1002/aqc.3052.
Ritchie, J., 2013: A pedagogy of biocentric relationality.
Rizvanovic, M., J. D. Kennedy, D. Nogues-Bravo and K. A. Marske, 2019: Persistence of genetic diversity and phylogeographic structure of three New Zealand forest beetles under climate change. *Diversity and Distributions*, **25** (1), 142-153, doi:10.1111/ddi.12834.
Robb, A. et al., 2019: Development Control And Vulnerable Coastal Lands: Examples Of Australian Practice. *Urban Policy and Research*, **37** (2), 199-214, doi:10.1080/08111146.2018.1489791.
Roberts, S. D. et al., 2019: Marine Heatwave, Harmful Algae Blooms and an Extensive Fish Kill Event During 2013 in South Australia. *Frontiers in Marine Science*, **6**, 610, doi:10.3389/fmars.2019.00610.
Robinson, C., G. James and P. Whitehead, 2016: Negotiating Indigenous benefits from payment for ecosystem service (PES) schemes. *Global Environmental Change*, **38**, 21-29.
Robinson, G. M. et al., 2018: Adapting to Climate Change: Lessons from Farmers and Peri-Urban Fringe Residents in South Australia. *Environments*, **5** (3), 40, doi:10.3390/environments5030040.
Robinson, L. M. et al., 2015: Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions. *Glob. Environ. Change*, **31**, 28-37, doi:10.1016/j.gloenvcha.2014.12.003.
Roche, M. and N. Argent, 2015: The fall and rise of agricultural productivism? An Antipodean viewpoint. *Progress in Human Geography*, **39** (5), 621-635, doi:10.1177/0309132515582058.
Rogelj, J., M. Meinshausen and R. Knutti, 2012: Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nat. Clim. Chang.*, **2** (4), 248-253, doi:10.1038/nclimate1385.
Rogers, B. C. et al., 2020a: An interdisciplinary and catchment approach to enhancing urban flood resilience: a Melbourne case. *Philos. Trans. A Math. Phys. Eng. Sci.*, **378** (2168), 20190201, doi:10.1098/rsta.2019.0201.
Rogers, B. C. et al., 2020b: Water Sensitive Cities Index: A diagnostic tool to assess water sensitivity and guide management actions. *Water Research*, 116411, doi:10.1016/j.watres.2020.116411.
Rogers, C., A. Gallant and N. Tapper, 2018: Is the urban heat island exacerbated during heatwaves in southern Australian cities? *Theor. Appl. Climatol.*, 1-17, doi:10.1007/s00704-018-2599-x.
Rolfe, M. I. et al., 2020: Social vulnerability in a high-risk flood-affected rural region of NSW, Australia. *Natural Hazards*, **101** (3), 631-650, doi:10.1007/s11069-020-03887-z.
Rosier, S. et al., 2015: Extreme Rainfall in Early July 2014 in Northland, New Zealand—Was There an Anthropogenic Influence? *Bulletin of the American Meteorological Society*, **96** (12), S136-S140, doi:10.1175/bams-d-15-00105.1.
Roth-Schulze, A. J. et al., 2018: The effects of warming and ocean acidification on growth, photosynthesis, and bacterial communities for the marine invasive macroalga Caulerpa taxifolia. *Limnology and Oceanography*, **63** (1), 459-471, doi:10.1002/lno.10739.
Rouse, H. et al., 2013: Coastal Adaptation to Climate Change: A New Zealand story. *Journal of Coastal Research*, **165**, 1957-1962, doi:10.2112/si65-331.1.

Rouse, H. L. et al., 2017: Coastal adaptation to climate change in Aotearoa-New Zealand. *N. Z. J. Mar. Freshwater Res.*, **51** (2), 183-222, doi:10.1080/00288330.2016.1185736.
Royal Society Te Apārangi, 2017: *Human Health Impacts of Climate Change for New Zealand - Evidence Summary*. Royal Society Te Apārangi, 18 [Available at: https://royalsociety.org.nz/assets/documents/Report-Human-Health-Impacts-of-Climate-Change-for-New-Zealand-Oct-2017.pdf].
RPS, 2020: *IS Rating scheme return on investment*. Infrastructure Sustainability Council of Australia, 32 [Available at: https://www.isca.org.au/getmedia/278ee8cb-0ea9-4688-9033-c41b5d43e2a8/19187-IS-Rating-ROI-Final-R2_1.pdf.aspx].
RSNZ, 2016: *Climate change implications for New Zealand*. Royal Society of New Zealand, 68.
Ruane, S., 2020: Applying the principles of adaptive governance to bushfire management: a case study from the South West of Australia. *Journal of Environmental Planning and Management*, **63** (7), 1215-1240, doi:10.1080/09640568.2019.1648243.
Rummukainen, M., 2015: Added value in regional climate modeling. *WIREs Climate Change*, **7**, 145–159.
Ruru, J., 2018: Listening to Papatūānuku: a call to reform water law. *J. R. Soc. N. Z.*, **48** (2-3), 215-224, doi:10.1080/03036758.2018.1442358.
Ruthrof, K. X. et al., 2016: How drought-induced forest die-off alters microclimate and increases fuel loadings and fire potentials. *International Journal of Wildland Fire*, **25** (8), 819, doi:10.1071/wf15028.
Ryan, P. A. et al., 2019: Establishment of wMel Wolbachia in Aedes aegypti mosquitoes and reduction of local dengue transmission in Cairns and surrounding locations in northern Queensland, Australia. *Gates Open Res*, **3**, 1547, doi:10.12688/gatesopenres.13061.2.
Rychetnik, L., P. Sainsbury and G. Stewart, 2019: How Local Health Districts can prepare for the effects of climate change: an adaptation model applied to metropolitan Sydney. *Aust. Health Rev.*, **43** (6), 601-610, doi:10.1071/AH18153.
SA Government, 2019a: *Directions for a Climate Smart South Australia*. Government of South Australia,12 pp.
SA Government, 2019b: *Murray-Darling Basin Royal Commission Report*. South Australia Government,746 pp.
Sadras, V. and M. F. Dreccer, 2015: Adaptation of wheat, barley, canola, field pea and chickpea to the thermal environments of Australia. *Crop & Pasture Science*, **66** (11), 1137-1150, doi:10.1071/cp15129.
Saft, M., M. C. Peel, A. W. Western and L. Zhang, 2016: Predicting shifts in rainfall-runoff partitioning during multiyear drought: Roles of dry period and catchment characteristics. *Water Resources Research*, **52** (12), 9290-9305, doi:10.1002/2016wr019525.
Salinger, M. J., B. B. Fitzharris and T. Chinn, 2019a: Atmospheric circulation and ice volume changes for the small and medium glaciers of New Zealand's Southern Alps mountain range 1977–2018. *International Journal of Climatology*, **39** (11), 4274-4287, doi:10.1002/joc.6072.
Salinger, M. J., B. B. Fitzharris and T. Chinn, 2021: Extending End-of-Summer-Snowlines for the Southern Alps Glaciers of New Zealand back to 1949. *International Journal of Climatology*, doi:10.1002/joc.7177.
Salinger, M. J. et al., 2020: Unparalleled coupled ocean-atmosphere summer heatwaves in the New Zealand region: drivers, mechanisms and impacts. *Climatic Change*, doi:10.1007/s10584-020-02730-5.
Salinger, M. J. et al., 2019b: The unprecedented coupled ocean-atmosphere summer heatwave in the New Zealand region 2017/18: drivers, mechanisms and impacts. *Environ. Res. Lett.*, **14** (4), 044023.
Salmon, G., 2019: Freshwater Decline. *Policy Quarterly*, **15** (3), doi:10.26686/pq.v15i3.5682.
Salvador-Carulla, L. et al., 2020: Rapid response to crisis: Health system lessons from the active period of COVID-19. *Health Policy Technol*, **9** (4), 578-586, doi:10.1016/j.hlpt.2020.08.011.
Sanderson, B. M. and R. A. Fisher, 2020: A fiery wake-up call for climate science. *Nat. Clim. Chang.*, **10** (3), 175-177, doi:10.1038/s41558-020-0707-2.
Sanderson, T., G. Hertzler, T. Capon and P. Hayman, 2015: A real options analysis of Australian wheat production under climate change. *Australian Journal of Agricultural and Resource Economics*, n/a-n/a, doi:10.1111/1467-8489.12104.
Sangha, K. K., J. Russell-Smith, J. Evans and A. Edwards, 2020: Methodological approaches and challenges to assess the environmental losses from natural disasters. *International Journal of Disaster Risk Reduction*, **49**, 101619, doi:10.1016/j.ijdrr.2020.101619.
Saunders, C. et al., 2016: *The Land and the Brand*. **AERU Research Report No. 339,**, Lincoln University: Agribusiness and Economics Research Unit.
Scanes, E., P. R. Scanes and P. M. Ross, 2020: Climate change rapidly warms and acidifies Australian estuaries. *Nat. Commun.*, **11** (1), 1803, doi:10.1038/s41467-020-15550-z.
Scarsbrook, M. R. and A. R. Melland, 2015: Dairying and water-quality issues in Australia and New Zealand. *Animal Production Science*, **55** (7), 856-868, doi:10.1071/an14878.
Schauber, E. M. et al., 2002: Masting by eighteen New Zealand plant apcies: The role of temperature as a synchronizing clue. *Ecology*, **83** (5), 1214-1225, doi:10.1890/0012-9658(2002)083[1214:mbenzp]2.0.co;2.
Schavemaker, P. and L. van der Sluis, 2017: *Electrical power system essentials*. John Wiley & Sons, Chichester, West Sussex.
Scheffers, B. R. et al., 2016: The broad footprint of climate change from genes to biomes to people. *Science*, **354** (6313), aaf7671, doi:10.1126/science.aaf7671.

Scheiter, S., S. I. Higgins, J. Beringer and L. B. Hutley, 2015: Climate change and long-term fire management impacts on Australian savannas. *New Phytol.*, **205** (3), 1211-1226.
Schenuit, F. et al., 2021: Carbon Dioxide Removal Policy in the Making: Assessing Developments in 9 OECD Cases. *Frontiers in Climate*, **3**, 7, doi:10.3389/fclim.2021.638805.
Schlosberg, D., L. B. Collins and S. Niemeyer, 2017: Adaptation policy and community discourse: risk, vulnerability, and just transformation. *Environmental Politics*, **26** (3), 413-437, doi:10.1080/09644016.2017.1287628.
Schneider, P., B. Glavovic and T. Farrelly, 2017: So Close Yet So Far Apart: Contrasting Climate Change Perceptions in Two "Neighboring" Coastal Communities on Aotearoa New Zealand's Coromandel Peninsula. *Environments*, **4** (3), 65, doi:10.3390/environments4030065.
Schneider, P. et al., 2020: A rising tide of adaptation action: Comparing two coastal regions of Aotearoa-New Zealand. *Climate Risk Management*, 100244, doi:10.1016/j.crm.2020.100244.
Schumacher, L., 2020: Legal Framework for Coastal Adaptation to Rising Sea Levels in New Zealand. *The Law of Coastal Adaptation*, 169-278, doi:10.1007/978-3-030-48962-5_4.
Schuster, S., 2013: Natural hazards and insurance. In: Climate Adaptation Futures [Palutikof, J., S. Boulter, A. Ash, M. Stafford Smith, M. Parry, M. Waschka and D. Guitart (eds.)]. John Wiley & Sons, Brisbane, Australia, 133-140.
Schweinsberg, S., S. Darcy and D. Beirman, 2020: 'Climate crisis' and 'bushfire disaster': Implications for tourism from the involvement of social media in the 2019--2020 Australian bushfires. *J. Int. Hosp. Leisure Tour. Manag.*
Schwerdtle, P., K. Bowen and C. McMichael, 2018: The health impacts of climate-related migration. *BMC Med.*, **16** (1), doi:10.1186/s12916-017-0981-7.
Scion, 2018: *Rural Fire Research*. Rural Fire Research, 4 [Available at: https://www.scionresearch.com/__data/assets/pdf_file/0005/64391/Rural_fire_research_infosheet.pdf].
Scott, D., C. M. Hall and S. Gössling, 2019a: Global tourism vulnerability to climate change. *Ann. Touris. Res.*, **77**, 49-61, doi:10.1016/j.annals.2019.05.007.
Scott, H. and S. Moloney, 2021: Completing the climate change adaptation planning cycle: monitoring and evaluation by local government in Australia. *Journal of Environmental Planning and Management*, 1-27, doi:10.1080/09640568.2021.1902789.
Scott, J. K., M. H. Friedel, A. C. Grice and B. L. Webber, 2018: Weeds in Australian Arid Regions. *On the Ecology of Australia's Arid Zone*, 307-330, doi:10.1007/978-3-319-93943-8_12.
Scott, J. K. et al., 2014: *AdaptNRM Weeds and Climate Change: Supporting weed management adaptation*. Adapt-NRM, 74 [Available at: https://adaptnrm.csiro.au/wp-content/uploads/2014/08/Adapt-NRM_M2_WeedsTechGuide_5.1_LR.pdf].
Scott, M., H. M. T. Andrew and M. Pratchett, 2017: A large predatory reef fish species moderates feeding and activity patterns in response to seasonal and latitudinal temperature variation. *Scientific Reports*, **7** (12966).
Scott, M. E. et al., 2019b: Latitudinal and seasonal variation in space use by a large, predatory reef fish, Plectropomus leopardus. *Funct. Ecol.*, **33** (4), 670-680, doi:10.1111/1365-2435.13271.
Sellberg, M. M. et al., 2018: From resilience thinking to Resilience Planning: Lessons from practice. *Journal of Environmental Management*, **217**, 906-918, doi:10.1016/j.jenvman.2018.04.012.
Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Serrao-Neumann, S. and D. L. Choy, 2018: Uncertainty and Future Planning: The Use of Scenario Planning for Climate Change Adaptation Planning and Decision. In: Communicating Climate Change Information for Decision-Making [SerraoNeumann, S., A. Coudrain and L. Coulter (eds.)], 79-90.
Serrao-Neumann, S., M. Cox and D. Low Choy, 2019a: Bridging Adaptive Learning and Desired Natural Resource Management Outcomes: Insights from Australian Planners. *null*, **34** (2), 149-167, doi:10.1080/02697459.2018.1549188.
Serrao-Neumann, S., G. Di Giulio and D. L. Choy, 2020: When salient science is not enough to advance climate change adaptation: Lessons from Brazil and Australia. *Environmental Science & Policy*, **109**, 73-82, doi:10.1016/j.envsci.2020.04.004.
Serrao-Neumann, S. et al., 2019b: Urban water metabolism information for planning water sensitive city-regions. *Land use policy*, **88**, 104144, doi:10.1016/j.landusepol.2019.104144.
Serrao-Neumann, S., G. Schuch, M. Cox and D. L. Choy, 2019c: Scenario planning for climate change adaptation for natural resource management: Insights from the Australian East Coast Cluster. *Ecosystem Services*, **38**, 100967, doi:10.1016/j.ecoser.2019.100967.
Shalders, T. C. et al., 2018: Potential climate-mediated changes to the distribution and density of pomacentrid reef fishes in south-western Australia. *Mar. Ecol. Prog. Ser.*, **604**, 223-235, doi:10.3354/meps12736.
Sharma-Wallace, L., S. J. Velarde and A. Wreford, 2018: Adaptive governance good practice: Show me the evidence! *J. Environ. Manage.*, **222**, 174-184, doi:10.1016/j.jenvman.2018.05.067.
Sharma, A., C. Wasko and D. P. Lettenmaier, 2018: If Precipitation Extremes Are Increasing, Why Aren't Floods? *Water Resources Research*, **54** (11), 8545-8551, doi:10.1029/2018wr023749.

Sharples, C. et al., 2020: Ocean Beach, Tasmania: A swell-dominated shoreline reaches climate-induced recessional tipping point? *Marine Geology*, **419**, 106081, doi:10.1016/j.margeo.2019.106081.
Shaw, J., C. Danese and L. Stocker, 2013: Spanning the boundary between climate science and coastal communities: Opportunities and challenges. *Ocean Coast. Manag.*, **86**, 80-87, doi:10.1016/j.ocecoaman.2012.11.008.
Shearer, H., 2011: Using Geographic Information Systems to explore the determinants of household water consumption and response to the Queensland Government demand-side policy measures imposed during the drought of 2006-2008. In: *5th State of Australian Cities National Conference*, 2011 [Whitzman, C. and R. Fincher (eds.)], Melbourne Organizing Committee and State of Australian Cities Conference Research Network (SOACRN).
Sheng, Y. and X. Xu, 2019: The productivity impact of climate change: Evidence from Australia's Millennium drought. *Econ. Model.*, **76**, 182-191, doi:10.1016/j.econmod.2018.07.031.
Shepherd, J. and K. van Vuuren, 2014: The Brisbane flood: CALD gatekeepers' risk communication role. *Disaster Prevention and Management*, **23** (4), 469-483.
Sheppard, C. S. and M. C. Stanley, 2014: Does Elevated Temperature and Doubled CO2 Increase Growth of Three Potentially Invasive Plants? *Invasive Plant Sci. Manage.*, **7** (2), 237-246, doi:10.1614/ipsm-d-13-00038.1.
Shoo, L. P. et al., 2014: Moving beyond the conceptual: specificity in regional climate change adaptation actions for biodiversity in South East Queensland, Australia. *Regional Environ. Change*, **14** (2), 435-447, doi:10.1007/s10113-012-0385-3.
Siebentritt, M., N. Halsey and M. Stafford Smith, 2014: *Regional Climate Change Adaptation Plan for the Eyre Peninsula*. Eyre Peninsula Integrated Climate Change Agreement Committee: South Australia. http://nrmrain.org.au/2015/07/applied-adaptation-pathways-on-the-eyre-peninsula-south-australia%e2%80%a8/.
Silva, D. P. et al., 2018: No deaths in the desert: Predicted responses of an arid-adapted bee and its two nesting trees suggest resilience in the face of warming climates. *Insect Conservation and Diversity*, **11** (5), 449-463, doi:10.1111/icad.12318.
Silva, L. G. M. et al., 2020: Mortality events resulting from Australia's catastrophic fires threaten aquatic biota. *Global Change Biology*, doi:10.1111/gcb.15282.
Simon, K., G. Diprose and A. C. Thomas, 2020: Community-led initiatives for climate adaptation and mitigation. *Kōtuitui: New Zealand Journal of Social Sciences Online*, **15** (1), 93-105, doi:10.1080/1177083x.2019.1652659.
Simpson, N. P. et al., 2021: A framework for complex climate change risk assessment. *One Earth*, **4** (4), 489-501, doi:10.1016/j.oneear.2021.03.005.
Sinclair, K., A. Rawluk, S. Kumar and A. Curtis, 2017: Ways forward for resilience thinking: lessons from the field for those exploring social-ecological systems in agriculture and natural resource management. *Ecol. Soc.*, **22** (4), doi:10.5751/ES-09705-220421.
Singels, A. et al., 2014: Predicting Climate Change Impacts on Sugarcane Production at Sites in Australia, Brazil and South Africa Using the Canegro Model. *Sugar Tech*, **16** (4), 347-355, doi:10.1007/s12355-013-0274-1.
Singh-Peterson, L., P. Salmon, C. Baldwin and N. Goode, 2015: Deconstructing the concept of shared responsibility for disaster resilience: a Sunshine Coast case study, Australia. *Natural Hazards*, **79** (2), 755-774, doi:10.1007/s11069-015-1871-y.
Singh, C. et al., 2020: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Climatic Change*, **162** (2), 255-277, doi:10.1007/s10584-020-02762-x.
Singh, S., E. G. Hanna and T. Kjellstrom, 2015: Working in Australia's heat: health promotion concerns for health and productivity. *Health Promot. Int.*, **30** (2), 239-250, doi:10.1093/heapro/dat027.
Skegg, D. C. and P. C. Hill, 2021: Defining covid-19 elimination. *BMJ*, **374**, n1794, doi:10.1136/bmj.n1794.
Slatyer, R., 2010: Climate change impacts on Australia's alpine ecosystems. *ANU Undergraduate Research Journal*, **2**, doi:10.22459/aurj.02.2010.05.
Smale, D. A. et al., 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9** (4), 306-312, doi:10.1038/s41558-019-0412-1.
Smith, E. F., S. N. Lieske, N. Keys and T. F. Smith, 2018: The socio-economic vulnerability of the Australian east coast grazing sector to the impacts of climate change. *Regional Environ. Change*, **18** (4), 1185-1199, doi:10.1007/s10113-017-1251-0.
Smith, H. et al., 2017: *Adaptation Strategies to Address Climate Change Impacts on Coastal Māori Communities in Aotearoa New Zealand: A Case Study of Dairy Farming in the Horowhenua- Kāpiti Coastal Zone*. Massey University, 140 [Available at: https://drive.google.com/file/d/1BLzuGU9-bpz_p05RMTzYXSUWw3GYzrfF/view?usp=drive_open&usp=embed_facebook].
Smith, K. and G. Lawrence, 2014: Flooding and Security: A Case Study of Community Resilience in Rockhampton. *Rural Society*, 5230-5249, doi:10.5172/rsj.2014.5230.
Smith, K. and G. Lawrence, 2018: From disaster management to adaptive governance? Governance challenges to achieving resilient food systems in Australia. *Journal of Environmental Policy & Planning*, **20** (3), 387-401, doi:10.1080/1523908x.2018.1432344.
Smith, K. A., C. E. Dowling and J. Brown, 2019: Simmered Then Boiled: Multi-Decadal Poleward Shift in Distribution by a Temperate Fish Accelerates During Marine Heatwave. *Frontiers in Marine Science*, **6**, 407, doi:10.3389/fmars.2019.00407.
Smith, M. H., 2013: *Assessing Climate Change Risks and Opportunities for Investors: Oil and Gas Sector*. ANU and Investor Group on Climate Change, unknown, 21 [Available at: http://dx.doi.org/10.13140/RG.2.1.3589.2721].

Smith, T., A. Leitch and D. Thomsen, 2016: *Community Engagement. CoastAdapt Information Manual 9*. National Climate Change Adaptation Research Facility, Gold Coast, Australia.
Smith, T. et al., 2015: Adapting Australian coastal regions to climate change: A case study of South-east Coast Queensland. In: Climate Change and the Coast. CRC Press, 269-284.
Sorensen, J. G., T. N. Kristensen and J. Overgaard, 2016: Evolutionary and ecological patterns of thermal acclimation capacity in Drosophila: is it important for keeping up with climate change? *Current Opinion in Insect Science*, **17**, 98-104, doi:10.1016/j.cois.2016.08.003.
Spector, S., N. A. Cradock-Henry, S. Beaven and C. Orchiston, 2019: Characterising rural resilience in Aotearoa-New Zealand: a systematic review. *Regional Environmental Change*, **19** (2), 543-557, doi:10.1007/s10113-018-1418-3.
Spinoni, J. et al., 2019: A new global database of meteorological drought events from 1951 to 2016. *J Hydrol Reg Stud*, **22**, 100593, doi:10.1016/j.ejrh.2019.100593.
Spurway, K. and K. Soldatic, 2016: Life just keeps throwing lemons": the lived experience of food insecurity among Aboriginal people with disabilities in the West Kimberley. *Local Environ.*, **21** (9), 1118-1131, doi:10.1080/13549839.2015.1073235.
Srinivasan, M. S., D. Bewsell, C. Jongmans and G. Elley, 2017: Just-in-case to justified irrigation: Applying co-innovation principles to irrigation water management. *Outlook Agric.*, **46** (2), 138-145, doi:10.1177/0030727017708491.
State of Tasmania, 2017a: *Climate Action 21: Tasmania's Climate Change Action Plan 2017 - 2021*. Tasmanian Climate Change Office Department of Premier and Cabinet,36 pp.
State of Tasmania, 2017b: *Tasmanian Planning Scheme - State planning provisions*.
Stats NZ, 2016: *National Population Projections: 2016(base)–2068*. Statistics New Zealand, 23.
Stats NZ, 2021: Estimated population of NZ.
Steane, D. A. et al., 2017: Evidence for adaptation and acclimation in a widespread eucalypt of semi-arid Australia. *Biol. J. Linn. Soc. Lond.*, **121** (3), 484-500, doi:10.1093/biolinnean/blw051.
Steffen, W., J. Hunter and L. Hughes, 2014: *Counting the costs: Climate change and coastal flooding*. Climate Council of Australia, 82 [Available at: https://www.climatecouncil.org.au/resources/coastalflooding/].
Steffen, W. et al., 2019: *Compound costs: How climate change is damaging Australia's economy*. Climate Council of Australia, 32 [Available at: https://www.climatecouncil.org.au/wp-content/uploads/2019/05/Costs-of-climate-change-report.pdf].
Steffen, W., A. Stock, D. Alexander and M. Rice, 2017: *Angry summer 2016/17*. Climate Council of Australia L [Available at: https://www.climatecouncil.org.au/resources/angry-summer-report/].
Steiger, R. et al., 2019: A critical review of climate change risk for ski tourism. *null*, **22** (11), 1343-1379, doi:10.1080/13683500.2017.1410110.
Stenhouse, V. et al., 2018: Modelled incubation conditions indicate wider potential distributions based on thermal requirements for an oviparous lizard. *J. Biogeogr.*, **45** (8), 1872-1883, doi:10.1111/jbi.13363.
Stephens, S. A., R. G. Bell and I. D. Haigh, 2020: Spatial and temporal analysis of extreme storm-tide and skew-surge events around the coastline of New Zealand. *Natural Hazards and Earth System Sciences*, **20** (3), 783-796, doi:10.5194/nhess-20-783-2020.
Stephens, S. A., R. G. Bell and J. Lawrence, 2017: Applying Principles of Uncertainty within Coastal Hazard Assessments to Better Support Coastal Adaptation. *J. Mar. Sci. Eng.*, **5** (3), 40, doi:10.3390/jmse5030040.
Stephens, S. A., R. G. Bell and J. Lawrence, 2018: Developing signals to trigger adaptation to sea-level rise. *Environmental Research Letters*, **13** (10), 104004, doi:10.1088/1748-9326/aadf96.
Stephenson, J. et al., 2018: *Communities and climate change: Vulnerability to rising seas and more frequent flooding*. Motu, 21 [Available at: https://www.deepsouthchallenge.co.nz/news-updates/coping-face-climate-change-research-announced-better-support-our-communities].
Stevens, C. and G. O'Connor, 2015: Combined art and science as a communication pathway in a primary school setting: paper and ice. *Journal of Science Communication*, **14** (04), A04, doi:10.22323/2.14040204.
Stevenson, T. et al., 2018: *Transitioning to zero net emissions by 2050: moving to a very low-emissions electricity system in New Zealand*. SAPERE Research Group.
Stewart, E. J. et al., 2016: Implications of climate change for glacier tourism. *Tourism Geographies*, **18** (4), 377-398, doi:10.1080/14616688.2016.1198416.
Stewart, J., M. Anda and R. Harper, 2019: Low-carbon development in remote Indigenous communities: Applying a community-directed model to support endogenous assets and aspirations. *Environ. Sci. Policy*, **95** (95), 11-19.
Stewart, M. and X. Wang, 2011: *Risk Assessment of Climate Adaptation Strategies for Extreme Wind Events in Queensland*. Commonwealth Scientific and Industrial Research Organisation, Csiro [Available at: http://dx.doi.org/10.4225/08/584EE81C22E7B
https://publications.csiro.au/rpr/pub?pid=csiro:EP112958].
Stewart, M. G., 2015: Risk and economic viability of housing climate adaptation strategies for wind hazards in southeast Australia. *Mitigation and Adaptation Strategies for Global Change*, **20** (4), 601-622, doi:10.1007/s11027-013-9510-y.
Stoerk, T., G. Wagner and R. E. T. Ward, 2018: Recommendations for Improving the Treatment of Risk and Uncertainty in Economic Estimates of Climate Impacts in the Sixth Intergovernmental Panel on Climate Change Assessment Report. *Review of Environmental Economics and Policy*, **12** (2).

Stone, G., R. Dalla Pozza, J. Carter and G. McKeon, 2019: Long Paddock: climate risk and grazing information for Australian rangelands and grazing communities. *The Rangeland Journal*, **41** (3), 225, doi:10.1071/rj18036.
Storey, B. and I. Noy, 2017: Insuring property under climate change. *Policy Quarterly*, **13** (4), doi:10.26686/pq.v13i4.4603.
Stroombergen, A., A. Tait, J. Renwick and K. Patterson, 2006: The relationship between New Zealand's climate, energy, and the economy in 2025. *New Zealand Journal of Social Sciences Online*, **1**, 139-160.
Strydom, S. et al., 2020: Too hot to handle: Unprecedented seagrass death driven by marine heatwave in a World Heritage Area. *Glob. Chang. Biol.*, **26** (6), 3525-3538, doi:10.1111/gcb.15065.
Stuart-Smith, R. D., C. J. Brown, D. M. Ceccarelli and G. J. Edgar, 2018: Ecosystem restructuring along the Great Barrier Reef following mass coral bleaching. *Nature*, **560** (7716), 92-96, doi:10.1038/s41586-018-0359-9.
Sultana, S. et al., 2017: Potential impacts of climate change on habitat suitability for the Queensland fruit fly. *Sci. Rep.*, **7** (1), doi:10.1038/s41598-017-13307-1.
Sultana, S. et al., 2020: Impacts of climate change on high priority fruit fly species in Australia. *PLOS ONE*, **15** (2), e0213820, doi:10.1371/journal.pone.0213820.
Sunday, J. M. et al., 2015: Species traits and climate velocity explain geographic range shifts in an ocean-warming hotspot. *Ecol. Lett.*, **18** (9), 944-953, doi:10.1111/ele.12474
10.1111/ele.12474. Epub 2015 Jul 20.
Sutton, P. J. H. and M. Bowen, 2019: Ocean temperature change around New Zealand over the last 36 years. *N. Z. J. Mar. Freshwater Res.*, 1-22, doi:10.1080/00288330.2018.1562945.
Swales, E. A., R. G. Bell and A. Lohrer, 2020: Estuaries and Lowland Brackish Habitats. In: Coastal Systems and Sea Level Rise: What to Look for in Future [C. Hendtlass, S. Morgan and D. Neale (eds.)]. NZ Coastal Society, 55-64.
Swann, T. and R. Campbell, 2016: *Great Barrier Bleached: Coral bleaching, the Great Barrier Reef and potential impacts on tourism*. Australia Institute.
Swiss Re, 2021: *The economics of climate change: no action not an option*. Swiss Re Management Institute, 30 [Available at: https://www.swissre.com/dam/jcr:e73ee7c3-7f83-4c17-a2b8-8ef23a8d3312/swiss-re-institute-expertise-publication-economics-of-climate-change.pdf].
Tait, A. and P. Pearce, 2019: Impacts and implications of climate change on Waituna Lagoon, Southland. *Sci. Conserv.*
Tait, A. et al., 2016: *Overall CCII Project. Synthesis Report. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100*. 24 [Available at: https://ccii.org.nz/app/uploads/2017/07/Overall-CCII-Project-synthesis-report1.pdf].
Tan, P.-L., D. George and M. Comino, 2015: Cumulative risk management, coal seam gas, sustainable water, and agriculture in Australia. *International Journal of Water Resources Development*, **31** (4), 682-700, doi:10.1080/07900627.2014.994593.
Tangney, P., 2019: Between conflation and denial – the politics of climate expertise in Australia. *Australian Journal of Political Science*, **54** (1), 131-149, doi:10.1080/10361146.2018.1551482.
Tangney, P. and M. Howes, 2016: The politics of evidence-based policy: A comparative analysis of climate adaptation in Australia and the UK. *Environment and Planning C: Government and Policy*, **34** (6), 1115-1134, doi:10.1177/0263774x15602023.
Tanner-McAllister, S. L., J. Rhodes and M. Hockings, 2017: Managing for climate change on protected areas: An adaptive management decision making framework. *J. Environ. Manage.*, **204** (Pt 1), 510-518, doi:10.1016/j.jenvman.2017.09.038.
TAO, 2020: *Sustainable Finance Forum: Roadmap for Action*. The Aotearoa Circle [Available at: https://static1.squarespace.com/static/5bb6cb19c2ff61422a0d7b17/t/5f9f7a83aa6e763a1b0f6759/1604287127400/20207-000234_Sustainable+Finance+Forum+Final.pdf].
Tapper, N., A. Coutts, M. Loughnan and D. Pankhania, 2014: Urban populations' vulnerability to climate extremes: mitigating urban heat through technology and water-sensitive urban design. In: Low carbon cities: Transforming urban systems [Lehmann, S. (ed.)]. Routledge, United Kingdom, 361-374.
Tapper, N. J., In Press: Creating Cooler, Healthier and More Liveable Australian Cities Using Irrigated Green Infrastructure. In: Urban Climate Science for Planning Healthy Cities [Ren, C. and G. McGregor (eds.)]. Springer.
Tasmanian Climate Change Office, 2012: *Coastal Adaptation Pathways. Developing Coastal Adaptation Pathways with Local Communities.* . [Available at: http://www.dpac.tas.gov.au/__data/assets/pdf_file/0017/229130/Example_Interim_Local_Area_Report_Coastal_module_3.PDF].
Tausz, M. et al., 2017: Can additional N fertiliser ameliorate the elevated CO2 -induced depression in grain and tissue N concentrations of wheat on a high soil N background? *Journal of Agronomy and Crop Science*, **203** (6), 574-583, doi:10.1111/jac.12209.
Taylor, C. et al., 2018: Trends in wheat yields under representative climate futures: Implications for climate adaptation. *Agric. Syst.*, **164**, 1-10.
Taylor, K. S., B. J. Moggridge and A. Poelina, 2017: Australian Indigenous Water Policy and the impacts of the ever-changing political cycle. *Australasian Journal of Water Resources*, **20** (2), 132-147, doi:10.1080/13241583.2017.1348887.

Taylor, M. A. P. and M. L. Philp, 2015: Investigating the impact of maintenance regimes on the design life of road pavements in a changing climate and the implications for transport policy. *Transp. Policy*, **41**, 117-135, doi:10.1016/j.tranpol.2015.01.005.
TCFD, 2017: *Recommendations of the Task Force on Climate-related Financial Disclosures*. Task Force on Climate-related Financial Disclosures, 74 [Available at: https://www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-2017-TCFD-Report-11052018.pdf].
Te Urunga Kea - Te Arawa Climate Change Working Group, 2021: *Te Ara ki Kōpū: Te Arawa Climate Change Strategy*. Te Arawa Lakes Trust, Rotorua, Aotearoa-New Zealand, 8 [Available at: https://tearawa.iwi.nz/seeking-feedback-on-our-draft-te-arawa-climate-change-strategy/].
Teagle, H., D. A. Smale and D. Schoeman, 2018: Climate-driven substitution of habitat-forming species leads to reduced biodiversity within a temperate marine community. *Diversity and Distributions*, **24** (10), 1367-1380, doi:10.1111/ddi.12775.
Temby, O., J. Sandall, R. Cooksey and G. M. Hickey, 2016: How do civil servants view the importance of collaboration and scientific knowledge for climate change adaptation? *Australasian Journal of Environmental Management*, **23** (1), 5-20, doi:10.1080/14486563.2015.1028111.
Teng, J. et al., 2012: Estimation of Climate Change Impact on Mean Annual Runoff across Continental Australia Using Budyko and Fu Equations and Hydrological Models. *Journal of Hydrometeorology*, **13** (3), 1094-1106, doi:10.1175/jhm-d-11-097.1.
Thamo, T. et al., 2017: Dynamics and the economics of carbon sequestration: common oversights and their implications. *Mitig Adapt Strateg Glob Change*, **22** (7), 1095-1111, doi:10.1007/s11027-016-9716-x.
Thi Tran, L., N. Stoeckl, M. Esparon and D. Jarvis, 2016: If climate change means more intense and more frequent drought, what will that mean for agricultural production? A case study in Northern Australia. *Australasian Journal of Environmental Management*, **23** (3), 281-297, doi:10.1080/14486563.2016.1152202.
Thompson, J. A., 2016: A MODIS-derived snow climatology (2000-2014) for the Australian Alps. *Climate Research*, **68** (1), 25-38, doi:10.3354/cr01379.
Thomsen, M. S. et al., 2019: Local Extinction of Bull Kelp (Durvillaea spp.) Due to a Marine Heatwave. *Frontiers in Marine Science*, **6**, 84, doi:10.3389/fmars.2019.00084.
Thomson, J. A. et al., 2015: Extreme temperatures, foundation species, and abrupt ecosystem change: an example from an iconic seagrass ecosystem. *Glob. Chang. Biol.*, **21** (4), 1463-1474, doi:http://dx.doi.org/10.1111/gcb.12694.
TIA, 2019: *Tourism 2025 and Beyond: A Sustainable growth framework. Kaupapa Whakapakari Ta-Poi*. Tourism Industry Aotearoa, 24 [Available at: https://tia.org.nz/assets/Uploads/d5156c4126/Tourism2025-and-Beyond.pdf].
Timbal, B. and H. Hendon, 2011: The role of tropical modes of variability in recent rainfall deficits across the Murray-Darling Basin. *Water Resources Research*, **47** (12), doi:10.1029/2010wr009834.
Tobler, R. et al., 2017: Aboriginal mitogenomes reveal 50,000 years of regionalism in Australia. *Nature*, **544** (7649), 180-184, doi:10.1038/nature21416.
Tolhurst, K. G. and G. McCarthy, 2016: Effect of prescribed burning on wildfire severity: a landscape-scale case study from the 2003 fires in Victoria. *Australian Forestry*, **79** (1), 1-14, doi:10.1080/00049158.2015.1127197.
Tombs, D and B. France-Hudson, 2018: Climate change compensation. *Policy Quarterly*, **14** (4), 50-56.
Tompkins, D. M., A. E. Byrom and R. P. Pech, 2013: Predicted responses of invasive mammal communities to climate-related changes in mast frequency in forest ecosystems. *Ecol. Appl.*, **23** (5), 1075-1085.
Tonmoy, F. N., S. M. Cooke, F. Armstrong and D. Rissik, 2020: From science to policy: Development of a climate change adaptation plan for the health and wellbeing sector in Queensland, Australia. *Environmental Science & Policy*, **108**, 1-13, doi:10.1016/j.envsci.2020.03.005.
Tonmoy, F. N. and A. El-Zein, 2018: Vulnerability to sea level rise: A novel local-scale indicator-based assessment methodology and application to eight beaches in Shoalhaven, Australia. *Ecological Indicators*, **85**, 295-307, doi:10.1016/j.ecolind.2017.10.010.
Tonmoy, F. N., D. Rissik and J. P. Palutikof, 2019: A three-tier risk assessment process for climate change adaptation at a local scale. *Clim. Change*, doi:10.1007/s10584-019-02367-z.
Tonmoy, F. N., D. Wainwright, D. C. Verdon-Kidd and D. Rissik, 2018: An investigation of coastal climate change risk assessment practice in Australia. *Environmental Science & Policy*, **80**, 9-20, doi:10.1016/j.envsci.2017.11.003.
Torabi, E., A. Dedekorkut-Howes and M. Howes, 2018: Adapting or maladapting: Building resilience to climate-related disasters in coastal cities. *Cities*, **72**, 295-309, doi:10.1016/j.cities.2017.09.008.
Torabi, E., A. Dedekorkut-Howes and M. Howes, 2021: A framework for using the concept of urban resilience in responding to climate-related disasters. *Urban Research & Practice*, 1-23, doi:10.1080/17535069.2020.1846771.
Tozer, C. R., D. C. Verdon-Kidd and A. S. Kiem, 2014: Temporal and spatial variability of the cropping limit in South Australia. *Climate Research*, **60** (1), 25-34, doi:10.3354/cr01218.
Tracey, D. and F. Hjorvarsdottir, 2019: *The state of knowledge of deep-sea corals in the New Zealand region*. NIWA Science and Technology Series, 140 [Available at: https://niwa.co.nz/sites/niwa.co.nz/files/Deepsea-corals-NZ-2019-NIWA-SciTechSeries-84.pdf].
Trancoso, R. et al., 2020: Heatwaves intensification in Australia: A consistent trajectory across past, present and future. *Sci. Total Environ.*, **742**, 140521, doi:10.1016/j.scitotenv.2020.140521.

Transpower, 2020: *Whakamana i Te Mauri Hiko – empowering our energy future*. Transpower, 89 [Available at: https://www.transpower.co.nz/sites/default/files/publications/resources/TP%20Whakamana%20i%20Te%20Mauri%20Hiko.pdf].
Trębicki, P. et al., 2015: Virus disease in wheat predicted to increase with a changing climate. **21** (9), 3511-3519.
Trewin, B. et al., 2020: An updated long-term homogenized daily temperature data set for Australia. *Geoscience Data Journal*, **7** (2), 149-169, doi:10.1002/gdj3.95.
Trivedi, N. S., M. S. Venkatraman, C. Chu and I. S. Cole, 2014: Effect of climate change on corrosion rates of structures in Australia. *Clim. Change*, **124** (1), 133-146, doi:10.1007/s10584-014-1099-y.
Troccoli, A. et al., 2012: Long-Term Wind Speed Trends over Australia. *Journal of Climate*, **25** (1), 170-183, doi:10.1175/2011jcli4198.1.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8** (5), e476, doi:10.1002/wcc.476.
Tschakert, P. et al., 2016: Micropolitics in collective learning spaces for adaptive decision making. *Glob. Environ. Change*, **40**.
TSRA, 2014: *Torres Strait Climate Change Strategy 2014-2018*. Land and Sea Management Unit, Torres Strait Regional Authority,36 pp.
TSRA, 2016: *Torres Strait Regional Adaptation and Resilience Plan 2016-2021*. Environmental Management Program, Torres Strait Regional Authority,108 pp.
TSRA, 2018: *Torres Strait Climate Change and Health – First Pass Risk Assessment*. Prepared by BMT Global for the Environmental Management Program, Torres Strait Regional Authority, Thursday Island, Queensland.
Tuckett, C. A., T. de Bettignies, J. Fromont and T. Wernberg, 2017: Expansion of corals on temperate reefs: direct and indirect effects of marine heatwaves. *Coral Reefs*, **36** (3), 947-956, doi:10.1007/s00338-017-1586-5.
Turton, S. M., 2014: Climate change and rainforest tourism in Australia. In: Rainforest Tourism, Conservation and Management: challenges for sustainable development [Prideaux, B. (ed.)]. Routledge, New York, NY USA, 70-86.
Turton, S. M., 2017: Expansion of the tropics: revisiting frontiers of geographical knowledge. *Geographical Research*, **55** (1), 3-12, doi:10.1111/1745-5871.12230.
Ukkola, A. M. et al., 2016: Reduced streamflow in water-stressed climates consistent with CO2 effects on vegetation. *Nature Climate Change*, **6** (1), 75-78, doi:10.1038/nclimate2831.
Ululru Statement, 2017: Uluru Statement from the Heart.
UN, 2018: Indigenous Peoples Disproportionately Impacted by Climate Change, Systematically Targeted for Defending Freedoms, Speakers Tell Permanent Forum.
UN, ADB and UNDP, 2018: *Transformation Towards Sustainable and Resilient Societies in Asia and the Pacific*. United Nations, Asian Development Bank, United Nations Development Programme, Escap, U. N., 65 [Available at: https://play.google.com/store/books/details?id=ZeIBugEACAAJ
http://dx.doi.org/10.22617/TCS189274-2
https://reliefweb.int/sites/reliefweb.int/files/resources/SDG_Resilience_Report.pdf].
UN DESA, 2019: World Urbanization Prospects. United Nations Department of Economic & Social Affairs.
UNEP, 2020: *Emissions Gap Report 2020*. United Nations Environment Programme (UNEP), United Nations Environment, P. and U. D. Partnership, 101 [Available at: https://www.unep.org/emissions-gap-report-2020].
UNESCO. Great Barrier Reef. [Available at: https://whc.unesco.org/en/list/154/]
Uthicke, S. et al., 2015: Outbreak of coral-eating Crown-of-Thorns creates continuous cloud of larvae over 320 km of the Great Barrier Reef. *Sci Rep*, **5**, 16885, doi:10.1038/srep16885.
van Dijk, A. I. J. M. et al., 2013: The Millennium Drought in southeast Australia (2001-2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research*, **49** (2), 1040-1057, doi:10.1002/wrcr.20123.
van Leeuwen, C. and P. Darriet, 2016: The Impact of Climate Change on Viticulture and Wine Quality. *Journal of Wine Economics*, **11** (1), 150-167, doi:10.1017/jwe.2015.21.
van Oldenborgh, G. J. et al., 2021: Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences*, **21** (3), 941-960, doi:10.5194/nhess-21-941-2021.
van Wettere, W. H. E. J. et al., 2021: Review of the impact of heat stress on reproductive performance of sheep. *J. Anim. Sci. Biotechnol.*, **12** (1), 26, doi:10.1186/s40104-020-00537-z.
Vardoulakis, S. et al., 2020: Bushfire smoke: urgent need for a national health protection strategy. *Med. J. Aust.*, doi:10.5694/mja2.50511.
Vargo, L. J. et al., 2020: Anthropogenic warming forces extreme annual glacier mass loss. *Nat. Clim. Chang.*, **10** (9), 856-861, doi:10.1038/s41558-020-0849-2.
Vaze, J. et al., 2010: Climate non-stationarity – Validity of calibrated rainfall–runoff models for use in climate change studies. *Journal of Hydrology*, **394** (3-4), 447-457, doi:10.1016/j.jhydrol.2010.09.018.
Vergés, A. et al., 2016: Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. *Proc. Natl. Acad. Sci. U. S. A.*, **113** (48), 13791-13796, doi:10.1073/pnas.1610725113.

Vermeulen, S. J. et al., 2018: Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change. *Frontiers in Sustainable Food Systems*, **2**, 65, doi:10.3389/fsufs.2018.00065.
Vertessy, R. A., 2013: Water information services for Australians. *Australian Journal of Water Resources*, **16**, 15.
Vertessy, R. V. et al., 2019: *Final Report of the Independent Assessment of the 2018-19 Fish Deaths in the Lower Darling*. Independent panel for the Australian Government, 99 [Available at: https://www.mdba.gov.au/sites/default/files/pubs/Final-Report-Independent-Panel-fish-deaths-lower%20Darling_4.pdf].
Vicedo-Cabrera, A. M. et al., 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Chang.*, **11** (6), 492-500, doi:10.1038/s41558-021-01058-x.
Victoria State Government DELWP, 2016: *Victoria's Climate Change Adaptation Plan 2017-2020*. Victoria State Government DELWP, Melbourne.
Victorian Council of Social Service, 2016: *Easing the crisis: Reducing risks for people experiencing homelessness in disasters and emergency events*. VCOSS, 20 [Available at: https://drive.google.com/file/d/1zQoTd6OhTg6Em5ti2RuL7eYQqRNGxUDl/view?usp=drive_open&usp=embed_facebook].
Virgilio, G. D. et al., 2019: Climate Change Increases the Potential for Extreme Wildfires. *Geophysical Research Letters*, **46** (14), 8517-8526, doi:10.1029/2019gl083699.
Virgilio, G. D. et al., 2020: Realised added value in dynamical downscaling of Australian climate change. doi:10.5194/egusphere-egu21-3855.
Vose, R. S. and S. Applequist, 2014: Monitoring and Understanding Changes in Extremes: Extratropical Storms, Winds, and Waves. *Bull. Am. Meteorol. Soc.*, **95**, 377-386.
WA Government, 2012: *Adapting to our changing climate*. Government of Western Australia, Department of Environment and Conservation, 12 [Available at: https://www.der.wa.gov.au/images/documents/your-environment/climate-change/adapting-to-our-changing-climate-october-2012.pdf].
WA Government, 2016: *Water for Growth: Urban - Western Australia's water supply and demand outlook to 2050*. Government of Western Australia, Department of Water, 25 [Available at: https://www.water.wa.gov.au/__data/assets/pdf_file/0016/8521/110200.pdf].
WAGA, 2020: How well are we adapting: How are Victorian councils responding to climate Change?
Wahl, M. et al., 2015: The responses of brown macroalgae to environmental change from local to global scales: direct versus ecologically mediated effects. *Perspectives in Phycology*, **2** (1), 11-29, doi:10.1127/pip/2015/0019.
Waitaki District Council, 2020: Lake Ohau fire one week on.
Walker, S., A. Monks and J. Innes, 2019: Thermal squeeze will exacerbate declines in New Zealand's endemic forest birds. *Biol. Conserv.*, **237**, 166-174, doi:10.1016/j.biocon.2019.07.004.
Walker, S., D. Stuart-Fox and M. R. Kearney, 2015: Has contemporary climate change played a role in population declines of the lizard Ctenophorus decresii from semi-arid Australia? *J. Therm. Biol.*, **54**, 66-77.
Wallace, J., N. Waltham, D. Burrows and D. McJannet, 2015: The temperature regimes of dry-season waterholes in tropical northern Australia: potential effects on fish refugia. *Freshw. Sci.*, **34** (2), 663-678.
Wallace, K. J. and B. D. Clarkson, 2019: Urban forest restoration ecology: a review from Hamilton, New Zealand. *null*, **49** (3), 347-369, doi:10.1080/03036758.2019.1637352.
Waller, N. L. et al., 2017: The Bramble Cay melomys Melomys rubicola (Rodentia: Muridae): a first mammalian extinction caused by human-induced climate change? *Wildl. Res.*, **44**, 9-21, doi:10.1071/WR16157.
Walsh, K. et al., 2016: Natural hazards in Australia: storms, wind and hail. *Clim. Change*, **139**, doi:DOI 10.1007/s10584-016-1737-7.
Walters, G. and L. Ruhanen, 2015: From White to Green. *Journal of Hospitality & Tourism Research*, **39** (4), 517-539, doi:10.1177/1096348013491603.
Wang, B. et al., 2018a: Australian wheat production expected to decrease by the late 21st century. *Global Change Biology*, **24** (6), 2403-2415, doi:10.1111/gcb.14034.
Wang, C.-H. et al., 2016: Rising tides: adaptation policy alternatives for coastal residential buildings in Australia. *Struct. Infrastruct. Eng.: Maint. Manage. Life-Cycle Des. Perform.*, **12** (4), 463-476, doi:10.1080/15732479.2015.1020500.
Wang, C.-H., Y. B. Khoo and X. Wang, 2015: Adaptation benefits and costs of raising coastal buildings under storm-tide inundation in South East Queensland, Australia. *Climatic Change*, **132** (4), 545-558, doi:10.1007/s10584-015-1454-7.
Wang, J. et al., 2018b: Vulnerability of Ecological Condition to the Sequencing of Wet and Dry Spells Prior to and during the Murray-Darling Basin Millennium Drought. *Journal of Water Resources Planning and Management*, **144** (8), doi:10.1061/(asce)wr.1943-5452.0000963.
Wang, S.-J. and L.-Y. Zhou, 2019: Integrated impacts of climate change on glacier tourism. *Advances in Climate Change Research*, **10**, 71-79.
Wang, X., D. Chen and Z. Ren, 2010: Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Build. Environ.*, **45**, 1663-1982, doi:10.1016/j.buildenv.2010.01.022.
Ward, M. et al., 2020: Impact of 2019-2020 mega-fires on Australian fauna habitat. *Nat Ecol Evol*, doi:10.1038/s41559-020-1251-1.

Wardell-Johnson, G. W., M. Calver, N. Burrows and G. Di Virgilio, 2015: Integrating rehabilitation, restoration and conservation for a sustainable jarrah forest future during climate disruption. *Pac. Conserv. Biol.*, **21** (3), 175-185.
Ware, D. and Z. Banhalmi-Zakar, 2020: Strategies for governments to help close the coastal adaptation funding gap. *Ocean Coast. Manag.*, **198**, 105223, doi:10.1016/j.ocecoaman.2020.105223.
Ware, D. et al., 2020: Using Historical Responses to Shoreline Change on Australia's Gold Coast to Estimate Costs of Coastal Adaptation to Sea Level Rise. *J. Mar. Sci. Eng.*, **8** (6), 380.
Warmenhoven, T. et al., 2014: *Climate Change and Community Resilience in the Waiapu Catchment*. MPI,76 pp.
Warner, K. et al., 2019: Cross-Chapter Box 10: Economic dimensions of climate change and land. In: Special Report on Climate Change and Land [IPCC (ed.)].
Warner, K., Z. Zommers and A. Wreford, 2020: The Real Economic Dimensions of Climate Change. *J. of Extr. Even.*, **07** (03), 2131001, doi:10.1142/S2345737621310011.
Warnken, J. and R. Mosadeghi, 2018: Challenges of implementing integrated coastal zone management into local planning policies, a case study of Queensland, Australia. *Marine Policy*, **91**, 75-84, doi:10.1016/j.marpol.2018.01.031.
Warren-Myers, G., A. Hurlimann and J. Bush, 2020a: Advancing capacity to adapt to climate change: addressing information needs in the Australian property industry. *Journal of European Real Estate Research*, **ahead-of-print** (ahead-of-print), doi:10.1108/JERER-03-2020-0017.
Warren-Myers, G., A. Hurlimann and J. Bush, 2020b: Barriers to climate change adaption in the Australian property industry. *Journal of Property Investment & Finance*, **38** (5), 449-462, doi:10.1108/jpif-12-2019-0161.
Wasko, C. and R. Nathan, 2019: Influence of changes in rainfall and soil moisture on trends in flooding. *Journal of Hydrology*, **575**, 432-441, doi:10.1016/j.jhydrol.2019.05.054.
Wasko, C. and A. Sharma, 2015: Steeper temporal distribution of rain intensity at higher temperatures within Australian storms. *Nature Geoscience*, **8** (7), 527-529, doi:10.1038/ngeo2456.
Wasko, C., A. Sharma and S. Westra, 2016: Reduced spatial extent of extreme storms at higher temperatures. *Geophysical Research Letters*, **43** (8), 4026-4032, doi:10.1002/2016gl068509.
WaterNz, 2018: *National Performance Review 2018-2019*. Water New Zealand, 80 [Available at: https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=4271].
Waters, E. and J. Barnett, 2018: Spatial imaginaries of adaptation governance: A public perspective. *Environment and Planning C: Politics and Space*, **36** (4), 708-725, doi:10.1177/2399654417719557.
Waters, E., J. Barnett and A. Puleston, 2014: Contrasting perspectives on barriers to adaptation in Australian climate change policy. *Climatic Change*, **124** (4), 691-702, doi:10.1007/s10584-014-1138-8.
Watson, P. J., 2020: Updated Mean Sea-Level Analysis: Australia. *Journal of Coastal Research*, **36** (5), 915, doi:10.2112/jcoastres-d-20-00026.1.
Watson, S. A. et al., 2018: Ocean warming has a greater effect than acidification on the early life history development and swimming performance of a large circumglobal pelagic fish. *Glob. Chang. Biol.*, doi:http://dx.doi.org/10.1111/gcb.14290.
Watt, M. S. et al., 2019: Assessment of multiple climate change effects on plantation forests in New Zealand. *Forestry: An International Journal of Forest Research*, **92(1)**, 1-15, doi:https://doi.org/10.1093/forestry/cpy024.
Webb, L. et al., 2014: Effect of ambient temperature on Australian northern territory public hospital admissions for cardiovascular disease among indigenous and non-indigenous populations. *Int. J. Environ. Res. Public Health*, **11** (2), 1942-1959, doi:10.3390/ijerph110201942.
Webb, L., R. Darbyshire, T. Erwin and I. Goodwin, 2017: A robust impact assessment that informs actionable climate change adaptation: future sunburn browning risk in apple. *Int. J. Biometeorol.*, **61** (5), 891-901, doi:10.1007/s00484-016-1268-y.
Webb, L. B. and K. Hennessy, 2015: *Climate change in Australia: Projections for selected Australian cities*. CSIRO and Bureau of Meteorology, Australia.
Webb, R. et al., 2019: Co-designing adaptation decision support: meeting common and differentiated needs. *Climatic Change*, **153** (4), 569-585, doi:10.1007/s10584-018-2165-7.
Weeks, E. S. et al., 2016: Conservation Science Statement. the demise of New Zealand's freshwater flora and fauna: A forgotten treasure. *Pac. Conserv. Biol.*, **22** (2), 110-115, doi:10.1071/PC15038.
Wen, J., T. Ying, D. Nguyen and S. Teo, 2020: Will tourists travel to post-disaster destinations? A case of 2019 Australian bushfires from a Chinese tourists' perspective. *Tourism Recreation Research*, **45** (3), 420-424, doi:10.1080/02508281.2020.1763025.
Wenger, C., 2017: The oak or the reed: how resilience theories are translated into disaster management policies. *Ecology and Society*, **22** (3), doi:10.5751/es-09491-220318.
Wernberg, T. et al., 2016: Climate-driven regime shift of a temperate marine ecosystem. *Science*, **353** (6295), 169-172, doi:10.1126/science.aad8745
10.1126/science.aad8745.
Westra, S. and S. A. Sisson, 2011: Detection of non-stationarity in precipitation extremes using a max-stable process model. *Journal of Hydrology*, **406** (1-2), 119-128, doi:10.1016/j.jhydrol.2011.06.014.
Wheeler, S., D. Garrick, A. Loch and H. Bjornlund, 2013: Evaluating water market products to acquire water for the environment in Australia. *Land use policy*, **30** (1), 427-436, doi:10.1016/j.landusepol.2012.04.004.

Wheeler, S. A., A. Zuo and A. Loch, 2018: Water torture: Unravelling the psychological distress of irrigators in Australia. *Journal of Rural Studies*, **62**, 183-194, doi:10.1016/j.jrurstud.2018.08.006.
Whetton, P. and F. Chiew, 2020: Climate Change in the Murray-Darling Basin. In: Murray-Darling Basin, Australia – Its Future Management [al, B. H. e. (ed.)]. Elsevier, 253-274.
White, C. J. et al., 2016a: *Tasmania's State Natural Disaster Risk Assessment*. University of Tasmania, Hobart, 191 [Available at: http://climatefutures.org.au/wp-content/uploads/2016/07/TSNDRA-2016.pdf].
White, I. and J. Lawrence, 2020: Continuity and change in national riskscapes: a New Zealand perspective on the challenges for climate governance theory and practice. *Cambridge Journal of Regions, Economy and Society*, doi:10.1093/cjres/rsaa005.
White, I. and P. O'Hare, 2014: From Rhetoric to Reality: Which Resilience, Why Resilience, and Whose Resilience in Spatial Planning? *Environment and Planning C: Government and Policy*, **32** (5), 934-950, doi:10.1068/c12117.
White, R. S. A., P. A. McHugh and A. R. McIntosh, 2016b: Drought survival is a threshold function of habitat size and population density in a fish metapopulation. *Glob. Chang. Biol.*, **22** (10), 3341-3348, doi:10.1111/gcb.13265.
White, R. S. A. et al., 2017: The scaling of population persistence with carrying capacity does not asymptote in populations of a fish experiencing extreme climate variability. *Proc. Biol. Sci.*, **284** (1856), doi:10.1098/rspb.2017.0826.
Whittenbury, K., 2013: Climate Change, Women's Health, Wellbeing and Experiences of Gender Based Violence in Australia. *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change*, 207-221, doi:10.1007/978-94-007-5518-5_15.
Whittle, L., 2019: Snapshot of Australia's Forest industry.
Williams, M. N., S. R. Hill and J. Spicer, 2016: Do hotter temperatures increase the incidence of self-harm hospitalisations? *Psychol. Health Med.*, **21** (2), 226-235, doi:10.1080/13548506.2015.1028945.
Williams, R. J. et al., 2015: An International Union for the Conservation of Nature Red List ecosystems risk assessment for alpine snow patch herbfields, South-Eastern Australia. *Austral Ecology*, **40** (4), 433-443, doi:10.1111/aec.12266.
Williams, S. E. et al., 2020: Research priorities for natural ecosystems in a changing global climate. *Global Change Biology*, **26** (2), 410-416, doi:10.1111/gcb.14856.
Wilson, S. et al., 2013: Separating Adaptive Maintenance (Resilience) and Transformative Capacity of Social-Ecological Systems. *Ecol. Soc.*, **18** (1), doi:10.5751/ES-05100-180122.
Wilson, S. and G. Swan, 2017: *A Complete Guide to Reptiles of Australia*. Reed New Holland, 560 pp.
Wintle, B. A., S. Legge and J. C. Z. Woinarski, 2020: After the Megafires: What Next for Australian Wildlife? *Trends Ecol. Evol.*, **35** (9), 753-757, doi:10.1016/j.tree.2020.06.009.
Wiseman, N. and D. Bardsley, 2016: Monitoring to learn, learning to monitor: a critical analysis of opportunities for Indigenous community-based monitoring of environmental change in Australian rangelands. *Geographical Research*, **54** (1), 52-71.
Wohling, M., 2009: The problem of scale in indigenous knowledge: a perspective from northern Australia. *Ecology and Society*, **14** (1).
Wong, T. H. F., N. Tapper, J., and S. P. Luby, 2020: Planetary health approaches for dry cities: water quality and heat mitigation. *British Medical Journal*, **371**, doi:10.1136/bmj.m4313
Woodroffe, C. et al., 2014: A framework for modelling the risks of climate-change impacts on Australian coasts. In: Applied Studies in Climate Adaptation [Palutikof, J. P., S. L. Boulter, J. Barnett and D. Rissik (eds.)]. John Wiley & Sons, Ltd, Chichester, UK, **88**, 181-189.
World Bank, 2018: Urban population.
World Bank, 2019: Urban population (% of total).
World Economic Forum, 2014: Global risks report.
Worth, J. R. P. et al., 2014: Environmental niche modelling fails to predict Last Glacial Maximum refugia: niche shifts, microrefugia or incorrect palaeoclimate estimates? *Glob. Ecol. Biogeogr.*, **23** (11), 1186-1197, doi:10.1111/geb.12239.
Wreford, A., K. Bayne, P. Edwards and A. Renwick, 2019: Enabling a transformation to a bioeconomy in New Zealand. *Environmental Innovation and Societal Transitions*, **31**, 184-199, doi:10.1016/j.eist.2018.11.005.
Wreford, A. et al., 2020: *Robust climate change adaptation decision-making under uncertainty: Real Options Analysis for water storage*. Wellington [Available at: https://deepsouthchallenge.co.nz/].
WSAA, 2016: *Climate Change Adaptation Guidelines*. Water Services Association of Australia, Australia, W. S. A. o., 89.
WTTC, 2018: Travel and tourism: Economic impact 2018 New Zealand.
Wu, W. et al., 2018: Mapping Dependence Between Extreme Rainfall and Storm Surge. *Journal of Geophysical Research: Oceans*, **123** (4), 2461-2474, doi:10.1002/2017jc013472.
Yazd, D. S., S. A. Wheeler and A. Zuo, 2020: Understanding the impacts of water scarcity and socio-economic demographics on farmer mental health in the Murray-Darling Basin. *Ecological Economics*, **169**, 106564, doi:https://doi.org/10.1016/j.ecolecon.2019.106564.
Yazd, S. D., S. A. Wheeler and A. Zuo, 2019: Exploring the Drivers of Irrigator Mental Health in the Murray–Darling Basin, Australia. *Sustainability*, **11** (21), 6097, doi:10.3390/su11216097.

Yen, J. D. L. et al., 2013: Identifying effective water-management strategies in variable climates using population dynamics models. *J. Appl. Ecol.*, **50** (3), 691-701, doi:10.1111/1365-2664.12074.
Yenneti, K. et al., 2020: Urban Overheating and Cooling Potential in Australia: An Evidence-Based Review. *Climate*, **8** (11), 126, doi:10.3390/cli8110126.
Yletyinen, J. et al., 2019: Understanding and Managing Social–Ecological Tipping Points in Primary Industries. *BioScience*, **69** (5), 335-347, doi:10.1093/biosci/biz031.
Young, I. R. and A. Ribal, 2019: Multiplatform evaluation of global trends in wind speed and wave height. *Science*, **364** (6440), 548-552, doi:10.1126/science.aav9527.
Zarco-Perello, S. et al., 2019: Overwintering tropical herbivores accelerate detritus production on temperate reefs. *Proc. Biol. Sci.*, **286** (1915), 20192046, doi:10.1098/rspb.2019.2046.
Zarco-Perello, S., T. Wernberg, T. J. Langlois and M. A. Vanderklift, 2017: Tropicalization strengthens consumer pressure on habitat-forming seaweeds. *Sci. Rep.*, **7** (1), 820, doi:http://dx.doi.org/10.1038/s41598-017-00991-2.
Zhang, X., J. A. Church, D. Monselesan and K. L. McInnes, 2017: Sea level projections for the Australian region in the 21st century. *Geophysical Research Letters*, **44** (16), 8481-8491, doi:10.1002/2017gl074176.
Zhang, X. S. et al., 2016: How streamflow has changed across Australia since the 1950s: evidence from the network of hydrologic reference stations. *Hydrology and Earth System Sciences*, **20** (9), 3947-3965, doi:10.5194/hess-20-3947-2016.
Zhang, Y. and P. J. Beggs, 2018: The Lancet Countdown down under: tracking progress on health and climate change in Australia. *Medical Journal of Australia*, **208** (7), 285-286, doi:10.5694/mja17.01245.
Zhang, Y., M. Nitschke and P. Bi, 2013: Risk factors for direct heat-related hospitalization during the 2009 Adelaide heatwave: a case crossover study. *Sci. Total Environ.*, **442**, 1-5.
Zhang, Y. and C. J. C. Phillips, 2019: Climatic influences on the mortality of sheep during long-distance sea transport. *animal*, **13** (5), 1054-1062, doi:10.1017/S1751731118002380.
Zheng, F., S. Westra and M. Leonard, 2015: Opposing local precipitation extremes. *Nature Climate Change*, **5** (5), 389-390, doi:10.1038/nclimate2579.
Zheng, H., F. H. S. Chiew, N. J. Potter and D. G. C. Kirono, 2019: Projections of water futures for Australia: an update. In: *23rd International Congress on Modelling and Simulation*, 2019, 1000 –1006.
Ziembicki, M. R., J. C. Z. Woinarski and B. Mackey, 2013: Evaluating the status of species using Indigenous knowledge: Novel evidence for major native mammal declines in northern Australia. *Biological Conservation*, **157**, 78-92, doi:10.1016/j.biocon.2012.07.004.
Zografos, C., I. Anguelovski and M. Grigorova, 2016: When exposure to climate change is not enough: Exploring heatwave adaptive capacity of a multi-ethnic, low-income urban community in Australia. *Urban Climate*, **17**, 248-265, doi:10.1016/j.uclim.2016.06.003.
Zscheischler, J. et al., 2018: Future climate risk from compound events. *Nat. Clim. Chang.*, **8** (6), 469-477, doi:10.1038/s41558-018-0156-3.
Zylstra, P. J., 2018: Flammability dynamics in the Australian Alps. *Austral Ecology*, **43** (5), 578-591.

Chapter 12: Central and South America

Coordinating Lead Authors: Edwin J. Castellanos (Guatemala), Maria Fernanda Lemos (Brazil)

Lead Authors: Laura Astigarraga (Uruguay), Noemí Chacón (Venezuela), Nicolás Cuvi (Ecuador), Christian Huggel (Switzerland), Liliana Miranda (Peru), Mariana Moncassim Vale (Brazil), Jean Pierre Ometto (Brazil), Pablo L. Peri, (Argentina), Julio C. Postigo (USA/Peru), Laura Ramajo (Chile/Spain), Lisandro Roco (Chile), Matilde Rusticucci (Argentina).

Contributing Authors: Júlia Alves Menezes (Brazil), Pedro Borges (Venezuela), Jhonattan Bueno (Venezuela), Francisco Cuesta (Ecuador), Fabian Drenkhan (Peru), Alex Guerra (Guatemala), Valeria Guinder (Argentina), Isabel Hagen (Switzerland), Jorgelina Hardoy (Argentina), Stella Hartinger (Peru), Gioconda Herrera (Ecuador), Cecilia Herzog (Brazil), Bárbara Jacob (Chile), Thais Kasecker (Brazil), Andrea Lampis (Colombia/Brazil), Izabella Lentino (Brazil), Luis C. S. Madeira Domingues (Brazil), José Marengo (Brazil), David Montenegro Lapola (Brazil), Ana Rosa Moreno (Mexico), Julia de Niemeyer Caldas (Brazil), Eduardo Pacay (Costa Rica/Guatemala), Roberto Pasten (Chile), Matias Piaggio (Uruguay), Osvaldo Rezende (Brazil), Alfonso J. Rodriguez-Morales (Colombia), Marina Romanello (Argentina/United Kingdom), Sadie J. Ryan (USA/ United Kingdom), Anna Stewart-Ibarra (USA/Ecuador), María Valladares (Chile/Spain)

Review Editors: Carlos Méndez (Venezuela), Avelino Suarez (Cuba)

Chapter Scientist: María Valladares (Chile/Spain)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Vulnerability and observed impacts:

Central and South America are highly exposed, vulnerable and strongly impacted by climate change, a situation amplified by inequality, poverty, population growth and high population density, land use change particularly deforestation with the consequent biodiversity loss, soil degradation, and high dependence of national and local economies on natural resources for production of commodities (*high confidence*[1]). Profound economic, ethnic and social inequalities are exacerbated by climate change. High levels of widespread poverty, weak water governance, unequal access to safe water and sanitation services and lack of infrastructure and financing reduce adaptation capacity, increasing and creating new population vulnerabilities (*high confidence*). {12.1.1, 12.2, 12.3, 12.5.5, 12.5.7, Figure 12.2}

The Amazon forest, one of the world's largest biodiversity and carbon repositories, is highly vulnerable to drought (*high confidence*). The Amazon forest was highly impacted by the unprecedented droughts and higher temperatures observed in 1998, 2005, 2010 and 2015/2016 attributed partly to climate change. This resulted in high tree mortality rates and basin-wide reductions in forest productivity, momentarily turning pristine forest areas from a carbon sink into a net source of carbon to the atmosphere (*high confidence*). Other terrestrial ecosystems in Central and South America have been impacted by climate change, through persistent drought or extreme climatic events. The combined effect of anthropogenic land use change and climate change increases the vulnerabilities of terrestrial ecosystems to extreme climate events and fires (*medium confidence*). {12.3, 12.4, Figure 12.7, Figure 12.9, Figure 12.10}

The distribution of terrestrial species has changed in the Andes due to increasing temperature (*very high confidence*). Species have shifted upslope leading to range contractions for highland species, and range contractions and expansions for lowland species, including crops and vectors of diseases (*very high confidence*). {12.3.2.4}

Ocean and coastal ecosystems in the region such as coral reefs, estuaries, salt marshes, mangroves and sandy beaches are highly sensitive and negatively impacted by climate change and derived-hazards (*high confidence*). Observed impacts include the reduction in coral abundance, density and cover in Central America, Northwest South America and Northeast South America and increasing number of coral bleaching events in Central America and Northeast South America; changes in the plankton community and in ocean and coastal food web structures, loss of vegetated wetlands and changes in macrobenthic communities in Central America, Northwest, Northern, and Southeast South America. {12.3, 12.5.2, Figure 12.8, Figure 12.9, Table SM12.3}

Global warming has caused glacier loss in the Andes from 30% to more than 50% of their area since the 1980s. Glacier retreat, temperature increase and precipitation variability, together with land-use change, have affected ecosystems, water resources, and livelihoods through landslides and flood disasters (*very high confidence*). In several areas of the Andes, flood and landslide disasters have increased, and water availability and quality and soil erosion have been affected by both climatic and non-climatic factors (*high confidence*). {12.3.2, 12.3.7, Figure 12.9, Figure 12.13, Table SM12.6}

The scientific evidence since the IPCC AR5 increased the confidence on the synergy among fire, land use change, particularly deforestation, and climate change, directly impacting human health, ecosystem functioning, forest structure, food security and the livelihoods of resource-dependent communities (*medium confidence*). Regional increase in temperature, aridity and drought increased the frequency and intensity of fire. On average, people in the region were more exposed to high fire danger between 1 and 26 additional days depending on the subregion for the years 2017-2020 compared to 2001-2004 (*high confidence*). {12.2, 12.3, Figure 12.9, Figure 12.10, Table 12.5}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Changes in timing and magnitude of precipitation and extreme temperatures are impacting agricultural production (*high confidence*). Since the mid-20th century, increasing mean precipitation has positively impacted agricultural production in Southeast South America, although extremely long dry spells have become more frequent affecting the economies of large cities in southeast Brazil. Inversely, reduced precipitation and altered rainfall at the start and end of the rainy season and during the mid-summer drought is impacting rainfed subsistence farming particularly in the Dry Corridor in Central America and in the tropical Andes compromising food security (*high confidence*). The crop growth duration for maize for those regions was reduced by at least 5% between 1981-2010 and 2015-2019. {12.3.1, 12.3.2, 12.3.6, Table 12.4}

Climate change affects the epidemiology of climate-sensitive infectious diseases in the region (*high confidence*). Examples are the effects of warming temperatures on increasing the suitability of transmission of vector-borne diseases, including endemic and emerging arboviral diseases such as dengue fever, chikungunya, and Zika (*medium confidence*). The reproduction potential for the transmission of dengue increased between 17% and 80% for the period 1950-54 to 2016-2021 depending on the subregion as a result of changes in temperature and precipitation (*high confidence*). {12.3.1, 12.3.2, 12.3.3, 12.3.5, 12.3.6, Table 12.1}

The Andes, northeast Brazil and the northern countries in Central America are among the more sensitive regions to climatic-related migrations and displacements, a phenomenon that has increased since AR5 (*high confidence*). Climatic drivers interact with social, political, geopolitical and economical drivers; the most common climatic drivers for migration and displacements are droughts, tropical storms and hurricanes, heavy rains and floods (*high confidence*). {12.3.1.4, 12.3.2.4, 12.3.3.4, 12.3.5.4, 12.5.8.4}

The impacts of climate change are not of equal scope for men and women (*high confidence*). Women, particularly the poorest, are more vulnerable and are impacted in greater proportion. Often they have less capacity to adapt, further widening structural gender gaps (*high confidence*). {12.3.7.3, 12.5.2.4, 12.5.2.5, 12.5.7.3, 12.5.8.1, 12.5.8.3, 12.5.8.4}

Current adaptation responses:

Ecosystem-based adaptation is the most common adaptation strategy for terrestrial and freshwater ecosystems (*high confidence*). There is a focus on the protection of native terrestrial vegetation through implementation of protected areas and payment for ecosystem services, especially those related to water provision. The adaptation measures in place, however, are insufficient to safeguard terrestrial and freshwater ecosystems in the CSA from negative impacts of climate change (*high confidence*). {12.5.1, 12.5.3, 12.6}

Adaptation initiatives in ocean and coastal ecosystems mainly focus on conservation, protection and restoration) (*high confidence*). The main adaptation measures are ocean zoning, the prohibition of productive activities (e.g., fisheries, aquaculture, mining, tourism) on marine ecosystems, the improvement of research and education programs, and the creation of specific national policies (*high confidence*). {12.5.2}

Adaptive water management has mainly centred on enhancing quantity and quality of water supply, including large infrastructure projects, which, however, are often contested and can exacerbate water related conflicts (*high confidence*). Inclusive water regimes that overcome social inequalities and approaches including nature-based solutions, such as wetland restoration and water storage and infiltration infrastructure, with synergies for ecosystem conservation and disaster risk reduction, have been found to be more successful for adaptation and sustainable development (*high confidence*). {12.5.3, 12.6.1, 12.6.3}

Adaptation strategies for agricultural production are increasing in the region as a response to current and projected changes in climate (*high confidence*). The main observed adaptation strategies in agriculture and forestry are soil and water management conservation, crop diversification, climate-smart agriculture, early warning systems, upward shifting for plantations to avoid warming habitat and pests and improved management of pastures and livestock. Adaptation requires governance improvements and new strategies to address changing climate; nevertheless, barriers limiting adaptive capacity persist such as lack of educational programs for farmers, adequate knowledge of site-specific adaptation and institutional and financial constraints (*high confidence*). {12.5.4}

Urban adaptation in the region includes solutions on regulation, planning, urban waters management and housing (*high confidence*). Regulation, planning and control systems are central tools on reducing risk associated with the security of the buildings, their location, and the proper supply of basic urban services and transport (*high confidence*). The adoption of nature-based solutions (e.g., urban agriculture and rivers restoration) and hybrid (grey-green) infrastructure are still incipient with weak connections to poverty and inequality reduction strategies (*medium confidence*). Focusing on risk reduction encompasses upgrading informal and precarious settlements, built-environments, and improving housing conditions, which offer an important but still limited contribution to urban adaptation (*high confidence*). {12.5.5, 12.5.7, 12.6.1}

Adaptation initiatives for the health sector are mainly focused on the development of climate services such as integrated climate-health surveillance and observatories, forecasting climate-related disasters and vulnerability maps (*high confidence*). Climate services for the health sector are largely focused on epidemic forecast tools and associated early warning systems for vector-borne diseases and heat and cold waves. Political, institutional and financial barriers reduce the feasibility of implementing these tools (*high confidence*). {12.5.6, Table 12.9, Table 12.11}

Indigenous knowledge and local knowledge are crucial for the adaptation and resilience of social-ecological systems (*high confidence*). Indigenous knowledge and local knowledge can contribute to reducing the vulnerability of local communities to climate change (*medium confidence*). {12.5.1, 12.5.8, 12.6.2}

What are the projected impacts and key risks?

Climate change is projected to convert existing risks in the region into severe key risks (*medium confidence*). Key risks are assessed as follows: 1. Risk of food insecurity due to droughts; 2. Risk to people and infrastructure due to floods and landslides; 3. Risk of water insecurity due to declining snow cover, shrinking glaciers and rainfall variability; 4. Risk of increasing epidemics particularly of vector-borne diseases; 5. Cascading risks surpassing public service systems; 6. Risk of large-scale changes and biome shifts in the Amazon; 7. Risks to coral reef ecosystems; and 8. Risks to coastal socio-ecological systems due to sea level rise, storm surges and coastal erosion. {12.3, 12.4, Figure 12.9, Figure 12.11, Table 12.6, Table SM12.5}

Impacts on rural livelihoods and food security, particularly for small and medium-sized farmers and Indigenous Peoples in the mountains, are projected to worsen, including the overall reduction of agricultural production, suitable farming area and water availability (*high confidence*). Projected yield reductions by 2050 under A2 scenario are: bean 19%, maize 4–21%, rice 23% in Central America with seasonal droughts projected to lengthen, intensify and increase in frequency. Small fisheries and farming of seafood will be negatively affected as ENSO events become more frequent and intense and ocean warming and acidification continues (*medium confidence*). {12.2, 12.3, 12.4, Figure 12.9, Figure 12.11, Table 12.4}

Extreme precipitation events, which result in floods, landslides and droughts, are projected to intensify in magnitude and frequency due to climate change (*medium confidence*). Floods and landslides pose a risk to life and infrastructure; a 1.5ºC increase would result in an increase of 100–200% in the population affected by floods in Colombia, Brazil and Argentina, 300% in Ecuador and 400% in Peru (*medium confidence*). {12.3, Figure 12.7, Figure 12.9, Table SM12.5}

Increasing water scarcity and competition over water are projected (*high confidence*). Disruption in water flows will significantly degrade ecosystems such as high-elevation wetlands and affect farming communities, public health and energy production (*high confidence*). {12.3, Figure 12.3, Figure 12.9, Figure 12.11}

In the next decades, endemic and emerging climate-sensitive infectious diseases are projected to increase (*medium confidence*). This can happen through expanded distribution of vectors, especially viral infectious diseases from zoonotic origin in transition areas between urban and suburban, or rural settings, and upslope in the mountains (*medium confidence*). {12.3.2, 12.3.5, 12.3.7, Figure 12.5, Figure 12.9, Figure 12.11, Table 12.6, Table SM12.5}

The positive feedback between climate change and land use change, particularly deforestation, is projected to increase the threat to the Amazon forest, resulting in the increase of fire occurrence, forest degradation (*high confidence*) and long-term loss of forest structure (*medium confidence*). The combined effect of both impacts will lead to a long-term decrease in carbon stocks in forest biomass, compromising Amazonia´s role as a carbon sink, largely conditional on the forest's responses to elevated atmospheric CO_2 (*medium confidence*). The southern portion of the Amazon has become a net carbon source to the atmosphere in the past decade (*high confidence*). {12.3.3, 12.3.4, Figure 12.9, Figure 12.11, Table 12.6, Table SM12.5}

Up to 85% of natural systems (plant and animal species, habitats and communities) evaluated in the literature for biodiversity-rich spots in the region are projected to be negatively impacted by climate change (*medium confidence*). Available studies focus mainly on vertebrates and plants of the Atlantic Forest and Cerrado in Brazil and in Central America, with a large knowledge gap on freshwater ecosystems {12.3, 12.5.1, CCP1}

Ocean and coastal ecosystems in the region will continue to be highly impacted by climate change (*high confidence*). Coral reefs are projected to lose their habitat, change their distribution range and suffer more bleaching events driven by ocean warming. In the RCP4.5 and RCP8.5 scenarios by 2050, virtually every coral reef will experience at least one severe bleaching event per year (*high confidence*). Under all RCP scenarios of climate change, there will be changes in the geographical distribution of marine species and ocean and coastal ecosystems such as mangroves, estuaries, rocky shores, as well as those species subjected to fisheries (*medium confidence*). {Figure 12.9, Table SM12.3, Table SM12.4}

Contribution of adaptation to solutions and barriers to adaptation

Policies and actions at multiple scales and the participation of actors from all social groups, including the most exposed and vulnerable populations, are critical elements for effective adaptation (*high confidence*). Engaging social movements and local actors in policy-making and planning for adaptation generates positive synergies and better results. Adaptation policies and programs that consider age, socioeconomic status, race, and ethnicity are more efficient, as these factors determine vulnerability and potential benefits of adaptation. Socio-economic and political factors that provide some level of safety and continuity of policies and actions are critical enablers of adaptation (*high confidence*). {12.5.1, 12.5.2, 12.5.7, 12.5.8, 12.6.4}

The knowledge and awareness of climate change as a threat has been increasing since AR5 due to the increasing frequency and magnitude of extreme weather events in the region, information available and climate justice activism (*high confidence*). Conflicts in which direct biophysical impacts of climate change play a major role can unleash protests and strengthen social movements (*medium confidence*). {12.5.8, 12.6.4}

Research approaches that integrate Indigenous knowledge and local knowledge systems, with natural and social sciences, have increased since AR5 (*high confidence*), and are helping to improve decision-making processes in the region, reduce maladaptation, and foster transformational adaptation through the integration with ecosystem-based adaptation and community-based adaptation (*high confidence*). {12.5.1, 12.5.8, 12.6.2}

The most reported obstacle for adaptation in terrestrial, freshwater, ocean and coastal ecosystems is financing (*high confidence*). There is also a significant gap in identifying limits to adaptation and weak institutional capacity for implementation. This hinders the development of comprehensive adaptation programs, even under adequate funding. {12.5.1, 12.5.2}

Climate Smart Agriculture technologies strengthening synergies among productivity and mitigation is growing as an important adaptation strategy in the region (*high confidence*). Pertinent information for farmers provided by Climate Information Services are helping them to understand the role of climate *vs.* other drivers in perceived productivity changes. Index insurance builds resilience and contributes to adaptation both by protecting farmers' assets in the face of major climate shocks, by promoting access to credit, and by the adoption of improved farm technologies and practices. {12.5.4}

Institutional instability, fragmented services and poor water management, inadequate governance structures, insufficient data and analysis of adaptation experience are barriers to address the water challenges in the region (*high confidence*). {12.5.3}

Inequality, poverty and informality shaping cities in the region increase vulnerability to climate change while policies, plans or interventions addressing these social challenges with inclusive approaches are opportunities for adaptation (*high confidence*). Initiatives to improve informal and precarious settlement, guaranteeing access to land and decent housing, are aligned with comprehensive adaptation policies that include development and reduction of poverty, inequality and disaster risk (*medium confidence*). {12.5.5, 12.5.7}

Adaptation policies often address climate impact drivers, but seldom include the social and economic underpinnings of vulnerability. This narrow scope limits adaptation results and compromises their continuity in the region (*high confidence*). In a context of unaddressed underdevelopment, adaptation policies tackling poverty and inequality are marginal, underfunded, and not clearly included at national, regional or urban levels. Dialogue and agreement including multiple actors are mechanisms to acknowledge trade-offs and promote dynamic, site-specific adaptation options (*medium confidence*). {12.5.7}

12.1 Introduction

12.1.1 The Central and South America Region

Central and South America (CSA) is a highly diverse region, both culturally and biologically. It harbours one of the highest biodiversity on the planet (Hoorn et al., 2010; Zador et al., 2015; IPBES, 2018a) (Cross-Chapter Paper 1: Biodiversity Hotspots) and a wealth of cultural diversity resulting from more than 800 Indigenous Peoples who share the territory with European and African descendants and more recent Asian migrants (CEPAL, 2014). Moreover, it is one of the most urbanized regions in the world, with some of the most populated metropolitan areas (UNDESA, 2019). Several countries in the region have experienced sustained economic growth in the last decades, making important advances in reducing poverty in the area. Yet, it is a region of substantial social inequality including the highest inequality in land tenure, where there still remains a large percentage of the population below the poverty line, unequally distributed between rural and urban areas and along aspects like gender and race; these groups are highly vulnerable to climate change and natural extreme events that frequently affect the region (*high confidence*) (ECLAC, 2019b; Busso and Messina, 2020; Poveda et al., 2020).

Land use changes in the region, particularly deforestation, are large, mostly due to agricultural production for export purposes, one of the main sources of income for the area (Salazar et al., 2016) (Figure 12.2c). Additional pressure on the land comes from illegal activities, pollution and induced fires. These changes exacerbate the impacts of climate change and make the region play a key role in the future of the world economy and food production (IPBES, 2018a). The region boasts the largest tropical forest on the planet and other important biomes of high biodiversity on mountains, lowlands and coastal areas. It can potentially continue its agricultural expansion and development at the expense of substantially reducing the areas of natural biomes. Indigenous Peoples and smallholder families are lacking adequate climate policies combined with institutions to protect their property rights; this could result in a more sustainable process of agricultural expansion, without substantially increasing greenhouse gas emissions and the vulnerability of those populations (*high confidence*) (Sá et al., 2017).

Central and South America (CSA) is divided into eight climatic sub-regions by WGI (Figure 12.1). Though the southern part of Mexico is included in the climatic sub-region SCA for WGI, Mexico is assessed in Chapter 14 (North America). In this chapter, we refer to this sub-region as Central America (CA) as it excludes southern Mexico. The climate change literature for the region occasionally includes Mexico and in those cases, our assessment makes reference to Latin America but when only southern Mexico is included, the term Mesoamerica is used. Figure 12.2 and Table SM12.1 summarize relevant characteristics of the sub-regions included in this chapter.

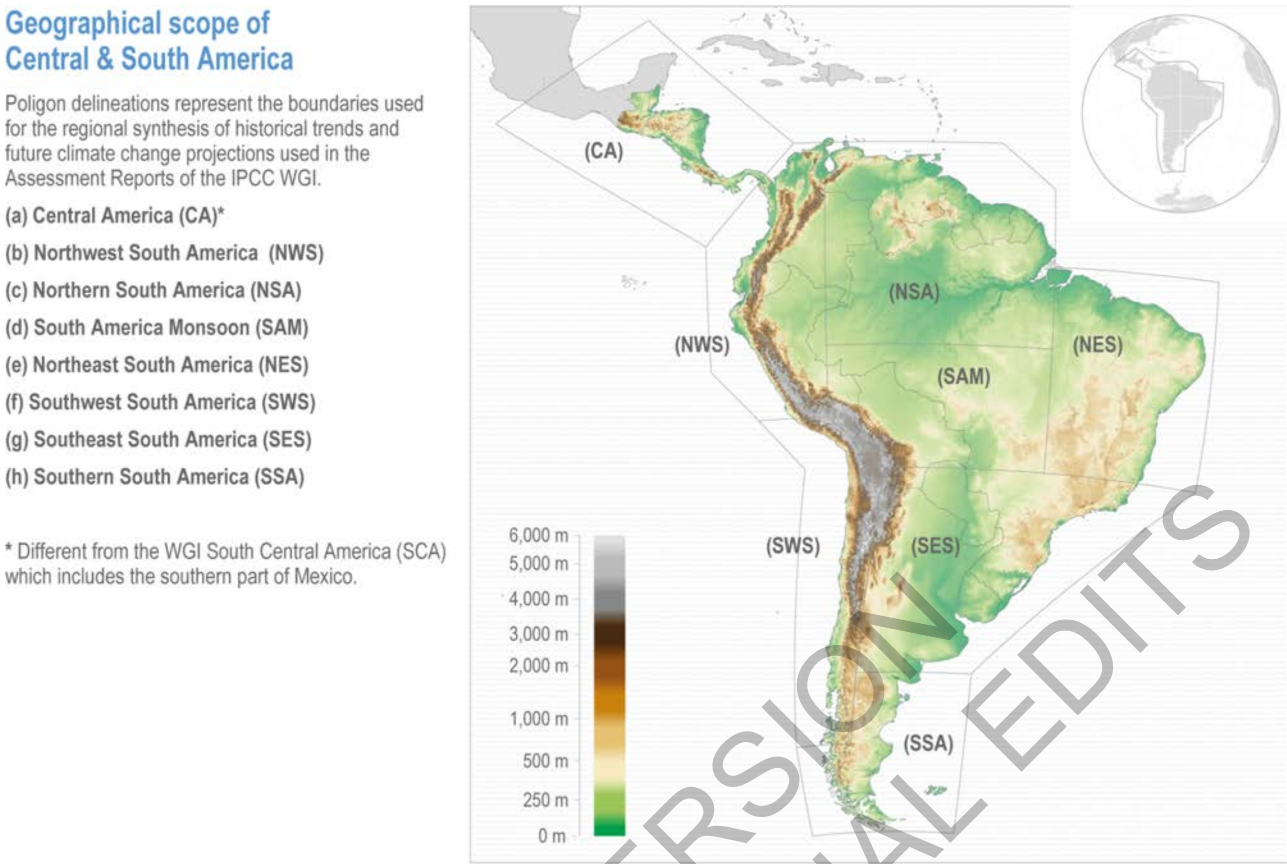


Figure 12.1: Sub-regions included in the Central and South America region. Note that the WGI climatic sub-region South Central America SCA corresponds to Central America CA in this chapter, as southern Mexico is included in Chapter 14. Small islands in the region are approached in Chapter 15 in more detail.

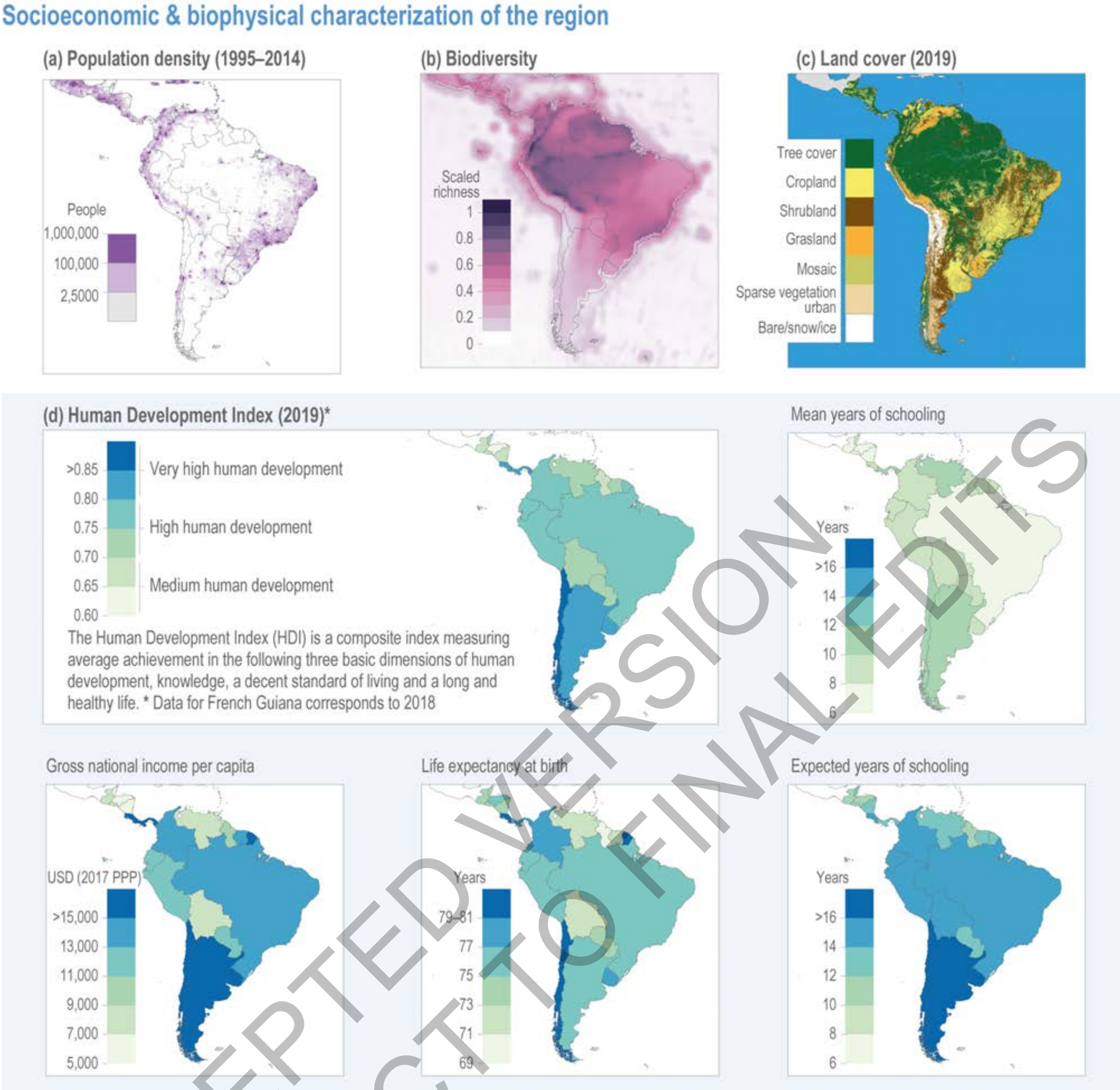


Figure 12.2: Characterization of the region. Population data from ISIMIP (2021) after Klein Goldewijk et al. (2017). Biodiversity expressed as marine and terrestrial species richness adapted from Gagné et al. (2020). Land cover data from ESA (2018). Human Development Index and its components from UNDP (2020). HDI and components for French Guiana from Global Data Lab (2020).

12.1.2 Approach and Storyline for the Chapter

The chapter is divided in two main sections. The first section follows an integrative approach in which hazards, exposure, vulnerability, impacts and risks are discussed following the eight climatically homogeneous sub-regions described in WGI AR6 (see Figure 12.1). The second section assesses the implemented and proposed adaptation practices by sector; in doing so, it connects to the WGII AR6 cross-chapters themes. The storyline is then a description of the hazards, exposure, vulnerability and impacts providing as much detail as available in the literature at the sub-regional level, followed by the identification of risks as a result of the interaction of those aspects. This integrated sub-regional approach ensures a balance in the text, particularly for countries that are usually underrepresented in the literature but that show a high level of vulnerability and impacts, such as those observed in CA. The sectoral assessment of adaptation that follows is useful for policy makers and implementers, usually focused and organized by sectors, governments' ministries or secretaries that can easily locate the relevant adaptation information for their particular sector. To ensure coherence in the chapter, a summary of the assessed adaptation options by key risks is presented, followed by a feasibility assessment for some relevant adaptation options. The chapter closes with case studies and a discussion of the knowledge gaps evidenced in the process of the assessment.

12.2 Summary of the Fifth Assessment Report and Recent IPCC Special Reports

Central and South America shows increasing trends of climatic change and variability and extreme events severely impacting the region, exacerbating problems of rampant and persistent poverty, precarious health systems and water and sanitation services, malnutrition and pollution. Inadequate governance and lack of participation escalates the vulnerability and risk to climate variability and change in the region (*high confidence*) (WGII AR5 Chapter 27) (Magrin et al., 2014).

Increasing trends in precipitation had been observed in Southeast South America (SES in Figure 12.1) in contrast with decreasing trends in CA and central-southern Chile (*high confidence*) (WGII AR5 Chapter 27) (Magrin et al., 2014). Frequency and intensity of droughts have increased in many parts of SA (IPCC, 2019c). Warming has been detected throughout CSA except for a cooling trend reported for the ocean off the Chilean coast.

Climate projections indicate increases in temperature for the entire region by 2100 for RCP4.5 and RCP8.5, but rainfall changes will vary geographically, with a notable reduction of –22% in Northeast Brazil and an increase of +25% in SES. Significant dependency on rainfed agriculture (>30% in Guatemala, Honduras, and Nicaragua) indicates high sensitivity to climatic variability and change, and challenge food security (*high confidence*) (SRCCL Chapter 5, Mbow et al., 2019). Undernutrition has worsened since 2014 in CSA (SRCCL Chapter 5, Mbow et al., 2019). Evidence of climate change impacts on food security is emerging from Indigenous knowledge and local knowledge studies in SA. Municipalities in CA with high proportion of subsistence crops tend to have less resources for adaptation and more vulnerable to climate change (SRCCL Chapter 5, Mbow et al., 2019). Rising temperature and decreased rainfall could reduce agricultural productivity by 2030, threatening food security of the poorest populations (WGII AR5 Chapter 27, Magrin et al., 2014). Though reduced suitability and yield for beans, coffee, maize, plantain, and rice is expected in CA (SRCCL Chapter 5, Mbow et al., 2019), limiting the warming to 1.5ºC, compared with 2ºC, is projected to result in smaller net reductions in yields of maize, rice, wheat and other cereal crops for CSA (*high confidence*) (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). The heat stress is expected to reduce the suitability of Arabica coffee in Mesoamerica but it can improve in high latitude areas in SA (SRCCL Chapter 4, Olsson et al., 2019). There is *limited evidence* that these declines in crop yields may result in significant population displacement from the tropics to the subtropics (SR15 Chapter 3, Hoegh-Guldberg et al., 2018).

There is a *high confidence* that heat waves will increase in frequency, intensity and duration, becoming, under high emission scenarios, extremely long, over 60 days in duration in SA; the risk of wildfires will also increase significantly in SA (SRCCL Chapter 2, Jia et al., 2019). These processes are and will lead to increased desertification that cost between 8 and 14% of gross agricultural product in many CSA countries (SRCCL Chapter 3, Mirzabaev et al., 2019). Distinguishing climate induced changes from land use changes is challenging, but 5–6% of biomes in SA are expected to change by 2100 due to climate change (SRCCL Chapter 4, Olsson et al., 2019).

Changes in weather and climatic patterns are negatively affecting human health in CSA, in part through the emergence of diseases in previously non-endemic areas (WGII AR5 Chapter 27, Magrin et al., 2014). Projections of potential impacts of climate change on malaria confirm that weather and climate are among the drivers of geographic range, intensity of transmission, and seasonality; the changes of risk become more complex with additional warming (*very high confidence*) (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). There is *high confidence* that constraining the warming to 1.5°C would reduce risks for unique and threatened ecosystems safeguarding the services they provide for livelihoods and sustainable development (food, water) in CA and Amazon (SR15 Chapter 5, Roy et al., 2018).

Observed changes in streamflow and water availability affect vulnerable regions (WGII AR5 Chapter 27, Magrin et al., 2014). Glacier mass changes in the Andes over the past decades are among the most negative ones worldwide (SROCC Chapter 2, Hock et al., 2019). This reduction has modified the frequency, magnitude and location of related natural hazards, while the exposure of people and infrastructure has increased because in relation with growing population, tourism and economic development (*high confidence*) (SROCC Chapter 2, Hock et al., 2019).

Negative impacts of climate change in the region are exacerbated by deforestation and land degradation attributed mainly to expansion and intensification of agriculture and cattle ranching, usually under insecure-tenure land. This conversion of natural ecosystems is the main cause of biodiversity and ecosystem loss and is an important source of greenhouse gas (GHG) emissions (*high confidence*) (WGII AR5 Chapter 27, Magrin et al., 2014).

The combination of continued anthropogenic disturbance, particularly deforestation, with global warming may result in dieback of forest in the region (*medium confidence*) (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). Loses as high as 40% of biomass are projected in CA with a warming of 3°C–4°C and the Amazon may experience a significant dieback at similar warming levels (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). Advances in second-generation bioethanol from sugarcane and other feedstock will be important for mitigation. However, agricultural expansion results in large conversions in tropical dry woodlands and savannas in SA (Brazilian Cerrado, Caatinga and Chaco) (*high confidence*) (SRCCL Chapter 1, Arneth et al., 2019). The expansion of soybean plantations in the Amazonian state of Mato Grosso in Brazil reached 16.8% yr^{-1} from 2000 to 2005; and oil palm, a significant biofuel crop, is also linked to recent deforestation in tropical CA (Costa Rica and Honduras) and SA (Colombia and Ecuador), although lower in magnitude compared to deforestation from soybean and cattle ranching (WGII AR5 Chapter 27, Magrin et al., 2014).

Ocean and coastal ecosystems in the region already show important changes due to climate change and global warming (SROCC Chapter 5, Bindoff et al., 2019).

Adaptation to future climate changes starts by reducing the vulnerability to present climate considering the deficient welfare of people in the region. Generalizing to the region cases of synergies among development, adaptation and mitigation planning requires a governance model where development needs, vulnerability reduction, and adaptation strategies are intertwined (WGII AR5 Chapter 27, Magrin et al., 2014).

12.3 Hazards, Exposure, Vulnerabilities and Impacts

12.3.1 Central America (CA) Sub-region

12.3.1.1 Hazards

Since the mid-20th century, extreme warm temperatures have increased and extreme cold temperatures have decreased in the region (*medium confidence*). The magnitude and frequency of extreme precipitation events have increased, but droughts have mixed signals (*low confidence*) (WGI AR6 Table 11.13, Table 11.14, Table 11.15, Seneviratne et al., 2021). There are spatially variable trends detected for the mid-summer drought (MSD) timing, the amount of rainy season precipitation, the number of consecutive and total dry days, and extreme wet events at the local scale since the 1980s. At the regional scale, a positive trend in the duration, but not the magnitude of the MSD was found (Anderson et al., 2019).

Significant increases in tropical cyclone (TC) intensification rates in the Atlantic basin, highly unusual compared to model-based estimates of internal climate variations has been observed (Bhatia et al., 2019). TC contributed approximately 10% of the annual precipitation (Khouakhi et al., 2017). During the TC season more TC-driven events of extreme sea level exceed a 10-year return period (Muis et al., 2019).

Massive heat wave events and increase in the frequency of warm extremes are projected at the end of the 21st century (*high confidence*). When comparing 2.0 with 1.5 degrees of warming, the longest annual warm wave is projected to increase more than 60 days (Taylor et al., 2018).

General decrease in the magnitude of heavy precipitation extremes (Chou et al., 2014; Giorgi et al., 2014) (in 1.5ºC projection) but increase in the frequency of extreme precipitation (R50mm) (Imbach et al., 2018) are projected for both 2ºC and 4ºC GWL. Strong declines in mean daily rainfall are projected for July in Belize

(Stennett-Brown et al., 2017; WGI AR6 Table 11.14, Seneviratne et al., 2021) and decreased rainfall through the year for all capital cities except Panama City (*medium confidence: limited evidence, high agreement*) (Pinzón et al., 2017).

The main climate impact drivers like extreme heat, drought, relative sea level rise, coastal flooding, erosion, marine heatwaves, ocean aridity, (*high confidence*) and aridity, drought and wildfires will increase by mid-century (*medium confidence*) (Figure 12.6, WGI AR6 Table 12.6, Ranasinghe et al., 2021).

The rainy season in CA will likely experience more pronounced MSD by the end of this century, with a signal for reduced minimum precipitation by the mid-century for the JJA and SON quarters, and a broader second peak is projected consistent with the future south displacement of the ITCZ (*high confidence*) (Fuentes-Franco et al., 2015; Hidalgo et al., 2017; Maurer et al., 2017; Imbach et al., 2018; Naumann et al., 2018; Ribalaygua et al., 2018; Corrales-Suastegui et al., 2020).

Climate projections indicate a decrease in frequency of tropical cyclones in CA accompanied with an increased frequency of intense cyclones (WGI AR6 Section 12.4.4.3, Ranasinghe et al., 2021).

12.3.1.2 Exposure

Of the 47 million Central Americans in 2015, 40% lived in rural areas with Belize being the least urbanized (54% rural) and Costa Rica the most (21% rural) (CELADE, 2019); 10.5 million lived in the Dry Corridor region, an area recently exposed to severe droughts that have resulted in 3.5 million people in need of humanitarian assistance (FAO, 2016a). Except in Belize and Panama, the majority of the countries' population —ranging from 56% in Honduras to 95% in El Salvador— is exposed to 2 or more risks derived from natural extreme events, affecting between 57% to 96% of the GDP of the countries (UNISDR and CEPREDENAC, 2014). Central America is one of the regions most exposed to climatic phenomena; with long coastlines and lowland areas, the region is repeatedly affected by drought, intense rains, cyclones and ENSO events (*high confidence*) (ECLAC et al., 2015).

Large urban centres are located on mountains or away from the shore, with the notable exceptions of Panama City, Belmopan and Managua, capital cities housing around 3 million people. Urban development in the capital cities and suburbs has almost tripled in the last forty years reaching population densities as high as 11,000 inhabitants per km^2 in Guatemala City and Tegucigalpa, with the spread of poor neighbourhoods in steep ravines and other marginal high risk areas (Programa Estado de la Nación - Estado de la Región, 2016).

12.3.1.3 Vulnerability

Climate change is exacerbating socioeconomic vulnerability in CA, a region with high levels of socioeconomic, ethnic and gender inequality, high rates of child and maternal mortality and morbidity, high levels of malnutrition and inadequate access to food and drinking water (ECLAC et al., 2015). Disasters from adverse natural events exacerbate CA's economic vulnerability, accounting for substantial human and economic losses (UNISDR and CEPREDENAC, 2014). Vulnerability in most sectors is considered high or very high (*high confidence*) (Figure 12.7).

Approximately 40% of the CA population are living in poverty. Guatemala (62%), Honduras (60%), Nicaragua (46%) and Belize (42%, 2009) had the highest poverty rates in CSA in 2018 (ECLAC, 2019b; BCIE, 2020). Rural poverty rates are higher, 82% in Honduras and 77% in Guatemala in 2014, and so is poverty among Indigenous Peoples, up to 79% in Guatemala. Rural poor are the most sensitive to climate extremes as their main economic activity is based on agriculture in vulnerable terrains (NU CEPAL, 2018). In 2014, all CA countries, except for El Salvador (excluding Belize), had higher GINI coefficients (more inequality) than the average for Latin America (0.473), which in itself is the most unequal region in the world (ECLAC, 2019b); in 2018 the situation remained similar with El Salvador showing the lowest GINI coefficient (40) and the rest of the countries showing values higher than the Latin-American average (BCIE, 2020).

12.3.1.4 Impacts

The countries in the region are consistently ranked with the highest risk in the world of being impacted by extreme events (*high confidence*). Economic cost of climate change impacts in 2010 was estimated from 2.9% of GDP for Guatemala to 7.7% for Belize (ECLAC et al., 2015). For the period 1992–2011, Honduras, Nicaragua and Guatemala were among the 10 most impacted countries in the world by extreme weather events (UNISDR and CEPREDENAC, 2014). The number of these events has increased 3% annually in the last 30 years (Bárcena et al., 2020a).

Human and economic losses, changing water availability and increasing food insecurity are the most studied impacts of climate change in CA (Figure 12.9; Harvey et al., 2018; Hoegh-Guldberg et al., 2019). Hydro-meteorological events, such as storm surges and tropical cyclones, are the most frequent extreme events and have the highest impact (*high confidence*) (Reyer et al., 2017). From 2005 to 2014, the cumulative impacts were over 3410 people dead, hundreds of thousands displaced, and damages estimated around USD 5.8 billion (Ishizawa and Miranda, 2016). One standard deviation in the intensity of a hurricane windstorm leads to a decrease in both the growth of total GDP per capita (0.9% to 1.6%) and total income and labour income by 3%, whereas it increases moderate and extreme poverty by 1.5% in CA (Ishizawa and Miranda, 2016).

Food insecurity is a serious impact of climate change in a region where 10% of the GDP depends on agriculture, livestock and fisheries (*very high confidence*) (ECLAC et al., 2015; CEPAL et al., 2018; Harvey et al., 2018; BCIE, 2020). Crop losses largely result from highly variable rainfall and seasonal droughts which have increased significantly in the last decades (Table 12.3; CEPAL and CAC-SICA, 2020), particularly the observed changes in the MSD that reduces rainfall at the onset of the rainy season (May-June) (Anderson et al., 2019). Small and subsistence farmers receive the highest impact as they practice rainfed agriculture (Imbach et al., 2017), and poor neighbourhoods, which face socioeconomic and physical barriers for adapting to climate change (Kongsager, 2017). In 2015, precipitation diminished between 50% to 70% of its historic average causing the loss of up to 80% of beans and 60% of maize, leaving 2.5 million people food insecure, 1.6 million of which were in the Dry Corridor of CA (ECLAC et al., 2015; FAO, 2016a). In 2019, the region entered its fifth consecutive drought year with 1.4 million people in need of food aid. Seasonal-scale droughts are projected to lengthen by 12–30%, intensify by 17–42% and increase in frequency by 21–42% in RCP4.5 and RCP8.5 scenarios by the end of the century (Depsky and Pons, 2021).

Studies have shown that the incidence of some vector-borne and zoonotic diseases in CA is correlated to climatic variables, particularly temperature and rainfall (*high confidence*) (Figure 12.4; Table 12.1). In Honduras, rainfall and relative humidity were positively correlated with the occurrence of hemorrhagic dengue cases (Zambrano et al., 2012). In Costa Rica, temperature and rainfall was correlated to cattle rabies outbreaks and mortality during 1985–2016 (Hutter et al., 2018); Incidence of leishmaniasis showed cycles of three years related to temperature changes (Chaves and Pascual, 2006); and snakebites were more likely to occur at high temperatures and was significantly reduced after the rainy season for the period 2005–2013 (Chaves et al., 2015). In Panama, rainfall was associated with the increased number of malaria cases among the Gunas, an Indigenous People with high vulnerability living in poverty conditions on small islands affected by sea-level rise (Hurtado et al., 2018). These correlations point to a possible change in disease incidence with climate change; evidence of that change is yet to be reported in the literature as longitudinal studies are lacking in the region.

Heat stress is another health concern in this already warm and humid part of the world (*high confidence*) (Table 12.2); it is an increasing occupational health hazard with potential impacts on kidney disease (Sheffield et al., 2013; Dally et al., 2018; Johnson et al., 2019). Sea-level rise exacerbating wave-driven flooding is expected to impact infrastructure and freshwater availability in small islands and atolls off the coast of Belize (Storlazzi et al., 2018). Observed and expected impacts in the coastal and ocean ecosystems of the sub-region are described in Figure 12.9.

Decreasing water availability is another impact of climate change (*high confidence*). Under a climate change scenario of 3.5°C warming and a 30% reduction of rainfall, a reduction in production and export of crops and livestock is projected affecting the wages and decreasing the GDP of Guatemala by 1.2%, thereby increasing food insecurity (Vargas et al., 2018b). By 2100, water availability per capita is projected to decrease 82% and 90% on average for the region under B2 (low emissions) and A2 (high emissions) scenarios respectively (CEPAL, 2010) (Figure 12.3).

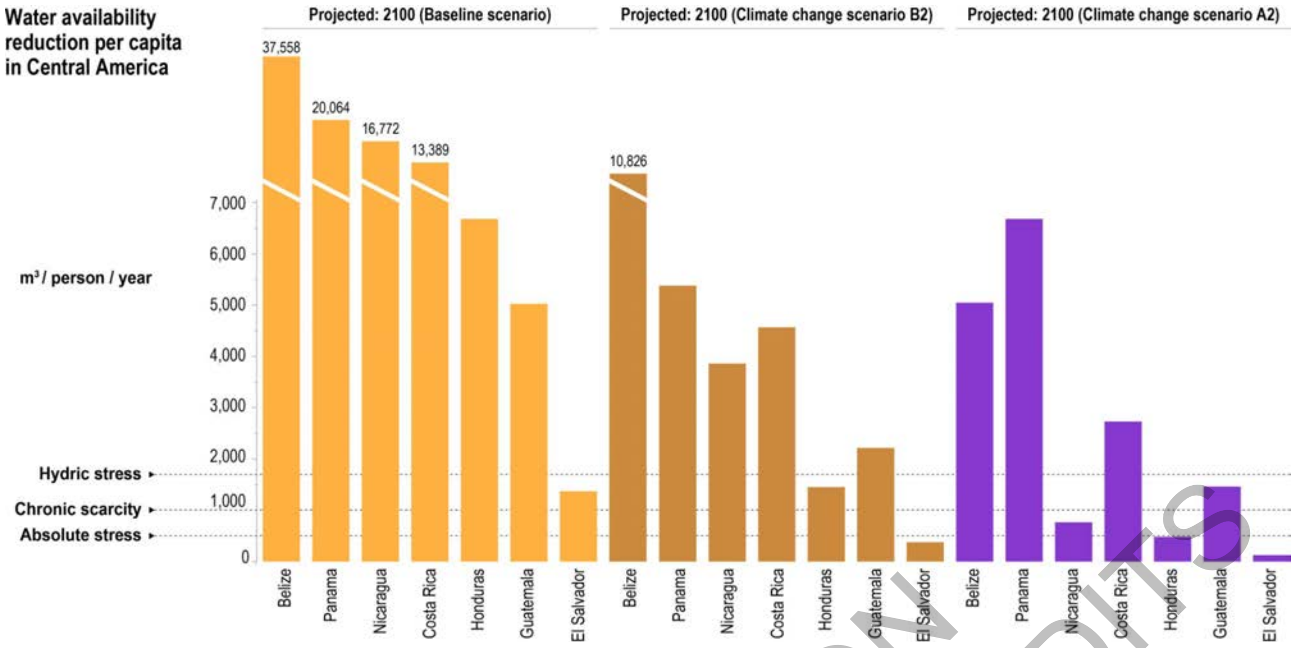


Figure 12.3: Reduction of water availability per capita projected to 2100 without climate change (baseline scenario) and with two climate change scenarios (CEPAL, 2010).

Impacts on rural livelihoods, particularly for small and medium-sized farmers and Indigenous Peoples on the mountains, include the overall reduction of the production, yield (Table 12.4), suitable farming area, and water availability (*high confidence*) (Walshe and Argumedo, 2016; Bouroncle et al., 2017; Hannah et al., 2017; Imbach et al., 2017; Harvey et al., 2018; Batzín, 2019; Donatti et al., 2019). Bean production in El Salvador, Nicaragua, Honduras, and Guatemala, is projected to decrease, using the Decision Support for Agro-Technology Transfer (DSSAT) under A2 scenario, by 19% for 2050, whereas maize production, depending on water retention capacity of soils, will drop between 4% and 21% by 2050 (CEPAL et al., 2018). In Guatemala, the yield of rainfed maize is expected to decrease by 16% by 2050 under RCP8.5 using the Global Gridded Crop Model Intercomparison GGCMI; yields for rainfed sugarcane are expected to drop by 44% and irrigated sugarcane by 36% under the same modelling conditions (Castellanos et al., 2018). Rice production is expected to decrease by 23% under scenario A2 by 2050 (CEPAL and CAC/SICA, 2013).

The extent and quality of suitable areas for basic grains are expected to contract (*high confidence*). The suitable area for maize will experience a 35% reduction of cultivated area expected by 2100 under A2 scenario. The area suitable for beans is expected to reduce by 2050. Projections show that suitable areas with excellent aptitude under current conditions will decrease by 14%, mainly in Panama (41%) Costa Rica (21%) and El Salvador (20%). Species Distribution Model, using the IPSL GCM, projects that the suitable zones for cacao and coffee will shrink between 25% to 75% under RCP6.0 (Fernandez-Manjarrés, 2018; Fernández Kolb et al., 2019). Warmer and dryer lower areas will become unsuitable for coffee and will drive its production to higher land (Läderach et al., 2013; Bunn et al., 2015). Under A2 climate change scenario, areas with excellent aptitude for Arabica coffee will decrease by 12% in Central America; coffee yield will decrease in suitable zones whereby the extent of high yield (> 0.8 T ha^{-1}) zones is project to shrink from 34% to 12% whereas low yield (< 0.3 T ha^{-1}) zone will expand from 14% to 36% by 2100 under A2 scenario (CEPAL and CAC/SICA, 2014).

The Mesoamerica, biodiversity-rich spot spanning through CA and southern Mexico is a global priority for terrestrial biodiversity conservation, and it is projected to be negatively impacted by climate change, especially through the contraction of distribution of native species at the area becomes increasingly dryer (*high confidence*) (Cross-Chapter Paper 1.2.2; Feeley et al., 2013; Manes et al., 2021) . A significant reduction in net primary productivity in tropical forests is expected under both RCP4.5 and RCP8.5 as a result of temperature increase, precipitation reduction, and droughts (Lyra et al., 2017; Castro et al., 2018; Stan et al., 2020). Models of aridity index show that the dry, sub humid vegetation of the dry corridor will expand to neighbouring areas and replace the humid forests in the Pacific lowlands and the northern parts of Guatemala by 2050 under RCP4.5 and RCP8.5 scenarios (Pons et al., 2018; CEPAL and CAC-SICA, 2020).

3°C warming would shrink the tropical rainforest and replace it with savannah grassland. Wetlands are also expected to be highly affected by climate change in the region (Hoegh-Guldberg et al., 2019).

12.3.2 Northwest South America (NWS) Sub-region

12.3.2.1 Hazards

Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Dereczynski et al., 2020; Dunn et al., 2020) was *likely*[2] observed (Figure 12.6; WGI AR6 Table 11.13, Seneviratne et al., 2021).

Insufficient data coverage and trends in available data are generally not significant for heavy precipitation (*low confidence*) (Dereczynski et al., 2020; Dunn et al., 2020; Sun et al., 2021) (Figure 12.6; WGI AR6 Table 11.14) (Seneviratne et al., 2021).

ENSO is the dominant phenomenon affecting weather conditions in all CSA, and along the Pacific Coast of NWS with effects of heavy rains, storms, floods, landslides, heat and cold waves and extreme sea level rise (Ashok et al., 2007; Reguero et al., 2015; Wang et al., 2017b; Muis et al., 2018; Rodríguez-Morata et al., 2018; Rodríguez-Morata et al., 2019; Cai et al., 2020). There is a *medium confidence* that extreme ENSO will increase long after 1.5°C warming stabilization according to CMIP5 (Cai et al., 2015; Wang et al., 2017b; Cai et al., 2018). It is *very likely* that ENSO rainfall variability, used for defining extreme El Niño and La Niña, will increase significantly, regardless of amplitude changes in ENSO SST variability, by the second half of the 21st century in scenarios SSP2-4.5, SSP3-7.0, and SSP5-8.5 (WGI AR6 Chapter 4; Lee et al., 2021).

Warming and drier conditions are projected through the reduction of total annual precipitation, extreme precipitation and consecutive wet days, and increase in consecutive dry days (Chou et al., 2014). Heat waves will increase in frequency and severity in places close to the equator as Colombia (Guo et al., 2018; Feron et al., 2019), with decrease but strong wetting in coastal areas, pluvial and river flood, and mean wind increase (Mora et al., 2014). Models project for a 2ºC GWL *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes. Nevertheless, models project inconsistent changes in the region for extreme precipitation (*low confidence*) (Figure 12.6; WGI AR6 Table 12.14; Ranasinghe et al., 2021). The main climate impact drivers in the region, like extreme heat, mean precipitation and coastal and oceanic will increase and snow, ice and permafrost will decrease with *high confidence* (WGI AR6 Table 12.6, Ranasinghe et al., 2021).

12.3.2.2 Exposure

There is *high confidence* that coastal lowlands are exposed to sea level rise in the form of coastal flooding and erosion, subsidence and saltwater intrusion (Hoyos et al., 2013). Those hazards can affect settlements, ports, industries and other infrastructures. Mangrove and aquaculture areas are among the most exposed systems (Gorman, 2018). The Eastern Tropical Pacific, particularly Sector Niño 3.4, will see the worst increase in sea surface temperature, affecting industrial and small-scale fisheries (*very high confidence*) (Castrejón and Defeo, 2015; Reguero et al., 2015; Eddy et al., 2019; Bertrand et al., 2020; Castrejón and Charles, 2020; Escobar-Camacho et al., 2021).

Settlements and agriculture of different scales, and hydroelectric infrastructures, especially near big rivers or in plains, are exposed to floods. Exposure and vulnerabilities to precipitation, overflows and related landslides, are increasing (Briones-Estébanez and Ebecken, 2017).

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

The Andean piedmont (500–1200 m.a.s.l.) ecosystems and crops and elevation ranges above the treeline are more exposed to thermal anomalies (*very high confidence*) (Urrutia and Vuille, 2009; Vuille et al., 2015; Aguilar-Lome et al., 2019; Pabón-Caicedo et al., 2020). Temperature rise, combined with precipitation and floods, leave people more exposed to epidemics (*very high confidence*) (Stewart-Ibarra and Lowe, 2013; Sippy et al., 2019; Petrova et al., 2020). A bigger exposure is related to lower socioeconomic conditions, poor health and marginalisation (Oliver-Smith, 2014).

12.3.2.3 Vulnerability

Local economies reliant on limited and specialized resources, highly dependent on ecosystem services such as water and soil fertility, as the alpaca and llama herders or small-scale fishers, are amongst the more vulnerable (*very high confidence*) (Hollowed et al., 2013; Postigo, 2013; Glynn et al., 2017; Duchicela et al., 2019). Also the agricultural sector in the face of extreme events (Coayla and Culqui, 2020). Their vulnerabilities increase as a result of unequal chains of value, incomplete transfers of technology and other socioeconomic and environmental drivers (*high confidence*) (Ariza-Montobbio and Cuvi, 2020; Gutierrez et al., 2020).

Informal housing and settlements, usually located in the highest risk land, exacerbates vulnerability (*very high confidence*) (Miranda Sara and Baud, 2014; Cuvi, 2015; Miranda Sara et al., 2016). The absence of proper drainage systems in urban areas increases the vulnerability, especially to floods. Most of the cities and infrastructure are considered highly vulnerable to climate change (*high confidence*) (Figure 12.7).

Regions dependent on glacier runoff are particularly vulnerable (Jiménez Cisneros et al., 2014; Mark et al., 2017; Polk et al., 2017). Also biodiversity and water dependent activities where seasonality and rainfall patterns are changing, and where other non-climatic sources of change, such as land use, affect the capacity of ecosystems to provide hydrological services (*very high confidence*) (Cerrón et al., 2019; Molina et al., 2020). The three countries are amongst the most vulnerable in terms of wellbeing and health Figure 12.7; Nagy et al., 2018).

12.3.2.4 Impacts

An increase in the frequency of climate related disasters has been reported (*high confidence*) (Huggel et al., 2015a; Stäubli et al., 2018) (WGI AR6 Chapter 12) (Ranasinghe et al., 2021). Scale studies indicate an increase of flood risk during the 21st century, consistent with more frequent floods, being worse in higher emission scenarios (*high confidence*) (Arnell and Gosling, 2013; Hirabayashi et al., 2013; Alfieri et al., 2017; WGI AR6 Chapter 12, Ranasinghe et al., 2021). Those living on riverbanks and slums built on steep slopes are among the most affected by floods of all kinds (*high confidence*) (Emmer et al., 2016; Emmer, 2017). There is still uncertainty in relation to future drought intensity and frequency (Pabón-Caicedo et al., 2020).

Increased sea surface temperature, coupled with stronger ENSO events, will affect marine life and fisheries by loss of productive habitat, disruption of nutrient structure, productivity, and altering the migration of species, leading to changes in fishing rates, impacting coastal livelihoods (*high confidence*) (Bayer et al., 2014; Cai et al., 2015; Ding et al., 2017; Mariano Gutiérrez et al., 2017; Bertrand et al., 2020). Figure 12.8 shows other observed sensitivities in several ecosystems and in places as the Galapagos and Malpelo islands, and the coastal Economic Exclusion Zone (EEZ).

ENSO events coupled with climate change, lead to warmer ocean temperatures, heavy rains, floods and heavy river discharges that have and will impact several activities, including small-scale fisheries infrastructure (*very high confidence*). In Peru alone, wet extremes are estimated to be at least 1.5 times more likely to happen compared to preindustrial times. The extremely wet ENSO event of 2017 left 6–9 billion USD in monetary losses in that country, 1.7 million inhabitants affected, and crops, roads, bridges, homes, schools, and health posts damaged or destroyed. Distinct types of ENSO events can have differentiated impacts (French and Mechler, 2017; Christidis et al., 2019; Takahashi and Martínez, 2019; Bertrand et al., 2020; Coayla and Culqui, 2020).

Irrigation, potable water, health and education infrastructures, as well as roads, bridges, cities, and housing buildings are frequently damaged or destroyed by extreme precipitations, having also impacts on sediment transport, river erosion and annual discharge (*very high confidence*) (Martínez et al., 2017; Morera et al., 2017; Isla, 2018; Rosales-Rueda, 2018; Salazar et al., 2018; Puente-Sotomayor et al., 2021). The increasing variability of precipitation has compromised rain-fed agriculture and power generation, particularly in the dry season (*high confidence*) (Bradley et al., 2006; Bury et al., 2013; Buytaert et al., 2017; Carey et al., 2017; Vuille et al., 2018; Orlove et al., 2019). For the Amazon-Andes transition zone, impacts of hydrological variability and transport of sediments have been noticed in riparian agriculture and biodiversity (*high confidence*) (Maeda et al., 2015; Espinoza et al., 2016; Vauchel et al., 2017; Ronchail et al., 2018; Ayes Rivera et al., 2019; Armijos et al., 2020; Figueroa et al., 2020; Pabón-Caicedo et al., 2020). Changes in seasonality and rain patterns are affecting coffee producers (Lambert and Eise, 2020).

Increases in vector-borne diseases can be related with the increase of rainfall and minimum temperatures during ENSO events (Stewart-Ibarra and Lowe, 2013) and the expansion of the diseases' altitudinal distribution (*high confidence*) (Lowe et al., 2017; Lippi et al., 2019; Portilla Cabrera and Selvaraj, 2020). ENSO events have been related with diseases such as dengue or leptospirosis (Quintero-Herrera et al., 2015; Sánchez et al., 2017; Arias-Monsalve and Builes-Jaramillo, 2019); they can also increase the incidence of Chikungunya (Section 7.2.2.1; Section 7.3.1.3). Precipitation, relative humidity and temperature have influenced dengue incidence over the last years (Mattar et al., 2013) (Table 12.1). Dengue cases are predicted to increase in the 1.5°C and the 3.7°C warming scenarios by 2050 and 2100, with increases ranging from 28,900 to 88,800 in Peru, 34,600 to 110,000 in Ecuador, and 97,400 to 317,000 in Colombia, although these scenarios do not consider the potential of vaccines or socioeconomic trajectories (Colón-González et al., 2018). Other studies found that *Aedes aegypti* (arbovirus vector) will shift into higher elevations, increasing the populations at risk (Lippi et al., 2019) (Figure 12.5). Climate change will contribute to increased malaria vectorial capacity (*high confidence*) (Laporta et al., 2015) (Section 7.2.2.1). Increases in minimum temperature were associated with historical malaria transmission when taking into consideration disease control interventions and climate factors (Fletcher et al., 2020). Figure 12.4 shows mixed changes in the number of months suitable for malaria transmission with low-lying areas in coastal regions becoming more suitable. Zoonotic tick-borne diseases and the epidemiology of tuberculosis are also influenced (Garcia-Solorzano et al., 2019; Rodriguez-Morales et al., 2019).

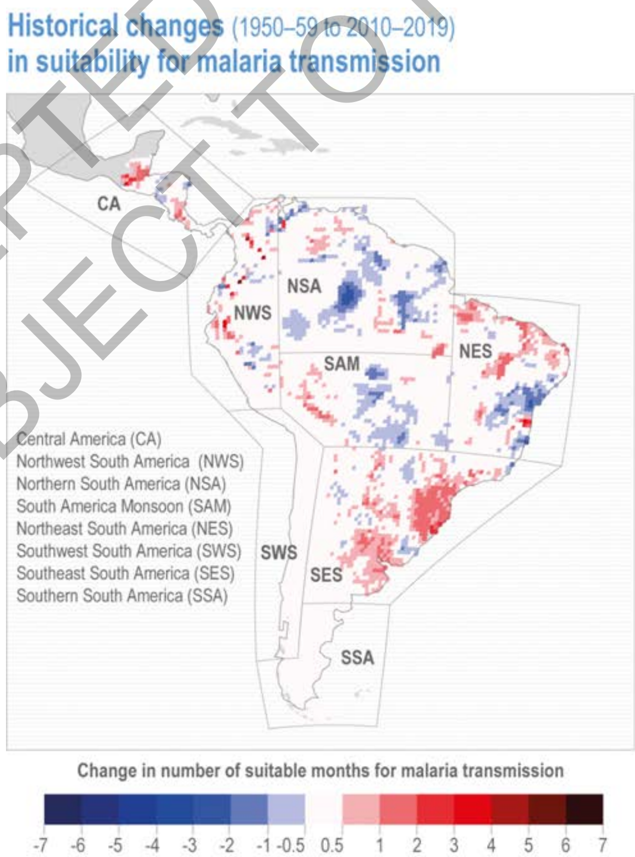


Figure 12.4: Change in the average number of months in a given year suitable for malaria transmission by *Plasmodium falciparum*, from 1950-1959 to 2010-2019. The threshold-based model used incorporates precipitation accumulation, average temperature, and relative humidity (Grover-Kopec et al., 2006; Romanello et al., 2021).

Accelerated warming is reducing tropical glaciers. Glacier volume loss and permafrost thawing will continue in all scenarios (*high confidence*) (Ranasinghe et al., 2021). On average, the tropical Andes have lost about 30% and more of their area since the 1980s (Basantes-Serrano et al., 2016; Mark et al., 2017; Thompson et al., 2017; Rabatel et al., 2018; Vuille et al., 2018; Reinthaler et al., 2019a; Seehaus et al., 2019; Masiokas et al., 2020). In a low emissions scenario, by the end of the 21st century, Peru will lose about 50% of the present glacier surface, while in a high-emission scenario there will remain very small areas of only about 3–5% on the highest peaks (Schauwecker et al., 2017).

Changing glaciers, snow and permafrost (Figure 12.13), in synergy with land use change, have implications for the occurrence, frequency and magnitude of derived floods and landslides (*high confidence*) (Huggel et al., 2007; Iribarren Anacona et al., 2015; Emmer, 2017; Mark et al., 2017). Also to landscape transformation through lakes' formation or drying, and to alteration of hydrological dynamics, with impacts on water for human consumption, agriculture, industry, hydroelectric generation, carbon sequestration and biodiversity (*high confidence*) (Michelutti et al., 2015; Carrivick and Tweed, 2016; Kronenberg et al., 2016; Emmer, 2017; Mark et al., 2017; Milner et al., 2017; Polk et al., 2017; Reyer et al., 2017; Young et al., 2017; Vuille et al., 2018; Cuesta et al., 2019; Drenkhan et al., 2019; Hock et al., 2019; Motschmann et al., 2020a).

Water flow has decreased in several basins as the Shullcas River in the Cordillera Huaytapallana in Peru and is expected to decrease in the near future in in places such as the Cordillera Blanca in Peru (*very high confidence*) (Baraer et al., 2012; Vuille et al., 2018; Somers et al., 2019; Molina et al., 2020). Disruptions in water flows will significantly degrade or disappear high-elevation wetlands (*high confidence*) (Bury et al., 2013; Dangles et al., 2017; Mark et al., 2017; Polk et al., 2017; Cuesta et al., 2019). Impacts on wetlands are affecting the wild vicuña and the domesticated alpaca (Duchicela et al., 2019). New lakes represent a source of future hazards and water scarcity, as well as an opportunity as water reservoirs (Colonia et al., 2017; Drenkhan et al., 2019). The timing and extent of peak water due to glacier shrinkage is spatially highly variable, and has passed for a large number of tropical Andes glaciers (Hock et al., 2019). Cities dependent on glacier melt have experienced high variability in domestic water supply (Chevallier et al., 2011; Soruco et al., 2015; Mark et al., 2017) as shown in Case Study 2.7.3, but the increase of the demand may also be determinant (Buytaert and De Bièvre, 2012). Water provision is related to socio economic issues (Drenkhan et al., 2015). Glacier retreat impacts Andean pastoralists (*high confidence*), as shown in Case Study 2.6.5.4.

NWS houses several global priority areas for biodiversity conservation, including the Tropical Andes and Tumbes-Chocó-Magdalena terrestrial biodiversity-rich spots (Cross-Chapter Paper 1.2.2; Manes et al., 2021) . Biodiversity in Tropical Andes and Tumbes-Chocó-Magdalena is projected to suffer negative impacts (*medium confidence: medium evidence, high agreement*) (Figure 12.9). Invasive plant species might benefit from climate change in these hotspots (Wang et al., 2017a). Species distribution is changing upslope due to increasing air temperature, leading to range contraction and local extinctions for highland species. Whereas, lowland species are experiencing range contractions at the rear end and expansions in the frontend, including vectors of diseases (*high confidence*) (Crespo-Pérez et al., 2015; Duque et al., 2015; Morueta-Holme et al., 2015; Moret et al., 2016; Aguirre et al., 2017; Cuesta et al., 2017a; Seimon et al., 2017; Fadrique et al., 2018; Tito et al., 2018; Zimmer et al., 2018; Cauvy-Fraunié and Dangles, 2019; Cuesta et al., 2019; Moret et al., 2020; Rosero et al., 2021). Vegetation in summits of the northern Andes is particularly vulnerable because of a high abundance of endemic species with narrow thermal niches, and lowland dispersal capacity in comparison to the Central Andes (Cuesta et al., 2020).

The upper limit of alpine vegetation (*paramo*) shifted upslope 500 m in the Chimborazo (Morueta-Holme et al., 2015). Yet, the upper forest limit (the ecotone between forest and alpine vegetation), is migrating at slower rates, or not migrating at all (Harsch et al., 2009; Rehm and Feeley, 2015b), so it is expected to be a major barrier to migration to several montane species, leading to population reductions and biodiversity losses (Lutz et al., 2013; Rehm and Feeley, 2015a). Shifts in tree species distribution may result in decreased above ground carbon stocks and productivity in tropical mountain forests (*high confidence*) (Feeley et al., 2011; Duque et al., 2015; Fadrique et al., 2018; Duque et al., 2021), a biomass loss that will only be partially offset through increased recruitment and growth of lowland species migrating upslope. Water scarcity can enhance tree mortality and decrease above ground carbon stocks (Álvarez-Dávila et al., 2017; McDowell et al., 2020). Agricultural frontier of crops, as potatoes or maize, is going upwards (*high confidence*), following the freezing level height upward displacement (Morueta-Holme et al., 2015; Skarbø and VanderMolen, 2016; Schauwecker et al., 2017; Vuille et al., 2018). Modelling exercises agree with the observed impacts in species, ecosystem processes, crop impacts and related pests and diseases (*high confidence*) (Cernusak et al., 2013; Tovar et al., 2013; Ramirez-Villegas et al., 2014; Ovalle-Rivera et al., 2015; van der Sleen et al., 2015; Lowe et al., 2017). Agricultural options are changing as a result of intra seasonal temperature variation (Ponce, 2020). Changes in timing and amount of precipitation are also impacting agriculture (Table 12.4; Heikkinen, 2017; Altea, 2020) .

Species distribution is changing in dry lowland forests, where deforestation is the more intense driver and climate change is intensely acting (Aguirre et al., 2017; Manchego et al., 2017). Extinctions in amphibians have been related with temperature raises acting in synergy with diseases (Catenazzi et al., 2014). The fungus *Batrachochytrium dendrobatidis* successfully accompanied and caused disease in high-elevation Andean frogs as they expanded their ranges to reach 5200–5400 m (Seimon et al., 2017). Several groups of freshwater species of the tropical Andes represent 35% of threatened freshwater species in the world (Gardner and Finlayson, 2018). Potential impacts of species turnover in key areas for biodiversity conservation have been identified (Cuesta et al., 2017b).

Climate change related hazards could foster rural poverty, and its impacts have led to the modification of agriculture calendars and irrigation adjustments (Postigo, 2014). Livestock is reducing due to rising temperatures, changing water flows and diminishing of pastures, particularly cattle and pig production (Bayer et al., 2014; Tapasco et al., 2015; Bergmann et al., 2021). In some cases farmers respond to extreme temperatures by increasing use of land and crop intensity (Aragón et al., 2021). Climate change has and will prompt internal and international migrations (Løken, 2019; Bergmann et al., 2021). A change in fire regimes and fire risk is expected in highland ecosystems, although it is difficult to determine the influence of human activities and climate change influence on fire patterns (Oliveras et al., 2014; Oliveras et al., 2018; Armenteras et al., 2020).

12.3.3 Northern South America (NSA) Sub-region

12.3.3.1 Hazards

A significant increase in the intensity and frequency of warm extremes and length of heat waves, and decrease in the frequency of cold extremes (Skansi et al., 2013) was *likely* observed (Figure 12.6; Donat et al., 2013; Almeida et al., 2017; WGI AR6 Table 11.13, Seneviratne et al., 2021). Precipitation showed increasing trends in annual and wet season totals over the eastern part and decreasing trends of the dry season (Almeida et al., 2017). Increase in the frequency of anomalous severe floods (Gloor et al., 2015) was observed but insufficient data coverage for extreme precipitation and trends in available data result in *low confidence* (Avila-Diaz et al., 2020; Dereczynski et al., 2020; Dunn et al., 2020; Sun et al., 2021) (WGI AR6 Table 11.14) (Seneviratne et al., 2021). Droughts presented mixed trends between subregions, but evidences indicate increasing length of dry periods (*low confidence*) (Skansi et al., 2013; Marengo and Espinoza, 2016; Spinoni et al., 2019; Avila-Diaz et al., 2020; Dereczynski et al., 2020; Dunn et al., 2020) (WGI AR6 Table 11.15) (Seneviratne et al., 2021) (WGI AR6 Table 12.3) (Ranasinghe et al., 2021).

An overall increase in temperature by the end of century is projected for all the seasons, from 2 to 6°C depending on the scenario (Chou et al., 2014). Projections also suggest increases in the intensity and frequency of hot extremes and decreases in the intensity and frequency of cold extremes (*very likely* for a 2ºC GWL) (López-Franca et al., 2016) (WGI AR6 Table 11.13) (Seneviratne et al., 2021). In all the region, extreme maximum temperature estimates under the RCP4.5 scenario are projected to increase. Tropical major cities are expected to be strongly affected by heat waves and daily record temperatures (Feron et al., 2019).

A decrease in precipitation over the tropical region but regional changes, such as increases in rainfall amounts in western NSA of up to 40 mm, are expected by mid-century under RCP8.5 (Teichmann et al., 2013; Sánchez et al., 2015). Changes in the dry season in the central part of South America due to the late onset and late retreat of monsoon, decreases in precipitation over the Amazon and central Brazil are expected (Coppola et al., 2014; Giorgi et al., 2014; Llopart et al., 2014). And with *medium confidence*: increase in the frequency and geographic extent of meteorological drought in the eastern Amazon, and the opposite in the west (Duffy et al., 2015). A decreasing of total annual precipitation, but increase in heavy precipitation (Seiler et al., 2013; Chou et al., 2014) are projected for a 2ºC GWL (Figure 12.6; WGI AR6 Table 11.15; Seneviratne et al., 2021).

Mean precipitation will decrease and heavy precipitation, aridity and drought will increase with *medium confidence,* mean temperature, extreme heat, fire weather, coastal and oceanic climate impact drivers all of them will increase with *high confidence* (Sun et al., 2019) (WGI AR6 Table 12.6; WGI AR6 Figure 12.8) (Ranasinghe et al., 2021).

12.3.3.2 Exposure

In NSA the percentage of the national population living in Low Elevation Coastal Zones (LECZ) and exposed to Sea Level Rise (SLR) is 68% for Suriname, 56% for Guyana and 6% Venezuela (Nagy et al., 2019). In these countries, exposure of populations, land areas and built capital to coastal floods is projected to continue and increase (Neumann et al., 2015; Reguero et al., 2015).

In the Amazon basin, approximately 80% of the population is concentrated in cities due to migrations in search of improvements in education, job opportunities, health and goods and services (Eloy et al., 2015; Pinho et al., 2015). These populations settle in areas prone to flooding combined with various levels of sanitation due to limited economic access to areas of lower risk (Pinho et al., 2015; Mansur et al., 2016; Andrade and Szlafsztein, 2018; Parry et al., 2018). In these areas, poor urban planning and high population densities increase exposure levels (Mansur et al., 2016). In this context, 41% of the total population of urban centres, of the Amazon Delta and Estuaries (ADE) are exposed to flooding (Mansur et al., 2016), while in Santarem, population and infrastructure are highly exposed to floods and flash floods (Andrade and Szlafsztein, 2018).

Exposure of the Brazilian Amazon to severe to extreme drought has increased from 8% in 2004/2005, to 16% in 2009/2010 and 16% in 2015/2016 (Anderson et al., 2018b); a similar trend is reported in other regions (Table 12.3). During the extreme drought of 2015/2016 in the Amazonian forests 10% or more of the area showed negative anomalies of the Minimum Cumulative Water Deficit (Anderson et al., 2018b). This extreme drought also caused an increase in the occurrence and spread of fires in the basin (*medium confidence: medium evidence, high agreement*) (Aragão et al., 2018; Lima et al., 2018; Silva Junior et al., 2019; Bilbao et al., 2020).The exposure to anomalous fires in ecosystems such as savannas, more fire-prone, increases the exposure and vulnerability of adjacent forest ecosystems not adapted to fire, such as seasonally flooded forests (Bilbao et al., 2020; Flores and Holmgren, 2021).

12.3.3.3 Vulnerability

NSA is one of the most vulnerable subregions in the region, after CA, as evidenced by its very high vulnerability in four of the six sectors assessed (Figure 12.7). LECZ of Venezuela, Guyana and Suriname are highly vulnerable to climate change due to SLR (*high confidence*) (CAF, 2014; Mycoo, 2014; Reguero et al., 2015; Villamizar et al., 2017; Nagy et al., 2019). In Guyana, the combined effect of increased rainfall intensity and SLR has caused flooding over the past two decades, increasing the vulnerability of the agriculture sector (Tomby and Zhang, 2019).

The unprecedented extreme events of floods (2009, 2012 and 2014) and drought (2010) in the Amazon basin led to increased societies vulnerability (*medium confidence*: *medium evidence, high agreement*) (Mansur et al., 2016; Debortoli et al., 2017; Marengo et al., 2018; Menezes et al., 2018). The disruption of the region natural hydrology dynamics, as a consequence of extreme events increases the sensitivity of the food and transport systems of the Indigenous Peoples and rural resource-dependent communities (Pinho et al., 2015).

Migration by Indigenous Peoples and rural resource-dependent communities to cities have increased due to urbanization, development of extractive activities, agroindustry and infrastructure. Upon migrating, they are forced to abandon their livelihoods in order to acquire temporary jobs and to live in poverty and exclusion conditions on the periphery of the city (Cardoso et al., 2018). Between 60–90% of the population in the urban centres of ADE live in conditions of moderate to high degree of vulnerability (Mansur et al., 2016) (Figure 12.7). Amazon populations located in remote urban centres with limited or non-existing roads are more vulnerable to extreme events in relation to more connected urban centres (Parry et al., 2018). These highly vulnerable circumstances reduce the adaptive capacity of these populations (Cardoso et al., 2018). Nevertheless, the dynamics of the adaptive capacity of the Indigenous Peoples and rural resource-dependent communities is a complex issue. There is robust and growing literature showing that resource-dependent communities located in remote areas, address climate anomalies by reducing the vulnerability of socio-ecological systems through Indigenous knowledge and local knowledge (*high confidence*) (Mistry et al., 2016; Vogt et al., 2016; Bilbao et al., 2019; Bilbao et al., 2020; Camico et al., 2021).

Amazonian forests constitute one of the major carbon (C) sinks on Earth (Pan et al., 2011), playing a pivotal role in the climate system and regional balance of C and water (Marengo et al., 2018; Molina et al., 2019). Deforestation, temperature increase and any factor affecting the forests ecosystem dynamics will have an impact on the atmospheric CO_2 concentration and hence on the global climate (Ruiz-Vásquez et al., 2020; Sullivan et al., 2020).There is robust scientific evidence of the high vulnerability of the Amazonian forests to increasing temperature and repeated extreme drought events (*high confidence*) (Figure 12.7; Brienen et al., 2015; Olivares et al., 2015; Feldpausch et al., 2016; Zhao et al., 2017; Anderson et al., 2018b; Anjos and De Toledo, 2018; Yang et al., 2018; Barkhordarian et al., 2019; Sampaio et al., 2019; Rammig, 2020; Sullivan et al., 2020) .

12.3.3.4 Impacts

Suriname has experienced coastal erosion and flooding, causing damage to infrastructure, agriculture and ecosystems while Georgetown has suffered a significant number of floods (CAF, 2014). In Guyana, coastal flooding has negatively impacted agricultural activity (Tomby and Zhang, 2018) (Figure 12.9). Sugarcane production has been one of the most impacted cash-crops. The impact on sugar production has affected Guyana's sugar industry (Tomby and Zhang, 2019). Among the main impacts observed in the sugar industry are an increase in production costs, greater use of pesticides and fertilizers, and a reduction in workers' income (Tomby and Zhang, 2018).

Indigenous Peoples and resource-dependent rural communities in the Amazon have been impacted over the last decade by extreme drought and flood events in various dimensions of their livelihoods (Pinho et al., 2015). Food security has been strongly impacted since it is based on fishing and small-scale agriculture, two sectors highly vulnerable to climate change. During extreme events, fishing decreases due to limited access to fishing grounds (*medium confidence*: *low evidence, high agreement*) (Figure 12.9; Pinho et al., 2015; Camacho Guerreiro et al., 2016. Overfishing, deforestation and dam construction are a threat to fishing in the subregion (Lopes et al., 2019) and therefore contribute to exacerbating the impacts of climate change. Small scale agriculture practices (e.g., floodplain agriculture and slash and burn), are highly coupled with natural hydrological cycles and therefore severely affected by extreme events (Figure 12.9; Cochran et al., 2016. Livelihoods are also impacted by disruptions in land and river transport, restrictions in drinking water access, increased incidence of forest fires and disease outbreaks (*medium confidence*: *medium evidence, high agreement*) (Figure 12.9; Marengo et al., 2013; Pinho et al., 2015; Marengo and Espinoza, 2016; Marengo et al., 2018). In addition, flood events have caused losses of homes and disruption of public and commercial services (Figure 12.9; Parry et al., 2018).

Several vector-driven diseases such as malaria and leishmaniasis are endemic of Amazon region, however socio-environmental changes are altering their natural dynamics (Confalonieri et al., 2014b). An important relationship between the outbreak of infectious diseases and changes in climatic events (e.g., droughts, floods, heat waves, ENSO) or environmental events (e.g., deforestation, dam construction and habitat fragmentation) have been found for the Brazilian Amazon (*medium confidence*: *medium evidence, high agreement*) (Pan et al., 2014; Filho et al., 2016; Nava et al., 2017; Ellwanger et al., 2020). These impacts are more severe in poor populations with limited access to health services (Pan et al., 2014; WHO and UNFCCC, 2020). In the case of Venezuela, the impact of climate change on the epidemiology of malaria has been studied, showing significant influence on transmission in the Amazonia area of the country (Figure 12.4; Laguna et al., 2017) . Other studies from Venezuela have documented the role of ENSO in dengue outbreaks (Vincenti-Gonzalez et al., 2018). Table 12.1 shows the changes observed in reproduction potential for dengue in the different subregions due to changes in rainfall and temperature. Forest fires are a major concern to public health in the region as they relate to an increase in hospital admissions due to respiratory problems, mainly among children and the elderly (Figure 12.5). The amount of air pollutants detected is sometimes higher than that observed in large urban areas, especially during dry seasons when biomass burning increases (Aragão et al., 2016; de Oliveira Alves et al., 2017; Paralovo et al., 2019).

Table 12.1: Environmental suitability for the transmission of dengue by *Aedes aegypti* as modelled by the influence of temperature and rainfall on vectorial capacity and vector abundance; this is overlaid with human population density data to estimate the reproduction potential for these diseases (R_0, the expected number of secondary infections resulting from one infected person). The Southwest South America (SWS) and Southern South America (SSA) subregions are not presented, as the vector is not abundant in these areas and the estimated R_0 is lower than 0.01. Data derived from Romanello et al. (2021).

Subregion	Average R_0 1950-1954	Average R_0 2016-2020	Absolute change in R_0 from 1950-54 to 2016-20	% change in R_0 from 1950-54 to 2016-21
Central America (CA)	3.00	3.53	0.53	18%
Northwest South America (NWS)	1.85	2.40	0.55	30%
Northern South America (NSA)	1.31	2.05	0.74	56%
South America Monsoon (SAM)	0.93	1.67	0.74	80%
Northeast South America (NES)	2.11	2.47	0.36	17%
Southeast South America (SES)	0.64	0.81	0.17	26%

Climate change impacts have also been observed in ocean, coastal ecosystems (coral reefs and mangroves), Exclusive Economic Zones (EEZ) and saltmarshes in NSA; further impacts are expected in coral reefs, estuaries, mangroves and EEZs in the sub-region (Figure 12.9). Species in freshwater ecoregions (e.g., the Orinoco and Amazon Rivers and their flooded forests) are predicted to suffer a decrease in range and climatic suitability (*medium confidence: low evidence, high agreement*) (Cross-Chapter Paper 1.2.3; Manes et al., 2021) . A significant decrease in climate refugia (90%) for multiple vertebrate and plant species in the region has been projected for a 4ºC scenario, with considerable benefits of mitigation and reducing risks to 40% for a 2ºC scenario (Warren et al., 2018).

Droughts in 2009/2010 and 2015/2016 increased tree mortality rate in Amazon forests (Doughty et al., 2015; Feldpausch et al., 2016; Anderson et al., 2018b), while productivity didn't show a consistent change; some authors report a drop in productivity (Feldpausch et al., 2016) and others found no significant changes (Brienen et al., 2015; Doughty et al., 2015). Nevertheless the combined effect of increasing tree mortality with variations in growth, results in a long-term decrease in C stocks in forest biomass compromising their role of these forests as C sink (*high confidence*) (Brienen et al., 2015; Rammig, 2020; Sullivan et al., 2020) (Figure 12.9). Under the RCP8.5 scenario for 2070, drought will increase the conversion of rainforest to savannahs (*medium confidence*: *medium evidence, high agreement*) (Anadón et al., 2014; Olivares et al., 2015; Sampaio et al., 2019). The transformation of rainforest into savannahs brings forth biodiversity loss and alterations in ecosystem functions and services (*medium confidence*: *medium evidence, high agreement*) (Anadón et al., 2014; Olivares et al., 2015; Sampaio et al., 2019). In the Amazon basin, the synergic effects of deforestation, fire, expansion of the agricultural frontier, infrastructure development, extractive activities, climate change and extreme events may exacerbate the risk of savannisation (*medium confidence*: *medium evidence, high agreement*) (Nobre et al., 2016b; Bebbington et al., 2019; Sampaio et al., 2019; Rammig, 2020).

12.3.4 South America Monsoon (SAM) Sub-region

12.3.4.1 Hazards

Temperature extremes have *likely* increased in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Donat et al., 2013; Bitencourt et al., 2016) (WGI AR6 Table 11.13) (Seneviratne et al., 2021). In a vast transition zone between the Amazon and the Cerrado Biomes within the region, analysis of seasonal precipitation trends suggested that almost 90% of the observational sites showed reduced in the length of the rainy season in the region (Debortoli et al., 2015), on a period from 1971 to 2014 (Marengo et al., 2018), confirming the growth in length of the dry season. Changes in the hydrological and precipitation regimes, characterized by reduction in rainfall in Southern Amazonia, contrasting to an increase in the northwest Amazonia, and overall increases in extreme precipitation and in the frequency of Consecutive Dry Days, is being reported by several authors (Fu et al., 2013; Almeida et al., 2017; Marengo et al., 2018; Espinoza et al., 2019a) with *low confidence* (WGI AR6 Table 11.14; Seneviratne et al., 2021) due to insufficient data coverage and trends in available data generally not significant.

The Amazon has been identified as one of the areas of persistent and emergent regional climate change hotspots in response to various representative concentration pathways (Diffenbaugh and Giorgi, 2012). In Bolivia, CMIP3/5 models projected an increase in temperature (2.5ºC–5.9ºC), with seasonal and regional differences. In the lowlands, both ensembles agreed on less rainfall (–19%) during drier months (June–August and September–November), with significant changes in inter-annual rainfall variability, but disagreed on changes during wetter months (January–March) (Seiler et al., 2013). As a consequence of higher temperatures and reduced rainfall, an increased water deficit would be expected in the Brazilian Pantanal (Marengo et al., 2016; Bergier et al., 2018; Llopart et al., 2020) with *high confidence*. The largest increases in warmer days and nights, and aridity, drought and significant increases in fire occurrence are calculated over the Amazon area (Huang et al., 2016). Over all the region, by mid-century (RCP4.5) there is *medium confidence* of increase of river and pluvial floods, aridity and mean wind speed, and extreme heat, fire weather and drought are projected to increase with *high confidence* (WGI AR6 Table 12.6; Ranasinghe et al., 2021).

12.3.4.2 Exposure

A large expansion in cropland area (soybean, corn and sugarcane) was observed in the past two decades in SAM, in response to an increased local and global demand for biofuels and agricultural commodities (*high confidence*) (Lapola et al., 2014; Cohn et al., 2016). Feedbacks to the climate system resulting from such land-use changes are intricate. The clear-cutting of Amazon forest and Cerrado savannah in the region lead to a local warming due to an increase in the energy balance and evapotranspiration (Malhado et al., 2010), contrastingly the replacement of pasture by agriculture leads to local cooling effect, due to changes in the surface albedo (*medium confidence: medium evidence, medium agreement*). Deforestation of the Amazon for pastures and soybean have decreased evapotranspiration during drought months and caused a localized lengthening of the dry season in Northwest SAM by 6.5 (± 2.5) days since 1979 (*medium confidence: medium evidence, medium agreement*) (Fu et al., 2013).

It is not surprising therefore that while SAM is the region in CSA that experienced the highest temperature increase in the last century, it is where most of the fire spots in the sub-continent are located, owing also to the prevalent use of fires in pasture lands (*medium confidence: medium evidence, high agreement*) (Bowman et al., 2009). Recently, da Silva Junior et al. (2020) reported 6,708,350 and 6,188,606 fire foci in Cerrado and Amazonia, between 1999 and 2018, corresponding to 80% of the total observed in Brazil. The occurrence of extreme droughts has affected the carbon and water cycles in large areas of the Amazon Forest (*high confidence*) (Lapola et al., 2014; Agudelo et al., 2019), in particular in its southern and eastern portions, where deforestation rates are higher. The loss of carbon in the Amazon region considering the combined effect of land use change in the southern portion of the region, bordering Cerrado and Pantanal, and global carbon emission scenarios, can be up to 38% at 4ºC of warming, but limited to 8% if the Paris agreed limit of 1.5°C is achieved (*medium confidence, medium evidence, high agreement*) (Burton et al., 2021), driving the region to be a net carbon source to the atmosphere (Gatti et al., 2021). A recent extreme drought was estimated to affect the photosynthetic capacity of 400,000 km^2 of the forest (Anderson et al., 2018b), nevertheless there are considerable uncertainties regarding the effects of CO_2 fertilization in tropical forests and ecosystems (*medium confidence: medium evidence, high agreement*) (Sampaio et al., 2021). Extreme drought events increase forest vulnerability to fire, directly affecting the biodiversity, the forest structure and its plant species distribution (*high agreement*) (Brando et al., 2014). Production sectors are also exposed. SAM is pointed out as a region where agricultural production will be especially impacted by climate change, affecting production of annual crops, fruits and livestock (*medium confidence: medium evidence, high agreement*) (Lapola et al., 2014; Zilli et al., 2020).

12.3.4.3 Vulnerability

The largest expanses of remaining vegetation in the Cerrado biome are located in SAM, but the region shows low number of protected areas (only 7.5% inside protected areas), which will leave fauna and flora with little room for moving across the landscape in the face of climate change. Protected areas —Indigenous lands included— have markedly detained forest clear-cutting in the Amazon deforestation arc (most of which is inside SAM) (*high confidence*) (Nolte et al., 2013). However nearly one hundred protected areas in the Amazon, Cerrado and Pantanal biomes inside SAM have been identified as highly or moderately vulnerable to future climate change and demand deep adaptation interventions (*medium confidence: medium evidence, high agreement*) (Feeley and Silman, 2016; Lapola et al., 2019b). Yet, the maintenance of these protected areas or even the halting of deforestation may do little to impede a large-scale ecosystem shift, persistently, to an alternative state (crossing a tipping point) of the Amazon forest or even more subtle changes caused by climate change in the region (*medium confidence: medium evidence, high agreement*) (Aguiar et al., 2016a; Boers et al., 2017; Lapola et al., 2018; Lovejoy and Nobre, 2018).

The agriculture in the region is highly dependent on the climate (*high confidence*), responsible for ¾ of the variability in agricultural yields in the region (Table 12.4). Irrigation is an important strategy for agriculture production in part of the region, nevertheless not accounting to more than 8% of the total agricultural area in South America and 7% in Central America (OECD and FAO, 2019). This practice faces potential impacts from reduction in surface water availability in future climate scenarios (Ribeiro Neto et al., 2016; Zilli et al., 2020), enhanced by non-climate drivers such as land use changes (*medium confidence: medium evidence, high agreement*) (Spera et al., 2020). The remaining fluctuation on yields relates to issues of infrastructure, market, economy, policy and social aspects. Good infrastructure, transport logistics, quality of roads and storage, strongly influences the vulnerability of the agriculture sector (Figure 12.7).

The combined effect of extreme climate events and ecosystem fragmentation, e.g., by deforestation or fire, lead to changes in forest structure, with the death of taller trees and reduction in diversity of plant species, loss of productivity and carbon storage (*high agreement*) (Brando et al., 2014; Reis et al., 2018). The rise of the large-scale soybean agroindustry in the early 2000's led to a faster increase in human development indicators in some regions, tightly linked to the agricultural production chain (*high confidence*) (Richards et al., 2015). Such a development also came at a considerable cost for the environment (e.g., Neill et al. (2013)) and the regional climate, even though a moratorium implemented in 2006 to refrain new soy plantations on deforested areas reduced deforestation by a factor of five (*high confidence*) (Macedo et al., 2012; Kastens et al., 2017). The same sort of supply chain interventions along with incentive-based public policies applied to the beef supply chain could minimize the need for agricultural expansion in the SAM deforestation frontier (*medium confidence: medium evidence, high agreement*) (Nepstad et al., 2014; Pompeu et al., 2021).

SAM has a low population density, and the majority of population is located in cities. The population of some of these cities are indicated as highly vulnerable considering the enormous social inequalities embedded in these cities (*high confidence*) (Filho et al., 2016). Inequalities and uneven access to infrastructure, housing and health support, increase population vulnerability to atmospheric pollution and drier conditions (*high confidence*) (Rodrigues et al., 2019; IPAM, 2020; Machado-Silva et al., 2020).

12.3.4.4 Impacts

The Amazon and the Cerrado are amongst the largest and unique phytogeographical domains in South America. The Brazilian Cerrado is amongst the richest biodiversity in the world, with more than 12,600 plant species, being 35% endemic (*high confidence*) (Forzza et al., 2012). Historic land cover change and concurrent climate change in the region strongly impacted the biodiversity and led to the extinction of 657 plant species for the Cerrado, which is more than four-fold the global recorded plant extinctions (*high confidence*) (Strassburg et al., 2017; Green et al., 2019). Effects of climate change, expressed by drought and heat waves, lead to plant stress, compromising growth and increasing mortality (Yu et al., 2019). The fauna dependent on dew water was strongly impacted due to a temperature rise of 1.6ºC from 1961 to 2019 (*medium confidence: medium evidence, medium agreement*) (Hofmann et al., 2021). Modelling outcomes project impacts in forest ecosystems in the region, with persistent warming and significant moisture reduction (Anjos et al., 2021), leading to a potential change in the ecosystem structure and distribution in the region (*medium confidence: medium evidence, medium agreement*) (Government of Brazil, 2020).

The observed impact on plant species in SAM is projected to worsen in a warmer world (Warszawski et al., 2013). An increasing dominance of drought-affiliated genera of tree species has been reported in the southern part of the Amazon forest in the last 30 years (*medium confidence: medium evidence, medium agreement*) (Esquivel-Muelbert et al., 2019). Due to the tight relation of drought and fire occurrence, an increase of 39 to 95% of burned area is modelled to impact the Cerrado region under RCP4.5 and RCP8.5, while under RCP2.6, a 22% overshoot in temperature is estimated to impact the area in 2050 decreasing to 11% overshoot by 2100 (Silva et al., 2019d), leading to high impact on agriculture production (*high confidence*).

SAM hosts the headwaters of important SA rivers such as the Paraguay, Madeira, Tocantins-Araguaia and Xingu. The impact from climate change is expressed differently among several sub-regions. Extreme floods in Southern Amazon and Bolivian Amazon floodplains were described and related to exceptionally warm subtropical South Atlantic ocean (*high confidence*) (Espinoza et al., 2014), causing high economic impact (losses in crop and livestock production and infrastructure) and number of fatalities (*very high confidence)* (Ovando et al., 2016). Contrastingly, decline in stream flow, particularly in the dry season, expressed by the ratio between runoff and rainfall, is observed for the southern part of the Amazon basin (*high evidence*) (Molina-Carpio et al., 2017; Espinoza et al., 2019b; Heerspink et al., 2020). Observed precipitation reduction in the Cerrado region impacted main water supply reservoir for important cities in the Brazilian central region, leading to a water crisis in 2016/2017 (Government of Brazil, 2020) and affecting energy hydropower generation (Ribeiro Neto et al., 2016). Modelling studies project decreases in river discharge rate in the order of 27% for the Tapajós basin and 53% for the Tocantins-Araguaia basin for the end of the century, which may affect freshwater biodiversity, navigation and generation of hydroelectric power (*medium confidence: medium evidence, high agreement*) (Marcovitch et al., 2010; Mohor et al., 2015). This region also holds one of the largest floodplains in the globe, the Pantanal. The climatic connection of Pantanal regions to the Amazon, and the influence of deforestation in local precipitation (Marengo et al., 2018) has implications for conservation of ecosystem services and water security in Pantanal (*high confidence*) (Bergier et al., 2018). Impacts of extreme drought, with increasing numbers of dry days, and peak of fire foci was recently reported (*robust evidence*) (Lázaro et al., 2020; Garcia et al., 2021). Projected impacts of climate change shall lead to profound changes in the annual flood dynamics for the Pantanal wetland, altering ecosystem functioning and severely affecting biodiversity (*high confidence*) (Thielen et al., 2020; Marengo et al., 2021)

Soybean and corn yields, in the Cerrado region, will suffer one of the strongest negative impacts under RCP4.5 and RCP8.5 scenarios estimate and will demand high investments for adaptation should it continue to be cultivated in the same localities as today (*high confidence*) (Oliveira et al., 2013; Camilo et al., 2018). Changes in precipitation patterns were related to reduction of agriculture productivity and revenues in the southern portion of the Amazon region (*medium confidence: medium evidence, high agreement*) (Costa et al., 2019; Leite-Filho et al., 2021). As such, the future socio-economic vigour of the region will be, to a large extent, connected to an unlikely stability of the regional climate and eventual fluctuations of global markets potentially affecting the agricultural supply chain (*high confidence*) (Nepstad et al., 2014).

Observations from recent past droughts in SAM indicates how the incidence of respiratory diseases may worsen under a drier and warmer climate. Northwest SAM had a ~54% increase in the incidence of respiratory diseases associated with forest fires during the 2005 drought compared to a no-drought 10-year mean (*high confidence*) (Ignotti et al., 2010; Pereira et al., 2011; Smith et al., 2014). It is estimated that more than 10 million people are exposed to forest fires in the deforestation arc, a region comprising several Brazilian states in the southern and western parts of the Amazon forest, with several impacts on human health including potential exacerbation the COVID-19 crisis in Amazonia (*medium confidence: medium evidence, high agreement*) (de Oliveira et al., 2020) (Table 12.5). Increases in hospital admissions, asthma, DNA damage and lung cell death due to inhalation of fine particulate matter, represents an increase in public health system costs (*high confidence*) (Ignotti et al., 2010; Silva et al., 2013; de Oliveira Alves et al., 2017; Machin et al., 2019).The patchy landscape created by forest clearing contribute to a rising risk of zoonotic disease emergence by increasing interactions between wildlife, livestock and humans (*medium confidence: low evidence, medium agreement*) (Dobson et al., 2020; Tollefson, 2020). Recent studies also suggested the influence of climate change in zoonotic diseases, such as Orthohantavirus and Chapare virus infections, rodent-borne diseases, in some areas of Bolivia (Escalera-Antezana et al., 2020a; Escalera-Antezana et al., 2020b). Extreme fluctuation in the river level in the amazon was associated to a significant increase in the incidence of diarrhoea, leptospirosis and dermatitis (de Souza Hacon et al., 2019; Government of Brazil, 2020). A comprehensive characterization of future heatwaves, and alternative RCPs scenarios, Brazilian urban areas at SAM region are projected to face increasing related mortality from 400 to 500% in the period from 2031 to 2080 compared to the period of 1971–2020, under the highest emission scenario and high-variant population scenario (*medium confidence: low evidence, medium agreement*) (Guo et al., 2018). Table 12.2 shows the increase in days of exposure to heatwaves already observed in the region.

Table 12.2: Average change in the mean number of days exposed to heatwaves (defined as a period of at least two days where both the daily minimum and maximum temperatures are above the 95th percentile of their respective climatologies) in the population over 65 years of age in 2016-2020 relative to 1986-2005. Temperature data taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset; calculations derived from Romanello et al. (2021).

Country	Number of additional days of heatwave exposure in 2016-2020 relative to 1986-2005
Argentina	4.9
Belize	8.8
Bolivia	2.2
Brazil	3.1
Chile	3.3
Colombia	9.3
Costa Rica	0.8
Ecuador	7.6
El Salvador	2.2
Guatemala	8.4
Guyana	8.2
Honduras	11.2
Nicaragua	2.2
Panama	2.6
Paraguay	2.6
Peru	3.6
Suriname	15.2
Uruguay	2.7
Venezuela	8.5

The high risk of floods (high-frequency and high-incurred damage) is centred in the Brazilian states of Acre, Rondônia, Southern Amazonas and Pará (Andrade et al., 2017). Global-scale studies indicate an increase of flood risk for the SAM region during the 21st century (consistent with floods that are more frequent) (*high confidence*) (Hirabayashi et al., 2013; Arnell et al., 2016; Alfieri et al., 2017). Higher emission scenarios result in substantially higher flood risks than low emission scenarios (Alfieri et al., 2017).

12.3.5 Northeast South America (NES) Sub-region

12.3.5.1 Hazards

The region has *likely* experienced an increase in temperature, with significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Donat et al., 2013) (WGI AR6 Table 11.13, Seneviratne et al., 2021).

A decrease in the frequency and magnitude of extreme precipitation was observed but with *low confidence*, due to insufficient data coverage and trends in available data generally not significant. An increase in drought duration was observed with *high confidence* but *medium confidence* on the increase of drought intensity (WGI AR6 Table 11.14, Seneviratne et al., 2021). Table 12.3 shows the estimates of changes in land area per subregion affected by drought events, being this subregion which presented the highest changes in CSA.

Table 12.3: Change in the percentage of land area affected by extreme drought in 2010-19, with respect to 1950-59 using the Standardised Precipitation-Evapotranspiration Index (SPEI); extreme drought is defined as SPEI ≤ -1.6 (Federal Office of Meteorology and Climatology MeteoSwiss, 2021). Data derived from Romanello et al. (2021).

	Average change in the percentage of land area in drought in 2010-19 with respect to 1950-59		
Subregion	**At least 1 month in drought**	**At least 3 months in drought**	**At least 6 months in drought**
Central America (CA)	38.8%	17.6%	6.1%
Northwest South America (NWS)	51.8%	25.3%	7.0%
Northern South America (NSA)	52.5%	18.3%	2.5%
South America Monsoon (SAM)	48.0%	34.4%	12.2%
Northeast South America (NES)	64.5%	38.4%	12.0%
Southeast SouthAmerica (SES)	16.4%	6.7%	0.4%
Southwest South America (SWS)	20.5%	13.9%	7.5%
Southern South America (SSA)	-23.5%	-8.8%	--

The projected warming for the extreme annual maximum temperatures over NES is TXx: +2°C for the 1.5°C scenario and about +2.5°C for 2°C scenario (Hoegh-Guldberg et al., 2018). An increased number of tropical nights with minimum temperatures exceeding the 20°C threshold is projected (Orlowsky and Seneviratne, 2012). In general, extreme heat will increase and cold spells decrease with *high confidence*. A decrease in total precipitation is projected with *high confidence* with an increase in heavy precipitation events and an increase in dryness (*medium confidence*). Increase in drought severity due to the combination of increased temperatures, less rainfall, and lower atmospheric humidity (5 to 15% relative humidity reduction) create water deficits, projected for the entire region after 2041 (3–4 mm day^{-1} reduction), particularly over western NES and over the semiarid region (Marengo and Bernasconi, 2015; Marengo et al., 2017). Fire will significantly increase (*high confidence*) (Figure 12.6).

12.3.5.2 Exposure

NES is home to about 60 million people (estimate from IBGE (2019)), with >70% living in urban areas (data from IBGE (2010); Silva et al. (2017)), and high poverty levels (> 50%, data from IBGE (2003)). People are exposed to intense drought and famine (*high confidence*), and about 94% of the region has moderate to high susceptibility to desertification (Marengo and Bernasconi, 2015; Spinoni et al., 2015; Vieira et al., 2015; Mariano et al., 2018; Tomasella et al., 2018; Marengo et al., 2020c). The most severe dry spell of 2012–2013 affected about 9 million people, which were exposed to water, food and energy scarcity (Marengo and Bernasconi, 2015).

People, infrastructure and economic activities are exposed to sea level rise in the 3800 km of coastline (*medium confidence*). The high concentration of cities on the coast is a concern (Martins et al., 2017), with all state capital cities but one on the coast, totalling almost 12 million exposed people (estimate from IBGE (2019)). The ports of São Luís, Recife and Salvador are important exporters of Brazilian commodities, and the beaches in the subregion are an international touristic destination, producing considerable revenues (Pegas et al., 2015; Ribeiro et al., 2017).

Natural systems in NES are also exposed to climate change. In terrestrial ecosystems, 913,000 km^2 of NES' dry forest Caatinga vegetation (Silva et al., 2017) is exposed to predicted increase in dryness. Despite what has been previously suggested, the Caatinga has high biodiversity and endemism (Silva et al., 2017), which is exposed to habitat reduction due to climate change and agriculture expansion (Silva et al., 2019b). Fifty-two percent of the freshwater fish (203 species) are endemic (Lima et al., 2017) and are exposed to predicted reduction in river flow due to climate change (Marengo et al., 2017; de Jong et al., 2018). The coastal waters contain a separate marine ecoregion due to its uniqueness (Spalding et al., 2007). The region is responsible for 99% of the Brazilian shrimp production, exposed to sea level rise and increases in ocean temperature and acidification (Gasalla et al., 2017). Most coral reefs in the Southern Atlantic Ocean are along NES's coast (Leão et al., 2016), increasing its conservation and touristic value. The 685 km^2 of coral reefs along NES's coast (likely underestimated - Moura et al. (2013); UNEP-WCMC et al. (2018)) are exposed to increased sea temperatures.

12.3.5.3 Vulnerability

NES is the world's most densely populated semi-arid land and its population is highly vulnerable to droughts (*high confidence*), which have well-documented impacts on water and food security, human health and well-being in the region (e.g., Confalonieri et al. (2014a); Marengo et al. (2017); Bedran-Martins et al. (2018)) (Figure 12.7). The region's relative low economic development and poor social and health indicators increase vulnerability, especially of poor farmers and traditional communities (Confalonieri et al., 2014a; Bech Gaivizzo et al., 2019). In state capital cities, about 45% of the population live in poverty (data from IBGE (2003)), often in slums with already deficient water supply and sewage systems and poor access to health and education. Climate change will increase pressures on water availability, threatening water, energy and food security (Marengo et al., 2017).

Natural systems in NES are also vulnerable (Figure 12.7). The Caatinga vegetation is particularly sensitive to variations in water availability and climate change (Seddon et al., 2016; Rito et al., 2017; Dantas et al., 2020). It has already lost about 50% of its original vegetation cover (Souza et al., 2020), with only about 2% of the remaining vegetation within fully protected areas (CNUC and MMA, 2020). Caatinga's high vulnerability to climate change is further increased by the extensive conversion of native vegetation (*high confidence*) (Rito et al., 2017; Silva et al., 2019b; Silva et al., 2019c).

Studies with terrestrial animals show that habitat loss increases the vulnerability of species to climate change (*high confidence*) (de Oliveira et al., 2012; Arnan et al., 2018; da Silva et al., 2018b). NES' coral reefs have shown some resilience to bleaching, but vulnerability is intensified by the synergism between chronic heat stress caused by increased sea surface temperature (Teixeira et al., 2019) and other well-documented stressors, such as coastal runoff, urban development, marine tourism, overexploitation of reef organisms and oil extraction (*high confidence*) (Figure 12.8; Leão et al., 2016).

12.3.5.4 Impacts

Impacts of intense drought have been reported in NES since 1780, with severe losses in agricultural production, livestock death, increase in agricultural prices, and human death (Figure 12.9; Marengo et al., 2017; Martins et al., 2019; Government of Brazil, 2020; Marengo et al., 2020c; Silva et al., 2020) (). The rural population already suffers from natural water scarcity in the countryside. In 2012, the drought was responsible for reducing up to 99% of the corn production in Pernambuco state (Government of Brazil, 2020). A predicted increase in drought, coupled with inadequate soil management practices by small farmers and agribusiness, increases the region's susceptibility to desertification (Spinoni et al., 2015; Vieira et al., 2015; Mariano et al., 2018; Tomasella et al., 2018; Marengo et al., 2020c). In NES, 70,000 km^2 have reached a point at which agriculture is no longer possible (Government of Brazil, 2020). Intense droughts has triggered migration to urban centres in and outside NES (Confalonieri et al., 2014a; Government of Brazil, 2020). More than 10 million people have been impacted by the drought of 2012/14 in the region, which was responsible for water shortage and contamination, increasing death by diarrhoea (Marengo and Bernasconi, 2015; Government of Brazil, 2020).

There is growing evidence on the impacts of climate change on human health in NES, mostly linked to food and water insecurity caused by recurrent long droughts (e.g., gastroenteritis and hepatitis) (*high confidence*) (Figure 12.9; Sena et al., 2014; de Souza Hacon et al., 2019; Marengo et al., 2019; Government of Brazil, 2020; Salvador et al., 2020) . From 2071 to 2099, thermal conditions in NES might improve for vectors of dengue, chikungunya and Zika (de Souza Hacon et al., 2019). Additionally, a high risk of mortality associated with climatic stress in the period 2071–2099 is expected in São Francisco river basin (de Oliveira et al., 2019; de Souza Hacon et al., 2019).

Recent studies predict strong negative impact of climate change on NES' agriculture (*high confidence*) (Ferreira Filho and Moraes, 2015; Nabout et al., 2016; Gateau-Rey et al., 2018) (Figure 12.9; Table 12.4). NES concentrates the bulk of the predicted loss of regional gross domestic product associated with agriculture in Brazil (Ferreira Filho and Moraes, 2015; Forcella et al., 2015). Although agriculture gives a modest contribution to the regions' economy, its drop could have a severe impact on the poorest rural household, by shrinking the agricultural labour market and increasing food prices (Ferreira Filho and Moraes, 2015; Government of Brazil, 2020). Expected increase in dryness is also predicted to impact the region's hydroelectric power generation (Marengo et al., 2017; de Jong et al., 2018). Sea level rise has also been reported to impact coastal cities such as Salvador, destroying urban constructions (Government of Brazil, 2020). Sea level rise, increased ocean temperature and acidification may also negatively impact NES's shrimp aquaculture production (Figure 12.8; Gasalla et al., 2017) . Along with climate change, overfishing has driven exploited marine fish species to collapse (Verba et al., 2020).

Biodiversity in NES is highly threatened by climate change in terrestrial (*medium confidence: medium evidence, high agreement*) and freshwater (*low confidence: low evidence, high agreement*) ecosystems (Figure 12.9). There are few studies projecting the likely impact of climate change on NES' biodiversity, especially on its endemic freshwater fish. Recent studies have already reported the reduction in several endemic plant species affecting pollination and seed dispersal (Bech Gaivizzo et al., 2019; Cavalcante and Duarte, 2019; Silva et al., 2019b). Studies with terrestrial animals predict that most groups would be negatively impacted by climate change (de Oliveira et al., 2012; Arnan et al., 2018; da Silva et al., 2018b; Montero et al., 2018). Changes in the abundance of coral reef community and extreme reduction in coral cover have been observed in NES (de Moraes et al., 2019; Duarte et al., 2020). A number of observed coral bleaching events associated with abnormal increase in sea temperatures have occurred in NES (Krug et al., 2013; Leão et al., 2016; de Oliveira Soares et al., 2019) (Figure 12.8), but thus far mortality remained low and corals have been able return to normal values or remain stable after sea water temperature rise (*medium confidence: medium evidence, high agreement*) (Leão et al., 2016). Mangroves in the region have shown increased mortality, but have also expanded their range inland (Figure 12.6; Godoy and Lacerda, 2015; Cohen et al., 2018) . Future projections include mangrove landward expansion and lower migration rates by 2100 (Cohen et al., 2018).

12.3.6 Southeast South America (SES) Sub-region

12.3.6.1 Hazards

The increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes was observed with *high confidence* (Rusticucci et al., 2017; Wu and Polvani, 2017) (WGI AR6 Table 11.13) (Seneviratne et al., 2021). There is *low confidence* that the decrease in hot extremes over SES is related with an increase of extreme precipitation (Wu and Polvani, 2017).

Over SES most of the stations have registered an increase in annual rainfall, largely attributable to changes in the warm season; this is one of few sub-regions where a robust positive trend in precipitation and significant intensification of heavy precipitation has been detected since the beginning of the 20th century (*high confidence*) but with *medium confidence* in a reduction of hydrological droughts (Vera and Díaz, 2015; Saurral et al., 2017; Lovino et al., 2018; Avila-Diaz et al., 2020; Carvalho, 2020; Dereczynski et al., 2020; Dunn et al., 2020; Marengo et al., 2020a; Olmo et al., 2020) (WGI AR6 Table 11.14) (Seneviratne et al., 2021). A higher observed frequency of extratropical cyclones in the region has been detected (Parise et al., 2009; Reboita et al., 2018) with three cyclogenetic foci: South-southeast Brazil, extreme south of Brazil and Uruguay, and southeast of Argentina.

In Montevideo, mean sea-levels increased over the past 20 years, reaching 11 cm from 1902 to 2016, and a recent accelerating trend has been observed (Gutiérrez et al., 2016b). A value of water-level rise and its acceleration for Buenos Aires was calculated from a record of annual mean water levels obtained from hourly levels (1905–2003). Annual mean water level showed a trend of $+1.7 \pm 0.05$ mm yr^{-1}, and an acceleration of $+0.019 \pm 0.005$ mm yr^{-2} (D'Onofrio et al., 2008).

Increasing trends in mean air temperature and extreme heat, and decreasing cold spells are projected (*high confidence*) (WGI AR6 Table 12.6Ranasinghe et al., 2021). The increase in the frequency of warm nights is larger than that projected for warm days consistent with observed past changes that have been related with changes in cloud cover that affect differently daytime temperatures as compared to night time temperatures (López-Franca et al., 2016; Menéndez et al., 2016; Feron et al., 2019).

Increases in mean precipitation (*high confidence*), pluvial floods and river floods are projected (*medium confidence*) (Nunes et al., 2018) (WGI AR6 Table 12.6) (Ranasinghe et al., 2021). Droughts in the La Plata Basin will be more frequent in the medium-term (2011-2040) and the distant future (2071-2100) (with respect to the 1979-2008 period), but also shorter and more severe, for the more extreme emission scenario (RCP8.5) (*low confidence*) (Carril et al., 2016).

Negative trend in the annual number of cyclone events in the long-term future of 3.6 to 6.5% (2070-2098) are projected, that showed an increase of 3 to 11% (2080-2100 for the A1B scenario) (Grieger et al., 2014; Reboita et al., 2018). All coastal and oceanic climate impact drivers (relative sea level, coastal flood and erosion, marine heatwaves and ocean aridity) are expected to increase by mid-century in the RCP8.5 scenario (*high confidence*) (WGI AR6 Table 12.6, Ranasinghe et al., 2021).

12.3.6.2 Exposure

Higher temperatures and rising sea levels, changes in rainfall patterns, increased frequency and intensity of extreme weather events, could generate risks to the energy and the infrastructure sectors, and to the mining and metals network. In the Plata basin, urban floods have become more frequent, causing infrastructure damage and sometimes substantial mortality (*high confidence*) (Barros et al., 2015; Zambrano et al., 2017; Nagy et al., 2019; Mettler-Grove, 2020; Morales-Yokobori, 2021; Oyedotun and Ally, 2021). A large increase in landslides and flash floods is also predicted for the Brazilian portion of SES, where they are responsible for the majority of the deaths related to natural disasters in the country (*high confidence*) (Debortoli et al., 2017; Haque et al., 2019; Saito et al., 2019; Marengo et al., 2020d; da Fonseca Aguiar and Cataldi, 2021). Due to uncontrolled urban growth, 21.5 million people living in the large Brazilian cities of São Paulo, Rio de Janeiro and Belo Horizonte (estimate from IBGE (2019)) are expected to be exposed to water scarcity, despite great water availability in the region (*medium evidence, medium agreement*) (Marengo et al., 2017; Lima and Magaña Rueda, 2018; Marengo et al., 2020b).

The expected increase in temperature also exposes the population in large cities to extreme heat. Urban heat islands are already a reality in large cities in the region, such as Buenos Aires (*high confidence*) (Wong et al., 2013; Sarricolea and Meseguer-Ruiz, 2019; Wu et al., 2019; Mettler-Grove, 2020), Rio de Janeiro (*high* *confidence*) (Ceccherini et al., 2016; Neiva et al., 2017; Geirinhas et al., 2018; Peres et al., 2018; Sarricolea and Meseguer-Ruiz, 2019; Wu et al., 2019; de Farias et al., 2021) and São Paulo (*high confidence*) (Mishra et al., 2015; Barros and Lombardo, 2016; Ceccherini et al., 2016; Vemado and Pereira Filho, 2016; de Azevedo et al., 2018; Lima and Magaña Rueda, 2018; Ferreira and Duarte, 2019; Lapola et al., 2019a; Sarricolea and Meseguer-Ruiz, 2019; Wu et al., 2019), with reported impact on human health in the latter (*medium confidence: medium evidence, medium agreement*) (e.g., Araujo et al. (2015); Son et al. (2016); Diniz et al. (2020)). These cities alone represent 22 million people exposed to increased heat (estimate from IBGE (2019) and from INDEC (2010)).

The sub-region presents a high frequency of occurrence of intense severe convection events (Section 12.3.6.1). Because of this situation, strong winds from the south or southeast and high water levels affect the whole Argentine coast, as well as the Rio de la Plata shores, Uruguay, and southern Brazil (Isla and Schnack, 2009). The coast of the Plata River is subject to flooding when there are strong winds from the southeast (sudestadas). As sea level rises as a result of global climate change, storm surge floods will become more frequent in this densely populated area, particularly in low-lying areas (*high confidence*) (Figure 12.8; D'Onofrio et al., 2008; Nagy et al., 2014a; Santamaria-Aguilar et al., 2017; Nagy et al., 2019 impacts and adaptation in Central and South America coastal areas; Cerón et al., 2021) .

The region's natural systems are also exposed to climate change. SES region houses two important biodiversity hotspots, with high levels of species endemism: the Cerrado and the Atlantic Forest, where about 72% of Brazil's threatened species can be found (PBMC, 2014).

12.3.6.3 Vulnerability

The Rio de la Plata basing and the city of Buenos Aires are highly vulnerable to recurring floods, and the increasing number of newcomers to the area reduce the collective cultural adaptation developed by older neighbours (*high confidence*) (Barros, 2006; Nagy et al., 2019; Mettler-Grove, 2020; Morales-Yokobori, 2021; Oyedotun and Ally, 2021). Extreme events, including storm surges and coastal inundation/flooding caused injuries and economic/environmental losses on the urbanized coastline of Southern Brazil (States of Sao Paulo and Santa Catarina) (*high confidence*) (Muehe, 2010; Khalid et al., 2020; Ohz et al., 2020; de Souza and Ramos da Silva, 2021; Quadrado et al., 2021; Silva de Souza et al., 2021).

Cities like Rio de Janeiro and São Paulo are overpopulated, where most people live in poor conditions of inadequate housing and sanitation, such as slums, with little and no trees and high temperatures. These people have low access to sanitation, public health and residential cooling and are vulnerable to the effects of heat islands on human comfort and health (Figure 12.7). These include cardiopulmonary and vector-borne diseases, and even death (*medium confidence: medium evidence, medium agreement*) (Araujo et al., 2015; Mishra et al., 2015; Geirinhas et al., 2018; Peres et al., 2018). Heat stress is known to worsen cardiovascular, diabetic and respiratory conditions (Lapola et al., 2019a). As an effect of Heat islands, these people are also vulnerable to injuries and casualties due to increased thunderstorms, causing economic losses and other social problems (Vemado and Pereira Filho, 2016).

12.3.6.4 Impacts

Despite the observed increase in rainfall amount in the region, between 2014 and 2016 Brazil endured a water crisis that affected the population and economy of major capital cities in the SES region Brazil (Blunden and Arndt, 2014; Nobre et al., 2016a). Extremely long dry spells have become more frequent in southeast of Brazil, affecting 40 million people and the economies in cities such as Rio de Janeiro, São Paulo and Belo Horizonte, which are the industrial pole of the country (*medium confidence: medium evidence, medium agreement*) (PBMC, 2014; Nobre et al., 2016a; Cunningham et al., 2017; Marengo et al., 2017; Lima and Magaña Rueda, 2018; Marengo et al., 2020b). It also impacted agriculture, affecting food supply and rural livelihoods, especially in Minas Gerais (Nehren et al., 2019). Agricultural prices increased by 30% in some cases and harvest yields of sugar cane, coffee and fruits suffered a reduction of 15–40% in the region. The number of fires increased by 150%, and energy prices increased by 20–25%, as most electricity from hydroelectric power (Nobre et al., 2016a). In Argentina, projected changes in hydrology of Andean rivers associated to glacier retreat are predicted to have negative impacts on the region's fruit production (*low evidence, medium agreement*) (Barros et al., 2015).

Heat islands affect ecosystems by increasing the energy consumption for cooling, the concentration of pollutants and the incidence of fires (*high confidence*) (Wong et al., 2013; Akbari and Kolokotsa, 2016; Singh et al., 2020b; Ulpiani, 2021). It also affects human health, as well increasing the incidence of respiratory, cardiovascular diseases (*medium confidence: medium evidence, medium agreement*) (Araujo et al., 2015; Barros and Lombardo, 2016; de Azevedo et al., 2018; Geirinhas et al., 2018).

Warming temperatures have been implicated in the emergence of dengue in temperate latitudes increasing populations of *Aedes aegypti* (*high confidence*) (Natiello et al., 2008; Robert et al., 2019; Estallo et al., 2020; Robert et al., 2020; López et al., 2021) (Table 12.1), and field studies have shown the role of local climate in vector activity (Benitez et al., 2021). Figure 12.5 shows the modelled transmission suitability for dengue for two climate change scenarios. Future increase in the number of months suited for transmission of dengue is highest in SES (see SM12.8 for additional information). There is additional evidence of the spread of arbovirus transmission into southern temperate latitudes (Basso et al., 2017), however a longer historical time series is needed to understand climate-disease interactions, given the relatively recent emergence in this region.

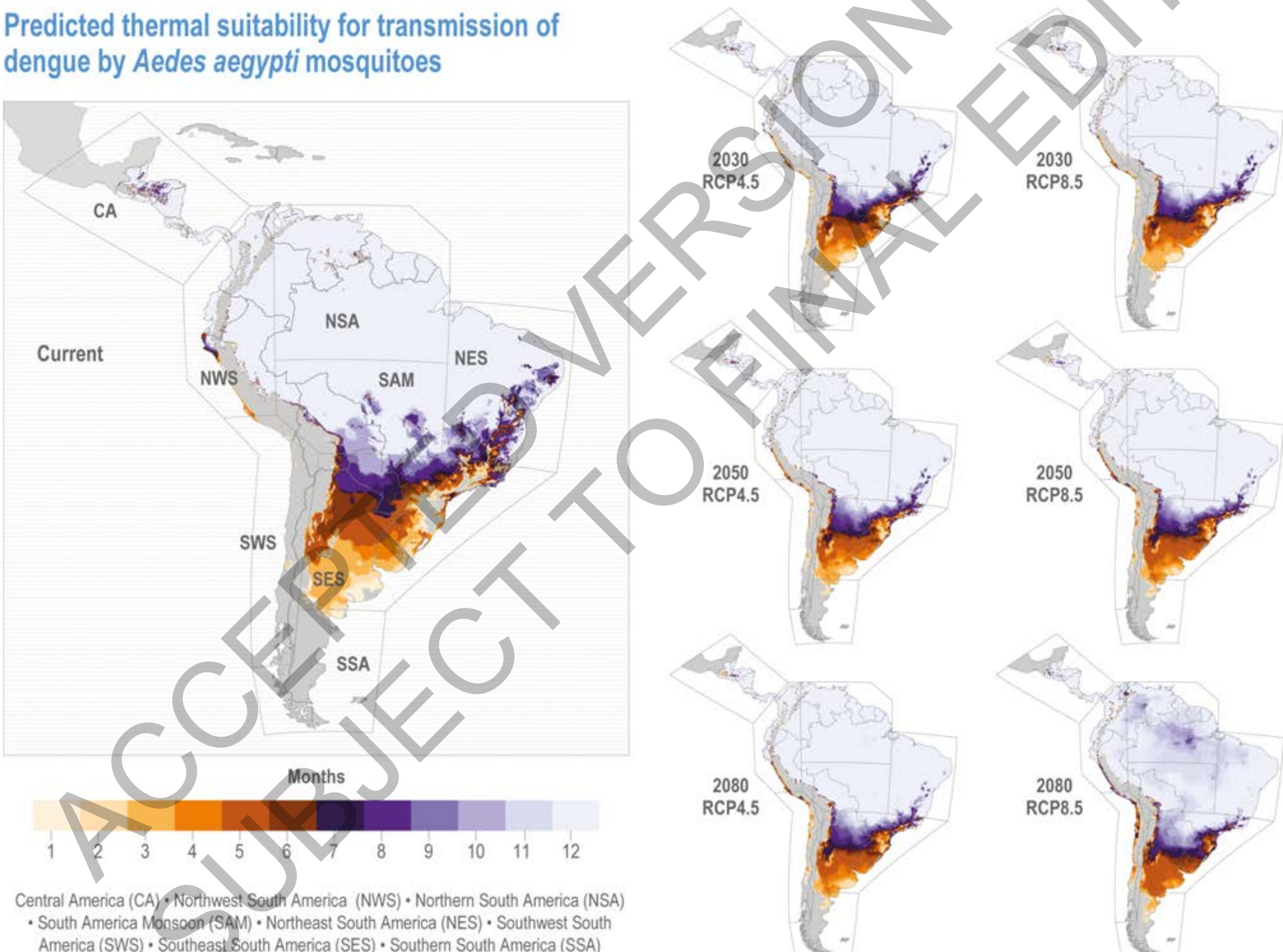


Figure 12.5: Predicted thermal suitability for transmission of dengue by *Aedes aegypti* mosquitoes, mapped as the number of months of the year suitable under baseline or current conditions (2015), and in 2030, 2050, 2080 under two representative concentration pathways, RCP4.5 and RCP8.5. Adapted from Ryan et al. (2019). See SM12.8 for additional data on population at risk for dengue and Zika in the subregions and methodological details.

Sea-level rise impacted the port complex in Santa Catarina, which during the last six years interrupted its activities 76 times due to strong winds or big waves with estimated losses varying between USD 25,000 and USD 50,000 for each 24 idle hours (Ohz et al., 2020). Historically, extratropical cyclones associated with frontal systems cause storm surges in Santos city. Although there are no fatality records, these events cause several socio-economic losses, especially in vulnerable regions including the Port of Santos, the largest port in Latin America (São Paulo). According to 88-year time span (1928-2016), the frequency of storm surge events were three times more frequent in the last 17 years (2000-2016), than in the previous period of 71 years (1928-1999) (Souza et al., 2019).

There are many projected impacts of climate change on natural systems. The impacts of sea-level rise are habitat destruction and the invasion of exotic species, affecting biodiversity and the provision of ecosystem services (Figure 12.8; Nagy et al., 2019) ().

SES is a global priority for terrestrial biodiversity conservation, housing two important biodiversity hotspots—the Atlantic Forest and Cerrado—which are among the World's most studied biodiversity-rich spots in terms of climate change impact on biodiversity, especially for terrestrial vertebrates (Cross-Chapter Paper 1.2.2; Manes et al., 2021) . An increasing number of studies show that the Atlantic Forest and Cerrado are at risk of biodiversity loss, largely due to projected reduction of species' geographic distributions in many different taxa (e.g., Loyola et al. (2012); Ferro et al. (2014); Loyola et al. (2014); Hoffmann et al. (2015); Martins et al. (2015); Aguiar et al. (2016b); Vale et al. (2018); Borges et al. (2019); Braz et al. (2019); Vale et al. (2021)). Cerrado savannas are projected to be the hotspot most negatively impacted by climate change within South America, mostly though range contraction of plant species (*very high confidence*), while the Atlantic Forest is projected to be highly impacted especially though the contraction of the distribution of endemic species (*very likely*) (Cross-Chapter Paper 1.2.2; Figure 12.10; Manes et al., 2021) . Reductions in species' distribution are also projected in the La Plata Basin for subtropical amphibians (Schivo et al., 2019) and the river tiger (*Salminus brasiliensis*), a keystone fish of economic value (Ruaro et al., 2019). Farming of mussels and oysters in the region is predicted to be negatively impacted by climate change, particularly sea-level rise, and ocean warming and acidification (Gasalla et al., 2017). Some more localized habitats are also at risk of losing area due to climate change, such as the meadows of northwest Patagonia (Crego et al., 2014) and mangroves of southern Brazil (Godoy and Lacerda, 2015). Predicted changes in global climate along with agricultural expansion will strongly affect South American wetlands, which comprise around 20% of the continent and bring many benefits, such as biodiversity conservation and water availability (Junk, 2013).

12.3.7 Southwest South America (SWS) Sub-region

12.3.7.1 Hazards

Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes have *likely* been observed for the region (Skansi et al., 2013; Ceccherini et al., 2016; Meseguer-Ruiz et al., 2018; Vicente-Serrano et al., 2018; Dereczynski et al., 2020; Dunn et al., 2020; Olmo et al., 2020) (WGI AR6 Table 11.13) (Seneviratne et al., 2021). In particular, a significant increment in the duration and frequency of heatwaves mainly in central Chile from 1961 to 2016 has been observed (Piticar, 2018).

A robust drying trend for Chile (30ºS–48°S) has been recorded (*medium confidence*) (Saurral et al., 2017; Boisier et al., 2018). However, inconsistent trends over the region in the magnitude of precipitation extremes with both decreases and increases (Chou et al., 2014; Giorgi et al., 2014; Heidinger et al., 2018; Meseguer-Ruiz et al., 2018) (WGI AR6 Table 11.14) (Seneviratne et al., 2021) have been observed (*low confidence*). The glacier equilibrium line altitude has presented an overall increase over central Chilean Andes (Barria et al., 2019).

For central Chile, a significant increase (5% to 20% in the last 60 years) in wave heights in the sea has been observed (Martínez et al., 2018). From 1982 to 2016, sea level at central Chile have increased 5 mm yr^{-1}, where El Niño events of 1982-1983 and 1997-1998 caused an extreme increase of 15 to 20 cm in the mean sea level (Campos-Caba, 2016; Martínez et al., 2018).

From 1946 to 2017, the number of fires and areas burned have increased significantly in Chile (*high confidence*) (González et al., 2011; Jolly et al., 2015; Úbeda and Sarricolea, 2016; de la Barrera et al., 2018; Urrutia-Jalabert et al., 2018). Fires are attributed to changes in the temperatures regimes (González et al., 2011; de la Barrera et al., 2018; Gómez-González et al., 2018) and precipitation regimes (*medium confidence*) (Gómez-González et al., 2018; Urrutia-Jalabert et al., 2018).

The glaciers of the Southern Andes (including the SWS and SSA regions) show the highest glacier mass loss rates worldwide (*high confidence*) contributing to sea level rise (Jacob et al., 2012; Gardner et al., 2013; Dussaillant et al., 2018; Braun et al., 2019; Zemp et al., 2019). Since 1985, the glacier area loss in the sub-region is in a range of 20 up to 60% (Braun et al., 2019; Reinthaler et al., 2019b).

Four sets of downscaling simulations based on the Eta Regional Climate Model forced by two global climate models (Chou et al., 2014) projected warmer conditions (more than 1°C) for all the sub-region by 2050 under the RCP4.5 scenario (*medium confidence*). Extremely warm December-January-February days as well as the number of heatwaves per season are expected to increase by 5–10 times in the northern Chile (Feron et al., 2019)*, likely* increasing in the intensity and frequency of hot extremes over all the region (WGI AR6 Table 11.13) (Seneviratne et al., 2021). Drier conditions (*medium confidence*), by mean of the decrease of total annual and extreme precipitations, are expected to increase for Southern Chile but inconsistent changes in the sub-region (*low confidence*) (Chou et al., 2014) (WGI AR6 Table 11.14) (Seneviratne et al., 2021) with *high confidence* on increase of fire weather and decrease of permafrost and snow extent (WGI AR6 Table 12.6, Ranasinghe et al., 2021).

Regional sea-level change for the region predicted by 2100 show that total mean SLR along the coast will lie between 34 cm and 52 cm for the RCP4.5 scenario, and between 46 cm and 74 cm for the RCP8.5 scenario with *high confidence* (Albrecht and Shaffer, 2016; WGI AR6 Table 12.6, Ranasinghe et al., 2021).

12.3.7.2 Exposure

There is *high confidence* that age and socio-economic status are key factors determining health exposure and quality of life in SWS where low-income areas show an insufficient number of public spaces to provide acceptable environmental quality in comparison with the high-income areas (Romero-Lankao et al., 2013; Fernández and Wu, 2016; Paz et al., 2016; Hystad et al., 2019; Smith and Henríquez, 2019; Jaime et al., 2020; Pino-Cortés et al., 2020).

Profound social inequalities, urban expansion and the inadequate city planning (e.g., drainage network) increase exposure to flooding events and landslides (*high confidence*) (Müller and Höfer, 2014; Rojas et al., 2017; Lara et al., 2018), heat hazards such as heatwaves (*high confidence*) (Welz et al., 2014; Qin et al., 2015; Inostroza et al., 2016; Welz and Krellenberg, 2016; Krellenberg and Welz, 2017), and the loss and fragmentation of green infrastructure (Hernández-Moreno and Reyes-Paecke, 2018). SWS cities show the highest levels of air pollution of CSA (*medium confidence: medium evidence*, *high agreement*) (Pino et al., 2015; Huneeus et al., 2020; González-Rojas et al., 2021), where the state air quality alerts have limited effect on protective health behaviours, being the public perception about air pollution highly dissimilar among the population (Boso et al., 2019). In particular, human communities living in coastal cities show a negative safety perception about the performance of the infrastructure and coastal defences to flood events (*low confidence*) (González and Holtmann-Ahumada, 2017; Igualt et al., 2019).

Although climate change is critically important for the current and future status of mining activity in SWS (Odell et al., 2018), and SWS areas subjected to mining activities are highly exposed to water risk (Northey et al., 2017), to date, there is *low evidence* of climate change impacting mining activities (Corzo and Gamboa, 2018; Odell et al., 2018).

12.3.7.3 Vulnerability

Rapid changes in temperature and precipitation regimes make terrestrial ecosystems highly vulnerable to climate change (*high confidence*) (Salas et al., 2016; Fuentes-Castillo et al., 2020) (Figure 12.7). Terrestrial ecosystems dominated by exotic species (e.g., pine) with lower landscape heterogeneity, degraded soils and close to settlements and roads are highly vulnerable to wildfires in comparison to forests dominated by native trees (*high confidence*) (Altamirano et al., 2013; Castillo-Soto et al., 2013; Cóbar-Carranza et al., 2014; Salas et al., 2016; Bañales-Seguel et al., 2018; Gómez-González et al., 2018; Sarricolea et al., 2020). Changes in the land use, artificial forestation, deforestation, agricultural abandonment and urbanization have provoked a permanent degradation of old-growth forest putting at risk the biodiversity, recreation and ecotourism (*medium confidence: medium evidence, high agreement*) (Rojas et al., 2013; Nahuelhual et al., 2014). Marine coastal ecosystems such as dunes, sandy beaches and wetlands show a high deterioration decreasing the ability to mitigate extreme events (*medium confidence: low evidence*, *high agreement*) (González and Holtmann-Ahumada, 2017; Ministerio de Medio Ambiente de Chile, 2019).

Water sector shows a very high vulnerability (*high confidence*) (Figure 12.7) mainly due the weak water governance focused on market aspects (e.g., inter-sectoral water transactions, setting rates, granting concessions, waiving the water right) (*high confidence*) (Hurlbert and Diaz, 2013; Valdés-Pineda et al., 2014; Barría et al., 2019; Hurlbert and Gupta, 2019; Muñoz et al., 2020a; Urquiza and Billi, 2020b). Potable water and adequate sanitization is available in SWS; however, water availability along Chile is unevenly distributed in rural communities (*high confidence*) (Valdés-Pineda et al., 2014; Nelson-Nuñez et al., 2019). Spatial differences on water availability are enhanced by the strong population growth, economic development, mining activities, and the high dependence of agriculture to irrigation (*high confidence*) (Stathatou et al., 2016; Northey et al., 2017; Fercovic et al., 2019). Droughts in SWS are a major threat to water security (*high confidence*) (Aitken et al., 2016; Núñez et al., 2017) as river streamflow are highly dependent on the inter-annual to decadal climate conditions, snow melting processes, rainfall events (Boisier et al., 2016), and impacted by land uses and changes in irrigated agriculture (*medium confidence: medium evidence, high agreement*) (Vicuña et al., 2013; Fuentes et al., 2021).

Energy and water needs of large-scale mining activities make this socio economic sector particularly vulnerable to climate change; additionally, the relative lack of power of resource-poor communities living in areas where such mining is making claims on water and energy resources renders these communities even more vulnerable (Odell et al., 2018). Given new conditions generated by changes in a growing demand and climate change, mining industries will need to increase resilience to extreme events; additionally, the declining concentrations of mineral of interest in the raw material require greater energy input for extraction and processing and new methods to avoid associated emissions are required (Hodgkinson and Smith, 2018).

Urban and agriculture sectors are vulnerable to climate change (*medium confidence: medium evidence, high agreement*) (Figure 12.7) increasing problems and demand for water (*high confidence*) (Monsalves-Gavilán et al., 2013; Meza et al., 2014; Fercovic et al., 2019). Important health problems (e.g., pathogenic infections, changes in vector-borne diseases, mortality by heat, lower neurobehavioral performance, among others) have been associated with agriculture, mining and thermal power production activities along SWS (*high confidence*) (Muñoz-Zanzi et al., 2014; Valdés-Pineda et al., 2014; Pino et al., 2015; Cortés, 2016; Berasaluce et al., 2019; Muñoz et al., 2019a; Ramírez-Santana et al., 2020).

The large-scale agricultural growth has increased the vulnerability to climate change by favouring the detriment of traditional agriculture, the homogenization of the biophysical landscape and the replacement of traditional crops and native forests with exotic species like pines and eucalyptus (*high confidence*) (Torres et al., 2015) where farmers' climate change perception is highly dependent on the education level and the access to meteorological information (*low confidence*) (Roco et al., 2015). Agricultural systems owned by Indigenous Peoples (i.e., Mapuche, Quechua and Aymara farmers) seem to present lower vulnerability to drought and higher response capacity than non-indigenous farmers thanks to the use of the traditional knowledge of specific management techniques and the tendency to conserve species or varieties of crops tolerant to water scarcity (*low confidence*) (Montalba et al., 2015; Saylor et al., 2017; Meldrum et al., 2018). Fishery and aquaculture-related livelihoods are vulnerable to climate and non-climate drivers (*medium confidence: medium evidence, high agreement)* such as sea surface warming and precipitation reduction (Handisyde et al., 2017; Soto et al., 2019; González et al., 2021), changes in upwelling intensity (*low confidence*) (Oyarzún and Brierley, 2019; Ramajo et al., 2020), eutrophication and harmful algal bloom (HAB) events (Almanza et al., 2019), the lack of observational elements and data management (Garçon et al., 2019), and events such as earthquakes and tsunamis (Marín, 2019).

Chile has experienced an accelerated economic growth which has reduced poverty, however important geographical, economic and educational inequalities are still present (Repetto, 2016). Chilean healthcare system has become more equitable and responsive to the population necessities (e.g., Health reform AUGE program); however, the high relative inequalities in terms of income (OECD, 2018), education level, and the rural–urban factor are determinants of the quality of care, the health system barriers, and the health differential access (*high confidence*) (Frenz et al., 2014). Exposure and vulnerability to psychosocial risks in SWS shows significant inequalities to natural disasters such as earthquakes according to socio-economic, geographic and gender factors (*high confidence*) (Labra, 2002; Vitriol et al., 2014; Quijada et al., 2018) which are increased by the absence of local planning and drills and the lack of coordination (Vitriol et al., 2014). Indigenous Peoples have the highest levels of vulnerability in Chile in terms of income, basic needs, and access to services to climate change (*low confidence*) (Parraguez-Vergara et al., 2016).

12.3.7.4 Impacts

Increasing temperatures in SWS have impacted temperate forests (*high confidence*) (Peña et al., 2014; Urrutia-Jalabert et al., 2015; Camarero and Fajardo, 2017; Fontúrbel et al., 2018; Venegas-González et al., 2018b; Peña-Guerrero et al., 2020). Increasing temperatures and decreasing precipitations have increased the impacts of wildfires on terrestrial ecosystems (*high confidence*) (Boisier et al., 2016; Díaz-Hormazábal and González, 2016; Martinez-Harms et al., 2017; de la Barrera et al., 2018; Gómez-González et al., 2018; Urrutia et al., 2018; Bowman et al., 2019), creating conditions for future landslides and floods (de la Barrera et al., 2018).

Future projections show important changes in the productivity, structure and biogeochemical cycles in SWS temperate and rainforests (*medium confidence: medium evidence, high agreement*) (Gutiérrez et al., 2014; Correa-Araneda et al., 2020), and their fauna (*low confidence*) (Glade et al., 2016; Bourke et al., 2018). The "Chilean Winter Rainfall-Valdivian Forests" is a biodiversity-rich spot (Manes et al., 2021) (Cross-Chapter Paper 1.2.2) projected to suffer habitat change, with loss of vegetation cover in the future due to climate change (*medium confidence: medium evidence, high agreement*) (Jantz et al., 2015; Mantyka-Pringle et al., 2015). Species are projected to suffer changes in their distribution, including decrease in climatic refugia for vertebrates (*low confidence*) (Cuyckens et al., 2015; Warren et al., 2018).

Increasing temperatures have enlarged the number and area extent of glacier lakes in Central Andes, Northern Patagonia and Southern Patagonia (*high confidence*) (Wilson et al., 2018), while decreased rainfall and rapid glacier melting have provoked changes in the environmental, biogeochemical and biological properties of the central-southern and Andes Chilean lakes (*low confidence*) (Pizarro et al., 2016).

Increasing glacier lake outburst floods (GLOF), ice and rock avalanches, debris flows, and lahars from ice-capped volcanoes have been observed in SWS (Iribarren Anacona et al., 2015; Jacquet et al., 2017; Reinthaler et al., 2019b). There is *low evidence* about the effects of warming and degrading permafrost on slope instability and landslides in these regions (Iribarren Anacona et al., 2015).

Increasing temperatures, decreasing precipitation regimes, and an unprecedented long-term drought have decreased the annual average rivers streamflow that supply SWS megacities such as Santiago (*high confidence*) (Meza et al., 2014; Muñoz et al., 2020a), with important and negative effects over the water quality (Bocchiola et al., 2018; Yevenes et al., 2018) threatening irrigated agriculture activities (*medium confidence: medium evidence, high agreement*) (Yevenes et al., 2018; Oertel et al., 2020; Peña-Guerrero et al., 2020). Large reductions in the groundwater availability of the SWS region (Meza et al., 2014) and a sustained decreasing of the mean annual flows (Ragettli et al., 2016; Bocchiola et al., 2018), especially during the snowmelt season (Vargas et al., 2013) have been observed in SWS. Drought has affected wetlands (*low confidence*) (Zhao et al., 2016; Domic et al., 2018), and desert ecosystems (*medium confidence: medium evidence, high agreement)* (Acosta-Jamett et al., 2016; Neilson et al., 2017; Díaz et al., 2019).

There is *low evidence* about shoreline retreat attributed to climate change (Martínez et al., 2018; Ministerio de Medio Ambiente de Chile, 2019) although increasing wind intensity along the central Chilean coast has caused important damages in the coastal infrastructure and buildings (Winckler et al., 2017) and changes of seawater properties and processes (*low confidence*) (Schneider et al., 2017; Aguirre et al., 2018). Ocean and coastal ecosystems in SWS are sensitive to upwelling intensity which affect the abundance, diversity, physiology and survivorship of coastal species (*high confidence*) (Anabalón et al., 2016; Jacob et al., 2018; Ramajo et al., 2020) (Figure 12.8). Increasing radiation and temperatures, and reduced precipitations in conjunction with increased nutrient load have increased HAB events producing massive fauna mortalities (*high confidence*) (León-Muñoz et al., 2018; IPCC, 2019b, SPM A8.2 and B8.3; Quiñones et al., 2019; Soto et al., 2019; Armijo et al., 2020). Multiple resources subjected to fisheries and aquaculture are highly vulnerable to storms, alluvial disasters, ocean warming, ocean acidification, increasing ENSO extreme events, and lower oxygen availability (*high confidence*) (Figure 12.8; García-Reyes et al., 2015; Silva et al., 2015; Duarte et al., 2016; Lagos et al., 2016; Navarro et al., 2016; Lardies et al., 2017; Duarte et al., 2018; IPCC, 2019b; Mellado et al., 2019; Ramajo et al., 2019; Silva et al., 2019a; Bertrand et al., 2020). Ocean and coastal ecosystems, especially the EEZ will be highly impacted by climate change in the near and long-term (*high confidence*) (Figure 12.8; Table SM12.3; Silva et al., 2015; Silva et al., 2019a).

Changes in the temperature and drought have impacted crops significantly (*medium confidence: medium evidence, high agreement*) (Ray et al., 2015; Zambrano et al., 2016; Lesjak and Calderini, 2017; Ferrero et al., 2018; Piticar, 2018; Haddad et al., 2019; Zúñiga et al., 2021). Table 12.4 shows the changes in crop growth duration, which affect the yields. Higher negative numbers then indicate yield reduction for the crop. Increasing temperatures and decreasing precipitation are expected to impact the agriculture sector (i.e., fruits crops, and forests) across the entire sub-region with the largest impacts in the northern and central zone (*high confidence*) (Mera et al., 2015; Zhang et al., 2015; Silva et al., 2016; Lizana et al., 2017; Reyer et al., 2017; Toro-Mujica et al., 2017; Beyá-Marshall et al., 2018; Lobos et al., 2018; O'Leary et al., 2018; Aggarwal et al., 2019; Ávila-Valdés et al., 2020; Fernandez et al., 2020; Melo and Foster, 2021). Observed impacts and future projections warn that increasing temperatures and decreasing precipitation will largely impact on water demand by agricultural sectors (*high confidence*) (Novoa et al., 2019; Peña-Guerrero et al., 2020; Webb et al., 2020). Extreme climate events have provoked that Indigenous Peoples (e.g., Mapuche, Uru and Aymara) suffer scarcity of water, reduction of agricultural production, and a displacement of their traditional knowledge and practices (*medium confidence: low evidence, high agreement*) (Parraguez-Vergara et al., 2016; Meldrum et al., 2018; Perreault, 2020).

Table 12.4: Average percentage change in crop growth duration for the period 2015-19. Crop growth duration refers to the time taken in a year for crops to accumulate the reference period (1981-2010) average growing season Accumulated Temperature Total (ATT). As temperatures rise, the ATT is reached earlier (higher negative changes), the crop matures too quickly, and thus yields are lower. "No data" means no data is available for the growth of that crop, in the specified region. NP means that the crop is not present in significant areas in that region. Data derived from Romanello et al. (2021).

Region	Winter wheat	Spring wheat	Rice	Maize	Soybean
Central America (CA)	-4.8%	No data	-1.9%	-5.0%	-4.7%
Northwest South America (NWS)	-3.8%	-5.2%	-5.2%	-5.6%	-3.1%
Northern South America (NSA)	NP	NP	-0.7%	-3.1%	0.0%
South America Monsoon (SAM)	-5.3%	-0.7%	-1.4%	-2.9%	-1.5%
Northeast South America (NES)	-1.0%	-1.3%	-0.7%	-3.5%	-2.6%
Southeast South America (SES)	-2.3%	-3.5%	-2.3%	-2.4%	-2.7%
Southwest South America (SWS)	-2.3%	-5.2%	-10.0%	-5.2%	No data
Southern South America (SSA)	-0.8%	-6.5%	No data	-1.6%	No data

SWS cities have been largely impacted by wildfires, water scarcity and landslides affecting highways and local roads, as well as, potable water supply (Sepúlveda et al., 2015; Araya-Muñoz et al., 2016). Increasing temperature and heat extreme events in cities have increased the demand for water, the damage of urban infrastructure (Monsalves-Gavilán et al., 2013), and accelerated the ageing and the death of trees (*high confidence*) (Moser-Reischl et al., 2019). Increasing temperature will modify the energy demand in cities in northern and central Chile (Rouault et al., 2019).

Increasing temperature, heat extreme events and air pollution in SWS have significantly impacted the population health (cardiac complications, heat stroke, and respiratory diseases) (*high confidence*) (Table 12.2; Leiva G et al., 2013; Monsalves-Gavilán et al., 2013; Pino et al., 2015; Herrera et al., 2016; Henríquez and Urrea, 2017; Ugarte-Avilés et al., 2017; de la Barrera et al., 2018; Johns et al., 2018; Bowman et al., 2019; González et al., 2019; Matus C and Oyarzún G, 2019; Sánchez et al., 2019; Terrazas et al., 2019; Cakmak et al., 2021; Zenteno et al., 2021).There is *low confidence* about area changes of Chagas disease (Tapia-Garay et al., 2018; Garrido et al., 2019), and transmission rates in the future (Ayala et al., 2019).

12.3.8 Southern South America (SSA) Sub-region

12.3.8.1 Hazards

There were inconsistent trends and insufficient data coverage about extreme temperatures and precipitation (*low confidence*) but with *medium confidence* an increase in the frequency of meteorological droughts was observed (Dereczynski et al., 2020; Dunn et al., 2020; WGI AR6 Tables 11.13, 11.14, 11.15, Seneviratne et al., 2021; WGI AR6 Table 12.3, Ranasinghe et al., 2021). An increase in precipitation in Trelew, no change for Comodoro Rivadavia, both stations located at Eastern Patagonia, and negative trends in austral summer rainfall in southern Andes were observed (Vera and Díaz, 2015; Saurral et al., 2017). Chile's wildfires in Patagonia (fire frequency and intensity) have grown at an alarming rate (Úbeda and Sarricolea, 2016). Decreasing rainfall pattern in Punta Arenas is closely associated with the variability at inter-annual to inter-decadal time scales of the main forcing system for climate in Patagonia. Snow Cover Extension (SCE) and Snow Cover Duration decreased by an average of ~13 ± 2% and 43 ± 20 days respectively from 2000 to 2016, due to warming rather than drying (Rasmussen et al., 2007). In particular, the analysis of spatial pattern of SCE indicates a slightly greater reduction on the eastern side (~14 ± 2%) of the Andes Cordillera compared to the western side (~12 ± 3%). The longest time series of glacier mass balance data in the Southern Hemisphere, the Echaurren Norte Glacier, lost 65% of its original area in the period 1955–2015 and disaggregated into two ice bodies in the late 1990s (Malmros et al., 2018; Pérez et al., 2018).

Mean temperatures in the SSA sub-region are projected to continue to rise up to +2.5°C in 2080 with respect to the present climatology (Kreps et al., 2012). A rise in temperature means that the isotherm of 0°C will move up the mountains leaving less surface for accumulation of snow (Barros et al., 2015).

An increase in the intensity and frequency of hot extremes and a decrease in the intensity and frequency of cold extremes is *likely* projected (WGI AR6 Table 11.13, Seneviratne et al., 2021); CMIP6 models project an increase in the intensity and frequency of heavy precipitation (*medium confidence*).

It is expected that an increase in the intensity of heavy precipitation, droughts and fire weather will intensify through the 21st century in SSA but mean wind will decrease (*medium confidence*) (Kitoh et al., 2011; WGI AR6 Tables 11.14 and Table 11.15, Seneviratne et al., 2021). The probability of having extended droughts, such as the recently experienced mega-drought (2010-2015), increases to up to 5 events/100 yr (Bozkurt et al., 2017). Snow, glaciers, permafrost and ice sheets will decrease with *high confidence* (WGI AR6 Table 12.6, Ranasinghe et al., 2021). The observed area and the elevation changes indicate that the Echaurren Norte Glacier may disappear in the coming years if negative mass balance rates prevail (*medium confidence*) (Farías-Barahona et al., 2019).

12.3.8.2 Exposure

Grasslands make a significant contribution to food security in Patagonia through providing part of the feed requirements of ruminants used for meat, wool and milk production. There is a lack of information regarding the combined effect of climate change and overgrazing and the consequences for pastoral livelihoods that depend on rangelands. Temperature and the amount and seasonal distribution of precipitation were important controls of vegetation structure in Patagonian rangelands (Gaitán et al., 2014). They found that over two-thirds of the total effect of precipitation on above-ground net primary production (ANPP) was direct, and the other third was indirect (via the effects of precipitation on vegetation structure). Thus, if evapotranspiration and drought stress increase as temperature increases and rainfall decrease in water-limited ecosystems, it would be expected a greater exposure of ranchers due to a reduction of stocking rate and therefore families' income (*medium confidence*). The number of farmers (mainly family enterprises) exposed to climatic hazards (drought) is approximately 70–80 thousand that have 14–15 million sheep in Argentina (Peri et al., 2021).

Argentinian Patagonia main cities have developed as the result of oil and gas extraction, which demand massive quantities of water due to fracking and drilling techniques. Vaca Muerta is the major region in South America where those techniques are used to extract oil and gas, and this will lead to an exacerbation of current water scarcity and to competition with irrigated agriculture (Rosa and D'Odorico, 2019) which in the context of drought may exacerbate socio-environmental conflicts (*medium confidence*).

12.3.8.3 Vulnerability

There are reports related to a decrease in survival, growth and higher vulnerability to drought and fire-severity for species of native forest due to climate change and wildfire (*high confidence*) (Mundo et al., 2010; Landesmann et al., 2015; Whitlock et al., 2015; Jump et al., 2017; Camarero et al., 2018; Venegas-González et al., 2018a). There is a reported coincidence between major changes in regional decline in the growth of forests with severe droughts due to climatic variations over northern Patagonia (Rodríguez-Catón et al., 2016). Once the forest decline begins, other contributing factors such as insects (e.g., defoliator outbreaks) increase the forest vulnerability or accelerate the loss of forest health of previously stressed trees (Piper et al., 2015). This region hosts unique temperate rainforests and it is particularly rich in endemic and long-lived conifer species (e.g., *Fitzroya cupressoides*), which may be vulnerable to declines in soil moisture availability (Camarero and Fajardo, 2017). Patagonia will probably be vulnerable by a decrease in precipitation regimes due to climate change, and consequently many species that rely on meadows in an arid environment will also be impacted (Crego et al., 2014). The floods triggered by strong ENSOs caused significant changes in the crop production (Isla et al., 2018).

The development of various human activities and water infrastructure are decreasing water sources, changing river basins from exoreic to endoreic and the disappearance of one lake in 2016 (Scordo et al., 2017). Numerous dams for irrigation, some also used for hydropower, have been and are planned to be built despite wind power generation potential (Silva, 2016). Oil and gas have played an important role in the rise of Neuquén-Cipolletti as Patagonia's most populous urban area, and in the growth of Comodoro Rivadavia, Punta Arenas, and Rio Grande, as well.

12.3.8.4 Impacts

The potential impact of climate change is of special concern in arid and semi-arid Patagonia, a >700,000 km^2 region of steppe-like plains in Argentina. Thus, melting snow and ice in the glaciers of Patagonia and the Andes will alter surface runoff into interior wetlands; sea level rise of between 20 and 60 cm will destroy coastal marshes; and an increase in extreme events, such as storms, floods, and droughts, will affect biodiversity in wet grasslands (*medium confidence: low evidence, high agreement*) (after Junk et al. 2013; Joyce et al. 2016). Three species of lizard from Patagonia are at risk of extinction as a result of global warming (Kubisch et al., 2016).

Patagonian ice fields in South America are the largest bodies of ice outside of Antarctica in the southern hemisphere. They are losing volume due partly to rapid changes in their outlet glaciers which end up in lakes or the oceans, becoming the largest contributors to eustatic sea level rise (SLR) in the world, per unit area (Foresta et al., 2018; Moragues et al., 2019; Zemp et al., 2019). Most calving glaciers in the Southern Patagonia ice field retreated during the last century (*high confidence*). Upsala Glacier retreat generated slope instability and a landslide movement destroyed the western edge in 2013. The Upsala Argentina Lake has become potentially unstable and may generate new landslides (Moragues et al., 2019). The climate effect on the summer stratification of piedmont lakes is another issue in relation to glacier dynamics (Isla et al., 2010).

Between 41º and 56° South latitude, the absolute glacier area loss was 5450 km^2 (19%) in the last ∼150 years, with an annual area reduction increase of 0.25% a^{-1} for the period 2005–2016 (Meier et al., 2018). The small glaciers in the north of the Northern Patagonian Ice field had over all periods the highest rates of 0.92% a^{-1}. In this sub-region, increased melting of ice is leading to changes in the structure and functioning of river ecosystems and in freshwater inputs to coastal marine ecosystems (*medium confidence: low evidence, high agreement*) (Aguayo et al., 2019). In addition, in the case of coastal areas, the importance of tides and rising sea levels in the behaviour of river floods has been demonstrated (Jalón-Rojas et al., 2018).

Suitable areas for meadows (very productive areas for livestock production) will decrease by 7.85% by 2050 given predicted changes in climate (*low confidence*) (Crego et al., 2014).

A major drought from 1998 to 1999 coincident with a very hot summer led to extensive dieback in a Nothofagus species (Suarez et al., 2004). In another dominant Nothofagus species, several periodic droughts have triggered forest decline as of the 1940s (Rodríguez-Catón et al., 2016).

Climate change impacted ocean ecosystems by reducing kelps coverage, increasing reproductive failure and chick mortality of penguins, and poleward expansion of saltmarshes in the Atlantic Patagonia. SSA houses the Patagonian Steppe Global-200 terrestrial ecoregion being a conservation priority at global scale, but with a clear lack of studies on likely future climate change impacts (Cross-Chapter Paper 1.2.2.2; Manes et al., 2021). The Patagonian Steppe may suffer pronounced expansion in invasive species' ranges under climate change (*low confidence*) (Wang et al., 2017a).

Fire has been found to promote or halt biological invasions (*medium confidence: medium evidence, high agreement*). For example, an analysis of *Pinus* spreading after wildfires in Patagonia reveals that there is a high risk of pines becoming invasive if ignition frequency increases as a result of climate change (Raffaele et al., 2016). According to Inostroza et al. (2016), the Magellan Region is one of the most fragile regions in Patagonia and despite its low population densities, it is under a silent process of anthropogenic alteration where between 53.1% and 68.1% of the area needs to be considered as influenced by human activity whom are occupying pristine ecosystems even extensive conservation designations (Inostroza et al., 2016). Fire exposure can result in several health problems for human populations; Table 12.5 shows that SSA is the region with the highest exposure to wildfire danger.

Table 12.5: Change in population-weighted exposure to very high or extremely high wildfire risk. Data derived from the Fire Danger Indices FDI produced by the Copernicus Emergency Management Service for the European Forest Fire Information System EFFIS (available at Copernicus Emergency Management Service (2021)). High and very high wildfire danger defined as FDI >= 5. Data derived from Romanello et al. (2021).

	Population-weighted mean days of exposure to extremely high and very high wildfire danger		
Subregion	**In 2001-04**	**In 2017-20**	**Change from 2001-04 to 2017-20**
Central America (CA)	30.4	26.9	-3.5
Northwest South America (NWS)	4.2	4.6	0.5
Northern South America (NSA)	19.7	21.2	1.5
South America Monsoon (SAM)	16.0	27.8	11.8
Northeast South America (NES)	47.9	53.3	5.4
Southeast SouthAmerica (SES)	4.2	8.2	4.0
Southwest SouthAmerica (SWS)	31.9	58.4	26.5
Southern South America (SSA)	88.7	104.9	16.2

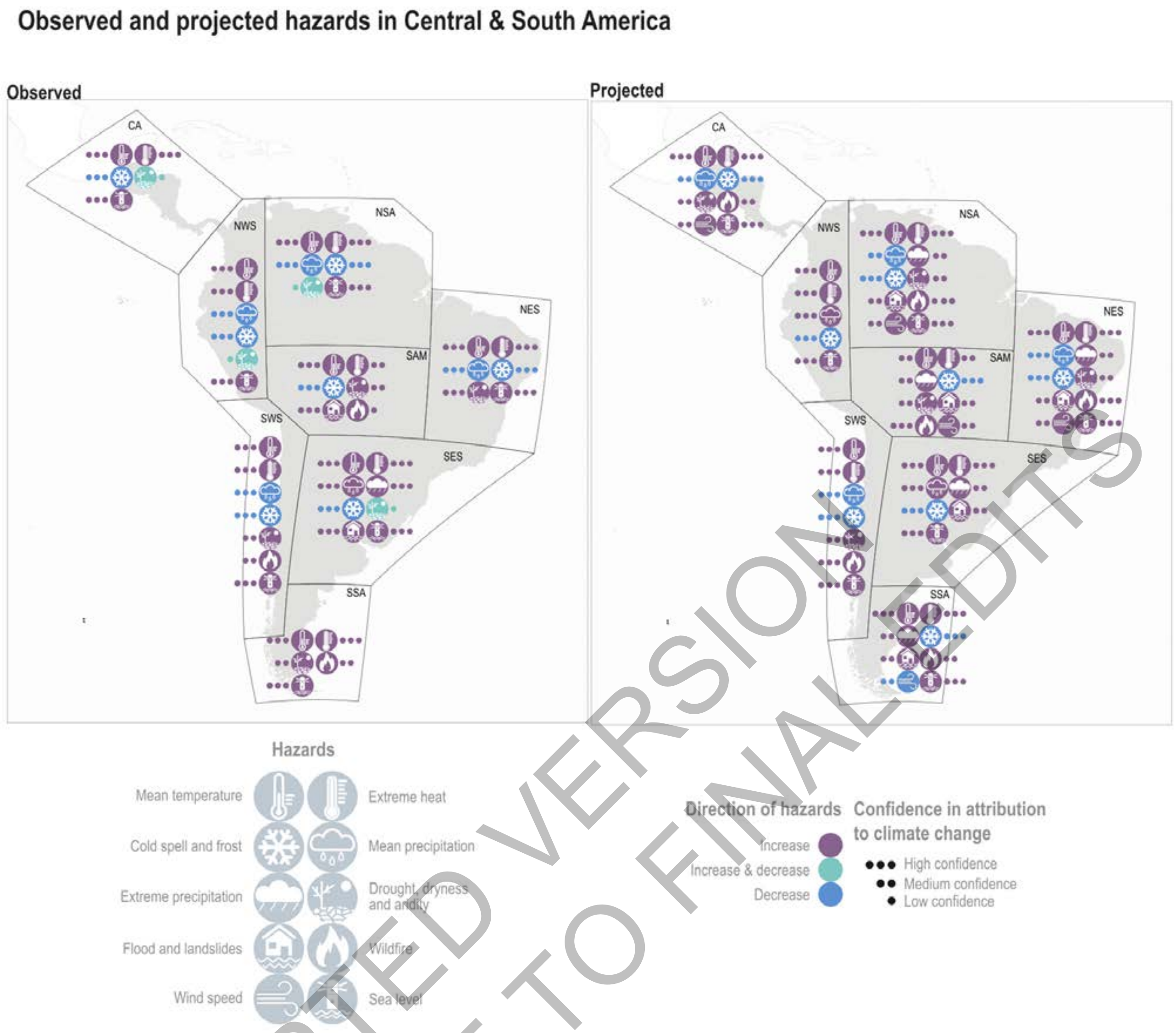
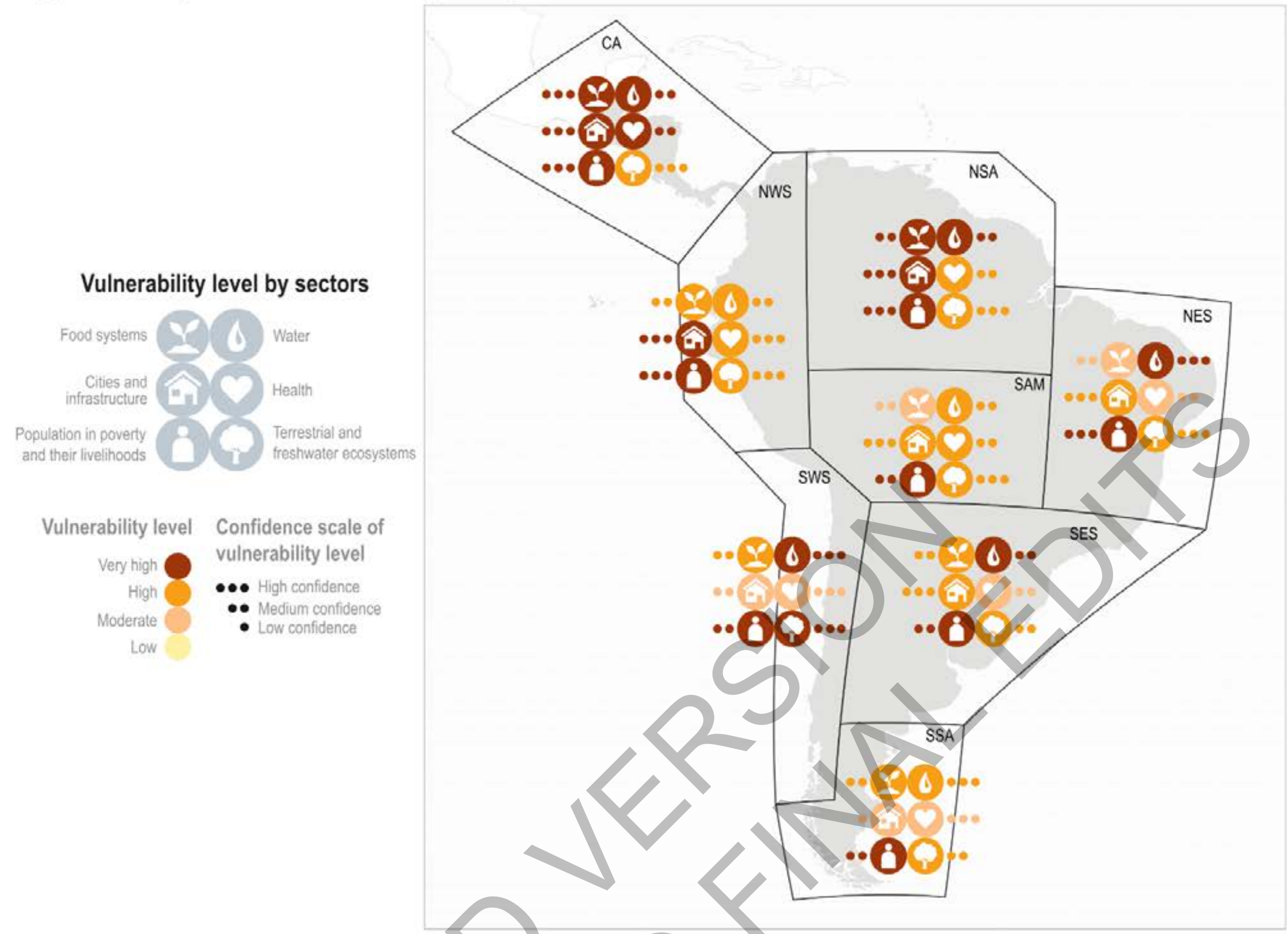


Figure 12.6: Observed trends (WGI AR6 Tables 11.13, 11.14, 11.15) (Seneviratne et al., 2021) and summary of confidence in direction of projected change in climatic impact-drivers, representing their aggregate characteristic changes for mid-century for scenarios RCP4.5, SSP3-44 4.5, SRES A1B, or above within each AR6 region, approximately corresponding (for CIDs that are independent of sea-level rise) to global warming levels between 2°C and 2.4°C (WGI AR6 Table 12.6) (Ranasinghe et al., 2021).

Sectoral distribution of vulnerability to climate change for Central and South America

(a) Vulnerability and confidence level by subregion and sector



(b) References used and vulnerability level attributed by subregion and sector

Sectors	CA	NES	NSA	NWS	SAM	SES	SSA	SWS
Food Systems	4,6,9,11, 14,19,21, 27,35, 40,47	6,9,16, 21,22,27, 35,47	6,9,11,14, 19,21,27, 35,45,47	6,14,19,21 ,22,27,35, 40,45	6,21,27, 35,47	6,9,14,2 1,22,27, 35,47	6,14,21, 22,27,35, 39,47	6,14,21, 22,27,35, 39,40, 45
Cities and infrastructure	5,35	5,31,25	5,35	5,35	5,35	5,35	5,35	5,35
Population in poverty and their livelihoods	7,15,10, 12,13,23 ,25,40	10,12,13 ,15,17,2 5,28,49	10,12,13, 15,17,25, 28,33	10,12,13, 15,25,40	10,12,13, 15,17,25	10,12,13, 15,17,25, 28	10,12,13, 15,25	10,12,13, 15,25,40, 44
Water	26,35,41	26,35,48, 49,50	24,26,35	24,26,35	24,26,35	24,26,35, 41	24,26,35, 39	24,26,35, 39
Health	20,30,35	20,30,35 ,50	20,30,35	20,30,35	20,30,35	20,30,35	20,30,35	20,30,35
Terrestrial and freshwater ecosystems	29,35,38	2,29,32, 35,37,38 42	2,29,35, 37,38	2,8,24, 29,35,3 7,38	2,29,35, 37,38	29,35,38	24,29,35, 38	3,18,24, 29,35,38 ,46

Figure 12.7: Sectoral distribution of vulnerability levels to climate change for the subregions. The vulnerability levels are based on studies that include: i) databases with climate change vulnerability indexes by country and sector, ii) researches that implement climate change vulnerability indexes by sector at the local, national, regional or global scale, and iii) studies that define some vulnerability level based on the authors' expert judgment. **Panel (a)** shows the vulnerability and confidence levels for each subregion. **Panel (b)** indicates the references used and the level of vulnerability attributed by subregion. The numbers within the table indicate the reference used for the assessment in the following order: 1) Aitken et al. (2016); 2) Anderson et al. (2018b); 3) Bañales-Seguel et al. (2018); 4) Bouroncle et al. (2017); 5) CAF (2014); 6) Carrão et al. (2016); 7) Donatti et al. (2019); 8) Eguiguren-Velepucha et al. (2016); 9) FAO (2020a); 10) FAO (2020b); 11) FAO (2021a); 12) FAO (2021b); 13) FAO (2021c); 14) FAO et al. (2021); 15) FAO and

ECLAC (2020); 16) Ferreira Filho and Moraes (2015); 17) Filho et al. (2016); 18) Fuentes-Castillo et al. (2020); 19) FSIN and Global Network Against Food Crisis (2021); 20) Global Health Security Index (2019); 21) Godber and Wall (2014); 22) Handisyde et al. (2017); 23) Hannah et al. (2017); 24) Immerzeel et al. (2020); 25) Inform Risk Index (2021); 26) Koutroulis et al. (2019); 27) Krishnamurthy et al. (2014); 28) Lapola et al. (2019a); 29) Li et al. (2018); 30) Lin et al. (2020); 31) Mansur et al. (2016); 32) Martins et al. (2017); 33) Menezes et al. (2018); 34) Nagy et al. (2018);35) ND-Gain (2020); 36) Northey et al. (2017); 37) Olivares et al. (2015); 38) Pacifici et al. (2015); 39) Qin et al. (2020); 40) Romeo et al. (2020); 41) Liu and Chen (2021); 42) Silva et al. (2019b); 43) Soto Winckler and Del Castillo Pantoja (2019); 44) Soto et al. (2019); 45) Tomby and Zhang (2019); 46) Venegas-González et al. (2018b); 47) Yeni and Alpas (2017); 48) Marengo et al. (2017); 49) Bedran-Martins et al. (2018); 50) Confalonieri et al. (2014a). Detailed methodology can be found in SM12.2.

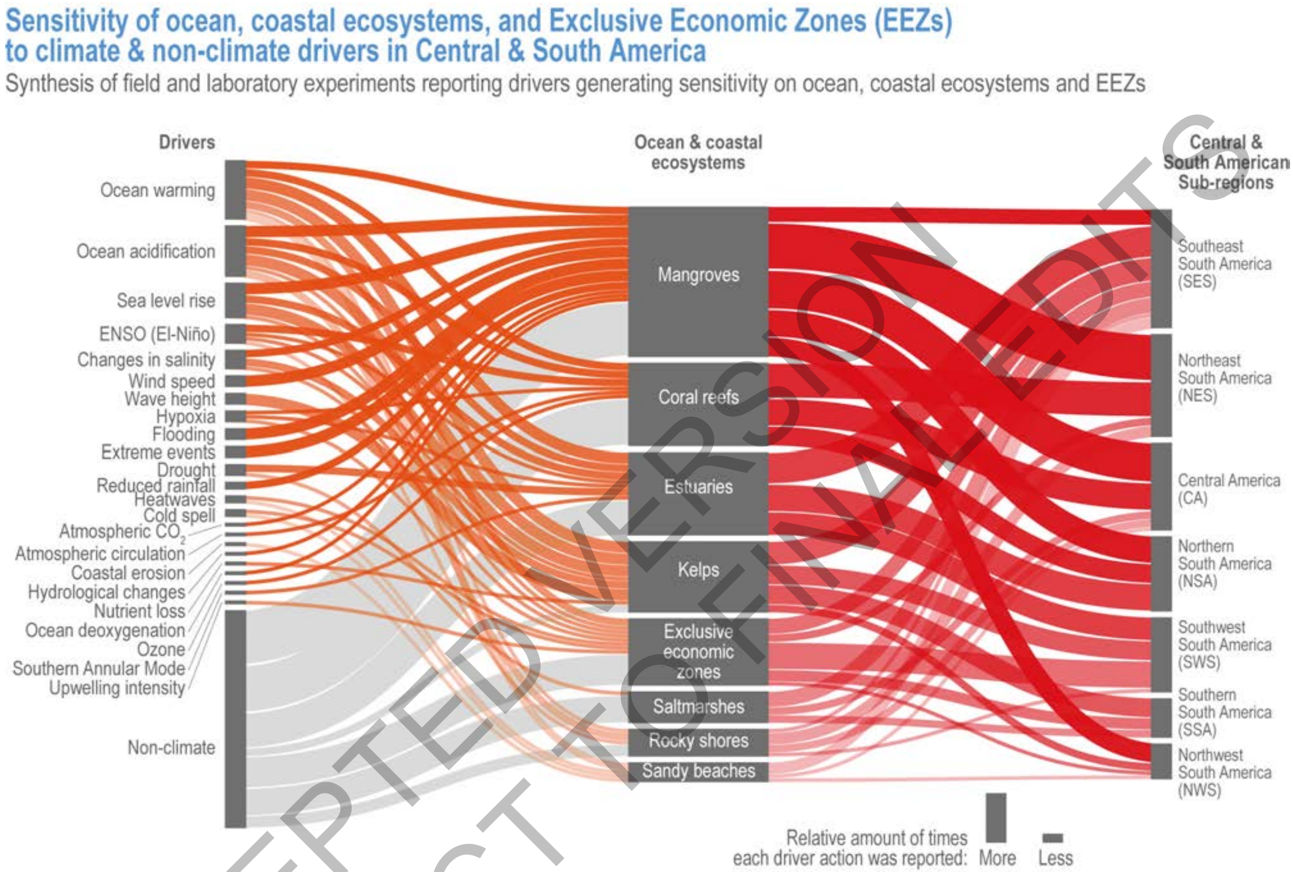


Figure 12.8: Climate and non-climate sensitivity drivers of ocean, coastal ecosystems and Exclusive Economic Zones (EEZs) of Central and South America.

12.4 Key Impacts and Risks

This section synthesizes key risks across the Central and South America CSA region. It follows the definition and concept of risk provided in AR5, distinguishing the risk components, climatic hazard, exposure and vulnerability of people and assets (IPCC, 2014). This concept is further developed in AR6, defining key risks as potentially severe risks (Section 16.5). Key risks may refer to present or future conditions, with a focus on the 21st century. Both mitigation and adaptation can moderate the extent or severity of risks. The identification and evaluation of risks imply socio-cultural values, which may vary across individuals, communities or cultures.

In line with chapter 16 of this report, this chapter uses a risk outcome perspective, i.e., the focus is on the consequences related to risks, which potentially can result from different combinations of hazards, exposure and vulnerabilities. There is limited literature with a focus on severe risks in the CSA region, and scant studies specifically and explicitly considering risk drivers such as level of warming, level of exposure, vulnerability and adaptation.

Criteria for identifying key risks for this chapter include the magnitude of the consequences, in particular the number of people potentially affected; the severity of the negative effects of the risk (e.g., lives threatened, major negative effect on livelihoods, well-being, or the economy); the importance of the affected system (e.g., for vital ecosystem services, for large population groups); the irreversibility of either the process leading to the risk or the consequences; and the potential to reduce the risk.

Several of the key risks identified for the CSA region align well with the overarching key risks assessed in AR5 (Oppenheimer et al., 2014) and later in O'Neill et al. (2017), as well as with the representative key risks assessed in Section 16.5 of this report. The identified key risks include KR1: risk of food insecurity due to frequent and/or extreme droughts; KR2: risk to life and infrastructure due to floods and landslides; KR3: risk of water insecurity; KR4: risk of severe health effects due to increasing epidemics (in particular vector-borne diseases); KR5: systemic risks of surpassing infrastructure and public service systems KR6: risk of large-scale changes and biome shifts in the Amazon; KR7: risk to coral reef ecosystems due to coral bleaching; KR8: risks to coastal socio-ecological systems due to sea level rise, storm surges and coastal erosion (Table 12.6; Figure 12.11; Table SM12.5).

Table 12.6: Synthesis of key risks identified and assessed for the Central and South America region

Consequence that would make the risk severe	**Associated changes in hazards**	**Associated changes in exposure**	**Associated changes in vulnerability**
1. Risk of food insecurity due to frequent/extreme droughts			
Substantial decrease in yield for key crops, disruption of food provision chains, reduced capacity or production of goods, reduced food security and increased malnutrition.	More frequent and/or longer drought periods. Decrease in annual rainfall, severe decrease in rainfall at onset of rainy season. Desertification of semiarid regions.	More people exposed to food insecurity due to spatially more extensive drought; high population growth rate (including rural areas) and more population dependent on agricultural goods.	Reduced capacity of farmers (especially small-scale) to adapt to changing climatic conditions. Soil degradation. Insufficient government support of adaptation measures, financial contributions, infrastructure, insurance, and research efforts. Inefficient water management.
2. Risk to life and infrastructure due to floods and landslides			
Death and severe health effects, disruption of critical infrastructure and service systems.	More frequent and severe storms and heavy precipitation events. Changing snow conditions and thawing permafrost. Retreating glaciers, formation of glacier lakes, increased glacier lake outburst flood hazard.	More people exposed to floods and landslides due to changing hazards, land-use and increased population; occupation of more risk-prone areas such as flood plains and steep slopes.	Low income and marginal populations, low resilience of infrastructure and critical service systems. Limited government support through insurance, monitoring, early warning systems and recovery.
3. Risk of water insecurity			
Seasonal water availability change and decline due to glacier shrinkage, snow cover	Glacier shrinkage, snow cover change, more pronounced dry periods,	Increase in population dependent on contribution of glacier/snow melt,	Unequal water consumption systems, failed water management

change, more pronounced dry periods and poor or failed water management and governance.	precipitation and circulation changes.	especially during drought conditions. Increased demand from intensification of agriculture, mining, hydropower and urbanisation.	and government capacities, low water infrastructure efficiency, growing urban areas.

4. Risk of severe health effects due to increasing epidemics (in particular vector-borne diseases)

Increased rate of epidemics of vector-borne diseases (malaria, dengue, Zika, leishmaniasis) together with diarrheal diseases. Severe health effects and damage to health systems in countries with low adaptive capacity and where original endemicity is high and control status poor.	Higher temperatures increase the geographical range of vectors, leading to expansion of climate suitable areas.	Increased population density and mobility through urbanization results in high transmission rate. Increased population exposed to arboviruses due to expansion of vectors, including higher altitudes and latitudes.	Poor sanitation conditions, particularly in low-income communities and for Indigenous Peoples. Insufficient coverage of appropriate water provision and sewage systems. Low structural or economic capacity to cope; underfunding of health systems. Increase in infections can increase incidence of more severe forms of dengue.

5. Systemic risks of surpassing infrastructure and public service systems

Breakdown of public service systems, including infrastructure and health services due to cascading impacts of natural hazards and epidemics, affecting a large part of the population.	Higher frequency and magnitude of climate-related events (storms, floods, landslides) together with an increase in spatial and temporal distribution of pathogens/vectors for malaria, dengue, Zika and leishmaniasis.	More people and infrastructure exposed to climate/weather events. Increase in population exposed to arboviruses due to spatial expansion of vectors.	Increasing vulnerability of public service and infrastructure systems. Insufficient disaster management. Little improvement, maintenance and expansion of public health care systems. Low system resilience.

6. Risk of large-scale changes and biome shifts in the Amazon

Transition from tropical forest into other biomes such as seasonal forest or savannah through forest degradation and deforestation. Risk of shifting from carbon sink to source.	More frequent, stronger and persistent drought periods. Temperature increase and reduction in annual rainfall.	Reduced availability of natural sources for local people. Land use and land cover change (mining, deforestation). Loss of biodiversity and ecosystem services. Health impacts from increased forest fires particularly for Indigenous Peoples.	Strong dependence on non-climatic drivers, in particular land-use change, deforestation, forest fire practices. Low capacity to monitor and control deforestation.

7. Risk to coral reef ecosystems due to coral bleaching

Degradation and possible death of the Mesoamerican coral reef, the second largest reef in the world. Severe damage to habitat for marine species, degrading coastal protection and other ecosystem services, decreased food security from fisheries, lack of income from tourism.	Ocean sea surface temperature increase, lowered seawater pH and carbonate levels due to increased atmospheric CO_2 levels, leading to ocean acidification and coral bleaching.	Continued exposure to increased atmospheric CO_2 levels and sea surface temperatures together with destruction from coastal development, fishing practices and tourism.	Ecosystem highly sensitive to water temperature and pH fluctuations. High levels of negative human interference with reefs including runoff and pollution..

8. Risks to coastal socio-ecological systems due to sea level rise, storm surges and coastal erosion

Coastal flooding and erosion causing severe damage to coastal population and infrastructure. Loss of fisheries, reef degradation and decline in coastal protection due to increased storm surges and waves. Salt water intrusion and land subsidence.	High continuing trajectories of sea level rise. More intense and persistent coastal flooding, salt water intrusion, coastal erosion.	Coastal population growth. Increased number of people, infrastructure and services (coastal tourism) exposed; need of relocation of millions of people.	Poor planning in coastal development and infrastructure, disproportionate vulnerability and limited adaptation options for rural communities and Indigenous Peoples, increasing urbanisation in coastal cities. Large economic losses and unemployment from declining tourism.

Identification and assessment of key risks are informed by observed and projected impacts in the different sub-regions of CSA (Section 12.3). Figure 12.10 shows the summary of different levels of observed and future impacts per sub-region for different sectors, based on a detailed assessment of climate change impacts on various systems and components for the respective sector (Figure 12.9). This assessment is consistent with and complementary to the assessment in Section 12.3. A synthesis of these impacts (Figure 12.10) indicates the following: Climate change has a major impact on observed and future decline of Andean glaciers and snow (*high confidence*), and leads to degradation of permafrost and destabilization of related landscapes (*medium evidence, high agreement*). Water quality is a major concern across the region but there is *limited evidence* of impacts of climate change on water quality as well as on groundwater. Climate change has had a high impact on terrestrial and freshwater ecosystems in the NWS, SES and SWS sub-regions, and a medium impact in the other subregions but the level of confidence is varying across sub-region. Projections indicate a strong impact of climate change on these ecosystems for the future (*medium confidence: medium evidence, high agreement*). Many aspects and assets of ocean and coastal ecosystems (e.g., mangroves, coral reefs, saltmarshes) were identified to be strongly impacted by climate change, both for observed and future periods (*high confidence*) (Section 12.5.2; Figure 12.9).

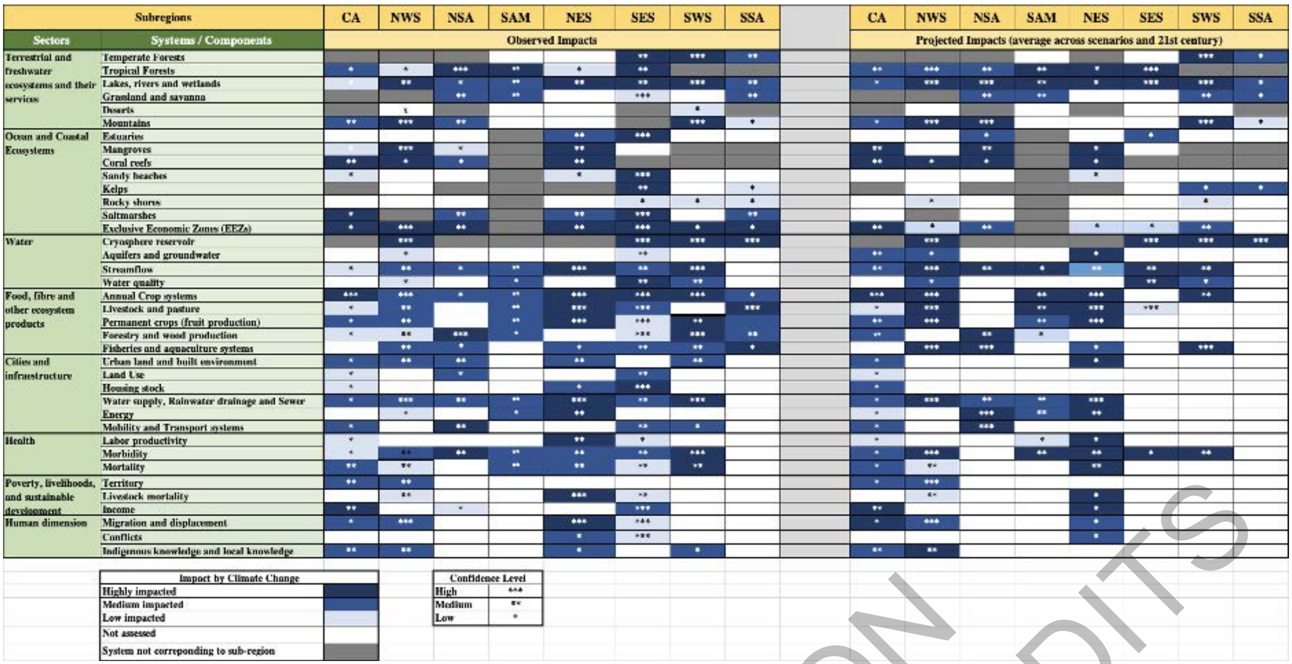


Figure 12.9: Observed and projected impacts for the subregions of Central and South America. Impacts are distinguished for main sectors and for their corresponding systems (or components). Observed impacts refer to a time-period of the last several decades. Projected impacts represent a synthesis across several emission and warming scenarios, indicative of a time-period from mid- to end of the 21st century. For each system (e.g., coral reefs) it is distinguished whether the impact of climate change is low, medium or high. The references underlying this assessment can be found in SM12.4.1.

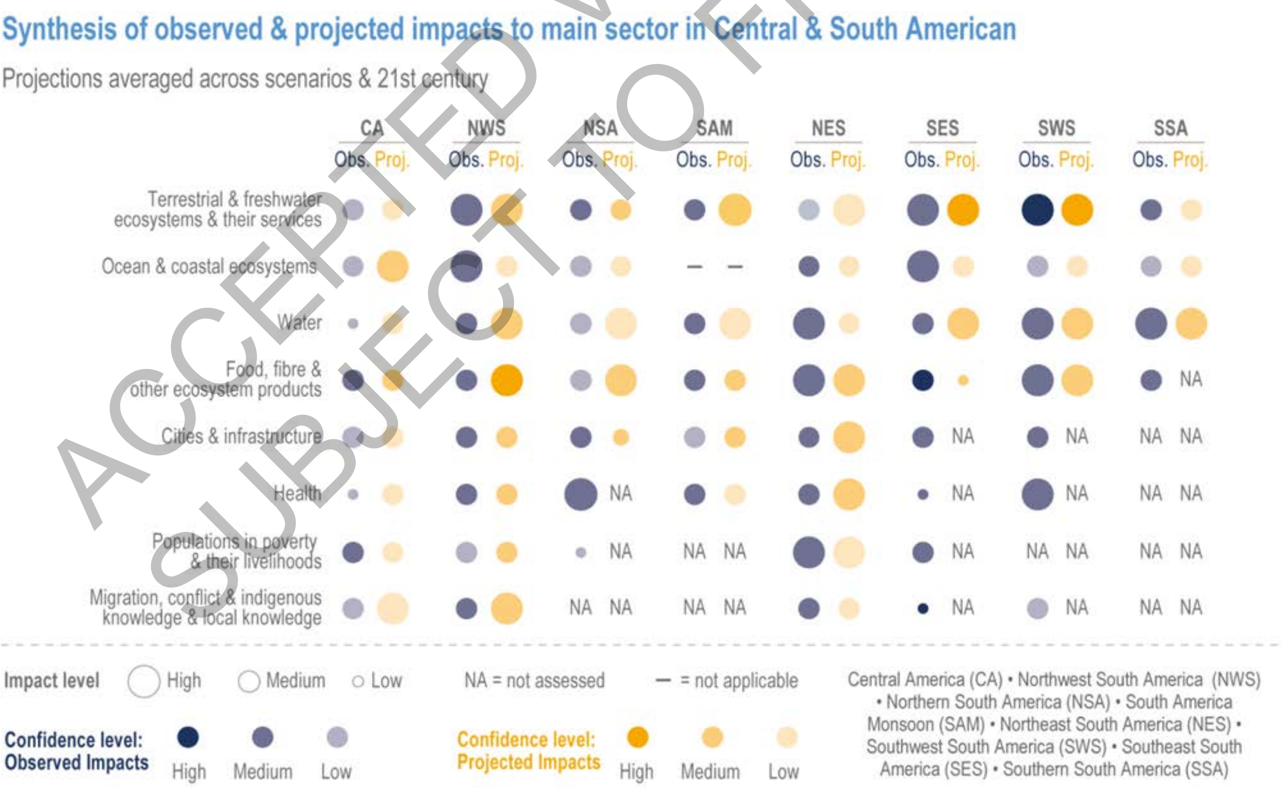


Figure 12.10: Synthesis of observed and projected impacts, distinguished for different sectors and each subregion of Central and South America. Observed impacts refer to a time-period of the last several decades. Projected impacts represent a synthesis across several emission and warming scenarios, indicative of a time-period from mid- to end of the 21st century. For each sector (e.g., health) it is distinguished whether the impact of climate change is low, medium or high. The references underlying this assessment can be found in SM12.4.1 and the methodology to complete the synthesis is found in SM12.4.2.

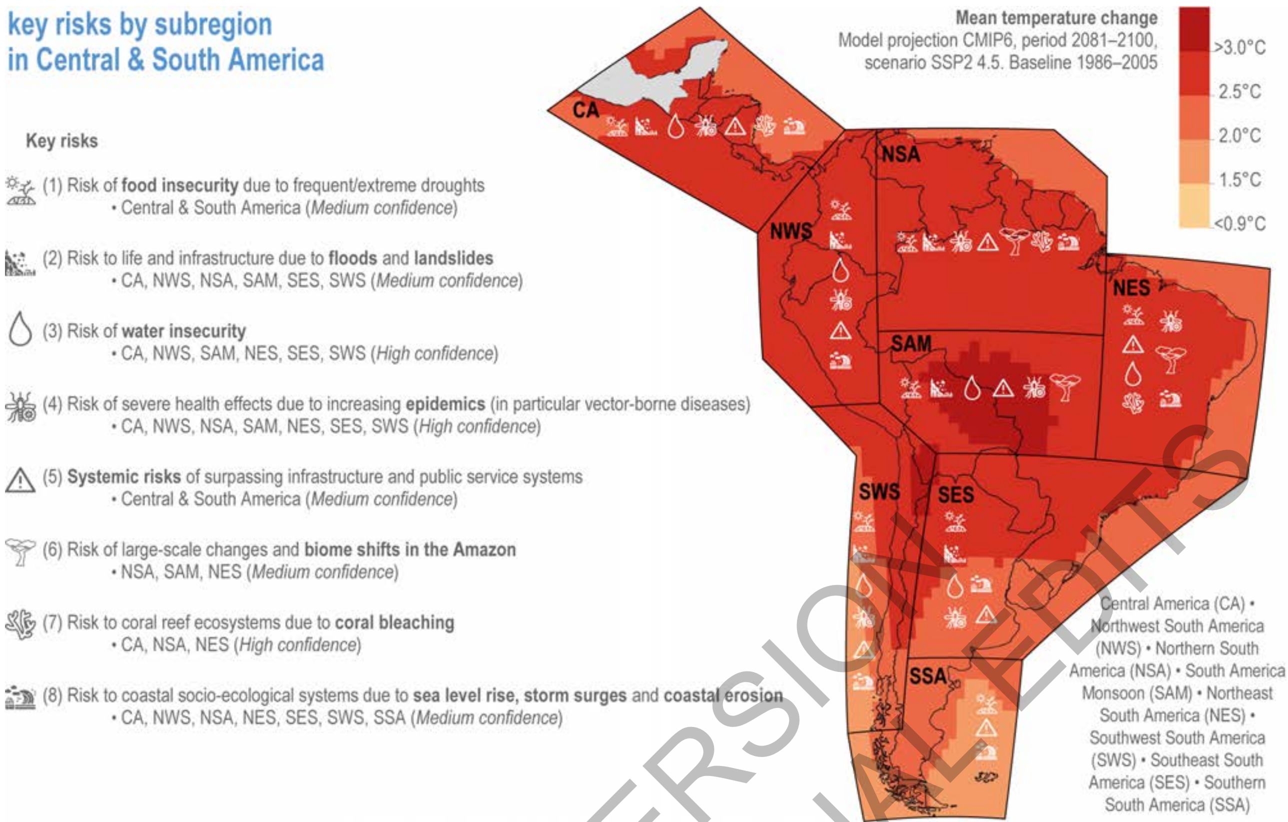


Figure 12.11: Synthesis of key risks for the Central and South America region. The base map indicates the mean temperature change between the scenario SSP2 4.5 using CMIP6 model projections for 2081-2100, and a baseline period of 1986-2005 (WGI AR6 Atlas, Gutiérrez et al., 2021).

In most sub-regions, crop, livestock, fisheries and food systems in general show medium to high impacts of climate change over the observed period and similarly for the future of the 21st century (*medium confidence: medium evidence, high agreement*). For some sub-regions, the available literature does not allow the assessment of impacts on several human systems, including cities and infrastructure, health, poverty, livelihoods, migration, conflict, Indigenous knowledge and local knowledge, especially for future time periods. This points to important knowledge gaps about climate change impacts on human systems. Indication of high impacts for several human systems and sub-regions points to the need to close these knowledge gaps.

The assessment of key observed and projected impacts and risks shows that in the CSA region several systems are already approaching critical thresholds under current warming levels, in particular glaciers in the Andes and coral reefs in Central America (*high confidence*), and further ocean and coastal ecosystems in virtually all sub-regions (*medium confidence: medium evidence, high agreement*). Some systems could cross these thresholds with different levels of reversibility depending on the degrees of future warming, namely glaciers in the Andes and coral reefs in Central America which will show partial but irreversible loss already under low levels of warming (RCP2.6) (*high confidence*). The risk of large-scale ecological changes and biome shifts of the Amazon forest, i.e., a transition from tropical forest into other biomes such as seasonal forest or savannah, is now assessed with *medium confidence*, with the extent of the changes depending on the level of future warming and non-climatic drivers (land-use change, deforestation, forest fire practices).

Systemic risks where critical infrastructure and public service system capacities are surpassed due to storms, floods and epidemics, with cascading impacts through vulnerable systems and populations and economic sectors, have the potential to affect large parts of the population and are therefore of major concern (*medium confidence: limited evidence, high agreement*). The COVID-19 crisis has exposed the existing vulnerabilities in important systems, in particular health systems and public service (Phillips et al., 2020). However, tipping points in social systems are poorly understood (Bentley et al., 2014; Milkoreit et al., 2018), and there is *limited evidence* to inform understanding about which level of compound climatic, environmental and socio-economic stressors social systems withstand in CSA.

Overall, most key risks and their severity and extent are strongly driven and determined by the system's exposure, vulnerability and adaptive capacity. In particular, the high vulnerability of large populations, infrastructure and service systems such as health, food and energy production and supply are important factors, along with high inequalities and poor governance, for creating and increasing key risks (*high confidence*). Prevailing low levels of available information and understanding exacerbate the uncertainties surrounding key risks, and hence pose limitations to adaptation. An example is Central America with high levels of vulnerability and exposure but there is *limited evidence* and understanding on impacts and risks, making this region susceptible to inappropriate adaptation to expected future climate change impacts.

12.5 Adaptation

Adaptation initiatives across the region have increased since AR5. National Communications (NC), Nationally Determined Contributions (NDC) and National Adaptation Plans (NAP) (https://unfccc.int) recently published are providing guidance for adaptation in CSA. There is also a diversity of non-governmental adaptation initiatives, both at the national and sub-national levels. In this context, this section assesses, through a sectoral approach, the main challenges, opportunities, trends and initiatives to adapt to climate change in the region.

12.5.1 Terrestrial and Freshwater Ecosystems and their Services

CSA is one of the most biodiverse regions in the World, hosting unique socio ecosystems that will be strongly impacted by climate change (*high confidence*) (Section 12.3; Cross-Chapter Paper 1; CAF, 2014; Camacho Guerreiro et al., 2016; IPBES, 2018a; Li et al., 2018; Retsa et al., 2020) . Warming has generated extreme heat events in many parts of CSA (IPCC, 2019a) that, together with droughts and floods, will seriously affect the integrity of terrestrial and freshwater ecosystems in the entire region (Section 12.3; CAF, 2014) . A reduction in net primary productivity in tropical forests and glacier retreat in the Andes, for example, are expected to cause significant negative socioecological impacts (Feldpausch et al., 2016; Lyra et al., 2017; Cuesta et al., 2019) (see Case Study, 12.7.1). Biodiversity-rich spots in the region are well assessed in the literature as compared to other regions of the World, especially for the Atlantic Forest, Mesoamerica and Cerrado (Cross-Chapter Paper 1.2.2; Manes et al., 2021) . Up to 85% of of evaluated natural systems (species, habitats and communities) in the literature for biodiversity-rich spots since AR5 were projected to be negative impacted by climate change (*high confidence*), with 26% of projections predicting species extinctions (Cross-Chapter Paper 1.2.2; Manes et al., 2021) . Indigenous knowledge and local knowledge play an important role in adaptation and are vital components of many socioecological systems, while also being threatened by climate change (*high confidence*) (Box 7.1; Valdivia et al., 2010; Tengö et al., 2014; Mistry et al., 2016; Harvey et al., 2017; Diamond and Ansharyani, 2018; Camico et al., 2021) .

12.5.1.1 Challenges and opportunities

The conversion of natural ecosystems to agriculture, pasture and other land uses in CSA has been identified as a major challenge to climate change adaptation in the region (*high confidence*) (Scarano et al., 2018; IPCC, 2019a). In the last three decades, South America has been a significant contributor of the growth of agricultural production worldwide (OECD/Food and Agriculture Organization of the United Nations, 2015), driven partly by increased international demand for commodities, especially soybeans and meat (IPCC, 2019a). Between 2001 and 2015 about 65% of all forest disturbance in the region was associated with commodity-driven deforestation (Curtis et al., 2018). High rates of native vegetation conversion in Argentina, Bolivia, Brazil, Colombia, Ecuador, Paraguay and Peru threaten important ecosystems (Amazon, Cerrado, Chacos and Llanos savannas, Atlantic rainforest, Caatinga and Yungas) (Graesser et al., 2015; FAO, 2016c). Almost 2/3 of soy consumed in EU+ comes from Brazil, Argentina and Paraguay (IDH, 2020), increasing conversion risk in the Amazon, Cerrado, and Gran Chaco. Despite growing commodities production traceability, in 2018 only 19% of the soybean meal consumed in EU+ was certified deforestation-free, and 38% compliant with the FEFAC Soy Sourcing Guidelines (IDH, 2020), which is a great challenge at the international level (Negra et al., 2014; Curtis et al., 2018; Lambin et al., 2018; IDH, 2020).

Investing in actions aimed at protection, restoration and sustainable use of biodiversity and ecosystems is a good approach for maintaining critical ecosystem services, and is part of a common strategy for adaptation, mitigation and disaster risk reduction in the region (*high confidence*) (Kabisch et al., 2016; Scarano et al., 2018). These strategies also meet the forest and water conservation international agendas, optimizing resources and solutions (Strassburg et al., 2019). Global conservation and sustainable development commitments, such as the Aichi Targets (CDB), Sustainable Development Goals (UN), the Nationally Determined Contribution (NDC) under the Paris Agreement, and the New York Declaration on Forests strongly rely on nature-based solutions (NbS) to achieve their objectives (Brancalion et al., 2019) (Figure 12.12). The COVID–19 outbreak also brought attention to the need for preserving tropical forests as a mean to prevent spill over of viruses from wildlife to humans, with concerns over that risk in the Amazon (Allen et al., 2017b; Dobson et al., 2020; IPBES, 2020; Ferreira et al., 2021). These represent an important opportunity for Ecosystem Based Adaptation (EbA) to be at the core of NbS for climate change, access finance and promote climate resilient development pathways in CSA.

The Declaration on Protected Areas and Climate Change, presented by 18 CSA countries during the UNFCCC COP21, highlights the fundamental role of protected areas in providing the “green infrastructure” needed for implementing climate change mitigation and adaptation, and safeguard the provision of essential ecosystem services and the livelihoods of Indigenous Peoples and local communities (Gross et al., 2016). Protected Areas systems in CSA are underfunded (*very high confidence*). Latin American (including Mexico) governments allocate just about 1% of national environmental budgets on protected areas (about USD 1.18 ha^{-1} on average). This figure only covers 54% of their basic needs, resulting in insufficient management. The financing gap to achieve optimal needs for protected areas in CSA is approximately USD 700 million yr^{-1} (Bovarnick et al., 2010). This seriously compromises the management and delivery capacity of protected areas for climate change adaptation, and preparedness for ongoing ecological transformation (van Kerkhoff et al., 2019). Furthermore, in order to become a relevant mechanism for resilience, protected areas need to be managed for this purpose (Mansourian et al., 2009). About 40% of protected areas in Latin America and Caribbean (including Mexico), have management effectiveness evaluations being undertaken (UNEP-WCMC and IUCN, 2020a). This is hardly representative of Aichi’s Goal 11, although far better than the 11% global average. Collaborations with the Indigenous Peoples and local communities are also an important issue to consolidate protected areas (Gross et al., 2016). In addition to protected areas as solutions for climate change adaptation and mitigation, there is also a need to protect or restore ecosystems outside the protected areas, as illustrated by the Mesoamerican Biological Corridor (Imbach et al., 2013).

Despite some local and specific assessments (e.g., Warner (2016)), there is a significant gap on identifying barriers to adaptation or maladaptation in the region (Dow et al., 2013). In their National Communications (NC), Nationally Determined Contributions (NDC) and/or National Adaptation Plans (NAP) (https://unfccc.int), most countries identified inadequate financing and access to technology as barriers for adaptation relevant to terrestrial and freshwater socio-ecosystems (*high confidence*). Insufficient institutional coordination is also frequently mentioned (Rangecroft et al., 2013; Cameron et al., 2015). These limitations could be partially addressed through multilateral cooperation, incorporation of synergies from the local to the national scales, local empowerment, and poverty alleviation (Rangecroft et al., 2013; Harvey et al., 2017; Murcia et al., 2017; Calispa, 2018; Chain-Guadarrama et al., 2018).

12.5.1.2 Governance and financing

All CSA countries have formulated policies that include measures relevant for socio-ecosystem adaptation in their NCs, NDCs and NAPs (https://unfccc.int), with an emphasis on protection and restoration of water and forests (*high confidence*). Existing proposed measures, instruments and programs, however, do not yet reflect the vision needed to integrate the ecosystem and human dimensions of vulnerability. The administration coordination and the progress in adaptive ecosystem management are incipient, due in part to the lack of stable financial resources and scientific, Indigenous knowledge and local knowledge (IK and LK) about adapting ecosystems to climate change (Bustamante et al., 2020). Brazil was an exception, showing dramatic policy-driven reduction in deforestation in the Amazon between 2004–2012, with a concomitant 70% increase in soy production, the most profitable Amazon crop (Hansen et al., 2013; Nepstad et al., 2014). Policies included territorial planning (protected areas, Indigenous territories and land tenure), satellite monitoring, market and credit restrictions on high-deforesting municipalities, plus some incentives to small farmers (Boucher et al., 2013; Hansen et al., 2013; Nepstad et al., 2014; Castelo, 2015; Cunha et al., 2016a). It is important to highlight the important role of Indigenous territories, in addition to protected areas, in forest conservation in the Amazon (*high evidence, medium agreement*) (Schwartzman et al., 2013; Barber et al., 2014; Nepstad et al., 2014; Walker et al., 2014b). These policies were partially funded by results-based compensation through the Amazon Fund. Since 2012, however, policies and institutions have weakened, and Amazon deforestation rates started to rise (Carvalho et al., 2019), sharpening in recent years (Silva Junior et al., 2021). Conservation incentives, a new complementary and allegedly cost-effective approach, is increasingly being implemented in the region (Magrin et al., 2014). They include payment for ecosystem services, REDD+, environmental certification and conservation easements, but remain controversial, and more research is needed on their effectiveness, possible negative side effects, participatory management systems and collective decision-making processes (Larson and Petkova, 2011; Locatelli et al., 2011; Pinho et al., 2014; Strassburg et al., 2014; Mistry et al., 2016; Gebara and Agrawal, 2017; Scarano et al., 2018; Ruggiero et al., 2019; To and Dressler, 2019; Vallet et al., 2019).

12.5.1.3 Adaptation options to avert and reduce key risks on terrestrial and freshwater ecosystems

Research, monitoring systems and other initiatives for knowledge management are promoted in the region on terrestrial and freshwater socio-ecosystem adaptation (*high confidence*) (NCs, NDCs and NAPs, https://unfccc.int). In Chile, for example, the Eco-social Observatory of Climate Change Effects for High Altitude Wetlands of Tarapacá has been collecting information on physical, biological and social variables since 2013 (Uribe Rivera et al., 2017). Other examples in the Andes are the GLORIA-Andes network (Cuesta et al., 2017a), the Andean Forest Network (Malizia et al., 2020) and the Initiative of Hydrological Monitoring in the Andes (IMHEA), with measures to optimize watershed management and protection, and reduce the risk of water insecurity (Correa et al., 2020).

Poverty is a driver of climate change risk, while sustainable use of ecosystems fosters adaptation (Kasecker et al., 2018) (*high confidence*). Most of 398 “Ecosystem-based Adaptation hotspots” identified in Brazil on this premise are located in some of the most vulnerable ecosystems to climate change (Kasecker et al., 2018). Although conservation and restoration is reported as effective to reduce risk (*medium confidence: medium evidence, high agreement*) (Anderson et al., 2010; Borsdorf et al., 2013; Keenan, 2015; Pires et al., 2017; Ramalho et al., 2021), their effectiveness depends on the integration of conservation actions with enhancement of local socioeconomic conditions (*medium confidence: medium evidence, high agreement*) (Scarano and Ceotto, 2015; Pires et al., 2017; Kasecker et al., 2018; de Siqueira et al., 2021; Vale et al., 2021).

Since AR5, there has been an increase in the number of adaptation measures through natural resources and ecosystem services management. The main approaches are EbA and Community-based Adaptation (CbA) (*high confidence*) (NCs, NDCs and NAPs, https://unfccc.int). IK/LK can be very detailed and usually relates to people’s priorities identified by collective decision-making (Box 7.1; (Hurlbert et al., 2019, SRCCL Section 7.6.4); SRCCL Cross-Chapter Box ILK in Chapter 13; (de Coninck et al., 2018, SR1.5 Section 4.3.5.5). In Manaus, central Amazon, fishermen perceive reductions on fish size, diversity and capture levels caused by droughts; while recognizing that floods hinders access to fishing grounds (Keenan, 2015; Camacho Guerreiro et al., 2016). In the Amazon floodplains, small-scale fisher and farmer’s communities incorporate their knowledge on natural hydrologic and ecological processes into management systems that reduce climate change risk and impacts (Oviedo et al., 2016). Smallholder grain farmers in Guatemala and Honduras implement EbA practices based on local knowledge (e.g., live fences, home gardens, shade trees in coffee plantations, dispersed trees in corn fields and other food insecurity risk reduction practices) (Harvey et al., 2017; Chain-Guadarrama et al., 2018). There is, therefore, a great potential for terrestrial and freshwater ecosystem adaptation to climate change in CSA, provided that the right incentives and sociocultural protective measures are in place (*high confidence*) (Section 12.5.10.4; Table SM12.7).

Disarticulation between policy and implementation is a common problem. Ecuadorian climate public policy points towards a CbA approach, but it is often downsized in the implementation (Calispa, 2018). Important adaptation actions have been undertaken in Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, El Salvador, Paraguay, Peru and Uruguay; both in policymaking and institutional arrangements, but they tend to be poorly coordinated with policies on development, land planning and other sectoral policies (Ryan, 2012). Some type of community participation mechanisms is present in most country strategies, but their levels of implementation vary considerably (*medium confidence: medium evidence, high agreement*) (Ryan, 2012; Pires et al., 2017; Calispa, 2018).

There is an ecosystem bias in adaptation priorities for research and implementation, hindering the development of comprehensive adaptation programs. Most scientific research on adaptation in Peru focuses on the highlands and coastal regions while mitigation research focuses on forests (Chazarin et al., 2014). Combined adaptation and mitigation strategies can produce positive results, but they are often disconnected (Locatelli et al., 2015). Most reviewed cases in agriculture and forestry in Latin America (84% of 274 cases) reported positive synergies between adaptation and mitigation. Nevertheless, research on Latin American forests tend to focus on mitigation, while studies on agriculture are usually oriented towards adaptation (*high confidence*) (Locatelli et al., 2015; Locatelli et al., 2017).

Rural communities in the Cusco Region, Peru, ground their ability to adapt to climate change on four cultural values, known in Quechua as ayni (reciprocity), ayllu (collectiveness), yanantin (equilibrium) and chanincha (solidarity), but policies oriented towards “modernization” undermine these traditional mechanisms. Adaptation strategies could benefit from integrating these and other insights from traditional cultures, fostering risk reduction and transformational adaptation towards intrinsically sustainable systems (*medium confidence: medium evidence, high agreement*) (Walshe and Argumedo, 2016).

Protected areas have become an important component as enablers of national climate change adaptation strategies. They increase ecosystem’s adaptive potential, reducing climate risk and delivering numerous ecosystem services, sustainable development benefits while playing an important role in climate change mitigation (*high confidence*) (Mackey et al., 2008; Dudley et al., 2010; Gross et al., 2016; Bebber and Butt, 2017; Dinerstein et al., 2019; IPCC, 2019a). CSA already has a greater percentage of land (24.1%) under protected status than the world average (14.7%) (UNEP-WCMC and IUCN, 2020b). Some countries, including Belize, Bolivia, Brazil, Guatemala, Nicaragua and Venezuela already met or surpassed the 30% CDB and IUCN goal (Dinerstein et al., 2019), and others like Costa Rica and Honduras are very close to doing so. In some cases, the establishment of protected areas not accompanied by collective decision-making processes has displaced local people or denied them access to natural resources, increasing their vulnerability to climate change (Brockington and Wilkie, 2015).

In addition to better managing and expanding protected areas networks, Other Effective Area-based Conservation Measures (OECMs), recently defined by the Parties to the Convention on Biological Diversity (Dudley et al., 2018), could also enhance ecosystem resilience (*low confidence*). Private Protected Areas in the mountain regions of the Americas (e.g., Andes), play an important role in closing the gaps in fragmented biomes and expanding protection in underrepresented areas (Hora et al., 2018). In Brazil, there is also a huge potential for conservation and sustainable management in private areas, as roughly 53% of the country’s native vegetation is within private land (Lapola et al., 2014; Soares-Filho et al., 2014).

Large-scale restoration is also seen as pivotal to limiting both climate change (IPCC, 2019a) and species extinction (IPBES, 2018a) (*very high confidence*). A new multi-criteria approach for optimizing multiple restoration outcomes (for biodiversity, climate change mitigation, and cost), for example, indicate that South America has the greatest extension of converted lands, evenly distributed in the top 50% of global priorities (Strassburg et al., 2020).

12.5.2 Ocean and Coastal Ecosystems and their Services

Ocean and coastal ecosystems provide suitable habitats to a high number of species that support important local fisheries, the tourism sector and the economy of the region (*high confidence*) (Section 3.5; Table 3.9; González and Holtmann-Ahumada, 2017; Venerus and Cedrola, 2017; CEPAL, 2018; Carvache-Franco et al., 2019; SROCC Section 5.4 Bindoff et al., 2019). There is *high confidence* that CSA ocean and coastal ecosystems are already impacted by climate change (Figure 12.9, 12.10; Table SM12.3; Section 3.4; , Section 5.4 in SROCC, Bindoff et al., 2019), and highly sensitive to non-climate stressors (Figure 12.8; Table SM12.3; Section 3.4). Projections for CSA ocean and coastal ecosystems alert about significant and negative impacts (*high confidence*) which include major loss of ecosystem structure and functionality, changes in the distributional range of several species and ecosystems, major mortality rates, and increasing number of coral bleaching events (Figure 12.9; Figure 12.10; Table SM12.3; Section 3.4; SROCC Sections 5.3, 5.4, Bindoff et al., 2019).

CSA subregions are highly dependent on ocean and coastal ecosystems, and thus vulnerable to climate change (FAO, 2018). Fisheries and aquaculture contribute significantly to food security and livelihoods by creating employment (more than two million people), income and economic growth for the region (Section 3.5; FAO, 2018) (). More than 45% of the total fisheries in CSA are based on marine products (CEPALSTAT, 2019). Peru, Chile, Argentina and Ecuador are among the 15 countries with the largest marine capture production worldwide (Gutiérrez et al., 2016a; FAO, 2018; Vannuccini et al., 2018), while more than 90% of the hydrological resources produced by aquaculture in CSA have a marine origin (CEPALSTAT, 2019). There is *high confidence* about important current and future impacts of climate change hazards in marine resources subjected to fisheries, however there is *low evidence* about the impacts on regional economies (Figure 12.9, 12.10; Table SM12.3).

12.5.2.1 Adaptation measures and strategies applied on oceans and coasts of CSA

Similar to those pointed by WGII AR5 Chapter 27 (Magrin et al., 2014) and Chapter 3 (Section 3.5; Section 3.6.2; Box SLR in Chapter 3), adaptation strategies in ocean and coastal ecosystems in CSA are still focused on the ecosystem protection and restoration, and the sustainable use of marine resources (*high confidence*). There is *low evidence* about how coastal urban areas and touristic settlements of CSA countries are adapting to SLR and extreme events (Calil et al., 2017; Villamizar et al., 2017). Some of this strategies include planned relocation (Dannenberg et al., 2019) and the use of grey infrastructures as seawalls and bulkheads (Silva et al., 2014; Isla et al., 2018) .

There is *medium confidence* that Ecosystem-based Adaptation (EbA) is the main strategy used in CSA coral reefs ecosystems. The set of strategies applied include the protection, restoration (e.g., coral gardening, larval propagation), and conservation of coral reefs areas through the application of the spatial ocean zoning schemes such as Marine Protected Areas (MPAs), marine managed areas (MMAs), National Parks, Wildlife Refuges, Special Zones of Marine Protection, Special Management Zones, Responsible Fishing Areas, and the establishment of management plans with some level of participatory processes. These strategies are complemented with actions that promote the development of research and education programs, recreational and cultural activities, the use of community-based approaches, and the creation of national specific laws (Graham, 2017) and the adhesion of international treaties (e.g., Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITIES), AGENDA 21, United Nations Convention on the Law of the Sea (UNCLOS), Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat) (Cruz-Garcia and Peters, 2015; Gopal et al., 2015; Graham, 2017; Bayraktarov et al., 2020).

Adaptation measures in mangroves ecosystems are mainly focused on the application of EbA strategies (*high confidence*). This measures include the application of restoration programs, the creation of management plans (which also have significant co-benefits with mitigation (Section 3.6.2.1), and the establishment of coastal protected areas, followed by the development of research activities, the creation of specific mangrove policies through new laws and resolutions (e.g., Colombia) (Cvitanovic et al., 2014; Krause, 2014; Blanco-Libreros and Estrada-Urrea, 2015; Carter et al., 2015; Estrada et al., 2015; Ferreira and Lacerda, 2016; Oliveira-Filho et al., 2016; Rodríguez-Rodríguez et al., 2016; Alvarado et al., 2017; Álvarez-León and Álvarez Puerto, 2017; Baptiste et al., 2017; Borges et al., 2017; Jaramillo et al., 2018; Salazar et al., 2018; Armenteras et al., 2019; Blanco-Libreros and Álvarez-León, 2019; Maretti et al., 2019; Ellison et al., 2020)

The use of territorial planning tools, the promotion of sustainable resource exploitation, the adherence to certification schemes, and the implementation of management instruments such as Ecosystem-based Management (EbM) followed by the use of an integrated coastal zone management, coastal marine spatial planning, capacity building, ecological risk assessments have been the mains strategies used to ensure the sustainability of marine resources subjected to fisheries across EEZs of CSA (*high confidence*) (Hellebrandt et al., 2014; Gelcich et al., 2015; Singh-Renton and McIvor, 2015; Gutiérrez et al., 2016a; Karlsson and Bryceson, 2016; Oyanedel et al., 2016; Debels et al., 2017; Isaac and Ferrari, 2017; Mariano Gutiérrez et al., 2017; Barragán and Lazo, 2018; Bertrand et al., 2018; Lluch-Cota et al., 2018; Guerrero-Gatica et al., 2020).

Other strategies include the application of local regulations (e.g., closed seasons) (Fontoura et al., 2016), and the use of participative instances (Hellebrandt et al., 2014; Arroyo Mina et al., 2016; Matera, 2016).

12.5.2.2 Adaptation success in ocean and coastal ecosystems of CSA

There is *low evidence* about how the strategies and actions taken and implemented in ocean and coastal systems of CSA have contributed to advance in the protection and conservation of ocean and coastal ecosystems. However, some important advances are visible in Colombian Pacific areas with coral reefs (new conservation plans, research monitoring and conservation practices) (*low confidence*) (Cruz-Garcia and Peters, 2015; Alvarado et al., 2017; Bayraktarov et al., 2020). In Panama, actions taken have allowed the protection of a high number of marine areas with coral reefs, as well as the incorporation of management approaches that include several sectors such as fisheries, tourism, coral protection and coral conservation (*low confidence*) (Alvarado et al., 2017). In the case of Costa Rica, 80% of coral habitats are located inside of MPAs, multiple research coral-related activities have been performed, and several training activities have favoured the engagement of the local community in their protection against climate and non-climate hazards (*low confidence*) (Alvarado et al., 2017).

There is *low evidence* of how the incorporation of mangroves as Ramsar sites, the reforms of legislations (e.g., fines and stronger regulations), and the creation of reserves and private protection initiatives (e.g., Belize Association of Private Protected Areas BAPPA), and capacity-building projects or new educational programs have promoted the protection of mangroves in CSA countries such as Honduras, Guatemala and Belize (Cvitanovic et al., 2014; Carter et al., 2015; Ellison et al., 2020). In Brazil, between 75–84% of mangroves are under some level of protection which has improved the forest structures, and multiple research programs (e.g., Mangrove Dynamics and Management, MADAM, and 'GEF-Mangle') have been developed (*medium confidence*) (Krause, 2014; Medeiros et al., 2014; Estrada et al., 2015; Ferreira and Lacerda, 2016; Oliveira-Filho et al., 2016; Borges et al., 2017; Maretti et al., 2019; Strassburg et al., 2019). In Colombia, research projects (e.g., Mangroves of Colombia Projects, MCP), the installation of a geographic information system for mangroves (e.g., SIGMA Sistema de Información para la Gestión de los Manglares en Colombia), surveillance monitoring plans (e.g., EGRETTA Herramientas para el Control y Vigilancia de los Manglares), and the establishment of protected areas have contributed to decrease loss of the mangrove forest (*high confidence*) (Blanco-Libreros and Estrada-Urrea, 2015; Rodríguez-Rodríguez et al., 2016; Álvarez-León and Álvarez Puerto, 2017; Baptiste et al., 2017; Jaramillo et al., 2018; Salazar et al., 2018; Armenteras et al., 2019; Blanco-Libreros and Álvarez-León, 2019).

There is *low evidence* whether the establishment of MPAs and the creation of legal instruments have allowed the development of new research activities have increased the environmental awareness, decreased the illegal extraction, and improved the local coordination which have promoted the sustainable use of marine resources, and improved the community-government cooperation in marine ecosystems (Alvarado et al., 2017). The experience in countries like Chile demonstrates the importance of implementing robust management plans that guarantee the protection objectives and the sustainability through the implementation of EbA measures such as MPAs (Petit et al., 2018).

There is *low confidence* about how measures adopted are ensuring the sustainability of marine resources subjected to fisheries. In Peru, the industrial fishery follows an adaptive management approach (i.e., stock assessments, catch limits), while in Chile, the small-scale fishery of benthic-demersal resources is managed through the granting of exclusive territorial use rights (called TURFS) with established quotas defined by the central authority (Bertrand et al., 2018). In addition, MPAs in Chile are playing a key role in climate change adaptation for fisheries (*medium confidence*) (Gelcich et al., 2015; Petit et al., 2018), and an increasing amount of funds have been invested in initiatives to reduce the vulnerability of fishery and aquaculture sectors to climate change (OECD, 2017). Since 2016, Argentina has been developing a strategy to implement EbM on fisheries with support from the Global Environment Facility program (GEF). Also, Argentina and Chile, are promoting the local consumption of seafood and the certification of its fishery products (OECD, 2017), while Brazil and Chile have advanced in their actions to climate change through the development of new research studies and methodologies incorporating research institutions (Nagy et al., 2015). Uruguay is incorporating stakeholders in their climate change adaptation strategies (*low confidence*) (Nagy et al., 2015), while Colombia is supporting the capacity building of fishers promoting livelihood diversification to increase the resilience of the sector (*medium confidence: medium evidence, high agreement*) (Hellebrandt et al., 2014; Arroyo Mina et al., 2016; Matera, 2016). Chile and Peru have showed certain advances in the development of guidelines for the management of the coast line and the implementation of the EbM which has favoured the collaboration of diverse and multiple stakeholders (fishers, academics, municipal institutions), the development of outreach and educational activities, and the creation of networks, and the interest of other fishery communities to implement EbM (*medium confidence: medium evidence, high agreement*) (Hellebrandt et al., 2014; Gelcich et al., 2015; Gutiérrez et al., 2016a; Oyanedel et al., 2016; Guerrero-Gatica et al., 2020). In countries like Peru and Chile, there is an increasing presence of intergovernmental and international cooperation agencies, and new funding (e.g., GEF), and projects (Inter-American Development, SPINCAM) related to change adaptation for the fishery sector (*medium confidence: medium evidence, high agreement*) (Galarza and Kámiche, 2015; Barragán and Lazo, 2018).

12.5.2.3 National climate change commitments for ocean and coasts

Beyond the protection, conservation and climate change adaptation strategies implemented on CSA ocean and coastal areas and their ecosystems, a high number of adaptation goals to face climate change impacts on ocean and coastal ecosystems and their services are incorporated in most of the national climate change adaptation commitments of CSA countries (Table 12.7).

Table 12.7: National plans with adaptation goals for ocean and coasts in CSA.

CSA country	Adaptation Initiatives	Year
Argentina	Plan Nacional de Adaptación y Mitigación al Cambio Climático[1]	2019
Brazil	National Adaptation Plan to Climate Change (Volume 1); General Strategies[2]	2016
	National Adaptation Plan to Climate Change (Volume 2); Sectoral and thematic strategies[3]	2016
Chile	Plan Nacional de Adaptación al Cambio Climático[4]	2014
	Plan Sectorial de Adaptación al Cambio Climático en Biodiversidad[5]	2014
	Plan Sectorial de Adaptación al Cambio Climático en Pesca y Acuicultura[6]	2015
	Plan de Adaptación y Mitigación de los Servicios de Infraestructura al Cambio Climático[7]	2017
	Plan de Adaptación al Cambio Climático Sector Salud[8]	2017
Colombia	Plan Nacional de Adaptación al Cambio Climático[9]	2016
Costa Rica	Política Nacional de Adaptación al Cambio Climático[10]	2018
Ecuador	Plan Nacional de Cambio Climático[11]	2015
El Salvador	Plan Nacional de Cambio Climático[12]	2015
Guatemala	Plan de Acción Nacional de Cambio Climático[13]	2018
Guyana	Política de Adaptación y Plan de Implementación[14]	2001
Honduras	Plan Nacional de Adaptación al Cambio[15]	2018
Nicaragua	Plan de Adaptación a la Variabilidad y el Cambio Climático en el Sector Agropecuario, Forestal y Pesca[16]	2013
Peru	Plan Nacional de Adaptación al Cambio Climático del Peru[17]	2021
Suriname	Suriname National Adaptation Plan[18]	2019
Uruguay	Plan Nacional de Respuesta al Cambio Climático[19]	2010
Belize	Not Available	2019
Panamá	Not Available	
Venezuela	Not Available	

References: [1](Ministerio de Ambiente y Desarrollo Sostenible de la República de Argentina, 2019) [2](Ministry of Environment of Brazil, 2016a) [3](Ministry of Environment of Brazil, 2016b) [4](Ministerio de Medio Ambiente de Chile, 2014b) [5](Ministerio de Medio Ambiente de Chile, 2014a) [6](Ministerio de Economía Fomento y Turismo de Chile, 2015) [7](Ministerio de Medio Ambiente de Chile, 2017) [8](Ministerio de Salud de Chile, 2017) [9](Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2016) [10](Ministerio de Ambiente y Energía de la República de Costa Rica, 2018) [11](Gobierno Nacional de la República del Ecuador, 2015) [12](Ministerio de Medio Ambiente y Recursos Naturales de El Salvador, 2015) [13](Consejo Nacional de Cambio Climático y la Secretaría de Planificación y Programación de la Presidencia de Guatemala, 2018) [14](National Ozone Action Unit of Guyana, 2016) [15](Secretaría de Recursos Naturales y Ambiente del Gobierno de la República de Honduras, 2018) [16](Ministerio Agropecuario y Forestal de Nicaragua, 2013) [17](Ministerio del Ambiente Gobierno del Perú, 2021)

[18](Government of Suriname, 2019) [19](Ministerio de Vivienda Ordenamiento Territorial y Medio Ambiente de la República de Uruguay, 2010)

Current goals in national and sectoral adaptation plans attempt to promote research and monitoring (e.g., new research actions, modelling, knowledge management), the development of new legislation tools and policies (e.g., inter-institutional and territorial coordination, improvement of public policies), the conservation of ocean and coastal ecosystems and their biodiversity (e.g., new MPAs establishment, protection tools), the management of climate risks (e.g., alert systems), the management of productive activities (e.g., diversification of resources), the promotion of the construction of new infrastructure and technology (e.g., grey-green infrastructure - GGI), the creation of new financial tools (e.g., insurances), the improvement of the capacity building (e.g., education, awareness), the management of water and residues (e.g., sewages and freshwater availability), the social inclusion (e.g., strategies to support vulnerable sectors, gender inclusion), and the incorporation of traditional practices (e.g., restoring traditional practices including Indigenous knowledge). However, the amount and the type of adaptation goals per country differ enormously among countries (Figure 12.12).

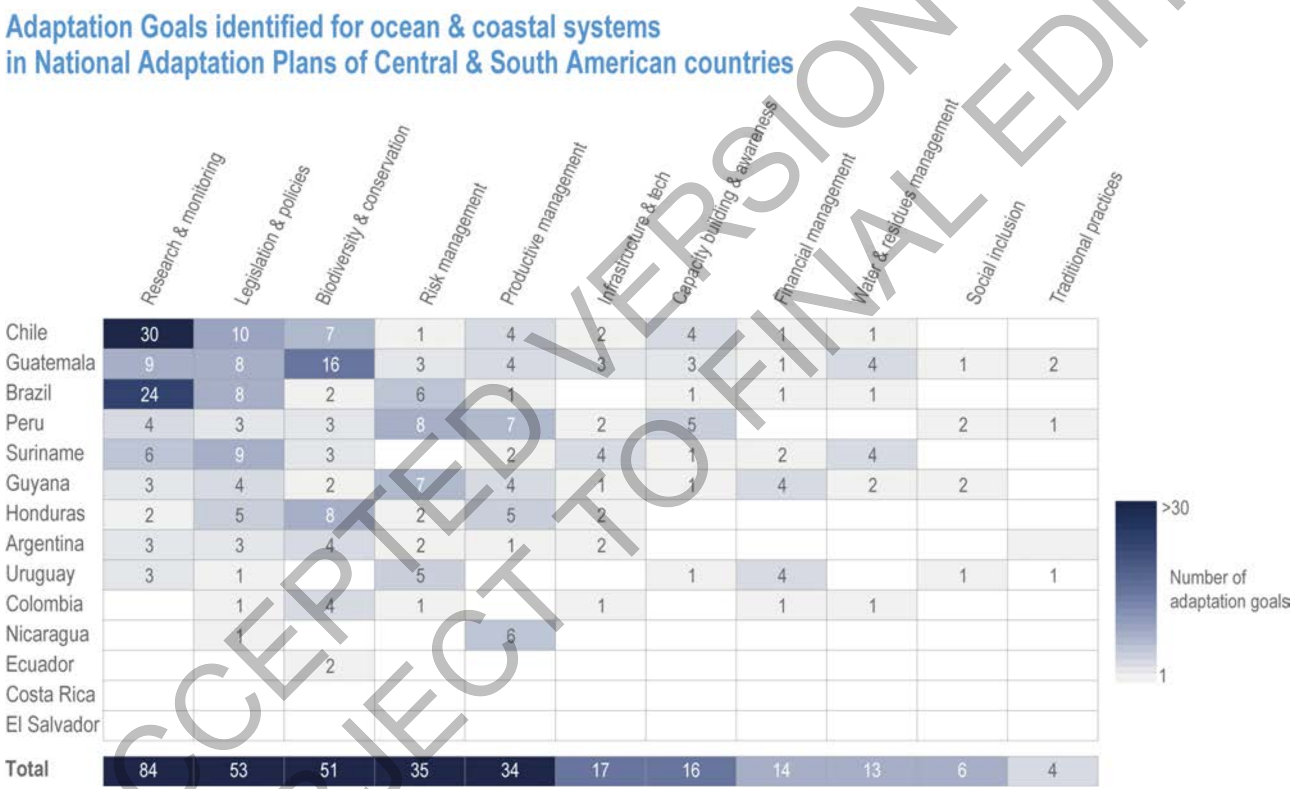


Figure 12.12: Type and amount of adaptation goals identified in National Adaptation Plans for ocean and coastal systems of CSA countries.

12.5.2.4 Limits and barriers for adaptation in ocean and coastal ecosystems

Although current national adaptation plans and many other actions and strategies are focused on improving the conservation and restoration of ocean and coastal ecosystems, as well as, the suitability of marine resources along CSA, these measures are still not able to reduce the vulnerability and sensitivity of these ecosystems to climate change hazards (*high confidence*) (Figure 12.6; Table SM12.3; Leal Filho, 2018; Nagy et al., 2019) . There is *high confidence* that sandy beaches ecosystems of CSA countries show an important loss of dunes as a consequence of the construction of infrastructures which have generate an interruption of the natural dynamic of beaches decreasing the protection to tides, waves, extreme events or tsunamis (*high confidence*) (Amaral et al., 2016; Bernardino et al., 2016; González and Holtmann-Ahumada, 2017; Obraczka et al., 2017). Also, adaptation measures to cope with SLR and coastal extreme events sometimes fail as they exacerbate coastal erosion and damage (*medium confidence: medium evidence, high agreement*) (Spalding et al., 2014; Lins-de-Barros and Parente-Ribeiro, 2018). There is *medium evidence* but *high agreement* that the most barriers limiting the success of adaptation strategies in ocean and coastal systems in CSA are due to the lack of coordination (e.g., absence of participatory processes, overlapping among fishing and protection activities), the lack of knowledge (e.g., poor monitoring, poor control and surveillance, no long-term studies), lack of adequate metrics for evaluating adaptation actions informing decision-makers hinder the continuity and adjustment of measures, weak governance (e.g., perverse incentives, resource overexploitation, conflicts), lack of financial resources and long-term commitments (e.g., crisis, lack of budgets, market fluctuations), weak policies, cultural constraints, poverty, low flexibility, lack of awareness of climate risks, and lack of engagement by stakeholders (Leal Filho, 2018; Nagy et al., 2019; Moreno et al., 2020b; Aburto et al., 2021).

Some important limits and barriers have been detected for productive systems such as fisheries and tourism in CSA (*medium confidence: medium evidence, high agreement*). Brazilian major fisheries management do not follow an ecosystem approach, although some small-scale fisheries apply a precautionary approach (Singh-Renton and McIvor, 2015). The management of Peruvian artisanal (medium and small-scale fisheries) are minimal with an important lack of regulations, control, and management actions (Bertrand et al., 2018). In Argentina, marine recreational fisheries have been largely unregulated with a lack of monitoring programs which have contributed to the overexploitation of some key coastal stocks (Venerus and Cedrola, 2017). Moreover, the participation of women fishers in CSA is not equally considered being excluded from the decision-making processes (FAO, 2016b; Bruguere and Williams, 2017). Due to the lack of monitoring programs, it is unknown how this tourism industry will respond to long-term changes driven by climate change (Weatherdon et al., 2016).

12.5.2.5 Challenge and Opportunities

There is *low evidence and high agreement* that empower the local stakeholders (e.g., multilateral fisheries agreements) improve the public awareness and simplify regulations and increase the flexibility and sustainability of marine resources subjected to fisheries under future scenarios (Weatherdon et al., 2016; Kalikoski et al., 2019). Ecosystem-Based Fishery Management (EBFM) arises as a suitable tool to minimize the risk to climate change, avoid the degradation of the ecosystems and its services (Gullestad et al., 2017) and maintain the long-term socioeconomic benefits when include climate complexity and the relationships among species within the ecological systems (Long et al., 2015). There is *high confidence* that EbA is more successful and feasible than hard coastal defences for the protection, management and restoration of ocean and coastal ecosystems and their resources (Spalding et al., 2014; González and Holtmann-Ahumada, 2017; Scarano, 2017).

There is *high confidence* that ecological and social resilience is improved by the presence of adequate metrics evaluating adaptation measures that allow dynamic changes, increasing basic research and climate data (Moreno et al., 2020b), the existence of early warning systems, improved local institutions, the construction of adequate infrastructure, major funding for capacity building, and the enhanced engagement and empowerment of women (FAO, 2016b; Harper et al., 2017; Frangoudes and Gerrard, 2018; Gallardo-Fernández and Saunders, 2018; Leal Filho, 2018).

12.5.3 Water

CSA is one of the regions most affected by current and future hydrological risks to water security with an increasing number of vulnerable people depending on water from mountain (*high confidence*) (Sections 4.3, 4.4, 4.5; Immerzeel et al., 2020; Viviroli et al., 2020; WWAP, 2020). Adaptation to changing water availability is therefore a priority, but most efforts are documented only in the grey literature (e.g., governmental documents, project reports) with highly variable standards of quality and evidence. Most of the documented adaptation initiatives are in an early planning or implementation stage and evidence on successful outcomes is quite limited (Berrang-Ford et al., 2021). However, the growing number of adaptation initiatives across the CSA region has contributed to improved understanding of complex interlinkages of climate change, human vulnerabilities, local policies, and feasible adaptation approaches (McDowell et al., 2019).

12.5.3.1 Challenges and opportunities

In several regions of CSA, water scarcity is a serious challenge to local livelihoods and economic activities. Particularly (seasonally) dry regions, partly with large populations and increasing water demand, exhibit major water stress. These include the dry corridor in CA, coastal areas of Peru (SWS) and Northern Chile (SWS), the Bolivian-Peruvian Altiplano (NWS, SAM), the Dry Andes of Central Chile (SWS),Western Argentina and Chaco in Northwest Paraguay (SES), and Sertão in Northeast Brazil (NES) (*high confidence*) (Kummu et al., 2016; Mekonnen and Hoekstra, 2016; Schoolmeester et al., 2018). In NWS and SWS, downstream areas are increasingly affected by decreasing and unreliable river runoff due to rapid glacier shrinkage (*high confidence*) (Table SM12.6; Carey et al., 2014; Drenkhan et al., 2015; Buytaert et al., 2017). Many regions in CSA rely heavily on hydroelectric energy, and as a result of rising energy demand, hydropower capacity is constantly extended (Schoolmeester et al., 2018). Worldwide, SA features the second-fastest growth with about 5.2 GW additional annual capacity installed in 2019 (IHA, 2020). This development requires additional water storage options, which entail the construction of large dams and reservoirs with important social-ecological implications. River fragmentation and corresponding loss of habitat connectivity due to dam constructions have been described for e.g., the NSA, SAM, NES and SES (*high confidence*) (Grill et al., 2015; Anderson et al., 2018a) with important implications for freshwater biota, such as fish migration (*medium confidence*) (Pelicice et al., 2015; Herrera-R et al., 2020). Furthermore, examples in e.g., the NWS (Carey et al., 2012; Duarte-Abadía et al., 2015; Hommes and Boelens, 2018) and SWS (Muñoz et al., 2019b) showcase unresolved water-related conflicts between local villagers, peasant communities, hydropower operators and governmental institutions in a context of distrust and lack of water governance (*high confidence*).

Increasing water scarcity is also shaped by poor water quality, which has barely been assessed in CSA. Declining water quality can be observed e.g., due to intense agricultural and industrial activities in SWS, SES and SSA (*medium confidence*) (Mekonnen et al., 2015; Gomez et al., 2021), mining in Andean headwaters (NWS, SWS and Western SAM) and tropical lowlands (Eastern SAM and NSA) (*medium confidence*) (Bebbington et al., 2015 risk and climate resilience; Vuille et al., 2018), urban domestic use (Desbureaux and Rodella, 2019), decreasing meltwater contribution (Milner et al., 2017) and acid rock drainages from recently exposed glacial sediments (Santofimia et al., 2017; Vuille et al., 2018). The level of water pollution is often exacerbated by missing water treatment infrastructure and low governance levels (*medium confidence*) (Mekonnen et al., 2015) with considerable negative implications for human health (Lizarralde Oliver and Ribeiro, 2016).

Water scarcity risks are projected to affect a growing number of people in the near and mid-term future in view of growing water demand in most regions (*medium confidence: medium evidence, high agreement*) (Veldkamp et al., 2017; Schoolmeester et al., 2018; Viviroli et al., 2020), expected precipitation reductions in Western and Northern SAM and SWS (*medium confidence: medium evidence, medium agreement*) (Neukom et al., 2015; Schoolmeester et al., 2018), substantial vanishing of glacier extent in NWS, SAM and SWS (Table SM12.6; Rabatel et al., 2018; Vuille et al., 2018; Cuesta et al., 2019; Drenkhan et al., 2019), and increasing evaporation rates in CA (*medium confidence*) (CEPAL, 2017). Furthermore, flood risk is a serious concern (Arnell et al., 2016) and expected to increase especially in NWS, SAM, SES and SWS in the mid and long-term future (*high confidence*) (Arnell and Gosling, 2016; Alfieri et al., 2017).
Risks of water scarcity and flood are threatening people unevenly across the region. In CSA, about 26% (130 million people) of the population have no access to safe drinking water and strong disparities prevail regarding its spatial distribution, e.g., in Chile 99% of the population have access, compared to 50% in Peru, 73% in Colombia, 52% in Nicaragua or 56% in Guatemala (*high confidence*) (UNICEF and WHO, 2019). Inequalities can be further exacerbated by unregulated or privately owned water rights and allocation systems (e.g., in Chile) (Muñoz et al., 2020a). The most vulnerable people belong to low-income groups in rural areas and informal settlements of large urban areas (*high confidence*) (WWAP, 2020).

Considerable uncertainties remain concerning future hydrological risks that strongly depend on the respective pathways of human intervention, management, adaptation and socioeconomic development. The combination of (seasonally) reduced water supply, growing water demand, declining water quality, ecosystem deterioration and habitat loss, and low water governance could lead to increasing competition and conflict associated with high economic losses (*high confidence*) (Vergara et al., 2007; Vuille et al., 2018; Desbureaux and Rodella, 2019). This situation threatens human water security on the long term and poses an increasing risk to adaptation success in CSA (*high confidence*) (Drenkhan et al., 2015; Huggel et al., 2015b; Urquiza and Billi, 2020a).

Important progress has been made on climate change and water management policies in combination with more inclusive stakeholder processes. For instance, the implementation of NDCs in most countries of the region provides an important baseline for improving water efficiency, quality and governance at multi-sectoral level, and thus long-term adaptation planning (UNEP, 2015).

12.5.3.2 Main concepts and approaches

Adaptation in the water sector includes a broad set of responses to improve and transform, among others, water infrastructure, ecosystem functions, institutions, capacity building and knowledge production, habits and culture, and local-national policies (Section 4.6).

Most adaptive water management approaches in CSA centre around extending the water supply side including large infrastructure projects. However, 'hard path' interventions are now strongly contested due to negative effects exacerbating local water conflicts (Carey et al., 2012; Boelens et al., 2019; Drenkhan et al., 2019), potentially leading to increasing water demand, vulnerabilities and water shortage risks (Di Baldassarre et al., 2018), and, hence, limiting adaptive capacity (*high confidence*) (Ochoa-Tocachi et al., 2019). More integrated approaches focus on multi-use of water storage with shared stakeholder vision, responsibilities, rights and costs, as well as risks and benefits, and often integrating water and risk management (Branche, 2017; Haeberli et al., 2017; Drenkhan et al., 2019). In this chapter, a feasibility assessment was carried out for six major dimensions of multi-use water storage for the entire CSA (see Table 12.11). While geophysical and economic aspects allow for the implementation of water storage projects with multi-use approach, the institutional, social and environmental dimensions pose a major barrier (see Section 12.5.3). Further demand-oriented approaches focus on incentives for the reduction of water use through changes in people's habits, efficiency increase and smart water management (Gleick, 2002). These are promoted in some regions, such as in CA and NWS (e.g., Colombia, Ecuador and Peru), to foster a sustainable water culture (Bremer et al., 2016; Paerregaard et al., 2016).

Major attention has been put on nature-based solutions (NbS), i.e., catchment interventions that are inspired and supported by nature and leverage natural processes and ecosystem services to contribute to the improved management of water. NbS potentially enhances water infiltration, groundwater recharge and surface storage, contributes to disaster risk reduction and can replace or complement grey (i.e., conventionally built) infrastructure that is often socio-environmentally contested (WWAP, 2018). Some examples include the reactivation of ancestral infiltration enhancement systems in the Peruvian Andes (NWS) (Ochoa-Tocachi et al., 2019), the use of erosion control structures in the Bolivian Altiplano (SAM) (Hartman et al., 2016), and the potential improvement of drinking water quality and flood risk reduction in urban areas of CSA (Tellman et al., 2018, Section 12.5.5.3.2). Additionally, NbS in combination with ecosystem and community-based adaptation potentially generate important co-benefits including increasing water security and the attenuation of social conflicts in Chile (SWS) (Reid et al., 2018), water conservation in coastal Peru (NWS), and flood protection in Guyana (NSA) (*medium confidence: medium evidence, medium agreement*) (Spencer et al., 2017). However, evaluation of implementation success of NbS is often hampered by limited evidence on actual benefits (WWAP, 2018).

In recent years, the inclusion of Indigenous knowledge (IK) and local knowledge (LK) into current adaptation baselines has gained increasing attention, particularly in regions with a high share of Indigenous Peoples (NWS, SAN, SWS, NSA) (*high confidence*) (Reyes-García et al., 2016; Schoolmeester et al., 2018; McDowell et al., 2019). One example is the adapted use of agrobiodiversity when dealing with more frequent and intense tidal floods in the Amazon delta (NSA) (Vogt et al., 2016). In another context, IK and LK have been considered for the evaluation of water scarcity and glacier lake outburst flood risks in Peru (NWS) (Motschmann et al., 2020b). Additionally, local citizen science based initiatives (Buytaert et al., 2014; Tellman et al., 2016; Njue et al., 2019) can support the production of multiple knowledge with flexible and extensive data collection. Important questions centre around how to integrate IK, LK and other types of knowledge from the early planning stages on, to achieve enhanced or transformational adaptation building on co-produced knowledge (Kates et al., 2012; Klenk et al., 2017). NbS combined with community engagement and integration of diverse knowledge can foster transformational adaptation of social-ecological systems (Palomo et al., 2021).

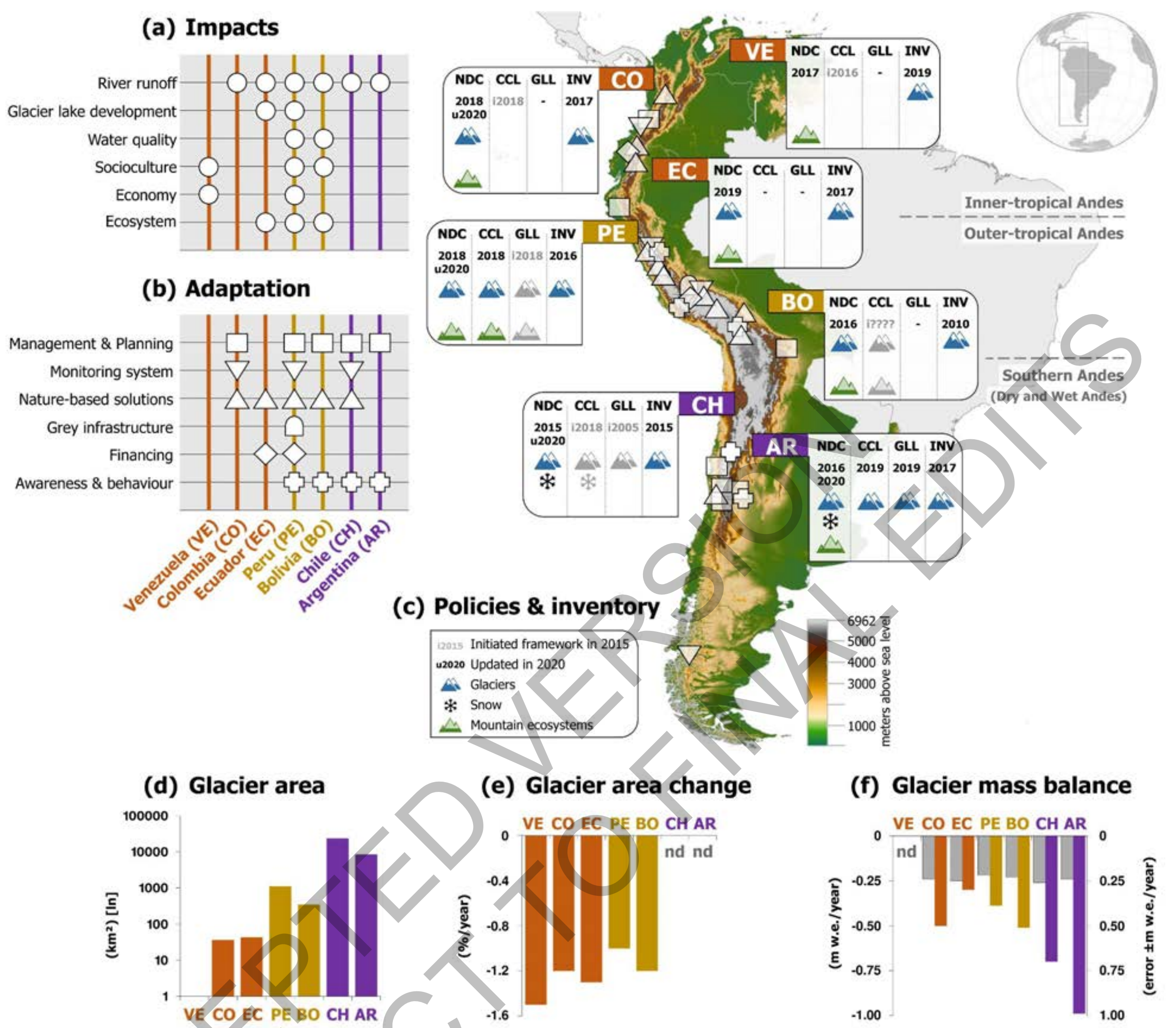


Figure 12.13: Overview map of observed glacier changes, associated impacts, adaptation and policy efforts across the Andes. (a) Selected impacts from glacier shrinkage. (b) Selected adaptation efforts (see upper-right map for the location of each adaptation measure), (c) Policies and glacier inventory: NDC = submission year(s) of Nationally Determined Contributions (u = update), CCL = climate change law, GLL = glacier law (i = initialized framework), INV = last national glacier inventory. The explicit mention of glaciers, snow and mountain ecosystems within each law/inventory is highlighted with the corresponding symbols (grey colour = not come into force). (d) Glacier area (km²) according to last national inventory. (e) Glacier area change (%/year) according to the baseline of the last national inventory. (f) Geodetic glacier mass balance (m w.e./year) and error estimate (±m w.e./year) retrieved from Dussaillant et al. (2019). nd = no data available. Further details can be found in the Appendix in Table SM12.6.

12.5.3.3 Policies, governance and financing

National policies on climate change, water protection, regulation and management laws are important focal areas of adaptation in the water sector (Section 4.7). Notable in the jurisdiction field is the Glacier Protection Law in place in Argentina (2010-2019), and under construction in Chile (since 2005). This first glacier law in the world represents a milestone for high-mountain conservation but is also criticized for hindering effective disaster risk adaptation measures and excluding local socioeconomic needs (Anacona et al., 2018). Furthermore, the first Framework Law on Climate Change was implemented in Peru (2018), and is underway in Colombia, Chile and Venezuela (Figure 12.13; Table SM12.6). Overarching regional institutions (e.g., OAS (2016)) and most countries in CSA promote a move towards more integrative and sustainable management of water resources through new legislations and financing mechanisms. For instance, new water laws including principles of Integrated Water Resources Management (IWRM) have entered into force, e.g., in Nicaragua (2007), Peru (2009), Ecuador (2014) and Costa Rica (2014) or are underway, such as in Colombia (since 2009). However, current realities in all regions show major challenges in implementing IWRM mechanisms and policies, related but not limited to political and institutional instabilities, governance structures, fragmented service provision, lack of economies of scale and scope, corruption and social conflicts (*high confidence*) (WWAP, 2020).

Many water-related conflicts in CSA are rooted in inequitable water governance that excludes water users from decisions on water allocation (*high confidence*) (Drenkhan et al., 2015; Vuille et al., 2018). In turn, inclusive water regimes leverage long-term adaptation planning. These have been addressed in some national strategies, such as in Brazil (Ministry of Environment of Brazil, 2016a). At the local level, a decentralized and participatory bottom-up water governance model was induced by civil society and research institutions to foster rainwater harvesting technologies reducing drought risk in semi-arid Brazil (NES) (Lindoso et al., 2018).

Water fund programs can generate important co-benefits for Sustainable Development contributing to improved governance and conservation of watershed systems in CSA. Nevertheless, only a few experiences have been evaluated as successful due to insufficient implementation, low decision-making of some stakeholder groups and poor evidence-based approaches (*medium confidence*) (Bremer et al., 2016; Leisher et al., 2019). Furthermore, financing mechanisms that produce incentives for sustainable water management have been promoted, tested or implemented. Payments for Ecosystem Services (PES) for water provision represent such an example and have been implemented across CSA since the 1990s (Grima et al., 2016).

Only about 50–70% of required financial resources are currently allocated per year to meet the national targets in the water, sanitation and hygiene (WASH) sector for the Sustainable Development Agenda (SDG 6) in several regions of CSA. This share drops down to less than 50% in NSA (Venezuela) and SES (Argentina, Uruguay, Paraguay), except for Panama in CA allocating more than 75% of required financial resources. For the implementation of NbS, evidence suggests that the overall expenditure remains well below 1% of total investment in water resources management infrastructure (WWAP, 2018). These funding deficits pose important limitations for future water provision, adaptation to changing water resources, and the achievement of the SDGs by 2030 (*high confidence*) (WHO, 2017).

12.5.3.4 Successful adaptation and limitations

Although a growing body of adaptation initiatives exists for CSA, evidence on effectiveness is scarce. In many parts of CSA the level of success of respective adaptation measures depends much on the governance of projects and stakeholder-based processes and is closely related to their effectiveness, efficiency, social equity and socio-political legitimacy (*high confidence*) (Adger et al., 2005; Rasmussen, 2016b; Moulton et al., 2021). Several Payments for Ecosystem Services experiences across CSA have been described as successful measures for watershed conservation and adaptation (*high confidence*). An example of success represents the Quito water fund in Ecuador which aims at improving the city's water quality by integrating public and private stakeholder interests with ecosystem conservation and local community development since the 2000's (Bremer et al., 2016; Grima et al., 2016) (case study 12.6.1). At the same time, in Moyobamba in Peru the development of a watershed protection program was leveraged by a multi-stakeholder platform process that enabled deep social learning (Lindsay, 2018). In turn, initiatives that do not consider the entire set of social-ecological dimensions and dynamics of adaptation or unintentionally increase vulnerabilities of human or natural systems, are at risk to lead to reduced outcomes (McDowell et al., 2021) or maladaptation (Reid et al., 2018; McDowell et al., 2019; Eriksen et al., 2021). However, systematic assessments of maladaptation in the water sector have barely been provided for CSA.

In CSA, only limited information on limits of adaptation in relation to water is available, for instance on possible path dependency of institutions and associated resistance to change (Barnett et al., 2015). Examples of soft adaptation limits (i.e., options to avoid intolerable risks currently not available) include the lack of trust and stakeholder flexibility, associated with unequal power relations that lead to reduced social learning, and poor outcomes for improved water management, as reported in e.g., NWS (Lindsay, 2018). An example for hard adaptation limits (i.e., intolerable risks cannot be avoided) in the region is the loss of livelihoods and cultural values associated with glacier shrinkage in NWS (Jurt et al., 2015).

Most barriers to advance adaptation in CSA correspond to soft limits associated with missing links of science-society-policy processes, institutional fragilities, pronounced hierarchies, unequal power relations and top-down water governance regimes (*high confidence*). One example is the abandonment of hydrological long-term monitoring sites within tropical Andean ecosystems (paramo) in Venezuela (Rodríguez-Morales et al., 2019) due to the lack of governmental support within a political crisis. In that regard, the collection and availability of consistent hydroclimatic and socioeconomic data at adequate scales represent an important challenge in CSA. Major adaptation barriers are furthermore reported from Central Chile in the context of a mega-drought since 2010, related to socioeconomic characteristics and a deficient bottom-up approach to public policy informing and development (Aldunce et al., 2017). These gaps could be bridged by strengthening transdisciplinary approaches at the science-policy interface (Lillo-Ortega et al., 2019) with blended bottom-up and top-down adaptation to include scientific knowledge with impact and scenario assessments into local adaptation agendas (Huggel et al., 2015b). For instance, a new allocation rule for the Laja reservoir in Southern Chile (SWS), based on consistent water balance modelling results, could inform policy and water management and potentially improve local water management and reduce water conflicts on the long term (Muñoz et al., 2019b).

12.5.4 Food, Fibre and other Ecosystem Products

The CSA region globally has the greatest agricultural land and water availability per capita. With 15% of the world's land area, it receives 29% of global precipitation and has 33% of globally available renewable resources (Flachsbarth et al., 2015). Agricultural commodities (coffee, bananas, sugar, soybean, corn, sugarcane, beef livestock) are some of the highest users of ecosystem resources such as land, water, nutrients and technology. These exports have gained importance in the past two decades as international trade and globalization of markets have shaped the global agri-food system. However continuous overuse on the environment might account for resource depletion (deforestation, land degradation, nutrient depletion, pollution), affecting the natural capital base. The effects of climate change on humans, via ecological systems, exacerbate the impact related to depletion of ecosystem services (Scholes, 2016; IPBES, 2018b; Castaneda Sanchez et al., 2019; Clerici et al., 2019; Tellman et al., 2020; Pacheco et al., 2021).

12.5.4.1 Challenges and opportunities

Even though there are large improvements in food availability in several regions, there is also a tendency of a decline in food self-sufficiency in many countries (Porkka et al., 2013; Rolando et al., 2017). Drought conditions in Central America and the Caribbean increased in line with climate model predictions (Herrera et al., 2018a). The direct social and economic consequences for the sector are evident in Central America's so-called Dry Corridor with a growing dependence on food imports (Porkka et al., 2013) and these degrees of dependency make the region more vulnerable to price variability, climatic conditions (Bren d'Amour et al., 2016; ECLAC, 2018) and therefore, to food insecurity if adaptation actions are not taken (*high confidence*) (Porkka et al., 2013; Bren d'Amour et al., 2016; López Feldman and Hernández Cortés, 2016; Eitzinger et al., 2017; Imbach et al., 2017; Lachaud et al., 2017; Harvey et al., 2018; Niles and Salerno, 2018; del Pozo et al., 2019; Alpízar et al., 2020; Anaya et al., 2020).

Given these circumstances, some regions in CSA (Andes region and Central America) will just meet, or fall below, the critical food supply/demand ratio for their population (Bacon et al., 2014; Barbier and Hochard, 2018b). Meanwhile, the more temperate part of South America in the south is projected to have agricultural production surplus (*low confidence*) (Webb et al., 2016; Prager et al., 2020). The challenge for this region will be to retain the ability to feed and adequately nourish its internal population as well as making an important contribution to the food supplies available to the rest of the world.

The access of agricultural products from the region to other markets might be conditioned on the adoption of low-carbon agriculture measures. Achieving net-zero emissions while improving standards of living is possible but requires developing transition policy frameworks to attain the target (Frank et al., 2019; Mahlknecht et al., 2020; Cárdenas et al., 2021).

12.5.4.2 Governance and barriers for adaptation

The governance of adaptation for CSA implies modifying agricultural, socio-economic and institutional systems in response to and in preparation for actual or expected impacts of climate variability and change, to reduce harmful effects and exploit beneficial opportunities (*high confidence*). CSA agriculture has a diversity of systems and segments of producers. While small-scale farmers have a big contribution to food production and food security, especially in developing economies, they face global policies oriented towards global commodity markets (Knapp, 2017; Fernández et al., 2019). Climate action initiatives that consider CSA's high levels of poverty and inequality to reduce these pervasive problems are central for adapting the region (Crumpler et al., 2020; Locatelli et al., 2020).

Since AR5, important advances at institutional level are observed based on the development and implementation of national adaptation plans for the agriculture and forestry sector among countries. Adapting to climate change entails the interaction of decision-makers, stakeholders, and institutions at different scales of government from the local to the national. The Climate-Adapted Sustainable Agriculture Strategy for the region of the Central American Integration System (EASAC) of the Central American Agricultural Council of Ministers of Agriculture, constitutes a valuable example of how undertake climate action in the agricultural sector, as a block of countries and in an intersectoral manner, to enhance results and make better use of resources (IICA, 2019).

In Brazil, the Low Carbon Agriculture program (Programa ABC) funds practices for reducing GHG emission in the sector (Government of Brazil, 2012), allocating about 15% of the total agriculture official finance portfolio, although it faces challenges to advance (Souza Piao et al., 2021). Costa Rica offers an example on how reforestation can help achieve Paris Agreement objectives. Reforestation through natural regeneration on abandoned pastures boosted forest cover from 48% in 2005 to 53.4% in 2010 (Reid et al., 2019; Cárdenas et al., 2021). Some key success factors included a strong institutional context, fiscal and financial incentives for reforestation, conservation measures such as payment for environmental services, cattle ranch subsidy reform, and a historically strong enforcement and focus on land titles that favoured the restoration of lands. Uruguay offers another example, with the farm sector contribution of 32.8% of all exports and 73.8% of the country's emissions, so decarbonisation is not just an environmental issue but an economic competitiveness one as well. In the INDCs submitted to the UNFCCC in 2015, Uruguay set a specific target for the agriculture sector to reduce enteric methane emissions intensity per kilogram of beef (live-weight) by 33% to 46% in 2030 through improving efficiency of beef production by controlling the grazing intensity to increase animal intake, reproductive efficiency, and daily weight gain (Picasso et al., 2014).

It is relevant to generate conditions for the development of sustainable agricultural practices in a frame where factors associated with climate have become important for producers, given recent experiences of drought and lack of water (*high confidence*) (Clarvis and Allan, 2014; Roco et al., 2016; Hurlbert and Gupta, 2017; Pérez-Escamilla et al., 2017; Cruz et al., 2018; Zúñiga et al., 2021). Solutions that consider relevant drivers that have demonstrated positive effect in diffusion of adaptation strategies are more efficient (Table 12.8). Some conditions such as the promotion of education programs; participation in cooperatives; credit access; land tenure security can help in this task. In the same line, in CSA some elements such as technology and information access, and local knowledge, reinforce climate change adaptation (Khatri-Chhetri et al., 2019; Piggott-McKellar et al., 2019). As is stated in Table 12.8 barriers of different origin persist for climate change adaptation in the region increasing vulnerability of farming systems and rural livelihoods.

Limited information regarding cost-benefit analyses of adaptation is available in the region as well as avoiding maladaptation effects and promoting site-specific and dynamic adaptation options considering available technologies (*medium confidence*) (Roco et al., 2017; Zavaleta et al., 2018; Ponce, 2020; Shapiro-Garza et al., 2020).

Climate Information Services has an important role in climate change adaptation and there is a recognized gap between climate science and farmers (*high confidence*) (Vaughan et al., 2017; Loboguerrero et al., 2018; Tall et al., 2018; Thornton et al., 2018; Ewbank et al., 2019). Such services should address the challenges of ensuring that climate information and advisory services are relevant to the decisions of small-holder and family farmers, providing timely climate services access to remote rural communities with marginal infrastructure and ensuring that farmers own climate services and shape their design and delivery. An interesting case facing this gap is the implementation of local technical agro-climatic committees in Colombia which allow to share and to validate climatic and weather forecasts; and crop model results to seasonal drought events (Loboguerrero et al., 2018). Another example is the web service, AdaptaBrasil-MCTI, forecasting the risk of climate change impact on strategic sectors (e.g., food, energy, water) in Brazil (Government of Brazil and Ministry of Science Technology and Innovation Secretariat of Policies and Programs, 2021).

Barriers to financial access are present in the region restricting effective adaptation to extreme weather events (*high confidence*) (Chen et al., 2018; Fisher et al., 2019; Piggott-McKellar et al., 2019; Vidal Merino et al., 2019; de Souza Filho et al., 2021). In 2014, the penetration rate of this type of insurance in the region averaged 0.03% of GDP, and a few countries dominate the market (Brazil, Argentina). Beyond these three countries, some initiatives also exist in Uruguay, Paraguay, Chile and Ecuador. In most Latin American and Caribbean countries, the public sector plays an important role in providing insurance or reinsurance and coexists with private sector companies (Cárdenas et al., 2021). Insurance protections represent a strategy to transfer climate risk to protect the wellbeing of vulnerable small farmers and accelerate uptake (recovery) after a climate-related extreme weather event. Lack of finance and proper infrastructure is compounded by limited knowledge of sustainable farming practices and high rates of financial illiteracy (*high confidence*) (Hurlbert and Gupta, 2017; Piggott-McKellar et al., 2019).

Insufficient access to digital services and technologies further widens the gap between the rural poor and more urban populations of Latin America and the Caribbean (*medium confidence: insufficient evidence, high agreement*). In turn, these factors compromise productivity and competitiveness. Support for this group can be focused on both economic competitiveness and social development. Finally, to align identified adaptation options as a priority for achieving future food security in the NDCs of CSA countries to mitigation commitments, it will be essential to highlight synergies by generating evidence (national research) in relation to progress towards increasing productivity, resilience and reducing GHG; and also demonstrating its added value as a development initiative (Rudel et al., 2015 sustainable; Loboguerrero et al., 2019).

12.5.4.3 Adaptation options

In order to contextualize the adaptation options at the regional level, the majority of the NDC of the CSA countries reported the observed and/or projected climate-related hazards: occurrence of droughts and floods (80% of countries each), followed by storms (45%) and landslides (30%), as well as extreme heat, wildfire and invasion by pests and non-native species in agriculture (25% each) (Crumpler et al., 2020).

Main adaptation options for climate change in the region include preventive measures against soil erosion; climate-smart agriculture which provide a framework for synergies between adaptation, mitigation and improved food security; climate information systems; land use planning; shifting plantations in high altitude to avoid temperature increases and plagues; improved varieties of pastures and cattle (Lee et al., 2014; Jat et al., 2016; Crumpler et al., 2020; Moreno et al., 2020a; Aragón et al., 2021). Agricultural technologies are not necessarily changing, but the economic activity is shifting to accommodate increasing climate variation and adapt to changes in water availability and ideal growing conditions (*high confidence*) as is observed in Argentina, Colombia and Brazil (McMartin et al., 2018; Rolla et al., 2018; Sloat et al., 2020; Gori Maia et al., 2021). Coffee plantations are moving further up mountain regions with the land at lower elevations converted for other uses. In Brazil, crop modelling suggests the need for the development of new cultivars, with a longer crop cycle and with higher tolerance to high temperatures, a necessary technological advance for maize, an essential staple crop, to be produced in the future. Additionally, irrigation becomes essential for sustaining productivity in adverse climate change scenarios in several regions of CSA (McMartin et al., 2018; Lyons, 2019; Reay, 2019).

Livestock production is for small farmers one of the main sources of protein and contributes to food security (Rodríguez et al., 2016). The importance of this sub-sector in CSA, will continue to increase as the demand for meat products does as well in the coming years, driven by growing incomes in the region (OECD and FAO, 2019). However, the increase in animal production has been associated with land degradation, triggered by the conversion of native vegetation to pastureland and aggravated by overgrazing and abandoning of the degraded pastures (Baumann et al., 2017; ECLAC, 2018; Müller-Hansen et al., 2019). Sá et al. (2017) simulated the adoption of agricultural systems based on Low-Carbon Agriculture (LCA) strategies towards 2050. According to the simulation, the adoption of LCA strategies in the SA region can alter the growing trend of Land Use and Land Use Change emissions and at the same time, it can increase meat production by 55Mt for the entire period (2016–2050). The restoration of degraded pasture and livestock intensification account for 71.2%, and integrated crop-livestock-forestry system contributes 28.8% of total meat production for the entire period. These results indicate that combined actions in agricultural management systems in SA, can result in synergistic responses that can be used to make agriculture and livestock production an important part of the solution of global climate change and advance food security (*medium confidence: insufficient evidence and high agreement*) (Zu Ermgassen et al., 2018; Pompeu et al., 2021). Crop-Livestock-Forestry-Systems are also important for climate change adaptation as they provide multiple benefits, including the coproduction of food, animal feed, organic fertilizers and soil organic carbon sequestration (Sharma et al., 2016; Rodríguez et al., 2021), achieving mitigation and adaptation goals (*high confidence*) (Picasso et al., 2014; Modernel et al., 2016; Modernel et al., 2019; Rolla et al., 2019; Locatelli et al., 2020). A recent analysis of agroforestry in Brazil, has shown positive and relevant impacts on the heads/pasture area rate in livestock production and that the system may have also stimulated a shift toward other production activities with higher gross added value (Gori Maia et al., 2021). Agroforestry has also proven to have protective benefits to obtain more stable, less fluctuating yields due to climate damages in coffee production (*high confidence*) (Bacon et al., 2017; Durand-Bessart et al., 2020; Ovalle-Rivera et al., 2020). In the same way, the production of plant-based fibre can be less vulnerable to economic and climatic variability through farming systems diversification. Textile fibre crops for the case of cotton include crop rotation, agroecological intercropping and agroforestry (Oliveira Duarte et al., 2019).

Adaptation strategies also concern Indigenous agriculture, i.e., the vast majority of the 44 million Amerindians (CEPAL, 2014). Indigenous knowledge and local knowledge (IK and LK) can play an important role in adaptation (Zavaleta et al., 2018). On one hand, they preserve the conservation of a very rich agrobiodiversity that is likely to meet the challenges of climate change (*high confidence*) (Carneiro da Cunha and Morim de Lima, 2017; Magni, 2017; Emperaire, 2018; Donatti et al., 2019) and on the other hand, the sustainability of large territories that assure their livelihood (Singh and Singh, 2017; Mustonen et al., 2021). In the Andes, ancient technologies increased the quantity of crops produced and allowed for coping with climatic changes and water scarcity, while nutrition conditions were improved (*high confidence*) (López Feldman and Hernández Cortés, 2016; Parraguez-Vergara et al., 2018; Carrasco-Torrontegui et al., 2020 food). Also, fire prevention management, protection against forest and biodiversity loss, are recognized as important elements in Indigenous knowledge (Mistry et al., 2016; Bowman et al., 2021).

Table 12.8: Recent studies related to climate change adaptation of agricultural systems and its determinants in the CSA Region.

Authors, year	Countries	Sample size (n)	Approach of the study	Crop systems	Adaptation strategies	Main drivers promoting climate change adaptation	Main barriers limiting climate change adaptation	Main barriers detected
de Souza Filho et al. (2021)	Brazil	175	Quant.	Cattle farmers	Integrated crop-livestock and livestock-forestry systems	Credit access Extension services	Lack of resources	Lack of agricultural market access strategies
Magalhães et al. (2021)	Brazil	94	Qual.	Several crops	Farm management	Previous experience with risks	Inadequate infrastructure Low purchasing power	Infrastructure limiting opportunities
Carrer et al. (2020)	Brazil	175	Quant.	Several crops	Agricultural insurance	Schooling	Higher risk propensity	Limited financial

						Technical assistance		market access
Quiroga et al. (2020)	Nicaragua	212	Quant.	Coffee	Several adaptation measures	Farm size Awareness of climate change Schooling	Limited access to rain-water	Absence of climate change education
Bro et al. (2019)	Nicaragua	236	Quant.	Coffee	Crop Soil and water	Schooling Participation in cooperatives Radio	Household size	Institutional framework to promote cooperatives
Leroy (2019)	Venezuela and Colombia	73	Qual.	Several crops in high altitudes	Irrigation management	Perception of water scarcity Local knowledge	Degradation of fragile areas	Ineffectiveness of local institutions
Cherubin et al. (2019)	Colombia	6	Quant.	Several crops and pasture	Agroforestry systems	Improving soil quality and biota	Degradation of conventional pasture	Lack of crop diversification
Harvey et al. (2018)	Costa Rica, Honduras and Guatemala	860	Quant.	Coffee, beans and maize	Several adaptation practices	Awareness of climate change	Affordability of adaptation practices	Lack of adaptation involving agroecological and socioeconomic contexts
Chen et al. (2018)	Costa Rica and Nicaragua	559	Quant.	Several crops	Intensification and diversification	Access to weather information Participation in organizations Credit access Farming experience	Land renting	Lack of crop and practices diversification
Vidal Merino et al. (2019)	Peru	137	Quant.	Several crops	Water management	Farm size Capital Irrigated proportion	Limited access to off-farm activities Small cultivated area	Lack of site-specific design of interventions
Meldrum et al. (2018)	Bolivia	193	Quant.	Potato, quinoa and others	Diversification of crop portfolio	Weather information	Loss to traditional knowledge	Lack of resilience and actions to

								expand and maintain variety portfolio
Lan et al. (2018)	Nicaragua	180	Quant.	Cocoa	Crop management	Schooling Household size Farm size	Lack of income	Income inequality Gaps of profitability of practices Benefits of practices depends of its costs
Kongsager (2017)	Belize	125	Qual.	Maize	Alley cropping	Schooling	Land tenure Market distance Degradation of fragile areas	Lack of land tenure Lack of market access Lack of trust
Schembergue et al. (2017)	Brazil	5485*	Quant.	Several crops	Agroforestry systems	Financing Presence of associations Credit access	High potential for agriculture Lack of climate information	Adaptation conditioned by agricultural, socioeconomic and climatic conditions
Harvey et al. (2017)	Guatemala, Honduras and Costa Rica	300	Quant.	Coffee and maize	Ecosystem based adaptation	Schooling Age Farming experience Access to technological support	Lack of land tenure	Lack of access to training and finance
Roco et al. (2016)	Chile	665	Quant.	Several crops	Water management	Farm size Access to weather information	Locations Age	Lack of availability and access to climate change information
Mussetta and	Argentina	41	Qual.	Vine and others	Crop and water management	Organization of producers	Water allocation system	Lack of water managem

Barrientos (2015)						Labour availability Knowledge and information access Technology access		ent and distribution strategies

Table Notes:
*: municipalities; Quant.: mainly quantitative; Qual.: mainly qualitative.

12.5.5 Cities, Settlements and Infrastructure

CSA is the second most urbanized region of the world, with 5 megacities and half of urban population in 129 secondary cities (UNDESA, 2019), huge metropolitan areas concentrated on the coast and an increasing number of small cities by the sea (Barragán and de Andrés, 2016). Besides the many climatic events threatening urban areas in the region (extreme heat, droughts, heavy storms, floods, landslides), cities by the coast are also exposed to sea level rise (SLR) (Section 12.3; Figure 12.6; Dawson et al., 2018; Leal Filho et al., 2018; Le, 2020). Main determinants of urban vulnerability assessed in the region are poor and unevenly distributed infrastructure, housing deficits, poverty, informality and the occupation of risk areas, including low elevation coastal zones (Section 12.3). Those features of urban systems increase the risks to health, ecosystems and its services, water, food and energy supply (Section 12.4). Impacts of climate events on urban water supply, drainage and sewer infrastructures are the most reported in the region (Section 12.3; Figure 12.9).

12.5.5.1 Challenges and opportunities

Inequality, poverty and informality shaping cities in the region increase vulnerability to climate change (*high confidence*) (Romero-Lankao et al., 2014; Rasch, 2017; Filho et al., 2019), and can hinder adaptation (Section 12.5.7.1), while interventions addressing these social challenges and the existing development deficits (e.g., build or improve infrastructure and housing applying climate-adapted patterns), can go hand in hand with adaptation and mitigation (*medium confidence: high agreement, medium evidence*) (Section 12.5.7.3; Creutzig et al., 2016; Le, 2020; Satterthwaite et al., 2020). Over 20% of urban population in LAC lives in slums and many in other forms of precarious and segregated neighbourhoods, settled in risk areas and lacking infrastructure (Rasch, 2017; UN-Habitat, 2018; Rojas, 2019). This vulnerable condition is boosted by unstable political and governmental institutions, which recurrently suffer from corruption, weak governance and reduced capacity to finance adaptation (Rasch, 2016). Facing governance challenges by including diverse stakeholders and encouraging and learning from community-based experiences has been also an opportunity to improve adaptation strategies (Archer et al., 2014). The Regional Climate Change Adaptation Plan of Santiago is an example of this (Krellenberg and Katrin, 2014).

12.5.5.2 Governance and Financing

Lack of a high multilevel and intersectoral governance capacity with strong multi-players horizontal and vertical coordination and long-term support are limiting adaptation in the region (*high confidence*) (Anguelovski et al., 2014; Bai et al., 2016; Chu et al., 2016; Schaller et al., 2016; Miranda Sara et al., 2017). The ability to enrol stakeholders and include community based initiatives can be determinant for adaptation success particularly considering its impact in the decision-making arena (*high confidence*) (Section 12.5.8.1; Section 6.4; Anguelovski et al., 2014; Archer et al., 2014; Chu et al., 2017; Rosenzweig et al., 2018) .

Lima's Climate Action Strategy is an example (Metropolitan Municipality of Lima, 2014). It was approved after a participatory and consultative process with the technical group on climate change from the Metropolitan Environmental Commission, focusing on the reduction of water vulnerabilities to drought and heavy rain, on the basis of which 10 (out of 51 with Callao) Lima districts municipalities are developing and starting to implement their adaptation measures (Foro Ciudades Para la Vida, 2021). In 2021 Lima Municipality also approved its Local Climate Change Plan (Metropolitan Municipality of Lima, 2021) under a similar process. The engagement of local players was central to spreading and mobilizing different types of knowledge and creating networks able to support adaptation (Section 12.6.3; Miranda Sara and Baud, 2014; Miranda Sara et al., 2017) . The inclusive process is also a goal on the example of Chile Municipalities Network Facing Climate Change (RedMuniCC) engaged in developing participatory strategic plans for climate adaptation and mitigation (RedMuniCC, 2021).

New forms of financing and leadership focused on community-based approaches have been developed to overcome the funding challenge and enable adaptation in the region (*medium confidence: medium evidence, medium agreement*) (Castán Broto and Bulkeley, 2013; Archer et al., 2014; Paterson and Charles, 2019). Also systems for measuring, reporting and verifying adaptation financing, as in Colombia (Guzmán et al., 2018), as much as national legislation geared to adaptation can help access funds. Peruvian Law on the Retribution Mechanism of Eco-Systemic Services and Code (Miranda Sara and Baud, 2014; MINAM Peru, 2016) in addition to the Ley Marco de la Gestión y Prestación de los Servicios de Saneamiento and its Code (Ministerio de Vivienda, 2017), allowed the potable water companies to add 1% to the tariff to guarantee ecosystem services, water treatment and reuse with green infrastructure. Another 4% of tariffs go to develop and implement adaptation plans and measures (Government of Peru, 2016).

12.5.5.3 Adaptation options in urban design and planning

Both the shape and activities of the city have an impact on carbon emissions, adaptation and mitigation opportunities (*high confidence*) (Raven et al., 2018; Satterthwaite et al., 2018). Combining urgent measures, strategic action (Chu et al., 2017) to long-term planning is central for a transformative adaptation and to avoid maladaptation (Filho et al., 2019). Urban planning, considering climate risk assessments, and regulation (e.g., land-use and building codes), including climate-adapted parameters, are central to coordinate and foster private and public investments in adaptation, reducing risks related to the built environment conditions (infrastructure and buildings) and the occupation of risk areas (e.g., threatened by floods and landslides) (Rosenzweig et al., 2018). Lack of information at local scale, human resources and clear liability for climate change response planning can limit adaptation (Aylett, 2015).

Strategic adaptation approaches have been adopted by many cities in dealing with the multilevel and intersectoral complexity of urban systems, with gains in fostering leadership and facing the predominant pattern of uneven urban development in the region (*medium confidence: limited evidence, high agreement*) (Chu et al., 2017). Medellin's metropolitan green belt, for example, focuses on problems such as irregular settlements, inequality and poor governance, articulating programs and projects of the Municipality of Medellin and the municipalities of the Vale do Aburra in a strategic long-term planning. Places with informal and precarious settlements were aimed to be transformed with the belt's integration areas: eco parks and eco-gardens (Alcaldía de Medellín, 2012; Chu et al., 2017).

12.5.5.3.1 Housing, informality and risk areas

Informality and precariousness in housing is one of the most sensitive issues for adaptation in CSA cities (*medium confidence: medium evidence, high agreement*) (Satterthwaite et al., 2018; UN-Habitat, 2018). Housing deficit in 2009, as a regional baseline, estimated that 37% of households suffered from quantitative or qualitative deficiencies, due to the high cost of housing and the incidence of poverty (Blanco Blanco et al., 2014; McTarnaghan et al., 2016; NU CEPAL et al., 2016; Vargas et al., 2018a; Rojas, 2019).

Policies and programs have been implemented accumulating good practices and reducing the percentage of population in informal and precarious settlements (33.7% in 1990 to 21% in 2014) (NU CEPAL et al., 2016; Satterthwaite et al., 2018; Teferi and Newman, 2018; UN-Habitat, 2018). Slum Upgrading and built-environment interventions (housing and infrastructure improvement and provision) in informal settlements can enhance adaptation (*high confidence*) (Teferi and Newman, 2018; Núñez Collado and Wang, 2020; Satterthwaite et al., 2020) while reducing floods, landslides and cascading impacts of storms, floods and epidemics, as observed on the "incremental housing approach" in Quinta Monroy (Rojas, 2019) and the "social urbanism" in Medellin (Garcia Ferrari et al., 2018).

The climate adaptation plans of several large CSA cities include efficient land use and occupation planning and urban control systems (comprising regulation, monitoring), fostering interlocution with housing and environmental policy (by means of intersectoral and multilevel governance), inhibiting and reducing the occupation of risk areas (mainly flooding and landslides risks); increasing population density in areas already served by infrastructure; expanding slums urbanization and technical assistance programs for improvements and expansion of social housing (*high confidence*) (Municipio del Distrito Metropolitano de Quito, 2020; Prefeitura Municipal do Salvador, 2020; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021; Prefeitura do Município de São Paulo, 2021).

Housing programs and initiatives that consider resilient construction, and site selection strategies, are still in nascent stages (Martin et al., 2013). Initiatives in slum upgrading, social housing improvement and regularizing land tenure, associated with infrastructure provision, do not usually focus on adaptation, although they often focus on risk reduction. Those initiatives, associated with a housing policy that guarantees access to land and decent housing, a comprehensive intervention in vulnerable neighbourhoods for their adaptation to climate change, and CbA (community-based adaptation) strategies, including housing self-management and the participation of cooperatives, shows the need and opportunity to move to an transformative urban agenda that encompasses sustainable development, poverty reduction, disaster-risk reduction, climate-change adaptation, and climate-change mitigation (*high confidence*) (Muntó, 2018; UN-Habitat, 2018; Valadares and Cunha, 2018; Bárcena et al., 2020b; Núñez Collado and Wang, 2020; Satterthwaite et al., 2020).

Several large cities are implementing municipal risk management plans and management and restoration plans for hydrologically relevant areas, considering threats of drought and heat waves, integrated watershed management and flood control programs (*high confidence*) (Municipio del Distrito Metropolitano de Quito, 2020; Prefeitura Municipal do Salvador, 2020; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021; Prefeitura do Município de São Paulo, 2021). Quito and Rio de Janeiro are considered two examples of comprehensive and effective city-level climate action that includes creating environment protected areas, managing appropriate land use, household relocation and EWS in vulnerable to high-precipitation areas associate to EbA, such as reforestation projects, to face natural hazards (ELLA, 2013; Anguelovski et al., 2014; Calvello et al., 2015; Alcaldía de Quito, 2017; Sandholz et al., 2018; Prefeitura da Cidade do Rio de Janeiro, 2021) (Section 12.6.1). EWS and the use of mapping tools experienced in La Paz showed to be an effective adaptation measure facing increasing hydro-climatic extreme events (Aparicio-Effen et al., 2018).

12.5.5.3.2 Green and grey infrastructure

Hybrid solutions, combining green and grey infrastructure (GGI), have been adopted for better efficiency in flooding control (Ahmed et al., 2019; Drosou et al., 2019; Romero-Duque et al., 2020), sanitation, water scarcity, landslide prevention and coastal protection (*high confidence*) (Section 12.5.6.4; Mangone, 2016; Depietri and McPhearson, 2017; Leal Filho et al., 2018; McPhearson et al., 2018). The adoption of nature-based solutions (NbS), which embraces well-known approaches such as green infrastructure (GI) and ecosystem-based adaptation (EbA) (Pauleit et al., 2017; Le, 2020) has increased (Box 1.3). The Fund for the Protection of Water (FONAG) and the Participative Urban Agriculture (AGRUPAR) are initiatives using NbS in Quito (Section 12.6.1). Example of GGI is a stormwater detention pond, as a water storage solution to flooding prevention, also allowing multiple uses of an urban space, adapting and revitalizing a degraded area in Mesquita, Rio's metropolitan region (Jacob et al., 2019). These systemic and holistic solutions still need to overcome governance and sectorial barriers to be more widely adopted (Herzog and Rozado, 2019; Wamsler et al., 2020; Valente de Macedo et al., 2021).

Managing water in cities in an adaptive way has been central to reducing impacts such as floods and contributes to water security (*high confidence*) (Van Leeuwen et al., 2016; Okumura et al., 2021). Many cities facing frequent heavy storms that impact mostly underprivileged communities, slums and vulnerable areas could benefit from the integrated NbS for disaster risk reduction and adaptation (*high confidence*) (Sandholz et al., 2018; Ronchi and Arcidiacono, 2019). A study covering 70 Latin American cities estimates that 96 million people would benefit from improving main watersheds with green infrastructure (Tellman et al., 2018). In several municipal climate plans, NbS were introduced mainly to enhance rainwater management, reduce energy consumption and urban heat areas, water quality, prevent landslides and offer green areas (*high confidence*) (Gobierno de la Ciudad de Buenos Aires, 2020; Municipio del Distrito Metropolitano de Quito, 2020; Prefeitura Municipal de Curitiba, 2020; Alcaldía de Medellín, 2021; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021; Prefeitura do Município de São Paulo, 2021). Sao Paulo's project for Jaguaré river proposes a large-scale landscape transformation applying innovative multifunctional NbS instead of exclusively large, expensive and monofunctional hard engineered solutions to manage stormwater (Marques et al., 2018; Herzog and Rozado, 2019). In Bogotá, the Humedales foundation has restored wetlands to enhance areas near the reserve Van Der Hammen to improve water quality and quantity, restore habitat for biodiversity, and provide flood protection (Portugal Del Pino et al., 2020). In Petrópolis, a medium-sized city in the hills of Rio de Janeiro state, the water service company has implemented 10 NbS multifunctional micro wastewater treatment plants in low-income areas, helping to reduce cascading impacts of storms, floods and epidemics (Herzog and Rozado, 2019). In Costanera Sur, Buenos Aires, a public initiative to protect an auto-regenerated Plata riverbank, which had received demolition material to create land, nowadays offers numerous ecosystem services for residents and attract visitors activating the tourist industry and helping reducing riverine floods (Bertonatti, 2021; OICS, 2021).

Hybrid solution on water management that can merge traditional interventions on urban areas with sustainable urban drainage systems (SUDS) (Davis and Naumann, 2017), considering small scale low-impact development (LID) measures scattered over the watershed instead of concentrate huge hydraulic grey structures, can help reduce the risk and damage of flooding (*high confidence*) (Miguez et al., 2014; Miguez et al., 2015a; Depietri and McPhearson, 2017; Da Silva et al., 2018a; de Macedo et al., 2018). Quito's climate plan explicitly cites the strategy for implementing blue and grey infrastructure to reduce risk due to extreme precipitation and its associated impacts such as flooding and landslides and the possible impact of water scarcity (Municipio del Distrito Metropolitano de Quito, 2020). The Integrated Iguaçu-Sarapuí River Basin Flood Control Master Plan, in Rio's metropolitan area, combined different solutions for flood protection, focusing on river restoration by retrofitting levee systems combined with adapting land use to provide a multifunctional landscapes as an alternative to bring together green and grey solutions, composing urban parks to prevent further paving and avoid irregular occupation of river banks and provide storage capacity for damping flood peaks (Miguez et al., 2015b).

Many cities are implementing adaptation measures on integrated water and flood management systems (Sarkodie and Strezov, 2019), improving basic sanitation services (*medium confidence: medium evidence, high agreement*). Main strategies are established by NAPs recurrently focusing on improving water distribution network and reservoir systems, as Honduras (Government of Honduras, 2018) and Ecuador (Mills-Novoa et al., 2020), sewage and effluent treatment, as Guatemala, Brazil and Paraguay (Government of Brazil, 2007; Government of Guatemala, 2016; Government of Paraguay, 2017), facing water scarcity and environmental degradation. Local authorities follow this guideline as in the effort to maintain and upgrade existing drainage systems in Georgetown (Mycoo, 2014), or in Medellin, focusing on improving drainage systems to prevent landslides or flooding (Núñez Collado and Wang, 2020; Alcaldía de Medellín, 2021). Rio de Janeiro has constructed three large stormwater detention reservoirs to deal with frequent flood, (Prefeitura da Cidade do Rio de Janeiro, 2015), adopting a set of exclusively grey solutions, not combined to NbS that could improve urban flood resilience (Rezende et al., 2019). The main proposed actions still consider the traditional approach in improving the hydraulic capacity of urban drainage systems as an adaptive measure (*high confidence*) (Gobierno de la Ciudad de Buenos Aires, 2020; Prefeitura Municipal do Salvador, 2020; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021). In addition to this strategy, several local plans propose actions for the retention and storage of rainwater, both in the urban drainage network with a smaller intervention scale (Prefeitura Municipal de Curitiba, 2020), as well as along rivers and canals with large-scale works (*medium confidence: medium evidence, high agreement*) (Gobierno de la Ciudad de Buenos Aires, 2020; Prefeitura Municipal de Curitiba, 2020; Alcaldía de Medellín, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021).

12.5.5.3.3 Mobility and transport system

Mobility and transport systems have a key role in urban resilience (*high confidence*) (Walker et al., 2014a; Caprì et al., 2016; Espinet et al., 2016; Lee and Lee, 2016; Ford et al., 2018; Mehrotra et al., 2018; Quinn et al., 2018). Examples reported in scientific literature assessed are focusing on mitigation strategies even when labelled as adaptation (da Silva and Buendía, 2016; Di Giulio et al., 2018; Valderrama et al., 2019; Goes et al., 2020).

The integration of transport and land use planning and the improvement of public transport, also as important mitigation actions, appears as a consensus in countries' adaptation plans, nevertheless the emphasis on mobility and transport systems on the many NAP published is low (*medium confidence: medium evidence, high agreement*). Honduras, Costa Rica and El Salvador's NAP are not approaching adaptation or mitigation in the sector, while Peru, Ecuador, Guatemala and Paraguay ones focus on mitigation only. Chile, Colombia and Brazil's NAP focus on both mitigation and adaptation of mobility and transport systems. Chile and Colombia's plans dedicated specific action lines to adapt mobility and transport systems to climate change, whilst Brazil published a NAP's complementary volume dedicated exclusively to the sectoral strategies, although presents only general guidelines (Government of Peru, 2010; Government of Chile, 2014; Government of Ecuador, 2015; Government of Brazil, 2016; Government of Colombia, 2016; Government of Guatemala, 2016; Government of Paraguay, 2017; Government of Costa Rica, 2018; Government of Honduras, 2018; Government of El Salvador, 2019).

In municipal scale, assessing the biggest cities, São Paulo, Rio de Janeiro Lima and Santiago stands out for including mobility and transport as one of the strategic axes of its climatic plans, but yet prioritizing mitigation, while Buenos Aires and Bogotá do not deepen the issue in their plans (Gobierno de la Ciudad de Buenos Aires, 2015; Prefeitura da Cidade do Rio de Janeiro, 2016; Alcaldía Mayor de Bogotá D.C., 2018; Municipalidad de Lima, 2021; Municipalidad de Santiago, 2021; Prefeitura do Município de São Paulo, 2021). Most of those same cities have sectoral mobility plans, which are key tools to urban resilience. Those plans, however, do not focus on adaptation actions, although emphasizing mitigation (Government of Peru, 2005; Gobierno de la Ciudad de Buenos Aires, 2011; Prefeitura do Município de São Paulo, 2015; Alcaldía Mayor de Bogotá D.C., 2017; Ilustre Municipalidad de Santiago, 2019; Município de Rio de Janeiro, 2019).

12.5.6 Health and Wellbeing

The most common adaptation strategies include the development of climate services such as epidemic forecast tools, integrated climate-health surveillance and observatories and forecasting climate-related disasters (floods, heat waves). GIS technologies are being used to identify locations where vulnerable populations are exposed to climate hazards and associated health risks.

12.5.6.1 Climate services for health

The measures most directly linked to diminishing risk are those related to climate services for health (*high confidence*). Climate services provide tailored, sector-specific information from climate forecasts to support decision making (WHO and WMO, 2016); they allow decision makers and practitioners to plan interventions in anticipation of a weather/climate event (Mahon et al., 2019). More recently, climate services, such as early warning systems (EWS) and forecast models, have been promoted for the health sector (WHO and WMO, 2012; WMO, 2014; WHO and WMO, 2016; Thomson and Mason, 2018) and are an important adaptation measure to reduce the impacts of climate on health (*high confidence*). To guide this process, the Global Framework for Climate Services (GFCS) issued a Health Exemplar (Lowe et al., 2014; WMO, 2014) which aims for stakeholder engagement between health and climate actors at all levels to promote the effective use of climate information within health research, policy and practice.

There exist at least 24 EWS in SA to avoid deaths and injuries from floods in the countries such as Argentina, Colombia, Ecuador, Bolivia, Brazil, Peru, Uruguay and Venezuela (Bravo et al., 2010; Bidegain, 2014; Moreno et al., 2014; Dávila, 2016; del Granado et al., 2016; López-García et al., 2017; Carrizo Sineiro et al., 2018). A total of 149 emergency prevention and response systems are reported in CA (UNESCO, 2012). In addition, some countries implement programs for the relocation of families who are in risk condition, like in Bogotá and Medellin, Colombia (World Bank, 2014; Watanabe, 2015).

Epidemic forecast tools are an example of an adaptation measure being developed and/or implemented in this region (*high confidence*). Climate-driven forecast models have been developed for dengue in Ecuador, Puerto Rico, Peru, Brazil, Mexico, Dominican Republic, and Colombia (Lowe et al., 2013; Eastin et al., 2014; Johansson et al., 2016; Lowe et al., 2017; Johansson et al., 2019); for Zika virus infections across the Americas (Muñoz et al., 2017); for cutaneous leishmaniasis in Costa Rica and Brazil (Chaves and Pascual, 2006; Lewnard et al., 2014); for Aedes-borne diseases across the Americas (Muñoz et al., 2020b); and a nowcast model for chikungunya virus infections across the Americas (Johansson et al., 2014). In Ecuador, a prototype system utilized forecasts of seasonal climate and ENSO forecasts of to predict dengue transmission, providing the health sector with warnings of increased transmission several months ahead of time (Stewart-Ibarra and Lowe, 2013; Lowe et al., 2017). Despite these advances, few tools have become operational and mainstreamed in decision making processes. However, Brazil and Panama have been able to operationalize an early warning system for the surveillance of dengue fever transmission (Codeço et al., 2016; McDonald et al., 2016).

One of the most promising climate services for the health sector are heat and cold early warning and alert systems (*medium confidence*). These have been developed by the national meteorological institutes in Peru, Argentina, and Uruguay (Bidegain, 2014). A heat alert system was implemented in Argentina in 2017 and daily alerts are issued for 57 localities across the country. A stoplight colour scheme is used to issue alerts, identifying specific groups at risk and actions to be taken to reduce the risk (Herrera et al., 2018b).

The public dissemination of climate-health warnings via bulletins, websites, and other outlets can be an adaptation measure to climate change and weather variability to diminish health risk (*high confidence*). The information produced is systematized to be communicated to the authorities and general public. The Caribbean Health-Climatic Bulletin has been issued quarterly since 2018 to health ministries across the region, including CA and NSA. Regional climate and health authorities meet to review 3 month climate forecasts and issue statements about the probable impacts on health (Trotman et al., 2018). In Panamá, information on dengue is distributed in a monthly bulletin that is used by health authorities to inform vector control activities (McDonald et al., 2016). Another example was the climate-driven forecast of dengue risk that was produced prior to Brazil's 2014 FIFA World Cup to inform disease prevention interventions (Lowe et al., 2014; Lowe et al., 2016). In Colombia, the Intersectoral National Technical Commission for Environmental Health publishes a monthly bulletin with regional weather forecast and potential effects on health (CONASA, 2019). Paraguay improves epidemiological surveillance and trains first level health staff via information campaigns on the prevention of climate sensitive diseases, and promotes health networks with the participation of civil society (Environmental Secretariat of Paraguay, 2011).

12.5.6.2 Integrated climate-health surveillance and observatories

Integrated health-climate surveillance systems are another key adaptation strategy (*medium confidence*). This information can be used by the health sector to inform decision making about when and where to deploy a public health intervention. It can also feed into an EWS, particularly if the data are compatible in format and spatiotemporal scales. An integrated health-climate surveillance system for vector borne disease control was developed in southern coastal Ecuador through a partnership among the climate and health sectors and academia (Borbor-Cordova et al., 2016; Lowe et al., 2017). Additionally, an interdisciplinary multinational team working at the border of Ecuador and Peru created a cooperation network for climate-informed dengue surveillance (Quichi et al., 2016) and successful binational collaboration resulted in the local elimination of malaria (Krisher et al., 2016). Similar is the innovative community-based data collection to understand and find solutions to rainfall-related diarrheal diseases in Ecuador (Palacios et al., 2016).

Climate and health observatories are a promising strategy being developed at subnational, national (e.g., Brazil, Argentina) and regional levels (*high confidence*) (Muñoz et al., 2016; Rusticucci et al., 2020). The Brazilian Observatory of Climate and Health brings together climate and health information for the Amazon region of Manaus (Barcellos et al., 2016). At a national level, Brazil has created the climate and health observatory, where information and data visualizations are available for various climate-sensitive health indicators (Ministério da Saúde and FIOCRUZ, 2021).

12.5.6.3 Vulnerability and risk maps

Vulnerability and risk maps have been widely used as an adaptation strategy to understand the potential impacts of climate on health outcomes both directly (e.g., maps of disease risk) and indirectly (e.g., maps of populations vulnerable to climate disasters) (*high confidence*). There are many examples where climate services have been used to construct vulnerability maps for health outcomes, including maps in the aforementioned Climate-Health Observatories. Dengue, malaria, and Zika vulnerability maps using climate, social, and environmental information has been developed in Brazil and Colombia (Cunha et al., 2016b; López-Álvarez, 2016; Pereda, 2016; IDEAM, 2017). Argentina is focused on improving the health system by using Climate Change Risk Map System as a tool that identifies the risks and allows assessing their management (OPS and WHO, 2018).

Vulnerability and risk maps for climate disasters have been developed at the city level, for example in Bogotá, Cartagena de Indias, and Mocoa in Colombia (Yamin et al., 2013; Guzman Torres and Barrera Arciniegas, 2014; Tehelen and Pacha, 2017; Zamora, 2018); and for the metropolitan district of Quito in Ecuador (Tehelen and Pacha, 2017). In addition, vulnerability maps were created for the primary road network of Colombia (Tehelen and Pacha, 2017). At the regional level, vulnerability maps using climate change probability, disaster risk and food insecurity variables has been produced for the Andean region (WFP, 2014). In Brazil, vulnerability maps considering exposure, sensitivity, and adaptive capacity, coupled to climate scenarios, were designed to support the National Adaptation Plan on a municipal scale (Chang and Garcia, 2018; Duval et al., 2018; Marinho and Silva, 2018; Menezes, 2018; Santos and Marinho, 2018; Silva et al., 2018). A Climate Change Vulnerability Index was used to generate vulnerability maps for countries of Latin American and Caribbean region (Vörösmarty et al., 2013; CAF, 2014).

12.5.6.4 Other adaptation actions

Diverse adaptation measures are being implemented through public policies, private households' responses, or communal management that directly or indirectly reduce the impacts of climate change on human health (*high confidence*) (Table 12.9). Private and communal management measures could be considered indirect measures, because they might be adopted even in the absence of climate change.

Table 12.9: Hazards from climate change that impact human health and examples of adaptation strategies proposed or implemented in CSA. Based in McMichael et al. (2006); Miller et al. (2013a); Miller et al. (2013b); Miller et al. (2013c); Miller et al. (2013d); Hardoy et al. (2014); IPCC (2014); Janches et al. (2014); Lee et al. (2014); Mejia (2014); Sosa-Rodriguez (2014); Vergara et al. (2014); Lemos et al. (2016); Villamizar et al. (2017); Magoni and Munoz (2018); Zhao et al. (2019).

Hazard and impacts on human health	**Examples of adaptation strategies**		
	Public	**Private**	**Communal**
Extreme heat and cold: deaths / illness by thermal stress	• Creation of urban green spaces/ • Health promotion campaigns. • Establish shelters during heat waves • Technology transfer for home heating	• Cooling by swamp coolers, air conditioning, open windows, wet the floors, shade trees. • Bioclimatic building design	• Training of community health volunteers to recognize and treat heat strain.
Extreme rainfall, wildfire, wind speed: injury / deaths from floods, storms, cyclones, bushfires and landslides (Key risk 2, Table 12.6).	• Early warning systems (EWS) for extreme climate events. • Safe housing programs and relocation • Green-grey infrastructure (e.g., channels, drainage systems)	• Green-grey infrastructure to prevent landslides. • Insurance mechanisms and financing for long-term recovery.	• Communal efforts to clear debris from canals to reduce flood risk • Cooperative efforts to rebuild following a flood event
Drought and dryness: poor nutrition due to reduced food yields and dehydration due to limited or inadequate management of freshwater (Key risk 1, Table 12.6).	• Formalizing land ownership for small farmers and Indigenous people. • Address emerging water conflicts.	• Water infrastructure and irrigation. • Soil moisture retention techniques • Insurance mechanisms. • Selection of drought resistant crops.	• Incorporation of local stakeholders in formulating adaptation responses. • Recognition of Indigenous and local wisdom and knowledge.

Changes in climate that promote microbial proliferation: food poisoning, and unsafe drinking water (Key risk 3, Table 12.6).	• Restoration of watersheds • Integrated health-climate surveillance • Improve access to drinking water, drainage, sanitation and waste removal.	• Water disinfection: boiling, chlorination. • Purchasing water or water filters.	• Participatory water management strategies, including protection of drinking water sources.
Changes in climate that affect vector-pathogen host relations and infectious disease geography/seasonality (Key risk 4, Table 12.6).	• Vector control • EWS for epidemics • Nature-based solutions (NbS) (e.g., forest conservation)	• Use of bed nets and screens • Use of repellent and insecticides. • Elimination of standing water.	• Community volunteers to collect blood smears for malaria diagnosis • Community-led elimination of vector habitat.
Sea level rise and storm surges: impaired crop, livestock and fisheries yields; unsafe drinking water, leading to impaired nutrition (Key risk 8, Table 12.6).	• Improve governance of water utilities. • Address emerging water conflicts. • Protection, restoration and soil conservation to recharge aquifers.	• Improve water efficiency in agriculture.	• Incorporation of local stakeholders in formulating adaptation responses. • Recognition of Indigenous and local wisdom and knowledge.
Environmental degradation: loss of livelihoods and displacement leading to poverty and adverse health outcomes (related to Key risk 6, Table 12.6).	• Long-term risk management planning for cities. • Sustainable forestry programs. • Protection and restoration of lacustrine areas.	• Identification of alternative livelihoods.	• Community-led efforts to reforest and restore/protect watersheds.

Participatory management can be relevant in the case of mosquito-borne disease prevention (e.g., dengue fever or malaria), where the reduction in mosquito habitat in one area or 'hot spot' can reduce the risk for all surrounding households. This approach is also relevant when considering new places where vector-borne diseases can emerge because of changes in climate (Andersson et al., 2015).

Adaptation strategies implemented by the public sector include a diverse suite of strategies ranging from creation of green spaces in urban areas, relocation of families located in disaster prone areas, ecosystem restoration, improved access to clean water, among many others (*high confidence*) (Table 12.9). Building green-grey infrastructure (GGI) has been a popular public adaptation measure to reduce deaths and injuries because of floods (Section 12.5.5.3.2). Infrastructure has been improved at schools, public buildings and drainage systems in cities such as Bogota, Colombia (World Bank, 2014) and La Paz, Bolivia (Fernández and Buss, 2016). In Brazil, channel works were implemented to reduce the flooding of the Tiete River, which crosses the metropolitan area of Sao Paulo; these projects were designed based on simulated flood scenarios (Hori et al., 2017).

Another example of a public adaptation measure is protection and restoration of natural areas, which have the potential to decrease the transmission of water- and vector-borne infectious diseases (*medium confidence: robust evidence, low agreement*). Studies have shown that these measures can diminish the cases of malaria and diarrhoea in Brazil, and cases of diarrhoea in children in Colombia (Bauch et al., 2015; Herrera et al., 2017; Chaves et al., 2018). However, deforestation and malaria have a complex relationship that relies on local context interactions, where land use and land cover change present an important role due to vector ecology alterations and social conditions of human settlements (Rubio-Palis et al., 2013). Forest conservation can improve hydrological cycle control and soil erosion that can help to improve water quality and reduce the burden of water-borne diseases. In addition, forest cover can help to diminish the habitat for larval mosquitoes that transmit malaria. These measures can help to design policies in sites where these problems do not currently exist but can emerge as a consequence of climate change and the increase in the frequency of weather extreme events.

12.5.6.5 Challenges and opportunities

Despite the proliferation of disaster EWS in the region, only 37 can be considered operational, because many of these systems are not operating or functioning properly, or do not meet the requirements to be considered EWS (UNESCO, 2012). Sustainable financing and political support are needed to ensure the functioning of disaster EWS (*high confidence*) (Table 12.11). Several studies identified difficulties in implementing disaster EWS due to a lack of community engagement and response to the alerts that are issued (del Granado et al., 2016; López-García et al., 2017). To address these challenges, the document "Developing Early Warning Systems: A Checklist" provides guidance for the implementation of a *people centred approach to early warning systems* as proposed in the Hyogo Framework for Action 2005–2015 (Wiltshire, 2006).

With respect to the development of climate-driven epidemic forecasts, efforts are needed to improve the utility of such forecasts for the health sector. Few such forecasts have been operationalized to inform health sector decision making. A review of 73 studies that predicted and forecasted Zika virus infections (42% from the Americas) identified a high degree of variation in access, reproducibility, timeliness, and incorporation of uncertainty (Kobres et al., 2019). A recent systematic review of epidemic forecasting and prediction studies found that no reporting guidelines exist; the development of guidance to improve transparency, quality and implementation of forecast models in the public health sector was recommended (Pollett et al., 2020). An earlier review of dengue early warning models found that few models incorporated both spatial and temporal aspects of disease risk (Racloz et al., 2012), limiting their potential application as an adaptation strategy by the health sector. Advances have been made in the last decade with respect to modelling and computing tools, increasing access to digital climate information and health records, and the use of earth observations to forecast climate sensitive diseases (Fletcher et al., 2021; Wimberly et al., 2021).

The growing field of implementation science –defined as "a discipline focused on systematically examining the gap between knowledge and action"– is another opportunity to address the challenges and barriers to using climate information for health sector decision making (Boyer et al., 2020). Implementation science in the health sector in CSA is nascent; research in this area could help to address barriers to mainstreaming climate information in the health sector as an adaptation strategy (Table 12.11; Table SM12.7).

12.5.6.6 Governance and Financing.

A description of the governance and financing dimensions of the feasibility of implementing EWS is presented in Table 12.11 and Table SM12.7.

12.5.6.6.1 National Health Plans

Some countries have developed national plans on health including the role of climate. Chile has a Climate Change Adaptation Plan of the Health Sector that proposes several actions to enhance monitoring, institutions and citizens information and education (Ministry of Health of Chile and Ministry of Environment of Chile, 2016). Based on the identification of vulnerability to climate change, Colombia has developed eleven regional adaptation plans to strengthen institutional capacities; climate change education for behavioural changes; and cost estimation to promote health resilience (WHO and UNFCCC, 2015). In addition, El Salvador implemented actions to strengthen health infrastructure through high latrines for housing in flood communities, as well as other measures focused on water supply and quality based on an education and awareness program (Ministry of Environment and Natural Resources of El Salvador, 2013). Only Brazil and Peru have implemented actions so far in the region derived from national health adaptation plans, and only Brazil completed a national assessment of impacts, vulnerability and adaptation for health (Watts et al., 2018). Some countries include health as a priority sector in their National Adaptation Plans, as is the case of Ecuador, and Costa Rica, which has a national plan addressing the prevention and care of climate-sensitive diseases coupled to a National Health Plan (2016-2020) (Ministry of Health Costa Rica, 2016; Jiménez, n.d.).

12.5.6.6.2 National Disaster Management Plans

National Risk Management Plans or National Disaster Response Plans are tools for adapting to climate change that can help to diminish death and injuries because of disasters (*high confidence*). These Plans are generally promoted by governments as national instruments that guide the processes of estimating, preventing and reducing disaster risk. An updated national risk management plans has been found for Guatemala (CONRED, 2014), Honduras (COPECO, 2014), El Salvador (Ministry of Health of El Salvador, 2017), Costa Rica (CNE, 2016), Ecuador (SGR, 2018), Peru (SGRD et al., 2014), Argentina (Ministerio de Seguridad de Argentina, 2018), Bolivia (VIDECI, 2017), Chile (ONEMI, 2015) and Colombia (UNGRD, 2015). It has been shown in Brazil that information on drought conditions can be used to reduced health impacts of drought using a national disaster risk reduction framework (Sena et al., 2016).

12.5.7 Poverty, Livelihood and Sustainable Development

Climate change impacts are increasing and exacerbating poverty and social inequalities, affecting those already vulnerable and disfavoured, generating new and concatenated risk challenging climate resilient development pathways (*high confidence*) (Section 8.2.1.4; Shi et al., 2016; Otto et al., 2017; Johnson et al., 2021) (). Poverty, high levels of inequalities and pre-existing vulnerabilities also can be worsened by climate change policies (Antwi-Agyei et al., 2018; IPCC, 2018; Roy et al., 2018; Eriksen et al., 2021). Those already suffering are losing their livelihoods and reducing their development options; poor populations and countries are more vulnerable and have lower adaptive capacity to climate change (*very high confidence*) (Section 8.5.2.1; Rao et al., 2017).

Inequality is growing, being a CSA structural characteristic; Gini index average for Latin American countries (including Mexico) was decreasing to 0.466 in 2017, where 1% richest got 22 times more income than 10% poorest (ECLAC, 2019b; Busso and Messina, 2020), but in 2018, 29.6% of Latin America were poor population (increased to 182 million) and extreme poverty 10.2%; in 2018 (increased to 63 million) (ECLAC, 2019b) and in 2020, due to COVID crisis, Gini coefficient projection of increases are ranging from 1.1% to 7.8% (ECLAC and PAHO, 2020), poverty increased to 33.7% (209 millions) and extreme poverty to 12.5% (78 millions) (ECLAC and PAHO, 2020; ECLAC, 2021). Those poverty and extreme poverty rates are higher among children, young people, women, Indigenous Peoples (Reckien et al., 2017; Busso and Messina, 2020), migrant (Dodman et al., 2019) and rural population. Climate change impacts in differentiated ways, even within a household there may be important differences in relation to age, gender, health and disability; these factors may intersect with one another (*high confidence*) (Reckien et al., 2017; Busso and Messina, 2020).

In IPCC's TAR, AR4 and AR5, WG II recognized higher risks associated with poor living conditions, substandard housing, inadequate services, location in hazardous sites due to no alternatives and the need to work more strongly on strengthening governance structures involving residents, community organizations amongst others (Wilbanks et al., 2007; Revi et al., 2014). The AR5 CSA chapter stated that poverty levels remained high (45% for CA and 30% for SA in 2010) despite years of sustained economic growth. Poor and vulnerable groups are disproportionately affected in negative ways by climate change (Section 8.2.1.4; Section 8.2.2.3; SR15 Section 5.2 and Section 5.2.1, Roy et al., 2018)) due to physical exposure derived from the place where they live or work, illiteracy, low income and skills, political and institutional marginalization tied to lack of recognition of informal settlements and employments, poor access to good quality services and infrastructure, resources, information, and other factors (*very high confidence*) (UN-Habitat, 2018; SR15 Sections 5.2.1, 5.6.2, 5.6.3, 5.6.4, Roy et al., 2018).

International agreements aim for climate resilient development pathways where efforts to eradicate poverty, reduce inequalities and promote fair and cross-scalar adaptation and mitigation are strengthened. The Sustainable Development Goals (SDG) first and second objectives aim to reduce poverty leaving no one behind (UN General Assembly, 2015). Although researchers argue that poverty is mischaracterized having multiple dimensions (Castán Broto and Bulkeley, 2013) (Section 8.1.1), that biodiversity loss, climate change and pollution will undermine efforts on 80% of assessed SDG targets, that biodiversity and climate change must be tackle together (Pörtner et al., 2021; United Nations Environment Programme, 2021) and LAC countries due to COVID crisis have uneven SDG progress (*high confidence*) (ECLAC, 2020).

12.5.7.1 Challenges and Opportunities

Climate change exacerbates pre-existing conditions and moving in the opposite direction in the search for resilience, equity and sustainable development (Tanner et al., 2015b; Bartlett and Satterthwaite, 2016; Kalikoski et al., 2018; Bárcena et al., 2020a). Existing inequalities in the provision and consumption of services are bound to be exacerbated by future risks and uncertainties associated with climate change scenarios (Miranda Sara et al., 2017). Climate change will be a major obstacle in reducing poverty (*high confidence*) (Bartlett and Satterthwaite, 2016; Allen et al., 2017a; Hallegatte et al., 2018; UN-Habitat, 2018; United Nations Environment Programme, 2021), even affecting wealthier populations that become vulnerable facing climate change scenarios (WGI AR6 Chapter 12, Ranasinghe et al., 2021), dragging them into poverty, erasing decades of work and asset accumulation.

CSA is highly urbanized, the poor vast majority live in urban areas (except in Central America) while urban extreme poverty is becoming more relevant (Rosenzweig et al., 2018; Dodman et al., 2019; Almansi et al., 2020; Sette Whitaker Ferreira et al., 2020), with those living in informal settlements and working within informal economy are critical on each city's economy (Satterthwaite et al., 2018; Satterthwaite et al., 2020). Many households in the region's cities live in precarious neighbourhoods with insufficient infrastructure and substandard housing (Adler et al., 2018; Rojas, 2019). On average, between 21% and 25% of the urban population lives in informal settlements (Jaitman, 2015; UN-Habitat, 2015; Rojas, 2019; Sandoval and Sarmiento, 2019). This hides important disparities: Habitat III reports by individual countries the percentage of urban population living in informal settlements ranged from 5% to 60%; in absolute terms 105 million people living in precarious conditions (106 million estimated in 1990) (Section 12.5.5; Sandoval and Sarmiento, 2019).

High levels of inequality and informality remain the biggest challenges for adaptation measures being effective (Rosenzweig et al., 2018; Dodman et al., 2019). The interaction of projected impacts with existing vulnerabilities in the region (as hunger, malnutrition and health inequalities, arising from its social, economic and demographic profile), affect CSA development and well-being in different ways (Reyer et al., 2017) increasing poverty and inequality risking the paths for sustainable development (Section 18.1.1; Reckien et al., 2017).

The uneven enforcement of land-use regulations, relocations and evictions on behalf of environmental risk management and climate adaptation is contested (Brockington and Wilkie, 2015; Lavell, 2016; Quimbayo Ruiz and Vásquez Rodríguez, 2016a; Quimbayo Ruiz and Vásquez Rodríguez, 2016b; Anguelovski et al., 2018; Anguelovski et al., 2019; Shokry et al., 2020; Chávez Eslava, 2021; Oliver-Smith, 2021). This points to caution in framing climate adaptation and resilience related interventions as equally benefiting everyone (*high confidence*) (Brown, 2014; Chu et al., 2016; Connolly, 2019; Romero-Lankao and Gnatz, 2019; Johnson et al., 2021) and the need for incorporating equality and justice dimensions (*very high confidence*) (Section 18.1.2.2; Agyeman et al., 2016; Meerow and Newell, 2016; Romero-Lankao et al., 2016; Shi et al., 2016; Reckien et al., 2017; Leal Filho et al., 2021) ().

Poor rural households in marginal territories with low productive potential and/or far away from markets and infrastructure are highly vulnerable to climate change and easily fall into poverty-environment traps (*high confidence*) (Barbier and Hochard, 2019; Heikkinen, 2021). Climate change is one of the main threats to rural livelihoods in Central America, being agriculture a pillar for rural economies and food security, especially for the poorest sectors that rely on subsistence crops in areas with low soil fertility and rainfall seasonality (Bouroncle et al., 2017).

Impacts are likely to occur simultaneously, exacerbating those of the poorer but also creating new groups at-risk (Miranda Sara et al., 2016; Rosenzweig et al., 2018; Dodman et al., 2019). The material basis for poor and vulnerable urban and rural populations' adaptation are in a critical state across the CSA region, magnifying extreme events' impacts, making CSA less resilient. The consequences in terms of social vulnerability and livelihood will be widely felt, insofar the security and protection of critical assets (housing, infrastructure, services - water, land and ecosystem services) continues to lay behind. Small businesses are usually conducted within the same home and if the house is affected so is the business (Stein and Moser, 2015) adding another layer of vulnerability for them.

As productivity declines, they seek outside income generation opportunities and rely on resource extraction for subsistence and as an income generation activity, further increasing their vulnerability to climate change (Barbier and Hochard, 2018a). Cycles of declining productivity, environmental degradation, wildlife poaching and trafficking, search of outside employment, reduced incomes, livelihood opportunities and poverty have been registered in rural El Salvador, Honduras, Amazonia (López-Feldman, 2014; Graham, 2017; Barbier and Hochard, 2018a). The protection of communities that defend and are dependent on wildlife and natural environments requires immediate attention. In Latin America there are 8 million forest-dependent people which represents about 82% of the region's rural extreme poor (FAO and UNEP, 2020).

Poverty and disaster risk reduction interlinked with climate change adaptation share a focus on identifying and acting on local risks and their root causes, even having different lenses through which to view risk (*very high confidence*) (IPCC, 2014; Allen et al., 2017a; Satterthwaite et al., 2018; UN-Habitat, 2018; Satterthwaite et al., 2020). Construction of climate knowledge and risk perceptions affect decision-making to define implementation priorities; the poor are less able to cope and to adapt avoiding "adaptation injustices" (*high confidence*) (Mansur et al., 2016; Miranda Sara et al., 2017; Reckien et al., 2017; Hardoy et al., 2019).

Adaptation, social policies, poverty reduction and inequality are weakly articulated to daily or chronic risk reduction. Poor residents are often caught in 'risk traps', accumulated cycles of everyday risks and small-scale disasters (*medium confidence: medium evidence, high agreement*) (Bartlett and Satterthwaite, 2016 ; Mansur et al., 2016; Allen et al., 2017a; Leal Filho et al., 2021), being exacerbated by climate risks and COVID pandemic with the most vulnerable populations suffering. Chronic and every day risks (poor access to infrastructure, services, incomes, housing, tenure, education, security, location and poor-quality environment, networks and having a voice) are often exacerbated and generate new unknown risks by climate change (*medium confidence: medium evidence, high agreement*) (Bartlett and Satterthwaite, 2016; Mansur et al., 2016; Satterthwaite et al., 2018; Leal Filho et al., 2021), extreme events and risks related to ENSO oscillation. All these risks need to be considered simultaneously (UN-Habitat, 2018). Risks are seldom distributed equally highlighting socioeconomic inequalities and governance failures (*high confidence*) (IPCC, 2014; Bartlett and Satterthwaite, 2016; Rasch, 2016; Romero-Lankao et al., 2018).

Adaptation, disaster risk reduction together with social and poverty reduction policies contribute to sustainable development (Hallegatte et al., 2018; Satterthwaite et al., 2020), and improve prospects of climate resilient pathways (Section 18.1.1). Without pro-poor interventions, adaptation options could reinforce poverty cycles (Kalikoski et al., 2018). Secure locations, good quality infrastructure, services and housing are critical to reduce risks from extreme climate events (Satterthwaite et al., 2018; Dodman et al., 2019).

12.5.7.2 Governance and Finance

Poor and most vulnerable groups evidence limited political influence, fewer capacities and opportunities to participate in decision and policy making, are less able to leverage government support to invest on adaptation measures linked with poverty, inequality and vulnerability reduction (*very high confidence)* (Chapter 8; Miranda Sara et al., 2017; Reyer et al., 2017; Kalikoski et al., 2018; Dodman et al., 2019; Satterthwaite et al., 2020).

Existing unbalances on power relations, corruption, structural historic problems and high levels of risk tolerance (Miranda Sara et al., 2016) constitute climate governance barriers for implementing more effective adaptation and preventive measures. Corruption, particularly in the construction and infrastructure sector, has proven to be a barrier for CSA development even reproducing and reconstructing risks (French and Mechler, 2017; Vergara, 2018; Durand, 2019). Critical infrastructure and valuable assets continue to be placed in vulnerable areas (Calil et al., 2017; Escalante Estrada and Miranda, 2020) evidencing the persistence of maladaptation and adaptation deficit (Villamizar et al., 2017).

Social organization, participation and governance reconfiguration are essential for building climate resilience (*very high confidence*) (Stein and Moser, 2015; Kalikoski et al., 2018; Satterthwaite et al., 2018; Stein et al., 2018; Hardoy et al., 2019; Stein, 2019; Satterthwaite et al., 2020; Miranda Sara, 2021). Adaptation measures have trade-offs that need to be acknowledged and acted upon, most importantly by developing the capacity to convene discussions that draw in all key actors and commit them to do things differently (Almeida et al., 2018; Hardoy et al., 2019). Collaborative approaches integrating groups and organizations (e.g., saving, women's groups, clubs, vendor associations, cooperatives) contributing to the exchange of information, to visibilize people's needs, to generate safety networks, and to negotiate for improvements and enhance adaptive capacity.

12.5.7.3 Adaptation options

Effective adaptation can be achieved by addressing pre-existing development deficits, particularly the needs and priorities of informal settlements and economies (Revi et al., 2014; UN-Habitat, 2018). There is urgency for social systems to better respond to climate related risks and increase their adaptive capacity (Lemos et al., 2016) focus on path dependency, lock ins and poor specific needs (Leal Filho et al., 2021).

The linkages between climate adaptation and poverty are not clearly addressed at national level (Kalikoski et al., 2018). A revision of some NDCs presented by CSA countries (https://unfccc.int), shows that NDCs are developed with almost no connection to poverty and livelihoods. Exceptions include Bolivia whose NDC developed the "Good life" concept, as an alternative development pathway, supporting sustainable livelihoods as a mean to eradicate poverty; Honduras asserts that climate action should improve living conditions; Peru defined a poverty and vulnerability reduction approach and El Salvador conditioned its NDCs to macroeconomic stability, economic growth and poverty reduction. A sustainable development approach permeates in proposed actions for sectors as energy, agriculture, transport, water, and forestry.

Adaptive capacity is linked to addressing climate related risks (specific capacity) and structural deficits (generic capacity), synergies and a strategic balance between both is necessary (Eakin et al., 2014; Lemos et al., 2016). Adaptation institutional context can undermine one form of capacity with repercussions on the other compromising overall adaptation and sustainable development (Eakin et al., 2014).

Literature assessing the effectiveness of pro-poor or community based adaptation practices and livelihood options continues to be weak, even though are increasingly documented, as in AR5 (Magrin et al., 2014). Great variety of measures are being applied, financial instruments to strengthen and protect livelihoods and assets; collective insurance schemes, micro-credits, financial instruments for transferring risks, as agricultural insurance and Payments for Ecosystem Services (PES) (Dávila, 2016; Hardoy and Velásquez, 2016; Lemos et al., 2016; Porras et al., 2016; Kalikoski et al., 2018). Small-scale household running businesses in poor neighbourhoods develop adaptation strategies to keep business going, showing how household level adaptation strategies are multipurpose (Stein et al., 2018; Stein, 2019). There are emerging interinstitutional communities of practice with the purpose of sharing practices and lessons learned (ECLAC, 2013; ECLAC, 2015; ECLAC, 2019a).

There is also increasing evidence of human mobility associated with climate change and disaster risk (IOM, 2021) and the adoption of sustainable tourism, diversification of livelihoods strategies, climate forecasts, appropriate construction techniques, neighbourhood layout, integral urban upgrading initiatives, territorial and urban planning, regulatory frameworks, water harvesting and nature-based solutions (NbS) (Stein and Moser, 2014; Hardoy and Mastrangelo, 2016; Almeida et al., 2018; Barbier and Hochard, 2018a; Desmaison et al., 2018; Satterthwaite et al., 2018; Villafuerte et al., 2018; Hidalgo, 2020; Satterthwaite et al., 2020). Mostly, socio-economical and socio-political factors which show safety and continuity measures are critical enablers of adaptation.

At municipal level study in Central America highlighted that adaptive capacity in rural areas is associated with basic needs satisfaction (safe drinking water, school, quality dwelling, gender parity index), access to resources for innovation and action (road density, economically active population with non-agricultural employment, and rural demographic dependency ratio), and access to credit and technical support (Bouroncle et al., 2017).

CSA adaptation initiatives to reduce poverty, improve livelihoods and achieve sustainable development range in scale and scope, from planned and collective interventions to autonomous and individual actions. Many of them are bottom up, community-led initiatives together with civil society organizations; others are government-led, including local governments, or a combination of them (McNamara and Buggy, 2017; Berrang-Ford et al., 2021). Vulnerable groups are a focus to achieve equity at planning and as a target including mainly rural low-income, Indigenous Peoples and women and migrants in most references. Responses detected were focused on behavioural and cultural, followed by ecosystem-based responses, institutional, and technological/infrastructural responses. Out of 55 articles analysed from CSA (Berrang-Ford et al., 2021) about poverty, equity and adaptation options, half of them covered adaptation planning and early implementation but only 2% could show evidence of risk reduction associated with adaptation efforts.

Tensions and conflicts may result from differing perceptions and knowledge on vulnerabilities and risk which can hinder the acceptance of adaptation measures and implementing stronger adaptive or preventive actions (Miranda Sara et al., 2016). There is a need to better understand complex interactions and community responses to climate change in the Amazonian and Andean region. Climate change hotspot impacts, showed that poverty reduction measures alone were not enough to improve adaptive capacity, as people will not necessarily invest to enhance them (Pinho et al., 2014; Filho et al., 2016; Nelson et al., 2016; Lapola et al., 2018; Zavaleta et al., 2018). Current adaptation strategies and methods may be neglecting cultural values, even eroding them, in Peruvian Andes, pointing that success of adaptation practices is tied to deep cultural values (Walshe and Argumedo, 2016).

Limits to adaptation include access to land, territory and resources (Mesclier et al., 2015), poor labour opportunities coupled with knowledge gaps, weak multi actor coordination, and lack of effective policies and supportive frameworks (Berrang-Ford et al., 2021).

Low participation of women in income earning opportunities contrasts with their role in unpaid activities (ECLAC, 2019b). Despite progresses, gender differences in labour markets remain an unjustifiable form of inequality (OIT, 2019) and women easily fall back to the informal labour market during crisis situations such as those generated by climate events (Collodi et al., 2020).

Participatory processes are leveraging adaptation measures throughout CSA; they contribute to prioritization of specific adaptation measures as well as strengthening local capacities. Showing that climate adaptation needs to be part of larger transformation processes to reduce vulnerability drivers (Stein and Moser, 2015; Stein et al., 2018; Stein, 2019) but stronger national policies interlinking poverty and inequality reduction to adaptation, considering the coupled human-environmental systems to comprehend poor and vulnerable groups' capacity to adapt are urgent. CSA does not fare very well, and several downward trends might become even more acute. More effective decisive actions need to be undertaken coupled with inclusive long-term planning to protect the poor and improve their underlying conditions, to meet the SDG.

12.5.8 Cross-cutting Issues in the Human Dimension

12.5.8.1 Public policies, social movements and participation

Public policies related to adaptation must be seen in the wider context of environmental policies and governance, as they usually address climatic processes in synergy with other environmental and socioeconomic drivers (*very high confidence*) (Ding et al., 2017; Aldunce Ide et al., 2020; Comisión Europea, 2020; Lampis et al., 2020; Scoville-Simonds et al., 2020). Some people rather point to education, sanitation or social assistance, among other sectors (Bonatti et al., 2019). In Brazil, for example, it would be difficult to clearly separate climate change adaptation and urban policies (*high confidence*) (PBMC, 2016; Barbi and da Costa Ferreira, 2017; Marques Di Giulio et al., 2017; Empresa de Pesquisa Energética, 2018; Checco and Caldas, 2019; Canil et al., 2020).

Many public policies related to climate change have become symbolic, in conflict with prevailing economic policies and practices (*medium confidence: low evidence, high agreement*). Urban adaptation plans can be in conflict with other policies and there may exist insufficient support in multiple areas such as social attitudes and behaviour, knowledge, education and human capital, finance, governance, institutions and policy (Villamizar et al., 2017; Koch, 2018). Some policies around climatic related displacements and migrants have been considered in NDCs (Priotto and Salvador Aruj, 2017; Yamamoto et al., 2018; de Salles Cavedon-Capdeville et al., 2020).

As there are asymmetries among populations regarding the vulnerability and benefits of adaptation, along the lines of gender, age, socioeconomic conditions and ethnicity, it has been noticed that adaptation policies and programs must be adequate to diverse conditions and actors (*very high confidence*) (Kaijser and Kronsell, 2014; Walshe and Argumedo, 2016; Baucom and Omelsky, 2017; Harvey et al., 2018).

Effective adaptation and mitigation depend on policies and measures at multiple scales, especially on the involvement of the more exposed and vulnerable people. The participation of experts, communities and citizens has shown to be effective (FAO and Fundación Futuro Latinoamericano, 2019) particularly through partnership of grassroots organizations with impoverished communities providing valued expertise and capacities to support the implementation of government climate resilience strategies (World Bank Group, 2015). More inclusive planning processes correspond to higher climate equity and justice outcomes in the short term, but also an emphasis on building dedicated multi-sector governance institutions may enhance long-term programs stability, while ensuring civil society voice in adaptation planning and implementation (Chu et al., 2016). Some local organizations and people have succeeded when they were in charge of their own resiliency efforts, where international projects and protocols proved less effective (Doughty, 2016). At times, decentralized governmental programs have tried to increase public responsiveness to the adaptation needs of people; however, proving to only be mildly successful and provoking the mobilization of communities against existing governance structures (Thompson, 2016).

Indigenous knowledge and local knowledge (IK and LK) participation is thought to be more considered in adaptation policies, as it has good results (*high confidence*) (Nagy et al., 2014b; Jurt et al., 2015; Arias et al., 2016; Stensrud, 2016). IK has been adaptive for long periods in the Andes (Cuvi, 2018), but there might be limits to adaptation in the face of present climatic and other environmental and socioeconomic drivers (Postigo, 2019). Approaches integrating IK with more formal sciences, to address research and policies, have improved adaptation processes, but they are no exempt of complications (*high confidence*) (Doswald et al., 2014; Metternicht et al., 2014; Tengö et al., 2014; Drenkhan et al., 2015; Keenan, 2015; Lasage et al., 2015; Camacho Guerreiro et al., 2016; Hurlbert and Gupta, 2016; Roco et al., 2016; Santos et al., 2016; Walshe and Argumedo, 2016; Uribe Rivera et al., 2017; Kasecker et al., 2018; Cuesta et al., 2019; Ulloa, 2019; Ariza-Montobbio and Cuvi, 2020). More interdisciplinary and transdisciplinary research helps to better understand and manage the relationship between governance, implementation, management priorities, wealth distribution and trade-offs between adaptation, mitigation and the Sustainable Development Goals (SDG).

Representations of climate change can also emerge as critiques and resistances, that expose that climate change labelled politics or interventions have posed even bigger risks, or do not address poverty issues (*medium confidence: medium evidence, high agreement*) (Lampis, 2013; Pokorny et al., 2013; Ojeda, 2014). Indigenous and social movements have joined with climate justice activists, claiming for action against climate change (Hicks and Fabricant, 2016; Ruiz-Mallén et al., 2017; Charles, 2021). The Bolivian Platform against Climate Change, a coalition of civil society and social movement organizations working to address the effects of global warming in Bolivia and to influence the broader global community, reflects an innovative dimension that, albeit at time conflictual, has flagged how increasing climate variability hinders the right of Indigenous Peoples to the conservation of their culture and practices and illustrates how grass-root movements are increasingly appropriating climate change policy in the region (Hicks and Fabricant, 2016). Social movements have engaged with international networks as Blokadia, which surged after COP 23, whose vindications try to go beyond the protection of the environment, delving into issues of democracy and resource control (Martínez-Alier et al., 2018).

Many social movements address adaptation to climate change. Some engage and participate in policy and planning, often having good results at the local level. On the contrary, top-down approaches without participation have shown to be less effective (*high confidence*) (Krellenberg and Katrin, 2014; Nagy et al., 2014b; Stein and Moser, 2014; Ruiz-Mallén et al., 2015; Sherman et al., 2015; Waylen et al., 2015; Bizikova et al., 2016; Chelleri et al., 2016; Merlinsky, 2016; Villamizar et al., 2017).

Some conflicts in which the direct biophysical impacts of climate change play a major role can unleash social protests and strengthen social movements (Section 12.6.4). In Cartagena, since 2010, the increase in precipitation increasingly impacted the *barrio* Policarpa, causing the residents to claim solutions for the problems caused by the coupled effect of flooding and industrial pollution. Also, in El Cambray II, in Guatemala City, in 2015 the nearby hill collapsed, causing the death of 280 people, 70 disappeared and the destruction of hundreds of homes. The affected community entered into a conflict with the municipality asking for resettlement and a reform of land-use planning (Stein Heinemann, 2018).

12.5.8.2 Perceptions

Perception and understanding of climate change can be seen as an adaptive feature. In CSA, the consciousness of it as a threat is burgeoning, a situation related to a growth in climate justice activism, as well as to the occurrence of extreme weather events of all kinds (*high confidence*) (Forero et al., 2014; Magrin et al., 2014; Capstick et al., 2015). Perception is positively associated across countries with the Human Development Index and ND-Gain Readiness Index, and negatively associated with the Vulnerability Index, and within countries, with the education level, while they are negatively associated with the degree of political affinity for the market economy (Azócar et al., 2021). Anyhow, some communities do not associate their problems with the scientific concept, so discussions as if it is human induced, the causes, or relations with other problems, can become irrelevant (Sapiains Arrué and Ugarte Caviedes, 2017). Even communities affected by the same changes do not necessarily perceive them in the same way (Bonatti et al., 2016). The interpretations of change, its causes and effects, can widely vary (Paerregaard, 2018; Scoville-Simonds, 2018). Rather than adapting to climate change, some peoples adapt climate change to their social worlds (Rasmussen, 2016a).

Perceptions tend to be different in rural and urban areas (Sherman et al., 2015). In the rural areas, it is highly related with temperature rise and changes in rainfall patterns, changes in agriculture (pests, calendars), biodiversity loss, solar radiation or changes in the oceans, and their impacts sometimes are related or even more attributed to socioeconomic and environmental drivers, and also related with financial negative outcomes (*high confidence*) (Infante and Infante, 2013; Postigo, 2014; Jacobi et al., 2015; Barrucand et al., 2017; Harvey et al., 2018; Martins and Gasalla, 2018; Meldrum et al., 2018; Córdoba Vargas et al., 2019; Leroy, 2019; Viguera et al., 2019; Gutierrez et al., 2020; Iniguez-Gallardo et al., 2020; Lambert and Eise, 2020). In places as the Amazonia, there is an increased perception with age (Funatsu et al., 2019). In Mediterranean Chile, younger, more educated producers and those who own their land tend to have a clearer perception than older, less educated, or tenant farmers, but they do not have a clear perception or how it may affect their yields and farming operation (Roco et al., 2015). In some dry and humid Ecuadorian montane forests, peasants perceive in the same way as scientific data, but they are at odds to predict the changes and consider that they may not be prepared and only can be reactive (Herrador-Valencia and Paredes, 2016). In an Andean community, perceptions of climate change are homogeneous and do not vary according to gender, age or ethnicity (Cáceres-Arteaga et al., 2020). Among representatives of five municipalities of Lima, it was found that climate change is not well understood and they have trouble distinguishing it from other environmental issues (Siña et al., 2016). In an Amazonian region, farmers provided a more accurate description than regional institutions of how it affects the local livelihood system (Altea, 2020). In Cuenca Auqui peasants attribute recently experienced challenges in agricultural production mainly to perceived changes in precipitation patterns, but statistical analyses of daily precipitation records at nearby stations do not corroborate those perceived changes (Gurgiser et al., 2016).

12.5.8.3 Gender and intersectionality

There is ample empirical evidence that the impacts of climate change are not of equal scope for men and women. Women, particularly the poorest, are more vulnerable and are impacted in greater proportion. Often, for several economic and social reasons, they have less capacity to adapt, further widening structural gender gaps (*high confidence*) (Box 7.4; Arana Zegarra, 2017; Casas Varez, 2017; Segnestam, 2017; Acosta et al., 2019; Aldunce Ide et al., 2020; Olivera et al., 2021; Silva Rodríguez de San Miguel et al., 2021). Gender equity is thought to be central to discussions on climate change adaptation policies. In issues such as drinking water, energy, natural disasters, impacts on health and agriculture, capacity to migrate, women (poor women in particular) are affected in greater proportion, further widening structural gender gaps. In a rural community vulnerable to drought, short-term coping was more common among the women, especially among female heads of household, while adaptive actions were more usual among the men; there are gendered inequalities in access to and control over different forms of capital that lead to a gender-differentiated capacity to adapt, where men are better able to adapt and women experience a downward spiral in their capacity to adapt and increasing vulnerability to drought (Segnestam, 2017).

However, women are not always the more vulnerable group. While in a broad sense climate change impacts more severely on women, there are situations where they have reacted, adapted better to, and been more resilient. Grassroots women self-help groups can be active agents of change for their communities, designing and delivering gender-responsive adaptation solutions (Huairou Commission, 2019). Some studies suggest that women establish a friendlier relationship with the environment and towards natural resources; studies on masculinities and environment confirm this tendency (Brough et al., 2016). In a multi country study, some female headed households tend to be slightly less vulnerable and more resilient than male headed households, even though some exceptions were found when looking at sub-groups (Andersen et al., 2017). In Chile, women are more likely to modernize irrigation and infrastructure, and gender appears as an important element for drought adaptation (Roco et al., 2016). A change to agro-ecological practices has improved gender equalities and adaptive capacity to climate change (Cáceres-Arteaga et al., 2020).

Recent studies emphasize that a gender approach to social inequalities ought to move beyond just looking at men and women as experiencing the impacts in a differentiated manner; rather, an intersectional analysis illuminates how different individuals and groups relate differently to climate change, due to their situatedness in power structures based on context-specific and dynamic social categorizations (*high confidence*) (Kaijser and Kronsell, 2014; Djoudi et al., 2016; Thompson-Hall et al., 2016; Olivera et al., 2021). Thus, the relationship between gender and adaptation demands an analytical framework that connects environmental problems with social inequalities in a complex way (Godfrey, 2012). An intersectional approach contributes to better capture the diversity of adaptive strategies that men and women adopt vis-à-vis climate change. Particular constellations of race, gender, class, age or nationality reveal more complex realities (*high confidence*).

12.5.8.4 Migrations and displacements

Migration and displacements are multi-causal phenomena, and climate may exacerbate political, social, economic or other environmental drivers (*high confidence*) (Kaenzig and Piguet, 2014; Brandt et al., 2016; Priotto and Salvador Aruj, 2017; Sudmeier-Rieux et al., 2017; Radel et al., 2018; Heslin et al., 2019; Hoffmann et al., 2020; Silva Rodríguez de San Miguel et al., 2021). In the region there are many case studies, but data to assess and monitor precisely the effects of climate -and weather- related disasters in migration and displacements in a broad perspective is still inaccurate (Priotto and Salvador Aruj, 2017; Abeldaño Zuñiga and Fanta Garrido, 2020). The most common climatic drivers include tropical storms and hurricanes, heavy rains, floods and droughts (Kaenzig and Piguet, 2014). Positive climatic conditions also can facilitate migration (Gray and Bilsborrow, 2013). Peru, Colombia and Guatemala are amongst the countries with the largest average displacements caused by hydro meteorological causes; Brazil had 295,000 people displaced because of disasters in 2019 (Global Internal Displacement Database, https://www.internal-displacement.org/database/displacement-data).

These processes can be interpreted as impacts in vulnerable peoples, but also as adaptation strategies to manage the risks and reduce the exposure, when people continue with their lives, temporary or permanently, in a different but stable situation, or when members of the families send remittances to those that remain in the affected areas (Section 7.4.3.2; Cross-Chapter Box MIGRATE in Chapter 7). The remittances create opportunities for adaptive capacity building, as they reduce some vulnerabilities in the form of infrastructures, agricultural supplies, food, education or health, as in northern CA (NU CEPAL, 2018). Anyhow, migration as adaptation is not available to everyone (Kaenzig and Piguet, 2014), and the idea has also been contested as it may not help to overcome structural problems or point to *in situ* options (Radel et al., 2018; Ruiz-de-Oña et al., 2019). The causal processes are complex. Surveys of migrants usually find that the main reported reason for migration is to find a job or to increase the household income (Wrathall and Suckall, 2016; OIM, 2017; Radel et al., 2018), but the underlying reason for the lack of job or income is rarely examined, and at times may be related with climatic hazards.

Migration most often originates in rural areas, with people moving to other rural or urban areas within their home countries (Table Cross-Chapter Box MIGRATE 1 in Chapter 7). In the Amazon, approximately 80% of the population is concentrated in cities due to rural-urban migrations in search of better income, livelihoods and services, in cases associated with extreme floods and droughts (Pinho et al., 2015). In Ecuador, environmental variables are most likely to enhance international than internal migration (Gray and Bilsborrow, 2013). Hurricanes have been seen as positive triggers for international migration in CA (Spencer and Urquhart, 2018). In the highlands of Peru, there are different patterns, including daily circular migration to combine the scarce income from agricultural production with urban income, rather than abandoning the farming land (Milan and Ho, 2014; Zimmerer, 2014; Bergmann et al., 2021).

Migration to cities can mean opportunities for migrants and for the urban areas, but also can worsen the problems, as urban poor people can become even more exposed and vulnerable, and the pressure on urban capacities may not be well absorbed (*high confidence*) (Chisari and Miller, 2016; Gemenne et al., 2020). Internal migration to cities is likely to exacerbate pre-existing vulnerabilities related to inequality, poverty, indigence and informality (Warn and Adamo, 2014). Immigration can make cities/residents more vulnerable to climate change risks (Section 12.5.5; Section 12.5.7). Groups as children, Indigenous Peoples or the poor are usually amongst the most vulnerable in the migrations and displacements, which poses challenges to national policies and international aid (Sedeh, 2014; Gamez, 2016; Ulla, 2016; Priotto and Salvador Aruj, 2017; Ramos and de Salles Cavedon-Capdeville, 2017; Amar-Amar et al., 2019; Gemenne et al., 2020). In forced migration or displacement by climatic effects, women are prone to lose their leadership, autonomy and voice, especially in new organizational structures imposed by authorities. This is especially the case in temporary accommodation camps created after disasters, exacerbating differentiated vulnerabilities existing (Aldunce Ide et al., 2020). International migration has become more dangerous and difficult as border controls have become stricter, but programs such as the one of temporary agricultural workers from Guatemala to Canada have proven to be successful (Gabriel and Macdonald, 2018). At the same time, emigration may lead to the loss of IK and LK for adaptation (Moreno et al., 2020b).

Some areas are more sensitive to generate climatic migration: the Andes, the dry areas of the Amazonia, northern Brazil, and the northern countries in CA (*high confidence*). Northeast Brazil would lose population that will move to the south, deepening the existing inequalities (Oliveira and Pereda, 2020). In a study of 8 countries around the world, including Guatemala and Peru, a link was found between rainfall variability and food insecurity which could lead to migration in areas of high prevalence of rainfed agriculture and low diversification (Warner and Afifi, 2014). In CA, younger individuals are more likely to migrate in response to hurricanes and especially to droughts (Baez et al., 2017).

The perception of gradual changes lowers the likelihood for internal migration, while sudden-onset events increase movement (Koubi et al., 2016). On the other hand, it has been seen that extreme events like floods or droughts can hinder population mobility, immobilizing them in their localities (Thiede et al., 2016). These immobilized populations are supposed to face a double set of risks: they are unable to move away from environmental threats, and their lack of capital makes them especially vulnerable to environmental changes (Black et al., 2011). In CSA, migrating to the U.S. is becoming dangerous and expensive, as that country is restricting the entries; these trends expose local populations to the risk of becoming immobile in the near future in a place where they are extremely vulnerable (Ruano and Milan, 2014; McLeman, 2019). A survey in Guatemala found no correlation between migration to the U.S. and severe food insecurity in households, but the correlation became significant if the level of food insecurity was moderate, suggesting that families in extreme hardship did not have the resources to migrate (Aguilar et al., 2019). At the same time, some populations just have chosen not to move, as in Peru, where immobility in dissatisfied people is more likely to be caused by attachment to place than resource constraints (Adams, 2016; Correia and Ojima, 2017). Some populations have chosen to adapt relying in their IK and LK (Boillat and Berkes, 2013).

Migration is often the last resort for rural communities facing water stress problems (Magrin et al., 2014; Ruano and Milan, 2014). In Bolivia, glacial retreat has not triggered new migration flows and had a limited impact on the existing migratory patterns (Kaenzig, 2015). In SA, climatic variability increases the likelihood of inter-province migration, rather than trapping populations. In a study of interprovincial migration motivated by temperature, an exception arose in Bolivia, and even if that could suggest an immobilized population (Thiede et al., 2016), it is not clear if they want to stay and adapt. In some cases, people want to move but wait for relocation after the climate related disasters (Priotto and Salvador Aruj, 2017).

12.5.8.5 Financing

Climate change financing is unequally distributed among CSA countries (*high confidence*). Financing of climate change adaptation remains very much delegated to multilateral and bilateral cooperation and the governments in the region have heavily relied on it. Still, there are some concerns regarding justice in the distribution of these funds (Khan et al., 2020). The UNFCCC has created financing mechanisms throughout its functioning years, but there is a wide range of issues that can present challenges for access by the recipients (Hickmann et al., 2019). These include; lack of technical capacity; difficulties in following the procedures established by the various financial entities; and low levels of awareness about the need for action, as well as the different sources of funds available. The fiscal policies of the different countries have contributed to government financing in the fight against climate change (World Bank, 2021). Since the Paris Agreement, countries have pledged NDCs which introduce the need to design and implement carbon budgets with respective consideration of the efficiency and costs and benefits involved in each mitigation or adaptation to climate change projects (Fragkos, 2020).

According to UNFCCC, Latin America and the Caribbean, for the period 2015–2016 obtained 22% of climate finance from multilateral climate funds. In this section we use data from: https://climatefundsupdate.org/data-dashboard, most of the reported information for Latin-American and the Caribbean includes Mexico, since the scope of this chapter does not includes Mexico we have rely in the raw data included in the data-dashboard mentioned in the link (see also: Guzmán et al. (2016)). 76% went to mitigation projects with the remaining 24% going to adaptation. Of the total finance provided by the multilateral climate funds to the Region, 51% took the form of concessional loans, while 47% was provided as grants. For the region, approvals in the 2015–2016 period were concentrated in Argentina, Chile, Brazil, and Colombia, where large-scale mitigation projects were launched supported by the Green Climate Fund (GCF) and the Clean Technology Fund (CTF). For the period 2003-2019, total contribution to South America and the Caribbean is about USD 3,558 million. The largest contributors to climate finance in the region come from the GCF, which approved USD 824.2 million for 23 projects. Brazil is the top recipient with USD 195 million, followed by Argentina with about USD 162 million. The second provider is the Amazon Fund with USD 717 million assigned to 102 projects in Brazil. In 2018, the CTF has become the third source of financing with USD 483 million dollars approved for 24 projects; the main recipient is Chile with USD 16,207 million followed by Colombia with USD 170 million. The five largest projects approved in the region in 2018 were through the GCF. Brazil (USD 195 million) received support for reducing energy intensity across Brazilian cities, while Argentina (USD 103 million) received support to scale up investments by Small and Medium sized Enterprises (SMEs) in renewable energy and energy efficiency. In both cases finance is predominantly provided as concessional loans.

Climate financing in CSA is mainly focused on mitigation actions (*high confidence*). In South America and the Caribbean, 73% (USD 2,579 million) of funding to date has supported mitigation. Only 21% (USD 761 million) of the funding supports adaptation projects and the remaining 4% (USD 217 million) supports multi-focus projects. Of the 51 new projects in South America and the Caribbean approved in 2018-2019, the GCF financed USD 508 million in ten projects. Amazon Fund was next with USD 81 million in 10 projects. While 32 the GCF focuses on large and transformative projects and programs and on a broader reform of the policy framework in the Region, the Amazon Fund targets smaller project interventions.

Climate finance in the region is concentrated in Brazil receiving one third of the region's funding, and 41 mitigation activities receiving more than six times that of adaptation from multilateral climate funds. By the size of its PGB, Brazil is receiving the largest amount of financing; this leaves the poorest countries with little or no financing and therefore reinforces a vicious circle of poverty and vulnerability. If this is due to Brazil being more successful presenting eligible projects, lack of commitment from other developing countries or some other structural factors is an open question. In any case, compensation schemes for the most vulnerable countries appear as required, given the differences in vulnerability to climate damages (Antimiani et al., 2017). This is aggravated by the fact that funds management is in the hands of supranational entities while inequalities remain in regions within a country, particularly in countries highly centralized as is the case for countries in the region.

COVID-19 recovery plans can present synergistic effects for climate change adaptation (*medium confidence: low evidence, high agreement*). A key decision point for adaptation will be how the world responds to the pandemic. The global recovery can serve as a catalyst to increased and more equitable climate financing. Globally, recovery packages will likely have the power to change the global trajectory towards meeting the targets of the Paris Agreement and building a more just future (Forster et al., 2020). Several factors are relevant to the design of economic recovery packages: the long run economic multiplier, contributions to the productive asset base and national wealth, speed of implementation, affordability, simplicity, impact on inequality, and various political considerations (Hepburn et al., 2020). A key objective of any recovery package is to stabilize expectations, restore confidence, and to channel surplus desired savings into productive investment. However, 'business as usual' implies temperature increases over 3°C, implying great future uncertainty, instability, and climate damages. An alternative way to restore confidence is to steer investment towards a productive and balanced portfolio of sustainable physical capital, human capital, social capital, intangible capital, and natural capital assets (Zenghelis et al., 2020), consistent with global goals on climate change. Finally, any recovery package, including climate-friendly recovery, is unlikely to be implemented unless it also addresses existing societal and political concerns—such as poverty alleviation, inequality, and social inclusion—which vary from country to country.

12.5.9 Adaptation Options to Address Key Risks in CSA

This section integrates, in the table 12.10 below, the sectoral assessment of adaptation options (see Sections 12.5.1 to 12.5.8) with the eight key risks assessed in the region (see Section 12.4). Table 12.10 presents a list of the summarized adaptation options, which are detailed in their adaptation sections, from 12.5.1 to 12.5.8 in this chapter.

Table 12.10: Adaptation options addressing key risks organized by sector. See the note at the end for descriptions of the sector names abbreviations.

1. Risk of food insecurity due to frequent/extreme droughts	
T&F. ecosystems	Ecosystem-based adaptation (EbA): Agroecosystem resilience practices
O&C ecosystems	Not Assessed (NA)
Water	Water infrastructure and irrigation; Nature-based solution (NbS) & Payment for ecosystem services (PES); Participatory water management; Multi-purpose water use
Food	Climate information services; Early warning system (EWS); Insurance; Land use planning; Low-Carbon Agriculture (LCA) strategies; Agroforestry; Indigenous Knowledge and Local knowledge (IK and LK)
Cities	NA
Health and wellbeing	EWS; Insurance; Participatory water management; Water infrastructure and irrigation
Poverty and SD	Community-based adaptation (CbA); Government and institutional support
Human Dimension	Participatory management; Incorporation of IK and LK in water and crop management; Education and communication
2. Risk to life and infrastructure due to floods and landslides	
T&F ecosystems	NA
O&C ecosystems	NA
Water	NbS; Land-use regulation; EWS; Integrated risk management.
Food	NA

Cities	Urban planning; Climate-adapted parameters in land use and building regulation; Intersectoral and multilevel governance; Slum upgrading; Social housing improvement; Urban control systems; CbA; Risk management plans; Integrated watershed management; Flood control programs; Environment protected areas; Households relocation; EWS; NbS; Mapping tools; Green-grey infrastructure (GGI); Water storage solutions; Wetland restoration; sustainable urban drainage systems (SUDS); low-impact development (LID); River restoration; Multifunctional landscapes; Improving basic sanitation services
Health and wellbeing	EWS; GGI; Community led and managed relocation; Insurance
Poverty and SD	Secure location; Social housing policies; EWS
Human dimensions	Education and communication
3. Risk of water insecurity	
T&F ecosystems	Monitoring Systems; EbA; Forest protection and restoration; Watershed protection
O&C ecosystems	CbA; Land use and development regulation
Water	Water infrastructure and irrigation; NbS & PES; Participatory water management; Multi-purpose water use
Food	Management and planning; NbS; Soil and water conservation
Cities	Intersectoral and multilevel governance; CbA; Risk management plans; Integrated watershed management; Environment protected areas; NbS; GGI; Wetland restoration; Improving basic sanitation services; Reservoir system
Health and wellbeing	Protection and restoration; National Adaptation Plans; Participatory water management
Poverty and SD	NbS: Water harvesting; Equitable water distribution
Human dimensions	Participatory management; Incorporation of IK and LK in water management; Education and communication
4. Risk of severe health effects due to increasing epidemics	
T&F ecosystems	NA
O&C ecosystems	NA
Water	Water infrastructure; Sanitation improvement
Food	NA
Cities	NA
Health and wellbeing	EWS; Health-climate surveillance systems; National plans on health; Communal management; GGI; Protection and Restoration.
Poverty and SD	CbA; Transparent democratic governance; Equitable services; Education
Human dimensions	Education and communication

5. Systemic risks of surpassing infrastructure and public service systems	
T&F ecosystems	NA
O&C ecosystems	EWS; EbA; Territorial planning; CbA; Land use and development regulation; GGI
Water	Water infrastructure; Land-use regulation; Water retention capacity; EWS; Capacity building
Food	NA
Cities	Urban planning; Climate-adapted parameters in land use and building regulation; Intersectoral and multilevel governance; Slum upgrading; Social housing improvement; CbA; Improving basic sanitation services; Micro wastewater treatment plants
Health and wellbeing	EWS; Vulnerability and risk maps; National Adaptation Plans; GGI
Poverty and SD	Transparent, democratic governance
Human dimensions	NA
6. Risk of large-scale changes and biome shifts in the Amazon	
T&F ecosystems	Monitoring Systems; EbA; Protected areas; Forest protection and restoration and restoration; Watershed protection
O&C ecosystems	NA
Water	Integrated water resource management
Food	Territorial planning
Cities	NA
Health and wellbeing	Protection and restoration
Poverty and SD	Insurance; Micro-credits; PES; CbA
Human dimensions	Participatory management; Incorporation of IK and LK in forest management; Education and communication
7. Risk to coral reef ecosystems due to coral bleaching	
T&F ecosystems	NA
O&C ecosystems	Zoning schemes; MPAs; EbA; CbA; Adhesion of international treaties
Water	NA
Food	NA

Cities	NA
Health and wellbeing	Protection and restoration
Poverty and SD	NA
Human dimensions	NA
8. Risks to coastal socio-ecological systems due to sea level rise, storm surges and coastal erosion	
T&F ecosystems	NA
O&C ecosystems	EbA; Planned relocation; GGI
Water	NA
Food	NA
Cities	Urban planning; Climate-adapted patterns in land use and building regulation; Intersectoral and multilevel governance; CbA; Risk management plans; Households relocation; NbS; GGI
Health and wellbeing	GGI; Communal management; Protection and restoration
Poverty and SD	Secure location; CbA relocation
Human dimensions	Participatory management; Education and communication

Table Notes:
Some sectors are presented by abbreviations: Terrestrial and freshwater ecosystems and their services (T&F. ecosystems); Ocean and coastal ecosystems and their services (O&C ecosystems); Food, fibre and other ecosystem products (Food); Cities, settlements and key infrastructure (Cities); Poverty, livelihood and sustainable development (Poverty and SD); Cross cutting issues in the Human Dimension (Human Dimensions).

12.5.10 Feasibility Assessment of Adaptation Options

This section assesses the feasibility of selected adaptations options by sector, relevant for CSA, in five dimensions (economic, technological, institutional, social, environmental and geophysical), according to the methodology developed by Singh et al. (2020a). Table 12.11 shows the summary of results and Table SM12.7 the details of the assessment and the supporting literature.

Table 12.11: Feasibility assessment of selected adaptation options for CSA region.

System	Adaptation option	Evidence	Agreement	Dimension assessed					
				Economic	Technological	Institutional	Social	Environmental	Geophysical

Food, fibre and other ecosystem products	Agroforestry	*Medium*	*High*	Insignificant barriers	Mixed effect	Significant barriers	Mixed effect	Insignificant barriers	Mixed effect
Health and wellbeing	Early warning systems	*Robust*	*High*	Insignificant barriers	Mixed effect	Significant barriers	Mixed effect	Insignificant barriers	Mixed effect
Water	Multi-use of water storage approaches	*Robust*	*Medium*	Insignificant barriers	Mixed effect	Mixed effect	Mixed effect	Mixed effect	Insignificant barriers
Freshwater and terrestrial ecosystems	Ecosystem-based adaptation (EbA)	*Medium*	*High*	Insignificant barriers	Mixed effect	Mixed effect	Insignificant barriers	Insignificant barriers	Insignificant barriers

12.5.10.1 Food, fibre and other ecosystem products - Agroforestry

For the agri-food systems, the adoption of agroforestry provides a more diverse and sustainable agricultural production, where farmers maintain or improve their current production by incorporating suitable trees that ameliorate climatic conditions. Thus, in the same unit of land, these systems incorporate exotic tree species or managed native forests into farming systems allowing the simultaneous production of trees, crops and livestock with different spatial arrangements or temporal sequences. On the other hand, it is recognized that the initial investment and time until trees start to produce may create economic vulnerability. Therefore, there is a need to design adequate programs and allocate resources for agroforestry systems implementation, as well technical assistance and training (*medium confidence*). Also, some market schemes such as payment for ecosystem services and certification can assist to reduce this vulnerability.

12.5.10.2 Health and Wellbeing - Early Warning Systems

For the health sector, we assessed the barriers and facilitators for the implementation of climate-driven early warning systems under natural disasters and epidemic situations. We found institutional dimensions as potential barriers, including the legal and regulatory feasibility, the institutional capacity and administrative feasibility, transparency, and political acceptability (*high confidence*). The fewest barriers were identified for the economic and environmental dimensions.

One of the main institutional challenges is the lack of policy with climate-health linkages. Opportunities include a national plan for the health sector to address the impacts of climate by formalizing collaborations via agreements (MOUs). Another key barrier is that relatively few institutions in the region have the human technical and administrative capacity to implement and operate an EWS. Regional platforms may provide a solution for technical assistance at national levels.

On the other hand, the economic dimensions had relatively few barriers, although the initial costs of designing, implementing, equipping, and maintaining the system are a potential barrier for health sectors with reduced budgets. However, the health benefits and economic savings (due to averted epidemics or damages from disasters) may offset these costs. The resilience built in the health sector by these systems may be applicable to other economic sectors that can benefit from an early warning of an oncoming extreme event and associated health impacts.

12.5.10.3 Water - Multi-use of water storage approaches

For the water sector, geophysical and economic dimensions do not pose a major barrier due to the potential reduction of flood hazard exposure, physical-technical viability of project implementation, different suitable economic mechanisms for joint public-private financing and more efficient water use. However, limited institutional capacities and the social-environmental impacts of large water infrastructure (Section 12.5.3) reduce the institutional, social, environmental and, to some extent, technological feasibility. This may be a potential barrier to the adaptive approach of multi-use water storage (*medium confidence*).

12.5.10.4 Freshwater and terrestrial ecosystems - Ecosystem-based adaptation (EbA)

In the terrestrial and freshwater ecosystems sector, we assessed the feasibility of implementing EbA options in the CSA region. Given that EbA encompasses a wide range of projects, techniques and political and socioeconomic arrangements, extreme care should be taken to apply these general findings to particular cases. EbA can enhance food sovereignty and carbon stocks and foster SDG by protecting and restoring ecosystems health and productivity. EbA is a strategy that frequently involves bottom-up decision making and local communities' empowerment and usually contributes to inequality reduction. EbA tends to benefit vulnerable groups, but aspects such as the impact on socioeconomic inequalities when implemented should be taken into account.

In general, EbA does not require high technologies for local communities. However, limitations in technical assistance and funding for specific key technologies and training may act as a barrier for EbA adoption (*medium confidence*). EbA practices can reduce risk in several ways by increasing awareness among communities and providing food diversity and production. EbA is recognized as a desirable policy for most stakeholders in CSA, particularly for being a strategy that incorporates environmental and social concerns. Nonetheless, it is important that all stakeholders agree on the goals and methods for EbA to be effective. Lack of institutional coordination, clear goals and strategies were identified as a potential barrier for EbA implementation. EbA is heavily based in local and Indigenous knowledge, as well as ecological academic knowledge.

For the adaptation options analysed, significant barriers and mixed effects were observed for the institutional dimension, which indicates the relevance of the design and implementation of public policies and institutional arrangements for effective adaptation in the region. Considering the results, there is a need to advance initiatives, programs and projects that facilitate adaptation to climate change. In the same way, barriers were evidenced in the technological dimension, which indicates the importance of increasing access and diffusion of appropriate techniques and technologies in order to face the challenges of climate change in the region.

12.6 Case Studies

12.6.1 Nature-based Solutions in Quito, Ecuador

Nature-based Solutions (NbS) are related to the maintenance, enhancement, and restoration of biodiversity and ecosystems as a means to address multiple concerns simultaneously (Kabisch et al., 2016). NbS can trigger sustainability transitions. For example, conservation and restoration of natural ecosystems are prone to promote synergy between mitigation, adaptation and sustainable development. Ecosystem-based Adaptation- EbA can be seen as a type of NbS deployed in response to climate change vulnerability and risk (Greenwalt et al., 2018), combining the objectives of reducing the vulnerability of human and increasing the resilience of natural systems (IPCC, 2014).

The Municipal Quito District in Ecuador covers 4235 km^2 of mountainous territory that ranges from 500 to 5000 m.a.s.l. That territory has followed a pattern of urbanization common in Latin America: its population has increased from around 500,000 people in the 1970s, to nearly 3 million inhabitants by 2020, of which

80% live in urban areas (Municipio del Distrito Metropolitano de Quito, 2016). A massive inflow of people immigrated in the early 1970s due to various causes, including the search for the rents created as a result of the oil boom in the Ecuadorian Amazon, better working conditions, health, education and cultural services, in comparison with the rural areas or in mid-sized cities. As a result, the city underwent an exponential growth, claiming valuable agricultural and forestry areas, and natural ecosystems, in the peripheries. Many of the new neighbourhoods were established through land invasions or informal markets, in many cases over steep slopes, in water sources and agricultural or conservation areas (*high confidence*) (Cuvi, 2015; Gómez Salazar and Cuvi, 2016). That exponential population growth, coupled with urban sprawl, poses many challenges to the city, including those related to climate change.

Mean air temperature and annual rainfall (measured through instruments since 1891 and inferred through historical records of rogation ceremonies since 1600), are increasing, combined with an increase in seasonality (i.e., longer periods of drought) and extreme weather events, particularly stronger precipitations (Serrano Vincenti et al., 2017; Domínguez-Castro et al., 2018). Two impacts related to warmer air conditions are the displacement of the freezing line currently placed at 5100 m.a.s.l. (Basantes-Serrano et al., 2016), followed by glacier retreat and the upward displacement of mountainous ecosystems (*very high confidence*) (Vuille et al., 2018; Cuesta et al., 2019). The key ecosystem that regulates water provision for the city is the paramo, and only about 5% of this process is related with glaciers, so the combined effects of climate change on both systems, coupled with land use change and fires, can reduce the availability of water for agriculture, human consumption and hydropower. Other important climatic hazards and impacts are the increase of solar radiation, the heat island effect and fires (*high confidence*) (Anderson et al., 2011; Armenteras et al., 2020; Ranasinghe et al., 2021). Almost half of the days of each year, Quito's population is exposed to levels of UV radiation above 11 according to the World Health Organization scale (Municipio del Distrito Metropolitano de Quito, 2016).

Various policies, programs and projects have been created for the promotion of urban green spaces, protected areas, water sources and watersheds monitoring, conservation and ecosystem restoration, air pollution monitoring and control, and urban agriculture. Among those actions, three recent are commonly highlighted. The first is the Fund for the Protection of Water (FONAG), established in 2000 with funds of national and international organizations, to promote the protection of the water basins that supply most of the drinking water. It is a PES-Scheme (Payment for Ecosystem Services) enabled through a public-private escrow. The projects include conservation, ecological restoration, and environmental education for a new culture of water, in a context opposed to the commodification of natural resources (Kauffman, 2014; Bremer et al., 2016; Coronel T, 2019). FONAG was innovative in the use of trust funds in a voluntary, decentralized mechanism and has inspired more than 21 other water funds in the region; nevertheless, its narrative of success has also been said to over-simplify and misrepresent some complex interactions between stakeholders as well as within communities and their land management practices (Joslin, 2019).

The second highlighted initiative is the project AGRUPAR (Participative Urban Agriculture), launched as a public initiative in 2002 with international cooperation funds at the beginning. It was aimed to provide assistance to poorer urban and peri-urban populations, to initiate and manage orchards as well as domestic animals such as chickens and guinea pigs, dedicated for self-sustenance and commerce. AGRUPAR provides and finances training, seeds and seedlings, greenhouses, certifications and marketing support, spaces where farmers can sell directly their products to consumers. In 2016, AGRUPAR gave assistance to more than 4000 farmers managing orchards of various scales that combined produce, annually, more than 500 tonnes. The program has direct impacts on nutrition, generation of work for women, production of healthy food, reduction of runoff, recycling of organic waste, social cohesion, among others (*very high confidence)* (Thomas, 2014; Cuvi, 2015; Rodríguez-Dueñas and Rivera, 2016; Clavijo Palacios and Cuvi, 2017).

A third initiative is the creation of a municipal system of protected areas, locally named Áreas de Conservación y Uso Sustentable (ACUS). This system covers an area of 1320 km², nearly one third of the Municipal Quito District. Half of this landscape (680 km^2) is covered by montane forests and *paramos* (Torres and Peralvo, 2019). These forests provide direct water, food and fibres for about 20,000 people, and indirectly a rural landscape for a growing number of urban citizens and foreign tourists that practice ecotourism and look for fresh and healthy food. During the last three decades, this area has witnessed a high density of public and private conservation and restoration efforts that aim to regain ecological integrity and improve human well-being in deforested and degraded landscapes (Mansourian, 2017; Zalles, 2018; Wiegant et al., 2020). Quito's system of protected areas constitutes a primary strategy for fostering links between urban and rural citizens as a means of understanding the ecological dependence of urban metropolises to their surrounding natural landscapes. Along the same lines, these areas constitute a key element to increase the adaptive capacity of rural livelihoods and contribute to mitigating climate change through landscape restoration, sustainable production and forest conservation (*high confidence*).

Other NbS' actions have been the restoration of small basins, locally named quebradas, under different schemes of management and participation (*medium evidence, very high agreement*) (da Cruz e Sousa and Ríos-Touma, 2018), or the transformation since 2013 of a larger portion of the old Quito airport into an urban park. Nevertheless, Quito city still has to deal with challenges in social, economic, infrastructural and environmental spheres. A major pending environmental issue is air pollution, as there is a high level of pollutants affecting the city in general, and specially the most vulnerable groups (*high confidence*) (Zalakeviciute et al., 2018; Alvarez-Mendoza et al., 2019; Estrella et al., 2019; Hernandez et al., 2019; Rodríguez-Guerra and Cuvi, 2019). Another major issue is the continuous sprawl of new neighbourhoods, mainly through informal processes, that diminish the urban resilience because of the destruction of conservation and food production areas, sources of water, and the dispersion of settlements without primary services, among other consequences (Gómez Salazar and Cuvi, 2016).

12.6.2 Anthropogenic Soils, an Option for Mitigation and Adaptation to Climate Change in Central and South America. Learning from the "Terras Pretas de Índio" in the Amazon

Amazon Dark Earths (ADEs), also known as "Terras Pretas de Índio", are anthropogenic soils derived from the activities associated to settlements and agricultural practices of pre-Hispanic societies in the Amazon (Woods and McCann, 1999; Lehmann et al., 2003; Sombroek et al., 2003). Most of the ADEs identified so far are 500 to 2500 years old (de Souza et al., 2019). According to Maezumi et al. (2018a) polyculture agroforestry allowed the development of complex societies in the eastern Amazon around 4500 years ago. Agroforestry was combined with the cultivation of multiple crops and the active and progressive increase in the proportion of edible plant species in the forest, along with hunting and fishing. The formation of ADEs, as a result of these activities, provided the basis for a food production system that supported a growing human populations in the area (Maezumi et al., 2018a).

Amazon Dark Earths are the result of the accumulation and incomplete combustion of waste materials such as ceramic artefacts and organic residues from harvest, weeding, food processing (including cooking) and other activities (Lima et al., 2002; Hecht, 2003; Kämpf et al., 2003). ADEs are characterized by their increased fertility in relation to adjacent soils; with high contents of organic carbon (C) (mainly as charcoal) as well as inorganic nutrients, especially phosphorus (P) and calcium (Ca); and high Carbon/Nitrogen ratios (*high confidence*) (Moline and Coutinho, 2015; Alho et al., 2019; Barbosa et al., 2020; Pandey et al., 2020; Soares et al., 2021; Zhang et al., 2021). They also exhibit high cation exchange capacity (CEC) and moisture retention among others properties (Hecht, 2003; Kämpf et al., 2003; Falcão et al., 2009). Charcoal content is a key indicator of pre-Hispanic fire activity and sedentary occupation, which is evidence of the anthropic origin of these soils (*high confidence*) (Hecht, 2017; Maezumi et al., 2018b; Alho et al., 2019; Barbosa et al., 2020; Iriarte et al., 2020; Montoya et al., 2020; Shepard et al., 2020).

Accumulation of organic residues and low intensity fires management are recognized as key elements for ADEs formation. ADEs originating around settlements show a relatively high density of ceramic artefacts and are named *Terras pretas.* They present a higher content of Ca and P than those originated from agriculture activities which are known as *Terras mulatas* (Hecht, 2003).

There is a robust and growing body of research from different disciplines that gives high relevance to ADEs in the region. It has been shown through archaeological and paleoclimatic data that Amazonian societies which based their agricultural management on "Terras Pretas de Índio", were more resilient to the changing climate due to increased soil fertility and water retention capacity (de Souza et al., 2019). Additionally, low organic carbon degradability over long time periods, associated with high contents of charcoal or pyrogenic carbon, makes these soils an important C sink (*medium confidence*: *robust evidence, medium agreement*) (Lehmann et al., 2003; Guo, 2016; Trujillo et al., 2020), which is particularly relevant in an area like the Amazon, that could change from a net carbon sinks to a net carbon source as a consequence of anthropogenic climate change (Maezumi et al., 2018b).

The Indigenous agricultural practices which originated ADEs are thought to be associated with a more sedentary agricultural model than the current slash and burn and shifting cultivation practices. Although this is a controversial topic, as the precise definition of slash and burn and shifting cultivation is presently under discussion (Hecht, 2003); several present-day local and Indigenous agricultural practices, including in-field burning and nutrient additions from food processing and residue management, have been recognized as promoting high organic carbon and nutrient soil contents similar to the ones found in ADEs (Hecht, 2003; Winklerprins, 2009).

At present, ADEs are estimated to cover up to 3.2% of the Amazon basin and are highly valued for their persistent fertility, becoming a key resource for sustainable agriculture for Amazon communities in a climate change context (Altieri and Nicholls, 2013; Maezumi et al., 2018a; de Souza et al., 2019). Based on the lessons learned from the Terras Pretas de Índio, some researches have proposed the development of technologies to promote a new generation of anthropogenic soils (e.g., Kern et al. (2009); Lehmann (2009); Schmidt et al. (2014); Bezerra et al. (2016); Kern et al. (2019)). Among the technologies based on ADEs learnings Biochar, obtained by slow pyrolysis of agricultural residues, is the most explored application found in literature (Mohan et al., 2018; Matoso et al., 2019; Amoah-Antwi et al., 2020). The dual purpose of increased soil fertility and carbon sequestration is considered an important goal in order to develop sustainable agriculture in a climate change context (Kern et al., 2019).

Preservation of the practices and knowledge associated with these soils is vital for sustainable agriculture in a climate change scenario in the Amazon. It will greatly contribute to the preservation of valuable Indigenous knowledge as well as the contribution to the development of new adaptation and mitigation technologies among other unexplored solutions.

12.6.3 Towards a Metropolitan Water-related Climate Proof Governance (re)configuration? The case of Lima, Perú

Lima-Callao Metropolitan City, capital of Perú is facing recurrent climate disasters showing lessons on water-related climate-proof governance reconfiguration: 1) when disasters affect the poor and rich population, dominant actors prioritize the integral city's resilience and development, and coordinate and collaborate within a *concertation* manner across institutional levels and geographical scales (Hommes and Boelens, 2017; Miranda Sara, 2021), even having different ideas, discourses, and power, recognizing that no one single actor has enough power; 2) water-related climate change scenarios require comprehensive, transverse, multi-sectoral, multi-scalar, multiple types of actor´s knowledge (expert, tacit, codified and contextual embedded (Pfeffer, 2018) and transparent information to manage the tensions and even conflicts when some knowledge is not shared or restricted particularly when lower risk perception and higher risk tolerance are present; 3) a *concertative* (processes which involve a variety of actors and has become mandatory in Peru) strategy to *localize* the climate action shows quicker, more effective and transparent results (*medium confidence, robust evidence, medium agreement*) (Miranda Sara and Baud, 2014; Pepermans and Maeseele, 2016; Siña et al., 2016; Miranda Sara et al., 2017).

Being the second driest city in the world, Lima is highly vulnerable to drought and heavy rainfall in the nearby Andean highlands (Schütze et al., 2019). Located on the Pacific Coast with more than 10 million inhabitants, suffers from both flooding, mudslides disasters and water stress, being more frequently affected by heavy rain peak events (1970, 1987, 1998, 2012, 2014, 2015 and 2017) (*very high confidence*) (Mesclier et al., 2015; Miranda Sara et al., 2016; French and Mechler, 2017; Vázquez-Rowe et al., 2017; Escalante Estrada and Miranda, 2020). In addition to water unequal distribution in quantity and pricing, one million inhabitants lack water connections (Ioris, 2016; Miranda Sara et al., 2017; Vázquez-Rowe et al., 2017) as a result of a lack of long-term city planning and lack of integration with water and risk management. Climate change scenarios were ignored or denied, particularly when the budget allocation for preventive actions was necessary (*high confidence*) (Miranda Sara et al., 2016; Allen et al., 2017a).

In 2014, the Water Company (SEDAPAL) together with the Lima Metropolitan Municipality (LMM), ANA, and other organizations agreed on a Lima Action Plan for Water (Schütze et al., 2019). The same year, the Lima Metropolitan Municipality (LMM) approved the Climate Change Strategy defining adaptation and mitigation measures (Miranda Sara and Baud, 2014), based on technical and scientific action research within interactive, and iterative *concertation* multi-actor processes.

However, in 2015, municipal elections shifted Lima's and later Peru's political power to parties associated with climate deniers at a high cost to the people, city infrastructure, and housing. Beginning of 2017, buildings along rivers, ravines, and slopes suffered from floods, *huaycos* (mudslides), the whole city suffered potable water cuts (Vázquez-Rowe et al., 2017) and vector-borne diseases affecting particularly the poorer but also richer inhabitants.

"Coastal Niño", affected the whole country, as a consequence, in 2018, the Peruvian government passed the Framework Law for Climate Change, Law No. 30754, a unique political decision, to assure the integration of climate change concerns in public policies and investment projects. The law defines local governments mandates on Local Climate Action Plans. The 2019 municipal elections brought new local authorities to Lima and by 2020, 19 district municipalities developed their Adaptation Measures adopting the Metropolitan Climate Change Strategy with support of Cities for Life Foro and GIZ (Foro Ciudades Para la Vida, 2021), in 2021 LMM approved its Local Climate Change Plan (LCCP) and other 10 (out of 51 with Callao) municipalities concluded the elaboration of their LCCP with support of the Global Covenant of Mayors and the European Union.

The institutionalized culture of participation in Peru did lead to a broader concept of *concertation*, wherein practices of collaborative planning were developed to allow actors to build up socially supported agreements, decisions and take actions without losing sight of their principles. These processes have been applied to reduce risks, to adapt and to anticipate uncertain and unknown futures; and introducing climate change concerns within a complex political and institutional environment surrounded by corruption scandals (Vergara, 2018; Durand, 2019) and growing political polarization.

Several processes have been set in motion to engage citizen participation and promote climate action planning: 1) The LMM with the Climate Action Plan processes reopened the Climate Change Technical Group of the Municipal Environmental Commission whose work ended in the approval of the Lima Local Action Plan of Climate Change (MML, 2021), 2) The River Basin Council is developing the River Basin Management Plan led by the National Authority of Water (ANA); 3) The Metropolitan Lima Urban Development Plan is finalizing a citizen consultation, with the support of a high-level Consultation Group.

Such processes include strong discussions, conflicts, and the recognition of other's discourses and types of knowledge, to build up scenarios that "visualize" and anticipate what might happen. These processes require democratic, transparent, and decentralized institutions, providing clear mandates and strong political will to support them, so the views of the poor and vulnerable are included, being able to make themselves heard, even if their power remains limited (Chu et al., 2016). Opportunities for the reconfiguration of socio-political and technological water governance are emerging based on socially supported agreements (Miranda Sara and Baud, 2014; Miranda Sara, 2021). Although the water governance configuration faces the paradox that current water demands of all users combined may no longer be feasible within ecological limits and future climate change consequences (Miranda Sara et al., 2016; Schütze et al., 2019).

12.6.4 Strengthening Water Governance for Adaptation to Climate Change: Managing Scarcity and Excess of Water in the Pacific Coastal area of Guatemala

Guatemala experiences high climate inter-annual variability now increased from the effect of climate change (INSIVUMEH, 2018; Bardales et al., 2019). Impacts on human settlements, agriculture and ecosystems result from both excess and reduced precipitation (*high confidence*) (Section 12.3.1.4). Guerra (2016) argues that deficient integrated water resource management in the country is the main reason for those impacts. A case in point is that of rivers Madre Vieja and Achiguate where an intense El Niño event triggered dryer conditions and, in turn, a crisis and conflict that reached national proportions. Progress in local water governance helped to solve that crisis and contributed to tackle challenges posed by reduced precipitation and flood risk in southern Guatemala.

The ENSO event that started in November 2014 and ended in July 2016 (CIIFEN, 2016) has been the most intense since records commenced in 1950 (NOAA, 2019). Its effects were felt in different parts of the world and, Guatemala and the rest of Central America experienced an intense water scarcity due to a significant reduction in rainfall (*high confidence*) (IICA, 2015; Scientific American, 2015). River flow in the dry months is related to precipitation levels in the previous rainy season and thus, ENSO has an effect on river flow rates. Two of the main rivers in the Pacific coast of Guatemala, Madre Vieja and Achiguate, dried out completely at the beginning of 2016, triggering a nearly violent local conflict that caught attention at the national level (Guerra, 2016; Gobernación de Escuintla et al., 2017). In addition to the severe drought, the rivers dried because of over-extraction by multiple users (60 in the case of Madre Vieja). This had happened before to a lesser extent in the last 20 years during the critical months of the dry season. Lack of regulation, coordination mechanisms, information, and other elements of water governance was the root cause of the problem, exacerbated by the drier conditions during the intense El Niño resulting in the intensification of an existing conflict (*high confidence*) (Guerra, 2016).

Roundtables were set up to foster dialogue between numerous stakeholders including communities, agri-export companies, governmental organisations, municipalities, all led by the local governor (Gobernación de Escuintla et al., 2017). Agreements included: to keep a minimum of the rivers flowing all the way to the sea; to set up a monitoring and verification system for levels of river flow; and to restore riparian forests. A system was set up to monitor river flow in different points along the rivers on a daily basis in the dry season using a simple WhatsApp-based system to communicate the warnings and monitor compliance. Four years on, the rivers had not dried out and conflict was kept to a minimum. Rural communities can use rivers for recreational purposes and for fishing all year round, whilst plantations (large and small) can use water for irrigation (rationally) and keep producing. Similar schemes and interactions started happening in other rivers in the Pacific coast of Guatemala, with positive results, particularly keeping the rivers flowing all through the dry season as can be seen in the report of river flows for years 2017, 2018 and 2019 (ICC, 2019b).

A key actor in the improvement of water governance has been the Private Institute for Climate Change Research (ICC). This is a unique initiative that was created in 2010 and is funded primarily by the private sector of Guatemala to help the country advance in climate change mitigation and adaptation (Guerra, 2014). The institute works alongside local governments, communities and private companies in several topics apart from integrated water management. Its role is merely technical-scientific, being in charge of the water monitoring system, generating data on weather and hydrology, and providing support to other stakeholders.

Local governance was also essential for the implementation of flood risk management actions (*high confidence*). Guerra et al. (2017) explained how impacts were significantly reduced in the Coyolate river watershed, also in the Pacific coast of Guatemala, thanks to flood protection that was designed and implemented in a technical and integrated manner. This was a result of strong and active participation of local communities, companies and the local municipality who demanded the central government to invest effectively. The stakeholders provided some resources (financial and in-kind) and inspected the works. Some flat areas of the lower Coyolate watershed used to flood annually causing economic damage for communities. The areas covered by flood risk measures have not flooded which has avoided losses as well as created conditions for investment to come and create jobs, improving life conditions for locals. Other processes of participation and interaction between the authorities, the private sector and communities have taken place in other watersheds for planning, action and investment for flood risk management. The ICC has played a role by studying flood-prone areas, building capacities in communities, fostering public-private coordination mechanisms, and providing much-needed technical assistance to local governments (ICC, 2019a).

Although some may argue that water governance is in the realm of development, it has made contributions in reducing direct and indirect impacts of climate events and therefore, it can be seen as a key element for climate adaptation (*high confidence*).

12.7 Knowledge Gaps

Data deficiencies and heterogeneity in quantity, quality and geographical bias in knowledge limit the understanding of climate change, the evaluation of its impacts, and the implementation of adaptation and mitigation measures (Harvey et al., 2018) in CSA. The number of publications is not representative with respect to the sensitivity to climate change and vulnerability contexts of different subregions and sectors.

This lack of representation in the mainstream literature may lead to a bias and, therefore, an underestimation of the overall climate-related impact for some CSA subregions (Sietsma et al., 2021). The reason for relatively few quantitative studies might be the complexities of socio-demographic and economic factors, and the lack of long-term and reliable data in these areas (Harvey et al., 2018), along with other social, economic and technical constraints.

Most studies that assess vulnerability to climate change do not yet follow the concept adopted since the Fifth Assessment Report (AR5) which separates exposure as an external variable (WGII AR5 Figure SPM 1) (IPCC, 2014), and many still use the A and B system of climate change scenarios from AR4, as adoption of the RCP models has been slow. There is still limited literature on severe risks and little specific and explicit consideration of risk drivers in the region. Moreover, limits to adaptation and the effectiveness of adaptation measures in CSA remain largely understudied.

The research of the interactions between climate change and socioeconomic processes is underdeveloped (Barnes et al., 2013; Leichenko and O'Brien, 2019; Thomas et al., 2019). There is limited understanding of the multilevel synergistic effects of climate change and other drivers including economic development from household to country level (Wilbanks and Kates, 2010; Leichenko and Silva, 2014; Tanner et al., 2015a; Carey et al., 2017). In the region, this deficit is deeper for sectors other than agriculture, water and food.

12.7.1 Knowledge Gaps in the Subregions

The knowledge gaps in the eight subregions are quite heterogeneous. In CA, climate change research is notably insufficient in all sectors included in this report, considering that climatic change, variability, and extremes are and will severely impact this subregion, and the vulnerability of the social and natural systems is high. Data deficiencies must be overcome as renewed research on climate change updates models, scenarios, and projected impacts across sectors and levels (i.e., household to country). In NWS, there is a lack of studies on the relationships with increased fire events, and the impacts on the infrastructure of all kinds, on certain lowland, marine and coastal ecosystems, and on ecosystem functioning and the provision of environmental services. Experimental studies are rare, most necessary to identify critical ecological thresholds to support the decision-making processes, linking glacier retreat to its consequences on biodiversity and ecosystems, combined with different land-use trajectories. Complex interactions with processes such as peace agreements in Colombia are yet to be studied (Salazar et al., 2018). In NSA, there is still a limited amount of peer-reviewed literature, addressing the implications of climate change on Indigenous cultures and their livelihoods. In SAM, further data are needed on the vulnerability of traditional populations, impacts on water availability and soil degradation, risks to biodiversity and resilience of ecosystems, attributed to climate change.

There is a knowledge gap about the likely impact of climate change on NES biodiversity, soil degradation, and best adaptation measures. SES is the most urbanized sub-region of CSA, but there is a strong knowledge deficits related to the design, implementation and evaluation of adaptation policy plans to climate change. Forecasts related to risk prevention require new studies that address down-scaled climate change models with concrete solutions to increase the city's resilience. In SWS, there is a lack of long-term studies addressing climate change impacts in terrestrial, freshwater and marine ecosystems which is mainly due to the lack of integrated observational systems. There is a lack of studies projecting future impacts of climate change on the cryosphere, water resources, hazards, risks and disasters on natural and human systems. This is mainly due to the lack of systematic documentation, analysis and evaluation of adaptation strategies adopted, as well as their limitations and the lessons learned from maladaptation processes. There is low evidence about transformational adaptation to climate change and systems resilience. In SSA, there is a need for information related to vulnerability and impacts of the direct effects of future climate change on cities, energy infrastructure and health. Also, there is a gap of knowledge about financing of climate change adaptation in SSA.

12.7.2 Knowledge Gaps by Sector

12.7.2.1 Terrestrial and Freshwater Ecosystems and their Services

Advances on scientific knowledge on risks of climate change impact, vulnerability and resilience of ecosystems is needed (Bustamante et al., 2020). Persistent climate change in tropical rainforest needs further understanding, overall on the role of nutrients, deep-water availability and biodiversity. Further research is needed to understand feedback to the climate systems of large-scale changes in the land surface in South America biomes. The region has important freshwater Global-200 Ecoregions, including the Orinoco River and Flooded Forests, Upper Amazon river and streams, and Amazon River and Flooded Forests being, therefore, a priority for freshwater biodiversity conservation at a global scale (Manes et al., 2021) (Cross-Chapter Paper 1; Figure 12.8). There is, however, a clear knowledge gap on the impacts of climate change on freshwater biodiversity in the region (Cross-Chapter Paper 1.2.3; Manes et al., 2021) . Lastly, more interdisciplinary research is needed regarding conservation strategies and stable financial resources focusing on adaptation of ecosystems in the region (Mistry et al., 2016; Gebara and Agrawal, 2017; Ruggiero et al., 2019; To and Dressler, 2019).

12.7.2.2 Ocean and Coastal Ecosystems and their Service

There is an important lack of knowledge about the health state of the ocean and coastal ecosystems along CSA (i.e., social-ecological data integration, poor sampling efforts, lack of information about the value of ecosystem services, lack of information about ecosystems cover and distribution, lack of studies about climate change perception and social concerns), including marine fisheries (i.e., landing statistics not available, lack of reliable information on the scope of resource extraction, among others). Poor or absent monitoring programs (physical, environmental and biological variables) that feed alert and surveillance systems are missing for CSA. There is a general absence of a continuous line of scientific research or an adequate baseline information about the impacts of climate change, as well as a continuous monitoring of the adaptation plans adopted in ocean and coastal ecosystems which limit the formulation of adequate conservation and management programs. When studies are performed, inadequate access to data limits the analyses of the existing information making difficult to detect climate change trends and impacts, as well as the development of effective adaptation strategies.

12.7.2.3 Water

As in other sectors and environmental systems, for the water sector there are important limitations in terms of monitoring and data collection. High-quality, long-term hydrological data are unevenly available for different subregions and limit a better understanding of changes in river runoff, lake or groundwater changes. Groundwater data is particularly scarce. There are important gaps related to projections of water resources for the future. Much of the current knowledge on future changes in water resources and water scarcity and flood risks is based on information from global-scale studies because studies specific to this region are scarce. Several elements which are important for integrated water resource management such as water quality, water demand, privatization and other economic dynamics, and nutrient, pollutant and sediment flux, are poorly known currently due to missing data and insufficient efforts to monitor them.

12.7.2.4 Food, Fibre and other Ecosystem Products

Integrative evaluation on impacts on food security, including agricultural production, distribution and access, leading to adaptation strategies is limited within the region. Limited information regarding cost-benefit analyses of adaptation in the food production sector is available in the region. It is also important to advance in a better understanding of the adaptation effects to avoid maladaptation and promote site-specific and dynamic adaptation options considering available technologies. Compiling and systematizing existing scientific and local knowledge on the relationship between forest, land cover/use, and hydrological services, is a gap to be filled, in a broader perspective in the region, that can contribute to provide recommendations and inform restoration practices and policies. The literature also highlights widespread gaps between farmers' information needs and services that are routinely available. There is evidence that when Climate Information Services are constructed with farmer input and are targeted in a timely and inclusive manner, they are a positive determinant of adaptation through the adoption of more resilient farm level practices. However, currently assessments of the economic impact of Climate Information Services are scarce; hence increased frequency of such studies is needed

12.7.2.5 Cities, Settlements and Infrastructure

Despite the high level of urbanization in the region, studies on urban adaptation initiatives are still underreported by municipalities and several practical results have not yet been demonstrated (Araos et al., 2016). It is particularly relevant to medium sized cities, as most of the literature and data available on adaptation refers to the major capital cities. The potential of applying new resilient parameters in building and land use regulation for adaptation is virtually underreported. The same can be said about the impact of housing improvement and slum upgrading on climate resilience, even when initiatives are focused on reducing environmental and climate risk. Also relevant in the region is a gap in research about NbS applied to urban areas adaptation, as in the case of the urban forestry potential for adaptation (Barona et al., 2020). Even though the importance of urban ecological infrastructure in providing ecosystem services, as flood control, is reasonably documented, its practical application in urban planning in CSA is still limited (Romero-Duque et al., 2020). Added to this is the lack of monitoring data on adaptation initiatives in general, and in particular, on adaptation initiatives in water systems, that have already been implemented, and its effects on risk reduction. Lack of monitoring data contributes to the lack of information about maladaptation in urban areas and its consequences. Mobility and transport systems adaptation options are virtually non-studied, while mitigation options receive a lot of attention.

12.7.2.6 Health and Wellbeing

There is a growing body of evidence that climate variability and climate change (CVC) cause harm to human health in CSA. However, there is a lack of information about the current and future projected impact of CVC events on overall illness and death in this region. It is challenging to attribute specific health outcomes to CVC in models and field experiments due multiple factors including:

- lack of long-term high-quality health surveillance data
- multiple interacting infectious disease and chronic health issues
- mismatch in the spatial and temporal scales of CVC and health measurements
- complex climate and human system dynamics including nonlinear time-lags
- limited longitudinal data on non-climate factors that influence health outcomes (e.g., public health interventions, migration of human populations, seasonal patterns in livelihoods).

The uncertainty inherent in predictive models also makes it challenging to expand current localized knowledge on the impacts of infectious diseases associated with CVC to other regions or future climate scenarios (UNEP, 2018).

Improved risk assessments based on better models and empirical research are needed to bridge the knowledge gap and inform the design of adaptation strategies. A systematic multi-scalar analysis of the impact of CVC on human health is needed across distinct social-ecological contexts. Data collection systems need to be strengthened to accurately estimate the burden of mortality and morbidity from heat and extreme events. The data deficit is a common problem in functioning civil registration and vital statistics systems, including lack of information on causes of death (UNEP, 2018). In addition, there is a lack of consensus on globally accepted and operational definitions for both climate-related extremes and exposures/outcomes.

For infectious disease (vector-borne and water-borne), the technology available to estimate current and future risk areas is often limited by human or financial resource constraints in developing countries. There is a geographical mismatch between the areas producing the technology and knowledge (in the global north), and the areas most affected by CVC (in the global south). User-friendly tools that bring together climate and health information—without the need for modelling or GIS expertise— are needed for health sector decision makers.

There is a lack of studies that assess the feasibility of health adaptation measures (see Section 12.5.10), thus limiting the ability of decision makers to compare different health interventions and identify bottlenecks for implementation. The growing field of implementation science could help to address barriers to mainstreaming climate information in the health sector as an adaptation strategy.

Finally, there is an almost complete void of studies that address relationships of climate change with wellbeing in CSA, broadly understood as including emotions and moods, satisfaction with life, sense of meaning, and positive functioning, including the capacity for unimpaired cognitive functioning and economic productivity (Section 7.1.4.1).

12.7.2.7 Poverty, Livelihood and Sustainable Development

Climate change is becoming a major obstacle in reducing poverty and overcoming poverty traps. There is a need to better understand how poor and vulnerable communities are affected and the more effective ways to prevent it. The large majority of the poor in the region are living in urban areas (UNDESA, 2019); urban extreme poverty is increasingly more relevant, including the needs and priorities of informal settlements and economies, but less studied within the interaction with climate change. There is little reporting of major adaptation options implemented by or for vulnerable and poor urban dwellers (Ryan and Bustos, 2019; Berrang-Ford et al., 2021).

Adaptation options are progressively being documented for poverty-related impacts in spite of the uncertain context from climate impacts not being uniform across communities and the very local scale of the type of adaptation responses needed (Miranda Sara et al., 2016; Rosenzweig et al., 2018; Dodman et al., 2019). There is a huge gap in understanding how the poor are responding to climate change, what is needed to support them, and the interconnections between development policies, poverty and risk reduction with climate change actions (Ryan and Bustos, 2019; Satterthwaite et al., 2020).

The literature to assess the effectiveness of pro-poor or low-income adaptation options continues to be weak, a very small proportion show results associated with adaptation efforts (Magrin et al., 2014; Berrang-Ford et al., 2021). Without this kind of approach and in depth understanding there is the risk that top down climate change adaptation options could reinforce poverty cycles and neglect cultural values, even eroding them (Bartlett and Satterthwaite, 2016; Walshe and Argumedo, 2016; Allen et al., 2017a; Hallegatte et al., 2018; Kalikoski et al., 2018; UN-Habitat, 2018).

The impacts of climate change on vulnerable groups are still understudied. There is little or no climate data on remote mountain regions of CSA as well as research measuring the vulnerability of smallholders living there, making it hard to assess the expected changes or the possible adaptation measures (Pons et al., 2017; Donatti et al., 2019).

12.7.2.8 Cross Cutting Issues it the Human Dimension

There is a significant number of studies addressing the impacts of climate change on the Amazon forest (Brienen et al., 2015; Doughty et al., 2015; Feldpausch et al., 2016; Rammig, 2020; Sullivan et al., 2020); however, the assessment of tangible and intangible impacts of climate change on Indigenous Peoples cultures and livelihoods in this forest, need to be further advanced (Brondízio et al., 2016; Hoegh-Guldberg et al., 2018).

Studies on the perception of climate change in rural and urban populations throughout the region have increased, but there is a lack of more specific research on the perception of specific groups, such as economic or political actors, that influence public institutions and policies at the local, national level and regional.

While studies on climate change gender differentiated impacts have grown over the past ten years in Central and South America, studies on how gender intersects with other dimensions such as race, ethnicities, age or rural/urban settings are still needed. This will help to further understand how gender inequalities are connected to broader power structures of societies and, thus, to produce evidence on the importance of an intersectional approach to climate change.

Regarding the relation of social movements and climate change adaptation, institutions and politics, two major issues stem out: youth movements for climate change and the resistances, mainly urban, to climate change adaptation policies. Little connection is found in research concentrating on resistance to climate change adaptation policies and their interaction with the politics of place. Conflictivity related to climate change is another under-studied issue.

Although there are several case studies on migrations and displacements caused by strong and immediate climatic threats, such as hurricanes or floods, and on slow-onset impacts, such as droughts or temperature increase, there are gaps in the attribution or relative weight of climate change in these processes.

Still important to note is that synergies between mitigation, adaptation, risk reduction and sustainable development have not been jointly explored, which would better facilitate adaptation policy approaches.

There are critical knowledge gaps in the interlinkages between social and environmental dynamics that are important for climate change adaptation, as in Andean forest landscapes. A salient knowledge gap in this thematic area is the need to characterize how multilevel and multi-actor governance systems can enable sustainable land management practices, including ecosystem restoration (Mathez-Stiefel et al., 2017). More capacities are needed to increase the generation of relevant knowledge. Even small grant programs can sustain research projects that target the linkages between knowledge and decision making at multiple scales (Báez et al., 2020).

12.8 Conclusion

Central and South America (CSA) is a broadly heterogeneous region in its topography, ecosystems, urban and rural territories, demography, economy, cultures and climates. The region relies on a strong agrarian economy in which small producers and large industries participate, but also large industrialized urban centres, oil production and mining. The region is one of the most urbanized of the world and home to many Indigenous Peoples, some still in isolation, and exhibits one of the highest rates of inequality, which is a structural and growing characteristic in CSA. Poverty and extreme poverty rates are higher among children, young people, women, Indigenous Peoples, migrant and rural populations but urban extreme poverty is also growing (*very high confidence*). Socioeconomic challenges are intensified by COVID crisis. Most countries in CA are already ranked as the highest risk level worldwide due to its exposure combined to high vulnerability and low adaptive capacity; the lack of climate data and proper downscaling are challenging the adaptation process (*high confidence*).

Many extreme events are already impacting the region and projected to intensify including warming temperatures and dryness, sea level rise, coastal erosion, ocean and lake acidification resulting in coral bleaching, and increasing frequency and severity of droughts in some regions, with associated decrease in water supply, that impact agricultural production, traditional fishing, food security and human health (*high confidence*). In Central America (CA), 10.5 million people are living in the so-called Dry Corridor, a region with an extended dry season and now more erratic rainfall patterns. A water crisis in Brazil affected the major cities of the country between 2014 and 2016, becoming more frequent since then. Severe droughts have also been reported in Paraguay and Argentina. In contrast, the urbanised areas of Northern South America (NSA) are highly exposed to extreme floods (41% of urban population in the Amazon Delta and Estuaries). Urban areas in the region are vulnerable for many reasons, notably high rates of poverty and informality, poor and unevenly distributed infrastructure, housing deficits, and the recurrent occupation of risk areas (*high confidence*).

Socio-ecological systems in the region are highly vulnerable to climate change, which acts in synergy with other drivers such as land use change and deep socioeconomic inequalities. Most biodiversity-rich spots in the region will be negatively impacted. The Cerrado and the Atlantic Forest (two important biodiversity-rich spots where about 72% of Brazil's threatened species can be found) are exposed to different hazards (extreme events, mean temperature increase) due to climate change. Many coastal areas and its concentrated urban population and assets are exposed to sea level rise. Climate change is threatening several systems (glaciers in the Andes, coral reefs in Central America, the Amazon forest) that are already approaching critical conditions under risk of irreversible damage.

Extreme heat, droughts and floods will seriously affect CSA terrestrial and freshwater ecosystems. The high poverty level increases the vulnerability to droughts, both in cities and rural areas, where people already suffer from natural water scarcity (*high confidence*). The conversion of natural ecosystems to other land uses exacerbate the adaptation challenges. Indigenous knowledge and local knowledge play an important role in adaptation but are also threatened by climate change (*high confidence*). Ecosystem-based Adaptation (EbA) and Community-based Adaptation (CbA) have increased since AR5, with emphasis on freshwater ecosystems and forests, including protected areas. Inadequate access to finance and technology are widely identified as adaptation barriers (*high confidence*).

Many impacts in the economy are expected from climate change. Subsistence farmers and urban poor are expected to be the most impacted by droughts and variable rainfall in the region (*high confidence)*. The increasing water scarcity is and will continue to impact food security, human health and well-being. The impacts of the many landslides and floods affect mainly the urban poor neighbourhoods and are responsible for the majority of the deaths related to natural disasters. Sea-level rise and intense storm surges are expected to impact the tourism and industry in general. Internal and international migrations and displacements are expected to increase (*high confidence*). Climatic drivers such as droughts, tropical storms and hurricanes, heavy rains and floods, interact with social, political, geopolitical and economical drivers (*high confidence*).

The common patterns and problems, however, highlight also the possibilities for collaboration and learning among the countries and institutions in the region in order to strengthen the interface between knowledge and policy in climate change adaptation. All countries in the region have submitted their first and updated NDC, and many have published their NAP, establishing priorities and formulating their own policies to cope with climate change.

Various adaptation initiatives have been initiated in different sectors, focused on reducing poverty, improving livelihood and achieving sustainable and resilient development. There is an increase in planned and autonomous initiatives, led by community, government or the combination of both, engineering or Nature-based Solutions (NbS). Climate smart agriculture is an effective option, in several conditions and regions, to mitigate negative impacts of climate change. Disaster reduction solutions are increasingly used, such as Early Warning Systems (EWS). Many and diverse initiatives are still poorly reported and evaluated in the scientific literature, leading to challenges in its assessment and improvements, including the consideration of the tacit Indigenous knowledge and Local Knowledge (IK and LK). The lack of climate data and proper downscaling, weak governance, hindrance on financing, and inequality are constraining the adaptation process (*high confidence*).

Adaptation measures have been increased and improved since AR5 in ocean and coastal ecosystems. The majority of these measures are focused on EbA application through the application of protection and recovery of already impacted ecosystems. Another battery of measures is focused on the management and sustainability of marine resources subjected to fisheries, however these measures are not assessing current and future climate change impacts but they are focused on decreasing the impact of other non-climate factors such as overfishing or pollution. To date, along CSA there is an important lack of long-term research addressing ocean and coastal ecosystems health and their species through continuous monitoring which is one of the main barriers to adaptation. The number and type of adaptation measures for ocean and coastal ecosystems and their contributions to humans are highly different among CSA countries which highlight in number those measures related to increase the scientific research and monitoring followed by the conservation of biodiversity, and changes in legislation (*high confidence*). On the other hand, those measures that include the changes in financing (an important barrier) or the incorporation of traditional knowledge are not always considered in national adaptation plans by CSA countries.

In the water sector a lack of systematic analysis and evaluation of adaptation measures prevail, although important progress has been made since the AR5 in terms of understanding interlinkages between climate change, human vulnerabilities, governance, policies and adaptation success (*high confidence*). NbS, Payment for Ecosystems Services (PES), integrated water resource management, and integration of IK and LK have proven potential of success, in particular if adopting approaches with inclusive negotiation formats for water management with clear, just and transparent rights and responsibilities.

Climate change poses several challenges to the agri-food sector, impacting the agricultural production and productivity, and posing at risk the food and nutritional security and the economy (*high confidence*). Adapting agriculture while conserving the environment is a challenge for a sustainable and resilient food production (*high confidence*). Adaptation in the region presents persistent barriers and limitations (Table 12.8), associated with investments and knowledge gaps (*medium confidence*). Climate change urges to advance in initiatives to improve education, technology and innovation of farming systems in the CSA region.

Urban adaptation is limited by financing constraints, weak intersectoral and multilevel governance, and deficits in the housing and infrastructure sectors, the overcoming of which is an opportunity for transformative adaptation (*high confidence*). Short-term interventions are prevailing over long-term planning (*high confidence*). Adaptation experiences in planning, land use and building regulation, urban control systems and risk management have taken place throughout the region. Initiatives in social housing are reducing risk, overcoming urgent deficits, but also adding to a transformative adaptation pathway (*high confidence*). Hybrid (green-grey) infrastructure has been adopted for better efficiency in flood control, sanitation, water scarcity and landslide prevention and coastal protection (*high confidence*). NbS including green infrastructure and EbA are increasing in urban areas (*high confidence*), although isolated engineering solutions are still widely practiced. The integration of transport and land use plans and the improvement of public transport are key to urban adaptation; mitigation prevails over adaptation in the sector (*high confidence*).

There is a growing body of evidence that climate variability and climate change are causing harm to human health in CSA – including the increasing transmission of vector borne and zoonotic diseases, heat stress, respiratory illness associated with fires, food and water insecurity associated with drought, among others (*medium confidence*). In response, countries in the region are developing innovative adaptation strategies to inform health decision making such as integrated climate-health surveillance systems and observatories, forecasting of climate-related disasters, and epidemic forecast tools. However, institutional barriers (limited resources, administrative feasibility, and political mandates) need to be addressed to ensure the sustained implementation of adaptation strategies (*high confidence*).

Poor and vulnerable groups evidence limited political influence, fewer capacities and opportunities to participate in decision and policy making being less able to leverage government support to invest on adaptation measures (*very high confidence*). Participatory processes are developing adaptation measures strengthening local capacities; literature assessing the success of such initiatives remains limited. Limits to adaptation include access to land, territory and resources, labour and livelihood opportunities, knowledge gaps and poor multi actor coordination. Social organization, participation and governance reconfiguration are essential for building climate resilience (*very high confidence*).

Social organization, participation, governance, education and communications to increase perception and knowledge, are essential for building the resilience to adapt and overcome expected and unexpected climate impacts (*very high confidence*). The focus on inclusion and enrolling of the full range of actors in adaptation processes, including vulnerable populations, has shown good results in the region (*high confidence*). However, existing poverty and inequality, unbalances on power relations, corruption, weak governance and institutions, structural problems and high levels of risk tolerance may reinforce poverty and inequality cycles (*high confidence*). In addition, the continued exposure of critical infrastructure and valuable assets are signs of persisting maladaptation.

The development model prevailing in the region for the last decades has proven to be unsustainable, with the emphasis on financial sources based on natural resource depletion and extraction and the persistence and growing inequality. It is well recognized that climate adaptation measures, if carefully selected considering the coupled human-environment systems, will provide significant contributions to the sustainable development pathways of the region and to achieve the sustainable development goals (SDG) if implemented together with comprehensive strategies to reduce poverty, inequality, and risks (*high confidence*). Adaptation and the construction of resilience offer not only an opportunity to reduce climate change impacts, but also the opportunity to reduce inequality and development gaps, to achieve dynamic economies, and to regulate the sustainable use and transformation of the territory.

[START FAQ 12.1 HERE]

FAQ 12.1: How are inequality and poverty limiting options to adapt to climate change in Central and South America?

Poverty and inequality decrease human capacity to adapt to climate change. Limited access to resources may reduce the ability of individuals, households and societies to adapt to the impacts of climate change and variability because of the narrow response portfolio. Inequality limits responses available to vulnerable segments as most adaptation options are resource-dependent.

Though poverty in Central and South America has decreased over the last 12 years, inequality remains as a historic and structural characteristic of the region. In 2018, 29.5% of Latin America's population (including Mexico) were poor (182 million) and 10.2% were extremely poor (63 million), more than half of them living in urban areas. In 2020, due to COVID crisis Gini coefficient projection of increases is ranging from 1.1% to 7.8%, poverty increased to 33.7% (209 millions) and extreme poverty to 12.5% (78 millions).

Poor populations have little or no access to good quality education, information, health systems and financial services. They have lower chances to access resources such as land and water, good quality housing, risk reducing infrastructure and services such as running water, sanitation and drainage. Their lack of political clout and endowments limit their access to assets for withstanding and recovering from shocks and stresses. Poverty, inequality, and high vulnerability to climate change are inter–related processes. Poor populations are highly vulnerable to impacts from climate change and are usually located in areas of high exposure to extreme events. The constant loss of assets and livelihoods both in urban and rural areas drives communities into chronic poverty traps, exacerbating local poverty cycles and creating new ones.

For instance, climate–related reduced yields in crops, fisheries, and aquaculture have a substantial impact on the livelihoods and food security of families and affect their options to cope and adapt to climate change and variability. The impact of climate change in agriculture for Central and South America depends on determinants such as availability of natural resources, access to markets, diversity of inputs and production methods, quality and coverage of infrastructure, as well as socioeconomic characteristics of the population. Impacts from climate change on small–scale farmers compromise the livelihoods and food security of rural areas and consequently the food supply for urban areas.

Governments in the region have implemented several poverty–reduction programs. However, policies of income redistribution and poverty alleviation do not necessarily improve climate risk management, hence complementary policies integrating both social and material conditions are required. A study in Northern Brazil shows risk management strategies for droughts and food insecurity did not change poverty incidences between 1997–1998 and 2011–2012. Major shocks, such as climate and weather extreme events (e.g., floods, heavy rains, droughts, frosts), reduce and destroy public and private property. For instance, the ENSO event of 2017 in Peru caused losses estimated between USD 6 to 9 billion, affected more than a million inhabitants and generated 370,000 new poor. In total, losses by unemployment, deaths, destruction and damage of infrastructure and houses were around 1.3% of the Gross Domestic Product of Peru.

Low public expenditure on social infrastructure (health, education etc.), ethnic discrimination and social exclusion reduce healthcare access, leaving poor people in entire regions mostly undiagnosed or untreated. In a context of privatization policies of health care systems, research shows marginal people lack identifying documents needed to access public services in Buenos Aires (Argentina), Mexico City (Mexico) and Santiago de Chile (Chile), some of the most developed cities in the region. Consequences of this situation are under reporting, low diagnosis, and low treatment of diseases such as vector–borne diseases such as dengue and risk of diarrheal diseases originated by frequent floods in Amazonian riverine communities. Bias on reporting access to health–care and incidence of diseases in marginal populations are usually region–dependent. For example, in Brazil's Amazonian North in 2018, there were 2.2 medical doctors per 1000 inhabitants, while 4.95 medical doctors per 1000 inhabitants in São Paulo and 9.52 doctors in Santa Catarina. Another example: pregnant women in remote Amazonian municipalities receive less prenatal care than women in urban areas. These social inequities underlie systemic biases in health data–quality hindering reliable estimation of disease burdens such as distribution of disease or birth and death registrations. For Example, in Guatemala alternative Indigenous healthcare systems are responding to local needs by Mayan communities. However, this remains unrecognized. The existence of health institutions based on Indigenous knowledge can reinforce the lack of universal coverage by central government healthcare, addressing the miscalculation of morbidity, mortality, and cause–of–death among disadvantaged groups.

Inequality, informality and precariousness are particularly relevant barriers for adaptation. A significant part of the construction sector in the region is informal and does not follow regulations for land use and construction safety codes, and there is a lack of public strategies for housing access. Adaptive construction is based upon up–to–date regulation and codes, appropriate design and materials, and access to infrastructure and services. Decreasing inequality and eradicating poverty are crucial for achieving proper adaptation to climate change in the region. Some experiences to fight poverty such as savings groups, microfinance for improving housing or assets and community enterprises may also support specific adaptive measures. These mechanisms should be widely accessible to poor groups and be complemented by comprehensive poverty alleviation programs that include climate change adaptation.

[END FAQ 12.1 HERE]

[START FAQ 12.2 HERE]

FAQ 12.2: How have urban areas in Central and South America adapted to climate change so far, which further actions should be considered within the next decades and what are the limits of adaptation and sustainability?

Cities are becoming focal points for climate change impacts. The rapid urbanization in Central and South America, together with accelerating demand for housing, resource supplies and social and health services, put pressure on the already stretched physical and social infrastructure. In addition, migration is negatively affecting the opportunities of cities to adapt to climate change.

Central and South America is the second most urbanized region in the world after North America with 81% percent of its population being urban. 129 secondary cities with 500,000 inhabitants concentrate half of the region's urban population (222 million). Another 65 million people live in megacities over 10 million each. The population migrates among cities, resulting in more secondary cities and creating mega regions and urban corridors.

Rapid growth in cities has increased the urban informal housing sector (e.g., slums, marginal human settlements and others), which increased from 6 to 26 percent of the total residences from 1990 to 2015. Coastal areas in Central and South America increasingly concentrate more urban centres. Researchers indicate that between 3 to 4 million inhabitants will experience coastal flooding and erosion from sea–level rise in all emission scenarios by 2100 considering Southern America alone.

A study on cities with more than 100,000 inhabitants shows the number of coastal cities significantly increased from 42 to 420 between 1945 and 2014; they are located close to fragile ecosystems such as bays, estuaries and mangrove forests, resulting in higher concentrations of population and economic activities. This process degraded the ability of coastal ecosystems, such as mangroves, to reduce risks and provide essential ecosystem services which help to prevent coastal erosion or maintain fish stocks. Moreover, it reduced ports, tourism, along with income opportunities.

Climate change impacts on cities in Central and South America are strongly influenced by El Niño Southern Oscillation (ENSO) associated with an increase of more extreme rainfall events. Urban areas are increasingly dealing with floods, landslides, storms, tropical cyclones, water stress, fires, spread of vector–borne and infectious diseases, damaging infrastructure, economic activities, built and natural environments and the population's overall well–being.

Glacier retreat in the mountains will affect water runoff and water provision to Metropolitan cities such as Lima, La Paz, Quito and Santiago who rely on rivers that originate in the high Andes. Lima, the second driest capital city in the world, is vulnerable to drought and heavy rain peak events associated with climate change. In Bogota lower precipitations and a tendency of increasing extreme events are expected in the coming decades. Hence, the protection of fragile ecosystems such as 'paramo' (fields at 3000 to 4000 m.a.s.l.) will be crucial for water supply to the city.

Sea level rise impacts cities located in low elevation coastal zones, not only because of direct coastal flooding, coastal erosion and subsidence; but also because it aggravates the impact of storm surges, heat wave energy and saltwater intrusion. 68 percent of the population of Surinam and 31 percent of the population in Guyana live below 5 meters above sea level, while many sectors of Georgetown, the capital of Guyana, are below sea level. Floods with increased frequency and severity of storm surges will also impact the Rio de la Plata estuary and lower delta of the Parana River where Metropolitan Buenos Aires is located.

Over 80 percent of losses associated with climate-related risks concentrate in urban areas, and between 40 and 70 percent losses occur in cities with less than 100,000 inhabitants, most probably as a result of limited capacities to manage disaster risks and low level of investments.

Despite consistent political and economic barriers, many cities in the region have adopted sustainable local development agendas, which work to address a balanced urban development. The shortcomings of poor development patterns are still very present in the cities and present important obstacles to adaptation investment, as public investment in basic needs (mainly housing and sanitation) must be prioritized.

Cities struggle to address the immediate needs of their population while addressing longer–term needs associated with climate adaptation, emissions reduction and sustainable development. Some cities are moving forward to transformative adaptation, addressing drivers of vulnerability, building robust systems and anticipating impacts. Besides government–led adaptation planning and action, individuals, communities and enterprises have been incrementally adapting to climate changes autonomously over time. Municipalities from Argentina, Peru, Chile, Equator, Brazil and Costa Rica are developing and implementing their Local Climate Action Plans, experimenting and displaying best practices in adaptation. Both anticipatory adaptation measures–choosing safe locations, building structurally–safe houses, choosing elevated places to store valuables, building on stilts–and reactive adaptation measures are used; the latter incorporating measures such as relocation, stabilization of slopes, afforestation, and greening of riverbanks. With variations, these cities have included mechanisms to work across sectors and actors understanding it is collective planning and actions, which will ensure that long term programs continue independently of particular city administrations.

Cities are interconnected systems operating beyond administrative boundaries. Improved collaboration and coordination is needed for integrated responses. Aside from good planning, cities need access to external adaptation funds. Climate change adaptation requires long–term funding and investments, which are beyond cyclical political terms. It is key to re–think how to make international adaptation funds reach cities and innovate. For example, member cities of Global Covenant of Mayors in the region, together with Cities for Life Forum in Peru, the Red Argentina de Municipios por el Cambio Climático (RAMCC), the Capital Cities of the Americas facing Climate Change (CC35) and others, are pursuing this goal and applying directly for international grants. New funding sources are required to help local governments and civil society. Cities and locally driven adaptation initiatives can be funded by national governments and international organizations.

[END FAQ 12.2 HERE]

[START FAQ 12.3 HERE]

FAQ 12.3: How do climatic events and conditions affect migration and displacement in Central and South America, will this change due to climate change, and how can communities adapt?

Migration and displacements associated with climatic hazards are becoming more frequent in Central and South America, and it is expected they will continue to increase. These complex processes require comprehensive actions in the places of origin and reception, both to improve adaptation in the more affected places, and the conditions of the mobilizations.

Migration of individuals, families and groups, voluntary and involuntary, is common in Central and South America. People migrate nationally and internationally, temporarily or permanently, predominantly from rural areas – often immersed in poverty – to urban areas. Common social drivers of migration in the region are the economy, politics, land tenure and land management change, lack of access to markets, lack of infrastructures, and violence; environmental drivers include loss of water, crops and livestock, land degradation and sudden or gradual onset of climate hazards.

The increasing frequency and magnitude of droughts, tropical storms, hurricanes, and heavy rains producing landslides and floods, have amplified internal movements, overall rural to urban. For instance, rural to urban migration in Northern Brazil, or international migration from Guatemala, Honduras and El Salvador to North America, are partly a consequence of prolonged droughts, which have increased the stress of food availability in these highly impoverished regions. Diminished access to water is also a result of privatization of that resource. In Central America, the majority of migrants are young men, reducing the labour force in the places of origin. However, the migrants send back substantial amounts of money that have become the main source of foreign exchange for their countries, and the main source of income for their families.

As poor people have less resources to adapt to changing conditions, they are usually the most impacted by climate hazards, as they are already struggling to survive under normal conditions. These populations are the most susceptible to migration, chiefly because of the loss of their livelihoods, their precarious housing and settlements and the lack of money and international aid. Other important factors are the minimal governmental support and assistance through social safety nets and extension services, the scarcity and low quality of education and health services, the isolation and marginality, and the insecurity of land rights. These same conditions, though, may hinder their mobility or even render them immobile. Nevertheless, in some cases, despite worsening conditions, people decide not to move.

The magnitude and frequency of droughts and hurricanes are projected to keep increasing by 2050, which may force millions of people to leave their homes. Climate models show some dry regions will become even dryer in the coming decades, increasing the stress on small farmers who rely on rainfall to water their fields. Glacier retreat and water scarcity are becoming strong drivers of migration in the Andes. Sea level rise influences activities such as fishing and tourism, which will foster further migration. In Brazil, at least 0.9 million more people will migrate inter–regionally under future climate conditions.

Addressing migration and displacement requires diverse interventions: in dry regions it is recommended to improve the water management in the places of origin of migration, including storage, distribution and irrigation. Wet regions, lowlands, and floodplains will benefit from preventing construction on areas prone to landslides and flooding. Government and international aid are also important for improving people's options to adapt and enhance their resilience to climate impacts. In northern Brazil, for example, government financial support has significantly reduced the migration caused by droughts. Between Guatemala and Canada there is a temporary migration program to bring in migrant workforce during the harvest season. The United States is also increasing these types of legal temporary migration.

[END FAQ 12.3 HERE]

[START FAQ 12.4 HERE]

FAQ 12.4: How is climate change impacting and expected to impact food production in Central and South America in the next 30 years and what effective adaptation strategies are and can be adopted in the region?

Agriculture is a fundamental sector to the development of societies from the economic and social perspectives, and so it is a major component of the adaptive strategies for Central and South America countries. Implementation of sustainable agriculture practices such as improved management on native grasslands or agroforestry systems for crop and livestock production, can increase productivity while improving adaptability.

Over the last two decades, countries throughout Central and South America have been developing rapidly. The agriculture sector is fundamental to this development from economic and social perspectives. Some countries of the region are amongst major food exporters in the world:

- Corn: three of the top ten exporters are Brazil, Argentina and Paraguay;
- Soybean exports: Brazil and Argentina are among the top five; Paraguay and Bolivia figure within the twelfth;
- Coffee exports: five of the top ten export countries are Brazil, Colombia, Honduras, Peru and Guatemala;
- Fruits: two of the top 10 fresh fruit export countries are Chile and Ecuador,
- Fishmeal exports globally are led by Peru, Chile and Ecuador;
- Beef: four of the top exporting countries are from this region – Brazil, Argentina, Uruguay and Paraguay.

CSA is one of the regions with the highest potential to increase food supplies particularly to more densely populated regions in Asia, Middle East and Europe. Better understanding the impact of the economy on the environment and the contribution of the environment to the economy, is critical to identify opportunities for innovation and promoting activities that could lead to sustainable economic growth without depleting natural resources and increasing sensitivity to climate change and climate variability. The consideration of food as a commodity instead of a common resource, leads to the accumulation of under-priced food resources at the expense of natural capital. Without serious emissions reduction measures, climate models project an average 1 to 4°C increase in maximum temperatures, and a 30 percent decrease in rainfall towards 2050, across Central and South America. Tropical South America is projected to warm at higher rates than the southern part of South America. Given these circumstances, some regions in Central and South America (Andes region and Central America) will just meet, or fall below, the critical food supply/demand ratio for their population. Meanwhile, the more temperate part of South America in the south is projected to have agricultural production surplus. The challenge for this region will be to retain the ability to feed and adequately nourish its internal population as well as making an important contribution to the food supplies available to the rest of the world.

The Nationally Determined Contributions (NDCs) of most of the countries of Central and South America expressly included agriculture as a major component of their adaptive strategy. From the recommendations presented, five general adaptive themes, or imperatives, emerge: 1) inclusion of climate change projections as a key element for Ministries of Agriculture and research institutes in their decision-making processes; 2) support research and adoption of drought- and heat-tolerant crop varieties; 3) promotion of sustainable irrigation as an effective adaptive strategy; 4) recovery of degraded lands and sustainable intensification of agriculture to prevent further deforestation; and 5) implementation of climate smart practices and technologies to increase productivity while improving adaptability.

Climate smart-practices provide a framework to operationalize actions aimed at understanding synergies among productivity, adaptation and mitigation. Significant amount of evidence supports the potential for climate smart-practices technologies to produce such triple wins as natural pastoral systems in the southern region of South America. Such systems allow the combination of food production and environmental sustainability. The production of meat based on native grasslands with grazing management that optimizes forage allowance can achieve high production levels, while providing multiple ecosystem benefits. Optimal forage allowance means offering the animals enough forage in order to meet requirements and while avoiding overgrazing. This management practice simultaneously increases productivity, reduces greenhouse gas emissions while improving soil carbon sequestration, and minimizes other environmental impacts such as excess of nutrients, fossil energy use, and biodiversity loss. Pastoral farming systems that manage grazing and feeding efficiently, are an example of integration between food security, environmental conservation and nature-based adaptation to climate change.

Agroforestry systems are present in the tropical region of Central and Southern America. Trees are present in a large part of the agricultural landscape of this region, either dispersed or in lines; supporting the production of coffee, cocoa, fruits, pastures and livestock in various agroforestry configurations. In Central America, shade-grown coffee reduces weed control and improves quality and taste of the product. Agroforestry uses nitrogen-fixing trees (*Leguminosae*), such as Leucaena in Colombia, Inga in Brazil, to restore soil nitrogen fertility. Tropical forest soils are generally nutrient-poor and unsuited to long-term agricultural use. Land converted to agriculture by cutting and burning natural vegetation tends to remain productive for only a few years. Agroforestry and the so called silvopastoral systems, which incorporate trees into crop and livestock systems, have been shown to make a dramatic impact on the maintenance and restoration of long term productivity in agricultural landscapes, including degraded and abandoned land. Agroforestry systems can provide major benefits through enhanced food security, stronger local economies, and increased ecosystem services such as carbon storage, regulation of climate and water cycles, control of pests and diseases, and maintenance of soil fertility. Because of these multiple goods and services, agroforestry practices are considered one of the key strategies for the development of climate smart agriculture.

[END FAQ 12.4 HERE]

[START FAQ 12.5 HERE]

FAQ 12.5: How can Indigenous knowledge and practices contribute to adaptation initiatives in Central and South America?

Indigenous Peoples have knowledge systems and practices that allow them to adapt to many climatic changes. Adaptation initiatives based on Indigenous knowledge and practices are more sustainable and legitimate among local communities. It is important to build effective and respectful partnerships among Indigenous and non–indigenous researchers to co–produce climate relevant knowledge to enhance adaptation planning and action in the region.

There are 28 million Indigenous Peoples in Central and South America (around 6.6% of the whole population of the region). They belong to more than 800 groups living in territories covering a wide range of ecosystems – from drylands to tropical forests to savannahs, coasts to mountains – and that share the land with many other cultural and ethnic groups. In the region, Indigenous Peoples are often categorized as a group highly vulnerable to climate change as they are frequently affected by socioeconomic inequalities and the dominance by external powers. They often experience internal and external pressures over their communal lands in forms of pollution, oil and mining, industrial agriculture, and urbanization. On the other hand, it is important to recognize that Indigenous Peoples have knowledge systems and practices that allow them to adapt to many climatic changes. Increasing scientific evidence shows that adaptation initiatives based on Indigenous knowledge and practices are more sustainable and legitimate among local communities.

The wide range of adaptation practices based on Indigenous knowledge in the region include, among others: increasing species and genetic diversity in agricultural systems through community seed exchanges; promotion of highly diverse crop systems; ancient systems to collect and conserve water; fire prevention strategies; observing and monitoring changes in communal ecological–agricultural calendar cycles; recognizing changes in ecological indicators like migration patterns in birds, behaviour of insects and other invertebrates and phenology of fruit and flowering species; and systematization and knowledge exchange among communities. These practices represent a valuable cultural and biological heritage.

The Kichwa in the Ecuadorian Amazon cultivate Chakras (plots) within the rainforest. These plots combine crops and medicinal herbs for both self–consumption and selling. Similar systems, like the Chakras in the high Andes, the Milpas in Central America, and the Conucos in northern South America have been resilient to social and environmental disturbances due to their outstanding agrobiodiversity (more than 40 species and varieties can be present in one plot), microhabitat management and the associated knowledge and institutions.

Traditional fire management among Indigenous Peoples of Venezuela, Brazil and Guyana is another adaptation strategy based on a fine–tuned understanding of environmental indicators, associated with their culture and worldviews. In these countries, Indigenous lands have the lowest incidence of wildfires, significantly contributing to maintaining and enhancing biodiversity. These traditional practices have helped to prevent large–scale and destructive wildfires, reducing the risk from rising temperature and dryness due to climate change.

Traditional agriculture of Mapuche Indigenous Peoples in Chile includes a series of practices that result in a system more resilient to climate and non–climate stressors. Practices include water management, native seed conservation and exchange with other producers (trafkintu), crop rotation, polyculture, and tree–crop association. Similar practices can be found in Mayan communities in Guatemala at the other end of the subcontinent.

Despite the increasing recognition and integration of Indigenous knowledge in adaptation practices and policies in the region, important barriers for a more effective and transformative integration remain. Some of the most relevant barriers include limited participation of Indigenous Peoples and local communities in adaptation planning and the lack of sufficient consideration of non–climatic socioeconomic drivers of vulnerability such as poverty and inequality. Also, scientific knowledge is commonly prioritized over traditional, Indigenous knowledge, and local knowledge. However, some transformative efforts are emerging Bolivian Indigenous organizations provide a notable example by contesting normative conceptions of development as economic growth with more comprehensive views like harmony with Mother Earth and "Sumak Kawsay" or "Good Living".

Several strategies have been proposed to overcome existing barriers, including building effective and respectful partnerships among Indigenous and non–indigenous researchers to co–produce climate change–relevant knowledge, and recognizing Indigenous Peoples as active actors who are continually developing autonomous strategies to preserve their practices, beliefs and knowledge. The implementation of these and other strategies can significantly enhance adaptation planning and action in the region.

[END FAQ 12.5 HERE]

References

Abeldaño Zuñiga, R. A. and J. Fanta Garrido, 2020: Internal Displacement Due to Disasters in Latin America and the Caribbean. In: *Climate Change, Hazards and Adaptation Options: Handling the Impacts of a Changing Climate* [Leal Filho, W., G. J. Nagy, M. Borga, P. D. Chávez Muñoz and A. Magnuszewski (eds.)]. Springer International Publishing, Cham, pp. 389-409. ISBN 978-3-030-37425-9.

Aburto, J. A., W. Stotz, G. Cundill and C. Tapia, 2021: Toward understanding the long-term persistence of a local governance system among artisanal fishers in Chile. *Ecology and Society*, **26**(3), doi:10.5751/ES-12479-260305.

Acosta-Jamett, G. et al., 2016: El Niño Southern Oscillation drives conflict between wild carnivores and livestock farmers in a semiarid area in Chile. *Journal of Arid Environments*, **126**, 76-80, doi:10.1016/j.jaridenv.2015.08.021.

Acosta, M., F. Howland, J. Twyman and J.-F. Le Coq, 2019: *Inclusión de género en las políticas de agricultura, cambio climático, seguridad alimentaria y nutrición en Honduras y Guatemala. Hallazgos de un análisis de políticas, leyes y estrategias nacionales.* CCAFS Info Note, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), 5 pp. Available at: https://hdl.handle.net/10568/99696 (accessed 03/08/2021).

Adams, H., 2016: Why populations persist: mobility, place attachment and climate change. *Population and Environment*, **37**(4), 429-448, doi:10.1007/s11111-015-0246-3.

Adger, W. N., N. W. Arnell and E. L. Tompkins, 2005: Successful adaptation to climate change across scales. *Global Environmental Change*, **15**(2), 77-86, doi:10.1016/j.gloenvcha.2004.12.005.

Adler, V. et al., 2018: *Vivienda ¿Qué viene?: de pensar la unidad a construir la ciudad* [Adler, V. and F. Vera (eds.)]. Interamerican Development Bank, 574 pp. Available at: http://dx.doi.org/10.18235/0001594 (accessed 25/08/2021).

Aggarwal, P. et al., 2019: Importance of considering technology growth in impact assessments of climate change on agriculture. *Global Food Security*, **23**, 41-48, doi:10.1016/j.gfs.2019.04.002.

Aguayo, R. et al., 2019: The glass half-empty: climate change drives lower freshwater input in the coastal system of the Chilean Northern Patagonia. *Climatic Change*, **155**(3), 417-435, doi:10.1007/s10584-019-02495-6.

Agudelo, J., P. A. Arias, S. C. Vieira and J. A. Martínez, 2019: Influence of longer dry seasons in the Southern Amazon on patterns of water vapor transport over northern South America and the Caribbean. *Climate Dynamics*, **52**(5), 2647-2665, doi:10.1007/s00382-018-4285-1.

Aguiar, A. P. D. et al., 2016a: Land use change emission scenarios: anticipating a forest transition process in the Brazilian Amazon. *Global Change Biology*, **22**(5), 1821-1840, doi:10.1111/gcb.13134.

Aguiar, L. M. S. et al., 2016b: Should I stay or should I go? Climate change effects on the future of Neotropical savannah bats. *Global Ecology and Conservation*, **5**, 22-33, doi:10.1016/j.gecco.2015.11.011.

Aguilar-Lome, J. et al., 2019: Elevation-dependent warming of land surface temperatures in the Andes assessed using MODIS LST time series (2000–2017). *International Journal of Applied Earth Observation and Geoinformation*, **77**, 119-128, doi:10.1016/j.jag.2018.12.013.

Aguilar, I., J. Pernillo and E. Cameros, 2019: *"Mojados" por la sequía: hambre y migración en el corredor seco de Guatemala*. OXFAM, Guatemala. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/Mojados%20por%20la%20sequ%C3%ADa%20Documento%20OXFAM%2020190423.pdf (accessed 03/06/2021).

Aguirre, C. et al., 2018: Insight into anthropogenic forcing on coastal upwelling off south-central Chile. *Elementa Science of Anthropocene*, **6**(1), 59-72, doi:10.1525/elementa.314.

Aguirre, N. et al., 2017: Potential impacts to dry forest species distribution under two climate change scenarios in southern Ecuador. *Neotropical Biodiversity*, **3**(1), 18-29, doi:10.1080/23766808.2016.1258867.

Agyeman, J., D. Schlosberg, L. Craven and C. Matthews, 2016: Trends and Directions in Environmental Justice: From Inequity to Everyday Life, Community, and Just Sustainabilities. *Annual Review of Environment and Resources*, **41**(1), 321-340, doi:10.1146/annurev-environ-110615-090052.

Ahmed, S., M. Meenar and A. Alam, 2019: Designing a Blue-Green Infrastructure (BGI) Network: Toward Water-Sensitive Urban Growth Planning in Dhaka, Bangladesh. *Land*, **8**(9), doi:10.3390/land8090138.

Aitken, D., D. Rivera, A. Godoy-Faúndez and E. Holzapfel, 2016: Water Scarcity and the Impact of the Mining and Agricultural Sectors in Chile. *Sustainability*, **8**(2), 128, doi:10.3390/su8020128.

Akbari, H. and D. Kolokotsa, 2016: Three decades of urban heat islands and mitigation technologies research. *Energy and Buildings*, **133**, 834-842, doi:10.1016/j.enbuild.2016.09.067.

Albrecht, F. and G. Shaffer, 2016: Regional Sea-Level Change along the Chilean Coast in the 21st Century. *Journal of Coastal Research*, **32**(6), 1322-1332, doi:10.2112/JCOASTRES-D-15-00192.1.

Alcaldía de Medellín, 2012: *Cinturón verde metropolitano*, Alcaldía de Medellín, Medellín, Colombia, 84 pp. Available at: https://www.medellin.gov.co/irj/go/km/docs/wpccontent/Sites/Subportal%20del%20Ciudadano/Medio%20Ambiente/Secciones/Publicaciones/Documentos/2012/ForoCiudadesSostenibles/1.%20Presentaci%C3%B3n%20CVM_Cinturones%20Verdes%20para%20ciudades%20sostenibles.pdf (accessed 17/06/2021).

Alcaldía de Medellín, 2021: *Plan de Acción Climática Medellín 2020-2050*, Medellín, Colombia. Available at: https://www.medellin.gov.co/irj/portal/medellin?NavigationTarget=contenido/8891-Plan-de-Accion-Climatica (accessed 01/09/2021).
Alcaldía de Quito, 2017: *Quito resiliente. Estrategia de Resiliencia. Distrito Metropolitano de Quito*. Primera ed., Quito, A. d., Alcadía de Quito, Quito, Ecuador, 146 pp. Available at: http://gobiernoabierto.quito.gob.ec/wp-content/uploads/documentos/resiliente/resilencia.pdf (accessed 03/06/2021).
Alcaldía Mayor de Bogotá D.C., 2017: *Plan Maestro de Movilidad para Bogotá D.C.*, Bogotá, Colombia. Available at: https://www.movilidadbogota.gov.co/web/plan-maestro-movilidad (accessed 01/09/2021).
Alcaldía Mayor de Bogotá D.C., 2018: *Plan Distrital de Gestión de Riesgos de Desastres y del Cambio Climático para Bogotá D.C., 2018-2030*, Instituto Distrital de Gestión de Riesgos y Cambio Climático, Alcadía Mayor de Bogotá D.C., , Bogotá, Colombia, 25 pp. Available at: http://www.ambientebogota.gov.co/c/document_library/get_file?uuid=e5ae62a8-5687-46b0-8460-ab65723e1a74&groupId=10157 (accessed 17/10/2020).
Aldunce Ide, P. et al., 2020: Sociedad, gobernanza, inequidad y adaptación. In: *Adaptación frente a los riesgos del cambio climático en los países iberoamericanos. Informe RIOCCADAPT* [Moreno, J. M., C. Laguna-Defior, V. Barros, E. Calvo Buendía, J. A. Marengo and Ú. Oswald Spring (eds.)]. McGraw-Hill, Madrid, España, pp. 49-89. ISBN 9788448621643.
Aldunce, P. et al., 2017: Local perception of drought impacts in a changing climate: The mega-drought in central Chile. *Sustainability* **9**(11), 2053, doi:10.3390/su9112053.
Alfieri, L. et al., 2017: Global projections of river flood risk in a warmer world. *Earth's Future*, **5**(2), 171-182, doi:10.1002/2016EF000485.
Alho, C. F. B. V. et al., 2019: Spatial variation of carbon and nutrients stocks in Amazonian Dark Earth. *Geoderma*, **337**, 322-332, doi:10.1016/j.geoderma.2018.09.040.
Allen, A. et al., 2017a: De la mitigación de desastres a la interrupción de trampas de riesgo: la experiencia de aprendizaje-acción de clima sin riesgo. *Reder*, **1**(1), 6-28.
Allen, T. et al., 2017b: Global hotspots and correlates of emerging zoonotic diseases. *Nature Communications*, **8**(1), 1124, doi:10.1038/s41467-017-00923-8.
Almansi, F., J. M. Motta and J. Hardoy, 2020: Incorporating a resilience lens into the social and urban transformation of informal settlements: the participatory upgrading process in Villa 20, Buenos Aires (2016–2020). *Environment and Urbanization*, **32**(2), 407-428, doi:10.1177/0956247820935717.
Almanza, V. et al., 2019: Association between trophic state, watershed use, and blooms of cyanobacteria in south-central Chile. *Limnologica*, **75**, 30-41, doi:10.1016/j.limno.2018.11.004.
Almeida, C. T. et al., 2017: Spatiotemporal rainfall and temperature trends throughout the Brazilian Legal Amazon, 1973–2013. *International Journal of Climatology*, **37**(4), 2013-2026, doi:10.1002/joc.4831.
Almeida, O. et al., 2018: Resiliencia urbana y amenazas climáticas: Vulnerabilidad y planificación de adaptación para ciudades pequeñas en el delta y estuario del rio Amazonas. *Medio Ambiente y Urbanización*, **88**(1), 95-122.
Alpízar, F. et al., 2020: Determinants of food insecurity among smallholder farmer households in Central America: recurrent versus extreme weather-driven events. *Regional Environmental Change*, **20**(1), 22, doi:10.1007/s10113-020-01592-y.
Altamirano, A. et al., 2013: Influencia de la heterogeneidad del paisaje en la ocurrencia de incendios forestales en Chile Central. *Revista de Geografía Norte Grande*, **55**, 157-170, doi:10.4067/S0718-34022013000200011
Altea, L., 2020: Perceptions of climate change and its impacts: a comparison between farmers and institutions in the Amazonas Region of Peru. *Climate and Development*, **12**(2), 134-146, doi:10.1080/17565529.2019.1605285.
Altieri, M. A. and C. I. Nicholls, 2013: The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change*, doi:10.1007/s10584-013-0909-y.
Alvarado, J. J. et al., 2017: Coral Reef Conservation in the Eastern Tropical Pacific. In: *Coral Reefs of the Eastern Tropical Pacific: Persistence and Loss in a Dynamic Environment* [Glynn, P. W., D. P. Manzello and I. C. Enochs (eds.)]. Springer Netherlands, Dordrecht, pp. 565-591. ISBN 978-94-017-7499-4.
Álvarez-Dávila, E. et al., 2017: Forest biomass density across large climate gradients in northern South America is related to water availability but not with temperature. *PloS one*, **12**(3), e0171072, doi:10.1371/journal.pone.0171072.
Álvarez-León, R. and J. R. Álvarez Puerto, 2017: Legislación colombiana relacionada con los ecosistemas de manglar. *Arquivos de Ciências do Mar*, **49**(2), 115, doi:10.32360/acmar.v49i2.6587.
Alvarez-Mendoza, C. I., A. Teodoro and L. Ramirez-Cando, 2019: Spatial estimation of surface ozone concentrations in Quito Ecuador with remote sensing data, air pollution measurements and meteorological variables. *Environmental Monitoring and Assessment*, **191**(3), 155, doi:10.1007/s10661-019-7286-6.
Amar-Amar, J. J., C. I. D. l. H.-D. Real, M. B. Martínez-González and L. López-Muñoz, 2019: Adaptation strategies and care practices among climate-displaced communities: Colombian case. *Psicologia em Estudo*, **24**.
Amaral, A. C. Z. et al., 2016: Brazilian sandy beaches: characteristics, ecosystem services, impacts, knowledge and priorities. *Brazilian Journal of Oceanography*, **64**(2), 5-16, doi:10.1590/S1679-875920160933064sp2
Amoah-Antwi, C. et al., 2020: Restoration of soil quality using biochar and brown coal waste: A review. *Science of the Total Environment*, **722**, 137852-137852, doi:10.1016/j.scitotenv.2020.137852.

Anabalón, V. et al., 2016: Micro-phytoplankton community structure in the coastal upwelling zone off Concepción (central Chile): Annual and inter-annual fluctuations in a highly dynamic environment. *Progress in Oceanography*, **149**, 174-188, doi:10.1016/j.pocean.2016.10.011.
Anacona, P. I. et al., 2018: Glacier protection laws: Potential conflicts in managing glacial hazards and adapting to climate change. *Ambio*, **47**(8), 835–845, doi:10.1007/s13280-018-1043-x.
Anadón, J. D., O. E. Sala and F. T. Maestre, 2014: Climate change will increase savannas at the expense of forests and treeless vegetation in tropical and subtropical Americas. *Journal of Ecology*, **102**(6), 1363-1373, doi:10.1111/1365-2745.12325.
Anaya, J. A. et al., 2020: Drivers of Forest Loss in a Megadiverse Hotspot on the Pacific Coast of Colombia. *Remote Sensing*, **12**(8), 1235, doi:10.3390/rs12081235
Andersen, L. E., D. Verner and M. Wiebelt, 2017: Gender and Climate Change in Latin America: An Analysis of Vulnerability, Adaptation and Resilience Based on Household Surveys. *Journal of International Development*, **29**(7), 857-876, doi:10.1002/jid.3259.
Anderson, E. et al., 2011: Consequences of Climate Change for Ecosystems and Ecosystem Services in the Tropical Andes. *Climate Change and Biodiversity in the Tropical Andes*.
Anderson, E. P. et al., 2018a: Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Science Advances*, **4**(1), eaao1642, doi:10.1126/sciadv.aao1642.
Anderson, E. P., Maldonado-Ocampo and J. A, 2010: A Regional Perspective on the Diversity and Conservation of Tropical Andean Fishes. *Conservation Biology*, **25**(1), 30-39, doi:10.1111/j.1523-1739.2010.01568.x.
Anderson, L. O. et al., 2018b: Vulnerability of Amazonian forests to repeated droughts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **373**(1760), 20170411, doi:10.1098/rstb.2017.0411.
Anderson, T. G., K. J. Anchukaitis, D. Pons and M. Taylor, 2019: Multiscale trends and precipitation extremes in the Central American Midsummer Drought. *Environmental Research Letters*, **14**(12), 124016, doi:10.1088/1748-9326/ab5023.
Andersson, N. et al., 2015: Evidence based community mobilization for dengue prevention in Nicaragua and Mexico (Camino Verde, the Green Way): Cluster randomized controlled trial. *BMJ (Online)*, **351**, doi:10.1136/bmj.h3267.
Andrade, M. M. N. d. et al., 2017: Flood Risk Mapping in the Amazon. In: *Flood Risk Management* [Hromadka, T. and P. Rao (eds.)]. IntechOpen, pp. 41-54.
Andrade, M. M. N. d. and C. F. Szlafsztein, 2018: Vulnerability assessment including tangible and intangible components in the index composition: An Amazon case study of flooding and flash flooding. *Science of the Total Environment*, **630**, 903-912, doi:10.1016/j.scitotenv.2018.02.271.
Anguelovski, I., E. Chu and J. Carmin, 2014: Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South. *Global Environmental Change*, **27**, 156-167, doi:10.1016/j.gloenvcha.2014.05.010.
Anguelovski, I., J. Connolly and A. L. Brand, 2018: From landscapes of utopia to the margins of the green urban life. *City*, **22**(3), 417-436, doi:10.1080/13604813.2018.1473126.
Anguelovski, I., C. Irazábal-Zurita and J. J. T. Connolly, 2019: Grabbed Urban Landscapes: Socio-spatial Tensions in Green Infrastructure Planning in Medellín. *International Journal of Urban and Regional Research*, **43**(1), 133-156, doi:10.1111/1468-2427.12725.
Anjos, L. J. S. et al., 2021: Future projections for terrestrial biomes indicate widespread warming and moisture reduction in forests up to 2100 in South America. *Global Ecology and Conservation*, **25**, e01441, doi:10.1016/j.gecco.2020.e01441.
Anjos, L. J. S. and P. M. De Toledo, 2018: Measuring resilience and assessing vulnerability of terrestrial ecosystems to climate change in South America. *PLoS ONE*, **13**(3), 1-15, doi:10.1371/journal.pone.0194654.
Antimiani, A. et al., 2017: The Green Climate Fund as an effective compensatory mechanism in global climate negotiations. *Environmental Science & Policy*, **77**, 49-68, doi:10.1016/j.envsci.2017.07.015.
Antwi-Agyei, P., A. J. Dougill, L. C. Stringer and S. N. A. Codjoe, 2018: Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Clim. Risk Manag.*, **19**, 83-93, doi:10.1016/j.crm.2017.11.003.
Aparicio-Effen, M. et al., 2018: A Successful Early Warning System for Hydroclimatic Extreme Events: The Case of La Paz City Mega Landslide. In: *Climate Change Adaptation in Latin America: Managing Vulnerability, Fostering Resilience* [Leal Filho, W. and L. Esteves de Freitas (eds.)]. Springer International Publishing, Cham, pp. 241-264. ISBN 978-3-319-56946-8.
Aragão, L. E. O. C. et al., 2018: 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, **9**(1), 536, doi:10.1038/s41467-017-02771-y.
Aragão, L. E. O. C. et al., 2016: Assessing the Influence of Climate Extremes on Ecosystems and Human Health in Southwestern Amazon Supported by the PULSE-Brazil Platform. *American Journal of Climate Change*, **5**(3), 399-416, doi:10.4236/ajcc.2016.53030
Aragón, F. M., F. Oteiza and J. P. Rud, 2021: Climate Change and Agriculture: Subsistence Farmers' Response to Extreme Heat. *American Economic Journal: Economic Policy*, **13**(1), 1-35, doi:10.1257/pol.20190316.
Arana Zegarra, M. T., 2017: *Género y Cambio Climático en América Latina* [(CDKN), A. C. y. D. (ed.)]. 22 pp. Available at: https://cdkn.org/wp-content/uploads/2017/07/Arana_G%C3%A9nero-y-cambio-clim%C3%A1tico-en-Am%C3%A9rica-Latina-ULTIMOS-CAMBIOS_05-de-JULIO-1.pdf (accessed 03/08/2021).

Araos, M. et al., 2016: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science & Policy*, **66**, 375-382, doi:10.1016/j.envsci.2016.06.009.
Araujo, R. V. et al., 2015: São Paulo urban heat islands have a higher incidence of dengue than other urban areas. *Brazilian Journal of Infectious Diseases*, **19**, 146-155, doi:10.1016/j.bjid.2014.10.004
Araya-Muñoz, D. et al., 2016: Assessing urban adaptive capacity to climate change. *Journal of Environmental Management*, **183**, 314-324, doi:10.1016/j.jenvman.2016.08.060.
Archer, D. et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Climate and Development*, **6**(4), 345-356, doi:10.1080/17565529.2014.918868.
Arias-Monsalve, C. and A. Builes-Jaramillo, 2019: Impact of El Niño-Southern oscillation on human leptospirosis in Colombia at different spatial scales. *The Journal of Infection in Developing Countries*, **13**(12), doi:10.3855/jidc.11702.
Arias, P. A. et al., 2016: Reducing Social Vulnerability to Environmental Change: Building Trust through Social Collaboration on Environmental Monitoring. *Weather, Climate, and Society*, **8**(1), 57-66, doi:10.1175/WCAS-D-15-0049.1.
Ariza-Montobbio, P. and N. Cuvi, 2020: Ecosystem-based Adaptation in Ecuador: Good Practices for Adaptive Co-Management. *Ambiente & Sociedade*, **23**, doi:10.1590/1809-4422asoc20180315r2vu2020L3AO.
Armenteras, D. et al., 2020: Incendios en ecosistemas del norte de Suramérica: avances en la ecología del fuego tropical en Colombia, Ecuador y Perú. *Caldasia*, **42**(1), doi:10.15446/caldasia.v42n1.77353.
Armenteras, D., L. Schneider and L. M. Dávalos, 2019: Fires in protected areas reveal unforeseen costs of Colombian peace. *Nature Ecology & Evolution*, **3**(1), 20-23, doi:10.1038/s41559-018-0727-8.
Armijo, J. et al., 2020: The 2016 red tide crisis in southern Chile: Possible influence of the mass oceanic dumping of dead salmons. *Marine Pollution Bulletin*, **150**, 110603, doi:10.1016/j.marpolbul.2019.110603.
Armijos, E. et al., 2020: Rainfall control on Amazon sediment flux: synthesis from 20 years of monitoring. *Environmental Research Communications*, **2**(5), 051008, doi:10.1088/2515-7620/ab9003.
Arnan, X. et al., 2018: Increased anthropogenic disturbance and aridity reduce phylogenetic and functional diversity of ant communities in Caatinga dry forest. *Science of The Total Environment*, **631-632**, 429-438, doi:10.1016/j.scitotenv.2018.03.037.
Arnell, N. W. et al., 2016: The impacts of climate change across the globe: A multi-sectoral assessment. *Climatic Change*, **134**(3), 457-474, doi:10.1007/s10584-014-1281-2.
Arnell, N. W. and S. N. Gosling, 2013: The impacts of climate change on river flow regimes at the global scale. *Journal of Hydrology*, **486**, 351-364, doi:10.1016/j.jhydrol.2013.02.010.
Arnell, N. W. and S. N. Gosling, 2016: The impacts of climate change on river flood risk at the global scale. *Climatic Change*, **134**(3), 387-401, doi:10.1007/s10584-014-1084-5.
Arneth, A. et al., 2019: Framing and Context. In: *Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* In Press.
Arroyo Mina, J. S., D. A. Revollo Fernández, A. Aguilar Ibarra and N. Georgantzis, 2016: Economic behavior of fishers under climate-related uncertainty: Results from field experiments in Mexico and Colombia. *Fisheries Research*, **183**, 304-317, doi:10.1016/j.fishres.2016.05.020.
Ashok, K. et al., 2007: El Niño Modoki and its possible teleconnection. *Journal of Geophysical Research: Oceans*, **112**(C11), doi:10.1029/2006JC003798.
Avila-Diaz, A. et al., 2020: Assessing current and future trends of climate extremes across Brazil based on reanalyses and earth system model projections. *Climate Dynamics*, **55**(5-6), 1403-1426, doi:10.1007/s00382-020-05333-z.
Ávila-Valdés, A. et al., 2020: Tuber yield and quality responses of potato to moderate temperature increase during Tuber bulking under two water availability scenarios. *Field Crops Research*, **251**, 107786, doi:10.1016/j.fcr.2020.107786.
Ayala, S. et al., 2019: Estimando el efecto del cambio climático sobre el riesgo de la enfermedad de Chagas en Chile por medio del número reproductivo. *Revista médica de Chile*, **147**(6), 683-692, doi:10.4067/S0034-98872019000600683
Ayes Rivera, I. et al., 2019: Decline of Fine Suspended Sediments in the Madeira River Basin (2003–2017). *Water*, **11**(3), 514, doi:10.3390/w11030514.
Aylett, A., 2015: Institutionalizing the urban governance of climate change adaptation: Results of an international survey. *Urban Climate*, **14**, 4-16, doi:10.1016/j.uclim.2015.06.005.
Azócar, G. et al., 2021: Climate change perception, vulnerability, and readiness: inter-country variability and emerging patterns in Latin America. *Journal of Environmental Studies and Sciences*, **11**(1), 23-36, doi:10.1007/s13412-020-00639-0.
Bacon, C. M. et al., 2014: Explaining the 'hungry farmer paradox': Smallholders and fair trade cooperatives navigate seasonality and change in Nicaragua's corn and coffee markets. *Global Environmental Change*, **25**, 133-149, doi:10.1016/j.gloenvcha.2014.02.005.
Bacon, C. M., W. A. Sundstrom, I. T. Stewart and D. Beezer, 2017: Vulnerability to Cumulative Hazards: Coping with the Coffee Leaf Rust Outbreak, Drought, and Food Insecurity in Nicaragua. *World Development*, **93**, 136-152, doi:10.1016/j.worlddev.2016.12.025.

Baez, J., G. Caruso, V. Mueller and C. Niu, 2017: Droughts augment youth migration in Northern Latin America and the Caribbean. *Climatic Change*, **140**(3-4), 423-435, doi:10.1007/s10584-016-1863-2.
Báez, S., M. Mazzarino, M. Peralvo and R. Sears, R., 2020: Evaluating the Impacts of a Small-Grants Program on Sustainable Development and Biodiversity Conservation in Andean Forest Landscapes. *Mountain Research and Development*, **40**(2), D1-D7, doi:10.1659/MRD-JOURNAL-D-19-00066.1.
Bai, X. et al., 2016: Defining and advancing a systems approach for sustainable cities. *Current Opinion in Environmental Sustainability*, **23**, 69-78, doi:10.1016/j.cosust.2016.11.010.
Bañales-Seguel, C., F. De la Barrera and A. Salazar, 2018: An analysis of wildfire risk and historical occurrence for a mediterranean biosphere reserve, Central Chile. *Journal of Environmental Engineering and Landscape Management*, **26**(2), 128-140, doi:10.3846/16486897.2017.1374280.
Baptiste, B. et al., 2017: Greening peace in Colombia. *Nature Ecology & Evolution*, **1**(4), 0102, doi:10.1038/s41559-017-0102.
Baraer, M. et al., 2012: Glacier recession and water resources in Peru's Cordillera Blanca. *Journal of Glaciology*, **58**(207), 134-150, doi:10.3189/2012JoG11J186.
Barber, C. P., M. A. Cochrane, C. M. Souza and W. F. Laurance, 2014: Roads, deforestation, and the mitigating effect of protected areas in the Amazon. *Biological Conservation*, **177**, 203-209, doi:10.1016/j.biocon.2014.07.004.
Barbi, F. and L. da Costa Ferreira, 2017: Governing Climate Change Risks: Subnational Climate Policies in Brazil. *Chinese Political Science Review*, **2**(2), 237-252, doi:10.1007/s41111-017-0061-3.
Barbier, E. B. and J. P. Hochard, 2018a: The Impacts of Climate Change on the Poor in Disadvantaged Regions. *Review of Environmental Economics and Policy*, **12**(1), 26-47, doi:10.1093/reep/rex023.
Barbier, E. B. and J. P. Hochard, 2018b: Poverty, rural population distribution and climate change. *Environment and Development Economics*, **23**(3), 234-256, doi:10.1017/S1355770X17000353.
Barbier, E. B. and J. P. Hochard, 2019: Poverty-Environment Traps. *Environmental and Resource Economics*, **74**(3), 1239-1271, doi:10.1007/s10640-019-00366-3.
Barbosa, J. Z. et al., 2020: Elemental signatures of an Amazonian Dark Earth as result of its formation process. *Geoderma*, **361**, 114085, doi:10.1016/j.geoderma.2019.114085.
Barcellos, C., D. Xavier and V. Pascoal de Matos, 2016: The Brazilian Observatory of Climate and Health: Experience of organizing and disseminating climate and health information in Manaus, Amazon region. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 114-117.
Bárcena, A., J. Samaniego, W. Peres and J. Alatorre, 2020a: *La emergencia del cambio climático en América Latina y el Caribe. ¿Seguimos esperando la catástrofe o pasamos a la acción?* [Cepal (ed.)]. CEPAL, Santiago de Chile, 383 pp. Available at: https://www.cepal.org/es/publicaciones/45677-la-emergencia-cambio-climatico-america-latina-caribe-seguimos-esperando-la (accessed 16/06/2021).
Bárcena, A., J. Samaniego, W. Peres and J. E. Alatorre, 2020b: *The climate emergency in Latin America and the Caribbean: the path ahead – resignation or action?* ECLAC Books Sustainable Development, **160**, United Nations, Caribbean, E. C. f. L. A. a. t., Santiago, Chile, 357 pp. Available at: https://repositorio.cepal.org/bitstream/handle/11362/45678/10/S1900710_en.pdf (accessed 17/10/2020).
Bardales, W., C. Castañón and L. Herrera, 2019: Clima de Guatemala. Tendencias observadas e índices de cambio climático. In: *Primer Reporte de Evaluación del Conocimiento sobre Cambio Climático en Guatemala* [Castellanos, E., A. Paiz-Estévez, J. Escribá, M. Rosales-Alconero and A. Santizo (eds.)]. Editorial Universitaria UVG, Guatemala, pp. 396.
Barkhordarian, A. et al., 2019: A Recent Systematic Increase in Vapor Pressure Deficit over Tropical South America. *Scientific Reports*, **9**(1), 15331, doi:10.1038/s41598-019-51857-8.
Barnes, J. et al., 2013: Contribution of anthropology to the study of climate change. *Nature Clim. Change*, **3**(6), 541-544, doi:10.1038/nclimate1775.
Barnett, J. et al., 2015: From barriers to limits to climate change adaptation: path dependency and the speed of change. *Ecology and Society*, **20**(3), 5, doi:10.5751/ES-07698-200305.
Barona, C. O. et al., 2020: Trends in Urban Forestry Research in Latin America & The Caribbean: A Systematic Literature Review and Synthesis. *Urban Forestry & Urban Greening*, **47**, 126544, doi:10.1016/j.ufug.2019.126544.
Barragán, J. M. and M. de Andrés, 2016: Expansión urbana en las áreas litorales de América Latina y Caribe. *Revista de geografía Norte Grande*,(64), 129, doi:10.4067/S0718-34022016000200009.
Barragán, J. M. and Ó. Lazo, 2018: Policy progress on ICZM in Peru. *Ocean & Coastal Management*, **157**, 203-216, doi:10.1016/j.ocecoaman.2018.03.003.
Barria, I., J. Carrasco, G. Casassa and P. Barria, 2019: Simulation of Long-Term Changes of the Equilibrium Line Altitude in the Central Chilean Andes Mountains Derived From Atmospheric Variables During the 1958–2018 Period. *Front. Environ. Sci.*, **7**(October), doi:10.3389/fenvs.2019.00161.
Barría, P. et al., 2019: Anthropocene and streamflow: Long-term perspective of streamflow variability and water rights. *Elementa* **7**(1), doi:10.1525/elementa.340.
Barros, H. R. and M. A. Lombardo, 2016: A ilha de calor urbana e o uso e cobertura do solo no município de São Paulo-SP. *GEOUSP Espaço e Tempo (Online)*, **20**(1), 160-177, doi:10.11606/issn.2179-0892.geousp.2016.97783.

Barros, V., 2006: *Adaptation to climate trends: Lessons from the Argentine experience* [(AIACC), A. o. I. a. A. t. C. C. (ed.)]. AIACC Working Paper, 42 pp. Available at: https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/latin-america-and-caribbean/uruguay-argentina/Barros.--2006.--Argentina-CC-Adaptation-Lessons..pdf (accessed 31/10/2020).
Barros, V. R. et al., 2015: Climate change in Argentina: Trends, projections, impacts and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(2), 151-169, doi:10.1002/wcc.316.
Barrucand, M. G., C. Giraldo Vieira and P. O. Canziani, 2017: Climate change and its impacts: perception and adaptation in rural areas of Manizales, Colombia. *Climate and Development*, **9**(5), 415-427, doi:10.1080/17565529.2016.1167661.
Bartlett, S. and D. Satterthwaite, 2016: *Cities on a Finite Planet: Towards transformative responses to climate change*. Routledge, 306 pp. ISBN 9781138184107.
Basantes-Serrano, R. et al., 2016: Slight mass loss revealed by reanalyzing glacier mass-balance observations on Glaciar Antisana 15α (inner tropics) during the 1995–2012 period. *Journal of Glaciology*, **62**(231), 124-136, doi:10.1017/jog.2016.17.
Basso, C. et al., 2017: Scaling Up of an Innovative Intervention to Reduce Risk of Dengue, Chikungunya, and Zika Transmission in Uruguay in the Framework of an Intersectoral Approach with and without Community Participation. *The American Journal of Tropical Medicine and Hygiene*, **97**(5), 1428-1436, doi:10.4269/ajtmh.17-0061.
Batzín, R., 2019: Conocimiento indígena y cambio climático. In: *Primer reporte de evaluación del conocimiento sobre cambio climático en Guatemala* [Castellanos, E., A. Paiz-Estévez, J. Escribá, M. Rosales-Alconero and A. Santizo (eds.)]. Editorial Universitaria UVG, Guatemala, pp. 329.
Bauch, S. C., A. M. Birkenbach, S. K. Pattanayak and E. O. Sills, 2015: Public health impacts of ecosystem change in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*, **112**(24), 7414-7419, doi:10.1073/pnas.1406495111.
Baucom, I. and M. Omelsky, 2017: Knowledge in the Age of Climate Change. *South Atlantic Quarterly*, **116**(1), 1-18, doi:10.1215/00382876-3749271.
Baumann, M. et al., 2017: Deforestation and cattle expansion in the Paraguayan Chaco 1987–2012. *Regional Environmental Change*, **17**(4), 1179-1191, doi:10.1007/s10113-017-1109-5.
Bayer, A. M. et al., 2014: An unforgettable event: a qualitative study of the 1997–98 El Niño in northern Peru. *Disasters*, **38**(2), 351-374, doi:10.1111/disa.12046.
Bayraktarov, E. et al., 2020: Coral reef restoration efforts in Latin American countries and territories. *PLOS ONE*, **15**(8), e0228477, doi:10.1371/journal.pone.0228477.
BCIE, 2020: *Centroamérica en Cifras*. Banco Centroamericano de Integración Económica, Tegucigalpa, Honduras, 89 pp. Available at: https://www.bcie.org/novedades/publicaciones/publicacion/centroamerica-en-cifras (accessed 03/08/2021).
Bebber, D. P. and N. Butt, 2017: Tropical protected areas reduced deforestation carbon emissions by one third from 2000–2012. *Scientific Reports*, **7**(1), 14005, doi:10.1038/s41598-017-14467-w.
Bebbington, A. J., D. H. Bebbington and L. A. Sauls, 2019: *Assessment and Scoping of Extractive Industry and Infrastructure in Relation to Deforestation: Global and Synthesis Report*. Climate and Land Use Alliance, 68 pp. Available at: http://www.climateandlandusealliance.org/wp-content/uploads/2018/12/Global-Synthesis-Impacts-of-EII-on-Forests-1.pdf (accessed 25/06/2021).
Bebbington, A. J., J. Bury, N. Cuba and J. Rogan, 2015: Mining, risk and climate resilience in the 'other' Pacific: Latin American lessons for the South Pacific. *Asia Pacific Viewpoint*, **56**(2), 189-207, doi:10.1111/apv.12098.
Bech Gaivizzo, L. H. et al., 2019: Resilience to climate change in Fundo de Pasto Communities in the semiarid region of Bahia State. *Sociedade & Natureza*, **31**, 1-22, doi:10.14393/SN-v31-2019-46331.
Bedran-Martins, A. M., M. C. Lemos and A. Philippi, 2018: Relationship between subjective well-being and material quality of life in face of climate vulnerability in NE Brazil. *Climatic Change*, **147**(1), 283-297, doi:10.1007/s10584-017-2105-y.
Benitez, E. M. et al., 2021: Understanding the role of temporal variation of environmental variables in predicting Aedes aegypti oviposition activity in a temperate region of Argentina. *Acta Tropica*, **216**, 105744, doi:10.1016/j.actatropica.2020.105744.
Bentley, R. A. et al., 2014: Social tipping points and Earth systems dynamics. *Front. Environ. Sci.*, **2**, doi:10.3389/fenvs.2014.00035.
Berasaluce, M. et al., 2019: Soil and indoor dust as environmental media of human exposure to As, Cd, Cu, and Pb near a copper smelter in central Chile. *Journal of Trace Elements in Medicine and Biology*, **54**, 156-162, doi:10.1016/j.jtemb.2019.04.006.
Bergier, I. et al., 2018: Amazon rainforest modulation of water security in the Pantanal wetland. *Science of The Total Environment*, **619-620**, 1116-1125, doi:10.1016/j.scitotenv.2017.11.163.
Bergmann, J. et al., 2021: *Assessing the Evidence: Climate Change and Migration in Peru*. Potsdam Institute for Climate Impact Research (PIK) and International Organization for Migration (IOM), Geneva, Switzerland, 238 pp. Available at: https://publications.iom.int/system/files/pdf/assessing-the-evidence-peru.pdf.

Bernardino, A. F. et al., 2016: Benthic estuarine communities in Brazil: moving forward to long term studies to assess climate change impacts. *Brazilian Journal of Oceanography*, **64**(2), 81-96, doi:10.1590/S1679-875920160849064sp2.
Berrang-Ford, L. et al., 2021: A global systematic stocktake of evidence on human adaptation to climate change. *Nature Climate Change*.
Bertonatti, C., 2021: *Una reserva natural para cada ciudad*. Fundación de História Natural Felix de Azara, Buenos Aires, Argentina. Available at: https://www.fundacionazara.org.ar/img/libros/Una-reserva-natural-para-cada-ciudad-2021.pdf (accessed 01/09/2021).
Bertrand, A. et al., 2020: *El Niño Southern Oscillation (ENSO) effects on fisheries and aquaculture*. FAO Fisheries and Aquaculture Technical Paper, FAO, FAO, Rome, Italy, 264 pp. Available at: https://doi.org/10.4060/ca8348en (accessed 22/10/2020).
Bertrand, A., R. Vögler and O. Defeo, 2018: Chapter 15: Climate change impacts, vulnerabilities and adaptations: Southwest Atlantic and Southeast Pacific marine fisheries. In: *Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Barhi, M. C. M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations, Rome, pp. 325-346.
Beyá-Marshall, V. et al., 2018: The effect of water status on productive and flowering variables in young 'Arbequina' olive trees under limited irrigation water availability in a semiarid region of Chile. *Horticulture, Environment, and Biotechnology*, **59**(6), 815-826, doi:10.1007/s13580-018-0088-x.
Bezerra, J. et al., 2016: The promises of the Amazonian soil: shifts in discourses of Terra Preta and biochar.
Bhatia, K. T. et al., 2019: Recent increases in tropical cyclone intensification rates. *Nature Communications*, **10**(1), 1-9, doi:10.1038/s41467-019-08471-z.
Bidegain, M., 2014: *Servicios climaticos en Uruguay y la región*. Instituto Uruguayo de Meteorología. Available at: https://www.inumet.gub.uy/reportes/escuela/ciclosmb.pdf (accessed 01/10/2019).
Bilbao, B., J. Mistry, A. Millán and A. Berardi, 2019: Sharing multiple perspectives on burning: Towards a participatory and intercultural fire management policy in Venezuela, Brazil, and Guyana. *Fire*, **2**(3), 39, doi:10.3390/fire2030039.
Bilbao, B. et al., 2020: Wildfires. In: *Adaptation to Climate Change Risks in Ibero-American Countries - RIOCCADAPT Report* [Moreno, J. M., C. Laguna-Defior, V. Barros, E. Calvo Buendía, J. A. Marengo and U. Oswald Spring (eds.)]. McGraw Hill, Madrid, Spain, pp. 435-496. ISBN 9788448621667.
Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *An IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. [Pörtner, H.-O., D. Roberts, M. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. In press.
Bitencourt, D. P., M. V. Fuentes, P. A. Maia and F. T. Amorim, 2016: Frequência, Duração, Abrangência Espacial e Intensidadedas Ondas de Calor no Brasil. *Revista Brasileira de Meteorologia*, **31**(4), 506-517, doi:10.1590/0102-778631231420150077.
Bizikova, L. et al., 2016: Climate resilience and food security in Central America: a practical framework. *Climate and Development*, **8**(5), 397-412, doi:10.1080/17565529.2015.1064806.
Black, R., S. R. G. Bennett, S. M. Thomas and J. R. Beddington, 2011: Migration as adaptation. *Nature*, **478**(7370), 447-449, doi:10.1038/478477a.
Blanco-Libreros, J. F. and R. Álvarez-León, 2019: Regreso a los manglares de Colombia en una era de datos abiertos, cambios globales y transiciones sociopolíticas: homenaje a Heliodoro Sánchez-Páez. *Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales*, **43**(166), 84-97, doi:10.18257/raccefyn.780.
Blanco-Libreros, J. F. and E. A. Estrada-Urrea, 2015: Mangroves on the Edge: Anthrome-Dependent Fragmentation Influences Ecological Condition (Turbo, Colombia, Southern Caribbean). *Diversity*, **7**(3), 206-228, doi:10.3390/d7030206.
Blanco Blanco, A., V. Fretes Cibils and A. Muñoz Miranda, 2014: *Rental Housing Wanted: Policy Options for Latin America and the Caribbean*. Inter-American Development Bank, Washington D.C., United States, 55 pp. Available at: https://publications.iadb.org/en/publication/17426/rental-housing-wanted-policy-options-latin-america-and-caribbean (accessed 17/10/2020).
Blunden, J. and D. S. Arndt, 2014: *State of the Climate in 2013*. Bulletin of the American Meteorological Society, **95**, American Meteorological Society, S1-S257 pp. Available at: http://www.jstor.org/stable/26219389 (accessed 16/06/2021).
Bocchiola, D., A. Soncini, A. Senese and G. Diolaiuti, 2018: Modelling Hydrological Components of the Rio Maipo of Chile, and Their Prospective Evolution under Climate Change. *Climate*, **6**(3), doi:10.3390/cli6030057.
Boelens, R., E. Shah and B. Bruins, 2019: Contested knowledges: Large dams and mega-hydraulic development. *Water*, **11**(3), 416, doi:10.3390/w11030416.
Boers, N., N. Marwan, H. M. J. Barbosa and J. Kurths, 2017: A deforestation-induced tipping point for the South American monsoon system. *Scientific Reports*, **7**(1), 41489, doi:10.1038/srep41489.
Boillat, S. and F. Berkes, 2013: Perception and Interpretation of Climate Change among Quechua Farmers of Bolivia: Indigenous Knowledge as a Resource for Adaptive Capacity. *Ecology and Society*, **18**(4), 21, doi:10.5751/ES-05894-180421.

Boisier, J. P. et al., 2018: Anthropogenic drying in central-southern Chile evidenced by long-term observations and climate model simulations. *Elementa Science of Anthropocene*, **6**(1), 74, doi:10.1525/elementa.328.

Boisier, J. P., R. Rondanelli, R. D. Garreaud and F. Muñoz, 2016: Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile. *Geophysical Research Letters*, **43**(1), 413-421, doi:10.1002/2015GL067265.

Bonatti, M. et al., 2019: Social representations of climate change and climate adaptation plans in southern Brazil: Challenges of genuine participation. *Urban Climate*, **29**, 100496, doi:10.1016/j.uclim.2019.100496.

Bonatti, M. et al., 2016: Climate vulnerability and contrasting climate perceptions as an element for the development of community adaptation strategies: Case studies in Southern Brazil. *Land Use Policy*, **58**, 114-122, doi:10.1016/j.landusepol.2016.06.033.

Borbor-Cordova, M. et al., 2016: Case study 5B: Vector-virus microclimate surveillance system for dengue control in Machala, Ecuador. In: *Climate Services for Health: Improving public health decision-making in a new climate*. World Meteorological Association and World Health Organization, Geneva, Switzerland, pp. 104-107.

Borges, F. J. A., B. R. Ribeiro, L. E. Lopes and R. Loyola, 2019: Bird vulnerability to climate and land use changes in the Brazilian Cerrado. *Biological Conservation*, **236**, 347-355, doi:10.1016/j.biocon.2019.05.055.

Borges, R., A. C. Ferreira and L. D. Lacerda, 2017: Systematic Planning and Ecosystem-Based Management as Strategies to Reconcile Mangrove Conservation with Resource Use. *Frontiers in Marine Science*, **4**, 353.

Borsdorf, A., M. Mergili and L. A. Ortega, 2013: La Reserva de la Biósfera Cinturón Andino, Colombia. ¿Una región modelo de estrategias de adaptación al cambio climático y el desarrollo regional sustentable? *Revista de Geografia Norte Grande*.

Boso, À. et al., 2019: Examining Patterns of Air Quality Perception: A Cluster Analysis for Southern Chilean Cities. *SAGE Open*, **9**(3), doi:10.1177/2158244019863563.

Boucher, D., S. Roquemore and E. Fitzhugh, 2013: Brazil's Success in Reducing Deforestation. *Tropical Conservation Science*, **6**(3), 426-445, doi:10.1177/194008291300600308.

Bourke, J., K. Busse and W. Böhme, 2018: Potential effects of climate change on the distribution of the endangered Darwin's frog. *North-Western Journal of Zoology*, **14**(2), 165-170.

Bouroncle, C. et al., 2017: Mapping climate change adaptive capacity and vulnerability of smallholder agricultural livelihoods in Central America: ranking and descriptive approaches to support adaptation strategies. *Climatic Change*, **141**(1), 123-137, doi:10.1007/s10584-016-1792-0.

Bovarnick, A., J. Fernandez-Baca, J. Galindo and H. Negret, 2010: *Financial Sustainability of Protected Areas in Latin America and the Caribbean: Investment Policy Guidance*. United Nations Development Programme (UNDP) and The Nature Conservancy (TNC), 162 pp. Available at: https://www.cbd.int/financial/finplanning/g-planscorelatin-undp.pdf (accessed 16/06/2021).

Bowman, D. M. J. S. et al., 2009: Fire in the Earth System. *Science*, **324**(5926), 481-484, doi:10.1126/science.1163886 %J Science.

Bowman, D. M. J. S. et al., 2019: Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires. *Ambio*, **48**(4), 350-362, doi:10.1007/s13280-018-1084-1.

Bowman, K. W. et al., 2021: Environmental degradation of indigenous protected areas of the Amazon as a slow onset event. *Current Opinion in Environmental Sustainability*, **50**, 260-271, doi:10.1016/j.cosust.2021.04.012.

Boyer, C. J. et al., 2020: Using Implementation Science For Health Adaptation: Opportunities For Pacific Island Countries. *Health Affairs*, **39**(12), 2160-2167, doi:10.1377/hlthaff.2020.01101.

Bozkurt, D., M. Rojas, J. P. Boisier and J. Valdivieso, 2017: Climate change impacts on hydroclimatic regimes and extremes over Andean basins in central Chile. *Hydrol. Earth Syst. Sci. Discuss.*, **2017**, 1-29, doi:10.5194/hess-2016-690.

Bradley, R. S., M. Vuille, H. F. Diaz and W. Vergara, 2006: Threats to Water Supplies in the Tropical Andes. *Science*, **312**(5781), 1755, doi:10.1126/science.1128087.

Brancalion, P. H. S. et al., 2019: Global restoration opportunities in tropical rainforest landscapes. *Science Advances*, **5**(7), eaav3223, doi:10.1126/sciadv.aav3223.

Branche, E., 2017: The multipurpose water uses of hydropower reservoir: The SHARE concept. *Comptes Rendus Physique*, **18**(7), 469-478, doi:10.1016/j.crhy.2017.06.001.

Brando, P. M. et al., 2014: Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proceedings of the National Academy of Sciences*, **111**(17), 6347-6352, doi:10.1073/pnas.1305499111.

Brandt, R., R. Kaenzig and S. Lachmuth, 2016: Migration as a Risk Management Strategy in the Context of Climate Change: Evidence from the Bolivian Andes. In: *Migration, Risk Management and Climate Change: Evidence and Policy Responses* [Milan, A., B. Schraven, K. Warner and N. Cascone (eds.)]. Springer International Publishing, Cham, pp. 43-61. ISBN 978-3-319-42922-9.

Braun, M. H. et al., 2019: Constraining glacier elevation and mass changes in South America. *Nature Climate Change*, **9**(2), 130-136, doi:10.1038/s41558-018-0375-7.

Bravo, L., R. Hernández, I. Llatas and A. Salcedo, 2010: Desarrollo de un sistema de alerta temprano comunitario en el estado Vargas, Venezuela. *Temas de Coyuntura*, **61**, 169–178.

Braz, A. G., M. L. Lorini and M. M. Vale, 2019: Climate change is likely to affect the distribution but not parapatry of the Brazilian marmoset monkeys (Callithrix spp.). *Diversity and Distributions*, **25**(4), 536-550, doi:10.1111/ddi.12872.

Bremer, L. L. et al., 2016: One size does not fit all: Natural infrastructure investments within the Latin American Water Funds Partnership. *Ecosystem Services*, **17**, 217-236, doi:10.1016/j.ecoser.2015.12.006.

Bren d'Amour, C. et al., 2016: Teleconnected food supply shocks. *Environmental Research Letters*, **11**(3), 035007, doi:10.1088/1748-9326/11/3/035007.

Brienen, R. J. W. et al., 2015: Long-term decline of the Amazon carbon sink. *Nature*, **519**(7543), 344-348, doi:10.1038/nature14283.

Briones-Estébanez, K. M. and N. F. F. Ebecken, 2017: Occurrence of emergencies and disaster analysis according to precipitation amount. *Natural Hazards*, **85**(3), 1437-1459, doi:10.1007/s11069-016-2635-z.

Bro, A. S., D. C. Clay, D. L. Ortega and M. C. Lopez, 2019: Determinants of adoption of sustainable production practices among smallholder coffee producers in Nicaragua. *Environment, Development and Sustainability*, **21**(2), 895-915, doi:10.1007/s10668-017-0066-y.

Brockington, D. and D. Wilkie, 2015: Protected areas and poverty. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**, doi:10.1098/rstb.2014.0271.

Brondízio, E. S., A. C. B. de Lima, S. Schramski and C. Adams, 2016: Social and health dimensions of climate change in the Amazon. *Annals of Human Biology*, **43**(4), 405-414, doi:10.1080/03014460.2016.1193222.

Brough, A. R. et al., 2016: Is Eco-Friendly Unmanly? The Green-Feminine Stereotype and Its Effect on Sustainable Consumption. *Journal of Consumer Research*, **43**(4), 567-582, doi:10.1093/jcr/ucw044.

Brown, K., 2014: Global environmental change I: A social turn for resilience? *Progress in Human Geography*, **38**(1), 107-117, doi:10.1177/0309132513498837.

Bruguere, C. and M. Williams, 2017: *Women in aquaculture profile*. Genderaquafish, 9 pp. Available at: https://genderaquafish.org/portfolio/women-in-aquaculture/ (accessed 16/06/2021).

Bunn, C., P. Läderach, O. Ovalle Rivera and D. Kirschke, 2015: A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change*, **129**(1-2), 89-101, doi:10.1007/s10584-014-1306-x.

Burton, C. et al., 2021: South American fires and their impacts on ecosystems increase with continued emissions. *Climate Resilience and Sustainability*, **n/a**(n/a), e8, doi:10.1002/cli2.8.

Bury, J. et al., 2013: New Geographies of Water and Climate Change in Peru: Coupled Natural and Social Transformations in the Santa River Watershed. *Annals of the Association of American Geographers*, **103**(2), 363-374, doi:10.1080/00045608.2013.754665.

Busso, M. and J. Messina, 2020: *La crisis de la desigualdad. América Latina y el Caribe en la encrucijada*. Inter-American Development Bank, 401 pp. Available at: https://publications.iadb.org/es/la-crisis-de-la-desigualdad-america-latina-y-el-caribe-en-la-encrucijada (accessed 16/06/2021).

Bustamante, M. et al., 2020: Ecosistemas terrestres y acuáticos continentales. In: *Adaptación frente a los riesgos del cambio climático en los países iberoamericanos - Informe RIOCCADAPT* [Moreno, J. M., C. Laguna-Defior, V. Barros, E. Calvo Buendía, J. A. Marengo and U. Oswald Spring (eds.)]. McGraw-Hill, Madrid, España, pp. 91-129. ISBN 9788448621643.

Buytaert, W. and B. De Bièvre, 2012: Water for cities: The impact of climate change and demographic growth in the tropical Andes. *Water Resources Research*, **48**(8), 1-13, doi:10.1029/2011WR011755.

Buytaert, W. et al., 2017: Glacial melt content of water use in the tropical Andes. *Environmental Research Letters*, **12**(11), 114014, doi:10.1088/1748-9326/aa926c.

Buytaert, W. et al., 2014: Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, **2**(October), 1-21, doi:10.3389/feart.2014.00026.

Cáceres-Arteaga, N., K. Maria and D. Lane, 2020: Agroecological Practices as a Climate Change Adaptation Mechanism in Four Highland Communities in Ecuador. *Journal of Latin American Geography*, **19**(3), 47-73, doi:10.1353/lag.2020.0071.

CAF, 2014: *Vulnerability Index to climate change in the Latin American and Caribbean Region*. CAF Development Bank of Latin America, Caracas, Venezuela, 206 pp. Available at: http://scioteca.caf.com/handle/123456789/509 (accessed 17/09/2019).

Cai, W. et al., 2020: Climate impacts of the El Niño–Southern Oscillation on South America. *Nature Reviews Earth & Environment*, **1**(4), 215-231, doi:10.1038/s43017-020-0040-3.

Cai, W. et al., 2015: ENSO and greenhouse warming. *Nature Climate Change*, **5**(9), 849-859, doi:10.1038/nclimate2743.

Cai, W. et al., 2018: Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature*, **564**(7735), 201-206, doi:10.1038/s41586-018-0776-9.

Cakmak, S., C. Blanco-Vidal, A. O. Lukina and R. Dales, 2021: The association between air pollution and hospitalization for patients with systemic lupus erythematosus in Chile: A daily time series analysis. *Environmental Research*, **192**, 110469, doi:10.1016/j.envres.2020.110469.

Calil, J. et al., 2017: Comparative Coastal Risk Index (CCRI): A multidisciplinary risk index for Latin America and the Caribbean. *PLOS ONE*, **12**(11), e0187011, doi:10.1371/journal.pone.0187011.

Calispa, E., 2018: Políticas Públicas De Cambio Climático En Ecuador: Un Análisis Crítico De Ideas, Políticas Y Discurso. *Revista Desarrollo Local Sostenible*, **11**(32), 1-22.

Calvello, M. et al. (eds.), The Community-Based Alert and Alarm System for Rainfall Induced Landslides in Rio de Janeiro, Brazil. Engineering Geology for Society and Territory - Volume 2, 2015//, Cham, Springer International Publishing, 653-657 pp. ISBN 978-3-319-09057-3.
Camacho Guerreiro, A. I., R. J. Ladle and V. da Silva Batista, 2016: Riverine fishers' knowledge of extreme climatic events in the Brazilian Amazonia. *Journal of Ethnobiology and Ethnomedicine*, **12**(50), 1-10, doi:10.1186/s13002-016-0123-x.
Camarero, J. J. and A. Fajardo, 2017: Poor acclimation to current drier climate of the long-lived tree species Fitzroya cupressoides in the temperate rainforest of southern Chile. *Agricultural and Forest Meteorology*, **239**, 141-150, doi:10.1016/j.agrformet.2017.03.003.
Camarero, J. J., A. Gazol, G. Sangüesa-Barreda and A. Fajardo, 2018: Coupled climate–forest growth shifts in the Chilean Patagonia are decoupled from trends in water–use efficiency. *Agricultural and Forest Meteorology*, **259**, 222-231, doi:10.1016/j.agrformet.2018.04.024.
Cameron, L. et al., 2015: *Trends and opportunities in multilateral climate funds*. ECN, 68 pp. Available at: https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-E--15-014 (accessed 16/06/2021).
Camico, Z., M. Díaz, A. Felicien and N. Chacón, 2021: Agricultural knowledge of the Uwǫttüją people in the ecological restoration of the Amazon rainforest. In: *Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change* [Mustonen, T., S. L. Harper, M. Rivera Ferre, J. Postigo, A. Ayanlade, T. Benjaminsen, R. Morgan and A. Okem (eds.)]. Snowchange Cooperative, Kontiolahti, Finland, pp. 20-25.
Camilo, J. A. et al., 2018: Impact of Climate Change on Maize Grown in the Brazilian Cerrado. In: *2018 ASABE Annual International Meeting*, St. Joseph, MI, ASABE, pp. 1, doi:10.13031/aim.201800967.
Campos-Caba, R. V., 2016: Análisis de marejadas históricas y recientes en las costas de Chile. Universidad de Valparaiso, 210 pp.
Canil, K., A. Lampis and K. L. d. Santos, 2020: Vulnerabilidade e a construção social do risco: uma contribuição para o planejamento na macrometrópole paulista. *Cadernos Metrópole*, **22**(48), 397-416, doi:10.1590/2236-9996.2020-4803
Caprì, S., M. Ignaccolo, G. Inturri and M. Le Pira, 2016: Green walking networks for climate change adaptation. *Transportation Research Part D: Transport and Environment*, **45**, 84-95, doi:10.1016/j.trd.2015.08.005.
Capstick, S. et al., 2015: International trends in public perceptions of climate change over the past quarter century. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(1), 35-61, doi:10.1002/wcc.321.
Cárdenas, M., J. P. Bonilla and F. Brusa, 2021: *Climate Policies in Latin America and the Caribbean: Success Stories and Challenges in the Fight against Climate Change* [Bank, I.-A. D. (ed.)]. **IDB Monograph 929**, Inter-American Development Bank, 179 pp. Available at: http://dx.doi.org/10.18235/0003239 (accessed 30/06/2021).
Cardoso, A. C., H. Silva, A. C. Melo and D. Araújo, 2018: Urban Tropical Forest: Where Nature and Human Settlements Are Assets for Overcoming Dependency, but How Can Urbanisation Theories Identify These Potentials? In: *Emerging Urban Spaces: A Planetary Perspective* [Horn, P., P. Alfaro d'Alencon and A. C. Duarte Cardoso (eds.)]. Springer International Publishing, Cham, pp. 177-199. ISBN 978-3-319-57816-3.
Carey, M. et al., 2014: Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru). *Journal of Hydrology*, **518**(A), 60-70, doi:10.1016/j.jhydrol.2013.11.006.
Carey, M., A. French and E. O'Brien, 2012: Unintended effects of technology on climate change adaptation: an historical analysis of water conflicts below Andean Glaciers. *Journal of Historical Geography*, **38**(2), 181-191, doi:10.1016/j.jhg.2011.12.002.
Carey, M. et al., 2017: Impacts of Glacier Recession and Declining Meltwater on Mountain Societies. *Annals of the American Association of Geographers*, **107**(2), 350-359, doi:10.1080/24694452.2016.1243039.
Carneiro da Cunha, M. and A. G. Morim de Lima, 2017: How Amazonian Indigenous Peoples contribute to Biodiversity. In: *Knowing our Lands and Resources: Indigenous and Local Knowledge of Biodiversity and Ecosystem Services in the Americas. Knowledges of Nature 11* [Baptiste, B., D. Pacheco, M. Carneiro da Cunha and S. Diaz (eds.)]. UNESCO, Paris, France, pp. 65-81.
Carrão, H., G. Naumann and P. Barbosa, 2016: Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change*, **39**, 108-124, doi:10.1016/j.gloenvcha.2016.04.012.
Carrasco-Torrontegui, A., C. A. Gallegos-Riofrío, F. Delgado-Espinoza and M. Swanson, 2020: Climate Change, Food Sovereignty and Ancestral Farming Technologies in the Andes. *Current Developments in Nutrition*, nzaa073, doi:10.1093/cdn/nzaa073.
Carrer, M. J., R. L. F. d. Silveira, M. d. M. B. Vinholis and H. M. De Souza Filho, 2020: Determinants of agricultural insurance adoption: evidence from farmers in the state of São Paulo, Brazil. *RAUSP Management Journal*, **55**(4), 547-566, doi:10.1108/RAUSP-09-2019-0201.
Carril, A. F. et al., 2016: Extreme events in the la Plata basin: A retrospective analysis of what we have learned during CLARIS-LPB project. *Climate Research*, **68**(2-3), 95-116, doi:10.3354/cr01374.
Carrivick, J. L. and F. S. Tweed, 2016: A global assessment of the societal impacts of glacier outburst floods. *Global and Planetary Change*, **144**, 1-16, doi:10.1016/j.gloplacha.2016.07.001.

Carrizo Sineiro, C., Y. M. Ferreyra, D. Astudillo and S. Soldá, 2018: Sustentabilidad y gestión de riesgo. Respuesta, reparación y prevención frente a inundaciones desde un análisis de caso/Sustainability and risk management. Response, repair and prevention against floods from a case analysis. *Letras Verdes. Revista Latinoamericana de Estudios Socioambientales*,(24), 105-123, doi:10.17141/letrasverdes.24.2018.3328.
Carter, H. N., S. W. Schmidt and A. C. Hirons, 2015: An International Assessment of Mangrove Management: Incorporation in Integrated Coastal Zone Management. *Diversity*, **7**(2), 74-104, doi:10.3390/d7020074.
Carvache-Franco, W., M. Carvache-Franco, O. Carvache-Franco and A. B. Hernández-Lara, 2019: Segmentation of foreign tourist demand in a coastal marine destination: The case of Montañita, Ecuador. *Ocean and Coastal Management*, **167**(November 2018), 236-244, doi:10.1016/j.ocecoaman.2018.10.035.
Carvalho, L. M. V., 2020: Assessing precipitation trends in the Americas with historical data: A review. *WIREs Climate Change*, **11**(2), e627, doi:10.1002/wcc.627.
Carvalho, W. D. et al., 2019: Deforestation control in the Brazilian Amazon: A conservation struggle being lost as agreements and regulations are subverted and bypassed. *Perspectives in Ecology and Conservation*, **17**(3), 122-130, doi:10.1016/j.pecon.2019.06.002.
Casas Varez, M., 2017: *La transversalización del enfoque de género en las políticas públicas frente al cambio climático en América Latina*. CEPAL, Santiago.
Castán Broto, V. and H. Bulkeley, 2013: A survey of urban climate change experiments in 100 cities. *Global Environmental Change*, **23**(1), 92-102, doi:10.1016/j.gloenvcha.2012.07.005.
Castaneda Sanchez, J. P., J. Carrera and D. Rexhepi, 2019: *Towards Natural Capital Accounting in Guatemala: Synthesis Report*. The World Bank, Washington DC, USA, 32 pp. Available at: https://seea.un.org/es/node/2785 (accessed 29/06/2021).
Castellanos, E., T. Thomas and S. Dunston, 2018: *Climate Change, Agriculture, and Adaptation Options for Guatemala*. International Food Policy Research Institute, 1789 ed., Ifpri, Washington D.C., USA, 66 pp. Available at: https://www.ifpri.org/publication/climate-change-agriculture-and-adaptation-options-guatemala (accessed 31/08/2021).
Castelo, T. B., 2015: Legislação florestal brasileira e políticas do governo de combate ao desmatamento na Amazônia legal. *Ambiente & Sociedade*, **18**(4), 221-242, doi:10.1590/1809-4422ASOC1216V1842015.
Castillo-Soto, M. E., J. R. Molina-Martínez, F. Rodríguez y Silva and G. H. J. Alvear, 2013: A territorial fire vulnerability model for Mediterranean ecosystems in South America. *Ecological Informatics*, **13**, 106-113, doi:10.1016/j.ecoinf.2012.06.004.
Castrejón, M. and A. Charles, 2020: Human and climatic drivers affect spatial fishing patterns in a multiple-use marine protected area: The Galapagos Marine Reserve. *PLOS ONE*, **15**(1), e0228094, doi:10.1371/journal.pone.0228094.
Castrejón, M. and O. Defeo, 2015: Co-governance of Small-Scale Shellfisheries in Latin America: Institutional Adaptability to External Drivers of Change. In: *Interactive Governance for Small-Scale Fisheries: Global Reflections* [Jentoft, S. and R. Chuenpagdee (eds.)]. Springer International Publishing, Cham, pp. 605-625. ISBN 978-3-319-17034-3.
Castro, S. M., G. A. Sanchez-Azofeifa and H. Sato, 2018: Effect of drought on productivity in a Costa Rican tropical dry forest. *Environmental Research Letters*, **13**(4), 045001, doi:10.1088/1748-9326/aaacbc.
Catenazzi, A., E. Lehr and V. T. Vredenburg, 2014: Thermal Physiology, Disease, and Amphibian Declines on the Eastern Slopes of the Andes. *Conservation Biology*, **28**(2), 509-517, doi:10.1111/cobi.12194.
Cauvy-Fraunié, S. and O. Dangles, 2019: A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, **3**(12), 1675-1685, doi:10.1038/s41559-019-1042-8.
Cavalcante, A. d. M. B. and A. d. S. Duarte, 2019: Modeling the Distribution of Three Cactus Species of the Caatinga Biome in Future Climate Scenarios. *International Journal of Ecology and Environmental Sciences*, **45**.
Ceccherini, G. et al., 2016: Magnitude and frequency of heat and cold waves in recent decades: the case of South America. *Natural Hazards and Earth System Sciences*, **16**(3), 821-831, doi:10.5194/nhess-16-821-2016.
CELADE, 2019: Latin America and the Caribbean: Population estimates and projections, ECLAC. Available at: https://www.cepal.org/en/topics/demographic-projections/latin-america-and-caribbean-population-estimates-and-projections.
CEPAL, 2010: *The economics of climate change in Central America: Summary 2010*. The economics of climate change in Central America: summary 2010, México, C., Ciudad de Mexico, 143 pp. Available at: https://repositorio.cepal.org/handle/11362/35229 (accessed 04/08/2021).
CEPAL, 2014: *Guaranteeing indigenous people's rights in Latin America, Summary. Progress in the past decade and remaining challenges*. CEPAL, Santiago, Chile, 115 pp. Available at: https://repositorio.cepal.org/bitstream/handle/11362/37051/S1420782_en.pdf?sequence=4&isAllowed=y (accessed 30/10/2020).
CEPAL, 2017: *Impactos potenciales del cambio climático en el ámbito hidroeléctrico en Panamá y la República Dominicana*. Comisión Económica para América Latina y el Caribe (CEPAL), Ciudad de México, 136 pp. Available at: https://www.cepal.org/es/publicaciones/42426-impactos-potenciales-cambio-climatico-ambito-hidroelectrico-panama-la-republica (accessed 28/09/2019).
CEPAL, 2018: *The effects of climate change in the coastal areas of Latin America and the Caribbean. Evaluation of systems for protecting corals and mangroves in Cuba*. Santiago de Chile, 32 pp. Available at:

https://www.cepal.org/en/publications/44265-effects-climate-change-coastal-areas-latin-america-and-caribbean-evaluation (accessed 16/06/2021).
CEPAL and CAC-SICA, 2020: *Análisis espacial de datos históricos y escenarios de cambio climático en México, Centroamérica, Cuba, Haití y la República Dominicana*. Comisión Económica para América Latina y el Caribe and Consejo Agropecuario Centroamericano del Sistema de la Integración Centroamericana, Ciudad de México, 282 pp. Available at: https://repositorio.cepal.org/handle/11362/46499 (accessed 03/08/2021).
CEPAL and CAC/SICA, 2013: *Impactos potenciales del cambio climático sobre los granos básicos en Centroamérica*. ECLAC, 137 pp. Available at: https://www.cepal.org/es/publicaciones/27171-impactos-potenciales-cambio-climatico-granos-basicos-centroamerica (accessed 16/06/2021).
CEPAL and CAC/SICA, 2014: Impactos potenciales del cambio climático sobre el café en Centroamérica. ECLAC, México D.F., México, 131 pp.
CEPAL et al., 2018: Cambio climático y seguridad alimentaria y nutricional en Centroamérica y la República Dominicana: Propuestas metodológicas. vol. LC/MEX/TS.2018/19, CEPAL, Ciudad de México, México, 153 pp. Available at: https://repositorio.cepal.org/bitstream/handle/11362/44056/1/S1800858_es.pdf (accessed 13/08/2020).
CEPALSTAT, 2019: Databases and Statistical Publications, Economic Comission for Latin America and the Caribbean (ECLAC). Available at: https://estadisticas.cepal.org/cepalstat/WEB_CEPALSTAT/estadisticasIndicadores.asp?idioma=i (accessed 21/10/2020).
Cernusak, L. A. et al., 2013: Tropical forest responses to increasing atmospheric CO2: current knowledge and opportunities for future research. *Functional plant biology*, **40**(6), 531-551, doi:10.1071/fp12309.
Cerón, W. L. et al., 2021: Recent intensification of extreme precipitation events in the La Plata Basin in Southern South America (1981–2018). *Atmospheric Research*, **249**, 105299, doi:10.1016/j.atmosres.2020.105299.
Cerrón, J. et al., 2019: *Relación entre árboles, cobertura y uso de la tierra y servicios hidrológicos en los Andes Tropicales: Una síntesis del conocimiento.* Occasional Paper No. 27, **27**, Centro Internacional de Investigación Agroforestal (ICRAF), Consorcio para el Desarrollo Sostenible de la Ecorregión Andina (CONDESAN), Lima, Perú. Available at: http://dx.doi.org/10.5716/OP19056.PDF (accessed 26/08/2021).
Chain-Guadarrama, A. et al., 2018: Adaptación basada en Ecosistemas en pequeñas fincas de granos básicos en Guatemala y Honduras. *Agronomía Mesoamericana*, **29**(3), 571-583, doi:10.15517/ma.v29i3.32678.
Chang, M. and P. d. S. P. Garcia, 2018: *Relatório do Projeto Construção de Indicadores de Vulnerabilidade da População como Insumo para a Elaboração das Ações de Adaptação à Mudança do Clima no Brasil: Volume: Paraná*. Fundação Oswaldo Cruz, Ministério do Meio Ambiente e Fundo Nacional sobre Mudança do Clima FIOCRUZ, Rio de Janeiro, RJ, 130 pp. Available at: https://antigo.mma.gov.br/images/arquivo/80182/Vulnerabilidade%20%C3%A0%20Mudan%C3%A7a%20do%20Clima/Relat%C3%B3rio_Final_Paran%C3%A1_Novo.pdf (accessed 03/09/2021).
Charles, A., 2021: *Communities, conservation and livelihoods*. IUCN and CCRN, Gland, Switzerland and Halifax, Canada, 132 pp. Available at: https://doi.org/10.2305/IUCN.CH.2021.01.en (accessed 25/08/2021).
Chaves, L. F., T.-W. Chuang, M. Sasa and J. M. Gutiérrez, 2015: Snakebites are associated with poverty, weather fluctuations, and El Niño. *Science Advances*, **1**(8), e1500249, doi:10.1126/sciadv.1500249.
Chaves, L. F. and M. Pascual, 2006: Climate Cycles and Forecasts of Cutaneous Leishmaniasis, a Nonstationary Vector-Borne Disease. *PLOS Medicine*, **3**(8), e295, doi:10.1371/journal.pmed.0030295.
Chaves, L. S. M., J. E. Conn, R. V. M. López and M. A. M. Sallum, 2018: Abundance of impacted forest patches less than 5 km2 is a key driver of the incidence of malaria in Amazonian Brazil. *Scientific Reports*, **8**(1), 7077, doi:10.1038/s41598-018-25344-5.
Chávez Eslava, A. W., 2021: Resistance and resilience of the community of Belén, Iquitos, Peru, to resettlement. In: *Rethinking Urban Risk and Resettlement in the Global South* [Johnson, C., G. Jain and A. Lavell (eds.)]. UCL Press, pp. 154-168. ISBN 9781787358294.
Chazarin, F., B. Locatelli and M. Garay-Rodríguez, 2014: Mitigación en la selva, adaptación en la sierra y la costa: ¿Oportunidades perdidas de sinergias frente al cambio climático en Perú? *Ambiente y Desarrollo*, **18**(35), 95-106, doi:10.11144/javeriana.ayd18-35.msas.
Checco, G. B. and E. d. L. Caldas, 2019: Governos subnacionais e a Política de Mudanças Climáticas de São Paulo: uma análise a partir da multiposição dos atores na cidade de São Paulo. *Confins. Revue franco-brésilienne de géographie*,(39), doi:10.4000/confins.18818.
Chelleri, L., G. Minucci and E. Skrimizea, 2016: Does community resilience decrease social–ecological vulnerability? Adaptation pathways trade-off in the Bolivian Altiplano. *Regional Environmental Change*, **16**(8), 2229-2241, doi:10.1007/s10113-016-1046-8.
Chen, M. et al., 2018: Diversification and intensification of agricultural adaptation from global to local scales. *PLOS ONE*, **13**(5), e0196392, doi:10.1371/journal.pone.0196392.
Cherubin, M. R., J. P. Chavarro-Bermeo and A. M. Silva-Olaya, 2019: Agroforestry systems improve soil physical quality in northwestern Colombian Amazon. *Agroforestry Systems*, **93**(5), 1741-1753, doi:10.1007/s10457-018-0282-y.

Chevallier, P., B. Pouyaud, W. Suarez and T. Condom, 2011: Climate change threats to environment in the tropical Andes: glaciers and water resources. *Regional Environmental Change*, **11**(1), 179-187, doi:10.1007/s10113-010-0177-6.
Chisari, O. O. and S. J. Miller, 2016: *Climate Change and Migration: A CGE Analysis for Two Large Urban Regions of Latin America*. Inter-American Development Bank, 52 pp. Available at: https://publications.iadb.org/en/climate-change-and-migration-cge-analysis-two-large-urban-regions-latin-america (accessed 16/06/2021).
Chou, S. C. et al., 2014: Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. *American Journal of Climate Change*, **3**(5), 512-527, doi:10.4236/ajcc.2014.35043.
Christidis, N., R. A. Betts and P. A. Stott, 2019: The Extremely Wet March of 2017 in Peru. *Bulletin of the American Meteorological Society*, **100**(1), S31-S35, doi:10.1175/BAMS-D-18-0110.1.
Chu, E., I. Anguelovski and J. Carmin, 2016: Inclusive approaches to urban climate adaptation planning and implementation in the Global South. *Climate Policy*, **16**(3), 372-392, doi:10.1080/14693062.2015.1019822.
Chu, E., I. Anguelovski and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**, 378-387, doi:10.1016/j.cities.2016.10.016.
CIIFEN, 2016: Condiciones Oceánicas-Atmosféricas. Evolución y perspectivas. Agosto 2016. 5. Available at: https://ciifen.org/wp-content/uploads/2020/09/8-EL-NINO-AGOSTO-2016.pdf (accessed 19/08/2021).
Clarvis, M. H. and A. Allan, 2014: Adaptive capacity in a Chilean context: A questionable model for Latin America. *Environmental Science & Policy*, **43**, 78-90, doi:10.1016/j.envsci.2013.10.014.
Clavijo Palacios, C. E. and N. Cuvi, 2017: La Sustentabilidad de huertas urbanas y periurbanas con base agroecológica en Quito. *Letras Verdes. Revista Latinoamericana de Estudios Socioambientales*, 68 pp., doi:10.17141/letrasverdes.21.2017.2608.
Clerici, N. et al., 2019: Spatio-temporal and cumulative effects of land use-land cover and climate change on two ecosystem services in the Colombian Andes. *Science of The Total Environment*, **685**, 1181-1192, doi:10.1016/j.scitotenv.2019.06.275.
CNE, 2016: *Plan Nacional de Gestión del Riesgo 2016-2020 Costa Rica*. San José, 1-64 pp. Available at: http://politica.cne.go.cr/index.php/plan/plan (accessed 16/06/2021).
CNUC and MMA, 2020: Cadastro Nacional de Unidades de Conservação por Bioma, Ministério do Meio Ambiente do Brasil. Available at: https://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs.html (accessed 28/09/2020).
Coayla, E. and E. Culqui, 2020: Vulnerability Assessment and Adaptation Costs of Agriculture to Climate Change in the Lima Region, Peru. *International Journal of Environmental Science and Development*, **11**(1), doi:10.18178/ijesd.2020.11.1.1221
Cóbar-Carranza, A. J., R. A. García, A. Pauchard and E. Peña, 2014: Effect of Pinus contorta invasion on forest fuel properties and its potential implications on the fire regime of Araucaria araucana and Nothofagus antarctica forests. *Biological Invasions*, **16**(11), 2273-2291, doi:10.1007/s10530-014-0663-8.
Cochran, F. V. et al., 2016: Indigenous ecological calendars define scales for climate change and sustainability assessments. *Sustainability Science*, **11**(1), 69-89, doi:10.1007/s11625-015-0303-y.
Codeço, C. T. et al., 2016: InfoDengue: a nowcasting system for the surveillance of dengue fever transmission. *bioRxiv*, 046193-046193, doi:10.1101/046193.
Cohen, M. C. L. et al., 2018: Decadal-scale dynamics of an Amazonian mangrove caused by climate and sea level changes: Inferences from spatial–temporal analysis and digital elevation models. *Earth Surf. Process. Landforms*, **43**(14), 2876-2888, doi:10.1002/esp.4440.
Cohn, A. S. et al., 2016: Patterns and processes of pasture to crop conversion in Brazil: Evidence from Mato Grosso State. *Land Use Policy*, **55**, 108-120, doi:10.1016/j.landusepol.2016.03.005.
Collodi, J. et al., 2020: How do you build back better so no one is left behind? Lessons from Sint Maarten, Dutch Caribbean, following Hurricane Irma. *Disasters*, **n/a**(n/a), doi:10.1111/disa.12423.
Colón-González, F. J. et al., 2018: Limiting global-mean temperature increase to 1.5-2 °C could reduce the incidence and spatial spread of dengue fever in Latin America. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(24), 6243-6248, doi:10.1073/pnas.1718945115.
Colonia, D. et al., 2017: Compiling an Inventory of Glacier-Bed Overdeepenings and Potential New Lakes in De-Glaciating Areas of the Peruvian Andes: Approach, First Results, and Perspectives for Adaptation to Climate Change. *Water*, **9**(5), 336, doi:10.3390/w9050336.
Comisión Europea, 2020: *La acción para el empoderamiento climático y su potencial transformador en América Latina*. Dirección General de Desarrollo y Cooperación - EuropeAid, Bruselas.
CONASA, 2019: *Clima y Salud*. Gobierno de Colombia, Bogotá, 19 pp. Available at: http://www.ideam.gov.co/documents/21021/79866851/03_Boletin_Clima_y_Salud_2019_marzo.pdf/7a69d840-e628-4cfc-84e0-f9f53c39019c?version=1.0 (accessed 16/06/2021).
Confalonieri, U. E. C., A. C. L. Lima, I. Brito and A. F. Quintão, 2014a: Social, environmental and health vulnerability to climate change in the Brazilian Northeastern Region. *Climatic Change*, **127**(1), 123-137, doi:10.1007/s10584-013-0811-7.
Confalonieri, U. E. C., C. Margonari and A. F. Quintão, 2014b: Environmental change and the dynamics of parasitic diseases in the Amazon. *Acta Tropica*, **129**(1), 33-41, doi:10.1016/j.actatropica.2013.09.013.

Connolly, J. J. T., 2019: From Jacobs to the Just City: A foundation for challenging the green planning orthodoxy. *Cities*, **91**, 64-70, doi:10.1016/j.cities.2018.05.011.
CONRED, 2014: *Plan Nacional de Gestión Integral para la Reducción de Riesgo a los Desastres en la Temporada de Lluvias y Huracanes para la República de Guatemala, 2014*. Coordinadora Nacional para la Reducción de Desastres -CONRED- Secretaría Ejecutiva, Guatemala, 51 pp. Available at: https://reliefweb.int/report/guatemala/plan-nacional-de-gesti-n-integral-para-la-reducci-n-de-riesgo-los-desastres-en-la-1 (accessed 16/06/2021).
Consejo Nacional de Cambio Climático y la Secretaría de Planificación y Programación de la Presidencia de Guatemala, 2018: *Plan de Acción Nacional de Cambio Climático, Gobierno de la República de Guatemala, Segunda Edición*. Consejo Nacional de Cambio Climático y la Secretaría de Planificación y Programación de la Presidencia, S., Guatemala, 213 pp. (accessed 29/08/2021).
COPECO, 2014: *Plan Nacional de Gestión Integral de Riesgos de Honduras -PNGIRH- Periodo 2014-2019*. Tegucigalpa, Honduras, 185 pp. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/HN-PNGIRH_2014-19_Version_Final-COPECO-20170608.pdf (accessed 16/06/2021).
Copernicus Emergency Management Service, 2021: Fire danger indices historical data from the Copernicus Emergency Management Service. Available at: https://doi.org/10.24381/cds.0e89c522.
Coppola, E. et al., 2014: Present and future climatologies in the phase I CREMA experiment. *Climatic Change*, **125**(1), 23-38, doi:10.1007/s10584-014-1137-9.
Córdoba Vargas, C. A., S. Hortúa Romero and T. León-Sicard, 2019: Resilience to climate variability: the role of perceptions and traditional knowledge in the Colombian Andes. *Agroecology and Sustainable Food Systems*, 1-27.
Coronel T, L., 2019: *Los caminos del agua. FONAG: trabajos y aprendizajes*. Fondo para la Protección del Agua (FONAG), Quito, 63 pp.
Corrales-Suastegui, A., R. Fuentes-Franco and E. G. Pavia, 2020: The mid-summer drought over Mexico and Central America in the 21st century. *International Journal of Climatology*, **40**(3), 1703-1715, doi:10.1002/joc.6296.
Correa-Araneda, F. et al., 2020: Extreme climate events can slow down litter breakdown in streams. *Aquatic Sciences*, **82**(2), 25, doi:10.1007/s00027-020-0701-9.
Correa, A. et al., 2020: A concerted research effort to advance the hydrological understanding of tropical páramos. *Hydrological Processes*, **34**(24), 4609-4627, doi:10.1002/hyp.13904.
Correia, I. A. and R. Ojima, 2017: Emigração e imobilidade no nordeste brasileiro: adaptação ou resistência? *RDE - Revista de Desenvolvimento Econômico*, **3**, 175-192, doi:10.21452/rde.v3i38.5080.
Cortés, M. E., 2016: Drought, environmental degradation, work and education: A brief comment on the current reality of agricultural communities in the Limarí Province, Chile. *Idesia*, **34**(4), 73-76, doi:10.4067/S0718-34292016005000013.
Corzo, A. and N. Gamboa, 2018: Environmental impact of mining liabilities in water resources of Parac micro-watershed, San Mateo Huanchor district, Peru. *Environment, Development and Sustainability*, **20**(2), 939-961, doi:10.1007/s10668-016-9899-z.
Costa, M. H. et al., 2019: Climate risks to Amazon agriculture suggest a rationale to conserve local ecosystems. *Frontiers in Ecology and the Environment*, **17**(10), 584-590, doi:10.1002/fee.2124.
Crego, R. D., C. K. Nielsen and K. A. Didier, 2014: Climate change and conservation implications for wet meadows in dry Patagonia. *Environmental Conservation*, **41**(2), 122-131, doi:10.1017/S037689291300026X.
Crespo-Pérez, V. et al., 2015: Changes in the distribution of multispecies pest assemblages affect levels of crop damage in warming tropical Andes. *Global Change Biology*, **21**(1), 82-96, doi:10.1111/gcb.12656.
Creutzig, F. et al., 2016: Urban infrastructure choices structure climate solutions. *Nature Climate Change*, **6**(12), 1054-1056, doi:10.1038/nclimate3169.
Crumpler, K. et al., 2020: *Regional analysis of the nationally determined contributions in Latin America: Gaps and opportunities in the agriculture and land use sectors* [Nations, F. a. A. O. o. T. U. (ed.)]. Environment and Natural Resources Management Working Papers, FAO, FAO, Rome, Italy, 130 pp. Available at: https://doi.org/10.4060/ca8249en (accessed 30/06/2021).
Cruz-Garcia, G. S. and P. J. E. Peters, 2015: Conservation of Corals in the Colombian Caribbean. In: *Ethnobiology of Corals and Coral Reefs* [Narchi, N. and L. L. Price (eds.)]. Springer International Publishing, Cham, pp. 209-234. ISBN 978-3-319-23763-3.
Cruz, G. et al., 2018: Thirty Years of Multilevel Processes for Adaptation of Livestock Production to Droughts in Uruguay. *Weather, Climate, and Society*, **10**(1), 59-74.
Cuesta, F. et al., 2019: New land in the Neotropics: a review of biotic community, ecosystem, and landscape transformations in the face of climate and glacier change. *Regional Environmental Change*, **19**(6), 1623-1642, doi:10.1007/s10113-019-01499-3.
Cuesta, F. et al., 2017a: Latitudinal and altitudinal patterns of plant community diversity on mountain summits across the tropical Andes. *Ecography*, **40**(12), 1381-1394, doi:10.1111/ecog.02567.
Cuesta, F. et al., 2017b: Priority areas for biodiversity conservation in mainland Ecuador. *Neotropical Biodiversity*, **3**(1), 93-106, doi:10.1080/23766808.2017.1295705.
Cuesta, F. et al., 2020: Thermal niche traits of high alpine plant species and communities across the tropical Andes and their vulnerability to global warming. *Journal of Biogeography*, **47**(2), 408-420, doi:10.1111/jbi.13759.

Cunha, F. A. F. d. S. et al., 2016a: The implementation costs of forest conservation policies in Brazil. *Ecological Economics*, **130**, 209-220, doi:10.1016/j.ecolecon.2016.07.007.
Cunha, M. d. C. M., J. M. Pessanha and W. T. Caiaffa, 2016b: Understanding the sensitivity of dengue to climate and urban risk factors in Minas Gerais State, Brazil. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 72-75.
Cunningham, C. et al., 2017: Climate change and drought in Brazil. In: *Reduction o vulnerability to disasters: from knowledge to action* [Marchezini, V., B. Wisner, S. Saito and L. Londe (eds.)], pp. 361-375. ISBN 978-85-7656-050-0.
Curtis, P. G. et al., 2018: Classifying drivers of global forest loss. *Science*, **361**(6407), 1108-1111, doi:10.1126/science.aau3445.
Cuvi, N., 2015: Un análisis de la resiliencia en Quito, 1980-2015. *Bitácora Urbano Territorial*, **25**(2), 35-42, doi:10.15446/bitacora.v2n25.52036.
Cuvi, N., 2018: Chapter 3: Indigenous Imprints and Remnants in the Tropical Andes. In: *A Living Past. Environmental Histories of Modern Latin America* [Soluri, J., C. Leal and J. A. Pádua (eds.)]. Berghahn Books, New York, USA, pp. 310. ISBN 9781785333903.
Cuyckens, G. A. E., M. M. Morales and M. F. Tognelli, 2015: Assessing the distribution of a Vulnerable felid species: threats from human land use and climate change to the kodkod Leopardus guigna. *Oryx*, **49**(4), 611-618, doi:10.1017/S003060531300135X.
Cvitanovic, C. et al., 2014: Utility of primary scientific literature to environmental managers: An international case study on coral-dominated marine protected areas. *Ocean & Coastal Management*, **102**, 72-78, doi:10.1016/j.ocecoaman.2014.09.003.
D'Onofrio, E. E., M. M. E. Fiore and J. L. Pousa, 2008: Changes in the regime of storm surges at Buenos Aires, Argentina. *Journal of Coastal Research*, **24**(1A), 260-265, doi:10.2112/05-0588.1.
da Cruz e Sousa, R. and B. Ríos-Touma, 2018: Stream restoration in Andean cities: learning from contrasting restoration approaches. *Urban Ecosystems*, **21**(2), 281-290, doi:10.1007/s11252-017-0714-x.
da Fonseca Aguiar, L. and M. Cataldi, 2021: Social and environmental vulnerability in Southeast Brazil associated with the South Atlantic Convergence Zone. *Natural Hazards*, doi:10.1007/s11069-021-04926-z.
da Silva, A. T. and M. P. Buendía, 2016: Megacities in climate governance: the case of Rio de Janeiro. *Meridiano 47 - Journal of Global Studies*, **17**, e17013, doi:10.20889/M47e17013.
Da Silva, C., A. Schardong, J. Garcia and C. Oliveira, 2018a: Climate Change Impacts and Flood Control Measures for Highly Developed Urban Watersheds. *Water*, **10**(7), 829, doi:10.3390/w10070829.
da Silva Junior, C. A. et al., 2020: Persistent fire foci in all biomes undermine the Paris Agreement in Brazil. *Scientific Reports*, **10**(1), 16246, doi:10.1038/s41598-020-72571-w.
da Silva, U. B. T., M. Delgado-Jaramillo, L. M. de Souza Aguiar and E. Bernard, 2018b: Species richness, geographic distribution, pressures, and threats to bats in the Caatinga drylands of Brazil. *Biological Conservation*, **221**, 312-322, doi:10.1016/j.biocon.2018.03.028.
Dally, M. et al., 2018: The impact of heat and impaired kidney function on productivity of Guatemalan sugarcane workers. *PLOS ONE*, **13**(10), e0205181, doi:10.1371/journal.pone.0205181.
Dangles, O. et al., 2017: Ecosystem sentinels for climate change? Evidence of wetland cover changes over the last 30 years in the tropical Andes. *PLOS ONE*, **12**(5), e0175814, doi:10.1371/journal.pone.0175814.
Dannenberg, A. L., H. Frumkin, J. J. Hess and K. L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: public health implications. *Climatic Change*, **153**(1), 1-14, doi:10.1007/s10584-019-02382-0.
Dantas, B. F. et al., 2020: Rainfall, not soil temperature, will limit the seed germination of dry forest species with climate change. *Oecologia*, **192**(2), 529-541, doi:10.1007/s00442-019-04575-x.
Dávila, D., 2016: *Sistemas de Alerta Temprana ante Inundaciones en América Latina*. Soluciones Prácticas, Lima, Perú, 64 pp. Available at: https://solucionespracticas.org.pe/Sistemas-de-alerta-temprana-ante-inundaciones-en-America-Latina (accessed 16/06/2021).
Davis, M. and S. Naumann, 2017: Making the Case for Sustainable Urban Drainage Systems as a Nature-Based Solution to Urban Flooding. In: *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* [Kabisch, N., H. Korn, J. Stadler and A. Bonn (eds.)]. Springer International Publishing, Cham, pp. 123-137. ISBN 978-3-319-56091-5.
Dawson, R. J. et al., 2018: Urban Areas in Coastal Zones. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W. D. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal and S. Ali Ibrahim (eds.)]. Cambridge University Press, New York, United States of America, pp. 319–362. ISBN 9781316603338.
de Azevedo, T. S., B. P. Bourke, R. Piovezan and M. A. M. Sallum, 2018: The influence of urban heat Islands and socioeconomic factors on the spatial distribution of Aedes aegypti larval habitats. *Geospatial Health*, **13**(1), 179-187, doi:10.4081/gh.2018.623.
de Coninck, H. et al., 2018: Strengthening and implementing the global response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate*

change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.

de Farias, H. S., A. J. de Lucena and V. F. V. V. de Miranda, 2021: Urban Environmental Changes in South America: A Study on Air Pollution and Urban Heat Island over Rio de Janeiro. In: *Practices in Regional Science and Sustainable Regional Development: Experiences from the Global South* [Singh, R. B., S. Chatterjee, M. Mishra and A. J. de Lucena (eds.)]. Springer Singapore, Singapore, pp. 171-197. ISBN 978-981-16-2221-2.

de Jong, P. et al., 2018: Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability. *Science of The Total Environment*, **634**, 1540-1553, doi:10.1016/j.scitotenv.2018.03.256.

de la Barrera, F. et al., 2018: Megafires in Chile 2017: Monitoring multiscale environmental impacts of burned ecosystems. *Science of the Total Environment*, **637-638**, 1526-1536, doi:10.1016/j.scitotenv.2018.05.119.

de Macedo, M. B., C. A. Ferreira do Lago, E. M. Mendiondo and M. H. Giacomoni, 2018: Decentralized Low Impact Development (LID) Practices Addressing the Security of the Water-Energy-Food Nexus. In: *International Low Impact Development Conference 2018*. American Society of Civil Engineers, pp. 30-39.

de Moraes, F. C. et al., 2019: Long-term temporal and spatial patterns in bioeroding sponge distribution at the Abrolhos Bank, Brazil, Southwestern Atlantic. *Marine Ecology*, **40**(3), e12531, doi:10.1111/maec.12531.

de Oliveira Alves, N. et al., 2017: Biomass burning in the Amazon region causes DNA damage and cell death in human lung cells. *Scientific Reports*, **7**(1), 10937, doi:10.1038/s41598-017-11024-3.

de Oliveira, B. F. A. et al., 2019: Human heat stress risk prediction in the Brazilian semiarid region based on the wet-bulb globe temperature. *Anais da Academia Brasileira de Ciencias*, **91**, e20180748, doi:10.1590/0001-3765201920180748.

de Oliveira, G. et al., 2012: Conserving the Brazilian semiarid (Caatinga) biome under climate change. *Biodiversity and Conservation*, **21**(11), 2913-2926, doi:10.1007/s10531-012-0346-7.

de Oliveira, G. et al., 2020: Smoke pollution's impacts in Amazonia. *Science*, **369**(6504), 634, doi:10.1126/science.abd5942.

de Oliveira Soares, M. et al., 2019: Thermal stress and tropical reefs: mass coral bleaching in a stable temperature environment? *Marine Biodiversity*, **49**(6), 2921-2929, doi:10.1007/s12526-019-00994-4.

de Salles Cavedon-Capdeville, F. et al., 2020: Climate Change, Extreme Events and Human Mobility in Latin America: Exploring the Links Through National Laws and Policies. In: *Climate Change, Hazards and Adaptation Options: Handling the Impacts of a Changing Climate* [Leal Filho, W., G. J. Nagy, M. Borga, P. D. Chávez Muñoz and A. Magnuszewski (eds.)]. Springer International Publishing, Cham, pp. 679-700. ISBN 978-3-030-37425-9.

de Siqueira, L. P. et al., 2021: Gender inclusion in ecological restoration. *Restoration Ecology*, e13497, doi:10.1111/rec.13497.

de Souza, D. C. and R. Ramos da Silva, 2021: Ocean-Land Atmosphere Model (OLAM) performance for major extreme meteorological events near the coastal region of southern Brazil. *Climate Research*, **84**, 1-21, doi:10.3354/cr01651.

de Souza Filho, H. M., M. M. B. Vinholis, M. J. Carrer and R. Bernardo, 2021: Determinants of adoption of integrated systems by cattle farmers in the State of Sao Paulo, Brazil. *Agroforestry Systems*, **95**(1), 103-117, doi:10.1007/s10457-020-00565-8.

de Souza Hacon, S., B. F. A. de Oliveira and I. Silveira, 2019: A Review of the Health Sector Impacts of 4 °C or more Temperature Rise. In: *Climate Change Risks in Brazil* [Nobre, C. A., J. A. Marengo and W. R. Soares (eds.)]. Springer International Publishing, Cham, pp. 67-129. ISBN 978-3-319-92881-4.

de Souza, J. G. et al., 2019: Climate change and cultural resilience in late pre-Columbian Amazonia.

Debels, P. et al., 2017: The CLME+ Strategic Action Programme: An ecosystems approach for assessing and managing the Caribbean Sea and North Brazil Shelf Large Marine Ecosystems. *Environmental Development*, **22**, 191-205, doi:10.1016/j.envdev.2016.10.004.

Debortoli, N. S., P. I. M. Camarinha, J. A. Marengo and R. R. Rodrigues, 2017: An index of Brazil's vulnerability to expected increases in natural flash flooding and landslide disasters in the context of climate change. *Natural Hazards*, **86**(2), 557-582, doi:10.1007/s11069-016-2705-2.

Debortoli, N. S. et al., 2015: Rainfall patterns in the Southern Amazon: a chronological perspective (1971–2010). *Climatic Change*, **132**(2), 251-264, doi:10.1007/s10584-015-1415-1.

del Granado, S. et al., 2016: *Sistemas de Alerta Temprana para Inundaciones: Análisis Comparativo de Tres Países Latinoamericanos* [03/2016, D. R. W. P. S. (ed.)]. Institute for Advanced Development Studies, 24 pp. Available at: http://www.inesad.edu.bo/pdf/wp2016/wp03_2016.pdf (accessed 10/08/2021).

del Pozo, A. et al., 2019: Climate Change Impacts and Adaptation Strategies of Agriculture in Mediterranean-Climate Regions (MCRs). *Sustainability*, **11**(10), doi:10.3390/su11102769.

Depietri, Y. and T. McPhearson, 2017: Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In: *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* [Kabisch, N., H. Korn, J. Stadler and A. Bonn (eds.)]. Springer International Publishing, Cham, pp. 91-109. ISBN 978-3-319-56091-5.

Depsky, N. and D. Pons, 2021: Meteorological Droughts Are Projected to Worsen in Central America's Dry Corridor Throughout the 21st Century. *Environmental Research Letters*, **16**(1), 14001, doi:10.1088/1748-9326/abc5e2.

Dereczynski, C. et al., 2020: Downscaling of climate extremes over South America – Part I: Model evaluation in the reference climate. *Weather and Climate Extremes*, **29**, 100273, doi:10.1016/j.wace.2020.100273.
Desbureaux, S. and A.-S. Rodella, 2019: Drought in the city: The economic impact of water scarcity in Latin American metropolitan areas. *World Development*, **114**, 13-27, doi:10.1016/j.worlddev.2018.09.026.
Desmaison, B., C. Boano and G. Astolfo, 2018: CASA [Ciudades Auto-Sostenibles Amazónicas]: desafíos y oportunidades para la sostenibilidad de los proyectos de reasentamiento poblacional preventivo en la Amazonía Peruana. *Medio Ambiente y Urbanización*, **88**, 145-176.
Di Baldassarre, G. et al., 2018: Water shortages worsened by reservoir effects. *Nature Sustainability*, **1**(11), 617-622, doi:10.1038/s41893-018-0159-0.
Di Giulio, G. M. et al., 2018: Mainstreaming climate adaptation in the megacity of São Paulo, Brazil. *Cities*, **72**, 237-244, doi:10.1016/j.cities.2017.09.001.
Diamond, S. K. and I. Ansharyani, 2018: Mismatched priorities, smallholders, and climate adaptation strategies: landuse scientists, it's time to step up. *Journal of Land Use Science*, **13**(4), 447-453, doi:10.1080/1747423X.2018.1537313.
Díaz-Hormazábal, I. and M. E. González, 2016: Spatio-temporal analyses of wildfires in the region of Maule, Chile. *Bosque (Valdivia)*, **37**(1), 147-158, doi:10.4067/S0717-92002016000100014.
Díaz, F. P. et al., 2019: Multiscale climate change impacts on plant diversity in the Atacama Desert. *Global Change Biology*, **25**(5), 1733-1745, doi:10.1111/gcb.14583.
Diffenbaugh, N. S. and F. Giorgi, 2012: Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change*, **114**(3-4), 813-822, doi:10.1007/s10584-012-0570-x.
Dinerstein, E. et al., 2019: A Global Deal For Nature: Guiding principles, milestones, and targets. *Science Advances*, **5**(4), eaaw2869, doi:10.1126/sciadv.aaw2869.
Ding, Q., X. Chen, R. Hilborn and Y. Chen, 2017: Vulnerability to impacts of climate change on marine fisheries and food security. *Marine Policy*, **83**, 55-61, doi:10.1016/j.marpol.2017.05.011.
Diniz, F., F. Gonçalves and S. Sheridan, 2020: Heat Wave and Elderly Mortality: Historical Analysis and Future Projection for Metropolitan Region of São Paulo, Brazil. *Atmosphere*, **11**, 933, doi:10.3390/atmos11090933.
Djoudi, H. et al., 2016: Beyond dichotomies: Gender and intersecting inequalities in climate change studies. *Ambio*, **45**(3), 248-262, doi:10.1007/s13280-016-0825-2.
Dobson, A. P. et al., 2020: Ecology and economics for pandemic prevention. *Science*, **369**(6502), 379-381, doi:10.1126/science.abc3189.
Dodman, D., D. Archer and D. Satterthwaite, 2019: Editorial: Responding to climate change in contexts of urban poverty and informality. *Environment and Urbanization*, **31**(1), 3-12, doi:10.1177/0956247819830004.
Domic, A. I. et al., 2018: Two Thousand Years of Land-Use and Vegetation Evolution in the Andean Highlands of Northern Chile Inferred from Pollen and Charcoal Analyses. *Quaternary*, **1**(3), doi:10.3390/quat1030032.
Domínguez-Castro, F., R. García-Herrera and S. M. Vicente-Serrano, 2018: Wet and dry extremes in Quito (Ecuador) since the 17th century. *International Journal of Climatology*, **38**(4), 2006-2014, doi:10.1002/joc.5312.
Donat, M. G. et al., 2013: Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *Journal of Geophysical Research: Atmospheres*, **118**(5), 2098-2118, doi:10.1002/jgrd.50150.
Donatti, C. I. et al., 2019: Vulnerability of smallholder farmers to climate change in Central America and Mexico: current knowledge and research gaps. *Climate and Development*, **11**(3), 264-286, doi:10.1080/17565529.2018.1442796.
Doswald, N. et al., 2014: Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, **6**(2), 185-201, doi:10.1080/17565529.2013.867247.
Doughty, C. A., 2016: Building climate change resilience through local cooperation: a Peruvian Andes case study. *Regional Environmental Change*, **16**(8), 2187-2197, doi:10.1007/s10113-015-0882-2.
Doughty, C. E. et al., 2015: Drought impact on forest carbon dynamics and fluxes in Amazonia. *Nature*, **519**(7541), 78-82, doi:10.1038/nature14213.
Dow, K. et al., 2013: Limits to adaptation. *Nature Climate Change*, **3**(4), 305-307, doi:10.1038/nclimate1847.
Drenkhan, F. et al., 2015: The changing water cycle: climatic and socioeconomic drivers of water-related changes in the Andes of Peru. *Wiley Interdisciplinary Reviews: Water*, **2**(6), 715-733, doi:10.1002/wat2.1105.
Drenkhan, F., C. Huggel, L. Guardamino and W. Haeberli, 2019: Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin. *Science of the Total Environment*, **665**, 465-483, doi:10.1016/j.scitotenv.2019.02.070.
Drosou, N. et al., 2019: Key Factors Influencing Wider Adoption of Blue–Green Infrastructure in Developing Cities. *Water*, **11**(6), doi:10.3390/w11061234.
Duarte-Abadía, B., R. Boelens and T. Roa-Avendaño, 2015: Hydropower, Encroachment and the Re-patterning of Hydrosocial Territory: The Case of Hidrosogamoso in Colombia. *Human Organization*, **74**(3), 243-254, doi:10.17730/0018-7259-74.3.243.
Duarte, C. et al., 2016: Ocean acidification induces changes in algal palatability and herbivore feeding behavior and performance. *Oecologia*, **180**(2), 453-462, doi:10.1007/s00442-015-3459-3.

Duarte, C. et al., 2018: The energetic physiology of juvenile mussels, Mytilus chilensis (Hupe): The prevalent role of salinity under current and predicted pCO2 scenarios. *Environmental Pollution*, **242**, 156-163, doi:10.1016/j.envpol.2018.06.053.
Duarte, G. A. S. et al., 2020: Heat Waves Are a Major Threat to Turbid Coral Reefs in Brazil. *Frontiers in Marine Science*, **7**, 179, doi:10.3389/fmars.2020.00179.
Duchicela, S. A. et al., 2019: Indicators for assessing tropical alpine rehabilitation practices. *Ecosphere*, **10**(2), e02595, doi:10.1002/ecs2.2595.
Dudley, N. et al., 2018: The essential role of other effective area-based conservation measures in achieving big bold conservation targets. *Global Ecology and Conservation*, **15**, e00424, doi:10.1016/j.gecco.2018.e00424.
Dudley, N. et al., 2010: *Natural Solutions: Protected areas helping people cope with climate change*. IUCN-WCPA, TNC, UNDP, WCS, The World Bank and WWF, Gland, Switzerland, Washington DC and New York, USA. ISBN 978-2-88085-308-2.
Duffy, P. B., P. Brando, G. P. Asner and C. B. Field, 2015: Projections of future meteorological drought and wet periods in the Amazon. *Proceedings of the National Academy of Sciences*, **112**(43), 13172-13177, doi:10.1073/pnas.1421010112.
Dunn, R. J. H. et al., 2020: Development of an Updated Global Land In Situ-Based Data Set of Temperature and Precipitation Extremes: HadEX3. *Journal of Geophysical Research: Atmospheres*, **125**(16), e2019JD032263, doi:10.1029/2019JD032263.
Duque, A. et al., 2021: Mature Andean forests as globally important carbon sinks and future carbon refuges. *Nature Communications*, **12**(1), 2138, doi:10.1038/s41467-021-22459-8.
Duque, A., P. R. Stevenson and K. J. Feeley, 2015: Thermophilization of adult and juvenile tree communities in the northern tropical Andes. *Proceedings of the National Academy of Sciences*, **112**(34), 10744-10749, doi:10.1073/pnas.1506570112.
Durand-Bessart, C. et al., 2020: Analysis of interactions amongst shade trees, coffee foliar diseases and coffee yield in multistrata agroforestry systems. *Crop Protection*, **133**, 105137, doi:10.1016/j.cropro.2020.105137.
Durand, F., 2019: The Odebrecht Tsunami. *NACLA Report on the Americas*, **51**(2), 146-152, doi:10.1080/10714839.2019.1617475.
Dussaillant, I., E. Berthier and F. Brun, 2018: Geodetic Mass Balance of the Northern Patagonian Icefield from 2000 to 2012 Using Two Independent Methods. *Frontiers in Earth Science*, **6**, 8, doi:10.3389/feart.2018.00008.
Dussaillant, I. et al., 2019: Two decades of glacier mass loss along the Andes. *Nat. Geosci.*, **12**(10), 802-808, doi:10.1038/s41561-019-0432-5.
Duval, I. d. B., P. d. S. P. Garcia and R. B. d. Santos, 2018: *Relatório do Projeto Construção de Indicadores de Vulnerabilidade da População como Insumo para a Elaboração das Ações de Adaptação à Mudança do Clima no Brasil: Volume: Mato Grosso do Sul*. Fundação Oswaldo Cruz, Ministério do Meio Ambiente e Fundo Nacional sobre Mudança do Clima FIOCRUZ, Rio de Janeiro, RJ, 112 pp. Available at: https://www.mma.gov.br/images/arquivo/80182/Vulnerabilidade%20%C3%A0%20Mudan%C3%A7a%20do%20Clima/Relat%C3%B3rio_Final_MatoGrossodoSul_Novo.pdf (accessed 11/10/2020).
Eakin, H. C., M. C. Lemos and D. R. Nelson, 2014: Differentiating capacities as a means to sustainable climate change adaptation. *Global Environmental Change*, **27**, 1-8, doi:10.1016/j.gloenvcha.2014.04.013.
Eastin, M. D. et al., 2014: Intra- and interseasonal autoregressive prediction of dengue outbreaks using local weather and regional climate for a tropical environment in Colombia. *American Journal of Tropical Medicine and Hygiene*, **91**(3), 598-610, doi:10.4269/ajtmh.13-0303.
ECLAC, 2013: *Gestión integral de riesgos y seguros agropecuarios en Centroamérica y la República Dominicana: Situación actual y líneas de acción potenciales* ECLAC, 119 pp. Available at: https://repositorio.cepal.org/bitstream/handle/11362/27170/M20130038_es.pdf?sequence=1 (accessed 31/08/2021).
ECLAC, 2015: *Microseguros agropecuarios y gestión integral de riesgos en Centroamérica y la República Dominicana: lineamientos estratégicos para su desarrollo y fortalecimiento*. ECLAC, Ciudad de Mexico, Mexico, 221 pp. Available at: http://hdl.handle.net/11362/39115 (accessed 31/08/2021).
ECLAC, 2018: *Economics of climate change in Latin America and the Caribbean: A graphic view*. Economic Commission for Latin America and the Caribbean, ECLAC, Santiago, Chile, 59 pp. Available at: https://www.cepal.org/en/publications/43889-economics-climate-change-latin-america-and-caribbean-graphic-view (accessed 09/08/2021).
ECLAC, 2019a: *Índices climáticos, políticas de aseguramiento agropecuario y gestión integral de riesgos en Centroamérica y la República Dominicana: Experiencias internacionales y avances regionales*. ECLAC, Ciudad de México, Mexico, 265 pp. Available at: http://hdl.handle.net/11362/45023 (accessed 31/08/2021).
ECLAC, 2019b: *Social Panorama of Latin America, 2018*. Economic Comission for Latin America and the Caribbean (ECLAC), Santiago, Chile, 220 pp. Available at: https://www.cepal.org/en/publications/44396-social-panorama-latin-america-2018 (accessed 21/09/2019).
ECLAC, 2020: *The 2030 Agenda for Sustainable Development in the new global and regional context: Scenarios and projections in the current crisis*. ECLAC, Santiago, Chile, 59 pp. Available at: https://sustainabledevelopment.un.org/content/documents/26088ECLAC_contribution_2020.pdf (accessed 25/08/2021).

ECLAC, 2021: *Social Panorama of Latin America 2020*. ECLAC, 252 pp. Available at: https://www.cepal.org/en/publications/46688-social-panorama-latin-america-2020 (accessed 01/09/2021).
ECLAC et al., 2015: Climate Change in Central America: Potential Impacts and Public Policy Options. CEPAL, México city, México, 173 pp. Available at: https://repositorio.cepal.org/bitstream/handle/11362/39150/S1800827_en.pdf?sequence=7&isAllowed=y (accessed 12/08/2020).
ECLAC and PAHO, 2020: *COVID-19 Report*. ECLAC. Available at: https://repositorio.cepal.org/bitstream/handle/11362/45841/4/S2000461_en.pdf (accessed 31/08/2021).
Eddy, T. D., A. M. Friedlander and P. Salinas de León, 2019: Ecosystem effects of fishing & El Niño at the Galápagos Marine Reserve. *PeerJ*, **7**, e6878, doi:10.7717/peerj.6878.
Eguiguren-Velepucha, P. A. et al., 2016: Tropical ecosystems vulnerability to climate change in southern Ecuador. *Tropical Conservation Science*, **9**(4), doi:10.1177/1940082916668007.
Eitzinger, A. et al., 2017: Assessing high-impact spots of climate change: spatial yield simulations with Decision Support System for Agrotechnology Transfer (DSSAT) model. *Mitigation and Adaptation Strategies for Global Change*, **22**(5), 743-760, doi:10.1007/s11027-015-9696-2.
ELLA, 2013: *Evidences and lessons from Latin America: City-level climate change adaptation and mitigation*. ELLA area: Environmental Management, ELLA Network - south south research, exchange and learning, ELLA, Lima, Peru, 16 pp. Available at: http://ella.practicalaction.org/wp-content/uploads/files/131204_ENV_CitAdaMit_GUIDE.pdf (accessed 17/10/2020).
Ellison, A. M., A. J. Felson and D. A. Friess, 2020: Mangrove Rehabilitation and Restoration as Experimental Adaptive Management. *Frontiers in Marine Science*, **7**, 327, doi:10.3389/fmars.2020.00327.
Ellwanger, J. H. et al., 2020: Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health. *Anais da Academia Brasileira de Ciências*, **92**(1), 1-33, doi:10.1590/0001-3765202020191375.
Eloy, L., E. S. Brondizio and R. Do Pateo, 2015: New Perspectives on Mobility, Urbanisation and Resource Management in Riverine Amazônia. *Bulletin of Latin American Research*, **34**(1), 3-18, doi:10.1111/blar.12267.
Emmer, A., 2017: Geomorphologically effective floods from moraine-dammed lakes in the Cordillera Blanca, Peru. *Quaternary Science Reviews*, **177**, 220-234, doi:10.1016/j.quascirev.2017.10.028.
Emmer, A. et al., 2016: 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods. *CATENA*, **147**, 269-279, doi:10.1016/j.catena.2016.07.032.
Emperaire, L., 2018: *Quais inovações para os sistemas agrícolas tradicionais?* ARU : Revista de Pesquisa Intercultural da Bacia do Rio Negro, **2**, 21-27 pp. Available at: https://www.documentation.ird.fr/hor/fdi:010073891 (accessed 09/08/2021).
Empresa de Pesquisa Energética, 2018: *Plano Decenal de Expansão de Energia 2027*. EPE, Energia, M. d. M. e., Brasilia, Brazil, 345 pp. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/Documents/PDE%202027_aprovado_OFICIAL.pdf (accessed 24/10/2020).
Environmental Secretariat of Paraguay, 2011: *Segunda Comunicación Nacional Cambio Climático Paraguay*. Asunción, Uruguay, 181 pp. Available at: http://euroclimaplus.org/intranet/_documentos/repositorio/02%20Comunicacion%20Convencion%20ONU%20Cambio%20Climatico%20Paraguay%20(2011).pdf (accessed 16/06/2021).
Eriksen, S. et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383, doi:10.1016/j.worlddev.2020.105383.
ESA, 2018: Land Cover CCI Climate Research Data Package (CRDP), European Space Agency. Available at: http://www.esa-landcover-cci.org/?q=node/164 (accessed 07/06/2021).
Escalante Estrada, C. and L. Miranda, 2020: The hillside poor at risk? Land trafficking in Jose Carlos Maritegui at the outskirts of Lima, Peru. In: *Communities, Land and Social Innovation* [Van den Broeck, P., A. Sadiq, I. Hiergens, M. Quintana Molina, H. Verschure and F. Moulaert (eds.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 109-124. ISBN 9781788973762.
Escalera-Antezana, J. P. et al., 2020a: Clinical features of fatal cases of Chapare virus hemorrhagic fever originating from rural La Paz, Bolivia, 2019: A cluster analysis. *Travel Medicine and Infectious Disease*, **36**, 101589, doi:10.1016/j.tmaid.2020.101589.
Escalera-Antezana, J. P. et al., 2020b: Orthohantavirus pulmonary syndrome in Santa Cruz and Tarija, Bolivia, 2018. *International Journal of Infectious Diseases*, **90**, 145-150, doi:10.1016/j.ijid.2019.10.021.
Escobar-Camacho, D. et al., 2021: Oceanic islands and climate: using a multi-criteria model of drivers of change to select key conservation areas in Galapagos. *Regional Environmental Change*, **21**(2), 47, doi:10.1007/s10113-021-01768-0.
Espinet, X., A. Schweikert, N. van den Heever and P. Chinowsky, 2016: Planning resilient roads for the future environment and climate change: Quantifying the vulnerability of the primary transport infrastructure system in Mexico. *Transp. Policy*, **50**, 78-86, doi:10.1016/j.tranpol.2016.06.003.
Espinoza, J. C. et al., 2014: The extreme 2014 flood in south-western Amazon basin: the role of tropical-subtropical South Atlantic SST gradient. *Environmental Research Letters*, **9**(12), 124007, doi:10.1088/1748-9326/9/12/124007.

Espinoza, J. C., J. Ronchail, J. A. Marengo and H. Segura, 2019a: Contrasting North–South changes in Amazon wet-day and dry-day frequency and related atmospheric features (1981–2017). *Climate Dynamics*, **52**(9), 5413-5430, doi:10.1007/s00382-018-4462-2.
Espinoza, J. C. et al., 2016: Evolution of wet-day and dry-day frequency in the western Amazon basin: Relationship with atmospheric circulation and impacts on vegetation. *Water Resources Research*, **52**(11), 8546-8560, doi:10.1002/2016WR019305.
Espinoza, J. C. et al., 2019b: Regional hydro-climatic changes in the Southern Amazon Basin (Upper Madeira Basin) during the 1982–2017 period. *Journal of Hydrology: Regional Studies*, **26**, 100637, doi:10.1016/j.ejrh.2019.100637.
Esquivel-Muelbert, A. et al., 2019: Compositional response of Amazon forests to climate change. *Global Change Biology*, **25**(1), 39-56, doi:10.1111/gcb.14413.
Estallo, E. L. et al., 2020: A decade of arbovirus emergence in the temperate southern cone of South America: dengue, Aedes aegypti and climate dynamics in Córdoba, Argentina. *Heliyon*, **6**(9), e04858, doi:10.1016/j.heliyon.2020.e04858.
Estrada, G. C. D., M. L. G. Soares, V. Fernadez and P. M. M. de Almeida, 2015: The economic evaluation of carbon storage and sequestration as ecosystem services of mangroves: a case study from southeastern Brazil. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **11**(1), 29-35, doi:10.1080/21513732.2014.963676.
Estrella, B. et al., 2019: Air pollution control and the occurrence of acute respiratory illness in school children of Quito, Ecuador. *Journal of Public Health Policy*, **40**(1), 17-34, doi:10.1057/s41271-018-0148-6.
Ewbank, R. et al., 2019: Building resilience to El Niño-related drought: experiences in early warning and early action from Nicaragua and Ethiopia. *Disasters*, **43**(S3), S345-S367, doi:10.1111/disa.12340.
Fadrique, B. et al., 2018: Widespread but heterogeneous responses of Andean forests to climate change. *Nature*, **564**(7735), 207-212, doi:10.1038/s41586-018-0715-9.
Falcão, N. P. S., C. R. Clement, S. M. Tsai and N. B. Comerford, 2009: Pedology, fertility, and biology of central amazonian dark earths. In: *Amazonian Dark Earths: Wim Sombroek's Vision* [Springer (ed.)], Dordrecht, pp. 213-228. ISBN 9781402090301.
FAO, 2016a: Corredor Seco América Central. Informe de Situación-Junio 2016. 3 Available at: http://www.fao.org/3/a-br092s.pdf (accessed 16/06/2021).
FAO, 2016b: *El Rol de la Mujer en la Pesca y La Acuicultura en Chile, Colombia, Paraguay y Peru*. Food and Agriculture Organization of the United Nations, Santiago de Chile, 38 pp. Available at: http://www.fao.org/3/i5774s/i5774s.pdf (accessed 16/06/2021).
FAO, 2016c: *State of the World's Forests 2016*. Forests and agriculture: land-use challenges and opportunities, FAO, Rome, Italy, 126 pp. Available at: http://www.fao.org/3/a-i5588e.pdf (accessed 14/09/2020).
FAO, 2018: *The state of world fisheries and aquaculture. Meeting the sustainable development goals*. **3**, Food and Agriculture Organization of the United Nations, Rome, 227 pp. Available at: http://www.fao.org/3/i9540en/i9540en.pdf (accessed 25/09/2019).
FAO, 2020a: *The dual threat of extreme weather and the COVID-19 crisis: Anticipating the impacts on food availability*. FAO, Roma, Italy. Available at: https://doi.org/10.4060/cb0206en (accessed 29/06/2021).
FAO, 2020b: *Impact of COVID-19 on informal workers*. Rome, Italy. Available at: https://doi.org/10.4060/ca8560en (accessed 29/06/2021).
FAO, 2021a: *Crop Prospects and Food Situation - Quarterly Global Report No. 1, March 2021*. FAO, Rome, Italy, 46 pp. Available at: https://doi.org/10.4060/cb3672en (accessed 29/06/2021).
FAO, 2021b: *FAO's work on climate change - Fisheries and aquaculture 2020*. FAO, Rome, Italy, 79 pp. Available at: https://doi.org/10.4060/cb3414en (accessed 29/06/2021).
FAO, 2021c: *The impact of COVID-19 on fisheries and aquaculture food systems. Possible responses: Information paper, November 2020*. FAO, Rome, Italy. ISBN 9789251337684.
FAO and ECLAC, 2020: *Food systems and COVID-19 in Latin America and the Caribbean: Impact and risks in the labour market. Bulletin 5*. Rome, Italy, 18 pp. Available at: https://doi.org/10.4060/ca9237en (accessed 29/06/2021).
FAO and Fundación Futuro Latinoamericano, 2019: *Resiliencia climática rural en América Latina, Una reseña de experiencias, lecciones aprendidas y escalamiento*. FAO and Fundación Futuro Latinoamericano, Quito, 20 pp. Available at: http://www.fao.org/3/ca4632es/ca4632es.pdf (accessed 25/09/2019).
FAO et al., 2021: *Regional Overview of Food Security and Nutrition in Latin America and the Caribbean 2020 – Food security and nutrition for lagging territories.* . FAO, I., PAHO, WFP, UNICEF, Santiago, Chile, 150 pp. Available at: https://doi.org/10.4060/cb2242en (accessed 30/06/2021).
FAO and UNEP, 2020: *The State of the World's Forests 2020. Forests, biodiversity and people*. Rome, Italy, 214 pp. Available at: https://doi.org/10.4060/ca8642en (accessed 25/08/2021).
Farías-Barahona, D. et al., 2019: Geodetic mass balances and area changes of Echaurren Norte Glacier (Central Andes, Chile) between 1955 and 2015. *Remote Sensing*, **11**(3), 260, doi:10.3390/rs11030260.
Federal Office of Meteorology and Climatology MeteoSwiss, 2021: SPI and SPEI. Available at: https://www.meteoswiss.admin.ch/home/climate/swiss-climate-in-detail/climate-indicators/drought-indices/spi-and-spei.html.

Feeley, K. J. et al., 2013: Compositional shifts in Costa Rican forests due to climate-driven species migrations. *Global Change Biology*, **19**(11), 3472-3480, doi:10.1111/gcb.12300.
Feeley, K. J. and M. R. Silman, 2016: Disappearing climates will limit the efficacy of Amazonian protected areas. *Diversity and Distributions*, **22**(11), 1081-1084, doi:10.1111/ddi.12475.
Feeley, K. J. et al., 2011: Upslope migration of Andean trees. *Journal of Biogeography*, **38**(4), 783-791, doi:10.1111/j.1365-2699.2010.02444.x.
Feldpausch, T. R. et al., 2016: Amazon forest response to repeated droughts. *Global Biogeochemical Cycles*, **30**(7), 964-982, doi:10.1002/2015GB005133.
Fercovic, J., W. Foster and O. Melo, 2019: Economic development and residential water consumption in Chile. *Environment and Development Economics*, **24**(1), 23-46, doi:10.1017/S1355770X18000463.
Fernandez-Manjarrés, J., 2018: Using Ecological Modelling Tools to Inform Policy Makers of Potential Changes in Crop Distribution: An Example with Cacao Crops in Latin America. In: *Economic Tools and Methods for the Analysis of Global Change Impacts on Agriculture and Food Security* [Quiroga, S. (ed.)]. Springer, Cham, Switzerland, pp. 11-23. ISBN 331999462X.
Fernández, C. and S. Buss, 2016: *Ocurrencia y Gestión de inundaciones en América Latina y el Caribe – Factores claves y experiencia adquirida*. Banco Interamericano de Desarrollo (BID), 27 pp. Available at: https://publications.iadb.org/es/publicacion/15599/ocurrencia-y-gestion-de-inundaciones-en-america-latina-y-el-caribe-factores (accessed 16/06/2021).
Fernandez, E., C. Whitney, I. F. Cuneo and E. Luedeling, 2020: Prospects of decreasing winter chill for deciduous fruit production in Chile throughout the 21st century. *Climatic Change*, **159**(3), 423-439, doi:10.1007/s10584-019-02608-1.
Fernández, F. J. et al., 2019: Implications of climate change for semi-arid dualistic agriculture: a case study in Central Chile. *Regional Environmental Change*, **19**(1), 89-100, doi:10.1007/s10113-018-1380-0.
Fernández, I. C. and J. Wu, 2016: Assessing environmental inequalities in the city of Santiago (Chile) with a hierarchical multiscale approach. *Applied Geography*, **74**, 160-169, doi:10.1016/j.apgeog.2016.07.012.
Fernández Kolb, P. et al., 2019: *Climate Smart Coffee in El Salvador*. International Center for Tropical Agriculture (CIAT), Cali, Colombia, 22 pp. Available at: https://hdl.handle.net/10568/103773.
Feron, S. et al., 2019: Observations and Projections of Heat Waves in South America. *Scientific Reports*, **9**(1), 8173-8173, doi:10.1038/s41598-019-44614-4.
Ferreira, A. C. and L. D. Lacerda, 2016: Degradation and conservation of Brazilian mangroves, status and perspectives. *Ocean & Coastal Management*, **125**, 38-46, doi:10.1016/j.ocecoaman.2016.03.011.
Ferreira Filho, J. B. d. S. and G. I. d. Moraes, 2015: Climate change, agriculture and economic effects on different regions of Brazil. *Environment and Development Economics*, **20**(1), 37-56, doi:10.1017/S1355770X14000126.
Ferreira, L. S. and D. H. S. Duarte, 2019: Exploring the relationship between urban form, land surface temperature and vegetation indices in a subtropical megacity. *Urban Climate*, **27**, 105-123, doi:10.1016/j.uclim.2018.11.002.
Ferreira, M. N. et al., 2021: Drivers and causes of zoonotic diseases: an overview. *PARKS*, **27**, doi:10.2305/IUCN.CH.2021.PARKS-27-SIMNF.en.
Ferrero, R., M. Lima and J. L. Gonzalez-Andujar, 2018: Crop production structure and stability under climate change in South America. *Ann. Appl. Biol.*, **172**(1), 65-73, doi:10.1111/aab.12402.
Ferro, V. G., P. Lemes, A. S. Melo and R. Loyola, 2014: The reduced effectiveness of protected areas under climate change threatens Atlantic forest tiger moths. *PLoS ONE*, **9**(9), e107792, doi:10.1371/journal.pone.0107792.
Figueroa, M. et al., 2020: On the relationship between reversal of the river stage (repiquetes), rainfall and low-level wind regimes over the western Amazon basin. *Journal of Hydrology: Regional Studies*, **32**, 100752, doi:10.1016/j.ejrh.2020.100752.
Filho, J. P. D., D. M. Lapola, R. R. Torres and M. C. Lemos, 2016: Socio-climatic hotspots in Brazil: how do changes driven by the new set of IPCC climatic projections affect their relevance for policy? *Climatic Change*, **136**(3), 413-425, doi:10.1007/s10584-016-1635-z.
Filho, W. L. et al., 2019: Assessing the impacts of climate change in cities and their adaptive capacity: Towards transformative approaches to climate change adaptation and poverty reduction in urban areas in a set of developing countries. *Science of The Total Environment*, **692**, 1175-1190, doi:10.1016/j.scitotenv.2019.07.227.
Fisher, E., J. Hellin, H. Greatrex and N. Jensen, 2019: Index insurance and climate risk management: Addressing social equity. *Development Policy Review*, **37**(5), 581-602, doi:10.1111/dpr.12387.
Flachsbarth, I. et al., 2015: The Role of Latin America's Land and Water Resources for Global Food Security: Environmental Trade-Offs of Future Food Production Pathways. *PLOS ONE*, **10**(1), e0116733, doi:10.1371/journal.pone.0116733.
Fletcher, I. K. et al., 2021: Climate services for health: From global observations to local interventions. *Med*, **2**(4), 355-361, doi:10.1016/j.medj.2021.03.010.
Fletcher, I. K. et al., 2020: The Relative Role of Climate Variation and Control Interventions on Malaria Elimination Efforts in El Oro, Ecuador: A Modeling Study. *Front. Environ. Sci.*, **8**, 135, doi:10.3389/fenvs.2020.00135.
Flores, B. M. and M. Holmgren, 2021: White-Sand Savannas Expand at the Core of the Amazon After Forest Wildfires. *Ecosystems*, doi:10.1007/s10021-021-00607-x.
Fontoura, N. F. et al., 2016: Aspects of fish conservation in the upper Patos Lagoon basin. *Journal of Fish Biology*, **89**(1), 315-336, doi:10.1111/jfb.13005.

Fontúrbel, F. E., A. Lara, D. Lobos and C. Little, 2018: The cascade impacts of climate change could threaten key ecological interactions. *Ecosphere*, **9**(12), e02485, doi:10.1002/ecs2.2485.
Forcella, D., R. Moser and L. Gonzalez, 2015: Rural Microfinance and Climate Change: Geographical Credits Allocation and Vulnerability. An Analysis of Agroamigo in Brazil's Northeastern States. *SSRN*, doi:10.2139/ssrn.2599056.
Ford, A., R. Dawson, P. Blythe and S. Barr, 2018: Land-use transport models for climate change mitigation and adaptation planning. *J. Transp. Land Use*, **11**(1), 83-101, doi:10.5198/jtlu.2018.1209.
Forero, E., Y. Hernández and C. Zafra, 2014: Percepción Latinoamericana de cambio climático: metodologías, herramientas y estrategias de adaptación en comunidades locales. Una revisión. *Revista U.D.C.A Actualidad & Divulgación Científica*, **17**(1), 73-85.
Foresta, L. et al., 2018: Heterogeneous and rapid ice loss over the Patagonian Ice Fields revealed by CryoSat-2 swath radar altimetry. *Remote Sensing of Environment*, **211**, 441-455, doi:10.1016/j.rse.2018.03.041.
Foro Ciudades Para la Vida, 2021: Observatorio Climático Local - Perú, Peru.
Forster, P. M. et al., 2020: Current and future global climate impacts resulting from COVID-19. *Nature Climate Change*, **10**(10), 913-919, doi:10.1038/s41558-020-0883-0.
Forzza, R. C. et al., 2012: New Brazilian Floristic List Highlights Conservation Challenges. *BioScience*, **62**(1), 39-45, doi:10.1525/bio.2012.62.1.8.
Fragkos, P., 2020: Global Energy System Transformations to 1.5 °C: The Impact of Revised Intergovernmental Panel on Climate Change Carbon Budgets. *Energy Technology*, **8**(9), 2000395, doi:10.1002/ente.202000395.
Frangoudes, K. and S. Gerrard, 2018: (En)Gendering Change in Small-Scale Fisheries and Fishing Communities in a Globalized World. *Maritime Studies*, **17**(2), 117-124, doi:10.1007/s40152-018-0113-9.
Frank, S. et al., 2019: Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target. *Nature Climate Change*, **9**(1), 66-72, doi:10.1038/s41558-018-0358-8.
French, A. and R. Mechler, 2017: *Managing El Niño Risks Under Uncertainty in Peru: Learning from the past for a more disaster-resilient future*. International Institute for Applied Systems Analysis, Laxenburg, Austria, 39 pp. Available at: http://pure.iiasa.ac.at/id/eprint/14849/1/French_Mechler_2017_El%20Ni%C3%B1o_Risk_Peru_Report.pdf (accessed 21/09/2019).
Frenz, P., I. Delgado, J. S. Kaufman and S. Harper, 2014: Achieving effective universal health coverage with equity: evidence from Chile. *Health Policy and Planning*, **29**(6), 717-731, doi:10.1093/heapol/czt054.
FSIN and Global Network Against Food Crisis, 2021: *Global Report on Food Crises 2021*. Rome, Italy. Available at: https://www.wfp.org/publications/global-report-food-crises-2021 (accessed 29/06/2021).
Fu, R. et al., 2013: Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proceedings of the National Academy of Sciences*, **110**(45), 18110-18115, doi:10.1073/pnas.1302584110.
Fuentes-Castillo, T., H. J. Hernández and P. Pliscoff, 2020: Hotspots and ecoregion vulnerability driven by climate change velocity in Southern South America. *Regional Environmental Change*, **20**(1), 27, doi:10.1007/s10113-020-01595-9.
Fuentes-Franco, R. et al., 2015: Inter-annual variability of precipitation over Southern Mexico and Central America and its relationship to sea surface temperature from a set of future projections from CMIP5 GCMs and RegCM4 CORDEX simulations. *Climate Dynamics*, **45**(1-2), 425-440, doi:10.1007/s00382-014-2258-6.
Fuentes, I., R. Fuster, D. Avilés and W. Vervoort, 2021: Water scarcity in central Chile: the effect of climate and land cover changes on hydrologic resources. *Hydrological Sciences Journal*, **66**(6), 1028-1044, doi:10.1080/02626667.2021.1903475.
Funatsu, B. M. et al., 2019: Perceptions of climate and climate change by Amazonian communities. *Global Environmental Change*, **57**, 101923, doi:10.1016/j.gloenvcha.2019.05.007.
Gabriel, C. and L. Macdonald, 2018: After the International Organization for Migration: recruitment of Guatemalan temporary agricultural workers to Canada. *Journal of Ethnic and Migration Studies*, **44**(10), 1706-1724, doi:10.1080/1369183X.2017.1354062.
Gagné, T. O. et al., 2020: Towards a global understanding of the drivers of marine and terrestrial biodiversity. *PLOS ONE*, **15**(2), e0228065, doi:10.1371/journal.pone.0228065.
Gaitán, J. J. et al., 2014: Vegetation structure is as important as climate for explaining ecosystem function across patagonian rangelands. *Journal of Ecology*, **102**(6), 1419-1428, doi:10.1111/1365-2745.12273.
Galarza, E. and J. Kámiche, 2015: *Pesca Artesanal: Oportunidades para del desarrollo regional*. Universidad del Pacífico, Lima, Peru, 120 pp. ISBN 978-9972-57-342-2.
Gallardo-Fernández, G. L. and F. Saunders, 2018: "Before we asked for permission, now we only give notice": Women's entrance into artisanal fisheries in Chile. *Maritime Studies*, **17**(2), 177-188, doi:10.1007/s40152-018-0110-z.
Gamez, L., 2016: Lost in the definition: Environmental displacement in Salgar, Colombia. In: *The State of Environmental Migration 2016: A review of 2015* [Gemenne, F., C. Zickgraf and D. Ionesco (eds.)]. Presses Universitaires de Liège, Lieja, pp. 106-122.
García-Reyes, M. et al., 2015: Under Pressure: Climate Change, Upwelling, and Eastern Boundary Upwelling Ecosystems. *Frontiers in Marine Science*, **2**, 109.

Garcia-Solorzano, F. O. et al., 2019: El Niño Southern Oscillation and tuberculosis: Is there an association? *Journal of Infection and Public Health*, **12**(2), 292-293, doi:10.1016/j.jiph.2018.11.007.
Garcia Ferrari, S., H. Smith, F. Coupe and H. Rivera, 2018: City profile: Medellin. *Cities*, **74**, 354-364, doi:10.1016/j.cities.2017.12.011.
Garcia, L. C. et al., 2021: Record-breaking wildfires in the world's largest continuous tropical wetland: Integrative fire management is urgently needed for both biodiversity and humans. *Journal of Environmental Management*, **293**, 112870, doi:10.1016/j.jenvman.2021.112870.
Garçon, V. et al., 2019: Multidisciplinary Observing in the World Ocean's Oxygen Minimum Zone Regions: From Climate to Fish — The VOICE Initiative. *Frontiers in Marine Science*, **6**, 722.
Gardner, A. S. et al., 2013: A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009. *Science*, **340**(6134), 852-857, doi:10.1126/science.1234532.
Gardner, R. C. and C. Finlayson, 2018: *Global Wetland Outlook: State of the World's Wetlands and Their Services to People*. Ramsar Convention Secretariat, 89 pp. Available at: https://ssrn.com/abstract=3261606 (accessed 24/10/2020).
Garrido, R. et al., 2019: Potential impact of climate change on the geographical distribution of two wild vectors of Chagas disease in Chile: Mepraia spinolai and Mepraia gajardoi. *Parasites & Vectors*, **12**(1), 478, doi:10.1186/s13071-019-3744-9.
Gasalla, M. A., P. R. Abdallah and D. Lemos, 2017: Potential Impacts of Climate Change in Brazilian Marine Fisheries and Aquaculture. In: *Climate Change Impacts on Fisheries and Aquaculture* [Phillips, B. F. and M. Pérez-Ramírez (eds.)]. Wiley, pp. 454-477. ISBN 9781119154044.
Gateau-Rey, L. et al., 2018: Climate change could threaten cocoa production: Effects of 2015-16 El Niño-related drought on cocoa agroforests in Bahia, Brazil. *PLoS ONE*, **13**(7), e0200454, doi:10.1371/journal.pone.0200454.
Gatti, L. V. et al., 2021: Amazonia as a carbon source linked to deforestation and climate change. *Nature*, **595**(7867), 388-393, doi:10.1038/s41586-021-03629-6.
Gebara, M. F. and A. Agrawal, 2017: Beyond rewards and punishments in the Brazilian Amazon: Practical implications of the REDD+ discourse. *Forests*, **8**(3), 1-27, doi:10.3390/f8030066.
Geirinhas, J. L. et al., 2018: Climatic and synoptic characterization of heat waves in Brazil. *International Journal of Climatology*, **38**(4), 1760-1776, doi:10.1002/joc.5294.
Gelcich, S. et al., 2015: Alternative strategies for scaling up marine coastal biodiversity conservation in Chile. *Maritime Studies*, **14**(1), 5, doi:10.1186/s40152-015-0022-0.
Gemenne, F. et al., 2020: Transformative climate action in cities. *Forced Migration Review*,(63), 32-35.
Giorgi, F. et al., 2014: Changes in extremes and hydroclimatic regimes in the CREMA ensemble projections. *Climatic Change*, **125**(1), 39-51, doi:10.1007/s10584-014-1117-0.
Glade, F. E., M. D. Miranda, F. J. Meza and W. J. D. van Leeuwen, 2016: Productivity and phenological responses of natural vegetation to present and future inter-annual climate variability across semi-arid river basins in Chile. *Environmental Monitoring and Assessment*, **188**(12), 676, doi:10.1007/s10661-016-5675-7.
Gleick, P. H., 2002: Water management: Soft water paths. *Nature*, **418**(6896), 373, doi:10.1038/418373a.
Global Data Lab, 2020: Human Development Indices, Global Data Lab. Available at: https://globaldatalab.org/shdi/shdi/ (accessed 20/05/2021).
Global Health Security Index, 2019: *Global Health Security Index: Building Collective Action and Accountability*. 324 pp. Available at: https://www.ghsindex.org/wp-content/uploads/2020/04/2019-Global-Health-Security-Index.pdf (accessed 29/06/2021).
Gloor, M. et al., 2015: Recent Amazon climate as background for possible ongoing and future changes of Amazon humid forests. *Global Biogeochemical Cycles*, **29**(9), 1384-1399, doi:10.1002/2014GB005080.
Glynn, P. W. et al., 2017: El Niño-Southern Oscillation: Effects on Eastern Pacific Coral Reefs and Associated Biota. In: *Coral Reefs of the Eastern Tropical Pacific: Persistence and Loss in a Dynamic Environment* [Glynn, P. W., D. P. Manzello and I. C. Enochs (eds.)]. Springer Netherlands, Dordrecht, pp. 251-290. ISBN 978-94-017-7499-4.
Gobernación de Escuintla, Acción Contra el Hambre and Instituto Privado de Cambio Climático, 2017: *Sistematización de la experiencia de las mesas técnicas de los ríos Madre Vieja y Achiguate en el Departamento de Escuintla*. Instituto Privado de Cambio Climático ICC, Guatemala, 47 pp.
Gobierno de la Ciudad de Buenos Aires, 2011: *El Plan de Movilidad Sustentable de la Ciudad de Buenos Aires*, Secretaría de Transporte, Buenos Aires, Argentina, 37 pp. Available at: https://pt.slideshare.net/dianamondino/transporte-buenos-aires-2020-plan-de-movilidad-20-g-krantzer (accessed 17/10/2020).
Gobierno de la Ciudad de Buenos Aires, 2015: *Plan de Acción frente al Cambio Climático 2020*, Buenos Aires, Argentina. Available at: http://cdn2.buenosaires.gob.ar/espaciopublico/apra/pacc_2020.pdf (accessed 01/09/2021).
Gobierno de la Ciudad de Buenos Aires, 2020: *Plan de Acción frente al Cambio Climático 2020*, Buenos Aires, Argentina. Available at: http://cdn2.buenosaires.gob.ar/espaciopublico/apra/pacc_2020.pdf (accessed 01/11/2020).
Gobierno Nacional de la República del Ecuador, 2015: *Plan Nacional de Cambio Climático*, Ecuador, 55 pp. Available at: https://info.undp.org/docs/pdc/Documents/ECU/PLAN%20NACIONAL%20DE%20CAMBIO%20CLIM%C3%81TICO.pdf (accessed 16/06/2021).

Godber, O. F. and R. Wall, 2014: Livestock and food security: Vulnerability to population growth and climate change. *Global Change Biology*, **20**(10), 3092-3102, doi:10.1111/gcb.12589.
Godfrey, P. C., 2012: Introduction: Race, Gender & Class and Climate Change. *Race, Gender & Class*, **19**(1/2), 3-11.
Godoy, M. D. P. and L. D. d. Lacerda, 2015: Mangroves Response to Climate Change: A Review of Recent Findings on Mangrove Extension and Distribution. *Anais da Academia Brasileira de Ciências*, **87**, 651-667, doi:10.1590/0001-3765201520150055.
Goes, G. V. et al., 2020: MRV framework and prospective scenarios to monitor and ratchet up Brazilian transport mitigation targets. *Climatic Change*, **162**(4), 2197-2217, doi:10.1007/s10584-020-02767-6.
Gómez-González, S., F. Ojeda and P. M. Fernandes, 2018: Portugal and Chile: Longing for sustainable forestry while rising from the ashes. *Environmental Science & Policy*, **81**, 104-107, doi:10.1016/j.envsci.2017.11.006.
Gomez, L. et al., 2021: Use of isotopes techniques to reveal the origin of water salinity in an arid region of Central-Western Argentina. *Science of The Total Environment*, **763**, 142935, doi:10.1016/j.scitotenv.2020.142935.
Gómez Salazar, A. and N. Cuvi, 2016: Asentamientos informales y medio ambiente en Quito. *Areas. Revista Internacional de Ciencias Sociales*,(35), 101-119.
González-Rojas, C. H. et al., 2021: Short-term air pollution events in the Atacama desert, Chile. *Journal of South American Earth Sciences*, **105**, 103010, doi:10.1016/j.jsames.2020.103010.
González, J. E., B. Yannicelli and W. Stotz, 2021: The interplay of natural variability, productivity and management of the benthic ecosystem in the Humboldt Current System: Twenty years of assessment of Concholepas concholepas fishery under a TURF management system. *Ocean & Coastal Management*, **208**, 105628, doi:10.1016/j.ocecoaman.2021.105628.
González, M. E., A. Lara, R. Urrutia and J. Bosnich, 2011: Cambio climático y su impacto potencial en la ocurrencia de incendios forestales en la zona centro-sur de Chile (33º - 42º S). *Bosque (Valdivia)*, **32**(3), 215-219, doi:10.4067/s0717-92002011000300002.
González, P., A. Dominguez and A. M. Moraga, 2019: The effect of outdoor PM2.5 on labor absenteeism due to chronic obstructive pulmonary disease. *International Journal of Environmental Science and Technology*, **16**(8), 4775-4782, doi:10.1007/s13762-018-2111-2.
González, S. A. and G. Holtmann-Ahumada, 2017: Quality of tourist beaches of northern Chile: A first approach for ecosystem-based management. *Ocean & Coastal Management*, **137**, 154-164, doi:10.1016/j.ocecoaman.2016.12.022.
Gopal, S. et al., 2015: Modeling Coastal and Marine Environmental Risks in Belize: the Marine Integrated Decision Analysis System (MIDAS). *Coastal Management*, **43**(3), 217-237, doi:10.1080/08920753.2015.1030292.
Gori Maia, A. et al., 2021: The economic impacts of the diffusion of agroforestry in Brazil. *Land Use Policy*, **108**, 105489, doi:10.1016/j.landusepol.2021.105489.
Gorman, D., 2018: Historical Losses of Mangrove Systems in South America from Human-Induced and Natural Impacts. In: *Threats to Mangrove Forests: Hazards, Vulnerability, and Management* [Makowski, C. and C. W. Finkl (eds.)]. Springer International Publishing, Cham, pp. 155-171. ISBN 978-3-319-73016-5.
Government of Brazil, 2007: *National Adaptation Plan to Climate Change*, 46 pp. Available at: https://www.mma.gov.br/clima/politica-nacional-sobre-mudanca-do-clima/plano-nacional-sobre-mudanca-do-clima (accessed 16/06/2021).
Government of Brazil, 2012: *Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura*. Ministério da Agricultura, Pecuária e Abastecimento, 173 pp. Available at: https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/plano-abc/arquivo-publicacoes-plano-abc/download.pdf (accessed 03/09/2021).
Government of Brazil, 2016: *Plano Nacional de Adaptação à Mudança do Clima. Volume 2: estratégias setoriais e temáticas Portaria MMA no150 de 10 de maio de 2016*, **2**, Ambiente, M. d. M., Republica Federativa do Brasil, Brasilia, Brazil. Available at: http://adaptaclima.mma.gov.br/conteudos/18 (accessed 01/09/2021).
Government of Brazil, 2020: *Fourth National Communication of Brazil*, UNFCCC, 537 pp. Available at: https://unfccc.int/documents/267657 (accessed 29/06/2021).
Government of Brazil and Ministry of Science Technology and Innovation Secretariat of Policies and Programs, 2021: AdaptaBrasil MCTI. Available at: https://adaptabrasil.mcti.gov.br/.
Government of Chile, 2014: *Plan de Adaptacion al Cambio Climatico*. 80 pp. Available at: https://mma.gob.cl/wp-content/uploads/2016/02/Plan-Nacional-Adaptacion-Cambio-Climatico-version-final.pdf (accessed 16/06/2021).
Government of Colombia, 2016: *Plan Nacional De Adaptación Al Cambio Climático*, 100 pp. Available at: https://www.minambiente.gov.co/index.php/component/content/article/476-plantilla-cambio-climatico-%2032 (accessed 16/06/2021).
Government of Costa Rica, 2018: *Política Nacional de Adaptación al Cambio Climático de Costa Rica 2018-2030*, 84 pp. Available at: http://www.pgrweb.go.cr/DocsDescargar/Normas/No%20DE-41091/Version1/Politica_ADAPTACION_24_abril.pdf (accessed 17/10/2020).
Government of Ecuador, 2015: *Plan Nacional del Cambio Climático 2015-2018*, 55 pp. Available at: https://info.undp.org/docs/pdc/Documents/ECU/PLAN%20NACIONAL%20DE%20CAMBIO%20CLIM%C3%81TICO.pdf (accessed 16/06/2021).
Government of El Salvador, 2019: *Plan Nacional de Adaptación al Cambio Climático: Construyendo resiliencia climática en El Salvador*, Naturales, M. d. M. A. y. R., 58 pp. Available at:

http://rcc.marn.gob.sv/bitstream/handle/123456789/371/PlanNacionalAdaptacionCC.pdf?sequence=1&isAllowed=y (accessed 17/10/2020).
Government of Guatemala, 2016: *Plan de Accion Nacional de Cambio Climatico*. Available at: http://www.segeplan.gob.gt/nportal/index.php/biblioteca-documental/file/480-plan-de-accion-de-cambio-climatico (accessed 16/06/2021).
Government of Honduras, 2018: *Plan Nacional de Adaptación al Cambio Climatico Honduras*, Ambiente, S. d. R. N. y., Gobierno de la República de Honduras, 64 pp. Available at: http://www.miambiente.gob.hn/media/adjuntos/pdf/DNCC/2018-05-10/16%3A35%3A53.282976%2B00%3A00/PNA.pdf (accessed 01/09/2021).
Government of Paraguay, 2017: *Plan Nacional de Adaptación al Cambio Climatico*, Government de Paraguay, Asunción, Paraguay, 160 pp. Available at: https://www4.unfccc.int/sites/NAPC/Documents/Parties/Plan%20Nacional%20de%20Adaptaci%C3%B3n%20al%20Cambio%20Clim%C3%A1tico_Paraguay_final.pdf (accessed 16/06/2021).
Government of Peru, 2005: *Plan Maestro de Transporte Urbano para el Área Metropolitana de Lima y Callao en la República del Perú (Fase 1): Informe Final (Volumen - I)*, **I**, Ministerio de Transportes y Comunicaciones de la Republica del Perú, Lima, Perú, 86 pp. Available at: https://openjicareport.jica.go.jp/pdf/11798261_01.pdf (accessed 17/10/2020).
Government of Peru, 2010: Plan de Acción de Adaptación y Mitigación Frente al Cambio climático. Government of Peru, Lima, 152 pp.
Government of Peru, 2016: Legislative Decree 1280, art. 27 and article 141 of the Decree´s Code, Peru. Available at: https://www.minam.gob.pe/wp-content/uploads/2017/04/Decreto-Legislativo-N%C2%B0-1280.pdf (accessed 01/09/2021).
Government of Suriname, 2019: *Suriname National Adaptation Plan (NAP), 2019- 2029*, Suriname, 176 pp. Available at: https://www4.unfccc.int/sites/NAPC/Documents/Parties/Suriname%20Final%20NAP_apr%202020.pdf (accessed 23/10/2020).
Graesser, J., T. M. Aide, H. R. Grau and N. Ramankutty, 2015: Cropland/pastureland dynamics and the slowdown of deforestation in Latin America. *Environmental Research Letters*, **10**(3), 034017, doi:10.1088/1748-9326/10/3/034017.
Graham, K., 2017: International Intent and Domestic Application of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES): The Case of the Ocelot (Leopardus pardalis). *Journal of International Wildlife Law & Policy*, **20**(3-4), 253-294, doi:10.1080/13880292.2017.1403797.
Gray, C. and R. Bilsborrow, 2013: Environmental Influences on Human Migration in Rural Ecuador. *Demography*, **50**(4), 1217-1241, doi:10.1007/s13524-012-0192-y.
Green, J. M. H. et al., 2019: Linking global drivers of agricultural trade to on-the-ground impacts on biodiversity. *Proceedings of the National Academy of Sciences*, **116**(46), 23202, doi:10.1073/pnas.1905618116.
Greenwalt, J., N. Raasakka and K. Alverson, 2018: Chapter 12 - Building Urban Resilience to Address Urbanization and Climate Change. In: *Resilience* [Zommers, Z. and K. Alverson (eds.)]. Elsevier, pp. 151-164. ISBN 978-0-12-811891-7.
Grieger, J. et al., 2014: Southern Hemisphere winter cyclone activity under recent and future climate conditions in multi-model AOGCM simulations. *International Journal of Climatology*, **34**(12), 3400-3416, doi:10.1002/joc.3917.
Grill, G. et al., 2015: An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, **10**(1), 015001, doi:10.1088/1748-9326/10/1/015001.
Grima, N., S. J. Singh, B. Smetschka and L. Ringhofer, 2016: Payment for Ecosystem Services (PES) in Latin America: Analysing the performance of 40 case studies. *Ecosystem Services*, **17**, 24-32, doi:10.1016/j.ecoser.2015.11.010.
Gross, J. E., S. Woodley, L. A. Welling and J. E. M. Watson, 2016: Adapting to Climate Change: Guidance for protected area managers and planners. IUCN, Gland, Switzerland, 129 pp.
Grover-Kopec, E. K. et al., 2006: Web-based climate information resources for malaria control in Africa. *Malaria Journal*, **5**(1), 38, doi:10.1186/1475-2875-5-38.
Guerra, A., 2014: Participación del sector privado en manejo del cambio climático: el Instituto Privado de Investigación sobre Cambio Climático. In: *El cambio climático: enfoques latinoamericanos e internacionales ante sus amenazas.* [Leal (ed.)]. Instituto de Desarrollo Sostenible, Universidad Galileo, Guatemala.
Guerra, A., 2016: La crisis como oportunidad: analisis de la sequía en la costa sur de Guatemala en 2016. *Revista de la Red Nacional de Formación e Invstigación Ambiental*,(17), 21-27.
Guerra, A. et al., 2017: Gestión de riesgo de inundaciones en el río Coyolate: ejemplo de adaptación al cambio climático en Guatemala. *Revista Mesoamericana de Biodiversidad y Cambio Climático*, **2**(3), 27-37.
Guerrero-Gatica, M. et al., 2020: Traditional and Local Knowledge in Chile: Review of Experiences and Insights for Management and Sustainability. *Sustainability*, **12**(5), 1767, doi:10.3390/su12051767.
Gullestad, P. et al., 2017: Towards ecosystem-based fisheries management in Norway – Practical tools for keeping track of relevant issues and prioritising management efforts. *Marine Policy*, **77**(November 2016), 104-110, doi:10.1016/j.marpol.2016.11.032.

Guo, M., 2016: Pyrogenic Carbon in Terra Preta Soils. *Agricultural and Environmental Applications of Biochar: Advances and Barriers*, 15-27, doi:10.2136/sssaspecpub63.2014.0035.5.
Guo, Y. et al., 2018: Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLOS Medicine*, **15**(7), e1002629-e1002629, doi:10.1371/journal.pmed.1002629.
Gurgiser, W. et al., 2016: Comparing peasants' perceptions of precipitation change with precipitation records in the tropical Callejón de Huaylas, Peru. *Earth Syst. Dynam.*, **7**(2), 499-515, doi:10.5194/esd-7-499-2016.
Gutiérrez, A. G., J. J. Armesto, M. F. Díaz and A. Huth, 2014: Increased Drought Impacts on Temperate Rainforests from Southern South America: Results of a Process-Based, Dynamic Forest Model. *PLOS ONE*, **9**(7), e103226, doi:10.1371/journal.pone.0103226.
Gutiérrez, D., M. Akester and L. Naranjo, 2016a: Productivity and sustainable management of the Humboldt current large marine ecosystem under climate change. *Environmental Development*, **17**, 126-144, doi:10.1016/j.envdev.2015.11.004.
Gutierrez, H. et al., 2020: Perceptions of Local Vulnerability and the Relative Importance of Climate Change in Rural Ecuador. *Human Ecology*, **48**(4), 383-395, doi:10.1007/s10745-020-00165-1.
Gutiérrez, J. M. et al., 2021: Atlas. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Gutiérrez, O. et al., 2016b: Climate teleconnections and indicators of coastal systems response. *Ocean & Coastal Management*, **122**, 64-76, doi:10.1016/j.ocecoaman.2016.01.009.
Guzmán, S., M. Castillo and A. Moncada, 2016: Afinancing efforts against climate change in Latin America. *Política, Globalidad y Ciudadanía*, **3**(5), 65, doi:10.29105/pgc3.5-5.
Guzmán, S., T. Guillén and J. Manda, 2018: *A review of domestic data sources for climate finance flows in recipient countries*. UNDP.
Guzman Torres, C. M. and J. A. Barrera Arciniegas, 2014: Metodologia para la microzonificación de riesgos frente a amenazas naturales: caso de estudio deslizamiento e inundaciones municipio de Mocoa Departamento de Putumayo. Universidad Católica de Colombia, Bogotá, 118 pp. pp.
Haddad, E. A. et al., 2019: *A Bad Year? Climate Variability and the Wine Industry in Chile*. Working Papers Department of Economics **37**. Available at: https://ideas.repec.org/p/spa/wpaper/2019wpecon37.html (accessed 28/08/2021).
Haeberli, W., Y. Schaub and C. Huggel, 2017: Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, **293**(Part B), 405-417, doi:10.1016/j.geomorph.2016.02.009.
Hallegatte, S. et al., 2018: *Shock Waves: Managing the Impacts of Climate Change on Poverty. Climate Change and Development.*, World Bank Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/22787 (accessed 31/10/2020).
Handisyde, N., T. C. Telfer and L. G. Ross, 2017: Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish and Fisheries*, **18**(3), 466-488, doi:10.1111/faf.12186.
Hannah, L. et al., 2017: Regional modeling of climate change impacts on smallholder agriculture and ecosystems in Central America. *Climatic Change*, **141**(1), 29-45, doi:10.1007/s10584-016-1867-y.
Hansen, M. C. et al., 2013: High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, **342**(6160), 850-853, doi:10.1126/science.1244693.
Haque, U. et al., 2019: The human cost of global warming: Deadly landslides and their triggers (1995–2014). *Science of The Total Environment*, **682**, 673-684, doi:10.1016/j.scitotenv.2019.03.415.
Hardoy, J., E. Gencer and M. Winograd, 2019: Participatory planning for climate resilient and inclusive urban development in Dosquebradas, Santa Ana and Santa Tomé. *Environment and Urbanization*, **31**(1), 33-52, doi:10.1177/0956247819825539.
Hardoy, J., I. Hernández, J. A. Pacheco and G. Sierra, 2014: Institutionalizing climate change adaptation at municipal and state level in Chetumal and Quintana Roo, Mexico. *Environment and Urbanization*, **26**(1), 69-85, doi:10.1177/0956247813519053.
Hardoy, J. and L. S. Velásquez, 2016: Chapter 8 in Cities on a Finite Planet. doi:10.4324/9781315645421.
Hardoy, J. H. V. and D. Mastrangelo, 2016: Chapter 11, in Cities on a Finite Planet: Towards transformative responses to climate change, Bartlett Sheridan and David Satterthwaite (eds). doi:10.4324/9781315645421.
Harper, S., C. Grubb, M. Stiles and U. R. Sumaila, 2017: Contributions by Women to Fisheries Economies: Insights from Five Maritime Countries. *Coastal Management*, **45**(2), 91-106, doi:10.1080/08920753.2017.1278143.
Harsch, M. A., P. E. Hulme, M. S. McGlone and R. P. Duncan, 2009: Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology Letters*, **12**(10), 1040-1049, doi:10.1111/j.1461-0248.2009.01355.x.
Hartman, B. D., B. Bookhagen and O. A. Chadwick, 2016: The effects of check dams and other erosion control structures on the restoration of Andean bofedal ecosystems. *Restoration Ecology*, **24**(6), 761–772, doi:10.1111/rec.12402.

Harvey, C. A. et al., 2017: The use of Ecosystem-based Adaptation practices by smallholder farmers in Central America. *Agriculture, Ecosystems & Environment*, **246**, 279-290, doi:10.1016/j.agee.2017.04.018.
Harvey, C. A. et al., 2018: Climate change impacts and adaptation among smallholder farmers in Central America. *Agriculture & Food Security*, **7**(1), 57, doi:10.1186/s40066-018-0209-x.
Hecht, S. B., 2003: Indigenous Soil Management and the Creation of Amazonian Dark Earths: Implications of Kayapó Practice. In: *Amazonian Dark Earths*. Springer, Dordrecht, pp. 355-372.
Hecht, S. B., 2017: Domestication, domesticated landscapes, and tropical natures. In: *The Routledge Companion to the Environmental Humanities*, 1st edition ed. [Heise, U. K. C. J. and M. Niemann (eds.)]. Taylor & Francis, pp. 37-50.
Heerspink, B. P., A. D. Kendall, M. T. Coe and D. W. Hyndman, 2020: Trends in streamflow, evapotranspiration, and groundwater storage across the Amazon Basin linked to changing precipitation and land cover. *Journal of Hydrology: Regional Studies*, **32**, 100755, doi:10.1016/j.ejrh.2020.100755.
Heidinger, H. et al., 2018: A new assessment in total and extreme rainfall trends over central and southern Peruvian Andes during 1965–2010. *International Journal of Climatology*, **38**(S1), e998-e1015, doi:10.1002/joc.5427.
Heikkinen, A., 2017: Climate Change in the Peruvian Andes: A Case Study on Small-Scale Farmers' Vulnerability in the Quillcay River Basin. *Iberoamericana – Nordic Journal of Latin American and Caribbean Studies*, **46**(1), 77-88, doi:10.16993/iberoamericana.211.
Heikkinen, A. M., 2021: Climate change, power, and vulnerabilities in the Peruvian Highlands. *Regional Environmental Change*, **21**(3), 82, doi:10.1007/s10113-021-01825-8.
Hellebrandt, D., E. H. Allison and A. Delaporte, 2014: Food Security and Artisanal Fisheries: Critical Analysis of Initiatives in Latin America. *Desenvolvimento e Meio Ambiente*, **32**, 7-27, doi:10.5380/dma.v32i0.35548.
Henríquez, G. and C. Urrea, 2017: Material particulado y gases contaminantes en la comuna de El Bosque ¿cuánto influyen en la cantidad de consultas por enfermedades respiratorias? *Revista médica de Chile*, **145**(11), 1371-1377, doi:10.4067/s0034-98872017001101371
Hepburn, C. et al., 2020: Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Review of Economic Policy*, **36**(Supplement_1), S359-S381, doi:10.1093/oxrep/graa015.
Hernández-Moreno, Á. and S. Reyes-Paecke, 2018: The effects of urban expansion on green infrastructure along an extended latitudinal gradient (23°S–45°S) in Chile over the last thirty years. *Land Use Policy*, **79**, 725-733, doi:10.1016/j.landusepol.2018.09.008.
Hernandez, W., A. Mendez, A. M. Diaz-Marquez and R. Zalakevic, 2019: Robust Analysis of PM2. 5 Concentration Measurements in the Ecuadorian Park La Carolina. *Sensors*, **19**(21), 4648, doi:10.3390/s19214648.
Herrador-Valencia, D. and M. Paredes, 2016: Cambio climático y agricultura de pequeña escala en los Andes ecuatorianos: un estudio sobre percepciones locales y estrategias de adaptación. *Journal of Latin American Geography*, **15**(2), 101-121, doi:10.1353/lag.2016.0021.
Herrera-R, G. A. et al., 2020: The combined effects of climate change and river fragmentation on the distribution of Andean Amazon fishes. *Global Change Biology*, **26**(10), 5509-5523, doi:10.1111/gcb.15285.
Herrera, D. et al., 2017: Upstream watershed condition predicts rural children's health across 35 developing countries. *Nature Communications*, **8**(1), 811, doi:10.1038/s41467-017-00775-2.
Herrera, D. A. et al., 2018a: Exacerbation of the 2013–2016 Pan-Caribbean Drought by Anthropogenic Warming. *Geophysical Research Letters*, **45**(19), 10,619-610,626, doi:10.1029/2018GL079408.
Herrera, N. et al., 2018b: *Sistema de Alerta Temprana por Olas de Calor y Salud (SAT-OCS)*. Nota Técnica SMN 2018-50, Servicio Meteorológico Nacional, Buenos Aires, Argentina, 16 pp. Available at: http://repositorio.smn.gob.ar/handle/20.500.12160/772 (accessed 10/08/2021).
Herrera, R. et al., 2016: Proximity to mining industry and respiratory diseases in children in a community in Northern Chile: A cross-sectional study. *Environmental Health*, **15**(1), 66, doi:10.1186/s12940-016-0149-5.
Herzog, C. and C. A. Rozado, 2019: *The EU – Brazil Sector Dialogue on nature-based solutions: Contribution to a Brazilian roadmap on nature-based solutions for resilient cities*. European Commission, Brussels, 136 pp. pp.
Heslin, A., N. D. Deckard, R. Oakes and A. Montero-Colbert, 2019: Displacement and Resettlement: Understanding the Role of Climate Change in Contemporary Migration. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, pp. 237-258. ISBN 978-3-319-72026-5.
Hickmann, T., O. Widerberg, M. Lederer and P. Pattberg, 2019: The United Nations Framework Convention on Climate Change Secretariat as an orchestrator in global climate policymaking. *International Review of Administrative Sciences*, **87**(1), 21-38, doi:10.1177/0020852319840425.
Hicks, K. and N. Fabricant, 2016: The Bolivian Climate Justice Movement: Mobilizing Indigeneity in Climate Change Negotiations. *Latin American Perspectives*, **43**(4), 87-104, doi:10.1177/0094582x16630308.
Hidalgo, C., 2020: Procesos colaborativos en acción: la provisión de servicios climáticos y la elaboración de pronósticos por impacto en el sur de Sudamérica. *Medio Ambiente y Urbanización*, **92**(1), 63-92.
Hidalgo, H. G., E. J. Alfaro and B. Quesada-Montano, 2017: Observed (1970–1999) climate variability in Central America using a high-resolution meteorological dataset with implication to climate change studies. *Climatic Change*, **141**(1), 13-28, doi:10.1007/s10584-016-1786-y.
Hirabayashi, Y. et al., 2013: Global flood risk under climate change. *Nature Climate Change*, **3**, 816-821, doi:10.1038/nclimate1911.

Hock, R. et al., 2019: High Mountain Areas. In: *An IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. Roberts, M. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. In press.
Hodgkinson, J. H. and M. H. Smith, 2018: Climate change and sustainability as drivers for the next mining and metals boom: The need for climate-smart mining and recycling. *Resources Policy*, doi:10.1016/j.resourpol.2018.05.016.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5ºC of Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press, pp. 175-311. ISBN 9781107671812.
Hoegh-Guldberg, O. et al., 2019: The human imperative of stabilizing global climate change at 1.5°C. *Science*, **365**(6459), eaaw6974, doi:10.1126/science.aaw6974.
Hoffmann, D., M. F. d. Vasconcelos and R. P. Martins, 2015: How climate change can affect the distribution range and conservation status of an endemic bird from the highlands of eastern Brazil: the case of the Gray-backed Tachuri, Polystictus superciliaris (Aves, Tyrannidae). *Biota Neotropica*, **15**(2), 1-12, doi:10.1590/1676-060320150075.
Hoffmann, R. et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change*, **10**(10), 904-912, doi:10.1038/s41558-020-0898-6.
Hofmann, G. S. et al., 2021: The Brazilian Cerrado is becoming hotter and drier. *Global Change Biology*, **27**(17), 4060-4073, doi:10.1111/gcb.15712.
Hollowed, A. B. et al., 2013: Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science*, **70**(5), 1023-1037, doi:10.1093/icesjms/fst081.
Hommes, L. and R. Boelens, 2017: Urbanizing rural waters: Rural-urban water transfers and the reconfiguration of hydrosocial territories in Lima. *Political Geography*, **57**, 71-80, doi:10.1016/j.polgeo.2016.12.002.
Hommes, L. and R. Boelens, 2018: From natural flow to 'working river': hydropower development, modernity and socio-territorial transformations in Lima's Rímac watershed. *Journal of Historical Geography*, **62**, 85-95, doi:10.1016/j.jhg.2018.04.001.
Hoorn, C. et al., 2010: Amazonia Through Time: Andean Uplift, Climate Change, Landscape Evolution, and Biodiversity. *Science*, **330**(6006), 927-931, doi:10.1126/science.1194585.
Hora, B., C. Marchant and A. Borsdorf, 2018: Private Protected Areas in Latin America: Between conservation, sustainability goals and economic interests. A review. *eco.mont*, **10**(1), 87-94, doi:10.1553/eco.mont-10-1s87.
Hori, T. et al., 2017: *Lessons Learnt from Japan and Latin America and Caribbean Countries in Management of Hazard Resilient Infrastructure: A JICA-IDB Joint Research*. 55 pp. Available at: https://publications.iadb.org/en/lessons-learnt-japan-and-latin-america-and-caribbean-countries-management-hazard-resilient (accessed 17/06/2021).
Hoyos, N. et al., 2013: Impact of the 2010–2011 La Niña phenomenon in Colombia, South America: The human toll of an extreme weather event. *Applied Geography*, **39**, 16-25, doi:10.1016/j.apgeog.2012.11.018.
Huairou Commission, 2019: *Grassroots Women-led Resilient Community Development*. Annual Report, New York, United States of America, 42 pp. Available at: https://huairou.org/wp-content/uploads/2020/12/Huairou_Commission_Annual_Report_web.pdf (accessed 01/09/2021).
Huang, J. et al., 2016: Accelerated dryland expansion under climate change. *Nature Climate Change*, **6**(2), 166-171, doi:10.1038/nclimate2837.
Huggel, C. et al., 2007: Review and reassessment of hazards owing to volcano–glacier interactions in Colombia. *Annals of Glaciology*, **45**, 128-136, doi:10.3189/172756407782282408.
Huggel, C. et al., 2015a: How useful and reliable are disaster databases in the context of climate and global change? A comparative case study analysis in Peru. *Nat. Hazards Earth Syst. Sci.*, **15**(3), 475-485, doi:10.5194/nhess-15-475-2015.
Huggel, C. et al., 2015b: A framework for the science contribution in climate adaptation: Experiences from science-policy processes in the Andes. *Environmental Science & Policy*, **47**, 80-94, doi:10.1016/j.envsci.2014.11.007.
Huneeus, N. et al., 2020: Evaluation of anthropogenic air pollutant emission inventories for South America at national and city scale. *Atmospheric Environment*, **235**, 117606, doi:10.1016/j.atmosenv.2020.117606.
Hurlbert, M. and J. Gupta, 2016: Adaptive Governance, Uncertainty, and Risk: Policy Framing and Responses to Climate Change, Drought, and Flood. *Risk Analysis*, **36**(2), 339-356, doi:10.1111/risa.12510.
Hurlbert, M. and J. Gupta, 2017: The adaptive capacity of institutions in Canada, Argentina, and Chile to droughts and floods. *Regional Environmental Change*, **17**(3), 865-877, doi:10.1007/s10113-016-1078-0.
Hurlbert, M. et al., 2019: Risk Management and Decision making in Relation to Sustainable Development. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)]. In Press, pp. 1-128.

Hurlbert, M. A. and H. Diaz, 2013: Water Governance in Chile and Canada: a Comparison of Adaptive Characteristics. *Ecology and Society*, **18**(4), doi:10.5751/ES-06148-180461.

Hurlbert, M. A. and J. Gupta, 2019: An institutional analysis method for identifying policy instruments facilitating the adaptive governance of drought. *Environmental Science & Policy*, **93**, 221-231, doi:10.1016/j.envsci.2018.09.017.

Hurtado, L. A. et al., 2018: Climatic fluctuations and malaria transmission dynamics, prior to elimination, in Guna Yala, República de Panamá. *Malaria Journal*, **17**(1), 85, doi:10.1186/s12936-018-2235-3.

Hutter, S. E. et al., 2018: Assessing changing weather and the El Niño Southern Oscillation impacts on cattle rabies outbreaks and mortality in Costa Rica (1985–2016). *BMC Veterinary Research*, **14**(1), 285, doi:10.1186/s12917-018-1588-8.

Hystad, P. et al., 2019: Health Effects of Household Solid Fuel Use: Findings from 11 Countries within the Prospective Urban and Rural Epidemiology Study. *Environmental Health Perspectives*, **127**(5), 057003, doi:10.1289/EHP3915.

IBGE, 2003: Cidades e Estados, Brazilian Institute of Geography and Statistics. Available at: https://cidades.ibge.gov.br/.

IBGE, 2010: Cidades e Estados, Brazilian Institute of Geography and Statistics. Available at: https://cidades.ibge.gov.br/.

IBGE, 2019: Cidades e Estados, Brazilian Institute of Geography and Statistics. Available at: https://cidades.ibge.gov.br/.

ICC, 2019a: *Informe de Labores 2018*. **Instituto Privado de Investigación sobre Cambio Climático ICC**, Guatemala, 96 pp. Available at: https://icc.org.gt/wp-content/uploads/2019/05/Informe-de-labores-ICC-2018-BR.pdf (accessed 16/06/2021).

ICC, 2019b: *Síntesis del sistema de información de los ríos de la costa sur de Guatemala: promedios de caudales comparativos en la temporada seca de los años 2017, 2018 y 2019*. Instituto Privado de Investigación sobre Cambio Climático ICC, Guatemala, 52 pp. Available at: https://icc.org.gt/wp-content/uploads/2019/08/S%C3%ADntesis-del-Sistema-de-Informaci%C3%B3n-r%C3%ADos-Costa-Sur-2017-a-2019.pdf (accessed 17/06/2021).

IDEAM, 2017: *Perspectivas de los servicios climáticos en Colombia*. Ministerio de Ambiente, Presidencia de la República de Colombia,Instituto de Hidrología, Meteorología y Estudios Ambientales,Centro Internacional de Agricultura Tropical, Bogotá, 32 pp. Available at: http://www.ideam.gov.co/documents/21021/71699963/Perspectivas+de+los+servicios+clim%C3%A1tico+.pdf/7bf734cb-e16d-4b2c-b8d5-d2d75f6103b4 (accessed 17/06/2021).

IDH, 2020: European Soy Monitor: Insights on European responsible and deforestation-free soy consumption in 2018 IDH, The sustainable Trade Initiative, 62 pp.

Ignotti, E. et al., 2010: Air pollution and hospital admissions for respiratory diseases in the subequatorial Amazon: a time series approach. *Cadernos de Saúde Pública*, **26**, 747-761, doi:10.1590/S0102-311X2010000400017.

Igualt, F., W. A. Breuer, M. Contreras-López and C. Martínez, 2019: Effects of climate change on the urban tourist and coastal area of Viña del Mar: Survey of damage for flooding by storm surge and perception of security. *Revista 180*, **44**, 120-133, doi:10.32995/rev180.Num-44.(2019).art-626.

IHA, 2020: *2020 - Hydropower Status Report - Sector trends and insights*. International Hydropower Association, 83 pp. Available at: https://www.hydropower.org/publications/2020-hydropower-status-report (accessed 01/11/2020).

IICA, 2015: Fenómeno de "El Niño" intensifica su paso por Centroamérica. Available at: http://www.iica.int/es/prensa/noticias/fen%C3%B3meno-de-%E2%80%9Cel-ni%C3%B1o%E2%80%9D-intensifica-su-paso-por-centroam%C3%A9rica (accessed 17/06/2021).

IICA, 2019: *Política agropecuaria de la región SICA 2019-2030*. Instituto Interamericano de Cooperación para la Agricultura, Instituto Interamericano de Cooperación para la Agricultura, San José, Costa Rica, 46 pp. Available at: https://repositorio.iica.int/handle/11324/7946 (accessed 30/06/2021).

Ilustre Municipalidad de Santiago, 2019: *Plan Integral de Movilidad 2019-2029*, Secretaria Comunal de Planificación, Santiago, Chile, 176 pp. Available at: https://issuu.com/munistgo/docs/pim_2019-2029_final (accessed 17/10/2020).

Imbach, P. et al., 2017: Climate change, ecosystems and smallholder agriculture in Central America: an introduction to the special issue. *Climatic Change*, **141**(1), 1-12, doi:10.1007/s10584-017-1920-5.

Imbach, P. et al., 2018: Future climate change scenarios in Central America at high spatial resolution. *PLoS ONE*, **13**(4), 1-21, doi:10.1371/journal.pone.0193570.

Imbach, P. A. et al., 2013: Climate change and plant dispersal along corridors in fragmented landscapes of Mesoamerica. *Ecology and Evolution*, **3**(9), 2917-2932, doi:10.1002/ece3.672.

Immerzeel, W. W. et al., 2020: Importance and vulnerability of the world's water towers. *Nature*, **577**(7790), 364-369, doi:10.1038/s41586-019-1822-y.

INDEC, 2010: Proyecciones elaboradas en base a resultados del Censo Nacional de Población, Hogares y Viviendas 2010. Available at: https://www.indec.gob.ar/.

Infante, A. L. and F. C. Infante, 2013: Percepciones y estrategias de los campesinos del secano para mitigar el deterioro ambiental y los efectos del cambio climático en Chile. *Agroecología*, **8**(1), 71-78.

Inform Risk Index, 2021: Inform Risk Index 2021. Available at: https://drmkc.jrc.ec.europa.eu/inform-index/ (accessed 29/06/2021).

Iniguez-Gallardo, V., I. Bride and J. Tzanopoulos, 2020: Between concepts and experiences: people's understandings of climate change in southern Ecuador. *Public Understanding of Science*.
Inostroza, L., M. Palme and F. de la Barrera, 2016: A Heat Vulnerability Index: Spatial Patterns of Exposure, Sensitivity and Adaptive Capacity for Santiago de Chile. *PLOS ONE*, **11**(9), e0162464, doi:10.1371/journal.pone.0162464.
INSIVUMEH, 2018: *Variabilidad y cambio climático en Guatemala*. Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología INSIVUMEH, Guatemala, 135 pp.
IOM, 2021: *La movilidad humana derivada de desastres y el cambio climático en Centroamérica*. International Organization for Migration, Geneva, Switzerland. Available at: https://publications.iom.int/books/la-movilidad-humana-derivada-de-desastres-y-el-cambio-climatico-en-centroamerica (accessed 31/08/2021).
Ioris, A. A. R., 2016: Water scarcity and the exclusionary city: the struggle for water justice in Lima, Peru. *Water International*, **41**(1), 125-139, doi:10.1080/02508060.2016.1124515.
IPAM, 2020: *The Air is Unbearable. Health Impacts of Deforestation-Related Fires in the Brazilian Amazon*. Amazon Environmental Research Institute (IPAM). Available at: https://ipam.org.br/wp-content/uploads/2020/08/brazil0820_web.pdf (accessed 01/11/2020).
IPBES, 2018a: *The IPBES regional assessment report on biodiversity and ecosystem services for the Americas* [Rice, J. (ed.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
IPBES, 2018b: *Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for the Americas of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* [Rice, J., C. S. Seixas, M. E. Zaccagnini, M. Bedoya-Gaitán, N. Valderrama, C. B. Anderson, M. T. K. Arroyo, M. Bustamante, J. Cavender-Bares, A. Diaz-de-Leon, S. Fennessy, J. R. García Márquez, K. Garcia, E. H. Helmer, B. Herrera, B. Klatt, J. P. Ometo, V. Rodríguez Osuna, F. R. Scarano, S. Schill and J. S. Farinaci (eds.)]. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 41 pp. Available at: https://doi.org/10.5281/zenodo.3236252 (accessed 17/09/2019).
IPBES, 2020: *Workshop Report: IPBES Workshop on Biodiversity and Pandemics* IPBES, 7 pp. Available at: http://bit.ly/PandemicEmbargoed (accessed 29/10/2020).
IPCC, 2014: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 1-32.
IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. In Press.
IPCC, 2019a: *Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Press, I.
IPCC, 2019b: Summary for Policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In Press.
IPCC, 2019c: Summary for Policymakers. In: *Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. In Press.
Iriarte, J. et al., 2020: The origins of Amazonian landscapes: Plant cultivation, domestication and the spread of food production in tropical South America. *Quaternary Science Reviews*, **248**, 106582, doi:10.1016/j.quascirev.2020.106582.
Iribarren Anacona, P., A. Mackintosh and K. P. Norton, 2015: Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes. *Earth Surf. Process. Landforms*, **40**(1), 2-21, doi:10.1002/esp.3524.
Isaac, V. J. and S. F. Ferrari, 2017: Assessment and management of the North Brazil Shelf Large Marine Ecosystem. *Environmental Development*, **22**, 97-110, doi:10.1016/j.envdev.2016.11.004.
Ishizawa, O. A. and J. J. Miranda, 2016: *Weathering Storms: Understanding the Impact of Natural Disasters on the Poor in Central America*. World Bank, Washington, DC, 25 pp. Available at: https://openknowledge.worldbank.org/handle/10986/24528 (accessed 31/08/2021).
ISIMIP, 2021: Input data set: Historical, gridded population, Inter-Sectoral Impact Model Intercomparison Project. Available at: https://www.isimip.org/gettingstarted/details/31/.
Isla, F. I., 2018: ENSO-triggered floods in South America: correlation between maximum monthly discharges during strong events. *Hydrol. Earth Syst. Sci. Discuss.*, **2018**, 1-13, doi:10.5194/hess-2018-107.
Isla, F. I. et al., 2018: Erosion in Buenos Aires province: Coastal-management policy revisited. *Ocean & Coastal Management*, **156**, 107-116, doi:10.1016/j.ocecoaman.2017.09.008.
Isla, F. I., M. Espinosa and G. Bujalesky, 2010: Summer stratification of Andean lakes of Patagonia and Tierra del Fuego: Global warming or ENSO effects? *Revista Geográfica del Sur*, **2**, 55-71.

Isla, F. I. and E. J. Schnack, 2009: The Changing Coastlines of South America. In: *Developments in Earth Surface Processes* [Latrubesse, E. M. (ed.)]. Elsevier, pp. 49-73. ISBN 0928-2025.
Jacob, A. C. P. et al., 2019: Use of detention basin for flood mitigation and urban requalification in Mesquita, Brazil. *Water Science and Technology*, **79**(11), 2135-2144, doi:10.2166/wst.2019.212.
Jacob, B. G. et al., 2018: Major changes in diatom abundance, productivity, and net community metabolism in a windier and dryer coastal climate in the southern Humboldt Current. *Progress in Oceanography*, **168**, 196-209, doi:10.1016/j.pocean.2018.10.001.
Jacob, T., J. Wahr, W. T. Pfeffer and S. Swenson, 2012: Recent contributions of glaciers and ice caps to sea level rise. *Nature*, **482**(7386), 514-518, doi:10.1038/nature10847.
Jacobi, J. et al., 2015: Agroecosystem resilience and farmers' perceptions of climate change impacts on cocoa farms in Alto Beni, Bolivia. *Renewable Agriculture and Food Systems*, **30**(2), 170-183, doi:10.1017/S174217051300029X.
Jacquet, J. et al., 2017: Hydrologic and geomorphic changes resulting from episodic glacial lake outburst floods: Rio Colonia, Patagonia, Chile. *Geophysical Research Letters*, **44**(2), 854-864, doi:10.1002/2016GL071374.
Jaime, M. M., C. Chávez and W. Gómez, 2020: Fuel choices and fuelwood use for residential heating and cooking in urban areas of central-southern Chile: The role of prices, income, and the availability of energy sources and technology. *Resource and Energy Economics*, **60**, 101125, doi:10.1016/j.reseneeco.2019.101125.
Jaitman, L., 2015: Urban infrastructure in Latin America and the Caribbean: public policy priorities. *Latin American Economic Review*, **24**(1), 13, doi:10.1007/s40503-015-0027-5.
Jalón-Rojas, I. et al., 2018: To What Extent Multidecadal Changes in Morphology and Fluvial Discharge Impact Tide in a Convergent (Turbid) Tidal River. *Journal of Geophysical Research: Oceans*, **123**(5), 3241-3258, doi:10.1002/2017JC013466.
Janches, F., H. Henderson and L. Maccolman, 2014: *Urban Risk and Climate Change Adaptation in the Reconquista River Basin of Argentina*. Lincoln Institute of Land Policy, 91 pp. Available at: https://www.lincolninst.edu/sites/default/files/pubfiles/2486_1832_Janches%20WP14FJ1.pdf (accessed 30/10/2020).
Jantz, S. M. et al., 2015: Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. *Conservation Biology*, **29**(4), 1122-1131, doi:10.1111/cobi.12549.
Jaramillo, F. et al., 2018: Effects of Hydroclimatic Change and Rehabilitation Activities on Salinity and Mangroves in the Ciénaga Grande de Santa Marta, Colombia. *Wetlands*, **38**(4), 755-767, doi:10.1007/s13157-018-1024-7.
Jat, M. L. et al., 2016: Climate Change and Agriculture: Adaptation Strategies and Mitigation Opportunities for Food Security in South Asia and Latin America. In: *Advances in Agronomy* [Sparks, D. L. (ed.)]. Academic Press, pp. 127-235. ISBN 0065-2113.
Jia, G. et al., 2019: Land-Climate Interactions. In: *Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. In Press.
Jiménez, A., n.d.: *Latin America in Focus: Regional brief on National Adaptation Plans*. 15 pp. Available at: https://www.globalsupportprogramme.org/resources/knowledge-products/regional-brief-naps-latin-america-focus (accessed 31/10/2020).
Jiménez Cisneros, B. E. et al., 2014: Freshwater resources. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.
Johansson, M. A. et al., 2019: An open challenge to advance probabilistic forecasting for dengue epidemics. *Proceedings of the National Academy of Sciences*, **116**(48), 24268, doi:10.1073/pnas.1909865116.
Johansson, M. A. et al., 2014: Nowcasting the Spread of Chikungunya Virus in the Americas. *PLOS ONE*, **9**(8), e104915, doi:10.1371/journal.pone.0104915.
Johansson, M. A. et al., 2016: Evaluating the performance of infectious disease forecasts: A comparison of climate-driven and seasonal dengue forecasts for Mexico. *Scientific Reports*, **6**(1), 33707, doi:10.1038/srep33707.
Johns, R. et al., 2018: Meta-analysis of NOS3 G894T polymorphisms with air pollution on the risk of ischemic heart disease worldwide. *Toxics*, **6**(3), 1-16, doi:10.3390/toxics6030044.
Johnson, C., G. Jain and A. Lavell, 2021: *Rethinking Urban Risk and Resettlement in the Global South*. UCL Press. Available at: https://www.uclpress.co.uk/products/155742 (accessed 31/08/2021).
Johnson, R. J., C. Wesseling and L. S. Newman, 2019: Chronic Kidney Disease of Unknown Cause in Agricultural Communities. *New England Journal of Medicine*, **380**(19), 1843-1852, doi:10.1056/NEJMra1813869.
Jolly, W. M. et al., 2015: Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, **6**, 7537, doi:10.1038/ncomms8537.
Joslin, A. J., 2019: Unpacking 'Success': Applying Local Perceptions to Interpret Influences of Water Fund Payments for Ecosystem Services in the Ecuadorian Andes. *Society & Natural Resources*, **32**(6), 617-637, doi:10.1080/08941920.2018.1559379.
Joyce, C. B., M. Simpson and M. Casanova, 2016: Future wet grasslands: ecological implications of climate change. *Ecosystem Health and Sustainability*, **2**(9), e01240, doi:10.1002/ehs2.1240.

Jump, A. S. et al., 2017: Structural overshoot of tree growth with climate variability and the global spectrum of drought-induced forest dieback. *Global Change Biology*, **23**(9), 3742-3757, doi:10.1111/gcb.13636.
Junk, W. J., 2013: Current state of knowledge regarding South America wetlands and their future under global climate change. *Aquatic Sciences*, **75**(1), 113-131, doi:10.1007/s00027-012-0253-8.
Junk, W. J. et al., 2013: Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. *Aquatic Sciences*, **75**(1), 151-167, doi:10.1007/s00027-012-0278-z.
Jurt, C. et al., 2015: Local perceptions in climate change debates: insights from case studies in the Alps and the Andes. *Climatic Change*, **133**(3), 511-523, doi:10.1007/s10584-015-1529-5.
Kabisch, N. et al., 2016: Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, **21**(2), doi:10.5751/ES-08373-210239.
Kaenzig, R., 2015: Can glacial retreat lead to migration? A critical discussion of the impact of glacier shrinkage upon population mobility in the Bolivian Andes. *Population and Environment*, **36**(4), 480-496, doi:10.1007/s11111-014-0226-z.
Kaenzig, R. and E. Piguet, 2014: Migration and Climate Change in Latin America and the Caribbean. In: *People on the Move in a Changing Climate: The Regional Impact of Environmental Change on Migration* [Piguet, E. and F. Laczko (eds.)]. Springer, Dordrecht, pp. 155-176. ISBN 978-94-007-6985-4.
Kaijser, A. and A. Kronsell, 2014: Climate change through the lens of intersectionality. *Environmental Politics*, **23**(3), 417-433, doi:10.1080/09644016.2013.835203.
Kalikoski, D. C. et al., 2018: Chapter 2: Understanding the impacts of climate change for fisheries and aquaculture: applying a poverty lens. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. FAO, Rome, Italy, pp. 628.
Kalikoski, D. C., S. Jentoft, P. McConney and S. Siar, 2019: Empowering small-scale fishers to eradicate rural poverty. *Maritime Studies*, **18**(2), 121-125, doi:10.1007/s40152-018-0112-x.
Kämpf, N. et al., 2003: Classification of Amazonian Dark Earths and Other Ancient Anthropic Soils. In: *Amazonian Dark Earths: Origin Properties Management* [Lehmann, J., D. C. Kern, B. Glaser and W. I. Wodos (eds.)]. Springer Netherlands, Dordrecht, pp. 77-102. ISBN 978-1-4020-2597-6.
Karlsson, M. and I. Bryceson, 2016: Continuity and change: understanding livelihood shifts and adaptation in coastal Belize 1830–2012. *Local Environment*, **21**(2), 137-156, doi:10.1080/13549839.2014.926871.
Kasecker, T. P., M. B. Ramos-Neto, J. M. C. da Silva and F. R. Scarano, 2018: Ecosystem-based adaptation to climate change: defining hotspot municipalities for policy design and implementation in Brazil. *Mitigation and Adaptation Strategies for Global Change*, **23**(6), 981-993, doi:10.1007/s11027-017-9768-6.
Kastens, J. H. et al., 2017: Soy moratorium impacts on soybean and deforestation dynamics in Mato Grosso, Brazil. *PloS One*, **12**(4), e0176168, doi:10.1371/journal.pone.0176168.
Kates, R. W., W. R. Travis and T. J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(19), 7156–7161, doi:10.1073/pnas.1115521109.
Kauffman, C., 2014: Financing watershed conservation: Lessons from Ecuador's evolving water trust funds. *Agric. Water Manage.*, **145**, 39-49, doi:10.1016/j.agwat.2013.09.013.
Keenan, R. J., 2015: Climate change impacts and adaptation in forest management: a review. *Annals of Forest Science*, **72**(2), 145-167, doi:10.1007/s13595-014-0446-5.
Kern, D. C., M. De Lp Ruivo and F. J. L. Frazão, 2009: Terra preta nova: The dream of Wim Sombroek. In: *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer, Dordrecht, pp. 339-349. ISBN 9781402090301.
Kern, J. et al., 2019: What can we learn from ancient fertile anthropic soil (Amazonian Dark Earths, shell mounds, Plaggen soil) for soil carbon sequestration? *Catena*, doi:10.1016/j.catena.2018.08.008.
Khalid, A. et al., 2020: Hydrodynamic and Wave Responses During Storm Surges on the Southern Brazilian Coast: A Real-Time Forecast System. *Water*, **12**(12), doi:10.3390/w12123397.
Khan, M. et al., 2020: Twenty-five years of adaptation finance through a climate justice lens. *Climatic Change*, **161**(2), 251-269, doi:10.1007/s10584-019-02563-x.
Khatri-Chhetri, A. et al., 2019: Stakeholders prioritization of climate-smart agriculture interventions: Evaluation of a framework. *Agricultural Systems*, **174**, 23-31, doi:10.1016/j.agsy.2019.03.002.
Khouakhi, A., G. Villarini and G. A. Vecchi, 2017: Contribution of Tropical Cyclones to Rainfall at the Global Scale. *Journal of Climate*, **30**(1), 359-372, doi:10.1175/JCLI-D-16-0298.1.
Kitoh, A., S. Kusunoki and T. Nakaegawa, 2011: Climate change projections over South America in the late 21st century with the 20 and 60 km mesh Meteorological Research Institute atmospheric general circulation model (MRI-AGCM). *Journal of Geophysical Research: Atmospheres*, **116**(D6), doi:10.1029/2010JD014920.
Klein Goldewijk, K., A. Beusen, J. Doelman and E. Stehfest, 2017: Anthropogenic land use estimates for the Holocene – HYDE 3.2. *Earth Syst. Sci. Data*, **9**(2), 927-953, doi:10.5194/essd-9-927-2017.
Klenk, N., A. Fiume, K. Meehan and C. Gibbes, 2017: Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co-production. *WIREs Climate Change*, **8**(5), e475, doi:10.1002/wcc.475.

Knapp, G., 2017: Mountain Agriculture for Global Markets: The Case of Greenhouse Floriculture in Ecuador. *Annals of the American Association of Geographers*, **107**(2), 511-519, doi:10.1080/24694452.2016.1203282.
Kobres, P.-Y. et al., 2019: A systematic review and evaluation of Zika virus forecasting and prediction research during a public health emergency of international concern. *PLoS neglected tropical diseases*, **13**(10), e0007451, doi:10.1371/journal.pntd.0007451.
Koch, F., 2018: Mainstreaming adaptation: a content analysis of political agendas in Colombian cities. *Climate and Development*, **10**(2), 179-192, doi:10.1080/17565529.2016.1223592.
Kongsager, R., 2017: Barriers to the adoption of alley cropping as a climate-smart agriculture practice: lessons from maize cultivation among the Maya in southern Belize. *Forests*, **8**(7), 260, doi:10.3390/f8070260.
Koubi, V., G. Spilker, L. Schaffer and T. Böhmelt, 2016: The role of environmental perceptions in migration decision-making: evidence from both migrants and non-migrants in five developing countries. *Population and Environment*, **38**(2), 134-163, doi:10.1007/s11111-016-0258-7.
Koutroulis, A. G. et al., 2019: Global water availability under high-end climate change: A vulnerability based assessment. *Global and Planetary Change*, **175**(January), 52-63, doi:10.1016/j.gloplacha.2019.01.013.
Krause, G., 2014: The scientific challenge of bridging the gap from the local to the earth system level: lessons from the study of mangroves and people in North Brazil. *Regional Environmental Change*, **14**(6), 2089-2103, doi:10.1007/s10113-014-0636-6.
Krellenberg, K. and B. Katrin, 2014: Inter- and Transdisciplinary Research for Planning Climate Change Adaptation Responses: The Example of Santiago de Chile. *Interdisciplinary Science Reviews*, **39**(4), 360-375, doi:10.1179/0308018814Z.00000000097.
Krellenberg, K. and J. Welz, 2017: Assessing Urban Vulnerability in the Context of Flood and Heat Hazard: Pathways and Challenges for Indicator-Based Analysis. *Social Indicators Research*, **132**(2), 709-731, doi:10.1007/s11205-016-1324-3.
Kreps, G., G. Martínez Pastur and P. L. Peri, 2012: *Cambio climático en Patagonia Sur. Escenarios futuros en el manejo de los recursos naturales*. Instituto Nacional de Tecnología Agropecuaria, Buenos Aires, 101 pp. Available at: https://inta.gob.ar/documentos/cambio-climatico-en-patagonia-sur-escenarios-futuros-en-el-manejo-de-los-recursos-naturales (accessed 16/06/2021).
Krisher, L. K. et al., 2016: Successful malaria elimination in the Ecuador–Peru border region: epidemiology and lessons learned. *Malaria Journal*, **15**(1), 573-573, doi:10.1186/s12936-016-1630-x.
Krishnamurthy, P. K., K. Lewis and R. J. Choularton, 2014: A methodological framework for rapidly assessing the impacts of climate risk on national-level food security through a vulnerability index. *Global Environmental Change*, **25**(1), 121-132, doi:10.1016/j.gloenvcha.2013.11.004.
Kronenberg, M. et al., 2016: The Projected Precipitation Reduction over the Central Andes may Severely Affect Peruvian Glaciers and Hydropower Production. *Energy Procedia*, **97**, 270-277, doi:10.1016/j.egypro.2016.10.072.
Krug, L. A. et al., 2013: The construction of causal networks to estimate coral bleaching intensity. *Environmental Modelling and Software*, **42**, 157-167, doi:10.1016/j.envsoft.2013.01.003.
Kubisch, E. L., V. Corbalán, N. R. Ibargüengoytía and B. Sinervo, 2016: Local extinction risk of three species of lizard from Patagonia as a result of global warming. *Canadian Journal of Zoology*, **94**(1), 49-59, doi:10.1139/cjz-2015-0024.
Kummu, M. et al., 2016: The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*, **6**(December), 38495, doi:10.1038/srep38495.
Labra, M. E., 2002: La reinvención neoliberal de la inequidad en Chile: el caso de la salud. *Cadernos de Saúde Pública*, **18**(4), 1041-1052, doi:10.1590/S0102-311X2002000400010.
Lachaud, M. A., B. E. Bravo-Ureta and C. E. Ludena, 2017: Agricultural productivity in Latin America and the Caribbean in the presence of unobserved heterogeneity and climatic effects. *Climatic Change*, **143**(3), 445-460, doi:10.1007/s10584-017-2013-1.
Läderach, P. et al., 2013: *Mesoamerican Coffee: Building a Climate Change Adaptation Strategy*. CIAT Policy Brief No. 2, International Center for Tropical Agriculture (CIAT), Cali, Colombia, 4 pp. Available at: https://cgspace.cgiar.org/handle/10568/29001 (accessed 17/09/2019).
Lagos, N. A. et al., 2016: Effects of temperature and ocean acidification on shell characteristics of Argopecten purpuratus: implications for scallop aquaculture in an upwelling-influenced area. *Aquaculture Environment Interactions*, **8**, 357-370, doi:10.3354/aei00183.
Laguna, F., M. E. Grillet, J. R. León and C. Ludeña, 2017: Modelling malaria incidence by an autoregressive distributed lag model with spatial component. *Spatial and Spatio-temporal Epidemiology*, **22**, 27-37, doi:10.1016/j.sste.2017.05.001.
Lambert, N. J. and J. Eise, 2020: Farming in the Face of Uncertainty: How Colombian Coffee Farmers Conceptualize and Communicate Their Experiences With Climate Change. *International Journal of Communication*, **14**.
Lambin, E. F. et al., 2018: The role of supply-chain initiatives in reducing deforestation. *Nature Climate Change*, **8**(2), 109-116, doi:10.1038/s41558-017-0061-1.
Lampis, A., 2013: La adaptación al cambio climático: el reto de las dobles agendas. In: *Cambio climático, movimientos sociales y políticas públicas. Una vinculación necesaria*, 1 ed. [Postigo, J. (ed.)]. CLACSO, Pontificia Universidad Católica del Perú e Instituto de Ciencias Alejandro Lipschutz, Santiago de Chile, pp. 29-50. ISBN 978-956-351-460-5.

Lampis, A., P. H. Campello Torres, P. R. Jacobi and A. L. Leonel, 2020: A produção de riscos e desastres na América latina em um contexto de emergência climática. *O Social em Questão*,(48), 75–96.
Lan, L. et al., 2018: Farm-level and community aggregate economic impacts of adopting climate smart agricultural practices in three mega environments. *PLOS ONE*, **13**(11), e0207700, doi:10.1371/journal.pone.0207700.
Landesmann, J. B., J. H. Gowda, L. A. Garibaldi and T. Kitzberger, 2015: Survival, growth and vulnerability to drought in fire refuges: implications for the persistence of a fire-sensitive conifer in northern Patagonia. *Oecologia*, **179**(4), 1111-1122, doi:10.1007/s00442-015-3431-2.
Lapola, D. M. et al., 2019a: Heat stress vulnerability and risk at the (super) local scale in six Brazilian capitals. *Climatic Change*, **154**(3), 477-492, doi:10.1007/s10584-019-02459-w.
Lapola, D. M. et al., 2019b: A climate-change vulnerability and adaptation assessment for Brazil's protected areas. *Conservation Biology*, **34**(2), 427-437, doi:10.1111/cobi.13405.
Lapola, D. M. et al., 2014: Pervasive transition of the Brazilian land-use system. *Nature Climate Change*, **4**(1), 27-35, doi:10.1038/nclimate2056.
Lapola, D. M. et al., 2018: Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(46), 11671-11679, doi:10.1073/pnas.1721770115.
Laporta, G. Z. et al., 2015: Malaria vectors in South America: current and future scenarios. *Parasites & Vectors*, **8**(1), 426, doi:10.1186/s13071-015-1038-4.
Lara, M. et al., 2018: Landslide susceptibility maps of Santiago city Andean foothills, Chile. *Andean Geology*, **45**(3), 433-442, doi:10.5027/andgeoV45n3-3151.
Lardies, M. A. et al., 2017: Physiological and histopathological impacts of increased carbon dioxide and temperature on the scallops Argopecten purpuratus cultured under upwelling influences in northern Chile. *Aquaculture*, **479**, 455-466, doi:10.1016/j.aquaculture.2017.06.008.
Larson, A. M. and E. Petkova, 2011: An Introduction to Forest Governance, People and REDD+ in Latin America: Obstacles and Opportunities. *Forests*, **2**(1), doi:10.3390/f2010086.
Lasage, R. et al., 2015: A Stepwise, participatory approach to design and implement community based adaptation to drought in the Peruvian Andes. *Sustainability (Switzerland)*, **7**(2), 1742-1773, doi:10.3390/su7021742.
Lavell, A., 2016: *Colombia, Peru y Mexico: Reporte Regional Final para América Latina. Reducing Relocation Risk in Urban Areas*. The Bartlett Development Planning Unit, UCL. Available at: https://www.ucl.ac.uk/bartlett/development/sites/bartlett/files/wp4_closure_rep_flacso_esp.pdf (accessed 01/09/2021).
Lázaro, W. L. et al., 2020: Climate change reflected in one of the largest wetlands in the world: an overview of the Northern Pantanal water regime. *Acta Limnologica Brasiliensia*, **32**, e104, doi:10.1590/S2179-975X7619.
Le, T. D. N., 2020: Climate change adaptation in coastal cities of developing countries: characterizing types of vulnerability and adaptation options. *Mitigation and Adaptation Strategies for Global Change*, **25**(5), 739-761, doi:10.1007/s11027-019-09888-z.
Leal Filho, W., 2018: Climate Change in Latin America: An Overview of Current and Future Trends. In: *Climate Change Adaptation in Latin America : Managing Vulnerability, Fostering Resilience* [Leal Filho, W. and L. E. Freitas (eds.)]. Springer International Publishing, Cham, pp. 529-537. ISBN 1610-2010.
Leal Filho, W. et al., 2018: Fostering coastal resilience to climate change vulnerability in Bangladesh, Brazil, Cameroon and Uruguay: a cross-country comparison. *Mitigation & Adaptation Strategies for Global Change*, **23**(4), 579-602, doi:10.1007/s11027-017-9750-3.
Leal Filho, W. et al., 2021: Whose voices, whose choices? Pursuing climate resilient trajectories for the poor. *Environmental Science & Policy*, **121**, 18-23, doi:10.1016/j.envsci.2021.02.018.
Leão, Z. M. A. N. et al., 2016: Brazilian coral reefs in a period of global change: A synthesis. *Brazilian Journal of Oceanography*, **64**, 97-116, doi:10.1590/S1679-875920160916064sp2.
Lee, D. R. et al., 2014: Developing local adaptation strategies for climate change in agriculture: A priority-setting approach with application to Latin America. *Global Environmental Change*, **29**, 78-91, doi:10.1016/j.gloenvcha.2014.08.002.
Lee, J. Y. et al., 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Lee, T. and T. Lee, 2016: Evolutionary urban climate resilience: assessment of Seoul's policies. *International Journal of Climate Change Strategies and Management*, **8**(5), 597-612, doi:10.1108/IJCCSM-06-2015-0066.
Lehmann, J., 2009: Terra preta nova - Where to from here? In: *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer, Dordrecht, pp. 473-486. ISBN 9781402090301.
Lehmann, J. et al., 2003: Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, manure and charcoal amendments. *Plant and Soil*, doi:10.1023/A:1022833116184.
Leichenko, R. and J. A. Silva, 2014: Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(4), 539-556.
Leichenko, R. M. and K. L. O'Brien, 2019: *Climate and society: transforming the future*. Polity, Cambridge, 250 pp.

Leisher, C. et al., 2019: *Guía para el monitoreo y la evaluación de los Fondos de Agua*. The Nature Conservancy, 23 pp. Available at: https://s3.amazonaws.com/tnc-craft/library/Water-Funds_ME-Guide_0719_Es.pdf?mtime=20190910204650 (accessed 16/06/2021).
Leite-Filho, A. T. et al., 2021: Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications*, **12**(1), 2591, doi:10.1038/s41467-021-22840-7.
Leiva G, M. A. et al., 2013: A five-year study of particulate matter (PM2.5) and cerebrovascular diseases. *Environmental Pollution*, **181**, 1-6, doi:10.1016/j.envpol.2013.05.057.
Lemos, M. C. et al., 2016: Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil. *Global Environmental Change*, **39**, 170-179, doi:10.1016/j.gloenvcha.2016.05.001.
León-Muñoz, J., M. A. Urbina, R. Garreaud and J. L. Iriarte, 2018: Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016). *Scientific Reports*, **8**(1), 1330, doi:10.1038/s41598-018-19461-4.
Leroy, D., 2019: Farmers' Perceptions of and Adaptations to Water Scarcity in Colombian and Venezuelan Páramos in the Context of Climate Change. *Mountain Research and Development*, **39**(2), R21-R34, doi:10.1659/MRD-JOURNAL-D-18-00062.1.
Lesjak, J. and D. F. Calderini, 2017: Increased Night Temperature Negatively Affects Grain Yield, Biomass and Grain Number in Chilean Quinoa. *Front Plant Sci*, **8**, 352-352, doi:10.3389/fpls.2017.00352.
Lewnard, J. A. et al., 2014: Forecasting Temporal Dynamics of Cutaneous Leishmaniasis in Northeast Brazil. *PLOS Neglected Tropical Diseases*, **8**(10), e3283, doi:10.1371/journal.pntd.0003283.
Li, D. et al., 2018: Vulnerability of the global terrestrial ecosystems to climate change. *Global Change Biology*, **24**(9), 4095-4106, doi:10.1111/gcb.14327.
Lillo-Ortega, G. et al., 2019: On the evaluation of adaptation practices: a transdisciplinary exploration of drought measures in Chile. *Sustainability Science*, **14**(4), 1057–1069, doi:10.1007/s11625-018-0619-5.
Lima, C. H. R., A. AghaKouchak and J. T. Randerson, 2018: Unraveling the Role of Temperature and Rainfall on Active Fires in the Brazilian Amazon Using a Nonlinear Poisson Model. *Journal of Geophysical Research: Biogeosciences*, **123**(1), 117-128, doi:10.1002/2017JG003836.
Lima, G. N. d. and V. O. Magaña Rueda, 2018: The urban growth of the metropolitan area of Sao Paulo and its impact on the climate. *Weather and Climate Extremes*, **21**, 17-26, doi:10.1016/j.wace.2018.05.002.
Lima, H. N. et al., 2002: Pedogenesis and pre-Colombian land use of "Terra Preta Anthrosols" ("Indian black earth") of Western Amazonia. *Geoderma*, **110**(1-2), 1-17, doi:10.1016/S0016-7061(02)00141-6.
Lima, S. M. Q., T. P. A. Ramos, M. J. da Silva and R. de Souza Rosa, 2017: Diversity, Distribution, and Conservation of the Caatinga Fishes: Advances and Challenges. In: *Caatinga: The Largest Tropical Dry Forest Region in South America* [Silva, J. M. C. d., I. R. Leal and M. Tabarelli (eds.)]. Springer International Publishing, Cham, pp. 97-131. ISBN 978-3-319-68339-3.
Lin, Y.-C., W.-J. Chi, Y.-T. Lin and C.-Y. Lai, 2020: The spatiotemporal estimation of the risk and the international transmission of COVID-19: a global perspective. *Scientific Reports*, **10**(1), 20021, doi:10.1038/s41598-020-77242-4.
Lindoso, D. P. et al., 2018: Harvesting water for living with drought: Insights from the Brazilian Human Coexistence with Semi-Aridity approach towards achieving the sustainable development goals. *Sustainability*, **10**(3), 622, doi:10.3390/su10030622.
Lindsay, A., 2018: Social learning as an adaptive measure to prepare for climate change impacts on water provision in Peru. *Journal of Environmental Studies and Sciences*, **8**(4), 477–487, doi:10.1007/s13412-017-0464-3.
Lins-de-Barros, F. and L. Parente-Ribeiro, 2018: How Much Is a Beach Worth: Economic Use and Vulnerability to Coastal Erosion: The Case of Ipanema and Arpoador Beaches, Rio de Janeiro (Brazil). In: *Climate Change Adaptation in Latin America : Managing Vulnerability, Fostering Resilience* [Leal Filho, W. and L. E. Freitas (eds.)]. Springer International Publishing, Cham, pp. 207-222.
Lippi, C. A. et al., 2019: Geographic shifts in Aedes aegypti habitat suitability in Ecuador using larval surveillance data and ecological niche modeling: Implications of climate change for public health vector control. *PLOS Neglected Tropical Diseases*, **13**(4), e0007322, doi:10.1371/journal.pntd.0007322.
Liu, Y. and J. Chen, 2021: Future global socioeconomic risk to droughts based on estimates of hazard, exposure, and vulnerability in a changing climate. *Science of The Total Environment*, **751**, 142159, doi:10.1016/j.scitotenv.2020.142159.
Lizana, X. C., A. Avila, A. Tolaba and J. P. Martinez, 2017: Field responses of potato to increased temperature during tuber bulking: Projection for climate change scenarios, at high-yield environments of Southern Chile. *Agricultural and Forest Meteorology*, **239**, 192-201, doi:10.1016/j.agrformet.2017.03.012.
Lizarralde Oliver, S. and H. Ribeiro, 2016: Water Supply, Climate Change and Health Risk Factors: Example Case of Sao Paulo -Brazil. [Leal Filho, W., U. M. Azeiteiro and F. Alves (eds.)]. Springer, pp. 433-447.
Llopart, M. et al., 2014: Climate change impact on precipitation for the Amazon and La Plata basins. *Climatic Change*, **125**(1), 111-125, doi:10.1007/s10584-014-1140-1.
Llopart, M., M. Simões Reboita and R. Porfírio da Rocha, 2020: Assessment of multi-model climate projections of water resources over South America CORDEX domain. *Climate Dynamics*, **54**(1), 99-116, doi:10.1007/s00382-019-04990-z.

Lluch-Cota, S. E., F. Arreguín-Sánchez, C. J. Salvadeo and P. Del Monte Luna, 2018: Chapter 10: Climate change impacts, vulnerabilities and adaptations: Northeast Tropical Pacific marine fisheries. In: *Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Barhi, M. C. M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations, Rome, pp. 207-218.
Loboguerrero, A. M. et al., 2018: Bridging the gap between climate science and farmers in Colombia. *Clim. Risk Manag.*, **22**, 67-81, doi:10.1016/j.crm.2018.08.001.
Loboguerrero, A. M. et al., 2019: Food and Earth Systems: Priorities for Climate Change Adaptation and Mitigation for Agriculture and Food Systems. *Sustainability*, **11**(5), doi:10.3390/su11051372.
Lobos, T. E. et al., 2018: Regulated deficit irrigation effects on physiological parameters, yield, fruit quality and antioxidants of Vaccinium corymbosum plants cv. Brigitta. *Irrigation Science*, **36**(1), 49-60, doi:10.1007/s00271-017-0564-6.
Locatelli, B. et al., 2017: Research on climate change policies and rural development in Latin America: Scope and gaps. *Sustainability (Switzerland)*, **9**(10), 1-17, doi:10.3390/su9101831.
Locatelli, B. et al., 2011: Forests and Climate Change in Latin America: Linking Adaptation and Mitigation. *Forests*, **2**(1), doi:10.3390/f2010431.
Locatelli, B., C. Pavageau, E. Pramova and M. Di Gregorio, 2015: Integrating climate change mitigation and adaptation in agriculture and forestry: Opportunities and trade-offs. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(6), 585-598, doi:10.1002/wcc.357.
Locatelli, B. et al., 2020: Climate change policy networks: connecting adaptation and mitigation in multiplex networks in Peru. *Climate Policy*, **20**(3), 354-372, doi:10.1080/14693062.2020.1730153.
Løken, I., 2019: Climate-Induced Migration in the Ancash Region in Peru.
Long, R. D., A. Charles and R. L. Stephenson, 2015: Key principles of marine ecosystem-based management. *Marine Policy*, **57**, 53-60, doi:10.1016/j.marpol.2015.01.013.
Lopes, P. F. M. et al., 2019: The Challenge of Managing Amazonian Small-Scale Fisheries in Brazil. In: *Viability and Sustainability of Small-Scale Fisheries in Latin America and The Caribbean* [Salas, S., M. J. Barragán-Paladines and R. Chuenpagdee (eds.)]. Springer International Publishing, Cham, pp. 219-241. ISBN 978-3-319-76078-0.
López-Álvarez, L., 2016: Malaria sensitivity to climate in Colombia: The importance of data availability, quality and format. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 78-79.
López-Feldman, A., 2014: Shocks, Income and Wealth: Do They Affect the Extraction of Natural Resources by Rural Households? *World Development*, **64**, S91-S100, doi:10.1016/j.worlddev.2014.03.012.
López-Franca, N. et al., 2016: Changes in temperature extremes for 21st century scenarios over South America derived from a multi-model ensemble of regional climate models. *Climate Research*, **68**, 151-167, doi:10.3354/cr01393.
López-García, J., Y. Carvajal-Escobar and A. Enciso-Arango, 2017: Sistemas De Alerta Temprana Con Enfoque Participativo: Un Desafío Para La Gestión Del Riesgo En Colombia. *Luna Azul*,(44), 231-246, doi:10.17151/luaz.2017.44.14.
López Feldman, A. J. and D. Hernández Cortés, 2016: Climate Change and Agriculture: A Review of the Literature with Emphasis on Latin America. *Trimest. Econ.*, **83**(332), 459-496, doi:10.20430/ete.v83i332.231.
López, M. S. et al., 2021: Dengue emergence in the temperate Argentinian province of Santa Fe, 2009–2020. *Scientific Data*, **8**(1), 134, doi:10.1038/s41597-021-00914-x.
Lovejoy, T. E. and C. Nobre, 2018: Amazon Tipping Point. *Science Advances*, **4**(2), eaat2340, doi:10.1126/sciadv.aat2340.
Lovino, M. A., O. V. Müller, E. H. Berbery and G. V. Müller, 2018: How have daily climate extremes changed in the recent past over northeastern Argentina? *Global and Planetary Change*, **168**, 78-97, doi:10.1016/j.gloplacha.2018.06.008.
Lowe, R. et al., 2013: The development of an early warning system for climate-sensitive disease risk with a focus on dengue epidemics in Southeast Brazil. *Statistics in Medicine*, **32**(5), 864-883, doi:10.1002/sim.5549.
Lowe, R. et al., 2014: Dengue outlook for the World Cup in Brazil: an early warning model framework driven by real-time seasonal climate forecasts. *The Lancet Infectious Diseases*, **14**(7), 619-626, doi:10.1016/S1473-3099(14)70781-9.
Lowe, R. et al., 2016: Using climate knowledge to guide dengue prevention and risk communication ahead of Brazil's 2014 FIFA World Cup. [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 218-218.
Lowe, R. et al., 2017: Climate services for health: predicting the evolution of the 2016 dengue season in Machala, Ecuador. *The Lancet Planetary Health*, **1**(4), 142-151, doi:10.1016/S2542-5196(17)30064-5.
Loyola, R. D. et al., 2014: Clade-specific consequences of climate change to amphibians in Atlantic Forest protected areas. *Ecography*, **37**(1), 65-72, doi:10.1111/j.1600-0587.2013.00396.x.
Loyola, R. D. et al., 2012: Severe Loss of Suitable Climatic Conditions for Marsupial Species in Brazil: Challenges and Opportunities for Conservation. *PLOS ONE*, **7**(9), e46257, doi:10.1371/journal.pone.0046257.
Lutz, D. A., R. L. Powell and M. R. Silman, 2013: Four decades of Andean timberline migration and implications for biodiversity loss with climate change. *PloS one*, **8**(9), 1-9, doi:10.1371/journal.pone.0074496.

Lyons, W., 2019: Cloud Forests of Costa Rica: Ecosystems in Peril. *Weatherwise*, **72**(3), 32-37, doi:10.1080/00431672.2019.1586505.
Lyra, A. et al., 2017: Projections of climate change impacts on central America tropical rainforest. *Climatic Change*, **141**(1), 93-105, doi:10.1007/s10584-016-1790-2.
Macedo, M. N. et al., 2012: Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proceedings of the National Academy of Sciences*, **109**(4), 1341-1346, doi:10.1073/pnas.1111374109.
Machado-Silva, F. et al., 2020: Drought and fires influence the respiratory diseases hospitalizations in the Amazon. *Ecological Indicators*, **109**, 105817, doi:10.1016/j.ecolind.2019.105817.
Machin, A. B., L. F. Nascimento, K. Mantovani and E. B. Machin, 2019: Effects of exposure to fine particulate matter in elderly hospitalizations due to respiratory diseases in the South of the Brazilian Amazon. *Brazilian Journal of Medical and Biological Research*, **52**, 1-7, doi:10.1590/1414-431x20188130.
Mackey, B. G., J. E. M. Watson, G. Hope and S. Gilmore, 2008: Climate change, biodiversity conservation, and the role of protected areas: An Australian perspective. *Biodiversity*, **9**(3-4), 11-18, doi:10.1080/14888386.2008.9712902.
Maeda, E. E. et al., 2015: Disruption of hydroecological equilibrium in southwest Amazon mediated by drought. *Geophysical Research Letters*, **42**(18), 7546-7553, doi:10.1002/2015GL065252.
Maezumi, S. Y. et al., 2018a: The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. *Nature Plants*, **4**(8), 540-547, doi:10.1038/s41477-018-0205-y.
Maezumi, S. Y. et al., 2018b: New insights from pre-Columbian land use and fire management in Amazonian dark earth forests. *Frontiers in Ecology and Evolution*, doi:10.3389/fevo.2018.00111.
Magalhães, H. F., I. S. Feitosa, E. de Lima Araújo and U. P. Albuquerque, 2021: Perceptions of Risks Related to Climate Change in Agroecosystems in a Semi-arid Region of Brazil. *Human Ecology*, doi:10.1007/s10745-021-00247-8.
Magni, G., 2017: Indigenous knowledge and implications for the sustainable development agenda. *European Journal of Education*, **52**(4), 437-447, doi:10.1111/ejed.12238.
Magoni, M. and C. M. Munoz, 2018: Climate Change and Heat Waves in Colombia. Possible Effects and Adaptation Strategies. In: *Sustainable Urban Development and Globalization: New strategies for new challenges—with a focus on the Global South* [Petrillo, A. and P. Bellaviti (eds.)]. Springer International Publishing, Cham, pp. 351-361. ISBN 978-3-319-61988-0.
Magrin, G. O. et al., 2014: Central and South America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1499-1566. ISBN 9781107058163.
Mahlknecht, J., R. González-Bravo and F. J. Loge, 2020: Water-energy-food security: A Nexus perspective of the current situation in Latin America and the Caribbean. *Energy*, **194**, 116824, doi:10.1016/j.energy.2019.116824.
Mahon, R. et al., 2019: Fit for purpose? Transforming National Meteorological and Hydrological Services into National Climate Service Centers. *Climate Services*, **13**, 14-23, doi:10.1016/j.cliser.2019.01.002.
Malhado, A. C. M., G. F. Pires and M. H. Costa, 2010: Cerrado conservation is essential to protect the Amazon rainforest. *Ambio*, **39**(8), 580-584, doi:10.1007/s13280-010-0084-6.
Malizia, A. et al., 2020: Elevation and latitude drives structure and tree species composition in Andean forests: Results from a large-scale plot network. *PLOS ONE*, **15**(4), e0231553, doi:10.1371/journal.pone.0231553.
Malmros, J. K. et al., 2018: Snow cover and snow albedo changes in the central Andes of Chile and Argentina from daily MODIS observations (2000–2016). *Remote Sensing of Environment*, **209**, 240-252, doi:10.1016/j.rse.2018.02.072.
Manchego, C. E. et al., 2017: Climate change versus deforestation: Implications for tree species distribution in the dry forests of southern Ecuador. *PLOS ONE*, **12**(12), e0190092, doi:10.1371/journal.pone.0190092.
Manes, S. et al., 2021: Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, **257**, 109070, doi:10.1016/j.biocon.2021.109070.
Mangone, G., 2016: Constructing hybrid infrastructure: Exploring the potential ecological, social, and economic benefits of integrating municipal infrastructure into constructed environments. *Cities*, **55**, 165-179, doi:10.1016/j.cities.2016.04.004.
Mansourian, S., 2017: Governance and forest landscape restoration: A framework to support decision-making. *Journal for Nature Conservation*, **37**, 21-30, doi:10.1016/j.jnc.2017.02.010.
Mansourian, S., A. Belokurov and P. J. Stephenson, 2009: The role of forest protected areas in adaptation to climate change. In: *Adapting to climate change* [Nations, F. a. A. O. o. t. U. (ed.)]. Unasylva No. 231/232, Rome, pp. 63-69.
Mansur, A. V. et al., 2016: An assessment of urban vulnerability in the Amazon Delta and Estuary: a multi-criterion index of flood exposure, socio-economic conditions and infrastructure. *Sustainability Science*, **11**(4), 625-643, doi:10.1007/s11625-016-0355-7.
Mantyka-Pringle, C. S. et al., 2015: Climate change modifies risk of global biodiversity loss due to land-cover change. *Biological Conservation*, **187**, 103-111, doi:10.1016/j.biocon.2015.04.016.

Marcovitch, J., S. Margulis and C. B. S. Dubeux, 2010: *Economia da Mudança do Clima no Brasil: Custos e Oportunidades*. Ibep, G., São Paulo, 82 pp. Available at: http://www.colit.pr.gov.br/arquivos/File/Publicacoes/Economia_do_clima.pdf (accessed 27/09/2019).
Marengo, J. A. et al., 2020a: Trends in extreme rainfall and hydrogeometeorological disasters in the Metropolitan Area of São Paulo: a review. *Annals of the New York Academy of Sciences*, **1472**(1), 5-20, doi:10.1111/nyas.14307.
Marengo, J. A., L. M. Alves and R. R. Torres, 2016: Regional climate change scenarios in the Brazilian Pantanal watershed. *Clim Res*, **68**, 201-213, doi:10.3354/cr01324.
Marengo, J. A. et al., 2020b: Changing Trends in Rainfall Extremes in the Metropolitan Area of São Paulo: Causes and Impacts. *Frontiers in Climate*, **2**, 3, doi:10.3389/fclim.2020.00003.
Marengo, J. A. and M. Bernasconi, 2015: Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections. *Climatic Change*, **129**(1-2), 103-115, doi:10.1007/s10584-014-1310-1.
Marengo, J. A. et al., 2013: Recent Extremes of Drought and Flooding in Amazonia: Vulnerabilities and Human Adaptation. *American Journal of Climate Change*, **2**(2), 87-96, doi:10.4236/ajcc.2013.22009.
Marengo, J. A. et al., 2021: Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. *Frontiers in Water*, **3**(13), doi:10.3389/frwa.2021.639204.
Marengo, J. A. et al., 2019: Increase Risk of Drought in the Semiarid Lands of Northeast Brazil Due to Regional Warming above 4 °C. In: *Climate Change Risks in Brazil* [Nobre, C. A., J. A. Marengo and W. R. Soares (eds.)]. Springer International Publishing, Cham, pp. 181-200. ISBN 978-3-319-92881-4.
Marengo, J. A. et al., 2020c: Assessing drought in the drylands of northeast Brazil under regional warming exceeding 4 °C. *Natural Hazards*, **103**(2), 2589-2611, doi:10.1007/s11069-020-04097-3.
Marengo, J. A. and J. C. Espinoza, 2016: Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. *International Journal of Climatology*, **36**(3), 1033-1050, doi:10.1002/joc.4420.
Marengo, J. A. et al., 2020d: Central South America. In: *State of the Climate in 2019*. American Meteorological Society, pp. S344-S346.
Marengo, J. A. et al., 2018: Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. *Frontiers in Earth Science*, **6**, 1-21, doi:10.3389/feart.2018.00228.
Marengo, J. A., R. R. Torres and L. M. Alves, 2017: Drought in Northeast Brazil—past, present, and future. *Theoretical and Applied Climatology*, **129**(3), 1189-1200, doi:10.1007/s00704-016-1840-8.
Maretti, C. C. et al., 2019: Marine and coastal protected and conserved areas strategy in Brazil: Context, lessons, challenges, finance, participation, new management models, and first results. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **29**(S2), 44-70, doi:10.1002/aqc.3169.
Mariano, D. A. et al., 2018: Use of remote sensing indicators to assess effects of drought and human-induced land degradation on ecosystem health in Northeastern Brazil. *Remote Sensing of Environment*, **213**, 129-143, doi:10.1016/j.rse.2018.04.048.
Mariano Gutiérrez, T., P. Jorge Castillo, B. Laura Naranjo and M. J. Akester, 2017: Current state of goods, services and governance of the Humboldt Current Large Marine Ecosystem in the context of climate change. *Environmental Development*, **22**, 175-190, doi:10.1016/j.envdev.2017.02.006.
Marín, A., 2019: Adaptive Capacity to Coastal Disasters: Challenges and Lessons from Small-Scale Fishing Communities in Central-Southern Chile. In: *Viability and Sustainability of Small-Scale Fisheries in Latin America and The Caribbean* [Salas, S., M. J. Barragán-Paladines and R. Chuenpagdee (eds.)]. Springer International Publishing, Cham, pp. 51-78. ISBN 978-3-319-76078-0.
Marinho, D. P. and H. V. d. O. Silva, 2018: *Relatório do Projeto Construção de Indicadores de Vulnerabilidade da População como Insumo para a Elaboração das Ações de Adaptação à Mudança do Clima no Brasil: Volume: Pernambuco*. Fundação Oswaldo Cruz, Ministério do Meio Ambiente e Fundo Nacional sobre Mudança do Clima FIOCRUZ, Rio de Janeiro, RJ, 123 pp. Available at: https://www.mma.gov.br/images/arquivo/80182/Vulnerabilidade%20%C3%A0%20Mudan%C3%A7a%20do%20Clima/Relat%C3%B3rio_Final_Pernambuco_Novo.pdf (accessed 11/10/2020).
Mark, B. G. et al., 2017: Glacier loss and hydro-social risks in the Peruvian Andes. *Global and Planetary Change*, **159**, 61-76, doi:10.1016/j.gloplacha.2017.10.003.
Marques Di Giulio, G., A. M. Bedran-Martins, M. d. P. Vasconcellos and W. Costa Ribeiro, 2017: Mudanças climáticas, riscos e adaptação na megacidade de São Paulo, Brasil. *Sustainability in Debate/Sustentabilidade em Debate*, **8**(2), 75-87, doi:doi:10.18472/SustDeb.v8n2.2017.19868.
Marques, T. H. N., D. Rizzi, P. R. M. Pellegrino and N. C. B. Moura, 2018: Jaguaré Project: Requalification of urban hydrographic basins methodology. *Revista LABVERDE*, **9**(1), 12-27, doi:10.11606/issn.2179-2275.v9i1p12-27.
Martin, C., G. Campillo, H. Meirovich and J. Navarrete, 2013: *Climate Change Mitigation & Adaptation through Publically-Assisted Housing: Theoretical Framework for the IDB's Regional Policy Dialogue on Climate Change*. Inter-American Development Bank, United States, North America, 56 pp. Available at: https://publications.iadb.org/publications/english/document/Climate-Change-Mitigation--Adaptation-through-Publically-Assisted-Housing-Theoretical-Framework-for-the-IDB-Regional-Policy-Dialogue-on-Climate-Change.pdf (accessed 17/10/2020).
Martínez-Alier, J. et al., 2018: Blockadia: movimientos de base contra los combustibles fósiles y a favor de la justicia climática. *Anuario Internacional CIDOB*, 41-49.

Martinez-Harms, M. J., H. Caceres, D. Biggs and H. P. Possingham, 2017: After Chile's fires, reforest private land. *Science*, **356**(6334), 147-148, doi:10.1126/science.aan0701.

Martínez, C. et al., 2018: Coastal erosion in central Chile: A new hazard? *Ocean and Coastal Management*, **156**, 141-155, doi:10.1016/j.ocecoaman.2017.07.011.

Martínez, R. et al., 2017: Evolución, vulnerabilidad e impactos económicos y sociales de El Niño 2015-2016 en América Latina. *Investigaciones Geográficas*,(68), 65-78, doi:10.14198/INGEO2017.68.0.

Martins, A. C., D. P. Silva, P. De Marco and G. A. R. Melo, 2015: Species conservation under future climate change: the case of Bombusbellicosus, a potentially threatened South American bumblebee species. *Journal of Insect Conservation*, **19**(1), 33-43, doi:10.1007/s10841-014-9740-7.

Martins, I. M. and M. A. Gasalla, 2018: Perceptions of climate and ocean change impacting the resources and livelihood of small-scale fishers in the South Brazil Bight. *Climatic Change*, **147**(3), 441-456, doi:10.1007/s10584-018-2144-z.

Martins, K. A., P. d. Souza Pereira, R. Silva-Casarín and A. V. Nogueira Neto, 2017: The Influence of Climate Change on Coastal Erosion Vulnerability in Northeast Brazil. *Coastal Engineering Journal*, **59**(2), 1740007-1740001-1740007-1740025, doi:10.1142/S0578563417400071.

Martins, M. A., J. Tomasella and C. G. Dias, 2019: Maize yield under a changing climate in the Brazilian Northeast: Impacts and adaptation. *Agric. Water Manage.*, **216**, 339-350, doi:10.1016/j.agwat.2019.02.011.

Masiokas, M. H. et al., 2020: A Review of the Current State and Recent Changes of the Andean Cryosphere. *Frontiers in Earth Science*, **8**, 99.

Matera, J., 2016: Livelihood diversification and institutional (dis-)trust: Artisanal fishing communities under resource management programs in Providencia and Santa Catalina, Colombia. *Marine Policy*, **67**, 22-29, doi:10.1016/j.marpol.2016.01.021.

Mathez-Stiefel, S.-L. et al., 2017: Research Priorities for the Conservation and Sustainable Governance of Andean Forest Landscapes. *Mountain Research and Development*, **37**(3), 323-339, doi:10.1659/MRD-JOURNAL-D-16-00093.1.

Matoso, S. C. G., P. G. S. Wadt, V. S. De Souza Júnior and X. L. O. Pérez, 2019: Synthesis of enriched biochar as a vehicle for phosphorus in tropical soils. *Acta Amazonica*, **49**(4), 268-276, doi:10.1590/1809-4392201803852.

Mattar, S., V. Morales, A. Cassab and A. J. Rodríguez-Morales, 2013: Effect of climate variables on dengue incidence in a tropical Caribbean municipality of Colombia, Cerete, 2003–2008. *International Journal of Infectious Diseases*, **17**(5), e358-e359, doi:10.1016/j.ijid.2012.11.021.

Matus C, P. and M. Oyarzún G, 2019: Impact of Particulate Matter (PM2,5) and children's hospitalizations for respiratory diseases. A case cross-over study. *Revista Chilena de Pediatría*, **90**(2), 166-174, doi:10.32641/rchped.v90i2.750.

Maurer, E. P., N. Roby, I. T. Stewart-Frey and C. M. Bacon, 2017: Projected twenty-first-century changes in the Central American mid-summer drought using statistically downscaled climate projections. *Regional Environmental Change*, **17**(8), 2421-2432, doi:10.1007/s10113-017-1177-6.

Mbow, C. et al., 2019: Food Security. In: *Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* In Press.

McDonald, A. et al., 2016: Bio-climatic bulletins to forecast dengue vectors in Panama. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 132-135.

McDowell, G. et al., 2019: Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change? *Global Environmental Change*, **54**(September 2018), 19-30, doi:10.1016/j.gloenvcha.2018.10.012.

McDowell, G. et al., 2021: Lived experiences of 'peak water' in the high mountains of Nepal and Peru. *Climate and Development*, 1-14, doi:10.1080/17565529.2021.1913085.

McDowell, N. G. et al., 2020: Pervasive shifts in forest dynamics in a changing world. *Science*, **368**(6494), eaaz9463, doi:10.1126/science.aaz9463.

McLeman, R., 2019: International migration and climate adaptation in an era of hardening borders. *Nature Climate Change*, **9**(12), 911-918, doi:10.1038/s41558-019-0634-2.

McMartin, D. W. et al., 2018: Limitations of Water Resources Infrastructure for Reducing Community Vulnerabilities to Extremes and Uncertainty of Flood and Drought. *Environmental Management*, **62**(6), 1038-1047, doi:10.1007/s00267-018-1104-8.

McMichael, A. J., R. E. Woodruff and S. Hales, 2006: Climate change and human health: present and future risks. *The Lancet*, **367**(9513), 859-869, doi:10.1016/S0140-6736(06)68079-3.

McNamara, K. E. and L. Buggy, 2017: Community-based climate change adaptation: a review of academic literature. *Local Environment*, **22**(4), 443-460, doi:10.1080/13549839.2016.1216954.

McPhearson, T. et al., 2018: Urban Ecosystems and Biodiversity. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal and S. Ali Ibrahim (eds.)]. Cambridge University Press, New York, United States of America, pp. 257-318. ISBN 978-1-316-60333-8.

McTarnaghan, S., C. Martín, T. Srini and J. Collazos, 2016: *Revisão da literatura sobre habitação na América Latina e no Caribe* [Gold, A., M. Suminski and Y. Guzman (eds.)]. Fase I: Iniciativa Global de Pesquisa sobre Habitação, Urban Institute, Habitat for Humanity, Institute, U., 110 pp. Available at: https://www.habitat.org/sites/default/files/Global-Housing-Research-Initiative-PORTUGUESE-FINAL-Oct-2016.pdf (accessed 17/10/2020).
Medeiros, S. R. M. d., R. G. Carvalho and M. R. C. Pimenta, 2014: A proteção do ecossistema manguezal à luz da lei:12.651/2012: novos desafios para a sustentabilidade dos manguezais do Rio Grande do Norte. *Revista Geotemas*, **4**(2), 59-78.
Meerow, S. and J. P. Newell, 2016: Urban resilience for whom, what, when, where, and why? *Urban Geography*, **40**(3), 309-329, doi:10.1080/02723638.2016.1206395.
Mehrotra, S. et al., 2018: Urban Transportation. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W. D. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal and S. Ali Ibrahim (eds.)]. Cambridge University Press, New York, United States of America, pp. 491–518.
Meier, W. J. H., J. Grießinger, P. Hochreuther and M. H. Braun, 2018: An Updated Multi-Temporal Glacier Inventory for the Patagonian Andes With Changes Between the Little Ice Age and 2016. *Frontiers in Earth Science*, **6**, 62, doi:10.3389/feart.2018.00062.
Mejia, A., 2014: Water Scarcity in Latin America and the Caribbean. In: *Water for Americs: Challenges and Opportunities* [Garrido, A. and M. Shechter (eds.)]. Routledge, Oxford, pp. 1-34. ISBN 9781315774848.
Mekonnen, M. M. and A. Y. Hoekstra, 2016: Four billion people facing severe water scarcity. *Science Advances*, **2**(2), e1500323, doi:10.1126/sciadv.1500323.
Mekonnen, M. M. et al., 2015: Sustainability, efficiency and equitability of water consumption and pollution in Latin America and the Caribbean. *Sustainability*, **7**(2), 2086-2112, doi:10.3390/su7022086.
Meldrum, G. et al., 2018: Climate change and crop diversity: farmers' perceptions and adaptation on the Bolivian Altiplano. *Environment, Development and Sustainability*, **20**(2), 703-730, doi:10.1007/s10668-016-9906-4.
Mellado, C. et al., 2019: Ocean acidification exacerbates the effects of paralytic shellfish toxins on the fitness of the edible mussel Mytilus chilensis. *Science of The Total Environment*, **653**, 455-464, doi:10.1016/j.scitotenv.2018.10.399.
Melo, O. and W. Foster, 2021: Agricultural and Forestry Land and Labor Use under Long-Term Climate Change in Chile. *Atmosphere*, **12**(3), doi:10.3390/atmos12030305.
Menéndez, C. G., P. G. Zaninelli, A. F. Carril and E. Sánchez, 2016: Hydrological cycle, temperature, and land surface-atmosphere interaction in the la Plata Basin during summer: Response to climate change. *Climate Research*, **68**(2-3), 231-241, doi:10.3354/cr01373.
Menezes, J. A., 2018: *Relatório do Projeto Construção de Indicadores de Vulnerabilidade da População como Insumo para a Elaboração das Ações de Adaptação à Mudança do Clima no Brasil: Volume: Amazonas*. Fundação Oswaldo Cruz, Ministério do Meio Ambiente e Fundo Nacional sobre Mudança do Clima FIOCRUZ, Rio de Janeiro, RJ, 120 pp. Available at: https://www.mma.gov.br/images/arquivo/80182/Vulnerabilidade%20%C3%A0%20Mudan%C3%A7a%20do%20Clima/Relat%C3%B3rio_Final_Amazonas_Novo.pdf (accessed 11/10/2020).
Menezes, J. A. et al., 2018: Mapping human vulnerability to climate change in the Brazilian Amazon: The construction of a municipal vulnerability index. *PLoS ONE*, **13**(2), e0190808, doi:10.1371/journal.pone.0190808.
Mera, M., X. C. Lizana and D. F. Calderini, 2015: Chapter 6 - Cropping systems in environments with high yield potential of southern Chile. In: *Crop Physiology (Second Edition)* [Sadras, V. O. and D. F. Calderini (eds.)]. Academic Press, San Diego, pp. 111-140. ISBN 978-0-12-417104-6.
Merlinsky, M. G., 2016: Mists of the Riachuelo: River Basins and Climate Change in Buenos Aires. *Latin American Perspectives*, **43**(4), 43-55, doi:10.1177/0094582x15623764.
Mesclier, É., M. Piron and P. Gluski, 2015: Territories and Inclusion in the Peripheries of Lima (Peru): An Exploratory Approach Based on Data about Water Supply and Sewage Disposal. *L'Espace géographique*, **44**(3), 273-288.
Meseguer-Ruiz, O. et al., 2018: Spatial behaviour of daily observed extreme temperatures in Northern Chile (1966–2015): data quality, warming trends, and its orographic and latitudinal effects. *Stochastic Environmental Research and Risk Assessment*, **32**, 3503–3523, doi:10.1007/s00477-018-1557-6.
Metropolitan Municipality of Lima, 2014: Ordenanza 1836 - 2014 - MML. Estrategia de Adaptación y Acciones de Mitigación de la provincia de Lima al Cambio Climático, Municipalidad Metropolitana de Lima, Lima, Perú. Available at: http://smia.munlima.gob.pe/normas/detalle/76 (accessed 16/06/2021).
Metropolitan Municipality of Lima, 2021: Local Climate Change Plan (Plan Local de Cambio Climático de Lima). Available at: https://www.descubrelima.pe/plan-local-cambio-climatico/#plcc-lima.
Metternicht, G., A. Sabelli and J. Spensley, 2014: Climate change vulnerability, impact and adaptation assessment lessons from Latin America. *International Journal of Climate Change Strategies and Management*, **6**(4), 442-476, doi:10.1108/IJCCSM-06-2013-0076.
Mettler-Grove, J., 2020: *Impactos en la salud pública y desigualdades frente al cambio climático en América Latina: Una aproximación hacia las consecuencias diferenciales de las inundaciones y olas de calor en la Cuenca Matanza Riachuelo./Public health impacts and inequalities in the face of climate change in Latin America: an*

approach towards the differential consequences of floods and heat waves in the Matanza Riachuelo watershed. Available at: https://digitalcollections.sit.edu/isp_collection/3304/ (accessed 02/09/2021).
Meza, F. J. et al., 2014: Assessing water demands and coverage sensitivity to climate change in the urban and rural sectors in central Chile. *Journal of Water and Climate Change*, **5**(2), 192-203, doi:10.2166/wcc.2014.019.
Michelutti, N., C. A. Cooke, W. O. Hobbs and J. P. Smol, 2015: Climate-driven changes in lakes from the Peruvian Andes. *Journal of Paleolimnology*, **54**(1), 153-160, doi:10.1007/s10933-015-9843-5.
Miguez, M. G., J. M. Bahiense, O. M. Rezende and A. P. Veról, 2014: Sustainable Urban Drainage Approach, Focusing on LID Techniques, Applied to the Design of New Housing Subdivisions in the Context of a Growing City. *International Journal of Sustainable Development and Planning*, **9**(4), 538-552, doi:10.2495/SDP-V9-N4-538-552.
Miguez, M. G., O. M. Rezende and A. P. Veról, 2015a: City Growth and Urban Drainage Alternatives: Sustainability Challenge. *Journal of Urban Planning and Development*, **141**(3), 04014026, doi:10.1061/(asce)up.1943-5444.0000219.
Miguez, M. G., A. P. Veról, M. M. De Sousa and O. M. Rezende, 2015b: Urban Floods in Lowlands—Levee Systems, Unplanned Urban Growth and River Restoration Alternative: A Case Study in Brazil. *Sustainability*, **7**(8), 11068-11097, doi:10.3390/su70811068.
Milan, A. and R. Ho, 2014: Livelihood and migration patterns at different altitudes in the Central Highlands of Peru. *Climate and Development*, **6**(1), 69-76, doi:10.1080/17565529.2013.826127.
Milkoreit, M. et al., 2018: Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. *Environmental Research Letters*, **13**(3), 033005, doi:10.1088/1748-9326/aaaa75.
Miller, R. et al., 2013a: *Climate Change Adaptation Planning in Latin American and Caribbean Cities. Complete Report: Santos, Brazil*. ICF GHK, London, 134 pp. Available at: https://www.worldbank.org/en/results/2014/01/31/climate-change-adaptation-planning-in-latin-american-and-caribbean-cities (accessed 03/06/2021).
Miller, R. et al., 2013b: *Climate Change Adaptation Planning in Latin American and Caribbean Cities. Final Report: El Progreso, Honduras*. ICF GHK, London, 125 pp. Available at: https://www.worldbank.org/en/results/2014/01/31/climate-change-adaptation-planning-in-latin-american-and-caribbean-cities (accessed 03/06/2021).
Miller, R. et al., 2013c: *Climate Change Adaptation Planning in Latin American and Caribbean Cities. Final report: Estelí, Nicaragua*. London, 128 pp. Available at: https://www.worldbank.org/en/results/2014/01/31/climate-change-adaptation-planning-in-latin-american-and-caribbean-cities (accessed 03/06/2021).
Miller, R. et al., 2013d: *Climate Change Adaptation Planning in Latin American and Caribbean Cities. Final report: Cusco, Peru*. London, 132 pp. Available at: https://www.worldbank.org/en/results/2014/01/31/climate-change-adaptation-planning-in-latin-american-and-caribbean-cities (accessed 03/06/2021).
Mills-Novoa, M., R. Boelens, J. Hoogesteger and J. Vos, 2020: Governmentalities, hydrosocial territories & recognition politics: The making of objects and subjects for climate change adaptation in Ecuador. *Geoforum*, **115**, 90-101, doi:10.1016/j.geoforum.2020.06.024.
Milner, A. M. et al., 2017: Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, **114**(37), 9770-9778, doi:10.1073/pnas.1619807114.
MINAM Peru, 2016: Supreme Decree N°009-2016. Available at: https://www.minam.gob.pe/wp-content/uploads/2016/07/DS_009-2016-MINAM.pdf (accessed 01/09/2021).
Ministerio Agropecuario y Forestal de Nicaragua, 2013: *Plan de Adaptación a la Variabilidad y el Cambio Climático en el Sector Agropecuario, Forestal y Pesca en Nicaragua*, Ministerio Agropecuario y Forestal, Nicaragua, Nicaragua, 131 pp. Available at: https://www.yumpu.com/es/document/read/38160254/plan-de-adaptacion-a-la-variabilidad-y-el-cambio-climatico-magfor (accessed 26/10/2020).
Ministério da Saúde and FIOCRUZ, Observatório de Clima e Saúde. Available at: https://climaesaude.icict.fiocruz.br/.
Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2016: *Plan Nacional de Adaptación al Cambio Climático*, Departamento Nacional de Planeación, Ministerio de Ambiente y Desarrollo Sostenible República de Colombia, Colombia, 283 pp. Available at: https://www4.unfccc.int/sites/NAPC/Documents/Parties/Colombia%20NAP%20Spanish.pdf (accessed 22/10/2020).
Ministerio de Ambiente y Desarrollo Sostenible de la República de Argentina, 2019: *Plan Nacional de Adaptación y Mitigación al Cambio Climático de Argentina*, Ministerio de Ambiente y Desarrollo Sostenible, R. d. A., Argentina, 153 pp. (accessed 23/10/2020).
Ministerio de Ambiente y Energía de la República de Costa Rica, 2018: *Política Nacional de Adaptación al Cambio Climático de Costa Rica 2018- 2030*, Costa Rica, 84 pp. Available at: https://cambioclimatico.go.cr/wp-content/uploads/2017/12/final-politica-adaptacion-24-abril.pdf (accessed 22/10/2020).
Ministerio de Economía Fomento y Turismo de Chile, 2015: *Plan de Adaptación al Cambio Climático para la Pesca y Acuicultura*, Subsecretaria de Pesca y Acuicultura del Ministerio de Economía, Fomento y Turismo Departamento de Cambio Climático Ministerio de Medio Ambiente Chile, Chile, 39 pp. Available at: https://mma.gob.cl/wp-content/uploads/2016/12/Plan-Pesca-y-Acuicultura-CMS.pdf (accessed 21/10/2020).

Ministerio de Medio Ambiente de Chile, 2014a: *Plan de Adaptación al Cambio Climático en Biodiversidad*, Oficina de Cambio Climático y la División de Recursos Naturales y Biodiversidad del Ministerio de Medio Ambiente, Chile, Chile, 97 pp. Available at: http://metadatos.mma.gob.cl/sinia/PDF008.pdf (accessed 21/10/2020).

Ministerio de Medio Ambiente de Chile, 2014b: *Plan Nacional de Adaptación al Cambio Climático*, Departamento de Cambio Climático del Ministerio de Medio Ambiente, Chile, Chile, 80 pp. Available at: https://mma.gob.cl/wp-content/uploads/2016/02/Plan-Nacional-Adaptacion-Cambio-Climatico-version-final.pdf (accessed 21/10/2020).

Ministerio de Medio Ambiente de Chile, 2017: *Plan de Adaptación y Mitigación de los Servicios de Infraestructura al Cambio Climático*, Ministerio de Obras Públicas y Ministerio de Medio Ambiente, Chile, Chile, 126 pp. Available at: http://www.dgop.cl/Documents/PlanAccionMop.pdf (accessed 21/10/2020).

Ministerio de Medio Ambiente de Chile, 2019: *Resumen ejecutivo, en "Determinación del riesgo de los impactos del Cambio Climático en las costas de Chile"*, Ministerio de Medio Ambiente de Chile, Santiago de Chile, Chile, 94 pp. Available at: https://cambioclimatico.mma.gob.cl/wp-content/uploads/2020/04/2019-09-23-Informe-V00-CCCostas-Resumen-Ejecutivo-Rev1.pdf (accessed 10/03/2020).

Ministerio de Medio Ambiente y Recursos Naturales de El Salvador, 2015: *Plan Nacional de Cambio Climático del Salvador, Gobierno el Salvador*, Ministerio de Medio Ambiente y Recursos Naturales, El Salvador, 70 pp. Available at: http://www.cac.int/sites/default/files/Plan_Nacional_de_Cambio_Clim%C3%A1tico._MARN._2015.pdf (accessed 22/10/2020).

Ministerio de Salud de Chile, 2017: *Plan de Adaptación al Cambio Climático Sector Salud*, Ministerio de Salud, División de Cambio Climático del Ministerio de Medio Ambiente Chile, 34 pp. Available at: https://degreyd.minsal.cl/wp-content/uploads/2018/07/Plan-de-adaptacio%CC%81n-al-cambio-clima%CC%81tico-para-salud-2016.pdf (accessed 16/06/2021).

Ministerio de Seguridad de Argentina, 2018: *Plan Nacional para la Reducción del Riesgo de Desastres de Argentina 2018-2013*. 106 pp. Available at: http://www.senado.gov.ar/upload/26448.pdf (accessed 16/06/2021).

Ministerio de Vivienda, C. y. S. d. P., 2017: Supreme Decree 019–2017-Vivienda, Peru. Available at: https://www.minam.gob.pe/wp-content/uploads/2017/07/DS-019-2017-VIVIENDA-1.pdf (accessed 01/09/2021).

Ministerio de Vivienda Ordenamiento Territorial y Medio Ambiente de la República de Uruguay, 2010: *Plan Nacional de Respuesta al Cambio Climático*, Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente República de Uruguay, Montevideo, Uruguay, 101 pp. Available at: https://www.gub.uy/ministerio-ambiente/politicas-y-gestion/planes/plan-nacional-respuesta-cambio-climatico (accessed 23/10/2020).

Ministerio del Ambiente Gobierno del Perú, 2021: *Plan Nacional de Adaptación al Cambio Climático del Perú: un insumo para la actualización de la Estrategia Nacional ante el Cambio Climático*. Ministerio del Ambiente del Perú, Peru, 615 pp.

Ministry of Environment and Natural Resources of El Salvador, 2013: *Síntesis de la evaluación de necesidades tecnológicas (ENT) y Plan de acción para la transferencia de tecnologías priorizadas en adaptación al cambio climático, El Salvador*. San Salvador, 191-191 pp. Available at: https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/TNR_CRE/e9067c6e3b97459989b2196f12155ad5/8f4c345c13974d21ae4d4d2f5f39b04e.pdf (accessed 16/06/2021).

Ministry of Environment of Brazil, 2016a: *National Adaptation Plan to Climate Change. Genenal Strategy (volume 1)*, **1**, Ministry of Environment of Brazil, Brazil, 310 pp. Available at: https://www4.unfccc.int/sites/NAPC/Documents/Parties/Brazil%20NAP%20English.pdf (accessed 21/10/2020).

Ministry of Environment of Brazil, 2016b: *National Adaptation Plan to Climate Change. Sectoral and Thematic Strategies. Volume 2*, Ministry of Environment, Brazil, Brazil, 264 pp. Available at: https://www.mma.gov.br/images/arquivo/80182/BOOK_PNA_Volume%20II%20v4.pdf (accessed 21/10/2020).

Ministry of Health Costa Rica, 2016: *Plan Nacional de Salud 2016-2020*, Ministry of Health of Costa Rica, 209 pp. Available at: https://www.ministeriodesalud.go.cr/index.php/biblioteca-de-archivos/sobre-el-ministerio/politcas-y-planes-en-salud/planes-en-salud/964-plan-nacional-de-salud-2016-2020/file (accessed 01/11/2020).

Ministry of Health of Chile and Ministry of Environment of Chile, 2016: *Plan de Adaptación al Cambio Climático del Sector Salud*. Santiago de Chile, 50 pp. Available at: http://portal.mma.gob.cl/wp-content/uploads/2017/02/Plan-de-Adaptacion-al-CC-para-Salud-Version-Final.pdf (accessed 16/06/2021).

Ministry of Health of El Salvador, 2017: *Plan nacional de gestión de riesgos a desastres de El Salvador*. San Salvador, 120-120 pp. Available at: http://asp.salud.gob.sv/regulacion/pdf/planes/plan_gestion_de_riesgos_desastres_v1.pdf (accessed 2019/9/30).

Miranda Sara, L. and I. Baud, 2014: Knowledge-building in adaptation management: concertación processes in transforming Lima water and climate change governance. *Environment and Urbanization*, **26**(2), 505-524, doi:10.1177/0956247814539231.

Miranda Sara, L., S. Jameson, K. Pfeffer and I. Baud, 2016: Risk perception: The social construction of spatial knowledge around climate change-related scenarios in Lima. *Habitat International*, **54**, 136-149, doi:10.1016/j.habitatint.2015.12.025.

Miranda Sara, L., K. Pfeffer and I. Baud, 2017: Unfolding Urban Geographies of Water-Related Vulnerability and Inequalities: Recognising Risks in Knowledge Building in Lima, Peru. In: *Urban Water Trajectories* [Bell, S., A. Allen, P. Hofmann and T.-H. Teh (eds.)]. Springer International Publishing, Cham, pp. 81-98. ISBN 978-3-319-42686-0.

Miranda Sara, L. R., 2021: Knowledge building in configuring metropolitan water governance: Water-related climate risk scenarios, governance networks, concertacion processes and territorialities in Lima, Peru. University of Amsterdam, Lima, Peru, 200 pp.
Mirzabaev, A. et al., 2019: Desertification. In: *Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* In Press.
Mishra, V., A. R. Ganguly, B. Nijssen and D. P. Lettenmaier, 2015: Changes in observed climate extremes in global urban areas. *Environmental Research Letters*, **10**(2), 024005, doi:10.1088/1748-9326/10/2/024005.
Mistry, J., B. A. Bilbao and A. Berardi, 2016: Community owned solutions for fire management in tropical ecosystems: Case studies from Indigenous communities of South America. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1696), 20150174, doi:10.1098/rstb.2015.0174.
MML, 2021: Ordenanza N° 2353-2021, Lima, Peru. Available at: https://busquedas.elperuano.pe/normaslegales/ordenanza-que-declara-de-interes-metropolitano-el-desarrollo-ordenanza-no-2353-1960260-2/.
Modernel, P. et al., 2019: Grazing management for more resilient mixed livestock farming systems on native grasslands of southern South America. *Grass and Forage Science*, **74**(4), 636-649, doi:10.1111/gfs.12445.
Modernel, P. et al., 2016: Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America. *Environmental Research Letters*, **11**(11), 113002, doi:10.1088/1748-9326/11/11/113002.
Mohan, D. et al., 2018: Biochar production and applications in soil fertility and carbon sequestration-a sustainable solution to crop-residue burning in India. *RSC Advances*, **8**(1), 508-520, doi:10.1039/c7ra10353k.
Mohor, G. S., D. A. Rodriguez, J. Tomasella and J. L. Siqueira Júnior, 2015: Exploratory analyses for the assessment of climate change impacts on the energy production in an Amazon run-of-river hydropower plant. *Journal of Hydrology: Regional Studies*, **4**, 41-59, doi:10.1016/j.ejrh.2015.04.003.
Molina-Carpio, J. et al., 2017: Hydroclimatology of the Upper Madeira River basin: spatio-temporal variability and trends. *Hydrological Sciences Journal*, **62**(6), 911-927, doi:10.1080/02626667.2016.1267861.
Molina, O., T. T. Luong and C. Bernhofer, 2020: Projected Changes in the Water Budget for Eastern Colombia Due to Climate Change. *Water*, **12**(1), 65, doi:10.3390/w12010065.
Molina, R. D. et al., 2019: Forest-Induced Exponential Growth of Precipitation Along Climatological Wind Streamlines Over the Amazon. *Journal of Geophysical Research: Atmospheres*, **124**(5), 2589-2599, doi:10.1029/2018JD029534.
Moline, E. F. d. V. and E. L. M. Coutinho, 2015: Atributos químicos de solos da Amazônia Ocidental após sucessão da mata nativa em áreas de cultivo. *Revista de Ciências Agrarias - Amazon Journal of Agricultural and Environmental Sciences*, **58**(1), 14-20, doi:10.4322/rca.1683.
Monsalves-Gavilán, P., J. Pincheira-Ulbrich and F. Rojo Mendoza, 2013: Climate change and its effects on urban spaces in Chile: A summary of research carried out in the period 2000-2012. *Atmósfera*, **26**(4), 547-566, doi:10.1016/S0187-6236(13)71095-6.
Montalba, R. et al., 2015: Determinación de los niveles de riesgo socioecológico ante sequías en sistemas agrícolas campesinos de La Araucanía chilena. Influencia de la diversidad cultural y la agrobiodiversidad. *Papers. Revista de Sociologia: Riesgos ambientales, sostenibilidad y políticas de implicación ciudadana*, **100**, 607-624, doi:10.5565/rev/papers.2168.
Montero, N. et al., 2018: Warmer and wetter conditions will reduce offspring production of hawksbill turtles in Brazil under climate change. *PLOS ONE*, **13**(11), e0204188, doi:10.1371/journal.pone.0204188.
Montoya, E. et al., 2020: Human Contribution to Amazonian Plant Diversity: Legacy of Pre-Columbian Land Use in Modern Plant Communities. In: *Neotropical Diversification: Patterns and Processes* [Rull, V. and A. C. Carnaval (eds.)]. Springer International Publishing, Cham, pp. 495-520. ISBN 978-3-030-31167-4.
Mora, D. E. et al., 2014: Climate changes of hydrometeorological and hydrological extremes in the Paute basin, Ecuadorean Andes. *Hydrology and Earth System Sciences*, **18**(2), 631-648, doi:10.5194/hess-18-631-2014.
Moragues, S. et al., 2019: Slope instability analysis in South Patagonia applying multivariate and bivariate techniques on Landsat images during 2001–2015 period. *CATENA*, **174**, 339-352, doi:10.1016/J.CATENA.2018.11.024.
Morales-Yokobori, M. L. (ed.), Contribution to the Understanding of Rainfalls Occurring in Buenos Aires City (Argentina) Between 1960 and 2018. Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions (2nd Edition), Cham, Springer International Publishing, 949-955 pp. ISBN 978-3-030-51210-1.
Moreno, D., É. Quiñones and L. C. Tovar, 2014: Los Sistemas de Alerta Temprana, SAT, una herramienta para la prevención de desastres por inundación y efectos del cambio climático. *Ciencias e Ingeniería al Día, Revista Institucional de la Facultad de Ingeniería, Universidad de Cartagena*, **9**(1), 1-18.
Moreno, J. M. et al., 2020a: *Resumen para Responsables de Políticas. Adaptación frente a los riesgos del cambio climático en los países iberoamericanos – Informe RIOCCADAPT*. Madrid, Spain, 60 pp. Available at: http://rioccadapt.com/wp-content/uploads/00B_ResumenCambioClimatico.pdf (accessed 09/08/2021).
Moreno, J. M. et al., 2020b: *Adaptation to Climate Change Risks in Ibero-American Countries — RIOCCADAPT Report/Adaptación frente a los riesgos del cambio climático en los países iberoamericanos. Informe RIOCCADAPT*. Hill, M., Madrid, España, 676 pp. Available at: http://rioccadapt.com/wp-content/uploads/RIOCCADAPT-REPORT.pdf (accessed 28/08/2021).

Morera, S. B. et al., 2017: The impact of extreme El Niño events on modern sediment transport along the western Peruvian Andes (1968–2012). *Scientific Reports*, **7**(1), 11947-11947, doi:10.1038/s41598-017-12220-x.
Moret, P., M. d. l. Á. Aráuz, M. Gobbi and Á. Barragán, 2016: Climate warming effects in the tropical Andes: first evidence for upslope shifts of Carabidae (Coleoptera) in Ecuador. *Insect Conservation and Diversity*, **9**(4), 342-350, doi:10.1111/icad.12173.
Moret, P. et al., 2020: When the Ice Has Gone: Colonisation of Equatorial Glacier Forelands by Ground Beetles (Coleoptera: Carabidae). *Neotropical Entomology*, **49**(2), 213-226, doi:10.1007/s13744-019-00753-x.
Morueta-Holme, N. et al., 2015: Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt. *Proceedings of the National Academy of Sciences*, **112**(41), 12741-12745, doi:10.1073/pnas.1509938112.
Moser-Reischl, A. et al., 2019: Growth patterns and effects of urban micro-climate on two physiologically contrasting urban tree species. *Landscape and Urban Planning*, **183**, 88-99, doi:10.1016/j.landurbplan.2018.11.004.
Motschmann, A. et al., 2020a: Losses and damages connected to glacier retreat in the Cordillera Blanca, Peru. *Climatic Change*, **162**(2), 837-858, doi:10.1007/s10584-020-02770-x.
Motschmann, A., C. Huggel, R. Muñoz and A. Thür, 2020b: Towards integrated assessments of water risks in deglaciating mountain areas: water scarcity and GLOF risk in the Peruvian Andes. *Geoenvironmental Disasters*, **7**(26), 1–18, doi:10.1186/s40677-020-00159-7.
Moulton, H., M. Carey, C. Huggel and A. Motschmann, 2021: Narratives of ice loss: New approaches to shrinking glaciers and climate change adaptation. *Geoforum*, **125**, 47-56, doi:10.1016/j.geoforum.2021.06.011.
Moura, R. L. et al., 2013: Spatial patterns of benthic megahabitats and conservation planning in the Abrolhos Bank. *Continental Shelf Research*, **70**, 109-117, doi:10.1016/j.csr.2013.04.036.
Muehe, D., 2010: Brazilian coastal vulnerability to climate change. *Pan-American Journal of Aquatic Sciences*, **5**(2), 173-183.
Muis, S. et al., 2018: Influence of El Niño-Southern Oscillation on Global Coastal Flooding. *Earth's Future*, **6**(9), 1311-1322, doi:10.1029/2018EF000909.
Muis, S. et al., 2019: Spatiotemporal patterns of extreme sea levels along the western North-Atlantic coasts. *Scientific Reports*, **9**(1), 1-12, doi:10.1038/s41598-019-40157-w.
Müller-Hansen, F. et al., 2019: Can Intensification of Cattle Ranching Reduce Deforestation in the Amazon? Insights From an Agent-based Social-Ecological Model. *Ecological Economics*, **159**, 198-211, doi:10.1016/j.ecolecon.2018.12.025.
Müller, A. and R. Höfer, 2014: The Impacts of Climate and Land-Use Change on Flood and Heat Hazards. In: *Climate Adaptation Santiago* [Krellenberg, K. and B. Hansjürgens (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 107-126. ISBN 978-3-642-39103-3.
Mundo, I. A. et al., 2010: Austrocedrus chilensis growth decline in relation to drought events in northern Patagonia, Argentina. *Trees*, **24**(3), 561-570, doi:10.1007/s00468-010-0427-8.
Municipalidad de Lima, 2021: *Plan Local de Cambio Climático de la Provincia de Lima 2021-2030*, Lima, Peru. Available at: https://www.descubrelima.pe/plan-local-cambio-climatico/ (accessed 01/09/2021).
Municipalidad de Santiago, Plan de Acción para el Clima y la Energía Sostennible: Estratégias de mitigación y adaptación al cambio climático: 2020-2030. Available at: http://pactodealcaldes-la.eu/pt-br/biblioteca/plan-de-accion-climatica-santiago-chile/.
Município de Rio de Janeiro, 2019: Decreto Rio n. 45781, de 03 de abril de 2019, Prefeitura deo Rio de Janeiro, Rio de Janeiro, RJ, Brasil. Available at: https://www.rio.rj.gov.br/web/pmus/documentos/-/document_library_display/7QYh/view/9477225 (accessed 17/10/2020).
Municipio del Distrito Metropolitano de Quito, 2016: *Atlas Ambiental Quito sostenible 2016*. Municipio de Quito, Quito.
Municipio del Distrito Metropolitano de Quito, 2020: *Plan de Acción de Cambio Climático de Quito*, Quito, Ecuador. Available at: https://www.quitoneutral.com/pacq2020 (accessed 01/09/2021).
Muntó, A., 2018: La lucha por la vivienda en una ciudad capitalista. El caso de la cooperativa autogestiva 'El Molino' / The struggle for housing in a capitalist city. The case of self-managed cooperative 'El Molino' / A luta pela habitação em uma cidade capitalista. O caso da cooperativa auto-administrada 'El Molino'. *Psicología, Conocimiento y Sociedad*, **8**(1), 62-85, doi:10.26864/pcs.v8.n1.4.
Muñoz-Zanzi, C. et al., 2014: Leptospira Contamination in Household and Environmental Water in Rural Communities in Southern Chile. *International Journal of Environmental Research and Public Health*, **11**(7), 6666-6680, doi:10.3390/ijerph110706666.
Muñoz, A. A. et al., 2020a: Water Crisis in Petorca Basin, Chile: The Combined Effects of a Mega-Drought and Water Management. *Water*, **12**(3), doi:10.3390/w12030648.
Muñoz, A. A. et al., 2019a: Multidecadal environmental pollution in a mega-industrial area in central Chile registered by tree rings. *Science of The Total Environment*, **696**, 133915, doi:10.1016/j.scitotenv.2019.133915.
Muñoz, Á. G. et al., 2020b: AeDES: a next-generation monitoring and forecasting system for environmental suitability of Aedes-borne disease transmission. *Scientific Reports*, **10**(1), 12640, doi:10.1038/s41598-020-69625-4.
Muñoz, Á. G. et al. (eds.), Towards a ZIKV Climate-Health Service at the Latin American Observatory. 2016.
Muñoz, Á. G. et al., 2017: Could the Recent Zika Epidemic Have Been Predicted? *Frontiers in Microbiology*, **8**(1291), doi:10.3389/fmicb.2017.01291.

Muñoz, E. et al., 2019b: An adaptive basin management rule to improve water allocation resilience under climate variability and change-a case study in the Laja Lake basin in southern Chile. *Water*, **11**(8), 1733, doi:10.3390/w11081733.
Murcia, C., M. R. Guariguata, M. Peralvo and V. Gálmez, 2017: La restauración de bosques andinos tropicales: Avances, desafíos y perspectivas del futuro. *Center for International Forestry Research (CIFOR)*, doi:10.17528/cifor/006524.
Mussetta, P. and M. J. Barrientos, 2015: Vulnerabilidad de productores rurales de Mendoza ante el Cambio Ambiental Global: clima, agua, economía y sociedad. *Revista de la Facultad de Ciencias Agrarias UNCuyo*, **47**(2), 145-170.
Mustonen, T. et al., 2021: *2021 Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change*. Snowchange Cooperative, Snowchange Cooperative, Kontiolahti, Finland, 38 pp. Available at: http://www.snowchange.org/pages/wp-content/uploads/2021/06/Raportti_150ppi.pdf (accessed 30/06/2021).
Mycoo, M. A., 2014: Autonomous household responses and urban governance capacity building for climate change adaptation: Georgetown, Guyana. *Urban Climate*, **9**, 134-154, doi:10.1016/j.uclim.2014.07.009.
Nabout, J. C., M. R. Magalhães, M. A. de Amorim Gomes and H. F. da Cunha, 2016: The Impact of Global Climate Change on the Geographic Distribution and Sustainable Harvest of Hancornia speciosa Gomes (Apocynaceae) in Brazil. *Environmental Management*, **57**(4), 814-821, doi:10.1007/s00267-016-0659-5.
Nagy, G. J. et al., 2018: An Assessment of the Relationships between Extreme Weather Events, Vulnerability, and the Impacts on Human Wellbeing in Latin America. *International Journal of Environmental Research and Public Health*, **15**(9), 1802, doi:10.3390/ijerph15091802.
Nagy, G. J., M. Gómez-Erache and R. Kay, 2015: A risk-based and participatory approach to assessing climate vulnerability and improving governance in coastal Uruguay. In: *Climate Change and the Coast: Building Resilient Communities* [Glavovic, B., M. Kelly, R. Kay and A. Travers (eds.)]. CRC Press, Boca Raton, Florida, U.S.A., pp. 357–378.
Nagy, G. J. et al., 2019: Climate vulnerability, impacts and adaptation in Central and South America coastal areas. *Regional Studies in Marine Science*, **29**, 100683-100683, doi:10.1016/j.rsma.2019.100683.
Nagy, G. J. et al., 2014a: Adjusting to current climate threats and building alternative future scenarios for the Rio de la Plata coast and estuarine front, Uruguay. *Revista de Gestão Costeira Integrada - Journal of Integrated Coastal Zone Management*, **14**(4), 553-568, doi:10.5894/rgci472.
Nagy, G. J., L. Seijo, J. E. Verocai and M. Bidegain, 2014b: Stakeholders' climate perception and adaptation in coastal Uruguay. *International Journal of Climate Change Strategies and Management*, **6**(1), 63-84, doi:doi:10.1108/IJCCSM-03-2013-0035.
Nahuelhual, L., A. Carmona, M. Aguayo and C. Echeverria, 2014: Land use change and ecosystem services provision: A case study of recreation and ecotourism opportunities in southern Chile. *Landscape Ecology*, **29**, 329-344, doi:10.1007/s10980-013-9958-x.
Natiello, M. et al., 2008: Indigenous dengue fever, Buenos Aires, Argentina. *Emerg Infect Dis*, **14**(9), 1498-1499, doi:10.3201/eid1409.080143.
National Ozone Action Unit of Guyana, 2016: *National Climate Change Adaptation Policy and Implementation Plan, Caribbean: Planning for Adaptation to Global Climate Change*, Guyana, 74 pp.
Naumann, G. et al., 2018: Global Changes in Drought Conditions Under Different Levels of Warming. *Geophysical Research Letters*, **45**(7), 3285-3296, doi:10.1002/2017GL076521.
Nava, A., J. S. Shimabukuro, A. A. Chmura and S. L. B. Luz, 2017: The impact of global environmental changes on infectious disease emergence with a focus on risks for Brazil. *ILAR Journal*, **58**(3), 393-400, doi:10.1093/ilar/ilx034.
Navarro, J. M. et al., 2016: Ocean warming and elevated carbon dioxide: multiple stressor impacts on juvenile mussels from southern Chile. *ICES Journal of Marine Science*, **73**(3), 764-771, doi:10.1093/icesjms/fsv249.
ND-Gain, 2020: ND-GAIN Country Index, University of Notre Dame. Available at: https://gain.nd.edu/our-work/country-index/.
Negra, C. et al., 2014: Brazil, Ethiopia, and New Zealand lead the way on climate-smart agriculture. *Agriculture & Food Security*, **3**(1), 19, doi:10.1186/s40066-014-0019-8.
Nehren, U. et al., 2019: Natural Hazards and Climate Change Impacts in the State of Rio de Janeiro: A Landscape Historical Analysis. In: *Strategies and Tools for a Sustainable Rural Rio de Janeiro* [Nehren, U., S. Schlüter, C. Raedig, D. Sattler and H. Hissa (eds.)]. Springer Series on Environmental Management, Cham, pp. 313-330. ISBN 978-3-319-89644-1.
Neill, C. et al., 2013: Watershed responses to Amazon soya bean cropland expansion and intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **368**(1619), 20120425, doi:10.1098/rstb.2012.0425.
Neilson, J. W. et al., 2017: Significant Impacts of Increasing Aridity on the Arid Soil Microbiome. *mSystems*, **2**(3), e00195-00116, doi:10.1128/mSystems.00195-16.
Neiva, D. H., S. M. Da Silva and C. Cardoso, 2017: Analysis of Climate Behavior and Land Use in the City of Rio de Janeiro, RJ, Brazil. *Climate*, **5**(3), doi:10.3390/cli5030052.
Nelson-Nuñez, J., J. P. Walters and D. Charpentier, 2019: Exploring the challenges to sustainable rural drinking water services in Chile. *Water Policy*, **21**(6), 1251-1265, doi:10.2166/wp.2019.120.

Nelson, D. R., M. C. Lemos, H. Eakin and Y.-J. Lo, 2016: The limits of poverty reduction in support of climate change adaptation. *Environmental Research Letters*, **11**(9), 94011, doi:10.1088/1748-9326/11/9/094011.
Nepstad, D. et al., 2014: Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, **344**(6188), 1118-1123, doi:10.1126/science.1248525.
Neukom, R. et al., 2015: Facing unprecedented drying of the Central Andes? Precipitation variability over the period AD 1000–2100. *Environmental Research Letters*, **10**(8), 1-13, doi:10.1088/1748-9326/10/8/084017.
Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS ONE*, **10**(3), doi:10.1371/journal.pone.0118571.
Niles, M. T. and J. D. Salerno, 2018: A cross-country analysis of climate shocks and smallholder food insecurity. *PLOS ONE*, **13**(2), e0192928, doi:10.1371/journal.pone.0192928.
Njue, N. et al., 2019: Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. *Science of The Total Environment*, **693**, 133531, doi:10.1016/j.scitotenv.2019.07.337.
NOAA, 2019: Historical El Nino / La Nina episodes (1950-present). Cold and warm episodes by season. Available at: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml (accessed 17/06/2021).
Nobre, C. A. et al., 2016a: Some Characteristics and Impacts of the Drought and Water Crisis in Southeastern Brazil during 2014 and 2015. *Journal of Water Resource and Protection*, **8**(2), 252-262, doi:10.4236/jwarp.2016.82022.
Nobre, C. A. et al., 2016b: Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences*, **113**(39), 10759-10768, doi:10.1073/pnas.1605516113.
Nolte, C., A. Agrawal, K. M. Silvius and B. S. Soares-Filho, 2013: Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*, **110**(13), 4956-4961, doi:10.1073/pnas.1214786110.
Northey, S. A. et al., 2017: The exposure of global base metal resources to water criticality, scarcity and climate change. *Global Environmental Change*, **44**, 109-124, doi:10.1016/j.gloenvcha.2017.04.004.
Novoa, V. et al., 2019: Understanding agricultural water footprint variability to improve water management in Chile. *Science of The Total Environment*, **670**, 188-199, doi:10.1016/j.scitotenv.2019.03.127.
NU CEPAL, 2018: *Atlas of migration in Northern Central America*. Economic Comission for Latin America and the Caribbean (ECLAC), Santiago, Chile, 45 pp. Available at: https://www.cepal.org/en/publications/44288-atlas-migration-northern-central-america (accessed 17/06/2021).
NU CEPAL, MINURVI and ONU HABITAT, 2016: *América Latina y el Caribe: Desafíos, dilemas y compromisos de una agenda urbana común*. Comisión Económica para América Latina y el Caribe, Oficina Regional para América Latina y el Caribe del Programa de Naciones Unidas para los Asentamientos Humanos and Foro de Ministros y Autoridades Máximas de la Vivienda y el Urbanismo de América Latina y el Caribe Santiago, Chile, 62 pp. Available at: https://repositorio.cepal.org/bitstream/handle/11362/40656/1/S1600986_es.pdf (accessed 17/10/2020).
Nunes, L. H., R. Greco and J. A. Marengo, 2018: *Climate change in Santos Brazil: Projections, impacts and adaptation options*. 1-302 pp. ISBN 9783319965352.
Núñez Collado, J. R. and H.-H. Wang, 2020: Slum upgrading and climate change adaptation and mitigation: Lessons from Latin America. *Cities*, **104**, 102791, doi:10.1016/j.cities.2020.102791.
Núñez, J. et al., 2017: Reconciling Drought Vulnerability Assessment Using a Convergent Approach: Application to Water Security in the Elqui River Basin, North-Central Chile. *Water*, **9**(8), doi:10.3390/w9080589.
O'Neill, B. C. et al., 2017: IPCC reasons for concern regarding climate change risks. *Nature Climate Change*, **7**(1), 28-37, doi:10.1038/nclimate3179.
O'Leary, G. J. et al., 2018: Challenges and Responses to Ongoing and Projected Climate Change for Dryland Cereal Production Systems throughout the World. *Agronomy*, **8**(4), doi:10.3390/agronomy8040034.
OAS, 2016: *Inter-American Program for Sustainable Development (PIDS): 2016–2021*. Organization of American States. Department of Sustainable Development, Washington, United States, 34 pp. Available at: http://www.oas.org/en/sedi/pub/PIDS_2017.pdf (accessed 09/08/2021).
Obraczka, M., M. Beyeler, A. Magrini and L. Legey, 2017: Analysis of Coastal Environmental Management Practices in Subregions of California and Brazil. *Journal of Coastal Research*, **33**(6), 1315-1322, doi:10.2112/JCOASTRES-D-15-00239.1.
Ochoa-Tocachi, B. F. et al., 2019: Potential contributions of pre-Inca infiltration infrastructure to Andean water security. *Nature Sustainability*, **2**(7), 584-593, doi:10.1038/s41893-019-0307-1.
Odell, S. D., A. Bebbington and K. E. Frey, 2018: Mining and climate change: A review and framework for analysis. *The Extractive Industries and Society*, **5**(1), 201-214, doi:10.1016/j.exis.2017.12.004.
OECD, 2017: *OECD Review of Fisheries 2017 General Survey of Fisheries Policies*. OECD Publishing, Organisation for Economic Co-operation and Development, 117 pp. Available at: http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=TAD/FI(2017)14/FINAL&docLanguage=En (accessed 17/06/2021).
OECD, 2018: Income inequality. Available at: https://www.oecd-ilibrary.org/content/data/459aa7f1-en (accessed 18/10/2020).
OECD and FAO, 2019: *OECD-FAO Agricultural Outlook 2019-2028*. OECD Publishing and FAO, Paris, France and Rome, Italy. Available at: https://doi.org/10.1787/agr_outlook-2019-en (accessed 09/08/2021).

OECD/Food and Agriculture Organization of the United Nations, 2015: OECD-FAO Agricultural Outlook 2015-2024 OECD Publishing, Paris, France, 148 pp.
Oertel, M., F. J. Meza and J. Gironás, 2020: Observed trends and relationships between ENSO and standardized hydrometeorological drought indices in central Chile. *Hydrological Processes*, **34**(2), 159-174, doi:10.1002/hyp.13596.
Ohz, A., A. H. F. Klein and D. Franco, 2020: A Multiple Linear Regression-Based Approach for Storm Surge Prediction Along South Brazil. In: *Climate Change, Hazards and Adaptation Options: Handling the Impacts of a Changing Climate* [Leal Filho, W., G. J. Nagy, M. Borga, P. D. Chávez Muñoz and A. Magnuszewski (eds.)]. Springer International Publishing, Cham, pp. 27-50. ISBN 978-3-030-37425-9.
OICS, 2021: *Reserva Ecológica Costanera Sur. Parque ecológico Multifuncional*. Observatório de Inovação para Cidades Sustentáveis, Buenos Aires, Argentina. Available at: https://oics.cgee.org.br/estudos/-/estudo-de-caso/article/reserva-ecologica-costanera-sur_5ce70dae45e3fa1e7217bcff (accessed 01/09/2021).
OIM, 2017: *Encuesta sobre migración internacional de personas guatemaltecas y remesas 2016*. Organización Internacional para las Migraciones OIM, Guatemala.
OIT, 2019: *Panorama Laboral Temático 5: Mujeres en el mundo del trabajo. Retos pendientes hacia una efectiva equidad en América Latina y el Caribe*. OIT/Oficina Regional para América Latina y el Caribe, Lima, 200 pp. pp. Available at: https://www.ilo.org/wcmsp5/groups/public/---americas/---ro-lima/documents/publication/wcms_715183.pdf (accessed 17/06/2021).
Ojeda, D., 2014: Descarbonización y despojo: desigualdades socioambientales y las geografías del cambio climático. In: *Desigualdades socioambientales en América Latina* [Göbel, B., M. Góngora-Mera and A. Ulloa (eds.)]. Universidad Nacional de Colombia-Ibero-Amerikanisches Institut, Bogotá, pp. 255-290. ISBN 978-958-775-221-2.
Okumura, C. K. et al., 2021: Integrated water resouce management as a development driver – Prospecting a sanitation improvement cycle for the greater Rio de Janeiro using the city blueprint approach. *Journal of Cleaner Production*, **315**, 128054, doi:10.1016/j.jclepro.2021.128054.
Olivares, I., J. C. Svenning, P. M. van Bodegom and H. Balslev, 2015: Effects of Warming and Drought on the Vegetation and Plant Diversity in the Amazon Basin. *Botanical Review*, **81**(1), 42-69, doi:10.1007/s12229-014-9149-8.
Oliveira-Filho, R. R. d. et al., 2016: On the impact of the Brazilian Forest Code on mangroves: A comment to Ferreira and Lacerda (2016). *Ocean & Coastal Management*, **132**, 36-37, doi:10.1016/j.ocecoaman.2016.08.002.
Oliveira Duarte, L. et al., 2019: Textile natural fibers production regarding the agroforestry approach. *SN Applied Sciences*, **1**(8), 914, doi:10.1007/s42452-019-0937-y.
Oliveira, J. and P. Pereda, 2020: The impact of climate change on internal migration in Brazil. *Journal of Environmental Economics and Management*, **103**, 102340, doi:10.1016/j.jeem.2020.102340.
Oliveira, L. J. C., M. H. Costa, B. S. Soares-Filho and M. T. Coe, 2013: Large-scale expansion of agriculture in Amazonia may be a no-win scenario. *Environmental Research Letters*, **8**(2), 024021, doi:10.1088/1748-9326/8/2/024021.
Oliver-Smith, A., 2014: Climate Change Adaptation and Disaster Risk Reduction in Highland Peru. In: *Adapting to Climate Change: Lessons from Natural Hazards Planning* [Glavovic, B. C. and G. P. Smith (eds.)]. Springer Netherlands, Dordrecht, pp. 77-100. ISBN 978-94-017-8631-7.
Oliver-Smith, A., 2021: The choice of perils understanding resistance to resettlement for urban disaster risk reduction and climate change adaptation. In: *Rethinking Urban Risk and Resettlement in the Global South* [Johnson, C., G. Jain and A. Lavell (eds.)]. UCL Press, pp. 133-153. ISBN 9781787358294.
Olivera, M., M. G. Podcameni, M. C. Lustosa and L. Graça, 2021: *A dimensão de gênero no Big Push para a Sustentabilidade no Brasil. As mulheres no contexto da transformação social e ecológica da economia brasileira* [Stiftung, C. E. p. a. A. L. e. o. C. e. F. F. E. (ed.)]. CEPAL, Santiago and Sao Paulo. Available at: https://www.cepal.org/pt-br/publicaciones/46643-dimensao-genero-big-push-sustentabilidade-brasil-mulheres-contexto-transformacao (accessed 03/08/2021).
Oliveras, I., L. O. Anderson and Y. Malhi, 2014: Application of remote sensing to understanding fire regimes and biomass burning emissions of the tropical Andes. *Global Biogeochemical Cycles*, **28**(4), 480-496, doi:10.1002/2013GB004664.
Oliveras, I. et al., 2018: Fire effects and ecological recovery pathways of tropical montane cloud forests along a time chronosequence. *Global Change Biology*, **24**(2), 758-772, doi:10.1111/gcb.13951.
Olmo, M., M. L. Bettolli and M. Rusticucci, 2020: Atmospheric circulation influence on temperature and precipitation individual and compound daily extreme events: Spatial variability and trends over southern South America. *Weather and Climate Extremes*, **29**, 100267, doi:10.1016/j.wace.2020.100267.
Olsson, L. et al., 2019: Land Degradation. In: *Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* In Press.
ONEMI, 2015: *Plan Estratégico Nacional Para la Gestión del Riesgo de Desastres 2015-2018 de Chile*. Ministerio del Interior y Seguridad Pública, 177 pp. Available at: https://www.preventionweb.net/files/52889_52889planestrategicobaja.pdf (accessed 17/06/2021).

Oppenheimer, M. et al., 2014: Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.

OPS and WHO, 2018: *Taller Subregional Salud en Planes Nacionales de Adaptación al Cambio Climático: Centroamérica*. Organización Panamericana de la Salud (OPS) and World Health Organization (WHO), Ciudad de Panamá, 34 pp. Available at: https://www.paho.org/hq/index.php?option=com_docman&view=download&category_slug=manuals-training-materials-9890&alias=45593-taller-subregional-salud-planes-nacionales-adaptacion-al-cambio-climatico-centroamerica-2018-spanish-only-593&Itemid=270&lang=en (accessed 17/06/2021).

Orlove, B. et al., 2019: Framing climate change in frontline communities: anthropological insights on how mountain dwellers in the USA, Peru, and Italy adapt to glacier retreat. *Regional Environmental Change*, **19**(5), 1295-1309, doi:10.1007/s10113-019-01482-y.

Orlowsky, B. and S. I. Seneviratne, 2012: Global changes in extreme events: Regional and seasonal dimension. *Climatic Change*, **110**(3-4), 669-696, doi:10.1007/s10584-011-0122-9.

Otto, I. M. et al., 2017: Social vulnerability to climate change: a review of concepts and evidence. *Regional Environmental Change*, **17**(6), 1651-1662, doi:10.1007/s10113-017-1105-9.

Ovalle-Rivera, O. et al., 2015: Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. *PloS one*, **10**(4), e0124155-e0124155, doi:10.1371/journal.pone.0124155.

Ovalle-Rivera, O. et al., 2020: Assessing the accuracy and robustness of a process-based model for coffee agroforestry systems in Central America. *Agroforestry Systems*, **94**(5), 2033-2051, doi:10.1007/s10457-020-00521-6.

Ovando, A. et al., 2016: Extreme flood events in the Bolivian Amazon wetlands. *Journal of Hydrology: Regional Studies*, **5**, 293-308, doi:10.1016/j.ejrh.2015.11.004.

Oviedo, A. F. P., S. Mitraud, D. G. McGrath and M. Bursztyn, 2016: Implementing climate variability at the community level in the Amazon floodplain. *Environmental Science and Policy*, **63**, 151-160, doi:10.1016/j.envsci.2016.05.017.

Oyanedel, R., A. Marín, J. C. Castilla and S. Gelcich, 2016: Establishing marine protected areas through bottom-up processes: insights from two contrasting initiatives in Chile. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **26**(1), 184-195, doi:10.1002/aqc.2546.

Oyarzún, D. and C. M. Brierley, 2019: The future of coastal upwelling in the Humboldt current from model projections. *Climate Dynamics*, **52**(1-2), 599-615, doi:10.1007/s00382-018-4158-7.

Oyedotun, T. D. T. and N. Ally, 2021: Environmental issues and challenges confronting surface waters in South America: A review. *Environmental Challenges*, **3**, 100049, doi:10.1016/j.envc.2021.100049.

Pabón-Caicedo, J. D. et al., 2020: Observed and Projected Hydroclimate Changes in the Andes. *Frontiers in Earth Science*, **8**, 61, doi:10.3389/feart.2020.00061.

Pacheco, F. S. et al., 2021: Nutrient Balance and Use Efficiency in Agricultural Lands in the Vermelho River Watershed, Upper Pantanal, Brazil. *Journal of Geophysical Research: Biogeosciences*, **126**(3), e2020JG005673, doi:10.1029/2020JG005673.

Pacifici, M. et al., 2015: Assessing species vulnerability to climate change. *Nature Climate Change*, **5**(3), 215-224, doi:10.1038/nclimate2448.

Paerregaard, K., 2018: The climate-development nexus: using climate voices to prepare adaptation initiatives in the Peruvian Andes. *Climate and Development*, **10**(4), 360-368, doi:10.1080/17565529.2017.1291400.

Paerregaard, K., A. B. Stensrud and A. O. Andersen, 2016: Water Citizenship: Negotiating Water Rights and Contesting Water Culture in the Peruvian Andes. *Latin American Research Review*, **51**(1), 198–217, doi:10.1353/lar.2016.0012.

Palacios, J. et al., 2016: Innovative community-based data collection to understand and find solutions to rainfall-related diarrhoeal diseases in Ecuador. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 104-105.

Palomo, I. et al., 2021: Assessing nature-based solutions for transformative change. *One Earth*, **4**(5), 730-741, doi:10.1016/j.oneear.2021.04.013.

Pan, W., O. Branch and B. Zaitchik, 2014: Impact of Climate Change on Vector-Borne Disease in the Amazon. In: *Global Climate Change and Public Health* [Pinkerton, K. E. and W. N. Rom (eds.)]. Springer, pp. 193-210. ISBN 9781461484172.

Pan, Y. et al., 2011: A Large and Persistent Carbon Sink in the World's Forests. *Science*, **333**(6045), 988-993, doi:10.1126/science.1201609.

Pandey, S. D. et al., 2020: Properties of carbon particles in archeological and natural Amazon rainforest soils. *CATENA*, **194**, 104687, doi:10.1016/j.catena.2020.104687.

Paralovo, S. L. et al., 2019: Observations of particulate matter, NO2, SO2, O3, H2S and selected VOCs at a semi-urban environment in the Amazon region. *Science of The Total Environment*, **650**, 996-1006, doi:10.1016/j.scitotenv.2018.09.073.

Parise, C. K., L. J. Calliari and N. Krusche, 2009: Extreme storm surges in the south of Brazil: Atmospheric conditions and shore erosion. *Brazilian Journal of Oceanography*, **57**(3), 175-188, doi:10.1590/s1679-87592009000300002.
Parraguez-Vergara, E., J. R. Barton and G. Raposo-Quintana, 2016: Impacts of Climate Change in the Andean Foothills of Chile: Economic and Cultural Vulnerability of Indigenous Mapuche Livelihoods. *Journal of Developing Societies*, **32**(4), 454-483, doi:10.1177/0169796X16667874.
Parraguez-Vergara, E. et al., 2018: Does indigenous and campesino traditional agriculture have anything to contribute to food sovereignty in Latin America? Evidence from Chile, Peru, Ecuador, Colombia, Guatemala and Mexico. *Int. J. Agric. Sustain.*, **16**(4-5), 326-341, doi:10.1080/14735903.2018.1489361.
Parry, L. et al., 2018: Social Vulnerability to Climatic Shocks Is Shaped by Urban Accessibility. *Annals of the American Association of Geographers*, **108**(1), 125-143, doi:10.1080/24694452.2017.1325726.
Paterson, B. and A. Charles, 2019: Community-based responses to climate hazards: typology and global analysis. *Climatic Change*, **152**(3), 327-343, doi:10.1007/s10584-018-2345-5.
Pauleit, S. et al., 2017: Nature-Based Solutions and Climate Change – Four Shades of Green. In: *Nature-based Solutions to Climate Change Adaptation in Urban Areas: linkages between science, policy and practice* [Kabisch, N., H. Korn, J. Staddler and A. Bonn (eds.)]. Springer, Cham, Switzerland, pp. 29-49.
Paz, S., M. Negev, A. Clermont and M. S. Green, 2016: Health Aspects of Climate Change in Cities with Mediterranean Climate, and Local Adaptation Plans. *International Journal of Environmental Research and Public Health*, **13**(4), 438, doi:10.3390/ijerph13040438.
PBMC, 2014: *Impactos, vulnerabilidades e adaptação às mudanças climáticas. Contribuição do Grupo de Trabalho 2 do Painel Brasileiro de Mudanças Climáticas ao Primeiro Relatório da Avaliação Nacional sobre Mudanças Climáticas*. COPPE. Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brasil, 414 pp. ISBN 978-85-285-0207-7.
PBMC, 2016: *Mudanças Climáticas e Cidades. Relatório Especial Do Painel Brasileiro de Mudanças Climáticas* [Ribeiro, S. K. and A. S. Santos (eds.)]. Painel Brasileiro de Mudanças Climáticas, COPPE - UFRJ, Rio de Janeiro, Brasil, 116 pp. ISBN 978-85-285-0344-9.
Pegas, F. d. V., D. Weaver and G. Castley, 2015: Domestic tourism and sustainability in an emerging economy: Brazil's littoral pleasure periphery. *Journal of Sustainable Tourism*, **23**(5), 748-769, doi:10.1080/09669582.2014.998677.
Pelicice, F. M., P. S. Pompeu and A. A. Agostinho, 2015: Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. *Fish and Fisheries*, **16**(4), 697-715, doi:10.1111/faf.12089.
Peña-Guerrero, M. D. et al., 2020: Drought impacts on water quality and potential implications for agricultural production in the Maipo River Basin, Central Chile. *Hydrological Sciences Journal*, **65**(6), 1005-1021, doi:10.1080/02626667.2020.1711911.
Peña, M. P., J. Barichivich and A. Maldonado, 2014: Climatic drivers of tree growth in a swamp forest island in the semiarid coast of Chile. *Journal of Arid Environments*, **109**, 15-22, doi:10.1016/j.jaridenv.2014.05.003.
Pepermans, Y. and P. Maeseele, 2016: The politicization of climate change: problem or solution? *WIREs Climate Change*, **7**(4), 478-485, doi:10.1002/wcc.405.
Pereda, P., 2016: Predicting the impacts of climate on dengue in Brazil: integrated risk modelling and mapping. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 84-85.
Pereira, V. S. et al., 2011: Análise dos atendimentos ambulatoriais por doenças respiratórias no Município de Alta Floresta - Mato Grosso - Amazônia brasileira. *Epidemiologia e Serviços de Saúde*, **20**(3), 393-400, doi:10.5123/S1679-49742011000300014.
Peres, L. d. F., A. J. d. Lucena, O. C. Rotunno Filho and J. R. d. A. França, 2018: The urban heat island in Rio de Janeiro, Brazil, in the last 30 years using remote sensing data. *International Journal of Applied Earth Observation and Geoinformation*, **64**, 104-116, doi:10.1016/j.jag.2017.08.012.
Pérez-Escamilla, R., M. B. Gubert, B. Rogers and A. Hromi-Fiedler, 2017: Food security measurement and governance: Assessment of the usefulness of diverse food insecurity indicators for policy makers. *Global Food Security*, **14**, 96-104, doi:10.1016/j.gfs.2017.06.003.
Pérez, T., C. Mattar and R. Fuster, 2018: Decrease in Snow Cover over the Aysén River Catchment in Patagonia, Chile. *Water*, **10**, 619, doi:10.3390/w10050619.
Peri, P., G. Martínez and L. Nahuelhual, 2021: *Ecosystem Services in Patagonia. A Multi-Criteria Approach for an Integrated Assessment*, 1 ed. Natural and Social Sciences of Patagonia, Springer International Publishing, Switzerland. ISBN 978-3-030-69166-0.
Perreault, T., 2020: Climate Change and Climate Politics: Parsing the Causes and Effects of the Drying of Lake Poopó, Bolivia. *Journal of Latin American Geography*, **19**(3), 26-46, doi:10.1353/lag.2020.0070.
Petit, I. J. et al., 2018: Protected areas in Chile: are we managing them? *Revista Chilena de Historia Natural*, **91**(1), 1, doi:10.1186/s40693-018-0071-z.
Petrova, D. et al., 2020: The 2018–2019 weak El Niño: Predicting the risk of a dengue outbreak in Machala, Ecuador. *International Journal of Climatology*, **n/a**(n/a), doi:10.1002/joc.6744.
Pfeffer, K., 2018: *Knowing the city*. Twente University - ITC, 31 pp. Available at: https://webapps.itc.utwente.nl/librarywww/papers_2018/chap/pfeffer_kno.pdf (accessed 31/10/2020).

Phillips, C. A. et al., 2020: Compound climate risks in the COVID-19 pandemic. *Nature Climate Change*, **10**(7), 586-588, doi:10.1038/s41558-020-0804-2.
Picasso, V. D. et al., 2014: Sustainability of meat production beyond carbon footprint: a synthesis of case studies from grazing systems in Uruguay. *Meat Science*, **98**(3), 346-354, doi:10.1016/j.meatsci.2014.07.005.
Piggott-McKellar, A. E., K. E. McNamara, P. D. Nunn and J. E. M. Watson, 2019: What are the barriers to successful community-based climate change adaptation? A review of grey literature. *Local Environment*, **24**(4), 374-390, doi:10.1080/13549839.2019.1580688.
Pinho, P. F., J. A. Marengo and M. S. Smith, 2015: Complex socio-ecological dynamics driven by extreme events in the Amazon. *Regional Environmental Change*, **15**(4), 643-655, doi:10.1007/s10113-014-0659-z.
Pinho, P. F. et al., 2014: Ecosystem protection and poverty alleviation in the tropics: Perspective from a historical evolution of policy-making in the Brazilian Amazon. *Ecosystem Services*, **8**, 97-109, doi:10.1016/j.ecoser.2014.03.002.
Pino-Cortés, E. et al., 2020: Effect of socioeconomic status on the relationship between short-term exposure to PM2.5 and cardiorespiratory mortality and morbidity in a megacity: the case of Santiago de Chile. *Air Quality, Atmosphere & Health*, **13**(5), 509-517, doi:10.1007/s11869-020-00818-6.
Pino, P. et al., 2015: Chile Confronts its Environmental Health Future After 25 Years of Accelerated Growth. *Annals of Global Health*, **81**(3), 354-367, doi:10.1016/j.aogh.2015.06.008.
Pinzón, R. E., K. Hibino, I. Takayabu and T. Nakaegawa, 2017: Virtually experiencing future climate changes in Central America with MRI-AGCM: climate analogues study. *Hydrological Research Letters*, **11**(2), 106-113, doi:10.3178/hrl.11.106.
Piper, F. I., M. J. Gundale and A. Fajardo, 2015: Extreme defoliation reduces tree growth but not C and N storage in a winter-deciduous species. *Ann Bot*, **115**(7), 1093-1103, doi:10.1093/aob/mcv038.
Pires, A. P. F. et al., 2017: Forest restoration can increase the Rio Doce watershed resilience. *Perspectives in Ecology and Conservation*, **15**(3), 187-193, doi:10.1016/j.pecon.2017.08.003.
Piticar, A., 2018: Changes in heat waves in Chile. *Global and Planetary Change*, **169**(October 2017), 234-246, doi:10.1016/j.gloplacha.2018.08.007.
Pizarro, J., P. M. Vergara, S. Cerda and D. Briones, 2016: Cooling and eutrophication of southern Chilean lakes. *Science of The Total Environment*, **541**, 683-691, doi:10.1016/j.scitotenv.2015.09.105.
Pokorny, B. et al., 2013: From large to small: Reorienting rural development policies in response to climate change, food security and poverty. *Forest Policy Econ.*, **36**, 52-59, doi:10.1016/j.forpol.2013.02.009.
Polk, M. H. et al., 2017: Exploring hydrologic connections between tropical mountain wetlands and glacier recession in Peru's Cordillera Blanca. *Applied Geography*, **78**, 94-103, doi:10.1016/j.apgeog.2016.11.004.
Pollett, S. et al., 2020: Identification and evaluation of epidemic prediction and forecasting reporting guidelines: A systematic review and a call for action. *Epidemics*, **33**, 100400, doi:10.1016/j.epidem.2020.100400.
Pompeu, J. et al., 2021: Is domestic agricultural production sufficient to meet national food nutrient needs in Brazil? *PLOS ONE*, **16**(5), e0251778, doi:10.1371/journal.pone.0251778.
Ponce, C., 2020: Intra-seasonal climate variability and crop diversification strategies in the Peruvian Andes: A word of caution on the sustainability of adaptation to climate change. *World Development*, **127**, 104740, doi:10.1016/j.worlddev.2019.104740.
Pons, D. et al., 2018: Escenarios de aridez para Guatemala para los años 2030, 2050 y 2070 utilizando modelos de cambio climático. *Revista Yu'am*, **2**(4), 4-16.
Pons, D. et al., 2017: On the Production of Climate Information in the High Mountain Forests of Guatemala. 1 ed. Routledge, pp. 87-99. ISBN 1138066974;9781138066977;.
Porkka, M., M. Kummu, S. Siebert and O. Varis, 2013: From Food Insufficiency towards Trade Dependency: A Historical Analysis of Global Food Availability. *PLOS ONE*, **8**(12), e82714, doi:10.1371/journal.pone.0082714.
Porras, I., P. Steele and E. Y. Mohammed, 2016: *Upscaling solutions: The role of conditional transfers for poverty reduction and ecosystem management*. IIED, London, 48 pp. Available at: https://pubs.iied.org/pdfs/16050IIED.pdf (accessed 17/06/2021).
Portilla Cabrera, C. V. and J. J. Selvaraj, 2020: Geographic shifts in the bioclimatic suitability for Aedes aegypti under climate change scenarios in Colombia. *Heliyon*, **6**(1), e03101, doi:10.1016/j.heliyon.2019.e03101.
Pörtner, H. O. et al., 2021: *IPBES-IPCC co-sponsored workshop report synopsis on biodiversity and climate change*. IPBES and IPCC. Available at: https://zenodo.org/record/4920414#.YSaj0o77SUk (accessed 25/08/2021).
Portugal Del Pino, D., S. Borelli and S. Pauleit, 2020: Nature-Based Solutions in Latin American Cities. In: *The Palgrave Handbook of Climate Resilient Societies*. Springer International Publishing, Cham, pp. 1-28. ISBN 978-3-030-32811-5.
Postigo, J. C., 2013: Adaptation of Andean Herders to Political and Climatic Changes. In: *Continuity and Change in Cultural Adaptation to Mountain Environments: From Prehistory to Contemporary Threats* [Lozny, L. R. (ed.)]. Springer New York, New York, NY, pp. 229-258. ISBN 978-1-4614-5702-2.
Postigo, J. C., 2014: Perception and Resilience of Andean Populations Facing Climate Change. *Journal of Ethnobiology*, **34**(3), 383-400, doi:10.2993/0278-0771-34.3.383.
Postigo, J. C., 2019: Multi-temporal Adaptations to Change in the Central Andes. In: *Climate and Culture: Multidisciplinary Perspectives on a Warming World* [Feola, G., H. Geoghegan and A. Arnall (eds.)]. Cambridge University Press, Cambridge, pp. 117-140. ISBN 1108422500.

Poveda, G. et al., 2020: High Impact Weather Events in the Andes. *Frontiers in Earth Science*, **8**, 162.
Prager, S. et al., 2020: *Vulnerability to Climate Change and Economic Impacts in the Agriculture Sector in Latin America and the Caribbean*. **IDB Technical Note IDB-TN-01985**, Inter-American Development Bank (IDB) and International Center for Tropical Agriculture (CIAT), Cali, Colombia, 155 pp. Available at: http://dx.doi.org/10.18235/0002580.
Prefeitura da Cidade do Rio de Janeiro, 2015: *Plano Municipal de Saneamento Básico da Cidade do Rio de Janeiro. Drenagem e Manejo de Águas Pluviais Urbanas*, Prefeitura da Cidade do Rio de Janeiro. Available at: http://www.rio.rj.gov.br/web/rio-aguas/exibeconteudo?id=5825189 (accessed 27/10/2020).
Prefeitura da Cidade do Rio de Janeiro, 2016: *Estratégia de Adaptação às Mudanças Climáticas da Cidade do Rio de Janeiro*, Prefeitura da Cidade do Rio de Janeiro, Rio de Janeiro, Brazil, 90 pp. Available at: http://www.rio.rj.gov.br/dlstatic/10112/6631312/4179912/ESTRATEGIA_PORT.pdf (accessed 17/10/2020).
Prefeitura da Cidade do Rio de Janeiro, 2021: *Plano de Desenvolvimento Sustentável e Ação Climática da Cidade do Rio de Janeiro*, Rio de Janeiro, Brazil. Available at: rio.rj.gov.br/web/planejamento/pds (accessed 01/09/2021).
Prefeitura do Município de São Paulo, 2015: *Plano de Mobilidade de São Paulo: PlanMob/SP 2015*, Secretaria Municipal de Transportes, São Paulo, SP, Brasil, 201 pp. Available at: https://www.prefeitura.sp.gov.br/cidade/secretarias/upload/chamadas/planmobsp_v072__1455546429.pdf (accessed 17/10/2020).
Prefeitura do Município de São Paulo, 2021: *PlanClimaSP: Plano de Ação climática do Município de São Paulo 2020-2050*, Prefeitura do Município de São Paulo, Sao Paulo, Brazil, 342 pp. Available at: https://www.prefeitura.sp.gov.br/cidade/secretarias/upload/meio_ambiente/arquivos/PlanClimaSP_BaixaResolucao.pdf (accessed 01/09/2021).
Prefeitura Municipal de Curitiba, 2020: *PlanClima Plano de Mitigação e Adaptação às Mudanças Climáticas*, Curitiba, Brazil. Available at: https://mid.curitiba.pr.gov.br/2020/00306556.pdf (accessed 01/09/2021).
Prefeitura Municipal do Salvador, 2020: *Plano de Mitigação e Adaptação às Mudanças do Clima de Salvador*, Salvador, Brazil. Available at: http://www.prodeturssa.salvador.ba.gov.br/images/prodeturssa/documentos/PMAMC.pdf (accessed 01/09/2021).
Priotto, G. and R. Salvador Aruj, 2017: *Migraciones, ambiente y cambio climático. Estudios de Caso en América del Sur*. Cuadernos Migratorios, OIM, Buenos Aires, Argentina. Available at: file:///C:/Users/Maria/Downloads/migraciones_ambiente_y_cambio_climatico_estudio_de_casos_en_america_del_sur_0.pdf (accessed 25/08/2021).
Programa Estado de la Nación - Estado de la Región, 2016: *Fifth State of the Region Report on Sustainable Human Development. Summary*. PEN CONARE, San José, Costa Rica, 69 pp. Available at: http://repositorio.conare.ac.cr/bitstream/handle/20.500.12337/731/Fifth%20State%20of%20the%20Region%20Report%20on%20Susteinable%20Human%20Development%202016_libro.pdf?sequence=1&isAllowed=y (accessed 17/06/2021).
Puente-Sotomayor, F., A. Egas and J. Teller, 2021: Land policies for landslide risk reduction in Andean cities. *Habitat International*, **107**, 102298, doi:10.1016/j.habitatint.2020.102298.
Qin, H., P. Romero-Lankao, J. Hardoy and A. Rosas-Huerta, 2015: Household responses to climate-related hazards in four Latin American cities: A conceptual framework and exploratory analysis. *Urban Climate*, **14**, 94-110, doi:10.1016/j.uclim.2015.05.003.
Qin, Y. et al., 2020: Agricultural risks from changing snowmelt. *Nature Climate Change*, **10**(5), 459-465, doi:10.1038/s41558-020-0746-8.
Quadrado, G. P., S. R. Dillenburg, E. S. Goulart and E. G. Barboza, 2021: Historical and geological assessment of shoreline changes at an urbanized embayed sandy system in Garopaba, Southern Brazil. *Regional Studies in Marine Science*, **42**, 101622, doi:10.1016/j.rsma.2021.101622.
Quichi, E. et al., 2016: Ecuador–Peru cooperation for climate-informed dengue surveillance: creating an interdisciplinary multinational team. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 12-13.
Quijada, Y. et al., 2018: Social Inequality and Mental Health in Chile, Ecuador, and Colombia. *Latin American Perspectives*, **46**(6), 92-108, doi:10.1177/0094582X18803682.
Quimbayo Ruiz, G. and F. Vásquez Rodríguez, 2016a: *Ecología política urbana: Otra aproximación al modelo de ciudad en Colombia*. Naturaleza urbana, Instituto Alexander von Humboldt, Bogotá, Colombia. Available at: https://www.ecologiapolitica.info/?p=6020 (accessed 01/09/2021).
Quimbayo Ruiz, G. A. and F. Vásquez Rodríguez, 2016b: *Hacia una ecología política de la urbanización en América Latina*. Ecología Política, 43-51 pp. Available at: https://www.ecologiapolitica.info/?p=6020 (accessed 01/09/2021).
Quinn, A. D. et al., 2018: Adaptation Becoming Business as Usual: A Framework for Climate-Change-Ready Transport Infrastructure. *Infrastructures*, **3**(2), 10, doi:10.3390/infrastructures3020010.
Quintero-Herrera, L. L. et al., 2015: Potential impact of climatic variability on the epidemiology of dengue in Risaralda, Colombia, 2010–2011. *Journal of Infection and Public Health*, **8**(3), 291-297, doi:10.1016/j.jiph.2014.11.005.
Quiñones, R. A. et al., 2019: Environmental issues in Chilean salmon farming: a review. *Reviews in Aquaculture*, **11**(2), 375-402, doi:10.1111/raq.12337.

Quiroga, S., C. Suárez, J. Diego Solís and P. Martinez-Juarez, 2020: Framing vulnerability and coffee farmers' behaviour in the context of climate change adaptation in Nicaragua. *World Development*, **126**, 104733, doi:10.1016/j.worlddev.2019.104733.
Rabatel, A. et al., 2018: Toward an imminent extinction of Colombian glaciers? *Geografiska Annaler: Series A, Physical Geography*, **100**(1), 75-95, doi:10.1080/04353676.2017.1383015.
Racloz, V., R. Ramsey, S. Tong and W. Hu, 2012: Surveillance of Dengue Fever Virus: A Review of Epidemiological Models and Early Warning Systems. *PLOS Neglected Tropical Diseases*, **6**(5), e1648, doi:10.1371/journal.pntd.0001648.
Radel, C., B. Schmook, L. Carte and S. Mardero, 2018: Toward a Political Ecology of Migration: Land, Labor Migration, and Climate Change in Northwestern Nicaragua. *World Development*, **108**, 263-273, doi:10.1016/j.worlddev.2017.04.023.
Raffaele, E., M. A. Nuñez, J. Eneström and M. Blackhall, 2016: Fire as mediator of pine invasion: evidence from Patagonia, Argentina. *Biological Invasions*, **18**(3), 597-601, doi:10.1007/s10530-015-1038-5.
Ragettli, S., W. W. Immerzeel and F. Pellicciotti, 2016: Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proceedings of the National Academy of Sciences*, **113**(33), 9222-9227, doi:10.1073/pnas.1606526113.
Ramajo, L. et al., 2019: Physiological responses of juvenile Chilean scallops (Argopecten purpuratus) to isolated and combined environmental drivers of coastal upwelling. *ICES Journal of Marine Science*, **76**(6), 1836-1849, doi:10.1093/icesjms/fsz080.
Ramajo, L. et al., 2020: Upwelling intensity modulates the fitness and physiological performance of coastal species: Implications for the aquaculture of the scallop Argopecten purpuratus in the Humboldt Current System. *Science of The Total Environment*, **745**, 140949, doi:10.1016/j.scitotenv.2020.140949.
Ramalho Q. et al., 2021: Reforestation can compensate negative effects of climate change on amphibians. *Biological Conservation*, **260**, 109187, doi:10.1016/j.biocon.2021.109187.
Ramírez-Santana, M. et al., 2020: Reduced neurobehavioral functioning in agricultural workers and rural inhabitants exposed to pesticides in northern Chile and its association with blood biomarkers inhibition. *Environmental Health*, **19**(1), 84, doi:10.1186/s12940-020-00634-6.
Ramirez-Villegas, J. et al., 2014: Using species distributions models for designing conservation strategies of Tropical Andean biodiversity under climate change. *Journal for Nature Conservation*, **22**(5), 391-404, doi:10.1016/j.jnc.2014.03.007.
Rammig, A., 2020: Tropical carbon sinks are out of sync. *Nature*, **579**(7797), 38-39, doi:10.1038/d41586-020-00423-8.
Ramos, E. P. and F. de Salles Cavedon-Capdeville, 2017: Regional responses to climate change and migration in Latin America. In: *Research Handbook on Climate Change, Migration and the Law* [Mayer, B. and F. Crépeau (eds.)]. Edward Elgar Publishing, pp. 262–287.
Ranasinghe, R. et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Rangecroft, S. et al., 2013: Climate Change and Water Resources in Arid Mountains: An Example from the Bolivian Andes. *Ambio*, **42**(7), 852-863, doi:10.1007/s13280-013-0430-6.
Rao, N. D., B. J. van Ruijven, K. Riahi and V. Bosetti, 2017: Improving poverty and inequality modelling in climate research. *Nature Climate Change*, **7**(12), 857-862, doi:10.1038/s41558-017-0004-x.
Rasch, R., 2017: Income Inequality and Urban Vulnerability to Flood Hazard in Brazil. *Social Science Quarterly*, **98**(1), 299-325, doi:10.1111/ssqu.12274.
Rasch, R. J., 2016: Assessing urban vulnerability to flood hazard in Brazilian municipalities. *Environment and Urbanization*, **28**(1), 145-168, doi:10.1177/0956247815620961.
Rasmussen, L. A., H. Conway and C. F. Raymond, 2007: Influence of upper air conditions on the Patagonia icefields. *Global and Planetary Change*, **59**(1), 203-216, doi:10.1016/j.gloplacha.2006.11.025.
Rasmussen, M. B., 2016a: Unsettling Times: Living with the Changing Horizons of the Peruvian Andes. *Latin American Perspectives*, **43**(4), 73-86, doi:10.1177/0094582x16637867.
Rasmussen, M. B., 2016b: Water futures: Contention in the construction of productive infrastructure in the peruvian highlands. *Anthropologica*, **58**(2), 211–226, doi:10.3138/anth.582.T04.
Raven, J. et al., 2018: Urban planning and design. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal and S. Ali Ibrahim (eds.)]. Cambridge University Press, New York, United States of America, pp. 139–172. ISBN 978-1-316-60333-8.
Ray, D. K., J. S. Gerber, G. K. MacDonald and P. C. West, 2015: Climate variation explains a third of global crop yield variability. *Nature Communications*, **6**(1), 5989, doi:10.1038/ncomms6989.
Reay, D., 2019: Climate-Smart Coffee. In: *Climate-Smart Food* [Reay, D. (ed.)]. Springer International Publishing, Cham, pp. 93-104. ISBN 978-3-030-18206-9.

Reboita, M. S., R. P. da Rocha, M. R. de Souza and M. Llopart, 2018: Extratropical cyclones over the southwestern South Atlantic Ocean: HadGEM2-ES and RegCM4 projections. *International Journal of Climatology*, **38**(6), 2866-2879, doi:10.1002/joc.5468.

Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environment and Urbanization*, **29**(1), 159-182, doi:10.1177/0956247816677778.

RedMuniCC, Red Chilena de Municipios ante el Cambio Climático. Available at: https://www.redmunicc.cl/.

Reguero, B. G. et al., 2015: Effects of climate change on exposure to coastal flooding in Latin America and the Caribbean. *PLoS ONE*, **10**(7), 1-19, doi:10.1371/journal.pone.0133409.

Rehm, E. M. and K. J. Feeley, 2015a: Freezing temperatures as a limit to forest recruitment above tropical Andean treelines. *Ecology*, **96**(7), 1856-1865, doi:10.1890/14-1992.1.

Rehm, E. M. and K. J. Feeley, 2015b: The inability of tropical cloud forest species to invade grasslands above treeline during climate change: potential explanations and consequences. *Ecography*, **38**(12), 1167-1175, doi:10.1111/ecog.01050.

Reid, H. et al., 2018: Chapter 16 - A Framework for Assessing the Effectiveness of Ecosystem-Based Approaches to Adaptation. In: *Resilience* [Zommers, Z. and K. Alverson (eds.)]. Elsevier Inc., pp. 207-216. ISBN 9780128118917.

Reid, J. L. et al., 2019: The ephemerality of secondary forests in southern Costa Rica. *Conservation Letters*, **12**(2), e12607, doi:10.1111/conl.12607.

Reinthaler, J. et al., 2019a: Fast shrinkage of glaciers on active volcanoes in Latin America. *Journal of Glaciology*.

Reinthaler, J. et al., 2019b: Area changes of glaciers on active volcanoes in Latin America between 1986 and 2015 observed from multi-temporal satellite imagery. *Journal of Glaciology*, **65**(252), 542-556, doi:10.1017/jog.2019.30.

Reis, S. M. et al., 2018: Climate and fragmentation affect forest structure at the southern border of Amazonia. *Plant Ecology & Diversity*, **11**(1), 13-25, doi:10.1080/17550874.2018.1455230.

Repetto, A., 2016: Crecimiento, pobreza y desigualdad: la vía chilena. *Economía y Política*, **3**(1), 71-101, doi:10.15691/07194714.2016.003.

Retsa, A. et al., 2020: Biodiversity and Ecosystem Services A business case for re/insurance. Swiss Re Management Ltd, Zurich, Switzerland 60 pp.

Revi, A. et al., 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.

Reyer, C. P. O. et al., 2017: Climate change impacts in Latin America and the Caribbean and their implications for development. *Regional Environmental Change*, **17**(6), 1601-1621, doi:10.1007/s10113-015-0854-6.

Reyes-García, V. et al., 2016: Local indicators of climate change: The potential contribution of local knowledge to climate research. *Wiley Interdisciplinary Reviews: Climate Change*, **7**(1), 109–124, doi:10.1002/wcc.374.

Rezende, O. M., F. M. Miranda, A. N. Haddad and M. G. Miguez, 2019: A Framework to Evaluate Urban Flood Resilience of Design Alternatives for Flood Defence Considering Future Adverse Scenarios. *Water*, **11**(7), 1485, doi:10.3390/w11071485.

Ribalaygua, J., E. Gaitán, J. Pórtoles and R. Monjo, 2018: Climatic change on the Gulf of Fonseca (Central America) using two-step statistical downscaling of CMIP5 model outputs. *Theoretical and Applied Climatology*, **132**(3-4), 867-883, doi:10.1007/s00704-017-2130-9.

Ribeiro, L. C. S., E. O. V. Silva, J. R. L. Andrade and K. B. Souza, 2017: Tourism and regional development in the Brazilian Northeast. *Tourism Economics*, 23(3), 717–727. Available at: 10.1177/1354816616652752.

Ribeiro Neto, A., A. R. da Paz, J. A. Marengo and S. C. Chou, 2016: Hydrological Processes and Climate Change in Hydrographic Regions of Brazil. *Journal of Water Resource and Protection*, **08**(12), 1103-1127, doi:10.4236/jwarp.2016.812087.

Richards, P., H. Pellegrina, L. VanWey and S. Spera, 2015: Soybean Development: The Impact of a Decade of Agricultural Change on Urban and Economic Growth in Mato Grosso, Brazil. *PLOS ONE*, **10**(4), e0122510, doi:10.1371/journal.pone.0122510.

Rito, K. F. et al., 2017: Precipitation mediates the effect of human disturbance on the Brazilian Caatinga vegetation. *Journal of Ecology*, **105**(3), 828-838, doi:10.1111/1365-2745.12712.

Robert, M. A., A. M. Stewart-Ibarra and E. L. Estallo, 2020: Climate change and viral emergence: evidence from *Aedes*-borne arboviruses. *Current opinion in virology*, **40**, 41-47, doi:10.1016/j.coviro.2020.05.001.

Robert, M. A. et al., 2019: Arbovirus emergence in the temperate city of Córdoba, Argentina, 2009–2018. *Scientific Data*, **6**(1), 276, doi:10.1038/s41597-019-0295-z.

Roco, L., B. Bravo-Ureta, A. Engler and R. Jara-Rojas, 2017: The Impact of Climatic Change Adaptation on Agricultural Productivity in Central Chile: A Stochastic Production Frontier Approach. *Sustainability*, **9**(9), 1648, doi:10.3390/su9091648.

Roco, L., A. Engler, B. E. Bravo-Ureta and R. Jara-Rojas, 2015: Farmers' perception of climate change in mediterranean Chile. *Regional Enviromental Change*, **15**(5), 867-879, doi:10.1007/s10113-014-0669-x.

Roco, L., D. Poblete, F. Meza and G. Kerrigan, 2016: Farmers' Options to Address Water Scarcity in a Changing Climate: Case Studies from two Basins in Mediterranean Chile. *Environmental Management*, **58**(6), 958-971, doi:10.1007/s00267-016-0759-2.
Rodrigues, M. G. d. A. et al., 2019: The role of deforestation on American cutaneous leishmaniasis incidence: spatial-temporal distribution, environmental and socioeconomic factors associated in the Brazilian Amazon. *Tropical Medicine & International Health*, **24**(3), 348-355, doi:10.1111/tmi.13196.
Rodríguez-Catón, M., R. Villalba, M. Morales and A. Srur, 2016: Influence of droughts on Nothofagus pumilio forest decline across northern Patagonia, Argentina. *Ecosphere*, **7**(7), 1-17, doi:10.1002/ecs2.1390.
Rodríguez-Dueñas, A. and I. P. Rivera, 2016: *Quito siembra: Agricultura urbana*. Agencia de Promoción Económica ConQuito Quito, A. d., Quito, Ecuador, 43 pp. Available at: http://www.conquito.org.ec/wp-content/uploads/2016/11/QUITO_SIEMBRA_AGRICULTURA_URBANA_CONQUITO.pdf (accessed 17/06/2021).
Rodríguez-Guerra, A. and N. Cuvi, 2019: Contaminación del Aire y Justicia Ambiental en Quito, Ecuador. *Fronteiras: Journal of Social, Technological and Environmental Science*, **8**(3), 13-46, doi:10.21664/2238-8869.2019v8i3.p13-46.
Rodriguez-Morales, A. J. et al., 2019: Epidemiology of zoonotic tick-borne diseases in Latin America: Are we just seeing the tip of the iceberg? *F1000Research*, **7**(1988), doi:10.12688/f1000research.17649.2.
Rodríguez-Morales, M. et al., 2019: Ecohydrology of the Venezuelan páramo: water balance of a high Andean watershed. *Plant Ecology and Diversity*, **12**(6), 573–591, doi:10.1080/17550874.2019.1673494.
Rodríguez-Morata, C. et al., 2018: Linking atmospheric circulation patterns with hydro-geomorphic disasters in Peru. *International Journal of Climatology*, **38**(8), 3388-3404, doi:10.1002/joc.5507.
Rodríguez-Morata, C. et al., 2019: The anomalous 2017 coastal El Niño event in Peru. *Climate Dynamics*, **52**(9), 5605-5622, doi:10.1007/s00382-018-4466-y.
Rodríguez-Rodríguez, J. A., J. E. Mancera-Pineda and J. M. Rodríguez-P, 2016: Validación y aplicación de un modelo de restauración de manglar basado en individuos para tres especies en la Ciénaga Grande de Santa Marta. *Caldasia*, **38**(2), 285-299, doi:10.15446/caldasia.v38n2.55360.
Rodríguez, D. I., G. Anríquez and J. L. Riveros, 2016: Food security and livestock: The case of Latin America and the Caribbean. *Ciencia e investigación agraria*, **43**(1), 5-15, doi:10.4067/S0718-16202016000100001
Rodríguez, L. et al., 2021: Agroforestry systems impact soil macroaggregation and enhance carbon storage in Colombian deforested Amazonia. *Geoderma*, **384**, 114810, doi:10.1016/j.geoderma.2020.114810.
Rojas, C., J. Pino, C. Basnou and M. Vivanco, 2013: Assessing land-use and -cover changes in relation to geographic factors and urban planning in the metropolitan area of Concepción (Chile). Implications for biodiversity conservation. *Applied Geography*, **39**, 93-103, doi:10.1016/j.apgeog.2012.12.007.
Rojas, E., 2019: "No time to waste" in applying the lessons from Latin America's 50 years of housing policies. *Environment and Urbanization*, **31**(1), 177-192, doi:10.1177/0956247818781499.
Rojas, O. et al., 2017: Urban Growth and Flood Disasters in the Coastal River Basin of South-Central Chile (1943–2011). *Sustainability*, **9**(2), doi:10.3390/su9020195.
Rolando, J. L. et al., 2017: Key ecosystem services and ecological intensification of agriculture in the tropical high-Andean Puna as affected by land-use and climate changes. *Agriculture, Ecosystems & Environment*, **236**, 221-233, doi:10.1016/j.agee.2016.12.010.
Rolla, A. L. et al., 2018: Climate impacts on crop yields in Central Argentina. Adaptation strategies. *Agricultural Systems*, **160**, 44-59, doi:10.1016/j.agsy.2017.08.007.
Rolla, A. L., M. N. Nuñez, J. J. Ramayón and M. E. Ramayón, 2019: Impacts of climate change on bovine livestock production in Argentina. *Climatic Change*, **153**(3), 439-455, doi:10.1007/s10584-019-02399-5.
Romanello, M., A. McGushin and C. Di Napoli, 2021: *The 2021 Report of the Lancet Countdown on Health and Climate Change*. Lancet, T. Available at: https://www.thelancet.com/countdown-health-climate/about (accessed 25/08/2021).
Romeo, R., F. Grita, F. Parisi and L. Russo, 2020: *Vulnerability of mountain peoples to food insecurity: updated data and analysis of drivers*. FAO and UNCCD, Rome, Italy, 124 pp. Available at: https://doi.org/10.4060/cb2409en (accessed 29/06/2021).
Romero-Duque, L. P., J. M. Trilleras, F. Castellarini and S. Quijas, 2020: Ecosystem services in urban ecological infrastructure of Latin America and the Caribbean: How do they contribute to urban planning? *Science of The Total Environment*, **728**, 138780, doi:10.1016/j.scitotenv.2020.138780.
Romero-Lankao, P. et al., 2018: Urban transformative potential in a changing climate. *Nature Climate Change*, **8**(9), 754-756, doi:10.1038/s41558-018-0264-0.
Romero-Lankao, P. and D. Gnatz, 2019: Risk Inequality and the Food-Energy-Water (FEW) Nexus: A Study of 43 City Adaptation Plans. *Frontiers in Sociology*, **4**(31), doi:10.3389/fsoc.2019.00031.
Romero-Lankao, P., D. M. Gnatz, O. Wilhelmi and M. Hayden, 2016: Urban Sustainability and Resilience: From Theory to Practice. *Sustainability*, **8**(12), doi:10.3390/su8121224.
Romero-Lankao, P. et al., 2014: Scale, urban risk and adaptation capacity in neighborhoods of Latin American cities. *Habitat International*, **42**, 224-235, doi:10.1016/j.habitatint.2013.12.008.

Romero-Lankao, P., H. Qin and M. Borbor-Cordova, 2013: Exploration of health risks related to air pollution and temperature in three Latin American cities. *Social Science & Medicine*, **83**, 110-118, doi:10.1016/j.socscimed.2013.01.009.
Ronchail, J. et al., 2018: The flood recession period in Western Amazonia and its variability during the 1985–2015 period. *Journal of Hydrology: Regional Studies*, **15**, 16-30, doi:10.1016/j.ejrh.2017.11.008.
Ronchi, S. and A. Arcidiacono, 2019: Adopting an Ecosystem Services-Based Approach for Flood Resilient Strategies: The Case of Rocinha Favela (Brazil). *Sustainability*, **11**(1), doi:10.3390/su11010004.
Rosa, L. and P. D'Odorico, 2019: The water-energy-food nexus of unconventional oil and gas extraction in the Vaca Muerta Play, Argentina. *Journal of Cleaner Production*, **207**, 743-750, doi:10.1016/j.jclepro.2018.10.039.
Rosales-Rueda, M., 2018: The impact of early life shocks on human capital formation: evidence from El Niño floods in Ecuador. *Journal of Health Economics*, **62**, 13-44, doi:10.1016/j.jhealeco.2018.07.003.
Rosenzweig, C. et al., 2018: Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W. D. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal and S. Ali Ibrahim (eds.)]. Cambridge University Press, New York, United States of America, pp. xvii-xlii. ISBN 9781316603338.
Rosero, P. et al., 2021: Multi-taxa colonisation along the foreland of a vanishing equatorial glacier. *Ecography*, **44**(7), 1010-1021, doi:10.1111/ecog.05478.
Rouault, F., F. Ossio, P. González-Levín and F. Meza, 2019: Impact of Climate Change on the Energy Needs of Houses in Chile. *Sustainability*, **11**(24), doi:10.3390/su11247068.
Roy, J. et al., 2018: Sustainable development, poverty eradication and reducing inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.
Ruano, S. and A. Milan, 2014: *Climate change, rainfall patterns, livelihoods and migration in Cabrican, Guatemala*. UNU-EHS Reports, **14**, United Nations University, Bonn, 76 pp. pp. Available at: http://i.unu.edu/media/ehs.unu.edu/news/3774/11648.pdf (accessed 17/06/2021).
Ruaro, R. et al., 2019: Climate change will decrease the range of a keystone fish species in La Plata River Basin, South America. *Hydrobiologia*, **836**(1), 1-19, doi:10.1007/s10750-019-3904-0.
Rubio-Palis, Y. et al., 2013: Malaria entomological risk factors in relation to land cover in the Lower Caura River Basin, Venezuela. *Memórias do Instituto Oswaldo Cruz*, **108**, 220-228, doi:10.1590/0074-0276108022013015.
Rudel, T. K. et al., 2015: LivestockPlus: Forages, sustainable intensification, and food security in the tropics. *Ambio*, **44**(7), 685-693, doi:10.1007/s13280-015-0676-2.
Ruggiero, P. G. C., J. P. Metzger, L. Reverberi Tambosi and E. Nichols, 2019: Payment for ecosystem services programs in the Brazilian Atlantic Forest: Effective but not enough. *Land Use Policy*, **82**(November 2018), 283-291, doi:10.1016/j.landusepol.2018.11.054.
Ruiz-de-Oña, C., P. Rivera-Castañeda and Y. Merlín-Uribe, 2019: Coffee, Migration and Climatic Changes: Challenging Adaptation Dichotomic Narratives in a Transborder Region. *Social Sciences*, **8**(12), 323, doi:10.3390/socsci8120323
Ruiz-Mallén, I., E. Corbera, D. Calvo-Boyero and V. Reyes-García, 2015: Participatory scenarios to explore local adaptation to global change in biosphere reserves: Experiences from Bolivia and Mexico. *Environmental Science and Policy*, **54**, 398-408, doi:10.1016/j.envsci.2015.07.027.
Ruiz-Mallén, I., Á. Fernández-Llamazares and V. Reyes-García, 2017: Unravelling local adaptive capacity to climate change in the Bolivian Amazon: the interlinkages between assets, conservation and markets. *Climatic Change*, **140**(2), 227-242, doi:10.1007/s10584-016-1831-x.
Ruiz-Vásquez, M., P. A. Arias, J. A. Martínez and J. C. Espinoza, 2020: Effects of Amazon basin deforestation on regional atmospheric circulation and water vapor transport towards tropical South America. *Climate Dynamics*, **54**(9-10), 4169-4189, doi:10.1007/s00382-020-05223-4.
Rusticucci, M., M. Barrucand and S. Collazo, 2017: Temperature extremes in the Argentina central region and their monthly relationship with the mean circulation and ENSO phases. *International Journal of Climatology*, **37**(6), 3003-3017, doi:10.1002/joc.4895.
Rusticucci, M. et al., 2020: Hacia un Observatorio Latinoamericano de Clima y Salud: Seminario sobre Instrumentos y Metodologías. *Revista de Salud Ambiental*, **20**(2), 119–128.
Ryan, D., 2012: *Report on the Status and Quality of Public Policies on Climate Change and Development in Latin America - Agriculture and Forestry Sector*. Plataforma Climática Latinoamericana, 26 pp. pp.
Ryan, D. and E. Bustos, 2019: Knowledge gaps and climate adaptation policy: a comparative analysis of six Latin American countries. *Climate Policy*, **19**(10), 1297-1309, doi:10.1080/14693062.2019.1661819.
Ryan, S. J., C. J. Carlson, E. A. Mordecai and L. R. Johnson, 2019: Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *PLOS Neglected Tropical Diseases*, **13**(3), e0007213, doi:10.1371/journal.pntd.0007213.

Sá, J. C. d. M. et al., 2017: Low-carbon agriculture in South America to mitigate global climate change and advance food security. *Environment International*, **98**, 102-112, doi:10.1016/j.envint.2016.10.020.
Saito, S. M. et al., 2019: Urban population exposed to risks of landslides, floods and flash floods in Brazil. *Sociedade & Natureza*, **31**, doi:
10.14393/SN-v31-2019-46320.
Salas, C. et al., 2016: The Forest Sector in Chile: An Overview and Current Challenges. *Journal of Forestry*, **114**(5), 562-571, doi:10.5849/jof.14-062.
Salazar, A. et al., 2016: Deforestation changes land–atmosphere interactions across South American biomes. *Global and Planetary Change*, **139**, 97-108, doi:10.1016/j.gloplacha.2016.01.004.
Salazar, A. et al., 2018: The ecology of peace: preparing Colombia for new political and planetary climates. *Frontiers in Ecology and the Environment*, **16**(9), 525-531, doi:10.1002/fee.1950.
Salvador, C. et al., 2020: Effects of droughts on health: Diagnosis, repercussion, and adaptation in vulnerable regions under climate change. Challenges for future research. *Science of The Total Environment*, **703**, 134912, doi:10.1016/j.scitotenv.2019.134912.
Sampaio, G. et al., 2019: Assessing the possible impacts of a 4 °C or higher warming in Amazonia. In: *Climate Change Risks in Brazil* [Nobre, C., J. Marengo and W. Soares (eds.)]. Springer, Cham, pp. 201-218. ISBN 9783319928814.
Sampaio, G. et al., 2021: CO2 physiological effect can cause rainfall decrease as strong as large-scale deforestation in the Amazon. *Biogeosciences*, **18**(8), 2511-2525, doi:10.5194/bg-18-2511-2021.
Sánchez, A. L., N. E. Sánchez and A. M. Gómez Sánchez, 2017: Climatic phenomenon and meteorological variables influencing the dengue fever incidence in Colombian South Pacific region: modeling study. *Annals of Tropical Medicine and Public Health*, **10**(6), 1489-1495.
Sánchez, E. et al., 2015: Regional climate modelling in CLARIS-LPB: a concerted approach towards twentyfirst century projections of regional temperature and precipitation over South America. *Climate Dynamics*, **45**(7-8), 2193-2212, doi:10.1007/s00382-014-2466-0.
Sánchez, T. et al., 2019: Association between air pollution and sleep disordered breathing in children. *Pediatric Pulmonology*, **54**(5), 544-550, doi:10.1002/ppul.24256.
Sandholz, S., W. Lange and U. Nehren, 2018: Governing green change: Ecosystem-based measures for reducing landslide risk in Rio de Janeiro. *International Journal of Disaster Risk Reduction*, **32**, 75-86, doi:10.1016/j.ijdrr.2018.01.020.
Sandoval, V. and J. P. Sarmiento, 2019: *A neglected issue: Informal settlements, urban development, and disaster risk reduction in Latin America and the Caribbean*. UNDRR Global Assessment Report on Disaster Risk Reduction (GAR 2019), United Nations Office for Disaster Risk Reduction UNDRR, Geneva, 26 pp. Available at: https://www.preventionweb.net/go/66656 (accessed 31/10/2020).
Santamaria-Aguilar, S., M. Schuerch, A. T. Vafeidis and S. C. Carretero, 2017: Long-Term Trends and Variability of Water Levels and Tides in Buenos Aires and Mar del Plata, Argentina. *Frontiers in Marine Science*, **4**(380), doi:10.3389/fmars.2017.00380.
Santofimia, E. et al., 2017: Acid rock drainage in Nevado Pastoruri glacier area (Huascarán National Park, Perú): hydrochemical and mineralogical characterization and associated environmental implications. *Environmental Science and Pollution Research*, **24**(32), 25243-25259, doi:10.1007/s11356-017-0093-0.
Santos, J., J. Monteiro, D. Ceballos and J. Soto, 2016: Lecciones aprendidas al enfrentar los efectos de eventos hidrometeorológicos extremos en los sistemas agrícolas y servicios ecosistémicos en América Latina. *La Granja*, **24**(2), 69-82, doi:10.17163/lgr.n24.2016.06.
Santos, R. B. d. and D. P. Marinho, 2018: *Relatório do Projeto Construção de Indicadores de Vulnerabilidade da População como Insumo para a Elaboração das Ações de Adaptação à Mudança do Clima no Brasil: Volume: Espírito Santo*. Fundação Oswaldo Cruz, Ministério do Meio Ambiente e Fundo Nacional sobre Mudança do Clima FIOCRUZ, Rio de Janeiro, RJ, 120 pp. Available at: https://www.mma.gov.br/images/arquivo/80182/Vulnerabilidade%20%C3%A0%20Mudan%C3%A7a%20do%20Clima/Relat%C3%B3rio_Final_EspiritoSanto_Novo.pdf (accessed 11/10/2020).
Sapiains Arrué, R. and A. M. Ugarte Caviedes, 2017: Contribuciones de la Psicología al abordaje de la dimensión humana del cambio climático en Chile (Segunda parte). *Interdisciplinaria. Revista de Psicología y Ciencias Afines*, **34**(2), 259-274, doi:10.16888/interd.2017.34.1.6.
Sarkodie, S. A. and V. Strezov, 2019: Economic, social and governance adaptation readiness for mitigation of climate change vulnerability: Evidence from 192 countries. *Science of The Total Environment*, **656**, 150-164, doi:10.1016/j.scitotenv.2018.11.349.
Sarricolea, P. and O. Meseguer-Ruiz, 2019: Urban Climates of Large Cities: Comparison of the Urban Heat Island Effect in Latin America. In: *Urban Climates in Latin America* [Henríquez, C. and H. Romero (eds.)]. Springer International Publishing, Cham, pp. 17-32. ISBN 978-3-319-97013-4.
Sarricolea, P. et al., 2020: Recent wildfires in Central Chile: Detecting links between burned areas and population exposure in the wildland urban interface. *Science of The Total Environment*, **706**, 135894, doi:10.1016/j.scitotenv.2019.135894.
Satterthwaite, D. et al., 2020: Building Resilience to Climate Change in Informal Settlements. *One Earth*, **2**(2), 143-156, doi:10.1016/j.oneear.2020.02.002.

Satterthwaite, D. et al., 2018: *Responding to climate change in cities and in their informal settlements and economies. Background paper prepared for the IPCC International Scientific Conference on Cities and Climate Change in Edmonton, March 2018*. International Institute for Environment and Development (IIED) and IIED-América Latina, 61 pp. Available at: https://pubs.iied.org/pdfs/G04328.pdf (accessed 21/09/2019).
Saurral, R. I., I. A. Camilloni and V. R. Barros, 2017: Low-frequency variability and trends in centennial precipitation stations in southern South America. *International Journal of Climatology*, **37**(4), 1774-1793, doi:10.1002/joc.4810.
Saylor, C. R., K. A. Alsharif and H. Torres, 2017: The importance of traditional ecological knowledge in agroecological systems in Peru. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **13**(1), 150-161, doi:10.1080/21513732.2017.1285814.
Scarano, F. R., 2017: Ecosystem-based adaptation to climate change: concept, scalability and a role for conservation science. *Perspectives in Ecology and Conservation*, **15**(2), 65-73, doi:10.1016/j.pecon.2017.05.003.
Scarano, F. R. and P. Ceotto, 2015: Brazilian Atlantic forest: impact, vulnerability, and adaptation to climate change. *Biodiversity and Conservation*, **24**(9), 2319-2331, doi:10.1007/s10531-015-0972-y.
Scarano, F. R. et al., 2018: Chapter 6: Options for governance and decision-making across scales and sectors. In: *IPBES (2018): The IPBES regional assessment report on biodiversity and ecosystem services for the Americas* [Rice, J., C. S. Seixas, M. E. Zaccagnini, M. Bedoya-Gaitán and N. Valderrama (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, pp. 521-581. ISBN 9783947851010.
Schaller, S., N. Jean-Baptiste and P. Lehmann, 2016: Oportunidades y obstáculos para la adaptación urbana frente al cambio climático en América Latina: Casos de la Ciudad de México, Lima y Santiago de Chile. *EURE (Santiago)*, **42**(127), 257-278, doi:10.4067/S0250-71612016000300011.
Schauwecker, S. et al., 2017: The freezing level in the tropical Andes, Peru: An indicator for present and future glacier extents. *Journal of Geophysical Research: Atmospheres*, **122**(10), 5172-5189, doi:10.1002/2016JD025943.
Schembergue, A. et al., 2017: Sistemas Agroflorestais como Estratégia de Adaptação aos Desafios das Mudanças Climáticas no Brasil. *Revista de Economia e Sociologia Rural*, **55**(1), 9-30, doi:10.1590/1234-56781806-94790550101
Schivo, F., V. Bauni, P. Krug and R. D. Quintana, 2019: Distribution and richness of amphibians under different climate change scenarios in a subtropical region of South America. *Applied Geography*, **103**(February 2018), 70-89, doi:10.1016/j.apgeog.2019.01.003.
Schmidt, M. J. et al., 2014: Dark earths and the human built landscape in Amazonia: A widespread pattern of anthrosol formation. *Journal of Archaeological Science*, doi:10.1016/j.jas.2013.11.002.
Schneider, W., D. Donoso, J. Garcés-Vargas and R. Escribano, 2017: Water-column cooling and sea surface salinity increase in the upwelling region off central-south Chile driven by a poleward displacement of the South Pacific High. *Progress in Oceanography*, **151**, 38-48, doi:10.1016/j.pocean.2016.11.004.
Scholes, R. J., 2016: Climate change and ecosystem services. *WIREs Climate Change*, **7**(4), 537-550, doi:10.1002/wcc.404.
Schoolmeester, T. et al., 2018: *The Andean Glacier and Water Atlas – The Impact of Glacier Retreat on Water Resources*. UNESCO and GRID-Arendal, Paris, France and Arendal, Norway, 77 pp. ISBN 978-92-3-100286-1.
Schütze, M., J. Seidel, A. Chamorro and C. León, 2019: Integrated modelling of a megacity water system – The application of a transdisciplinary approach to the Lima metropolitan area. *Journal of Hydrology*, **573**, 983-993, doi:10.1016/j.jhydrol.2018.03.045.
Schwartzman, S. et al., 2013: The natural and social history of the indigenous lands and protected areas corridor of the Xingu River basin. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **368**(1619), 20120164, doi:10.1098/rstb.2012.0164.
Scientific American, 2015: El Niño golpea con fuerza a Centroamérica y trae sequía, inundaciones y hambre. *Scientific American Español*. Available at: http://www.scientificamerican.com/espanol/noticias/el-nino-golpea-con-fuerza-a-centroamerica-y-trae-sequia-inundaciones-y-hambre/ (accessed 17/06/2021).
Scordo, F. et al., 2017: Evolution of Water Resources in the "Bajo de Sarmiento" (Extraandean Patagonia): Natural and Anthropogenic Impacts. *Anuário do Instituto de Geociências - UFRJ*, **40**(2), 106-117, doi:10.11137/2017_2_106_117.
Scoville-Simonds, M., 2018: Climate, the Earth, and God – Entangled narratives of cultural and climatic change in the Peruvian Andes. *World Development*, **110**, 345-359, doi:10.1016/j.worlddev.2018.06.012.
Scoville-Simonds, M., H. Jamali and M. Hufty, 2020: The Hazards of Mainstreaming: Climate change adaptation politics in three dimensions. *World Development*, **125**, 104683, doi:10.1016/j.worlddev.2019.104683.
Secretaría de Recursos Naturales y Ambiente del Gobierno de la República de Honduras, 2018: *Plan Nacional de Adaptación al Cambio Climático de Honduras*, Honduras, 67 pp.
Seddon, A. W. R. et al., 2016: Sensitivity of global terrestrial ecosystems to climate variability. *Nature*, **531**, 229-232, doi:10.1038/nature16986.
Sedeh, V., 2014: Floods and displacement in Bolivia. In: *The State of Environmental Migration 2014: Review of the Year 2013* [Gemenne, F., P. Brücker and D. Ionesco (eds.)]. International Organization for MIgration and SciencesPo, Sc, pp. 175-187.

Seehaus, T. et al., 2019: Changes of the tropical glaciers throughout Peru between 2000 and 2016 - Mass balance and area fluctuations. *The Cryosphere Discussions*, 1-34, doi:10.5194/tc-2018-289.
Segnestam, L., 2017: Gendered Experiences of Adaptation to Drought: Patterns of Change in El Sauce, Nicaragua. *Latin American Research Review*, **52**(5), 807-823, doi:10.25222/larr.220.
Seiler, C., R. W. A. Hutjes and P. Kabat, 2013: Likely Ranges of Climate Change in Bolivia. *Journal of Applied Meteorology and Climatology*, **52**(6), 1303-1317, doi:10.1175/JAMC-D-12-0224.1.
Seimon, T. A. et al., 2017: Long-term monitoring of tropical alpine habitat change, Andean anurans, and chytrid fungus in the Cordillera Vilcanota, Peru: Results from a decade of study. *Ecology and Evolution*, **7**(5), 1527-1540, doi:10.1002/ece3.2779.
Sena, A., C. Barcellos, C. Freitas and C. Corvalan, 2014: Managing the health impacts of drought in Brazil. *International Journal of Environmental Research and Public Health*, **11**(10), 10737-10751, doi:10.3390/ijerph111010737.
Sena, A., C. Barcellos, C. Freitas and C. Corvalan, 2016: Managing the health impacts of drought in Brazil: A comprehensive risk reduction framework. In: *Climate Services for health: Improving public health decision-making in a new climate - Case studies* [Shumake-Guillemot, J. and L. Fernandez-Montoya (eds.)]. World Meteorological Organization and World Health Organization, Geneva, pp. 166-169.
Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Sepúlveda, S. A., S. M. Moreiras, M. Lara and A. Alfaro, 2015: Debris flows in the Andean ranges of central Chile and Argentina triggered by 2013 summer storms: characteristics and consequences. *Landslides*, **12**(1), 115-133, doi:10.1007/s10346-014-0539-0.
Serrano Vincenti, S., J. C. Ruiz and F. Bersosa, 2017: Heavy rainfall and temperature projections in a climate change scenario over Quito, Ecuador. *La Granja: Revista de Ciencias de la Vida*, **25**(1), 16-32, doi:10.17163/lgr.n25.2017.02.
Sette Whitaker Ferreira, J. et al., 2020: Housing policies and the roles of local governments in Latin America: recent experiences. *Environment and Urbanization*, **32**(2), 333-350, doi:10.1177/0956247820935699.
SGR, 2018: *Plan Nacional de Respuesta ante Desastres de Ecuador*. Secretaría de Gestión de Riesgos, 448 pp. Available at: https://www.gestionderiesgos.gob.ec/wp-content/uploads/downloads/2018/08/Plan-Nacional-de-Respuesta-SGR-RespondeEC.pdf (accessed 17/06/2021).
SGRD et al., 2014: *Plan Nacional de Gestión del Riesgo de Desastres 2014-2021 de Perú*. Lima, 70 pp. Available at: https://www.indeci.gob.pe/wp-content/uploads/2019/01/fil20140605171327.pdf (accessed 17/06/2021).
Shapiro-Garza, E. et al., 2020: A participatory framework for feasibility assessments of climate change resilience strategies for smallholders: lessons from coffee cooperatives in Latin America. *Int. J. Agric. Sustain.*, **18**(1), 21-34, doi:10.1080/14735903.2019.1658841.
Sharma, N. et al., 2016: Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development. *Food and Energy Security*, **5**(3), 165-183, doi:10.1002/fes3.87.
Sheffield, P. E. et al., 2013: Current and Future Heat Stress in Nicaraguan Work Places under a Changing Climate. *Industrial Health*, **51**(1), 123-127, doi:10.2486/indhealth.2012-0156.
Shepard, G. H. et al., 2020: Ancient and Traditional Agriculture in South America: Tropical Lowlands. *Environmental Science*, doi:10.1093/acrefore/9780199389414.013.597.
Sherman, M. et al., 2015: Vulnerability and adaptive capacity of community food systems in the Peruvian Amazon: a case study from Panaillo. *Natural Hazards*, **77**(3), 2049-2079, doi:10.1007/s11069-015-1690-1.
Shi, L. et al., 2016: Roadmap towards justice in urban climate adaptation research. *Nature Climate Change*, **6**(2), 131-137, doi:10.1038/nclimate2841.
Shokry, G., J. J. T. Connolly and I. Anguelovski, 2020: Understanding climate gentrification and shifting landscapes of protection and vulnerability in green resilient Philadelphia. *Urban Climate*, **31**, 100539, doi:10.1016/j.uclim.2019.100539.
Sietsma, A. J., J. D. Ford, M. W. Callaghan and J. C. Minx, 2021: Progress in climate change adaptation research. *Environmental Research Letters*, **16**(5), 054038, doi:10.1088/1748-9326/abf7f3.
Silva, A. M. C. d., I. E. Mattos, E. Ignotti and S. d. S. Hacon, 2013: Material particulado originário de queimadas e doenças respiratórias *Revista de Saúde Pública*, **47** 345-352, doi:10.1590/S0034-8910.2013047004410.
Silva, C., F. Leiva and J. Lastra, 2019a: Predicting the current and future suitable habitat distributions of the anchovy (Engraulis ringens) using the Maxent model in the coastal areas off central-northern Chile. *Fisheries Oceanography*, **28**(2), 171-182, doi:10.1111/fog.12400.
Silva, C. et al., 2015: Forecasts of swordfish (Xiphias gladius) and common sardine (Strangomera bentincki) off Chile under the A2 IPCC climate change scenario. *Progress in Oceanography*, **134**, 343-355, doi:10.1016/j.pocean.2015.03.004.
Silva de Souza, K. I., P. L. Borges Chaffe, T. M. Portela Nogueira and C. R. Silva de Carvalho Pinto, 2021: Environmental damage of urbanized stream corridors in a coastal plain in Southern Brazil. *Ocean & Coastal Management*, **211**, 105739, doi:10.1016/j.ocecoaman.2021.105739.

Silva, E., 2016: Patagonia, without Dams! Lessons of a David vs. Goliath campaign. *The Extractive Industries and Society*, **3**(4), 947-957, doi:10.1016/J.EXIS.2016.10.004.
Silva, H. et al., 2016: Effect of water availability on growth, water use efficiency and omega 3 (ALA) content in two phenotypes of chia (Salvia hispanica L.) established in the arid Mediterranean zone of Chile. *Agric. Water Manage.*, **173**(2016), 67-75, doi:10.1016/j.agwat.2016.04.028.
Silva, H. V. d. O., D. P. Marinho and F. C. V. Marincola, 2018: *Relatório do Projeto Construção de Indicadores de Vulnerabilidade da População como Insumo para a Elaboração das Ações de Adaptação à Mudança do Clima no Brasil: Volume: Maranhão*. Fundação Oswaldo Cruz, Ministério do Meio Ambiente e Fundo Nacional sobre Mudança do Clima FIOCRUZ, Rio de Janeiro, RJ, 160 pp. Available at: https://www.mma.gov.br/images/arquivo/80182/Vulnerabilidade%20%C3%A0%20Mudan%C3%A7a%20do%20Clima/Relat%C3%B3rio_Final_Maranhao_Novo.pdf (accessed 11/10/2020).
Silva, J. L. B. d. et al., 2020: Changes in the water resources, soil use and spatial dynamics of Caatinga vegetation cover over semiarid region of the Brazilian Northeast. *Remote Sensing Applications: Society and Environment*, **20**, 100372, doi:10.1016/j.rsase.2020.100372.
Silva, J. L. S. E. et al., 2019b: Climate change will reduce suitable Caatinga dry forest habitat for endemic plants with disproportionate impacts on specialized reproductive strategies. *PLoS ONE*, **14**(5), e0217028, doi:10.1371/journal.pone.0217028.
Silva, J. M. C., L. C. F. Barbosa, I. R. Leal and M. Tabarelli, 2017: The Caatinga: Understanding the Challenges. In: *Caatinga: The Largest Tropical Dry Forest Region in South America*, 1st ed. [Silva, J. M. C. d., I. R. Leal and M. Tabarelli (eds.)]. Springer, Cham, Switzerland, pp. 3-19. ISBN 978-3-319-68339-3.
Silva, J. M. C. d., A. Rapini, L. C. F. Barbosa and R. R. Torres, 2019c: Extinction risk of narrowly distributed species of seed plants in Brazil due to habitat loss and climate change. *PeerJ*, **7**, e7333, doi:10.7717/peerj.7333.
Silva Junior, C. H. L. et al., 2019: Fire Responses to the 2010 and 2015/2016 Amazonian Droughts. *Frontiers in Earth Science*, **7**(97), doi:10.3389/feart.2019.00097.
Silva Junior, C. H. L. et al., 2021: The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. *Nature Ecology & Evolution*, **5**(2), 144-145, doi:10.1038/s41559-020-01368-x.
Silva, P. S. et al., 2019d: Impacts of the 1.5 °C global warming target on future burned area in the Brazilian Cerrado. *Forest Ecology and Management*, **446**, 193-203, doi:10.1016/j.foreco.2019.05.047.
Silva, R. et al., 2014: Present and Future Challenges of Coastal Erosion in Latin America. *Journal of Coastal Research*, **71**(sp1), 1-16, doi:10.2112/SI71-001.1.
Silva Rodríguez de San Miguel, J. A., E. Martínez Díaz and D. M. Monroy Becerril, 2021: The relationship between climate change and internal migration in the Americas. *Management of Environmental Quality: An International Journal*, **32**(4), 822-839, doi:10.1108/MEQ-01-2021-0020.
Singh-Renton, S. and I. McIvor, 2015: *Review of current fisheries management performance and conservation measures in the WECAFC area*. FAO Fisheries and Aquaculture Technical Paper, Bridgetown, Barbados, 293 pp. pp. Available at: http://www.fao.org/documents/card/en/c/da5cd80f-0e6e-427b-9ac1-9f0be50cf1c5/ (accessed 17/06/2021).
Singh, C. et al., 2020a: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Climatic Change*, **162**(2), 255-277, doi:10.1007/s10584-020-02762-x.
Singh, N., S. Singh and R. K. Mall, 2020b: Chapter 17 - Urban ecology and human health: implications of urban heat island, air pollution and climate change nexus. In: *Urban Ecology* [Verma, P., P. Singh, R. Singh and A. S. Raghubanshi (eds.)]. Elsevier, pp. 317-334. ISBN 978-0-12-820730-7.
Singh, R. and G. S. Singh, 2017: Traditional agriculture: a climate-smart approach for sustainable food production. *Energy, Ecology and Environment*, **2**(5), 296-316, doi:10.1007/s40974-017-0074-7.
Siña, M. et al., 2016: Understanding Perceptions of Climate Change, Priorities, and Decision-Making among Municipalities in Lima, Peru to Better Inform Adaptation and Mitigation Planning. *PLOS ONE*, **11**(1), e0147201, doi:10.1371/journal.pone.0147201.
Sippy, R. et al., 2019: Seasonal patterns of dengue fever in rural Ecuador: 2009-2016. *PLOS Neglected Tropical Diseases*, **13**(5), e0007360, doi:10.1371/journal.pntd.0007360.
Skansi, M. d. l. M. et al., 2013: Warming and wetting signals emerging from analysis of changes in climate extreme indices over South America. *Global and Planetary Change*, **100**, 295-307, doi:10.1016/j.gloplacha.2012.11.004.
Skarbø, K. and K. VanderMolen, 2016: Maize migration: key crop expands to higher altitudes under climate change in the Andes. *Climate and Development*, **8**(3), 245-255, doi:10.1080/17565529.2015.1034234.
Sloat, L. L. et al., 2020: Climate adaptation by crop migration. *Nature Communications*, **11**(1), 1243, doi:10.1038/s41467-020-15076-4.
Smith, L. T., L. E. O. C. Aragão, C. E. Sabel and T. Nakaya, 2014: Drought impacts on children's respiratory health in the Brazilian Amazon. *Scientific Reports*, **4**, 3726, doi:10.1038/srep03726.
Smith, P. and C. Henríquez, 2019: Public Spaces as Climate Justice Places? Climate Quality in the City of Chillán, Chile. *Environmental Justice*, **12**(4), 164-174, doi:10.1089/env.2018.0041.
Soares-Filho, B. et al., 2014: Cracking Brazil's Forest Code. *Science*, **344**(6182), 363-364, doi:10.1126/science.1246663.
Soares, M. D. R. et al., 2021: Land-use change and its impact on physical and mechanical properties of Archaeological Black Earth in the Amazon rainforest. *CATENA*, **202**, 105266, doi:10.1016/j.catena.2021.105266.

Sombroek, W. et al., 2003: Amazonian Dark Earths as Carbon Stores and Sinks. In: *Amazonian dark earths*. Springer, Dordrecht, pp. 125-139.

Somers, L. D. et al., 2019: Groundwater Buffers Decreasing Glacier Melt in an Andean Watershed—But Not Forever. *Geophysical Research Letters*, **46**(22), 13016-13026, doi:10.1029/2019GL084730.

Son, J. Y. et al., 2016: The impact of temperature on mortality in a subtropical city: effects of cold, heat, and heat waves in São Paulo, Brazil. *International Journal of Biometeorology*, **60**(1), 113-121, doi:10.1007/s00484-015-1009-7.

Soruco, A. et al., 2015: Contribution of glacier runoff to water resources of La Paz city, Bolivia (16° S). *Annals of Glaciology*, **56**(70), 147-154, doi:10.3189/2015AoG70A001.

Sosa-Rodriguez, F. S., 2014: From federal to city mitigation and adaptation: climate change policy in Mexico City. *Mitigation and Adaptation Strategies for Global Change*, **19**(7), 969-996, doi:10.1007/s11027-013-9455-1.

Soto, D. et al., 2019: Salmon farming vulnerability to climate change in southern Chile: understanding the biophysical, socioeconomic and governance links. *Reviews in Aquaculture*, **11**(2), 354-374, doi:10.1111/raq.12336.

Soto Winckler, J. and G. Del Castillo Pantoja, 2019: Agua como recurso estratégico: Desafíos para Chile en un escenario de cambio climático. *Revista Política y Estrategia*, **134**, 55-92, doi:10.26797/rpye.v0i134.787.

Souza, C. M. et al., 2020: Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. *Remote Sensing*, **12**(17), doi:10.3390/rs12172735.

Souza, C. R. d. G., A. P. Souza and J. Harari, 2019: Long Term Analysis of Meteorological-Oceanographic Extreme Events for the Baixada Santista Region. In: *Climate Change in Santos Brazil: Projections, Impacts and Adaptation Options* [Nunes, L. H., R. Greco and J. A. Marengo (eds.)]. Springer International Publishing, Cham, pp. 97-134. ISBN 978-3-319-96535-2.

Souza Piao, R., V. L. Silva, I. Navarro del Aguila and J. de Burgos Jiménez, 2021: Green Growth and Agriculture in Brazil. *Sustainability*, **13**(3), doi:10.3390/su13031162.

Spalding, M. D. et al., 2007: Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. *BioScience*, **57**(7), 573-583, doi:10.1641/b570707.

Spalding, M. D. et al., 2014: The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean and Coastal Management*, **90**, 50-57, doi:10.1016/j.ocecoaman.2013.09.007.

Spencer, B. et al., 2017: Case studies in co-benefits approaches to climate change mitigation and adaptation. *Journal of Environmental Planning and Management*, **60**(4), 647-667, doi:10.1080/09640568.2016.1168287.

Spencer, N. and M.-A. Urquhart, 2018: Hurricane Strikes and Migration: Evidence from Storms in Central America and the Caribbean. *Weather, Climate, and Society*, **10**(3), 569-577, doi:10.1175/WCAS-D-17-0057.1.

Spera, S. A., J. M. Winter and T. F. Partridge, 2020: Brazilian maize yields negatively affected by climate after land clearing. *Nature Sustainability*, **3**(10), 845-852, doi:10.1038/s41893-020-0560-3.

Spinoni, J. et al., 2019: A new global database of meteorological drought events from 1951 to 2016. *Journal of Hydrology: Regional Studies*, **22**, 100593, doi:10.1016/j.ejrh.2019.100593.

Spinoni, J. et al., 2015: Towards identifying areas at climatological risk of desertification using the Köppen–Geiger classification and FAO aridity index. *International Journal of Climatology*, **35**(9), 2210-2222, doi:10.1002/joc.4124.

Stan, K. et al., 2020: Climate change scenarios and projected impacts for forest productivity in Guanacaste Province (Costa Rica): lessons for tropical forest regions. *Regional Environmental Change*, **20**(1), 14, doi:10.1007/s10113-020-01602-z.

Stathatou, P. M. et al., 2016: Vulnerability of water systems: a comprehensive framework for its assessment and identification of adaptation strategies. *Desalination and Water Treatment*, **57**(5), 2243-2255, doi:10.1080/19443994.2015.1012341.

Stäubli, A. et al., 2018: Analysis of Weather- and Climate-Related Disasters in Mountain Regions Using Different Disaster Databases. In: *Climate Change, Extreme Events and Disaster Risk Reduction: Towards Sustainable Development Goals* [Mal, S., R. B. Singh and C. Huggel (eds.)]. Springer International Publishing, Cham, pp. 17-41. ISBN 978-3-319-56469-2.

Stein, A., 2019: Adaptación al cambio climático en ciudades con altos niveles de riesgo social y ambiental: El caso de dos barrios populares en Tegucigalpa, Honduras. *Medio Ambiente y Urbanización*, **90**(1), 169-204.

Stein, A. and C. Moser, 2014: Asset planning for climate change adaptation: Lessons from Cartagena, Colombia. *Environment and Urbanization*, **26**(1), 166-183, doi:10.1177/0956247813519046.

Stein, A. and C. Moser, 2015: *La planificación de activos para la adaptación al cambio climático: lecciones de Cartagena, Colombia*. Medio Ambiente y Urbanización, **83**, Latina, I.-A., 49-70 pp. Available at: https://www.ingentaconnect.com/contentone/iieal/meda/2015/00000083/00000001/art00003 (accessed 31/10/2020).

Stein, A., C. Moser and I. Vance, 2018: *Asset Planning for Climate Change Adaptation in Poor Neighborhoods of Tegucigalpa, Honduras*. Inter-American Development Bank, 94 pp. Available at: https://publications.iadb.org/publications/english/document/Asset-Planning-for-Climate-Change-Adaptation-in-Poor-Neighborhoods-of-Tegucigalpa-Honduras.pdf (accessed 31/10/2020).

Stein Heinemann, A., 2018: Cambio climático y conflictividad socioambiental en América Latina y el Caribe. *América Latina Hoy*, **79**, 9-39, doi:10.14201/alh201879939.

Stennett-Brown, R. K., J. J. P. Jones, T. S. Stephenson and M. A. Taylor, 2017: Future Caribbean temperature and rainfall extremes from statistical downscaling. *International Journal of Climatology*, **37**(14), 4828-4845, doi:10.1002/joc.5126.
Stensrud, A. B., 2016: Harvesting Water for the Future: Reciprocity and Environmental Justice in the Politics of Climate Change in Peru. *Latin American Perspectives*, **43**(4), 56-72, doi:10.1177/0094582x16637866.
Stewart-Ibarra, A. M. and R. Lowe, 2013: Climate and non-climate drivers of dengue epidemics in southern coastal Ecuador. *The American Journal of Tropical Medicine and Hygiene*, **88**(5), 971-981, doi:10.4269/ajtmh.12-0478.
Storlazzi, C. D. et al., 2018: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, **4**(4), eaap9741, doi:10.1126/sciadv.aap9741.
Strassburg, B. B. N. et al., 2019: Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. *Nature Ecology & Evolution*, **3**(1), 62-70, doi:10.1038/s41559-018-0743-8.
Strassburg, B. B. N. et al., 2017: Moment of truth for the Cerrado hotspot. *Nature Ecology & Evolution*, **1**(4), 0099, doi:10.1038/s41559-017-0099.
Strassburg, B. B. N. et al., 2020: Global priority areas for ecosystem restoration. *Nature*, doi:10.1038/s41586-020-2784-9.
Strassburg, B. B. N. et al., 2014: Biophysical suitability, economic pressure and land-cover change: a global probabilistic approach and insights for REDD+. *Sustainability Science*, **9**(2), 129-141, doi:10.1007/s11625-013-0209-5.
Suarez, M. L., L. Ghermandi and T. Kitzberger, 2004: Factors predisposing episodic drought-induced tree mortality in Nothofagus– site, climatic sensitivity and growth trends. *Journal of Ecology*, **92**(6), 954-966, doi:10.1111/j.1365-2745.2004.00941.x.
Sudmeier-Rieux, K. et al., 2017: *Identifying emerging issues in disaster risk reduction, migration, climate change and sustainable development*. Springer, Switzerland. ISBN 3319338781.
Sullivan, M. J. P. et al., 2020: Long-term thermal sensitivity of Earth's tropical forests. *Science* **368**(6493), 869-874, doi:10.1126/science.aaw7578.
Sun, Q. et al., 2019: Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. *Environment International*, **128**, 125-136, doi:10.1016/j.envint.2019.04.025.
Sun, Q. et al., 2021: A global, continental, and regional analysis of changes in extreme precipitation. *Journal of Climate*, **34**(1), 243-258, doi:10.1175/JCLI-D-19-0892.1.
Takahashi, K. and A. G. Martínez, 2019: The very strong coastal El Niño in 1925 in the far-eastern Pacific. *Climate Dynamics*, **52**(12), 7389-7415, doi:10.1007/s00382-017-3702-1.
Tall, A., J. Y. Coulibaly and M. Diop, 2018: Do climate services make a difference? A review of evaluation methodologies and practices to assess the value of climate information services for farmers: Implications for Africa. *Climate Services*, **11**, 1-12, doi:10.1016/j.cliser.2018.06.001.
Tanner, T. et al., 2015a: Livelihood resilience in the face of climate change. *Nature Climate Change*, **5**(1), 23-26, doi:10.1038/nclimate2431.
Tanner, T. et al., 2015b: *The Triple Dividend of Resilience. Realising development goals through the multiple benefits of disaster risk management*. Overseas Development Institute, International Bank of Reconstruction and Development and World Bank, London, UK and Washington D.C., United States of America, 37 pp. Available at: https://www.gfdrr.org/sites/default/files/publication/The_Triple_Dividend_of_Resilience.pdf (accessed 31/08/2021).
Tapasco, J. et al., 2015: *Impactos Económicos del Cambio Climático en Colombia: Sector Ganadero*. Monografía No. 254, Banco Interamericano de Desarrollo, Washington D.C., United States, 45 pp. Available at: https://publications.iadb.org/publications/spanish/document/Impactos-econ%C3%B3micos-del-cambio-clim%C3%A1tico-en-Colombia-sector-ganadero.pdf (accessed 25/08/2021).
Tapia-Garay, V. et al., 2018: Assessing the risk zones of Chagas' disease in Chile, in a world marked by global climatic change. *Memórias do Instituto Oswaldo Cruz*, **113**(1), 24-29, doi:10.1590/0074-02760170172.
Taylor, M. A. et al., 2018: Future Caribbean climates in a world of rising temperatures: The 1.5 vs 2.0 Dilemma. *Journal of Climate*, **31**(7), 2907-2926, doi:10.1175/JCLI-D-17-0074.1.
Teferi, Z. A. and P. Newman, 2018: Slum Upgrading: Can the 1.5 °C Carbon Reduction Work with SDGs in these Settlements? *Urban Planning*, **3**(2), doi:10.17645/up.v3i2.1239.
Tehelen, K. and M. J. Pacha, 2017: *Estudios de vulnerabilidad en América Latina y el Caribe: recomendaciones a través de la experiencia*. CDKN, 28 pp. Available at: https://cdkn.org/wp-content/uploads/2017/05/Guia-Vulnerabilidad-ok.pdf (accessed 17/06/2021).
Teichmann, C. et al., 2013: How does a regional climate model modify the projected climate change signal of the driving GCM: A study over different CORDEX regions using REMO. *Atmosphere*, **4**(2), 214-236, doi:10.3390/atmos4020214.
Teixeira, C. D. et al., 2019: Sustained mass coral bleaching (2016–2017) in Brazilian turbid-zone reefs: taxonomic, cross-shelf and habitat-related trends. *Coral Reefs*, **38**(4), 801-813, doi:10.1007/s00338-019-01789-6.
Tellman, B. et al., 2018: Opportunities for natural infrastructure to improve urban water security in Latin America. *PLOS ONE*, **13**(12), e0209470, doi:10.1371/journal.pone.0209470.

Tellman, B., J. E. Saiers and O. A. R. Cruz, 2016: Quantifying the impacts of land use change on flooding in data-poor watersheds in El Salvador with community-based model calibration. *Regional Environmental Change*, **16**(4), 1183-1196, doi:10.1007/s10113-015-0841-y.

Tellman, B. et al., 2020: Illicit Drivers of Land Use Change: Narcotrafficking and Forest Loss in Central America. *Global Environmental Change*, **63**, 102092, doi:10.1016/j.gloenvcha.2020.102092.

Tengö, M. et al., 2014: Connecting Diverse Knowledge Systems for Enhanced Ecosystem Governance: The Multiple Evidence Base Approach. *AMBIO*, **43**(5), 579-591, doi:10.1007/s13280-014-0501-3.

Terrazas, C., J. A. Castro-Rodriguez, C. A. Camargo Jr and A. Borzutzky, 2019: Solar radiation, air pollution, and bronchiolitis hospitalizations in Chile: An ecological study. *Pediatric Pulmonology*, **54**(9), 1466-1473, doi:10.1002/ppul.24421.

Thiede, B., C. Gray and V. Mueller, 2016: Climate variability and inter-provincial migration in South America, 1970–2011. *Global Environmental Change*, **41**, 228-240, doi:10.1016/j.gloenvcha.2016.10.005.

Thielen, D. et al., 2020: Quo vadis Pantanal? Expected precipitation extremes and drought dynamics from changing sea surface temperature. *PLOS ONE*, **15**(1), e0227437, doi:10.1371/journal.pone.0227437.

Thomas, G., 2014: *Ciudades más verdes en América Latina y el Caribe. Un informe de la FAO sobre la Agricultura Urbana y Periurbana en la región*. FAO (Organización de las Naciones Unidas para la Agricultura y la Alimentación), Roma, 51 pp. Available at: http://www.fao.org/ag/agp/greenercities/pdf/GGCLAC/Ciudades-mas-verdes-America-Latina-Caribe.pdf (accessed 17/06/2021).

Thomas, K. et al., 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10**(2), e565, doi:10.1002/wcc.565.

Thompson-Hall, M., E. R. Carr and U. Pascual, 2016: Enhancing and expanding intersectional research for climate change adaptation in agrarian settings. *Ambio*, **45**(3), 373-382, doi:10.1007/s13280-016-0827-0.

Thompson, D., 2016: Community adaptations to environmental challenges under decentralized governance in southwestern Uruguay. *J. Rural Stud.*, **43**, 71-82, doi:10.1016/j.jrurstud.2015.11.008.

Thompson, L. G. et al., 2017: Impacts of Recent Warming and the 2015/2016 El Niño on Tropical Peruvian Ice Fields. *Journal of Geophysical Research: Atmospheres*, **122**(23), 12,688-612,701, doi:10.1002/2017JD026592.

Thomson, M. C. and S. J. Mason, 2018: *Climate information for public health action*. Routledge, London.

Thornton, P. K. et al., 2018: A framework for priority-setting in climate smart agriculture research. *Agricultural Systems*, **167**, 161-175, doi:10.1016/j.agsy.2018.09.009.

Tito, R., H. L. Vasconcelos and K. J. Feeley, 2018: Global climate change increases risk of crop yield losses and food insecurity in the tropical Andes. *Global Change Biology*, **24**(2), e592-e602, doi:10.1111/gcb.13959.

To, P. and W. Dressler, 2019: Rethinking 'success': The politics of payment for forest ecosystem services in Vietnam. *Land Use Policy*, **81**(February 2019), 582-593, doi:10.1016/j.landusepol.2018.11.010.

Tollefson, J., 2020: Why deforestation and extinctions make pandemics more likely. *Nature*, **584**, 175-176, doi:10.1038/d41586-020-02341-1.

Tomasella, J. et al., 2018: Desertification trends in the Northeast of Brazil over the period 2000–2016. *International Journal of Applied Earth Observation and Geoinformation*, **73**, 197-206, doi:10.1016/j.jag.2018.06.012.

Tomby, S. and J. Zhang, 2018: Impacts of Climate Change: Floods and Guyana Sugar Industry. *International Journal of Scientific and Research Publications*, **8**(2), 479-486.

Tomby, S. and J. Zhang, 2019: Vulnerability assessment of Guyanese sugar to floods. *Climatic Change*, **154**(1), 179-193, doi:10.1007/s10584-019-02412-x.

Toro-Mujica, P., C. Aguilar, R. R. Vera and F. Bas, 2017: Carbon footprint of sheep production systems in semi-arid zone of Chile: A simulation-based approach of productive scenarios and precipitation patterns. *Agricultural Systems*, **157**, 22-38, doi:10.1016/j.agsy.2017.06.012.

Torres, R. et al., 2015: Vulnerability and resistance to neoliberal environmental changes: An assessment of agriculture and forestry in the Biobio region of Chile (1974–2014). *Geoforum*, **60**, 107-122, doi:10.1016/j.geoforum.2014.12.013.

Torres, R. and M. Peralvo, 2019: *Dinámicas Territoriales en el Chocó Andino del Distrito Metropolitano de Quito: Estado actual, tendencias y estrategias para la conservación, restauración y uso sostenible*. Consorcio para el Desarrollo Sostenible de la Ecorregión Andina (CONDESAN), Secretaría de Ambiente del MDMQ y Fundación Imaymana, Quito, Ecuador.

Tovar, C., C. A. Arnillas, F. Cuesta and W. Buytaert, 2013: Diverging responses of tropical Andean biomes under future climate conditions. *PloS one*, **8**(5), e63634, doi:10.1371/journal.pone.0063634.

Trotman, A. et al., 2018: *Fortalecimiento de los servicios climáticos para el sector de la salud en el Caribe*. **67**, World Meteorological Organization, 14-19 pp. Available at: https://public.wmo.int/es/resources/bulletin/fortalecimiento-de-los-servicios-clim%C3%A1ticos-para-el-sector-de-la-salud-en-el (accessed 10/08/2021).

Trujillo, L. et al., 2020: Respiração do solo e dinâmica da liteira fina em Terra Preta de Índio e solos adjacentes, na Amazônia Central. *Revista Brasileira De Ciências Da Amazônia*, **9**(4), 07-20, doi:10.47209/2317-5729.v.9.n.4.p.07-20.

Úbeda, X. and P. Sarricolea, 2016: Wildfires in Chile: A review. *Global and Planetary Change*, **146**, 152-161, doi:10.1016/j.gloplacha.2016.10.004.

Ugarte-Avilés, T., C. Manterola, R. Cartes-Velásquez and T. Otzen, 2017: Impact of proximity of thermoelectric power plants on bronchial obstructive crisis rates. *BMC Public Health*, **17**(1), 96, doi:10.1186/s12889-016-4008-7.

Ulla, T., 2016: El Niño floods in Argentina: A story of displacement and vulnerability. In: *The State of Environmental Migration 2016: A review of 2015* [Gemenne, F., C. Zickgraf and D. Ionesco (eds.)]. Presses Universitaires de Liège, Liège, Belgium, pp. 123-147.
Ulloa, A., 2019: Indigenous Knowledge Regarding Climate in Colombia: Articulations and Complementarities among Different Knowledges. In: *Climate and Culture: Multidisciplinary Perspectives on a Warming World* [Arnall, A., G. Feola and H. Geoghegan (eds.)]. Cambridge University Press, Cambridge, pp. 68-92. ISBN 9781108422505.
Ulpiani, G., 2021: On the linkage between urban heat island and urban pollution island: Three-decade literature review towards a conceptual framework. *Science of The Total Environment*, **751**, 141727, doi:10.1016/j.scitotenv.2020.141727.
UN-Habitat, 2015: *Informal Settlements*. United Nations Human Settlements Programme, New York, N.Y., 9 pp. Available at: http://habitat3.org/wp-content/uploads/Habitat-III-Issue-Paper-22_Informal-Settlements-2.0.pdf (accessed 31/10/2020).
UN-Habitat, 2018: *Thematic guide: Addressing the Most Vulnerable First: Pro-Poor Climate Action in Informal Settlements*. United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenya, 60 pp. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/Pro-poor%20Climate%20Action%20in%20Informal%20Settlements%20-%20WEB.pdf (accessed 17/06/2021).
UN General Assembly, 2015: Transforming our world: the 2030 Agenda for Sustainable Development, 35 pp.
UNDESA, 2019: *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. United Nations, Department of Economic and Social Affairs, Population Division, New York, 103 pp. Available at: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf (accessed 24/09/2019).
UNDP, 2020: 2020 Human Development Report, United Nations Development Programme Available at: http://hdr.undp.org/en/data (accessed 20/05/2021).
UNEP-WCMC and IUCN, 2020a: Global Partnership on Aichi Target 11, UNEP-WCMC and IUCN, Cambridge, UK. Available at: https://www.protectedplanet.net/en/thematic-areas/global-partnership-on-aichi-target-11 (accessed 14/09/2020).
UNEP-WCMC and IUCN, 2020b: Protected Planet: The World Database on Protected Areas (WDPA) [Online], UNEP-WCMC and IUCN, Cambridge, UK. Available at: www.protectedplanet.net (accessed 24/10/2020).
UNEP-WCMC, WorldFish Centre, WRI and TNC, 2018: *Global distribution of warm-water coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project. Version 4.0. Includes contributions from IMaRS-USF and IRD (2005), IMaRS-USF (2005) and Spalding et al. (2001)*. UN Environment World Conservation Monitoring Centre, Cambridge, UK. Available at: http://data.unep-wcmc.org/datasets/1 (accessed 27/10/2020).
UNEP, 2015: *Aportes Legislativos de América Latina y el Caribe en Materia de Cambio Climático* [Ipenza Peralta, C. A. (ed.)]. UNEP, Ciudad de Panamá, Panamá, 162 pp. Available at: https://sinia.minam.gob.pe/documentos/aportes-legislativos-america-latina-caribe-materia-cambio-climatico (accessed 17/09/2019).
UNEP, 2018: *The Adaptation Gap Report 2018*. United Nations Environment Programme, Nairobi, Kenya, 104 pp. Available at: https://www.unep.org/resources/adaptation-gap-report-2018 (accessed 28/08/2021).
UNESCO, 2012: Documento de Sistematización: Proyecto de Fortalecimiento de Capacidades en los Sistemas de Alerta Temprana en América Central , desde una Perspectiva de Multiamenaza. 30 pp.
UNGRD, 2015: *Plan Nacional de Gestión del Riesgo de Desastres de Colombia*. Bogotá, 63 pp. Available at: http://portal.gestiondelriesgo.gov.co/Documents/PNGRD-2015-2025-Version-Preliminar.pdf (accessed 17/06/2021).
UNICEF and WHO, 2019: *Progress on household drinking water, sanitation and hygiene 2000-2017: Special focus on inequalities*. United Nations Children's Fund (UNICEF) and World Health Organization (WHO), 138 pp. Available at: https://www.who.int/water_sanitation_health/publications/jmp-report-2019/en/ (accessed 28/09/2020).
UNISDR and CEPREDENAC, 2014: *Informe Regional del Estado de la Vulnerabilidad y Riesgos de Desastres en Centroamérica*. UNISDR, Panama, 229 pp.
United Nations Environment Programme, 2021: *Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies*. UNEP, Nairobi, Kenya, 166 pp. Available at: https://www.unep.org/resources/making-peace-nature (accessed 25/08/2021).
Uribe Rivera, D., C. Vera Burgos, M. Paicho and G. Espinoza, 2017: Observatorio ecosocial para el seguimiento del cambio climático en ecosistemas de altura en la Región de Taracapá: Propuestas, avances y proyecciones. *Diálogo andino*, 63-82, doi:10.4067/S0719-26812017000300063.
Urquiza, A. and M. Billi, 2020a: *Seguridad hídrica y energética en América Latina y el Caribe: definición y aproximación territorial para el análisis de brechas y riesgos de la población*. CEPAL, Santiago, Chile, 130 pp. Available at: https://repositorio.cepal.org/bitstream/handle/11362/46408/1/S2000631_es.pdf (accessed 09/08/2021).
Urquiza, A. and M. Billi, 2020b: Water markets and social–ecological resilience to water stress in the context of climate change: an analysis of the Limarí Basin, Chile. *Environment, Development and Sustainability*, **22**(3), 1929-1951, doi:10.1007/s10668-018-0271-3.

Urrutia-Jalabert, R. et al., 2018: Climate variability and forest fires in central and south-central Chile. *Ecosphere*, **9**(4), e02171, doi:10.1002/ecs2.2171.
Urrutia-Jalabert, R. et al., 2015: Environmental correlates of stem radius change in the endangered Fitzroya cupressoides forests of southern Chile. *Agricultural and Forest Meteorology*, **200**, 209-221, doi:10.1016/j.agrformet.2014.10.001.
Urrutia, J. et al., 2018: Hydrogeology and sustainable future groundwater abstraction from the Agua Verde aquifer in the Atacama Desert, northern Chile. *Hydrogeology Journal*, **26**(6), 1989-2007, doi:10.1007/s10040-018-1740-3.
Urrutia, R. and M. Vuille, 2009: Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century. *Journal of Geophysical Research: Atmospheres*, **114**(D2), doi:10.1029/2008JD011021.
Valadares, R. G. and T. A. d. Cunha, 2018: The participation of cooperatives in housing public policies in Brazil and Uruguay. *Cadernos EBAPE.BR*, **16**(4), 667-678, doi:10.1590/1679-395167443
Valderrama, M. E., Á. I. Cadena Monroy and E. Behrentz Valencia, 2019: Challenges in greenhouse gas mitigation in developing countries: A case study of the Colombian transport sector. *Energy Policy*, **124**(C), 111-122.
Valdés-Pineda, R. et al., 2014: Water governance in Chile: Availability, management and climate change. *Journal of Hydrology*, **519**, 2538-2567, doi:10.1016/j.jhydrol.2014.04.016.
Valdivia, C. et al., 2010: Adapting to Climate Change in Andean Ecosystems: Landscapes, Capitals, and Perceptions Shaping Rural Livelihood Strategies and Linking Knowledge Systems. *Annals of the Association of American Geographers*, **100**(4), 818-834, doi:10.1080/00045608.2010.500198.
Vale, M. M. et al., 2021: Climate Change and Biodiversity in the Atlantic Forest: Best Climatic Models, Predicted Changes and Impacts, and Adaptation Options. In: *The Atlantic Forest: History, Biodiversity, Threats and Opportunities of the Mega-diverse Forest* [Marques, M. C. M. and C. E. V. Grelle (eds.)]. Springer International Publishing, Cham, pp. 253-267. ISBN 978-3-030-55322-7.
Vale, M. M., T. V. Souza, M. A. S. Alves and R. Crouzeilles, 2018: Planning protected areas network that are relevant today and under future climate change is possible: the case of Atlantic Forest endemic birds. *PeerJ*, **6**, e4689, doi:10.7717/peerj.4689.
Valente de Macedo, L. S., M. E. Barda Picavet, J. A. Puppim de Oliveira and W.-Y. Shih, 2021: Urban green and blue infrastructure: A critical analysis of research on developing countries. *Journal of Cleaner Production*, **313**, 127898, doi:10.1016/j.jclepro.2021.127898.
Vallet, A. et al., 2019: Linking equity, power, and stakeholders’ roles in relation to ecosystem services. *Ecology and Society*, **24**(2), doi:10.5751/ES-10904-240214.
van der Sleen, P. et al., 2015: No growth stimulation of tropical trees by 150 years of CO2 fertilization but water-use efficiency increased. *Nat. Geosci.*, **8**(1), 24-28, doi:10.1038/ngeo2313.
van Kerkhoff, L. et al., 2019: Towards future-oriented conservation: Managing protected areas in an era of climate change. *Ambio*, **48**(7), 699-713, doi:10.1007/s13280-018-1121-0.
Van Leeuwen, C. J., S. H. A. Koop and R. M. A. Sjerps, 2016: City Blueprints: baseline assessments of water management and climate change in 45 cities. *Environment, Development and Sustainability*, **18**(4), 1113-1128, doi:10.1007/s10668-015-9691-5.
Vannuccini, S. et al., 2018: Chapter 3: Understanding the impacts of climate change for fisheries and aquaculture: global and regional supply and demand trends and prospects 41 Stefania. In: *Impacts of climate change on fisheries and aquaculture Synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Barhi, M. C. M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations, Rome, pp. 41-61.
Vargas, J. et al., 2018a: *RED 2017. Urban growth and access to opportunities: a challenge for Latin America* [America, C. A. F. D. B. o. L. (ed.)]. Report on Economic Development (RED 2017), Bogotá, Colombia. ISBN 980-6810-01-5.
Vargas, R. et al., 2018b: Climate risk and food availability in Guatemala. *Environment and Development Economics*, **23**(5), 558-579, doi:10.1017/S1355770X18000335.
Vargas, X. et al. (eds.), Water availability in a mountainous Andean watershed under CMIP5 climate change scenarios. Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections Proceedings of H02, IAHS-IAPSO-IASPEI Assembly, July 2013, Gothenburg, Sweden, 33-38 pp.
Vauchel, P. et al., 2017: A reassessment of the suspended sediment load in the Madeira River basin from the Andes of Peru and Bolivia to the Amazon River in Brazil, based on 10years of data from the HYBAM monitoring programme. *Journal of Hydrology*, **553**, 35-48, doi:10.1016/j.jhydrol.2017.07.018.
Vaughan, C. et al., 2017: Creating an enabling environment for investment in climate services: The case of Uruguay's National Agricultural Information System. *Climate Services*, **8**, 62-71, doi:10.1016/j.cliser.2017.11.001.
Vázquez-Rowe, I., G. Larrea-Gallegos, P. Villanueva-Rey and A. Gilardino, 2017: Climate change mitigation opportunities based on carbon footprint estimates of dietary patterns in Peru. *PLOS ONE*, **12**(11), e0188182, doi:10.1371/journal.pone.0188182.
Veldkamp, T. I. E. et al., 2017: Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nature Communications*, **8**(1), 15697, doi:10.1038/ncomms15697.
Vemado, F. and A. J. Pereira Filho, 2016: Severe Weather Caused by Heat Island and Sea Breeze Effects in the Metropolitan Area of São Paulo, Brazil. *Advances in Meteorology*, **2016**, 13, doi:10.1155/2016/8364134.

Venegas-González, A., F. R. Juñent, A. G. Gutiérrez and M. T. Filho, 2018a: Recent radial growth decline in response to increased drought conditions in the northernmost Nothofagus populations from South America. *Forest Ecology and Management*, **409**, 94-104, doi:10.1016/j.foreco.2017.11.006.
Venegas-González, A. et al., 2018b: Efecto de la variabilidad climática sobre los patrones de crecimiento y establecimiento de Nothofagus macrocarpa en Chile central *Bosque*, **39**(1), 81-93, doi:10.4067/S0717-92002018000100081.
Venerus, L. A. and P. V. Cedrola, 2017: Review of marine recreational fisheries regulations in Argentina. *Marine Policy*, **81**, 202-210, doi:10.1016/j.marpol.2017.03.007.
Vera, C. S. and L. Díaz, 2015: Anthropogenic influence on summer precipitation trends over South America in CMIP5 models. *International Journal of Climatology*, **35**(10), 3172-3177, doi:10.1002/joc.4153.
Verba, J. T., M. G. Pennino, M. Coll and P. F. M. Lopes, 2020: Assessing drivers of tropical and subtropical marine fish collapses of Brazilian Exclusive Economic Zone. *Science of The Total Environment*, **702**, 134940, doi:10.1016/j.scitotenv.2019.134940.
Vergara, A., 2018: Latin America's Shifting Politics: Virtue, Fortune, and Failure in Peru. *Journal of Democracy*, **29**(4), 65-76, doi:10.1353/jod.2018.0063.
Vergara, W. et al., 2007: Economic impacts of rapid glacier retreat in the Andes. *Eos, Transactions American Geophysical Union*, **88**(25), 261-264, doi:10.1029/2007EO250001.
Vergara, W., A. R. Rios, P. Trapido and H. Malarín, 2014: *Agriculture and Future Climate in Latin America and the Caribbean: Systemic Impacts and Potential Responses*. Discussion Paper Climate Change and Sustainability Division, **IDB-DP-329**, 1-20 pp. Available at: https://www.uncclearn.org/wp-content/uploads/library/idb40.pdf (accessed 31/10/2020).
Vicente-Serrano, S. M. et al., 2018: Recent changes in monthly surface air temperature over Peru, 1964–2014. *International Journal of Climatology*, **38**(1), 283-306, doi:10.1002/joc.5176.
Vicuña, S. et al., 2013: Exploring possible connections between hydrological extreme events and climate change in central south Chile. *Hydrological Sciences Journal*, **58**(8), 1598-1619, doi:10.1080/02626667.2013.840380.
Vidal Merino, M., D. Sietz, F. Jost and U. Berger, 2019: Archetypes of Climate Vulnerability: a Mixed-method Approach Applied in the Peruvian Andes. *Climate and Development*, **11**(5), 418-434, doi:10.1080/17565529.2018.1442804.
VIDECI, 2017: *Programa Nacional de Gestión de Riesgos de Bolivia*. 44 pp. Available at: http://www.defensacivil.gob.bo/web/uploads/pdfs/PNGRD2017.pdf (accessed 17/06/2021).
Vieira, R. M. S. P. et al., 2015: Identifying areas susceptible to desertification in the Brazilian northeast. *Solid Earth*, **6**(1), 347-360, doi:10.5194/se-6-347-2015.
Viguera, B. et al., 2019: Percepciones de cambio climático y respuestas adaptativas de caficultores costarricenses de pequeña escala. *Agronomía Mesoamericana*, **30**, 333-351.
Villafuerte, J., J. Rodriguez, K. Limones and L. Pérez, 2018: Adaptación autónoma al cambio climático: experiencias de emprendimientos rurales de Ecuador. *Letras Verdes. Revista Latinoamericana de Estudios Socioambientales*, **24**, 57-82, doi:10.17141/letrasverdes.24.2018.3273.
Villamizar, A. et al., 2017: Climate adaptation in South America with emphasis in coastal areas: the state-of-the-art and case studies from Venezuela and Uruguay. *Climate and Development*, **9**(4), 364-382, doi:10.1080/17565529.2016.1146120.
Vincenti-Gonzalez, M. F., A. Tami, E. F. Lizarazo and M. E. Grillet, 2018: ENSO-driven climate variability promotes periodic major outbreaks of dengue in Venezuela. *Scientific Reports*, **8**(1), 5727, doi:10.1038/s41598-018-24003-z.
Vitriol, V. et al., 2014: Respuesta de los centros de atención primaria en salud mental después del terremoto y tsunami del 2010 en la Región del Maule. *Revista médica de Chile*, **142**(9), 1120-1127, doi:10.4067/S0034-98872014000900005.
Viviroli, D. et al., 2020: Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, doi:10.1038/s41893-020-0559-9.
Vogt, N. et al., 2016: Local ecological knowledge and incremental adaptation to changing flood patterns in the Amazon delta. *Sustainability Science*, **11**(4), 611-623, doi:10.1007/s11625-015-0352-2.
Vörösmarty, C. J. et al., 2013: Extreme rainfall, vulnerability and risk: a continental-scale assessment for South America. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **371**(2002), 20120408, doi:10.1098/rsta.2012.0408.
Vuille, M. et al., 2018: Rapid decline of snow and ice in the tropical Andes – Impacts, uncertainties and challenges ahead. *Earth-Science Reviews*, **176**, 195-213, doi:10.1016/j.earscirev.2017.09.019.
Vuille, M. et al., 2015: Impact of the global warming hiatus on Andean temperature. *Journal of Geophysical Research: Atmospheres*, **120**(9), 3745-3757, doi:10.1002/2015JD023126.
Walker, B. J. A., W. N. Adger and D. Russel, 2014a: Institutional barriers to climate change adaptation in decentralised governance structures: Transport planning in England. *Urban Studies*, **52**(12), 2250-2266, doi:10.1177/0042098014544759.
Walker, W. et al., 2014b: Forest carbon in Amazonia: the unrecognized contribution of indigenous territories and protected natural areas. *Carbon Management*, **5**(5-6), 479-485, doi:10.1080/17583004.2014.990680.

Walshe, R. and A. Argumedo, 2016: Ayni, Ayllu, Yanantin and Chanincha: The Cultural Values Enabling Adaptation to Climate Change in Communities of the Potato Park, in the Peruvian Andes. *GAIA*, **25**(3), 166-173, doi:10.14512/gaia.25.3.7.
Wamsler, C. et al., 2020: Environmental and climate policy integration: Targeted strategies for overcoming barriers to nature-based solutions and climate change adaptation. *Journal of Cleaner Production*, **247**, 119154, doi:10.1016/j.jclepro.2019.119154.
Wang, C.-J., J.-Z. Wan and Z.-X. Zhang, 2017a: Expansion potential of invasive tree plants in ecoregions under climate change scenarios: an assessment of 54 species at a global scale. *Scandinavian Journal of Forest Research*, **32**(8), 663-670, doi:10.1080/02827581.2017.1283049.
Wang, G. et al., 2017b: Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nature Climate Change*, **7**(8), 568-572, doi:10.1038/nclimate3351.
Warn, E. and S. B. Adamo, 2014: *The impact of climate change: migration and cities in South America*. World Meteorological Organization **63**.
Warner, B. P., 2016: Understanding actor-centered adaptation limits in smallholder agriculture in the Central American dry tropics. *Agriculture and Human Values*, **33**(4), 785-797, doi:10.1007/s10460-015-9661-4.
Warner, K. and T. Afifi, 2014: Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. *Climate and Development*, **6**(1), 1-17, doi:10.1080/17565529.2013.835707.
Warren, R. et al., 2018: The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Climatic Change*, **147**(3), 395-409, doi:10.1007/s10584-018-2158-6.
Warszawski, L. et al., 2013: A multi-model analysis of risk of ecosystem shifts under climate change. *Environmental Research Letters*, **8**(4), 044018, doi:10.1088/1748-9326/8/4/044018.
Watanabe, M., 2015: *Gestión del riesgo de desastres en ciudades de América Latina*. Apuntes de investigación, Practical Action, Perú, 17 pp. Available at: https://solucionespracticas.org.pe/Gestion-del-riesgo-de-desastres-en-ciudades-de-America-Latina (accessed 17/06/2021).
Watts, N. et al., 2018: The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *The Lancet*, **391**(10120), 581--630, doi:10.1016/ S0140-6736(17)32464-9.
Waylen, K. A. et al., 2015: Can scenario-planning support community-based natural resource management? Experiences from three countries in Latin America. *Ecology and Society*, **20**(4), doi:10.5751/ES-07926-200428.
Weatherdon, L. V. et al., 2016: Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. *Frontiers in Marine Science*, **3**, 48.
Webb, M. F. et al., 2016: Exploring mechanisms of food insecurity in indigenous agricultural communities in Guatemala: a mixed methods study. *BMC Nutrition*, **2**(1), 55, doi:10.1186/s40795-016-0091-5.
Webb, M. J. et al., 2020: Water, agriculture, and climate dynamics in central Chile's Aconcagua River Basin. *Physical Geography*, 1-21, doi:10.1080/02723646.2020.1790719.
Welz, J. and K. Krellenberg, 2016: Vulnerabilidad frente al cambio climático en la Región Metropolitana de Santiago de Chile: Posiciones teóricas versus evidencias empíricas. *Eure*, **42**(125), 251-272, doi:10.4067/S0250-71612016000100011.
Welz, J., A. Schwarz and K. Krellenberg, 2014: Understanding Hazard Exposure for Adaptation in a Climate Change Context. In: *Climate Adaptation Santiago* [Krellenberg, K. and B. Hansjürgens (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 127-147. ISBN 978-3-642-39103-3.
WFP, 2014: *Seguridad Alimentaria, Desastres y Cambio Climático en la Región Andina, factores que contribuyen a la vulnerabilidad de la población ante la Inseguridad Alimentaria en Relación a los Riesgos de Desastres y el Cambio Climático*. World Food Programme, 1 pp. Available at: https://cdn.wfp.org/wfp.org/publications/andean_map_final_es_96px.pdf (accessed 03/09/2021).
Whitlock, C. et al., 2015: Past and Present Vulnerability of Closed-Canopy Temperate Forests to Altered Fire Regimes: A Comparison of the Pacific Northwest, New Zealand, and Patagonia. *BioScience*, **65**(2), 151-163, doi:10.1093/biosci/biu194.
WHO, 2017: *Financing universal Water, Sanitation and Hygiene under the Sustainable Development Goals - GLAAS 2017 report*. UN-Water global analysis and assessment of sanitation and drinking-water (GLAAS): 2017 report, **220**, World Health Organization (WHO), Geneva, 96 pp. Available at: http://www.who.int/water_sanitation_health/publications/glaas-report-2017/en/ (accessed 17/09/2019).
WHO and UNFCCC, 2015: *Climate and health country profile – 2015 Colombia*. World Health Organization and United Nations Framework Convention on Climate Change, 8 pp. Available at: https://apps.who.int/iris/bitstream/handle/10665/208859/WHO_FWC_PHE_EPE_15.05_eng.pdf?sequence=1 (accessed 17/06/2021).
WHO and UNFCCC, 2020: *Health & Climate Change: Country profile 2020 - Guyana. Small Island Developing States Initiative*. World Health Organization and United Nations Framework Convention on Climate Change,, 17 pp. Available at: https://cdn.who.int/media/docs/default-source/climate-change/who-unfccc-cch-country-profile-guyana.pdf?sfvrsn=7fd8e6db_2&download=true (accessed 25/06/2021).
WHO and WMO, 2012: *Atlas of health and climate*. World Health Organization and World Meteorological Organization, Geneva, 68 pp. Available at: https://www.who.int/globalchange/publications/atlas/report/en/ (accessed 17/06/2021).

WHO and WMO, 2016: *Climate Services for Health: Improving public health decision-making in a new climate*. World Health Organization (WHO) and World Meteorological Organization, Geneva, 218 pp. pp.
Wiegant, D., M. Peralvo, P. van Oel and A. Dewulf, 2020: Five scale challenges in Ecuadorian forest and landscape restoration governance. *Land Use Policy*, **96**, 104686, doi:10.1016/j.landusepol.2020.104686.
Wilbanks, T. J. and R. W. Kates, 2010: Beyond Adapting to Climate Change: Embedding Adaptation in Responses to Multiple Threats and Stresses. *Annals of the Association of American Geographers*, **100**(4), 719 - 728, doi:10.1080/00045608.2010.500200.
Wilbanks, T. J. et al., 2007: Industry, settlement and society. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, pp. 357-390.
Wilson, R. et al., 2018: Glacial lakes of the Central and Patagonian Andes. *Global and Planetary Change*, **162**, 275-291, doi:10.1016/j.gloplacha.2018.01.004.
Wiltshire, A. (ed.), Developing early warning systems: a checklist. Third International Conference on Early Warning: From concept to action 27-29 March 2006, Bonn, Germany.
Wimberly, M. C., K. M. de Beurs, T. V. Loboda and W. K. Pan, 2021: Satellite Observations and Malaria: New Opportunities for Research and Applications. *Trends in parasitology*, **37**(6), 525-537, doi:10.1016/j.pt.2021.03.003.
Winckler, P. et al., 2017: El temporal del 8 de agosto de 2015 en las regiones de Valparaíso y Coquimbo, Chile Central. *Latin American Journal of Aquatic Research*, **45**(4), 622-648, doi:10.3856/vol45-issue4-fulltext-1.
Winklerprins, A., 2009: Sweep and Char and the Creation of Amazonian Dark Earths in Homegardens. In: *Amazonian Dark Earths: Wim Sombroek's Vision* [Woods, W. I., W. G. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins and L. Rebellato (eds.)]. Springer Netherlands, Dordrecht, pp. 205-211. ISBN 978-1-4020-9031-8.
WMO, 2014: *Health Exemplar to the User Interface Platform of the Global Framework for Climate Services*. World Meteorological Organization (WMO), Geneva, Switzerland, 72 pp. Available at: https://gfcs.wmo.int/sites/default/files/Priority-Areas/Health/GFCS-HEALTH-EXEMPLAR-FINAL-14152_en.pdf (accessed 17/06/2021).
Wong, K. V., A. Paddon and A. Jimenez, 2013: Review of World Urban Heat Islands: Many Linked to Increased Mortality. *Journal of Energy Resources Technology*, **135**(2), 022101, doi:10.1115/1.4023176.
Woods, W. I. and J. M. McCann (eds.), The anthropogenic origin and persistence of Amazonian dark earths. Conference of Latin Americanist Geographers, 1999, University of Texas Press, 7-14 pp.
World Bank, 2014: *Bogota Disaster Vulnerability Reduction Project in Support on the Second Phase of the Disaster Vulnerability Reduction Program*. 67 pp. Available at: https://documents.worldbank.org/curated/en/474671468261324583/pdf/ICR29520P0857270Box385299B00OUO090.pdf (accessed 03/06/2021).
World Bank, 2021: *Climate Change Action Plan 2021-2015: Supporting Green, Resilient, and Inclusive Development*. The World Bank Group, Washington DC, United States, 49 pp. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/35799/CCAP-2021-25.pdf?sequence=2&isAllowed=y (accessed 25/08/2021).
World Bank Group, 2015: *Community-led Partnerships for Resilience*. Global Facility for Disaster Reduction and Recovery, Washington D.C., United States of America, 72 pp. Available at: https://huairou.org/wp-content/uploads/2015/12/WBGFDRR_S.GuptaCommunity_led_partnership_JUNE24_1lowres-1_0.pdf (accessed 01/09/2021).
Wrathall, D. J. and N. Suckall, 2016: Labour migration amidst ecological change. *Migration and Development*, **5**(2), 314-329, doi:10.1080/21632324.2015.1022967.
Wu, X. et al., 2019: Investigating Surface Urban Heat Islands in South America Based on MODIS Data from 2003–2016. *Remote Sensing*, **11**(10), doi:10.3390/rs11101212.
Wu, Y. and L. M. Polvani, 2017: Recent trends in extreme precipitation and temperature over Southeastern South America: The dominant role of stratospheric ozone depletion in the CESM large ensemble. *Journal of Climate*, **30**(16), 6433-6441, doi:10.1175/JCLI-D-17-0124.1.
WWAP, 2018: *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. UNESCO, Paris, France, 139 pp. ISBN 978-92-3-100264-9.
WWAP, 2020: *United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO, Paris, France, 219 pp. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en (accessed 01/11/2020).
Yamamoto, L., D. A. Serraglio and F. d. S. Cavedon-Capdeville, 2018: Human mobility in the context of climate change and disasters: a South American approach. *International Journal of Climate Change Strategies and Management*, **10**(1), 65-85, doi:10.1108/IJCCSM-03-2017-0069.
Yamin, L. E., F. Ghesquiere, O. D. Cardona and M. G. Ordaz, 2013: *Modelación probabilista para la gestión del riesgo de desastre - El caso de Bogotá, Colombia*. Banco Mundial and Universidad de los Andes, Bogotá, 183 pp. Available at: https://www.gfdrr.org/sites/default/files/publication/modelacionprobabilistaparalagestiondelriesgodedesastre_elcasodebogotacolombia_reduced.pdf (accessed 03/06/2021).

Yang, J. et al., 2018: Amazon drought and forest response: Largely reduced forest photosynthesis but slightly increased canopy greenness during the extreme drought of 2015/2016. *Global Change Biology*, **24**(5), 1919-1934, doi:10.1111/gcb.14056.
Yeni, F. and H. Alpas, 2017: Vulnerability of global food production to extreme climatic events. *Food Research International*, **96**, 27-39, doi:10.1016/j.foodres.2017.03.020.
Yevenes, M. A., R. Figueroa and O. Parra, 2018: Seasonal drought effects on the water quality of the Biobío River, Central Chile. *Environmental Science and Pollution Research*, **25**(14), 13844-13856, doi:10.1007/s11356-018-1415-6.
Young, K. R., A. G. Ponette-González, M. H. Polk and J. K. Lipton, 2017: Snowlines and Treelines in the Tropical Andes. *Annals of the American Association of Geographers*, **107**(2), 429-440, doi:10.1080/24694452.2016.1235479.
Yu, D., Y. Liu, P. Shi and J. Wu, 2019: Projecting impacts of climate change on global terrestrial ecoregions. *Ecological Indicators*, **103**, 114-123, doi:10.1016/j.ecolind.2019.04.006.
Zador, M. et al., 2015: *Tropical Andes Biodiversity Hotspot. Ecosystem Profile Technical Summary*. NatureServe and EcoDecisión, 1-53 pp. Available at: https://www.cepf.net/sites/default/files/tropical_andes_profile_final_4_2015.pdf (accessed 29/06/2021).
Zalakeviciute, R., Y. Rybarczyk, J. López-Villada and M. V. Diaz Suarez, 2018: Quantifying decade-long effects of fuel and traffic regulations on urban ambient PM2.5 pollution in a mid-size South American city. *Atmospheric Pollution Research*, **9**(1), 66-75, doi:10.1016/j.apr.2017.07.001.
Zalles, J. I., 2018: Turismo basado en naturaleza y conservación biológica: decisiones de uso de suelo en Mindo. *Letras Verdes. Revista Latinoamericana de Estudios Socioambientales*, **23**, 178-198, doi:10.17141/letrasverdes.23.2018.2861.
Zambrano, F., M. Lillo-Saavedra, K. Verbist and O. Lagos, 2016: Sixteen Years of Agricultural Drought Assessment of the BioBío Region in Chile Using a 250 m Resolution Vegetation Condition Index (VCI). *Remote Sensing*, **8**(6), doi:10.3390/rs8060530.
Zambrano, L., R. Pacheco-Muñoz and T. Fernández, 2017: A spatial model for evaluating the vulnerability of water management in Mexico City, Sao Paulo and Buenos Aires considering climate change. *Anthropocene*, **17**, 1-12, doi:10.1016/j.ancene.2016.12.001.
Zambrano, L. I. et al., 2012: Potential impacts of climate variability on Dengue Hemorrhagic Fever in Honduras, 2010. *Tropical Biomedicine*, **29**(4), 499-507.
Zamora, N., 2018: The Landslide Hazard Map of Bogota an Updating. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **XLII-4/W8**, 233-244, doi:10.5194/isprs-archives-XLII-4-W8-233-2018.
Zavaleta, C. et al., 2018: Multiple non-climatic drivers of food insecurity reinforce climate change maladaptation trajectories among Peruvian Indigenous Shawi in the Amazon. *PLOS ONE*, **13**(10), e0205714, doi:10.1371/journal.pone.0205714.
Zemp, M. et al., 2019: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, **568**(7752), 382-386, doi:10.1038/s41586-019-1071-0.
Zenghelis, D., A. Manley and J. Wdowin, 2020: *Public debt, public wealth and economic dynamics* [Cambridge, U. o. (ed.)]. Bennett Institute Working Paper, University of Cambridge, 14 pp. Available at: https://www.bennettinstitute.cam.ac.uk/publications/public-debt-public-wealth-and-economic-dynamics/ (accessed 25/08/2021).
Zenteno, J. S., P. F. Rosende, B. C. Manzur and I. S. Vega, 2021: Breast cancer incidence and the air pollution level in the communes of Chile: an ecological study. *Ecancermedicalscience*, **15**, 1191-1191, doi:10.3332/ecancer.2021.1191.
Zhang, Q. et al., 2021: Water dispersible colloids and related nutrient availability in Amazonian Terra Preta soils. *Geoderma*, **397**, 115103, doi:10.1016/j.geoderma.2021.115103.
Zhang, X. et al., 2015: Mapping Drought Risk (Wheat) of the World. In: *World Atlas of Natural Disaster Risk* [Shi, P. and R. Kasperson (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 227-242. ISBN 978-3-662-45430-5.
Zhao, Q. et al., 2019: The association between heatwaves and risk of hospitalization in Brazil: A nationwide time series study between 2000 and 2015. *PLOS Medicine*, **16**(2), e1002753, doi:10.1371/journal.pmed.1002753.
Zhao, W. et al., 2017: Climatic factors driving vegetation declines in the 2005 and 2010 Amazon droughts. *PLoS ONE*, **12**(4), 1-19, doi:10.1371/journal.pone.0175379.
Zhao, Y. et al., 2016: Detailed dynamic land cover mapping of Chile: Accuracy improvement by integrating multi-temporal data. *Remote Sensing of Environment*, **183**, 170-185, doi:10.1016/j.rse.2016.05.016.
Zilli, M. et al., 2020: The impact of climate change on Brazil's agriculture. *Science of The Total Environment*, **740**, 139384, doi:10.1016/j.scitotenv.2020.139384.
Zimmer, A. et al., 2018: Time lag between glacial retreat and upward migration alters tropical alpine communities. *Perspectives in Plant Ecology, Evolution and Systematics*, **30**, 89-102, doi:10.1016/j.ppees.2017.05.003.
Zimmerer, K. S., 2014: Conserving agrobiodiversity amid global change, migration, and nontraditional livelihood networks: the dynamic uses of cultural landscape knowledge. *Ecology and Society*, **19**(2), doi:10.5751/ES-06316-190201.

Zu Ermgassen, E. K. H. J. et al., 2018: Results from On-The-Ground Efforts to Promote Sustainable Cattle Ranching in the Brazilian Amazon. *Sustainability*, **10**(4), doi:10.3390/su10041301.

Zúñiga, F., M. Jaime and C. Salazar, 2021: Crop farming adaptation to droughts in small-scale dryland agriculture in Chile. *Water Resources and Economics*, **34**, 100176, doi:10.1016/j.wre.2021.100176.

Chapter 13: Europe

Coordinating Lead Authors: Birgit Bednar-Friedl (Austria), Robbert Biesbroek (The Netherlands), Daniela N. Schmidt (United Kingdom/Germany)

Lead Authors: Peter Alexander (United Kingdom), Knut Yngve Børsheim (Norway), Jofre Carnicer (Spain), Elena Georgopoulou (Greece), Marjolijn Haasnoot (Netherlands), Gonéri Le Cozannet (France), Piero Lionello (Italy), Oksana Lipka (Russian Federation), Christian Möllmann (Germany), Veruska Muccione (Switzerland/Italy), Tero Mustonen (Finland), Dieter Piepenburg (Germany), Lorraine Whitmarsh (United Kingdom)

Contributing Authors: Magnus Benzie (Sweden), Pam Berry (United Kingdom), Sara Burbi (United Kingdom), Erika Coppola (Italy), Mladen Domazet (Croatia), Frank Ewert (Germany), Federica Gasbarro (Italy), Matthias Gauly (Italy), François Gemenne (Belgium), Peter Greve (Austria/Germany), Ana Iglesias (Spain), Elizabeth Kendon (United Kingdom), Heidi Kreibich (Germany), Nikos Koutsias (Greece), Anna Laine-Petäjäkangas (Finland), Dimitris Lalas (Greece), Cristina Linares Gil (Spain), Danijela Markovic (Germany), Sadie McEvoy (Netherlands/Ireland), Ana Mijic (United Kingdom), Raya Muttarak (Austria/Thailand), Rita Nogherotto (Italy), Hans Orru (Estonia), Mark Parrington (United Kingdom), Jeff Price (United Kingdom), Kaisa Raitio (Sweden), Marta Guadalupe Rivera Ferre (Spain), Jan C. Semenza (Switzerland), Rubén Valbuena (United Kingdom), Michelle van Vliet (The Netherlands), Heidi Webber (Germany), Laura Wendling (Finland), Katherine Yates (United Kingdom), Monika Zurek (United Kingdom).

Chapter Scientists: Sadie McEvoy (The Netherlands/Ireland), Phoebe O'Brien (United Kingdom/Sweden)

Review Editors: Georg Kaser (Austria/Italy), Jose Manuel Moreno (Spain)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Where are we now?

Our current 1.1°C warmer world is already affecting natural and human systems in Europe (*very high confidence*[1]). Since AR5, there has been a substantial increase in detected or attributed impacts of climate change in Europe, including extreme events (*high confidence*). Compound hazards of warming and precipitation have become more frequent (*medium confidence*). Climate change has resulted in losses of and damages to people, ecosystems, food systems, infrastructure, energy and water availability, public health, and the economy (*very high confidence*) {13.1.4;13.2.1;13.3.1;13.4.1;13.5.1;13.6.1;13.7.1;13.8.1;13.10.1}.

As impacts vary both across and within European regions, sectors, and societal groups (*high confidence*), inequalities have deepened (*medium confidence*). Southern regions tend to be more negatively affected, while some benefits have been observed, alongside negative impacts in northern and central regions. Traditional lifestyles, for example in the European Arctic, are threatened already (*high confidence*). Poor households have lower capacity to adapt to, and recover from, impacts (*medium confidence*) {13.5.1;13.6.1;13.7.1;13.8.1.;13.8.2;13.10.1;Box 13.2}.

The range of options available to deal with climate-change impacts has increased in most of Europe since AR5 (*high confidence*). Growing public perception and adaptation knowledge in public and private sectors, increasing number of policy and legal frameworks, and dedicated spending on adaptation are all clear indications that the availability of options has expanded (*high confidence*). Information provision, technical measures, and government policies are the most common adaptation actions implemented. Nature-based solutions (NbS) that restore or recreate ecosystems, build resilience and produce synergies with adaptation and mitigation are increasingly used. Many cities are taking adaptation action, but with large differences in level of ambition and implementation (*high confidence*) {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.10.2;13.11.1;13.11.2;13.11.3}.

Observed adaptation actions are largely incremental with only a few examples of local transformative action; adaptation actions have demonstrated different degrees of effectiveness in reducing impacts and feasibility of implementation *(high confidence*). For example, adaptation actions such as flood defences and early warning systems have reduced flood damages and heat-related mortality in parts of Europe. Despite progress on adaptation, impacts are observed. Adaptation actions in the private sector are limited, with many businesses and regions remaining under-prepared. A gap remains between planning and implementation of adaptation action (*high confidence*) {13.2.2;13.5.2;13.6.2;13.7.2;13.11}.

What are the future risks?

Warming in Europe will continue to rise faster than the global mean, widening risk disparities across Europe in the 21st century (*high confidence*). Largely negative impacts are projected for southern regions (e.g., increased cooling needs and water demand, losses in agricultural production, and water scarcity) and some short-term benefits anticipated in the north (e.g. increased crop yields and forest growth) {13.1.4;13.2.1;13.3.1;13.4.1;13.5.1;13.6;13.7.1;13.10.2}.

Four key risks (KR) have been identified for Europe, with most becoming more severe at 2°C GWL compared to 1.5°C GWL in scenarios with low to medium adaptation (*high confidence*). From 3°C GWL and even with high adaptation, severe risks remain for many sectors in Europe (*high confidence*). Key risks are: mortality and morbidity of people and ecosystems disruptions due to heat (KR1: heat); loss in agricultural production due to combined heat and droughts (KR2: agriculture); water scarcity across sectors (KR3: water scarcity); impacts of floods on people, economies and infrastructure (KR4: flooding) {13.10.2}.

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

KR1: The number of deaths and people at risk of heat stress will increase two- to threefold at 3°C compared to 1.5°C GWL (*high confidenc*e). Risk consequences will become severe more rapidly in Southern and Western Central Europe and urban areas (*high confidence*). Thermal comfort hours during summer will decrease significantly (*high confidence*), by as much as 74% in Southern Europe at 3°C GWL. Above 3°C GWL, there are limits to the adaptation potential of people and existing health systems, particularly in Southern Europe and Eastern Europe and areas where health systems are under pressure (*high confidence*) {13.6.1;13.6.2;13.7.1;13.7.2;13.8.1;13.10.2.1}.

KR1: Warming will decrease suitable habitat space for current terrestrial and marine ecosystems and irreversibly change their composition, increasing in severity above 2°C GWL (*very high confidence*). Fire-prone areas are projected to expand across Europe, threatening biodiversity and carbon sinks (*medium confidence*). Adaptation actions, e.g. habitat restoration and protection, fire and forest management, and agroecology, can increase the resilience of ecosystems and their services. Trade-offs between adaptation and mitigation options (e.g., coastal infrastructure and Nature based Solutions) will result in risks for the integrity and function of ecosystems (*medium confidence*) {13.3.1;13.3.2;13.4.1;13.4.2;13.10.2.1; Cross-Chapter Box SLR in Chapter 3; Cross-Chapter Box NATURAL in Chapter 2}.

KR2: Due to a combination of heat and drought, substantive agricultural production losses are projected for most European areas over the 21st century, which will not be offset by gains in Northern Europe (*high confidence*). Yield losses for maize will reach 50% in response to 3°C GWL, especially in Southern Europe. Yields of some crops, e.g. wheat, may increase in Northern Europe when warming does not exceed 2°C (*medium confidence*). While irrigation is an effective adaptation option for agriculture, the ability to adapt using irrigation will be increasingly limited by water availability, especially in response to GWL above 3°C (*high confidence*) {13.5.1;13.5.2;13.10.2.2}.

KR3: Risk of water scarcity will become high at 1.5°C and very high at 3°C GWL in Southern Europe (*high confidence*) and increase from moderate to high in Western Central Europe (*medium confidence*). In Southern Europe, more than a third of the population will be exposed to water scarcity at 2°C GWL; under 3°C GWL, this risk will double, and significant economic losses in water and energy dependent sectors may arise (*medium confidence*). The risk of water scarcity is strongly increasing for Western Central and Southern Europe, and many cities under 3°C GWL. Adaptation becomes increasingly difficult at 3°C GWL and above, due to geophysical and technological limits; hard limits are *likely*[2] first reached in parts of Southern Europe {13.2.1;13.2.2;13.6.1;13.10.2.3}.

KR4: Due to warming, changes in precipitation and sea level rise, risks to people and infrastructures from coastal, riverine, and pluvial flooding will increase in Europe (*high confidence*). Risks of inundation and extreme flooding will increase with accelerating pace of sea level rise along Europe's coasts (*high confidence*). Above 3°C GWL, damage costs and people affected by precipitation and river flooding may double. Coastal flood damage is projected to increase at least 10-fold by the end of the 21st century, and even more or earlier with current adaptation and mitigation (*high confidence*). Sea level rise represents an existential threat for coastal communities and their cultural heritage, particularly beyond 2100 {13.2.1;13.2.2;13.6.2;13.10.2.4;Box 13.1; Cross-Chapter Box SLR in Chapter 3).

European cities are hotspots for multiple risks of increasing temperatures and extreme heat, floods, and droughts (*high confidence*). Warming beyond 2°C GWL is projected to result in widespread impacts on infrastructure and businesses (*high confidence*). These include increased risks for energy supply (*high confidence*) and transport infrastructure (*medium confidence*), increases in air conditioning needs (*very high confidence*), and high water demand (*high confidence*) {13.2.2;13.6.1;13.7.1;13.10.2}.

---

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

European regions are affected by multiple key risks, with more severe consequences in the south than in the north (*high confidence*). These risks may co-occur and amplify each other, but there is uncertainty about their interactions and their quantifications. There is *high confidence* that consequences for socio-economic and natural systems will be substantial; the number of people exposed to KRs and economic losses are projected to at least double at 3°C GWL compared to 1.5°C GWL (*medium confidence*); and increased risks are also projected for biodiversity and ecosystem services, such as carbon regulation. The risks resulting from changes in climatic and non-climatic drivers in many sectors is a key gap in knowledge (high confidence). This gap prevents the precise assessment of systemic risks, socio-ecological tipping points and limits to adaptation {13.10.2;13.10.3;13.10.4}.

Climate risks from outside Europe are emerging due to a combination of the position of European countries in the global supply chain and shared resources (*high confidence*). There is emerging evidence that climate risks in Europe may also impact financial markets, food production and marine resources beyond Europe. Exposure of European countries to interregional risks can be reduced by international governance and collaboration on adaptation in other regions (*medium confidence*){13.5.2;13.9.1; 13.9.2;13.11; Cross-Chapter Box INTEREG in Chapter16}.

What are the solutions, limits and opportunities of adaptation?

There is a growing range of adaptation options available today to deal with future climate risks (*high confidence*). Examples for adaptation to the key risks include: behavioural change combined with building interventions, space cooling and urban planning to manage heat risks (KR1); restoration, expansion and connection of protected areas for ecosystems, while generating adaptation and mitigation benefits for people (KR1: heat); irrigation, vegetation cover, changes in farming practices, crop and animal species, and shifting planting (KR2: agriculture); efficiency improvements, water storage, water reuse, early warning systems, and land use change (KR3: water scarcity); early warning systems, reserving space for water and ecosystem based adaptation, sediment or engineering based options, land use change and managed retreat (KR4: flooding). Nature-based solutions for flood protection and heat alleviation are themselves under threat from warming, extreme heat, drought and sea level rise (*high confidence*) {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.9.4;13.10.2;13.11}.

In many parts of Europe, existing and planned adaptation measures are not sufficient to avoid the residual risk, especially beyond 1.5°C GWL (*high confidence*). Residual risk can result in losses of habitat and ecosystem services, heat related deaths (KR1), crop failures (KR2), water rationing during droughts in SEU (KR3), and loss of land (KR4) (*medium confidence)*. At 3°C GWL and beyond, a combination of many, maybe even all, adaptation options are needed, including transformational changes, to reduce residual risk (*medium confidence*). {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.9.4;13.10.2;13.11}.

Although adaptation is happening across Europe, it is not implemented at the scale, depth and speed needed to avoid the risks (*high confidence*). Many sectors and systems, such as flood risk management, critical infrastructure and reforestation, are on self-reinforcing development paths that can result in lock-ins and prevent changes needed to reduce risks in the long term and achieve adaptation targets. Forward-looking and adaptive planning can avoid path-dependencies, maladaptation, and ensure timely action (*high confidence*). Monitoring climate change, socio-economic developments and progress on implementation is critical to assess if and when further actions are needed, and evaluating whether adaptation is successful {13.2.2;13.10.2;13.11.1;13.11.2;13.11.3;Cross-Chapter Box DEEP in Chapter 17}.

Systemic barriers constrain the implementation of adaptation options in vulnerable sectors, regions and societal groups (*high confidence*). Key barriers are limited resources, lack of private sector and citizens engagement, insufficient mobilisation of finance, lack of political leadership, and low sense of urgency. Most of the adaptation options to the key risks depend on limited water and land resources, creating competition and trade-offs, also with mitigation options and socio-economic developments (*high confidence*). Europe will face difficult decisions balancing these trade-offs. Novel adaptation options are pilot tested across Europe, but upscaling remains challenging. Prioritisation of options and transitions from incremental to transformational adaptation are limited due to vested interests, economic lock-ins, institutional path-dependencies, and prevalent practices, cultures, norms, and belief systems {13.11.1;13.11.2;13.11.3}.

Several windows of opportunity emerge to accelerate climate resilient development (CRD) (*medium confidence*). Such windows are either institutionalised (e.g. budget cycles, policy reforms and evaluations, infrastructure investment cycles), or open unexpectedly (e.g. extreme events, COVID-19 recovery programs). These windows can be used to accelerate action through mainstreaming and transformational actions (*medium confidence*). CRD is visible in European cities, particularly in green infrastructure, energy-efficient buildings and construction, and where co-benefits (e.g. to health, biodiversity) have been identified. Private sector adaptation takes place mostly in response to extreme events or regulatory, shareholder, or consumer pressures and incentives (*medium confidence*) {13.11.3; Box13.3;Cross-Chapter Box COVID in Chapter 7}.

Closing the adaptation gap requires moving beyond short-term planning and ensuring timely and adequate implementation (*high confidence*). Inclusive, equitable and just adaptation pathways are critical for climate resilient development. Such pathways require consideration of SDGs, gender, and Indigenous knowledge and local knowledge and practices. The success of adaptation will depend on our understanding of which adaptation options are feasible and effective in their local context (*high confidence*). Long lead times for nature-based and infrastructure solutions or planned relocation require implementation in the coming decade to reduce risks in time. To close the adaptation gap, political commitment, persistence and consistent action across scales of government, and upfront mobilization of human and financial capital is key (*high confidence*), even when the benefits are not immediately visible {13.2.2;13.8;13.11;Cross-Chapter Box GENDER in Chapter 18}.

13.1 Point of Departure

13.1.1 Introduction and Geographical Scope

This regional chapter on climate-change impacts, vulnerabilities and adaptations in Europe examines the impacts on the sectors, regions and vulnerable populations of Europe, assesses the causes of vulnerability, and analyses ways to adapt, thereby considering socio-economic developments, land use change, and other non-climatic drivers. Compared to AR5 and in the context of the Paris Agreement (2015), we have placed emphasis on the planned and implemented solutions, assessed their feasibility and effectiveness, considered the Sustainable Development Goals (SDG) and shared socioeconomic pathways (SSPs). Global warming level (GWL) refers to global climate change emissions relative to preindustrial levels, expressed as global surface air temperature (Chen et al., 2021, 1.6.2).

The chapter generally follows the overall structure of AR6 WGII. We first present our point of departure (13.1) followed by the key sectors, starting with water, as water is interconnected and of fundamental importance to subsequent sections (13.2-13.8). For each section, we assess the observed impacts and projected risks, solution space and adaptation options, and knowledge gaps. The solution space is defined as the space within which opportunities and constraints determine why, how, when, and who adapts to climate risks (Haasnoot et al., 2020a). Section 13.9 discusses impacts and adaptation beyond Europe, followed by the key risks for Europe (13.10). The chapter ends with an assessment of adaptation solution space, climate resilient development pathways, and SDGs (13.11), although recognizing that scientific literature on these aspects is only slowly beginning to emerge.

With the rapidly growing body of scientific literature since WGII AR5 (Callaghan et al., 2020) our assessment prioritized systematic reviews, meta-analyses, and synthesis papers and reports. Feasibility and effectiveness assessments used revised methods developed for the Special Report of Global warming of 1.5° (de Coninck et al., 2018; Singh et al., 2020). Protocols, as well as supporting material for figures and tables, can be found in the Supplementary Material.

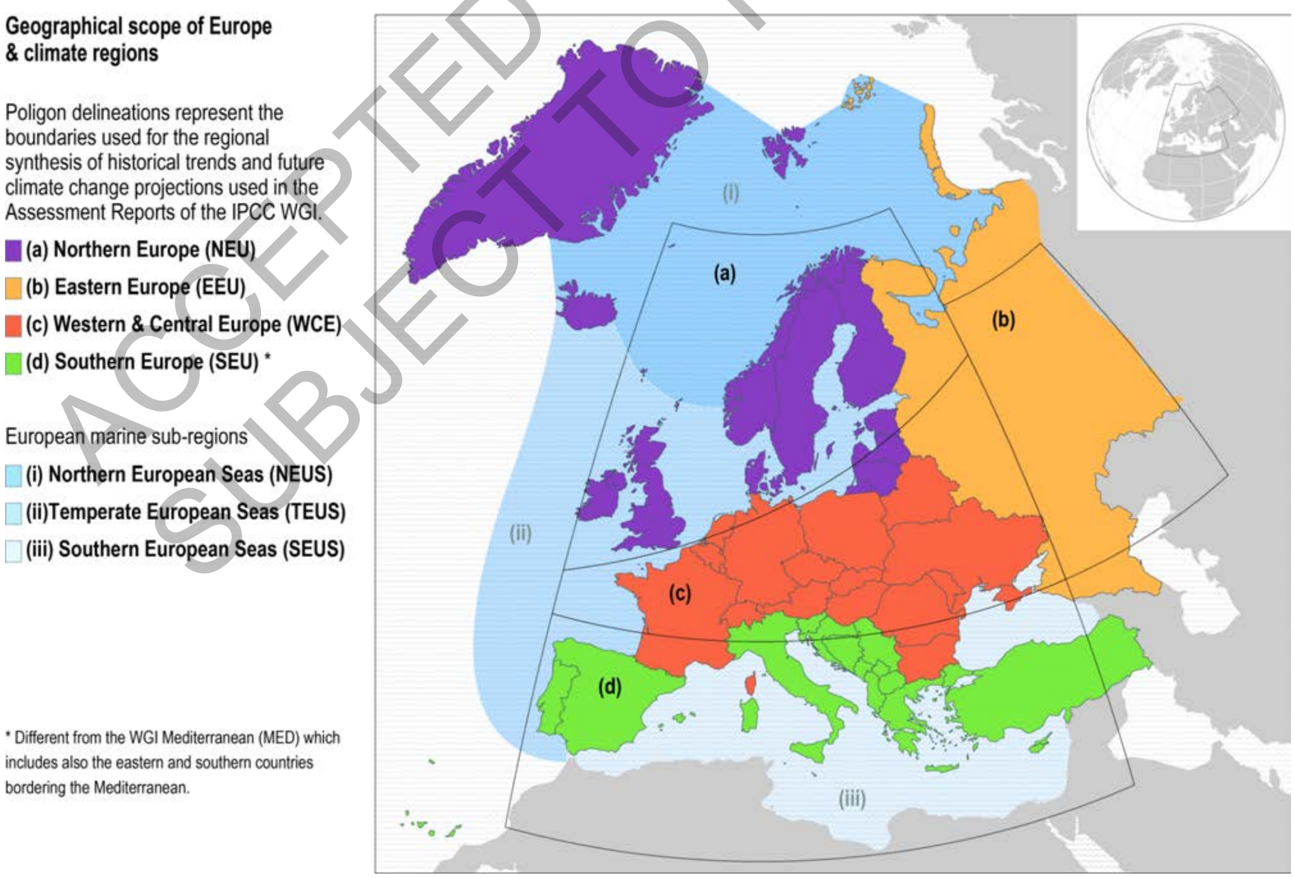


Figure 13.1: Geographical subdivision of land (a, b, c, d) and ocean (i, ii, iii) regions of Europe. The overlay represents the WGI AR6 subdivisions for climate-change projections of land, while the colour coding indicates the European

countries (or, in case of the Russian Federation, the European part of the country (EEU) used for this chapter. Note that for WGI AR6 region MED includes both southern Europe and northern Africa while this chapter only includes the northern (European) part of the MED region.

The geographical scope and subdivision of European land, coastal and ocean regions is largely the same as in WGII AR5 Chapter 23 (Kovats et al., 2014): Southern Europe (SEU), Western Central Europe (WCE), Eastern Europe (EEU) and Northern Europe (NEU). Note that WGI assesses a larger region for the Mediterranean (MED) which includes north Africa and the Middle East compared to the assessment in this chapter (SEU). The European part of the Arctic region is not systematically assessed here as it is extensively captured in Cross-Chapter Paper (CCP) 6. Information relevant to Europe is also synthesised in the CCPs, including European biodiversity hotspots (CCP 1), coastal cities and settlements (CCP 2), Mediterranean region (CCP 4) and mountains (CCP 5). European seas are broadly divided by latitude into (i) European Arctic waters (NEUS), (ii) European Temperate Seas (TEUS) and (iii) Southern Seas with the Mediterranean and Black Sea (SEUS) (Figure 13.1).

13.1.2 Socio-Economic Boundary Conditions

The adaptive capacity, as measured by GDP per capita, tends to be higher in northern and western parts of Europe (Figure 13.2a). In the last decades, climate change has led to substantial losses and damages to people and assets across Europe, mostly from riverine flooding, heatwaves, and storms (Figure 13.2b). Public concern about climate change, which is an indicator of the intention to mitigate and adapt, is particularly high in parts of Southern and Western Central Europe (Figure 13.2c). Current vulnerability to extreme weather and climatic events in European countries is low to moderate compared to the rest of the world (Figure 13.2d).

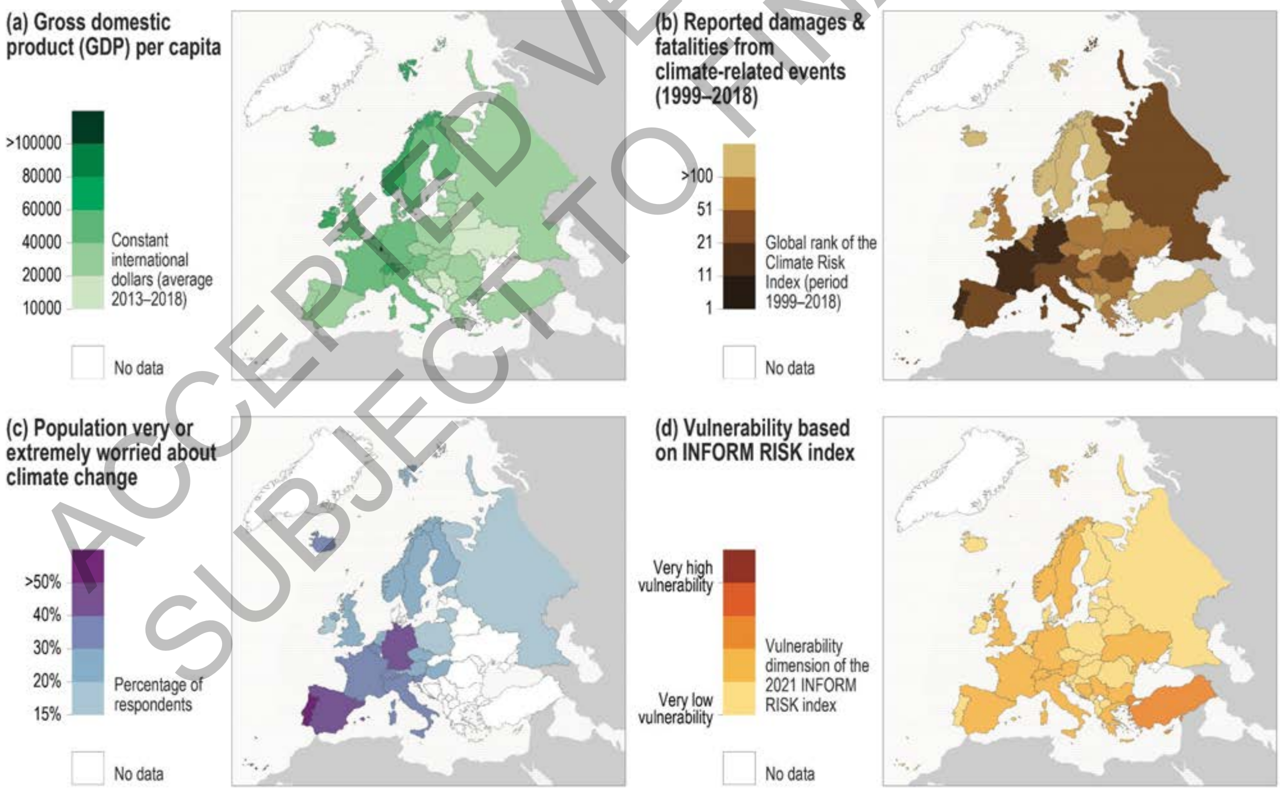


Figure 13.2: Indicators of reported damages to people and assets, vulnerability and adaptive capacity across European countries: (a) GDP per capita (average 2013-2018), in constant 2011 international dollars (WorldBank, 2020); (b) Exposure as measured by the global rank of the Climate Risk Index, which is based on economic damages and fatalities due to climate-related extreme weather events between 1999 and 2018 (Germanwatch, 2020); (c) Level of climate change concern among a representative weighted sample of residents 15 years and older in private households (European Social Survey, 2020) and (d) Vulnerability to disasters and humanitarian crisis in 2021; the index is based on socioeconomic factors (development, inequality, aid dependency) and vulnerable groups (DRMKC, 2020).

13.1.3 Impact Assessment of Climate Change based on Previous Reports

The main findings of previous reports, particularly the WGII AR5 (Kovats et al., 2014) and the Special Report of Global warming of 1.5°C GWL (Hoegh-Guldberg et al., 2018), highlighted the impacts of warming and rainfall variations and their extremes on Europe, particularly southern Europe and mountainous areas. At 2°C GWL, 9% of Europe's population was projected to be exposed to aggravated water scarcity, and 8% of the territory of Europe were characterized to have a high or very high sensitivity to desertification (UNEP/UNECE, 2016). These impacts are driven by changes in temperature, precipitation, irrigation developments, population growth, agricultural policies, and markets (EEA, 2017a). Heat is a main hazard for high-latitude ecosystems (Kovats et al., 2014; Jacob et al., 2018; Hock et al., 2019). The majority of mountain glaciers lost mass during the last two decades, and permafrost in the European Alps and Scandinavia is reducing (Hock et al., 2019). In central Europe, Scandinavia and Caucasus, mountain glaciers were projected to lose 60% to 80% of their mass by the end of the 21st century (Hock et al., 2019). The combined impacts on tourism, agriculture, forestry, energy, health and infrastructure were suggested to make southern Europe highly vulnerable and increase the risks of failures and vulnerability for urban areas (Kovats et al., 2014). Previous reports stated that the adaptive capacity in Europe is high compared to other regions of the world, but that there are also limits to adaptation from physical, social, economic, and technological factors. Evidence suggested that staying within 1.5°C GWL would strongly increase Europe's ability to adapt to climate change (de Conick and Revi, 2018).

13.1.4 European Climate: Main Conclusions of WGI AR6

Changes of several climatic impact-drivers have already emerged in all regions of Europe: increases in mean temperature and extreme heat and decreases of cold spells (Ranasinghe et al., 2021; Seneviratne et al., 2021). Lake and river ice has decreased in NEU, WCE and MED and sea ice in NEUS (Fox-Kemper et al., 2021; Ranasinghe et al., 2021). With increasing warming, confidence in projections is increasing for more drivers (Figure 13.3). Mean and maximum temperatures, frequencies of warm days and nights, and heat waves have increased since 1950, while the corresponding cold indices have decreased (*high confidence*) (Ranasinghe et al., 2021; Seneviratne et al., 2021). Average warming will be larger than the global mean in entire Europe, with largest winter warming in NEU and EEU and largest summer warming in the MED (*high confidence*) (Gutiérrez et al., 2021; Ranasinghe et al., 2021). An increase of hot days and a decrease of cold days are *very likely* (Figure 13.4.a,b). Projections suggest a substantial reduction of European ice glacier volumes and of snow cover below elevations of 1500-2000 m, as well as further permafrost thawing and degradation, during the 21st century even at a low GWL (*high confidence*) (Ranasinghe et al., 2021).

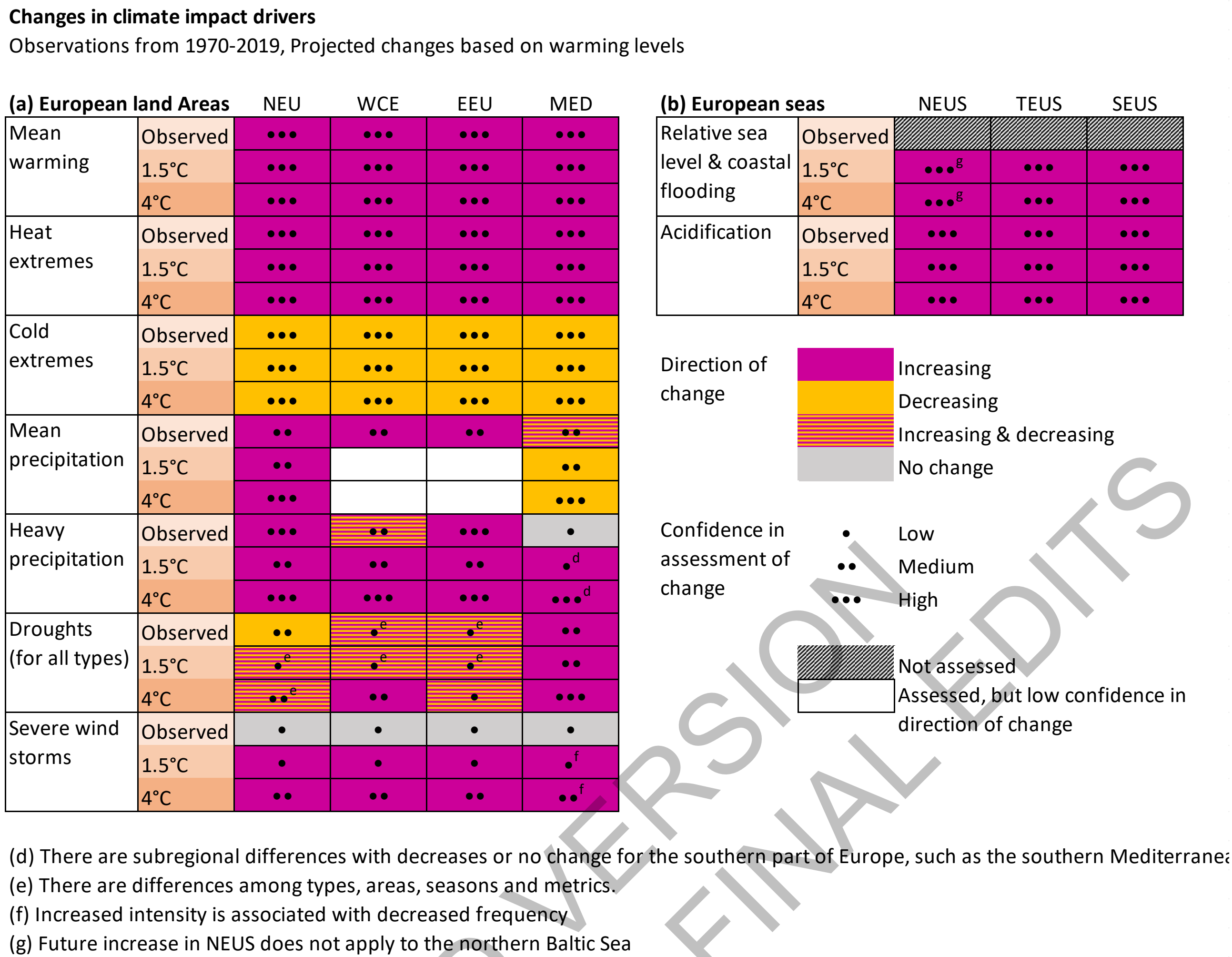


Figure 13.3: Observed and projected direction of change of climate impact drivers at 1.5°C and 4°C GWL for European sub-regions and European Seas (assessment from Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021)

The assessment of climate change in WGI AR 6 concludes that during recent decades mean precipitation has increased over NEU, WCE and EEU, while magnitude and sign of observed trends depend substantially on time period and study region in MED (*medium confidence*) (Douville et al., 2021; Gutiérrez et al., 2021; Ranasinghe et al., 2021). Precipitation extremes have increased in NEU, and EEU (*high confidence*) (Seneviratne et al., 2021), vary spatially in WCE (*medium confidence*), and have not changed in MED *(low confidence*). For >2°C GWL, of mean precipitation in NEU in winter is increasing and decreasing in MED in summer (*high confidence*). A widespread increase of precipitation extremes is projected for > 2°C GWL for all subregions (*high confidence)*, except for MED where no change or decrease is projected in some areas (Figure 13.4c,d, Gutiérrez et al., 2021; Ranasinghe et al., 2021). WGI assessed projections for meteorological, agricultural/ecological, hydrological drought (Ranasinghe et al., 2021) with *low confidence* in the direction of change in NEU, WCE, EEU at 1.5°C GWL. MED is projected to be most affected within Europe with all types of droughts increasing for 1.5°C (*medium confidence*) and 4°C GWL (*high confidence*). At 4°C GWL, hydrological droughts in NEU, WCE and EEU will increase (*medium confidence*). Projections for the 21[st] century show increases of storms across all Europe (*medium confidence*) for >2°C GWL with a decrease of their frequency in the MED (Ranasinghe et al., 2021).

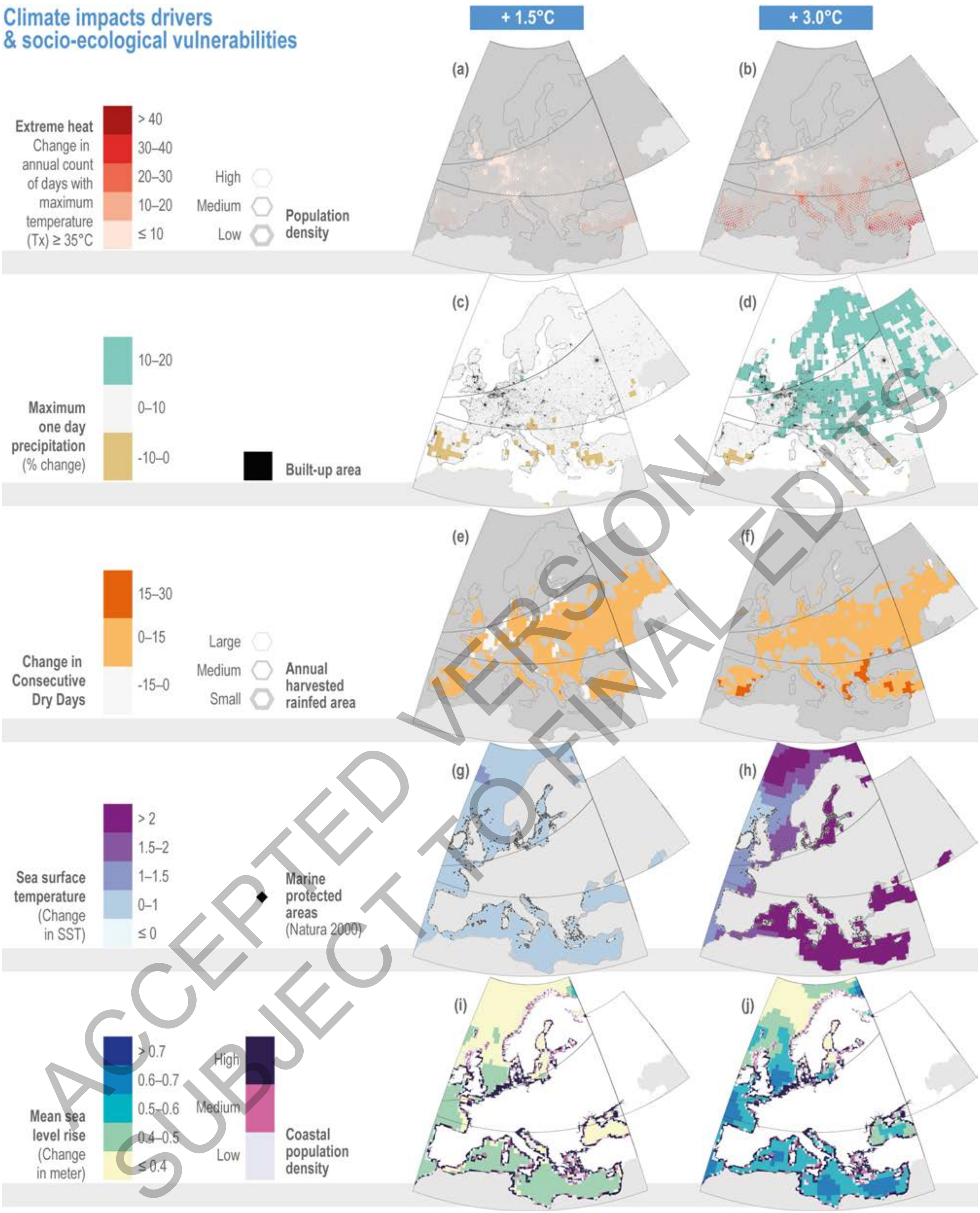


Figure 13.4: Changes of climate hazards with respect to the CMIP6 baseline (Gutiérrez et al., 2021) for global warming levels of 1.5°C and 3°C GWL and present exposure or vulnerability: (a,b) number of days with temperature maximum above 35°C (TX35) and population density (European Comission, 2019); (c,d) daily precipitation maximum (Rx1day) and built up area (JRCdatacatalogue, 2018); (e,f) consecutive dry days (CDD) and annual harvested rainfed area (Portmann et al., 2010); (g,h) sea surface temperature (TOS) and Marine Protected Areas (EEA, 2021b); and (k,l) sea level rise (SLR) and coastal population (Merkens et al., 2016). SLR data consider the long term period (2081-2100) and SSP1-2.6 for (i) and SSP3-7.0 for (j).

Sea surface warming between 0.25°C and 1°C has been observed in all regions over the last decades (*high confidence*) (Ranasinghe et al., 2021) and projected to continue increasing (*high confidence*), particularly in the SEUS and at the NEUS (Figure 13.4 g,h, Gutiérrez et al., 2021). Salinity has increased in the SEUS and decreased in northern European seas and projected to continue (*medium confidence*) (Fox-Kemper et al., 2021). European waters have been and will continue acidifying (*virtually certain*) (Eyring et al., 2021; Naik et al., 2021), resulting in a mean decrease of surface pH of about 0.1 and 0.3 pH units at 1.5°C and 3.0°C GWL with largest changes at high latitudes (Gutiérrez et al., 2021).

Relative sea level has risen along the European coastlines (Ranasinghe et al., 2021), regionally mitigated by post-glacial rise of land masses in Scandinavia (Fox-Kemper et al., 2021). SLR will *very likely* continue to increase during the 21st century (Figure 13.4 k,l) (*high confidence*), with regional deviations from global mean sea level rise (*low confidence*). Extreme water levels, coastal floods, and sandy coastline recession are projected to increase along many European coastlines (*high confidence*) (Ranasinghe et al., 2021).

13.2 Water

13.2.1 Observed Impacts and Projected Risks

13.2.1.1 Risk of Coastal Flooding and Erosion

Almost 50 million European citizens live within 10 m above mean sea level (Vousdoukas et al., 2020; McEvoy et al., 2021). Without further adaptation (section 13.2.2), flood risks along Europe's low-lying coasts and estuaries will increase due to sea level rise (SLR) compounded by storm surges, rainfall and river runoff (*high confidence*) (Mokrech et al., 2015; Arns et al., 2017; Sayol and Marcos, 2018; Vousdoukas et al., 2018a; Bevacqua et al., 2019; Couasnon et al., 2020). The population at risk of a 100-year flood event starts to rapidly increases beyond 2040 (Vousdoukas et al., 2018a) reaching 10 million people under RCP8.5 by 2100 but stays just below the 10 million under RCP2.6 by 2150 (Figure 13.5, Haasnoot et al., 2021b) assuming present population and protection. The number of people at risk is projected to increase and risk to materialise earlier particularly under SSP5 due to increasing population trends(Vousdoukas et al., 2018a; Haasnoot et al., 2021b). Under high rates of SLR resulting from rapid ice-sheet loss from Antarctica, risks may increase by a third by 2150 (Haasnoot et al., 2021b). Expected annual (direct) damages due to coastal flooding are projected to rise from €1.3 billion today to €13–39 billion by 2050 between 2°C and 2.5°C GWL and €93–960 billion by 2100 between 2.5° and 4.4°C GWL, largely depending on socio-economic developments (Cross-Chapter Box SLR in Chapter 3, Vousdoukas et al., 2018a) (*high confidence* in the sign; *low confidence* in the numbers). UNESCO World Heritage sites in the coastal zone are at risk due to SLR, coastal erosion and flooding (CCP4, Section 13.8.1.3, Marzeion and Levermann, 2014; Reimann et al., 2018b) as are coastal landfills and other key infrastructure in Europe (AR6/SROCC, Brand et al., 2018; Beaven et al., 2020).

Observations indicate that soft cliffs and beaches are most affected by erosion in Europe, with e.g. 27 to 40% of Europe's sandy coast eroding today, without climate change being identified as the main driver so far (Pranzini et al.; Luijendijk et al., 2018; Mentaschi et al., 2018; Oppenheimer et al., 2019). SLR will increase coastal erosion of sandy shorelines (*high confidence*) (Ranasinghe et al., 2021), but there is *low confidence* in quantitative values assessment of erosion rates and amounts (Athanasiou et al., 2019; Le Cozannet et al., 2019; Thieblemont et al., 2019). Without nourishment or other natural or artificial barriers to erosion, sandy shorelines can retreat by about 100m in Europe at 4°C GWL; limiting warming to 3°C GWL can reduce this value by one third (Vousdoukas et al., 2020).

[START BOX 13.1 HERE]

Box 13.1: Venice and its Lagoon

Venice and its lagoon are a UNESCO World Heritage Site. This socio-ecological system is the result of millennia of interactions between people and the natural environment. It is exposed to climatic and non-climatic hazards: more frequent floods, warming, pollution, invasive species, reduction of salt marshes, hydrodynamic and bathymetric changes, and waves generated by cruise ships and boat traffic.

The elevation of the average city pedestrian level and of its inner historic area are respectively 105cm and 55cm above the present relative mean sea level (RMSL). Consequently, even small surges and compound events cause floods when they coincide with high tide (Lionello et al., 2021a). During the 20th century, RMSL has risen at about 2.5 mm/yr due to SLR and land subsidence (Zanchettin et al., 2021). The frequency of floods affecting the city has increased from once per decade in the first half of the 20th century to 40 times per decade in the period 2010-2019 (Figure Box 13.1.1a).

In 1973, the Italian government established a legal framework for safeguarding Venice and its lagoon. Construction of the flood protection system started in 2003 and were used for the first time in October 2020 to protect the city from floods (Lionello et al., 2021b). This system of mobile barriers (MoSE) closes the lagoon inlets to avoid floods when needed, while under normal conditions they lay on the seabed, thus allowing ship traffic and the exchange between the lagoon and the sea (Molinaroli et al., 2019). To prevent the flooding of the central monument area, additional measures are proposed including inlets, expansion of saltmarshes, and pumping seawater into deep brackish aquifers to raise the city's level (Umgiesser, 1999; Umgiesser, 2004; Teatini et al., 2011).

Without adaptation, potential economic damages between €7 and €17 billion have been estimated for the next 50 years (Caporin and Fontini, 2016). Additionally, the ecosystem is vulnerable to warming (Solidoro et al., 2010) and sea level rise (Day Jr et al., 1999; Marani et al., 2007). The duration of the closure of the lagoon inlets is expected to increase from 2 to 3 weeks per year for RMSL rises of 30 cm, to 2 months per year for 50 cm and 6 months per year for 75cm (Umgiesser, 2020; Lionello et al., 2021b) (Figure Box 13.1.1b), resulting in disconnection from the sea for most of the time for RMSL rise exceeding 75 cm. Frequent closures of the inlets would prevent ship traffic and in/outflow of water. For Venice, adaptation pathways considering the full range of plausible RMSL (Figure Box 13.1.1c) levels are not available, indicating a long-term adaptation gap. As planning and implementation of adaptation of this extent can take several decades (Haasnoot et al., 2020b, Cross-Chapter Box SLR in Chapter 3) this increases the risk that the city will not be prepared in case of rapid sea level rise.

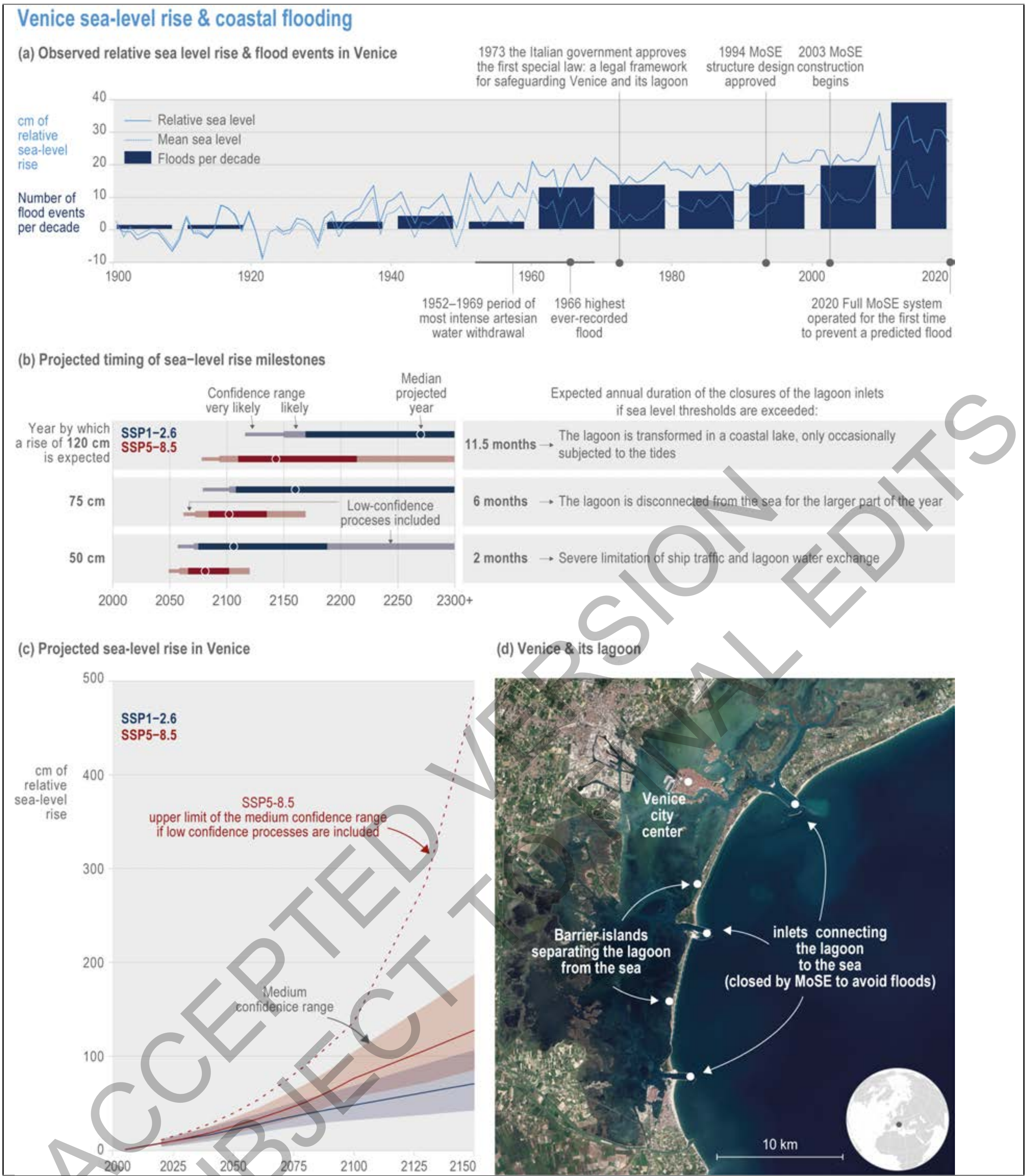


Figure Box 13.1.1: Venice sea level rise and coastal flooding. (a) Evolution of relative and mean sea level in Venice and decadal frequency of floods above the safeguard level in the city centre (Frederikse et al., 2020; Lionello et al., 2021a; Lionello et al., 2021b; Zanchettin et al., 2021). (b) Projected relative sea level rise at the Venetian coast (Fox-Kemper et al., 2021) and (c) timing when critical relative sea level thresholds will be reached depending on scenarios and confidence level (Lionello, 2012; Umgiesser, 2020; Lionello et al., 2021a). Panel d: landsat view of Venice, its lagoon with the three inlets connecting it to the Adriatic Sea.

[END BOX 13.1 HERE]

13.2.1.2 Risks Related to Inland Water

13.2.1.2.1 Riverine and Pluvial Flooding

Precipitation has raised river flood hazards in WCE and UK by 11% per decade from 1960-2010 and decreased in EEU and SEU by 23% per decade (Douville et al., 2021; Ranasinghe et al., 2021). The most recent three decades had the highest number of floods in the past 500 years with increases in summer (Blöschl et al., 2020). Economic flood damages increased strongly, reflecting increasing exposure of people and assets (Visser et al., 2014; Hoegh-Guldberg et al., 2018; Merz et al., 2021).

Projections indicate a continuation of the observed trends of river floods hazards in WCE (*high confidence*) of 10% at 2°C GWL and 18% at 4.4°C GWL and a decrease in NEU and SEU (*medium confidence*) with respectively 5% and 11% in NEU and SEU for a 100-year peak flow, making Europe one of the regions with the largest projected increase in flood risk (Di Sante et al., 2021; Ranasinghe et al., 2021). While there is disagreement on the magnitude of economic losses and people affected, there is *high agreement* on direction of change, particularly in WCE (Alfieri et al., 2018). New research increases confidence in AR5 statements that without adaptation measures, increases in extreme rainfall will substantially increase direct flood damages (e.g., Madsen et al., 2014; Alfieri et al., 2015a; Alfieri et al., 2015b; Blöschl et al., 2017; Dottori et al., 2020; Mentaschi et al., 2020). With low adaptation, damages from river flooding are projected to be 3 times higher at 1.5°C GWL, 4 times at 2°C GWL, and 6 times at 3°C GWL (Alfieri et al., 2018; Dottori et al., 2020). At 2°C GWL, incidence of summer floods is expected to decrease across the whole alpine region, whereas winter and spring floods will increase due to extreme precipitation (Gobiet et al., 2014) and snow melt driven runoff (Coppola et al., 2018).

Pluvial flooding and flash floods due to intense rainfall constitute most flood events in SEU and a substantial risk in other European regions (CCP4, Llasat et al., 2016; Rudd et al., 2020). The majority (56 %) of flood events between 1860-2016 were flash floods (Paprotny et al., 2018a). These had considerable impacts including danger to human lives, e.g. causing total economic damage of USD 1 billion in Copenhagen (Denmark) 2011 (Wójcik et al., 2013), a damage to private households of more than €70 million in Münster (Germany) 2014 (Spekkers et al., 2017), and during the 2021 floods in Belgium, Germany and the Netherlands over 200 deaths, damage to thousands of homes and disrupted water and electricity supply (Kreienkamp et al., 2021). The intensity and frequency of heavy rainfall events is projected to increase (*high confidence*) (Figure 13.3, Ranasinghe et al., 2021). Combined with increasing urbanization, the risk of pluvial flooding is projected to increase (Westra et al., 2014; Rosenzweig et al., 2018; Papalexiou and Montanari, 2019). Small catchments, steep river channels and cities are particularly vulnerable due to large areas of impermeable surfaces where water cannot penetrate (Section 13.6).

13.2.1.2.2 Low Flows and Water Scarcity

The frequency and severity of low flows are projected to increase, making streamflow drought and water scarcity more severe and persistent in SEU and WCE (*medium confidence*) (Figure 13.3, Ranasinghe et al., 2021), but decreases are projected in most of NEU except southern UK (Forzieri et al., 2014; Prudhomme et al., 2014; Schewe et al., 2014; Roudier et al., 2016; Ranasinghe et al., 2021). In EEU, uncertainty about changes in water scarcity pose distinct challenges for adaptation (Greve et al., 2018). At 1.5°C GWL, the number of days with water scarcity (water availability vs water demand) and drought will increase slightly in SEU (Schleussner et al., 2016; Naumann et al., 2018), resulting in 18% of the population exposed to at least moderate water scarcity, increasing to 54% at 2°C GWL (Byers et al., 2018). Moderate water scarcity is emerging in some parts of WCE (Bisselink et al., 2018) increasing to16% of the population under 2°C GWL and SSP2 (Byers et al., 2018). Under 4°C GWL, areas in WCE experience water scarcity, especially in summer and autumn. Future intensive water use can aggravate the situation, in particular in southern Europe (13.5.1 and 13.10.3).

Groundwater abstraction rates reach up to 100 million m³/year across WCE and SEU, and exceed 100 million m³/year in parts of SEU (Wada, 2016). Low recharge rates lead to a depletion of groundwater resources in parts of SEU and WCE (Doll et al., 2014; Wada, 2016; de Graaf et al., 2017), increasing the impacts on water scarcity in SEU. Groundwater pumping and declines in groundwater discharge already threaten environmental flow limits in many European catchments, especially in SEU, extending to almost all basins and sub-basins within the next 30-50 years (de Graaf et al., 2019).

The combined effect of increasing water demand and successive dry climatic conditions further exacerbates groundwater depletion and lowers groundwater levels in SEU but also WCE (Goderniaux et al., 2015).

Declines in groundwater recharge of up to 30% further increase groundwater depletion (Aeschbach-Hertig and Gleeson, 2012) especially in SEU and semi-arid to arid regions (Moutahir et al., 2017). Even in WCE and NEU projected increases in groundwater abstraction will impact groundwater discharge, threatening sustaining environmental flows under dry conditions (de Graaf et al., 2019).

The risks for soil moisture drought are projected to increase in WCE and SEU for all climate scenarios (Grillakis, 2019; Tramblay et al., 2020; Ranasinghe et al., 2021). At 3°C GWL compared to 1.5°C GWL, the drought area will increase by 40% and the population under drought by up to 42%, especially affecting SEU, and to a lesser extent in WCE (Samaniego et al., 2018).

13.2.1.2.3 Water Temperature and Quality

Water temperatures in rivers and lakes have increased over the past century by ~1 to 3°C in major European rivers (CBS, 2014; EEA, 2017b; Woolway et al., 2017). Warming is accelerating for all European river basins (Wanders et al., 2019) increasing by 0.8°C in response to 1.5°C GWL and 1.2°C for 3°C GWL relative to 1971-2000 (van Vliet et al., 2016a) aggravated by declines in summer river flow.

(Ground)water extractions or drainage have caused saltwater intrusions (Rasmussen et al., 2013; Ketabchi et al., 2016). During summer, seawater will also penetrate estuaries further upstream in response to reduced river flow and SLR and result in more frequent closure of water inlets in the downstream part of the rivers in a period when water is most needed (e.g., Haasnoot et al., 2020b) (*high agreement, low evidence*).

13.2.2 Solution Space and Adaptation Options

In recent decades water management in Europe has increasingly shifted towards integrated and adaptive strategies, with most noticeable shifts in WCE (*high confidence*) (e.g., Kreibich et al., 2015; Bubeck et al., 2017). While adaptive strategies are increasingly considered as an approach to strengthen flexibility and implement climate change adaptation actions, given deep uncertainty about the future (Ranger et al., 2013; Klijn et al., 2015; Bloemen et al., 2019; Hall et al., 2019; Pot et al., 2019), more traditional water management approaches still dominate across Europe (OECD, 2013; OECD, 2015; Wiering et al., 2017). Current measures focus on structural flood protection and water resources supply and play an important role to preserve present land use and development patterns. The long-term effectiveness of such measures is increasingly challenged by their reinforcing path-dependency (e.g. flood defence and water supply attract developments which require further protection and supply); this path-dependency limits the solution space and may hamper implementation of transformative measures such as land use change to accommodate the water system *(medium confidence*) (CCP2, Di Baldassarre et al., 2015; Kreibich et al., 2015; Alfieri et al., 2016; Gralepois et al., 2016; Welch et al., 2017; Di Baldassarre et al., 2018; Haer et al., 2020).

Water laws, policies and guidance documents increasingly mainstream climate impacts and adaptation options (Runhaar et al., 2018; Mehryar and Surminski, 2021), though not everywhere. Differences are apparent for example in coastal adaptation where most but not all countries are planning for SLR (Figure 13.5) (McEvoy et al., 2021). Although the planning horizon of 2100 and 1m SLR are most common (adjusted for local conditions), there are significant differences between countries (e.g. the high-end SLR value in 2100 ranges from 0.3 to 3m), which may lead to unequal impacts, over time (McEvoy et al., 2021).

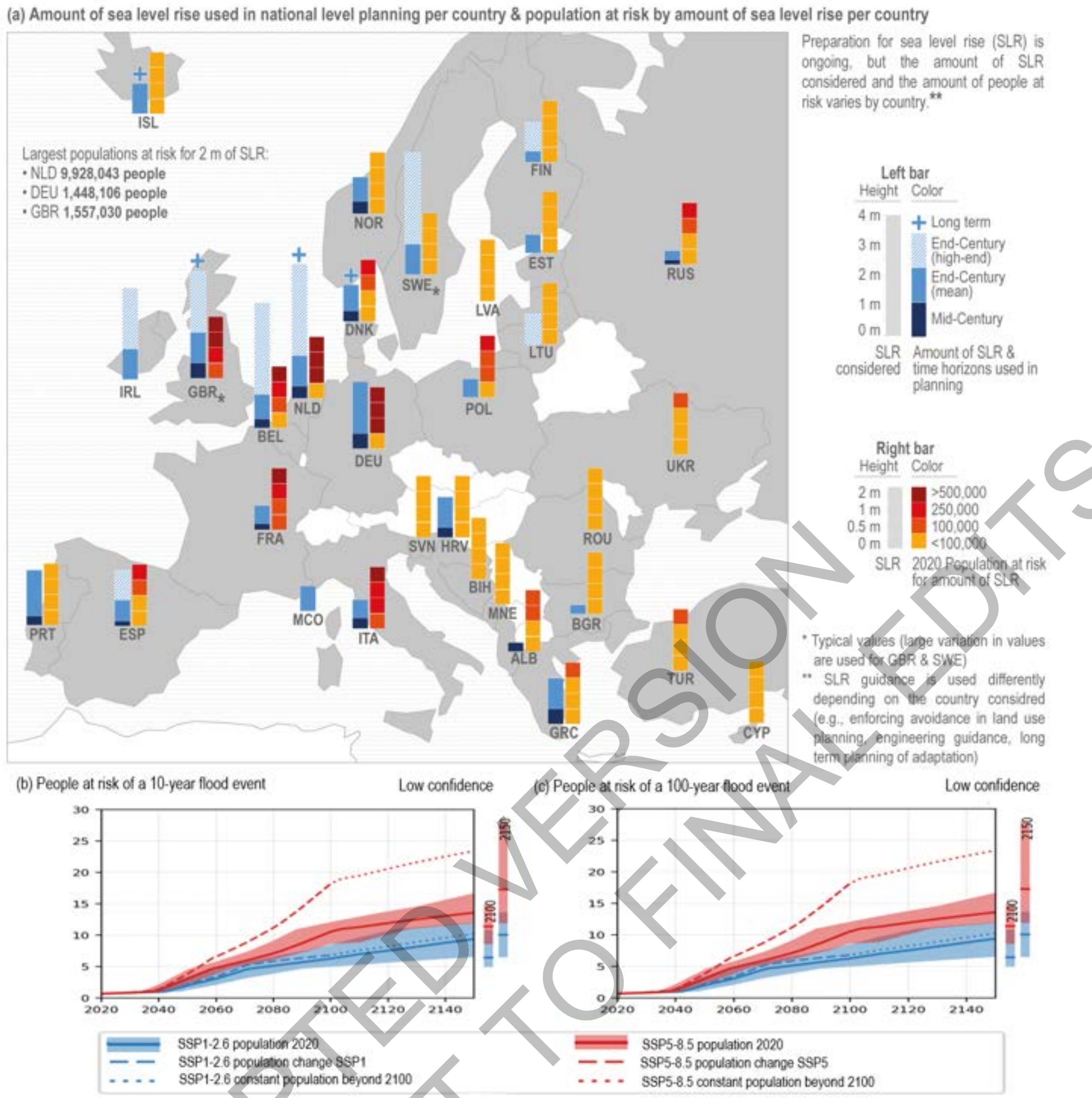


Figure 13.5: Sea level rise (SLR) vulnerability and national planning in Europe. (a) Map of countries in Europe summarizing the amount of SLR each country is planning for, at different time horizons (blue bars) and present population (2020) at risk of a 100-year coastal flood event (orange bars) (Haasnoot et al., 2021b). The amounts of SLR and time horizons reflect national guidance or planning; local or project-based levels may differ (McEvoy et al., 2021). (b) Projected population at risk to a 1 in 10-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5 assuming present protection and population, as well as population change according to respectively, SSP1 and SSP5, based on Merkens (2016); and (c) projected population at risk to 1 in 100-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5, assuming present protection and population, as well as population change according to respectively, SSP1 and SSP5, based on Merkens (2016) (Haasnoot et al., 2021b).

13.2.2.1 Flood Risk Management

Across Europe a range of measures have been implemented to address flood risk (Figure 13.6), with protection as a most used strategy (*high confidence*). Early warning and flood protection have been successful in reducing vulnerability to coastal and riverine flooding (Jongman et al., 2015; Kreibich et al., 2015; Bouwer and Jonkman, 2018). Consequently, fatalities due to river flooding have decreased in Europe, despite similar numbers of people exposed (1990-2010 compared to 1980-1989) (Jongman et al., 2015; Paprotny et al., 2018a).

Coastal flood risk management

Further protection against coastal flooding is considered economically beneficial for densely populated areas (Lincke and Hinkel, 2018; Tiggeloven et al., 2020). At least 83% of flood damages due to coastal flooding could be avoided by elevating dykes along ~23-32% of Europe's coastline by 2100 (RCP4.5-SSP1, RCP8.5-SSP5) (Vousdoukas et al., 2020). Limitations of building flood defences include cost-benefit considerations in rural areas, available land, and social acceptability in densely populated areas (Haasnoot et al., 2018; Hinkel et al., 2018; Meyerhoff et al., 2021).

Nature-based (NbS, e.g. wetlands) and sediment-based (e.g. sand nourishment) solutions are increasingly considered for environmental, economic and/or societal reasons (Cross-Chapter Box NATURAL in Chapter 2, Stive et al., 2013; Pranzini et al., 2015; Pinto et al., 2020; de Schipper et al., 2021). Coastal wetlands can be effective to reduce wave height and form habitats, but their feasibility and effectiveness is limited for densely populated areas with competing land use, runoff of pollution, sediment starved deltas like the Rhine delta (Edmonds et al., 2020) and rapid SLR (Kirwan et al., 2016; Oppenheimer et al., 2019; Haasnoot et al., 2020b). While losses of wetlands could be minor if warming stays below 1.7°C GWL, at high warming or SLR above 0.5m large scale losses of these habitats impact their ecological importance, ecosystem function (Section 13.4, Key Risk 1, 13.10) and their ability to protect coastlines (Roebeling et al., 2013; van der Spek, 2018; Wang et al., 2018; Xi et al., 2021). A combination with structural defences could reduce risk in urbanized coastal regions (*high confidence*). Accommodation through elevated or floating houses have been implemented and proposed locally within cities as part of a hybrid strategy together with protection and as a way of innovative urban development (13.6.2, CCP2, Penning-Rowsell, 2020; Storbjörk and Hjerpe, 2021).

Avoidance through restricting new developments in flood prone areas is applied along the coast of WCE and SEU (Harman et al., 2015; Lincke et al., 2020) and is considered a low-cost alternative to coastal defence at lower SLR. In SEU, an Integrated Coastal Zone Management (ICZM) protocol has been developed which requires a setback zone of 100m from the coast in unprotected areas. Setback zones are projected to reduce impacts considerably in urbanized regions (Lincke et al., 2020). Planned relocation is increasingly considered as a realistic adaptation option in case of extreme SLR (Haasnoot et al., 2021a; Lincke and Hinkel, 2021; Mach and Siders, 2021), e.g UK Shoreline Management Plans (Nicholls et al., 2013; Buser, 2020). Retreat is rarely applied in Europe (*medium confidence*), though it can have larger benefit-cost outcomes than protection, particularly in less populated parts of Europe (Lincke and Hinkel, 2021). Along parts of the coast in the UK (e.g., The Wash), Germany (e.g., Langeoog Island), and the Netherlands (e.g., Westerschelde) retreat has been applied to restore salt marshes and to aid coastal defence (Haasnoot et al., 2019; Kiesel et al., 2020). (Lincke and Hinkel, 2021)

Riverine and pluvial flood risk management

Structural flood protection (e.g. levees) is considered economically beneficial in densely populated areas (Alfieri et al., 2016; Dottori et al., 2020) and could reduce flood damage of ~45% is estimated under 1.5°C GWL and ~70% under 3°C GWL (Dottori et al., 2020).

Providing more room for water through NbS is increasingly considered (Kreibich et al., 2015) as they can reduce risk effectively at lower costs, except in places with limited space or in areas with large protection. Such measures include (forest) restoration for upstream retention, restoration of river channels, and widening riverbeds for natural flood retention (Kreibich et al., 2015; Barth and Döll, 2016; Wyżga et al., 2018). Natural retention areas are estimated to be the most effective option to reduce riverine flood risk across Europe in the 21st century, followed by protection (*low evidence*) (Dottori et al., 2020).

Wet and dry proofing of buildings can be applied at household level. While measures taken at household levels can reduce the risk of flooding, there is often insufficient investment (Bamberg et al., 2017; Aerts et al., 2018) (*medium confidence*). Reasons include low awareness or under-estimation of the risk (Kellens et al., 2013), low perceived efficacy of adaptation measures (van Valkengoed and Steg, 2019), and lack of financial support (Kreibich, 2011). In the long-term, risk reduction measures by governments are projected to outweigh floodproofing at household level, in particular in WCE, while for near-term household adaptation or regionally in SEU this could reduce risk more effectively (Haer et al., 2019). Relocation of households has occurred in response to river flood events, e.g. the 2013 flood events along the Danube river in Austria, with financial compensation playing a crucial role (Mayr et al., 2020; Thaler and Fuchs, 2020; Thaler, 2021).

Urban drainage infrastructure is designed based on historical rainfall intensities, and thus may not have sufficient capacity for increased future intensities (Dale et al., 2018). Adaptation options to pluvial flooding include large retention ponds , local green spaces and green roofs within cities (Zölch et al., 2017; Maragno et al., 2018; Babovic and Mijic, 2019; Ribas et al., 2020).

Effectiveness & feasibility of adaptation options for water-related climate impacts & risk in Europe

Impact Type	Adaptation Option	Effectiveness	Feasibility						Confidence	
			Economic	*Technological*	*Institutional*	*Socio-cultural*	*Ecological*	*Geophysical*	*Evidence*	*Agreement*
Flooding - Coast/River	Flood defenses (Protect)	H	M	H	H	NL	L	H 1	H	H
	Flood preparedness & early warning plans (Protect/Accommodate)	L 2	H	H	H	NL	H	NL	H	M
	Planned relocation (Retreat)	H	H	H	H	L	H	H	M	H
	No-build zone, restrict new developments (Avoidance)	M	H	H	M	NL	NL	NL	M	H
	Flood insurance (Supporting)	L	M	H	H	H	M	NL	M	H
Flooding - Coast	Ecosystem based (e.g. wetlands, oyster	M	H	H	NL	NL	H	M 1	M	H
	Sediment based (e.g. nourishment) (Protect)	M	M	M	H	NL	M	M 4	H	H
	Wet & dry proofing (Accommodate)	L	M	NL	H	H	NL	NL	L	H
Flooding - River	Ecosystem based (e.g. floodplain restoration, widening riverbed) (Protect)	H	M	M	NL	NL	H	M	M	H
	Retention & diversion (Accommodate)	M	H	H	NL	NL	NL	NL	L	H
	Wet & dry proofing (Accommodate)	M	M	M	H	H	NL	NL	H	M
Flooding - Pluvial	Retention: green roofs (Accommodate)	L	NL	NL	NL	NL	H	M	M	H
	Retention: parks (Accommodate)	H	NL	M	NL	NL	H	M	M	H
	Update drainage systems & pumps (Accommodate)	NL	L	NL	NL	NL	NL	M	M	H
Water Scarcity	Supply: Storage (reservoirs)	M	L	M	M 5	M	L	M	H	M
	Supply: Water diversion & transfer	L 6	L	M	H	M	M	NL	M	H
	Supply: Desalinization	H 7	L	H	H	H	L	H	M	H
	Supply: Water reuse	M 7	M	M	M	L	M	NL	H	H
	Demand: Water saving & efficiency	L	M	M	H	M	M	M	H	M
	Demand: Regulate distribution	M	H	M	M	NL	NL	NL	M	H
	Demand: Economic instruments	M	H	M	H	M	NL	NL	H	M
	Demand: Land management & cover change	M	H	M	H	NL	M	M	M	L
	Monitoring & operational management,	L	H	M	H	NL	H	NL	M	M

Legend	
High = H	1 Physically hampered in highly urbanized regions
Medium = M	2 Low on preventing damage, medium on preventing fatalities
Low = L	3 Availability of sand can hamper feasibility in SEU
No/Limited Evidence	4 Low in SEU, high in NLU, WCE
	5 In SEU, no evidence for other parts of Europe
	6 Medium in SEU & high in WCE/NLU

Figure 13.6: Effectiveness and feasibility of water-related adaptation options to achieve objectives under increasing climate hazards (SM13.1, SM13.9).

Early warning systems, insurance and behaviour change can complement protect and accommodate measures to limit residual risk (*high confidence*). Early warning systems have high monetary benefits (Pappenberger et al., 2015). Behavioural adaptation to flooding relies on recognition of the threat and capacity to respond, both of which are often lacking (Section 13.11.2.2, Bamberg et al., 2017; Haer et al., 2019). Flood risk insurance and compensation systems vary across European countries, ranging from post-disaster payments by governments, compulsory flood insurance, to public-private partnerships where the state acts as reinsurer (Keskitalo et al., 2014; Surminski et al., 2015; Hanger et al., 2018). Risk-based insurance premiums can induce risk averting behaviour but may become unaffordable to poor households and some households in high risk zones (Hudson, 2018; Surminski, 2018). Increasing future flood risks due to both climatic and socioeconomic change could overburden government budgets (*medium confidence*) (Section 13.11.2, Paudel et al., 2015; Mysiak and Perez-Blanco, 2016; Schinko et al., 2017; Mochizuki et al., 2018), result in unavailable or unaffordable insurance for private customers (13.8.3, Hudson et al., 2016; Surminski, 2018), and underfunding and insufficient solvency of insurance companies (Section 13.6.2.5, Lamond and Penning-Rowsell, 2014). Local knowledge about disastrous flood events in the past can be lost across generations, reverting behaviours to avoid settlement in risky areas (Fanta et al., 2019).

Limits to adaptation to extremely high sea level rise scenarios have been identified for coastal defences, such as the Venice MoSE barrier (box 13.1), Thames Barrier in the UK (Ranger et al., 2013) and the Maeslant Barrier in the Netherlands (Kwadijk et al., 2010; Haasnoot et al., 2020b). However, the scale and pace of adaptation required to face high-end SLR scenarios along all coasts of Europe is poorly studied. Given the lead and long lifetime of large critical infrastructure, there is a growing need to look beyond 2100 to support the design of new infrastructure (Cross-Chapter Box SLR in Chapter 3).

13.2.2.2 Water Resources Management

Planning adaptation to water scarcity has centred on increasing availability and supply of fresh water through water storage, diversification of sources and water diversion and transfer (*high confidence*). Reservoirs are costly, have negative environmental impacts, and will not be sufficient under higher warming levels in every place (Papadaskalopoulou et al., 2015a; Di Baldassarre et al., 2018; Garnier and Holman, 2019). Waste water reuse is considered a low-cost and effective measure where wastewater is available (Lavrnic et al., 2017; De Roo et al., 2020), but public acceptance for domestic reuse is presently limited (*high confidence*) (Papadaskalopoulou et al., 2015b; Morote et al., 2019). Increasing desalination capacity is used particularly in SEU but has high energy demands and produces brine waste (Garnier and Holman, 2019; Jones et al., 2019; Morote et al., 2019).

Adaptation measures on the demand side include monitoring (e.g., water meters, early warning systems of drought) and regulating demand, e.g. water restrictions, water pricing, water saving and efficiency measures and land management and cover change (Papadaskalopoulou et al., 2015b; Varela-Ortega et al., 2016; Manouseli et al., 2018; Garnier and Holman, 2019). Prolonged water restrictions and prioritising sectoral supply could result in economic losses e.g. for irrigated agriculture (Section 13.5.2, Wimmer et al., 2014; Salmoral et al., 2019). Economic instruments, such as water pricing, can be effective when combined with incentives for water saving and efficiency (Kayaga and Smout, 2014; Esteve et al., 2018; Crespo et al., 2019). Water saving and efficiency measures, such as leakage repair, education and improved irrigation, could limit conflicts across sectors, but necessitate technological advances and changes of practice together with a willingness to cooperate (Garnier and Holman, 2019; Papadimitriou et al., 2019; Teotónio et al., 2020). Increased irrigation efficiency has reduced water scarcity, particularly in SEU (13.5, De Roo et al., 2020), and occur at farm level in WCE and NEU (Papadaskalopoulou et al., 2015b; van Duinen et al., 2015; Rey et al., 2017), but come with increasing path-dependency on supply and trade-offs which may not be sustainable on the long-term (*high confidence*) (Di Baldassarre et al., 2018).

The assessment of the effectiveness and feasibility of adaptation options shows that a portfolio of supply and demand measures is needed to reduce water scarcity (Key Risk 3, Section 13.10.3), although locally demand-side measures could be sufficient (Kingsborough et al., 2016). Under high warming levels, adaptation to drought and low flows by water saving and efficiency measures may not be sufficient to counteract reduced availability (*medium agreement, low evidence*) (Collet et al., 2015; De Roo et al., 2020). Successful adaptation in the water sector depends on integrating water considerations into sectoral policies (Collet et al., 2015; Papadaskalopoulou et al., 2016). Inclusive and participatory approaches where (local) stakeholders are actively involved in the initiation and execution of water management can enhance problem ownership, quality and democratic legitimacy of processes and decisions, enhance support and accelerate decisions (Edelenbos et al., 2017; Begg, 2018).

13.2.3 Knowledge Gaps

An assessment of the full solution space of adaptation options and pathways under low to high GWLs including the long-term is lacking. A quantification of the effectiveness of measures in reducing risk is limited in the scientific literature. Available assessments consider adaptation by incremental measures. Transformative options, such as land use changes, planned relocation from exposed areas or restricting future development, are rarely considered. While high-end scenarios, describing *low confidence* processes and scenarios beyond 2100 are considered to be useful for risk-averse decision making, in particular coastal adaptation (Hinkel et al., 2019; Haasnoot et al., 2020b), they are rarely considered in practice.

13.3 Terrestrial and Freshwater Ecosystems and their Services

13.3.1 Observed Impacts and Projected Risks

13.3.1.1 Observed Impacts on Terrestrial and Freshwater Ecosystems

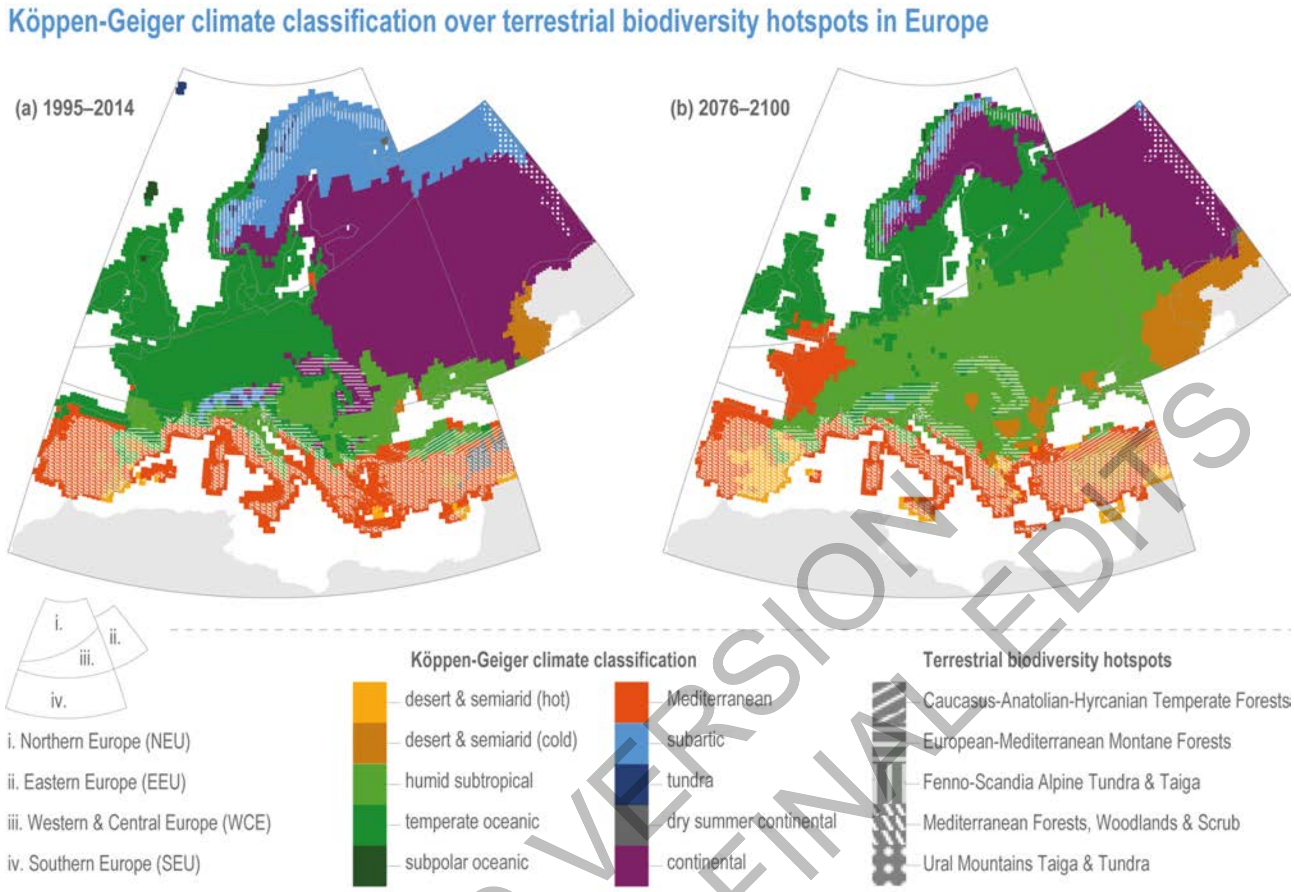


Figure 13.7: Köppen-Geiger climate classification and biodiversity hotspots in Europe. Boundaries of the (a) Northern (NEU), (b) Western-Central (WCE), (c) Southern (SEU), and (d) Eastern (EEU) European regions for 1985-2014 (left) and 2076-2100 (right, A1FI scenario, ~4°C GWL), based on Rubel and Kottek (2010).

European land and freshwater ecosystems (Figure 13.7) are already strongly impacted by a range of anthropogenic drivers (*very high confidence*), particularly habitats at the southern and northern margins, along the coasts, up mountains and in freshwater systems (CCP1). Interacting with climate change are non-climatic hazards, such as habitat loss and fragmentation, over-exploitation, water abstraction, nutrient enrichment, and pollution, all of which reduce resilience of biotas and ecosystems (*very high confidence*). Peatlands in NEU and EEU and other historically important cultural landscapes in Europe are overexploited for forestry, agriculture, and peat mining (Page and Baird, 2016; Tanneberger et al., 2017; Ojanen and Minkkinen, 2020). Inland wetland RAMSAR convention sites in Europe, which constitute 47% of the global sites, have lost area in WCE and gained in SEU from 1980 to 2014 (Xi et al., 2021). Forests in WCE were impacted by the extreme heat and drought event of 2018, with effects lasting into 2019 (Schuldt et al., 2020) and losses in conifer timber sales in Europe (Hlásny et al., 2021).

Extirpation, e.g. local losses of species, have been observed in response to climate change in Europe (*medium confidence*) (Wiens, 2016; EEA, 2017a; Soroye et al., 2020). Strong climate-induced declines have been detected in thermosensitive taxa (Hellmann et al., 2016), including many freshwater groups, insects (Habel et al., 2019; Harris et al., 2019; Seibold et al., 2019; Soroye et al., 2020), amphibians, reptiles (Falaschi et al., 2019), birds (Lehikoinen et al., 2019) and fishes (Myers et al., 2017a; Jarić et al., 2019). The loss of native species, especially specialised taxa, is changing biodiversity; however overall biodiversity could remain stable because losses may be compensated by range shifts of native and the establishment of non-native species (Dornelas et al., 2014; McGill et al., 2015; Hillebrand et al., 2018; Outhwaite et al., 2020).

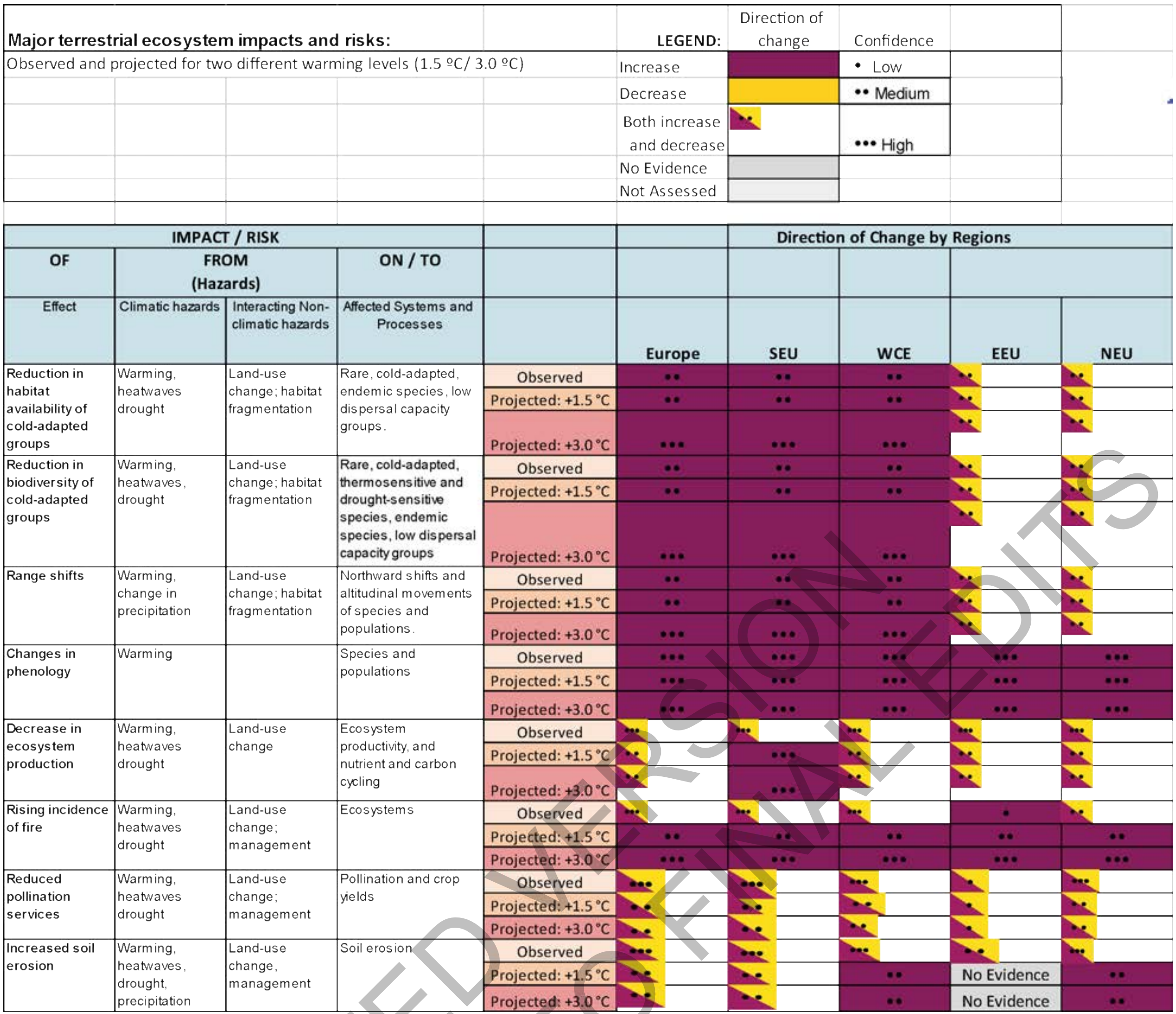


Figure 13.8: Summary of major impacts on and risks for terrestrial and freshwater ecosystems in Europe for 1.5ºC and 3ºC GWL (Table SM13.2).

Range shifts are leading to northward and upward expansions of warm-adapted taxa (*very high confidence*) (Figure 13.8 and Chapter 2). These shifts altered species living in the boreal and alpine tundra (Elmhagen et al., 2015; Post et al., 2019; Mekonnen et al., 2021) and are greening the high Arctic tundra with shrubs and trees (Myers-Smith et al., 2020). Plants display more stable distributions at low than at higher mountain altitudes (Rumpf et al., 2018). Microclimatic variability in some locations can buffer warming impacts (*medium confidence*) (Suggitt et al., 2018; Zellweger et al., 2020; Carnicer et al., 2021). Northward shifts of tree species distributions is documented in North Western Europe (Bryn and Potthoff, 2018; Mamet et al., 2019) but not consistently detected (Cudlín et al., 2017; Vilà-Cabrera et al., 2019).

The timing of many processes, including spring leaf unfolding and autumn senescence and flight dates changed in response to changes in seasonal temperatures, water and light availability (*very high confidence*) (Chapter 2, Szabó et al., 2016; Asse et al., 2018; Peaucelle et al., 2019; Menzel et al., 2020; Rosbakh et al., 2021), resulting e.g. in earlier arrival dates for many birds and butterflies (Karlsson, 2014; Bobretsov et al., 2019; Lehikoinen et al., 2019). Greatest growing season lengthening in plants has been detected in WCE, NEU and EEU, but shortening in parts of SEU driven by later senescence (Garonna et al., 2014), increasing population growth for butterflies and moths (Macgregor et al., 2019) and birds (Halupka and Halupka, 2017), and residence time for migrant birds (Newson et al., 2016).

13.3.1.2 Projected Risks for Terrestrial and Freshwater Ecosystems

Risks for terrestrial ecosystems will increase with warming (*very high confidence*) with high impacts at > 2.4ºC GWL and very high impacts > 3.5ºC GWL (*medium confidence*) (13.10.3.1). Land use changes will increase extirpation and extinction risk (Vermaat et al., 2017) (*very high confidence*). In NEU, biodiversity vulnerability is projected to be lower as new climate and habitat space is becoming available (Warren et al., 2018; Harrison et al., 2019). Warming < 1.5ºC GWL would limit risks to biodiversity, while 4ºC GWL and intensive land use may lead to a loss of suitable climate and habitat space for most species (*low confidence*) (Warren et al., 2018; Harrison et al., 2019).

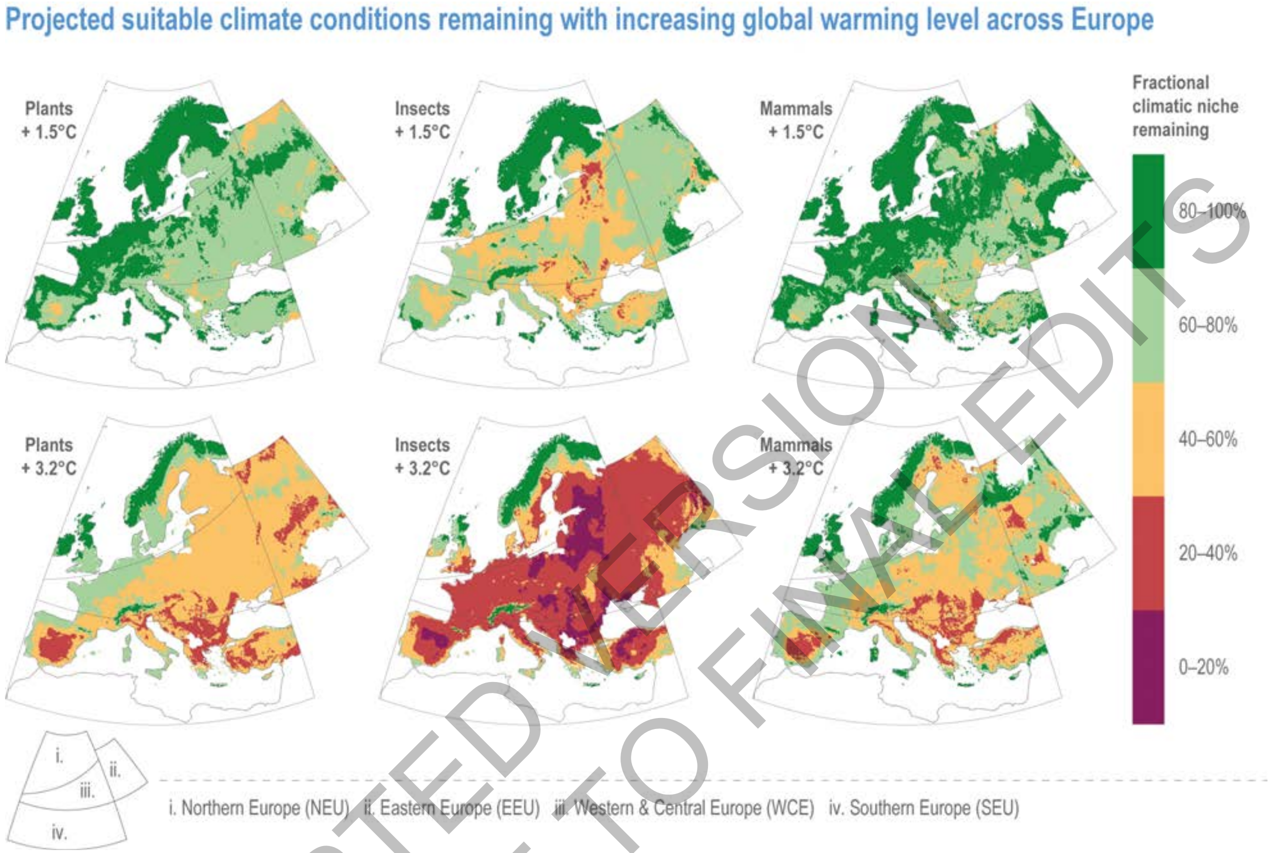


Figure 13.9: Species projected to remain within their suitable climate conditions at increasing levels of climate change. Colour shading represent proportion of species projected to remain within their suitable climates averaged over 21 CMIP5 climate models (Warren et al., 2018). Areas shaded in green retain a large number of species with suitable climate conditions, while those in purple represent areas where climates become unsuitable for more than 80% of the without dispersal (Table SM13.3).

Disruption of habitat connectivity reduces resilience and is projected to impact 30% of lake and river catchments in Europe by 2030, through drought and reduced river flows (Markovic et al., 2017) (*medium evidence*). Average wetland area is not projected to change at 1.7°C GWL across Europe, while for > 4°C GWL expanding sites in NEU are not sufficient to balance losses in SEU and WCE (*high confidence*) (Xi et al., 2021). At 3°C GWL the alpine tundra habitat and its associated species are projected to be lost in the Pyrenees and shrink dramatically in NEU, WCE and EEU (Anisimov et al., 2017; Barredo et al., 2020).

Population range shifts (Figure 13.7, 13.10) are projected to continue (Figure 13.8) (*medium confidence* at 1.5° GWL, *high confidence* at 3.0°C GWL). The largest losses of suitable climatic conditions are projected for plants and insects, with different taxon-specific regions of highest risk, while proportions of species projected to loose suitable climates are lower for other groups (*medium confidence*) (Figure Box 13.1.1, Table SM13.3, Warren et al., 2018). > 1.5°C GWL will lead to a progressive subtropicalisation in SEU, expanding into WCE at > 3°C GWL, a northward shifting of the temperate domain into NEU (Feyen et al., 2020) (*medium confidence*), and an expansion of desert biomes in EEU (Sergienko and Konstantinov, 2016). Changes in distribution are projected for major tree species in all European regions at 1.7°C GWL (Dyderski et al., 2018; Leskinen et al., 2020), with economic implications for managed forests (13.5.1.4). The longer growth season in NEU and WCE will support the establishment of invasive species (CCP1). < 1.5ºC GWL would limit expansion and novel appearances of pests while > 3.4ºC GWL will make large parts of SEU and WCE suitable for pest, e.g. wood beetles (Urvois et al., 2021), and increase economic losses due to lower harvest quality of timber (Toth et al., 2020).

Risks emerging from climate change for phenology are uncertain, given asynchrony between species, taxa and trophic responses (Thackeray et al., 2016; Posledovich et al., 2018; Keogan et al., 2021) and the complexity of phenological events and their cues (Delgado et al., 2020; Ettinger et al., 2020) (*medium confidence*). Spring events may continue to occur earlier (Gaüzère et al., 2016), but reduced chilling may decrease this temporal shift (Wang et al., 2020). Projections for autumn are mixed, with continuing delays (Prislan et al., 2019) or earlier onset of leaf senescence (Wu et al., 2018), but reduced chilling may also decrease these developments (Wang et al., 2020). Advancement, combined with longer autumn growth, may extend the growing season of trees by two days per decade in SEU (Prislan et al., 2019). Warming to > 3°C GWL will impact forest planning in NEU (Caffarra et al., 2014).

13.3.1.3 Observed Impacts and Projected Risks of Wildfires

Fires affect over 400,000 ha every year in the European Union (San-Miguel-Ayanz et al., 2019), with 85% of the area located in SEU (Khabarov et al., 2016; de Rigo et al., 2017; Costa et al., 2020), where 'fire weather' conditions (determined by temperature, precipitation, wind speed and relative humidity) are most pronounced (Figure 13.10). Fire hazard conditions, including heat waves (Boer et al., 2017), have increased throughout Europe from 1980 to 2019 (Figure 13.10), with substantive increases in SEU and WCE (*high confidence*) (Urbieta et al., 2019; Di Giuseppe et al., 2020; Fargeon et al., 2020). Extreme wildfires have been observed in recent years, including 2017 in Portugal, 2018 in Sweden (Krikken et al., 2021) and 2021 in south-eastern Europe. In SEU, WCE and NEU human activities caused more than 90-95% of the fires, while natural ignition accounts for a substantial portion of burnt area in EEU (Wu et al., 2015; Filipchuk et al., 2018).

Except for Portugal, burnt area in SEU has shown a slightly decreasing trend since 1980, with high inter-annual variability (CCP 4, Turco et al., 2016; de Rigo et al., 2017). In SEU, burned terrestrial biomass declined from 2003 to 2019 (Turco et al., 2016), despite increasing fire risks. This trend is parallel to increasing fire management measures implemented (Fernandez-Anez et al., 2021). The slight increase in burned biomass in WCE and NEU is associated with more hazardous landscape configurations and warming in recent decades (Turco et al., 2016; Urbieta et al., 2019).

Projections of wildfire risks are uncertain due to multiple factors, including compound events, fire-vegetation interaction and social factors (Thompson and Calkin, 2011; San-Miguel-Ayanz et al., 2019). Wildfire risks can increase across all regions of Europe at 1.5°C and 3°C GWL (*medium* to *high confidence*) (Figure 13.8). In SEU, the frequency of heat-induced fire-weather is projected to increase by 14% at 2.5°C GWL and rising to 30% at 4.4°C GWL (Turco et al., 2018; Costa et al., 2020; Ruffault et al., 2020). In the European Arctic, the extent and duration of extreme fire seasons will increase because of increasing extreme fire weather, increased lightning activity, and drier vegetation and ground fuel conditions due to prolonged droughts (McCarty et al., 2021). Projections suggest that new fire-prone regions in Europe could emerge, particularly in WCE and NEU where wildfires have been uncommon and fire management capacity is slowly increasing (Wu et al., 2015; Forzieri et al., 2021).

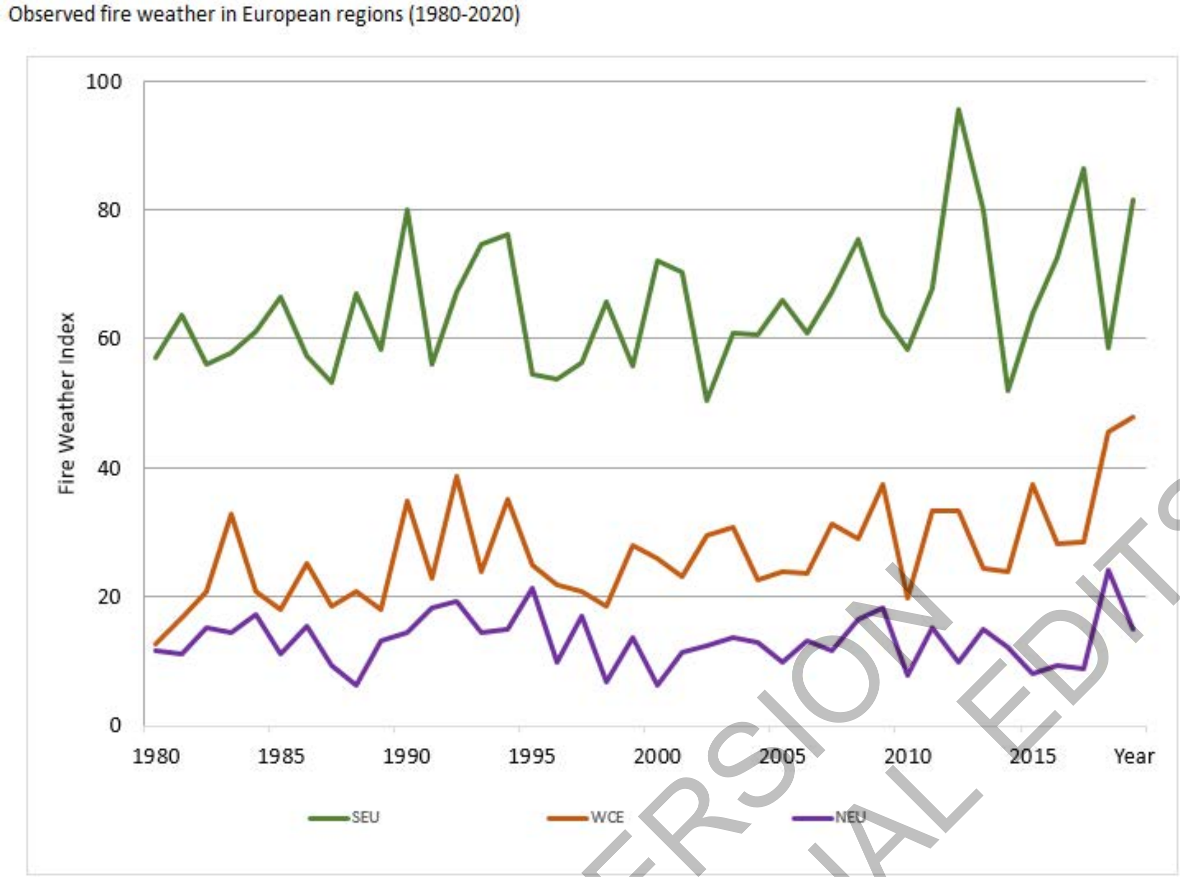


Figure 13.10: Geographical variability and dynamic changes in fire danger in Europe over the last decades. Significant increases in fire hazard at the multidecadal scale and unprecedented years of elevated fire hazard have occurred over the last decade in Southern and Western and Central Europe (SEU, WCE). The environmental conditions required for fires to spread and intensify were evaluated using fire hazard estimates ('Fire Weather Index' (FWI) based on meteorological variables such as temperature, precipitation, wind speed and relative humidity). FWI trends were calculated with the ECMWF ERA-5 FWI reanalysis dataset (Copernicus, 2019; Copernicus, 2020a; Copernicus, 2020b).

13.3.1.4 Observed Impacts and Projected Risks on Ecosystem Functions and Regulating Services

European temperate and boreal forests, wetlands and peatlands hold important carbon stocks (Bukvareva and Zamolodchikov, 2016; Yousefpour et al., 2018). Effects of warming and increasing droughts on soil moisture, respiration and carbon sequestration have been detected across European regions (*high confidence*) (Tab. 13.3, Sanginés de Cárcer et al., 2018; Carnicer et al., 2019; Green et al., 2019; Schuldt et al., 2020). Forest expansion in boreal regions results in net warming (Bright et al., 2017), possibly influencing cloud formation and rainfall patterns (*medium confidence*) (Teuling et al., 2017). These changes are affecting climate, pollination and soil protection services (Table 3.3, Verhagen et al., 2018). If not managed through increased reforestation/revegetation or peatland restoration, future climate change impacts will progressively limit the climate regulation capacity of European terrestrial ecosystems (*medium confidence*) (Figure 13.8), especially in SEU (Peñuelas et al., 2018; Xu et al., 2019). Predominantly positive CO_2 fertilization effects at current warming will change into increasingly negative effects of warming and drought on forests at higher temperatures (*medium confidence*) (Peñuelas et al., 2017; Green et al., 2019; Ito et al., 2020; Wang 2020; Yu et al., 2021). In NEU and EEU, peatlands are projected to shrink with 1.7°C GWL, and become carbon sources at 3°C GWL (Qiu et al., 2020), peat bogs to lose 50% carbon at 2°C GWL, and blanket peatland to shrink or regionally disappear (Gallego-Sala et al., 2010; Ferretto et al., 2019)

Declines in pollinator ranges in response to climate are occurring for many groups in Europe (h*igh confidence*) (Figure Box 13.1.1, Table 13.3, Kerr et al., 2015; Soroye et al., 2020; Zattara and Aizen, 2020), with observed shifts to higher elevations of southern and lower elevation in northern species (Kerr et al., 2015) resulting in higher pollinator richness in NEU (Franzén and Öckinger, 2012). Lags in responses to climate change suggest current impacts on pollination have not been fully realized (IPBES, 2018).

Pollinators are also declining due to lack of suitable habitat, pollution, pesticides, pathogens and competing invasive alien species (Settele et al., 2016; Steele et al., 2019).

Projected climate impacts on pollinators show mixed responses across Europe, but are greater under 3°C GWL (*medium confidence*) (Rasmont et al., 2015). Increasing homogenisation of populations may increase vulnerability to extreme events (Vasiliev and Greenwood, 2021). Geographic changes to the climatic niche of pollinators are similar to insects, with mixed trends, depending on group and location (Figure 13.9, Kaloveloni et al., 2015; Rasmont et al., 2015; Radenković et al., 2017). In NEU, species richness may increase for some groups (Rasmont et al., 2015), with unclear trends for bumblebees (Fourcade et al., 2019; Soroye et al., 2020). Future land use will have important effects on pollinator distribution (Marshall, 2018) as habitat fragmentation in densely populated Europe decreases opportunities for range shifts and micro-climatic buffering (Vasiliev and Greenwood, 2021).

Soil erosion varies across Europe, with higher rates in parts of SEU and WCE, but lower in NEU (*high confidence*) (Table 13.3, Petz et al., 2016; Polce et al., 2016; Borrelli et al., 2020), related to vegetation type and amount of cover, slope and soil type (Panagos et al., 2015a). Short-term, land use change and management may impact soil erosion more than climate (Verhagen et al., 2018). Where conservation agriculture is practised or vegetation cover increasing, erosion is slightly decreasing (Panagos et al., 2015b; Guerra et al., 2016). Reduced soil loss due to reduced spring snow melt has been observed in EEU (Golosov et al., 2018) , while fire exacerbates soil loss, especially in SEU (Borrelli et al., 2016; Borrelli et al., 2017).

Projected increase in rainfall could increase soil erosion, while warming enhances vegetation cover, leading to overall mixed responses (*medium confidence*) (Berberoglu et al., 2020; Ciampalini et al., 2020). In Europe, rainfall erosivity could increase by >81% (Panagos et al., 2017) at 2°C GWL, especially in NEU (Borrelli et al., 2020) where risks can be limited by soil erosion control (Polce et al., 2016). Decreased rainfall projected for parts of SEU could reduce erosion, although increases in rainfall intensity could offset this (Serpa et al., 2015). Soil losses from fire will increase in SEU in response to 2°C GWL (Pastor et al., 2019), especially if combined with extreme rainfall (Morán-Ordóñez et al., 2020). In northern regions, reduced soil losses are projected during spring snowmelt (Svetlitchnyi, 2020).

13.3.2 Solution Space and Adaptation Options

Autonomous species adaptation, via range shifts towards higher latitudes and altitudes and changes in phenology, but extirpation have been documented in all European regions (Figure 13.8) (*very high confidence*). Lowering vulnerability by reducing other anthropogenic impacts (Gillingham et al., 2015), such as land use change, habitat fragmentation (Eigenbrod et al., 2015; Oliver et al., 2017; Wessely et al., 2017), pollution, and deforestation (Chapter 2), enhances adaptation capacity and biodiversity conservation (*high confidence*) (Ockendon et al., 2018). Protected areas, such as the EU Natura 2000 network, have contributed to biodiversity protection (*medium confidence*) (Gaüzère et al., 2016; Sanderson et al., 2016; Santini et al., 2016; Hermoso et al., 2018) but 60% of terrestrial species in these sites could lose suitable climate niches at 4°C GWL (Figure Box 13.1.1, EEA, 2017a).

Most protected areas are static and thus do not take species migration into consideration (*high confidence*) (Gillingham et al., 2015; Heikkinen et al., 2020b). More dynamic areas of protection, such as networks of protected areas with corridors, buffer zones and zoning, can facilitate population shifts (Barredo et al., 2016; Nila et al., 2019; Crick et al., 2020; Keeley et al., 2021) and thereby reduce but not eliminate vulnerability (Wessely et al., 2017; Pavón-Jordán et al., 2020).

Rehabilitation and restoration of land (Prober et al., 2019), particularly abandoned agricultural areas in SEU and NEU (Terres et al., 2015), are long-term strategies to improve regulating services and enhance biodiversity conservation (Morecroft et al., 2019; Campos et al., 2021). Their success will depend on consideration of the future climate niche when restoring peatlands (Bellis et al., 2021) or long-lived species with limited mobility (Hazarika et al., 2021) (*high confidence*). Combination of supporting the resilience of species, increasing functional diversity of habitats, and assisted migration of species at the limit of their adaptive capacity (Park and Talbot, 2018) are needed to protect and restore ecosystems, e.g. forests (Boiffin et al., 2017; Messier et al., 2019). Successful interventions consider habitat and the ecological and evolution interactions of species (Šeho et al., 2019; Diallo et al., 2021) combined with monitoring to assess their effectiveness (Casazza et al., 2021).

Fire management plans and programs are in place in most of SEU, and increasingly developed in the parts of Europe where wildfires are less common (Fernandez-Anez et al., 2021). Capacity to implement and maintain these options remains limited, however (*medium confidence*). The dominant fire management paradigm of fire suppression in some regions of SEU has been questioned, as it contributes to fuel accumulation. Approaches are advocated which combining fire-risk mitigation, prevention, and preparation (Moreira et al., 2020), recovery through post-fire management (Lucas-Borja et al., 2021), diverse fuels treatment (Mirra et al., 2017), including prescribed burning (Fernandes et al., 2013).

Ecosystem-based adaptations (EbA) and nature-based solutions (NbS) that restore or recreate ecosystems, build resilience and produce synergies with adaptation and mitigation in other sectors are increasingly used in Europe (*high confidence*)(Cross-Chapter Box NATURAL in Chapter 2, Berry et al., 2015; Chausson et al., 2020). Planting trees or recreating wetlands can function as part of natural flood management (Dadson et al., 2017; Cooper et al., 2021), whilst urban green infrastructure can reduce flooding (13.2.2) and heat stress and provide recreation opportunities and health benefits (13.6.2.3; Box 13.3) (Kabisch et al., 2016; Choi et al., 2021).

Appropriately implemented ecosystem-based mitigation, such as reforestation with climate-resilient native species (13.3.1.4), peatland and wetland restoration and agroecology (13.5.2), can enhance carbon sequestration or storage (*medium confidence*) (Seddon et al., 2020). Saltmarsh protection or recreation can increase carbon storage capacity, enhance coastal flood protection and provide cultural services (Beaumont et al., 2014; Bindoff et al., 2019). Trade-offs between ecosystem protection, their services and human adaptation and mitigation needs can generate challenges, such as loss of habitats, increased emissions from restored wetlands (Günther et al., 2020) and conflicts between carbon capture services, and provisioning of bioenergy, food, timber and water (Lee et al., 2019; Krause et al., 2020) (*medium confidence*).

The solution space for responding to climate-change risks for terrestrial ecosystem has increased in parts of Europe (*medium confidence*). For example, EbA and NbS figure prominently in the EU Adaptation Strategy (2021a) and climate change adaptation is mainstreamed in the EU Biodiversity Strategy for 2030 (European Comission, 2020), the EU Forest Strategy for 2030 (European Comission, 2021b), the EU Green Infrastructure Strategy (European Comission, 2013a), as well as several national and regional policies. Yet, in the northern parts of EEU and NEU (e.g. Greenland, Iceland, NW Russian Arctic), areas which are often sites of pronounced biodiversity shifts and changes, solutions are lacking or slow in emergence, due to remoteness, lack of resources and sparse populations (Canosa et al., 2020). In the EU, innovative financing schemes such as the Natural Capital Financing Facility are being explored by the European Investment Bank and the European Commission which supports projects delivering on biodiversity and climate adaptation through tailored loans and investments. Multiple EU-level service platforms have been promoted to track climate change impacts on land ecosystems and adaptation (e.g. Climate-Adapt, Copernicus Land and Fire Monitoring Service, Forest Information System of Europe) (13.11.1).

Despite an expanding solution space, widespread implementation and monitoring of natural and planned adaptation across Europe is currently limited, due to high management costs, undervaluation of nature, and conservation laws and regulations that do not consider species shifts under future socioeconomic and climatic changes (*high confidence*) (Kabisch et al., 2016; Prober et al., 2019; Fernandez-Anez et al., 2021). Climate risks are not perceived as urgent due to a continuing perception of high adaptive capacity of ecosystems (Uggla and Lidskog, 2016; Esteve et al., 2018; Vulturius et al., 2018). Limited financial resources prevent widespread implementation of large-scale and connected conservation areas (*high confidence*) (Hermoso et al., 2017; Lee et al., 2019; Krause et al., 2020). Particularly in WCE, competition for land use with other functions, including mitigation options, is a critical barrier to implementation of adaptation. Risks to terrestrial and freshwater ecosystems are rarely integrated into regional and local land use planning, land development plans, and agro-system management (*medium confidence*) (Nila et al., 2019; Heikkinen et al., 2020a) .

13.3.3 Knowledge gaps

Despite growing evidence of climate change impacts and risk, including attributed changes to terrestrial ecosystems (13.10.1), this information is geographically not equally distributed, leaving clear gaps for some processes or regions *(high confidence*). For processes such as wildfire, the Fire Weather Index (13.3.1.3) suggests increasing risks for fires in Europe but robust projections on incidents and magnitudes of wildfire and their impacts on ecosystems and other sectors is currently limited, particularly for NEU, EEU and WCE (*high confidence*).

Many studies consider only individual climate drivers, though new research shows strong interactions between hazards such as warming and drought (13.3.1), as well as non-climatic drivers (Chapter 2). This creates uncertainty about the emergence of extinctions and the magnitudes of impacts for European ecosystems and the services they provide (*high confidence*), such as pollination on food production. RCP-SSP combinations to assess risks are only just emerging (Harrison et al., 2019).

Assessments of the long-term effectiveness of adaptation actions is missing, due to the time lag in determining effectiveness of an action and attributing risk reduction (Morecroft et al., 2019). For example, many landscape restoration actions are discussed but it is unclear which would bring highest benefits and which species should be used for the restoration (Ockendon et al., 2018). Further, adaptation actions will depend on local implementation and benefit from being assessed using cultural and Indigenous knowledge where applicable, but this is hardly studied (*medium confidence*).

13.4 Ocean and Coastal Ecosystems and their Services

13.4.1 Observed Impacts and Projected Risks

13.4.1.1 Observed Impacts

Warming continues to be the key climate hazard for European seas (Figure 13.1). Interacting with other climatic and non-climatic drivers, it has detectable and attributable impacts at a wide range of biological and ecological organisational levels (Figure 13.11).

Major marine ecosystem impacts and risks:

Observed and projected for two different warming levels (1.5 °C/ 3.0 °C)

LEGEND:	Direction of change	Confidence
Increase		• Low
Decrease		•• Medium
Increase and decrease	I/D	••• High
No evidence	No evidence	
Not assessed	Not assessed	

IMPACT / RISK	Hazards: Climatic hazards	Hazards: Interacting non-climatic hazards	ON / TO (Affected systems & processes)		EUROPE	SEUS	TEUS	NEUS
A. Loss of habitat availability	Warming Heatwaves Sea-level rise Sea-ice decline	Fishing, eutrophication, coastline modification, pollution	Ecosystems	Observed Impacts	•••	•••	No evidence	••
				Projected Risks at +1.5 °C	•••	•••	••	••
				Projected Risks at +3.0 °C	•••	•••	•••	•••
B. Shifts in ranges (incl. invasions), compositions (taxonomic, functional), phenologies	Warming, acidification	Shipping	Populations, Species, communities, biomes	Observed Impacts	•••	•••	•••	•••
				Projected Risks at +1.5 °C	•••	•••	•••	•••
				Projected Risks at +3.0 °C	•••	•••	•••	•••
C. Reduction in growth and reproductive success	Warming, acidification		Species	Observed Impacts	I/D ••	I/D ••	I/D ••	I/D ••
				Projected Risks at +1.5 °C	I/D ••	No evidence	I/D ••	No evidence
				Projected Risks at +3.0 °C	•	•	•	No evidence
D. Loss in biodiversity	Warming Heatwaves Sea-ice decline	Fishing, eutrophication, coastline modification, pollution	Populations, Species, Communities	Observed Impacts	I/D •••	I/D •••	I/D •••	I/D •••
				Projected Risks at +1.5 °C	I/D ••	••	I/D ••	I/D ••
				Projected Risks at +3.0 °C	•••	•••	••	••
E. Decline in production	Warming	Eutrophication	Ecosystems: - Production	Observed Impacts	I/D •••	No evidence	•••	•••
				Projected Risks at +1.5 °C	I/D ••	I/D ••	•••	••
				Projected Risks at +3.0 °C	I/D ••	I/D ••	•••	••
F. Emergence of harmful algal blooms and pathogens	Warming, acidification, deoxygenation	Eutrophication	Species, communities, ecosystems	Observed Impacts	•*	•*	•*	No evidence
				Projected Risks at +1.5 °C	•	•	•	•
				Projected Risks at +3.0 °C	•	•	•	•
G. Reduction in ecosystem services	Warming, acidification, deoxygenation, sea-level rise	Fishing, eutrophication, coastline modification, pollution	Ecosystems: - Regulating - Provisioning - Coastal protection	Observed Impacts	I/D •	•	•	No evidence
				Projected Risks at +1.5 °C	I/D •••	•	•	•
				Projected Risks at +3.0 °C	I/D •••	•	I/D ••	I/D ••

Figure 13.11: Major impacts and risks for marine and coastal ecosystems in Europe for observed and projected 1.5 °C and 3.0 °C GWL (Table SM13.4).

Particularly habitat loss in shallow coastal waters and at the coasts themselves, and northward distribution shifts of populations and communities are evident across all European marine subregions (Figure 13.11: *high confidence*; Chapter 3). Marine heatwaves have had severe ecological impacts in SEUS (*high confidence*) (CCP 4), threatening sessile benthic biotas and coastal habitats (Munari, 2011; Kersting et al., 2013; Rivetti et al., 2014; Garrabou et al., 2019). Range contractions, extirpations (*medium confidence*) (Smale, 2020) and species redistributions have been observed (*high confidence*) in TEUS (Cottier-Cook et al., 2017) and SEUS (Castellanos-Galindo et al., 2020). Habitat losses, range shifts, species invasions and species thermal preferences altered community compositions (Vasilakopoulos et al., 2017), resulting in the 'subtropicalisation' of TEUS and 'tropicalisation' of SEUS (Chapter 3; CCP 4) and temperature-dependent timing of abundance and reproduction cycles (Hjerne et al., 2019; Polte et al., 2021; Uriarte et al., 2021).

Reductions in growth and reproductive success of calcifying species are not yet unambiguously detected and attributed in European seas (Figure 13.11) (*medium confidence*), as many show resilience (Kroeker et al., 2010; Wall et al., 2015). However, fish population sizes are shrinking (Queirós et al., 2018; Ikpewe et al., 2021), and growth, reproduction and recruitment are negatively impacted (Lindegren et al., 2018; Goldberg et al., 2019; Hidalgo et al., 2019; Vieira et al., 2019; Denechaud et al., 2020; Maynou et al., 2020; Polte et al., 2021), though positive effects also occur (Sguotti et al., 2019; Tanner et al., 2019). Biodiversity changes depend on region, habitat, and taxon (Figure 13.11) (*medium confidence*) overall resulting in the redistribution of biodiversity in Europe (García Molinos et al., 2016), and biodiversity declines in some subregions (*high confidence*) (IPBES, 2018).

Biological and ecological impacts have cascading effects for marine ecosystem functioning (Chivers et al., 2017; Baird et al., 2019) and biogeochemical cycling (Huete-Stauffer et al., 2011; Munari, 2011; Kersting et al., 2013; Rivetti et al., 2014; Garrabou et al., 2019). In TEUS, increased water-column stratification (Section 13.1) and decreasing eutrophication, result in reduced primary production (*high confidence*) (Figure 13.11, Capuzzo et al., 2018) and productivity at higher trophic levels (Free et al., 2019) (*high confidence*), while in NEUS sea-ice decline resulted in primary production increase by 40-60% (Figure 13.11) (*high confidence*) (Arrigo and van Dijken, 2015; Borsheim, 2017; Lewis et al., 2020). Climate-related deoxygenation impacts are small in most European waters (Figure 13.11) (*medium confidence*), expect for semi-enclosed seas such as the Baltic and Black Seas (Frolov et al., 2014; Jacob et al., 2014; Reusch et al., 2018). Here warming and eutrophication altered ecosystem functioning (*high confidence*), reduced potential fish yield, increased harmful algal blooms (Alekseev et al., 2014; Carstensen et al., 2014; Berdalet et al., 2017; Daskalov et al., 2017; Riebesell et al., 2018; Stanev et al., 2018), and the risks of *Vibrio* pathogens and vibriosis (Section 13.7.1, Baker-Austin et al., 2017; Semenza et al., 2017). Across all European seas there is only *low confidence* of a consistent change in provisioning ecosystem services (e.g., fishing yields, Section 13.5), because of interregional variability, but *high confidence* in the decrease in regulating services and coastal protection because of cascading effects of ecosystem impacts (Figure 13.11).

13.4.1.2 Projected Risks

Risks to marine and coastal European ecosystems are *very likely* to intensify (Figure 13.11) in response to projected further warming. Since the capacity of natural systems for autonomous adaptation is limited (Thomsen et al., 2017; Miller et al., 2018; Bindoff et al., 2019) (*medium confidence*), pronounced changes in community composition and biodiversity patterns are projected by 2100 for TEUS and the eastern Mediterranean Sea (SEUS) for> 3°C GWL (García Molinos et al., 2016), challenging conservation efforts (Corrales et al., 2018; Cramer et al., 2018; Kim et al., 2019). At 1.5°C GWL, particularly in winter, Mediterranean coastal fish communities are projected to lose ~10% of species, increasing to ~60% at 4°C GWL (Dahlke et al., 2020), exacerbating regime shifts linked to overexploitation (Clark et al., 2020) (*medium confidence*). Warming at this level will threaten many species currently living in Marine Protected Areas (MPA) in TEUS and NEUS (Bruno et al., 2018). Increasing marine heatwaves (MWH), particularly in SEUS at 4°C GWL (Darmaraki et al., 2019a), elevate risks for species (Galli et al., 2017), coastal biodiversity, and ecosystem functions, goods and services (Smale et al., 2019). However, MWH-related risk levels differ among biotas (Pansch et al., 2018) and across European seas (Smale et al., 2015).

Marine primary production is projected to further decrease by 2100 in most European seas between 0.3% at 1.5°C GWL to 2.7% at 4°C GWL (Figure 13.11) (*high confidence*), mainly caused by stratification-driven reductions in nutrient availability, impacting food webs (Doney et al., 2012; Laufkoetter et al., 2015; Wakelin et al., 2015; Salihoglu et al., 2017; Holt et al., 2018; Bryndum-Buchholz et al., 2019; Carozza et al., 2019; Kwiatkowski et al., 2019). In the Barents Sea, however, largely stable primary production is projected under all scenarios in response to sea-ice decline (Slagstad et al., 2011) and in the eastern Mediterranean due to reduced stratification (Macias et al., 2015; Moullec et al., 2019). These changes in productivity are projected to increase of fish and macroinvertebrate biomass between 5 and 22% (Moullec et al., 2019). Decreasing net primary production will impact higher trophic levels (Section 13.5.1), e.g., in TEUS (Holt et al., 2016; Holt et al., 2018). Marine animal biomass is projected to *likely* decline in most European waters, with decreases < 10% under all scenarios until the 2030s but losses growing to 25% at 2°C GWL and 50% at 4°C GWL in coastal waters of the NE Atlantic (Lotze et al., 2019; Bryndum-Buchholz et al., 2020).

Ocean acidification and its biological and ecological risks are projected to rise in European waters by impeding growth and reproductive success of vulnerable calcifying organisms (Figure 13.11) (*medium confidence*). Coralline algae are projected to reduce skeletal performance at 3°C GWL, with negative consequences for habitat formation (Ragazzola et al., 2016) (*medium confidence*). Regionally (Brodie et al., 2014), differences in species-specific vulnerability will result in community shifts from calcifying macroalgae (Ragazzola et al., 2013) (*medium confidence*) to non-calcifying macroalgae (Gordillo et al., 2016) *(high confidence*). Experimental studies demonstrated high resilience of some important habitat formers, such as the deep-water coral Lophelia pertusa (Wall et al., 2015; Morato et al., 2020), and habitat engineers, such as Mediterranean limpets (Langer et al., 2014), . facilitated by energy reallocation. However, if not supported by sufficient food availability (Thomsen et al., 2013; Clements and Darrow, 2018), such energy reallocation will negatively impact growth or reproduction (*medium confidence*) (Büscher et al., 2017). (Thomsen et al., 2013)This suggests that acidification risks will be amplified by increased stratification and reduced primary production (*medium confidence*). The emergence of harmful algal blooms and pathogens at higher GWLs is unclear across all European seas (Figure 13.11) (*low confidence*).

Risks to marine biotas and ecosystems in European seas are projected to impact important ecosystem services (Figure 13.11). Elevated CO_2 levels predicted at 4°C GWL will affect the C/N ratio of organic-matter export and, hence, the efficiency of the biological pump (*low confidence*), depending on the shifts in plankton composition and, hence, food-web structure (Taucher et al., 2020). Atlantic herring (*Clupea harengus*) will benefit with enhanced larval growth and survival from indirect food-web effects (Sswat et al., 2018a), whereas Atlantic cod (*Gadus morhua*) will face overall negative impacts (*medium confidence*) (Section 13.5, Stiasny et al., 2018; Stiasny et al., 2019). Anoxic dead zones in the Black (Altieri and Gedan, 2015) and the Baltic (Jokinen et al., 2018; Reusch et al., 2018) Seas are projected to increase, e.g., by 5% in the Baltic Sea at 4°C GWL (Saraiva et al., 2019). Europe's coastal vegetated 'blue-carbon' ecosystems (subtidal seagrass meadows and intertidal salt marshes) are highly vulnerable (Spencer et al., 2016; Schuerch et al., 2018; Spivak et al., 2019), particularly in microtidal areas such as the Baltic and Mediterranean coast. Losses are projected for *Posidonia oceanica* seagrass habitats in the Mediterranean by of up to 75% at 2.5°C GWL (*low confidence*) (Chapter 3). The Wadden Sea, the world's largest system of intertidal flats, is projected to reduce in surface area and height, as the sediment transport capacity limits the possibility of growth with rapidly rising sea levels (Wang et al., 2018; Jiang et al., 2020). For the Dutch Wadden Sea, the critical rate of 6 to 10 mm yr^{-1}, at which intertidal flats will start to 'drown', will be reached by 2030 at 1.5°C GWL (*medium confidence*), or even earlier through subsidence due to human activities (van der Spek, 2018). European coastal zones provided a total of €494 billion of ecosystem services in 2018, and 4.2 to 5.1% of this value will be lost due to coastal erosion by 2100 at 2.5°C and 4.6°C GWL, respectively (*medium confidence*) (Paprotny et al., 2021).

13.4.2 Solution Space and Adaptation Options

Human adaptation options for marine systems encompass socio-institutional adaptation, technology, and measures supporting autonomous adaptation (Chapter 3). Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP) are frameworks for addressing climate-change adaptation needs, as well as operationalizing and enforcing marine conservation. However, ICZM and MSP do commonly not explicitly take climate-change adaptation into consideration (Elliott et al., 2015), Transboundary ICZM and/or MSP (Gormley et al., 2015) will become even more important with the projected acceleration of range extensions and ecological regime shifts due to climate change (IPCC, 2019).

Many climate-change adaptation governance and implementation measures are embedded in international strategies, such as HELCOM (Baltic Marine Environment Protection Commission (HELCOM) (Backer et al., 2010), OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic) (OSPAR, 2009), and the Marine Strategy Framework Directive (MFSD) and European Water Framework Directive (EWFD) of the European Union. In the Russian Arctic, mainly the Barents Sea, conservation priority areas (CPA) have been identified as Ecologically and Biologically Significant Areas (EBSA) (Solovyev et al., 2017). However, plans are generally at a relatively early stage (Miller et al., 2018), and assessments of the effectiveness of these policy frameworks to accelerate climate-change adaptation are ongoing (Haasnoot et al., 2020a).

'Green' adaptations, either 'Ecosystem based Adaptations' or 'Nature based Solutions, are part of adaptive management strategies (European Comission, 2011) that facilitate coastal flood protection (Section 13.2.2; Chapter 3; CCC SLR) and generate benefits beyond habitat creation (*medium confidence*), e.g., from avoided expenditures for flood defence infrastructure and avoided loss of the built assets (Gedan et al., 2010). Marine Protected Areas (MPAs) have been identified as adaptation options for natural areas, including permitted and non-permitted uses (Chapter 3, Selig et al., 2014; Hopkins et al., 2016a; Roberts et al., 2017). The extent of MPAs has been increasing in Europe, albeit with strong regional variations (Figure 13.12). MPAs provide protection from local stressors, such as commercial exploitation, and enhance the resilience of marine and coastal ecosystems and thus lessen the impacts of climate change (*medium confidence*) (Narayan et al., 2016; Roberts et al., 2017). However, climate change risk reduction is only a limited MPA objective (Hopkins et al., 2016b; Rilov et al., 2019). The implementation of the legal frameworks, such as the EC Habitats Directive and EC Birds Directive, allows for enabling adaptation (Verschuuren, 2015) as does the incorporation of climate considerations in management of Natura 2000 sites (European Comission, 2013b).

There is evidence that better international cooperation is required to increase effectiveness of the MSFD (Cavallo et al., 2019), and the Good Environmental Status is currently not effectively monitored (Machado et al., 2019).

The greatest benefits are obtained from large, long established, no-take MPAs (Edgar et al., 2014). Yet most MPAs in Europe are partially protected or multi-use areas, and existing no-take areas tend to be very small (< 50 km^2). No take areas are accounting in total for less than 0.4% of the area European waters (Figure 13.12) and are often nested within multi-use MPAs. In some partially protected MPAs, local stressors, such as fishing, are higher than adjacent unprotected areas (*medium confidence*) (Zupan et al., 2018a; Mazaris et al., 2019). Despite evidence for climate mitigation benefits of no-take zones (Roberts et al., 2017), the efficacy of partial protected MPAs is debated and dependent on local management (Zupan et al., 2018b). MPAs of all types require effective management to contribute to mitigating climate change impacts, including effective monitoring and enforcement (Watson et al., 2014), yet the management effectiveness of European MPAs has repeatedly been called into question (Batista and Cabral, 2016; Amengual and Alvarez-Berastegui, 2018; Fraschetti et al., 2018; Rilov et al., 2019). Many MPAs lack management plans, and insufficient resources are frequently an issue (Álvarez-Fernández et al., 2017; Schéré et al., 2020). Thus, whilst substantial in potential, the current capacity of the European MPA network to reduce climate change impacts is limited (Jones et al., 2016; Claudet et al., 2020).

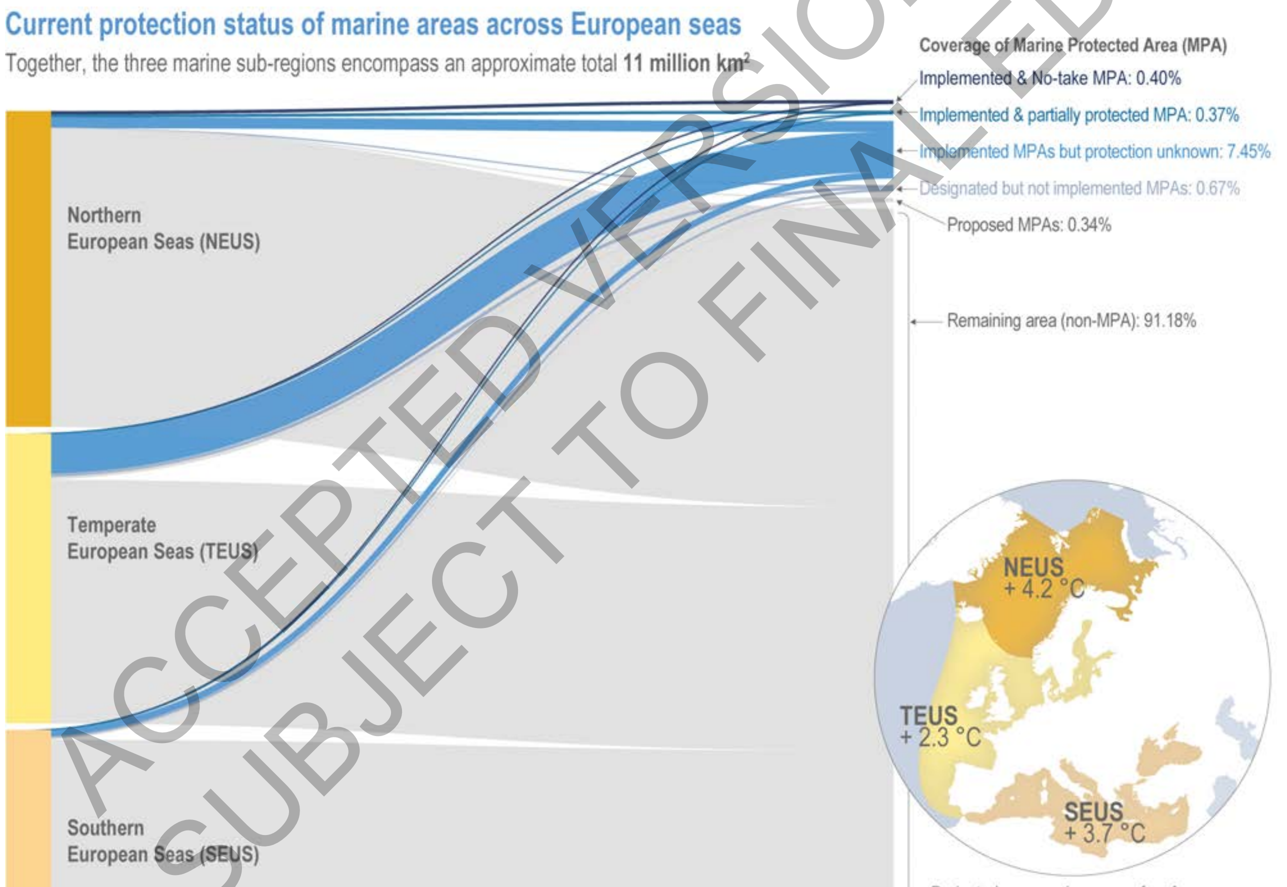


Figure 13.12: Marine Protected Areas (MPA) in European seas. Proportions of designated and proposed MPAs in the total areas of northern (NEUS), temperate (TEUS) and southern (SEUS) European seas, as well as the shares of no-take, partial, unimplemented and unknown protection levels of designated MPAs (Marine Conservation Institute, 2021). Moreover, the average increase of surface-sea temperatures (SST) at 4.0°C GWL by 2100 in NEUS, TEUS and SEUS is indicated.

Conservation approaches (MPAs, climate refugia), habitat restoration efforts (Bekkby et al., 2020), and further ecosystem-based management policies do support alleviation of or adaptation to climate-change impacts (*medium confidence*) but are themselves impacted by climate change (Chapter 3). Moreover, the interaction of adaptation and mitigation measures poses risks to marine systems. Many coastal regions of the North Sea, especially in the south, are particularly susceptible to rising sea levels because of the strong tidal regime and the effects of storm surges (Figure 13.3). Hard measures to protect human infrastructure against sea level rise (Section 13.2) will lead to loss of coastal habitats, with negative impacts on marine biodiversity (Cross-Chapter Box SLR in Chapter 3, Airoldi and Beck, 2007; Cooper et al., 2016). While rising sea levels will also directly threaten intertidal and beach ecosystems, coastal wetlands will benefit (*medium confidence*), in case lateral accommodation space and the opportunity for systems to migrate landwards and upwards is provided, enhancing their ability to capture and store carbon (Rogers et al., 2019) (WGIII AR6 Chapter 4). In general, European coastal blue-carbon ecosystems, e.g. seagrass meadows, kelp forests, tidal marshes (Bekkby et al., 2020) are potentially effective as carbon sinks in climate mitigation, akin to reforestration efforts on land (section 13.3). However, their expansion has the potential to interfere with other ecosystem services (Cadier et al., 2020) and biodiversity conservation (Howard et al., 2017; Chausson et al., 2020). The 'Blue Growth' strategy of the European Commission with the aim to increase offshore activities (European Comission, 2012) will increase the pressures on the marine environments (*medium confidence*). Large-scale offshore wind-park infrastructure is currently developed in European seas, mostly in the North Sea (WindEuropeBusinessIntelligence, 2019), as a major component of climate-change mitigation efforts (WGIII AR6 Chapter 6). The introduction of novel hard-substrate intertidal habitats has and will have profound ecological ramifications for marine systems, including hydrodynamic changes, stepping-stones for non-native species, noise and vibration, and changes of the food web (Lindeboom et al., 2011; De Mesel et al., 2015; Gill et al., 2018; Dannheim et al., 2019) (*high confidence*).

13.4.3 Knowledge Gaps

Major knowledge gaps are uncertainties and shortcomings in our understanding of combined, cascading and interacting impacts of climatic and non-climatic pressures on European marine and coastal socio-ecological systems (Korpinen et al., 2021). Further observational, experimental, and modelling work will enhance the insight into multiple drivers, processes and their interactions, strengthen the confidence of risk projections and provide a foundation for future adaptation actions.

There is limited knowledge about the connectivity among populations, species, and ecosystems which would provide new recruits, enable gene flow in Marine Protected Areas (MPA) networks (Dubois et al., 2016; Sahyoun et al., 2016), and facilitate assisted migration. MPAs cover a wide range of protection status with *limited evidence* which level of protection and connectivity is needed to achieve adaptations goals in response to future warming.

Although European seas and coasts are comparatively well-studied on a global scale, the spatial and temporal resolution and coverage of open-access data is still limited in many regions, particularly in eastern Europe. The detection and attribution of ongoing or emerging environmental and biological changes is therefore limited. Some efforts are in place, such as the six 'Sea-basin Checkpoints' (North Sea, Mediterranean Sea, Arctic, Atlantic, Baltic, Black Sea) that were established since 2013 under The European Marine Observation and Data Network, but high quality observations of key ocean characteristics at the level of regional sea-basins are still too scarce to support decision-making for marine adaptation (Míguez et al., 2019).

13.5 Food, Fibre, and Other Ecosystem Products

13.5.1 Observed Impacts and Projected Risks

13.5.1.1 Crop Production

Agriculture is the primary user of land in Europe. In 2013, Europe provided 28% of cereals, 59% of sugar beet and 60% of wine produced globally, as well as being part of a globalized food system with a third of the commodities produced and consumed in Europe traded internationally (FAOSTAT, 2019).

Observed climate change has led to a northward movement of agro-climatic zones in Europe and earlier onset of the growing season (Ceglar et al., 2019) (*high confidence*). Warming and precipitation changes since 1990 explain continent-wide reductions in yield of wheat and barley and increases in maize and sugar beet (*high confidence*) (Fontana et al., 2015; Moore and Lobell, 2015; Ray et al., 2015; Ceglar et al., 2017). Heat stress has increased in southern Europe in spring, in summer throughout central and southern Europe, and recently expanded into the southern boreal zone (Fontana et al., 2015; Ceglar et al., 2019). Drought, excessive rain, and the compound hazards of drought and heat (13.2.1, 13.3.1, 13.10.2) increased costs and cause economic losses in forest productivity (Schuldt et al., 2020) and annual and permanent crops and livestock farming (Stahl et al., 2016), including losses in wheat production in the EU (van der Velde et al., 2018) and EEU (Ivanov et al., 2016; Loboda et al., 2017) (*high confidence*), with the severity of impacts from extreme heat and drought tripling over last 50 years (Brás et al., 2021). Meteorological extremes due to compound effects of cold winters, excessive autumn and spring precipitation, and summer drought caused production losses (up to 30% relative to trend expectations) in 2012, 2016, 2018 (Ben-Ari et al., 2018; van der Velde et al., 2018; Zscheischler et al., 2018; Toreti et al., 2019b) that were exceptional compared to recent decades (Webber et al., 2020). Regionally, warming caused increases in yields of field grown fruiting vegetables, decreases in root vegetables, tomatoes and cucumbers (Potopová et al., 2017) and earlier flowering of olive trees (Garcia-Mozo et al., 2015) (*high confidence*). Delayed harvest due to both wet conditions and earlier harvests in central Europe in response to warming impacted wine quality (Cook and Wolkovich, 2016; van Leeuwen and Darriet, 2016; Di Lena et al., 2019).

Evidence for growing regional differences of projected climate risks is increasing since AR5 (*high confidence*). While there is high agreement of the direction of change, the absolute yield losses are uncertain due to differences in model parameterization and whether adaptation options are represented (*high confidence*) (Donatelli et al., 2015; Moore and Lobell, 2015; Knox et al., 2016; Webber et al., 2018). At 1.5°C GWL, compound events which led to recent large wheat losses are projected to become 12% more frequent (Ben-Ari et al., 2018). Growing regions will shift northward or expand for melons (Bisbis et al., 2019), tomatoes and grapevines reaching NEU and EEU in 2050 under 1.5°C GWL (Hannah et al., 2013; Litskas et al., 2019) (*high confidence*), while warming would increase yields of onions, Chinese cabbage and French beans (Bisbis et al., 2019) (*medium confidence*). In response to 2°C GWL, agro-climatic zones in Europe are expected to move northward 25-135 km/decade, fastest in EEU (Ceglar et al., 2019). Negative impacts of warming and drought are counterbalanced by CO_2 fertilization for crops such as winter wheat (*medium confidence, medium agreement*), resulting in some regional yield increases with climate change (Zhao et al., 2017; Webber et al., 2018).

Reductions in agricultural yields will be higher in the south at 4°C GWL, with lower losses or gains in the north (Figure 13.5, Trnka et al., 2014; Webber et al., 2016; Szewczyk et al., 2018) (*high confidence*). Largest impacts of warming are projected for maize in SEU (Deryng et al., 2014; Knox et al., 2016) (*high confidence*) with yield losses across Europe of 10-25% at 1.5-2°C GWL and 50-100% at 4°C GWL (Deryng et al., 2014; Webber et al., 2018; Feyen et al., 2020).

Use of longer season varieties can compensate for heat stress on maize in WCE and lead to yield increases for Northern Europe, but not SEU for 4°C GWL (Siebert et al., 2017; Ceglar et al., 2019) (*medium confidence*). Irrigation can reduces projected heat and drought stress, e.g., for wheat and maize (Ruiz-Ramos et al., 2018; Feyen et al., 2020), but use is limited by water availability (13.2.1; KR3). The advantages of a longer growing season in NEU and EEU are outbalanced by the increased risk of early spring and summer heat waves (Ceglar et al., 2019).

Warming causes range expansion and alters host pathogen association of pests, diseases and weeds affecting health for European crops (Caffarra et al., 2012; Pushnya and Shirinyan, 2015; Latchininsky, 2017) *(high confidence*) with high risk for contamination of cereals (Moretti et al., 2019). Regionally predicted reduction in rainfall (13.1) can lead to carryover of herbicides (Karkanis et al., 2018).

Net yield losses will reduce economic output in the EU from agriculture, reaching a reduction of 7% for the EU and UK combined, and 10% in SEU at 4°C GWL (Naumann et al., 2021). Farmland values are projected to decrease by 5-9% per degree of warming in SEU (Van Passel et al., 2017). Increased heat and drought stress and reduced irrigation water availability will decreased profitability and cause abandonment of farmland in SEU (Holman et al., 2017) (*limited evidence, low confidence*).

13.5.1.2 Livestock Production

Heat and humidity affect livestock directly exposed in open barns and outdoors, such as dairy cows and goats (Gauly et al., 2013; Bernabucci et al., 2014; Silanikove and Koluman, 2015), and cold adapted husbandry (Box 13.2, Section 13.8.3) (*high confidence*). Heat impacts animal health (Sanker et al., 2013; Lambertz et al., 2014), nutrition, behaviour and welfare (Heinicke et al., 2019), performance and product quality (Gauly and Ammer, 2020). Climate change also impacts grassland production, fodder composition and quality, particularly in SEU (Dumont et al., 2015) and EEU (Bezuglova et al., 2020), as well as altering the prevalence, distribution and load of pathogens and their vectors (2.4.2.7.3) (Morgan et al., 2013; Charlier et al., 2016) (*high confidence*). Projected impacts on poultry and pigs are low due to temperature control in large parts of Europe, but greater in SEU where open systems prevail (Chapter 5).

Warming increases the pasture growing season and farming period in NEU and at higher altitudes (Fuhrer et al., 2014), while longer drought periods and thunderstorms can influence abandonment of remote Alpine pastures, reducing cultural and landscape ecosystem services and losing traditional farming practices (Herzog and Seidl, 2018) (*high confidence*) (Section 13.8.3). At 2-4°C GWL grassland biomass production for forage-fed animals will increase in NEU and the northern Alps, while forage production will decrease in SEU and the southern Alps due to heat and water scarcity (Gauly et al., 2013; Jäger et al., 2020), causing regional reductions of cow milk production in WCE and SEU (Silanikove and Koluman, 2015) (*high confidence*).

13.5.1.3 Aquatic Food Production

Seafood production in Europe provides jobs for >250,000 people, predominantly in SEU (Carvalho et al., 2017). Marine fisheries contribute 80% to European aquatic food production, while marine aquaculture provides 18% and freshwater production 3% (Blanchet et al., 2019). The Russian Federation provides 1/4 of seafood production in Europe (FAOSTAT, 2019).

Climate change has impacted European marine food production (*high confidence*). However, extraction is still the major impact on commercially important fish stocks in Europe (Mullon et al., 2016), with 69% of stocks overfished and 51% outside safe biological limits (Froese et al., 2018). The North Sea, the Iberian coastal Sea and Celtic Sea-Biscay Shelf are globally among the areas most negatively affected by warming with losses of 15-35% in maximum sustainable yields (MSY) during the last decades (Free et al., 2019). Warming caused ongoing northward movement and range expansion of Northeast Atlantic fish stocks (13.4, Baudron et al., 2020). In the North Sea, cuttlefish (van der Kooij et al., 2016; Oesterwind et al., 2020) and tuna (Bennema, 2018; Faillettaz et al., 2019) became new target species (*medium confidence*). In SEU, warm-water species increasingly dominate fisheries landings (Fortibuoni et al., 2015; Teixeira et al., 2016; Vasilakopoulos et al., 2017).

European countries are assessed to be globally among the least vulnerable to the impacts of climate change on fisheries-related food security risks (*high confidence*) due to low levels of exposure to climate hazards, low dependency of economies on fisheries and a high adaptive capacity (Barange et al., 2014; Ding et al., 2017). European freshwater production is suggested to be less vulnerable than marine sectors and marine production vulnerability increases with latitude (Blanchet et al., 2019). In the aquaculture sector Norway is highly vulnerable due to high sensitivity of salmon farming to warming and high per-capita production (Handisyde et al., 2017). In the fisheries sector, vulnerability for fishing communities is highest in SEU and UK (Figure 13.9A , Handisyde et al., 2017; Payne et al., 2021), while for aquaculture sectors it is highest in SEU and some NEU and WCE countries (Figure 13.9B, 2020).

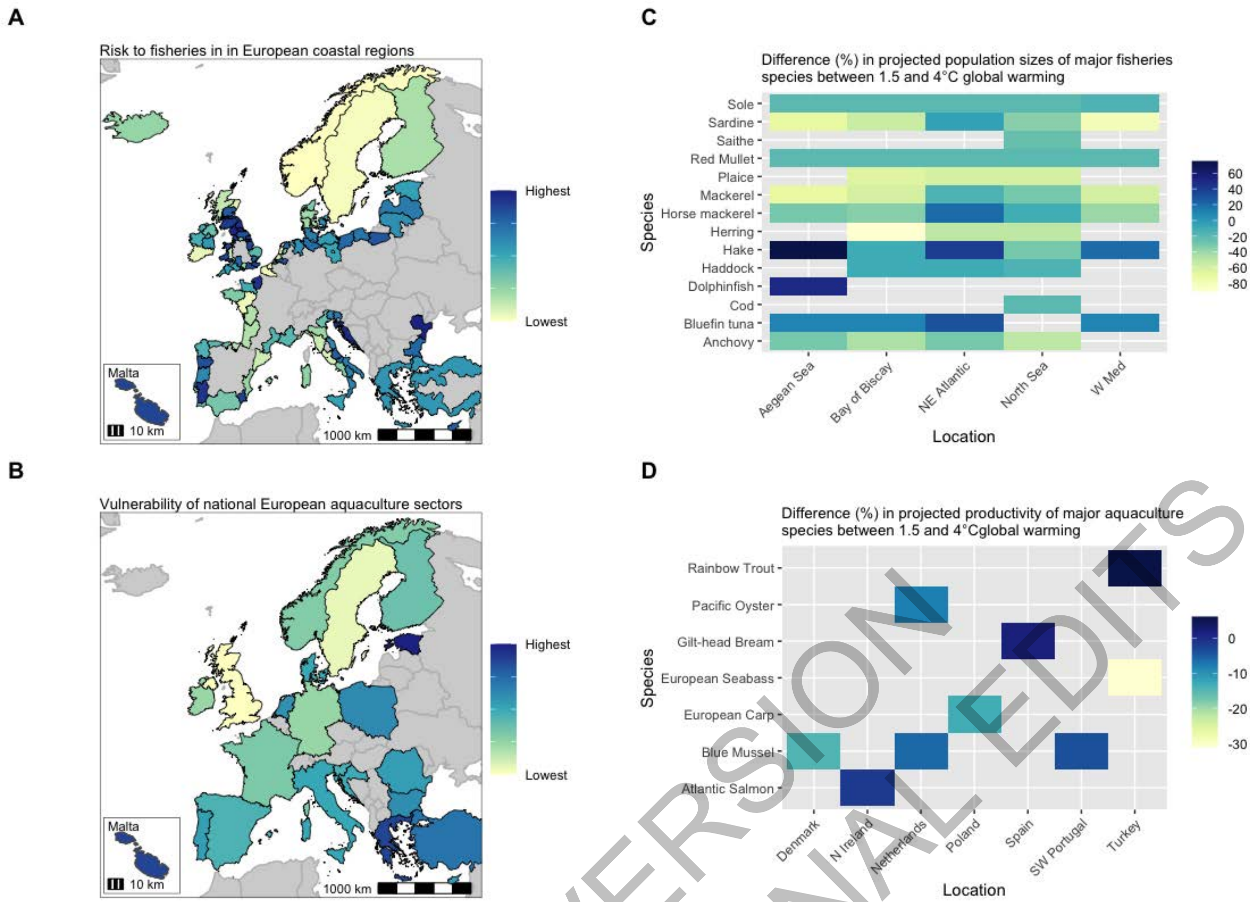


Figure 13.13: Future vulnerability and risks for aquatic food production. (a) Vulnerability for fisheries in 105 coastal regions across 26 countries based on biological traits and physiological metrics of 556 resource populations (Payne et al., 2021); (b) Vulnerability of major aquaculture species in European countries on physiological attributes, farming methods and economic output (Peck et al., 2020); (c-d) Differences (%) between projected changes for 1.5°C and 4°C global warming (Peck et al., 2020), with (c) changes in abundance of major fish species by region, and (d) changes in productivity of major aquaculture species by country.

Future vulnerabilities, risks and opportunities are projected to strongly vary regionally and between major fisheries and aquaculture species (Peck et al., 2020) (Figure 13.13 c,d). Assuming MSY-management, projections suggest reduced abundance of most commercial fish stocks in European waters of 35% (up to 90% for individual stocks) between 1.5°C and 4.0°C GWL (Peck et al., 2020; Payne et al., 2021) (*medium confidence*) (Figure 13.13). In response to 4°C GWL, higher trophic level biomass is projected to increase in the SEUS mainly due to increases of small pelagic and thermophilic, often exotic species (Moullec et al., 2019).

Ocean acidification (Section 13.4, Chapter 4) will develop into a major risk for marine food production in Europe under 4°C GWL (*high confidence*), affecting recruitment of important European fish stocks such as those of cod in the Western Baltic and Barents Sea by 8 and 24%, respectively (Sswat et al., 2018b; Stiasny et al., 2018; Voss et al., 2019). Acidification is also projected to negatively affect marine shellfish production and aquaculture in Europe with 4°C GWL (*medium confidence*) (Fernandes et al., 2017; Narita and Rehdanz, 2017; Mangi et al., 2018).

13.5.1.4 Forestry and Forest Products

Climate change is altering the structure and function of European forests via changes in temperature, precipitation and atmospheric CO_2 as well as through interaction with pests and fire (13.3.1) (Moreno et al., 2018; Morin et al., 2018; Senf et al., 2018; Orlova-Bienkowskaja et al., 2020) (*high confidence*). Species-specific responses of trees to drier summers (Vitali et al., 2018) shape regional variability in European forest productivity in response to water and nutrient availability, heat wave and evaporative demand (Reyer et al., 2014; Kellomäki et al., 2018). While warming and extended growing seasons have positive impacts on forest growth in cold areas in WCE and NEU (Pretzsch et al., 2014; Matskovsky et al., 2020), EEU (Tei et al., 2017) and higher altitude (Sedmáková et al., 2019), drought stress across Europe has been increasing (Primicia et al., 2015; Marqués et al., 2018; Ruiz-Pérez and Vico, 2020) (*high confidence*). Combined with land-use, climate change has increased large scale forest mortality since the 1980s (Senf et al., 2018). Extreme events such as the 2018 drought in WCE caused widespread leaf shedding and mortality of trees (Buras et al., 2020) with carryovers into 2019 (Schuldt et al., 2020) and bark beetle outbreaks (Netherer et al., 2019) resulting in felling and cuttings of more than 1 Million ha of spruce forest and disrupting timber markets (Mauser, 2021).

In response to 3°C GWL, forest productivity is projected to increase in NEU and altitudes, show mix trends in WCE and decreases in SEU (Reyer et al., 2014) (*medium confidence*). This trend is driven by increases in productivity of pine and spruce and decreases of beech and oak and excludes disturbances and management options (Reyer et al., 2014). Water stress exacerbates the incidence from and effects of fire and other natural disturbances (13.3.1), resulting in forest productivity declines or cancelling out productivity gains from CO_2 (Seidl et al., 2014; Reyer et al., 2017) (*high confidence*). In response to 1.7 °C GLW, managed forest and unmanaged woodland areas are projected to decrease only minimally, while at >2.5°C GLW declines increasing for managed forest and unmanaged woodland area increases (Harrison et al., 2019). Reducing warming from 4°C GLW to below 1.7 °C GLW would reduce the Europe wide impacts on managed forest by 34% (Harrison et al., 2019).

13.5.2 Solution Space and Adaptation Options

The solution space for climate change adaption for food and timber includes production related options (13.5.2.1 - 13.5.2.3) and market-based changes to consumer demand and trade (13.5.2.4). The assessment of effectiveness and feasibility of options in the food system is summarised in Figure 13.14.

Effectiveness & feasibility of adaptation options for food system to climate impacts & risk in Europe

Impact Type	Adaptation Option	Effectiveness	Feasibility						Confidence	
			Economic	*Technological*	*Institutional*	*Socio-cultural*	*Ecological*	*Geophysical*	*Evidence*	*Agreement*
Heat stress	Irrigation	M	M	H	M	L	L	L	M	M
	Change of sowing/harvest date	M	H	H	NL	M	M	H	H	M
	Change of cultivars	L	M	M	NL	M	M	H	M	M
Drought	Irrigation	H	H	M	M	H	L	L	H	H
	Change of sowing/harvest date	M	H	H	NL	M	M	H	M	M
	Change of cultivars	L	M	M	NL	M	M	H	H	M
	Soil management	M	M	M	H	M	H	M	L	M
Flooding	Change of sowing/harvest date	L	L	M	NL	H	M	L	L	M
Compound & extreme weather	Plant & livestock breeding, including GMO	M	M	L	L	M	M	M	M	M
	Mixed use - agroecology & agroforestry	H	M	M	L	L	H	M	M	M
	Agricultural policy changes	M	M	M	M	M	M	H	L	H
	Training & information	L	M	NL	M	M	M	H	L	M
	Crop selection changes	M	H	H	NL	L	L	L	L	L
	Land cover change, incl. agricultural land abandonment	L	M	M	L	L	L	L	L	L
Disease pathogen & vectors	Plant & livestock breeding, including GMO	NL	NL	L	L	L	NL	NL	L	NL
	Management, including high frequency rotations	NL	NL	NL	NL	NL	NL	NL	L	NL
Combined impacts on productivity	International trade changes	M	M	NL	L	M	L	M	L	M
	Consumer shifts in consumption	NL	M	NL	NL	L	NL	NL	L	M

Legend
High = H
Medium = M
Low = L
No/Limited Evidence = NL

Figure 13.14: Effectiveness and feasibility of the main adaptation options for food systems in Europe. (SM13.9 and Table SM13.5).

13.5.2.1 Crops and Livestock

Farm management adaptations options to climate change include changing sowing and harvest dates, changes in cultivars, irrigation and selecting alternative crops (Figure 13.14, 13.15) (Donatelli et al., 2015). Irrigation is effective at reducing yield loss from heat stress and drought, e.g., for wheat and maize (Figure 13.14, 13.15), but increases demand for water withdrawals (Siebert et al., 2017; Ruiz-Ramos et al., 2018; Feyen et al., 2020). Where sufficient water and infrastructure is available, irrigation of wheat reverses yield losses across Europe at 2°C GWL to become gains, while yield losses in maize in SEU are reduced from up to 80% to 11% (Feyen et al., 2020). Extensive droughts during the last two decades caused many irrigated systems in southern Europe to cease production (Stahl et al., 2016) indicating limited adaptive capacity to heat and drought (*medium confidence*). Water management for food production on land is becoming increasingly complex due to the need to satisfy other social and environmental water demands (KR3, 13.10) and is limited by costs and institutional coordination (Iglesias and Garrote, 2015). Agricultural water management adaptation practices include irrigation, reallocating of water to other crops, improving use efficiency, and soil water conservation practices (Iglesias and Garrote, 2015). In-season forecasts of climate impacts on yield have successfully been used in the 2018 drought for European wheat (van der Velde et al., 2018).

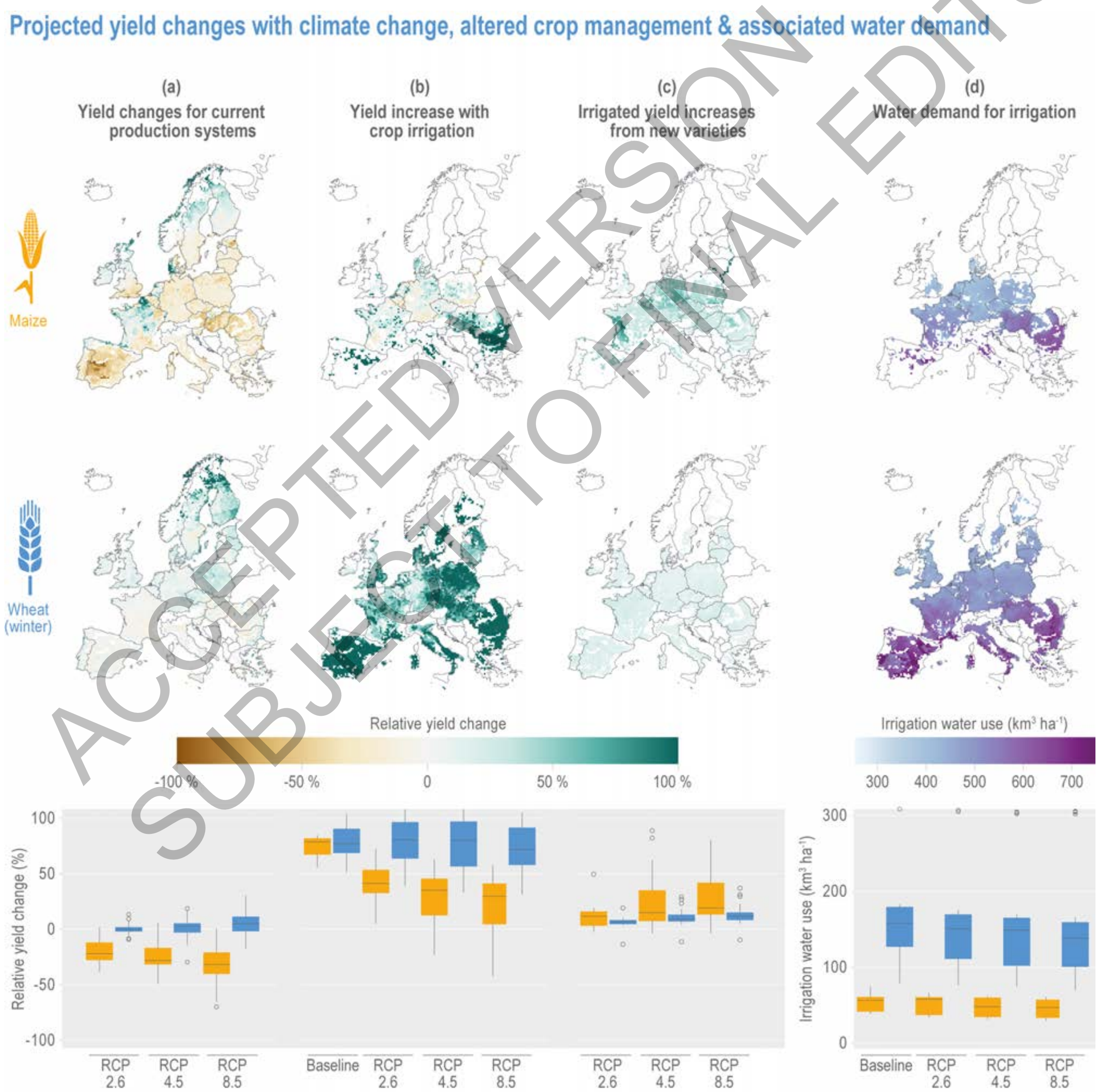


Figure 13.15: Projected yield changes with climate change for 1.5 °C GWL (RCP 2.6), 1.7 °C (RCP4.5) and 2°C GWL (RCP8.5) and altered crop management, and associated water demand, showing: (a) relative yield changes under climate change and elevated CO_2 for current production systems, i.e. rainfed and irrigated simulations weighted by

current share of rainfed and irrigated areas; (b) yield increase if current predominantly rainfed areas are full irrigated; (c) additional yield increases for irrigated production systems if new varieties used to avoid losses associated with faster development and earlier maturity under climate change; and, (d) water demand for irrigated systems with current varieties in currently rainfed areas (Webber et al., 2018). Relative yield changes to a period centred on 2055 to a baseline period centred on 1995. Boxplots are Europe aggregate results considering current production areas (a) or current rainfed areas (b, c) with boxplots showing uncertainty across crop models and GCMs. The maps are for the crop model median for RCP 4.5 (1.7°C GWL) with GFDL-CM3.

Changes to cultivars and sowing dates can reduce yield losses (Figure 13.15), but are insufficient to fully ameliorate losses projected >3℃ GWL, with an increase of risk from north to south and for crops growing later in the season such as maize and wheat (*high confidence*) (Ruiz-Ramos et al., 2018; Feyen et al., 2020). Adaptations for early maturing reduce yield loss by moving the cycle towards a cooler part of year, and also constrains the increases in irrigation water demands, but reduce the period for photosynthesis and grain filling (*high confidence*) (Ruiz-Ramos et al., 2018; Holzkämper, 2020). Crop breeding for drought and heat tolerance can improve sustainability of agricultural production under future climate (Costa et al., 2019), particularly in SEU where drought tolerant varieties provide 30% higher yields than drought-sensitive varieties at 3°C GWL (Senapati et al., 2019). Soil management practices, such as crop residue retention or improved crop rotations, generally undertaken as a mitigation option to increase soil carbon sequestration, are not commonly evaluated for adaptation in European agriculture (Hamidov et al., 2018).

Adaptation practices for livestock systems on European farms commonly focus on controlling cooling, shade provision and management of feeding times (Gauly et al., 2013). These options are used in indoors reared species (Gauly et al., 2013), but limited in mountain pastures (Deléglise et al., 2019) (*high confidence)*. Response options to insufficient amount and quality of fodder include changing feeding strategies (Kaufman et al., 2017; Ammer et al., 2018), feed additives (Ghizzi et al., 2018), relocating livestock linked to improved pasture management, organic farming (Rojas-Downing et al., 2017; EEA, 2019c), importing fodder and reducing stock (Toreti et al., 2019b). Dairy systems that maximize the use of grazed pasture are considered more environmentally sustainable, but are not fully supported by policy and markets (Hennessy et al., 2020) (*medium confidence*). Genetic adaptation of crops, pasture and animals could be a long-term adaptation strategy (Anzures-Olvera et al., 2019; Deléglise et al., 2019). Control strategies for pathogens and vectors include indoor or outdoor rearing and applying new diagnostic tools or drugs (Bett et al., 2017; Vercruysse et al., 2018), and regulations to ensure safe trade and reduce risks of introducing or spreading pests (European Comission, 2016).

Agro-ecological systems provide adaptation options that rely on ecological process (e.g., soil organic matter recycling and functional diversification) to lower inputs without impacting productivity (Cross-Chapter Box NATURAL in Chapter 2 , Aguilera et al., 2020). High frequency rotational grazing and mixed livestock systems are agro-ecological strategies to control pathogens (Aguilera et al., 2020). Agroforestry, integrating trees with crops (silvoarable), livestock (silvopasture), or both (agrosilvopasture) can enhance resilience to climate change (Chapter 5), but implementation in Europe needs improved training programs and policy support (Hernández-Morcillo et al., 2018) (*high confidence*).

Technological innovations including “smart farming” and knowledge training can strengthen farmers’ responses to climate impacts (Deléglise et al., 2019; Kernecker et al., 2019), although strong belief in “technosalvation” by farmers (Ricart et al., 2019) can reduce the solution space and timing of adaptation options. Agricultural policy, market prices, new technology and socio-economic factors play a more important role in short-term farm-level investment decisions than climate change impacts (Juhola et al., 2016; Hamidov et al., 2018) (*high confidence*).

Effective policy guidance is needed to increase the climate-resilience of agriculture (Spinoni et al., 2018; Toreti et al., 2019b). Financial measures include simplifying procedures for obtaining subsidies and insurance premiums and interest rates that incentivise adoption of climate friendly agricultural methods (Garrote et al., 2015; Iglesias and Garrote, 2015; Zakharov and Sharipova, 2017; Hamidov et al., 2018; Wiréhn, 2018). The EU’s Common Agricultural Policy has increasingly focused on environmental outcomes (AllianceEnvironnement, 2018) but does not sufficiently provide for adaptation measures (Leventon et al., 2017; Pe'er et al., 2020). Limits to European farm-level adaptation include lack of resources for investment, political urgency to adapt, institutional capacity, access to adaptation knowledge and information from other countries (EEA, 2019c).

13.5.2.2 Aquatic Food

Climate-resilient fish production in Europe is the goal of the European Union's Common Fisheries Policy (CFP) rebuilding fish stocks to maximum sustainable yield (MSY) levels, but success has been variable (Froese et al., 2018; Stecf, 2019). Adaptation is largely ignored in related EU policy frameworks such as the CFP, the Marine Strategy Framework Directive, and the "Strategic guidelines for the sustainable development of EU aquaculture." (Pham et al., 2021). A major governance challenge for adaptation will be the redistribution of the fixed allocation scheme for total allowable catches (Harte et al., 2019; Baudron et al., 2020). Inflexible and non-adaptive allocation schemes can result in conflicts among European countries (*medium confidence*), as demonstrated by the case of the North East Atlantic mackerel (Spijkers and Boonstra, 2017).

The development of adaptation strategies for seafood production since the Paris Agreement is insufficient in Europe (*high confidence*) (Kalikoski et al., 2018; Pham et al., 2021). Concrete plans for adaptation planning towards climate-ready fisheries and aquaculture are lacking in all parts of Europe (European Comission, 2018), especially accounting for the expected reduced landings of traditional target species and in preparation for a new portfolio of resource species (Blanchet et al., 2019).

Recent scientific progress towards adaptation in European fisheries and aquaculture include conceptual guidance and demonstration cases on climate adaptation planning (Pham et al., 2021) and climate vulnerability assessments (Blanchet et al., 2019; Peck et al., 2020; Payne et al., 2021). Socio-political scenarios for European aquatic resources have been developed and have the potential to inform adaptation planning by European fisheries and aquaculture sectors (Kreiss et al., 2020; Hamon et al., 2021; Pinnegar et al., 2021).

13.5.2.3 Forests

Forest management has been adopted as a frequent strategy to cope with drought, reduce fire risk, and maintain biodiverse landscapes and rural jobs (Hlásny et al., 2014; Fernández-Manjarrés et al., 2018). Successful adaptation strategies include altering the tree species composition to enhance the resilience of European forests (Schelhaas et al., 2015; Zubizarreta-Gerendiain et al., 2017; Pukkala, 2018) (*high confidence*). Greater diversity of tree species reduces vulnerability to pests and pathogens (Felton et al., 2016) and increases resistance to natural disturbances (Jactel et al., 2017; Pukkala, 2018; Pardos et al., 2021) (*high confidence*). Depending on forest successional history (Sheil and Bongers, 2020), tree composition change can increase carbon sequestration (Liang et al., 2016), biodiversity and water quality (Felton et al., 2016) (*high confidence*). Conservation areas can also help climate change adaptation by keeping the forest cover intact, creating favourable microclimates and protecting biodiversity (Jantke et al., 2016) (*low confidence*).

Reforestation reduces warming rates (Zellweger et al., 2020) and extremely warm days (Sonntag et al., 2016) inside forests reducing natural disturbances and fires (*high confidence*). Active management approaches can limit the impact of fires (13.3.1) on forest productivity, including fuel reduction management, prescribed burning, changing from conifers to deciduous, less flammable species, and recreating mixed forests (Feyen et al., 2020) and agroforestry (Damianidis et al., 2020).

13.5.2.4 Demand and Trade

An increasing globalized food system makes European nations sensitive to supply chain disturbances in other parts of the world, but also provides capacity to adapt to production shifts within Europe through changes in international trade (Section 13.9.1) (Alexander et al., 2018; Challinor et al., 2018; Ercin et al., 2021). Consumer demand for food and timber products can adapt to productivity changes and be mediated by price (e.g., in response to production changes or policies on food related taxation), reflect changes in preferences (e.g., towards plant-based foods motivated by environmental, ethical or health concerns), or reductions in food waste (Alexander et al., 2019; Willett et al., 2019) (*high confidence*). Although mitigation potentials of dietary changes have received increasing attention, evidence is lacking on potential for adaptation through changes in European food consumption and trade, despite these socio-economic factors being a strong driver for change (Harrison et al., 2019, Kebede, 2021, Integrated assessment of the food-water-land-ecosystems nexus in Europe: Implications for sustainability) (*medium confidence*). Calls are increasing across Europe for sustainable and resilient agri-food systems acknowledging interdependencies between producers and consumers to deliver healthy, safe and nutritional foods and services (Venghaus and Hake, 2018) (Section 13.7).

13.5.3 Knowledge Gaps

Aggregated projections of impacts, especially of combined hazards, are still rare despite many physiological papers on species specific response to warming in all food sectors (*high confidence*). This is specifically true for scenarios that consider land use change and population growth, though Agri SSPs are currently being developed (Mitter et al., 2019). Effectiveness of adaptation options is predominantly qualitatively mentioned but not assessed and effectiveness of combinations of measures is rarely assessed (Ewert et al., 2015; Holman et al., 2018; Müller et al., 2020) (*high confidence)*. Effective adaptation planning would be supported by better modelling and scenario development including improved coupled nature-human interactions, e.g., with more realistic representation of behaviours beyond economic rationality and 'bottom-up' autonomous farmer adaptations, as well as greater stakeholder involvement.

Coverage of impacts and adaptation options in Europe are biased towards the EU28 and have gaps within the eastern part of WCE and EEU, despite dramatic changes in land use over the recent decades in Russia and Ukraine (*high confidence*) which have the potential to increase production and export of agricultural products, especially wheat, meat and milk (Swinnen et al., 2017).

A bias towards modelling of cereals, specifically wheat and maize, results in gaps in knowledge for fruit and vegetables, especially for temperate regions in Europe (Bisbis et al., 2019). The assessment of irrigation needs and the impact of CO_2 and O_3 tend to focus on individual species and processes hindering upscaling to multiple stressors and mixed production (Challinor et al., 2016; Webber et al., 2016) (*high confidence*).

There is a lack of actionable adaptation strategies for European fisheries and aquaculture. Knowledge gaps include adaptive capacities of local fishing communities to a new mix of target species and the consumer acceptance of the product. Increased knowledge on the effects on freshwater fisheries and their resources is also needed.

13.6 Cities, Settlements and Key Infrastructure

Urban areas in Europe offer home to 547 million inhabitants, corresponding to 74% of the total European population (UN/DESA, 2018). In the EU-28, 39% of the total population lives in metropolitan regions (i.e., areas with at least one million inhabitants) where 47% of the total GDP is generated (Eurostat, 2016). Apart from urban settlements, this section also covers energy and transport systems, as well as tourism, industrial and business sectors which are key for livelihood, economic prosperity and well-being of residents.

13.6.1 Observed Impacts and Projected Risks

13.6.1.1 Energy Systems

The energy sector in Europe already faces impacts from climate extremes (*high confidence*). Significant reductions and interruptions of power supply have been observed during exceptionally dry and/or hot years of the recent 20-year period, e.g. in France, Germany, Switzerland and UK during the extremely hot summer of 2018 which led to water cooling constraints on power plants (van Vliet et al., 2016b; Abi-Samra, 2017; Vogel et al., 2019). Heating degree days decreased and cooling degree days increased during 1951-2014, with clearer trends after 1980 (De Rosa et al., 2015; Spinoni et al., 2015; EEA, 2017b). Projected climate risks for energy supply are summarized in Figure 13.16.

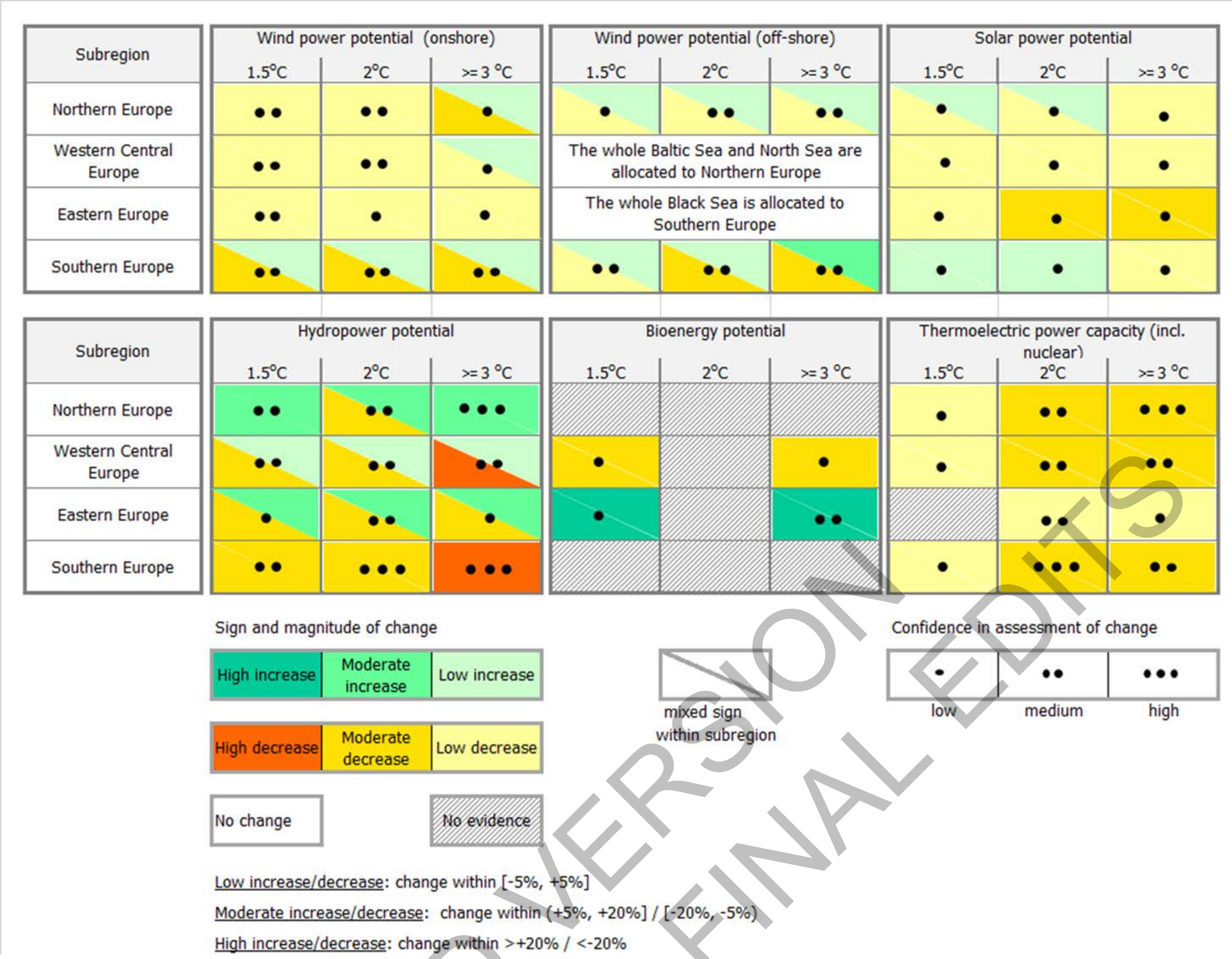


Figure 13.16: Projected climate change risks for energy supply in Europe for major sources and under 1.5 °C, 2 °C and >3 °C GWL (Tables SM13.5.6-13).

New studies reinforce the findings of AR5 on risks for thermoelectric power and regional differences between NEU and SEU regarding risks for hydropower (Figure 13.16). In NEU and EEU, extremely high water inflows to dams are projected to increase flooding risks for plant and nearby settlements (Chernet Haregewoin et al., 2014; Porfiriev et al., 2017), while increasing temperatures could reduce the efficiency of steam and gas turbines (Porfiriev et al., 2017; Cronin et al., 2018; Klimenko et al., 2018a). Water scarcity may limit onshore carbon capture and storage in some regions (Byers et al., 2016; Murrant et al., 2017; EEA, 2019a).

Reduced surface wind speeds during 1979-2016 (Frolov et al., 2014; Perevedentsev and Aukhadeev, 2014; Tian et al., 2019) support projected trends in decreasing onshore wind energy potential. Seasonal changes may result in reductions in many areas in summer (by 8-30% in Southern Europe) and increases in most of NEU during winter. Increasing probabilities and persistence of high winds over the Aegean and Baltic Seas (Weber et al., 2018a) could create new opportunities for offshore wind. The future configuration of the wind fleet will affect the spatial and temporal variability of wind power production (Tobin et al., 2016). Total backup energy needs in Europe could increase by 4-7% by 2100 (Wohland et al., 2017) with potentially larger seasonal changes (Weber et al., 2018b).

There is *low evidence* and *limited agreement* on projections of solar power potential due to differences in the integration of aerosols and the estimated cloud cover between climate models (Bartok et al., 2017; Boé et al., 2020; Gutiérrez et al., 2020). Studies on climate risks for bioenergy are also limited.

Energy demand is projected to display regional differences in response to global warming beyond 2ºC GWL, with a the significant southwest-to-northeast decrease of heating degree days by 2100 (particularly in northern Scandinavia and Russia), and a smaller north-to-south increase of cooling degree days (Porfiriev et al., 2017; Spinoni et al., 2018; Coppola et al., 2021). Under present population numbers, total energy demand would decrease in almost all Europe, whereas it could increase in some countries (e.g. UK, Spain, Norway) when considering Eurostat's population projections (Klimenko et al., 2018b; Spinoni et al., 2018).There is *medium confidence* that peak load will increase in SEU and decrease in NEU (Damm et al., 2017; Wenz et al., 2017; Bird et al., 2019). Beyond 2ºC GWL, a shift of peak load from winter to summer in many countries is possible (Wenz et al., 2017). Together with water-cooling constraints for thermal power, this change in load may challenge the stability of electricity networks during heatwaves (EEA, 2019a). Technological factors, increased electricity use and adaptation influence significantly the temperature sensitivity of electricity demand and consequently risks (Damm et al., 2017; Wenz et al., 2017; Cassarino et al., 2018; Figueiredo et al., 2020). Potential power curtailments or outages during climatic extremes may increase electricity prices (Pechan and Eisenack, 2014; Steinhäuser and Eisenack, 2020).

13.6.1.2 Transport

Heatwaves in 2015 and 2018 in parts of WCE and NEU caused road melting, railway asset failures, and speed restrictions to reduce the likelihood of track buckling (Ferranti et al., 2018; Vogel et al., 2019). Recent studies on projected risks focus mainly on infrastructure and much less on transport flows and disruptions.

Sea level rise (section 13.2) may disrupt port operations and surrounding areas, mainly in parts of NEU and WCE (Christodoulou et al., 2018), while changes of waves agitation could increase non-operability hours of some Mediterranean ports beyond 2°C GWL (Sierra et al., 2016; Camus et al., 2019; Izaguirre et al., 2021). Low water level days at some critical locations for inland navigation at the Rhine river are projected to increase beyond 2ºC GWL, while decreases at the Danube river are possible (van Slobbe et al., 2016; Christodoulou et al., 2020).

Risks of rutting and blow-ups of roads (particularly in low altitudes) due to high summer temperatures are expected to increase in WCE and EEU at 3ºC GWL (*medium confidence*) (Frolov et al., 2014; Matulla et al., 2018; Yakubovich and Yakubovich, 2018). In EEU and northern Scandinavia, the higher number of freezing-thawing cycles of construction materials will increase risks for roads (Frolov et al., 2014; Yakubovich and Yakubovich, 2018; Nilsen et al., 2021) while warming beyond 2ºC GWL could significantly reduce road maintenance costs in NEU (Lorentzen, 2020), but limiting off-road overland transport in north-western Russia (Gädeke et al., 2021). Beyond 3ºC GWL, more frequent hourly precipitation extremes are projected over WCE and NEU in summer (e.g. 2-fold and 10-fold increase for events exceeding the present-day 99.99th percentile in Germany and UK) but more widely across Europe in autumn and winter (increase higher than 10-fold for 99.99th percentile events in southern Europe in autumn (Chan et al., 2020), potentially severely damaging roads as happened in Mandra, Greece in 2017 (Diakakis et al., 2020). Landslide risks in WCE and SEU could increase beyond a 2ºC GWL, threatening road networks (Schlogl and Matulla, 2018; Rianna et al., 2020).

Current flood risk for railways could double or triple at 1.5-3°C GWL, particularly in WCE, increasing public expenditure for rail transport in Europe by €1.22 billion annually under 3°C GWL and no adaptation (Bubeck et al., 2019). Thermal discomfort in urban underground railways is expected to increase, even at a high level of saloon cooling (Jenkins et al., 2014a).

The number of airports vulnerable to inundation from sea level rise and storm surges may double between 2030 and 2080 without adaptation, especially close to the North Sea and Mediterranean coasts (Christodoulou and Demirel, 2018). Rising temperatures reducing lift generation could impose weight restrictions for large aircraft at 2ºC GWL and beyond in airports of France, UK and Spain (Coffel et al., 2017). There is a lack of studies quantifying the effect of future extreme events on flight arrivals at and departures from European airports.

13.6.1.3 Business and Industry

European industrial and service sectors contribute 85% to Gross Value Added in EU-28 (Eurostat, 2020); while their direct exposure and vulnerability is smaller compared to sectors directly reliant on weather, they are directly and indirectly affected by heat, flooding, water scarcity and drought (Weinhofer and Busch, 2013; Gasbarro and Pinkse, 2016; Meinel and Schule, 2018; Schiemann and Sakhel, 2018; TEG, 2019). Heat reduces the productivity of labour particularly in construction, agriculture and manufacturing (García-León et al., 2021; Schleypen et al., 2021) (section 13.7.1). Direct losses from floods in Europe are highest for manufacturing, utilities, transportation; indirect losses arise e.g. for manufacturing, construction, and banking and insurance (Koks et al., 2019a; Sieg et al., 2019; Mendoza-Tinoco et al., 2020). Drought and water scarcity directly affect European industries in the sectors of pulp and paper, chemical and plastic manufacturing and food and beverages (Gasbarro et al., 2019; Teotónio et al., 2020); additionally, drought may indirectly affect sectors relying on shipping, hydropower, or public water supply (Naumann et al., 2021). The European financial and insurance sector is affected by climate change impacts via their customers and financial markets (Bank of England, 2015; Georgopoulou et al., 2015; Battiston et al., 2017; TCFD, 2017; Bank of England, 2019; de Bruin et al., 2020; Monasterolo, 2020).

The vulnerability to climate hazards varies by European region, type of risk, sector and business characteristics (Gasbarro et al., 2016; Forzieri et al., 2018; ECB, 2021a; Kouloukoui et al., 2021). Current damages are mainly related to river floods and storms, but heat and drought will become major drivers in the future (*medium confidence*); until 2050, the probability of default of firms located in particularly exposed locations may increase to up to four times of that of an average firm in all sectors (ECB, 2021a).

Many European sectors are exposed to multiple and cross-cutting risks (Gasbarro et al., 2019; Schleypen et al., 2021). Indirect effects via supply chains, transport and electricity networks can be as high as or substantially higher than direct effects (*medium confidence*) (Koks et al., 2019a; Koks et al., 2019b; Knittel et al., 2020).

13.6.1.4 Tourism

Snow cover duration and snow depth in the Alps decreased since the 1960s (Klein et al., 2016; Schöner et al., 2019; Matiu et al., 2021). Despite snowmaking, the number of skiers to French resorts at low elevations during the extraordinary warm/dry winters of 2006/2007 and 2010/2011 was 12-26% lower (Falk and Vanat, 2016).

Due to reduced snow availability and hotter summers, damages are projected for the European tourism industry, with larger losses in SEU (*high confidence*) and some smaller gains in the rest of Europe (*medium confidence*) (Ciscar et al., 2014; Roson and Sartori, 2016; Dellink et al., 2019).

At 2°C GWL, the operation of low altitude resorts without snowmaking will *likely* be discontinued, while beyond 3°C GWL snowmaking will be a necessary but not always sufficient for most resorts in many European mountains and parts of NEU (Pons et al., 2015; Joly and Ungureanu, 2018; Scott et al., 2019; Spandre et al., 2019). Expanding snowmaking is capital-intensive and will strongly increase water and energy consumption, particularly at 3°C GWL and beyond (Spandre et al., 2019; Morin et al., 2021), adversely affecting the financial stability of small resorts (Pons et al., 2015; Falk and Vanat, 2016; Spandre et al., 2016; Joly and Ungureanu, 2018; Moreno-Gené et al., 2018; Steiger and Scott, 2020). Permafrost degradation due to rising temperatures is expected to create stability risks for ropeway transport infrastructure at high-altitude Alpine areas (Duvillard et al., 2019).

Climatic conditions from May to October at 1.5-2°C GWL are projected to become more favourable for summer tourism in NEU and parts of WCE and EEU, while there is *medium confidence* on opposite trends for SEU from June to August (Grillakis et al., 2016; Scott et al., 2016; Jacob et al., 2018; Koutroulis et al., 2018). The amenity of European beaches may decrease as a result of sea level rise amplifying coastal erosion and inundation risks, although less in NEU (Ebert et al., 2016; Toimil et al., 2018; Lopez-Doriga et al., 2019) (Section 13.2 and Ranasinghe et al., 2021 Section 12.4.5).

13.6.1.5 Built Environment, Settlements and Communities

Expected shift of European residents to large cities and coastal areas will increase assets at risk (Section 13.2). The share of urban population in Europe is projected to increase from 74% in 2015 to 84% in 2050, corresponding to 77 million new urban residents (UN/DESA, 2018), with most of this increase in SEU and WCE (particularly in Turkey and France). In the EU-28, urban residents in 2100 may increase by about 30 million under SSP1 and SSP5, and decrease by 90-110 million under SSP3 and SSP4 (Terama et al., 2019).

About 32% of 571 European cities in the GISCO Urban Audit 2014 dataset show a medium to high or relatively high vulnerability against heatwaves, drought and floods (Tapia et al., 2017). Under current vulnerabilities, future climate hazards will augment climate risks for several cities, particularly beyond 3°C GWL (Figure 13.17). In many NEU cities, a high increase in pluvial flooding risk by the end of the century is possible, while in WCE cities may face a high increase in pluvial flooding risks, moderate to very high increase in extreme heat risk, and to some extent moderate to high increase in drought risk. Many SEU cities could face a high to very high increase in risks from extreme heat and meteorological drought.

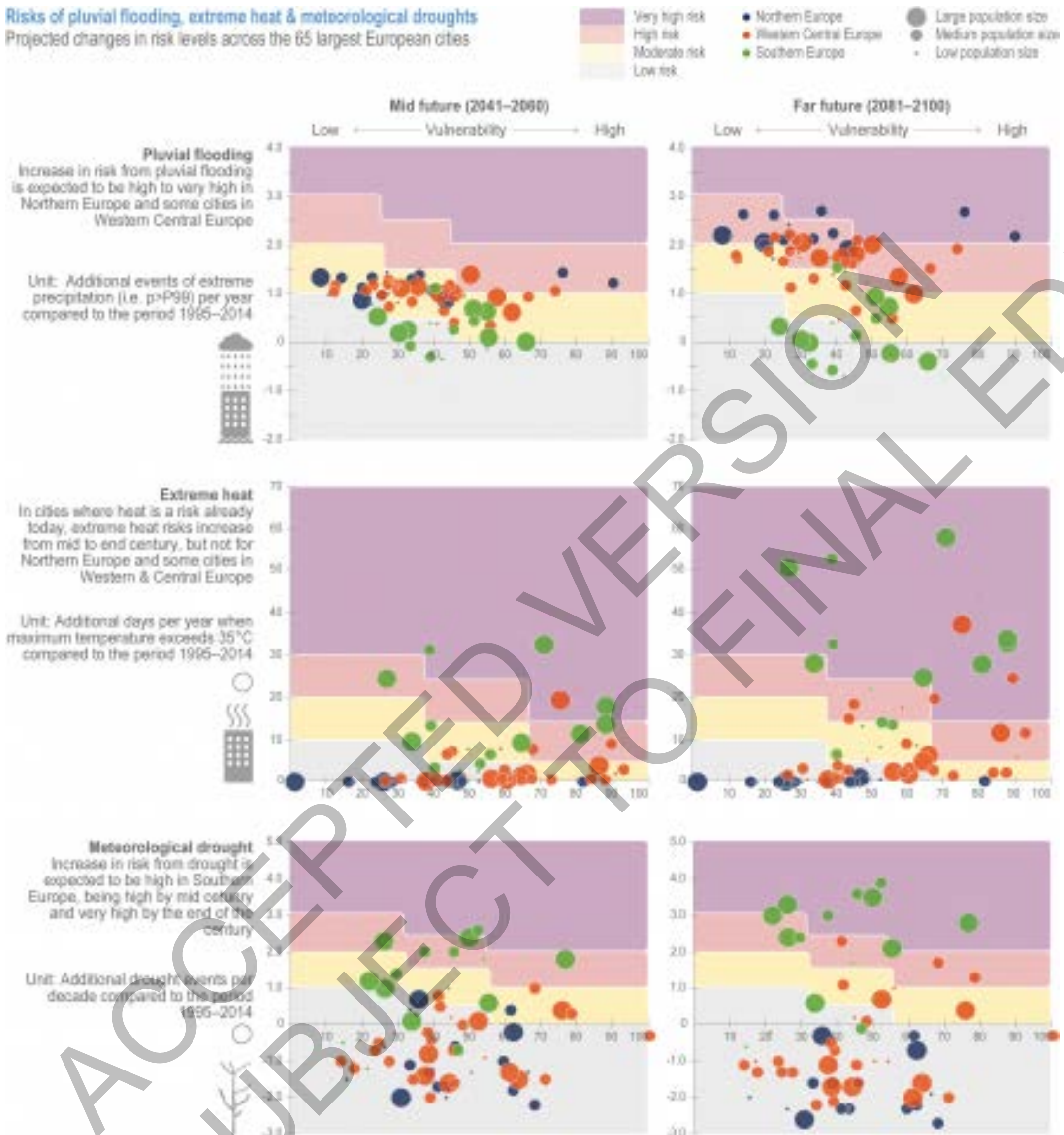


Figure 13.17: Projected changes in pluvial flooding, extreme heat and meteorological drought risks for the 65 largest cities in EU-28 plus Norway and Switzerland for 2.5°C GWL and 4.4°C GWL compared with the baseline (1995-2014) (Tapia et al., 2017). Exposure is expressed in terms of current population. Values of climatic impact-drivers are derived from the Euro-CORDEX regional climate model ensemble.

13.6.1.5.1. Risks from coastal, river and pluvial flooding

New studies increase confidence in AR5 statements that flood damages will increase in coastal areas due to sea level rise and changing social and economic conditions (section 13.2.1.1). Except for areas affected by land uplift, it is projected that further adaptation will be required to maintain risks at the present level for most coastal cities and settlements (Haasnoot et al., 2013; Ranger et al., 2013; Malinin et al., 2018; Hinkel et al., 2019; Umgiesser, 2020).

In many cities, the sewer system is older than 40 years, potentially reducing their capacity to deal with more intense pluvial flooding (EEA, 2020c). Apart from climate change, urbanization is an important driver for increases in flooding risks as it results in growth of impervious surfaces. Flash floods are particularly challenging, causing the overburdening of drainage systems (Dale et al., 2018), urban transport disruptions, and health and pollution impacts due to untreated sewage discharges (Kourtis and Tsihrintzis, 2021).

More than 25% of the population in nearly 13% of the EU-cities lives within potential river floodplains. In many of these, e.g. 50% of UK cities, a significant increase of the 10-year high river flow is possible beyond 2°C GWL under a high-impact scenario (i.e. 90th percentile of projections) (Guerreiro et al., 2018; EEA, 2020c).

13.6.1.5.2 Risks from heatwaves, cold waves and drought

Heatwave days and number of long heatwaves increased in most capitals from 1998-2015 compared to 1980-1997 (Morabito et al., 2017; Seneviratne et al., 2021). In the summer of 2018, many cities suffered from heatwaves attributed to climate change (Vogel et al., 2019; Undorf et al., 2020). As a result, indoor overheating and reduced outdoor thermal comfort, often coupled with urban heat island (UHI) effect, have already impacted European cities (Di Napoli et al., 2018; EEA, 2020c) (see also Section 13.7.1).

Heatwaves are *likely* to become a major threat not only for SEU but also for WCE and EEU cities (Russo et al., 2015; Guerreiro et al., 2018; Lorencova et al., 2018; Smid et al., 2019).At 2ºC GWL and SSP3, half of1.1 the European population will be under very high risk of heat stress in summer (Rohat et al., 2019). The UHI effect will further increase urban temperatures (Estrada et al., 2017). In many cities, hospitals and social housing tend to be located within the intense UHI, thus increasing exposure to vulnerable groups (EEA, 2020c). There is *high confidence* that overheating during summer in buildings with insufficient ventilation and/or solar protection will increase strongly , with thermal comfort hours potentially decreasing by 74% in locations of southern Europe at 3ºC GWL (Jenkins et al., 2014a; Hamdy et al., 2017; Heracleous and Michael, 2018; Dino and Meral Akgül, 2019; Shen et al., 2020). Highly insulated buildings, following present building standards, will be vulnerable to overheating, particularly under high GWL levels, unless adequate adaptation measures are applied (Williams et al., 2013; Virk et al., 2014; Mulville and Stravoravdis, 2016; Fosas et al., 2018; Ibrahim and Pelsmakers, 2018; Salem et al., 2019; Tian et al., 2020). Cities in NEU and WCE are more vulnerable due to limited solar shading and fewer air conditioning installations (Ward et al., 2016; Thomson et al., 2019). Cooling energy demand in SEU buildings has been projected to increase by 81-104% by 2035 and by 91-244% after 2065 compared to 1961-1990 depending on GWL (Cellura et al., 2018). Increases of 31-73% by 2050 and by 165-323% by 2100 compared to 1996-2005 were estimated for buildings in NEU (Dodoo and Gustavsson, 2016) with risks modified by adaptation (Viguié et al., 2020) (see section 13.6.2). Cold waves beyond 3ºC GWL will not represent an effective threat for European cities at the end of the century, and only a marginal hazard under 2ºC GWL (Smid et al., 2019).

At 2ºC GWL and beyond, cities in SEU and large parts of WCE would exceed the historical maximum 12-month Drought Severity Index of the past 50-years (on drought risks see Section 13.2) and 30% will have at least 30% probability of exceeding this maximum every month (Guerreiro et al., 2018). This could adversely affect the operation of municipal water services (Kingsborough et al., 2016). For example, under 2ºC GWL, the reservoir storage volume is predicted to decrease for all of England and Wales catchments, resulting in a probability of years with water use restrictions doubling by 2050 and quadrupling by 2100 compared to 1975-2004 (Dobson et al., 2020). The combination of high temperatures, drought, and extreme winds, potentially coupled with insufficient preparedness and adaptation, may amplify the damage of wildfires in peri-urban environments (13.3.1.3). High fuel load combined with proximity of the built environment to wildland highly increases fire risks (EEA, 2020c).

Extreme heat and drought causes shrinking and swelling of clays, threatening the stability of small houses in peri-urban environments (Pritchard et al., 2015), with damage costs of € 0.9-1 billion during the 2003 heatwave (Corti et al., 2011). In WCE and SEU, mean annual damage costs could increase by 50% for 2°C GWL, and by a factor of 2 for 3°C GWL (Naumann et al., 2021).

13.6.1.5.3 Risks from thaw of permafrost and mudflows

Increasing temperatures in NEU and the Alps lead to accelerated degradation of permafrost, negatively affecting the stability of infrastructures (Stoffel et al., 2014; Beniston et al., 2018; Duvillard et al., 2019). In the Caucasus, glacial mudflows due to permafrost degradation and modern tectonic processes pose a significant danger to the infrastructure (Vaskov, 2016). In the last 30 years, the permafrost temperature in the European part of the Russian Arctic has increased by 0.5-2.0°C, resulting to damages of buildings, roads and pipelines and to significant expenditure for stabilizing soils (Porfiriev et al., 2017; Konnova and Lvova, 2019). Beyond 3ºC GWL, the bearing capacity for infrastructure in the permafrost region of the European Russia could decrease by 32-75% by mid-century and by 95% by 2100, potentially affecting settlements in northern EEU (Shiklomanov et al., 2017; Streletskiy et al., 2019). Increasing number of cycles of freezing and thawing, observed in EEU, led to accelerated aging of building envelopes (Frolov et al., 2014) (13.8.1.4). Permafrost degradation due to higher temperatures could increase the potential of debris flow detachment in Alpine locations (13.6.1.4, Damm and Felderer, 2013).

Increased precipitation falling on local topography can increase landslide and mudflow risks, as seen in settlements at the Caucasus mountainous region (Marchenko et al., 2017; Efremov and Shulyakov, 2018; Kerimov et al., 2020). At the Umbria region in Italy, landslide events could increase by 16-53% under 2ºC GWL and by 24-107% beyond 3ºC GWL, mostly during winter (Ciabatta et al., 2016). Risks from shallow landslides are expected to increase in the Alps and Carpathians if no adequate risk mitigation measures are in place (CCP5.3.2, Gariano and Guzzetti, 2016).

13.6.2 Solution Space and Adaptation Options

Monetary assessments of future damages from climate extremes on critical infrastructures show a sevenfold escalating figures by 2080s (Figure 13.18) compared to the baseline (Forzieri et al., 2018), highlighting the need for adaptation.

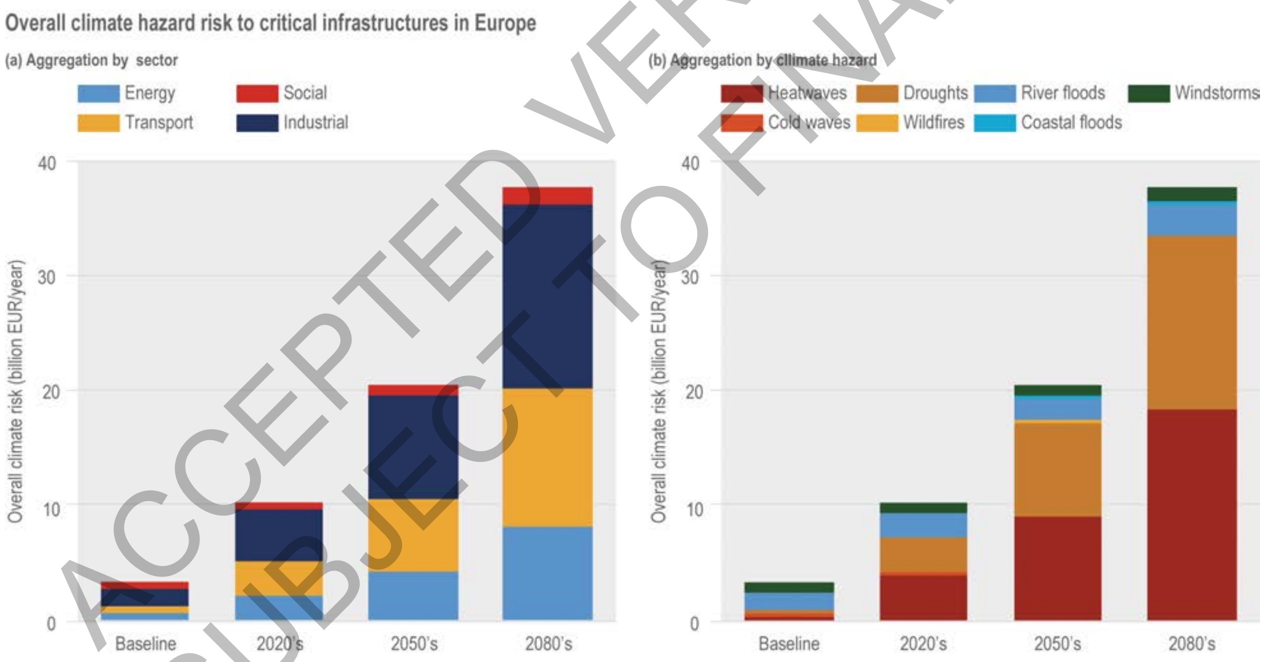


Figure 13.18: Climate risks to critical infrastructures, aggregated at European (EU+) level under the SRES A1B scenario (Forzieri et al., 2018). Baseline: 1981-2010. 2020s: 2011–2040. 2050s: 2041–2070. 2080s: 2071–2100.

13.6.2.1 Current Status of Adaptation

There is new evidence on increasing adaptation planning in cities, settlements, and key infrastructure, but less on implemented adaptation (Table 13.1; Box 13.3; Figure 13.36), adaptation by private actors and by cities against sea level rise (Chapter 16; CCP2).

Table 13.1: Present status of planned and implemented adaptation in cities, energy sector, tourism sector, transport and industry in Europe

	General commitments / Adaptation Plans	Implemented adaptation actions
Cities	• Increasing number of cities acknowledging the critical role of adaptation in building resilience to climate change. • Of 9609 European municipalities in the Covenant of Mayors for Climate & Energy (CoM), 2221 reported on adaptation through the CoM platform, 429 provided some information on adaptation goals, risk and vulnerability assessments/action plans, and 230-290 reported adaptation goals and funds for adaptation. Extreme heat, droughts and forest fires are the most often reported hazards. • Most urban adaptation plans include ecosystem-based measures (but often with insufficient baseline information and lack of convincing implementation actions). • Adaptation to risks from climate extremes (mostly flooding) is often addressed through municipal emergency plans.	• Large cities are in the process of implementation (e.g., Helsinki, Copenhagen, Rotterdam, Barcelona, Madrid, London, Moscow). • Many cities have implemented measures potentially supporting adaptation but not labelled as such. • Current climate policies implemented at city-scale are primarily addressing mitigation and, to a lesser extent adaptation. • Increasing use of Nature-based Solutions (NbS) and ecosystem-based adaptation (EbA) to address urban heating and the discontinuity of the urban water cycle due to surface sealing and limited infiltration. • Strategic, tactical, and emergency measures applied for drought management (e.g., London, Istanbul)
Energy	• 29 countries (in place in 14 and in progress in 15). • Few countries have considered specific adaptation actions (mostly preparatory) in their national or energy-specific risk assessments.	• 11 countries (actions implemented in 5 and in progress in 6)
		• Measures undertaken by some distribution system operators (DSOs) and energy companies, focusing on adaptation of transmission lines, water cooling, dams for avoiding flooding during intense precipitation events, actions to avoid flooding and to secure fuel supply.
Tourism	• Consideration of tourism in national adaptation strategies is limited, and national tourism strategies rarely mention adaptation. • Tourism operators do not consider longer term adaptation strategies to be relevant. • Legally binding consideration of climate change when constructing new tourism units (e.g., the 2016 French Mountain Act).	• 18-67% of ski slopes (67% in Austria, 39% in Switzerland, 18% in Bavaria-Germany, 20% in French Alps, and 45% in Spain apply snowmaking. • Resorts offering nocturnal skiing (e.g., Spain) and other snow-based activities. Transformation to all-year mountain resorts (e.g., 70% of Spanish ski resorts).
		• Some diversification of tourism products offered in Mediterranean coastal destinations. • Implementation of water saving measures, primarily for cost reduction.
Transport	• Only 10 countries have started coordination activities or identified adaptation measures. • An integrated, trans-modal approach to adaptation is lacking. • Few countries are mainstreaming of adaptation within transport planning and decision-making (e.g., the 'Low-water Rhine' action plan and in Germany).	• Only in 5 countries. • Majority of actions are preparatory. • Actions mostly focus on infrastructure and much less on services, although the latter have started gaining ground (e.g., operational forecasts for water levels in rivers). • Transport modes often compete for public funds, and political priorities for specific modes often influence adaptation
	• Some action is undertaken in the public and private sector, e.g., revised manuals/guidelines/ protocols to consider climate change impacts and extreme events (e.g., Deutsche Bahn, Norwegian Public Roads Administration).	• Some public and private actors are moving faster: new railway drainage standards (Network Rail/ UK), prediction of adverse weather events (Spanish rail service operator), measures against coastal flooding (Copenhagen Metro), measures for sea level rise (Rotterdam port and France).
Industry and business	• Recommendation of the High Level Expert Group on Sustainable Finance ((HLEG) that the European Commission endorses and implements the guidelines provided by the Task force on Climate-Related Financial Disclosure in 2019.	• 50 of European large listed companies publicly disclosed their climate risks in 2020; yet only a small share provided specifics on sectoral risks, how risks differ over time and by different climate scenarios • Large national/multinational companies, and companies regulated by mitigation policy are first movers in corporate adaptation, while small and medium-sized enterprises often lack knowledge and resources to address risks and adaptation options. • Development of different tools (stress testing, scenario analysis, value at risk) by climate service providers, insurance companies and central banks

Legend: Well-established adaptation | Advancing adaptation | Low adaptation

Although urban adaptation is underway, many small, economically weak (i.e. with low GDP/capita) or cities facing high climate change risks lack adaptation planning (Reckien et al., 2015; EEA, 2016). While almost all large municipalities in NEU and WCE report implemented actions at least in one sector, this is not the case for 39% of municipalities in SEU (Aguiar et al., 2018). In the UK, the legal requirement to develop urban adaptation plans has been a significant driver for their widespread adoption (Reckien et al., 2015). The availability of and access to funding for adaptation is also crucial for plan development (section 13.11.1). Network membership (e.g., ICLEI, C40, Covenant of Mayors for Climate & Energy) is an important driver for city planning and transfer of best practices (Heikkinen et al., 2020a). Stakeholder engagement is key for successful adaptation (Bertoldi et al., 2020)(see Chapter 17).

Only 29% of local adaptation plans are mainstreamed in cities, which could reduce the effectiveness of implementing adaptation (Reckien et al., 2019) (13.11.1.2). Although large municipalities usually fund the implementation of their adaptation plans, smaller and less populated municipalities (particularly in SEU and EEU) often depend on intergovernmental, international and national funding.

13.6.2.2 Adaptation Options as a Function of Impacts

Examples of adaptation options in Europe are presented in Figure 13.19.

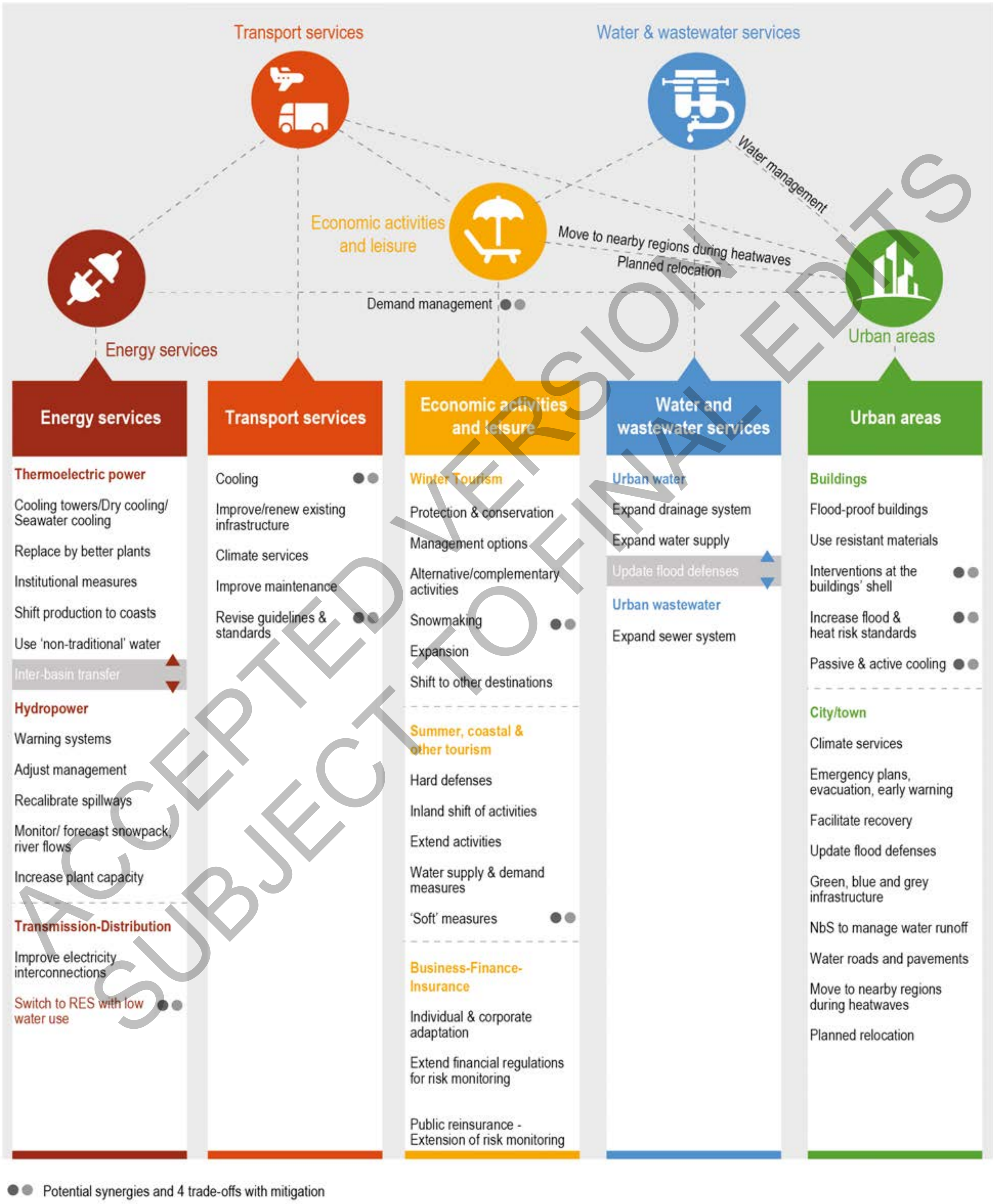


Figure 13.19: Adaptation options in cities, settlements, and key infrastructure in Europe (Table SM13.7).

Nature-based solutions (NbS) and ecosystem-based adaptation (EbA) such as green spaces, ponds, wetlands and green roofs for urban stormwater management and vegetation for heat mitigation represent an emerging adaptation option in cities. Combined with traditional water infrastructure, they can contribute to managing urban flood events (Kourtis and Tsihrintzis, 2021), playing a role in mitigating flood peaks (Pour et al., 2020) and protecting critical urban infrastructure (Ossa-Moreno et al., 2017). For example, in the Augustenborg district of Malmö, Sweden, using nature to manage stormwater runoff resulted in capturing an estimated 90% of runoff from impervious surfaces and reduced the total annual runoff volume from the district by about 20% compared to the conventional system (EEA, 2020c). Urban greening is associated with lower ambient air temperature and relatively higher thermal comfort during warm periods (Bowler et al., 2010; Oliveira et al., 2011; Cohen et al., 2012; Cameron et al., 2014). The scale and relative degree of management or integration of approaches drawing on nature with ‘engineered’ solutions affect their vulnerability to climate change. Small-scale urban NbS are relatively less vulnerable due to increased capacity for intervention, while the relatively greater contact between stakeholders and urban NbS (compared with larger-scale, rural approaches) provides greater opportunity for human intervention to ensure the survival of urban vegetation during droughts or heatwaves.

When selecting and combining adaptation options, challenges remain on how to address uncertainties of climate projections and climatic extremes (Fowler et al., 2021) and to translate scientific input into practical guidance for adaptation (Dale, 2021) (Section 13.11.1.3).

An assessment of the feasibility and effectiveness of main adaptation options, based on literature, is presented in Figure 13.20; for adaptation to flood risk, see Figure 13.6.

Effectiveness & feasibility of main adaptation options to climate impacts & risk for cities, settlements & key infrastructure in Europe

Impact types	Adaptation options	Effectiveness	Feasibility: Economic	Technological	Institutional	Socio-cultural	Ecological	Geophysical	Confidence: Evidence	Agreement
Reduction of thermal comfort due to increasing temperatures & extreme heat	Interventions in the building shell	M	M	L	M	L	NL	M	M	M
	Ventilation (natural/mechanical, incl. night)	M	M	H	M	L	NL	M	H	M
	Air conditioning	H	L	NL	NL	L	NL	M	L	M
	Shading	M	L	H	L	M	NL	L	M	M
	Green roofs, green walls	L	M	M	L	M	M	M	M	M
	Urban green spaces	L	L	M	L	M	M	M	L	M
	Use of 'cool' paints & coatings	L	H	M	L	M	NL	H	M	M
	Escape to nearby non-urban destinations	NL	NL	NL	NL	M	NL	NL	L	H
Loss of critical services due to heatwaves & drought	Improvements in cooling systems	M	L	M	M	NL	NL	M	H	M
	Shifting production to less water-intensive plants	M	M	M	L	NL	NL	NL	L	H
	Regulatory measures	L	M	NL	M	NL	NL	NL	L	M
	Management measures	M	M	M	M	NL	L	M	M	M
	Use of heat-resilient materials	L	H	L	M	M	NL	NL	L	H
	Replace vulnerable infrastructure with resilient one	L	M	NL	NL	NL	NL	NL	L	H

Legend
High = H
Medium = M
Low = L
No/Limited Evidence = NL

Figure 13.20: Effectiveness and feasibility of main adaptation options for cities, settlements and key infrastructure in Europe (SM13.9 and Table SM13.8).

There are gaps of knowledge on the social, environmental and geophysical dimension of feasibility for many options and a holistic assessment of different options is largely lacking. This latter could reveal unintended impacts from and synergies or trade-offs between options, as in water and wastewater services (Dobson and Mijic, 2020).

13.6.2.3 Adaptation Limits, Residual Risks, Incremental and Transformative Adaptation

Adaptation in cities, settlements and key infrastructure in Europe faces technical, environmental, economic and social limits (Figure 13.21).

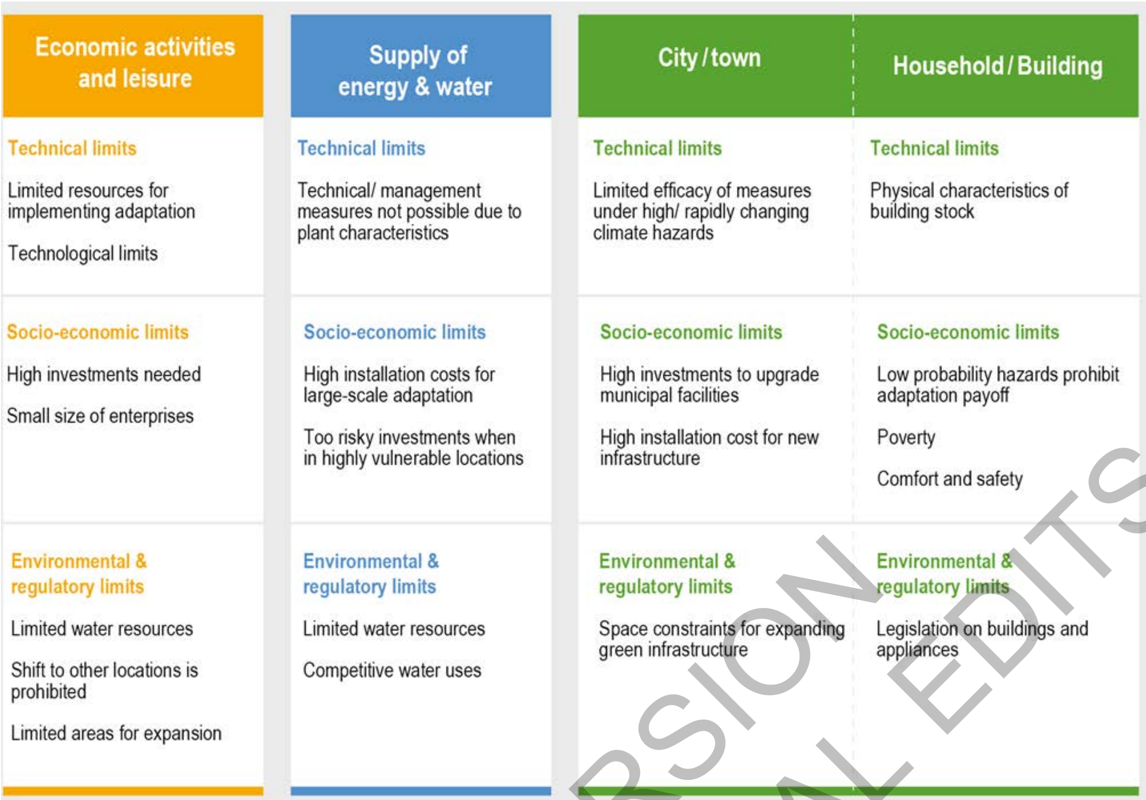


Figure 13.21: Indicative adaptation limits in cities, settlements and key infrastructure in Europe (Table SM13.16).

Adaptation options for many sectors will not be sufficient to remove residual risks, e.g. regarding overheating in buildings under high GWL, (Tillson et al., 2013; Virk et al., 2014; Dodoo and Gustavsson, 2016; Mulville and Stravoravdis, 2016; Hamdy et al., 2017; Heracleous and Michael, 2018; Dino and Meral Akgül, 2019); snowmaking beyond 3°C GWL (Scott et al., 2019; Steiger et al., 2020; Steiger and Scott, 2020); hydropower (Gaudard et al., 2013; Ranzani et al., 2018); electricity transmission and demand (Bollinger and Dijkema, 2016; EEA, 2019a; Palkowski et al., 2019); urban subways (Jenkins et al., 2014a); and flood mitigation in cities (Skougaard Kaspersen et al., 2017; Umgiesser, 2020). Some adaptation actions in a sector may also have side-effects on others, increasing their vulnerability (Pranzini et al., 2015) (sections 13.2.2 and 13.2.3).

Examples of transformative adaptation in urban areas are observed (e.g., the Benthemplein water square, the Floating Pavilion in Rotterdam and the Hafencity flood proofing in Hamburg), but they often remain policy experiments and prove challenging to upscale (Jacob, 2015; Restemeyer et al., 2015; Restemeyer et al., 2018; Holscher et al., 2019). The active involvement of local stakeholders, public administration and political leaders are drivers for community transformation, whereas lack of local resources and/or capacities are frequently reported barriers to change (Fünfgeld et al., 2019; Thaler et al., 2019).

13.6.2.4 Governance and Insurance

Urban adaptation plans can enhance resilience and their development is mandatory in the UK, France, and Denmark (Reckien et al., 2019). There is *medium confidence* that the development of urban adaptation planning is much more influenced by a city's population size, present adaptive capacity and GDP per capita than by anticipated climate risks (Reckien et al., 2018). A high organizational capacity in a municipality may not be a necessary condition for forward-looking investment decisions on urban water infrastructure, although enablers differ for small versus medium-to-large municipalities (Pot et al., 2019). There is large in-country variation in policy mixes utilized by local governments for supporting adaptation (Lesnikowski et al., 2019). In early adapter cities (e.g., Rotterdam), adaptation is institutionally embedded in climate, resilience and sustainability-related actions and collaboration between city departments, government levels, businesses, and rest stakeholders (Holscher et al., 2019). In most other cities however, adaptation planners rarely consider collaborations with citizens and there are difficulties in departmental coordination and upscaling from pilot projects (Brink and Wamsler, 2018).

The level and type of collaboration between the public and private sector in managing climate risks varies across Europe (Wiering et al., 2017; Alkhani, 2020). For example, in flood management (also section 13.2), the private sector involvement in Rotterdam is much more pronounced and there are joint public–private responsibilities throughout most of the policy process due to the large share of private ownership of land and real estate (Mees et al., 2014).

In large infrastructure networks, the lack of a leading and powerful institutional body, with sufficient research resources targeted to climate change risk assessment, may limit adaptive capacity, as for example in railways (Rotter et al., 2016).

The European insurance industry has developed tailored products for specific climate risks threatening cities, settlements and key infrastructure, such as risk-based flood insurance for homeowners and companies (section 13.2.3). The European insurance industry is developing new services (such as risk analysis and catastrophe modelling embedding climate change, early warning and post-event recovery recommendations) and it has recently started to play a role as communicator of future risks and as institutional investor with the aim of risk reduction (Jones and Phillips, 2016; Marchal et al., 2019).

13.6.2.5 Links between Adaptation and Mitigation

Evidence from transport in Europe shows that adaptation actions do not consider enough long-term transition paths embedded in mitigation, while mitigation strategies are often not assessed under future climate scenarios (Aparicio, 2017). Without rapid decarbonization of electricity supply, greenhouse gas emissions will increase due to the increased use of air-conditioning installations in cities. This trade-off can be reduced to some extent through use of more efficient cooling technologies (IEA, 2018) and complementary adaptation measures such as large-scale urban greening, building policies and behavioural changes in air conditioning use (Viguié et al., 2020; Sharifi, 2021; Viguié et al., 2021). Greenhouse gas emissions from transport may increase due to the temporary relocation of city residents to cooler locations during heatwaves (Juschten et al., 2019), and from increased energy use for snowmaking in European ski resorts (Scott et al., 2019).

13.6.3 Knowledge Gaps

A key knowledge gap is the lack of a quantitative European-wide integrated assessment of future climate change risks on water and energy, including different socio-economic futures. Models capable of representing integrated policies for energy and water are lacking (Khan et al., 2016) including quantitative modelling of impacts on energy transmission and coastal energy infrastructure (Cronin et al., 2018). These lacks are especially pertinent when combined with the small number of studies considering SSP population projections, and adaptation tipping points. The limited social vulnerability assessments, mapping, and validation (Rufat et al., 2019) contribute further to these knowledge gaps.

While compound, concurrent, and consecutive climate extremes become more frequent, there is limited knowledge on sectoral risks or on cascading risks for through transport, telecommunications, water, and banking and finance. While heat is well studies, studies on risks for cities and key infrastructure from hailstorms and lightning are missing.

Empirical data on the damage of transport infrastructure (e.g., railways) covering different European countries is not systematically collected and indirect economic effects of interruptions of transport networks are not well studied (Bubeck et al., 2019). These deficits result in uncertainties associated with impacts of climate change on transport flows and indirect impacts (delays, economic losses).

There is limited knowledge on interactions created by synchronous adaptation in ski tourism supply and demand, and models are not yet including individual snowmaking capacity and a higher time resolution (Steiger et al., 2019). Furthermore, there is no European-wide assessment of coastal flooding risks on tourism.

Many studies lack consideration of market characteristics (e.g., competitors) in their risk assessment which would be improved by location- and sector-specific knowledge on climate risks for firm assets, operations, business, industry, finance and insurance needed to inform adaptation actions (de Bruin et al., 2020; Feridun and Güngör, 2020; Monasterolo, 2020).

13.7 Health, Wellbeing and the Changing Structure of Communities

13.7.1 Observed Impacts and Projected Risks

13.7.1.1 Mortality due to Heat and Other Extreme Events

Attribution studies show that human-induced climate change is increasing the frequency and intensity of heat waves and has already impacted human health in Europe (Section 13.10.1, Vicedo-Cabrera et al., 2021); for example the 2010 heatwave in EEU resulted in 55,000 heat-related deaths (Barriopedro et al., 2011; Russo et al., 2015); the 2018 heatwave in NEU (Ebi et al., 2021) and the 2019 heatwave in WCE and NEU both had significant health impacts (Cross-Chapter Box DISASTER in Chapter 4, Vautard et al., 2020; Watts et al., 2021). Elderly, children, (pregnant) women, socially isolated people and those with low physical fitness are particularly exposed and vulnerable to heat-related risks, as are those people suffering from pre-existing medical conditions, including cardiovascular disease, kidney disorders, diabetes and respiratory diseases (de'Donato et al., 2015; Sheridan and Allen, 2018; Naik et al., 2021). An aging population in Europe is increasing the pool of vulnerable individuals, resulting in higher risk of heat-related mortality (Montero et al., 2012; Carmona et al., 2016b; WHO, 2018b; Watts et al., 2021).

1.5°C GWL warming could result in 30,000 annual deaths due to extreme heat, with up to three-fold the number under 3°C GWL (*high confidence*) (Roldán et al., 2015; Forzieri et al., 2017; Kendrovski et al., 2017; Naumann et al., 2020). The risk of heat stress, including mortality and discomfort, is dependent on socioeconomic development (Rohat et al., 2019; Ebi et al., 2021) (Figure 13.22). Heat stress risks will be lower under SSP1 than SSP3 or SSP4 scenarios (*high confidence*) (Hunt et al., 2017; Rohat et al., 2019; Wang et al., 2020; Ebi et al., 2021). The incidence of heat-related mortality and morbidity will be highest in SEU, where their magnitude is also expected to increase more rapidly (Forzieri et al., 2017; Gasparrini et al., 2017; Guo et al., 2018; Díaz et al., 2019; Vicedo-Cabrera et al., 2021). WCE, NEU, SEU will experience accelerating negative consequences beyond 1.5°C GWL, particularly under SSP3 and SSP4 due to higher vulnerability compared with SSP1 (Figure 13.22, Rohat et al., 2019). The number of heat-related respiratory hospital admissions is projected to increase from 11,000 (1981-2010) to 26,000 annually (2021-2050), particularly in SEU mainly due to a relative increase in the number of extremely hot days (Åström et al., 2013). Cold spells are projected to decrease across Europe, particularly in southern Europe, but do not compensate for the additional heat related deaths projected (Lhotka and Kysely, 2015; Carmona et al., 2016a; Martinez et al., 2018).

74% of Europeans live in urban areas (section 13.6), where the effect of heat waves on human health is exacerbated by microclimates due to buildings and infrastructure, heat island effects, and air pollution (WHO, 2018a; Smid et al., 2019). In large European cities, stabilizing climate warming at 1.5°C GWL would decrease premature deaths by 15–22% in summer compared with stabilization at 2°C GWL (Mitchell et al., 2018) (*high confidence*).

Although there is *very high confidence* that risk consequences will inevitably be more pervasive and widespread in a warmer Europe, evidence of higher heat tolerance is also emerging across most European regions (Todd and Valleron, 2015; Åström Daniel et al., 2016 Sweden, 1901–2009; Follos et al., 2020). Future projections of mortality rates in Europe under the assumption of complete acclimatization suggest constant or even decreasing rates of mortality in spite of global warming (Åström et al., 2017; Guo et al., 2018; Díaz et al., 2019). However, there are large uncertainties in the ability to adapt to future heat extremes which might fall outside of historical ranges (Vanos et al., 2020).

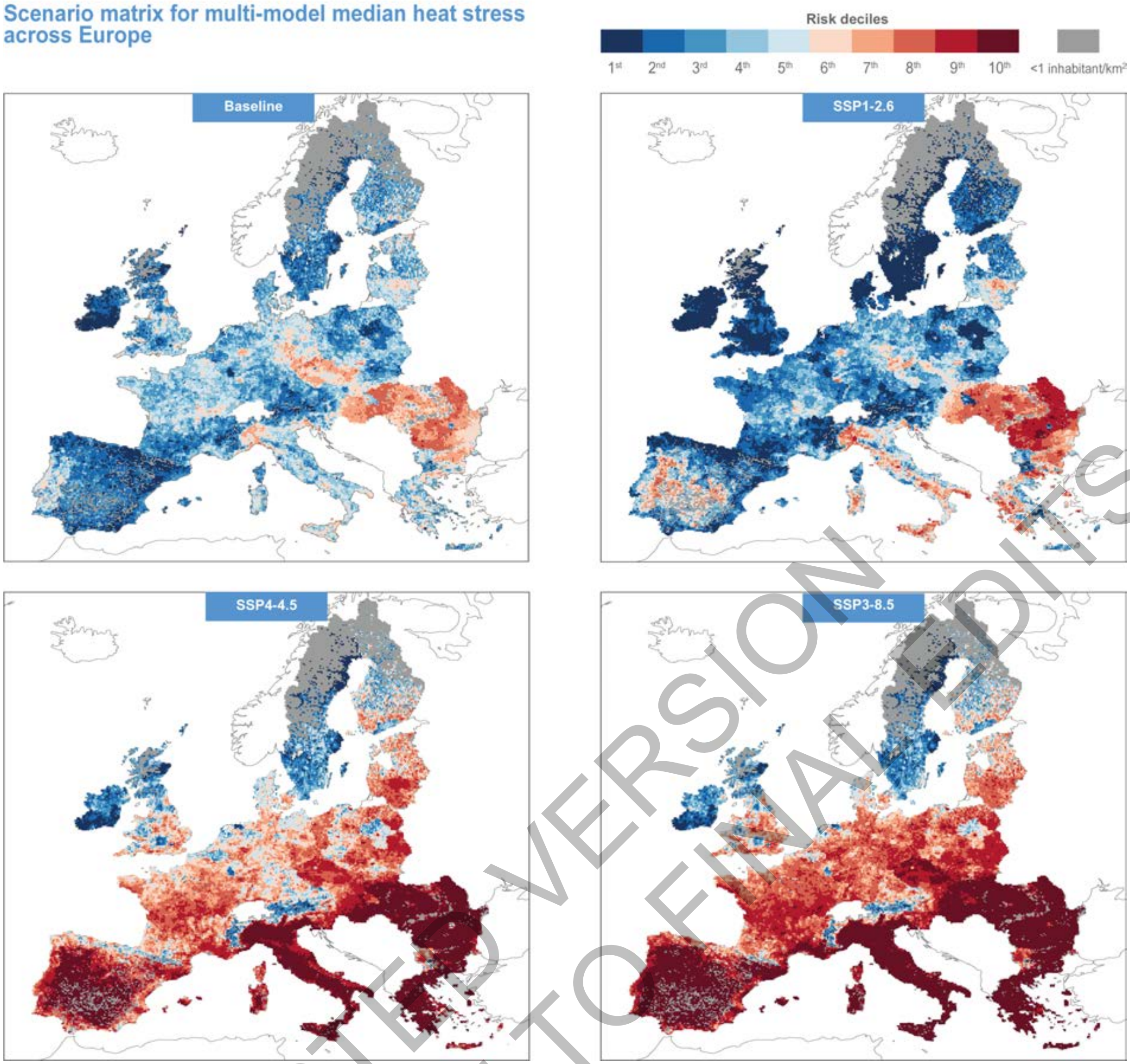


Figure 13.22: Scenario matrix for multi-model median heat stress risks for the baseline 1986-2005, and different SSP-RCP combinations for the period 2040-2060. SSPs are extended SSPs for Europe (EU28+). Heat stress risk is calculated by geometric aggregation of the hazard (heat wave days), population vulnerability and exposure. Risk values are normalised using a z-score rescaling with a factor 10-shift. Details of the methodology are provided in Rohat et al. (2019).

Other extreme events already result in major health risks across Europe. Between 2000 and 2014, for example, floods in Russia killed approximately 420 people, mainly older women (Belyakova et al., 2018). Fatalities associated with coastal and riverine flooding (13.2.2), wildfires (13.3.4), and windstorms could rise substantially by 2100 (Forzieri et al., 2017; Feyen et al., 2020). Lifetime exposure to extreme weather events for children born in 2020 will be about 50% larger at 3.5°C compared to 1.5°C GWL (Thiery et al., 2021).

13.7.1.2 Air Quality

Air pollution is already one of the biggest public health concerns in Europe; in 2016, roughly 412,000 people died prematurely due to long-term exposure to ambient PM2.5, 71,000 due to NO_2, and more than 15,000 premature mortalities occurred due to near surface ozone (EEA, 2019b; Lelieveld et al., 2019). Impacts of air pollution determined by air quality policies, changes to temperature, humidity, and precipitation (Naik et al., 2021). Climate change could increase air pollution health effects, with the size of the effect differing across European regions and pollutants (Jacob and Winner, 2009; Orru et al., 2017; Tarin-Carrasco et al., 2021) (*medium confidence*). Increases in temperature and changes in precipitation will impact future air quality due to increased risk of wildfires and related air pollution episodes. Data on the health impacts of wildfires in

Europe is currently limited (Section 13.3.1.4), but examples such as the 2017 fires suggest that more than 100 people died prematurely in Portugal alone as a result of poor air-quality (Oliveira et al., 2020).

At 2.5°C GWL, mortalities due to exposure to PM2.5 are projected to increase by up to 73% in Europe (*medium confidence*) (Silva et al., 2017; Lelieveld et al., 2019; Tarin-Carrasco et al., 2021). At 2°C GWL, annual premature mortalities due to exposure to near-surface ozone are projected to increase up to 11% in Western Central and Southern Europe and to decrease up to 9% in Northern Europe (under RCP4.5) (Orru et al., 2019) (*medium confidence*). Projected increase in wildfires and reduced air quality is expected to increase respiratory morbidity and mortality, especially in SEU (Slezakova et al., 2013; de Rigo et al., 2017). Constant or lower emissions combined with stricter regulations and new policy initiatives, might improve air quality in coming decades (*medium agreement, low evidence*). Aging population in Europe augments the future air quality mortality burden by 3-13% in 2050 (Geels et al., 2015; Orru et al., 2019). Beside ambient air quality, projected increases in flood risk and heavy rainfall could decrease indoor air quality (13.6.1.5.2) due to dampness and mould, leading to increased negative health impacts, including allergies, asthma and rhinitis (EASAC, 2019; EEA, 2019b).

13.7.1.3 Climate Sensitive Infectious Diseases

Figure 13.23 summarizes the observed and projected changes in climatic suitability and assesses the risk for selected climate-sensitive infectious diseases in Europe.

Among the tick-borne diseases, Lyme disease is the most prevalent disease in Europe. There has been a temperature-dependent range expansion of ticks that is projected to expand further north in Sweden, Norway and the Russian Arctic. (Jaenson et al., 2012; Jore et al., 2014; Tokarevich et al., 2017; Waits et al., 2018) and to higher elevations in Austria and the Czech Republic (Daniel et al., 2003; Heinz et al., 2015) (*medium confidence).* A potential habitat expansion of these ticks of 3.8% across Europe, relative to 1990-2010, is projected for 2°C GWL (Porretta et al., 2013; Boeckmann and Joyner, 2014). In contrast, there are projected habitat contractions for these ticks in SEU due to unfavourable climatic conditions (Semenza and Suk, 2018).

The Asian tiger mosquito (*Aedes albopictus*) is present in many European countries and can transmit Dengue, Chikungunya and Zika (Liu-Helmersson et al., 2016; Tjaden et al., 2017; Messina et al., 2019). There is a moderate climatic suitability projected for chikungunya transmission, notably across France, Spain, and Germany but also contractions, particularly in Italy. Europe experienced an exceptionally early and intense transmission season of West Nile virus in 2018, with elevated spring temperature abnormalities (Haussig et al., 2018; Marini et al., 2020). Projections for Europe show West Nile virus risk to expand; by 2025 the risk is projected to increase in SEU and south and eastern parts of WCE (*medium confidence*) (Semenza et al., 2016). Although climatic suitability for malaria transmission in Europe is increasing and will lead to a northward spread of the occurrences of *Anopheles* vectors, the risk from malaria to human health in Europe remains low due to economic and social development and access to health care (*medium confidence*) (Sudre et al., 2013; Hertig, 2019).

Water-borne diseases are also associated with changes in climate such as heavy precipitation events (Semenza, 2020). Warming has been linked with elevated incidence of campylobacteriosis outbreaks in different European countries (Yun et al., 2016; Lake et al., 2019). Marine bacteria such as vibrio thrive under elevated sea surface temperature and low salinity such as the Baltic Sea. Under further warming, the number of months with risk of Vibrio transmission increases and the seasonal transmission window expands, thereby increasing the risk to human health in the future (*high confidence*) (Baker-Austin et al., 2017; Semenza et al., 2017).

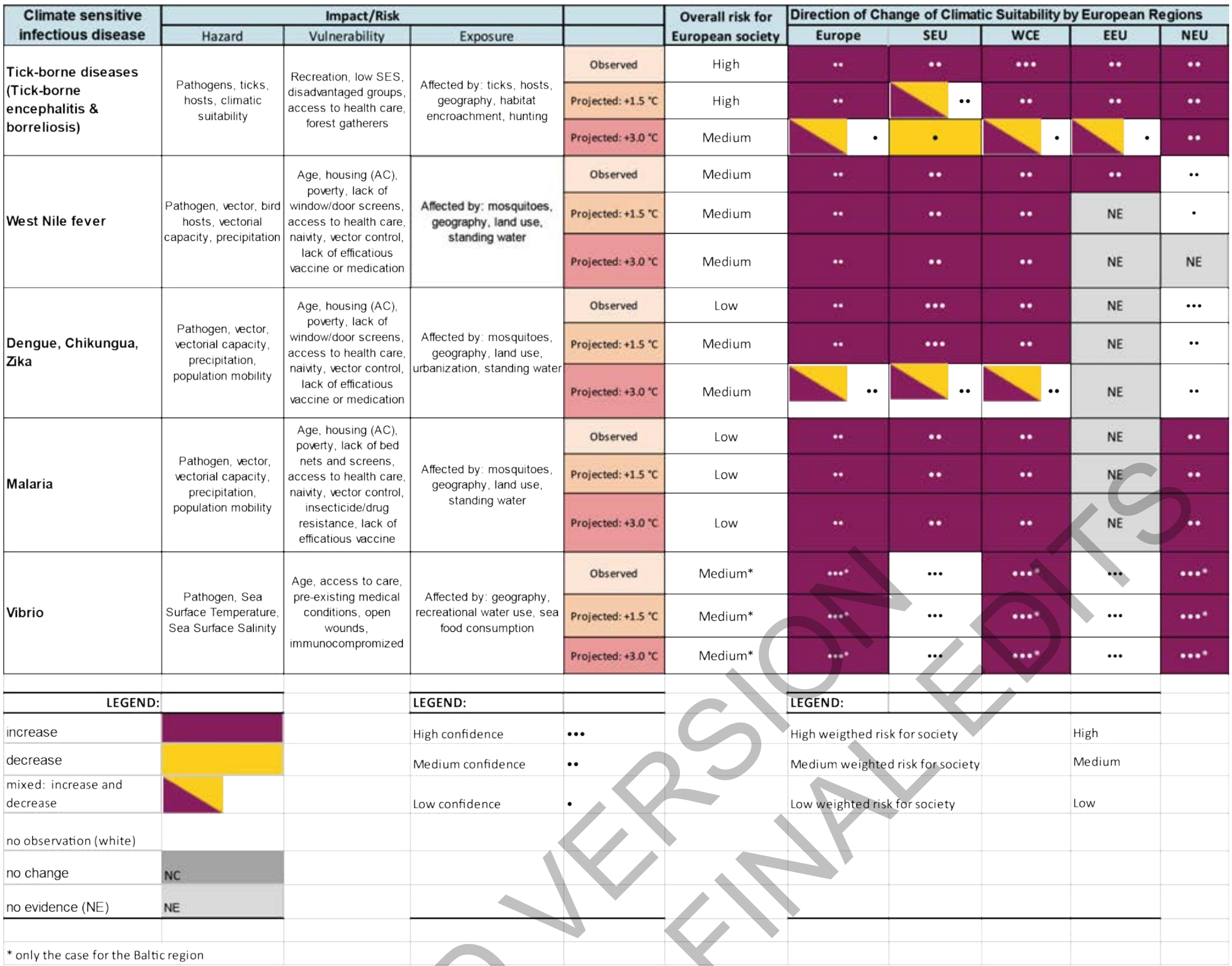


Figure 13.23: Assessment of climate sensitive infectious diseases. The assessment considers the main drivers of hazard (climatic impact drivers, pathogens and vectors), vulnerability (lack of safeguards and a predisposition to these hazards) and exposure (humans to be affected by these pathogens and vectors), the direction of change of climatic suitability (i.e. temperature, precipitation, relative humidity, extreme weather events) of observed changes and at 1.5°C and 3°C GWL, and assesses the overall infectious disease risks across Europe (Chapter 7.3 and 7.4, Lindgren et al., 2012; Semenza and Paz, 2021). The assessment does not consider incidence of disease infections through autochthonous transmission. (Table SM13.18).

13.7.1.4. Allergies and Pollen

The main drivers of allergies are predominantly non-climatic (e.g. increased urbanization, adoption of westernized lifestyles, social and genetic factor) but climate change strongly contributes to the spread of some allergenic plants, thus exacerbating existing and causing new allergies to humans across Europe (*high confidence*) (D'Amato et al., 2016; EASAC, 2019). The prevalence of hay fever (*allergic rhinitis*), for example, is between 4% and 30% among European adults (Pawankar et al., 2013). The invasive common ragweed is a key species already causing major allergy in late summers (including hay fever and asthma), particularly in Hungary, Romania and parts of Russia (Ambelas Skjøth et al., 2019). Across Europe, sensitization to ragweed is expected to increase from 33 million people in 1986–2005 to 77 million people at 2°C GWL (Lake et al., 2017).

Warming will result in an earlier start of the pollen season and extending it, but this differs across regions, species, traits and flowering periods (Ziello et al., 2012; Bock et al., 2014; EASAC, 2019; Revich et al., 2019). For instance in different parts of WCE and NEU, the start of the birch season flowering has been shifted and extended up to two weeks earlier during recent decades (Biedermann et al., 2019). Airborne pollen concentrations are projected to increase across Europe (Ziello et al., 2012). In south-eastern Europe, where pollen already has a substantive impact, the pollen count could increase more than 3 to 3.5 times at

2.5°C GWL and can become a more widespread health problem across Europe, particularly where it is currently uncommon (*medium agreement, low evidence*) (Lake et al., 2017).

13.7.1.5. Labour Productivity and Occupational Health

Extreme heat and cold waves have been linked to an increased risk of occupational injuries (Martinez-Solanas et al., 2018) and changes in labour productivity (Orlov et al., 2019; García-León et al., 2021) while evidence on the consequences of other extreme events is lacking. The sectors with a high percentage of high intensity outdoor work in Europe, mainly agriculture and construction, have the highest risk of increased injury and labour productivity losses, but also manufacturing and service sectors can be affected when air conditioning is not available (Gosling et al., 2018; Szewczyk et al., 2018; Dellink et al., 2019; Orlov et al., 2019) (13.6.1.3). The heatwaves of August 2003, July 2010 and July 2015 concentrated in SEU and led to reductions in monthly worker productivity of on average 3-3.5% in SEU, ranging up to 8-9% in Cyprus (2003, 2010) and in Italy (2015) (Orlov et al., 2019); in contrast, the heatwave of 2018 centred on NEU, but also led to pronounced productivity reductions in WCE and SEU (García-León et al., 2021); each of these major European heatwaves led to considerable economic losses in agriculture and construction (*high confidence*) and reduced GDP in Europe (except EEU) by 0.3-0.5% (García-León et al., 2021). At 2.5°C GWL and beyond, GDP losses are projected to increase fivefold compared to 1981-2010, ranging from 2-3.5% in SEU, to 0.5-1.5% in WCE, and below 0.5% in NEU and EEU (Roson and Sartori, 2016; Takakura et al., 2017; Szewczyk et al., 2018; Dellink et al., 2019; García-León et al., 2021) (13.10.3).

13.7.1.6. Food Quality and Nutrition

There is growing evidence that climate change will negatively affect food quality (diversity of food, nutrient density, and food safety) and food access, although the risks for European citizens are significantly lower compared to other regions (Fanzo et al., 2018; IFPRI, 2018). Projected changes in crop and livestock production (13.5.1), particularly reduced access to fruits and vegetables and foods with lower nutritional quality, will impact already vulnerable groups (Swinburn et al., 2019). The effects of climate change on food quality and access varies by income, livelihood, and nutrient requirements, with low income and more vulnerable societal groups in Europe most affected (IFPRI, 2018). Spikes in food prices due to changing growing conditions in Europe (13.5.1), increased competition for land (e.g., land-based climate change mitigation), and feedbacks from international markets, are expected to decrease access to affordable and nutritious food for European citizens (13.9.1) (EASAC, 2019; Loopstra, 2020). Reduced access to healthy and varied food could contribute to overweight and obesity which is a growing health concern across European countries (Springmann et al., 2016). Increased rates of obesity and diabetes further exacerbate risks from heat-related events (EASAC, 2019).

13.7.1.7. Mental Health and Wellbeing

Extreme weather events can trigger post-traumatic stress disorder (PTSD), anxiety and depression; this is well-documented for flooding in Europe (*high confidence*), but less for other extreme weather events. For example, in the UK, flooded residents suffered stress and identity loss from the flood event itself, but also from subsequent disputes with insurance and construction companies (Carroll et al., 2009; Greene et al., 2015). Residents displaced from their homes for at least one year due to 2013-2014 floods in England were significantly more *likely* to experience PTSD, depression and anxiety, with stronger effects in the absence of advance warning (Munro et al., 2017; Waite et al., 2017). There is emerging evidence across Europe that young people may be experiencing anxiety about climate change, though it is unclear how widespread or severe this is (Hickman, 2019). In northern Italy, the number of daily emergency psychiatric visits and mean daily air temperature has been linked (Cervellin et al., 2014).

13.7.2 Solution Space and Adaptation Options

Adaptation to health impacts has generally received less attention compared to other climate impacts across Europe (EASAC, 2019). Progress on health adaptation can be observed. Between 2012 and 2017, at least 20 European countries instituted new governance mechanisms, such as interdepartmental coordinating bodies for health adaptation and adopted health adaptation plans (Kendrovski and Schmoll, 2019). Progress on city level health adaptation is generally limited (Araos et al., 2015) , with most activities occurring in SEU (Paz et al., 2016) *(high agreement, medium evidence)*.

Figure 13.24 presents the assessment of the feasibility and effectiveness of key heat-related health adaptation actions. It shows that substantial social-cultural and institutional barriers complicate widespread implementation of measures; studies on the implementation of new blue-green spaces in existing urban structures in, for example Sweden (Wihlborg et al., 2019), UK (Carter et al., 2018), the Netherlands (Aalbers et al., 2019), point to important feasibility challenges (e.g., access to financial resources, societal opposition, competition for space) (*high confidence*). Lower perception of health risks has been observed amongst vulnerable groups which, in conjunction with perceived high costs of protective measures, act as barriers to implementing health adaptation plans (van Loenhout et al., 2016; Macintyre et al., 2018; Martinez et al., 2019). Key barriers to mental health adaptation actions include lack of funding, coordination, surveillance, and training (e.g., psychological first aid) (Hayes and Poland, 2018). Existing health measures, such as monitoring and early warning systems, play an important role in detecting and communicating emerging climate risks and weather extremes (Confalonieri et al., 2015; Casanueva et al., 2019; Linares et al., 2020)} (*high confidence*). Stricter enforcement of existing health regulation and policy can have a positive effect in reducing risks (Berry et al., 2018).

Effectiveness & feasibility of main adaptation options to reduce heat related impacts & risks to human health in Europe

Impact Type	Adaptation Option	Effectiveness	Feasibility						Confidence	
			Economic	*Technological*	*Institutional*	*Socio-cultural*	*Ecological*	*Geophysical*	*Evidence*	*Agreement*
Mortality, morbidity, exposure, stress from heat	Behavior change measures	M	NL	NL	H	H	NL	NL	M	L
	Natural cooling	L	NL	M	NL	M	NL	NL	H	L
	Building interventions	M	M	M	NL	M	NL	H	H	L
	Green infrastructures	M	M	M	M	M	H	M	M	H
	Heat proof land management	H	NL	M	M	H	H	M	M	M
	Heat health action plans	H	NL	M	H	H	NL	NL	H	H
	Bundle of options	H	H	NL	NL	NL	NL	H	M	L

Legend
High = H
Medium = M
Low = L
No/Limited Evidence = NL

Figure 13.24: Effectiveness and feasibility of the main adaptation options to reduce heat related impacts and risks to human health in Europe. (SM13.9 and Table SM13.19).

The effectiveness of most options in reducing climate induced health risks is determined by many co-founding factors, including the extent of the risk, existing socio-political structure and culture, and other adaptation options in place (*high agreement, medium evidence*). Successful examples include the implementation of heat wave plans (Schifano et al., 2012; van Loenhout and Guha-Sapir, 2016; De'Donato et al., 2018), improvements in health services, and infrastructure of homes (Vandentorren et al., 2006) (Section 13.10.2.1). A study of nine European cities, for example, showed lower numbers of heat-related deaths in Southern European cities, and attributed this to the implementation of heat prevention plans, a greater level of individual and household adaptation, and growing awareness of citizens about exposure to heat (de'Donato et al., 2015). Long-term national prevention programs in Northern Europe have been shown to reduce temperature-related suicide (Helama et al., 2013). Physical fitness of individuals may increase resilience to extreme heat (Schuster et al., 2017). Combining multiple types of adaptation options into a consistent policy portfolio may have an amplifying effect in reducing risks, particularly at higher GWL (Lesnikowski et al., 2019) (*medium confidence*) (Chapter 7).

Health adaptation actions have demonstrable synergies and trade-offs (Cross-Chapter Box HEALTH in Chapter 7). For example, increasing green-blue spaces in Europe's densely populated areas can be effective in improving micro-climates, reducing the impact of heat waves, improving air quality, and improving mental health by increasing access to fresh air and green (restorative) environment (Gascon et al., 2015; Kondo et al., 2018; Kumar et al., 2019). Health adaptations can also have negative trade-offs, be inconsistent with mitigation ambitions, and could lead to maladaptation. Green-blue spaces, for example, may create new nesting grounds for carriers of vector-borne diseases, increase pollen and allergies (Kabisch et al., 2016), enlarge freshwater use for irrigation (Reyes-Paecke et al., 2019), and could raise climate equity and justice issues such as green gentrification (Yazar et al., 2019). Similarly, air conditioning and cooling devices are considered highly effective but have low economic and social feasibility and negative trade-offs due to increasing energy consumption, raising energy costs which is particularly challenging for the poor (Section 13.8.1.1), enhancing the heat island effect, and increasing noise pollution (Fernandez Milan and Creutzig, 2015; Hunt et al., 2017; Macintyre et al., 2018).

The solution space for implementing health adaptation options is slowly expanding in Europe. Health adaptation can build on, and integrate into, established health system infrastructures but these differ significantly across Europe, as do existing capacities to deal with climate-related extreme events (Austin et al., 2016; Austin et al., 2018; Orru et al., 2018; Watts et al., 2018; Austin et al., 2019; Martinez et al., 2019). Despite some progress, limited mainstreaming of climate change is observed, particularly due to low societal pressure to change, confidence in existing health systems, and lack of awareness of links between human health and climate change (*medium confidence*) (Austin et al., 2016; WHO, 2018b; Watts et al., 2021). Coordination of health adaptation actions across scales and between public sectors is needed to ensure timely and effective responses for a diversity of health impacts *(high confidence)* (Austin et al., 2018; Ebi et al., 2018). Key enabling conditions to extend the solution space include increasing the role for national and regional governments in facilitating knowledge sharing across scales, allocating dedicated financial resources, and creating dedicated knowledge and policy programs on climate and health (Wolf et al., 2014; Akin et al., 2015; Curtis et al., 2017). Investing in public healthcare systems more broadly increases their capacity to respond to climate-related extreme events and will ensure wider societal benefits as the COVID-19 pandemic has demonstrated (Cross-Chapter Box COVID in Chapter 7).

Despite a range of options available, there are limits to how much adaptation can take place and residual risks remain. These are predominantly discussed in the context of excess mortality and morbidity to heat extremes (Hanna and Tait, 2015; Martinez et al., 2019). Future heat waves are expected to stretch existing adaptation interventions well beyond levels observed in response to the observed events of 2003 and 2010 (Hanna and Tait, 2015), see Section 13.10.2.1.

13.7.3 Knowledge Gaps

Literature on the link between public health, climate impacts, vulnerability and adaptation is skewed across Europe, with most studies focusing on region-specific impacts (e.g., flood injuries in WCE, heatwaves in SEU). In general, attributing health impacts to climate change remains challenging, particularly for mental health and wellbeing, (mal)nutrition and food quality, and climate sensitive infectious diseases, where other socio-economic determinants play an important role. The connection between climate change and health risks under different socio-economic development pathways is hardly studied comprehensively for Europe, with some exceptions for extreme events. However, these interactions seem to play an important role in better understanding projected risks and inform choices on adaptation planning.

Some climate-related health issues are emerging but evidence is too limited for a robust assessment, for example the links between climate change and violence in Europe (Fountoulakis et al., 2016; Mares and Moffett, 2016; Sanz-Barbero et al., 2018; Koubi, 2019).

The solution space for public health adaptation in Europe, and the effectiveness of levers for interventions, are hardly assessed. Although health adaptations are documented, these are particularly around mortality and injuries due to extreme events (predominantly floods (13.2.1) and heat waves (13.7.1.1). There are very few studies assessing the barriers and enablers of health adaptations, nor systematic assessment of the effectiveness of (portfolio of) options. Limited insights into what works and where hamper upscaling these insights across Europe and constrains the ability to evaluate whether investments in health adaptation have actually reduced risks.

13.8 Vulnerable Livelihoods and Social Inequality

This section addresses social consequences of climate change for Europe, by looking into consequences for poor households and minority groups; migration and displacement of people; livelihoods particularly vulnerable to climate change (indigenous and traditional communities); and cultural heritage.

13.8.1 Observed Impacts and Projected Risks

13.8.1.1 Poverty and Social Inequality

While climate change is not the main driver of social inequality in Europe, poor households and marginalized groups in Europe are affected more strongly than other social groups by flooding, heat and drought and risks to spreading diseases (*medium confidence*).

Urban poor and ethnic minorities often settle in more vulnerable settlement zones, and are therefore impacted more by flooding (*medium confidence*) (Medd et al., 2015; Župarić-Iljić, 2017; Efendić, 2018; Fielding, 2018; Winsemius et al., 2018; Puđak, 2019; Inuit Circumpolar Council, 2020). Yet, in some western European residential waterside developments this pattern is reversed by flooding impacting high income residents more strongly (Walker and Burningham, 2011).

The health of the poor is disproportionately affected e.g. during heat waves in the Mediterranean (Jouzel and Michelot, 2016). Women, those with disabilities and the elderly are disproportionately affected by heat (Section 13.7.1). Floods in the Western Balkans in 2014 resulted in heavy metal pollution of water and land threatening the health condition of the poorer rural population (Filijović and Đorđević, 2014). Access to water and sanitation is less available to poorer households and marginalized groups in Europe (Ezbakhe et al., 2019; Anthonj et al., 2020) which could be intensified by increasing water scarcity in parts of Europe under future climate change (Section 13.10.3).

Food self-provisioning is a widespread practice in many parts of Europe (Aleynikov et al., 2014; Corcoran, 2014; Church et al., 2015; Mustonen and Huusari, 2020), reaching over half of German rural areas (Vávra et al., 2018). While it strengthens resilience for disadvantaged households (Church et al., 2015; Boost and Meier, 2017; Promberger, 2017; Vávra et al., 2018; Ančić et al., 2019; Pungas, 2019) and renews their local knowledge, it can become at risk in regions with projected crop yield reductions (*high confidence*) (Hallegatte et al., 2016; Quiroga and Suárez, 2016; Myers et al., 2017b; Inuit Circumpolar Council, 2020), and after extreme weather events (Filijović and Đorđević, 2014).

Energy poor households often live in thermally inefficient homes and cannot afford air conditioning to adapt to overheating in summer (Sanchez-Guevara et al., 2019; Thomson et al., 2019). While energy poverty is much more prevalent in southern and eastern Europe (Bouzarovski and Petrova, 2015; Pye et al., 2015; Atsalis et al., 2016; Monge-Barrio and Sánchez-Ostiz Gutiérrez, 2018), climate change will also exacerbate energy poverty in European regions where heating was so far the major share of energy costs (*medium confidence*) (Sanchez-Guevara et al., 2019; Randazzo et al., 2020).

13.8.1.2 Migration and Displacement of People

Most migration and displacement due to climate change is taking place within national borders and single regions (Cross-Chapter Box MIGRATE in Chapter 7). There is *low confidence* in climate change contributing to migration from outside Europe into Europe (Gemenne, 2011; Topilin, 2016; Gemenne and Blocher, 2017; Selby et al., 2017). Some economic models project that asylum applications to the EU might increase by a third at 2.5°C GWL and more than double beyond 4°C GWL by end of the century (Missirian and Schlenker, 2017), but empirical evidence shows that applications might decrease due to growing economic and legal barriers in the capacity of populations to emigrate from Africa or other regions (Kelley et al., 2015; Zickgraf, 2018; Borderon et al., 2019).

Migration of people within Europe is predominantly triggered by economic disparities among European countries (Fischer and Pfaffermayr, 2018). There is *limited* and *inconclusive* evidence for climate-driven impacts on these movements (Hoffmann et al., 2020). Small scale climate-induced displacement within Europe occurs in the aftermath of flood and drought disasters and over short distances (Cattaneo et al., 2019). The unequal distribution of future climate risks (13.1) and adaptive capacity across European regions may increase pressure for internal migration (Williges et al., 2017; Forzieri et al., 2018). For instance, projected sea level rise (13.2.1, Cross-Chapter Box SLR in Chapter 3) may result in planned relocation of coastal settlements and inland migration in the UK, the Netherlands and the northern Mediterranean (Mulligan et al., 2014; Antonioli et al., 2017). The number of people living in areas at risk in Europe is projected to increase with future SSPs increasing exposure (Merkens et al., 2016; Byers et al., 2018; Harrison et al., 2019).

13.8.1.3 Loss and Damage to Vulnerable Livelihoods in Europe

A number of livelihoods maintaining unique cultures in Europe is particularly vulnerable to climate change (Table 13.2): indigenous communities in the European polar region because of their dependence on cryosphere ecosystems *(high confidence*) (CCP Polar, Hayashi, 2017; Huntington et al., 2017; Hock et al., 2019; Meredith et al., 2019; Inuit Circumpolar Council, 2020; Douville et al., 2021; Fox-Kemper et al., 2021) and communities dependent on small-scale fisheries, traditional farming and unique cultural landscapes (*medium confidence*) (Kovats et al., 2014; Ruiz-Díaz et al., 2020).

For Sámi reindeer herding impacts cascade due to a lack of access to key ecosystems, lakes and rivers thereby threatening traditional livelihoods, food security, cultural heritage (e.g. burial grounds, seasonal dwellings and routes), mental health (Box 13.2 and Figure 13.13, Feodoroff, 2021), and growing costs for example as a result of the need for artificial feeding of reindeer.

Table 13.2: Examples of losses and damages to vulnerable livelihoods in Europe, differentiating for different categories of non-economic loss and damage. (Table SM13.20.).

	Human life		Communal and production sites and intrinsic value
	Sense of place		Agency and identity
	Cultural artefacts		Psychological and emotional distress
	Biodiversity and ecosystems		

Climate hazard	Change in exposure and vulnerability	Observed impact / projected risk
Loss of livelihood, culture, health and wellbeing of the Sámi and the Nenets. 		
Decrease and alterations in snow and ice sheet, unstable winter weather, especially in the form of rain-on-snow events; increased precipitation and thawing permafrost, in tundra; unstable loss/flux of marine ice cover.	Land-use change (e.g. expansion of renewable energy) resulting in pasture loss and disconnection of ecosystems.	Loss of livelihood (e.g. reindeer herding), loss of food security (cold dependent species), culture, health (impact on safety; psychological impacts from stress to reindeer and Indigenous way of life), and cultural and linguistic wellbeing; release of anthrax from permafrost soils in the Nenets area.
Loss of key species in high-Arctic freshwater habitats, proliferation of introduced species and disruption of local food systems in Greenland, Finland, Sweden, NW Russia and Scotland. 		
Warmer water temperatures in high-Arctic freshwater habitats (13.3.1) increase productivity in oligotrophic systems and eventually	Introduced Pacific Pink Salmon has expanded in range since 1970s, affecting endemic species through competition and reducing their	Shifts in freshwater aquatic habitats and loss of endemic cold-dependent fish, such as Arctic Char and Arctic Salmon, cause disruptions to local

lead to loss of oxygen in water; warming temperatures and changes to ice cover and cryosphere lead to access issues to freshwater fisheries.	abundance. Increased nutrient loading of rivers and rapid expansion of algae increase the risks for cold-dependent fish.	food supply, and local extinctions threatens livelihood safety and cultural well-being.
Warmer winters lead to loss of income from ice fishing and cultural heritage in Finland.		
The start of ice cover on lakes, e.g. lake Puruvesi (Finland), has changed from November to February; ice breakup occurs much earlier in the year.	The quality of the water in the lakes used for fishing depend on ice cover during most of the year, and the season of open water is now much longer, increasing nutrient flow and loss of water quality in these lakes.	Lack of winter ice combined with delayed freeze up and earlier ice breakup reduce fish harvest for important species by up to 50% and impacts local safety, ecosystems, oral history maintenance and the local economy.
Changes to marine food web results in loss of Indigenous knowledge and food insecurity in Greenland.		
Warmer ocean waters moving further north (so-called "atlantification" of Greenland waters); higher temperatures removing sea ice	Traditional practices and knowledge based on sea ice uses and hunting are being lost; species are being replaced with southern fish.	Loss of Indigenous knowledge of how to deal with and use sea ice regarding species and navigation, loss of access to seals and walruses, food insecurity.
Reduced yields on managed alpine grasslands decreases the self-sufficiency of pastoral livestock farming in the Austrian, French and Swiss Alps		
Increase in heat, precipitation variability and agricultural as well as hydrological drought; less snow on the ground, increase in glacier melt, landslides susceptibility and erosion	Land-use change resulting in natural reforestation of abandoned pastoral land; shifts in alpine plant communities; more intensive cultivation of grasslands; change in agricultural markets and support policy.	Abandonment of summer pastures and farms, with negative consequences for farming income, tourism, cultural and aesthetic values.
Reduced yields on semi-natural grasslands, compromising livestock feeding in winter, and ultimately decreasing viability of pastoralism in the Spanish Pyrenees		
Higher temperatures and more variable precipitation, less snow, change in seasonality and drought	Demographic change, change in policy and market conditions, simplification of pastoral practices and agroecosystems, land abandonment or afforestation of marginal pastoral lands and intensification of more favourable lands in the lowlands, troublesome coexistence with tourism and nature conservation initiatives	Decreasing viability of pastoralism, concentration of pastoral production on most profitable locations for intensive rearing of livestock with abandonment of the rest of the land; pastoral land encroachment both by shrubs and other activities; grassland degradation; biodiversity loss
Retreating glaciers and changes in the landscape lead to loss of identity, culture and self-reliance in the Italian Alps (Alto Adige)		

Glacier volume loss from increasing temperatures	Vulnerability is mainly driven by reliance on tourism	Loss of sense of community through shared memories, and history. Sadness caused by the loss of what feels like "home". Loss of well-being due to uncertainty and fear of the future.
Drought results in a reduction of provisioning (water) and regulating services (protection against floods) in Western and Eastern Alps, Iberian Mountains, Dinaric Mountains		
Increase in drought, particularly under high-end GWL	Forest management strategies, including that of natural forests, can enhance or reduce vulnerability.	Critical importance of alpine natural forests and meadows for regulating services; Negative impacts of climate change are found mainly at low elevations and for specific species (Norway spruce); decrease in soil moisture due to abandonment of pastoralism result in reduced water provision for downstream water users
Increase of sea temperature leads to shifts in distribution of cold water species, reducing productivity at lower latitudes. Artisanal fisheries in Southern European coastal areas (Mediterranean) that rely on local, nearshore stocks can have difficulties to adapt		
Increase in sea temperature	Substitution of artisanal fisheries by industrial fisheries; less support by governments, shift in employment (e.g. tourism) which do not match the skill sets, education or desires of small-scale fishers; national quotas system leads to prices to high buy or lease quotas and immense amount of bureaucracy and regulations	Due to their low investment capacity and boat size, fishers are limited in their movement to other fishing places when local fish stocks decline. Increasing sea temperatures are increasing the threat of invasive species in coastal ecosystems.

[START BOX 13.2 HERE]

Box 13.2: Sámi Reindeer Herding in Sweden

Reindeer (*Rangifer tarandus*) are keystone species in northern landscapes (Vors and Boyce, 2009). Reindeer herding is a traditional, semi-nomadic livelihood of the Sámi. Reindeer migrate between seasonal pastures that cover 55% of Sweden and are simultaneously used for multiple other purposes (Sandström et al., 2016). Reindeer herding is recognized as an indigenous right, protected by the UN Declaration on the Rights of Indigenous Peoples, several UN conventions and through Swedish national legislation.

Temperatures in Arctic and sub-Arctic regions have increased on average by 2°C over the last 30 years (*very high confidence*) (Ranasinghe et al., 2021). Future warming is expected to further increase winter precipitation (*high confidence*) (Ranasinghe et al., 2021) and rain-on-snow events, creating a hard ice crust on the snow after refreezing (Bokhorst et al., 2016; Rasmus et al., 2018).

The documented and projected impacts on reindeer are complex and varied. Warming and CO_2 increase result in higher plant productivity (Section 13.3), changes in plant community composition, and higher parasite harassment; unstable ice conditions affect migration; extreme weather conditions during critical winter months, more frequent forest fires and changes in plant community composition reduce pasture quality (*medium confidence*) (Mallory and Boyce, 2018) (Figure Box 13.2.1). High snow depth and rain-on-snow events impede reindeer access to ground lichen in winter and delay spring green-up during critical calving period; both cause malnutrition and negative impacts on reindeer health, mortality and reproductive success (*medium confidence*) (Hansen et al., 2014; Forbes et al., 2016; Mallory and Boyce, 2018). Lower slaughter weights and increased mortality reduce the income of herders (*high confidence*) (Tyler et al., 2007; Helle and Kojola, 2008).

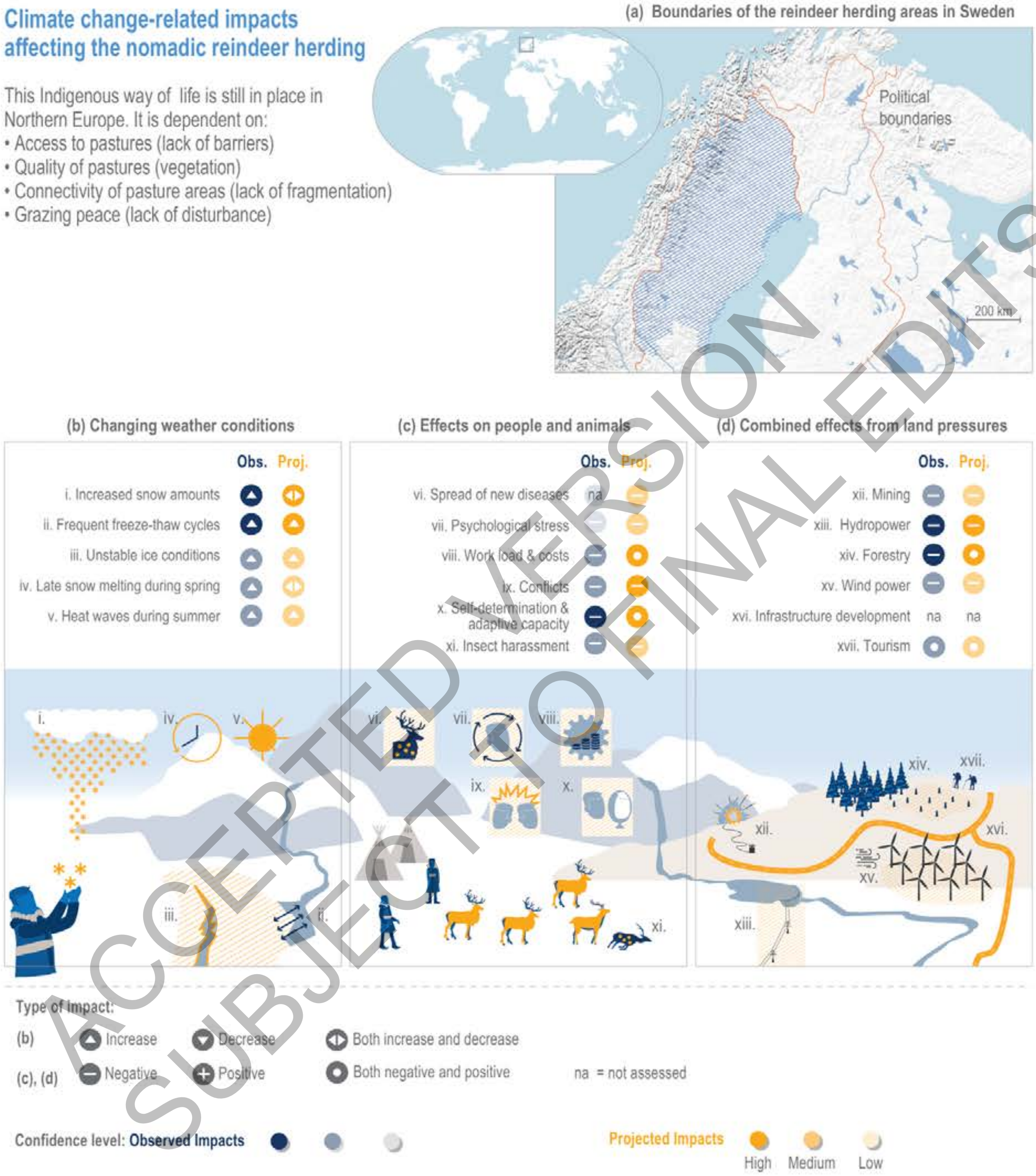


Figure Box 13.2.1: Cumulative impacts of climate and land use change on reindeer herding as a traditional, semi-nomadic Sámi livelihood (Table SM13.21).

Reindeer herders already autonomously adapts to changing conditions through flexible use of pastures and supplementary feeding (*high confidence*), reducing and thereby hiding some of the negative impacts of climate change (Uboni et al., 2016). However, adaptive herding practices have themselves added significant burden through increased workload, costs and stress (*high confidence*) (Furberg et al., 2011; Löf, 2013;

Rosqvist et al., 2021). Supplementary feeding increases risk for infectious diseases and implies culturally undesirable herding practices (*low confidence*) (Lawrence and Kløcker Larsen, 2019; Tryland et al., 2019).

Rapid land use change reduces the ability to adapt (*high confidence*) (Tyler, 2010; Löf, 2013). National and EU policies expand land uses for mining, wind energy and bioeconomy in the area, causing loss, fragmentation and degradation of pastures, and increasing human disturbance to animals *(medium confidence)* (Kivinen et al., 2012; Skarin and Åhman, 2014; Kivinen, 2015; Skarin et al., 2015; Sandström et al., 2016; Beland Lindahl et al., 2017; Österlin and Raitio, 2020). The cumulative impacts of these land-uses on pastures are not adequately assessed or recognized in land use planning (Kløcker Larsen et al., 2017; Kløcker Larsen et al., 2018). Herding communities face strong barriers to protecting their rights and halting further degradation of pastures (*medium confidence*) (Allard, 2018; Kløcker Larsen and Raitio, 2019; Raitio et al., 2020). Attempts by herding communities to stop mining projects have led to conflicts with other actors, including racist hate speech (Persson et al., 2017; Beland Lindahl et al., 2018). Combined with land use conflicts, climate impacts cause reduced psycho-social health and increase suicidal thoughts among herders *(low confidence)* (Kaiser et al., 2010; Furberg et al., 2011).

Reindeer herding is significantly affected by climate change directly and indirectly (Figure Box 13.2.1) (Pape and Löffler, 2012; Andersson et al., 2015). The cumulative effects of land use and climate change have already increased vulnerability and reduced the adaptive capacity of reindeer herding to the extent that its long-term sustainability is threatened (*medium confidence*) (Löf, 2013; Horstkotte et al., 2014; Kløcker Larsen et al., 2017).

Maintaining and improving the solution space to adapt reindeer herding is crucial for reducing existing impacts and projected risks of climate and land use change (Andersson et al., 2015; Turunen et al., 2016; AMAP, 2017; Hausner et al., 2020). Lack of control over land use is the biggest and most urgent threat to the adaptive capacity of reindeer herding and the right of Sámi to their culture (*high confidence*) (Pape and Löffler, 2012; Andersson et al., 2015; Kløcker Larsen and Raitio, 2019).

[END BOX 13.2 HERE]

13.8.1.4 Cultural and Natural Heritage

Climate change poses a serious threat to preservation of cultural heritage in Europe, both tangible and intangible (*high confidence*) (Haugen and Mattsson, 2011; Daire et al., 2012; Dupont and Van Eetvelde, 2013; Macalister, 2015; Phillips, 2015; Fatorić and Seekamp, 2017; Graham et al., 2017; Carroll and Aarrevaara, 2018; Sesana et al., 2018; Iosub et al., 2019; Daly et al., 2020). At higher GWL, building exteriors and valuable indoor collections become at risk (Leissner et al., 2015). Coastal heritage such along the North Sea and Mediterranean are under water-related threats (Reimann et al., 2018b; Walsh, 2018; Harkin et al., 2020) (Box 13.1 Venice; WGII AR6 CCP4).

Disappearing cultural heritage can reduce incomes due to loss of tourism (Hall et al., 2016), as exemplified by glacier retreat e.g. in the Swiss Alps and Greenland (Bjorst and Ren, 2015; Bosson et al., 2019) (CCP5.3.2.4). Glacier retreat can create a sense of discomfort, loss of sense of place, displacement and anxiety in people (Section 13.7) (Albrecht et al., 2007; Brugger et al., 2013; Allison, 2015; Jurt et al., 2015). Intangible cultural heritage, such as place names, and lost traditional practices can also be affected (Mustonen, 2018; Dastgerdi et al., 2019).

13.8.2 Solution Space and Adaptation Options

As climate change is interacting with many other drivers of poverty, improving the social position of the currently poor may increase their climate resilience (*low confidence*) (Hallegatte and Rozenberg, 2017; Fronzek et al., 2019). Some adaptation actions have the potential to alleviate poverty (Section 13.11.3), but adaptation can also increase social inequalities, e.g. when practices of disaster recovery focus on high visibility areas and not on low-income neighbourhoods or marginalized spaces (D'Alisa and Kallis, 2016). Risk communication and management reliant on new information technologies can exclude elderly and populations with lower educational attainment (Kešetović et al., 2017).

Unlike migration within the European Union, migration from outside Europe to Europe is heavily constrained by restrictive migration and asylum policies (Fielding, 2011; Mulligan et al., 2014), eventually leaving people to stay in more exposed and risk-prone regions (Benveniste et al., 2020). To reduce vulnerability in these regions, Europe can contribute to adaptation and development in regions outside Europe (section 13.9.4).

Indigenous and local knowledge, embedded e.g. in fishermen, farmers and navigators, can be a vehicle for detecting, monitoring and observing impacts (Arctic Council, 2013; Brattland and Mustonen, 2018; Madine et al., 2018; Meredith et al., 2019) (section 13.11.1.3). Regarding risks to northern traditional livelihoods and indigenous communities, small-scale adaptation is taking place, for example by ecological restoration of habitats (section 13.3) (Mustonen and Kontkanen, 2019). However, limited access to resources outside the jurisdictions of the communities limits the scope of community-based adaptation (Arctic Council, 2013; Mustonen et al., 2018; Meredith et al., 2019).

European cultural heritage in general and world heritage sites specifically lack adaptation strategies to preserve key cultural assets (Haugen and Mattsson, 2011; Howard, 2013; Heathcote et al., 2017; Reimann et al., 2018b; Harkin et al., 2020). Key reasons are the underdeveloped adaptation actions available, resources for implementing them, and absence of overarching policy guidance (Phillips, 2015; Fernandes et al., 2017; Sesana et al., 2018; Daly et al., 2020) (Sesana et al., 2018; Fatorić and Biesbroek, 2020; Sesana et al., 2020).

13.8.3 Knowledge Gaps

There is limited understanding of how different social groups are affected by the four European key risks under future climate change (13.11.2), and by adaptation to them. Similarly, the interaction of multiple risks across sectors and how this interaction results in displacement, migration, or immobility of people both within and from outside Europe is insufficiently understood. For indigenous and traditional livelihoods in Europe, the understanding of how risks will change at different warming levels is very limited, due to complex interactions with socio-economic and political change. For European cultural heritage, there is also a lack of tailored knowledge and understanding of the impacts and how to translate these into adaptation measures.

13.9 Interregional Impacts, Risks and Adaptation

This section addresses interregional risks between Europe and other parts of the world. Global risk pathways affecting sectors and supply chains relevant for European economies and societies involve (1) ecosystems, (2) people (e.g., through migration), (3) financial flows, and (4) trade, and these pathways ultimately impact security, health, wellbeing and food supply (Yokohata et al., 2019) (Cross-Chapter Box INTEREG in Chapter 16).

13.9.1 Consequences of Climate-change Driven Impacts, Risks and Adaptation Emerging in Other Parts of the World for Europe

Recent literature (Wenz and Levermann, 2016; Hedlund et al., 2018; Benzie et al., 2019) strengthens the confidence in the AR5 statement that "with increasing globalization, the impacts of climate change outside the European region are *likely* to have implications for countries within the region" (Kovats et al., 2014). The exposure of European countries to trans-European climate impact and risk pathways varies depending on their territorial settings, national policies and position in the global supply chain (*high confidence*) (Berry et al., 2015; Hedlund et al., 2018; Benzie et al., 2019). There is *limited evidence* that Europe is more exposed to interregional risks than North America, and less than Africa and Asia (Hedlund et al., 2018). The social and governance context in Europe make the region less vulnerable to conflicts driven by climate change than other regions, at least up to 2°C GWL (Buhaug et al., 2014; Mach et al., 2019; Ide et al., 2020).

Climate risks in other parts of the world can be transmitted to European economies via trade networks (Figure 13.25). European agricultural imports exert a high water footprint in originating countries already today (Dolganova et al., 2019; Ercin et al., 2019), and some crop imports such as tropical fruits are highly vulnerable to future climate change (Brás et al., 2019). Simultaneous breadbasket failures, and trade restrictions increase risks to food supply (*medium confidence*) (Fellmann et al., 2014; d'Amour et al., 2016; Gaupp et al., 2017; Gaupp et al., 2020). There is *high confidence* that the European economy could be negatively affected by supply chain disruptions due to flooding destroying facilities, heatwaves and malaria reducing productivity in labour intensive industries and regions (13.7.1), and sea level rise affecting ports and cities along coastlines (13.6.1.2) (Nicholls and Kebede, 2012; Challinor, 2016; Wenz and Levermann, 2016; Hedlund et al., 2018; Koks, 2018; Szewczyk et al., 2018; Willner et al., 2018; Knittel et al., 2020; Kulmer et al., 2020; Carter et al., 2021).

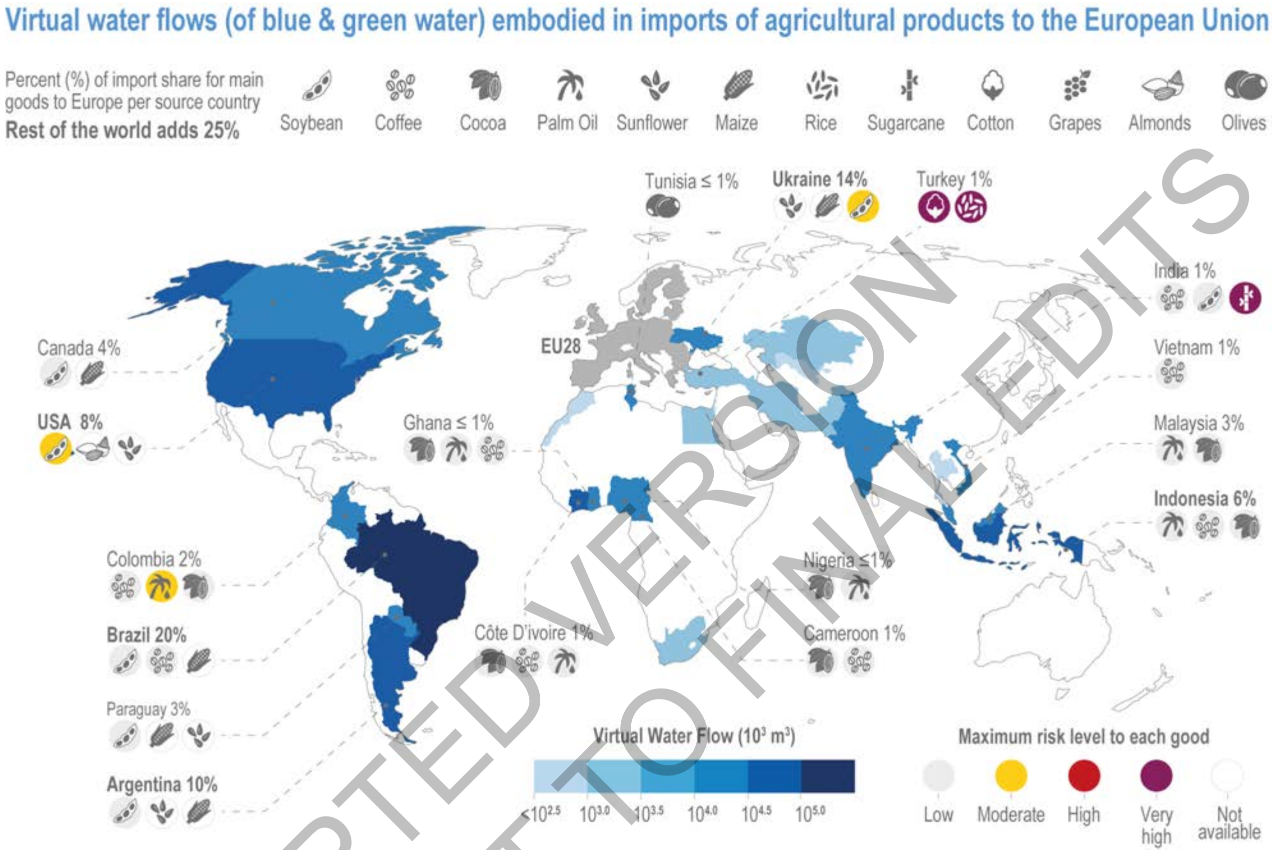


Figure 13.25: Trans-European climate risks in trade: virtual water flows embodied in agricultural imports to Europe in 2018 and the vulnerability to climate change of the most important crops in the originating countries (Dolganova et al., 2019; Ercin et al., 2019).

13.9.2 Interregional Consequences of Climate Risks and Adaptation Emerging from Europe

New literature since AR5 suggests that climate risks in Europe can propagate worldwide in response to 3°C GWL (*medium confidence*). Key concerns include climate impacts on European agriculture threatening global food security (Berry et al., 2017; van der Velde et al., 2018) (Section 13.5.1) and the European demand limiting the adaptation potential for ecosystems in South-America, Africa and Asia (IPBES, 2018; Pendrill et al., 2019; Fuchs et al., 2020). Emerging literature suggests that coastal and riverine flood risks in Europe could be amplified through the global financial system, and generate a systemic financial crisis (Mandel et al., 2021) (Figure 13.26). For 3°C GWL and without adaptation, northern Atlantic flight routes and European ports are projected to be increasingly disrupted by changing winds, waves, and sea level rise (Section 13.6.1.2) (Williams and Joshi, 2013; Irvine et al., 2016; Williams, 2016; Becker et al., 2018; Camus et al., 2019; Verschuur et al., 2020).

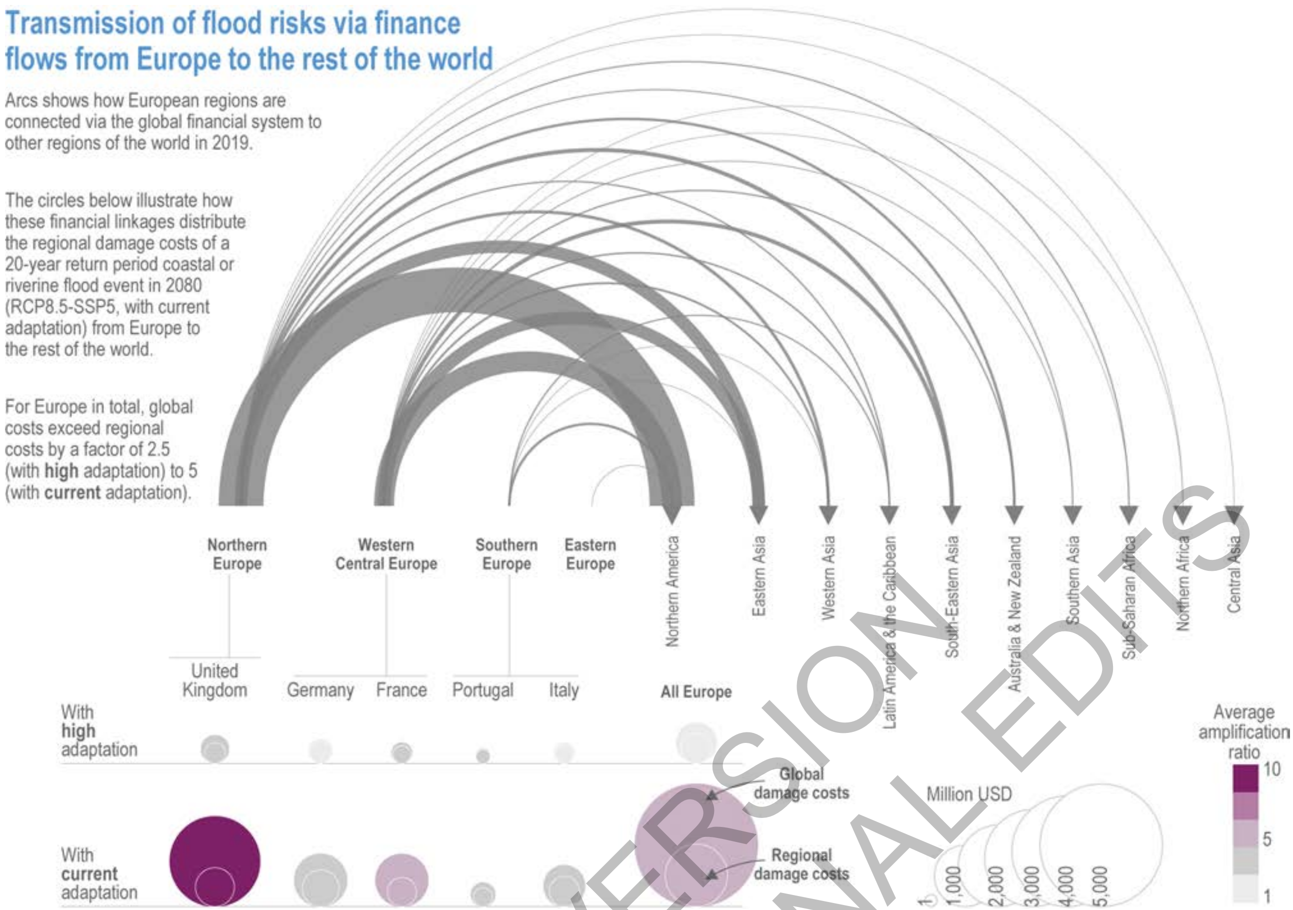


Figure 13.26: The transmission of coastal and riverine flood risks via finance flows from Europe to the Rest of the World. (Mandel et al., 2021).

13.9.3 European Territories Outside Europe

European territories outside Europe are critically exposed to climate risks such as increased forest fires (Russian Siberia) (Sitnov et al., 2017) (Chapter 10), climate change-induced biodiversity losses and sea level rise (UK, Spanish, Portuguese, French and Dutch overseas regions and territories) (Ferdinand, 2018; Sieber et al., 2018) (Chapters 12 and 15). Climate risks emerging from these territories include smoke and dust from Siberian forest fires (Sitnov et al., 2017), and, depending on European health-risk mitigation measures, dengue and other mosquito-transmitted diseases (13.7) (Schaffner and Mathis, 2014). Some marine protected areas (MPA, 13.4.3) in European overseas territories are increasingly affected by changes originating in far-field upstream areas. These changes ultimately undermine their ability to curb biodiversity losses and provide ecosystem services (Schaffner and Mathis, 2014; Robinson et al., 2017). Adaptation options and regulations developed within Europe apply in these territories, despite *low confidence* that they meet local and regional adaptation challenges and address the aspiration for social justice, promotion of local solutions and consideration of traditional knowledge (Ferdinand, 2018; Terorotua et al., 2020).

13.9.4 Solution Space and Adaptation Options

European countries can address interregional risks at the place of origin or destination, e.g., by developing local adaptation capacity in trading partner countries and in European territories outside Europe(Petit and Prudent, 2008; Benzie et al., 2019; Adams et al., 2020; Terorotua et al., 2020), by providing international adaptation finance (Dzebo and Stripple, 2015; BMUB, 2017), by developing insurance mechanisms suitable for adaptation, or European climate services to support global adaptation (Linnerooth-Bayer and Mechler, 2015; Brasseur and Gallardo, 2016; Street, 2016; Cavelier et al., 2017) (Cross-Chapter Box INTEREG in Chapter 16). Along the supply chain, risks can be reduced by trade diversification and alternative sourcing (Benzie and Persson, 2019; Adams et al., 2020). Within Europe, risks can be reduced by integrating interregional climate risks into national adaptation strategies and plans and mainstreaming into EU policies (e.g., Common Agricultural Policy, trade agreements) (Benzie et al., 2019; Benzie and Persson, 2019; Groundstroem and Juhola, 2019; Adams et al., 2020). There is *high confidence* that the exposure of European countries to interregional risks can be reduced by international governance (Dzebo and Stripple, 2015; Cramer et al., 2018; Persson and Dzebo, 2019) (Cross-Chapter Paper 4), e.g., fulfilling the targets of environmental agreements such as the Convention for Biological Diversity (IPBES, 2018). There is *emerging evidence* that supporting adaptation outside Europe may generate economic co-benefits for Europe (Román et al., 2018).

13.10 Detection and Attribution, Key Risks and Adaptation Pathways

13.10.1 Detection and Attribution of Impacts

Since AR5, scientific documentation of observed changes attributed to global warming have proliferated (*high confidence*). These include ecosystem changes detected in previous assessments, such as earlier annual greening and onset of faunal reproduction processes, and relocation of species towards higher latitudes and altitudes (*high confidence*), and impacts of heat on human health, and productivity (*high confidence*) (Figure 13.27 and Table SM13.22) (Vicedo-Cabrera et al., 2021). Formal attribution of impacts of compound events to anthropogenic climate change is just emerging for example in the recent crop failures due to heat and drought (Toreti et al., 2019a). Also, there is *high agreement* and *medium evidence* that particular events attributed to climate change have induced cascading impacts and other impact interactions (Smale et al., 2019; Vogel et al., 2019). In the recent decades (2000-2015), economic losses intensified in southern Europe (*high confidence*) and were detected for parts of WCE and NEU (*medium confidence*). The methodology for detection and attribution is presented in Chapter 16.2.

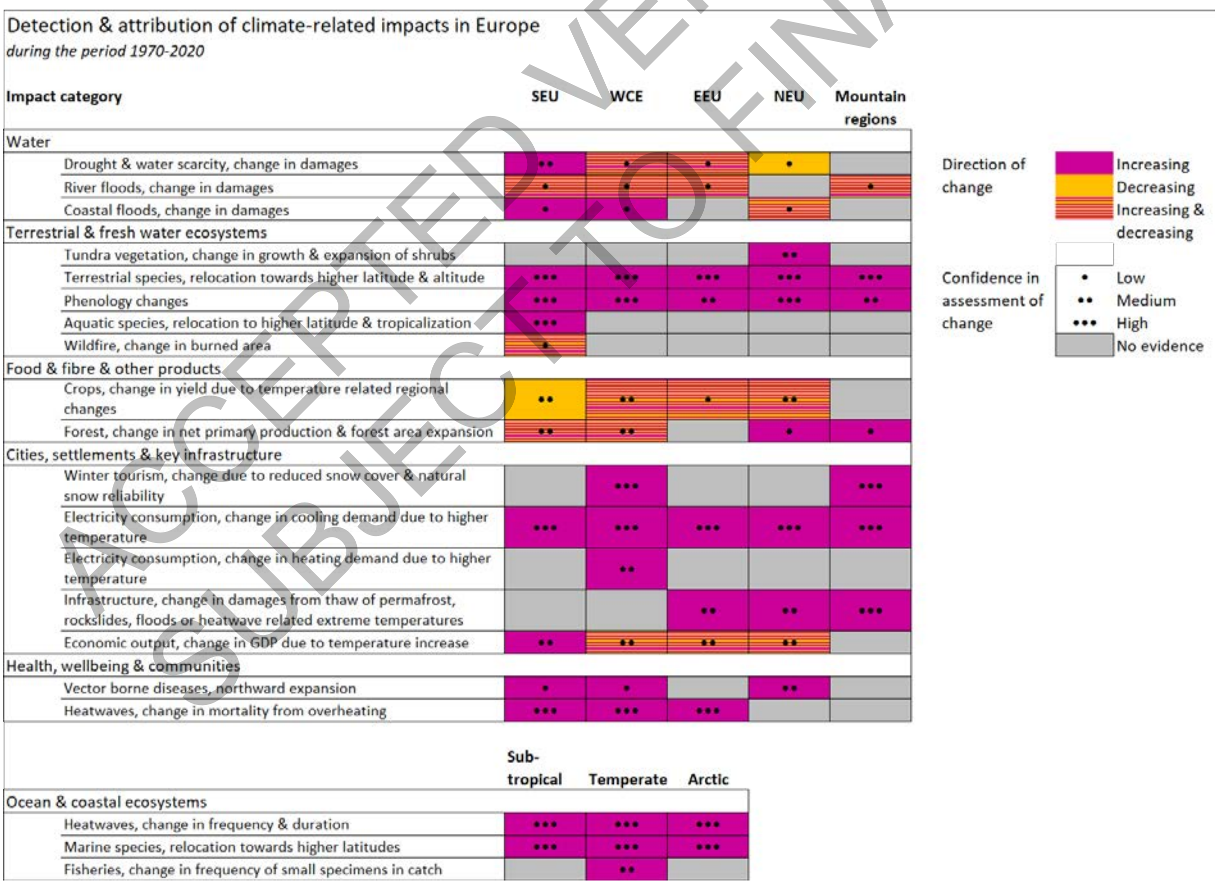


Figure 13.27: Detected changes and attribution (D&A) of climate-related impacts on land (top) and in the ocean (bottom). Assessment based on peer reviewed literature in this chapter that reported observed evidence with at least 90% significance and usually with 95% significance or more (Table SM13.22).

13.10.2 Key Risks Assessment for Europe

Key risks (KRs) are defined as a subset of climate risks which can potentially become or are already severe now (Section 16.5). The selection process included a review of KRs already identified in AR5 Chapter 23 and a review of the large number of new evidence on projected risks presented in Sections 13.2-13.9. Key risks are reinforced by evidence from the detection and attribution assessment (Section 13.10.1) and new evidence from WGI AR6 Chapters 11 and 12 on regional climatic impact drivers and extremes (Ranasinghe et al., 2021; Seneviratne et al., 2021). Several expert opinion workshops of lead and contributing authors led to further refinements, adjustment and consensus building around the key risks' characteristics, which ultimately guided the construction of the burning embers (Figures 13.28-13.32) (SM13.10). There is *high confidence* that under low or medium adaptation, high to very high risks are projected at 3°GWL (Figure 13.28 and Sections 13.10.2.1-13.10.2.4). Most risks are assessed as moderate up to 1.5°GWL (Figure 13.28).

This section also includes an assessment of the solution space using illustrative adaptation pathways which show alternative sequences of options to reduce risks as climate changes (SM13.10). Low effectiveness measures are followed by measures of a higher effectiveness, while accounting for path-dependency of decisions (Toreti et al., 2019b; Haasnoot et al., 2020a). The process to derive the pathways draws on evidence from the feasibility and effectiveness assessments (Sections 13.2, 13.5, 13.6, 13.7).

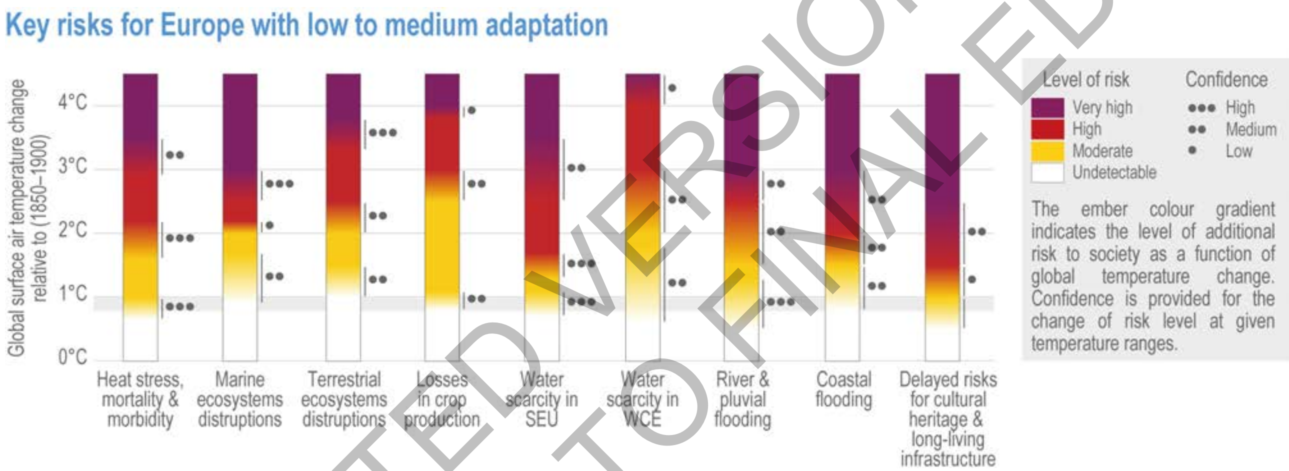


Figure 13.28: Burning ember diagrams for low to medium adaptation. More details on each burning ember are provided in Sections 13.10.2.1-13.10.2.4 and SM13.10. Some burning embers are shown again in Figure 13.29-13.34 alongside burning embers with high adaptation.

13.10.2.1 KR1: Risks of human mortality and heat stress and of ecosystems disruptions due to heat extremes and increase in average temperatures

This key risk cut across humans and ecosystems and severe consequences are mainly driven by an increasing frequency, intensity and duration of heat extremes and increasing average temperatures (*high confidence*) (Urban, 2015; Forzieri et al., 2017; Feyen et al., 2020; Naumann et al., 2020; Ranasinghe et al., 2021). The risk of human heat stress and mortality is largely influenced by underlying socio-economic pathways, with consequences being more severe under SSP3, SSP4 and SSP5 scenarios than SSP1 (*very high confidence*) (Figure 13.22, Section 13.6.1.5.2, Section 13.7.1.1, Hunt et al., 2017; Kendrovski et al., 2017; Rohat et al., 2019; Casanueva et al., 2020). SSPs impact natural systems as well but are not yet well studied. The impact of warming in marine systems are often synergistic with SLR in coastal systems and ocean acidification driven by the rise in CO_2, while habitat fragmentation and land use have important synergies in terrestrial systems (Sections 13.3.1.2 and 13.4.1.2, *high confidence*). More intense heatwaves on land and in the ocean, particularly in Mediterranean Europe (Section 13.4, CCP 4, Darmaraki et al., 2019b; Fox-Kemper et al., 2021), are expected to cause mass mortalities of vulnerable species and species extinction, altering the provision of important ecosystem goods and services (Marbà and Duarte, 2010).

The burning embers on risks for humans (Figure 13.29a) differentiate between present and medium adaptation conditions, drawing on SSP2 and SSP4 (and to a lesser extent SSP3), and high adaptation conditions, drawing on SSP1 and papers using various temperature adjustment methods (Table SM13.25). There is *high confidence* that the risk is already moderate now because it has been detected and attributed with *high confidence* (13.10.1). The transition from moderate to high risk for human health is assessed to happen after 1.5°C GWL in a scenario with present to medium adaptation and implies 2- 3 fold increase (compared to moderate risk levels) in magnitude of consequences such as mortality, morbidity, heat stress and thermal discomfort (Rohat et al., 2019; Casanueva et al., 2020; Naumann et al., 2020). At this level, the risk will also become more persistent across the continent due to increase in heat events exceeding critical thresholds for health (Ranasinghe et al., 2021) (*high confidence* on the direction of change and temperature transition, but *medium confidence* on the magnitude).

The burning embers on risk for terrestrial and marine ecosystems and some of their services is shown in Figure 13.28, second and third ember from left (Tables SM13.26 SM13.27). The transition to moderate risk is currently happening as warming already results in changes in timing of development, species migration northwards and upwards, desynchronization of species interactions, especially at the range limits, with cascading and cumulative impacts through ecosystems and food webs (Sections 13.3 and 13.4; Figure 13.8 and 13.12) (*high confidence*). While some terrestrial ecosystems are already impacted today such as Alpine, cryosphere and peatlands, the impacts are not widespread and severe yet across a wide range of terrestrial systems. Around 2°C GWL, losses accelerate in marine ecosystem and appear across systems, including habitat losses especially in coastal wetlands (Roebeling et al., 2013; Clark et al., 2020), biodiversity and biomass losses (Bryndum-Buchholz et al., 2019; Lotze et al., 2019) and ecosystem services such as fishing (Raybaud et al., 2017) (*high confidence* on the direction of change, but *medium confidence* on the local and regional magnitude). The transition is happening at slightly higher warming in terrestrial systems due to higher number of thermal refugia in terrestrial systems causing relocation but not already severe impacts (*medium confidence*) (Chapter 2).

There is *medium confidence* that high adaptation or conditions posing low challenges for adaptation (e.g. SSP1) in the context of human health can delay the transition from moderate to high risk (Åström et al., 2017; Ebi et al., 2021). The illustrative adaptation pathways in Figure 13.29b,c show the sequencing of options to a high adaptation future for NEU and SEU. Whether or not adaptation measures are effective to reduce risk severity for people's health depends on local context (*high confidence*) (Figure 13.29, Section 13.6.2 and 13.7.2). Some adaptation options are found to be highly effective across Europe irrespective of warming levels, including air conditioning and urban planning (*high confidence*) (Sections 13.6.2 and 13.7.2, Jenkins et al., 2014b; Donner et al., 2015; Dodoo and Gustavsson, 2016; Åström et al., 2017; Dino and Meral Akgül, 2019; Venter et al., 2020), although air conditioning increasingly faces some feasibility constraints (Figure 13.20). Building interventions alone have low to medium effectiveness independent of the region. Many behavioural changes such as personal and home heat protection have already been implemented in SEU (Section 13.7.2, Martinez et al., 2019). To reach high adaptation, a combination of low, medium, and high effectiveness measures in different sectors and sub-regions is needed, many of which entail systems' transformations (Chapter 16) (e.g., heat proof land management) and remain effective at higher warming levels (*medium confidence*) (Díaz et al., 2019). These transformations have long lead times, therefore requiring timely start of implementation including regions that are not yet experiencing high heat stress (e.g. NEU) (*high agreement, medium evidence*).

Autonomous adaptation of species via migration in response to climate change is well documented in contemporary, historical and geological records (Chapter 2, Cross-Chapter Box PALEO in Chapter 1). However, the projected rate of climate change can exceed migration potential, leading to evolutionary adaptation or increased extinction risk (Chapters 2 and 3; Sections 13.3 and 13.4). A reduction of non-climatic stressors, such as nutrient loads, resource extraction, habitat fragmentation or pesticides on land, are considered important adaptation options to increase the resilience to climate-change impacts (Sections 13.3 and 13.4, Ramírez et al., 2018) (*high confidence*). A major governance tool to reduce climatic and non-climatic impacts is the establishment of networks of protected areas (Sections 13.3.2 and 13.4.2) especially when aggregated, zoned or linked with corridors for migration (*high confidence*), as well as a cost-effective adaptation strategy with multiple additional co-benefits (Berry et al., 2015; Roberts et al., 2017). Reforestation, rewilding and habitat restoration are long term strategies for reducing risk for biodiversity loss supported by assisted migration and evolution (Section 13.3.2, 13.4) though current laws and regulations do not include species migration (*high confidence*) (Prober et al., 2019; Fernandez-Anez et al., 2021).

Very high risks are expected beyond 3°C GWL due to the magnitude and increased likelihood of serious consequences, as well as to the limited ability of humans and ecosystems to cope with these impacts. There is *high confidence* that even under high adaptation scenarios for human systems or autonomous adaptation of natural systems, the risk will still be high at 3°C GWL and beyond (Section 13.7.2, Hanna and Tait, 2015; Spencer et al., 2016) with *medium confidence* on the temperature range of the transition. Projected sea level rise will strongly impact coastal ecosystems (*high confidence*), minimising their contribution to shoreline protection (Section 13.10.2.4).

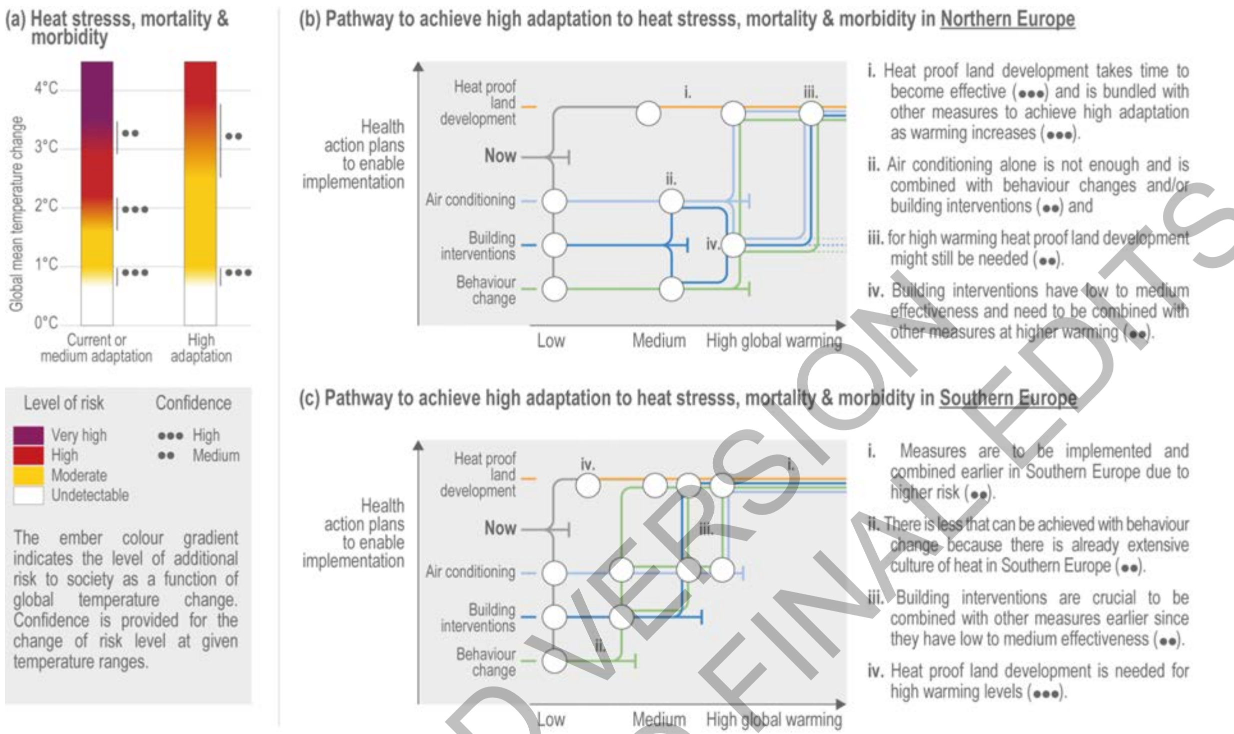


Figure 13.29: (a) Burning ember diagrams for the risk to human health from heat. The low/medium adaptation scenario corresponds to present, SSP2 and SSP4 socio-economic conditions. The high adaptation includes SSP1 and adaptation needed to maintain current risk levels. (b-c) Illustrative adaptation pathways for NEU (top) and SEU (bottom) and key messages based on the feasibility and effectiveness assessment in Figures 13.20 and 13.24. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point. (Tables SM13.24, SM13.25)

13.10.2.2 KR2: Risk of losses in crop production, due to compound heat and dry conditions, and extreme weather

KR2 encompasses agriculture productivity (Figure 13.30a). It is mainly driven by the increase in the likelihood of compound heat and dry conditions and extremes and their impact on crops. There is *high confidence* that climate change will increase the likelihood of concurrent extremely dry (Table SM13.28) and hot warm seasons with higher risks for WCE, EEU (particularly north-western Russia) and SEU leading to enhanced risk of crop failure and decrease in pasture quality (Section 13.5.1) (Zscheischler and Seneviratne, 2017; Sedlmeier et al., 2018; Seneviratne et al., 2021). The risk is already moderately severe due to multiple crop failures in the last decade in WCE and Russia (Section 13.5.1, Hao et al., 2018; Pfleiderer et al., 2019; Vogel et al., 2019). Under high-end scenarios, heat and drought extremes are projected to become more frequent and widespread as early as mid-century (Toreti et al., 2019a). For present to moderate adaptation and at least up to 2.5°GWL, negative consequences are mostly in SEU (Bird et al., 2016; EEA, 2019c; Moretti et al., 2019; Feyen et al., 2020). The transition from moderate to high risk is projected to happen around 2.7°C GWL when hazards and risk will become more persistent and widespread in other regions (Section 13.1, Deryng et al., 2014; Donatelli et al., 2015; Webber et al., 2018; Ceglar et al., 2019; Ranasinghe et al., 2021; Seneviratne et al., 2021). This temperature increase will trigger shift of agricultural zones, onset of early heat stress, losses in maize yield of up to 28% across EU-28, and regional disparity in losses and gains in wheat, which are not able to offset losses across the continent (Deryng et al., 2014; Szewczyk et al., 2018; Ceglar et al., 2019). There will be also broader adverse impacts such as reduction of grassland biomass production for fodder, increases in weeds and reduction in pollination (Castellanos-Frias et al., 2016; Nielsen et al., 2017; Brás et al., 2019) (*medium confidence*). Combined with socio-economic development, increased heat and drought stress and reduced irrigation water availability in SEU are projected to lead to abandonment of farmland (Holman et al., 2017). Around 4°C GWL, the risk is very high due to persistent heat and dry conditions (Ben-Ari et al., 2018) and the emergence of losses also in NEU which would be much higher without the assumed CO_2 fertilisation (Deryng et al., 2014; Szewczyk et al., 2018; Harrison et al., 2019).

Farmers have historically adapted to environmental changes and such autonomous adaptation will continue. Higher CO_2 levels have a fertilisation effect on plants that is considered to decrease production risks (Deryng et al., 2014). Adaptation solutions to heat and drought risks include changes in sowing and harvest dates, increased irrigation, changes in crop varieties, the use of cover crops, and mixed agricultural practices (Section 13.5.2; Figure 13.14 and Figure 13.30b). Under high adaptation, the use of irrigation can substantially reduce risk by both reducing canopy temperature and drought impacts (*high confidence*) (Section 13.5.2, Webber et al., 2018). Some reductions of maize yields in SEU are still possible, but are balanced by gains in other crops and regions (Deryng et al., 2014; Donatelli et al., 2015; Webber et al., 2018; Feyen et al., 2020). At 3°C GWL and beyond, the adaptive capacity is reduced (Ruiz-Ramos et al., 2018). Crop production is a major consumer of water in agriculture (Gerveni et al., 2020), yet a potentially scarcer supply of water in some regions must be distributed across many needs (KR3, Section 13.10.2.3), limiting availability to agriculture which is currently the main user of water in many regions of Europe (Section 13.5.1) (*high confidence*). Where the ability to irrigate is limited by water availability, other adaptation options are insufficient to mitigate crop losses in some sub-regions, particularly at 3°C GWL and above, with an increase of risk from north to south and higher risk for late-season crops such as maize (*high confidence*). Under these conditions, land abandonment is projected (Holman et al., 2017) (*low confidence*).

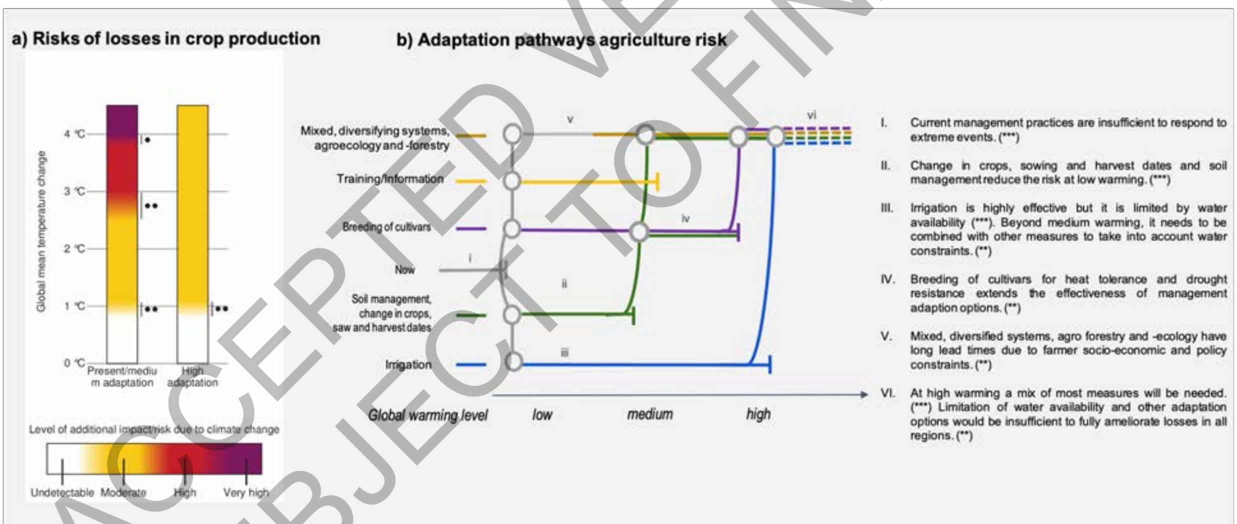


Figure 13.30: (a) Burning ember diagrams for losses in crop production with present or medium adaptation condition and with high adaptation. Panel (b) Illustrative adaptation pathways and key messages based on the feasibility and effectiveness assessment in Figure 13.14. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point (Table SM13.28).

13.10.2.3 KR3: Risk of water scarcity to multiple interconnected sectors

Risks related to water scarcity across multiple sectors can become severe in WCE and to a much larger extent in SEU based on projections of drought damage, population and sectors exposed and increases in water exploitation (Figure 13.31a; Table SM13.29). In EEU, uncertainty in hydrological drought projections and risk consequences is higher (Greve et al., 2018; Ranasinghe et al., 2021; Seneviratne et al., 2021) and the available number of publications is lower, not allowing a conclusion on how risk levels change with GWL. Yet, there is emerging evidence that drought related risks increase with warming beyond 3°C GWL also in

EEU (Seneviratne, 2021 #12291for hydrological drought and 4°C GWL, Kattsov and Porfiriev, 2020). Evidence from the D&A assessment suggests that the risk is already moderate in SEU (e.g. 48 million people exposed to moderate water scarcity between 1981-2010) (Section 13.10.1, Figure 13.31a) (*high confidence*).

Risks have a high potential to lead to cascading impacts well beyond the water sector since water scarcity affects a number of highly interconnected sectors in Europe, from agriculture and livestock farming to energy (hydropower and cooling of thermal power plants) and industry (e.g., shipping) (Blauhut et al., 2015; Stahl et al., 2016; Bisselink et al., 2020; Cammalleri et al., 2020). Extensive water extraction will augment pressures on water reserves, impacting the ecological status of rivers and ecosystems dependent on them (Grizzetti et al., 2017). Socioeconomic conditions contributing to severe consequences are when more residents settle in drought-prone regions, or when the share of agriculture in GDP declines (*high confidence*). For Europe, risks of water scarcity will be higher under SSP5 and SSP3 than under SSP1 (*medium confidence*) (Byers et al., 2018; Arnell et al., 2019; Harrison et al., 2019). Transition to high risks is projected to occur below 2°C GWL in SEU and associated with more persistent droughts (Section 13.1.3) and at 2°C GWL with 54% increase of the population facing at least moderate levels of water shortage (Byers et al., 2018). This transition will happen at higher warming in WCE since risks are projected to increase less rapidly (transition between 2-3°C GWL) (*medium confidence*) (Section 13.2.1.2, Byers et al., 2018). At 3°C GWL and beyond, water scarcity will become much more widespread and severe in already water scarce areas in SEU (*high confidence*) and will expand to currently non-water scarce regions in WCE (*medium confidence*) (Section 13.2.1.2, Bisselink et al., 2018; Naumann et al., 2018; Harrison et al., 2019; Koutroulis et al., 2019; Cammalleri et al., 2020; Spinoni et al., 2020). Decrease in hydropower potential in SEU and WCE are expected beyond 3°GWL (Figure 13.16).

To reduce risk severity, adaptation measures both at supply and demand level have been suggested (Section 13.2.2, Figure 13.6, Figure 13.31b, Garnier and Holman, 2019; Hagenlocher et al., 2019). Several measures are already in place, showing high technical and institutional feasibility (Section 13.2.2.2 and 13.5.2.1). The effectiveness of options varies regionally (in particular between northern and southern regions). For example, in SEU many water reservoirs are already in place. Irrigation is used to support agriculture where rainfed supplies are not sufficient (13.5.2). Their future extension depends on available precipitation. Also, wastewater reuse can only be effective if sufficient wastewater is available. Improvements in water efficiency and behavioural changes are very effective in SEU (>25% of damages avoided) (Section 13.2.2.2). Investments in large water infrastructures and advanced technologies (incl. storage), water transfer, water recycling and reuse and desalination allow to buy time and therefore to cope with additional warming (Papadaskalopoulou et al., 2016; Greve et al., 2018). Beyond 2.5°C GWL, transformational adaptation is needed to lower risk levels, such as planned relocation of industry, abandonment of farmland or the development of alternative livelihoods (Holman et al., 2017). In WCE the solution space to water scarcity is expanding with considerable potential for investments in large water infrastructure and advanced technologies (incl. storage), for reducing risks above 3°C GWL (Greve et al., 2018). Under medium warming a larger portfolio of measures might be needed in SEU in particular, although it may not be able to completely avoid water shortages at high warming.

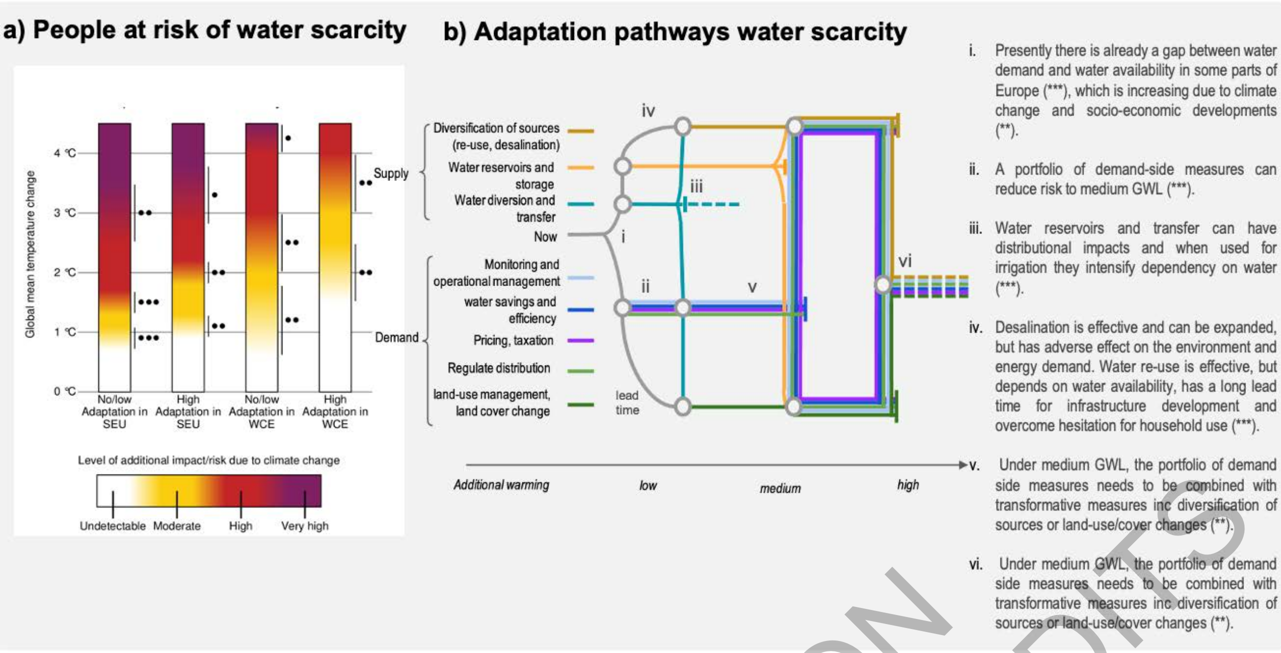


Figure 13.31: (a) Burning ember diagrams for the risk of water scarcity with no/low adaptation and with high adaptation for SEU and WCE. (b) Illustrative adaptation pathways and key messages (see Figure 13.6). Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point (Table SM13.29).

13.10.2.4 KR4: Risks to people, economies and infrastructures due to coastal and inland flooding

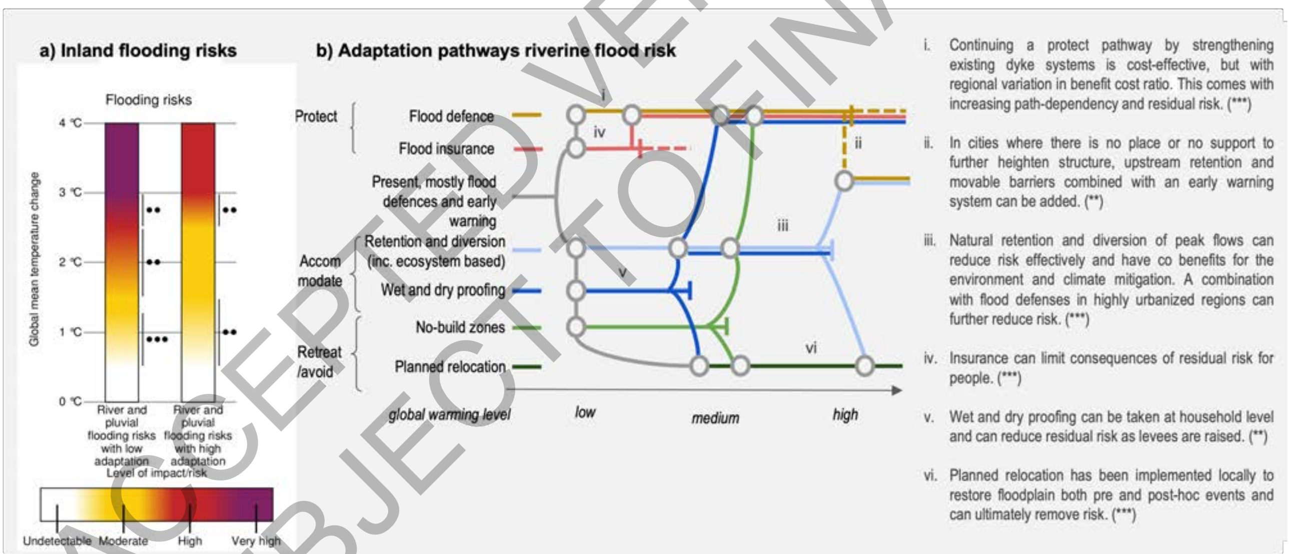
Damages and losses from coastal and river floods are projected to increase substantially in Europe over the 21st century (*high confidence*) (Section 13.2.1, SM13.10). Coastal areas have already started to be affected by sea level rise (Box13.1; Section 13.10.1) and human exposure to coastal hazards is projected to increase in the next decades (*high confidence*), but less under SSP1 (20%) than SSP5 (50%) by the end of the century (*medium confidence*) (Merkens et al., 2016; Reimann et al., 2018a). Under low adaptation (i.e. coastal defences are maintained but not further strengthened), severe consequences include increase in expected annual damage by a factor of at least 20 for 1.5-2.1°C GWL (i.e.. high risks) and by 2-3 orders of magnitude between 2 and 3°C GWL in EU-28 (i.e. very high risk) (*medium confidence*) (Figure 13.28, 13.34c; Section 13.2.1.1); (Vousdoukas et al., 2018b; Haasnoot et al., 2021b). Under high adaptation (i.e. lowlands are protected where it is economically efficient), expected annual damages still increase by a factor of 5 above 2°C GWL (Section13.2, Vousdoukas et al., 2020). Sea-levels are committed to rise for (Fox-Kemper et al., 2021), submerging at least 10% of the territory in 12 countries in Europe after millennia if GWL exceed 1.5-2.5°C (Clark et al., 2016), and this represents a major threat for the European and Mediterranean cultural heritage (Figure 13.28, Cross-Chapter Box SLR in Chapter 3, CCP4, Marzeion and Levermann, 2014; Reimann et al., 2018b).

Pluvial and riverine flood events in Europe have been attributed to climate change, but the associated damages and losses also depend on land use planning and flood risk management practices (*medium confidence*) (Section 13.10.1, Ranasinghe et al., 2021). Exposure to urban flooding will increase with urbanization (Jongman et al., 2012; Jones and O'Neill, 2016; Dottori et al., 2018; Paprotny et al., 2018b). Flooding is projected to rise with temperature in Europe, with e.g. a doubling of damage costs and people affected from river flood for low adaptation above 3°C GWL (Alfieri et al., 2018). Inland flooding represents a key risk for Europe due to the extent of settlements exposed, the frequency of the hazards, the risks to human lives associated with flash floods and the limited adaptation potential to pluvial flooding (e.g. difficulty to upgrade urban drainage systems (Dale et al., 2018; Dale, 2021). Hence, risks can become very high from 3°C GWL (Figure 13.32a).

A range of adaptation options to coastal flooding exists and adaptation is possible in many European regions if started on time (Section 13.2 and Figure 13.32d). Continuing a protection pathway is cost-effective in urbanized regions for this century (Vousdoukas et al., 2020), but there is *high agreement* that it comes with residual risk if coastal defences fail during a storm. This residual risk can be reduced through early warning and evacuations, insurance and accommodate measures (Section 13.2.2). Soft limits to protection have been identified under high GWL, in particular due to the rate of change and delayed impacts of long-term SLR (*medium confidence*) (Hinkel et al., 2018; Haasnoot et al., 2020a). Ecosystem based solutions such as wetlands can reduce waves' propagation, provide co-benefits for the environment and climate mitigation, and reduce costs for flood defences (*medium confidence*) (Section 13.2.2.1). At higher GWL, ecosystems are projected to experience reduced effectiveness due to temperature increase and increased rate of SLR combined with lack of sediment and human pressures (Cross-Chapter Box SLR in Chapter 3). Retention and diversion can be effective for compound flooding or for estuaries with a limited storm surge duration, but there is lack of knowledge on their effectiveness (Sections 13.2.2).

In the case of river flooding, adaptation has the potential to contain damage and losses up to 3°C GWL (Figure 13.32b, Jongman et al., 2014; Alfieri et al., 2016), provided they are implemented on time and that the technical, social and financial barriers are addressed (Sections 13.2.2 and 13.6.2). Residual risks can be reduced through early warning and evacuations, insurance and accommodate measures (see Section 13.2.2, Kreibich et al., 2015). Accommodation strategies such as retention and ecosystem-based solutions require space, which is not always available in cities. Both protection and flood retention are effective in reducing inland flooding risk across Europe, but with regional variation in the benefit-to-cost ratio (Alfieri et al., 2016; Dottori et al., 2020) (*medium confidence*). Furthermore, upgrading drainage systems to accommodate increase in pluvial flooding is costly, technically complex and requires time (Dale et al., 2018; Dale, 2021).

Avoiding developments in risk-prone areas can reduce both coastal and inland flooding risks and can be followed by planned relocation, particularly in less-populated areas. To align relocation with social goals and to achieve positive outcomes long lead times are needed (Haasnoot et al., 2021a).



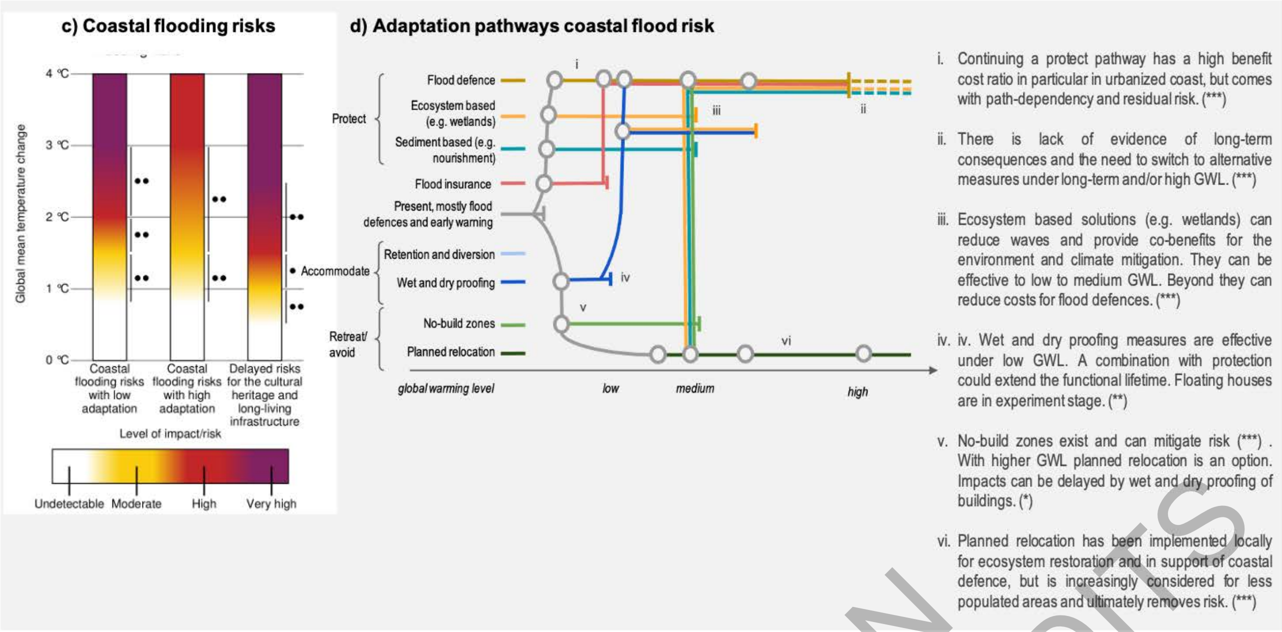


Figure 13.32: (a) Burning ember diagram for the risks from riverine and pluvial flooding with and without adaptation. (b) Illustrative adaptation pathways to riverine flooding risks. (c) Burning ember diagram for the risks from coastal flooding with and without adaptation. (d) Illustrative adaptation pathways to coastal flooding risks. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point.(Tables SM13.30, SM13.31)

13.10.3 Consequences of Multiple Climate Risks for Europe

European regions are affected by multiple key risks simultaneously; while there is a wide range in quantifications, there is high agreement that consequences for socio-economic and natural systems can be substantial, with more severe consequences in the south than in the north *(very high confidence*); there is some indication also for a west to east gradient, with higher uncertainty in eastern part of WCE and EEU which makes adaptation more challenging (*medium confidence*). Furthermore, the food-water-energy-land use nexus plays an important role in amplifying overall risk levels in Europe (*medium confidence*) (Forzieri et al., 2016; Harrison et al., 2016; Byers et al., 2018; Arnell et al., 2019; Harrison et al., 2019; Kebede et al., 2021). Southern Europe, European cities and coastal areas are projected to become hotspots of multiple risks (Cramer et al., 2018; Forzieri et al., 2018; Guerreiro et al., 2018) (*high confidence*). The number of people exposed to multiple KRs in Europe are projected to at least double at 3°C GWL compared to 1.5°C GWL (Forzieri et al., 2017; Byers et al., 2018; Arnell et al., 2019), but risk levels are already higher at 1.5°C GWL than today for a number of KRs (Figure 13.28) (*medium confidence*).

Economic losses and damages for European economies from multiple KRs are projected increase (*high confidence*) (Figure 13.34, Szewczyk et al., 2018; Feyen et al., 2020; Kalkuhl and Wenz, 2020), potentially quadruple at 3°C GWL compared to 1.5°C GWL (Feyen et al., 2020). Existing estimates of projected economic costs for Europe, based on integrated assessment or computable general equilibrium models, are however *likely* to be underestimations of the true costs because of incomplete coverage of biophysical impacts, in particular low-probability high impact events, and disruptive risk propagation channels (Lamperti et al., 2018; Stoerk et al., 2018; Schewe et al., 2019; Piontek et al., 2021). The main driver for this increase in economic losses and damages is mortality due to heat stress (*medium confidence*), followed by reduced labour productivity, coastal and inland flooding, water scarcity and drought (*medium confidence*) (Figure 13.33; Section 13.6.1.3). While losses are highest in SEU for both 1.5°C and 3°C GWL and increase by a factor of more than three between these GWLs, the projected economic damages and losses also increase significantly in WCE (by a factor of 4 from 1.5°C to 3°C GWL; 40% of total losses in EU-28 at 3°C GWL) and in NEU (almost 10% of total losses at 3°C GWL) (Szewczyk et al., 2018; Szewczyk et al., 2020). Adaptation is projected to reduce macroeconomic costs, but residual costs remain, particularly for warming above 3°C GWL (*medium confidence*) (De Cian et al., 2016; Bosello et al., 2018; Parrado et al., 2020).

Economic risk	Key Risk	GWL	NEU	WCE	EEU	SEU	references (n)
Change in agricultural yields	KR1, KR2	1.5°C	••	••	LE	••	3
		3°C	••	•	••	•••	6
Change in labour productivity	KR1	1.5°C	••	••	••	••	5
		3°C	••	••	•	•••	6
Change in energy demand	KR1	1.5°C	•	•	LE	•	2
		3°C	••	••	•	••	3
Change in mortality due to heat	KR1	1.5°C	••	••	LE	••	2
		3°C	••	••	•	••	5
Damage to economic sectors from water scarcity ad drought	KR3	1.5°C	•	•	LE	••	4
		3°C	•	••	LE	••	2
Change in energy supply	KR3	1.5°C	•	•	LE	•	2
		3°C	•	•	•	•	3
Damage to infrastructure from coastal flooding	KR4	1.5°C	••	••	LE	••	4
		3°C	••	••	••	•••	8
Damage to infrastructure from inland flooding	KR4	1.5°C	••	••	•	••	6
		3°C	••	••	•	••	7

Economic damage/loss (% of GDP or welfare)						Economic gain (% of GDP or welfare)
very high >1%	high 0.1% - 1%	moderate 0.01% - 0.1%	no <0.01%	moderate 0.01% - 0.1%	high 0.1% - 1%	very high >1%
Confidence: high (•••), medium (••), low (•)					both	LE (limited evidence)

Figure 13.33: Economic losses/damages and gains due to projected climate risks, for 1.5°C and 3°C GWL relative to no additional warming; macroeconomic effects measured in GDP or welfare. Effect for EEU report for Russia as a whole country, deviating from the definition of EEU in this chapter. Effects may deviate from sectoral assessments in Sections 13.2-13.7 due to different degree of coverage of risk channels (Table SM13.23).

13.10.4 Knowledge Gaps

Information on risk levels and development are available for 1.7°C, 2.5°C and > 4°C GWL, making the determination of transitions for the burning embers challenging and impairing a comprehensive assessment across key risks. Further efforts to extend the SSP narratives to Europe can contribute to a more disaggregated understanding of risk severity for different vulnerability and exposure conditions, but the evidence to date remains limited to few sectors (CCP4, Kok et al., 2019; Pedde et al., 2019; Rohat et al., 2019). There is only very *limited evidence* on the extent and timing of residual risks under different GWL, even with high adaptation.

There is *medium confidence* on the effectiveness of adaptation beyond 3°C GWL particularly where risks are high to very high (Figures 13.28-13.32). There is *limited evidence* on the effectiveness of specific adaptation options at different levels of warming that also include consideration of lead and lifetimes. An integrated assessment, which projects the impacts on crop production by examining the potential availability of water for agricultural purposes together with other adaptation measures, is missing.

Transboundary risks, interactions between commodity and financial markets, market imperfections, non-linear socio-economic responses, and loss of ecosystem services, may amplify losses for European economies. Available models may underestimate the full costs of climate change as they generally neglect systemic risks, tipping points, indirect and intangible losses and limits to adaptation (Dafermos et al., 2018; Lamperti et al., 2018; van Ginkel et al., 2020; Dasgupta et al., 2021; Ercin et al., 2021; Piontek et al., 2021). With increasing global warming, compound, low likelihood, or unprecedented extremes such as the European dry and hot summer 2018 or the extreme rainfall following storm Desmond in the UK in 2015, become more frequent (AR6 WGI Cross-Chapter Box 11.2). These events can have catastrophic consequences for Europe, but the extent of economic and non-economic damages and losses remain largely uncertain.

13.11 Societal Adaptation to Climate Change across Regions, Sectors and Scales

Building on our sectoral analysis in previous sections, this section looks across European sectors, vulnerable groups, and regions to assess how climate change impacts are being responded to in general by state (Section 13.11.1) and non-state (Section 13.11.2) actors, and their synergies and dependencies. Sections 13.11.3 assess if and how system transformations have emerged and implications for the SDGs and climate resilient development pathways (CRDPs).

13.11.1 Policy Responses, Options and Pathways

13.11.1.1 Progress on Adaptation Planning and Implementation

The solution space for climate change adaptation has expanded across European regions since AR5 (*high confidence*). European countries are increasingly planning to adapt to observed impacts and projected climate risks across scales of government (Lesnikowski et al., 2016; Russel et al., 2020) (*high confidence*). Whereas in 2009, only nine EU countries had developed a National Adaptation Strategy (NAS) (Biesbroek et al., 2010; EEA, 2014), by mid-2020 all EU Member States and several other European countries had adopted at least a NAS and/or revised and updated prior strategies (Figure 13.34, bottom, Klostermann et al., 2018; EEA, 2020a). Progress is also observed at the level of the European Union with the adoption of the new EU strategy on adaptation to climate change in 2021 (European Comission, 2021a) and regionally, particularly in federalist and decentralised states (Steurer and Clar, 2018; EEA, 2020c; Pietrapertosa et al., 2021), and locally, with an increasing number of European cities planning for climate risks (Aguiar et al., 2018; Reckien et al., 2018; Grafakos et al., 2020) (Section 13.6.2.1;Box 13.3;Chapter 6) (*high confidence*). There is evidence of action across sectors and scales, even in European countries where national adaptation frameworks are absent (Figure 13.34) (De Gregorio Hurtado et al., 2015; Pietrapertosa et al., 2018; Reckien et al., 2018) (*medium confidence*). However, the implementation gap identified in AR5 (Chambwera et al., 2014), i.e. the gap between defined goals and ambitions and actual implemented actions on the ground, persists in Europe (Aguiar et al., 2018; Russel et al., 2020; UNEP, 2021).

The drivers of adaptation progress in Europe differ across sectors and regions. Common drivers include: experienced climatic events, improved climatic information, societal pressures to act, projected economic and societal costs of climate change, participation in (city) networks, societal and political leadership, and changes in national and European policies and legislation (*medium evidence, high agreement*) (EEA, 2014; Massey et al., 2014; Reckien et al., 2018). The availability of human, knowledge, and financial resources appears important for proactive adaptation(Termeer et al., 2012; Sanderson et al., 2018)(Termeer et al., 2012; Sanderson et al., 2018)(Termeer et al., 2012; Sanderson et al., 2018)(Termeer et al., 2012; Sanderson et al., 2018), while adaptation is also strongly dependent on economic and social development (Sanderson et al., 2018) (*high confidence*). How adaptation is governed differs substantially across Europe (Clar, 2019; Lesnikowski et al., 2021). Political commitment, persistence and consistent action across scales of government is critical to move beyond planning for adaptation (Step A to C in Figure 13.34) and to ensure adequacy of implementation (Step D and E in Figure 13.34) (Howlett and Kemmerling, 2017; Lesnikowski et al., 2021; Patterson, 2021).

The scope of climate risks included in European adaptation policies and plans (Step B in Figure 13.34) is generally broad (EEA, 2018a). Systemic and cascading risks (Section 13.10) are often recognized, but most conventional risk assessment methods that inform adaptation planning are ill-equipped to deal with these effects (Adger et al., 2018). For example, transboundary risks emerging in regions outside of Europe are considered only by a few countries such as the UK and Germany (Section 13.9.3). European climate change adaptation strategies and national policies are generally weak on gender, LGBTQI+, and other social equity issues (Cross-Chapter Box GENDER in Chapter 18, Boeckmann and Zeeb, 2014; Allwood, 2020).

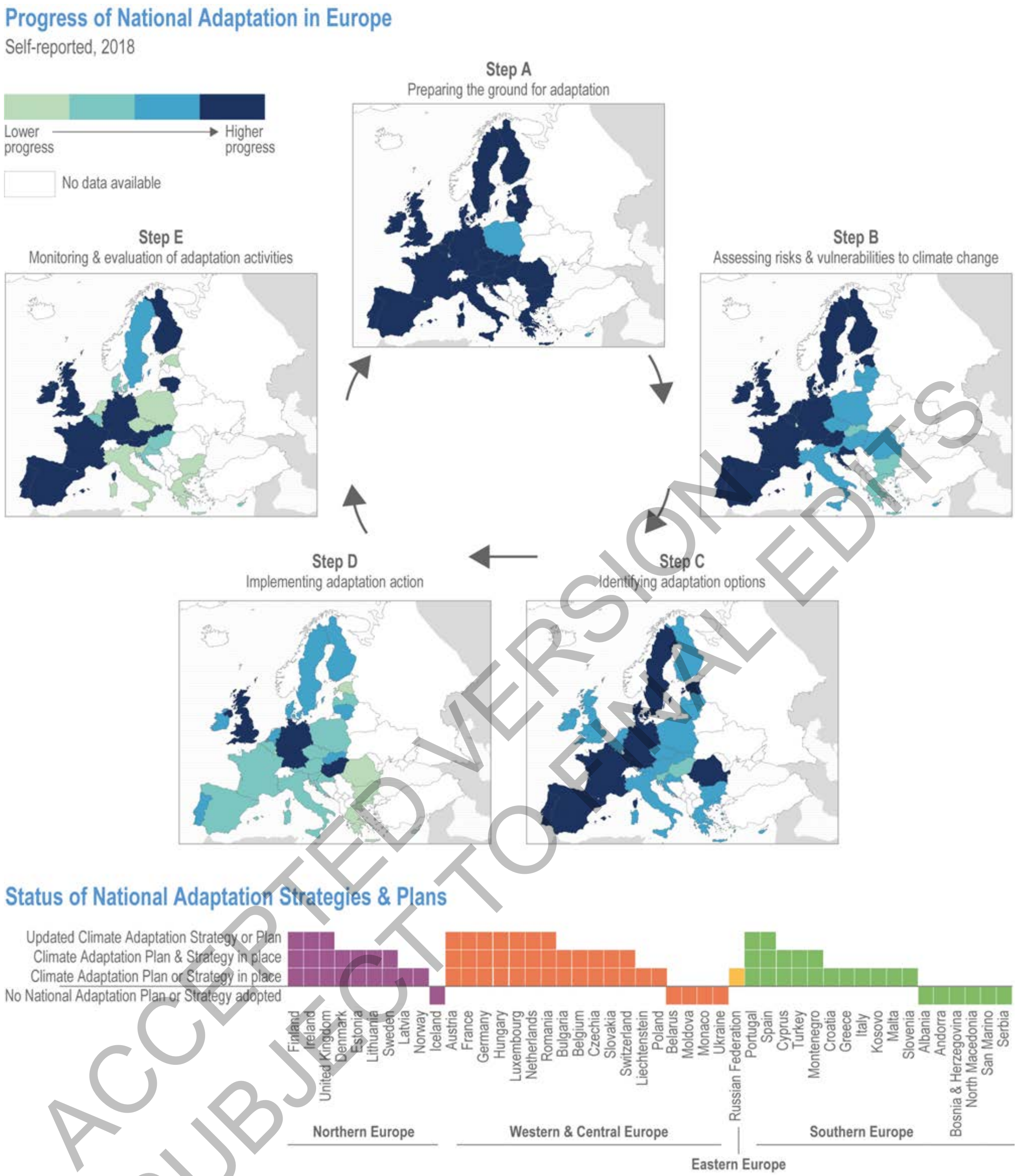


Figure 13.34: Progress of National Adaptation in Europe in 2018 and Status of National Adaptation Plans and Strategies in 2020. Data on the progress of national adaptation are from the self-reported status of EU members, as documented in the Adaptation Scoreboard for Country fiches (SWD(2018)460). The status of national adaptation plans and strategies data are from EEA Report 6/2020 (2020a), the ClimateADAPT portal (EEA, 2021a) and from the Grantham Institute database Climate Change Laws of the World (Grantham Research Institute, 2021).

Many near-term investment decisions have long-term consequences, and planning and implementation (Step C and D in Figure 13.34) can take up to decades, particularly for critical infrastructure planning in Europe (Zandvoort et al., 2017; Pot et al., 2018). Consequently, there are calls to expand planning horizons, to consider long-term uncertainties to prevent lock-in decision dependencies, to seize opportunities and synergies from other investments (e.g., socio-economic developments and systems transitions) and to broaden the range of considered possible impacts (e.g. Frantzeskaki et al., 2019; Marchau, 2019;

Oppenheimer et al., 2019; Haasnoot et al., 2020b). Yet, high GWL scenarios beyond 2100 are often not considered in climate change adaptation planning due to a lack of perceived usability, missing socio-economic information, constraining institutional settings, and conflicting decision-making timeframes (*medium confidence*) (Lourenco et al., 2019; Taylor et al., 2020). High GWL scenarios are often seen as having a low probability of occurrence, resulting in inaction or incremental rather than transformative adaptation responses to projected climate risks (Dunn et al., 2017). Extending planning horizons to beyond 2100 increases deep uncertainties for decision-makers as a result of unclear future socio-economic and climatic changes. For adaptation to sea level rise along Europe's coast, for example, there are already considerable uncertainties during this century (Fox-Kemper et al., 2021).

Adaptive planning and decision making are still limited across Europe (*high confidence*). Prominent examples of adaptive plans include the flood defence systems for the City of London (Ranger et al., 2013; Kingsborough et al., 2016; Hall et al., 2019) and the Netherlands (Van Alphen, 2016; Bloemen et al., 2019) Adaptation pathways have been also developed for planning of urban water supply (Kingsborough et al., 2016; Erfani et al., 2018), urban drainage (Babovic and Mijic, 2019) and wastewater systems (Sadr et al., 2020) (Cross-Chapter Box DEEP in Chapter 17). Flexible strategies are increasingly considered by European countries (e.g. Stive et al., 2013; Kreibich et al., 2015; Bubeck et al., 2017; Haasnoot et al., 2019), but require appropriate design to be effective (Metzger et al., 2021).

Monitoring and evaluation of adaptation action is only done in some European countries (Figure 13.34, part E), but is important for adjusting planning, if needed (Hermans et al., 2017; Haasnoot et al., 2018), and enhancing transparency and accountability of progress (Mees and Driessen, 2019). In the Netherlands, a comprehensive monitoring system has been put in place, including signals for adaptation that support decisions on when to implement adaptation options or to adjust plans (Hermans et al., 2017; Haasnoot et al., 2018; Bloemen et al., 2019).

13.11.1.2 Mainstreaming and Coordination

Coordinated responses are necessary to prevent inefficient and costly action (Biesbroek, 2021), balance under- and over-reaction to climate risks (Peters et al., 2017; Biesbroek and Candel, 2019), avoid redistributing vulnerability and maladaptive actions (Atteridge and Remling, 2018; Albizua et al., 2019; Neset et al., 2019), and ensure timely implementation (Benson and Lorenzoni, 2017) (*high confidence*). Since AR5, progress has been made to increase coordinated adaptation actions, but so far this is limited to a few sectors (mostly water management and agriculture) and European countries and regions (mostly SEU, WCE depending on impact) (Lesnikowski et al., 2016; Biesbroek and Delaney, 2020; Booth et al., 2020) (*high confidence*) (Section 13.11.2). Despite evidence of emerging bottom-up (e.g., citizens and business initiatives) and top-down initiatives (e.g., governmental plans and instruments to ensure action), there are considerable barriers to mainstreaming adaptation (Runhaar et al., 2018) (*high confidence*).

While mainstreaming of adaptation into other policy domains has been advocated as an enabler for adaptation, it may have resulted incremental rather than transformational adaptation, and may not be sufficient to close the adaptation gap (Andersson and Keskitalo, 2018; Remling, 2018; Scoville-Simonds et al., 2020).

13.11.1.3 Climate Services and Local Knowledge

Climate services to support adaptation decision-making of governments and businesses across Europe have rapidly increased since AR5, partly as a result of national and EU investments such as the Copernicus C3S service (*high confidence*) (Street, 2016; Soares and Buontempo, 2019). These services are increasingly used in NEU, SEU and WCE for example in energy and risk prevention in coastal and riverine cities, stimulating regulations and bottom-up initiatives (Cavelier et al., 2017; Le Cozannet et al., 2017; Reckien et al., 2018; Howard et al., 2020). However, climate service efficacy is rarely systematically evaluated (Cortekar et al., 2020). Barriers to use include: lack of perceived usefulness of climate information to organisations and expertise to use the information, outdated statistics, mismatch between needs and type of information made available, insufficient effective engagement between providers and recipients of climate information and lack of business models to sustain climate services over time (*high evidence, medium agreement*) (Cavelier et al., 2017; Räsänen et al., 2017; Bruno Soares et al., 2018; Christel et al., 2018; Oberlack and Eisenack, 2018; Hewitt et al., 2020). Adaptation decision support platforms also face challenges regarding updating, training and engagement with users (EEA, 2015; Palutikof et al., 2019).

In addition to scientific knowledge, traditional and local knowledges can enable adaptation action (Huntington et al., 2017) as is the case with indigenous-led ecosystem restoration in the European Arctic (Brattland and Mustonen, 2018). There is a need to draw on surviving Indigenous knowledge systems in Europe (Greenland, Nenets, Khanty, Sámi, Veps, Ingrian) as unique, endemic ways of knowing the world that can position present and historical change in context and offer unique reflections of change in the future (Ogar et al., 2020; Mustonen et al., 2021).

13.11.1.4 Financing Adaptation and Financial Stability

Dedicated financial resources for the implementation of NAS and plans are a key enabling factor for successful adaptation (*high confidence*) (Russel et al., 2020) (Chapter 17). Yet, only 14 EU countries have announced such budget allocations in their plans and strategies; and even if budget numbers are available, they are difficult to compare (EEA, 2020b). Current adaptation spending varies greatly across and within European countries, partly reflecting (sub-)national adaptation priorities or financing sources targeting investment projects (López-Dóriga et al., 2020; Russel et al., 2020) and competing statutory priorities (Porter et al., 2015). European government budgets are also burdened by climate change damages today, particularly after huge flooding events, and austerity following financial crises, limiting anticipatory action (Penning-Rowsell and Priest, 2015; Miskic et al., 2017; Schinko et al., 2017; Slavíková et al., 2020). National adaptation funding in EU member states is complemented by EU funding (e.g. European Structural and Investment Funds (ESIF), European Regional Development Funds, and LIFE program). While the EU spending target on climate action increased from 20% in 2016-2020 to 25% in 2021-2026, most spending is going into mitigation, not adaptation (Berkhout et al., 2015; Hanger et al., 2015; EEA, 2020b).

With higher warming levels, financing needs are *likely* to increase (*high confidence*) (Mochizuki et al., 2018; Bachner et al., 2019; Parrado et al., 2020) governments can address this higher need by cutting other expenditures, increasing taxes, or by increasing the fiscal deficit (Miskic et al., 2017; Mochizuki et al., 2018; Bachner et al., 2019). Yet, the requirement for fiscal consolidation that will be needed after the COVID-19 pandemic (Cross-Chapter Box COVID in Chapter 7) may also lead to a cessation of adaptation spending, as evidenced by the expenditure drop in coastal protection in Spain after the financial crisis 2008 (López-Dóriga et al., 2020). Governments can shift the financial burden to beneficiaries of adaptation, as e.g., suggested for coastal protection and riverine flooding (Jongman et al., 2014; Penning-Rowsell and Priest, 2015; Bisaro and Hinkel, 2018). There is also an increase in financial mechanisms to accelerate private adaptation actions, including adaptation loans, subsidies, direct investments, and novel public-private arrangements. For example, the European Investment Bank created a finance facility to support European regions through loans to implement adaptation projects (EEA, 2020b).

Since AR5, new evidence has emerged that climate change may deteriorate financial stability both at the global and European scale (Campiglio et al., 2018; Dafermos et al., 2018; Lamperti et al., 2019; ECB, 2021a). The European Central Bank, the European Systemic Risk Board, and several national central banks in NEU and WCE have started to systematically assess the consequences of climate risks for financial stability and plan to integrate climate stress testing into their supervisory tools (Batten et al., 2016; ECB, 2021a; ECB, 2021b).

13.11.2 Societal Responses, Options and Pathways

13.11.2.1 Private-sector

Within the private sector, there tends to be a preference for ‘soft’ (e.g., knowledge generation) than ‘hard’ (e.g., infrastructure) adaptation measures (Goldstein et al., 2019), in contrast to government-led responses typically favouring hard measures (Pranzini et al., 2015). However, there also remains diversity across sectors and organisations in the degree and type of adaptation response (Trawöger, 2014; Dannevig and Hovelsrud, 2016; Ray et al., 2017; Ricart et al., 2018). Whereas some sectors such as flood management, banking and insurance, and energy (Bank of England, 2015; Gasbarro and Pinkse, 2016; Bank of England, 2019; Wouter Botzen et al., 2019) have generally made moderate progress on adaptation planning across

Europe, there are key vulnerable economic sectors that are in earlier stages, including aviation (Burbidge, 2015), ports and shipping (Becker et al., 2018; Ng et al., 2018), and ICT (EEA, 2018b) (*high confidence*). There is also some evidence of 'short-sighted' adaptation or maladaptation; for example, in winter tourism there is a preference for technical and reactive solutions (e.g., artificial snow) that will not be sufficient under high levels of warming (Section 13.6.1.4).

Where adaptation is considered by companies, it is typically triggered either by the experience of extreme weather events that led to business disruptions (McKnight and Linnenluecke, 2019) or is included into corporate risk management in response to regulatory, shareholder or customer pressure (Averchenkova et al., 2016; Gasbarro et al., 2017). For instance, following the implementation of the recommendations of the Task Force on Climate-Related Financial Disclosure (TFCD) by the European Commission in 2019, 50 publicly listed companies revealed their exposure to their physical climate risks in 2020 (CDSB, 2020). But even if companies experience extreme weather events or stakeholder pressure, they may not adapt because they underestimate their vulnerability (Pinkse and Gasbarro, 2019) (Table 13.1). For example, key barriers to adaptation among Greek firms include both external (e.g., lack of support/guidance) and internal factors (e.g., few resources, managerial perceptions (Halkos et al., 2018). Lack of knowledge, feeling climate change is not a salient risk, and lack of social learning or collaboration, appear to be key barriers to private-sector adaptation (Dinca et al., 2014; André et al., 2017; Romagosa and Pons, 2017; Esteve et al., 2018; Luís et al., 2018; Ng et al., 2018) (Section 13.16.2.2). There remains little research on private-sector awareness of or responses to cascading or compound risks associated with climate change (Miller and Pescaroli, 2018; Pescaroli, 2018).

13.11.2.2 Communities, Households and Citizens

Planned behavioural adaptation remains limited amongst European households (*high confidence*), with few examples that can be considered transformative (e.g., structural, long-term, collective (Wilson et al., 2020)) (*medium confidence*). One Swedish survey of householders at risk of extreme weather events (e.g., floods, storms) found evidence of some organisational measures (e.g., bringing possessions inside prior to a storm, preparing for power cuts with candles, etc.) but very few households took any other (technical, social, nature-based, or economic) measures (Brink and Wamsler, 2019). Similarly, few at risk of flooding are taking action (Stojanov et al., 2015) (Sections 13.2.1, 13.6.1); for example, little public take-up of available municipal support for individual adaptation in Germany (Wamsler, 2016). Water efficiency measures in anticipation of, or response to, drought are also limited (Bryan et al., 2019), although water reuse in Mediterranean and some other EU (e.g., UK, Netherlands) countries is increasing (Aparicio, 2017) (Section 13.2). Amongst the adaptation responses recorded, few are perceived as opportunities (Taylor et al., 2014; Simonet and Fatorić, 2016). There is currently little European research on public responses to risks other than flooding, heat stress and drought, such as vector-borne disease, and to multiple and cascading risks (van Valkengoed and Steg, 2019) (Section 13.7).

Perceived personal responsibility for tackling climate change remains low across the EU (Figure 13.35) and partly explains why household adaptation remains limited (*high confidence*) (Taylor et al., 2014; van Valkengoed and Steg, 2019), despite risk perception apparently growing (Figure Box 13.2.1, Capstick et al., 2015; Poppel et al., 2015; BEIS, 2019). Householders' risk perception and concern about climate change fluctuates in response to media coverage and significant weather or socio-political events (*high confidence*) (Capstick et al., 2015). On average across Europe, and particularly in relation to gradual change, non-experts continue to under-estimate climate change risks compared to experts (*medium confidence*) (Taylor et al., 2014), have low awareness of adaptation options, and confuse adaptation and mitigation (Harcourt, 2019), suggesting a need for improved climate literacy amongst the public. Indeed, fostering learning and coping capacity supports robust adaptation pathways (Jäger et al., 2015).

There is strong public support for adaptation policy (e.g., building flood defences), particularly within the UK, France, Norway and Germany (Doran et al., 2018). Although, in some cases such public adaptation can undermine motivation for householders to take adaptation measures (Section 13.2), public adaptation can also increase householder motivations, with perceived efficacy of action a strong predictor of adaptation (*high confidence*) (Moser, 2014; van Valkengoed and Steg, 2019). However, there are also structural and economic barriers to household adaptation due to lack of policy incentives or regulations. For example, water-saving devices in homes could halve consumption, but lack of economic benefits to householders are barriers to adoption; while lack of standards as well as societal hesitation may explain low levels of water reuse in Europe (EEA, 2017c) (Section 13.2). Conversely, water meters and higher tariffs have been found to reduce water consumption only in combination with other measures (EEA, 2017c; Bryan et al., 2019).

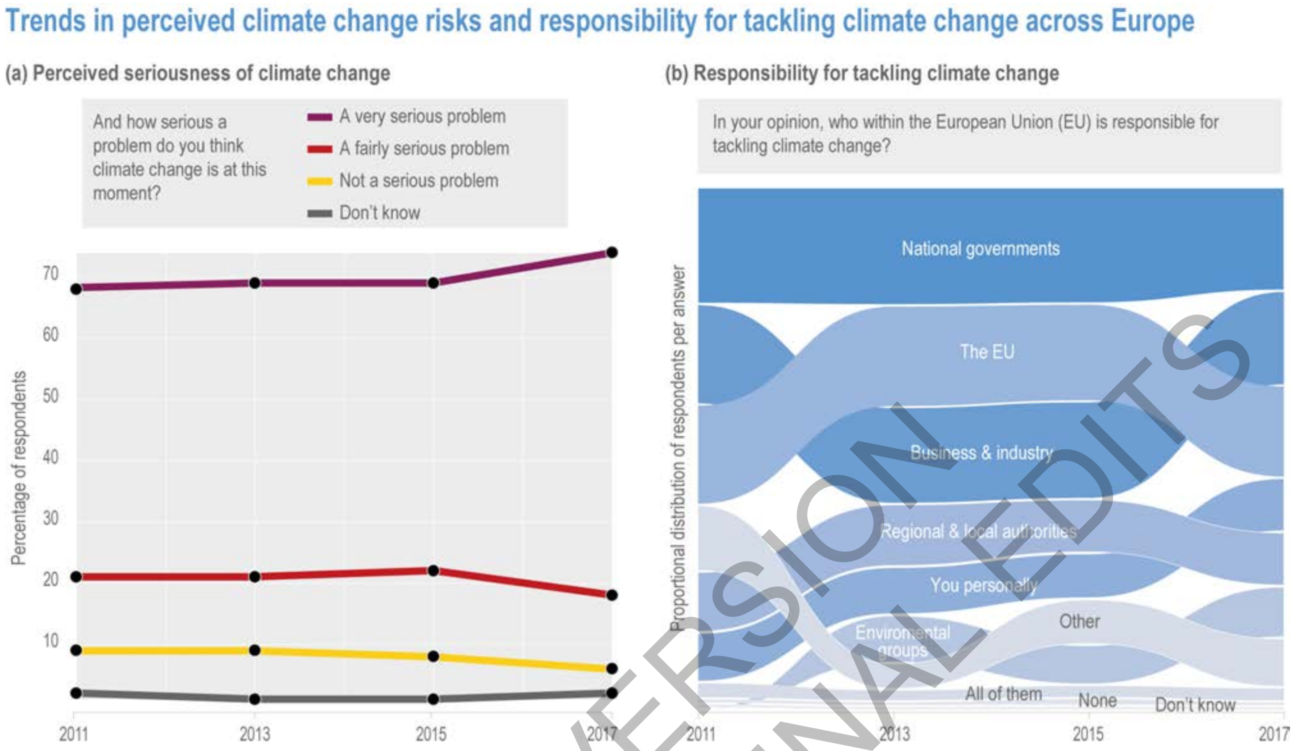


Figure 13.35: Trends in perceived climate change risks and responsibility for tackling climate change across EU-28; data collected from around 1,000 respondents per country for each year surveyed (European Comission, 2017)

As well as temporal trends in climate change risk perception, the literature since AR5 continues to show much heterogeneity (both within and between nations) amongst householders in respect of risk perception (*high confidence*). Higher climate change risk perceptions observed in Spain, Portugal, Iceland, and Germany (Figure 13.2); at individual level, women, younger age groups, more educated, left-leaning, and those with more 'self-transcendent' values perceive more negative impacts from climate change, although the strength of these relationships varies across European nations (Clayton et al., 2015; Doran et al., 2018; Poortinga et al., 2019; Duijndam and van Beukering, 2021). Stronger evidence exists since AR5 that experience of extreme weather events can shape climate change risk perceptions, if these events are attributed to climate change or evoke negative emotions (*high confidence*) (Clayton et al., 2015; Demski et al., 2017; Ogunbode et al., 2019). Proximity to climate hazards does not predict adaptation responses in a straightforward way: in Portugal, those living by the coast were more *likely* to attribute local natural hazards to climate change and to take some adaptive measures (Luís et al., 2017); while waterside residents in flood-prone regions of France and Austria were more resistant to relocation, due to higher place attachment (Adger et al., 2013; Rey-Valette et al., 2019; van Valkengoed and Steg, 2019; Seebauer and Winkler, 2020). Migration from threatened regions is discussed in Section 13.8.1.3.

13.11.3 Adaptation, Transformation and Sustainable Development Goals

The implementation of far-reaching and rapid systemic changes, including both adaptation and mitigation options (de Coninck et al., 2018) remains less researched in societal systems than natural ones (Salomaa, 2020) that enhance multilevel governance and institutional capabilities, and enables lifestyle/behavioural change and technology innovation. Adaptation responses across European regions and sectors, are more often incremental than transformative (*medium confidence*), with possible exceptions including water-related examples in for example the Netherlands (Section 13.2.2) and some cities (Box 13.3). Transformative options may be better able to exploit new opportunities and co-benefits (EEA, 2019a) (Box 13.3) (Cross-Chapter Box HEALTH in Chapter 7). Transitions towards more adaptive and climate resilient systems are often the result of responses to crises which create windows of opportunity for systemic changes (Johannessen et al., 2019) (cf. Chapter 18). This includes extreme weather events, financial crises (e.g., Malmö; (Anderson, 2014; Isaksson and Heikkinen, 2018)) and the COVID-19 pandemic (e.g., Milan), which have disrupted the status quo and accelerated innovation and implementation (e.g., Milan; Box 13.3, Cross-Chapter Box COVID in Chapter 7).

[START BOX 13.3 HERE]

Box 13.3: Climate Resilient Development Pathways in European Cities

Climate resilient development (CRD) in European cities offers synergies and co-benefits from integrating adaptation and mitigation with environmental, social and economic sustainability (Geneletti and Zardo, 2016; Grafakos et al., 2020). Climate networks (e.g., Covenant of Mayors), funding (e.g., Climate-KIC), research programs (e.g., Horizon Europe), European and national legislation, international treaties, and the identification of co-benefits, contribute to the prioritisation of climate action in European cities (Heidrich et al., 2016; Reckien et al., 2018; CDP, 2020). Still, mitigation and adaptation remain largely siloed and sectoral (Heidrich et al., 2016; Reckien et al., 2018; Grafakos et al., 2020). An assessment of the integration of mitigation and adaptation in urban climate change action plans in Europe found only 147 cases in a representative sample of 885 cities (Reckien et al., 2018).

In European cities, CRD is most evident in the areas of green infrastructure, energy efficient buildings and construction, and active and low-carbon transport (Pasimeni et al., 2019; Grafakos et al., 2020). Nature-based solutions (NbS), such as urban greening, often integrate adaptation and mitigation in sustainable urban developments and are associated with increasing natural and social capital in urban communities, improving health and wellbeing, and raising property prices (Geneletti and Zardo, 2016; Pasimeni et al., 2019; Grafakos et al., 2020). Barriers to CRD in European cities include limitations in: funding, local capacity, guidance documents and quantified information on costs, co-benefits and trade-offs (Grafakos et al., 2020). Pilot projects are used to initiate CRD transitions (Nagorny-Koring and Nochta, 2018). Malmö (Sweden) and Milan (Italy) are two examples to illustrate the strategies and challenges of two European cities attempting to implement CRDP.

Malmö (population 0.3M): Since the 1990s, Malmö has been transitioning toward an environmentally, economically and socially sustainable city, investing in eco-districts (redeveloped areas that integrate and showcase the city's sustainability strategies) and adopting ambitious adaptation and mitigation targets. The city has focused on energy efficient buildings and construction, collective and low carbon transportation, and green spaces and infrastructure (Anderson, 2014; Malmo Stad, 2018). Malmö has developed creative implementation mechanisms, including a "climate contract" between the city, the energy distributor and the water and waste utility to co-develop the climate-smart district, Hyllie (Isaksson and Heikkinen, 2018; Kanters and Wall, 2018; Parks, 2019). Flagship eco-districts play a central role in the city's transition, in the wider adoption of CRD and in securing implementation partners (Isaksson and Heikkinen, 2018; Stripple and Bulkeley, 2019). The city has also leveraged its status as a CRD leader to attract investment. The private sector views CRD as profitable, due to the high demand and competitive value of these developments (Holgersen and Malm, 2015). Malmö adopted the SDGs as local goals and the city's Comprehensive Plan is evaluated on these, e.g., considering gender in the use, access and safety of public spaces, and emphasizing development that facilitates climate resilient lifestyles (Malmo Stad, 2018). Malmö also engages stakeholders via dialogue with residents, collaboration with universities and partnerships with industry and service providers (Kanters and Wall, 2018; Parks, 2019). Despite measurable and monitored targets, and supportive institutional arrangements, sustainability outcomes for the flagship districts have been tempered by developers' market-oriented demands (Holgersen and Malm, 2015; Isaksson and Heikkinen, 2018) and there is limited low-income housing in climate-resilient districts (Anderson, 2014; Holgersen and Malm, 2015).

Milan (population 1.4M): Milan is taking a CRD approach to new developments (Comune di Milano, 2019). From 2020, new buildings must be carbon neutral and reconstructions must reduce the existing land footprint by at least 10%. The Climate and Air Plan (CAP) and the city's Master Plan (Comune di Milano, 2019) focus on low-carbon, inclusive and equitable development. The CAP is directed at municipal and private assets, and individual to city-scale actions. In 2020, Milan released a revised Adaptation Plan and the Open Streets project to ensure synergies between the COVID-19 response and longer-term CRD. Examples include strengthening neighbourhood-scale disaster response and reallocating street space for walking and cycling (Comune di Milano, 2020). Milan emphasizes institutionalization of CRD via a dedicated resilience department, and through active participation in climate networks and projects that support learning and exchange. Climate network commitments are cited in the city's Master Plan and CAP guidelines as driving more ambitious deadlines and emissions targets (Comune di Milano, 2019). Implementation of Milan's plans remains a challenge, despite dedicated resources and commitment.

[END BOX 13.3 HERE]

Considerable barriers exist that prevent system transitions from taking place in Europe, including institutional and behavioural lock-ins such as administrative routines, certain types of legislation, and dominant paradigms of problem solving (Johannessen et al., 2019; Roberts and Geels, 2019) (*high confidence*). For example, near-term and sectoral decision-making constrains transformative options for water-related risks (Section 13.2). Breaking through these lock-ins requires substantive (political) will, (un)learning of practices, resources, and evidence of what works. Trade-offs exist between the depth, scope, and pace of change in transforming from one system to another, suggesting that designing system transformations is a careful balancing act (Termeer et al., 2017). Aspiring in-depth and comprehensive transformational changes might create a consensus frame to work towards; but it might not offer concrete perspectives to act on the ground. Taking small steps and quick-wins offer an alternative pathway (Termeer and Dewulf, 2018).

Adaptation responses can also be understood in terms of their trade-offs and synergies with SDGs (Papadimitriou et al., 2019; Bogdanovich and Lipka, 2020). In terms of synergies, analysis of the Russian NAP found that successful completion of the NAP's first phase could lead to significant progress towards 15 of the 17 goals (Bogdanovich and Lipka, 2020). European water adaptation (e.g., flood protection) can similarly support freshwater provision; and water-secured environments support socio-economic growth (Sadoff et al., 2015) since people and assets tend to accumulate in areas protected from flooding and supplied with water, reducing the incentive for autonomous adaptation (de Moel et al., 2011; Hartmann and Spit, 2016; Di Baldassarre et al., 2018). In health, behavioural measures to reduce mental health impacts (e.g., gardening, active travel) can have broader health benefits (SDG 3) as well as help reduce emissions (Section 13.7; SDGs 7 and 13). Conversely, growing use of air conditioning for humans and livestock represents a potential trade-off between adaptation and mitigation (Sections 13.5,13.6, 13.7, 13.10). As noted in Section 13.8, addressing poverty (SDG 1) - including energy poverty (SDG 7) and hunger (SDG 2) - and inequalities (SDG 10) - including gender inequality (SDG 5) - improves resilience to climate impacts for those groups that are disproportionately affected (women, low-income and marginalised groups). Also, more inclusive and fair decision-making can enhance resilience (SDG 16; Section 13.4.4); although adaptation measures may also lead to resource conflicts (SDG 16; Section 13.7). Climate adaptation, particularly nature-based solutions, also supports ecosystem health (SDGs 14 and 15) (Dzebo et al., 2019). Economic trade-offs appear to be more common across adaptation strategies, for example reduced employment arising from land use change measures (Papadimitriou et al., 2019). There are also trade-offs between large-scale mitigation measures (e.g., wind farms) and adaptation options that rely on ecosystem services (e.g., water regulation; Section 13.3-13.4); and conversely, some adaptation options (e.g., air conditioning) may negatively impact mitigation. Figure 13.36 summarises the synergies between adaptation and SDGs as identified by 167 European cities in 2019; particularly prominent are reported biodiversity and health benefits most often arising from societal (e.g., informational) and structural (e.g., technological/engineering) measures. Beyond the urban context, biodiversity co-benefits from agro-ecology are also recognised (Section 13.5). Sustainable behaviour change measures have been found to be particularly *likely* to lead to synergies with SDGs (Papadimitriou et al., 2019).

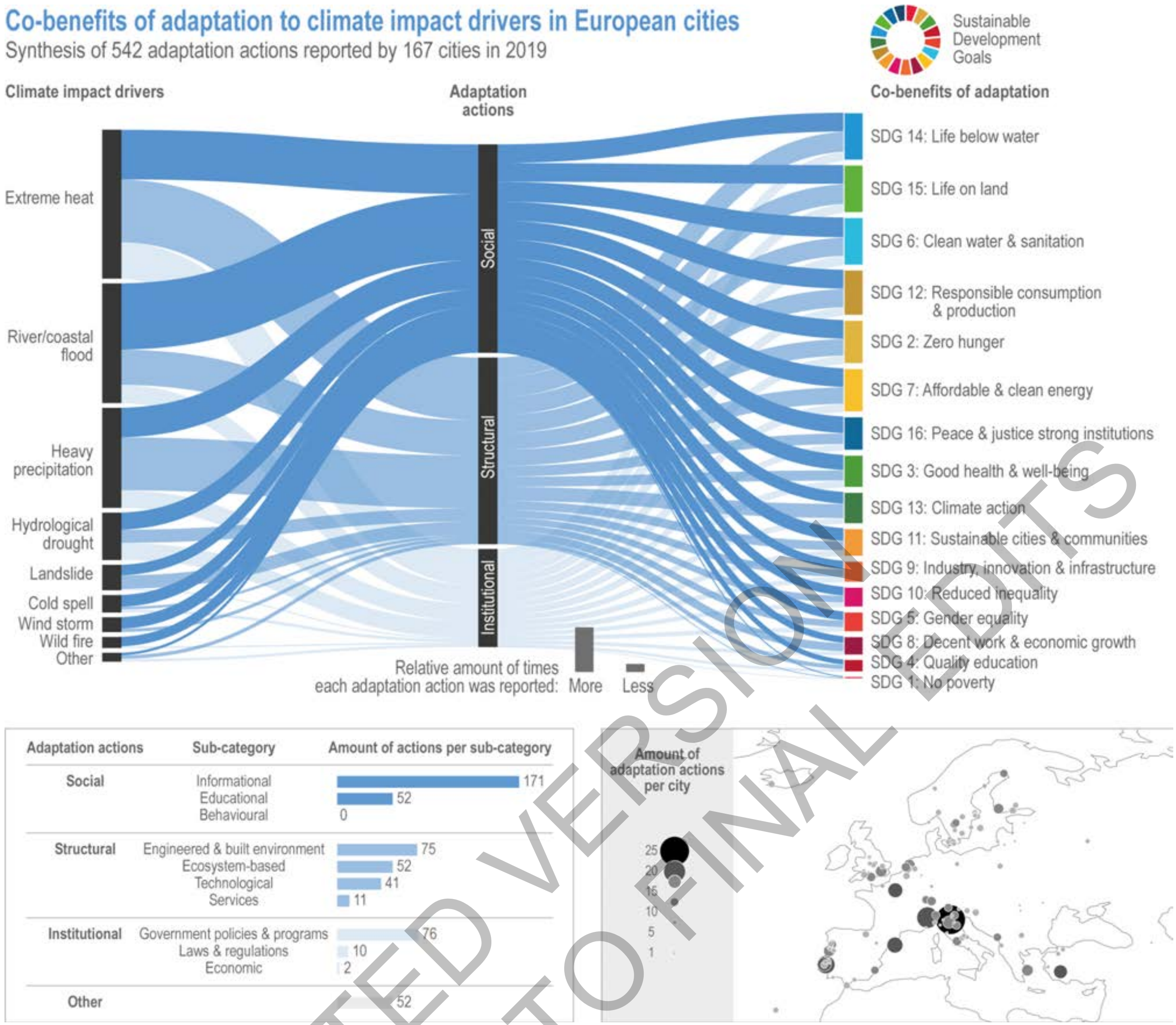


Figure 13.36: Co-benefits for SDGs from adaptation actions. Shows how European cities have assessed the sustainability co-benefits of taking adaptation actions. Data was extracted from the Carbon Disclosure Project (CDP) database using the 2019 dataset; of the 861 European cities submitting data, 167 provided data on their adaptation actions and so this data is shown here (CDP, 2019). CDP categories of climate hazards were recategorized into WG1 Climate Impact Drivers (e.g., cold spell, heavy precipitation); CDP adaptation actions were reclassified into AR5 adaptation options ('social', 'structural' and 'institutional'; 'other' includes actions falling outside these AR5 categories); and CDP co-benefits were recategorized as SDGs. Panel 2 shows that all SDGs except one (SDG 17) were identified as a co-benefit of adaptation, although more environmental co-benefits were identified than social or economic ones. Panel 2 shows that societal actions were most common, followed by structural, then institutional. Informational measures were particularly common. Panel 3 shows how many actions were taken by different European cities.

[START FAQ13.1 HERE]

FAQ 13.1: How can climate change affect social inequality in Europe?

The poor and those practising traditional livelihoods are particularly exposed and vulnerable to climate change. They rely more often on food self-provisioning and settle in flood-prone areas. They also often lack the financial resources or the rights to successfully adapt to climate-driven changes. Good practice examples demonstrate that adaptation can reduce inequalities.

Social inequalities in Europe arise from disparities in income, gender, ethnicity, age, as well as other social categorisations. In the European Union, about a fifth of the population (109 million people) at present, live under conditions of poverty or social exclusion. Moreover, poverty is unequally distributed across Europe, with higher poverty levels in the eastern parts of Europe. The oldest and youngest in society are often most vulnerable.

The poor and those practising traditional livelihoods are particularly vulnerable and exposed to climate risks. Many depend on food self-provisioning from lakes, the sea, and the land. With higher temperatures, the availability of these sources of food is *likely* to be reduced, particularly in southern Europe. Poorer households often settle in flood-prone areas and are therefore more exposed to flooding. Traditional pastoralist and fishing practices are also negatively affected by climate change across Europe. Semi-migratory reindeer herding, a way of life among Indigenous and traditional communities (Komi, Saami, Nenets) in the European Arctic, is threatened by reduced ice and snow cover. Almost 15% of the EU population (in some countries more than 25%) already cannot meet their healthcare needs for financial reasons, while they are at risk of health impacts from warming.

In addition to being more exposed to climate risks, socially vulnerable groups are also less able to adapt to these risks, because of financial and institutional barriers. More than 20% of people in the South and East of Europe live in dwellings that cannot be cooled to comfortable levels during summer. These people are particularly vulnerable to risks from increasing heatwave days in European cities e.g. when they already face energy poverty. They may also lack the means to protect against flooding or heat, e.g., when they do not own the property. Risk-based insurance premiums, which are intended to help people reduce climate risks, are potentially unaffordable for poor households. The ability to adapt is also often limited for Indigenous People, as they often lack the rights and governance of resources, particularly when in competition with economic interests such as resource mining, oil and gas, forestry, and expansion of bioenergy.

Adaptation actions by governments can both increase and decrease social inequality. The installation of new or the restoration of existing green spaces may increase land prices and rents due to a higher attractiveness of these areas, leading to potential displacement of population groups who cannot afford higher prices. On the other hand, rewilding and restoration of ecosystems can improve the access of less privileged people to ecosystem services and goods, such as the availability of freshwater. At city level, there are examples of good practice in climate-resilient development that consider social equity which integrate a gender-inclusive perspective in its sustainable urban planning, including designing public spaces and transit to ensure women, disabled people and other groups can access and feel safe using these public amenities (see Box 13.3).

[END FAQ13.1 HERE]

[START FAQ13.2 HERE]

FAQ 13.2: What are the limits of adaptation for ecosystems in Europe?

Land, freshwater and ocean organisms and ecosystems across Europe are facing increasing pressures from human activities. Climate change is rapidly becoming an additional and, in the future, a primary threat. Ongoing and projected future changes are too severe and happen too fast for many organisms and ecosystems to adapt. More expensive and better implemented environmental conservation and adaptation measures can slow down, halt, and potentially reverse biodiversity and ecosystem declines, but only at low or intermediate warming.

Ecosystem degradation and biodiversity loss have been evident across Europe since 1950, mainly due to land use and overfishing. However, climate-change is becoming a key threat. The unprecedented pace of environmental change has already surpassed the natural adaptive capability of many species, communities, and ecosystems in Europe. For instance, the space available for some land ecosystems has shrunk, especially in Europe's polar and mountain areas, due to warming and thawing of permafrost. Across Europe, heatwaves and droughts and their impacts such as wildfires add further acute pressures, as seen in the 2018 heatwave, which impacted forest ecosystems and their services. In the Mediterranean Sea, plants and animals cannot shift northward and are negatively affected by marine heatwaves. Food-web dynamics of European ecosystems are disrupted as climate change alters the timing of biological processes, such as spawning and migration of species, and ecosystem composition. Moreover, warming fosters the immigration of invasive species that compete with–and can even out-compete–the native flora and fauna.

In a future with further and even stronger warming, climate change and its many impacts will become increasingly more important threats. Several species and ecosystems are projected to be already at high risk at 2°C global warming, including fishes and lake and river ecosystems. At 3°C global warming, many European ecosystems, such as coastal wetlands, peatlands, and forests, are projected to be at much higher risk of being severely disrupted than in a 2°C warmer world. For example, Mediterranean seagrass meadows will *very likely* become extinct due to more frequent, longer, and more severe marine heat waves by 2050. Several wetland and forest plants and animals will be at high risk to be replaced by invasive species that are better adapted to increasingly dry conditions, especially in boreal and Arctic ecosystems.

Current protection and adaptation measures, such as the Natura 2000 network of protected areas, have some positive effects for European ecosystems. However, these policies are not sufficient to effectively curb overall ecosystem decline, especially for the projected higher risks above 2°C global warming. Nature-based solutions, such as the restoration of wetlands, peatlands, and forests, can serve both ecosystem protection and climate-change mitigation through strengthening carbon sequestration. Some climate change mitigation measures such as reforestation and restoration of coastal ecosystems can strengthen conservation measures. These approaches are projected to reduce risks for European ecosystems and biodiversity, especially when internationally coordinated.

Not all climate-change adaptation options are beneficial to ecosystems. When planning and implementing adaptation options and Nature-based Solutions, trade-offs and unintended side effects should be considered. On one hand, engineering coastal protection measures (seawalls, breakwaters, and similar infrastructure) in response to sea level rise reduce the space available for coastal ecosystems. One the other hand, Nature-based Solutions can also have unintended side effects, such as increased methane release from larger wetland areas and large-scale tree planting changing the albedo of the surface.

[END FAQ13.2 HERE]

[START FAQ13.3 HERE]

FAQ 13.3: How can people adapt at individual and community level to heat waves in Europe?

Heatwaves will become more frequent, more intense and will last longer. A range of adaptation measures are available for communities and individuals before, during and after a heat wave strikes. Implementing adaptation measures are important to reduce the risks of future heat waves.

Heat waves will affect people in different ways, risks are higher for the elderly, pregnant women, small children, people with pre-existing health conditions and low-income groups. By 2050, about half of the European population may be exposed to high or very high risk of heat stress during summer, particularly in Southern Europe and increasingly in Eastern and Western and Central Europe. The severity of heat-related risks will be highest in large cities, due to the urban heat island effect.

In southern Europe people are already aware of the risks of heat extremes. Consequently, governments and citizens have implemented a range of adaptation responses to reduce the impacts of heat waves. However, there are limits to how much adaptation can be implemented. At 3°C global warming there will be substantial risks to human lives and productivity, which cannot be avoided. In the parts of Europe where heat waves are a relatively new phenomena, such as many parts of North and Western and Central Europe, public awareness of heat extremes is increasing and institutional capacity to respond is growing.

Preparing for heat waves is an important first step. Implementing and sustaining effective measures, such as national or regional early warning and information systems, heat wave plans and guidelines, and raising public awareness through campaigns are successful responses. Evidence suggests that such measures have contributed to reduced mortality rates in Southern and Western and Central Europe. At city level, preparing for heat waves can sometimes require urban redesign. For example, green-blue spaces, such as recreational parks and ponds in cities, have been shown to reduce the average temperature in cities dramatically and to provide co-benefits, such as improved air quality and recreational space. The use of cool materials in asphalt, increasing reflectivity, green roofs, and building construction measures are being considered in urban planning for reducing heat risks. Citizens can prepare themselves by using natural ventilation, using approaches to stay cool in heat waves, green roofs and green facades in their buildings.

During heat waves, public information that is targeted at people and social care providers is critical, particularly for the most vulnerable citizens. Governments and NGOs play an important role in informing people about how to prepare and what to do to avoid health impacts and reduce mortality. Coordination between vital emergency and health services is critical. Individuals can take several actions to effectively protect themselves from heat: 1) decreasing exposure to high temperatures (e.g., avoid outdoor during hottest times of the day, access cool areas, wear protective and appropriate clothing); 2) keep hydrated (e.g., drink enough proper fluids, avoid alcohol, etc.), 3) be sensitive to the symptoms of heat illness (dizziness, heavy sweating, fatigue, cool and moist skin with goosebumps when in heat, etc.).

Once the heat wave has ended, evaluation of what worked well and how improvements can be made is key to prepare for the next heat wave. Governments can, for example, evaluate whether the early warning systems provided timely and useful information, whether coordination went smoothly, or assess estimated number of lives saved as results of the measures implemented. Sharing these lessons learned is critical to allow other cities and regions to plan for heat extremes. After the heatwave, citizens can reflect if their responses were sufficient, whether investments are needed to be better prepared, and draw key lessons about what (not) to do when the next heat wave strikes.

[END FAQ13.3 HERE]

[START FAQ13.4 HERE]

FAQ 13.4: What opportunities does climate change generate for human and natural systems in Europe?

Not all climate change impacts across Europe pose challenges and threats to natural communities and human society. In some regions, and for some sectors, opportunities will emerge . Although these opportunities do not outweigh the negative impacts of climate change, considering these in adaptation planning and implementation is important to benefit from them. Nevertheless, Europe will face difficult decisions balancing the trade-offs between the adaptation needs of different sectors, regions and adaptation and mitigation actions.

Opportunities of climate change can be 1) positive effects of warming for specific sectors and regions, such as agriculture in northern Europe and 2) co-benefits of transformation of cities or transport measures that reduce the speed and impact of climate-change while improving air quality, mental health and wellbeing. Windows of action for transformation opportunities for large-scale transitions and transformation of our society may be accelerated through new policy initiatives in response to the COVID crisis, such as the European New Green Deal and Building Back Better.

As warming and droughts impact southern Europe most strongly, direct opportunities from climate change are primarily in northern regions, thereby increasing existing inequalities across Europe. Across Europe, positive effects of climate change are fewer than negative impacts and are typically limited to some aspects of agriculture, forestry, tourism, and energy sectors. In the food sector, opportunities emerge by the northward movement of food production zones, increases in plant growth due to CO_2 fertilisation, and reduction of heating costs for livestock during cold winters. In the energy sector, positive effects include increased wind energy in the southwestern Mediterranean, and reduced energy demand for heating across Europe. While climatic conditions for tourist activities are projected to decrease for winter tourism (e.g. lacking sufficient snow) and summer tourism in some parts of Europe (e.g. too hot), conditions may improve during spring and autumn in many European locations. Fewer cold waves will reduce risks on transport infrastructure, such as cracking of road surface, in parts of Northern and Eastern Europe particularly by the end of the century.

Indirect opportunities emerge from the co-benefits of implementing adaptation actions. Some of these co-benefits are wide-spread but need careful consideration in order to be utilized. For example, Nature-based Solutions to adaptation can make cities and settlements more liveable, increase the resilience of agriculture, and protect biodiversity. Ecosystem-based adaptation can attract tourists and create recreational space. There are opportunities to mainstream adaptation into other developments and transitions, including the energy or agricultural transitions and COVID19 recovery plans. Transformative solutions to achieve sustainability may be accelerated through larger changes of, for example behaviour, energy, food or transport, to better exploit new opportunities and co-benefits. Implementation of adaptation actions can also help to make progress towards achieving the Sustainable Development Goals.

Inclusive, equitable and just adaptation is critical for climate resilient development considering SDGs, gender, as well as Indigenous knowledge and local knowledge and practices. Implementation requires political commitment, persistence and consistent action across scales of government. Upfront mobilization of political, human and financial capital in implementation of adaptation actions is key, even when the benefits are not immediately visible.

References

Aalbers, C. B. E. M., D. A. Kamphorst and F. Langers, 2019: Fourteen local governance initiatives in greenspace in urban areas in the Netherlands. Discourses, success and failure factors, and the perspectives of local authorities. *Urban Forestry & Urban Greening*, **42**, 82-99, doi:https://doi.org/10.1016/j.ufug.2019.04.019.

Abi-Samra, N., 2017: *Power Grid Resiliency for Adverse Conditions*. Power Engineering, Artech House, Norwood, MA, 280 pp. ISBN 9781630810177.

Adams, K. et al., 2020: *Climate-Resilient Trade and Production: The Transboundary Effects of Climate Change and Their Implications for EU Member States*. SEI, ODI, IDDRI.

Adger, W. N. et al., 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3**, 112-117, doi:10.1038/nclimate1666.

Adger, W. N., I. Brown and S. Surminski, 2018: Advances in risk assessment for climate change adaptation policy. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **376**(2121), doi:10.1098/rsta.2018.0106.

Aerts, J. C. J. H. et al., 2018: Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change*, **8**(3), 193-199, doi:10.1038/s41558-018-0085-1.

Aeschbach-Hertig, W. and T. Gleeson, 2012: Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience*, **5**(12), 853-861, doi:10.1038/ngeo1617.

Aguiar, F. C. et al., 2018: Adaptation to climate change at local level in Europe: An overview. *Environmental Science & Policy*, **86**, 38-63, doi:10.1016/j.envsci.2018.04.010.

Aguilera, E. et al., 2020: Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. *Agricultural Systems*, **181**(August 2019), 102809-102809, doi:10.1016/j.agsy.2020.102809.

Airoldi, L. and M. W. Beck, 2007: Loss, status and trends for coastal marine habitats of Europe. *Oceanography and Marine Biology, Vol 45*, **45**, 345-405.

Akin, S.-M., P. Martens and M. M. T. E. Huynen, 2015: Climate Change and Infectious Disease Risk in Western Europe: A Survey of Dutch Expert Opinion on Adaptation Responses and Actors. *International Journal of Environmental Research and Public Health*, **12**(8), 9726-9749.

Albizua, A., E. Corbera and U. Pascual, 2019: Farmers' vulnerability to global change in Navarre, Spain: large-scale irrigation as maladaptation. *Regional Environmental Change*, **19**(4), 1147-1158, doi:10.1007/s10113-019-01462-2.

Albrecht, G. et al., 2007: Solastalgia: The Distress Caused by Environmental Change. *Australasian Psychiatry*, **15**(1_suppl), S95-S98, doi:10.1080/10398560701701288.

Alekseev, G. V. et al., 2014: *Second assessment report on climate change and its consequences in the Russian Federation*. Roshydromet, Moscow, 1008 pp pp. ISBN 978-5-901579-52-7.

Alexander, P. et al., 2018: Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide. *Global Change Biology*, **24**(7), 2791-2809, doi:10.1111/gcb.14110.

Alexander, P. et al., 2019: Transforming agricultural land use through marginal gains in the food system. *Global Environmental Change*, **57**, doi:10.1016/j.gloenvcha.2019.101932.

Aleynikov, A. A. et al., 2014: Vaigach Island: nature, climate and people [in Russian]. WWF, Moscow.

Alfieri, L., P. Burek, L. Feyen and G. Forzieri, 2015a: Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, **19**(5), 2247-2260, doi:10.5194/hess-19-2247-2015.

Alfieri, L. et al., 2018: Multi-Model Projections of River Flood Risk in Europe under Global Warming. *Climate*, **6**(1), doi:10.3390/cli6010016.

Alfieri, L., L. Feyen and G. Di Baldassarre, 2016: Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. *Climatic Change*, **136**(3-4), 507-521, doi:10.1007/s10584-016-1641-1.

Alfieri, L., L. Feyen, F. Dottori and A. Bianchi, 2015b: Ensemble flood risk assessment in Europe under high end climate scenarios. *Global Environmental Change-Human and Policy Dimensions*, **35**, 199-212, doi:10.1016/j.gloenvcha.2015.09.004.

Alkhani, R., 2020: Understanding Private-Sector Engagement in Sustainable Urban Development and Delivering the Climate Agenda in Northwestern Europe—A Case Study of London and Copenhagen. *Sustainability*, **12**(20), doi:10.3390/su12208431.

Allard, C., 2018: The Rationale for the Duty to Consult Indigenous Peoples: Comparative Reflections from Nordic and Canadian Legal Contexts. *Arctic Review on Law and Politics*, **9**(0), doi:10.23865/arctic.v9.729.

AllianceEnvironnement, 2018: *Evaluation study of the impact of the CAP on climate change and greenhouse gas emissions*. ISBN 9789279857973.

Allison, E. A., 2015: The spiritual significance of glaciers in an age of climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(5), 493-508, doi:10.1002/wcc.354.

Allwood, G., 2020: Mainstreaming Gender and Climate Change to Achieve a Just Transition to a Climate-Neutral Europe. *JCMS: Journal of Common Market Studies*, **58**(S1), 173-186, doi:10.1111/jcms.13082.

Altieri, A. H. and K. B. Gedan, 2015: Climate change and dead zones. *Global Change Biology*, **21**(4), 1395-1406, doi:doi/10.1111/gcb.12754.

Álvarez-Fernández, I., N. Fernández, N. Sánchez-Carnero and J. Freire, 2017: The management performance of marine protected areas in the North-east Atlantic Ocean. *Marine Policy*, **76**, 159-168, doi:10.1016/j.marpol.2016.11.031.
AMAP, 2017: *Adaptation actions for a changing Arctic: perspectives from the Barents area*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. ISBN 978-82-7971-102-5.
Ambelas Skjøth, C. et al., 2019: Predicting abundances of invasive ragweed across Europe using a "top-down" approach. *Science of The Total Environment*, **686**, 212-222.
Amengual, J. and D. Alvarez-Berastegui, 2018: A critical evaluation of the Aichi Biodiversity Target 11 and the Mediterranean MPA network, two years ahead of its deadline. *Biological Conservation*, **225**, 187-196, doi:10.1016/j.biocon.2018.06.032.
Ammer, S. et al., 2018: Impact of diet composition and temperature–humidity index on water and dry matter intake of high-yielding dairy cows. *Journal of Animal Physiology and Animal Nutrition*, **102**(1), 103-113, doi:10.1111/jpn.12664.
Ančić, B., M. Domazet and D. Župarić-Iljić, 2019: "For my health and for my friends": Exploring motivation, sharing, environmentalism, resilience and class structure of food self-provisioning. *Geoforum*, **106**, 68-77, doi:10.1016/j.geoforum.2019.07.018.
Anderson, T., 2014: Malmo: A city in transition. *Cities*, **39**, 10-20, doi:https://doi.org/10.1016/j.cities.2014.01.005.
Andersson, E. and E. C. H. Keskitalo, 2018: Adaptation to climate change? Why business-as-usual remains the logical choice in Swedish forestry. *Global Environmental Change*, **48**, 76-85, doi:10.1016/j.gloenvcha.2017.11.004.
Andersson, L. et al., 2015: *Underlag till kontrollstation 2015 för anpassning till ett förändrat klimat*. SMHI, SE-601 76, Norrköping, Sverige. Available at: https://www.smhi.se/polopoly_fs/1.86329!/Menu/general/extGroup/attachmentColHold/mainCol1/file/Klimatologi%20Nr%2012.pdf (accessed 2020/11/03/08:48:06).
André, K. et al., 2017: Analysis of Swedish forest owners' information and knowledge-sharing networks for decision-making: insights for climate change communication and adaptation. *Environmental management*, **59**(6), 885-897.
Anisimov, O., V. Kokorev and Y. Zhiltcova, 2017: Arctic Ecosystems and their Services Under Changing Climate: Predictive-Modeling Assessment. *Geographical Review*, **107**(1), 108-124, doi:10.1111/j.1931-0846.2016.12199.x.
Anthonj, C. et al., 2020: A systematic review of water, sanitation and hygiene among Roma communities in Europe: Situation analysis, cultural context, and obstacles to improvement. *International Journal of Hygiene and Environmental Health*, **226**, 113506, doi:10.1016/j.ijheh.2020.113506.
Antonioli, F. et al., 2017: Sea-level rise and potential drowning of the Italian coastal plains: Flooding risk scenarios for 2100. *Quaternary Science Reviews*, **158**, 29-43, doi:10.1016/j.quascirev.2016.12.021.
Anzures-Olvera, F. et al., 2019: The impact of hair coat color on physiological variables, reproductive performance and milk yield of Holstein cows in a hot environment. *Journal of Thermal Biology*, **81**(January), 82-88, doi:10.1016/j.jtherbio.2019.02.020.
Aparicio, Á., 2017: Transport adaptation policies in Europe: from incremental actions to long-term visions. *Transportation Research Procedia*, **25**, 3529-3537, doi:https://doi.org/10.1016/j.trpro.2017.05.277.
Araos, M., S. E. Austin, L. Berrang-Ford and J. D. Ford, 2015: Public Health Adaptation to Climate Change in Large Cities: A Global Baseline. *International Journal of Health Services*, **46**(1), 53-78, doi:10.1177/0020731415621458.
Arctic Council, 2013: *Arctic Biodiversity Assessment: status and trends in Arctic biodiversity* [Barry, T., D. Berteaux and H. Bültmann (eds.)]. The Conservation of Arctic Flora and Fauna, Akureyri, Iceland, 674 pp. ISBN 978-9935-431-22-6.
Arnell, N. W. et al., 2019: The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios. *Environmental Research Letters*, **14**(8), 084046, doi:10.1088/1748-9326/ab35a6.
Arns, A. et al., 2017: Sea-level rise induced amplification of coastal protection design heights. *Scientific Reports*, **7**, doi:10.1038/srep40171.
Arrigo, K. R. and G. L. van Dijken, 2015: Continued increases in Arctic Ocean primary production. *Progress in Oceanography*, **136**, 60-70, doi:doi/10.1016/j.pocean.2015.05.002.
Asse, D. et al., 2018: Warmer winters reduce the advance of tree spring phenology induced by warmer springs in the Alps. *Agricultural and Forest Meteorology*, **252**, 220-230, doi:https://doi.org/10.1016/j.agrformet.2018.01.030.
Åström, C. et al., 2017: Vulnerability Reduction Needed to Maintain Current Burdens of Heat-Related Mortality in a Changing Climate—Magnitude and Determinants. *International Journal of Environmental Research and Public Health*, **14**(7), doi:10.3390/ijerph14070741.
Åström, C. et al., 2013: Heat-related respiratory hospital admissions in Europe in a changing climate: a health impact assessment. *Bmj Open*, **3**(1), doi:10.1136/bmjopen-2012-001842.
Åström Daniel, O. et al., 2016: Evolution of Minimum Mortality Temperature in Stockholm, Sweden, 1901–2009. *Environmental Health Perspectives*, **124**(6), 740-744, doi:10.1289/ehp.1509692.
Athanasiou, P. et al., 2019: Global distribution of nearshore slopes with implications for coastal retreat. *Earth System Science Data*, **11**(4), 1515-1529, doi:10.5194/essd-11-1515-2019.
Atsalis, A., S. Mirasgedis, C. Tourkolias and D. Diakoulaki, 2016: Fuel poverty in Greece: Quantitative analysis and implications for policy. *Energy and Buildings*, **131**, 87-98, doi:10.1016/j.enbuild.2016.09.025.

Atteridge, A. and E. Remling, 2018: Is adaptation reducing vulnerability or redistributing it? *Wiley Interdisciplinary Reviews-Climate Change*, **9**(1), doi:10.1002/wcc.500.
Austin, S. E. et al., 2016: Public Health Adaptation to Climate Change in OECD Countries. *International journal of environmental research and public health*, **13**(9), 889, doi:10.3390/ijerph13090889.
Austin, S. E. et al., 2019: Enabling local public health adaptation to climate change. *Social Science & Medicine*, **220**, 236-244, doi:https://doi.org/10.1016/j.socscimed.2018.11.002.
Austin, S. E. et al., 2018: Intergovernmental relations for public health adaptation to climate change in the federalist states of Canada and Germany. *Global Environmental Change*, **52**, 226-237, doi:10.1016/j.gloenvcha.2018.07.010.
Averchenkova, A. et al., 2016: Multinational and large national corporations and climate adaptation: are we asking the right questions? A review of current knowledge and a new research perspective: Multinational and large national corporations and climate adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **7**(4), 517-536, doi:10.1002/wcc.402.
Babovic, F. and A. Mijic, 2019: The development of adaptation pathways for the long-term planning of urban drainage systems. *Journal of Flood Risk Management*, **12**(S2), e12538, doi:https://doi.org/10.1111/jfr3.12538.
Bachner, G., B. Bednar-Friedl and N. Knittel, 2019: How does climate change adaptation affect public budgets? Development of an assessment framework and a demonstration for Austria. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-019-9842-3.
Backer, H. et al., 2010: HELCOM Baltic Sea Action Plan - A regional programme of measures for the marine environment based on the Ecosystem Approach. *Marine Pollution Bulletin*, **60**(5), 642–649, doi:10.1016/j.marpolbul.2009.11.016.
Baird, D. et al., 2019: Ecosystem response to increasing ambient water temperatures due to climate warming in the Sylt-Rømø Bight, northern Wadden Sea, Germany. *Estuarine, Coastal and Shelf Science*, 106322, doi:10.1016/j.ecss.2019.106322.
Baker-Austin, C., J. Trinanes, N. Gonzalez-Escalona and J. Martinez-Urtaza, 2017: Non-Cholera Vibrios: The Microbial Barometer of Climate Change. *Trends in Microbiology*, **25**(1), 76-84, doi:doi/10.1016/j.tim.2016.09.008.
Bamberg, S., T. Masson, K. Brewitt and N. Nemetschek, 2017: Threat, coping and flood prevention – A meta-analysis. *Journal of Environmental Psychology*, **54**, 116-126, doi:https://doi.org/10.1016/j.jenvp.2017.08.001.
Bank of England, 2015: *The impact of climate change on the UK insurance sector*. London, 87 pp. Available at: https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/publication/impact-of-climate-change-on-the-uk-insurance-sector.pdf.
Bank of England, 2019: *A framework for assessing financial impacts of physical climate change - a practitioner's aide for the general insurance sector*. 85 pp.
Barange, M. et al., 2014: Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nature Climate Change*, **4**(3), 211-216, doi:10.1038/nclimate2119.
Barredo, J., G. Caudullo and A. Dosio, 2016: Mediterranean habitat loss under future climate conditions: Assessing impacts on the Natura 2000 protected area network. *Applied Geography*, **75**, 83-92, doi:10.1016/j.apgeog.2016.08.003.
Barredo, J. I., A. Mauri and G. Caudullo, 2020: *Impacts of climate change in European mountains — Alpine tundra habitat loss and treeline shifts under future global warming*. **EUR 30084 EN**, Publications Office of the European Union, Luxembourg, 64 pp.
Barriopedro, D. et al., 2011: The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science*, **332**(6026), 220-224, doi:10.1126/science.1201224.
Barth, N.-C. and P. Döll, 2016: Assessing the ecosystem service flood protection of a riparian forest by applying a cascade approach. *Ecosystem Services*, **21**, 39-52, doi:10.1016/j.ecoser.2016.07.012.
Bartok, B. et al., 2017: Projected changes in surface solar radiation in CMIP5 global climate models and in EURO-CORDEX regional climate models for Europe. *Climate Dynamics*, **49**(7-8), 2665-2683, doi:10.1007/s00382-016-3471-2.
Batista, M. I. and H. N. Cabral, 2016: An overview of Marine Protected Areas in SW Europe: Factors contributing to their management effectiveness. *Ocean & Coastal Management*, **132**, 15-23, doi:10.1016/j.ocecoaman.2016.07.005.
Batten, S., R. Sowerbutts and M. Tanaka, 2016: *Let's Talk About the Weather: The Impact of Climate Change on Central Banks*. Bank of England, London. Available at: https://www.ssrn.com/abstract=2783753 (accessed 2019/08/12/08:07:38).
Battiston, S. et al., 2017: A climate stress-test of the financial system. *Nature Climate Change*, **7**(4), 283-288, doi:10.1038/nclimate3255.
Baudron, A. R. et al., 2020: Changing fish distributions challenge the effective management of European fisheries. *Ecography*, **43**(4), 494-505, doi:10.1111/ecog.04864.
Beaumont, N. J. et al., 2014: The value of carbon sequestration and storage in coastal habitats. *Estuarine, Coastal and Shelf Science*, **137**, 32-40, doi:https://doi.org/10.1016/j.ecss.2013.11.022.
Beaven, R. P. et al., 2020: Future challenges of coastal landfills exacerbated by sea level rise. *Waste Management*, **105**, 92-101, doi:https://doi.org/10.1016/j.wasman.2020.01.027.

Becker, A., A. K. Y. Ng, D. McEvoy and J. Mullett, 2018: Implications of climate change for shipping: Ports and supply chains. *Wiley Interdisciplinary Reviews-Climate Change*, **9**(2), doi:10.1002/wcc.508.
Begg, C., 2018: Power, responsibility and justice: a review of local stakeholder participation in European flood risk management. *Local Environment*, **23**(4), 383-397, doi:10.1080/13549839.2017.1422119.
BEIS, 2019: BEIS Public Attitudes Tracker: Wave 29 – key findings. Available at: https://www.gov.uk/government/collections/public-attitudes-tracking-survey.
Bekkby, T. et al., 2020: Habitat Features and Their Influence on the Restoration Potential of Marine Habitats in Europe. *Frontiers in Marine Science*, **7**, 184, doi:10.3389/fmars.2020.00184.
Beland Lindahl, K., A. Johansson, A. Zachrisson and R. Viklund, 2018: Competing pathways to sustainability? Exploring conflicts over mine establishments in the Swedish mountain region. *Journal of Environmental Management*, **218**, 402-415, doi:10.1016/j.jenvman.2018.04.063.
Beland Lindahl, K. et al., 2017: The Swedish forestry model: More of everything? *Forest Policy and Economics*, **77**, 44-55, doi:10.1016/j.forpol.2015.10.012.
Bellis, J., M. Longden, J. Styles and S. Dalrymple, 2021: Using macroecological species distribution models to estimate changes in the suitability of sites for threatened species reintroduction. *Ecological Solutions and Evidence*, **2**(1), e12050, doi:https://doi.org/10.1002/2688-8319.12050.
Belyakova, P. A., V. M. Moreido and A. I. Pyankova, 2018: Flood fatalities age and gender structure analysis in Russia in 2000-2014. In: *Third Vinogradov's Readings. Facets of hydrology*, Saint Pitersburg, Russia, [Makarieva, O. M. (ed.)], High technology, pp. 849-853.
Ben-Ari, T. et al., 2018: Causes and implications of the unforeseen 2016 extreme yield loss in the breadbasket of France. *Nature Communications*, **9**(1), doi:10.1038/s41467-018-04087-x.
Beniston, M. et al., 2018: The European mountain cryosphere: a review of its current state, trends, and future challenges. *The Cryosphere*, **12**(2), 759-794, doi:10.5194/tc-12-759-2018.
Bennema, F. P., 2018: Long-term occurrence of Atlantic bluefin tuna Thunnus thynnus in the North Sea: contributions of non-fishery data to population studies. *Fisheries Research*, **199**(February 2017), 177-185, doi:10.1016/j.fishres.2017.11.019.
Benson, D. and I. Lorenzoni, 2017: Climate change adaptation, flood risks and policy coherence in integrated water resources management in England. *Regional Environmental Change*, **17**(7), 1921-1932, doi:10.1007/s10113-016-0959-6.
Benveniste, H., M. Oppenheimer and M. Fleurbaey, 2020: Effect of border policy on exposure and vulnerability to climate change. *Proceedings of the National Academy of Sciences*, **117**(43), 26692-26702, doi:10.1073/pnas.2007597117.
Benzie, M., T. R. Carter, H. Carlsen and R. Taylor, 2019: Cross-border climate change impacts: implications for the European Union. *Regional Environmental Change*, **19**(3), 763-776, doi:10.1007/s10113-018-1436-1.
Benzie, M. and A. Persson, 2019: Governing borderless climate risks: moving beyond the territorial framing of adaptation. *International Environmental Agreements: Politics, Law and Economics*, **19**, 369 – 393.
Berberoglu, S. et al., 2020: Spatial and temporal evaluation of soil erosion in Turkey under climate change scenarios using the Pan-European Soil Erosion Risk Assessment (PESERA) model. *Environmental Monitoring and Assessment*, **192**(8), 491, doi:10.1007/s10661-020-08429-5.
Berdalet, E. et al., 2017: GlobalHAB A New Program to Promote International Research, Observations, and Modeling of Harmful Algal Blooms in Aquatic Systems. *Oceanography*, **30**(1), 70-81, doi:doi/10.5670/oceanog.2017.111.
Berkhout, F. et al., 2015: European policy responses to climate change: progress on mainstreaming emissions reduction and adaptation. *Regional Environmental Change*, **15**(6), 949-959, doi:10.1007/s10113-015-0801-6.
Bernabucci, U. et al., 2014: The effects of heat stress in Italian Holstein dairy cattle. *Journal of Dairy Science*, **97**(1), 471-486, doi:10.3168/jds.2013-6611.
Berry, P., R. Betts, P. Harrison and A. Sanchez-Arcilla, 2017: High-end climate change in Europe. *Impacts, Vulnerability and Adaption*.
Berry, P. et al., 2018: Assessing Health Vulnerabilities and Adaptation to Climate Change: A Review of International Progress. *International Journal of Environmental Research and Public Health*, **15**(12), 2626.
Berry, P. M. et al., 2015: Cross-sectoral interactions of adaptation and mitigation measures. *Climatic Change*, **128**(3-4), 381-393, doi:10.1007/s10584-014-1214-0.
Bertoldi, P. et al., 2020: *Covenant of Mayors: 2019 Assessment* [JRC (ed.)]. JRC Science for Policy Report, Union, P. O. o. t. E., Luxembourg, 63 pp. Available at: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/covenant-mayors-2019-assessment.
Bett, B. et al., 2017: Effects of climate change on the occurrence and distribution of livestock diseases. *Preventive Veterinary Medicine*, **137**(November 2015), 119-129, doi:10.1016/j.prevetmed.2016.11.019.
Bevacqua, E. et al., 2019: Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. *Science Advances*, **5**(9), eaaw5531, doi:10.1126/sciadv.aaw5531.
Bezuglova, O. S., O. G. Nazarenko and I. N. Ilyinskaya, 2020: Dynamics of land degradation in the Rostov region. *Arid Ecosystems*, **26**, 10-15.
Biedermann, T. et al., 2019: Birch pollen allergy in Europe. *Allergy*, **74**(7), 1237-1248, doi:https://doi.org/10.1111/all.13758.

Biesbroek, G. R. et al., 2010: Europe adapts to climate change: Comparing National Adaptation Strategies. *Global Environmental Change*, **20**(3), 440-450, doi:10.1016/j.gloenvcha.2010.03.005.
Biesbroek, R., 2021: Policy integration and climate change adaptation. Current opinion in environmental sustainability, 75-81 pp.
Biesbroek, R. and J. J. L. Candel, 2019: Mechanisms for policy (dis)integration: explaining food policy and climate change adaptation policy in the Netherlands. *Policy Sciences*, doi:10.1007/s11077-019-09354-2.
Biesbroek, R. and A. Delaney, 2020: Mapping the evidence of climate change adaptation policy instruments in Europe. *Environmental Research Letters*, **15**(8), 83005-83005, doi:10.1088/1748-9326/ab8fd1.
Bindoff, N. L., W. L. Cheung and J. G. Kairo, 2019: Chapter 5: Changing Ocean, Marine ecosystems, and dependent communities. In: *SROOC*.
Bird, D. N. et al., 2016: Modelling climate change impacts on and adaptation strategies for agriculture in Sardinia and Tunisia using AquaCrop and value-at-risk. *Science of The Total Environment*, **543**, 1019-1027, doi:https://doi.org/10.1016/j.scitotenv.2015.07.035.
Bird, D. N. et al., 2019: Estimating the daily peak and annual total electricity demand for cooling in Vienna, Austria by 2050. *Urban Climate*, **28**, doi:10.1016/j.uclim.2019.100452.
Bisaro, A. and J. Hinkel, 2018: Mobilizing private finance for coastal adaptation: A literature review. *WIREs Climate Change*, **9**(3), e514, doi:10.1002/wcc.514.
Bisbis, M. B., N. S. Gruda and M. M. Blanke, 2019: Securing horticulture in a changing climate-a mini review. *Horticulturae*, **5**(3), doi:10.3390/horticulturae5030056.
Bisselink, B. et al., 2018: *Impact of a changing climate, land use, and water usage on Europe's water resources*. 86-86 pp. ISBN 9789279802874.
Bisselink, B. et al., 2020: *Climate change and Europe's water resources*. ISBN 9789276103981.
Bjorst, L. R. and C. Ren, 2015: Steaming Up or Staying Cool? Tourism Development and Greenlandic Futures in the Light of Climate Change. *Arctic Anthropology*, **52**(1), 91-101, doi:10.3368/aa.52.1.91.
Blanchet, M.-A. et al., 2019: How vulnerable is the European seafood production to climate warming? *Fisheries Research*, **209**, 251-258, doi:10.1016/j.fishres.2018.09.004.
Blauhut, V., L. Gudmundsson and K. Stahl, 2015: Towards pan-European drought risk maps: quantifying the link between drought indices and reported drought impacts. *Environmental Research Letters*, **10**(1), 014008, doi:10.1088/1748-9326/10/1/014008.
Bloemen, P. J. T. M. et al., 2019: DMDU into Practice: Adaptive Delta Management in The Netherlands. In: *Decision Making under Deep Uncertainty: From Theory to Practice* [Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen and S. W. Popper (eds.)]. Springer International Publishing, Cham, pp. 321-351. ISBN 978-3-030-05252-2.
Blöschl, G. et al., 2017: Changing climate shifts timing of European floods. *Science*, **357**(6351), 588-590, doi:10.1126/science.aan2506.
Blöschl, G. et al., 2020: Current European flood-rich period exceptional compared with past 500 years. *Nature*, **583**(7817), 560-566, doi:10.1038/s41586-020-2478-3.
BMUB, 2017: *Achieving aims together. The Federal Environment Ministry's International Climate Initiative. Review of Activities 2015 to 2016*. Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), Berlin.
Bobretsov, A. V., T. K. Tertitsa and V. P. Teplova, 2019: The Impact of climate change on the phenology of plants and animals of the south-eastern part of the Komi Republic (the Pechora-Ilych biosphere reserve) *Problems of Ecological Monitoring and Ecosystem Modelling*, **18**(4), 74-93, doi:DOI: 10.21513/0207-2564-2017-4-74-93.
Bock, A. et al., 2014: Changes in first flowering dates and flowering duration of 232 plant species on the island of Guernsey. *Global Change Biology*, **20**(11), 3508-3519, doi:10.1111/gcb.12579.
Boé, J., S. Somot, L. Corre and P. Nabat, 2020: Large discrepancies in summer climate change over Europe as projected by global and regional climate models: causes and consequences. *Climate Dynamics*, **54**(5), 2981-3002, doi:10.1007/s00382-020-05153-1.
Boeckmann, M. and T. A. Joyner, 2014: Old health risks in new places? An ecological niche model for *I.ricinus* tick distribution in Europe under a changing climate. *Health & place*, **30**, 70-77.
Boeckmann, M. and H. Zeeb, 2014: Using a Social Justice and Health Framework to Assess European Climate Change Adaptation Strategies. *International Journal of Environmental Research and Public Health*, **11**(12), 12389-12411.
Boer, M. M. et al., 2017: Changing Weather Extremes Call for Early Warning of Potential for Catastrophic Fire. *Earth's Future*, **5**(12), 1196-1202, doi:https://doi.org/10.1002/2017EF000657.
Bogdanovich, A. Y. and O. N. Lipka, 2020: The synergy of the climate global sustainable development goal and the National adapatation plan in Russia. *Problems of environmental monitoring and modelling of ecosystems*,(3-4), in press.
Boiffin, J., V. Badeau and N. Bréda, 2017: Species distribution models may misdirect assisted migration: insights from the introduction of Douglas-fir to Europe. *Ecological Applications*, **27**(2), 446-457, doi:https://doi.org/10.1002/eap.1448.
Bokhorst, S. et al., 2016: Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts. *Ambio*, **45**(5), 516-537, doi:10.1007/s13280-016-0770-0.

Bollinger, L. A. and G. P. J. Dijkema, 2016: Evaluating infrastructure resilience to extreme weather – The case of the Dutch electricity transmission network. *European Journal of Transport and Infrastructure Research*, **16**(1), 214-239.
Boost, M. and L. Meier, 2017: Resilient practices of consumption in times of crisis-Biographical interviews with members of vulnerable households in Germany. *International Journal of Consumer Studies*, **41**(4), 371-378, doi:10.1111/ijcs.12346.
Booth, L. et al., 2020: Simulating synergies between Climate Change Adaptation and Disaster Risk Reduction stakeholders to improve management of transboundary disasters in Europe. *International Journal of Disaster Risk Reduction*, **49**, 101668-101668, doi:https://doi.org/10.1016/j.ijdrr.2020.101668.
Borderon, M. et al., 2019: Migration influenced by environmental change in Africa: A systematic review of empirical evidence. *Demographic Research*, **41**(18), 491-454 494.
Borrelli, P. et al., 2016: Effect of Good Agricultural and Environmental Conditions on erosion and soil organic carbon balance: A national case study. *Land Use Policy*, **50**, 408-421, doi:https://doi.org/10.1016/j.landusepol.2015.09.033.
Borrelli, P. et al., 2017: An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, **8**(1), 2013, doi:10.1038/s41467-017-02142-7.
Borrelli, P. et al., 2020: Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences*, **117**(36), 21994-22001, doi:10.1073/pnas.2001403117.
Borsheim, K. Y., 2017: Bacterial and primary production in the Greenland Sea. *Journal of Marine Systems*, **176**, 54-63, doi:doi/10.1016/j.jmarsys.2017.08.003.
Bosello, F. et al., 2018: Economy-wide impacts of climate mitigation and adaptation strategies across European Regions. In: *Adapting to Climate Change in Europe* [H, S., H. M, R. D, P.-L. G and C. A (eds.)]. Elsevier Inc.
Bosson, J. B., M. Huss and E. Osipova, 2019: Disappearing World Heritage Glaciers as a Keystone of Nature Conservation in a Changing Climate. *Earth's Future*, **7**(4), 469-479, doi:10.1029/2018EF001139.
Bouwer, L. M. and S. N. Jonkman, 2018: Global mortality from storm surges is decreasing. *Environmental Research Letters*, **13**(1), 014008, doi:10.1088/1748-9326/aa98a3.
Bouzarovski, S. and S. Petrova, 2015: A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. *Energy Research & Social Science*, **10**, 31-40, doi:10.1016/j.erss.2015.06.007.
Bowler, D. E., L. Buyung-Ali, T. M. Knight and A. S. Pullin, 2010: Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, **97**(3), 147-155, doi:https://doi.org/10.1016/j.landurbplan.2010.05.006.
Brand, J. H., K. L. Spencer, F. T. O'shea and J. E. Lindsay, 2018: Potential pollution risks of historic landfills on low-lying coasts and estuaries. *WIREs Water*, **5**(1), e1264, doi:https://doi.org/10.1002/wat2.1264.
Brás, T. A., J. Jägermeyr and J. Seixas, 2019: Exposure of the EU-28 food imports to extreme weather disasters in exporting countries. *Food Security*, **11**(6), 1373-1393, doi:10.1007/s12571-019-00975-2.
Brás, T. A., J. Seixas, N. Carvalhais and J. Jägermeyr, 2021: Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environmental Research Letters*, doi:10.1088/1748-9326/abf004.
Brasseur, G. P. and L. Gallardo, 2016: Climate services: Lessons learned and future prospects. *Earths Future*, **4**(3), 79-89, doi:10.1002/2015ef000338.
Brattland, C. and T. Mustonen, 2018: How Traditional Knowledge Comes to Matter in Atlantic Salmon Governance in Norway and Finland. *ARCTIC*, **71**(4), 365-482, doi:https://doi.org/10.14430/arctic4751.
Bright, R. M. et al., 2017: Local temperature response to land cover and management change driven by non-radiative processes. *Nature Climate Change*, **7**, 296, doi:10.1038/nclimate3250
https://www.nature.com/articles/nclimate3250#supplementary-information.
Brink, E. and C. Wamsler, 2018: Collaborative Governance for Climate Change Adaptation: Mapping citizen–municipality interactions. *Environmental Policy and Governance*, **28**(2), 82-97, doi:10.1002/eet.1795.
Brink, E. and C. Wamsler, 2019: Citizen engagement in climate adaptation surveyed: The role of values, worldviews, gender and place. *Journal of Cleaner Production*, **209**, 1342-1353, doi:https://doi.org/10.1016/j.jclepro.2018.10.164.
Brodie, J. et al., 2014: The future of the northeast Atlantic benthic flora in a high CO_2 world. *Ecology and Evolution*, **4**(13), 2787--2798, doi:10.1002/ece3.1105.
Brugger, J., K. W. Dunbar, C. Jurt and B. Orlove, 2013: Climates of anxiety: Comparing experience of glacier retreat across three mountain regions. *Emotion, Space and Society*, **6**, 4-13, doi:https://doi.org/10.1016/j.emospa.2012.05.001.
Bruno, J. F. et al., 2018: Climate change threatens the world's marine protected areas. *Nature Climate Change*, **8**(6), 499-503, doi:doi/10.1038/s41558-018-0149-2.
Bruno Soares, M., M. Alexander and S. Dessai, 2018: Sectoral use of climate information in Europe: A synoptic overview. *Climate Services*, **9**, 5-20, doi:https://doi.org/10.1016/j.cliser.2017.06.001.
Bryan, K., S. Ward, S. Barr and D. Butler, 2019: Coping with Drought: Perceptions, Intentions and Decision-Stages of South West England Households. *Water Resources Management*, **33**(3), 1185-1202, doi:10.1007/s11269-018-2175-2.
Bryn, A. and K. Potthoff, 2018: Elevational treeline and forest line dynamics in Norwegian mountain areas – a review. *Landscape Ecology*, **33**(8), 1225-1245, doi:10.1007/s10980-018-0670-8.

Bryndum-Buchholz, A. et al., 2020: Climate-change impacts and fisheries management challenges in the North Atlantic Ocean. *MARINE ECOLOGY PROGRESS SERIES*, **648**, 1 - 17.
Bryndum-Buchholz, A. et al., 2019: Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. *Global Change Biology*, **25**(2), 459-472, doi:doi/10.1111/gcb.14512.
Bubeck, P. et al., 2019: Global warming to increase flood risk on European railways. *Climatic Change*, **155**(1), 19-36, doi:10.1007/s10584-019-02434-5.
Bubeck, P. et al., 2017: Explaining differences in flood management approaches in Europe and in the USA – a comparative analysis. *Journal of Flood Risk Management*, **10**(4), 436-445, doi:10.1111/jfr3.12151.
Buhaug, H. et al., 2014: One effect to rule them all? A comment on climate and conflict. *Climatic Change*, **127**(3-4), 391-397.
Bukvareva, E. N. and D. G. Zamolodchikov, 2016: *Ecosystem Services of Russia: Prototype of the National Report* [Bukvareva, E. N. and D. G. Zamolodchikov (eds.)]. **Volume 1. Services of terrestrial ecosystems**
Publishing house of the Center for Wildlife Conservation, Moscow, 148 pp. Available at: https://teeb.biodiversity.ru/publications/Ecosystem-Services-Russia_V1_eng_web.pdf.
Buras, A., A. Rammig and C. S. Zang, 2020: Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences*, **17**(6), 1655-1672, doi:10.5194/bg-17-1655-2020.
Burbidge, R., 2015: Adapting aviation to a changing climate: Key priorities for action. *Journal of Air Transport Management*, **71**, 167-174, doi:10.1016/j.jairtraman.2018.04.004.
Büscher, J. V., A. U. Form and U. Riebesell, 2017: Interactive effects of ocean acidification and warming on growth, fitness and survival of the cold-water coral Lophelia pertusa under different food availabilities. *Frontiers in Marine Science*, **4**(APR), doi:10.3389/fmars.2017.00101.
Buser, M., 2020: Coastal Adaptation Planning in Fairbourne, Wales: lessons for Climate Change Adaptation. *Planning Practice & Research*, **35**(2), 127-147, doi:10.1080/02697459.2019.1696145.
Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, **13**(5), 55012-55012, doi:10.1088/1748-9326/aabf45.
Byers, E. A. et al., 2016: Water and climate risks to power generation with carbon capture and storage. *Environmental Research Letters*, **11**(2), 024011, doi:10.1088/1748-9326/11/2/024011.
Cadier, C., E. Bayraktarov, R. Piccolo and M. F. Adame, 2020: Indicators of Coastal Wetlands Restoration Success: A Systematic Review. *Frontiers in Marine Science*, **7**, 600220, doi:10.3389/fmars.2020.600220.
Caffarra, A. et al., 2012: Modelling the impact of climate change on the interaction between grapevine and its pests and pathogens: European grapevine moth and powdery mildew. *Agriculture, Ecosystems & Environment*, **148**, 89-101, doi:https://doi.org/10.1016/j.agee.2011.11.017.
Caffarra, A., F. Zottele, E. Gleeson and A. Donnelly, 2014: Spatial heterogeneity in the timing of birch budburst in response to future climate warming in Ireland. *International Journal of Biometeorology*, **58**(4), 509-519, doi:10.1007/s00484-013-0720-5.
Callaghan, M. W., J. C. Minx and P. M. Forster, 2020: A topography of climate change research. *Nature Climate Change*, **10**(2), 118-123, doi:10.1038/s41558-019-0684-5.
Cameron, R. W. F., J. E. Taylor and M. R. Emmett, 2014: What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. *Building and Environment*, **73**, 198-207, doi:https://doi.org/10.1016/j.buildenv.2013.12.005.
Cammalleri, C. et al., 2020: *Global warming and drought impacts in the EU*. JRC Technical report, **EUR 29956 EN**, Luxembourgh. Available at: https://ec.europa.eu/jrc.
Campiglio, E. et al., 2018: Climate change challenges for central banks and financial regulators. *Nature Climate Change*, **8**(6), 462-468, doi:10.1038/s41558-018-0175-0.
Campos, J. C. et al., 2021: Using fire to enhance rewilding when agricultural policies fail. *Science of The Total Environment*, **755**, 142897, doi:https://doi.org/10.1016/j.scitotenv.2020.142897.
Camus, P. et al., 2019: Probabilistic assessment of port operation downtimes under climate change. *Coastal Engineering*, **147**, 12-24, doi:https://doi.org/10.1016/j.coastaleng.2019.01.007.
Canosa, I. V. et al., 2020: Progress in climate change adaptation in the Arctic. *Environmental Research Letters*, **15**(9), 093009, doi:10.1088/1748-9326/ab9be1.
Caporin, M. and F. Fontini, 2016: Chapter 5 - Damages Evaluation, Periodic Floods, and Local Sea Level Rise: The Case of Venice, Italy. In: *Handbook of Environmental and Sustainable Finance* [Ramiah, V. and G. N. Gregoriou (eds.)]. Academic Press, San Diego, pp. 93-110. ISBN 978-0-12-803615-0.
Capstick, S. et al., 2015: International trends in public perceptions of climate change over the past quarter century. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(1), 35-61, doi:10.1002/wcc.321.
Capuzzo, E. et al., 2018: A decline in primary production in the North Sea over 25 years, associated with reductions in zooplankton abundance and fish stock recruitment. *Global Change Biology*, **24**(1), e352--e364, doi:10.1111/gcb.13916.
Carmona, R. et al., 2016a: Geographical variation in relative risks associated with cold waves in Spain: the need for a cold wave prevention plan. *Environment international*, **88**, 103-111.
Carmona, R. et al., 2016b: Mortality attributable to extreme temperatures in Spain: A comparative analysis by city. *Environment International*, **91**, 22-28, doi:https://doi.org/10.1016/j.envint.2016.02.018.

Carnicer, J. et al., 2019: Phenotypic biomarkers of climatic impacts on declining insect populations: A key role for decadal drought, thermal buffering and amplification effects and host plant dynamics. *Journal of Animal Ecology*, **88**(3), 376-391, doi:10.1111/1365-2656.12933.

Carnicer, J. et al., 2021: Forest resilience to global warming is strongly modulated by local-scale topographic, microclimatic and biotic conditions. *Journal of Ecology*.

Carozza, D. A., D. Bianchi and E. D. Galbraith, 2019: Metabolic impacts of climate change on marine ecosystems: Implications for fish communities and fisheries. *Global Ecology and Biogeography*, **28**(2), 158-169, doi:doi/10.1111/geb.12832.

Carroll, B., H. Morbey, R. Balogh and G. Araoz, 2009: Flooded homes, broken bonds, the meaning of home, psychological processes and their impact on psychological health in a disaster. *Health & Place*, **15**(2), 540-547, doi:10.1016/j.healthplace.2008.08.009.

Carroll, P. and E. Aarrevaara, 2018: Review of Potential Risk Factors of Cultural Heritage Sites and Initial Modelling for Adaptation to Climate Change. *Geosciences*, **8**(9), 322, doi:10.3390/geosciences8090322.

Carstensen, J., J. H. Andersen, B. G. Gustafsson and D. J. Conley, 2014: Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences*, 201323156, doi:10.1073/pnas.1323156111.

Carter, J. G., J. Handley, T. Butlin and S. Gill, 2018: Adapting cities to climate change – exploring the flood risk management role of green infrastructure landscapes. *Journal of Environmental Planning and Management*, **61**(9), 1535-1552, doi:10.1080/09640568.2017.1355777.

Carter, T. R. et al., 2021: A conceptual framework for cross-border impacts of climate change. *Global Environmental Change*, **69**, 102307.

Carvalho, N. et al., 2017: *The 2017 annual economic report on the EU fishing fleet (STECF 17-12)*. ISBN 978-92-79-73426-7.

Casanueva, A. et al., 2019: Overview of Existing Heat-Health Warning Systems in Europe. *International Journal of Environmental Research and Public Health*, **16**(15), doi:10.3390/ijerph16152657.

Casanueva, A. et al., 2020: Escalating environmental summer heat exposure—a future threat for the European workforce. *Regional Environmental Change*, **20**(2), 40, doi:10.1007/s10113-020-01625-6.

Casazza, G. et al., 2021: Combining conservation status and species distribution models for planning assisted colonisation under climate change. *Journal of Ecology*, **109**(6), 2284-2295, doi:https://doi.org/10.1111/1365-2745.13606.

Cassarino, T., E. Sharp and M. Barrett, 2018: The impact of social and weather drivers on the historical electricity demand in Europe. *Applied Energy*, **229**, 176-185, doi:10.1016/j.apenergy.2018.07.108.

Castellanos-Frias, E., D. Garcia De Leon, F. Bastida and J. L. Gonzalez-Andujar, 2016: Predicting global geographical distribution of *Lolium rigidum* (rigid ryegrass) under climate change. *The Journal of Agricultural Science*, **154**(5), 755-764, doi:10.1017/S0021859615000799.

Castellanos-Galindo, G. A., D. R. Robertson and M. E. Torchin, 2020: A new wave of marine fish invasions through the Panama and Suez canals. *Nature Ecology & Evolution*, **29**, 1-3, doi:doi/10.1038/s41559-020-01301-2.

Cattaneo, C. et al., 2019: Human Migration in the Era of Climate Change. *Review of Environmental Economics and Policy*, **13**(2), 189-206, doi:10.1093/reep/rez008.

Cavallo, M. et al., 2019: Impediments to achieving integrated marine management across borders: The case of the EU Marine Strategy Framework Directive. *Marine Policy*, **103**, 68-73, doi:doi/10.1016/j.marpol.2019.02.033.

Cavelier, R. et al., 2017: Conditions for a market uptake of climate services for adaptation in France. *Climate Services*, **6**, 34-40, doi:https://doi.org/10.1016/j.cliser.2017.06.010.

CBS, 2019: Water en milieu - Temperatuur oppervlaktewater, 1910-2013. Available at: http://www.clo.nl/nl0566

CDP, 2019: Open Data Portal. Available at: https://data.cdp.net/.

CDP, 2020: The co-benefits of climate action: Accelerating city-level ambition. doi:https://www.cdp.net/en/research/global-reports/co-benefits-climate-action#671b3beee69d9180412202b6528ec8f7.

CDSB, 2020: *The state of EU Environmental Disclosure in 2020*. Climate Disclosure Standards Board (CDSB), London, UK. Available at: https://www.cdsb.net/nfrd2020 (accessed 2021/08/17/11:14:41).

Ceglar, A., M. Turco, A. Toreti and F. J. Doblas-Reyes, 2017: Linking crop yield anomalies to large-scale atmospheric circulation in Europe. *Agricultural and Forest Meteorology*, **240-241**, 35-45, doi:10.1016/j.agrformet.2017.03.019.

Ceglar, A., M. Zampieri, A. Toreti and F. Dentener, 2019: Observed Northward Migration of Agro-Climate Zones in Europe Will Further Accelerate Under Climate Change. *Earth's Future*, **7**(9), 1088-1101, doi:10.1029/2019EF001178.

Cellura, M., F. Guarino, S. Longo and G. Tumminia, 2018: Climate change and the building sector: Modelling and energy implications to an office building in southern Europe. *Energy for Sustainable Development*, **45**, 46-65, doi:https://doi.org/10.1016/j.esd.2018.05.001.

Cervellin, G. et al., 2014: The number of emergency department visits for psychiatric emergencies is strongly associated with mean temperature and humidity variations. Results of a nine year survey. *Emergency Care Journal*, **10**(1).

Challinor, 2016: UK Climate Change Risk Assessment Evidence Report 2017.

Challinor, A. J. et al., 2016: Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nature Climate Change*, **6**(10), 954-958, doi:10.1038/nclimate3061.
Challinor, A. J. et al., 2018: Improving the use of crop models for risk assessment and climate change adaptation. *Agricultural Systems*, **159**(November 2016), 296-306, doi:10.1016/j.agsy.2017.07.010.
Chambwera, M. et al., 2014: Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge
Chan, S. C. et al., 2020: Europe-wide precipitation projections at convection permitting scale with the Unified Model. *Climate Dynamics*, **55**(3), 409-428, doi:10.1007/s00382-020-05192-8.
Charlier, J. et al., 2016: Climate-driven longitudinal trends in pasture-borne helminth infections of dairy cattle. *International Journal for Parasitology*, **46**(13-14), 881-888, doi:10.1016/j.ijpara.2016.09.001.
Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, **67**, 6134-6155, doi:doi/10.1111/gcb.15310.
Chen, D. et al., 2021: Framing, Context, and Methods In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Chernet Haregewoin, H., K. Alfredsen and H. Midttømme Grethe, 2014: Safety of Hydropower Dams in a Changing Climate. *Journal of Hydrologic Engineering*, **19**(3), 569-582, doi:10.1061/(ASCE)HE.1943-5584.0000836.
Chivers, W. J., A. W. Walne and G. C. Hays, 2017: Mismatch between marine plankton range movements and the velocity of climate change. *Nature Communications*, **8**, 14434, doi:doi/10.1038/ncomms14434.
Choi, C., P. Berry and A. Smith, 2021: The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. *J Environ Manage*, **291**, 112583, doi:10.1016/j.jenvman.2021.112583.
Christel, I. et al., 2018: Introducing design in the development of effective climate services. *Climate Services*, **9**, 111-121, doi:https://doi.org/10.1016/j.cliser.2017.06.002.
Christodoulou, A., P. Christidis and B. Bisselink, 2020: Forecasting the impacts of climate change on inland waterways. *Transportation Research Part D: Transport and Environment*, **82**, 102159, doi:https://doi.org/10.1016/j.trd.2019.10.012.
Christodoulou, A., P. Christidis and H. Demirel, 2018: Sea-level rise in ports: a wider focus on impacts. *Maritime Economics & Logistics*, doi:10.1057/s41278-018-0114-z.
Christodoulou, A. and H. Demirel, 2018: Impacts of climate change on transport: A focus on airports, seaports and inland waterways, Luxembourg, 50 pp.
Church, A., R. Mitchell, N. Ravenscroft and L. M. Stapleton, 2015: 'Growing your own': A multi-level modelling approach to understanding personal food growing trends and motivations in Europe. *Ecological Economics*, **110**, 71-80, doi:10.1016/j.ecolecon.2014.12.002.
Ciabatta, L. et al., 2016: Assessing the impact of climate-change scenarios on landslide occurrence in Umbria Region, Italy. *Journal of Hydrology*, **541**, 285-295, doi:https://doi.org/10.1016/j.jhydrol.2016.02.007.
Ciampalini, R. et al., 2020: Modelling soil erosion responses to climate change in three catchments of Great Britain. *Science of The Total Environment*, **749**, 141657, doi:https://doi.org/10.1016/j.scitotenv.2020.141657.
Ciscar, J.-C. et al., 2014: Climate impacts in Europe-The JRC PESETA II project. *EUR – Scientific and Technical Research*, **26586**, 155.
Clar, C., 2019: Coordinating climate change adaptation across levels of government: the gap between theory and practice of integrated adaptation strategy processes. *Journal of Environmental Planning and Management*, 1-20, doi:10.1080/09640568.2018.1536604.
Clark, N. J., J. T. Kerry and C. I. Fraser, 2020: Rapid winter warming could disrupt coastal marine fish community structure. *Nature Climate Change*, **10**(9), 862-867, doi:10.1038/s41558-020-0838-5.
Clark, P. U. et al., 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, **6**(4), 360-369, doi:10.1038/nclimate2923.
Claudet, J., C. Loiseau, M. Sostres and M. Zupan, 2020: Underprotected Marine Protected Areas in a Global Biodiversity Hotspot. *One Earth*, **2**(4), 380-384, doi:doi/10.1016/j.oneear.2020.03.008.
Clayton, S. et al., 2015: Psychological research and global climate change. *Nature Climate Change*, **5**, 640-646, doi:10.1038/nclimate2622.
Clements, J. C. and E. S. Darrow, 2018: Eating in an acidifying ocean: a quantitative review of elevated CO2 effects on the feeding rates of calcifying marine invertebrates. *Hydrobiologia*, **820**(1), 1-21, doi:10.1007/s10750-018-3665-1.
Coffel, E. D., T. R. Thompson and R. M. Horton, 2017: The impacts of rising temperatures on aircraft takeoff performance. *Climatic Change*, **144**(2), 381-388, doi:10.1007/s10584-017-2018-9.
Cohen, P., O. Potchter and A. Matzarakis, 2012: Daily and seasonal climatic conditions of green urban open spaces in the Mediterranean climate and their impact on human comfort. *Building and Environment*, **51**, 285-295, doi:https://doi.org/10.1016/j.buildenv.2011.11.020.

Collet, L. et al., 2015: Water supply sustainability and adaptation strategies under anthropogenic and climatic changes of a meso-scale Mediterranean catchment. *Science of The Total Environment*, **536**, 589-602, doi:https://doi.org/10.1016/j.scitotenv.2015.07.093.
Comune di Milano, 2019: *Milano 2030: Visione, Costruzione, Strategie, Spazi*.
Comune di Milano, 2020: *Milan 2020. Adaptation strategy - Open Streets*.
Confalonieri, U., J. Menezes and C. de Souza, 2015: Climate change and adaptation of the health sector: the case of infectious diseases. *Virulence*, **6**(6), 550-553, doi:10.1080/21505594.2015.1023985.
Cook, B. I. and E. M. Wolkovich, 2016: Climate change decouples drought from early wine grape harvests in France. *Nature Climate Change*, **6**(7), 715-719, doi:10.1038/nclimate2960.
Cooper, J. A. G., M. C. O'Connor and S. McIvor, 2016: Coastal defences versus coastal ecosystems: A regional appraisal. *Marine Policy*, doi:doi/10.1016/j.marpol.2016.02.021.
Cooper, M. M. D. et al., 2021: Role of forested land for natural flood management in the UK: A review. *WIREs Water*, **8**(5), e1541, doi:https://doi.org/10.1002/wat2.1541.
Copernicus, 2019: *Copernicus Europe State of the Climate report*. Available at: https://climate.copernicus.eu/sites/default/files/2020-07/ESOTC2019_summary_v2.pdf.
Copernicus, 2020a: *Copernicus Emergency Management Service*. Available at: https://emergency.copernicus.eu/ (accessed 1/10/2020).
Copernicus, 2020b: *ECMWF and Copernicus Atmosphere Monitoring Service*. Available at: https://atmosphere.copernicus.eu/ (accessed 1/10/2020).
Coppola, E. et al., 2021: Assessment of the European Climate Projections as Simulated by the Large EURO-CORDEX Regional and Global Climate Model Ensemble. *Journal of Geophysical Research: Atmospheres*, **126**(4), e2019JD032356, doi:https://doi.org/10.1029/2019JD032356.
Coppola, E., F. Raffaele and F. Giorgi, 2018: Impact of climate change on snow melt driven runoff timing over the Alpine region. *Climate Dynamics*, **51**(3), 1259-1273, doi:10.1007/s00382-016-3331-0.
Corcoran, M., 2014: *From Private Initiatives to Public Goods: A Comparative Analysis of European Urban Agricultural Practices in the Age of Austerity*. XVIII ISA World Congress of Sociology (July 13-19, 2014), Isaconf. Available at: https://isaconf.confex.com/isaconf/wc2014/webprogram/Paper65556.html.
Corrales, X. et al., 2018: Future scenarios of marine resources and ecosystem conditions in the Eastern Mediterranean under the impacts of fishing, alien species and sea warming. *Scientific Reports*, **8**, 1-16, doi:10.1038/s41598-018-32666-x.
Cortekar, J., M. Themessl and K. Lamich, 2020: Systematic analysis of EU-based climate service providers. *Climate Services*, **17**, doi:10.1016/j.cliser.2019.100125.
Corti, T., M. Wüest, D. Bresch and S. I. Seneviratne, 2011: Drought-induced building damages from simulations at regional scale. *Nat. Hazards Earth Syst. Sci.*, **11**(12), 3335-3342, doi:10.5194/nhess-11-3335-2011.
Costa, H. et al., 2020: *European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions*. Luxembourg, 59 pp.
Costa, J. M. et al., 2019: Opportunities and Limitations of Crop Phenotyping in Southern European Countries. *Front. Plant Sci.*, **10**, 1-16, doi:10.3389/fpls.2019.01125.
Cottier-Cook, E. J. et al., 2017: Non-native species. In: *MCCIP Science Review*. Marine Climate Change Impacts Partnership, pp. 47-61.
Couasnon, A. et al., 2020: Measuring compound flood potential from river discharge and storm surge extremes at the global scale. *Natural Hazards and Earth System Sciences*, **20**(2), 489-504, doi:10.5194/nhess-20-489-2020.
Cramer, W. et al., 2018: Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, **8**(11), 972-980, doi:10.1038/s41558-018-0299-2.
Crespo, D. et al., 2019: Tradeoffs between Water Uses and Environmental Flows: A Hydroeconomic Analysis in the Ebro Basin. *Water Resources Management*, **33**(7), 2301-2317, doi:10.1007/s11269-019-02254-3.
Crick, H. Q. P. et al., 2020: *Nature Networks: A Summary for Practitioners* [England, N. (ed.)]. Natural England Research Report NERR082, York.
Cronin, J., G. Anandarajah and O. Dessens, 2018: Climate change impacts on the energy system: a review of trends and gaps. *Climatic Change*, **151**(2), 79-93, doi:10.1007/s10584-018-2265-4.
Cudlín, P. et al., 2017: Drivers of treeline shift in different European mountains. *Climate Research*, **73**, 135-150, doi:https://doi.org/10.3354/cr01465.
Curtis, S. et al., 2017: Adaptation to extreme weather events in complex health and social care systems: The example of older people's services in England. *Environment and Planning C: Politics and Space*, **36**(1), 67-91, doi:10.1177/2399654417695101.
D'Amato, G. et al., 2016: Climate Change and Air Pollution: Effects on Respiratory Allergy. *Allergy Asthma & Immunology Research*, **8**(5), 391-395, doi:10.4168/aair.2016.8.5.391.
d'Amour, C. B. et al., 2016: Teleconnected food supply shocks. *Environmental Research Letters*, **11**(3), doi:10.1088/1748-9326/11/3/035007.
D'Alisa, G. and G. Kallis, 2016: A political ecology of maladaptation: Insights from a Gramscian theory of the State. *Global Environmental Change*, **38**, 230-242, doi:10.1016/j.gloenvcha.2016.03.006.

Dadson, S. J. et al., 2017: A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **473**(2199), 20160706, doi:doi:10.1098/rspa.2016.0706.
Dafermos, Y., M. Nikolaidi and G. Galanis, 2018: Climate Change, Financial Stability and Monetary Policy. *Ecological Economics*, **152**, 219-234, doi:10.1016/j.ecolecon.2018.05.011.
Dahlke, F. T., S. Wohlrab, M. Butzin and H.-O. Pörtner, 2020: Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, **369**(6499), 65-70, doi:doi/10.1126/science.aaz3658.
Daire, M.-Y. et al., 2012: Coastal Changes and Cultural Heritage (1): Assessment of the Vulnerability of the Coastal Heritage in Western France. *The Journal of Island and Coastal Archaeology*, **7**(2), 168-182, doi:10.1080/15564894.2011.652340.
Dale, M., 2021: Managing the effects of extreme sub-daily rainfall and flash floods;a practitioner's perspective. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **379**(2195), 20190550, doi:doi:10.1098/rsta.2019.0550.
Dale, M. et al., 2018: Understanding how changing rainfall may impact on urban drainage systems; lessons from projects in the UK and USA. *Water Practice and Technology*, **13**(3), 654-661, doi:10.2166/wpt.2018.069.
Daly, C. et al., 2020: Climate change adaptation planning for cultural heritage, a national scale methodology. *Journal of Cultural Heritage Management and Sustainable Development*, **ahead-of-print**(ahead-of-print), doi:10.1108/JCHMSD-04-2020-0053.
Damianidis, C. et al., 2020: Agroforestry as a sustainable land use option to reduce wildfires risk in European Mediterranean areas. *Agroforestry Systems*, **0123456789**, doi:10.1007/s10457-020-00482-w.
Damm, A. et al., 2017: Impacts of +2°C global warming on electricity demand in Europe. *Climate Services*, **7**, 12-30, doi:https://doi.org/10.1016/j.cliser.2016.07.001.
Damm, B. and A. Felderer, 2013: Impact of atmospheric warming on permafrost degradation and debris flow initiation: A case study from the eastern European Alps. *E&G Quaternary Sci. J.*, **62**(2), 136-149, doi:10.3285/eg.62.2.05.
Daniel, M. et al., 2003: Shift of the tick *Ixodes ricinus* and tick-borne encephalitis to higher altitudes in Central Europe. *European Journal of Clinical Microbiology & Infectious Diseases*, **22**(5), 327-328, doi:10.1007/s10096-003-0918-2.
Dannevig, H. and G. K. Hovelsrud, 2016: Understanding the need for adaptation in a natural resource dependent community in Northern Norway: issue salience, knowledge and values. *Climatic Change*, **135**(2), 261-275, doi:10.1007/s10584-015-1557-1.
Dannheim, J. et al., 2019: Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. *ICES Journal of Marine Science*, **107**, 223-217, doi:doi/10.1093/icesjms/fsz018.
Darmaraki, S., S. Somot, F. Sevault and P. Nabat, 2019a: Past Variability of Mediterranean Sea Marine Heatwaves. *Geophysical Research Letters*, **0**(0), doi:10.1029/2019GL082933.
Darmaraki, S. et al., 2019b: Future evolution of Marine Heatwaves in the Mediterranean Sea. *Climate Dynamics*, **53**(3), 1371-1392, doi:10.1007/s00382-019-04661-z.
Dasgupta, P., B. Great and Treasury, 2021: *Economics of Biodiversity: The Dasgupta Review*. ISBN 978-1-911680-29-1.
Daskalov, G. M. et al., 2017: Architecture of collapse: regime shift and recovery in an hierarchically structured marine ecosystem. *Global Change Biology*, **23**(4), 1486-1498, doi:doi/10.1111/gcb.13508.
Dastgerdi, A. S., M. Sargolini and I. Pierantoni, 2019: Climate Change Challenges to Existing Cultural Heritage Policy. *Sustainability*, **11**(19), 5227, doi:10.3390/su11195227.
Day Jr, J. et al., 1999: Soil accretionary dynamics, sea-level rise and the survival of wetlands in Venice Lagoon: a field and modelling approach. *Estuarine, Coastal and Shelf Science*, **49**(5), 607-628.
De'Donato, F. et al., 2018: Temporal variation in the effect of heat and the role of the Italian heat prevention plan. *Public Health*, **161**, 154-162, doi:10.1016/j.puhe.2018.03.030.
de Bruin, K. et al., 2020: Physical Climate Risks and the Financial Sector—Synthesis of Investors’ Climate Information Needs. In: *Handbook of Climate Services* [Leal Filho, W. and D. Jacob (eds.)]. Springer International Publishing, Cham, pp. 135-156. ISBN 978-3-030-36874-6 978-3-030-36875-3.
De Cian, E. et al., 2016: Alleviating inequality in climate policy costs: an integrated perspective on mitigation, damage and adaptation. *Environmental Research Letters*, **11**(7), 74015-74015, doi:10.1088/1748-9326/11/7/074015.
de Conick, H. and A. Revi, 2018: Chapter 4: Strengthening and implementing the Global Response. In: *1.5 report* [IPCC (ed.)].
de Coninck, H. et al., 2018: Strengthening and implementing the global response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. MoufoumaOkia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. 313-443.
de Graaf, I. E. M. et al., 2019: Environmental flow limits to global groundwater pumping. *Nature*, **574**(7776), 90-94, doi:10.1038/s41586-019-1594-4.

de Graaf, I. E. M. et al., 2017: A global-scale two-layer transient groundwater model: Development and application to groundwater depletion. *Advances in Water Resources*, **102**, 53-67, doi:https://doi.org/10.1016/j.advwatres.2017.01.011.
De Gregorio Hurtado, S. et al., 2015: Understanding How and Why Cities Engage with Climate Policy: An Analysis of Local Climate Action in Spain and Italy. *TeMA - Journal of Land Use, Mobility and Environment*, **0**(0 SE - ECCA 2015), doi:10.6092/1970-9870/3649.
De Mesel, I. et al., 2015: Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. *Hydrobiologia*, **756**(1), 37-50, doi:doi/10.1007/s10750-014-2157-1.
de Moel, H., J. C. J. H. Aerts and E. Koomen, 2011: Development of flood exposure in the Netherlands during the 20th and 21st century. *Global Environmental Change*, **21**(2), 620-627, doi:https://doi.org/10.1016/j.gloenvcha.2010.12.005.
de Rigo, D. et al., 2017: *Forest fire danger extremes in Europe under climate change: variability and uncertainty*. Luxembourg.
De Roo, A. et al., 2020: *Assessing the effects of water saving measures on Europe's water resources; BLUE2 project – Freshwater quantity. JRC Technical Report*. ISBN 9789276215363.
De Rosa, M., V. Bianco, F. Scarpa and L. A. Tagliafico, 2015: Historical trends and current state of heating and cooling degree days in Italy. *Energy Conversion and Management*, **90**, 323-335, doi:https://doi.org/10.1016/j.enconman.2014.11.022.
de Schipper, M. A. et al., 2021: Beach nourishment has complex implications for the future of sandy shores. *Nature Reviews Earth & Environment*, **2**(1), 70-84, doi:10.1038/s43017-020-00109-9.
de'Donato, F. et al., 2015: Changes in the effect of heat on mortality in the last 20 years in nine European cities. Results from the PHASE project. *International journal of environmental research and public health*, **12**(12), 15567-15583.
Deléglise, C. et al., 2019: A method for diagnosing summer mountain pastures' vulnerability to climate change, developed in the French alps. *Mountain Research and Development*, **39**(2), D27-D41, doi:10.1659/MRD-JOURNAL-D-18-00077.1.
Delgado, M. D. M. et al., 2020: Differences in spatial versus temporal reaction norms for spring and autumn phenological events. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(49), 31249-31258, doi:10.1073/pnas.2002713117.
Dellink, R., E. Lanzi and J. Chateau, 2019: The Sectoral and Regional Economic Consequences of Climate Change to 2060. *Environmental and Resource Economics*, **72**(2), 309-363, doi:10.1007/s10640-017-0197-5.
Demski, C. et al., 2017: Experience of extreme weather affects climate change mitigation and adaptation responses. *Climatic Change*, **140**(2), 149-164, doi:10.1007/s10584-016-1837-4.
Denechaud, C. et al., 2020: A century of fish growth in relation to climate change, population dynamics and exploitation. *Global Change Biology*, **26**(10), 5661-5678, doi:10.1111/gcb.15298 PMID - 32741054.
Deryng, D. et al., 2014: Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters*, **9**(3), doi:10.1088/1748-9326/9/3/034011.
Di Baldassarre, G. et al., 2015: Debates - Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resources Research*, **51**(6), 4770-4781, doi:10.1002/2014WR016416.
Di Baldassarre, G. et al., 2018: Water shortages worsened by reservoir effects. *Nature Sustainability*, **1**(11), 617-622, doi:10.1038/s41893-018-0159-0.
Di Giuseppe, F. et al., 2020: Fire Weather Index: the skill provided by the European Centre for Medium-Range Weather Forecasts ensemble prediction system. *Nat. Hazards Earth Syst. Sci.*, **20**(8), 2365-2378, doi:10.5194/nhess-20-2365-2020.
Di Lena, B., O. Silvestroni, V. Lanari and A. Palliotti, 2019: Climate change effects on cv. Montepulciano in some wine-growing areas of the Abruzzi region (Italy). *Theoretical and Applied Climatology*, **136**(3), 1145-1155, doi:10.1007/s00704-018-2545-y.
Di Napoli, C., F. Pappenberger and H. L. Cloke, 2018: Assessing heat-related health risk in Europe via the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, **62**(7), 1155-1165, doi:10.1007/s00484-018-1518-2.
Di Sante, F., E. Coppola and F. Giorgi, 2021: Projections of river floods in Europe using EURO-CORDEX, CMIP5 and CMIP6 simulations. *International Journal of Climatology*, **41**(5), 3203-3221, doi:10.1002/joc.7014.
Diakakis, M. et al., 2020: A systematic assessment of the effects of extreme flash floods on transportation infrastructure and circulation: The example of the 2017 Mandra flood. *International Journal of Disaster Risk Reduction*, **47**, 101542, doi:https://doi.org/10.1016/j.ijdrr.2020.101542.
Diallo, M. et al., 2021: Plant translocations in Europe and the Mediterranean: Geographical and climatic directions and distances from source to host sites. *Journal of Ecology*, **109**(6), 2296-2308, doi:https://doi.org/10.1111/1365-2745.13609.
Díaz, J. et al., 2019: Mortality attributable to high temperatures over the 2021–2050 and 2051–2100 time horizons in Spain: Adaptation and economic estimate. *Environmental Research*, **172**, 475-485, doi:https://doi.org/10.1016/j.envres.2019.02.041.

Dinca, A. I., C. Surugiu, M. Surugiu and C. Frent, 2014: Stakeholder perspectives on climate change effects on tourism activities in the northern Romanian Carpathians: Vatra Dornei resort case study. *Human Geographies*, **8**(1), 27.

Ding, Q., X. Chen, R. Hilborn and Y. Chen, 2017: Vulnerability to impacts of climate change on marine fisheries and food security. *Marine Policy*, **83**, 55-61, doi:10.1016/j.marpol.2017.05.011.

Dino, I. G. and C. Meral Akgül, 2019: Impact of climate change on the existing residential building stock in Turkey: An analysis on energy use, greenhouse gas emissions and occupant comfort. *Renewable Energy*, **141**, 828-846, doi:https://doi.org/10.1016/j.renene.2019.03.150.

Dobson, B. et al., 2020: The Spatial Dynamics of Droughts and Water Scarcity in England and Wales. *Water Resources Research*, **56**(9), e2020WR027187, doi:https://doi.org/10.1029/2020WR027187.

Dobson, B. and A. Mijic, 2020: Protecting rivers by integrating supply-wastewater infrastructure planning and coordinating operational decisions. *Environmental Research Letters*, **15**(11), 114025, doi:10.1088/1748-9326/abb050.

Dodoo, A. and L. Gustavsson, 2016: Energy use and overheating risk of Swedish multi-storey residential buildings under different climate scenarios. *Energy*, **97**, 534-548, doi:https://doi.org/10.1016/j.energy.2015.12.086.

Dolganova, I. et al., 2019: The Water Footprint of European Agricultural Imports: Hotspots in the Context of Water Scarcity. *Resources*, **8**(3), 141, doi:10.3390/resources8030141.

Doll, C. et al., 2014: Adapting rail and road networks to weather extremes: case studies for southern Germany and Austria. *Natural Hazards*, **72**(1), 63-85, doi:10.1007/s11069-013-0969-3.

Donatelli, M. et al., 2015: Climate change impact and potential adaptation strategies under alternate realizations of climate scenarios for three major crops in Europe. *Environmental Research Letters*, **10**(7), 075005, doi:10.1088/1748-9326/10/7/075005.

Doney, S. C. et al., 2012: Climate Change Impacts on Marine Ecosystems. *Annual Review of Marine Science*, **4**(1), 11-37, doi:10.1146/annurev-marine-041911-111611.

Donner, J., J. M. Müller and J. Köppel, 2015: Urban Heat: Towards Adapted German Cities? *Journal of Environmental Assessment Policy and Management*, **17**(02), 1550020, doi:10.1142/S1464333215500209.

Doran, R. et al., 2018: Consequence evaluations and moral concerns about climate change: insights from nationally representative surveys across four European countries. *Journal of Risk Research*, 1-17, doi:10.1080/13669877.2018.1473468.

Dornelas, M. et al., 2014: Assemblage Time Series Reveal Biodiversity Change but Not Systematic Loss. *Science*, **344**(6181), 296, doi:10.1126/science.1248484.

Dottori, F. et al., 2020: *Adapting to rising river flood risk in the EU under climate change*. Publications Office of the European Union, Luxembourg. ISBN 978-92-76-12946-2.

Dottori, F. et al., 2018: Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, **8**(9), 781-786, doi:10.1038/s41558-018-0257-z.

Douville, H. et al., 2021: Water Cycle Changes. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

DRMKC, 2020: INFORM Global Risk Index 2021 (release: 31 August 2020 v 0.5.0), EC Disaster Risk Management Knowledge Centre. Available at: https://drmkc.jrc.ec.europa.eu/inform-index/Portals/0/InfoRM/2021/INFORM_Risk_2021_v050.xlsx?ver=2021-09-02-170624-200
https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk/Results-and-data/moduleId/1782/id/419/controller/Admin/action/Results (accessed 2021/08/27/09:32:36).

Dubois, M. et al., 2016: Linking basin-scale connectivity, oceanography and population dynamics for the conservation and management of marine ecosystems. *Global Ecology and Biogeography*, **25**(5), 503-515, doi:doi/10.1111/geb.12431.

Duijndam, S. and P. van Beukering, 2021: Understanding public concern about climate change in Europe, 2008–2017: the influence of economic factors and right-wing populism. *Climate Policy*, **21**(3), 353-367, doi:10.1080/14693062.2020.1831431.

Dumont, B. et al., 2015: A meta-analysis of climate change effects on forage quality in grasslands: specificities of mountain and mediterranean areas. *Grass and Forage Science*, **70**(2), 239-254, doi:10.1111/gfs.12169.

Dunn, M. et al., 2017: To what extent are land resource managers preparing for high-end climate change in Scotland? *Climatic Change*, **141**(2), 181-195, doi:10.1007/s10584-016-1881-0.

Dupont, L. and V. Van Eetvelde, 2013: Assessing the potential impacts of climate change on traditional landscapes and their heritage values on the local level: Case studies in the Dender basin in Flanders, Belgium. *Land Use Policy*, **35**, 179-191, doi:10.1016/j.landusepol.2013.05.010.

Duvillard, P.-A., L. Ravanel, M. Marcer and P. Schoeneich, 2019: Recent evolution of damage to infrastructure on permafrost in the French Alps. *Regional Environmental Change*, **19**(5), 1281-1293, doi:10.1007/s10113-019-01465-z.

Dyderski, M. K., S. Paź, L. E. Frelich and A. M. Jagodziński, 2018: How much does climate change threaten European forest tree species distributions? *Global Change Biology*, **24**(3), 1150-1163, doi:10.1111/gcb.13925.

Dzebo, A., H. Janetschek, C. Brandi and G. Iacobuta, 2019: *Connections between the Paris Agreement and the 2030 Agenda: the case for policy coherence.* SEI Working Paper, Stockholm Environment Institute, Stockholm.
Dzebo, A. and J. Stripple, 2015: Transnational adaptation governance: An emerging fourth era of adaptation. *Global Environmental Change-Human and Policy Dimensions*, **35**, 423-435, doi:10.1016/j.gloenvcha.2015.10.006.
EASAC, 2019: The imperative of climate action to protect human health in Europe. Opportunities for adaptation to reduce the impacts, and for mitigation to capitalise on the benefits of decarbonisation. European Academies' Science Advisory Council, Germany.
Ebert, K., K. Ekstedt and J. Jarsjö, 2016: GIS analysis of effects of future Baltic sea level rise on the island of Gotland, Sweden. *Nat. Hazards Earth Syst. Sci.*, **16**(7), 1571-1582, doi:10.5194/nhess-16-1571-2016.
Ebi, K. L. et al., 2018: Monitoring and Evaluation Indicators for Climate Change-Related Health Impacts, Risks, Adaptation, and Resilience. *International Journal of Environmental Research and Public Health*, **15**(9), 1943.
Ebi, K. L. et al., 2021: Burning embers: synthesis of the health risks of climate change. *Environmental Research Letters*, **16**(4), 044042, doi:10.1088/1748-9326/abeadd.
ECB, 2021a: *Climate-related risk and financial stability*. ECB/ESRB Project Team on climate risk monitoring, Frankfurt, Germany. Available at: https://data.europa.eu/doi/10.2866/913118 (accessed 2021/08/17/11:22:10).
ECB, 2021b: Shining a light on climate risks: the ECB's economy-wide climate stress test. European Central Bank.
Edelenbos, J., A. Van Buuren, D. Roth and M. Winnubst, 2017: Stakeholder initiatives in flood risk management: exploring the role and impact of bottom-up initiatives in three "Room for the River' projects in the Netherlands. *Journal of Environmental Planning and Management*, **60**(1), 47-66, doi:10.1080/09640568.2016.1140025.
Edgar, G. J. et al., 2014: Global conservation outcomes depend on marine protected areas with five key features. *Nature*, **506**(7487), 216 - 220.
Edmonds, D. A., R. L. Caldwell, E. S. Brondizio and S. M. O. Siani, 2020: Coastal flooding will disproportionately impact people on river deltas. *Nature Communications*, **11**(1), 1-8, doi:10.1038/s41467-020-18531-4.
EEA, 2014: *National adaptation policy processes in European countries - 2014*. 136-136 pp. ISBN 9789292134846.
EEA, 2015: *Overview of climate change adaptation platforms in Europe*. EEA Technical report, European Environment Agency, Luxembourg, 79 pp. Available at: https://www.eea.europa.eu/publications/overview-of-climate-change-adaptation.
EEA, 2016: *Urban adaptation to climate change in Europe 2016 - Transforming cities in a changing climate*. Luxembourg, 135 pp. Available at: https://www.eea.europa.eu/publications/urban-adaptation-2016.
EEA, 2017a: *Climate change, impacts and vulnerability in Europe 2016 - An indicator-based report* [Agency, E. E. (ed.)]. EEA report, **EEA Report No 1/2017**, Luxembourh, 424 pp. Available at: https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016 (accessed 24/4/2019).
EEA, 2017b: *Climate change, impacts and vulnerability in Europe 2016 — An indicator-based report. EEA Report No 1/2017*. Luxemburg, 1-424 pp. Available at: https://www.eea.europa.eu/ds_resolveuid/31f53a5e9418419194f7f92e3cd04d3d.
EEA, 2017c: *Pricing and non-pricing measures for managing water demand in Europe* [EEA (ed.)]. 9 pp. Available at: https://www.eea.europa.eu/publications/water-management-in-europe-price.
EEA, 2018a: *Climate-Adapt, 2019, Climate-Adapt. Sharing adaptation information across Europe*. **EEA Report No 3/2018**. Available at: https://www.eea.europa.eu/publications/sharing-adaptation-information-across-europe/.
EEA, 2018b: *National climate change vulnerability and risk assessments in Europe, 2018*. European Environment Agency, 79-79 pp. Available at: https://www.eea.europa.eu/publications/national-climate-change-vulnerability-2018.
EEA, 2019a: *Adaptation challenges and opportunities for the European energy system - Building a climate-resilient low-carbon energy system*. European Envrionement Agency, Luxembourg, 122 pp. Available at: www.eea.europa.eu/publications/adaptation-in-energy-system.
EEA, 2019b: Air quality in Europe — 2019 report. European Environment Agency, Copenhagen, Denmark.
EEA, 2019c: Climate change adaptation in the agriculture sector in Europe.(04/2019), 112-112.
EEA, 2020a: *Monitoring and evaluation of national adaptation policies throughout the policy cycle*. Publications Office, LU.
EEA, 2020b: *Monitoring and evaluation of national adaptation policies throughout the policy cycle*. **06/2020**, European Envrionment Agency, Luxembourg. Available at: https://data.europa.eu/doi/10.2800/83221 (accessed 2020/10/21/08:20:40).
EEA, 2020c: *Urban adaptation in Europe: how cities and towns respond to climate change* [EEA (ed.)]. EEA Report, European Environment Agency (EEA), Luxembourg, 192 pp. Available at: https://www.eea.europa.eu/publications/urban-adaptation-in-europe.
EEA, Country Profiles — Climate-ADAPT, European Environment Agency. Available at: https://climate-adapt.eea.europa.eu/countries-regions/countries (accessed 2021/08/20/12:32:32).
EEA, 2021b: Natura 2000 data - the European network of protected sites [EEA (ed.)]. Available at: https://www.eea.europa.eu/data-and-maps/data/natura-12.
Efendić, A., 2018: The Role of Economic and Social Capital during the Floods in Bosnia and Herzegovina. In: *Crisis Governance in Bosnia and Herzegovina, Croatia and Serbia: The Study of Floods in 2014* [Džihić, V. and M. Solska (eds.)]. Peter Lang CH. ISBN 978-3-0343-2884-5 978-3-0343-2883-8 978-3-0343-2885-2 978-3-0343-2747-3.

Efremov, Y. V. and D. Y. Shulyakov, 2018: Actions for protection of infrastructure against mudflows of Western Caucasus (in the Lagonaki Highlands). In: *Debris Flows: Disasters, Risk, Forecast, Protection*. Universal, pp. 331-337. ISBN 978-5-89575-210-4.
Eigenbrod, F., P. Gonzalez, J. Dash and I. Steyl, 2015: Vulnerability of ecosystems to climate change moderated by habitat intactness. *Global Change Biology*, **21**(1), 275-286, doi:https://doi.org/10.1111/gcb.12669.
Elliott, M. et al., 2015: Force majeure: Will climate change affect our ability to attain Good Environmental Status for marine biodiversity? Viewpoint. *Marine pollution bulletin*, **95**(1), 7-27, doi:doi/10.1016/j.marpolbul.2015.03.015.
Elmhagen, B., J. Kindberg, P. Hellström and A. Angerbjörn, 2015: A boreal invasion in response to climate change? Range shifts and community effects in the borderland between forest and tundra. *AMBIO*, **44**(1), 39-50, doi:10.1007/s13280-014-0606-8.
Ercin, E., D. Chico and A. K. Chapagain, 2019: Vulnerabilities of the European Union's Economy to Hydrological Extremes Outside its Borders. *Atmosphere*, **10**(10), 593, doi:10.3390/atmos10100593.
Ercin, E., T. I. E. Veldkamp and J. Hunink, 2021: Cross-border climate vulnerabilities of the European Union to drought. *Nature Communications*, **12**(1), doi:10.1038/s41467-021-23584-0.
Erfani, T., K. Pachos and J. J. Harou, 2018: Real-Options Water Supply Planning: Multistage Scenario Trees for Adaptive and Flexible Capacity Expansion Under Probabilistic Climate Change Uncertainty. *Water Resources Research*, **54**(7), 5069-5087, doi:https://doi.org/10.1029/2017WR021803.
Esteve, P., C. Varela-Ortega and T. E. Downing, 2018: A stakeholder-based assessment of barriers to climate change adaptation in a water-scarce basin in Spain. *Regional environmental change*, **18**(8), 2505-2517.
Estrada, F., W. Botzen and R. Tol, 2017: A global economic assessment of city policies to reduce climate change impacts. *Nature Climate Change*, **7**(6), 403-+, doi:10.1038/NCLIMATE3301.
Ettinger, A. K. et al., 2020: Winter temperatures predominate in spring phenological responses to warming. *Nature Climate Change*, **10**(12), 1137-1142, doi:10.1038/s41558-020-00917-3.
European Comission, 2011: *The EU Biodiversity Strategy to 2020*. Luxembourg, 1-27 pp. ISBN 978-92-79-20762-4.
European Comission, 2012: Blue Growth opportunities for marine and maritime sustainable growth. European Commission.
European Comission, 2013a: Enhancing Europe's Natural Capital /* COM/2013/0249 final *. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0249.
European Comission, 2013b: *Guidelines on Climate Change and Natura 2000*. Brussels, 1-105 pp. Available at: https://ec.europa.eu/environment/nature/climatechange/pdf/Guidance%20document.pdf.
European Comission, 2016: Regulations (EU) 2016/2031 on protective measures against pests of plants, amending Regulations (EU) No 228/2013, (EU) No 652/2014 and (EU) No 1143/2014 of the European Parliament and of the Council and repealing Council Directives 69/46. *Official Journal of the European Union*, **317**(July), 4-103.
European Comission, 2017: *Special Eurobarometer 459*. Available at: https://ec.europa.eu/clima/sites/clima/files/support/docs/report_2017_en.pdf.
European Comission, 2018: *Evaluation of the EU Strategy on adaptation to climate change*. Available at: https://ec.europa.eu/info/sites/default/files/swd_evaluation-of-eu-adaptation-strategy_en.pdf.
European Comission, 2019: GHSL - Global Human Settlement Layer. *GHSL Data Package 2019 report* [JointResearchCentre (ed.)], Luxembourgh. Available at: https://ghsl.jrc.ec.europa.eu/download.php?ds=pop.
European Comission, 2020: EU biodiversity strategy for 2030.
European Comission, 2021a: *Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change* [Commission, E. (ed.)]. Communication from the Comission to the European Parliament, the Council, the European Economic and Social Comittee and the Committee of the regions, **COM(2021) 82 final**, European Commission, Brussels. Available at: https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/eu_strategy_2021.pdf.
European Comission, 2021b: New EU Forest Strategy for 2030. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0572.
European Social Survey, 2020: ESS Round 8: European Social Survey Round 8 Data (2016). Data file edition 2.2., Norwegian Centre for Research Data, Norway. Available at: https://www.europeansocialsurvey.org/data/download.html?r=8 (accessed 2021/08/27/09:46:39).
Eurostat, 2016: *Urban Europe — statistics on cities, towns and suburbs* [M., K., T. Brandmüller, I. Lupu, A. Önnerfors, L. Corselli-Nordblad, C. Coyette, A. Johansson, H. Strandell and P. Wolff (eds.)]. Eurostat, Luxembourg. Available at: https://ec.europa.eu/eurostat/documents/3217494/7596823/KS-01-16-691-EN-N.pdf/0abf140c-ccc7-4a7f-b236-682effcde10f.
Eurostat, 2020: Gross value added at current basic prices, 2009 and 2019 (% share of total gross value added). *EUROSTAT Statistics explained* [Eurostat (ed.)], EUROSTAT. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Gross_value_added_at_current_basic_prices,_2009_and_2019_(%25_share_of_total_gross_value_added).png#filelinks.
Ewert, F. et al., 2015: Crop modelling for integrated assessment of risk to food production from climate change. *Environmental Modelling and Software*, **72**, 287-303, doi:10.1016/j.envsoft.2014.12.003.
Eyring, V. et al., 2021: Human Influence on the Climate System. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate*

Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Ezbakhe, F., R. Giné-Garriga and A. Pérez-Foguet, 2019: Leaving no one behind: Evaluating access to water, sanitation and hygiene for vulnerable and marginalized groups. *Science of The Total Environment*, **683**, 537-546, doi:10.1016/j.scitotenv.2019.05.207.

Faillettaz, R., G. Beaugrand, E. Goberville and R. R. Kirby, 2019: Atlantic Multidecadal Oscillations drive the basin-scale distribution of Atlantic bluefin tuna. *Science Advances*, **5**(1), 2-10, doi:10.1126/sciadv.aar6993.

Falaschi, M., R. Manenti, W. Thuiller and G. F. Ficetola, 2019: Continental-scale determinants of population trends in European amphibians and reptiles. *Global Change Biology*, **25**(10), 3504-3515, doi:https://doi.org/10.1111/gcb.14739.

Falk, M. and L. Vanat, 2016: Gains from investments in snowmaking facilities. *Ecological Economics*, **130**, 339-349, doi:10.1016/j.ecolecon.2016.08.003.

Fanta, V., M. Šálek and P. Sklenicka, 2019: How long do floods throughout the millennium remain in the collective memory? *Nature Communications*, **10**(1), 1105, doi:10.1038/s41467-019-09102-3.

Fanzo, J., C. Davis, R. McLaren and J. Choufani, 2018: The effect of climate change across food systems: Implications for nutrition outcomes. *Global Food Security-Agriculture Policy Economics and Environment*, **18**, 12-19, doi:10.1016/j.gfs.2018.06.001.

FAOSTAT, 2019: FAO Online Database. Food and Agriculture Organization of the United Nations,, FAO, Rome. Available at: http://faostat.fao.org.

Fargeon, H. et al., 2020: Projections of fire danger under climate change over France: where do the greatest uncertainties lie? *Climatic Change*, **160**(3), 479-493, doi:10.1007/s10584-019-02629-w.

Fatorić, S. and R. Biesbroek, 2020: Adapting cultural heritage to climate change impacts in the Netherlands: barriers, interdependencies, and strategies for overcoming them. *Climatic Change*, **162**(2), 301-320, doi:10.1007/s10584-020-02831-1.

Fatorić, S. and E. Seekamp, 2017: Are cultural heritage and resources threatened by climate change? A systematic literature review. *Climatic Change*, **142**, 227-254, doi:https://doi.org/10.1007/s10584-017-1929-9.

Fellmann, T., S. Helaine and O. Nekhay, 2014: Harvest failures, temporary export restrictions and global food security: the example of limited grain exports from Russia, Ukraine and Kazakhstan. *Food Security*, **6**(5), 727-742, doi:10.1007/s12571-014-0372-2.

Felton, A. et al., 2016: How climate change adaptation and mitigation strategies can threaten or enhance the biodiversity of production forests: Insights from Sweden. *Biological Conservation*, **194**, 11-20, doi:10.1016/j.biocon.2015.11.030.

Feodoroff, P., 2021: Indigenous Female Bodies as Indicators of Change. In: *2021 Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change* [Mustonen, T., S. Harper, M. Rivera-Ferre, J. C. Postigo, A. Ayansina, T. Benjaminsen, R. Morgan and A. Okem (eds.)]. Snowchange Cooperative, Kontiolahti, Finland.

Ferdinand, M., 2018: Subnational climate justice for the French Outre-mer: postcolonial politics and geography of an epistemic shift. *Island Studies Journal*, **13**(1), 119-134.

Feridun, M. and H. Güngör, 2020: Climate-Related Prudential Risks in the Banking Sector: A Review of the Emerging Regulatory and Supervisory Practices. *Sustainability*, **12**(13), 5325, doi:10.3390/su12135325.

Fernandes, J. A. et al., 2017: Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. *Fish and Fisheries*, **18**(3), 389-411, doi:10.1111/faf.12183.

Fernandes, P. M. et al., 2013: Prescribed burning in southern Europe: developing fire management in a dynamic landscape. *Frontiers in Ecology and the Environment*, **11**(s1), e4-e14, doi:https://doi.org/10.1890/120298.

Fernandez-Anez, N. et al., 2021: Current Wildland Fire Patterns and Challenges in Europe: A Synthesis of National Perspectives. *Air, Soil and Water Research*, **14**, 11786221211028185, doi:10.1177/11786221211028185.

Fernández-Manjarrés, J. et al., 2018: Forest Adaptation to Climate Change along Steep Ecological Gradients: The Case of the Mediterranean-Temperate Transition in South-Western Europe. *Sustainability*, **10**(9), 3065, doi:10.3390/su10093065.

Fernandez Milan, B. and F. Creutzig, 2015: Reducing urban heat wave risk in the 21st century. *Current Opinion in Environmental Sustainability*, **14**, 221-231, doi:https://doi.org/10.1016/j.cosust.2015.08.002.

Ferranti, E. et al., 2018: The hottest July day on the railway network: insights and thoughts for the future. *Meteorological Applications*, **25**(2), 195-208, doi:10.1002/met.1681.

Ferretto, A. et al., 2019: Potential carbon loss from Scottish peatlands under climate change. *Regional Environmental Change*, **19**(7), 2101-2111, doi:10.1007/s10113-019-01550-3.

Feyen, L. et al., 2020: *JRC Science for Policy Report JRC PESETA IV final report*. ISBN 978-92-76-18123-1.

Fielding, A. J., 2011: The impacts of environmental change on UK internal migration. *Global Environmental Change*, **21**, S121-S130, doi:10.1016/j.gloenvcha.2011.08.003.

Fielding, J. L., 2018: Flood risk and inequalities between ethnic groups in the floodplains of England and Wales. *Disasters*, **42**(1), 101-123, doi:10.1111/disa.12230.

Figueiredo, R., P. Nunes, M. J. N. O. Panão and M. C. Brito, 2020: Country residential building stock electricity demand in future climate – Portuguese case study. *Energy and Buildings*, **209**, 109694, doi:https://doi.org/10.1016/j.enbuild.2019.109694.
Filijović, M. and I. Đorđević, 2014: Impact of "May" floods on state of human security in the Republic of Serbia. *Bezbednost, Beograd*, **56(3)**, 115-128.
Filipchuk, A., B. Moiseev, N. Malysheva and V. Strakhov, 2018: Russian forests: A new approach to the assessment of carbon stocks and sequestration capacity. *Environmental Development*, **26**, 68-75, doi:https://doi.org/10.1016/j.envdev.2018.03.002.
Fischer, L. B. and M. Pfaffermayr, 2018: The more the merrier? Migration and convergence among European regions. *Regional Science and Urban Economics*, **72**, 103-114, doi:10.1016/j.regsciurbeco.2017.04.007.
Follos, F. et al., 2020: The evolution of minimum mortality temperatures as an indicator of heat adaptation: The cases of Madrid and Seville (Spain). *Science of The Total Environment*, **747**, 141259, doi:https://doi.org/10.1016/j.scitotenv.2020.141259.
Fontana, G., A. Toreti, A. Ceglar and G. De Sanctis, 2015: Early heat waves over Italy and their impacts on durum wheat yields. *Nat. Hazards Earth Syst. Sci.*, **15**(7), 1631-1637, doi:10.5194/nhess-15-1631-2015.
Forbes, B. C. et al., 2016: Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. *Biology Letters*, **12**(11), 20160466, doi:10.1098/rsbl.2016.0466.
Fortibuoni, T. et al., 2015: Climate impact on Italian fisheries (Mediterranean Sea). *Regional Environmental Change*, **15**(5), 931-937, doi:10.1007/s10113-015-0781-6.
Forzieri, G. et al., 2018: Escalating impacts of climate extremes on critical infrastructures in Europe. *Global Environmental Change*, **48**(November 2017), 97-107, doi:10.1016/j.gloenvcha.2017.11.007.
Forzieri, G., A. Cescatti, F. B. e Silva and L. Feyen, 2017: Increasing risk over time of weather-related hazards to the European population: a data-driven prognostic study. *The Lancet Planetary Health*, **1**(5), e200-e208, doi:10.1016/S2542-5196(17)30082-7.
Forzieri, G. et al., 2014: Ensemble projections of future streamflow droughts in Europe. *Hydrol. Earth Syst. Sci.*, **18**(1), 85-108, doi:10.5194/hess-18-85-2014.
Forzieri, G. et al., 2016: Multi-hazard assessment in Europe under climate change. *Climatic Change*, **137**(1), 105-119, doi:10.1007/s10584-016-1661-x.
Forzieri, G. et al., 2021: Emergent vulnerability to climate-driven disturbances in European forests. *Nature Communications*, **12**(1), 1081, doi:10.1038/s41467-021-21399-7.
Fosas, D. et al., 2018: Mitigation versus adaptation: Does insulating dwellings increase overheating risk? *Building and Environment*, **143**, 740-759, doi:https://doi.org/10.1016/j.buildenv.2018.07.033.
Fountoulakis et al., 2016: Climate change but not unemployment explains the changing suicidality in Thessaloniki Greece (2000-2012). *Journal of Affective Disorders*, **193**, 331–338.
Fourcade, Y., S. Åström and E. Öckinger, 2019: Climate and land-cover change alter bumblebee species richness and community composition in subalpine areas. *Biodiversity and Conservation*, **28**(3), 639-653, doi:10.1007/s10531-018-1680-1.
Fowler, H. J. et al., 2021: Towards advancing scientific knowledge of climate change impacts on short-duration rainfall extremes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **379**(2195), 20190542, doi:10.1098/rsta.2019.0542.
Fox-Kemper, B. et al., 2021: Ocean, Cryosphere and Sea Level Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Frantzeskaki, N. et al., 2019: Transition pathways to sustainability in greater than 2°C climate futures of Europe. *Regional Environmental Change*, **19**(3), 777-789, doi:10.1007/s10113-019-01475-x.
Franzén, M. and E. Öckinger, 2012: Climate-driven changes in pollinator assemblages during the last 60 years in an Arctic mountain region in Northern Scandinavia. *Journal of Insect Conservation*, **16**(2), 227-238, doi:10.1007/s10841-011-9410-y.
Fraschetti, S. et al., 2018: Light and Shade in Marine Conservation Across European and Contiguous Seas.
Frederikse, T. et al., 2020: The causes of sea-level rise since 1900. *Nature*, **584**(7821), 393-397.
Free, C. M. et al., 2019: Impacts of historical warming on marine fisheries production. *Science*, **363**(6430), 979-983, doi:doi/10.1126/science.aau1758.
Froese, R. et al., 2018: Status and rebuilding of European fisheries. *Marine Policy*, **93**, 159-170, doi:10.1016/j.marpol.2018.04.018.
Frolov, A. V. et al., 2014: *Second Roshydromet Assessment Report on Climate Change and its consequences in Russian Federation* [Yasukevich, V. V., V. A. Govorkova, I. A. Korneva, T. V. Pavlova and E. N. Popova (eds.)]. Roshydromet, Roshydromet, Obninsk, Russia, 1004 pp. Available at: http://downloads.igce.ru/publications/OD_2_2014/v2014/htm/1.htm.
Fronzek, S. et al., 2019: Determining sectoral and regional sensitivity to climate and socio-economic change in Europe using impact response surfaces. *Regional Environmental Change*, **19**(3), 679-693, doi:10.1007/s10113-018-1421-8.

Fuchs, R., C. Brown and M. Rounsevell, 2020: Europe's Green Deal offshores environmental damage to other nations. *Nature*, **586**, 671-673, doi:https://doi.org/10.1038/d41586-020-02991-1.

Fuhrer, J., P. Smith and A. Gobiet, 2014: Implications of climate change scenarios for agriculture in alpine regions - A case study in the Swiss Rhone catchment. *Science of the Total Environment*, **493**, 1232-1241, doi:10.1016/j.scitotenv.2013.06.038.

Fünfgeld, H., K. Lonsdale and K. Bosomworth, 2019: Beyond the tools: supporting adaptation when organisational resources and capacities are in short supply. *Climatic Change*, **153**(4), 625-641, doi:10.1007/s10584-018-2238-7.

Furberg, M., B. Evengård and M. Nilsson, 2011: Facing the limit of resilience: perceptions of climate change among reindeer herding Sami in Sweden. *Global Health Action*, **4**(1), 8417, doi:10.3402/gha.v4i0.8417.

Gädeke, A. et al., 2021: Climate change reduces winter overland travel across the Pan-Arctic even under low-end global warming scenarios. *Environmental Research Letters*, **16**(2), 024049, doi:10.1088/1748-9326/abdcf2.

Gallego-Sala, A. V. et al., 2010: Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain. *Climate Research*, **45**, 151-162.

Galli, G., C. Solidoro and T. Lovato, 2017: Marine Heat Waves Hazard 3D Maps and the Risk for Low Motility Organisms in a Warming Mediterranean Sea. *Frontiers in Marine Science*, **4**(136), doi:10.3389/fmars.2017.00136.

García-León, D. et al., 2021: Current and projected regional economic impacts of heatwaves in Europe. *Nature Communications*.

Garcia-Mozo, H., J. Oteros and C. Galan, 2015: Phenological changes in olive (*Ola europaea* L.) reproductive cycle in southern Spain due to climate change. *Annals of Agricultural and Environmental Medicine*, **22**(3), 421-428, doi:10.5604/12321966.1167706.

García Molinos, J. et al., 2016: Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, **6**(1), 83-88, doi:10.1038/nclimate2769.

Gariano, S. L. and F. Guzzetti, 2016: Landslides in a changing climate. *Earth-Science Reviews*, **162**, 227-252, doi:https://doi.org/10.1016/j.earscirev.2016.08.011.

Garnier, M. and I. Holman, 2019: Critical Review of Adaptation Measures to Reduce the Vulnerability of European Drinking Water Resources to the Pressures of Climate Change. *Environmental Management*, **64**(2), 138-153, doi:10.1007/s00267-019-01184-5.

Garonna, I. et al., 2014: Strong contribution of autumn phenology to changes in satellite-derived growing season length estimates across Europe (1982–2011). *Global Change Biology*, **20**(11), 3457-3470, doi:https://doi.org/10.1111/gcb.12625.

Garrabou, J. et al., 2019: Collaborative Database to Track Mass Mortality Events in the Mediterranean Sea. *Frontiers in Marine Science*, **6**, 2775, doi:doi/10.3389/fmars.2019.00707.

Garrote, L. et al., 2015: Quantitative Assessment of Climate Change Vulnerability of Irrigation Demands in Mediterranean Europe. *Water Resources Management*, **29**(2), 325-338, doi:10.1007/s11269-014-0736-6.

Gasbarro, F., T. Daddi and F. Iraldo, 2019: The Role of Past Experience with a Single Climate Physical Risk in Adaptation Response to Multiple Climate Physical Risks: A Multiple Case Study of Italian Companies. *Journal of Management and Sustainability*, **9**(2), 162, doi:10.5539/jms.v9n2p162.

Gasbarro, F., F. Iraldo and T. Daddi, 2017: The drivers of multinational enterprises' climate change strategies: A quantitative study on climate-related risks and opportunities. *Journal of Cleaner Production*, **160**, 8-26, doi:10.1016/j.jclepro.2017.03.018.

Gasbarro, F. and J. Pinkse, 2016: Corporate Adaptation Behaviour to Deal With Climate Change: The Influence of Firm-Specific Interpretations of Physical Climate Impacts. *Corporate Social Responsibility and Environmental Management*, **23**(3), 179-192, doi:10.1002/csr.1374.

Gasbarro, F., F. Rizzi and M. Frey, 2016: Adaptation Measures of Energy and Utility Companies to Cope with Water Scarcity Induced by Climate Change. *Business Strategy and the Environment*, **25**(1), 54-72, doi:https://doi.org/10.1002/bse.1857.

Gascon, M. et al., 2015: Mental health benefits of long-term exposure to residential green and blue spaces: A systematic review. *International Journal of Environmental Research and Public Health*, **12**(4), 4354-4379, doi:10.3390/ijerph120404354.

Gasparrini, A. et al., 2017: Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health*, **1**(9), e360-e367, doi:https://doi.org/10.1016/S2542-5196(17)30156-0.

Gaudard, L., M. Gilli and F. Romerio, 2013: Climate Change Impacts on Hydropower Management. *Water Resources Management*, **27**(15), 5143-5156, doi:10.1007/s11269-013-0458-1.

Gauly, M. and S. Ammer, 2020: Challenges for dairy cow production systems arising from climate changes. *Animal*, **14**(S1), S196-S203, doi:10.1017/S1751731119003239.

Gauly, M. et al., 2013: Future consequences and challenges for dairy cow production systems arising from climate change in Central Europe – a review. *animal*, **7**(5), 843-859, doi:10.1017/S1751731112002352.

Gaupp, F., J. Hall, S. Hochrainer-Stigler and S. Dadson, 2020: Changing risks of simultaneous global breadbasket failure. *Nature Climate Change*, **10**(1), 54-57, doi:10.1038/s41558-019-0600-z.

Gaupp, F. et al., 2017: Dependency of Crop Production between Global Breadbaskets: A Copula Approach for the Assessment of Global and Regional Risk Pools: Dependency of Crop Production between Global Breadbaskets. *Risk Analysis*, **37**(11), 2212-2228, doi:10.1111/risa.12761.

Gaüzère, P., F. Jiguet and V. Devictor, 2016: Can protected areas mitigate the impacts of climate change on bird's species and communities? *Diversity and Distributions*, **22**(6), 625-637, doi:10.1111/ddi.12426.
Gedan, K. B. et al., 2010: The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change*, **106**(1), 7-29, doi:10.1007/s10584-010-0003-7.
Geels, C. et al., 2015: Future Premature Mortality Due to O-3, Secondary Inorganic Aerosols and Primary PM in Europe - Sensitivity to Changes in Climate, Anthropogenic Emissions, Population and Building Stock. *International Journal of Environmental Research and Public Health*, **12**(3), 2837-2869, doi:10.3390/ijerph120302837.
Gemenne, F., 2011: Why the numbers don't add up: A review of estimates and predictions of people displaced by environmental changes. *Global Environmental Change-Human and Policy Dimensions*, **21**, S41-S49, doi:10.1016/j.gloenvcha.2011.09.005.
Gemenne, F. and J. Blocher, 2017: How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *The Geographical Journal*, **183**(4), 336-347.
Geneletti, D. and L. Zardo, 2016: Ecosystem-based adaptation in cities: An analysis of European urban climate adaptation plans. *Land Use Policy*, **50**, 38-47, doi:https://doi.org/10.1016/j.landusepol.2015.09.003.
Georgopoulou, E. et al., 2015: A methodological framework and tool for assessing the climate change related risks in the banking sector. *Journal of Environmental Planning and Management*, **58**(5), 874-897, doi:10.1080/09640568.2014.899489.
Germanwatch, 2020: Global Climate Risk Index 2020. *germanwatch.org*.
Gerveni, M., A. Fernandes Tomon Avelino and S. Dall'erba, 2020: Drivers of Water Use in the Agricultural Sector of the European Union 27. *Environmental Science & Technology*, **54**(15), 9191-9199, doi:10.1021/acs.est.9b06662.
Ghizzi, L. G. et al., 2018: Effects of functional oils on ruminal fermentation, rectal temperature, and performance of dairy cows under high temperature humidity index environment. *Animal Feed Science and Technology*, **246**(October), 158-166, doi:10.1016/j.anifeedsci.2018.10.009.
Gill, A. B. et al., 2018: Implications for the marine environment of energy extraction in the sea. In: *Offshore Energy and Marine Planning* [Yates, K. L. and C. J. A. Bradshaw (eds.)]. Routledge Taylor and Francis Group, London and New York, pp. 132-169.
Gillingham, P. K. et al., 2015: The effectiveness of protected areas in the conservation of species with changing geographical ranges. *Biological Journal of the Linnean Society*, **115**(3), 707-717, doi:10.1111/bij.12506.
Gobiet, A. et al., 2014: 21st century climate change in the European Alps—A review. *Science of The Total Environment*, **493**, 1138-1151, doi:10.1016/j.scitotenv.2013.07.050.
Goderniaux, P. et al., 2015: Uncertainty of climate change impact on groundwater reserves – Application to a chalk aquifer. *Journal of Hydrology*, **528**, 108-121, doi:https://doi.org/10.1016/j.jhydrol.2015.06.018.
Goldberg, D. S., I. v. Rijn, M. Kiflawi and J. Belmaker, 2019: Decreases in length at maturation of Mediterranean fishes associated with higher sea temperatures. *ICES Journal of Marine Science*, **76**(4), 946-959, doi:10.1093/icesjms/fsz011.
Goldstein, A., W. R. Turner, J. Gladstone and D. G. Hole, 2019: The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, **9**(1), 18-25, doi:10.1038/s41558-018-0340-5.
Golosov, V. et al., 2018: Assessment of soil erosion rate trends in two agricultural regions of European Russia for the last 60 years. *Journal of Soils and Sediments*, **18**(12), 3388-3403, doi:10.1007/s11368-018-2032-1.
Gordillo, F. J. L. et al., 2016: Effects of simultaneous increase in temperature and ocean acidification on biochemical composition and photosynthetic performance of common macroalgae from Kongsfjorden (Svalbard). *Polar Biology*, **39**(11), 1993--2007, doi:10.1007/s00300-016-1897-y.
Gormley, K. S. G. et al., 2015: Adaptive management, international co-operation and planning for marine conservation hotspots in a changing climate. *Marine Policy*, **53**, 54-66, doi:doi/10.1016/j.marpol.2014.11.017.
Gosling, S. N. et al., 2018: *PESETA III: climate change impacts on labour productivity*. ISBN 978-92-79-96912-6.
Grafakos, S. et al., 2020: Integration of mitigation and adaptation in urban climate change action plans in Europe: A systematic assessment. *Renewable and Sustainable Energy Reviews*, **121**, 109623, doi:https://doi.org/10.1016/j.rser.2019.109623.
Graham, E., J. Humbly and T. Dawson, 2017: Scotland's eroding heritage: A collaborative response to the impact of climate change. doi:10.17863/CAM.23645.
Gralepois, M. et al., 2016: Is flood defense changing in nature? Shifts in the flood defense strategy in six European countries. *Ecology and Society*, **21**(4).
Grantham Research Institute, 2021: Climate Change Laws of the World.
Green, J. K. et al., 2019: Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature*, **565**(7740), 476-479, doi:10.1038/s41586-018-0848-x.
Greene, G., S. Paranjothy and S. Palmer, 2015: Resilience and Vulnerability to the Psychological Harm From Flooding: The Role of Social Cohesion. *American Journal of Public Health*, **105**(9), 1792-1795, doi:10.2105/AJPH.2015.302709.
Greve, P. et al., 2018: Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability*, **1**(9), 486-494, doi:10.1038/s41893-018-0134-9.
Grillakis, M., A. Koutroulis and I. Tsanis, 2016: The 2°C global warming effect on summer European tourism through different indices. *International Journal of Biometeorology*, **60**(8), 1205-1215, doi:10.1007/s00484-015-1115-6.

Grillakis, M. G., 2019: Increase in severe and extreme soil moisture droughts for Europe under climate change. *Science of the Total Environment*, **660**, 1245-1255, doi:10.1016/j.scitotenv.2019.01.001.
Grizzetti, B. et al., 2017: Human pressures and ecological status of European rivers. *Scientific Reports*, **7**(1), 205, doi:10.1038/s41598-017-00324-3.
Groundstroem, F. and S. Juhola, 2019: A framework for identifying cross-border impacts of climate change on the energy sector,. *Environment Systems and Decisions*, **39**(1), 3-15.
Guerra, C. A., M. J. Metzger, J. Maes and T. Pinto-Correia, 2016: Policy impacts on regulating ecosystem services: looking at the implications of 60 years of landscape change on soil erosion prevention in a Mediterranean silvo-pastoral system. *Landscape Ecology*, **31**(2), 271-290, doi:10.1007/s10980-015-0241-1.
Guerreiro, S. et al., 2018: Future heat-waves, droughts and floods in 571 European cities. *Environmental Research Letters*, **13**(3), doi:10.1088/1748-9326/aaaad3.
Günther, A. et al., 2020: Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature Communications*, **11**(1), 1644, doi:10.1038/s41467-020-15499-z.
Guo, Y. et al., 2018: Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLoS medicine*, **15**(7), e1002629.
Gutiérrez, C. et al., 2020: Future evolution of surface solar radiation and photovoltaic potential in Europe: investigating the role of aerosols. *Environmental Research Letters*, **15**, 034035, doi:10.1088/1748-9326/ab6666.
Gutiérrez, J. M. et al., 2021: Atlas. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Haasnoot, M. et al., 2020a: Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, **20**(2), 1-5, doi:doi/10.1007/s10113-020-01623-8.
Haasnoot, M. et al., 2020b: Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environmental Research Letters*, **15**(3), 034007, doi:10.1088/1748-9326/ab666c.
Haasnoot, M., J. Kwakkel, W. Walker and J. ter Maat, 2013: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change-Human and Policy Dimensions*, **23**(2), 485-498, doi:10.1016/j.gloenvcha.2012.12.006.
Haasnoot, M., J. Lawrence and A. K. Magnan, 2021a: Pathways to coastal retreat. *Science*, **372**(6548), 1287, doi:10.1126/science.abi6594.
Haasnoot, M., S. van 't Klooster and J. van Alphen, 2018: Designing a monitoring system to detect signals to adapt to uncertain climate change. *Global Environmental Change*, **52**, 273-285, doi:https://doi.org/10.1016/j.gloenvcha.2018.08.003.
Haasnoot, M. et al., 2019: Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. *Environmental Research Communications*.
Haasnoot, M. et al., 2021b: Long-term sea-level rise necessitates a commitment to adaptation: a first order assessment. *Climate Risk Management*.
Habel, J., M. Samways and T. Schmitt, 2019: Mitigating the precipitous decline of terrestrial European insects: Requirements for a new strategy. *Biodiversity and Conservation*, **28**(6), 1343-1360, doi:10.1007/s10531-019-01741-8.
Haer, T., W. J. W. Botzen and J. C. J. H. Aerts, 2019: Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach. *Environmental Research Letters*, **14**(4), 44022-44022, doi:10.1088/1748-9326/ab0770.
Haer, T., T. G. Husby, W. J. W. Botzen and J. C. J. H. Aerts, 2020: The safe development paradox: An agent-based model for flood risk under climate change in the European Union. *Global Environmental Change*, **60**, 102009, doi:10.1016/j.gloenvcha.2019.102009.
Hagenlocher, M. et al., 2019: Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda. *Environmental Research Letters*, **14**(8), 083002, doi:10.1088/1748-9326/ab225d.
Halkos, G., A. Skouloudis, C. Malesios and K. Evangelinos, 2018: Bouncing Back from Extreme Weather Events: Some Preliminary Findings on Resilience Barriers Facing Small and Medium-Sized Enterprises. *Business Strategy and the Environment*, **27**(4), 547-559, doi:10.1002/bse.2019.
Hall, C. M., T. Baird, M. James and Y. Ram, 2016: Climate change and cultural heritage: conservation and heritage tourism in the Anthropocene. *Journal of Heritage Tourism*, **11**(1), 10-24, doi:10.1080/1743873X.2015.1082573.
Hall, J. W., H. Harvey and L. J. Manning, 2019: Adaptation thresholds and pathways for tidal flood risk management in London. *Climate Risk Management*, **24**, 42-58, doi:https://doi.org/10.1016/j.crm.2019.04.001.
Hallegatte, S. et al., 2016: *Shock waves: managing the impacts of climate change on poverty*. Climate Change and Development Series, World Bank, Washington DC. Available at: doi:10.1596/978-1-4648-0673-5.
Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**(4), 250-256, doi:10.1038/nclimate3253.

Halupka, L. and K. Halupka, 2017: The effect of climate change on the duration of avian breeding seasons: a meta-analysis. *Proceedings of the Royal Society B: Biological Sciences*, **284**(1867), 20171710, doi:doi:10.1098/rspb.2017.1710.
Hamdy, M., S. Carlucci, P.-J. Hoes and J. L. M. Hensen, 2017: The impact of climate change on the overheating risk in dwellings—A Dutch case study. *Building and Environment*, **122**, 307-323, doi:https://doi.org/10.1016/j.buildenv.2017.06.031.
Hamidov, A. et al., 2018: Impacts of climate change adaptation options on soil functions: A review of European case-studies. *Land Degrad Dev*, **29**(8), 2378-2389, doi:10.1002/ldr.3006.
Hamon, K. G. et al., 2021: Future Socio-political Scenarios for Aquatic Resources in Europe: An Operationalized Framework for Marine Fisheries Projections. *Frontiers in Marine Science*, **8**(March), 1-21, doi:10.3389/fmars.2021.578516.
Handisyde, N., T. C. Telfer and L. G. Ross, 2017: Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish and Fisheries*, **18**(3), 466-488, doi:10.1111/faf.12186.
Hanger, S., C. Haug, T. Lung and L. Bouwer, 2015: Mainstreaming climate change in regional development policy in Europe: five insights from the 2007-2013 programming period. *Regional Environmental Change*, **15**(6), 973-985, doi:10.1007/s10113-013-0549-9.
Hanger, S. et al., 2018: Insurance, Public Assistance, and Household Flood Risk Reduction: A Comparative Study of Austria, England, and Romania. *Risk Analysis*, **38**(4), 680-693, doi:10.1111/risa.12881.
Hanna, E. G. and P. W. Tait, 2015: Limitations to Thermoregulation and Acclimatization Challenge Human Adaptation to Global Warming. *International journal of environmental research and public health*, **12**(7), 8034-8074, doi:10.3390/ijerph120708034.
Hannah, L. et al., 2013: Climate change, wine, and conservation. *Proceedings of the National Academy of Sciences*, **110**(17), 6907-6912, doi:10.1073/pnas.1210127110.
Hansen, B. B. et al., 2014: Warmer and wetter winters: characteristics and implications of an extreme weather event in the High Arctic. *Environmental Research Letters*, **9**(11), 114021, doi:10.1088/1748-9326/9/11/114021.
Hao, Z., F. Hao, V. P. Singh and X. Zhang, 2018: Changes in the severity of compound drought and hot extremes over global land areas. *Environmental Research Letters*, **13**(12), 124022, doi:10.1088/1748-9326/aaee96.
Harkin, D. et al., 2020: Impacts of climate change on cultural heritage. *MCCIP Science Review 2020*, 26-pages, doi:10.14465/2020.ARC26.CHE.
Harman, B. P., S. Heyenga, B. M. Taylor and C. S. Fletcher, 2015: Global Lessons for Adapting Coastal Communities to Protect against Storm Surge Inundation. *Journal of Coastal Research*, **31**(4), 790-801, doi:10.2112/JCOASTRES-D-13-00095.1.
Harris, J., N. Rodenhouse and R. Holmes, 2019: Decline in beetle abundance and diversity in an intact temperate forest linked to climate warming. *Biological Conservation*, **240**, doi:10.1016/j.biocon.2019.108219.
Harrison, P. A. et al., 2019: Differences between low-end and high-end climate change impacts in Europe across multiple sectors. *Regional Environmental Change*, **16**, 695-709, doi:10.1007/s10113-018-1352-4.
Harrison, P. A., R. W. Dunford, I. P. Holman and M. D. A. Rounsevell, 2016: Climate change impact modelling needs to include cross-sectoral interactions. *Nature Climate Change*, **6**(9), 885-+, doi:10.1038/nclimate3039.
Harte, M., R. Tiller, G. Kailis and M. Burden, 2019: Countering a climate of instability: the future of relative stability under the Common Fisheries Policy. *ICES Journal of Marine Science*, **76**(7), 1951-1958, doi:10.1093/icesjms/fsz109.
Hartmann, T. and T. Spit, 2016: Legitimizing differentiated flood protection levels – Consequences of the European flood risk management plan. *Environmental Science & Policy*, **55**, 361-367, doi:https://doi.org/10.1016/j.envsci.2015.08.013.
Haugen, A. and J. Mattsson, 2011: Preparations for climate change's influences on cultural heritage. *International Journal of Climate Change Strategies and Management*, **3**(4), 386-401, doi:10.1108/17568691111175678.
Hausner, V. H., S. Engen, C. Brattland and P. Fauchald, 2020: Sámi knowledge and ecosystem-based adaptation strategies for managing pastures under threat from multiple land uses. *Journal of Applied Ecology*, **57**(9), 1656-1665, doi:10.1111/1365-2664.13559.
Haussig, J. et al., 2018: Early start of the West Nile fever transmission season 2018 in Europe. *Eurosurveillance*, **23**(32), 7-12, doi:10.2807/1560-7917.ES.2018.23.32.1800428.
Hayashi, N., 2017: The human dimension of climate change research in Greenland: Towards a new form of knowledge generation. *Low Temperature Science*, **75**, 131-141, doi:10.14943/lowtemsci.75.131.
Hayes, K. and B. Poland, 2018: Addressing Mental Health in a Changing Climate: Incorporating Mental Health Indicators into Climate Change and Health Vulnerability and Adaptation Assessments. *International Journal of Environmental Research and Public Health*, **15**(9), 1806.
Hazarika, R. et al., 2021: Multi-actor perspectives on afforestation and reforestation strategies in Central Europe under climate change. *Annals of Forest Science*, **78**(3), 60, doi:10.1007/s13595-021-01044-5.
Heathcote, J., H. Fluck and M. Wiggins, 2017: Predicting and Adapting to Climate Change: Challenges for the Historic Environment. *The Historic Environment: Policy & Practice*, **8**(2), 89-100, doi:10.1080/17567505.2017.1317071.
Hedlund, J., S. Fick, H. Carlsen and M. Benzie, 2018: Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk. *Global Environmental Change-Human and Policy Dimensions*, **52**, 75-85, doi:10.1016/j.gloenvcha.2018.04.006.

Heidrich, O. et al., 2016: National climate policies across Europe and their impacts on cities strategies. *Journal of Environmental Management*, **168**, 36-45, doi:https://doi.org/10.1016/j.jenvman.2015.11.043.
Heikkinen, M. et al., 2020a: Transnational municipal networks and climate change adaptation: A study of 377 cities. *Journal of Cleaner Production*, **257**, 120474, doi:https://doi.org/10.1016/j.jclepro.2020.120474.
Heikkinen, R. K. et al., 2020b: Fine-grained climate velocities reveal vulnerability of protected areas to climate change. *Scientific Reports*, **10**(1), 1678, doi:10.1038/s41598-020-58638-8.
Heinicke, J., S. Ibscher, V. Belik and T. Amon, 2019: Cow individual activity response to the accumulation of heat load duration. *Journal of Thermal Biology*, **82**(March), 23-32, doi:10.1016/j.jtherbio.2019.03.011.
Heinz, F. et al., 2015: Emergence of tick-borne encephalitis in new endemic areas in Austria: 42 years of surveillance. *Eurosurveillance*, **20**(13), 9-16, doi:10.2807/1560-7917.ES2015.20.13.21077.
Helama, S., J. Holopainen and T. Partonen, 2013: Temperature-associated suicide mortality: contrasting roles of climatic warming and the suicide prevention program in Finland. *Environmental Health and Preventive Medicine*, **18**(5), 349-355, doi:10.1007/s12199-013-0329-7.
Helle, T. and I. Kojola, 2008: Demographics in an alpine reindeer herd: effects of density and winter weather. *Ecography*, **31**(2), 221-230, doi:10.1111/j.0906-7590.2008.4912.x.
Hellmann, F., R. Alkemade and O. Knol, 2016: Dispersal based climate change sensitivity scores for European species. *Ecological Indicators*, **71**, 41-46, doi:10.1016/j.ecolind.2016.06.013.
Hennessy, D., L. Delaby, A. van den Pol-van Dasselaar and L. Shalloo, 2020: Increasing grazing in dairy cow milk production systems in Europe. *Sustainability*, **12**(6), doi:10.3390/su12062443.
Heracleous, C. and A. Michael, 2018: Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions. *Energy*, **165**, 1228-1239, doi:https://doi.org/10.1016/j.energy.2018.10.051.
Hermans, L. M., M. Haasnoot, J. ter Maat and J. H. Kwakkel, 2017: Designing monitoring arrangements for collaborative learning about adaptation pathways. *Environmental Science & Policy*, **69**, 29-38, doi:https://doi.org/10.1016/j.envsci.2016.12.005.
Hermoso, V., M. Clavero, D. Villero and L. Brotons, 2017: EU's Conservation Efforts Need More Strategic Investment to Meet Continental Commitments. *Conservation Letters*, **10**(2), 231-237, doi:10.1111/conl.12248.
Hermoso, V., D. Villero, M. Clavero and L. Brotons, 2018: Spatial prioritisation of EU's LIFE-Nature programme to strengthen the conservation impact of Natura 2000. *Journal of Applied Ecology*, **55**(4), 1575-1582, doi:10.1111/1365-2664.13116.
Hernández-Morcillo, M. et al., 2018: Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science and Policy*, **80**(November 2017), 44-52, doi:10.1016/j.envsci.2017.11.013.
Hertig, E., 2019: Distribution of Anopheles vectors and potential malaria transmission stability in Europe and the Mediterranean area under future climate change. *Parasites & Vectors*, **12**, doi:10.1186/s13071-018-3278-6.
Herzog, F. and I. Seidl, 2018: Swiss alpine summer farming: Current status and future development under climate change. *Rangeland Journal*, **40**(5), 501-511, doi:10.1071/RJ18031.
Hewitt, C. D. et al., 2020: Making Society Climate Resilient: International Progress under the Global Framework for Climate Services. *Bulletin of the American Meteorological Society*, **101**(2), E237-E252.
Hickman, C., 2019: Children and Climate Change: Exploring Children's Feelings About Climate Change Using Free Association Narrative Interview Methodology. In: *Climate Psychology: On Indifference to Disaster* [Hoggett, P. (ed.)]. Springer International Publishing, Cham, pp. 41-59. ISBN 978-3-030-11741-2.
Hidalgo, M. et al., 2019: Accounting for ocean connectivity and hydroclimate in fish recruitment fluctuations within transboundary metapopulations. *Ecological Applications*, **29**(5), e01913, doi:10.1002/eap.1913 PMID - 31144784.
Hillebrand, H. et al., 2018: Biodiversity change is uncoupled from species richness trends: Consequences for conservation and monitoring. *Journal of Applied Ecology*, **55**(1), 169-184, doi:10.1111/1365-2664.12959.
Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8**(7), 570-578, doi:10.1038/s41558-018-0176-z.
Hinkel, J. et al., 2019: Meeting User Needs for Sea Level Rise Information: A Decision Analysis Perspective. *Earth's Future*, **7**(3), 320-337, doi:10.1029/2018EF001071.
Hjerne, O. et al., 2019: Climate Driven Changes in Timing, Composition and Magnitude of the Baltic Sea Phytoplankton Spring Bloom. *Frontiers in Marine Science*, **6**, 482, doi:10.3389/fmars.2019.00482.
Hlásny, T. et al., 2014: Climate change increases the drought risk in Central European forests: What are the options for adaptation? *Forestry Journal*, **60**(1), 5-18, doi:10.2478/forj-2014-0001.
Hlásny, T. et al., 2021: Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. *Forest Ecology and Management*, **490**, 119075, doi:https://doi.org/10.1016/j.foreco.2021.119075.
Hock, R. et al., 2019: High Mountain Areas. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. MoufoumaOkia, R. P. C. Péan, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. 1-94. ISBN 0321267974.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5°C of Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and*

related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,
sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, pp. 175-311.

Hoffmann, R. et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change*, **10**(10), 904-912, doi:10.1038/s41558-020-0898-6.

Holgersen, S. and A. Malm, 2015: "green fix" as crisis management. or, in which world is malmö the world's greenest city? *Geografiska Annaler: Series B, Human Geography*, **97**(4), 275-290, doi:10.1111/geob.12081.

Holman, I. P. et al., 2018: Improving the representation of adaptation in climate change impact models. *Regional Environmental Change*, **19**(3), 711-721, doi:10.1007/s10113-018-1328-4.

Holman, I. P., C. Brown, V. Janes and D. Sandars, 2017: Can we be certain about future land use change in Europe? A multi-scenario, integrated-assessment analysis. *Agricultural Systems*, **151**, 126-135, doi:https://doi.org/10.1016/j.agsy.2016.12.001.

Holscher, K., N. Frantzeskaki and D. Loorbach, 2019: Steering transformations under climate change: capacities for transformative climate governance and the case of Rotterdam, the Netherlands. *Regional Environmental Change*, **19**(3), 791-805, doi:10.1007/s10113-018-1329-3.

Holt, J. et al., 2018: Climate-Driven Change in the North Atlantic and Arctic Oceans Can Greatly Reduce the Circulation of the North Sea. *Geophysical Research Letters*, **45**(21), 11,827-811,836, doi:doi/10.1029/2018GL078878.

Holt, J. et al., 2016: Potential impacts of climate change on the primary production of regional seas: A comparative analysis of five European seas. *Progress in Oceanography*, **140**, 91-115, doi:doi/10.1016/j.pocean.2015.11.004.

Holzkämper, A., 2020: Varietal adaptations matter for agricultural water use – a simulation study on grain maize in Western Switzerland. *Agricultural Water Management*, **237**, 106202-106202, doi:https://doi.org/10.1016/j.agwat.2020.106202.

Hopkins, C. R., D. M. Bailey and T. Potts, 2016a: Perceptions of practitioners: Managing marine protected areas for climate change resilience. *Ocean & Coastal Management*, **128**, 18-28, doi:doi/10.1016/j.ocecoaman.2016.04.014.

Hopkins, Charlotte R., David M. Bailey and T. Potts, 2016b: Scotland's Marine Protected Area network: Reviewing progress towards achieving commitments for marine conservation. *Marine Policy*, **71**, 44-53, doi:10.1016/j.marpol.2016.05.015.

Horstkotte, T., C. Sandström and J. Moen, 2014: Exploring the Multiple Use of Boreal Landscapes in Northern Sweden: The Importance of Social-Ecological Diversity for Mobility and Flexibility. *Human Ecology*, **42**(5), 671-682, doi:10.1007/s10745-014-9687-z.

Howard, A. J., 2013: Managing global heritage in the face of future climate change: the importance of understanding geological and geomorphological processes and hazards. *International Journal of Heritage Studies*, **19**(7), 632-658, doi:10.1080/13527258.2012.681680.

Howard, J. et al., 2017: Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, **15**(1), 42-50, doi:doi/10.1002/fee.1451.

Howard, S., S. Howard and S. Howard, 2020: Quantitative market analysis of the European Climate Services sector – The application of the kMatrix big data market analytical tool to provide robust market intelligence. *Climate Services*, **17**, 100108-100108, doi:https://doi.org/10.1016/j.cliser.2019.100108.

Howlett, M. and A. Kemmerling, 2017: Calibrating climate change policies: the causes and consequences of sustained under-reaction. *Journal of Environmental Policy & Planning*, **19**(6), 625-637, doi:10.1080/1523908X.2017.1324772.

Hudson, P., 2018: A comparison of definitions of affordability for flood risk adaption measures: a case study of current and future risk-based flood insurance premiums in Europe. *Mitigation and Adaptation Strategies for Global Change*, **23**(7), 1019-1038, doi:10.1007/s11027-017-9769-5.

Hudson, P., W. Botzen, L. Feyen and J. Aerts, 2016: Incentivising flood risk adaptation through risk based insurance premiums: Trade-offs between affordability and risk reduction. *Ecological Economics*, **125**, 1-13, doi:10.1016/j.ecolecon.2016.01.015.

Huete-Stauffer, C. et al., 2011: *Paramuricea clavata* (Anthozoa, Octocorallia) loss in the Marine Protected Area of Tavolara (Sardinia, Italy) due to a mass mortality event. *Marine Ecology*, **32**(Suppl), 107--116, doi:10.1111/j.1439-0485.2011.00429.x.

Hunt, A. et al., 2017: Climate and weather service provision: Economic appraisal of adaptation to health impacts. *Climate Services*, **7**, 78-86, doi:https://doi.org/10.1016/j.cliser.2016.10.004.

Huntington, H. P. et al., 2017: How small communities respond to environmental change: patterns from tropical to polar ecosystems. *Ecology and Society*, **22**(3).

Ibrahim, A. and S. L. J. Pelsmakers, 2018: Low-energy housing retrofit in North England: Overheating risks and possible mitigation strategies. *Building Services Engineering Research and Technology*, **39**(2), 161-172, doi:10.1177/0143624418754386.

Ide, T., M. Brzoska, J. F. Donges and C. F. Schleussner, 2020: Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk. *Global Environmental Change-Human and Policy Dimensions*, **62**, doi:10.1016/j.gloenvcha.2020.102063.
IEA, 2018: *The Future of Cooling - Opportunities for energy efficient air conditioning*. International Energy Agency, France. Available at: https://webstore.iea.org/download/direct/1036?fileName=The_Future_of_Cooling.pdf.
IFPRI, 2018: *2018 Global food policy report*. International Food Policy Research Institute, Washington, DC. Available at: http://www.ifpri.org/publication/2018-global-food-policy-report.
Iglesias, A. and L. Garrote, 2015: Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management*, **155**, 113-124, doi:10.1016/j.agwat.2015.03.014.
Ikpewe, I. E., A. R. Baudron, A. Ponchon and P. G. Fernandes, 2021: Bigger juveniles and smaller adults: Changes in fish size correlate with warming seas. *Journal of Applied Ecology*, **58**(4), 847-856, doi:10.1111/1365-2664.13807.
Inuit Circumpolar Council, 2020: *Food sovereignty and self-governance: Inuit role in managing arctic marine resources*. Anchorage, AK. Available at: https://www.culturalsurvival.org/sites/default/files/FSSG%20Report_%20LR%20%281%29.pdf.
Iosub, M., A. Enea and I. Mine (eds.), Flash flood impact on the cultural heritage in Moldova region, Romania. Case Study: Jijia valley. 19th SGEM International Multidisciplinary Scientific GeoConference EXPO Proceedings, 2019/06/20/, Sofia.
IPBES, 2018: *The regional assessment report on biodiversity and ecosystem services for Europe and Central Asia* [Rounsevell, M., M. Fischer, A. Torre-Marin Rando and A. Mader (eds.)]. IPBES Secretariat, Secretariat, I., Bonn, Germany, 892 pp pp. Available at: http://www.ipbes.dk/wp-content/uploads/2018/09/EuropaCentralAsia_SPM_2018.pdf.
IPCC, 2019: *Special Report: The Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. 1170-1170 pp. Available at: https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_FullReport.pdf.
Irvine, E. A., K. P. Shine and M. A. Stringer, 2016: What are the implications of climate change for trans-Atlantic aircraft routing and flight time? *Transportation Research Part D-Transport and Environment*, **47**, 44-53, doi:10.1016/j.trd.2016.04.014.
Isaksson, K. and S. Heikkinen, 2018: Sustainability Transitions at the Frontline. Lock-in and Potential for Change in the Local Planning Arena. *Sustainability*, **10**(3), doi:10.3390/su10030840.
Ito, A. et al., 2020: Pronounced and unavoidable impacts of low-end global warming on northern high-latitude land ecosystems. *Environmental Research Letters*, **15**(4), 044006, doi:10.1088/1748-9326/ab702b.
Ivanov, V. P. et al., 2016: Invasion of the Caspian Sea by the Comb Jellyfish Mnemiopsis Leidyi (Ctenophora). *Biological Invasions*, **2**(3), 255--258, doi:10.1023/A:1010098624728.
Izaguirre, C. et al., 2021: Climate change risk to global port operations. *Nature Climate Change*, **11**(1), 14-20, doi:10.1038/s41558-020-00937-z.
Jacob, D. et al., 2018: Climate Impacts in Europe Under +1.5°C Global Warming Earth's Future. *Earth's Future*, **6**, 264-285, doi:10.1002/eft2.286.
Jacob, D. et al., 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, **14**(2), 563-578, doi:10.1007/s10113-013-0499-2.
Jacob, D. J. and D. A. Winner, 2009: Effect of climate change on air quality. *Atmospheric Environment*, **43**(1), 51-63, doi:https://doi.org/10.1016/j.atmosenv.2008.09.051.
Jacob, K. H., 2015: Sea level rise, storm risk, denial, and the future of coastal cities. *Bulletin of the Atomic Scientists*, **71**(5), 40-50, doi:10.1177/0096340215599777.
Jactel, H. et al., 2017: Tree Diversity Drives Forest Stand Resistance to Natural Disturbances. *Current Forestry Reports*, **3**(3), 223-243, doi:10.1007/s40725-017-0064-1.
Jaenson, T. et al., 2012: Changes in the geographical distribution and abundance of the tick Ixodes ricinus during the past 30 years in Sweden. *Parasites & Vectors*, **5**, doi:10.1186/1756-3305-5-8.
Jäger, H., G. Peratoner, U. Tappeiner and E. Tasser, 2020: Grassland biomass balance in the European Alps: current and future ecosystem service perspectives. *Ecosystem Services*, **45**(July), 101163-101163, doi:10.1016/j.ecoser.2020.101163.
Jäger, J. et al., 2015: Assessing policy robustness of climate change adaptation measures across sectors and scenarios. *Climatic Change*, **128**(3), 395-407, doi:10.1007/s10584-014-1240-y.
Jantke, K., J. Müller, N. Trapp and B. Blanz, 2016: Is climate-smart conservation feasible in Europe? Spatial relations of protected areas, soil carbon, and land values. *Environmental Science and Policy*, **57**, 40-49, doi:10.1016/j.envsci.2015.11.013.
Jarić, I. et al., 2019: Susceptibility of European freshwater fish to climate change: Species profiling based on life-history and environmental characteristics. *Global Change Biology*, **25**(2), 448-458, doi:10.1111/gcb.14518.
Jenkins, K. et al., 2014a: Implications of climate change for thermal discomfort on underground railways. *Transportation Research Part D: Transport and Environment*, **30**, 1-9, doi:https://doi.org/10.1016/j.trd.2014.05.002.
Jenkins, K. et al., 2014b: Probabilistic spatial risk assessment of heat impacts and adaptations for London. *Climatic Change*, **124**(1), 105-117, doi:10.1007/s10584-014-1105-4.

Jiang, L. et al., 2020: Effects of sea-level rise on tides and sediment dynamics in a Dutch tidal bay. *Ocean Sci*, **16**, 307-321, doi:uuid/E5C4F306-9A38-4407-8AED-A8523359437B.
Johannessen, Å. et al., 2019: Transforming urban water governance through social (triple-loop) learning. *Environmental Policy and Governance*, **0**(0), doi:10.1002/eet.1843.
Jokinen, S., J. J. Virtasalo, T. S. Jilbert and J. Kaiser, 2018: A 1500-year multiproxy record of coastal hypoxia from the northern Baltic Sea indicates unprecedented deoxygenation over the 20th century. *Biogeosciences*, **15**, 3975-4001, doi:doi/10.1016/S0016-7037(00)00539-1.
Joly, M. and E. I. Ungureanu, 2018: Global warming and skiing: analysis of the future of skiing in the Aosta valley. *Worldwide Hospitality and Tourism Themes*, **10**(2), 161-171, doi:doi:10.1108/WHATT-12-2017-0077.
Jones, A. W. and A. Phillips, 2016: Voluntary business engagement in climate change: A study of the ClimateWise principles. *Journal of Cleaner Production*, **137**, 131-143, doi:10.1016/j.jclepro.2016.07.064.
Jones, B. and B. C. O'Neill, 2016: Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environmental Research Letters*, **11**(8), doi:10.1088/1748-9326/11/8/084003.
Jones, E. et al., 2019: The state of desalination and brine production: A global outlook. *Science of The Total Environment*, **657**, 1343-1356, doi:https://doi.org/10.1016/j.scitotenv.2018.12.076.
Jones, P. J. S., L. M. Lieberknecht and W. Qiu, 2016: Marine spatial planning in reality: Introduction to case studies and discussion of findings. *Marine Policy*, **71**, 256-264, doi:doi/10.1016/j.marpol.2016.04.026.
Jongman, B. et al., 2014: Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change*, **4**(4), 264-268, doi:10.1038/NCLIMATE2124.
Jongman, B., P. J. Ward and J. Aerts, 2012: Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change-Human and Policy Dimensions*, **22**(4), 823-835, doi:10.1016/j.gloenvcha.2012.07.004.
Jongman, B. et al., 2015: Declining vulnerability to river floods and the global benefits of adaptation. *Proceedings of the National Academy of Sciences*, **112**(18), E2271-E2280, doi:10.1073/pnas.1414439112.
Jore, S. et al., 2014: Climate and environmental change drives Ixodes ricinus geographical expansion at the northern range margin. *Parasites & Vectors*, **7**, doi:10.1186/1756-3305-7-11.
Jouzel, J. and A. Michelot, 2016: La justice climatique : enjeux et perspectives pour la France. *Les avis du CESE*, **10**, 66.
JRCdatacatalogue, 2021: GHSL - Global Human Settlement Layer, JRC. Available at: https://ghsl.jrc.ec.europa.eu/ghs_bu2019.php.
Juhola, S., E. Glaas, B.-O. Linnér and T.-S. Neset, 2016: Redefining maladaptation. *Environmental Science & Policy*, **55**, 135-140, doi:10.1016/j.envsci.2015.09.014.
Jurt, C. et al., 2015: Local perceptions in climate change debates: insights from case studies in the Alps and the Andes. *Climatic Change*, **133**(3), 511-523, doi:10.1007/s10584-015-1529-5.
Juschten, M. et al., 2019: Out of the City Heat—Way to Less or More Sustainable Futures? *Sustainability*, **11**(1), 214.
Kabisch, N. et al., 2016: Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, **21**(2), doi:10.5751/ES-08373-210239.
Kaiser, N. et al., 2010: Depression and anxiety in the reindeer-herding Sami population of Sweden. *International Journal of Circumpolar Health*, **69**(4), 383-393, doi:10.3402/ijch.v69i4.17674.
Kalikoski, D. C. et al., 2018: Understanding the impacts of climate change for fisheries and aquaculture: applying a poverty lens. *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options.*, **FAO Fisher**(Paper No. 627).
Kalkuhl, M. and L. Wenz, 2020: The impact of climate conditions on economic production. Evidence from a global panel of regions. *Journal of Environmental Economics and Management*, **103**, 102360, doi:10.1016/j.jeem.2020.102360.
Kaloveloni, A. et al., 2015: Winners and losers of climate change for the genus Merodon (Diptera: Syrphidae) across the Balkan Peninsula. *Ecological Modelling*, **313**, 201-211, doi:https://doi.org/10.1016/j.ecolmodel.2015.06.032.
Kanters, J. and M. Wall, 2018: Experiences from the urban planning process of a solar neighbourhood in Malmö, Sweden. *Urban, Planning and Transport Research*, **6**(1), 54-80, doi:10.1080/21650020.2018.1478323.
Karkanis, A. et al., 2018: Interference of weeds in vegetable crop cultivation, in the changing climate of Southern Europe with emphasis on drought and elevated temperatures: A review. *Journal of Agricultural Science*, **156**(10), 1175-1185, doi:10.1017/S0021859619000108.
Karlsson, B., 2014: Extended season for northern butterflies. *International Journal of Biometeorology*, **58**, doi:10.1007/s00484-013-0649-8.
Kattsov, V. M. and B. N. Porfiriev (eds.), 2020: *Report on the scientific and methodological framework for adaptation strategies to climate change in the Russian Federation (in the field of competence of Roshydromet)*, Amirit, Moscow-Saratov, 120 pp.
Kaufman, J. D., K. R. Kassube and A. G. Ríus, 2017: Lowering rumen-degradable protein maintained energy-corrected milk yield and improved nitrogen-use efficiency in multiparous lactating dairy cows exposed to heat stress. *Journal of Dairy Science*, **100**(10), 8132-8145, doi:10.3168/jds.2017-13026.
Kayaga, S. and I. Smout, 2014: Tariff structures and incentives for water demand management. *Proceedings of the Institution of Civil Engineers - Water Management*, **167**(8), 448-456, doi:10.1680/wama.12.00120.

Kebede, A. S. et al., 2021: Integrated assessment of the food-water-land-ecosystems nexus in Europe: Implications for sustainability. *Science of the Total Environment*, **768**, 144461-144461, doi:10.1016/j.scitotenv.2020.144461.
Keeley, A. T. H., P. Beier and J. S. Jenness, 2021: Connectivity metrics for conservation planning and monitoring. *Biological Conservation*, **255**, 109008, doi:https://doi.org/10.1016/j.biocon.2021.109008.
Kellens, W., T. Terpstra and P. De Maeyer, 2013: Perception and Communication of Flood Risks: A Systematic Review of Empirical Research. *Risk Analysis*, **33**(1), 24-49, doi:10.1111/j.1539-6924.2012.01844.x.
Kelley, C. P. et al., 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(11), 3241-3246, doi:10.1073/pnas.1421533112.
Kellomäki, S. et al., 2018: Temporal and Spatial Change in Diameter Growth of Boreal Scots Pine, Norway Spruce, and Birch under Recent-Generation (CMIP5) Global Climate Model Projections for the 21st Century. *Forests*, **9**(3), 118, doi:10.3390/f9030118.
Kendrovski, V. et al., 2017: Quantifying Projected Heat Mortality Impacts under 21st-Century Warming Conditions for Selected European Countries. *International journal of environmental research and public health*, **14**(7), 729, doi:10.3390/ijerph14070729.
Kendrovski, V. and O. Schmoll, 2019: Priorities for protecting health from climate change in the WHO European Region: recent regional activities. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz*, **62**(5), 537-545, doi:10.1007/s00103-019-02943-9.
Keogan, K. et al., 2021: No evidence for fitness signatures consistent with increasing trophic mismatch over 30 years in a population of European shag Phalacrocorax aristotelis. *Journal of Animal Ecology*, **90**(2), 432-446, doi:https://doi.org/10.1111/1365-2656.13376.
Kerimov, A. M., Z. T. Akshayakov and H. A. Anakhaev, 2020: Mudflow risk in the Kabardino-Balkaria Republic (Central Caucasus) by the example of Chereck and Baksan river valleys. *Eurasian Union of Scientists*,(9), 6.
Kernecker, M. et al., 2019: Experience versus expectation: farmers' perceptions of smart farming technologies for cropping systems across Europe. *Precision Agric*, doi:10.1007/s11119-019-09651-z.
Kerr, J. T. et al., 2015: Climate change impacts on bumblebees converge across continents. *Science*, **349**(6244), 177 LP-180, doi:10.1126/science.aaa7031.
Kersting, D. K., N. Bensoussan and C. Linares, 2013: Long-term responses of the endemic reef-builder Cladocora caespitosa to Mediterranean warming. *PLoS One*, **8**(8), e70820, doi:doi/10.1371/journal.pone.0070820.
Kešetović, Ž., P. Marić and V. Ninković, 2017: Crisis Communication of Local Authorities in Emergency Situations – Communicating "May Floods" in the Republic of Serbia. *Lex localis - Journal of Local Self-Government*, **15**(1), 93-109, doi:10.4335/15.1.93-109(2017).
Keskitalo, E., G. Vulturius and P. Scholten, 2014: Adaptation to climate change in the insurance sector: examples from the UK, Germany and the Netherlands. *Natural Hazards*, **71**(1), 315-334, doi:10.1007/s11069-013-0912-7.
Ketabchi, H., D. Mahmoodzadeh, B. Ataie-Ashtiani and C. T. Simmons, 2016: Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. *Journal of Hydrology $V 535*, 235-255.
Khabarov, N. et al., 2016: Forest fires and adaptation options in Europe. *Regional Environmental Change*, **16**(1), 21-30, doi:10.1007/s10113-014-0621-0.
Khan, Z., P. Linares and J. García-González, 2016: Adaptation to climate-induced regional water constraints in the Spanish energy sector: An integrated assessment. *Energy Policy*, **97**, 123-135, doi:https://doi.org/10.1016/j.enpol.2016.06.046.
Kiesel, J. et al., 2020: Effective design of managed realignment schemes can reduce coastal flood risks. *Estuarine, Coastal and Shelf Science*, **242**, 106844, doi:10.1016/j.ecss.2020.106844.
Kim, G.-U., K.-H. Seo and D. Chen, 2019: Climate change over the Mediterranean and current destruction of marine ecosystem. *Scientific reports*, **9**(1), 9, doi:doi/10.1038/s41598-019-55303-7.
Kingsborough, A., E. Borgomeo and J. W. Hall, 2016: Adaptation pathways in practice: Mapping options and trade-offs for London's water resources. *Sustainable Cities and Society*, **27**, 386-397, doi:https://doi.org/10.1016/j.scs.2016.08.013.
Kirwan, M. et al., 2016: Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change*, **6**(3), 253-260, doi:10.1038/NCLIMATE2909.
Kivinen, S., 2015: Many a little makes a mickle: Cumulative land cover changes and traditional land use in the Kyrö reindeer herding district, northern Finland. *Applied Geography*, **63**, 204-211, doi:10.1016/j.apgeog.2015.06.013.
Kivinen, S. et al., 2012: Forest Fragmentation and Landscape Transformation in a Reindeer Husbandry Area in Sweden. *Environmental Management*, **49**(2), 295-304, doi:10.1007/s00267-011-9788-z.
Klein, G. et al., 2016: Shorter snow cover duration since 1970 in the Swiss Alps due to earlier snowmelt more than to later snow onset. *Climatic Change*, **139**(3), 637-649, doi:10.1007/s10584-016-1806-y.
Klijn, F., H. Kreibich, H. de Moel and E. Penning-Rowsell, 2015: Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. *Mitigation and Adaptation Strategies for Global Change*, **20**(6), 845-864, doi:10.1007/s11027-015-9638-z.
Klimenko, V. V., E. V. Fedotova and A. G. Tereshin, 2018a: Vulnerability of the Russian power industry to the climate change. *Energy*, **142**, 1010-1022, doi:https://doi.org/10.1016/j.energy.2017.10.069.

Klimenko, V. V., A. V. Klimenko, A. G. Tereshin and E. V. Fedotova, 2018b: Impact of Climate Change on Energy Production, Distribution, and Consumption in Russia. *Thermal Engineering*, **65**(5), 247-257, doi:10.1134/S0040601518050051.
Kløcker Larsen, R., C. Österlin and L. Guia, 2018: Do voluntary corporate actions improve cumulative effects assessment? Mining companies' performance on Sami lands. *The Extractive Industries and Society*, **5**(3), 375-383, doi:https://doi.org/10.1016/j.exis.2018.04.003.
Kløcker Larsen, R. and K. Raitio, 2019: Implementing the State Duty to Consult in Land and Resource Decisions: Perspectives from Sami Communities and Swedish State Officials. *Arctic Review on Law and Politics*, **10**(0), 4, doi:10.23865/arctic.v10.1323.
Kløcker Larsen, R., K. Raitio, M. Stinnerbom and J. Wik-Karlsson, 2017: Sami-state collaboration in the governance of cumulative effects assessment: A critical action research approach. *Environmental Impact Assessment Review*, **64**, 67-76, doi:10.1016/j.eiar.2017.03.003.
Klostermann, J. et al., 2018: Towards a framework to assess, compare and develop monitoring and evaluation of climate change adaptation in Europe. *Mitigation and Adaptation Strategies for Global Change*, **23**(2), 187-209, doi:10.1007/s11027-015-9678-4.
Knittel, N. et al., 2020: A global analysis of heat-related labour productivity losses under climate change—implications for Germany's foreign trade. *Climatic Change*, **160**(2), 251-269, doi:10.1007/s10584-020-02661-1.
Knox, J., A. Daccache, T. Hess and D. Haro, 2016: Meta-analysis of climate impacts and uncertainty on crop yields in Europe. *Environmental Research Letters*, **11**(11), 113004, doi:10.1088/1748-9326/11/11/113004.
Kok, K. et al., 2019: New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. *Regional Environmental Change*, **19**(3), 643-654, doi:10.1007/s10113-018-1400-0.
Koks, E., 2018: Moving flood risk modelling forwards. *Nature Climate Change*, **8**(7), 561-562, doi:10.1038/s41558-018-0185-y.
Koks, E., R. Pant, S. Thacker and J. W. Hall, 2019a: Understanding Business Disruption and Economic Losses Due to Electricity Failures and Flooding. *International Journal of Disaster Risk Science*, **10**(4), 421-438, doi:10.1007/s13753-019-00236-y.
Koks, E. E. et al., 2019b: The macroeconomic impacts of future river flooding in Europe. *Environmental Research Letters*, **14**(8), 084042, doi:10.1088/1748-9326/ab3306.
Kondo, M. C., J. M. Fluehr, T. McKeon and C. C. Branas, 2018: Urban Green Space and Its Impact on Human Health. *International Journal of Environmental Research and Public Health*, **15**(3), 445.
Konnova, L. A. and Y. V. Lvova, 2019: Permafrost degradation in security context livelihoods in the Arctic Zone of the Russian Federation. *Problems of technosphere risk management*,(3(51)), 27-33.
Korpinen, S. et al., 2021: Combined effects of human pressures on Europe's marine ecosystems. *Ambio*, **50**(7), 1325-1336, doi:10.1007/s13280-020-01482-x PMID - 33507497.
Koubi, V., 2019: Climate Change and Conflict. *Annual Review of Political Science*, **22**(1), 343-360, doi:10.1146/annurev-polisci-050317-070830.
Kouloukoui, D. et al., 2021: Factors influencing the perception of exposure to climate risks: Evidence from the world's largest carbon-intensive industries. *Journal of Cleaner Production*, **306**, 127160, doi:10.1016/j.jclepro.2021.127160.
Kourtis, I. M. and V. A. Tsihrintzis, 2021: Adaptation of urban drainage networks to climate change: A review. *Science of The Total Environment*, **771**, 145431, doi:https://doi.org/10.1016/j.scitotenv.2021.145431.
Koutroulis, A. G., M. G. Grillakis, I. K. Tsanis and D. Jacob, 2018: Mapping the vulnerability of European summer tourism under 2 °C global warming. *Climatic Change*, **151**(2), 157-171, doi:10.1007/s10584-018-2298-8.
Koutroulis, A. G. et al., 2019: Global water availability under high-end climate change: A vulnerability based assessment. *Global and Planetary Change*, **175**, 52-63, doi:https://doi.org/10.1016/j.gloplacha.2019.01.013.
Kovats, R. S. et al., 2014: Europe. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. XXX-YYY.
Krause, A., T. Knoke and A. Rammig, 2020: A regional assessment of land-based carbon mitigation potentials: Bioenergy, BECCS, reforestation, and forest management. *GCB Bioenergy*, **12**(5), 346-360, doi:10.1111/gcbb.12675.
Kreibich, H., 2011: Do perceptions of climate change influence precautionary measures? *International Journal of Climate Change Strategies and Management*, **3**(2), 189-199, doi:10.1108/17568691111129011.
Kreibich, H., P. Bubeck, M. Van Vliet and H. De Moel, 2015: A review of damage-reducing measures to manage fluvial flood risks in a changing climate. *Mitigation and Adaptation Strategies for Global Change*, **20**(6), 967-989, doi:10.1007/s11027-014-9629-5.
Kreienkamp, F. et al., 2021: *Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021* [worldweatherattribution (ed.)]. 51 pp. Available at:

https://www.worldweatherattribution.org/wp-content/uploads/Scientific-report-Western-Europe-floods-2021-attribution.pdf.
Kreiss, C. M. et al., 2020: Future Socio-Political Scenarios for Aquatic Resources in Europe: An Operationalized Framework for Aquaculture Projections. *Frontiers in Marine Science*, **7**(September), doi:10.3389/fmars.2020.568159.
Krikken, F. et al., 2021: Attribution of the role of climate change in the forest fires in Sweden 2018. *Nat. Hazards Earth Syst. Sci.*, **21**(7), 2169-2179, doi:10.5194/nhess-21-2169-2021.
Kroeker, K. J., R. L. Kordas, R. N. Crim and G. G. Singh, 2010: Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters*, **13**(11), 1419-1434, doi:10.1111/j.1461-0248.2010.01518.x PMID - 20958904.
Kulmer, V., M. Jury, S. Wong and D. Kortschak, 2020: Global resource consumption effects of borderless climate change: EU's indirect vulnerability. *Environmental and Sustainability Indicators*, **8**, 100071, doi:10.1016/j.indic.2020.100071.
Kumar, P. et al., 2019: The nexus between air pollution, green infrastructure and human health. *Environment International*, **133**, 105181, doi:https://doi.org/10.1016/j.envint.2019.105181.
Kwadijk, J. C. J. et al., 2010: Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdisciplinary Reviews-Climate Change*, **1**(5), 729-740, doi:10.1002/wcc.64.
Kwiatkowski, L., O. Aumont and L. Bopp, 2019: Consistent trophic amplification of marine biomass declines under climate change. *Global Change Biology*, **25**(1), 218-229, doi:doi/10.1111/gcb.14468.
Lake, I. et al., 2019: Exploring Campylobacter seasonality across Europe using The European Surveillance System (TESSy), 2008 to 2016. *Eurosurveillance*, **24**(13), 35-46, doi:10.2807/1560-7917.ES.2019.24.13.180028.
Lake, I. et al., 2017: Climate Change and Future Pollen Allergy in Europe. *Environmental Health Perspectives*, **125**(3), 385-391, doi:10.1289/EHP173.
Lambertz, C., C. Sanker and M. Gauly, 2014: Climatic effects on milk production traits and somatic cell score in lactating Holstein-Friesian cows in different housing systems. *Journal of Dairy Science*, **97**(1), 319-329, doi:10.3168/jds.2013-7217.
Lamond, J. and E. Penning-Rowsell, 2014: The robustness of flood insurance regimes given changing risk resulting from climate change. *Climate Risk Management*, **2**, 1-10, doi:https://doi.org/10.1016/j.crm.2014.03.001.
Lamperti, F., V. Bosetti, A. Roventini and M. Tavoni, 2019: The public costs of climate-induced financial instability. *Nature Climate Change*, **9**(11), 829-833, doi:10.1038/s41558-019-0607-5.
Lamperti, F. et al., 2018: Faraway, So Close: Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model. *Ecological Economics*, **150**, 315-339, doi:10.1016/j.ecolecon.2018.03.023.
Langer, G. et al., 2014: Limpets counteract ocean acidification induced shell corrosion by thickening of aragonitic shell layers. *Biogeosciences*, **11**(24), 7363--7368, doi:10.5194/bg-11-7363-2014.
Latchininsky, A. V., 2017: Climate changes and locusts: What to expect? *Scientific notes of the Russian State Hydrometeorological University*, **46**, 134-143.
Laufkoetter, C. et al., 2015: Drivers and uncertainties of future global marine primary production in marine ecosystem models. *Biogeosciences*, **12**(23), 6955-6984, doi:doi/10.5194/bg-12-6955-2015.
Lavrnic, S., M. Zapater-Pereyra and M. Mancini, 2017: Water Scarcity and Wastewater Reuse Standards in Southern Europe: Focus on Agriculture. *Water Air and Soil Pollution*, **228**(7), doi:10.1007/s11270-017-3425-2.
Lawrence, R. and R. Kløcker Larsen, 2019: *Fighting to Be Herd: Impacts of the Proposed Boliden Copper Mine in Laver, Älvsbyn, Sweden for the Semisjaur Njarg Sami Reindeer Herding Community*. Stockholm Environment Institute, Stockholm, 96 pp. Available at: https://www.sei.org/wp-content/uploads/2019/04/sei-report-fighting-to-be-herd-300419.pdf.
Le Cozannet, G. et al., 2019: Quantifying uncertainties of sandy shoreline change projections as sea level rises. *Scientific Reports*, **9**(1), 42, doi:10.1038/s41598-018-37017-4.
Le Cozannet, G. et al., 2017: Sea Level Change and Coastal Climate Services: The Way Forward. *Journal of Marine Science and Engineering*, **5**(4), doi:10.3390/jmse5040049.
Lee, H. et al., 2019: Implementing land-based mitigation to achieve the Paris Agreement in Europe requires food system transformation. *Environmental Research Letters*, **14**(10), 104009, doi:10.1088/1748-9326/ab3744.
Lehikoinen, A. et al., 2019: Declining population trends of European mountain birds. *Global Change Biology*, **25**(2), 577-588, doi:10.1111/gcb.14522.
Leissner, J. et al., 2015: Climate for Culture: assessing the impact of climate change on the future indoor climate in historic buildings using simulations. *Heritage Science*, **3**(1), 38, doi:10.1186/s40494-015-0067-9.
Lelieveld, J. et al., 2019: Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions. *European Heart Journal*, **40**(20), 1590-1596, doi:10.1093/eurheartj/ehz135.
Leskinen, P. et al. (eds.), 2020: *Russian forests and climate change. What Science Can Tell Us 11*.
Lesnikowski, A., R. Biesbroek, J. D. Ford and L. Berrang-Ford, 2021: Policy implementation styles and local governments: the case of climate change adaptation. *Environmental Politics*, **30**(5), 753-790, doi:10.1080/09644016.2020.1814045.
Lesnikowski, A. et al., 2016: National-level progress on adaptation. *Nature Climate Change*, **6**, 261-264.
Lesnikowski, A., J. D. Ford, R. Biesbroek and L. Berrang-Ford, 2019: A policy mixes approach to conceptualizing and measuring climate change adaptation policy. *Climatic Change*, doi:10.1007/s10584-019-02533-3.

Leventon, J. et al., 2017: Collaboration or fragmentation? Biodiversity management through the common agricultural policy. *Land Use Policy*, **64**, 1-12, doi:10.1016/j.landusepol.2017.02.009.

Lewis, K. M., G. L. van Dijken and K. R. Arrigo, 2020: Changes in phytoplankton concentration now drive increased Arctic Ocean primary production. *Science*, **369**(6500), 198-202, doi:doi/10.1126/science.aay8380.

Lhotka, O. and J. Kysely, 2015: Characterizing joint effects of spatial extent, temperature magnitude and duration of heat waves and cold spells over Central Europe. *International Journal of Climatology*, **35**(7), 1232-1244, doi:10.1002/joc.4050.

Liang, E. et al., 2016: Global warming-related tree growth decline and mortality on the north-eastern Tibetan plateau. *Climatic Change*, **134**(1-2), 163-176, doi:10.1007/s10584-015-1531-y.

Linares, C., G. Martinez, V. Kendrovski and J. Diaz, 2020: A new integrative perspective on early warning systems for health in the context of climate change. *Environmental Research*, **187**, doi:10.1016/j.envres.2020.109623.

Lincke, D. and J. Hinkel, 2018: Economically robust protection against 21st century sea-level rise. *Global Environmental Change*, **51**, 67-73, doi:10.1016/j.gloenvcha.2018.05.003.

Lincke, D. and J. Hinkel, 2021: Coastal Migration due to 21st Century Sea-Level Rise. *Earth's Future*, **9**(5), 1-14, doi:10.1029/2020ef001965.

Lincke, D. et al., 2020: The effectiveness of setback zones for adapting to sea-level rise in Croatia. *Regional Environmental Change*, **20**(2), doi:10.1007/s10113-020-01628-3.

Lindeboom, H. J. et al., 2011: Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters*, **6**(3), 035101-035114, doi:doi/10.1088/1748-9326/6/3/035101.

Lindegren, M. et al., 2018: Productivity and recovery of forage fish under climate change and fishing: North Sea sandeel as a case study. *Fisheries Oceanography*, **27**(3), 212-221, doi:doi/10.1111/fog.12246.

Lindgren, E. et al., 2012: Monitoring EU Emerging Infectious Disease Risk Due to Climate Change. *Science*, **336**(6080), 418-419, doi:10.1126/science.1215735.

Linnerooth-Bayer, J. and R. Mechler, 2015: Insurance for assisting adaptation to climate change in developing countries: a proposed strategy. In: *Climate Change and Insurance*. Routledge, pp. 29-44.

Lionello, P., 2012: The climate of the Venetian and North Adriatic region: Variability, trends and future change. *Physics and Chemistry of the Earth, Parts A/B/C*, **40**, 1-8.

Lionello, P. et al., 2021a: Extremes floods of Venice: characteristics, dynamics, past and future evolution. *Nat. Hazards Earth Syst. Sci.*, **21**, 2705–2731, doi:https://doi.org/10.5194/nhess-21-2705-2021.

Lionello, P., R. J. Nicholls, G. Umgiesser and D. Zanchettin, 2021b: Venice flooding and sea level: past evolution, present issues and future projections. *Nat. Hazards Earth Syst. Sci.*, **21**, 2633–2641, doi:https://doi.org/10.5194/nhess-21-2633-2021.

Litskas, V. D. et al., 2019: Impacts of climate change on tomato, a notorious pest and its natural enemy: small scale agriculture at higher risk. *Environmental Research Letters*, **14**(8), 084041, doi:10.1088/1748-9326/ab3313.

Liu-Helmersson, J. et al., 2016: Climate Change and Aedes Vectors: 21st Century Projections for Dengue Transmission in Europe. *Ebiomedicine*, **7**, 267-277, doi:10.1016/j.ebiom.2016.03.046.

Llasat, M. C. et al., 2016: Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia. *Journal of Hydrology*, **541**, 24-37, doi:10.1016/j.jhydrol.2016.05.040.

Loboda, T. et al., 2017: Land Management and the Impact of the 2010 Extreme Drought Event on the Agricultural and Ecological Systems of European Russia. ISBN 978-3-319-42636-5.

Löf, A., 2013: Examining limits and barriers to climate change adaptation in an Indigenous reindeer herding community. *Climate and Development*, **5**(4), 328-339, doi:10.1080/17565529.2013.831338.

Loopstra, R., 2020: An overview of food insecurity in Europe and what works and what doesn't work to tackle food insecurity. European Journal of Public Health.

Lopez-Doriga, U., J. Jimenez, H. Valdemoro and R. Nicholls, 2019: Impact of sea-level rise on the tourist-carrying capacity of Catalan beaches. *Ocean & Coastal Management*, **170**, 40-50, doi:10.1016/j.ocecoaman.2018.12.028.

López-Dóriga, U., J. A. Jiménez, A. Bisaro and J. Hinkel, 2020: Financing and implementation of adaptation measures to climate change along the Spanish coast. *Science of The Total Environment*, **712**, 135685, doi:10.1016/j.scitotenv.2019.135685.

Lorencova, E. et al., 2018: Participatory Climate Change Impact Assessment in Three Czech Cities: The Case of Heatwaves. *Sustainability*, **10**(6), doi:10.3390/su10061906.

Lorentzen, T., 2020: Climate change and winter road maintenance. *Climatic Change*, **161**(1), 225-242, doi:10.1007/s10584-020-02662-0.

Lotze, H. K. et al., 2019: Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences of the USA*, **116**(26), 12907-12912, doi:10.1073/pnas.1900194116.

Lourenco, T. C. et al., 2019: Are European decision-makers preparing for high-end climate change? *Regional Environmental Change*, **19**(3), 629-642, doi:10.1007/s10113-018-1362-2.

Lucas-Borja, M. E. et al., 2021: Changes in ecosystem properties after post-fire management strategies in wildfire-affected Mediterranean forests. *Journal of Applied Ecology*, **58**(4), 836-846, doi:https://doi.org/10.1111/1365-2664.13819.

Luijendijk, A. et al., 2018: The State of the World's Beaches. *Scientific Reports*, **8**(1), 6641, doi:10.1038/s41598-018-24630-6.

Luís, S. et al., 2017: Beliefs on the local effects of climate change: Causal attribution of flooding and shoreline retreat. *Journal of Integrated Coastal Zone Management*,(1), 19-35%V 17.
Luís, S. et al., 2018: Psychosocial drivers for change: Understanding and promoting stakeholder engagement in local adaptation to climate change in three European Mediterranean case studies. *Journal of Environmental Management*, **223**, 165-174, doi:10.1016/j.jenvman.2018.06.020.
Macalister, F., 2015: Preparing for the future: Mitigating disasters and building resilience in the cultural heritage sector. *Journal of the Institute of Conservation*, **38**(2), 115-129, doi:10.1080/19455224.2015.1068201.
Macgregor, C. J. et al., 2019: Climate-induced phenology shifts linked to range expansions in species with multiple reproductive cycles per year. *Nature Communications*, **10**(1), 4455, doi:10.1038/s41467-019-12479-w.
Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-+, doi:10.1038/s41586-019-1300-6.
Mach, K. J. and A. R. Siders, 2021: Reframing strategic, managed retreat for transformative climate adaptation. *Science*, **372**(6548), 1294-1299, doi:10.1126/science.abh1894.
Machado, I. et al., 2019: Assessment level and time scales of biodiversity indicators in the scope of the Marine Strategy Framework Directive – A case study for the NE Atlantic. *Ecological Indicators*, **105**, 242-253, doi:doi/10.1016/j.ecolind.2019.05.067.
Macias, D. M., E. Garcia-Gorriz and A. Stips, 2015: Productivity changes in the Mediterranean Sea for the twenty-first century in response to changes in the regional atmospheric forcing. *Frontiers in Marine Science*, **2**, 1-13, doi:10.3389/fmars.2015.00079.
Macintyre, H. L. et al., 2018: Assessing urban population vulnerability and environmental risks across an urban area during heatwaves – Implications for health protection. *Science of The Total Environment*, **610-611**, 678-690, doi:https://doi.org/10.1016/j.scitotenv.2017.08.062.
Madine, C., K. Mustonen and T. Mustonen, 2018: *Wave Knowledge, Traditional Wisdom*. Snowchange Cooperative. Available at: http://www.snowchange.org/pages/wp-content/uploads/2018/11/Cherish_29112018.pdf.
Madsen, H. et al., 2014: Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. *Journal of Hydrology*, **519**, 3634-3650, doi:10.1016/j.jhydrol.2014.11.003.
Malinin, V. N., S. M. Gordeeva, I. V. Mitina and A. A. Pavlovsky, 2018: The negative consequences of storm surges and the "age-old" level rise in the Neva Bay. *Вода и экология: проблемы и решения*, **1**(73), 48-58, doi:10.23968/2305–3488.2018.23.1.48–58.
Mallory, C. D. and M. S. Boyce, 2018: Observed and predicted effects of climate change on Arctic caribou and reindeer. *Environmental Reviews*, **26**(1), 13-25, doi:10.1139/er-2017-0032.
Malmo Stad, 2018: *Comprehensive Plan for Malmo*.
Mamet, S. D., C. D. Brown, A. J. Trant and C. P. Laroque, 2019: Shifting global Larix distributions: Northern expansion and southern retraction as species respond to changing climate. *Journal of Biogeography*, **46**(1), 30-44, doi:https://doi.org/10.1111/jbi.13465.
Mandel, A. et al., 2021: Risks on Global Financial Stability Induced by Climate Change. *Climatic Change*, **166**, 4, doi:https://doi.org/10.1007/s10584-021-03092-2.
Mangi, S. C. et al., 2018: The economic impacts of ocean acidification on shellfish fisheries and aquaculture in the United Kingdom. *Environmental Science & Policy*, **86**, 95-105, doi:10.1016/j.envsci.2018.05.008.
Manouseli, D., B. Anderson and M. Nagarajan, 2018: Domestic Water Demand During Droughts in Temperate Climates: Synthesising Evidence for an Integrated Framework. *Water Resources Management*, **32**(2), 433-447, doi:10.1007/s11269-017-1818-z.
Maragno, D. et al., 2018: Fine-scale analysis of urban flooding reduction from green infrastructure: An ecosystem services approach for the management of water flows. *Ecological Modelling*, **386**, 1-10, doi:https://doi.org/10.1016/j.ecolmodel.2018.08.002.
Marani, M. et al., 2007: Biologically-controlled multiple equilibria of tidal landforms and the fate of the Venice lagoon. *Geophysical Research Letters*, **34**(11).
Marbà, N. and C. M. Duarte, 2010: Mediterranean warming triggers seagrass (Posidonia oceanica) shoot mortality. *Global Change Biology*, **16**(8), 2366-2375, doi:10.1111/j.1365-2486.2009.02130.x.
Marchal et al., 2019: The (Re)Insurance Industry's Roles in the Integration of Nature-based Solutions for Prevention in Disaster Risk Reduction—Insights from a European Survey. *Sustainability*, **11**(22), 6212, doi:10.3390/su11226212.
Marchau, V. W., Warren Bloemen, Pieter, Popper, Steven (ed.), 2019: *Decision Making under Deep Uncertainty*, Springer.
Marchenko, P. E., M. M. Gyaurgieva, P. Dzhappuev and A. M. Khutuev, 2017: Susceptibility to mudflow processes of the upper Urukh River (Republic of North Ossetia-Alania). *News of the Kabardino-Balkarian Scientific Center of the Russian Academy of Sciences*,(5), 10.
Mares, D. M. and K. W. Moffett, 2016: Climate change and interpersonal violence: a "global" estimate and regional inequities. *Climatic Change*, **135**(2), 297-310, doi:10.1007/s10584-015-1566-0.
Marine Conservation Institute, 2021: The Marine Protection Atlas. Available at https://mpatlas.org/ (accessed: 2021/06/17).
Marini, G. et al., 2020: A quantitative comparison of West Nile virus incidence from 2013 to 2018 in Emilia-Romagna, Italy. *PLOS Neglected Tropical Diseases*, **14**(1), e0007953, doi:10.1371/journal.pntd.0007953.

Markovic, D. et al., 2017: Vulnerability of European freshwater catchments to climate change. *Global change biology*, **23**(9), 3567-3580.

Marqués, L. et al., 2018: Last-century forest productivity in a managed dry-edge Scots pine population: the two sides of climate warming. *Ecological Applications*, **28**(1), 95-105, doi:10.1002/eap.1631.

Martinez-Solanas, E. et al., 2018: Evaluation of the Impact of Ambient Temperatures on Occupational Injuries in Spain. *Environmental Health Perspectives*, **126**(6), doi:10.1289/EHP2590.

Martinez, G. S. et al., 2018: Cold-related mortality vs heat -related mortality in a changing climate: A case study in Vilnius (Lithuania). *Environmental Research*, **166**, 384-393, doi:10.1016/j.envres.2018.06.001.

Martinez, G. S. et al., 2019: Heat-health action plans in Europe: Challenges ahead and how to tackle them. *Environmental Research*, **176**, 108548, doi:https://doi.org/10.1016/j.envres.2019.108548.

Marzeion, B. and A. Levermann, 2014: Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environmental Research Letters*, **9**(3), doi:10.1088/1748-9326/9/3/034001.

Massey, E., R. Biesbroek, D. Huitema and A. Jordan, 2014: Climate policy innovation: The adoption and diffusion of adaptation policies across Europe. *Global Environmental Change-Human and Policy Dimensions*, **29**, 434-443, doi:10.1016/j.gloenvcha.2014.09.002.

Matiu, M. et al., 2021: Observed snow depth trends in the European Alps: 1971 to 2019. *The Cryosphere*, **15**(3), 1343-1382, doi:10.5194/tc-15-1343-2021.

Matskovsky, V. et al., 2020: Estimated influence of extreme climate events in the 21st century on the radial growth of pine trees in Povolzhie region (European Russia). *IOP Conf. Ser.: Earth Environ. Sci.*, **611**, 012047, doi:10.1088/1755-1315/611/1/012047.

Matulla, C. et al., 2018: Climate Change driven evolution of hazards to Europe's transport infrastructure throughout the twenty-first century. *Theoretical and Applied Climatology*, **133**(1), 227-242, doi:10.1007/s00704-017-2127-4.

Mauser, H., 2021: *Key questions on forests in the EU*. Knowledge to Action, **4**, European Forest Institute. Available at: https://efi.int/publications-bank/k2a.

Maynou, F., A. Sabatés and V. Raya, 2020: Changes in the spawning habitat of two small pelagic fish in the Northwestern Mediterranean. *Fisheries Oceanography*, **29**(2), 201-213, doi:10.1111/fog.12464.

Mayr, B., T. Thaler and J. Hübl, 2020: Successful small-scale household relocation after a millennial flood event in Simbach, Germany 2016. *Water (Switzerland)*, **12**(1), doi:10.3390/w12010156.

Mazaris, A. D. et al., 2019: Threats to marine biodiversity in European protected areas. *Science of The Total Environment*, **677**, 418-426, doi:10.1016/j.scitotenv.2019.04.333 PMID - 31059884.

McCarty, J. L. et al., 2021: Reviews & Syntheses: Arctic Fire Regimes and Emissions in the 21st Century. *Biogeosciences Discuss.*, **2021**, 1-59, doi:10.5194/bg-2021-83.

McEvoy, S., M. Haasnoot and R. Biesbroek, 2021: How are European countries planning for sea level rise? *Ocean and Coastal Management*, **203**, 105512, doi:https://doi.org/10.1016/j.ocecoaman.2020.105512.

McGill, B. J., M. Dornelas, N. J. Gotelli and A. E. Magurran, 2015: Fifteen forms of biodiversity trend in the Anthropocene. *Trends in Ecology & Evolution*, **30**(2), 104-113, doi:https://doi.org/10.1016/j.tree.2014.11.006.

McKnight, B. and M. K. Linnenluecke, 2019: Patterns of Firm Responses to Different Types of Natural Disasters. *Business & Society*, **58**(4), 813-840, doi:10.1177/0007650317698946.

Medd, W. et al., 2015: The flood recovery gap: a real-time study of local recovery following the floods of June 2007 in Hull, North East England: The flood recovery gap. *Journal of Flood Risk Management*, **8**(4), 315-328, doi:10.1111/jfr3.12098.

Mees, H. and P. Driessen, 2019: A framework for assessing the accountability of local governance arrangements for adaptation to climate change. *Journal of Environmental Planning and Management*, **62**(4), 671-691, doi:10.1080/09640568.2018.1428184.

Mees, H. L. P., P. P. J. Driessen and H. A. C. Runhaar, 2014: Legitimate adaptive flood risk governance beyond the dikes: the cases of Hamburg, Helsinki and Rotterdam. *Regional Environmental Change*, **14**(2), 671-682, doi:10.1007/s10113-013-0527-2.

Mehryar, S. and S. Surminski, 2021: National laws for enhancing flood resilience in the context of climate change: potential and shortcomings. *Climate Policy*, **21**(2), 133-151, doi:10.1080/14693062.2020.1808439.

Meinel, U. and R. Schule, 2018: The Difficulty of Climate Change Adaptation in Manufacturing Firms: Developing an Action-Theoretical Perspective on the Causality of Adaptive Inaction. *Sustainability*, **10**(2), doi:10.3390/su10020569.

Mekonnen, Z. A. et al., 2021: Arctic tundra shrubification: a review of mechanisms and impacts on ecosystem carbon balance. *Environmental Research Letters*, **16**(5), 053001.

Mendoza-Tinoco, D. et al., 2020: Flood Footprint Assessment: A Multiregional Case of 2009 Central European Floods. *Risk Analysis*, **40**(8), 1612-1631, doi:10.1111/risa.13497.

Mentaschi, L. et al., 2020: Independence of Future Changes of River Runoff in Europe from the Pathway to Global Warming. *Climate*, **8**(2), 22, doi:10.3390/cli8020022.

Mentaschi, L. et al., 2018: Global long-term observations of coastal erosion and accretion. *Scientific Reports*, **8**(1), 12876, doi:10.1038/s41598-018-30904-w.

Menzel, A. et al., 2020: Climate change fingerprints in recent European plant phenology. *Global Change Biology*, **26**(4), 2599-2612, doi:https://doi.org/10.1111/gcb.15000.

Meredith, M. et al., 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Merkens, J.-L., L. Reimann, J. Hinkel and A. T. Vafeidis, 2016: Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, **145**, 57-66, doi:https://doi.org/10.1016/j.gloplacha.2016.08.009.
Merz, B. et al., 2021: Causes, impacts and patterns of disastrous river floods. *Nature Reviews Earth & Environment*, doi:10.1038/s43017-021-00195-3.
Messier, C. et al., 2019: The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, **6**(1), 21, doi:10.1186/s40663-019-0166-2.
Messina, J. P. et al., 2019: The current and future global distribution and population at risk of dengue. *Nature Microbiology*, **4**(9), 1508-1515, doi:10.1038/s41564-019-0476-8.
Metzger, J. et al., 2021: The flexibility gamble: challenges for mainstreaming flexible approaches to climate change adaptation. *Journal of Environmental Policy & Planning*, **23**(4), 543-558, doi:10.1080/1523908X.2021.1893160.
Meyerhoff, J., K. Rehdanz and A. Wunsch, 2021: Preferences for coastal adaptation to climate change: evidence from a choice experiment. *Journal of Environmental Economics and Policy*, 1-17, doi:10.1080/21606544.2021.1894990.
Míguez, B. M. et al., 2019: The European Marine Observation and Data Network (EMODnet): Visions and Roles of the Gateway to Marine Data in Europe. *Frontiers in Marine Science*, **6**, 313, doi:10.3389/fmars.2019.00313.
Miller, D. D. et al., 2018: Adaptation strategies to climate change in marine systems. *Global Change Biology*, **24**(1), e1--e14, doi:10.1111/gcb.13829.
Miller, J. L. and G. Pescaroli, 2018: Psychosocial capacity building in response to cascading disasters: A culturally informed approach. *International Journal of Disaster Risk Reduction*, **30**, 164-171, doi:10.1016/j.ijdrr.2018.04.018.
Mirra, I. M., T. M. Oliveira, A. M. G. Barros and P. M. Fernandes, 2017: Fuel dynamics following fire hazard reduction treatments in blue gum (Eucalyptus globulus) plantations in Portugal. *Forest Ecology and Management*, **398**, 185-195, doi:https://doi.org/10.1016/j.foreco.2017.05.016.
Miskic, M., G. Coric and D. Vukosavljevic, 2017: Building financial and insurance resilience in the context of climate change. *Ekonomika poljoprivrede*, **64**(3), 1019-1033, doi:10.5937/ekoPolj1703019M.
Missirian, A. and W. Schlenker, 2017: Asylum applications respond to temperature fluctuations. *Science*, **358**(6370), 1610-1613, doi:10.1126/science.aao0432.
Mitchell, D. et al., 2018: Extreme heat-related mortality avoided under Paris Agreement goals. *Nature Climate Change*, **8**(7), 551-553, doi:10.1038/s41558-018-0210-1.
Mitter, H. et al., 2019: Exploring Farmers' Climate Change Perceptions and Adaptation Intentions: Empirical Evidence from Austria. *Environmental Management*, **63**(6), 804-821, doi:10.1007/s00267-019-01158-7.
Mochizuki, J., T. Schinko and S. Hochrainer-Stigler, 2018: Mainstreaming of climate extreme risk into fiscal and budgetary planning: application of stochastic debt and disaster fund analysis in Austria. *Regional Environmental Change*, **18**(7), 2161-2172, doi:10.1007/s10113-018-1300-3.
Mokrech, M. et al., 2015: An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe. *Climatic Change*, **128**(3-4), 245-260, doi:10.1007/s10584-014-1298-6.
Molinaroli, E., S. Guerzoni and D. Suman, 2019: Do the Adaptations of Venice and Miami to Sea Level Rise Offer Lessons for Other Vulnerable Coastal Cities? *Environmental Management*, **64**(4), 391-415, doi:10.1007/s00267-019-01198-z.
Monasterolo, I., 2020: Climate Change and the Financial System. *Annual Review of Resource Economics*, **12**(1), 299-320, doi:10.1146/annurev-resource-110119-031134.
Monge-Barrio, A. and A. Sánchez-Ostiz Gutiérrez, 2018: *Passive Energy Strategies for Mediterranean Residential Buildings*. Green Energy and Technology, Springer International Publishing, Cham. ISBN 978-3-319-69882-3 978-3-319-69883-0.
Montero, J. et al., 2012: Influence of local factors in the relationship between mortality and heat waves: Castile-La Mancha (1975–2003). *Science of the Total Environment*, **414**, 73-80.
Moore, F. C. and D. B. Lobell, 2015: The fingerprint of climate trends on European crop yields. *Proceedings of the National Academy of Sciences*, **112**(9), 2670-2675, doi:10.1073/pnas.1409606112.
Morabito, M. et al., 2017: Increasing Heatwave Hazards in the Southeastern European Union Capitals. *Atmosphere*, **8**(7), doi:10.3390/atmos8070115.
Morán-Ordóñez, A. et al., 2020: Future impact of climate extremes in the Mediterranean: Soil erosion projections when fire and extreme rainfall meet. *Land Degrad Dev*, **31**(18), 3040-3054, doi:https://doi.org/10.1002/ldr.3694.
Morato, T. et al., 2020: Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. *Global Change Biology*, **26**(4), 2181-2202, doi:10.1111/gcb.14996 PMID - 32077217.
Morecroft, M. D. et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366**(6471), eaaw9256, doi:10.1126/science.aaw9256.
Moreira, F. et al., 2020: Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters*, **15**(1), 011001, doi:10.1088/1748-9326/ab541e.

Moreno-Gené, J., L. Sánchez-Pulido, E. Cristobal-Fransi and N. Daries, 2018: The Economic Sustainability of Snow Tourism: The Case of Ski Resorts in Austria, France, and Italy. *Sustainability*, **10**(9), 3012.
Moreno, A., M. Neumann and H. Hasenauer, 2018: Climate limits on European forest structure across space and time. *Global and Planetary Change*, **169**, 168-178, doi:10.1016/j.gloplacha.2018.07.018.
Moretti, A., M. Pascale and A. F. Logrieco, 2019: Mycotoxin risks under a climate change scenario in Europe. *Trends in Food Science & Technology*, **84**, 38-40, doi:10.1016/j.tifs.2018.03.008.
Morgan, E. R. et al., 2013: Global change and helminth infections in grazing ruminants in europe: Impacts, trends and sustainable solutions. *Agriculture (Switzerland)*, **3**(3), 484-502, doi:10.3390/agriculture3030484.
Morin, C. W. et al., 2018: Unexplored Opportunities: Use of Climate- and Weather-Driven Early Warning Systems to Reduce the Burden of Infectious Diseases. *Current Environmental Health Reports*, **5**(4), 430-438, doi:10.1007/s40572-018-0221-0.
Morin, S. et al., 2021: Pan-European meteorological and snow indicators of climate change impact on ski tourism. *Climate Services*, 100215, doi:https://doi.org/10.1016/j.cliser.2021.100215.
Morote, Á.-F., J. Olcina and M. Hernández, 2019: The Use of Non-Conventional Water Resources as a Means of Adaptation to Drought and Climate Change in Semi-Arid Regions: South-Eastern Spain. *Water*, **11**(1), doi:10.3390/w11010093.
Moser, S. C., 2014: Communicating adaptation to climate change: the art and science of public engagement when climate change comes home. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(3), 337-358, doi:10.1002/wcc.276.
Moullec, F. et al., 2019: An end-to-end model reveals losers and winners in a warming Mediterranean Sea. *Frontiers in Marine Science*, **6**, 1-19, doi:10.3389/fmars.2019.00345.
Moutahir, H. et al., 2017: Likely effects of climate change on groundwater availability in a Mediterranean region of Southeastern Spain. *Hydrological Processes*, **31**(1), 161-176, doi:10.1002/hyp.10988.
Müller, B. et al., 2020: Modelling Food Security: Bridging the Gap between the Micro and the Macro Scale. *Global Environmental Change*, **63**.
Mulligan, M., S. Burke and C. Douglas, 2014: Environmental Change and Migration Between Europe and Its Neighbours. In: *People on the Move in a Changing Climate: The Regional Impact of Environmental Change on Migration* [Piguet, E. and F. Laczko (eds.)]. Springer Netherlands, Dordrecht, pp. 49-79. ISBN 978-94-007-6985-4.
Mullon, C. et al., 2016: Quantitative pathways for Northeast Atlantic fisheries based on climate, ecological–economic and governance modelling scenarios. *Ecological Modelling*, **320**, 273-291, doi:10.1016/j.ecolmodel.2015.09.027.
Mulville, M. and S. Stravoravdis, 2016: The impact of regulations on overheating risk in dwellings. *Building Research & Information*, **44**(5-6), 520-534, doi:10.1080/09613218.2016.1153355.
Munari, C., 2011: Effects of the 2003 European heatwave on the benthic community of a severe transitional ecosystem (Comacchio Saltworks, Italy). *Marine Pollution Bulletin*, **62**(12), 2761--2770, doi:10.1016/j.marpolbul.2011.09.011.
Munro, A. et al., 2017: Effect of evacuation and displacement on the association between flooding and mental health outcomes: a cross-sectional analysis of UK survey data. *Lancet Planet Health*, **1**(4), 134-141.
Murrant, D., A. Quinn, L. Chapman and C. Heaton, 2017: Water use of the UK thermal electricity generation fleet by 2050: Part 1 identifying the problem. *Energy Policy*, **108**, 844-858, doi:https://doi.org/10.1016/j.enpol.2017.05.011.
Mustonen, K., T. Mustonen, J. Kirillov and S. Council, 2018: *Traditional Knowledge of Northern Waters*. Snowchange Cooperative, Kontiolahti, Finland, 39 pp. Available at: http://www.snowchange.org/pages/wp-content/uploads/2018/12/TraditionalKnowledge.pdf.
Mustonen, T., 2018: Meaningful engagement and oral histories of the indigenous peoples of the north. *Nordia Geographical Publications*, **47**(5), 21-38.
Mustonen, T. et al., 2021: *2021 Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change*. Snowchange Cooperative, Kontiolahti, Finland.
Mustonen, T. and N. Huusari, 2020: How to know about waters? Finnish traditional knowledge related to waters and implications for management reforms. *Reviews in Fish Biology and Fisheries*, **30**, 699-718, doi:10.1007/s11160-020-09619-7.
Mustonen, T. and H. Kontkanen, 2019: Safe places: Increasing Finnish waterfowl resilience through human-made wetlands. *Polar Science*, **21**, 75-84, doi:10.1016/j.polar.2019.05.007.
Myers-Smith, I. H. et al., 2020: Complexity revealed in the greening of the Arctic. *Nature Climate Change*, **10**(2), 106-117, doi:10.1038/s41558-019-0688-1.
Myers, B. J. E. et al., 2017a: Global synthesis of the documented and projected effects of climate change on inland fishes. *Reviews in Fish Biology and Fisheries*, **27**(2), 339-361, doi:10.1007/s11160-017-9476-z.
Myers, S. S. et al., 2017b: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annual Review of Public Health*, **38**(1), 259-277, doi:10.1146/annurev-publhealth-031816-044356.
Mysiak, J. and C. Perez-Blanco, 2016: Partnerships for disaster risk insurance in the EU. *Natural Hazards and Earth System Sciences*, **16**(11), 2403-2419, doi:10.5194/nhess-16-2403-2016.

Nagorny-Koring, N. C. and T. Nochta, 2018: Managing urban transitions in theory and practice - The case of the Pioneer Cities and Transition Cities projects. *Journal of Cleaner Production*, **175**, 60-69, doi:https://doi.org/10.1016/j.jclepro.2017.11.072.

Naik, V. et al., 2021: Short-Lived Climate Forcers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Narayan, S. et al., 2016: The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One*, **11**(5), e0154735, doi:10.1371/journal.pone.0154735.

Narita, D. and K. Rehdanz, 2017: Economic impact of ocean acidification on shellfish production in Europe. *Journal of Environmental Planning and Management*, **60**(3), 500-518, doi:10.1080/09640568.2016.1162705.

Naumann, G. et al., 2018: Global Changes in Drought Conditions Under Different Levels of Warming. *Geophysical Research Letters*, **45**(7), 3285-3296, doi:10.1002/2017GL076521.

Naumann, G., C. Cammalleri, L. Mentaschi and L. Feyen, 2021: Increased economic drought impacts in Europe with anthropogenic warming. *Nature Climate Change*, **11**(June), doi:10.1038/s41558-021-01044-3.

Naumann, G. et al., 2020: *Global warming and human impacts of heat and cold extremes in the EU*. **JRC118540**, Luxembourg.

Neset, T.-S. et al., 2019: Maladaptation in Nordic agriculture. *Climate Risk Management*, **23**, 78-87, doi:https://doi.org/10.1016/j.crm.2018.12.003.

Netherer, S., B. Panassiti, J. Pennerstorfer and B. Matthews, 2019: Acute Drought Is an Important Driver of Bark Beetle Infestation in Austrian Norway Spruce Stands. *Frontiers in Forests and Global Change*, **2**(39), doi:10.3389/ffgc.2019.00039.

Newson, S. E. et al., 2016: Long-term changes in the migration phenology of UK breeding birds detected by large-scale citizen science recording schemes. *Ibis*, **158**(3), 481-495, doi:https://doi.org/10.1111/ibi.12367.

Ng, A. K. Y. et al., 2018: Port decision maker perceptions on the effectiveness of climate adaptation actions. *Coastal management*, **46**(3), 148-175.

Nicholls, R. J. and A. S. Kebede, 2012: Indirect impacts of coastal climate change and sea-level rise: the UK example. *Climate Policy*, **12**(sup01), S28-S52, doi:10.1080/14693062.2012.728792.

Nicholls, R. J. et al., 2013: Planning for long-term coastal change: Experiences from England and Wales. *Ocean Engineering*, **71**, 3-16, doi:10.1016/j.oceaneng.2013.01.025.

Nielsen, A., T. Reitan, A. W. Rinvoll and A. K. Brysting, 2017: Effects of competition and climate on a crop pollinator community. *Agriculture, Ecosystems & Environment*, **246**, 253-260, doi:https://doi.org/10.1016/j.agee.2017.06.006.

Nila, M. U. S. et al., 2019: Predicting the effectiveness of protected areas of Natura 2000 under climate change. *Ecological Processes*, **8**(1), 13, doi:10.1186/s13717-019-0168-6.

Nilsen, I. B., I. Hanssen-Bauer, O. E. Tveito and W. K. Wong, 2021: Projected changes in days with zero-crossings for Norway. *International Journal of Climatology*, **41**(4), 2173-2188, doi:https://doi.org/10.1002/joc.6913.

Oberlack, C. and K. Eisenack, 2018: Archetypical barriers to adapting water governance in river basins to climate change. *Journal of Institutional Economics*, **14**(3), 527-555, doi:10.1017/S1744137417000509.

Ockendon, N. et al., 2018: One hundred priority questions for landscape restoration in Europe. *Biological Conservation*, **221**, 198-208, doi:https://doi.org/10.1016/j.biocon.2018.03.002.

OECD, 2013: *Water and Climate Change Adaptation: Policies to Navigate Uncharted Waters*. OECD Studies on Water, OECD. ISBN 978-92-64-20043-2 978-92-64-20044-9.

OECD, 2015: *Water Resources Allocation: Sharing Risks and Opportunities*. OECD Studies on Water, OECD. ISBN 978-92-64-22962-4 978-92-64-22963-1 978-92-64-23406-2.

Oesterwind, D. et al., 2020: First evidence of a new spawning stock of Illex coindetii in the North Sea (NE-Atlantic). *Fisheries Research*, **221**, 105384, doi:10.1016/j.fishres.2019.105384.

Ogar, E., G. Pecl and T. Mustonen, 2020: Science Must Embrace Traditional and Indigenous Knowledge to Solve Our Biodiversity Crisis. *One Earth*, **3**(2), 162-165, doi:10.1016/j.oneear.2020.07.006.

Ogunbode, C. A., C. Demski, S. B. Capstick and R. G. Sposato, 2019: Attribution matters: Revisiting the link between extreme weather experience and climate change mitigation responses. *Global Environmental Change*, **54**, 31-39, doi:https://doi.org/10.1016/j.gloenvcha.2018.11.005.

Ojanen, P. and K. Minkkinen, 2020: Rewetting Offers Rapid Climate Benefits for Tropical and Agricultural Peatlands But Not for Forestry-Drained Peatlands. *Global Biogeochemical Cycles*, **34**(7), doi:10.1029/2019GB006503.

Oliveira, M., C. Delerue-Matos, M. Pereira and S. Morais, 2020: Environmental Particulate Matter Levels during 2017 Large Forest Fires and Megafires in the Center Region of Portugal: A Public Health Concern? *International Journal of Environmental Research and Public Health*, **17**(3), doi:10.3390/ijerph17031032.

Oliveira, S., H. Andrade and T. Vaz, 2011: The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon. *Building and Environment*, **46**(11), 2186-2194, doi:https://doi.org/10.1016/j.buildenv.2011.04.034.

Oliver, T. H. et al., 2017: Large extents of intensive land use limit community reorganization during climate warming. *Global Change Biology*, **23**(6), 2272-2283, doi:https://doi.org/10.1111/gcb.13587.

Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities. IPCC SR Ocean and Cryosphere. In: *SROOC* [Delmotte, V. M. (ed.)], pp. 1-169. ISBN 1095-9203 (Electronic) 0036-8075 (Linking).

Orlov, A. et al., 2019: Economic Losses of Heat-Induced Reductions in Outdoor Worker Productivity: a Case Study of Europe. *EconDisCliCha*, **3**(3), 191-211, doi:10.1007/s41885-019-00044-0.

Orlova-Bienkowskaja, M. J. et al., 2020: Current range of Agrilus planipennis Fairmaire, an alien pest of ash trees, in European Russia and Ukraine. *Annals of Forest Science*, **77**(2), doi:10.1007/s13595-020-0930-z.

Orru, H. et al., 2019: Ozone and heat-related mortality in Europe in 2050 significantly affected by changes in climate, population and greenhouse gas emission. *Environmental Research Letters*, **14**(7), doi:10.1088/1748-9326/ab1cd9.

Orru, H., K. L. Ebi and B. Forsberg, 2017: The Interplay of Climate Change and Air Pollution on Health. *Current Environmental Health Reports*, **4**(4), 504-513, doi:10.1007/s40572-017-0168-6.

Orru, K., M. Tillmann, K. L. Ebi and H. Orru, 2018: Making administrative systems adaptive to emerging climate change-related health effects: Case of Estonia. *Atmosphere*, **9**(6), doi:10.3390/atmos9060221.

OSPAR, 2009: *Assessment of climate change mitigation and adaptation* [Commission, O. (ed.)]. Monitoring and Assessment Series, London, 1-41 pp. Available at: https://www.ospar.org/documents?v=7157.

Ossa-Moreno, J., K. M. Smith and A. Mijic, 2017: Economic analysis of wider benefits to facilitate SuDS uptake in London, UK. *Sustainable Cities and Society*, **28**, 411-419, doi:https://doi.org/10.1016/j.scs.2016.10.002.

Österlin, C. and K. Raitio, 2020: Fragmented Landscapes and Planscapes—The Double Pressure of Increasing Natural Resource Exploitation on Indigenous Sámi Lands in Northern Sweden. *Resources*, **9**(9), 104, doi:10.3390/resources9090104.

Outhwaite, C. et al., 2020: Complex long-term biodiversity change among invertebrates, bryophytes and lichens. *Nature Ecology & Evolution*, **4**(3), 384-+, doi:10.1038/s41559-020-1111-z.

Page, S. E. and A. J. Baird, 2016: Peatlands and Global Change: Response and Resilience. *Annu. Rev. Environ. Resour.*, **41**(1), 35-57, doi:10.1146/annurev-environ-110615-085520.

Palkowski, C., S. von Schwarzenberg and A. Simo, 2019: Seasonal cooling performance of air conditioners: The importance of independent test procedures used for MEPS and labels. *International Journal of Refrigeration*, **104**, 417-425, doi:https://doi.org/10.1016/j.ijrefrig.2019.05.021.

Palutikof, J. P., R. B. Street and E. P. Gardiner, 2019: Decision support platforms for climate change adaptation: an overview and introduction. *Climatic Change*, **153**(4), 459-476, doi:10.1007/s10584-019-02445-2.

Panagos, P. et al., 2017: Towards estimates of future rainfall erosivity in Europe based on REDES and WorldClim datasets. *Journal of Hydrology*, **548**, 251-262, doi:https://doi.org/10.1016/j.jhydrol.2017.03.006.

Panagos, P. et al., 2015a: Estimating the soil erosion cover-management factor at the European scale. *Land Use Policy*, **48**, 38-50, doi:https://doi.org/10.1016/j.landusepol.2015.05.021.

Panagos, P. et al., 2015b: The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy*, **54**, 438-447, doi:https://doi.org/10.1016/j.envsci.2015.08.012.

Pansch, C. et al., 2018: Heat waves and their significance for a temperate benthic community: A near-natural experimental approach. *Global Change Biology*, **24**(9), 4357-4367, doi:doi/10.1111/gcb.14282.

Papadaskalopoulou, C. et al., 2015a: Challenges for water resources and their management in light of climate change: the case of Cyprus. *Desalination and Water Treatment*, **53**(12), 3224-3233, doi:10.1080/19443994.2014.933619.

Papadaskalopoulou, C. et al., 2016: Review of the current EU framework on adaptation to climate change and assessment of the relative adaptation framework in Cyprus. *Desalination and Water Treatment*, **57**(5), 2219-2231, doi:10.1080/19443994.2015.1107179.

Papadaskalopoulou, C. et al., 2015b: Review and assessment of the adaptive capacity of the water sector in Cyprus against climate change impacts on water availability. *Resources, Conservation and Recycling*, **105**, 95-112, doi:https://doi.org/10.1016/j.resconrec.2015.10.017.

Papadimitriou, L., I. P. Holman, R. Dunford and P. A. Harrison, 2019: Trade-offs are unavoidable in multi-objective adaptation even in a post-Paris Agreement world. *Science of The Total Environment*, **696**, 134027-134027, doi:https://doi.org/10.1016/j.scitotenv.2019.134027.

Papalexiou, S. M. and A. Montanari, 2019: Global and Regional Increase of Precipitation Extremes Under Global Warming. *Water Resources Research*, **55**(6), 4901-4914, doi:https://doi.org/10.1029/2018WR024067.

Pape, R. and J. Löffler, 2012: Climate Change, Land Use Conflicts, Predation and Ecological Degradation as Challenges for Reindeer Husbandry in Northern Europe: What do We Really Know After Half a Century of Research? *AMBIO*, **41**(5), 421-434, doi:10.1007/s13280-012-0257-6.

Pappenberger, F. et al., 2015: The monetary benefit of early flood warnings in Europe. *Environmental Science & Policy*, **51**, 278-291, doi:10.1016/j.envsci.2015.04.016.

Paprotny, D., A. Sebastian, O. Morales-Nápoles and S. N. Jonkman, 2018a: Trends in flood losses in Europe over the past 150 years. *Nature Communications*, **9**(1), 1985, doi:10.1038/s41467-018-04253-1.

Paprotny, D. et al., 2021: Future losses of ecosystem services due to coastal erosion in Europe. *Science of The Total Environment*, **760**, 144310, doi:10.1016/j.scitotenv.2020.144310 PMID - 33341636.

Paprotny, D. et al., 2018b: Compound flood potential in Europe. *Hydrol. Earth Syst. Sci. Discuss.*, **2018**, 1-34, doi:10.5194/hess-2018-132.

Pardos, M. et al., 2021: The greater resilience of mixed forests to drought mainly depends on their composition: Analysis along a climate gradient across Europe. *Forest Ecology and Management*, **481**, 118687, doi:https://doi.org/10.1016/j.foreco.2020.118687.
Park, A. and C. Talbot, 2018: Information Underload: Ecological Complexity, Incomplete Knowledge, and Data Deficits Create Challenges for the Assisted Migration of Forest Trees. *BioScience*, **68**(4), 251-263, doi:10.1093/biosci/biy001.
Parks, D., 2019: Energy efficiency left behind? Policy assemblages in Sweden's most climate-smart city. *European Planning Studies*, **27**(2), 318-335, doi:10.1080/09654313.2018.1455807.
Parrado, R. et al., 2020: Fiscal effects and the potential implications on economic growth of sea-level rise impacts and coastal zone protection. *Climatic Change*, **160**(2), 283-302, doi:10.1007/s10584-020-02664-y.
Pasimeni, M. R., D. Valente, G. Zurlini and I. Petrosillo, 2019: The interplay between urban mitigation and adaptation strategies to face climate change in two European countries. *Environmental Science & Policy*, **95**, 20-27, doi:https://doi.org/10.1016/j.envsci.2019.02.002.
Pastor, A. V. et al., 2019: Projecting Future Impacts of Global Change Including Fires on Soil Erosion to Anticipate Better Land Management in the Forests of NW Portugal. *Water*, **11**(12), 2617, doi:10.3390/w11122617.
Patterson, J. J., 2021: More than planning: Diversity and drivers of institutional adaptation under climate change in 96 major cities. *Global Environmental Change*, **68**, 102279, doi:10.1016/j.gloenvcha.2021.102279.
Paudel, Y., W. Botzen and J. Aerts, 2015: Influence of climate change and socio-economic development on catastrophe insurance: a case study of flood risk scenarios in the Netherlands. *Regional Environmental Change*, **15**(8), 1717-1729, doi:10.1007/s10113-014-0736-3.
Pavón-Jordán, D. et al., 2020: Positive impacts of important bird and biodiversity areas on wintering waterbirds under changing temperatures throughout Europe and North Africa. *Biological Conservation*, **246**, 108549, doi:https://doi.org/10.1016/j.biocon.2020.108549.
Pawankar, R. et al., 2013: *WAO White Book on Allergy: Update 2013*. World Allergy Organization, Milwaukee, Wisconsin.
Payne, M. R. et al., 2021: Climate-risk to European fisheries and coastal communities. *Proceedings of the National Academy of Sciences*.
Paz, S., M. Negev, A. Clermont and M. Green, 2016: Health Aspects of Climate Change in Cities with Mediterranean Climate, and Local Adaptation Plans. *International Journal of Environmental Research and Public Health*, **13**(4), doi:10.3390/ijerph13040438.
Pe'er, G. et al., 2020: Action needed for the EU Common Agricultural Policy to address sustainability challenges. *People and Nature*, **2**(2), 305-316, doi:10.1002/pan3.10080.
Peaucelle, M. et al., 2019: Spatial variance of spring phenology in temperate deciduous forests is constrained by background climatic conditions. *Nature Communications*, **10**(1), 5388, doi:10.1038/s41467-019-13365-1.
Pechan, A. and K. Eisenack, 2014: The impact of heat waves on electricity spot markets. *Energy Economics*, **43**, 63-71, doi:https://doi.org/10.1016/j.eneco.2014.02.006.
Peck, M. A. et al., 2020: *Climate change and European Fisheries and Aquaculture: 'CERES' Project Synthesis Report*. Universität Hamburg. Available at: https://www.fdr.uni-hamburg.de/record/804 (accessed 2020/10/01/08:38:00).
Pedde, S. et al., 2019: Archetyping shared socioeconomic pathways across scales: an application to central Asia and European case studies. *Ecology and Society*, **24**(4), doi:10.5751/ES-11241-240430.
Pendrill, F. et al., 2019: Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change*, **56**, 1-10, doi:https://doi.org/10.1016/j.gloenvcha.2019.03.002.
Penning-Rowsell, E., 2020: Floating architecture in the landscape: climate change adaptation ideas, opportunities and challenges. *Landscape Research*, **45**(4), 395-411, doi:10.1080/01426397.2019.1694881.
Penning-Rowsell, E. C. and S. J. Priest, 2015: Sharing the burden of increasing flood risk: who pays for flood insurance and flood risk management in the United Kingdom. *Mitigation and Adaptation Strategies for Global Change*, **20**(6), 991-1009, doi:10.1007/s11027-014-9622-z.
Peñuelas, J. et al., 2017: Shifting from a fertilization-dominated to a warming-dominated period. *Nature Ecology & Evolution*, **1**(10), 1438-1445, doi:10.1038/s41559-017-0274-8.
Peñuelas, J. et al., 2018: Assessment of the impacts of climate change on Mediterranean terrestrial ecosystems based on data from field experiments and long-term monitored field gradients in Catalonia. *Environmental and Experimental Botany*, **152**, 49-59, doi:https://doi.org/10.1016/j.envexpbot.2017.05.012.
Perevedentsev, Y. P. and T. R. Aukhadeev, 2014: Features of the Wind Regime in the Volga Federal District in the Last Decade. *Bulletin of the Udmurt University. Series: Biology. Sciences about the Earth*, **2**, 112-121.
Persson, A. and A. Dzebo, 2019: Exploring global and transnational governance of climate change adaptation. *International Environmental Agreements: Politics, Law and Economics*, **volume 19**, 357 – 367.
Persson, S., D. Harnesk and M. Islar, 2017: What local people? Examining the Gállok mining conflict and the rights of the Sámi population in terms of justice and power. *Geoforum*, **86**, 20-29, doi:10.1016/j.geoforum.2017.08.009.
Pescaroli, G., 2018: Perceptions of cascading risk and interconnected failures in emergency planning: Implications for operational resilience and policy making. *International Journal of Disaster Risk Reduction*, **30**, 269-280, doi:10.1016/j.ijdrr.2018.01.019.
Peters, B., A. Jordan and J. Tosun, 2017: Over-reaction and under-reaction in climate policy: an institutional analysis. *Journal of Environmental Policy & Planning*, **19**(6), 612-624, doi:10.1080/1523908X.2017.1348225.

Petit, J. and G. Prudent, 2008: *Climate change and biodiversity in the European Union overseas entities*. IUCN. ISBN 2831713153.
Petz, K. et al., 2016: *Indicators and modelling of land use, land management and ecosystem services. Methodological documentation.*, PBL Netherlands Environmental Assessment Agency, The Hague, 109 pp. Available at: https://www.pbl.nl/sites/default/files/downloads/pbl-2016-Indicators-and-modelling-of-land-use-land-management-and-ecosystem-services-2386.pdf.
Pfleiderer, P., C.-F. Schleussner, K. Kornhuber and D. Coumou, 2019: Summer weather becomes more persistent in a 2 °C world. *Nature Climate Change*, **9**(9), 666-671, doi:10.1038/s41558-019-0555-0.
Pham, T. T. T. et al., 2021: Guidelines for co-creating climate adaptation plans for fisheries and aquaculture. *Climatic Change*, **164**(3-4), doi:10.1007/s10584-021-03041-z.
Phillips, H., 2015: The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. *Environmental Science & Policy*, **47**, 118-125, doi:10.1016/j.envsci.2014.11.003.
Pietrapertosa, F., V. Khokhlov, M. Salvia and C. Cosmi, 2018: Climate change adaptation policies and plans: A survey in 11 South East European countries. *Renewable & Sustainable Energy Reviews*, **81**, 3041-3050, doi:10.1016/j.rser.2017.06.116.
Pietrapertosa, F. et al., 2021: Multi-level climate change planning: An analysis of the Italian case. *Journal of Environmental Management*, **289**, 112469, doi:10.1016/j.jenvman.2021.112469.
Pinkse, J. and F. Gasbarro, 2019: Managing Physical Impacts of Climate Change: An Attentional Perspective on Corporate Adaptation. *Business & Society*, **58**(2), 333-368, doi:10.1177/0007650316648688.
Pinnegar, J. K. et al., 2021: Future Socio-Political Scenarios for Aquatic Resources in Europe: A Common Framework Based on Shared-Socioeconomic-Pathways (SSPs). *Frontiers in Marine Science*, **7**(February), 1-19, doi:10.3389/fmars.2020.568219.
Pinto, C. A., T. M. Silveira and S. B. Teixeira, 2020: Beach nourishment practice in mainland Portugal (1950–2017): Overview and retrospective. *Ocean & Coastal Management*, **192**, 105211, doi:10.1016/j.ocecoaman.2020.105211.
Piontek, F. et al., 2021: Integrated perspective on translating biophysical to economic impacts of climate change. *Nature Climate Change*, 1-10, doi:10.1038/s41558-021-01065-y.
Polce, C. et al., 2016: Global change impacts on ecosystem services: a spatially explicit assessment for Europe. *One Ecosystem*, **1**, e9990.
Polte, P. et al., 2021: Reduced Reproductive Success of Western Baltic Herring (Clupea harengus) as a Response to Warming Winters. *Frontiers in Marine Science*, **8**, 589242, doi:10.3389/fmars.2021.589242.
Pons, M., J. Lopez-Moreno, M. Rosas-Casals and E. Jover, 2015: The vulnerability of Pyrenean ski resorts to climate-induced changes in the snowpack. *Climatic Change*, **131**(4), 591-605, doi:10.1007/s10584-015-1400-8.
Poortinga, W. et al., 2019: Climate change perceptions and their individual-level determinants: A cross-European analysis. *Global Environmental Change*, **55**, 25-35, doi:https://doi.org/10.1016/j.gloenvcha.2019.01.007.
Poppel, B., T. Andersen, H. Beach and N. Bernard, 2015: *SLiCA: Arctic living conditions: Living conditions and quality of life among Inuit, Saami and indigenous peoples of Chukotka and the Kola Peninsula*. Nordisk Ministerråd, Copenhagen.
Porfiriev, B. et al., 2017: Climate change impact on economic growth and specific sectors' development of the Russian Arctic. *Arctic Ecology and Economy*, **4**(28), 13, doi:10.25283/2223-4594-2017-4-4-17.
Porretta, D. et al., 2013: Effects of global changes on the climatic niche of the tick Ixodes ricinus inferred by species distribution modelling. *Parasites & Vectors*, **6**, doi:10.1186/1756-3305-6-271.
Porter, J. J., D. Demeritt and S. Dessai, 2015: The right stuff? informing adaptation to climate change in British Local Government. *Global Environmental Change*, **35**, 411-422, doi:https://doi.org/10.1016/j.gloenvcha.2015.10.004.
Portmann, F. T., S. Siebert and P. Döll, 2010: MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, **24**(1), doi:https://doi.org/10.1029/2008GB003435.
Posledovich, D. et al., 2018: Phenological synchrony between a butterfly and its host plants: Experimental test of effects of spring temperature. *Journal of Animal Ecology*, **87**(1), 150-161, doi:https://doi.org/10.1111/1365-2656.12770.
Post, E. et al., 2019: The polar regions in a 2°C warmer world. *Science Advances*, **5**(12), eaaw9883, doi:10.1126/sciadv.aaw9883.
Pot, W. D. et al., 2018: What makes long-term investment decisions forward looking: A framework applied to the case of Amsterdam's new sea lock. *Technological Forecasting and Social Change*, **132**, 174-190, doi:10.1016/j.techfore.2018.01.031.
Pot, W. D., A. Dewulf, G. R. Biesbroek and S. Verweij, 2019: What makes decisions about urban water infrastructure forward looking? A fuzzy-set qualitative comparative analysis of investment decisions in 40 Dutch municipalities. *Land Use Policy*, **82**, 781-795, doi:https://doi.org/10.1016/j.landusepol.2018.12.012.
Potopová, V. et al., 2017: The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014. *International Journal of Climatology*, **37**(3), 1648-1664, doi:10.1002/joc.4807.
Pour, S. H. et al., 2020: Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges. *Sustainable Cities and Society*, **62**, 102373, doi:https://doi.org/10.1016/j.scs.2020.102373.

Pranzini, E., L. Wetzel and A. T. Williams, 2015: Aspects of coastal erosion and protection in Europe. *Journal of Coastal Conservation*, **19**(4), 445-459, doi:10.1007/s11852-015-0399-3.
Pretzsch, H. et al., 2014: Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nature Communications*, **5**(1), doi:10.1038/ncomms5967.
Primicia, I. et al., 2015: Age, competition, disturbance and elevation effects on tree and stand growth response of primary Picea abies forest to climate. *Forest Ecology and Management*, **354**, 77-86, doi:10.1016/j.foreco.2015.06.034.
Prislan, P. et al., 2019: Growing season and radial growth predicted for Fagus sylvatica under climate change. *Climatic Change*, **153**(1), 181-197, doi:10.1007/s10584-019-02374-0.
Pritchard, O. G., S. H. Hallett and T. S. Farewell, 2015: Probabilistic soil moisture projections to assess Great Britain's future clay-related subsidence hazard. *Climatic Change*, **133**(4), 635-650, doi:10.1007/s10584-015-1486-z.
Prober, S. M. et al., 2019: Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. *Ecological Monographs*, **89**(1), e01333-e01333, doi:10.1002/ecm.1333.
Promberger, M., 2017: *Resilience among vulnerable households in Europe*. IAB-Discussion Paper, No. 12/2017, Institut für Arbeitsmarkt- und Berufsforschung (IAB), Nürnberg, 44 pp.
Prudhomme, C. et al., 2014: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences*, **111**(9), 3262 LP-3267, doi:10.1073/pnas.1222473110.
Puđak, J., 2019: Lessons (not) learned on climate change adaptation policy: qualitative research on the case of floods in Western Balkan countries. *Socijalna ekologija*, **28**(1), 3-26, doi:10.17234/SocEkol.28.1.1.
Pukkala, T., 2018: Effect of species composition on ecosystem services in European boreal forest. *J. For. Res.*, **29**(2), 261-272, doi:10.1007/s11676-017-0576-3.
Pungas, L., 2019: Food self-provisioning as an answer to the metabolic rift: The case of 'Dacha Resilience' in Estonia. *Journal of Rural Studies*, **68**, 75-86, doi:10.1016/j.jrurstud.2019.02.010.
Pushnya, M. V. and Z. A. Shirinyan, 2015: A new harmful pest of soyabean in Krasnodar Territory. *Zashchita i Karantin Rasteniĭ*,(No.10), 27-29.
Pye, S. et al., 2015: *Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures: INSIGHT_E*. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/INSIGHT_E_Energy%20Poverty%20-%20Main%20Report_FINAL.pdf.
Qiu, C. et al., 2020: The role of northern peatlands in the global carbon cycle for the 21st century. *Global Ecology and Biogeography*, **29**(5), 956-973, doi:https://doi.org/10.1111/geb.13081.
Queirós, A. M., J. Fernandes, L. Genevier and C. P. Lynam, 2018: Climate change alters fish community size-structure, requiring adaptive policy targets. *Fish and Fisheries*, **19**(4), 613-621, doi:10.1111/faf.12278.
Quiroga, S. and C. Suárez, 2016: Climate change and drought effects on rural income distribution in the Mediterranean: a case study for Spain. *Natural Hazards and Earth System Sciences*, **16**(6), 1369-1385, doi:10.5194/nhess-16-1369-2016.
Radenković, S. et al., 2017: Living on the edge: Forecasting the trends in abundance and distribution of the largest hoverfly genus (Diptera: Syrphidae) on the Balkan Peninsula under future climate change. *Biological Conservation*, **212**, 216-229, doi:https://doi.org/10.1016/j.biocon.2017.06.026.
Ragazzola, F. et al., 2013: Phenotypic plasticity of coralline algae in a High CO2 world. *Ecology and Evolution*, **3**(10), 3436--3446, doi:10.1002/ece3.723.
Ragazzola, F. et al., 2016: Impact of high CO2 on the geochemistry of the coralline algae *Lithothamnion glaciale*. *Scientific Reports*, **6**, 20572, doi:10.1038/srep20572
http://www.nature.com/articles/srep20572#supplementary-information.
Raitio, K., C. Allard and R. Lawrence, 2020: Mineral extraction in Swedish Sámi: The regulatory gap between Sami rights and Sweden's mining permitting practices. *Land Use Policy*, **99**, 105001, doi:10.1016/j.landusepol.2020.105001.
Ramírez, F. et al., 2018: Spatial congruence between multiple stressors in the Mediterranean Sea may reduce its resilience to climate impacts. *Scientific Reports*, **8**(1), 14871, doi:10.1038/s41598-018-33237-w.
Ranasinghe, R. et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Randazzo, T., E. De Cian and M. N. Mistry, 2020: Air conditioning and electricity expenditure: The role of climate in temperate countries. *Economic Modelling*, **90**, 273-287, doi:10.1016/j.econmod.2020.05.001.
Ranger, N., T. Reeder and J. Lowe, 2013: Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO Journal on Decision Processes*, **1**(3), 233-262, doi:10.1007/s40070-013-0014-5.
Ranzani, A. et al., 2018: Hydropower Future: Between Climate Change, Renewable Deployment, Carbon and Fuel Prices. *Water*, **10**(9), doi:10.3390/w10091197.

Räsänen, A. et al., 2017: The need for non-climate services – Empirical evidence from Finnish municipalities. *Climate Risk Management*, **16**, 29-42, doi:https://doi.org/10.1016/j.crm.2017.03.004.

Rasmont, P. et al., 2015: Climatic Risk and Distribution Atlas of European Bumblebees. *BioRisk*, **10**, 1-236.

Rasmus, S., S. Kivinen and M. Irannezhad, 2018: Basal ice formation in snow cover in Northern Finland between 1948 and 2016. *Environmental Research Letters*, **13**(11), 114009, doi:10.1088/1748-9326/aae541.

Rasmussen, P., T. O. Sonnenborg, G. Goncear and K. Hinsby, 2013: Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer. *Hydrology and Earth System Sciences*, **17**(1), 421-443, doi:10.5194/hess-17-421-2013.

Ray, A., L. Hughes, D. M. Konisky and C. Kaylor, 2017: Extreme weather exposure and support for climate change adaptation. *Global Environmental Change*, **46**, 104-113, doi:https://doi.org/10.1016/j.gloenvcha.2017.07.002.

Ray, D. K., J. S. Gerber, G. K. MacDonald and P. C. West, 2015: Climate variation explains a third of global crop yield variability. *Nature Communications*, **6**, 5989, doi:10.1038/ncomms6989 https://www.nature.com/articles/ncomms6989#supplementary-information.

Raybaud, V., M. Bacha, R. Amara and G. Beaugrand, 2017: Forecasting climate-driven changes in the geographical range of the European anchovy (Engraulis encrasicolus). *ICES Journal of Marine Science*, **74**(5), 1288-1299, doi:10.1093/icesjms/fsx003.

Reckien, D., J. Flacke, M. Olazabal and O. Heidrich, 2015: The Influence of Drivers and Barriers on Urban Adaptation and Mitigation Plans-An Empirical Analysis of European Cities. *Plos One*, **10**(8), doi:10.1371/journal.pone.0135597.

Reckien, D. et al., 2018: How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *Journal of Cleaner Production*, **191**, 207-219, doi:10.1016/j.jclepro.2018.03.220.

Reckien, D. et al., 2019: Dedicated versus mainstreaming approaches in local climate plans in Europe. *Renewable and Sustainable Energy Reviews*, **112**, 948-959, doi:https://doi.org/10.1016/j.rser.2019.05.014.

Reimann, L., J.-L. Merkens and A. T. Vafeidis, 2018a: Regionalized Shared Socioeconomic Pathways: narratives and spatial population projections for the Mediterranean coastal zone. *Regional Environmental Change*, **18**(1), 235-245, doi:10.1007/s10113-017-1189-2.

Reimann, L. et al., 2018b: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications*, **9**(1), 4161, doi:10.1038/s41467-018-06645-9.

Remling, E., 2018: Depoliticizing adaptation: a critical analysis of EU climate adaptation policy. *Environmental Politics*, **27**(3), 477-497, doi:10.1080/09644016.2018.1429207.

Restemeyer, B., M. van den Brink and J. Woltjer, 2018: Resilience unpacked – framing of 'uncertainty' and 'adaptability' in long-term flood risk management strategies for London and Rotterdam. *European Planning Studies*, **26**(8), 1559-1579, doi:10.1080/09654313.2018.1490393.

Restemeyer, B., J. Woltjer and M. van den Brink, 2015: A strategy-based framework for assessing the flood resilience of cities – A Hamburg case study. *Planning Theory & Practice*, **16**(1), 45-62, doi:10.1080/14649357.2014.1000950.

Reusch, T. B. H. et al., 2018: The Baltic Sea as a time machine for the future coastal ocean. *Science Advances*, **4**(5), doi:10.1126/sciadv.aar8195.

Revich, B. A., V. V. Maleev and M. D. Smirnova, 2019: *Climate change and public health: assessments, indicators, predictions* [Revich, B. A. and K. A.O. (eds.)]. INP RAS, Moscow.

Rey-Valette, H., S. Robert and B. Rulleau, 2019: Resistance to relocation in flood-vulnerable coastal areas: a proposed composite index. *Climate Policy*, **19**(2), 206-218, doi:10.1080/14693062.2018.1482823.

Rey, D., I. P. Holman and J. W. Knox, 2017: Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. *Regional Environmental Change*, **17**(5), 1527-1540, doi:10.1007/s10113-017-1116-6.

Reyer, C. et al., 2014: Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. *Annals of Forest Science*, **71**(2), 211-225, doi:10.1007/s13595-013-0306-8.

Reyer, C. P. O. et al., 2017: Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environmental Research Letters*, **12**(3), 034027, doi:10.1088/1748-9326/aa5ef1.

Reyes-Paecke, S. et al., 2019: Irrigation of green spaces and residential gardens in a Mediterranean metropolis: Gaps and opportunities for climate change adaptation. *Landscape and Urban Planning*, **182**(March 2018), 34-43, doi:10.1016/j.landurbplan.2018.10.006.

Rianna, G., A. Reder, L. Pagano and P. Mercogliano, 2020: Assessing Future Variations in Landslide Occurrence Due to Climate Changes: Insights from an Italian Test Case. 255-264.

Ribas, A., J. Olcina and D. Sauri, 2020: More exposed but also more vulnerable? Climate change, high intensity precipitation events and flooding in Mediterranean Spain. *Disaster Prevention and Management: An International Journal*, **29**(3), 229-248, doi:10.1108/DPM-05-2019-0149.

Ricart, S., J. Olcina and A. Rico, 2019: Evaluating Public Attitudes and Farmers' Beliefs towards Climate Change Adaptation: Awareness, Perception, and Populism at European Level. *Land*, **8**(1), 4.

Ricart, S., J. Olcina and M. A. Rico, 2018: Evaluating Public Attitudes and Farmers' Beliefs towards Climate Change Adaptation: Awareness, Perception, and Populism at European Level. *Land*, **8**(1), doi:10.3390/land8010004.

Riebesell, U. et al., 2018: Toxic algal bloom induced by ocean acidification disrupts the pelagic food web. *Nature Sci Data*, **8**(12), 1082-1086, doi:doi/10.1038/s41558-018-0344-1.

Rilov, G. et al., 2019: Adaptive marine conservation planning in the face of climate change: What can we learn from physiological, ecological and genetic studies? *Global Ecology and Conservation*, **17**, doi:10.1016/j.gecco.2019.e00566.
Rivetti, I. et al., 2014: Global Warming and Mass Mortalities of Benthic Invertebrates in the Mediterranean Sea. *PLoS One*, **9**(12), doi:doi/10.1371/journal.pone.0115655.
Roberts, C. and F. W. Geels, 2019: Conditions for politically accelerated transitions: Historical institutionalism, the multi-level perspective, and two historical case studies in transport and agriculture. *Technological Forecasting and Social Change*, **140**, 221-240, doi:https://doi.org/10.1016/j.techfore.2018.11.019.
Roberts, C. M. et al., 2017: Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences*, **114**(24), 6167-6175, doi:10.1073/pnas.1701262114.
Robinson, J. et al., 2017: Far-field connectivity of the UK's four largest marine protected areas: Four of a kind? *Earths Future*, **5**(5), 475-494, doi:10.1002/2016ef000516.
Roebeling, P. C., L. Costa, L. Magalhaes-Filho and V. Tekken, 2013: Ecosystem service value losses from coastal erosion in Europe: historical trends and future projections. *Journal of Coastal Conservation*, **17**(3), 389--395, doi:10.1007/s11852-013-0235-6.
Rogers, K. et al., 2019: Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. *Nature*, **567**(7746), 91-95, doi:doi/10.1038/s41586-019-0951-7.
Rohat, G. et al., 2019: Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe. *Global and Planetary Change*, **172**, 45-59, doi:10.1016/j.gloplacha.2018.09.013.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163, doi:10.1016/j.crm.2017.02.001.
Roldán, E., M. Gómez, M. Pino and J. Díaz, 2015: The impact of extremely high temperatures on mortality and mortality cost. *International journal of environmental health research*, **25**(3), 277-287.
Romagosa, F. and J. Pons, 2017: Exploring local stakeholders' perceptions of vulnerability and adaptation to climate change in the Ebro delta. *Journal of Coastal Conservation*, **21**(1), 223-232, doi:10.1007/s11852-017-0493-9.
Román, M. V., I. Arto and A. Ansuategi, 2018: International trade and the distribution of economy-wide benefits from the disbursement of climate finance. *Climate and Development*, 1-16, doi:10.1080/17565529.2018.1521330.
Rosbakh, S. et al., 2021: Siberian plants shift their phenology in response to climate change. *Global Change Biology*, **27**(18), 4435-4448, doi:https://doi.org/10.1111/gcb.15744.
Rosenzweig, B. R. et al., 2018: Pluvial flood risk and opportunities for resilience. *WIREs Water*, **5**(6), e1302, doi:https://doi.org/10.1002/wat2.1302.
Roson, R. and M. Sartori, 2016: Estimation of Climate Change Damage Functions for 140 Regions in the GTAP 9 Data Base. *Journal of Global Economic Analysis; Vol 1, No 2 (2016)*, doi:10.21642/JGEA.010202AF.
Rosqvist, N. Inga and P. Eriksson, 2021: Impacts of climate warming on reindeer herding demand new land use strategies. *AMBIO*.
Rotter, M., E. Hoffmann, A. Pechan and R. Stecker, 2016: Competing priorities: how actors and institutions influence adaptation of the German railway system. *Climatic Change*, **137**(3), 609-623, doi:10.1007/s10584-016-1702-5.
Roudier, P. et al., 2016: Projections of future floods and hydrological droughts in Europe under a +2°C global warming. *Climatic Change*, **135**(2), 341-355, doi:10.1007/s10584-015-1570-4.
Rubel, F. and M. Kottek, 2010: Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift*,(2), 135-141.
Rudd, A. C. et al., 2020: Investigating potential future changes in surface water flooding hazard and impact. *Hydrological Processes*, **34**(1), 139-149, doi:10.1002/hyp.13572.
Rufat, S., E. Tate, C. T. Emrich and F. Antolini, 2019: How Valid Are Social Vulnerability Models? *Annals of the American Association of Geographers*, **109**(4), 1131-1153, doi:10.1080/24694452.2018.1535887.
Ruffault, J. et al., 2020: Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *Scientific Reports*, **10**(1), 13790, doi:10.1038/s41598-020-70069-z.
Ruiz-Díaz, R. et al., 2020: Social-ecological vulnerability to climate change in small-scale fisheries managed under spatial property rights systems. *Marine Policy*, **121**, 104192, doi:10.1016/j.marpol.2020.104192.
Ruiz-Pérez, G. and G. Vico, 2020: Effects of Temperature and Water Availability on Northern European Boreal Forests. *Frontiers in Forests and Global Change*, **3**(34), doi:10.3389/ffgc.2020.00034.
Ruiz-Ramos, M. et al., 2018: Adaptation response surfaces for managing wheat under perturbed climate and CO2 in a Mediterranean environment. *Agricultural Systems*, **159**, 260-274, doi:10.1016/j.agsy.2017.01.009.
Rumpf, S. B. et al., 2018: Range dynamics of mountain plants decrease with elevation. *Proceedings of the National Academy of Sciences*, **115**(8), 1848, doi:10.1073/pnas.1713936115.
Runhaar, H. et al., 2018: Mainstreaming climate adaptation: taking stock about "what works" from empirical research worldwide. *Regional Environmental Change*, **18**(4), 1201-1210, doi:10.1007/s10113-017-1259-5.
Russel, D. et al., 2020: Policy Coordination for National Climate Change Adaptation in Europe: All Process, but Little Power. *Sustainability*, **12**(13), doi:10.3390/su12135393.
Russo, S., J. Sillmann and E. M Fischer, 2015: Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters*, **10**(12), 124003-124003, doi:10.1088/1748-9326/10/12/124003.
Sadoff, C. W. et al., 2015: Securing water, sustaining growth: Report of the GWP. OECD task force on water security and sustainable growth.

Sadr, S. M. K. et al., 2020: Strategic planning of the integrated urban wastewater system using adaptation pathways. *Water Research*, **182**, 116013, doi:https://doi.org/10.1016/j.watres.2020.116013.
Sahyoun, R., P. Guidetti, A. Di Franco and S. Planes, 2016: Patterns of Fish Connectivity between a Marine Protected Area and Surrounding Fished Areas. *PLoS One*, **11**(12), e0167441, doi:doi/10.1371/journal.pone.0167441.
Salem, R., A. Bahadori-Jahromi and A. Mylona, 2019: Investigating the impacts of a changing climate on the risk of overheating and energy performance for a UK retirement village adapted to the nZEB standards. *Building Services Engineering Research and Technology*, **40**(4), 470-491, doi:10.1177/0143624419844753.
Salihoglu, B., S. S. Arkin, E. Akoglu and B. A. Fach, 2017: Evolution of Future Black Sea Fish Stocks under Changing Environmental and Climatic Conditions. *Frontiers in Marine Science*, **4**, 113, doi:doi/10.3389/fmars.2017.00339.
Salmoral, G. et al., 2019: A Probabilistic Risk Assessment of the National Economic Impacts of Regulatory Drought Management on Irrigated Agriculture. *Earth's Future*, **7**(2), 178-196, doi:10.1029/2018EF001092.
Samaniego, L. et al., 2018: Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, **8**(5), 421-426, doi:10.1038/s41558-018-0138-5.
San-Miguel-Ayanz, J. et al., 2019: *Forest fires in Europe, Middle East and North Africa 2018*. EUR 29856 EN, Luxembourg. Available at: https://data.europa.eu/doi/10.2760/1128 (accessed 2020/11/04/19:50:09).
Sanchez-Guevara, C. et al., 2019: Assessing population vulnerability towards summer energy poverty: Case studies of Madrid and London. *Energy and Buildings*, **190**, 132-143, doi:10.1016/j.enbuild.2019.02.024.
Sanderson, F. J. et al., 2016: Assessing the Performance of EU Nature Legislation in Protecting Target Bird Species in an Era of Climate Change. *Conservation Letters*, **9**(3), 172-180, doi:10.1111/conl.12196.
Sanderson, H. et al. (eds.), 2018: *Adapting to Climate Change in Europe. Exploring Sustainable Pathways - From Local Measures to Wider Policies*, Elsevier, 368 pp. ISBN 9780128498873.
Sandström, P. et al., 2016: On the decline of ground lichen forests in the Swedish boreal landscape: Implications for reindeer husbandry and sustainable forest management. *Ambio*, **45**(4), 415-429, doi:10.1007/s13280-015-0759-0.
Sanginés de Cárcer, P. et al., 2018: Vapor–pressure deficit and extreme climatic variables limit tree growth. *Global Change Biology*, **24**(3), 1108-1122, doi:10.1111/gcb.13973.
Sanker, C., C. Lambertz and M. Gauly, 2013: Climatic effects in Central Europe on the frequency of medical treatments of dairy cows. *Animal*, **7**(2), 316-321, doi:10.1017/S1751731112001668.
Santini, L., S. Saura and C. Rondinini, 2016: Connectivity of the global network of protected areas. *Diversity and Distributions*, **22**(2), 199-211, doi:10.1111/ddi.12390.
Sanz-Barbero, B. et al., 2018: Heat wave and the risk of intimate partner violence. *Science of the total environment*, **644**, 413-419.
Saraiva, S. et al., 2019: Uncertainties in Projections of the Baltic Sea Ecosystem Driven by an Ensemble of Global Climate Models. *Frontiers in Earth Science*, **6**, 1, doi:doi/10.3389/feart.2018.00244.
Sayol, J. M. and M. Marcos, 2018: Assessing Flood Risk Under Sea Level Rise and Extreme Sea Levels Scenarios: Application to the Ebro Delta (Spain). *Journal of Geophysical Research: Oceans*, **123**(2), 794-811, doi:10.1002/2017jc013355.
Schaffner, F. and A. Mathis, 2014: Dengue and dengue vectors in the WHO European region: past, present, and scenarios for the future. *Lancet Infectious Diseases*, **14**(12), 1271-1280, doi:10.1016/s1473-3099(14)70834-5.
Schelhaas, M. J. et al., 2015: Alternative forest management strategies to account for climate change-induced productivity and species suitability changes in Europe. *Regional Environmental Change*, **15**(8), 1581-1594, doi:10.1007/s10113-015-0788-z.
Schéré, C. M., T. P. Dawson and K. Schreckenberg, 2020: Multiple conservation designations: what impact on the effectiveness of marine protected areas in the Irish Sea? *Int J Sustain Dev World Ecol*, **27**(7), 1-15, doi:10.1080/13504509.2019.1706058.
Schewe, J. et al., 2019: State-of-the-art global models underestimate impacts from climate extremes. *Nature Communications*, **10**(1), 1005, doi:10.1038/s41467-019-08745-6.
Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, **111**(9), 3245 LP-3250, doi:10.1073/pnas.1222460110.
Schiemann, F. and A. Sakhel, 2018: Carbon Disclosure, Contextual Factors, and Information Asymmetry: The Case of Physical Risk Reporting. *European Accounting Review*, 1-28, doi:10.1080/09638180.2018.1534600.
Schifano, P. et al., 2012: Changes in the effects of heat on mortality among the elderly from 1998–2010: results from a multicenter time series study in Italy. *Environmental Health*, **11**(1), 58.
Schinko, T., R. Mechler and S. Hochrainer-Stigler, 2017: A methodological framework to operationalize climate risk management: managing sovereign climate-related extreme event risk in Austria. *Mitigation and Adaptation Strategies For Global Change*, **22**(7), 1063-1086, doi:10.1007/s11027-016-9713-0.
Schleussner, C.-F. et al., 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5°C and 2°C. *Earth System Dynamics*, **7**(2), 327-351, doi:10.5194/esd-7-327-2016.
Schleypen, J. R., M. N. Mistry, F. Saeed and S. Dasgupta, 2021: Sharing the burden: quantifying climate change spillovers in the European Union under the Paris Agreement. *Spatial Economic Analysis*, 1-16, doi:10.1080/17421772.2021.1904150.
Schlogl, M. and C. Matulla, 2018: Potential future exposure of European land transport infrastructure to rainfall-induced landslides throughout the 21st century. *Natural Hazards and Earth System Sciences*, **18**(4), 1121-1132, doi:10.5194/nhess-18-1121-2018.

Schöner, W. et al., 2019: Spatiotemporal patterns of snow depth within the Swiss-Austrian Alps for the past half century (1961 to 2012) and linkages to climate change. *International Journal of Climatology*, **39**(3), 1589-1603, doi:10.1002/joc.5902.
Schuerch, M. et al., 2018: Future response of global coastal wetlands to sea-level rise. *Nature*, **561**(7722), 231-234, doi:doi/10.1038/s41586-018-0476-5.
Schuldt, B. et al., 2020: A first assessment of the impact of the extreme 2018 summer drought on Central European forests. *Basic and Applied Ecology*, **45**, 86-103, doi:https://doi.org/10.1016/j.baae.2020.04.003.
Schuster, C., J. Honold, S. Lauf and T. Lakes, 2017: Urban heat stress: novel survey suggests health and fitness as future avenue for research and adaptation strategies. *Environmental Research Letters*, **12**(4), 044021, doi:10.1088/1748-9326/aa5f35.
Scott, D., M. Rutty, B. Amelung and M. Tang, 2016: An Inter-Comparison of the Holiday Climate Index (HCI) and the Tourism Climate Index (TCI) in Europe. *Atmosphere*, **7**(6), 80.
Scott, D., R. Steiger, H. Dannevig and C. Aall, 2019: Climate change and the future of the Norwegian alpine ski industry. *Current Issues in Tourism*, 1-14, doi:10.1080/13683500.2019.1608919.
Scoville-Simonds, M., H. Jamali and M. Hufty, 2020: The Hazards of Mainstreaming: Climate change adaptation politics in three dimensions. *World Development*, **125**, 104683, doi:10.1016/j.worlddev.2019.104683.
Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Phil. Trans. R. Soc. B*, **375**, 2019012020190120, doi:http://doi.org/10.1098/rstb.2019.0120.
Sedlmeier, K., H. Feldmann and G. Schädler, 2018: Compound summer temperature and precipitation extremes over central Europe. *Theoretical and Applied Climatology*, **131**(3), 1493-1501, doi:10.1007/s00704-017-2061-5.
Sedmáková, D. et al., 2019: Growth-climate responses indicate shifts in the competitive ability of European beech and Norway spruce under recent climate warming in East-Central Europe. *Dendrochronologia*, **54**, 37-48, doi:https://doi.org/10.1016/j.dendro.2019.02.001.
Seebauer, S. and C. Winkler, 2020: Should I stay or should I go? Factors in household decisions for or against relocation from a flood risk area. *Global Environmental Change*, **60**, 102018, doi:https://doi.org/10.1016/j.gloenvcha.2019.102018.
Šeho, M., S. Ayan, G. Huber and G. Kahveci, 2019: A Review on Turkish Hazel (Corylus colurna L.): A Promising Tree Species for Future Assisted Migration Attempts. *South-east European forestry*, **10**(1), 53-63, doi:https://doi.org/10.15177/seefor.19-04.
Seibold, S. et al., 2019: Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature*, **574**(7780), 671-+, doi:10.1038/s41586-019-1684-3.
Seidl, R., M.-J. Schelhaas, W. Rammer and P. J. Verkerk, 2014: Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change*, **4**(9), 806-810, doi:10.1038/nclimate2318.
Selby, J., O. S. Dahi, C. Fröhlich and M. Hulme, 2017: Climate change and the Syrian civil war revisited. *Political Geography*, **60**, 232-244, doi:10.1016/j.polgeo.2017.05.007.
Selig, E. R. et al., 2014: Global Priorities for Marine Biodiversity Conservation. *PLoS One*, **9**(1), doi:10.1371/journal.pone.0082898.
Semenza, J. and J. Suk, 2018: Vector-borne diseases and climate change: a European perspective. *Fems Microbiology Letters*, **365**(2), doi:10.1093/femsle/fnx244.
Semenza, J. et al., 2016: Climate change projections of West Nile virus infections in Europe: implications for blood safety practices. *Environmental Health*, **15**, doi:10.1186/s12940-016-0105-4.
Semenza, J. C., 2020: Cascading risks of waterborne diseases from climate change. *Nat Immunol*, **21**(5), 484-487, doi:10.1038/s41590-020-0631-7.
Semenza, J. C. and S. Paz, 2021: Climate Change and Infectious Disease in Europe: Impact, Projection and Adaptation. *The Lancet Regional Health – Europe.*, doi:https://doi.org.10.1016/j.lanepe.2021.100204.
Semenza, J. C. et al., 2017: Environmental Suitability of Vibrio Infections in a Warming Climate: An Early Warning System. *Environmental Health Perspectives*, **125**(10), 107004.
Senapati, N., P. Stratonovitch, M. J. Paul and M. A. Semenov, 2019: Drought tolerance during reproductive development is important for increasing wheat yield potential under climate change in Europe. *Journal of Experimental Botany*, **70**(9), 2549-2560, doi:10.1093/jxb/ery226.
Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Senf, C. et al., 2018: Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nature Communications*, **9**(1), 4978, doi:10.1038/s41467-018-07539-6.
Sergienko, V. G. and A. V. Konstantinov, 2016: Forecast of influence of climate change on ecosystems and natural diversity species of Russian flora and fauna biotic complexes. *Proceedings of the St. Petersburg Research Institute of Forestry*,(2), 29-44.
Serpa, D. et al., 2015: Impacts of climate and land use changes on the hydrological and erosion processes of two contrasting Mediterranean catchments. *Science of The Total Environment*, **538**, 64-77, doi:https://doi.org/10.1016/j.scitotenv.2015.08.033.

Sesana, E., A. Gagnon, C. Bertolin and J. Hughes, 2018: Adapting Cultural Heritage to Climate Change Risks: Perspectives of Cultural Heritage Experts in Europe. *Geosciences*, **8**(8), 305, doi:10.3390/geosciences8080305.
Sesana, E., A. S. Gagnon, A. Bonazza and J. J. Hughes, 2020: An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *Journal of Cultural Heritage*, **41**, 211-224, doi:10.1016/j.culher.2019.06.013.
Settele, J., J. Bishop and S. G. Potts, 2016: Climate change impacts on pollination. *Nature Plants*, **2**(7), 16092-16092, doi:10.1038/nplants.2016.92.
Sguotti, C. et al., 2019: Non-linearity in stock–recruitment relationships of Atlantic cod: insights from a multi-model approach. *ICES Journal of Marine Science*, **77**(4), 1492-1502, doi:10.1093/icesjms/fsz113.
Sharifi, A., 2021: Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. *Science of The Total Environment*, **750**, 141642, doi:https://doi.org/10.1016/j.scitotenv.2020.141642.
Sheil, D. and F. Bongers, 2020: Interpreting forest diversity-productivity relationships: volume values, disturbance histories and alternative inferences. *Forest Ecosystems*, **7**(1), doi:10.1186/s40663-020-0215-x.
Shen, J. et al., 2020: An early-stage analysis of climate-adaptive designs for multi-family buildings under future climate scenario: Case studies in Rome, Italy and Stockholm, Sweden. *Journal of Building Engineering*, **27**, 100972, doi:https://doi.org/10.1016/j.jobe.2019.100972.
Sheridan, S. and M. Allen, 2018: Temporal trends in human vulnerability to excessive heat. *Environmental Research Letters*, **13**(4), doi:10.1088/1748-9326/aab214.
Shiklomanov, N. I., D. A. Streletskiy, T. B. Swales and V. A. Kokorev, 2017: Climate Change and Stability of Urban Infrastructure in Russian Permafrost Regions: Prognostic Assessment based on GCM Climate Projections. *Geographical Review*, **107**(1), 125-142, doi:10.1111/gere.12214.
Sieber, I. M., P. A. Borges and B. Burkhard, 2018: Hotspots of biodiversity and ecosystem services: the Outermost Regions and Overseas Countries and Territories of the European Union. *One Ecosystem 3 (2018)*.
Siebert, S., H. Webber, G. Zhao and F. Ewert, 2017: Heat stress is overestimated in climate impact studies for irrigated agriculture. *Environmental Research Letters*, **12**(5), 054023, doi:10.1088/1748-9326/aa702f.
Sieg, T. et al., 2019: Integrated assessment of short-term direct and indirect economic flood impacts including uncertainty quantification. *PLOS ONE*, **14**(4), e0212932, doi:10.1371/journal.pone.0212932.
Sierra, J. et al., 2016: Vulnerability of Catalan (NW Mediterranean) ports to wave overtopping due to different scenarios of sea level rise. *Regional Environmental Change*, **16**(5), 1457-1468, doi:10.1007/s10113-015-0879-x.
Silanikove, N. and D. N. Koluman, 2015: Impact of climate change on the dairy industry in temperate zones: Predications on the overall negative impact and on the positive role of dairy goats in adaptation to earth warming. *Small Ruminant Research*, **123**(1), 27-34, doi:10.1016/j.smallrumres.2014.11.005.
Silva, R. et al., 2017: Future global mortality from changes in air pollution attributable to climate change. *Nature Climate Change*, **7**(9), 647-651, doi:10.1038/NCLIMATE3354.
Simonet, G. and S. Fatorić, 2016: Does "adaptation to climate change" mean resignation or opportunity? *Regional Environmental Change*, **16**(3), 789-799, doi:10.1007/s10113-015-0792-3.
Singh, C. et al., 2020: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Climatic Change*, **162**(2), 255-277, doi:10.1007/s10584-020-02762-x.
Sitnov, S. A., I. I. Mokhov and A. V. Jola, 2017: Influence of Siberian fires on carbon monoxide content in the atmosphere over the European part of Russia in the summer of 2016. *Optics of the atmosphere and ocean*, **30**(2), 146-152.
Skarin, A. and B. Åhman, 2014: Do human activity and infrastructure disturb domesticated reindeer? The need for the reindeer's perspective. *Polar Biology*, **37**(7), 1041-1054, doi:10.1007/s00300-014-1499-5.
Skarin, A. et al., 2015: Wind farm construction impacts reindeer migration and movement corridors. *Landscape Ecology*, **30**(8), 1527-1540, doi:10.1007/s10980-015-0210-8.
Skougaard Kaspersen, P. et al., 2017: Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding. *Hydrol. Earth Syst. Sci.*, **21**(8), 4131-4147, doi:10.5194/hess-21-4131-2017.
Slagstad, D., I. H. Ellingsen and P. Wassmann, 2011: Evaluating primary and secondary production in an Arctic Ocean void of summer sea ice: An experimental simulation approach. *Progress in Oceanography*, **90**(1-4), 117-131, doi:10.1016/j.pocean.2011.02.009.
Slavíková, L., T. Hartmann and T. Thaler, 2020: Financial schemes for resilient flood recovery. *Environmental Hazards*, **19**(3), 223-227, doi:10.1080/17477891.2019.1703624.
Slezakova, K., S. Morais and M. Pereira, 2013: Forest fires in Northern region of Portugal: Impact on PM levels. *Atmospheric Research*, **127**, 148-153, doi:10.1016/j.atmosres.2012.07.012.
Smale, D. A., 2020: Impacts of ocean warming on kelp forest ecosystems. *New Phytologist*, **225**(4), 1447-1454, doi:doi/10.1111/nph.16107.
Smale, D. A. et al., 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9**(4), 306-312, doi:10.1038/s41558-019-0412-1.
Smale, D. A., A. L. E. Yunnie, T. Vance and S. Widdicombe, 2015: Disentangling the impacts of heat wave magnitude, duration and timing on the structure and diversity of sessile marine assemblages. *PeerJ*, **3**(1628), doi:10.7717/peerj.863.

Smid, M. et al., 2019: Ranking European capitals by exposure to heat waves and cold waves. *Urban Climate*, **27**, 388-402, doi:https://doi.org/10.1016/j.uclim.2018.12.010.
Soares, M. and C. Buontempo, 2019: Challenges to the sustainability of climate services in Europe. *Wiley Interdisciplinary Reviews-Climate Change*, **10**(4), doi:10.1002/wcc.587.
Solidoro, C. et al., 2010: Response of Venice Lagoon ecosystem to natural and anthropogenic pressures over the last 50 years. *Coastal lagoons: critical habitats of environmental change*, 483-511.
Solovyev, B. et al., 2017: Identifying a network of priority areas for conservation in the Arctic seas: Practical lessons from Russia. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **27**(1), 30--51, doi:10.1002/aqc.2806.
Soroye, P., T. Newbold and J. Kerr, 2020: Climate change contributes to widespread declines among bumble bees across continents. *Science*, **367**(6478), 685, doi:10.1126/science.aax8591.
Spandre, P., H. François, E. George-Marcelpoil and S. Morin, 2016: Panel based assessment of snow management operations in French ski resorts. *Journal of Outdoor Recreation and Tourism*, **16**, 24-36, doi:https://doi.org/10.1016/j.jort.2016.09.002.
Spandre, P. et al., 2019: Winter tourism under climate change in the Pyrenees and the French Alps: relevance of snowmaking as a technical adaptation. *The Cryosphere*, **13**(4), 1325-1347, doi:10.5194/tc-13-1325-2019.
Spekkers, M. et al., 2017: A comparative survey of the impacts of extreme rainfall in two international case studies. *Nat. Hazards Earth Syst. Sci.*, **17**(8), 1337-1355, doi:10.5194/nhess-17-1337-2017.
Spencer, T., M. Schuerch, R. J. Nicholls and J. H. G. a. Planetary, 2016: Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. *Marine Policy*, **139**, 15-30, doi:doi/10.1016/j.gloplacha.2015.12.018.
Spijkers, J. and W. J. Boonstra, 2017: Environmental change and social conflict: the northeast Atlantic mackerel dispute. *Regional Environmental Change*, **17**(6), 1835-1851, doi:10.1007/s10113-017-1150-4.
Spinoni, J. et al., 2020: Future Global Meteorological Drought Hot Spots: A Study Based on CORDEX Data. *Journal of Climate*, **33**(9), 3635-3661, doi:10.1175/JCLI-D-19-0084.1.
Spinoni, J., J. Vogt and P. Barbosa, 2015: European degree-day climatologies and trends for the period 1951–2011. *International Journal of Climatology*, **35**(1), 25-36, doi:10.1002/joc.3959.
Spinoni, J. et al., 2018: Changes of heating and cooling degree-days in Europe from 1981 to 2100. *International Journal of Climatology*, **38**, E191-E208, doi:10.1002/joc.5362.
Spivak, A. C. et al., 2019: Global-change controls on soil-carbon accumulation and loss in coastal vegetated ecosystems. *Nature Geoscience*, ***12***(9), 685–692, doi:10.1038/s41561-019-0435-2.
Springmann, M. et al., 2016: Global and regional health effects of future food production under climate change: a modelling study. *Lancet*, **387**(10031), 1937-1946, doi:10.1016/S0140-6736(15)01156-3.
Sswat, M. et al., 2018a: Growth performance and survival of larval Atlantic herring, under the combined effects of elevated temperatures and CO2. *PLoS One*, **13**(1), e0191947, doi:doi/10.1371/journal.pone.0191947.
Sswat, M. et al., 2018b: Food web changes under ocean acidification promote herring larvae survival. *Nature Ecology & Evolution*, **2**(5), 836-840, doi:doi/10.1038/s41559-018-0514-6.
Stahl, K. et al., 2016: Impacts of European drought events: insights from an international database of text-based reports. *Natural Hazards and Earth System Sciences*, **16**(3), 801-819, doi:10.5194/nhess-16-801-2016.
Stanev, E. V. et al., 2018: Understanding the Dynamics of the Oxic-Anoxic Interface in the Black Sea. *Geophysical Research Letters*, **45**(2), 864--871, doi:10.1002/2017GL076206.
Stecf, 2019: Monitoring the performance of the Common Fisheries Policy. Publications Office of the European Union, Luxembourg.
Steele, D. J. et al., 2019: Management and drivers of change of pollinating incests and pollination services. *The Department for Environment, Food and Rural Affairs, UK*,(January).
Steiger, R., E. Posch, G. Tappeiner and J. Walde, 2020: The impact of climate change on demand of ski tourism - a simulation study based on stated preferences. *Ecological Economics*, **170**, 106589, doi:https://doi.org/10.1016/j.ecolecon.2019.106589.
Steiger, R. and D. Scott, 2020: Ski tourism in a warmer world: Increased adaptation and regional economic impacts in Austria. *Tourism Management*, **77**, 104032, doi:https://doi.org/10.1016/j.tourman.2019.104032.
Steiger, R. et al., 2019: A critical review of climate change risk for ski tourism. *Current Issues in Tourism*, **22**(11), 1343-1379, doi:10.1080/13683500.2017.1410110.
Steinhäuser, J. M. and K. Eisenack, 2020: How market design shapes the spatial distribution of power plant curtailment costs. *Energy Policy*, **144**, 111591, doi:https://doi.org/10.1016/j.enpol.2020.111591.
Steurer, R. and C. Clar, 2018: The ambiguity of federalism in climate policy-making: how the political system in Austria hinders mitigation and facilitates adaptation. *Journal of Environmental Policy & Planning*, **20**(2), 252-265, doi:10.1080/1523908X.2017.1411253.
Stiasny, M. H. et al., 2018: Effects of parental acclimation and energy limitation in response to high CO2 exposure in Atlantic cod. *Scientific Reports*, **8**(1), 8348, doi:10.1038/s41598-018-26711-y.
Stiasny, M. H. et al., 2019: Divergent responses of Atlantic cod to ocean acidification and food limitation. *Global Change Biology*, **25**(3), 839-849, doi:10.1111/gcb.14554.
Stive, M. J. F. et al., 2013: A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. *Journal of Coastal Research*, 1001-1008, doi:10.2112/JCOASTRES-D-13-00070.1.

Stoerk, T., G. Wagner and R. E. T. Ward, 2018: Policy Brief—Recommendations for Improving the Treatment of Risk and Uncertainty in Economic Estimates of Climate Impacts in the Sixth Intergovernmental Panel on Climate Change Assessment Report. *Review of Environmental Economics and Policy*, **12**(2), 371-376, doi:10.1093/reep/rey005.
Stoffel, M., D. Tiranti and C. Huggel, 2014: Climate change impacts on mass movements — Case studies from the European Alps. *Science of The Total Environment*, **493**, 1255-1266, doi:https://doi.org/10.1016/j.scitotenv.2014.02.102.
Stojanov, R. et al., 2015: Adaptation to the Impacts of Climate Extremes in Central Europe: A Case Study in a Rural Area in the Czech Republic. *Sustainability*, **7**(9), doi:10.3390/su70912758.
Storbjörk, S. and M. Hjerpe, 2021: Climate-proofing coastal cities: What is needed to go from envisioning to enacting multifunctional solutions for waterfront climate adaptation? *Ocean & Coastal Management*, **210**, 105732, doi:10.1016/j.ocecoaman.2021.105732.
Street, R. B., 2016: Towards a leading role on climate services in Europe: a research and innovation roadmap. *Climate Services*, **1**, 2-5.
Streletskiy, D. A. et al., 2019: Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. *Environmental Research Letters*, **14**(2), 025003, doi:10.1088/1748-9326/aaf5e6.
Stripple, J. and H. Bulkeley, 2019: Towards a material politics of socio-technical transitions: Navigating decarbonisation pathways in Malmö. *Political Geography*, **72**, 52-63, doi:https://doi.org/10.1016/j.polgeo.2019.04.001.
Sudre, B. et al., 2013: Mapping Environmental Suitability for Malaria Transmission, Greece. *Emerging Infectious Diseases*, **19**(5), 784-786, doi:10.3201/eid1905.120811.
Suggitt, A. J. et al., 2018: Extinction risk from climate change is reduced by microclimatic buffering. *Nature Climate Change*, **8**(8), 713--717, doi:10.1038/s41558-018-0231-9.
Surminski, S., 2018: Fit for Purpose and Fit for the Future? An Evaluation of the UK's New Flood Reinsurance Pool. *Risk Management and Insurance Review*, **21**(1), 33-72, doi:10.1111/rmir.12093.
Surminski, S. et al., 2015: Reflections on the current debate on how to link flood insurance and disaster risk reduction in the European Union. *Natural Hazards*, **79**(3), 1451-1479, doi:10.1007/s11069-015-1832-5.
Svetlitchnyi, O., 2020: Long-term forecast of changes in soil erosion losses during spring snowmelt caused by climate within the plain part of Ukraine *Journal of Geology, Geography and Geoecology* **29**(3), 591-605, doi:https://doi.org/10.15421/112054.
Swinburn, B. et al., 2019: The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report. *Lancet*, **393**(10173), 791-846, doi:10.1016/S0140-6736(18)32822-8.
Swinnen, J. et al., 2017: Production potential in the "bread baskets" of Eastern Europe and Central Asia. *Global Food Security*, **14**(September 2016), 38-53, doi:10.1016/j.gfs.2017.03.005.
Szabó, B., E. Vincze and B. Czúcz, 2016: Flowering phenological changes in relation to climate change in Hungary. *Int J Biometeorol*, **60**(9), 1347-1356, doi:10.1007/s00484-015-1128-1.
Szewczyk, W., J. C. Ciscar, I. Mongelli and A. Soria, 2018: *JRC PESETA III project: Economic integration and spillover analysis, EUR 29456 EN*. Luxembourg. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113810/kjna29456enn_jrc113810.pdf.
Szewczyk, W. et al., 2020: *Economic analysis of selected climate impacts: JRC PESETA IV project : Task 14*. Luxembourg. ISBN 978-92-76-18459-1.
Takakura, J. y. et al., 2017: Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation. *Environmental Research Letters*, **12**(6), 064010, doi:10.1088/1748-9326/aa72cc.
Tanneberger, F. et al., 2017: The peatland map of Europe. *Mires and Peat*, **19**(2015), 1-17, doi:10.19189/MaP.2016.OMB.264.
Tanner, S. E. et al., 2019: Regional climate, primary productivity and fish biomass drive growth variation and population resilience in a small pelagic fish. *Ecological Indicators*, **103**, 530-541, doi:10.1016/j.ecolind.2019.04.056.
Tapia, C. et al., 2017: Profiling urban vulnerabilities to climate change: An indicator-based vulnerability assessment for European cities. *Ecological Indicators*, **78**, 142-155, doi:10.1016/j.ecolind.2017.02.040.
Tarin-Carrasco, P. et al., 2021: Contribution of fine particulate matter to present and future premature mortality over Europe: A non-linear response. *Environment International*, **153**, doi:10.1016/j.envint.2021.106517.
Taucher, J. et al., 2020: Changing carbon-to-nitrogen ratios of organic-matter export under ocean acidification. *Nature Climate Change*, **2**, 1-6, doi:doi/10.1038/s41558-020-00915-5.
Taylor, A. L., S. Dessai and W. Bruine de Bruin, 2014: Public perception of climate risk and adaptation in the UK: A review of the literature. *Climate Risk Management*, **4-5**, 1-16, doi:https://doi.org/10.1016/j.crm.2014.09.001.
Taylor, R. et al., 2020: Surveying perceptions and practices of high-end climate change. *Climatic Change*, **161**(1), 65-87, doi:10.1007/s10584-020-02659-9.
TCFD, 2017: *Implementing the Recommendations of the Task Force on Climate related Financial Disclosures*. Available at: https://www.fsb-tcfd.org/wp-content/uploads/2017/12/FINAL-TCFD-Annex-Amended-121517.pdf (accessed 2019/08/25/09:24:59).
Teatini, P. et al., 2011: A new hydrogeologic model to predict anthropogenic uplift of Venice. *Water Resources Research*, **47**(12).

TEG, 2019: *Taxonomy. Technical Report*. EU Technical Expert Group on Sustainable Finance, Brussels. Available at: https://ec.europa.eu/info/sites/info/files/business_economy_euro/banking_and_finance/documents/190618-sustainable-finance-teg-report-taxonomy_en.pdf (accessed 2019/08/21/20:43:23).

Tei, S. et al., 2017: Tree-ring analysis and modeling approaches yield contrary response of circumboreal forest productivity to climate change. *Global Change Biology*, **23**(12), 5179-5188, doi:https://doi.org/10.1111/gcb.13780.

Teixeira, C. M. et al., 2016: Environmental influence on commercial fishery landings of small pelagic fish in Portugal. *Regional Environmental Change*, **16**(3), 709-716, doi:10.1007/s10113-015-0786-1.

Teotónio, C., M. Rodríguez, P. Roebeling and P. Fortes, 2020: Water competition through the 'water-energy' nexus: Assessing the economic impacts of climate change in a Mediterranean context. *Energy Economics*, **85**, 104539, doi:https://doi.org/10.1016/j.eneco.2019.104539.

Terama, E. et al., 2019: Modelling population structure in the context of urban land use change in Europe. *Regional Environmental Change*, **19**(3), 667-677, doi:10.1007/s10113-017-1194-5.

Termeer, C., R. Biesbroek and M. van den Brink, 2012: Institutions for Adaptation to Climate Change: Comparing National Adaptation Strategies in Europe. *European Political Science*, **11**(1), 41-53, doi:10.1057/eps.2011.7.

Termeer, C. J. A. M. and A. Dewulf, 2018: A small wins framework to overcome the evaluation paradox of governing wicked problems. *Policy and Society*, 1-17, doi:10.1080/14494035.2018.1497933.

Termeer, C. J. A. M., A. Dewulf and G. R. Biesbroek, 2017: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management*, **60**(4), 558-576, doi:10.1080/09640568.2016.1168288.

Terorotua, H., V. K. E. Duvat, A. Maspataud and J. Ouriqua, 2020: Assessing Perception of Climate Change by Representatives of Public Authorities and Designing Coastal Climate Services: Lessons Learnt From French Polynesia. *Frontiers in Marine Science*, **7**, doi:10.3389/fmars.2020.00160.

Terres, J.-M. et al., 2015: Farmland abandonment in Europe: Identification of drivers and indicators, and development of a composite indicator of risk. *Land Use Policy*, **49**, 20-34, doi:https://doi.org/10.1016/j.landusepol.2015.06.009.

Teuling, A. J. et al., 2017: Observational evidence for cloud cover enhancement over western European forests. *Nature Communications*, **8**, 14065, doi:10.1038/ncomms14065
https://www.nature.com/articles/ncomms14065#supplementary-information.

Thackeray, S. J. et al., 2016: Phenological sensitivity to climate across taxa and trophic levels. *Nature*, **535**(7611), 241-U294, doi:10.1038/nature18608.

Thaler, T., 2021: Just retreat—how different countries deal with it: examples from Austria and England. *Journal of Environmental Studies and Sciences*, **3**(14), 412-419, doi:10.1007/s13412-021-00694-1.

Thaler, T. et al., 2019: Drivers and barriers of adaptation initiatives - How societal transformation affects natural hazard management and risk mitigation in Europe. *Science of the Total Environment*, **650**, 1073-1082, doi:10.1016/j.scitotenv.2018.08.306.

Thaler, T. and S. Fuchs, 2020: Financial recovery schemes in Austria: how planned relocation is used as an answer to future flood events. *Environmental Hazards*, **19**(3), 268-284, doi:10.1080/17477891.2019.1665982.

Thieblemont, R. et al., 2019: Likely and High-End Impacts of Regional Sea-Level Rise on the Shoreline Change of European Sandy Coasts Under a High Greenhouse Gas Emissions Scenario. *Water*, **11**(12), doi:10.3390/w11122607.

Thiery, W. et al., 2021: Age-dependent extreme event exposure. *Science*.

Thompson, M. P. and D. E. Calkin, 2011: Uncertainty and risk in wildland fire management: A review. *Journal of Environmental Management*, **92**(8), 1895-1909, doi:https://doi.org/10.1016/j.jenvman.2011.03.015.

Thomsen, J. et al., 2013: Food availability outweighs ocean acidification effects in juvenile Mytilus edulis: laboratory and field experiments. *Global Change Biology*, **19**(4), 1017--1027, doi:10.1111/gcb.12109.

Thomsen, J. et al., 2017: Naturally acidified habitat selects for ocean acidification-tolerant mussels. *Science Advances*, **3**(4), e1602411, doi:10.1126/sciadv.1602411.

Thomson, H., N. Simcock, S. Bouzarovski and S. Petrova, 2019: Energy poverty and indoor cooling: An overlooked issue in Europe. *Energy and Buildings*, **196**, 21-29, doi:https://doi.org/10.1016/j.enbuild.2019.05.014.

Tian, Q., G. Huang, K. M. Hu and D. Niyogi, 2019: Observed and global climate model based changes in wind power potential over the Northern Hemisphere during 1979-2016. *Energy*, **167**, 1224-1235, doi:10.1016/j.energy.2018.11.027.

Tian, Z., S. Zhang, J. Deng and B. Dorota Hrynyszyn, 2020: Evaluation on Overheating Risk of a Typical Norwegian Residential Building under Future Extreme Weather Conditions. *Energies*, **13**(3), 658.

Tiggeloven, T. et al., 2020: Global-scale benefit–cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. *Natural Hazards and Earth System Sciences*, **20**(4), 1025-1044, doi:https://doi.org/10.5194/nhess-20-1025-2020.

Tillson, A.-A., T. Oreszczyn and J. Palmer, 2013: Assessing impacts of summertime overheating: some adaptation strategies. *Building Research & Information*, **41**(6), 652-661, doi:10.1080/09613218.2013.808864.

Tjaden, N. et al., 2017: Modelling the effects of global climate change on Chikungunya transmission in the 21st century. *Scientific Reports*, **7**, doi:10.1038/s41598-017-03566-3.

Tobin, I. et al., 2016: Climate change impacts on the power generation potential of a European mid-century wind farms scenario. *Environmental Research Letters*, **11**(3), doi:10.1088/1748-9326/11/3/034013.

Todd, N. and A.-J. Valleron, 2015: Space–Time Covariation of Mortality with Temperature: A Systematic Study of Deaths in France, 1968–2009. *Environmental Health Perspectives*, **123**(7), 659-664, doi:10.1289/ehp.1307771.
Toimil, A., P. Diaz-Simal, I. Losada and P. Camus, 2018: Estimating the risk of loss of beach recreation value under climate change. *Tourism Management*, **68**, 387-400, doi:10.1016/j.tourman.2018.03.024.
Tokarevich, N. et al., 2017: Impact of air temperature variation on the ixodid ticks habitat and tick-borne encephalitis incidence in the Russian Arctic: the case of the Komi Republic. *International Journal of Circumpolar Health*, **76**, doi:10.1080/22423982.2017.1298882.
Topilin, A. V., 2016: Migration and the general labor market of the EAEU: challenges and ways of integration. *Migration and socio-economic development*, **1**(1), 39-62.
Toreti, A. et al., 2019a: The Exceptional 2018 European Water Seesaw Calls for Action on Adaptation. *Earth's Future*, **7**(6), 652-663, doi:10.1029/2019EF001170.
Toreti, A. et al., 2019b: Using reanalysis in crop monitoring and forecasting systems. *Agricultural Systems*, **168**, 144-153, doi:10.1016/j.agsy.2018.07.001.
Toth, D., M. Maitah, K. Maitah and V. Jarolínová, 2020: The Impacts of Calamity Logging on the Development of Spruce Wood Prices in Czech Forestry. *Forests*, **11**(3), 283.
Tramblay, Y. et al., 2020: Challenges for drought assessment in the Mediterranean region under future climate scenarios. *Earth-Science Reviews*, **210**, 103348, doi:10.1016/j.earscirev.2020.103348.
Trawöger, L., 2014: Convinced, ambivalent or annoyed: Tyrolean ski tourism stakeholders and their perceptions of climate change. *Tourism Management*, **40**, 338-351.
Trnka, M. et al., 2014: Adverse weather conditions for European wheat production will become more frequent with climate change. *Nature Climate Change*, **4**(7), 637-643, doi:10.1038/nclimate2242.
Tryland, M. et al., 2019: Infectious Disease Outbreak Associated With Supplementary Feeding of Semi-domesticated Reindeer. *Frontiers in Veterinary Science*, **6**, doi:10.3389/fvets.2019.00126.
Turco, M. et al., 2016: Decreasing Fires in Mediterranean Europe. *PLOS ONE*, **11**(3), e0150663, doi:10.1371/journal.pone.0150663.
Turco, M. et al., 2018: Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nature Communications*, **9**(1), 3821, doi:10.1038/s41467-018-06358-z.
Turunen, M. T. et al., 2016: Coping with difficult weather and snow conditions: Reindeer herders' views on climate change impacts and coping strategies. *Climate Risk Management*, **11**, 15-36, doi:10.1016/j.crm.2016.01.002.
Tyler, N. J. C., 2010: Climate, snow, ice, crashes, and declines in populations of reindeer and caribou (Rangifer tarandus L.). *Ecological Monographs*, **80**(2), 197-219, doi:10.1890/09-1070.1.
Tyler, N. J. C. et al., 2007: Saami reindeer pastoralism under climate change: Applying a generalized framework for vulnerability studies to a sub-arctic social–ecological system. *Global Environmental Change*, **17**(2), 191-206, doi:10.1016/j.gloenvcha.2006.06.001.
Uboni, A. et al., 2016: Long-Term Trends and Role of Climate in the Population Dynamics of Eurasian Reindeer. *PLOS ONE*, **11**(6), e0158359, doi:10.1371/journal.pone.0158359.
Uggla, Y. and R. Lidskog, 2016: Climate risks and forest practices: forest owners' acceptance of advice concerning climate change. *Scandinavian Journal of Forest Research*, **31**(6), 618-625, doi:10.1080/02827581.2015.1134648.
Umgiesser, G., 1999: Valutazione degli effetti degli interventi morbidi e diffusi sulla riduzione delle punte di marea a Venezia. *Chioggia e Burano, Atti Istituto Veneto di Scienze, Lettere ed Arti*, **157**, 231-286.
Umgiesser, G., 2004: Effetti idrodinamici prodotti da opere fisse alle bocche di porto della Laguna di Venezia. Parte II: Riduzione delle punte di marea ed effetti sul ricambio idrico. *Atti dell'Istituto Veneto di SS. LL. AA*, **162**(2), 335-376.
Umgiesser, G., 2020: The impact of operating the mobile barriers in Venice (MOSE) under climate change. *Journal for Nature Conservation*, **54**, 125783, doi:https://doi.org/10.1016/j.jnc.2019.125783.
UN/DESA, 2018: World Urbanization Prospects: The 2018 Revision, Online Edition, United Nations - Department of Economic and Social Affairs, Population Division. Available at: https://population.un.org/wup/Download/.
Undorf, S. et al., 2020: Learning from the 2018 heatwave in the context of climate change: are high-temperature extremes important for adaptation in Scotland? *Environmental Research Letters*, **15**, 034051, doi:10.1088/1748-9326/ab6999.
UNEP, 2021: *Adaptation Gap Report 2020*. United Nations Environment Programme (UNEP), Nairobi, Kenya. Available at: https://wedocs.unep.org/20.500.11822/34721.
UNEP/UNECE, 2016: *GEO-6 Assessment for the pan-European region (rev. 1).* [Programme, U. N. E. (ed.)]. Nairobi, Kenya.
Urban, M. C., 2015: Accelerating extinction risk from climate change. *Science*, **348**(6234), 571, doi:10.1126/science.aaa4984.
Urbieta, I. R., M. Franquesa, O. Viedma and J. M. Moreno, 2019: Fire activity and burned forest lands decreased during the last three decades in Spain. *Annals of Forest Science*, **76**(3), 90, doi:10.1007/s13595-019-0874-3.
Uriarte, I. et al., 2021: Opposite phenological responses of zooplankton to climate along a latitudinal gradient through the European Shelf. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsab008.
Urvois, T. et al., 2021: Climate change impact on the potential geographical distribution of two invading Xylosandrus ambrosia beetles. *Scientific Reports*, **11**(1), 1339, doi:10.1038/s41598-020-80157-9.

Van Alphen, J., 2016: The Delta Programme and updated flood risk management policies in the Netherlands. *Journal of Flood Risk Management*, **9**(4), 310-319, doi:10.1111/jfr3.12183.
van der Kooij, J., G. H. Engelhard and D. A. Righton, 2016: Climate change and squid range expansion in the North Sea. *Journal of Biogeography*, **43**(11), 2285-2298, doi:10.1111/jbi.12847.
van der Spek, A. J. F., 2018: The development of the tidal basins in the Dutch Wadden Sea until 2100: the impact of accelerated sea-level rise and subsidence on their sediment budget – a synthesis. *Netherlands Journal of Geosciences*, **97**(3), 71-78, doi:doi/10.1017/njg.2018.10.
van der Velde, M. et al., 2018: In-season performance of European Union wheat forecasts during extreme impacts. *Scientific Reports*, **8**, doi:10.1038/s41598-018-33688-1.
van Duinen, R., T. Filatova, P. Geurts and A. van der Veen, 2015: Coping with drought risk: empirical analysis of farmers' drought adaptation in the south-west Netherlands. *Regional Environmental Change*, **15**(6), 1081-1093, doi:10.1007/s10113-014-0692-y.
van Ginkel, K. C. H. et al., 2020: Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research. *Environmental Research Letters*, **15**(2), 023001, doi:10.1088/1748-9326/ab6395.
van Leeuwen, C. and P. Darriet, 2016: The Impact of Climate Change on Viticulture and Wine Quality. *Journal of Wine Economics*, **11**(1), 150-167, doi:10.1017/jwe.2015.21.
van Loenhout, J. A. F. and D. Guha-Sapir, 2016: How resilient is the general population to heatwaves? A knowledge survey from the ENHANCE project in Brussels and Amsterdam. *BMC research notes*, **9**(1), 499.
van Loenhout, J. A. F., J. M. Rodriguez-Llanes and D. Guha-Sapir, 2016: Stakeholders' Perception on National Heatwave Plans and Their Local Implementation in Belgium and The Netherlands. *International journal of environmental research and public health*, **13**(11), 1120, doi:10.3390/ijerph13111120.
Van Passel, S., E. Massetti and R. Mendelsohn, 2017: A Ricardian Analysis of the Impact of Climate Change on European Agriculture. *Environmental and Resource Economics*, **67**(4), 725-760, doi:10.1007/s10640-016-0001-y.
van Slobbe, E. et al., 2016: The future of the Rhine: stranded ships and no more salmon? *Regional Environmental Change*, **16**(1), 31-41, doi:10.1007/s10113-014-0683-z.
van Valkengoed, A. M. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, **9**(2), 158-163, doi:10.1038/s41558-018-0371-y.
van Vliet, M. et al., 2016a: Multi-model assessment of global hydropower and cooling water discharge potential under climate change. *Global Environmental Change-Human and Policy Dimensions*, **40**, 156-170, doi:10.1016/j.gloenvcha.2016.07.007.
van Vliet, M. T. H., J. Sheffield, D. Wiberg and E. F. Wood, 2016b: Impacts of recent drought and warm years on water resources and electricity supply worldwide. *Environmental Research Letters*, **11**(12), 124021, doi:10.1088/1748-9326/11/12/124021.
Vandentorren, S. et al., 2006: August 2003 heat wave in France: risk factors for death of elderly people living at home. *The European Journal of Public Health*, **16**(6), 583-591.
Vanos, J. K., J. W. Baldwin, O. Jay and K. L. Ebi, 2020: Simplicity lacks robustness when projecting heat-health outcomes in a changing climate. *Nature Communications*, **11**(1), 6079, doi:10.1038/s41467-020-19994-1.
Varela-Ortega, C. et al., 2016: How can irrigated agriculture adapt to climate change? Insights from the Guadiana Basin in Spain. *Regional Environmental Change*, **16**(1), 59-70, doi:10.1007/s10113-014-0720-y.
Vasilakopoulos, P., D. E. Raitsos, E. Tzanatos and C. D. Maravelias, 2017: Resilience and regime shifts in a marine biodiversity hotspot. *Scientific Reports*, **7**(1), 13647, doi:10.1038/s41598-017-13852-9.
Vasiliev, D. and S. Greenwood, 2021: The role of climate change in pollinator decline across the Northern Hemisphere is underestimated. *Science of The Total Environment*, **775**, 145788, doi:https://doi.org/10.1016/j.scitotenv.2021.145788.
Vaskov, I. M., 2016: Glacial mudflows of Central Caucasus at the beginning of XXI century. In: *IV International conference: Mud flows: disasters, risk, forecast, protection*, Irkutsk, Russia, [V.M., P., M. S.A., A. G.V. and S. A.I. (eds.)], Publishing House of V.B. Sochava Institute of Geography RAS, Siberian Branch, pp. 36-45.
Vautard, R. et al., 2020: Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe. *Environmental Research Letters*, **15**(9), doi:10.1088/1748-9326/aba3d4.
Vávra, J. et al., 2018: Food Self-provisioning in Europe: An Exploration of Sociodemographic Factors in Five Regions: Food Self-provisioning in Europe. *Rural Sociology*, **83**(2), 431-461, doi:10.1111/ruso.12180.
Venghaus, S. and J. F. Hake, 2018: Nexus thinking in current EU policies – The interdependencies among food, energy and water resources. *Environmental Science & Policy*, **90**, 183-192, doi:https://doi.org/10.1016/j.envsci.2017.12.014.
Venter, Z. S., N. H. Krog and D. N. Barton, 2020: Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway. *Science of The Total Environment*, **709**, 136193, doi:https://doi.org/10.1016/j.scitotenv.2019.136193.
Vercruysse, J. et al., 2018: Control of helminth ruminant infections by 2030. *Parasitology*, **145**(13), 1655-1664, doi:10.1017/S003118201700227X.
Verhagen, W., A. J. A. van Teeffelen and P. H. Verburg, 2018: Shifting spatial priorities for ecosystem services in Europe following land use change. *Ecological Indicators*, **89**, 397-410, doi:https://doi.org/10.1016/j.ecolind.2018.01.019.

Vermaat, J. E. et al., 2017: Differentiating the effects of climate and land use change on European biodiversity: A scenario analysis. *Ambio*, **46**(3), 277-290, doi:10.1007/s13280-016-0840-3.
Verschuur, J., E. E. Koks and J. W. Hall, 2020: Port disruptions due to natural disasters: Insights into port and logistics resilience. *Transportation Research Part D-Transport and Environment*, **85**, doi:10.1016/j.trd.2020.102393.
Verschuuren, J., 2015: Connectivity: is Natura 2000 only an ecological network on paper? In: *The Habitats Directive in its EU Environmental Law Context:* [Born, C. H., A. Cliquet, H. Schoukens, D. Misonne and G. Van Hoorick (eds.)]. Routledge, Abingdon, pp. 285-302.
Vicedo-Cabrera, A. M. et al., 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11**(6), 492-500, doi:10.1038/s41558-021-01058-x.
Vieira, A. R., S. Dores, M. Azevedo and S. E. Tanner, 2019: Otolith increment width-based chronologies disclose temperature and density-dependent effects on demersal fish growth. *ICES Journal of Marine Science*, **77**(2), 633-644, doi:10.1093/icesjms/fsz243.
Viguié, V. et al., 2021: When adaptation increases energy demand: A systematic map of the literature. *Environmental Research Letters*, **16**(3), 033004, doi:10.1088/1748-9326/abc044.
Viguié, V. et al., 2020: Early adaptation to heat waves and future reduction of air-conditioning energy use in Paris. *Environmental Research Letters*, **15**(7), 075006, doi:10.1088/1748-9326/ab6a24.
Vilà-Cabrera, A., A. C. Premoli and A. S. Jump, 2019: Refining predictions of population decline at species' rear edges. *Global Change Biology*, **0**(0), doi:10.1111/gcb.14597.
Virk, G. et al., 2014: The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in London: Direct and indirect effects in current and future climates. *Indoor and Built Environment*, **23**(3), 504-520, doi:10.1177/1420326X14527976.
Visser, H., A. C. Petersen and W. Ligtvoet, 2014: On the relation between weather-related disaster impacts, vulnerability and climate change. *Climatic Change*, **125**(3), 461-477, doi:10.1007/s10584-014-1179-z.
Vitali, V., U. Büntgen and J. Bauhus, 2018: Seasonality matters—The effects of past and projected seasonal climate change on the growth of native and exotic conifer species in Central Europe. *Dendrochronologia*, **48**, 1-9, doi:10.1016/j.dendro.2018.01.001.
Vogel, M. M. et al., 2019: Concurrent 2018 Hot Extremes Across Northern Hemisphere Due to Human-Induced Climate Change. *Earth's Future*, **7**(7), 692-703, doi:10.1029/2019ef001189.
Vors, L. S. and M. S. Boyce, 2009: Global declines of caribou and reindeer. *Global Change Biology*, **15**(11), 2626-2633, doi:10.1111/j.1365-2486.2009.01974.x.
Voss, R. et al., 2019: Ecological-economic sustainability of the Baltic cod fisheries under ocean warming and acidification. *Journal of Environmental Management*, **238**, 110-118, doi:10.1016/j.jenvman.2019.02.105.
Vousdoukas, M. I. et al., 2020: Economic motivation for raising coastal flood defenses in Europe. *Nature Communications*, **11**(1), 2119, doi:10.1038/s41467-020-15665-3.
Vousdoukas, M. I. et al., 2018a: Climatic and socioeconomic controls of future coastal flood risk in Europe. *Nature Climate Change*, **8**(9), 776-780, doi:10.1038/s41558-018-0260-4.
Vousdoukas, M. I. et al., 2018b: Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications*, **9**(1), 2360, doi:10.1038/s41467-018-04692-w.
Vulturius, G. et al., 2018: The relative importance of subjective and structural factors for individual adaptation to climate change by forest owners in Sweden. *Regional Environmental Change*, **18**(2), 511-520, doi:10.1007/s10113-017-1218-1.
Wada, Y., 2016: Modeling Groundwater Depletion at Regional and Global Scales: Present State and Future Prospects. *Surveys in Geophysics*, **37**(2), 419-451, doi:10.1007/s10712-015-9347-x.
Waite, T. et al., 2017: The English national cohort study of flooding and health: cross-sectional analysis of mental health outcomes at year one. *Bmc Public Health*, **17**, doi:10.1186/s12889-016-4000-2.
Waits, A. et al., 2018: Human infectious diseases and the changing climate in the Arctic. *Environment International*, **121**, 703-713, doi:10.1016/j.envint.2018.09.042.
Wakelin, S. L. et al., 2015: Modelling the combined impacts of climate change and direct anthropogenic drivers on the ecosystem of the northwest European continental shelf. *Journal of Marine Systems*, **152**, 51-63, doi:doi/10.1016/j.jmarsys.2015.07.006.
Walker, G. and K. Burningham, 2011: Flood risk, vulnerability and environmental justice: Evidence and evaluation of inequality in a UK context. *Critical Social Policy*, **31**(2), 216-240, doi:10.1177/0261018310396149.
Wall, M. et al., 2015: pH up-regulation as a potential mechanism for the cold-water coral Lophelia pertusa to sustain growth in aragonite undersaturated conditions. *Biogeosciences*, **12**(23), 6869--6880, doi:10.5194/bg-12-6869-2015.
Walsh, C., 2018: Metageographies of coastal management: Negotiating spaces of nature and culture at the Wadden Sea. *Area*, **50**(2), 177-185, doi:10.1111/area.12404.
Wamsler, C., 2016: From Risk Governance to City–Citizen Collaboration: Capitalizing on individual adaptation to climate change. *Environmental Policy and Governance*, **26**(3), 184-204, doi:10.1002/eet.1707.
Wanders, N. et al., 2019: High-Resolution Global Water Temperature Modeling. *Water Resources Research*, **55**(4), 2760-2778, doi:10.1029/2018WR023250.
Wang, J. et al., 2020: Anthropogenically-driven increases in the risks of summertime compound hot extremes. *Nature Communications*, **11**(1), 528, doi:10.1038/s41467-019-14233-8.

Wang , S., 2020: Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. *Science*, **370**(6522), 1295-1300, doi:DOI: 10.1126/science.abb7772.

Wang, Z. B., E. P. L. Elias, A. J. F. van der Spek and Q. J. Lodder, 2018: Sediment budget and morphological development of the Dutch Wadden Sea: impact of accelerated sea-level rise and subsidence until 2100. *Netherlands Journal of Geosciences*, **97**(3), 183-214, doi:doi/10.1017/njg.2018.8.

Ward, K., S. Lauf, B. Kleinschmit and W. Endlicher, 2016: Heat waves and urban heat islands in Europe: A review of relevant drivers. *Science of the Total Environment*, **569**, 527-539, doi:10.1016/j.scitotenv.2016.06.119.

Warren, R. et al., 2018: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*, **360**(6390), 791-795, doi:10.1126/science.aar3646.

Watson, J. E. M., N. Dudley, D. B. Segan and M. Hockings, 2014: The performance and potential of protected areas. *Nature*, **515**(7525), 67-73, doi:10.1038/nature13947 PMID - 25373676.

Watts, N. et al., 2021: The 2020 report of the Lancet Countdown on health and climate change: responding to converging crises. *Lancet*, **397**(10269), 129-170, doi:10.1016/s0140-6736(20)32290-x.

Watts, N. et al., 2018: The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come. *Lancet*, **392**(10163), 2479-2514, doi:10.1016/S0140-6736(18)32594-7.

Webber, H. et al., 2018: Diverging importance of drought stress for maize and winter wheat in Europe. *Nature Communications*, **9**(1), 4249, doi:10.1038/s41467-018-06525-2.

Webber, H. et al., 2016: Uncertainty in future irrigation water demand and risk of crop failure for maize in Europe. *Environmental Research Letters*, **11**(7), 1-10, doi:10.1088/1748-9326/11/7/074007.

Webber, H. et al., 2020: No perfect storm for crop yield failure in Germany. *Environmental Research Letters*.

Weber, J., F. Gotzens and D. Witthaut, 2018a: Impact of strong climate change on the statistics of wind power generation in Europe. *Energy Procedia*, **153**, 22-28, doi:https://doi.org/10.1016/j.egypro.2018.10.004.

Weber, J. et al., 2018b: Impact of climate change on backup energy and storage needs in wind-dominated power systems in Europe. *Plos One*, **13**(8), doi:10.1371/journal.pone.0201457.

Weinhofer, G. and T. Busch, 2013: Corporate Strategies for Managing Climate Risks. *Business Strategy and the Environment*, **22**(2), 121-144, doi:10.1002/bse.1744.

Welch, A. C., R. J. Nicholls and A. N. Lázár, 2017: Evolving deltas: Coevolution with engineered interventions. *Elementa: Science of the Anthropocene*, **5**, doi:10.1525/elementa.128.

Wenz, L. and A. Levermann, 2016: Enhanced economic connectivity to foster heat stress-related losses. *Science Advances*, **2**(6), doi:10.1126/sciadv.1501026.

Wenz, L., A. Levermann and M. Auffhammer, 2017: North-south polarization of European electricity consumption under future warming. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(38), E7910-E7918, doi:10.1073/pnas.1704339114.

Wessely, J. et al., 2017: Habitat-based conservation strategies cannot compensate for climate-change-induced range loss. *Nature Climate Change*, **7**(11), 823-827, doi:10.1038/nclimate3414.

Westra, S. et al., 2014: Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics*, **52**(3), 522-555, doi:https://doi.org/10.1002/2014RG000464.

WHO, 2018a: European health report 2018: More than numbers - evidence for all. WHO Regional Office for Europe, Copenhagen, Denmark.

WHO, 2018b: *Public health and climate change adaptation policies in the European Union: Final report.*, World Health Organization Regional Office for Europe., Copenhagen, Denmark. Available at: http://www.euro.who.int/en/health-topics/environment-and-health/Climate-change/publications/2018/public-health-and-climate-change-adaptation-policies-in-the-european-union-2018.

Wiens, J. J., 2016: Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLOS Biology*, **14**(12), e2001104, doi:10.1371/journal.pbio.2001104.

Wiering, M. et al., 2017: Varieties of flood risk governance in Europe: How do countries respond to driving forces and what explains institutional change? *Global Environmental Change*, **44**, 15-26, doi:https://doi.org/10.1016/j.gloenvcha.2017.02.006.

Wihlborg, M., J. Sörensen and J. Alkan Olsson, 2019: Assessment of barriers and drivers for implementation of blue-green solutions in Swedish municipalities. *Journal of Environmental Management*, **233**, 706-718.

Willett, W. et al., 2019: Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet*, **393**(10170), 447-492, doi:10.1016/S0140-6736(18)31788-4.

Williams, K. et al., 2013: Retrofitting England's suburbs to adapt to climate change. *Building Research & Information*, **41**(5), 517-531, doi:10.1080/09613218.2013.808893.

Williams, P. D., 2016: Transatlantic flight times and climate change. *Environmental Research Letters*, **11**(2), doi:10.1088/1748-9326/11/2/024008.

Williams, P. D. and M. M. Joshi, 2013: Intensification of winter transatlantic aviation turbulence in response to climate change. *Nature Climate Change*, **3**(7), 644-648, doi:10.1038/nclimate1866.

Williges, K., R. Mechler, P. Bowyer and J. Balkovic, 2017: Towards an assessment of adaptive capacity of the European agricultural sector to droughts. *Climate Services*, **7**, 47-63, doi:10.1016/j.cliser.2016.10.003.

Willner, S. N., C. Otto and A. Levermann, 2018: Global economic response to river floods. *Nature Climate Change*, **8**(7), 594-598, doi:10.1038/s41558-018-0173-2.

Wilson, R. S., A. Herziger, M. Hamilton and J. S. Brooks, 2020: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, **10**(3), 200-208, doi:10.1038/s41558-020-0691-6.
Wimmer, F. et al., 2014: Modelling the effects of cross-sectoral water allocation schemes in Europe. *Climatic Change*, **128**(3-4), 229-244, doi:10.1007/s10584-014-1161-9.
WindEuropeBusinessIntelligence, 2019: *Offshore Wind in Europe - Key trends and statistics 2018*. Key trends and statistics, WindEurope, Brussels, 40 pp. Available at: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2018.pdf.
Winsemius, H. C. et al., 2018: Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, **23**(3), 328-348, doi:10.1017/S1355770X17000444.
Wiréhn, L., 2018: Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production. *Land Use Policy*, **77**, 63-74, doi:10.1016/j.landusepol.2018.04.059.
Wohland, J., M. Reyers, J. Weber and D. Witthaut, 2017: More homogeneous wind conditions under strong climate change decrease the potential for inter-state balancing of electricity in Europe. *Earth System Dynamics*, **8**(4), 1047-1060, doi:10.5194/esd-8-1047-2017.
Wójcik, O. P. et al., 2013: Personal protective equipment, hygiene behaviours and occupational risk of illness after July 2011 flood in Copenhagen, Denmark. *Epidemiol Infect*, **141**(8), 1756-1763, doi:10.1017/s0950268812002038.
Wolf, T. et al., 2014: Protecting Health from Climate Change in the WHO European Region. *International Journal of Environmental Research and Public Health*, **11**(6), 6265-6280.
Woolway, R. I. et al., 2017: Warming of Central European lakes and their response to the 1980s climate regime shift. *Climatic Change*, **142**(3), 505-520, doi:10.1007/s10584-017-1966-4.
WorldBank, 2020: World Development Indicators. Available at: https://databank.worldbank.org/indicator/NY.GDP.PCAP.CD/1ff4a498/Popular-Indicators# (accessed 2020/11/05/08:52:32).
Wouter Botzen, W. J. et al., 2019: Integrated Disaster Risk Management and Adaptation. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, pp. 287-315. ISBN 978-3-319-72026-5.
Wu, C. et al., 2018: Contrasting responses of autumn-leaf senescence to daytime and night-time warming. *Nature Climate Change*, **8**(12), 1092-1096, doi:10.1038/s41558-018-0346-z.
Wu, M. et al., 2015: Sensitivity of burned area in Europe to climate change, atmospheric CO2 levels, and demography: A comparison of two fire-vegetation models. *Journal of Geophysical Research: Biogeosciences*, **120**(11), 2256-2272, doi:10.1002/2015JG003036.
Wyżga, B. et al., 2018: Comprehensive approach to the reduction of river flood risk: Case study of the Upper Vistula Basin. *Science of The Total Environment*, **631-632**, 1251-1267, doi:https://doi.org/10.1016/j.scitotenv.2018.03.015.
Xi, Y., S. Peng, P. Ciais and Y. Chen, 2021: Future impacts of climate change on inland Ramsar wetlands. *Nature Climate Change*, **11**(1), 45-51, doi:10.1038/s41558-020-00942-2.
Xu, C. et al., 2019: Increasing impacts of extreme droughts on vegetation productivity under climate change. *Nature Climate Change*, **9**(12), 948-953, doi:10.1038/s41558-019-0630-6.
Yakubovich, A. N. and I. A. Yakubovich, 2018: Analysis of the Multidimensional Impact of Climate Change on the Operation Safety of the Road Network of the Permafrost Zone of Russia. *Intelligence. Innovations. Investments*, **3**, 77-83.
Yazar, M. et al., 2019: From urban sustainability transformations to green gentrification: urban renewal in Gaziosmanpaşa, Istanbul. *Climatic Change*, doi:10.1007/s10584-019-02509-3.
Yokohata, T. et al., 2019: Visualizing the Interconnections Among Climate Risks. *Earths Future*, **7**(2), 85-100, doi:10.1029/2018ef000945.
Yousefpour, R. et al., 2018: Realizing Mitigation Efficiency of European Commercial Forests by Climate Smart Forestry. *Scientific Reports*, **8**(1), 345, doi:10.1038/s41598-017-18778-w.
Yu, J., P. Berry, B. P. Guillod and T. Hickler, 2021: Climate Change Impacts on the Future of Forests in Great Britain. *Frontiers in Environmental Science*, **9**(83), doi:10.3389/fenvs.2021.640530.
Yun, J. et al., 2016: Association between the ambient temperature and the occurrence of human Salmonella and Campylobacter infections. *Scientific Reports*, **6**, doi:10.1038/srep28442.
Zakharov, A. I. and R. B. Sharipova, 2017: Agro climate potential and basic problems of influence of climate changes on agricultural crop production in Ulyanovsk region. *Вестник Ульяновской государственной сельскохозяйственной академии*, **1**(37), 25-30, doi:10.18286/1816-4501-2017-1-25-30.
Zanchettin, D. et al., 2021: Sea-level rise in Venice: historic and future trends *Nat. Hazards Earth Syst. Sci.*, **21**, 2643–2678, doi:https://doi.org/10.5194/nhess-21-2643-2021.
Zandvoort, M. et al., 2017: Adaptation pathways in planning for uncertain climate change: Applications in Portugal, the Czech Republic and the Netherlands. *Environmental Science & Policy*, **78**, 18-26, doi:https://doi.org/10.1016/j.envsci.2017.08.017.
Zattara, E. E. and M. A. Aizen, 2020: Worldwide occurrence records reflect a global decline in bee species richness. *bioRxiv*, 869784-869784, doi:10.1101/869784.

Zellweger, F. et al., 2020: Forest microclimate dynamics drive plant responses to warming. *Science*, **368**(6492), 772, doi:10.1126/science.aba6880.
Zhao, C. et al., 2017: Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, **114**(35), 9326-9331, doi:10.1073/pnas.1701762114.
Zickgraf, C., 2018: Immobility. In: *Routledge handbook of environmental displacement and migration* [McLeman, R., Gemenne and F. (eds.)]. Routledge:, London, pp. 71–84.
Ziello, C. et al., 2012: Changes to Airborne Pollen Counts across Europe. *Plos One*, **7**(4), doi:10.1371/journal.pone.0034076.
Zölch, T., L. Henze, P. Keilholz and S. Pauleit, 2017: Regulating urban surface runoff through nature-based solutions – An assessment at the micro-scale. *Environmental Research*, **157**, 135-144, doi:10.1016/j.envres.2017.05.023.
Zscheischler, J. and S. I. Seneviratne, 2017: Dependence of drivers affects risks associated with compound events. *Science Advances*, **3**(6), e1700263, doi:10.1126/sciadv.1700263.
Zscheischler, J. et al., 2018: Future climate risk from compound events. *Nature Climate Change*, **8**(6), 469-477, doi:10.1038/s41558-018-0156-3.
Zubizarreta-Gerendiain, A., T. Pukkala and H. Peltola, 2017: Effects of wind damage on the optimal management of boreal forests under current and changing climatic conditions. *Can. J. For. Res.*, **47**(2), 246-256, doi:10.1139/cjfr-2016-0226.
Zupan, M. et al., 2018a: How good is your marine protected area at curbing threats? *Biological Conservation*, **221**, 237-245, doi:10.1016/j.biocon.2018.03.013.
Zupan, M. et al., 2018b: Marine partially protected areas: drivers of ecological effectiveness. *Frontiers in Ecology and the Environment*, **16**(7), 381-387, doi:10.1002/fee.1934.
Župarić-Iljić, D., 2017: *Environmental Change and Involuntary Migration: Environmental Vulnerability and Displacement Caused by the 2014 Flooding in South-Eastern Europe*. Ecology and Justice: Contributions from the margins, Institute for Political Ecology.

Chapter 14: North America

Coordinating Lead Authors: Jeffrey A. Hicke (USA), Simone Lucatello (Mexico), Linda D. Mortsch (Canada)

Lead Authors: Jackie Dawson (Canada), Mauricio Domínguez Aguilar (Mexico), Carolyn A.F. Enquist (USA), Elisabeth A. Gilmore (USA/Canada), David S. Gutzler (USA), Sherilee Harper (Canada), Kirstin Holsman (USA), Elizabeth B. Jewett (USA), Timothy A. Kohler (USA), Kathleen Miller (USA)

Contributing Authors: Taylor Armstrong (USA), Craig Brown (Canada), Polly C. Buotte (USA), Malinda Chase (USA), Cecilia Conde (Mexico), Nikki Cooley (USA), Karen Cozzetto (USA), Ashlee Cunsolo (Canada), Dalee Sambo Dorough (USA), Jeffrey Dukes (USA), Emile Elias (USA), Luis Fernandez (Mexico), Halley Froehlich (USA), Elliott Hazen (USA), Blas Perez Henriquez (Mexico), Melissa Kenney (USA), Salvador Lluch (Mexico), Dara Marks-Marino (USA), Deborah McGregor (Canada), Matto Mildenberger (Canada), Alejandro Monterrosso (Mexico), Michelle Rutty (Canada), Silvia Salas (Mexico), Miguel Sioui (Canada), Gustavo Sosa (Mexico), Kyle Whyte (USA)

Chapter Scientist: Polly C. Buotte (USA)

Review Editors: Margot Hurlbert (Canada), Linda Mearns (USA)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Since AR5, climate change impacts have become more frequent, intense, and have affected many millions of people from every region and sector across North America (Canada, US and Mexico). Accelerating climate change hazards pose significant risks to the wellbeing of North American populations and the natural, managed and human systems on which they depend (*high confidence*[1]). Addressing these risks have been made more urgent by delays due to misinformation about climate science that has sowed uncertainty, and impeded recognition of risk (*high confidence*). {14.2, 14.3}

Without limiting warming to 1.5°C, key risks to North America are expected to intensify rapidly by mid-century (*high confidence*). These risks will result in irreversible changes to ecosystems, mounting damages to infrastructure and housing, stress on economic sectors, and disruption of livelihoods, mental and physical health, leisure, and safety. Immediate, widespread, and coordinated implementation of adaptation measures aimed at reducing risks and focused on equity have the greatest potential to maintain and improve the quality of life for North Americans, ensure sustainable livelihoods, and protect the long-term biodiversity, and ecological and economic productivity in North America (*high confidence*). Enhanced sharing of resources and tools for adaptation across economic, social, cultural and national entities enables more effective short- and long-term responses to climate change. {14.2, 14.4, 14.5, 14.6, 14.7}

Past and Current Impacts and Adaptation

Over the past 20 years, climate change impacts across North America have become more frequent, intense and affect more of the population (*high confidence*). Despite scientific certainty of the anthropogenic influence on climate change, misinformation and politicization of climate change science has created polarization in public and policy domains in North America, particularly in the US, limiting climate action (*high confidence*). Vested interests have generated rhetoric and misinformation that undermines climate science and disregards risk and urgency (*medium confidence*). Resultant public misperception of climate risks and polarized public support for climate actions is delaying urgent adaptation planning and implementation (*high confidence*). Including Indigenous knowledge, communication and outreach as well as collaborations to co-create equitable solutions are critical for successful climate action. {Box 14.1, 14.3, 14.7}

Climate change has negatively impacted human health and wellbeing in North America (*very high confidence*). High temperatures have increased mortality and morbidity (*very high confidence*), with impacts that vary by age, gender, location, and socioeconomic conditions (*very high confidence*). Changes in temperature and precipitation have increased risk of vectorborne (*very high confidence*), waterborne (*high confidence*), and foodborne diseases (*very high confidence*). Changes in climate and extreme events have been linked to wide-ranging negative mental health outcomes (*high confidence*). The loss of access to marine and terrestrial sources of protein has impacted the nutrition of subsistence-dependent communities across North America (*high confidence*). Climate change has increased the extent of warmer and drier conditions favourable for wildfires (*medium confidence*) that increase respiratory distress from smoke (*very high confidence*). {14.5.2, 14.5.6, Box 14.2}

North American food production is increasingly affected by climate change (*high confidence*), with immediate impacts on the food and nutritional security of Indigenous Peoples. Climate change and extreme weather events have impacted North American agroecosystems (*high confidence*), with crop-specific effects that vary in direction and magnitude by event and location. Climate change has generally reduced agricultural productivity by 12.5% since 1961, with progressively greater losses moving south from Canada to Mexico and in drought-prone rainfed systems (*high confidence*) while favorable conditions increased yields of maize, soybeans in regions like the US Great Plains. Loss of availability and access to marine and terrestrial sources of protein has impaired food security and nutrition of subsistence-dependent

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Indigenous Peoples across North America (*high confidence*). Climate change has impacted aquaculture (*high confidence*) and induced rapid redistribution of species (*very high confidence*), and population declines of multiple key fisheries (*high confidence)*. {14.5.4, 14.5.6, 14.7}

Climate change has impaired North American freshwater resources and reduced supply security (*high confidence*). Reduced snowpack and earlier runoff (*high confidence*) have adversely affected aquatic ecosystems and freshwater availability for human uses (*medium confidence*). Recent severe droughts, floods and harmful algal and pathogen events have caused harm to large populations and key economic sectors *(high confidence*). Heavy exploitation of limited water supplies, especially in the western US and northern Mexico, and deteriorating freshwater management infrastructure, have heightened the risks (*high confidence*). Effective examples of freshwater resource adaptation planning are already underway, but coordinated adaptation implementation across multiple conflicting interests and users is complicated and time consuming (*high confidence*). {14.5.1, 14.5.2, 14.5.3}

Extreme events and climate hazards are adversely affecting economic activities across North America and have disrupted supply-chain infrastructure and trade (*high confidence).* Larger losses and adaptation costs are observed for sectors with high climate exposures, including tourism, fisheries, and agriculture (*high confidence*) and outdoor labor (*medium confidence)*. Disaster planning and spending, insurance, markets, and individual and household level adaptation have acted to moderate effects to date (*medium confidence)*. Entrenched socioeconomic vulnerabilities have amplified climate impacts for marginalized groups, including Indigenous Peoples due to the impact of colonialism and discrimination (*medium confidence*). {14.5.4, 14.5.5, 14.5.6, 14.5.7, 14.5.9, Box 14.1, Box 14.5, Box 14.6}

North American cities and settlements have been affected by increasing severity and frequency of climate hazards and extreme events *(high confidence*), which has contributed to, infrastructure damage, livelihood losses, damage to heritage resources, and safety concerns. Impacts are particularly apparent for Indigenous Peoples for whom culture, identity, commerce, health and wellbeing are closely connected to a resilient environment (*very high confidence*). Higher temperatures have been associated with violent and property crime in the US (*medium confidence*) yet the overall effects of climate change on crime and violence in North America are not well understood. {14.4, 14.5.5, 14.5.6, 14.5.8, 14.5.9, Box 14.1}

Terrestrial, marine, and freshwater ecosystems are being profoundly altered by climate change across North America (*very high confidence*). Rising air, water, ocean and ground temperatures have restructured ecosystems and contributed to the redistribution (*very high confidence*) and mortality (*high confidence*) of fish, bird, and mammal species. Extreme heat and precipitation trends on land have increased vegetation stress and mortality, reduced soil quality, and altered ecosystem processes including carbon and freshwater cycling (*very high confidence*). Warm and dry conditions associated with climate change have led to tree die-offs (*high confidence*) and increased prevalence of catastrophic wildfire (*medium confidence*) with an increase in the size of severely burned areas in western North America (*medium confidence*). Nature-based solutions and ecosystem-based management have been effective adaptation approaches in the past but are increasingly exceeded by climate extremes *(medium confidence*). {14.5.1-3, Box 14.7}

Climate-driven changes are particularly pronounced within Arctic ecosystems and are unprecedented based on observations from multiple knowledge systems (*very high confidence*). Climate change has contributed to cascading environmental and socio-cultural impacts in the Arctic (*high* to *very high confidence*) that have adversely, and often irreversibly, altered Northern livelihoods, cultural activities, essential services, health, food and nutritional security, community connectivity, and wellbeing (*high confidence*). {14.5.2, 14.5.4, 14.5.6, 14.5.7, 14.5.8, Box 14.6}

Future Risks and Adaptation

Climate hazards are projected to intensify further across North America (*very high confidence*). Heat waves over land and in the ocean as well as wildfire activity will intensify; sub-Arctic snowpack, glacial mass and sea ice will decline (*virtually certain*); and sea level rise will increase at geographically differential rates (*virtually certain*). Humidity-enhanced heat stress, aridification, and extreme precipitation events that lead to severe flooding, erosion, debris flows, and ultimately loss of ecosystem function, life and property, are projected to intensify (*high confidence*). {14.2}

Health risks are projected to increase this century under all future emissions scenarios (*very high confidence*) but the magnitude and severity of impacts depends on the implementation and effectiveness of adaptation strategies (*very high confidence*). Warming is projected to increase heat-related mortality (*very high confidence*) and morbidity (*medium confidence*). Vectorborne disease transmission, waterborne disease risks, food safety risks and mental health outcomes are projected to increase this century (*high confidence*). Available adaptation options will be less effective or unable to protect human health under high-emission scenarios (*high confidence*). {14.5.6, Box 14.2}

Climate-induced redistribution and declines in North American food production are a risk to future food and nutritional security (*very high confidence*). Climate change will continue to shift North American agricultural and fishery suitability ranges (*high confidence*) and intensify production losses of key crops (*high confidence*), livestock (*medium confidence*), fisheries (*high confidence*), and aquaculture products (*medium confidence*). In the absence of mitigation, incremental adaptation measures may not be sufficient to address rapidly changing conditions and extreme events, increasing the need for cross-sectoral coordination in implementation of mitigation and adaptation measures (*high confidence*). Combining sustainable intensification, Indigenous knowledge and local knowledge based-approaches, and ecosystem-based methods with inclusive and self-determined decision making will result in more equitable food and nutritional security (*high confidence*). {14.5.1-4, 14.5.6,14.7, Croxx-Chapter Box INDIG in Chapter 18, Cross-Chapter Box MOVING PLATE in Chapter 5}

Escalating climate change impacts on marine, freshwater, and terrestrial ecosystems (*high confidence*) will alter ecological processes (*high confidence*) and amplify other anthropogenic threats to protected and iconic species and habitats (*high confidence*). Hotter droughts and progressive loss of seasonal water storage in snow and ice will tend to reduce summer season stream flows in much of western North America, while population growth, extensive irrigated agriculture and the needs of threatened and endangered aquatic species will continue to place high demands on those flows (*high confidence*). {14.2.2, 14.5.1, 14.5.2, 14.5.3, 14.5.4, 14.5.6, Box 14.7.1}

Market and non-market economic damages are projected to increase to the end of the century from climate impacts (*high confidence*). Estimates for the costs of climate inaction are substantial across economic sectors, infrastructure, human health and disaster management. Hard limits to adaptation may be reached for outdoor labor (*medium confidence*) and nature-based winter tourism activities (*very high confidence*). At higher levels of warming, climate impacts may pose systemic risks to financial markets through impacts on transportation systems, supply-chains, and major infrastructure as well as global scale challenges to trade (*medium confidence).* {14.2.2, 14.5.4, 14.5.8, 14.5.7, 14.5.9, 14.5.5, Box 14.5, Box 14.6}

Solution Space, Governance

Self-determination for Indigenous Peoples is critical for effective adaptation in Indigenous communities (*very high confidence*). Throughout North America, Indigenous Peoples are actively addressing the compound impacts of climate change, and historical and ongoing forms of colonialism (*very high confidence*). Indigenous knowledge underpins successful understanding of, responses to, and governance of climate change risks. Western scientific practices and technology may not be sufficient in addressing future natural resource management challenges. Supporting Indigenous self-determination, recognizing Indigenous Peoples' rights, and supporting Indigenous knowledge based-adaptation are critical to reducing climate change risks to achieve adaptation success (*very high confidence*). {14.7.3, Box 14.1}

Equitable, inclusive and participatory approaches that integrate climate impact projections into near-term and long-term decision-making reduce future risks (*high confidence*). Government and private investment are increasingly investing in early warning and rapid response systems, climate and ecological forecasting tools, and integrated climate scenario planning methods. Widespread adoption of these practices and tools for infrastructure planning, disaster risk reduction, ecosystem management, budgeting practices, insurance, and climate risk reporting supports planning for a future with more climate risks (*high confidence)*. Increased capacity to support the equitable resolution of existing and emerging resource disputes (local to international) will reduce climate impacts on livelihoods and improve the effectiveness of resource management (*high confidence*). {14.5.5, 14.5.10, 14.7}

Near- and long-term adaptation planning, implementation, and coordination across sectors and jurisdictions supports equitable and effective climate solutions (*high confidence*). Recognition of the need for adaptation across North America is increasing but action has been mostly gradual, incremental, and reactive (*high confidence)*. Current practices will be increasingly insufficient without coordination and integration of efforts through equitable policy focused on modifying land use impacts, consumption patterns, economic activities, and emphasizing nature-based solutions (*high confidence*). Transformational, long-term adaptation action that reduces risk and increases resilience can address rapidly escalating impacts in the mid to latter part of the 21st century, especially if coupled with moderate to high mitigation measures (*high confidence*). {14.7}

14.1 Introduction and Point of Departure

Earth's climate is currently changing in significant ways as a result of human activities, and future projections indicate continued and possibly accelerating change without reductions in greenhouse gas (GHG) emissions (Gutiérrez et al., In Press; IPCC, In Press). Climate change affects human and natural systems; this chapter provides an assessment of present and future climate change impacts, risks, and adaptation for North America, including Mexico, Canada, and the United States (US) and coastal waters within the 370 km exclusive economic zone. We do not consider Hawaii and other island territories of the US in depth as they are assessed in Chapter 15 (Small Islands). Chapter 14 assesses evidence from Arctic Canada and Alaska, which is synthesized in the Polar Regions Cross-Chapter Paper (CCP6).

Evidence from Indigenous knowledge (IK) systems is included in this chapter to assess climate change risks and solutions in North America following the framing provided in Chapter 1 Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Abram et al., 2019) and Special Report on Climate Change and Land (SRCCL) (IPCC, 2019a). Indigenous Contributing Authors provided this assessment, reflecting the importance of meaningfully including IK in assessment processes (Ford, 2012; Ford et al., 2016; Hill et al., 2020). This addition represents an important advancement since AR5 (IPCC, 2013; IPCC, 2014).

Our main point of departure was the Fifth Assessment Report (AR5) for WGII (IPCC, 2014). Key findings drawn from the Executive Summary for the North America chapter are summarized in Table 14.1. Subsequent IPCC reports such as Special Report on Global Warming of 1.5°C (SR1.5) (Hoegh-Guldberg et al., 2018; IPCC, 2018), SROCC (IPCC, 2019b), and SRCCL (IPCC, 2019a) also informed the assessment. We additionally incorporated recent national climate assessments of the US (USGCRP, 2018) and Canada (Bush and Lemmen, 2019; Warren and Lulham, 2021) as well as the 6th Mexican national communication of climate change to the United Nations (SEMARNAT and INECC, 2018).

Table 14.1: Key findings from AR5 North America Chapter (Romero-Lankao et al., 2014b).

General topic	AR5 finding
Climate hazards	Climate has changed in North America, with some changes attributed to human activities.
	Climate hazards, especially related to heatwaves, heavy precipitation, and snowpack, are expected to change in ways that are adverse to natural and human systems.
Natural ecosystems	Warming, increasing carbon dioxide (CO_2) concentrations, sea level rise (SLR), and climate extremes are stressing ecosystems.
Human systems	Water resources that are already stressed in many parts of North America are expected to become further stressed by climate change. Current adaptation options can address water supply deficits but responses to flooding and water quality concerns are more limited.
	Climate change has affected yields of major crops, and projections indicate continued declines, although with variability.
	Extreme climate events have affected human health, although climate change-related trends and attribution to climate change were not confirmed.
	Multiple aspects of climate change have affected livelihoods, economic activities, infrastructure, and access to services.
	Much infrastructure is vulnerable to extreme weather events and unless adaptation investments are made, vulnerability to future climate change persists and increases.

	Most sectors of the North American economy have been affected by and have responded to extreme weather, including hurricanes, flooding, and intense rainfall.
Adaptation	Technological innovation, institutional capacity-building, economic diversification, and infrastructure design are adaptations for reducing current climate impacts as well as future risks due to a changing climate.
	Predominantly, North American governments have undertaken incremental adaptation assessment and planning at the municipal level. Limited proactive, anticipatory adaptation is directed at long-term investment for energy and public infrastructure.

Chapter 14 sections are organized to address themes and content as contained in the IPCC-approved outline for regions. Regional climate changes assessed within North America are keyed to Figure 14.1 using *italicized* four-letter abbreviations (e.g., *CA-ON, US-SE, MX-NW*). The assessment addresses recent and future climate for North America, the impacts, risks and adaptation within sectors, key risks (KR), the nature of adaptation and sustainable development pathways as well as two additional sections on Indigenous Peoples and perceptions of climate change. Seven Boxes are used to highlight topics of interdisciplinary nature while four Frequently Asked Questions (FAQ) were produced in plain language for communication to the public. The chapter utilizes the framework as well as designated terms in the standardized process for evaluating and characterizing the degree of certainty in assessment findings developed through the expert judgment process (Mach et al., 2017) (see WGII 1.3.4) (references to other relevant chapters in this WGII report are abbreviated in this manner). The WGII Glossary provides definitions for terms and concepts used across the report.

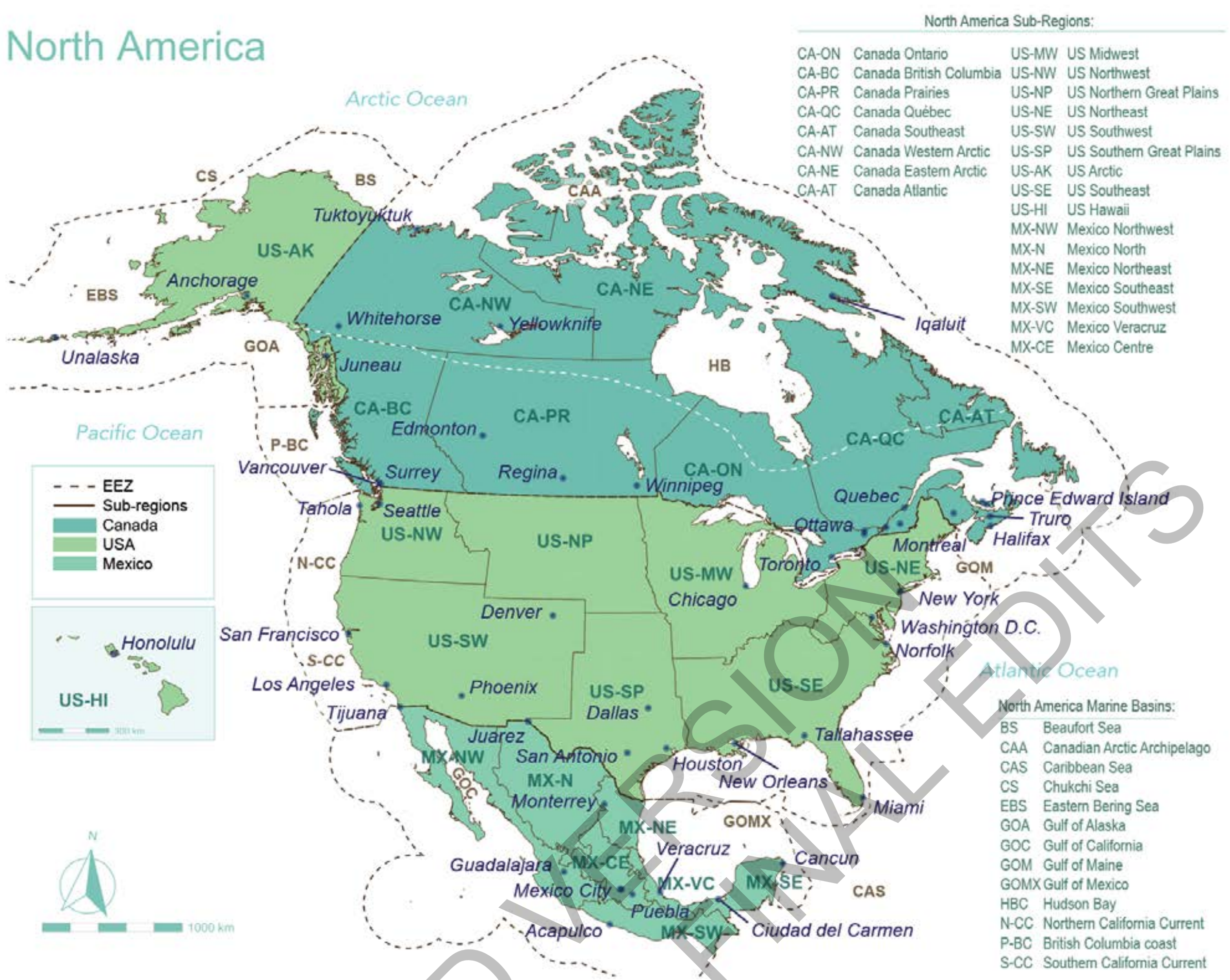


Figure 14.1: North American regions and subregions, adapted from national climate assessments, and city names, referred to in discussion of local and regional climate change impacts and adaptation.

14.1.1 Context

With a 2019 total population of over 494 million people (US 329 million, Mexico 128 million and Canada 37 million), North America comprises 6.4% of the global population. Relative to other countries, North America has low population densities (Mexico 64 people/km^2; US 35/km^2; Canada, 4/km^2) (United Nations, 2019). Population projections indicate a steady growth in the three countries, which will exert pressure on consumption and increase risks under climate change (United Nations, 2019). North America is also responsible for about a quarter of global greenhouse gas (GHG) emissions. Since 1990, North American GHG emissions have increased by almost 18% (Ritchie and Roser, 2020) and in 2019 the region was responsible for 5.9 MtCO_2 emissions worldwide (Friedlingstein et al., 2020). In terms of annual CO_2 emissions per capita, in 2019 Canada had 15 metric tons CO_2 per person (tCO_2/person), the US had 16 tCO_2/person, and Mexico had 3.4 tCO_2/person (Friedlingstein et al., 2020).

14.2 Current and Future Climate in North America

Trends in observed and projected physical climate variables, and changes in extreme weather and climate events, are summarized in this section. Many of the assessments here are adapted from AR6 WGI (IPCC, In Press), especially chapters 11 (Seneviratne et al., 2021) and 12 (Ranasinghe et al., 2021) and the WGI Atlas (Gutiérrez et al., In Press) (references to chapters in WGI are hereafter abbreviated I.11, I.12, I.Atlas, etc.). I.12.4.6 assesses North American climatic impact drivers without assessing their impacts or associated risks. WGI assessments are augmented in this section with regionally specific support from recent national climate assessments or original literature.

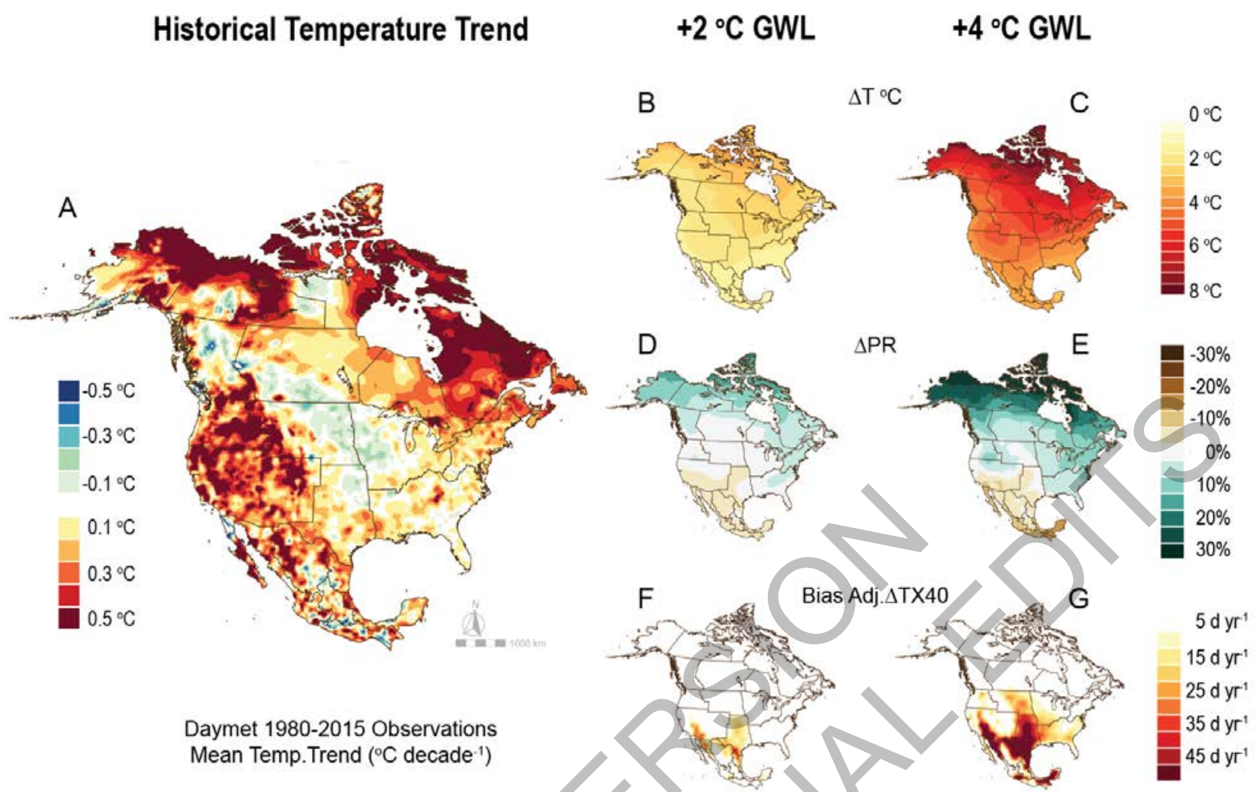


Figure 14.2: Observed and projected climate changes across North America. Black boundary lines delineate North American subregions (Fig. 14.1). Data were extracted from WGI online atlas, where data set details can be found. A) recent observations; (B)-(G) from an ensemble of CMIP6 projections. A) Observed annual mean temperature trend over land for period 1980-2015. B, C) Projected change in annual mean temperature over land relative to 1986-2005 average, associated with 2°C or 4°C global warming. D, E) Like (B, C), but for projected percentage change in annual precipitation. F, G) Like (B, C), but for projected change in number of days/year with maximum temperature > 40°C ("TX40").

14.2.1 Observed Changes in North American Climate

Climate changes directly related to increasing mean and extreme temperature, including reduced snowpack, sea and lake ice and glacier extent, and marine heatwaves, can be attributed to human activity and are affecting most of North America (*high confidence*). Upward trends in annual mean temperature across North America since 1960 are wide-spread (I.Atlas) but nonuniform (Figure 14.2a). Pronounced polar amplification of warming is observed in high latitudes (Figure 14.1a), particularly in winter (Vose et al., 2017; Zhang et al., 2019a) (I.Atlas). As average temperature rises, extreme high temperature records across North America are being set more frequently than extreme cold records (Meehl et al., 2016) and the probability of cold extreme events is reduced (I.11). Trends in daily maximum and minimum temperature are significant in high latitudes (*US-AK, CA-NW, CA-NE*). Summertime daily maximum temperature is increasing in southwestern desert regions (*US-SW, MX-NW*) (Martinez-Austria et al., 2016; Martinez-Austria and Bandala, 2017; Navarro-Estupinan et al., 2018).

Annual precipitation has increased in recent decades in northern and eastern areas (*CA-PR, CA-QU, US-NP, US-SP, US-MW, US-NE, US-AK*) (*high confidence*), and has decreased across the western part of the continent (*CA-BC, US-SW, US-NW, MX-NW*) (*medium confidence*), with considerable spatial variability within these regions (Zhang et al., 2019a; Gutiérrez et al., In Press). Elsewhere across North America there is *limited evidence* and *low agreement* on detection of observed trends in total precipitation and river flood hazards. The intensity and frequency of one-day heavy precipitation events have *very likely*[2] increased since the mid-20th Century across most of the US (*US-NP, US-MW, US-NE*, but not in *US-SE*) and in Mexico, but no detectable trend is reported in Canada (Zhang et al., 2019a) (I.11). Recent flooding events along the mid-latitude Pacific Coast have been attributed to increasingly intense atmospheric river (AR) events (Gershunov et al., 2019; Vano et al., 2019) (I.8) but there is *low confidence* in detecting trends in AR activity.

Snowpack and snow extent across much of Canada and the western US have declined as temperatures have increased (Kunkel et al., 2016; Mote et al., 2018; Mudryk et al., 2018; Derksen et al., 2019) (I.12; I.Atlas) (*very high confidence*). Warm "snow droughts", describing a deficit of snowpack available for runoff even in the absence of a winter precipitation deficit (Cooper et al., 2016; Harpold et al., 2017), have become more common in North American mountains (Sproles et al., 2016; Nicholls et al., 2018; Pershing et al., 2018). Glaciers have retreated over the past half-century at high elevation across North America (Frans et al., 2018; Zemp et al., 2019) and in the Arctic (Burgess, 2017; Box et al., 2019; Derksen et al., 2019). Lake ice in Canada, south of the Arctic region delineated in Figure 14.1, has declined (Alexeev et al., 2016; Derksen et al., 2019).

There is limited evidence of trends in meteorological or hydrologic droughts over the historical record (Wehner et al., 2017) (I.8 and I.11 discuss multiple perspectives on drought), but there is *medium confidence* in increasing atmospheric evaporative demand acting to intensify surface aridity during recent droughts (Williams et al., 2020) (I.11; *US-SW*). The ongoing multi-decadal dry period in the Colorado River Basin is as extreme as any drought in the past thousand years (Murphy and Ellis, 2019; Williams et al., 2020).

The proportion of hurricanes in stronger categories has *likely* increased globally over the past 40 years, with *medium confidence* that the onshore propagation speed of hurricanes making landfall in the US has slowed detectably since 1900 (Kossin, 2018) (I.11), contributing to detectable increases in local rainfall and coastal flooding associated with these storms. There is *high confidence* (I.11) that anthropogenic climate change contributed to extreme precipitation associated with recent intense hurricanes, such as Harvey in 2017.

North American sea ice extent and volume (thickness) have declined up to 10% per decade since 1981 (Ding et al., 2017; Mudryk et al., 2018; Derksen et al., 2019; IPCC, 2019c)(I.9), with changes accelerating during this time (Schweiger et al., 2019) (*robust evidence, high agreement*), resulting in longer and larger periods of open water (Wang et al., 2018a). Recent (2018) sea ice extent in the Bering Sea was the lowest in a 5,500 yr record and appears to lag atmospheric CO_2 by ~2 decades (Jones et al. 2021). High Arctic sea ice retreat since 1971 and increases in open water duration in the most recent decade are unprecedented (Box et al., 2019) and most pronounced in the Chukchi, Bearing, and Beaufort Seas (*US-AK, CA-NW*) (*high confidence*) (Wang and Overland, 2015; Jones et al., 2020).

Warming of North American offshore waters is significant and attributable to human activities, particularly along the Atlantic coast, contributing to sea level rise (SLR) through thermal expansion (IPCC, 2019c) (I.9) (*very high confidence*). Rates of SLR have accelerated along most North American coasts during the past three decades, excepting coastlines in southern Alaska and northeastern Canada where land is rising (I.12). Tidal flooding frequency has increased in the North Pacific from once every 1-3 years to every 6-12 mo (Sweet et al., 2014).

Acidification of North American coastal waters has occurred in conjunction with increased atmospheric CO_2 concentration (Mathis et al., 2015; Jewett and Romanou, 2017; Claret et al., 2018) combined with other local acidifying inputs such as nitrogen and sulphur deposition (Doney et al., 2007) and freshwater nutrient input (Strong et al., 2014; IPCC, 2019c) (*very high confidence*). Oxygen minimum zones, particularly in the North Pacific south of *US-AK*, have expanded in volume and O_2 has declined since 1970 (IPCC, 2019c).

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range

14.2.2 Projected Changes in North American Climate

Climate changes related to warming temperature, including more intense heat waves over land and in the ocean, diminished snowpack, sea ice reduction and SLR, are projected with *high confidence* and are strongly sensitive to future greenhouse gas concentrations (Figure 14.2). Climatic hazards affected by hydrologic change, including humidity-inclusive heat stress, extreme precipitation, and more intense storms, are projected to intensify.

Pronounced amplification of warming across the Arctic and continental intensification of warming (Figure 14.1bc) is projected with *high confidence* (Doney et al., 2007; Vose et al., 2017). Extreme heat waves are projected to intensify, particularly in *MX-NW, MX-N, MX-NE, US-SW, US-NP* and *US-SP* (Figure 14.2f-g) and become more frequent and longer in duration as average temperature rises across North America (I.11). Extreme cold events are projected to decrease in severity (Wuebbles et al., 2014)(I.12).

Total precipitation is projected to increase across the northern half of North America (*very high confidence*) and decrease in southwestern North America (*MX-SW, MX-NW, US-SW*) (*medium confidence*) (Fig 14.2d-e, I.Atlas). Further increases in the intensity of locally heavy precipitation are *very likely* across the continent, as a greater fraction of precipitation falls in intense events (Easterling et al., 2017; Prein et al., 2017a; Zhang et al., 2019a).

High-humidity hazards are projected to increase (*medium confidence*) in regions around the Gulf of Mexico and southeastern North America (*US-SE, US-SP, MX-NE, MX-SE*) (Zhao et al., 2015). In subtropical regions that are less influenced by moisture from the Gulf of Mexico (including *US-SW, US-SP, MX-NW* and *MX-N*), the combination of higher temperature and less total precipitation leads to projections of increased aridity: drier surface conditions, higher evaporative demand by plants, and more intense droughts-(Jones and Gutzler, 2016; Easterling et al., 2017; Escalante-Sandoval and Nuñez-Garcia, 2017) (I.12).

As temperatures rise, snow extent, duration of snow cover and accumulated snowpack are *virtually certain* to decline in sub-Arctic regions of North America (McCrary and Mearns, 2019; Mudryk et al., 2021) (I.Atlas), with corresponding effects on snow-related hydrologic changes (*high confidence*). These include declines in snowmelt runoff (Li et al., 2017); increased evaporative losses during snow ablation (Foster et al., 2016; Milly and Dunne, 2020); and increases in the frequency of rain-on-snow events (Jeong and Sushama, 2018a) and consecutive snow drought years in western North America (Marshall et al., 2019a).

Climate change is projected to magnify the impact of tropical cyclones in *US-NE, MX-NE, US-SP,* and *US-SE* by increasing rainfall (Patricola and Wehner, 2018) and extreme wind speed (*high confidence*) and slowing the speed of land-falling storms (Kossin, 2018)(I.11) (*limited evidence, low confidence*). The coastal region at severe risk from tropical storms is projected to expand northward within *US-NE* (Kossin et al., 2017) (*medium confidence*).

Additional reduction in polar sea ice is *virtually certain* (Mudryk et al., 2021)(I.12), with the North American Arctic projected to be seasonally ice-free at least once per decade under 2°C of global warming (*high confidence*) (Mudryk et al.; IPCC, 2019b; Mioduszewski et al., 2019). Duration of freshwater lake ice across the northern US and southern Canada is projected to diminish (*high confidence*) (Dibike et al., 2012; Mudryk et al., 2018; Sharma et al., 2019) (I.12).

Ocean surface temperature is *very likely* to increase in future decades in waters around North America (Jewett and Romanou, 2017; Greenan et al., 2019a), but at a slower rate than air temperature over the continent. Rates of change are projected to be relatively higher in northern latitudes, with most rapid warming in summer in the Arctic and Bering Sea (*US-AK, CA-NW*) (Wang and Overland, 2015; Wang et al., 2018a; Hermann et al., 2019).

SLR is *virtually certain* to continue along North American coastlines except for parts of *US-AK* with geographically variable rates of rise (I.9, I.12, Box 14.4). Relatively greater SLR is projected along the *US-SE, CA-AT* and *MX-SW* coastlines and relatively less along *CA-BC* and *US-NW* (Fasullo and Nerem, 2018; Greenan et al., 2019a; IPCC, 2019b) (I.9, I.12, Box 14.4).

Ocean acidification along North American coastlines is projected to increase (*very high confidence*) (Jewett and Romanou, 2017). The frequency and extent of oxygen minimum and hypoxic zones are projected to increase, with less confidence, exacerbated by climate-driven eutrophication and increasing stratification (Altieri and Gedan, 2015; IPCC, 2019b).

[START FAQ14.1 HERE]

FAQ 14.1: How has climate change contributed to recent extreme events in North America and their impacts?

Multiple lines of evidence indicate that climate change is already contributing to more intense and more frequent extreme events across North America. The impacts resulting from extreme events represent a huge challenge for adapting to future climate change.

Extreme events are a fundamental part of how we experience weather and climate. Exceptionally hot days, torrential rainfall, and other extreme weather events have a direct impact on people, communities, and ecosystems. Extreme weather can lead to other impactful events such as droughts, floods or wildfires. In a changing climate, people frequently ask whether extreme events are generally becoming more severe or more frequent, and whether an actual extreme event was caused by climate change.

Because really extreme events occur rarely (by definition), it can be very difficult to assess whether the overall severity or frequency of such events has been affected by changing climate. Nevertheless, careful statistical analysis shows that record-setting hot temperatures in North America are occurring more often than record-setting cold temperatures as the overall climate has gotten warmer in recent decades. The area burned by large wildfires in the western US has increased in recent decades. Observed trends in extreme precipitation events are more difficult to detect with confidence, because the natural variability of precipitation is so large and the observational database is limited.

Our understanding of how individual extreme weather events have been influenced by climate change has improved greatly in recent years. Climate scientists have developed a formal technique ("event attribution", described in Working Group I FAQ 11.3) for assessing how climate change affects the severity or frequency of a particular extreme event, such as a record-breaking rainfall event or a marine heat wave. This is a challenging task, because any particular event can be caused by a combination of natural variability and climate change. Event attribution is typically carried out using models to compare the probability of a specific event occurring in today's climatic environment, relative to the probability that the same event might have occurred in a modelled climate in which atmospheric greenhouse gases have not risen due to human activities. Using this strategy, multiple studies estimated that the historically extreme rainfall amount that fell across the Houston area from Hurricane Harvey (2017) was 3 to 10 times more *likely* as the result of climate change.

The *impacts* from extreme events depend not just on physical climate system hazards (temperature, precipitation, wind, etc.), but also on the exposure and vulnerability of humans or ecosystems to these events. For example, damage from landfalling hurricanes along the coast of the Gulf of Mexico is expected to increase as very strong hurricanes become more frequent and intense due to climate change. But damage would also increase with additional construction along the shoreline, because coastal development increases *exposure* to hurricanes. And if some structures are constructed to poor building standards, as was the case when hurricane Andrew made landfall in Florida in 1992, then *vulnerability* to hurricane-caused impacts is increased.

Climate change also contributes to impacts from extreme events by making some building codes and zoning restrictions inadequate or obsolete. Many North American communities limit development in areas known to be flood-prone, to minimize exposure to flooding. But as climate change expands the areas at risk of exposure to flooding beyond historical floodplains, the impacts of potential flooding are increased, as Hurricane Harvey demonstrated. Adapting to climate change may require retrofits for existing structures and revised zoning for new construction. Some structures and neighbourhoods may need to be abandoned altogether to accommodate expanded flooding risk.

Climate change can be an *added stress* that increases impacts from extreme events, combined with other non-climatic stressors. For example, climate change in western North America has contributed to more extreme fire weather. The devastating impacts of recent wildfire outbreaks, such as occurred across western Canada in 2016 and 2017, the western United States in 2018 and 2020, and both countries in 2021, are to some extent associated with expanded development and forest management practices (such as policies to suppress low-intensity fires, allowing fuel to accumulate). The effects of development and forest management have dramatically increased the exposure and vulnerability of communities to intense wildfires. Climate change has added to these stressors: warming temperature leads to more extreme weather conditions that are conducive to increasingly severe wildfires.

Biodiversity is affected by climate change in this way too. For example, numerous bird populations across North America are estimated to have declined by up to 30% over the past half-century. Multiple human-related factors, including habitat loss and agricultural intensification, contribute to these declines, with climate change as an added stressor. Increasingly extreme events such as severe storms and wildfires can decimate local populations of birds, adding to existing ecological threats.

[END FAQ 14.1 HERE]

14.3 Perception of Climate Change Hazards, Risks, and Adaptation in North America

14.3.1 Climate Change as a Salient Issue

The majority of the climate science community has reached consensus that mean global temperature has increased and human activity is a major cause (Oreskes, 2004; Anderegg et al., 2010; Cook et al., 2013; Cook et al., 2016; IPCC, In Press), setting the context for public policy action. Despite expert scientific consensus on anthropogenic climate change, there is polarization and an ongoing debate over the reality of anthropogenic climate change in the public and policy domains, with attendant risks to society (*high confidence*) (Doran and Zimmerman, 2009; Ballew et al., 2019; Druckman and McGrath, 2019; Hornsey and Fielding, 2020; Wong-Parodi and Feygina, 2020). Public perception of consensus regarding anthropogenic climate change can be an important gateway belief, which establishes a crucial precondition for public policy action (van der Linden et al., 2015; van der Linden et al., 2019) by influencing the assessment of climate change risks and opportunities, and formulation of appropriate mitigation and adaptation responses (Ding et al., 2011; Bolsen et al., 2015; Drews and Van den Bergh, 2016; Doll et al., 2017; Mase et al., 2017; Morton et al., 2017). Trust in experts, institutions and environmental groups is also important (Cologna and Siegrist, 2020; Termini and Kalafatis, 2021).

Rhetoric and misinformation on climate change and the deliberate undermining of science have contributed to misperceptions of the scientific consensus, uncertainty, disregarded risk and urgency, and dissent (*high confidence*) (Ding et al., 2011; Oreskes and Conway, 2011; Aklin and Urpelainen, 2014; Cook et al., 2017; van der Linden et al., 2017). Additionally, strong party affiliation and partisan opinion polarization contribute to delayed mitigation and adaptation action, most notably in the US (*high confidence)* (van der Linden et al., 2015; Cook and Lewandowsky, 2016; Bolsen and Druckman, 2018; Chinn et al., 2020) but with similar patterns in Canada (*medium confidence*) (Lachapelle et al., 2012; Kevins and Soroka, 2018). Vocal groups can affect public discourse and weaken public support for climate mitigation and adaptation policies (Aklin and Urpelainen, 2014; Lewandowsky et al., 2019) (*medium confidence*). Vested economic and political interests have organized and financed misinformation and "contrarian" climate change communication (Brulle, 2014; Farrell, 2016b; Farrell, 2016a; Supran and Oreskes, 2017; Bolsen and Druckman, 2018; Brulle, 2018). Traditional media – print and broadcast – frame and transmit climate change information and play a crucial role in shaping public perceptions, understanding, and willingness to act (Happer and Philo, 2013; Schmidt et al., 2013; Hmielowski et al., 2014; Bolsen and Shapiro, 2018; King et al., 2019; Chinn et al., 2020). The journalistic norm of "balance" (giving equal weight to climate scientists and contrarians in climate change reporting) biases coverage by unevenly amplifying certain messages that are not supported by science, contributing to politicization of science, spreading misinformation, and reducing public consensus on action (Boykoff and Boykoff, 2004; Boykoff and Boykoff, 2007; Cook et al., 2017). Much online social media discussion of climate change takes place in ''echo chambers'' – a social network amongst like-minded people in communities dominated by a single view that contributes to polarization (Williams et al., 2015; Pearce et al., 2019), and the spread of misinformation (Treen et al., 2020).

14.3.2 Public Perceptions, Opinions and Understanding of Climate Change

In a 2018 survey across 26 nations, people in Canada and Mexico ranked climate change as the top global threat, whereas in the US climate change ranked third (Poushter and Huang, 2019). The public's responses to the causes of climate change and risk perceptions in Canada (Mildenberger et al., 2016) and US (Howe et al., 2015) revealed variations among regions (Figure 14.3) and less acceptance of climate change in rural regions than in urban areas. Canadian regions have higher acceptance of climate change (e.g., recognize it is happening and attributable to human activity) than the most liberal areas in the US (Lachapelle et al., 2012; Mildenberger et al., 2016). Western Canadian regions with high carbon intensity economies had lower acceptance of climate change than the rest of Canada, whereas in the US perceptions were more stable across regions (Lachapelle et al., 2012). A recent survey in Mexico found that for 73% of respondents climate change represents a major economic, environmental and social threat, and in the most vulnerable states (*MX-SE*), the perception is that climate change impacts and extreme events have considerable implications for the way of life in communities (Zamora Saenz, 2018). In a 2017 survey, Azócar et al. (2021) found 85% of respondents from Mexico acknowledged anthropogenic climate change. Peoples' experience with extreme events (e.g., hurricanes, high temperatures), socio-demographic characteristics, level of marginalization and economic and social exclusion, as well as education levels were important factors influencing perception of climate change in Mexico (Corona-Jimenez, 2018; Alfie and Cruz-Bello, 2021; Azócar et al., 2021). Drawing upon Indigenous knowledge (Box 14.1) as well as lived experience of recent changes in ice, weather patterns, and species' phenology and distribution, Indigenous Peoples recognize that change is occurring in their communities and have effective solutions that are grounded in Indigenous worldviews (Harrington, 2006; Turner and Clifton, 2009; Norton-Smith et al., 2016a; Savo et al., 2016; Maldonado et al., 2017; Chisholm Hatfield et al., 2018).

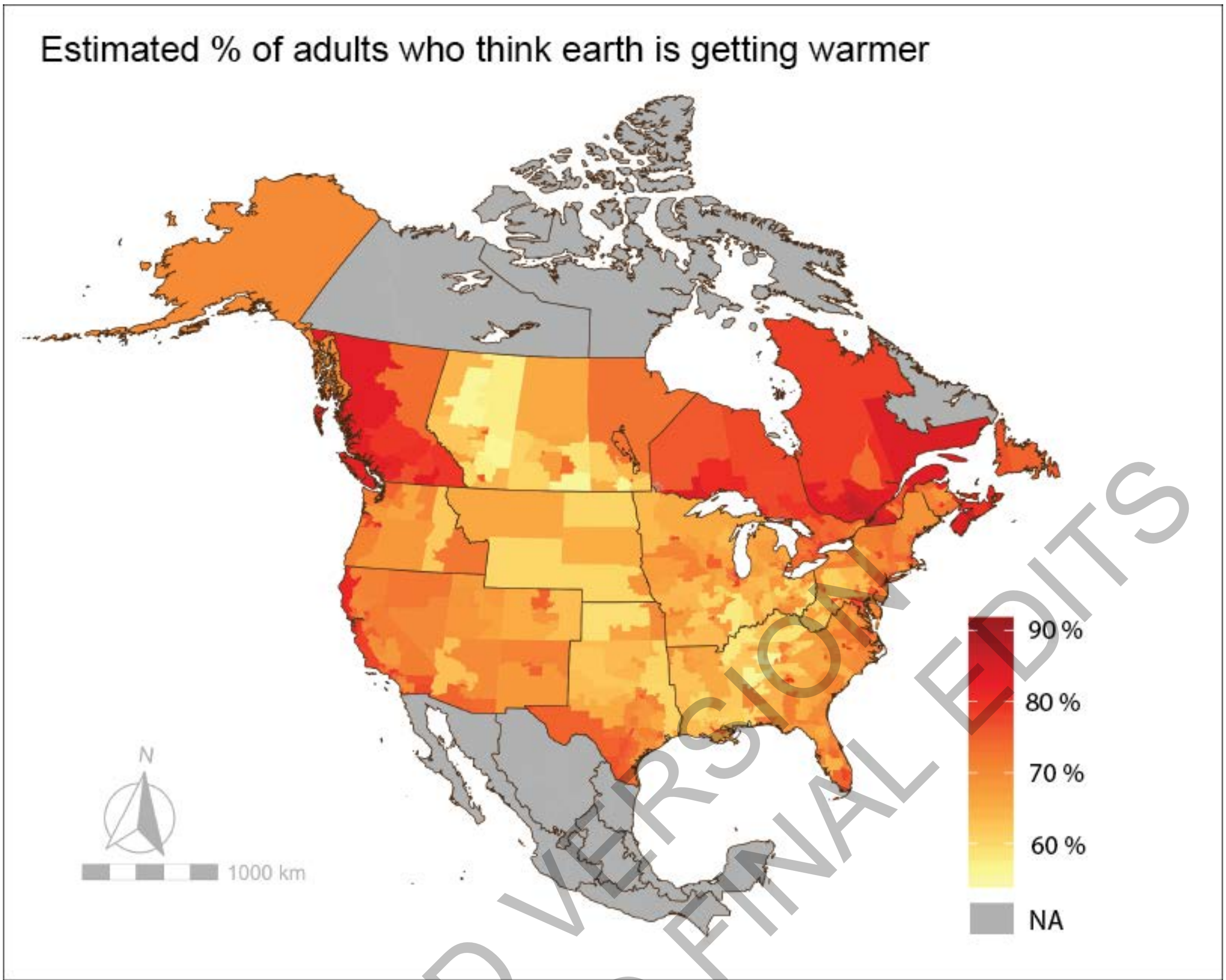


Figure 14.3: Regional distribution of public perception that "the Earth is getting warmer" as a surrogate for public acceptance that climate change is happening (% of population). Scale is the Canadian federal electoral district or riding level and US Congressional District. The three northern territories and Labrador, in Canada, did not meet population thresholds for modelling. The figure updates Mildenberger et al. (2016) and is based on equivalent public surveys in both countries -- Canadian "Earth is getting warmer" and US "global warming is happening" undertaken in 2019. Equivalent surveys and modelling for Mexico are not available at this time.

14.3.3 Building Consensus on Climate Change

Building consensus for action on climate change is influenced by individual factors (e.g., ideology, worldview, trust, partisan identity, religion, education, age) and the broader societal context (e.g., culture, media coverage and content, political climate, economic conditions) *(high confidence*) (McCright and Dunlap, 2011; Brulle et al., 2012; Hornsey et al., 2016; Arbuckle, 2017; Pearson et al., 2017; Bolsen and Shapiro, 2018; Ballew et al., 2020; Cologna and Siegrist, 2020; Goldberg et al., 2020). In a multi-country assessment of acceptance of global warming influenced by ideology (e.g., conspiratorial ideation, individualism, hierarchy, and left–right and liberal–conservative political orientation), the US uniquely had the strongest link to doubt out of 25 countries for all factors, while Canada's dominant influence on non-acceptance was conservative political ideology, and for Mexico, there were no ideological effects (Hornsey et al., 2018).

Political affiliation and partisan group identity contribute to polarization on the causes and state of climate change, most notably in the US (*medium confidence*). Fewer US Republicans hold the belief that human activity causes climate change than Democrats (Bolsen and Druckman, 2018; Druckman and McGrath, 2019). Partisanship in the US with respect to climate change has evolved over the period 1997 to 2016; initially, it was limited, but since 2008, there has been a widening, more entrenched partisan "divide" (Dunlap et al., 2016). The millennial generation (born 1980s, 1990s), emerging as the largest US population cohort, has a potentially important political influence – reduction in polarization – as they show relatively higher levels of concern and acceptance of climate change science than older age groups. Political affiliation does not have as strong an effect on their climate change beliefs (Corner et al., 2015; Ross et al., 2019).

Communicating to educate or enhance knowledge on climate change science or consensus does not necessarily lead individuals to revise their beliefs (Bolsen et al., 2015; Druckman and McGrath, 2019) (*medium confidence*). People may reject new information that conflicts with their beliefs or not consider it credible, as political ideology and partisan affiliation are strong influences (Arbuckle, 2017). The climate change issue may create resistance from individuals with conservative political ideologies and hierarchical, individualistic worldviews because it ascribes responsibility to developed, industrialized countries for emissions and brings about more environmental regulation (Stevenson et al., 2015). Lack of trust in scientific consensus on climate change may actually originate from opposition by US conservatives to the perceived advocacy for different climate change policy approaches that challenge their worldviews (Bolsen and Druckman, 2018).

14.3.4 Factors Influencing Perceptions of Climate Change Risks and Adaptation Action

Projected climate change risk, urgency and necessary adaptations are perceived and understood differently by the public, communities, professional groups, climate scientists, and public policy makers (*high confidence*) (Bolsen et al., 2015; Drews and Van den Bergh, 2016; Morton et al., 2017; Treuer et al., 2018). People can engage with climate change across three dimensions: cognitive - knowledge, affective - feelings, and behavioural - responses and actions (Galway, 2019; Brosch, 2021). Risk assessment can be influenced by values regarding the subject under evaluation (Allison and Bassett; Stevenson et al., 2015) and can interact with other risks and change over time (Mach et al., 2016). Communities and practitioners (e.g., farmers, foresters, water managers) are influenced in their willingness to modify current practices and adopt new measures based on how they perceive, understand, and experience climate change uncertainty, risk and urgency as well as political and social norms (van Putten et al., 2015; Doll et al., 2017; Mase et al., 2017; Morton et al., 2017; Zanocco et al., 2018). Place-based and local-focused assessments allow individuals to more readily assess and adapt to risks as well as identify roles and responsibilities in the face of multiple, interacting, and often unequally distributed climate change impacts (Khan et al., 2018; Galway, 2019). Interest in preserving local archaeological sites threatened by SLR initiated collaboration and co-production of knowledge among disparate US communities -- citizens, archaeologists, preservationists, planners, land managers, and Indigenous Peoples (Fatorić and Seekamp, 2019; Dawson et al., 2020).

Psychological distancing -- the perception that the greatest impacts occur sometime in the distant future and to people and places far away – can lead to discounting of risk and the need for adaptation (Leviston et al., 2014; Mildenberger et al., 2019) (*medium confidence*). Communication directed at local and personal framing of climate change impact and risk information is one option for addressing low salience (Bolsen et al., 2019), particularly related to established risks such as SLR, flooding, and wildfires in North America (Mildenberger et al., 2019). "Personalized" risk communications have had mixed results creating behavioural change and policy support, and even caused resistance (Schoenefeld and McCauley, 2016). Communication focused extensively on risks and dangers of climate change can produce fear or dread, lessen agency and create fatalism that hinders action (Giddens, 2015; Mayer and Smith, 2019); it also can be labelled alarmist (Leiserowitz, 2005). Detailed SLR flooding maps for the San Francisco Bay area did not increase climate risk assessment but lessened personal risk perception of those with a strong belief in climate change although policy preferences and support for adaptation did not change (Mildenberger et al., 2019). Defining coherent groups based on variations in beliefs, risk perceptions, and policy preferences offers opportunities for effectively engaging with segments of the population instead of using the same approach for everyone (*low confidence*) (Maibach et al., 2011; Chryst et al., 2018). As an example, the US population was segmented into a continuum ranging from the "Alarmed", the dominant group who were "Concerned", then the Cautious, Disengaged, Doubtful, and least prevalent, the Dismissive (Chryst et al., 2018).

[START BOX 14.1 HERE]

Box 14.1: Integrating Indigenous 'Responsibility-Based Thinking' into Climate Change Adaptation and Mitigation Strategies

Indigenous Peoples throughout North America have experienced five centuries of territorial expropriation, loss of access to natural resources and in many cases, barriers to the use of their sacred sites (Gabbert, 2004; Louis, 2007). The history of Indigenous struggles to preserve distinct cultural knowledges and assert autonomy in the face of colonialism has shaped land-use patterns and relationships with traditional territories (Alfred and Corntassel, 2005; Tuhiwai Smith, 2021) (Cross-Chapter Box INDIG, Chapter 18). Climate change is now creating additional challenges for Indigenous Peoples. For example, increased water scarcity due to higher temperatures and diminished precipitation have led to reduced crop yields for Maya farmers in the Yucatan (Sioui, 2019). Thawing permafrost in subarctic Canada (Quinton et al., 2019) has interfered with the land-based livelihoods of the Indigenous Dene Peoples (CCP6).

Recent climate-related changes represent cultural threats similar to the ones that occurred when European settlement began in the Americas over 500 years ago (Whyte, 2016; Whyte, 2017). Thus, for Indigenous Peoples, who often disproportionately bear the impacts of climate change, such changes are not novel, but seen as 'déjà vu' (Whyte, 2016). Since livelihoods and subsistence are often directly dependent on the land and water, Indigenous Peoples have direct insights into the localized impacts of global environmental change. Indeed, Indigenous Peoples consider themselves stewards of the land (and water), and have a spiritual duty to care for the land and its flora, fauna, and aquatic community, or 'Circle,' of beings. Indigenous knowledge (IK) has gained recognition for its potential to bolster western scientific research about climate change. Many recent examples demonstrate the scientific value of IK for resource management in climate change adaptation and mitigation (e.g. Kronik and Verner, 2010; Maldonado et al., 2013; Wildcat, 2013; Etchart, 2017; Nursey-Bray et al., 2019). For example, Indigenous practices have not only contributed to the present understanding of North American forest fires, but also that the practice of frequent small-scale anthropogenic fires, also called cultural burns, is a key method to prevent large-scale destructive fires (14.7.1). The growing interest and recognized value in these practices, particularly in California, has led to formal agreements with state and federal agencies (Long et al., 2020a; Lake, 2021).

Indigenous relationships with the land are commonly informed and guided by a cultural ethic of 'responsibility-based thinking' (Sioui and McLeman, 2014). The Indigenous cultural ethic informs and mediates personal and collective conduct with a sense of duty or responsibility toward human and other-than-human relations (see Sioui, 2020). The Indigenous responsibility-based outlook stems from a cultural paradigm that understands that it is human beings who must learn to live *with* the land (Cajete, 1999; Pierotti and Wildcat, 2000; McGregor et al., 2010a; McGregor, 2014). This way of thinking instils in its adherents an inherent awareness that the other-than-human realm is capable of existing and thriving without humans. Thus, it is for our own sake (as humans) that we learn to live according to certain, ever-shifting, parameters, requiring us to remain acutely attuned to our physical surroundings. This Indigenous cultural precept is perhaps among the most significant contributions of Indigenous Peoples to the rest of humanity in the face of climate change.

Indigenous relationships with natural systems continue to be mediated by cultural orders of governance and legal systems that pre-date, by several millennia, European traditions in North America. Napolean (2012) describes Indigenous legal orders as dynamic and encompassing knowledge that is simultaneously legal, religious, philosophical, social, and scientific. Customary Indigenous legal orders (e.g. Borrows, 2002; Napolean, 2012) stand in contrast to Eurocentric understandings of law, which are closely related to, and founded on, the Western principles of rights. Indigenous legal orders are based on duties, obligations and responsibilities to the land and all beings, including humans, animals, plants, future generations and the departed/ancestors (Borrows, 2002; Borrows, 2010a; Borrows, 2010b; Borrows, 2016). Indigenous spiritual laws centred on the values of responsibility and accountability to the land, and how these differ, in theory and in practice, from Western law, which is based on "universal" principles, with little consideration for the local environmental context (Craft, 2014). Research has elucidated these Indigenous understandings about how their land-based responsibilities act as the foundation of how humans must operate according to the land on which they live and depend.

With increasing climate change threats to land-based subsistence and cultural practices, Indigenous Peoples are increasingly taking their rightful leadership roles in resource co-management arrangements and other stewardship activities (14.5.2.2). Indeed, Indigenous Peoples are increasingly assuming leadership positions with regard to land governance and climate change action, as the stewards of their traditional territories since time immemorial. Therefore, it is imperative for Indigenous scholars, Elders, and knowledge holders to occupy leadership roles in climate change adaptation and mitigation, especially when their territories are concerned (14.7; CCP6). For instance, Indigenous "resurgence" paradigms draw on the strengths of traditional land-based culture and knowledge with regard to Indigenous leadership in land governance and stewardship (Alfred and Corntassel, 2005; Alfred, 2009; Simpson, 2011; Corntassel and Bryce, 2012; Coulthard, 2014; Alfred, 2015). Indigenous leadership in climate change policy, therefore, can ensure that Indigenous right to self-determination is respected and upheld to allow Indigenous Peoples to continue to carry out their cultural responsibilities to the land, for the benefit of all North Americans (Powless, 2012; Etchart, 2017).

In Northern Canada, a fusion of leading-edge western science and IK on permafrost informed the co-development of predictive decision support tools and risk management strategies to inventory and manage permafrost and adapt to permafrost thaw (CCP6). Permafrost thaw in the Dehcho region of Canada is widespread and occurring at unprecedented rates (WGI). The *Dehcho Collaborative on Permafrost* (DCoP) aims to improve the understanding of and ability to predict and adapt to permafrost thaw (http://scottycreek.com/DCoP/). DCoP's collaborative approach, which places Indigenous Peoples in leadership positions, generates the new knowledge, predictive capacity and decision-support tools to manage natural resources that support Indigenous Dene Peoples' ways of life. Indigenous-academic partnerships can enhance climate change adaptation and mitigation capacity and provide openings for more holistic co-management approaches that recognize and affirm the central role of Indigenous Peoples as stewards of their ancestral territories, especially as they face accelerating climate change impacts. Academic researchers and their Indigenous partners can support climate change resilience via mobilizing IK in stewardship and adaptation; researching governance arrangements, economic relationships and other factors that hinder Indigenous efforts in these areas; proposing evidence-based policy solutions at international and national scales; and outlining culturally relevant tools for assessing vulnerability and building capacity will also support climate change resilience. IK underpins successful climate change adaptation and mitigation (*very high confidence*) (see Green and Raygorodetsky, 2010; Kronik and Verner, 2010; Alexander et al., 2011; Powless, 2012; Ford et al., 2016; Nakashima et al., 2018). The inclusion of IK in adaptation and mitigation not only supports Indigenous cultural survival but also enables governments to recognize the territorial sovereignty of Indigenous Peoples.

Responsibility-based philosophies of Indigenous Peoples from across the continent support the development of climate change adaptation and mitigation strategies that promote responsible and respectful relationships with the environment over the long term. Adapting to change, in all its forms, has since time immemorial been one of the defining characteristics of Indigenous cultures on Turtle Island (the American continent). In the Yucatan, one Elder explained that with regards to climate change impacts in the region, the Maya have always dealt with "*k'ech*", or change, and that accepting and responding to change is part of the Maya identity and responsibility (Sioui, 2020). Given successive failures in adequately and effectively responding to climate change, it has become urgent for the rest of the human collective to (re)learn from Indigenous cultures to (re)consider our responsibility/ies to the land—the world over—and to reorient our societal imperatives to better respond and react to *change*. Such a process of learning from IK could foster the development of climate change policies that promote responsible and respectful relationships with the environment over the long term, and prove to be more effective and holistic. Although most inhabitants of North America are non-Indigenous, it is possible and beneficial for our societies to learn to think and act in a more responsibility-based way about our relations to the land, and, by extension, about climate change policy. A collective commitment to protecting and advancing Indigenous territorial rights, so Indigenous Peoples can continue to reassert their spiritual duty and role as stewards of their traditional territories, benefits of all human and other-than-human 'Peoples'.

[END BOX 14.1 HERE]

14.4 Indigenous Peoples and Climate Change

Indigenous knowledge and science are resources for understanding climate change impacts and adaptive strategies (*very high confidence*) (SM14.1, Table SM14.1). The Indigenous Peoples of North America have and continue to contribute substantially to the growing literature, scholarship, and research on climate change (Barreiro, 1999; Houser et al., 2001; Mustonen, 2005; Bennett et al., 2014; Maynard, 2014; Merculieff et al., 2017; FAQI, 2019; Ijaz, 2019; BIA, 2021). For thousands of years, Indigenous Peoples have developed and relied on their own knowledge systems for sustaining their health, cultures and arts, livelihoods, and political security (Battiste and Henderson, 2000; Colombi, 2012; Nelson and Shilling, 2018). Diverse Indigenous knowledge systems in North America consider weather and climate as major dimensions of understanding the relationship between society and the environment. Indigenous Peoples have distinct knowledge of climate change, over extensive temporal measures (Trosper, 2002; Barrera-Bassols and Toledo, 2005; Gearheard et al., 2013). The basis of this knowledge is often Indigenous Peoples' long and profound relationships to the environment, that is to the ecosystems, waters, ice, lands, territories, and resources in their homelands. The relationships were forged by adaptation to a particular environment and involve systematic activities. Indigenous harvesters, including hunters, fishers, agriculturalists, and plant gatherers, observe and monitor environmental change, and engage in systematic reflection with one another about trends over short term and long-term periods (Sakakibara, 2010; Sánchez-Cortés and Chavero, 2011; Kermoal and Altamirano-Jiménez, 2016; Metcalfe et al., 2020b). The holistic perspective of the interrelated and interdependent nature of ecosystems is a distinct characteristic of Indigenous knowledge and often contrasts with findings and results of science alone. Indigenous harvesters, agriculturalists, leaders, culture-bearers, educators, and government employees develop theoretical and practical knowledge of seasonal and climate change that seeks to furnish the best available knowledge and information to inform climate change policy and decisions (Barrera-Bassols and Toledo, 2005; McNeeley and Shulski, 2011). Examples of theoretical knowledge systems include Indigenous calendars of seasonal change and systems of laws and protocols for environmental stewardship (Kootenai Culture Committee, 2015; Donatuto et al., 2020) (Box 14.1).

The practice and use of Indigenous knowledge systems is recognized and affirmed by the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (UNGA, 2007), and consistent with reports and guidance from UN bodies including the High Commissioner for Human Rights (Bachelet, 2019), Expert Mechanism on the Rights of Indigenous Peoples (UNGA, 2015; UNGA, 2018), the Permanent Forum of Indigenous Issues (Dodson, 2007; Cunningham Kain et al., 2013; Sena and UNPFII, 2013; Sena, 2014; Quispe and UNPFII, 2015), and the Special Rapporteur on the Rights of Indigenous Peoples (Toledo, 2013; UNGA, 2017)(Cross-Chapter Box INDIG in Chapter 18). Rights to self-determination, to control over territorial development, and cultural integrity, make it important that climate scientists practice equitable engagement of Indigenous knowledge and Indigenous knowledge holders. There is a growing literature of success and lessons learned from co-production of knowledge between Indigenous knowledge systems and diverse scientific traditions relating to climate change (Behe et al., 2018; Latulippe and Klenk, 2020; Camacho-Villa et al., 2021).

Current and projected climate change impacts disproportionately harm Indigenous Peoples' livelihoods and economies (*very high confidence*). Indigenous Peoples' livelihoods in North America include a range of activities closely tied to traditional lands, waters, and territories. These activities support a core economic base and an array of sustenance, including financial stability, food security, health and nutrition, safety, and adequate provisions and reserves of important supplies and resources and the passing down of traditional knowledge. Indigenous lives and livelihoods are at risk in the following ways. Indigenous persons are more at risk of losing their lives due to factors that are exacerbated by climate change impacts (Ford et al., 2006; Barbaras, 2014; Khalafzai et al., 2019). Indigenous Peoples' livelihood practices are being distressed, interrupted, and in some cases, made entirely inaccessible. Livelihood activities known and anticipated to be impacted by climate change are food security (Meakin and Kurtvits, 2009; Wesche and Chan, 2010; Nyland et al., 2017), harvesting of fish, plants, and wildlife (Dittmer, 2013; Parlee et al., 2014; Jantarasami et al., 2018b; ICC Alaska, 2020), agriculture (St. Regis Mohawk Tribe, 2013; Shinbrot et al., 2019; Settee, 2020), transportation (Swinomish Indian Tribe Community, 2010; Hori et al., 2018a; Hori et al., 2018b), and tourism and recreation (ICC Canada, 2008). Indigenous Peoples have been active in gathering to assess the impacts of climate change on their livelihoods, one example being the Bering Sea Elders Advisory Group (Bering Sea Elders Advisory Group and Alaska Marine Conservation Council, 2011; Bering Sea Elders Group, 2016).

Climate change impacts have harmful effects on Indigenous Peoples' public health, physical health, and mental health, including harmful effects connected to the cultural and community foundations of health (*very high confidence*). Health and climate change is a major issue for Indigenous Peoples (Ford, 2012; Ford et al., 2014; Gamble et al., 2016; Jantarasami et al., 2018b; Middleton et al., 2020a; Donatuto et al., 2021)(14.5.6). Climate change impacts and risks affect Indigenous Peoples' health negatively in different ways. Indigenous health, as tied to nutrition and exercise, is threatened when local foods are less available and harvesting activities are less possible to practice (Norton-Smith et al., 2016b; Rosol et al., 2016; Gonzalez et al., 2018). Indigenous Peoples experience widespread public health concerns from severe droughts (Stewart et al., 2020; Schlinger et al., 2021; Wiecks et al., 2021), extreme heat (Doyle et al., 2013; Campo Caap, 2018; Kloesel et al., 2018a; Meadow et al., 2018; ITK, 2019; Ute Mountain Ute Tribe and Wood Environment Infrastructure Solutions Inc, 2019; Whyte et al., 2021), unpredictable precipitation patterns (Chavarria and Gutzler, 2018; Tom et al., 2018; Tlingit and Haida, 2019; Schlinger et al., 2021), flooding and coastal erosion (Jamestown S'klallam Tribe, 2016; Norton-Smith et al., 2016b; Puyallup Tribe of Indians, 2016; Marks-Marino, 2019; Ristroph, 2019; Marks-Marino, 2020b; Schlinger et al., 2021), wildfires and wildfire smoke (Edwin and Mölders, 2018; USEPA, 2018; Christianson et al., 2019a; ITK, 2019; Marks-Marino, 2020a; Mottershead et al., 2020; Woo et al., 2020; Wiecks et al., 2021), algal blooms (Peacock et al., 2018; Gobler, 2020; Donatuto et al., 2021; Preece et al., 2021; Schlinger et al., 2021), storms and hurricanes (Rioja-Rodríguez et al., 2018), influxes of invasive species (Pfeiffer and Huerta Ortiz, 2007; Pfeiffer and Voeks, 2008; Voggesser et al., 2013; Bad River Band of Lake Superior Tribe of Chippewa Indians and Abt Associates Inc., 2016; Scott et al., 2017; Reo and Ogden, 2018; Middleton et al., 2020a), and changing production systems (Rioja-Rodríguez et al., 2018). Indigenous Peoples' mental health is at risk and has already been affected negatively by climate change (Donatuto et al., 2021). Water security is one of the most serious concerns to Indigenous Peoples' health and wellbeing (Vanderslice, 2011; Cozzetto et al., 2013a; Redsteer et al., 2013; Hanrahan et al., 2014; Chief et al., 2016; Gamble et al., 2016; Jantarasami et al., 2018b; Kloesel et al., 2018a; Tom et al., 2018; Martin et al., 2020a; Arsenault, 2021). When some people are less able to practice traditional, cultural, social, and family activities, they can become alienated, compounding the negative effects of traumas Indigenous persons already experience. Traumas include historic and continuing land dispossession, assimilation, social marginalization and discrimination, and food and financial insecurities. The practice of cultural traditions are associated with education, harvesting and agriculture, exercise, positive social relationships, and family life, which play foundational roles in the achievement of physical, public, and mental health (Bell et al., 2010; Cunsolo Willox et al., 2015; Jantarasami et al., 2018b; Norgaard and Tripp, 2019; Billiot et al., 2020b; Adams et al., 2021; Donatuto et al., 2021).

Indigenous Peoples are affected dramatically by climate-related disasters and other climate-related extreme environmental events (*very high confidence*). Indigenous Peoples face numerous threats and have already been harmed by and are planning for extreme weather events with associations to climate change, including hurricanes and tornadoes (Oneida Nation Pre-Disaster Mitigation Plan Steering Committee and Bay-Lake Regional Planning Commission, 2016; Emanuel, 2019; Cooley, 2021; Marks-Marino, 2021; Zambrano et al., 2021), heat waves (Confederated Tribes of the Umatilla Indian Reservation, 2016; Wall, 2017; La Jolla Band of Luiseno Indians, 2019; Mashpee Wampanoag, 2019; Wiecks et al., 2021), ocean warming and marine heat waves (Hoh Indian Tribe, 2016; Port Gamble S'klallam Tribe, 2016; Port Gamble S'klallam Tribe, 2020; State of Alaska, 2020; Muckleshoot Tribal Council, 2021; Port Gamble S'klallam Tribe, 2021), wildfires (Voggesser et al., 2013; Billiot et al., 2020a; Cozzetto et al., 2021b; Gaughen et al., 2021; Morales et al., 2021; National Tribal Air Association, 2021; Zambrano et al., 2021), permafrost thaw (Haynes et al., 2018; Low, 2020), flooding (Riley et al., 2011; Ballard and Thompson, 2013; Brubaker et al., 2014; Thompson et al., 2014; Burkett et al., 2017; Quinault Indian Nation, 2017; Ristroph, 2019; Sharp, 2019; Thistlethwaite et al., 2020b), and drought (Knutson et al., 2007; Chief et al., 2016; Redsteer et al., 2018; Sioui, 2019; Bamford et al., 2020; Sauchyn et al., 2020). Some Indigenous Peoples are facing climate change impacts that generate community-led permanent relocation and resettlement as an adaptation option (Maldonado et al., 2021). Coastal erosion is one climate change issue that is often connected to Indigenous Peoples planning to resettle, including vulnerability connected to higher sea levels and storm surges (Quinault Indian Nation, 2017; Bronen et al., 2018; Affiliated Tribes of Northwest Indians, 2020). Adapting to new settlement areas threatens the continuity of communities. In a number of cases, Indigenous Peoples' having less access to adequate infrastructure is a driver of vulnerability to climate related disasters and extreme weather events (Doyle et al., 2018; Patrick, 2018; Cozzetto et al., 2021a; Indigenous Climate Action et al., 2021). Disasters and extreme events are particularly severe when their impacts are compounded by inadequate infrastructure. Lack of flood protection infrastructure on Indigenous reserve communities, leads to displacement, loss of homes, and perpetuates disproportionate levels of risk to extreme weather events (Cunsolo et al., 2020; Fayazi et al., 2020; Yellow Old Woman-Munro et al., 2021).

Indigenous self-determination and self-governance are the foundations of adaptive strategies that improve understanding and research on climate change, develop actionable community plans and policies on climate change, and have demonstrable influence in improving the design and allocation of national, regional, and international programs relating to climate change (*very high confidence*). Historical and contemporary developments have crystallized international norms recognizing the distinct status, role, and rights of Indigenous Peoples in the form of significant international human rights instruments. Premier among them is the UNDRIP (UNGA A/RES/61/295), which has received universal consensus since its adoption by the UN General Assembly. UN member States have affirmed the right of self-determination (Article 3, UNDRIP) regarded as the prerequisite to the exercise and enjoyment of all other human rights.

The integrity of the environment is impacting all of humanity, including Indigenous Peoples, their lands, territories, resources and their communities. Through self-determination, durable, sustainable, and robust contributions from those with close, symbiotic relationships with the environment can be revealed in favor of all humanity. Indigenous Peoples of North America have been engaged in wide-ranging activities to address climate change (Doolittle, 2010; Parker and Grossman, 2012; Abate and Kronk, 2013; STACCWG, 2021). They include actions in the spheres of education (Donatuto et al., 2020; McClain, 2021; Morales et al., 2021), development of Indigenous knowledge and science (Maldonado et al., 2016; AFN, 2020; Ferguson and Weaselboy, 2020; Huntington et al., 2021a; Jones et al., 2021; Sawatzky et al., 2021), adaptation planning and implementation (Angel et al., 2018a; Tribal Climate Adaptation Guidebook Writing Team et al., 2018; Hepler and Kronk Warner, 2019; Tribal Adaptation Menu Team, 2019; Metcalfe et al., 2020b), and political action and diplomacy (including treaty-based diplomacy) (Grossman, 2008; Kronk Warner and Abate, 2013; Callison, 2015).

14.5 Observed Impacts, Projected Risks, and Adaptation by Sector

14.5.1 Terrestrial and Freshwater Ecosystems and Communities

14.5.1.1 Terrestrial Ecosystems: Observed Impacts and Projected Risks

Evidence continues to mount about the impacts of recent climate change on species and ecosystems (Weiskopf et al., 2020) (Table 14.2) (*very high confidence*). Ranges and abundances of species continue to shift in response to warming throughout North America (Cavanaugh et al., 2014; Molina-Martínez et al., 2016; Tape et al., 2016; Miller et al., 2017; Pecl et al., 2017; Zhang et al., 2018a) (Cross-Chapter Box MOVING PLATE in Chapter 5) (*very high confidence*). Future climate change will continue to affect species and ecosystems (IPBES, 2018) (*high confidence*), with differential responses related to species characteristics and ecology (D'Orangeville et al., 2016; Weiskopf et al., 2019). Climate change is projected to adversely affect the range, migration, and habitat of caribou, an important food and cultural resource in the Arctic (Leblond et al., 2016; Masood et al., 2017; Barber et al., 2018b; Borish, Accepted) (CCP6).

Climate-induced shifts in the timing of biological events (phenology) continue to be a well-documented ecological response (Vose et al., 2017; Lipton et al., 2018; Vose et al., 2018; Molnar et al., 2021) (Table 14.2) (*very high confidence*). Reduced snow season length may potentially lead to adverse camouflage effects on animals that change coat colour (Mills et al., 2013; Mills et al., 2018). Human conflicts with bears are expected to increase in response to shifts in hibernation patterns (Johnson et al., 2018) and food resources (Wilder et al., 2017; Wilson et al., 2017).

Severe ecosystem consequences of warming and drying are well documented (*very high confidence*) (Table 14.2). Significant ecosystem changes are expected from projected climate change (*high confidence*), such as in Mexican cloud forests (Helmer et al., 2019), North American rangelands (Polley et al., 2013; Reeves et al., 2014), and montane forests (Stewart et al.; Wright et al., 2021). Permafrost thaw is projected to increase in Alaska and Canada (DeBeer et al., 2016) (see also AR6, WG I, Chapter 12), accelerating carbon release

(Schaefer, 2104) (CCP6, see also AR6, WG I, Chapter 5) and affecting hydrology. Predicting which species or ecosystems are vulnerable is challenging (Stephenson et al., 2019), although paleoecological data (e.g., pollen, tree rings) provide context from past events to better understand current and future transformations (Nolan et al., 2018).

Climate change impacts on natural disturbances have affected ecosystems (*very high confidence*) (Table 14.2 and Box 14.2), and these impacts will increase with future climate change (*medium confidence*). Facilitated by warm, dry conditions, "mega-disturbances" and synergies between disturbances that include wildfires, insect and disease outbreaks, and drought-induced tree mortality continue to affect large areas of North America (Cohen et al., 2016; Young et al., 2017a; Hicke et al., 2020), overwhelming adaptive capacities of species and degrading ecosystem services (Millar and Stephenson, 2015; Stewart et al., 2021). This era of mega-disturbances is expected to become more widespread and severe in coming decades (Cook et al., 2015; Seidl et al., 2017; Buotte et al., 2019), with potentially significant impacts on ecosystems (Allen et al., 2015; Crausbay et al., 2017; Schwalm et al., 2017; Coop et al., 2020; Dove et al., 2020 Thompson et al. 2020, Stewart et al. 2021). Effects include widespread tree mortality (Allen et al., 2015; Kane et al., 2017; van Mantgem et al., 2018) and accelerated ecosystem transformation (Guiterman et al., 2018; Crausbay et al., 2020; Munson et al., 2020) (*medium confidence*).

14.5.1.2 Freshwater Ecosystems: Observed Impacts and Projected Risks

Climate change, either directly (warming water) or indirectly (glacier and snow inputs), has affected biogeochemical cycling and species composition in North American aquatic ecosystems (Moser et al., 2005; Saros et al., 2010; Preston et al., 2016) (Table 14.2) (*very high confidence*), possibly amplifying other human-caused stresses on these systems (Richter et al., 2016). Excess nutrients associated with high farm animal density can be transported during intense rainfall events (expected to increase with climate change) causing algal blooms, fish kills, and other detrimental ecological effects (Huisman et al., 2017; Coffey et al., 2019).

Projected climate change will cause habitat loss, alter physical and biological processes, and decrease water quality in freshwater ecosystems (Poesch et al., 2016; Crozier et al., 2019) (*high confidence*). Projected river warming of 1-3ºC is expected to reduce thermal habitat for important salmon and trout species in the northwestern US by 5–31% (Isaak et al., 2018) and in Mexico (Meza-Matty et al., 2021), and for multiple fish species in Canada (Poesch et al., 2016). Cold-water streams at higher elevations will warm less and therefore may become climate refugia (Isaak et al., 2016). Projected warming of mountain lake ecosystems (Roberts et al., 2017b; Redmond, 2018) will affect ecosystem processes (Preston et al., 2016; Redmond, 2018; Moser et al., 2019). Loss of cold water inputs from retreating glaciers are expected to adversely affect alpine stream ecosystems (Fell et al., 2017; Giersch et al., 2017). For anadromous fish species (e.g., Chinook salmon), future warming will reduce habitat suitability from river headwaters to oceans (Crozier et al., 2021).

Freshwater ecosystems across North America are increasingly at risk from extreme drought, compounded by human demands for water (14.5.3) (Kovach et al., 2019). Implications for aquatic and riparian species can vary, but it is widely agreed that these systems are highly sensitive to fluctuations in the hydrologic cycle, which can increase competition by invasive species and compromise connectivity between potential cold-water refugia (Melis et al., 2016; Poff, 2019).

14.5.1.3 Adaptation in Terrestrial and Freshwater Ecosystems

Adaptation efforts to assess vulnerability of species and ecosystems, predict adaptive capacity, and identify conservation-oriented options have increased markedly across North America (e.g., Hagerman and Pelai, 2018; Keeley et al., 2018; Thurman et al., 2020; Peterson St-Laurent et al., 2021; Thompson et al., 2021). Scenario-based planning, an approach for addressing uncertainty, continues to gain traction and is regularly applied by the US National Park Service (Star et al., 2016). Nonetheless, barriers to implementation of specific actions often exist (e.g., inflexible policies, lack of resources and stakeholder buy-in, political will), hampering progress (Stein et al., 2013; Shi and Moser, 2021). Efforts to evaluate the efficacy of implemented adaptation actions are also lacking (Prober et al., 2019), but some cases show progress. For example, ongoing efforts are quantifying how variable water releases from the Colorado River's Glen

Canyon Dam affect endangered fish species (Melis et al., 2016). Nature-based solutions (NbS) for adaptation (Box 14.7) are increasingly evaluated, especially at larger scales.

Effective climate-informed ecosystem management requires a well-coordinated suite of adaptation efforts (e.g., assessment, planning, funding, implementation, and evaluation) that is co-produced among stakeholders, Indigenous Peoples, and across sectors (Millar and Stephenson, 2015; Dilling et al., 2019) (*high confidence*). New applications of conventional strategies can be modified to achieve conservation goals under climate change (USGCRP, 2019). For example, mechanical thinning and prescribed burning (to reduce fuel loads and benefit ecosystems) could be used in combination with planting species better suited to new conditions to build resilience in western US forests to longer and hotter drought conditions (Bradford and Bell, 2017; Vernon et al., 2018). Protection of buffer areas, such as riparian strips in arid regions and boreal ecosystems, reduces water temperature, builds resistance to invasive species, increases suitable habitat (Johnson and Almlof, 2016), and facilitates protection of freshwater systems from runoff during and after intense rain events (National Research Council, 2002).

Innovative approaches may facilitate species' responses to climate change, particularly when vulnerability is exacerbated by habitat loss and fragmentation. Strategies include improved landscape connectivity for species dispersal (Carroll et al., 2018; Littlefield et al., 2019; Lawler et al., 2020; Thomas, 2020) or assisted migration (also called managed relocation) to climatically suitable locations (Schwartz et al., 2012; Dobrowski et al., 2015). Examples include translocation of salmon in the Columbia River (Holsman et al., 2012), genetic rescue (assisted gene flow increases genetic diversity to address local maladaptation) (Aitken and Whitlock, 2013), and locating and conserving climate refugia, such as in alpine meadows of the Sierra Nevada (Javeline et al., 2015; Morelli et al., 2016). Maintaining diverse spawning habitats and salmon runs can increase resilience of salmonid populations to climate change (Schoen et al., 2017; Crozier et al., 2021). Newer modelling approaches can facilitate the visualization of future management scenarios, per a recent study of fires in the southwestern US (Loehman et al., 2018), in addition to technologies in genomics for monitoring species and modifying adaptive traits (Phelps, 2019).

Adaptation actions have important limitations (Dow et al., 2013), particularly in the context of biodiversity conservation goals. "Hard" limits include species extinctions and vegetation mortality events, despite conservation action (i.e., besides significant emissions reductions to mitigate warming, few if any interventions could have prevented these losses). In contrast, "soft" adaptation limits exist primarily as a function of the social-ecological value systems of local communities and government entities that are reflected as goals and objectives in their management plans for ecosystems and species across North America. Soft limits are often mutable or can be removed altogether (Dow et al., 2013). In contrast, human modifications of landscapes that change or irreparably damage can limit adaptation by reducing connectivity and therefore range shifts (Parks and Abatzoglou, 2020).

Table 14.2: Examples of observed climate change impacts on terrestrial and freshwater ecosystems.

Impact	References
local extinctions	(Pomara et al., 2014; Wiens, 2016)
greening and increased productivity of North American vegetation from CO_2 fertilization	(Smith et al., 2016b; Zhu et al., 2016; Huang et al., 2018).
changes in phenology, including migration as well as mismatches between species and with human visitation	(Mayor et al., 2017; Zaifman et al., 2017; Breckheimer et al., 2020)
vegetation conversions, including	
shifts to denser forests with smaller trees	(McIntyre et al., 2015)
trees to savannas and grasslands	(Bendixsen et al., 2015)
woody plant encroachment into grasslands	(Archer et al., 2017)
changes in tundra plant phenology and abundance	

	(Myers-Smith et al., 2019)
expansion of boreal and subalpine forests into tundra, meadows	(Juday et al., 2015; Lubetkin et al., 2017)
reduced or lack of recovery following severe fire	(Coop et al., 2020; O'Connor et al., 2020), Box 14.2
warmer droughts reducing plant productivity and carbon sequestration	(Mekonnen et al., 2017; Gampe et al., 2021)
slowing ecosystem function recovery of vegetation to pre-disturbance conditions following droughts	(Schwalm et al., 2017; Crausbay et al., 2020)
warming streams and lakes and changes in seasonal flows that have affected freshwater fish distributions and populations	(O'Reilly et al., 2015; Lynch et al., 2016; Poesch et al., 2016; Roberts et al., 2017b; Isaak et al., 2018; Christianson et al., 2019b; Zhong et al., 2019)
upstream expansion of human-mediated invasive hybridization and enhanced the risk of extinction of native salmonid species	(Muhlfeld et al., 2014)
declining wetlands in western North America important for bird migrations	(Donnelly et al., 2020)
increases in harmful freshwater algal blooms	Section 14.5.3

[START BOX 14.2 HERE]

Box 14.2: Wildfire in North America

Recent Observations, Attribution to Climate Change, and Projections

Anthropogenic climate change has led to warmer and drier conditions (i.e., fire weather) that favour wildland fires in North America (see AR6, WGI, Chapter 12; *high confidence*). In response, increased burned area in recent decades in western North America has been facilitated by anthropogenic climate change (*medium confidence*). Annual numbers of large wildland fires and area burned have risen in the last several decades in the western US (USGCRP, 2017; USGCRP, 2018), and area burned has increased in Canada (the number of large fires has declined slightly recently) (Gauthier et al., 2014; Natural Resources Canada, 2018; Hanes et al., 2019). Attribution studies have reported that climate change increased burned area in Canada (1959-1999) (Gillett et al., 2004) as well as the western US (1984–2015) (Abatzoglou and Williams, 2016) and California (1972-2018) (Williams et al., 2019a). Decreased precipitation was the primary climate change cause of increased burned area in the western US, with warming a secondary influence (Holden et al. 2018), whereas warming (through aridity) was most important in a California study (Williams et al., 2019a). A drier atmosphere (including reduced precipitation) has been linked to climate change through altered large-scale atmospheric circulation, which then facilitated greater burned area in the western US (Zhang et al., 2019c). Through anomalous warm and dry conditions, anthropogenic climate change contributed to the extreme fires of 2016 (Kirchmeier-Young et al., 2019; Tan et al., 2019) in western Canada and the extreme fire season in 2015 in Alaska (Partain et al., 2017). These studies did not include human activities that influence fire-climate relationships (Syphard et al., 2017).

Warming has led to longer fire seasons (Westerling, 2016) and drier fuels (Williams et al., 2019a). Warmer and drier fire seasons in the western US during 1985-2017 have contributed to greater burned area of severe fires (Parks and Abatzoglou, 2020). Simultaneity in fires increased during 1984-2015 (Podschwit and Cullen, 2020), challenging firefighting effectiveness and resource sharing. In Mexico, fires have been correlated with dry conditions (Kent et al., 2017; Marin et al., 2018; Zuniga-Vasquez et al., 2019). Wildland fire activity in the grasslands of the US Great Plains has increased during the last several decades (Donovan et al., 2017) related to antecedent precipitation or aridity that affected fuel quantity (Littell et al., 2009).

Climate change is projected to increase fire activity in many places in North America during the coming decades (see also AR6, WGI, Chapter 12) (Boulanger et al., 2014; Williams et al., 2016; Halofsky et al., 2020), via longer fire seasons (Wotton and Flannigan, 1993; USGCRP, 2017), long-term warming (Villarreal et al., 2019; Wahl et al., 2019), and increased lightning frequency in some areas of the US and Canada (Romps et al., 2014; Finney et al., 2018; Chen et al., 2021) (*medium confidence*). Unusually extensive and severe fires have occurred in the Arctic tundra during recent extremely warm and dry years, suggesting that continued warming may increase the probability of such fires in the future (Hu et al., 2015). In drier non-forest ecosystems in the western US, fires are limited by fuel availability and vegetation productivity; warming will decrease productivity, leading to lower burned area (Littell et al., 2018).

Impacts on Natural Systems

Although fire is a natural process in many North American ecosystems, increases in burned area and severity of wildland fires have had significant impacts on natural ecosystems (*medium confidence*). The length of streams and rivers impacted by fire has increased in the US along with burned area (Ball et al. 2021). Mega-fires can cause major changes in the structure and composition of ecosystems, particularly where human alterations are significant (Stephens et al., 2014; Loehman et al., 2020). Unusually severe fires may have led to the conversion of forest to grassland in the US Southwest (Haffey et al., 2018). Recent warming and drying have limited post-fire tree seedling and shrub establishment, limiting ecosystem recovery (Davis et al., 2019; O'Connor et al., 2020; Rodman et al., 2020). In boreal forests, soil carbon is being lost through increasingly severe or frequent fires (Walker et al., 2019).

Projected future fire activity will continue to affect ecosystems and alter their structure and function (*medium confidence*) (Coop et al., 2020; Loehman et al., 2020). Increased fire activity (Stevens-Rumann et al., 2018; Stevens-Rumann and Morgan, 2019; Turner et al., 2019a; Cadieux et al., 2020), further warming and drying that stresses tree seedlings, and model projections of stand-replacing fires at the forest-non-forest boundary in the western US (Parks et al., 2019) have raised the possibility of shifts in species composition or vegetation type (Halofsky et al., 2020). These projections suggest high variability in ecosystem responses depending on interactions between vegetation type, moisture stress, disturbances regimes, and human alterations (Hurteau et al., 2008; Kitzberger et al., 2017; Littell et al., 2018; Hurteau et al., 2019; Loehman et al., 2020; O'Connor et al., 2020).

Impacts on Human Systems

Increased fire activity, partly attributable to anthropogenic climate change, has had direct and indirect effects on mortality and morbidity, economic losses and costs, key infrastructure, cultural resources, and water resources (*medium confidence*), although other factors, such as increasing populations in the wildland-urban interface, also contributed. During 2000–2018, significant fire events claimed 315 lives in the US (NOAA, 2019); the economic impacts (capital, health, indirect losses from economic disruption) from the 2018 California fires were US$149 billion (Wang et al., 2021). Poor air quality from fires caused increased respiratory distress (*very high confidence*); exposure extends long distances from the fire source (Section 14.5.6.3). In addition to public and private property damage and loss, fires have caused irretrievable losses from archaeological and historical sites (Ryan et al., 2012). Post-fire conditions have created unanticipated challenges for communities' water supply operations (Bladon et al., 2014; Návar, 2015; Martin, 2016) by altering water quality and availability (Smith et al., 2011; Bladon et al., 2014; Robinne et al., 2020) or public safety by increasing exposure to mass wasting events after extreme rainfall events (Cui et al., 2019; Kean et al., 2019). California utilities have proactively shut down parts of their electricity grid to reduce risk of fire during extreme weather, and substantial numbers of people will be increasingly vulnerable to this action in the coming decades (Abatzoglou et al., 2020).

In the US, annual costs of federal wildland fire suppression have increased by a factor of 4 since 1985 (USGCRP, 2018) and were US$1.5-3B during 2016-202 (NIFC, 2021). Annual costs of fire protection in Canada have risen 2–3 fold from 1970–2017, to CAD$1.0-1.4B during 2015-2017 (2017 dollars) (Natural Resources Canada, 2021). In one of its worst fire seasons, British Columbia expended over CAD$500M in 2017 for fire suppression (Natural Resources Canada, 2018). The number of days of synchronous fire danger is expected to double in the western US by 2051-2080, thereby increasing demands on fire suppression resources (Abatzoglou et al., 2021).

The 2016 Fort McMurray fire ranks as the costliest natural disaster in Canada to date (CAD$3B in insured damages) (Mamuji and Rozdilsky, 2018; IBC, 2020). More than 88,000 people were evacuated; many were not aware of the high pre-existing fire risk and had limited warning to prepare and leave (McGee, 2019). The community subsequently required extensive social support and experienced mental health challenges (Government of Alberta, 2016; Cherry and Haynes, 2017; Mamuji and Rozdilsky, 2018; Brown et al., 2019a; McGee, 2019). Although a broad recovery plan was developed (Regional Municipality of Wood Buffalo, 2016), reconstruction and economic recovery has been slow (Mamuji and Rozdilsky, 2018).

Wildland fire was identified as a top climate change risk facing Canada (Council of Canadian Academies, 2019) and poses a challenge to communities and fire management (Coogan et al., 2019). Projected area burned in Canada using RCP2.6 will increase annual fire suppression costs to CAD$1B by end of century (60% increase relative to 1980-2009) and to CAD$1.4B using RCP8.5 (119% increase) (Hope et al., 2016). In the US, cumulative costs of fire response through 2100 are projected to be US$23B (2015 dollars) per year under RCP8.5 (EPA, 2017). Lower emissions scenarios reduce these future cumulative costs by US$55M (EPA, 2017) to US$7-9B (2005 dollars) (Mills et al., 2015a). Fire increases from future warming will reduce timber supply in eastern Canada (Gauthier et al., 2015; Chaste et al., 2019) and increase post-fire sedimentation in watersheds of the western US (Sankey et al., 2017).

Adaptation

Wildland fire risks are not equitably distributed as they intersect with exposure and socioeconomic attributes (e.g., age, income, ethnicity) to influence vulnerability and adaptive capacity (Wigtil et al., 2016; Davies et al., 2018; Palaiologou et al., 2019) (*medium confidence*). Individuals in rural areas, low-income neighbourhoods, and immigrant communities as well as renters in California had less capacity to prepare for and recover from fire (Davies et al., 2018). In the US, 29 million people live in areas with significant potential for wildfires and 12 million are socially vulnerable (Davies et al., 2018). In Canada, there are 117 million ha of wildland-human interface (14% of total land area), and 96% of populated places have some wildland-urban interface within 5 km (Johnston and Flannigan, 2018).

There is growing recognition of the need to shift fire management and suppression activities to co-exist with more fire on the landscape. This includes widespread use of prescribed fire across landscapes to increase ecological and community-based resilience (Schoennagel et al., 2017; McWethy et al., 2019; Tymstra et al., 2020) (*high agreement, medium evidence*). Otherwise, the unprecedented combination of increased human exposure and size of recent megafires creates community risks that may exceed conventional operational and forest management response capacity and budgets (Podur and Wotton, 2010; Wotton et al., 2017; Loehman et al., 2020; Moreira et al., 2020; Parisien et al., 2020) particularly with ongoing population and infrastructure expansion into the wildland-urban interface (Canadian Council of Forest Ministers, 2016; Coogan et al., 2019).

Climate-informed post-fire ecosystem recovery measures (e.g., strategic seeding, planting, natural regeneration), restoration of habitat connectivity, and managing for carbon sequestration (e.g., soil conservation through erosion control, preservation of old growth forests, sustainable agro-forestry) are critical to maximize long-term adaptation potential and reduces future risk through co-benefits with carbon mitigation (Davis et al., 2019; Hurteau et al., 2019; Coop et al., 2020; Stewart et al., 2021). Innovation in and scaling up the use of prescribed fire and thinning approaches are contributing to pre-and post-fire resilience goals, including use of Indigenous Peoples burning practices that are receiving a new level of awareness (Kolden, 2019; Marks-Block et al., 2019; Long et al., 2020b) (Box 14.1).

The tools FireSmart Canada (https://www.firesmartcanada.ca), Firewise USA (https://www.nfpa.org/) and Think-Hazard Mexico (https://thinkhazard.org) were devised to reduce fire risks and create fire-resilient communities. They provide design guidance at building, lot, subdivision and community scales, and instruct citizens on creating defensible space (National Fire Protection Association, 2013; Firesmart Canada, 2018). Implementation has been fragmented and variable as it depends on voluntary uptake by individuals, business and communities across a range of adaptive capacities and fire-exposed landscapes (Smith et al., 2016a).

Many vulnerable groups do not have access to financial or physical resources to reduce fire risk (Collins and Bolin, 2009; Palaiologou et al., 2019).

Although innovative, holistic approaches to wildland fire management are becoming more common across North America, broader application is necessary to address the growing risks (*medium confidence*). A social-ecological perspective blends ecosystem complexity, scale and processes into land use planning along with community values, perception, and capacities as well as institutional arrangements (Smith et al., 2016a; Spies et al., 2018). A risk assessment perspective expands from short-term, reactive fire response to landscape-scale, long-term prevention, mitigation, and preparedness with community and practitioner engagement (Coogan et al., 2019; Sherry et al., 2019; Johnston et al., 2020; Tymstra et al., 2020).

[END BOX 14.2 HERE]

14.5.2 Ocean and Coastal Social-Ecological Systems

14.5.2.1 Observed Impacts and Projected Risks of Climate Change

Warming of surface and subsurface ocean waters has been broadly observed across all North American marine ecosystems from the polar Arctic to the subtropics of Mexico (*virtually certain*) (Hobday et al., 2016; Jewett and Romanou, 2017; Pershing et al., 2018; Smale et al., 2019a). Higher ocean temperatures have directly affected food-web structure (Gibert, 2019) and altered physiological rates, distribution, phenology, and behaviour of marine species with cascading effects on food-web dynamics (*very high confidence*) (Gattuso et al., 2015; Pinsky and Byler, 2015; Sydeman et al., 2015; Poloczanska et al., 2016; Frölicher et al., 2018; Le Bris et al., 2018; Free et al., 2019; Stevenson and Lauth, 2019; Barbeaux et al., 2020; Dahlke et al., 2020). Pacific coastal waters from Mexico to Canada and US mid-Atlantic coastal waters have a high proportion of species (>5% of all marine species) near their upper thermal limit, representing hotspots of risk from marine heatwaves (*medium confidence*) (Smale et al., 2019a; Dahlke et al., 2020). Kelp, a macro-algae, forms important habitat for other marine species, and its biomass has decreased 85–99% in the past 4–6 decades off Nova Scotia, Canada, replaced by invasive and turf algae; this is associated directly with warming waters (Filbee-Dexter et al., 2016).

Climate change has induced phenological and spatial shifts in primary productivity with cascading impacts on foodwebs (*high confidence*) (Siddon et al., 2013; Stortini et al., 2015; Sydeman et al., 2015; Stanley et al., 2018). This includes widespread starvation events of fish, birds (e.g., tufted puffins in Bering Sea in 2016/2017 and Cassin's Auklets in British Columbia in 2014/2015) and marine mammals (gray whales along both coasts of North America) (Sydeman et al., 2015; Duffy-Anderson et al., 2019; Jones et al., 2019b; Cheung and Frölicher, 2020; Piatt et al., 2020), which challenge protected species and fisheries management (section 14.5.4) (Chasco et al., 2017; Wilson et al., 2018; Barbeaux et al., 2020; Free et al., 2020; Holsman et al., 2020). Climate change has altered foraging behaviour and distribution of North Atlantic right whales and their target copepod prey (Record et al., 2019) increasing entanglement rates in lobster and snow crab fishing gear on the East coast of the US and Canada as lobster and crab distributions also shift due to changing water temperatures (Meyer-Gutbrod et al., 2018; Davies and Brillant, 2019). Similarly, whale entanglements in fishing gear along the Pacific coast has increased 20 fold (Hazen et al., 2018). Projected shifts in the North Pacific Transition Zone (NPTZ) by up to 1000 km northward (by the end of the century under RCP8.5) combined with changes in coastal upwelling (Polovina et al., 2011; Hazen et al., 2013; Rykaczewski et al., 2015) could alter up to 35% of elephant seal and bluefin tuna foraging habitat (Robinson et al., 2009; Kappes et al., 2010).

In North American Arctic marine systems, rapid warming is significant, with cascading impacts beyond polar regions (CCP6), and presents limited opportunities (tourism, shipping, extractive) but high risks (shipping, and fishing industries, Indigenous subsistence and cultural activities) (*high confidence*)(Gaines et al., 2018; IPCC, 2019b; Samhouri et al., 2019; Free et al., 2020; Holsman et al., 2020) (see sections 14.5.4; 14.5.9; 14.5.11;CCP6). Both direct hazards and indirect food web alterations from sea ice loss have imperilled seabirds, marine mammals, small boat operators, subsistence hunters and coastal communities (Sigler et al., 2014; Allison and Bassett, 2015; Huntington et al., 2015; Hauser et al., 2018; Raymond-Yakoubian and Daniel, 2018; Dezutter et al.) (CCP6). Increasingly favourable environmental conditions due to warming combined with shipping and other activities has raised the rate of invasive species movement into the Arctic (Mueter et al., 2011). Sea ice loss due to climate change is expected to accelerate over the next century (14.2, WG1 9.3.1).

Coral reefs in Gulf of Mexico and along the coasts of Florida and Yucatan Peninsula are facing increasing risk of bleaching and mortality from warming ocean waters interacting with non-climate stressors (*very high confidence*) (Cinner et al., 2016; Hughes et al., 2018; Sully et al., 2019; Williams et al., 2019b). Coral reefs are contracting in equatorial regions and expanding poleward (Lluch-Cota et al., 2010; Jones et al., 2019a). Loss of coral habitat leads to loss of ecosystem structure, fish habitat, and food for coastal communities and impacts tourism opportunities (14.5.7) (Weijerman et al., 2015a; Weijerman et al., 2015b). Without mitigation to keep surface temperatures below a 2.0ºC increase by the end of the century, up to 99% of coral reefs will be lost. However, 95% of reefs will still be lost even if warming is kept below 1.5ºC (*high confidence)* (Hoegh-Guldberg et al.; Hoegh-Guldberg et al., 2019a). In Florida, by 2100, an estimated US$24–55B may be lost in recreational use and value derived by people knowing the reef exists and is healthy (Lane et al., 2013; Hoegh-Guldberg et al., 2019b) as coral reefs decline (14.5.9).

SLR has led to flooding, erosion and damage to infrastructure along the western Gulf of Mexico, the southeast US coasts, and the southern coast of the Gulf of St Lawrence (14.2) (Daigle, 2006; Lemmen et al., 2016; Frederikse et al., 2020) (*very high confidence*). Mangroves, important nurseries for fish and climate refugia for corals (Yates et al., 2014), are under threat from climate change along the east coast of Mexico (Pedrozo Acuña, 2012). SLR, storm surge and attendant erosion of coastlines and barrier habitats are projected to have large impacts on coastal ecosystems, maritime industries (14.5.9), urban centres and cities (14.5.5) along the Gulf of Mexico, Caribbean Sea, Southeast US, the southern Gulf of St Lawrence and the Pacific Coast of Mexico (Box 14.4) (Semarnat, 2014; Sweet et al., 2017; Vousdoukas et al., 2020). Coastal archaeological and historical sites are especially vulnerable to SLR (Anderson et al., 2017; Hestetune et al., 2018; Hollesen et al., 2018).

Future seawater CO_2 levels have been shown in laboratory studies to negatively impact Pacific and Atlantic squid, bivalve, crab, and fish species (Pacific cod), and indirectly alter food-web dynamics (Kaplan et al., 2013; Long et al., 2013b; Gledhill et al., 2015; Seung et al., 2015; Punt et al., 2016; Swiney et al., 2017; Hurst et al., 2019; Wilson et al., 2020) (*high confidence*). Long-term exposure to CO_2 reduced growth of Atlantic halibut (Gräns et al., 2014), whereas some cultured oysters (Fitzer et al., 2019) and key Alaskan commercial fish species show tolerance for high CO_2 waters (i.e., juvenile walleye pollock) (Hurst et al., 2012). Ocean acidification has already caused shellfish growers in the US and Canada to modify hatchery procedures and farming locations to protect the most vulnerable life-stages (Cross et al., 2016) and is projected to increasingly impact shellfish resources in the central and NE Pacific and Atlantic coasts (Seung et al., 2015; Punt et al., 2016) (Section 14.5.4).

Open ocean oxygen minimum zones (OMZ) are expanding in the North Atlantic, the North Pacific California Current and tropical oceans due to warming waters, stratification, and changes in precipitation (*medium confidence*) (Deutsch et al., 2015b; Breitburg et al., 2018; Claret et al., 2018; Ito et al., 2019) (WGI, 3.6.2). Hypoxic (extreme low oxygen) events along coasts, which are partially influenced by climate change, have been documented for all three countries, with events more prevalent on the east coast and around the Gulf of Mexico due to a regional oceanography dominated by rivers and estuaries carrying land-based nutrients (Breitburg et al., 2018). Hypoxia has directly caused large mortality events for fish and crabs in US estuaries in the Northwest Atlantic (Chesapeake Bay), Northeast Pacific (Puget Sound) and the Gulf of Mexico (Froehlich et al., 2015; Rakocinski and Menke, 2016; Sato et al., 2016; Kolesar et al., 2017). OMZs and hypoxic events are projected to increase over the next century and may limit where fish can move (*medium confidence*) (Deutsch et al., 2015b; Stortini et al., 2015; Bianucci et al., 2016; Li et al., 2016).

Favourable conditions for harmful algal blooms (HABs) have expanded due to warming, more frequent extreme weather events (Gobler et al., 2017; Pershing et al., 2018; Trainer et al., 2019) and increased stratification, CO_2 concentration, and nutrient inputs (Wells et al., 2015; Gobler et al., 2017; Griffith and Gobler, 2019) *(high confidence*). Increased occurrence of HABs (McCabe et al., 2016; Yang et al., 2016; Gobler et al., 2017; USGCRP, 2018) has induced ecological impacts and societal costs (see 14.5.4 for fishery closures). During the 2013–2016 Pacific Marine Heat Wave (MHW; Box 14.3), a *Pseudo-nitzschia* diatom bloom off the US West Coast caused extensive closures of crab and razor clam fisheries (Trainer et al., 2019), with economic and socio-cultural impacts beyond those in the fisheries sector (Ritzman et al., 2018).

Beaching of massive *Sargassum* seaweed mats (*Sargassum natans* and *S. fluitans*) have been reported across the Caribbean and Gulf of Mexico from 2011-present day, affecting US and Mexico nearshore ecosystems, human health and the tourism industry (Franks et al., 2016; Resiere et al.; Wang et al., 2019). Costs of beach clean-up is high, with Texas spending over USD$2.9 million annually (Webster and Linton, 2013). Attribution of *Sargassum* blooms to climate change is still tenuous and complicated by multiple drivers and few observational data sources (Wang et al., 2019) (*low confidence*).

[START BOX 14.3 HERE]

Box 14.3: Marine Heatwaves

Marine heat waves (MHWs) are periods of discrete anomalously high (compared to 30-year history) sea surface temperatures that persist for a minimum 5 days but up to several months (Hobday et al., 2016; Frölicher et al., 2018; Holbrook et al., 2019; Laufkötter et al., 2020). There have been MHWs attributed to climate change in every marine system of North America including large areas of the Northwest Atlantic (2012), Caribbean Sea (2015), Bering Sea (2016-2018), and central through Northeast Pacific (2013-2016) (NOAA, 2018; Holbrook et al., 2019; Smale et al.). MHW events have affected kelp forests (Arafeh-Dalmau et al., 2019), corals (Eakin et al., 2018), seagrasses, bottom-dwelling organisms, marine birds (Loredo et al., 2019; Smale et al., 2019a) mammals (Suryan et al., 2021), fish and shellfish and marine dependent human communities (Huntington et al., 2020; Fisher et al., 2021; Suryan et al., 2021). Increased sea temperatures directly increase metabolic demand and change productivity and behaviour of fish species (Stock et al., 2017; Free et al., 2019) as well as inducing rapid redistribution of species poleward and to deeper colder waters (Pecl et al., 2017; Rheuban et al., 2017; Crozier et al., 2019; Stevenson and Lauth, 2019; Yang et al., 2019; Barbeaux et al., 2020; Cheung and Frölicher, 2020). In the Pacific, from the Baja Peninsula to the Bering Sea, there is evidence of widespread shifts in coastal biota and multi-trophic level starvation of seabirds and whales from combined metabolic demand and reduced prey quality associated with protracted MHWs across multiple regions (CCP6)(Sydeman et al., 2015; Duffy-Anderson et al., 2019; Sanford et al., 2019; Smale et al., 2019a) (Suryan et al. 2021). The distribution of two economically important North American species, Bering Sea Pacific cod (Pinsky et al., 2013b; Stevenson and Lauth, 2019; Barbeaux et al., 2020; Spies et al., 2020) and American Lobster (Rheuban et al., 2017), have shifted north. MHW-induced loss of coral reefs across tropical North American waters has varied in severity regionally. For instance, in 2015 and 2016, extensive, severe bleaching affected more than 30% of corals off the southeast US and a large proportion of US Hawaiian Islands, but had moderate to no impact off the Mexican Yucatan Peninsula (Frieler et al., 2013; Weijerman et al., 2015a; Weijerman et al., 2015b; Cinner et al., 2016; van Hooidonk et al., 2016; Hughes et al., 2018; Sully et al., 2019; Williams et al., 2019b). Some reefs are exhibiting recovery following efforts focused at reducing non-climate stressors (e.g. overfishing, nutrient pollution and tourism use). MHWs are increasing in intensity and frequency(Hobday et al., 2016; Smale et al., 2019a) with largest increases in frequency and spatial coverage projected for the Gulf of Mexico, US southern East Coast and US Pacific Northwest (Ranasinghe et al., 2021) and pose a key risk to marine systems in North America (14.5.2, Ch 3, 16,).

[END BOX 14.3 HERE]

14.5.2.2 Adaptation: Current State, Barriers and Opportunities

Emerging technologies and cooperative marine management are approaches to facilitate adaptation but require coordination and investment for implementation.(Gattuso et al., 2018; Miller et al., 2018; Holsman et al., 2019; Karp et al., 2019) (*high confidence*). Advancements in oceanographic and ecological nowcasting and forecasting tools (i.e., O_2, pH, temperature, aragonite saturation state, sea ice conditions) can reduce climate impacts by supporting fisheries and aquaculture adaptation along US coasts (Section 14.5.4) (Cooley et al., 2015; Irby et al., 2015; Siedlecki et al., 2015; Siedlecki et al., 2016; Siddon and Zador, 2017).

Forecasts and warnings reduce human exposure to HAB toxins in the Great Lakes, the west coast of Florida, east coast of Texas and the Gulf of Maine (Anderson et al., 2019).

Ocean management that utilizes a portfolio of nested, multi-scale, climate-informed and ecosystem-based management approaches in North American waters can increase the resilience of marine ecosystems by addressing multiple stressors simultaneously (Marshall et al., 2018; Holsman et al., 2019; Smale et al., 2019a; Holsman et al., 2020) (*high confidence*). Integrated Ecosystem Assessments (Foley et al., 2013; Levin et al., 2014) are increasingly used to provide strategic advice and context for harvest allocations and bycatch avoidance (Zador et al., 2017) and early warnings of ecosystem-wide change (e.g., sentinel species, ecological indicators) (Cavole et al., 2016; Hazen et al., 2019; Moore and Kuletz, 2019). Dynamic ocean management policies may improve resilience of marine species and ecosystems to climate (Hyrenbach et al., 2000; Maxwell et al., 2015; Dunn et al., 2016; Tommasi et al., 2017a; Tommasi et al., 2017b; Hazen et al., 2018; Wilson et al., 2018; Holsman et al., 2019; Karp et al., 2019) (*medium confidence*). New proactive and rapid management approaches have been developed to minimize impacts of increasingly frequent entanglements of protected species, caused by climate-driven changes in prey and fishery activities (Corkeron et al., 2018; Meyer-Gutbrod et al., 2018). Dynamic closure areas are being used to address these issues and reduce loggerhead turtle bycatch in Hawaiian shallow-set longline fisheries (Howell et al., 2015; Lewison et al., 2015), blue whale ship-strike risk in near-real time (Hazen et al., 2017; Abrahms et al., 2019b), and bycatch of multiple top predator species in a West Coast drift gillnet fishery (Hazen et al., 2018).

Improved coordination and planning at multiple scales will be important for marine species conservation and recovery as species redistribute across fishery areas, marine protected zones, and international and jurisdictional boundaries (Cross-Chapter Box MOVING PLATE in Chapter 5) (Pinsky et al., 2018; Karp et al., 2019) (Section 14.5.4). Indigenous Peoples' co-management with federal and state partners of marine resources and protected species is an important approach (see Section 14.5.4, Chapter 5, Chapter 6, and CCP6) (Galappaththi et al., 2019).

Securing broodstocks for rebuilding and supplementation can be challenging for marine populations already in decline (e.g., blue king crab in Alaska, steelhead salmon in Puget Sound, white abalone in California, most groundfish in Northeast US and Canada) (14.5.4; Table SM14.8). Marine protected areas can attenuate climate impacts through trophic redundancy, preserving ecological processes, biodiversity, and climate refugia (Roberts et al., 2017a; Schoen et al.), although benefits decrease after mid-century (or sooner for high latitude marine protected areas) as species reach their thermal limit, unless coupled with greenhouse gas (GHG) mitigation (Bruno et al., 2018). Transport, relocation and cultivation of resistant breeds of salmon, oysters, corals, marine mammals, and other keystone species as well as hatchery supplementation of impaired populations of fish and shellfish are species conservation and recovery methods that will be in greater demand under climate change, although unintended environmental impacts must be considered. Options for protecting and restoring coral reefs to prevent loss of ecosystem function are under development with Florida reef species (Gattuso et al., 2018; National Academies of Sciences, 2019). An emerging approach for financing the protection of reefs involves re-categorizing reefs as "natural infrastructure" which has allowed for use of insurance to rebuild lost reefs (Storlazzi et al., 2019).

14.5.3 Water Resources

Climate change poses increasing threats to North American aquatic ecology, water quality, water availability for human uses, and flood exposure, through reductions in snow and ice, increases in extreme precipitation, and hotter droughts. Adaptation will be impeded in cases where there are conflicts over competing interests or unintended consequences of uncoordinated efforts, heightening the importance of cooperative, scenario-based water resource planning and governance (*high confidence*).

14.5.3.1 Observed Impacts

North American water resources continue to be affected by ongoing warming, with impacts driven by reductions in snow and ice, increases in extreme precipitation, and hotter droughts (Section 14.2) (Fleming and Dahlke, 2014; Mortsch et al., 2015; Dudley et al., 2017; Fyfe et al., 2017; McCabe et al., 2017; Chavarria and Gutzler, 2018; Lall et al., 2018; Bonsal et al., 2019; USGCRP, 2019) (*high confidence*). The cascading effects of severe droughts, floods, sediment mobilization, harmful algal blooms (HABs) and pathogen contamination episodes have revealed the vulnerability and exposure of large numbers of people and economic activities to those hazards.

North America's dams, levees, wastewater-management and water conveyance facilities have improved water supply safety and have reduced flood and drought risks, but a substantial portion of that infrastructure is aging and inadequate for modern conditions (Ho et al., 2017; Tellman et al., 2018; Carlisle et al., 2019; FEMA, 2019; ASCE, 2021). Increasingly heavy precipitation from a variety of storm types has affected parts of North America (Feng et al., 2016; Prein et al., 2017a; Kunkel and Champion, 2019; Kunkel et al., 2020), contributing to contamination from combined sewer overflows (Olds et al., 2018) and increased flood damages that are partially attributed to anthropogenic climate change (van der Wiel et al.; Davenport, 2021). Extreme precipitation events have overwhelmed water control infrastructure, imperilling public safety and contributing to extensive damages in parts of North America(Kytomaa et al., 2019; Vano et al., 2019; White et al., 2019). Damages stem from extremity of the event and prior land use and infrastructure decisions (*high confidence).*

In South Carolina, five days of heavy rainfall in October 2015 caused the failure of more than 50 dams and some levees, significantly magnifying destruction from the floodwaters (FEMA, 2016). Slow-moving, destructive storms like hurricanes Harvey (2017) and Florence (2018) have caused significant flooding (van Oldenborgh et al., 2017; Paul et al., 2019b). In those cases, urban sprawl may have altered storm dynamics (Zhang et al.), while increased asset exposure to the flood hazard amplified the multi-billion dollar losses (Klotzbach et al., 2018; Trenberth et al., 2018). A substantial fraction of the damage from hurricane Harvey's extreme rainfall has been attributed to anthropogenic climate change (Emanuel, 2017; Risser and Wehner, 2017) (Box 14.5). A near-disaster at California's Oroville dam in 2017 was caused by inadequate infrastructure design and maintenance together with an unusually large number of atmospheric river (AR) storms. The event required emergency reservoir spills while the state was beginning recovery from the extreme 2012–2016 drought (Vano et al., 2019; White et al., 2019).

In Mexico, some poor neighbourhoods and informal settlements are located in areas exposed to recurrent flooding. Residents often lack access to public services and technical resources for risk reduction, which heightens their vulnerability (Castro and De Robles, 2019).

Population growth and urban development have increased the exposure and vulnerability of Canadian communities to flood damages, with cumulative damages (including uninsured losses) exceeding US $10B in the past decade (The Geneva Association et al., 2020). Recurring floods are particularly costly (e.g., New Brunswick (Beltaos and Burrell, 2015; Kovachis et al., 2017)). Floods in High River, AB (2013) and Gatineau, QC (2017, 2019) initiated considerations of building flood resilience including planned retreat (Saunders-Hastings et al., 2020).

Extended and severe droughts in the western US, northern Mexico and Canadian Prairies, exacerbated by higher temperatures, have caused economic and environmental damage (Williams et al., 2013; AghaKouchak et al., 2015; Diaz et al., 2016; Bain and Acker, 2018; Lopez-Perez et al., 2018; Ortega-Gaucin et al., 2018; Xiao et al., 2018; Martinez-Austria et al., 2019; Bonsal et al., 2020; Martin et al., 2020b; Milly and Dunne, 2020; Overpeck and Udall, 2020). Droughts have intensified tensions among competing water use interests and accelerated depletion of groundwater resources (14.5.4) (Pauloo et al., 2020) *(high confidence)*.

Climate trends are affecting riverine, lake and reservoir water quality (*medium confidence*). Droughts and increased evapotranspiration have impaired water quality by concentrating pollutants in diminished water volumes (Paul et al., 2019a). Cyanobacterial blooms and pathogen exposure events are increasing in frequency, intensity, and duration in North America (Taranu et al., 2015). They are closely associated with observed changes in precipitation intensity and associated nutrient loading (e.g., agricultural runoff, sanitary sewer overflows), elevated water temperatures and eutrophication (Michalak et al., 2013; Michalak, 2016; Trtanj et al., 2016; Chapra et al., 2017; IBWC, 2017; Williamson et al., 2017; Olds et al., 2018; Coffey et al., 2019). These events endanger human and animal health, recreational and drinking water uses, aquatic ecosystem functioning, and cause economic losses (Michalak et al., 2013; Bullerjahn et al., 2016; Chapra et al., 2017; Huisman et al., 2018). Households and communities dependent on substandard wells, unimproved water sources, or deficient water provision systems are more *likely* than others to experience climate-related impairment of drinking water quality (14.5.6.5) (Allaire et al.; Baeza et al., 2018; California State Water Resources Control Board, 2021; Navarro-Espinoza et al., 2021; Water and Tribes Initiative, 2021).

14.5.3.2 Projected Impacts and Risks

Climate change is projected to amplify current trends in water resource impacts, potentially reducing water supply security, impairing water quality, and increasing flood hazards to varying degrees across North America (*high confidence*). Examples are presented in Table 14.3.

Table 14.3: Selected Projected Water Resource Impacts in North America.

Climatic Drivers and Processes	Examples of Future Risks/Impacts	Location (see Figure 14.1)	References
Warming-induced reductions in mountain snow and glacial mass	Projected decreases in annual and late-summer streamflow from high-elevation reaches of snow-fed rivers, affecting stream ecology and water supplies, (*high confidence*)	US-NW, US-SW CA-BC, CA-PR	(Jost et al., 2012; Solander et al., 2018; Bonsal et al., 2019; Milly and Dunne, 2020)
Earlier seasonal snowmelt runoff	Greater winter/early spring flooding risks and reduced summer surface water availability, intensifying seasonal mismatch with water demands *(high confidence*), Increased challenges for balancing multi-purpose reservoir objectives (e.g. flood-management, water supply, ecological protection and hydropower) (*high confidence*)	US-NW, US-SW CA-BC, CA-PR,	(Cohen et al., 2015; Dettinger et al., 2015; Bonsal et al., 2019; Bonsal et al., 2020; RMJOC, 2020; Bureau of Reclamation, 2021d)
Earlier seasonal snowmelt runoff	Possible reductions in water supply security *(medium confidence*); Reduced viability of some small-scale irrigation systems *(medium confidence)*	US-SW	(Medellin-Azuara et al., 2015; Ullrich et al., 2018; Bai et al., 2019; Milly and Dunne, 2020; Ray et al., 2020; Bureau of Reclamation, 2021b; Bureau of Reclamation, 2021a; Bureau of Reclamation, 2021c)
Changes in seasonal timing and/or total annual runoff	Impacts on electric power generation *(medium confidence*) varying by location and type of generation	US-SW, US-NW CA-QC	(Haguma et al., 2014; Bartos and Chester, 2015; Guay et al., 2015; Turner et al., 2019b; RMJOC, 2020; Bureau of Reclamation, 2021d)
Changes in seasonal timing and/or total annual runoff	Impacts on urban water supplies	CA-QC	(Foulon and Rousseau, 2019)

Warming-related increased imbalance between renewable surface water supplies and consumptive water demands	Greater pressures on groundwater resources, possible increased aquifer depletion, reduced baseflow into surface streams and reduced long-term water supply sustainability *(medium confidence*)	US-SW, US-SP, US-SE, MX-N, MX-NW	(Bauer et al., 2015; Molina-Navarro et al., 2016; Russo and Lall, 2017; Brown et al.; Nielsen-Gammon et al., 2020; Bureau of Reclamation, 2021b)
Warming-related drought amplification	Reduced water availability for human uses and ecological functioning *(medium to high confidence*) varying by location; increased evaporative losses from reservoirs.	Widespread especially: US-SW, US-NP, US-SP CA-PR MX-NW, MX-N	(Prein et al., 2016; Dibike et al., 2017; Lall et al., 2018; Paredes-Tavares et al., 2018; Martinez-Austria et al., 2019; Tam et al., 2019; Martin et al., 2020b; Milly and Dunne, 2020; Overpeck and Udall, 2020; Williams et al., 2020; Bureau of Reclamation, 2021b)
Heavier and/or prolonged rainfall events	Flooding, infrastructure and property damage *(medium to high confidence*) varying by location; increased erosion and debris flows with impacts on public safety, reservoir sedimentation and stream ecology -- hazards amplified in watersheds affected by wildfires.	Widespread; especially: US-SE, US-NE, US-NP, US-SP, US-SW CA-BC MX-CE; MX-NE; MX-SE	(Feng et al., 2016; Emanuel, 2017; Prein et al., 2017a; Prein et al., 2017b; Haer et al., 2018; Kossin, 2018; Mahoney et al., 2018; Thistlethwaite et al., 2018; Curry et al., 2019; Larrauri and Lall, 2019; Wobus et al., 2019; Ball et al., 2021)
Heavier and/or prolonged rainfall events	Water quality impairment, increasing HAB events due to increased sediment and nutrient loading together with warming. Greatest impacts in humid areas with extensive agriculture *(medium confidence to high confidence*) varying by location.	US-MW, US-NE, US-SE, US-NP, US-SP CA-ON, CA-AT, MX-NE, MX-NW	(Alam et al., 2017; Chapra et al., 2017; Sinha et al., 2017; Ballard et al., 2019)
Increasingly variable precipitation,	Highly variable precipitation poses challenges for water management, worsening water supply and flooding risks. Atmospheric River (AR) events are projected to increase variability by dominating future North American west coast precipitation *(medium confidence)*	US-SW, US-NW, CA-BC	(Gershunov et al., 2019; Huang et al., 2020)
Hotter summer season	Evaporative losses from reservoirs are projected to increase significantly (*very high confidence*)	US-SW, US-NW, US-NP	(Bureau of Reclamation, 2021b)

Projected long-term reduction in water availability in the US Southwest and northern Mexico, e.g., from the Colorado and Rio Grande Rivers, will have substantial ecological and economic impacts given the region's heavy water demands (*high confidence*) (Lall et al., 2018; Paredes-Tavares et al., 2018; Martinez-Austria et al., 2019; Milly and Dunne, 2020; Williams et al., 2020). Increased water scarcity will intensify the need to address competing interests across state and national boundaries, including honouring commitments to Indigenous Peoples who have long struggled with inadequate access to their water entitlements and marginalization in water resource planning (Mumme, 1999; Cozzetto et al., 2013b; Mumme, 2016; McNeeley, 2017; Radonic, 2017; Robison et al., 2018; Curley, 2019; Water and Tribes Initiative, 2020; Wilder et al., 2020).

Increased scarcity of renewable water relative to legally allocated or desired uses may develop in many parts of North America. A detailed analysis of projected water demands (consumptive uses) and availability found increasingly frequent shortages in several watersheds across the United States (Brown et al., 2019b). This might lead to maladaptive increased groundwater mining, or alternatively to policies promoting sustainable balancing of water consumption with renewable supplies, for example by facilitating voluntary water transfers or improving enforcement of groundwater rights (Colorado River Basin Stakeholders, 2015; California Natural Resources Agency et al., 2020; Colorado Water Conservation Board, 2020; Pauloo et al., 2020).

Climate change is projected to reduce groundwater recharge in major US Southwest aquifers (e.g., Southern High Plains, San Pedro and Wasatch Front), exacerbating their ongoing depletion due to unsustainable pumping. Other aquifers, especially those farther north, face uncertain or possibly increasing recharge (Meixner et al., 2016) *(medium confidence*).

Projected changes in temperature and precipitation present direct risks to North American water quality, varying with regional and watershed contexts (Chapra et al., 2017; Coffey et al., 2019; Paul et al., 2019a), and related to streamflow, population growth (Duran-Encalada et al., 2017) and land use practices (Mehdi et al., 2015) (*medium confidence*). HABs increase in frequency across the US (Wells et al., 2015) with the highest risk projected for the Great Plains and Northeast US, and greatest economic impacts from lost recreation value in Southeast US (Chapra et al., 2017).

The diversity of climate regimes across North America results in regional differences in water-related climate change risks (Figure 14.4).

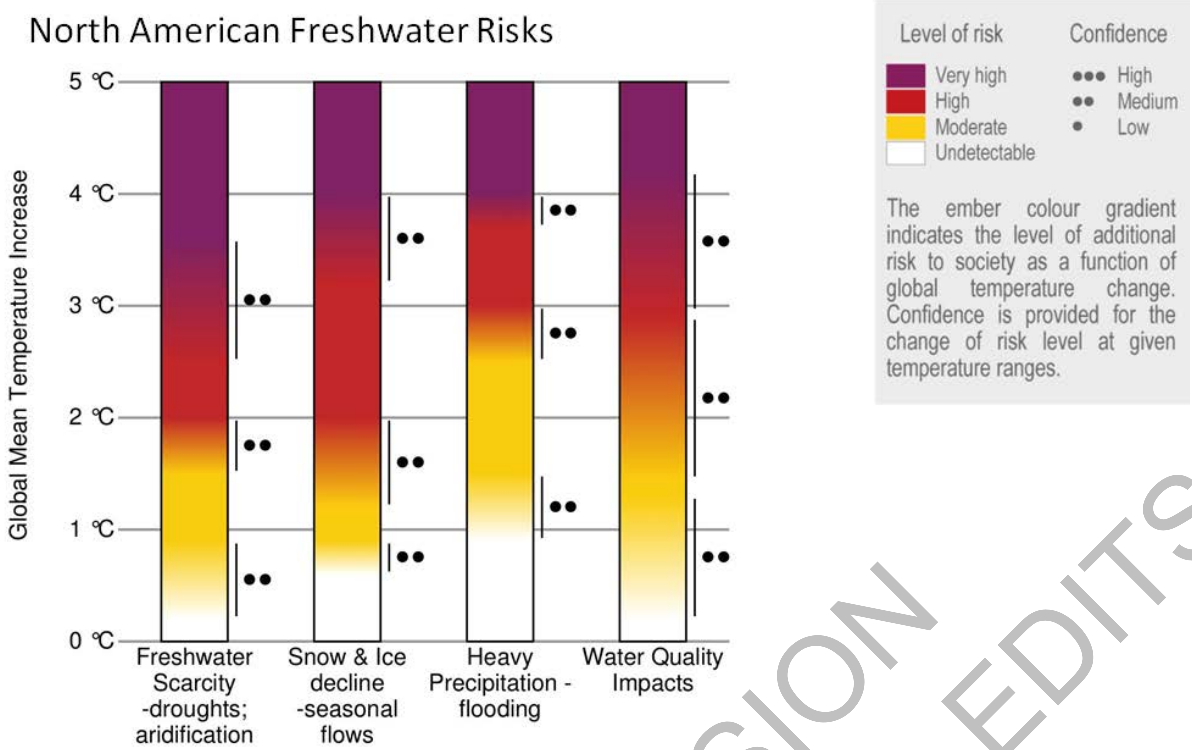


Figure 14.4: Freshwater resource risks as a function of global mean surface temperature increase relative to preindustrial (1850-1900). Estimated sensitivities are based on references cited in Table 14.3, see SM14.4.

14.5.3.3 Adaptation

North American water planners and policy makers have abandoned stationarity assumptions (Milly et al., 2015) to address climate change. Transboundary institutions, government agencies, and professional organizations are taking the lead on adaptation planning and implementation. (ASCE, 2018b; Clamen and Macfarlane, 2018; International Joint Commission (IJC), 2018). Major water agencies are using climate scenarios to identify vulnerabilities and evaluate adaptation options (Yates et al., 2015; Vogel et al., 2016; California Department of Water Resources, 2019; Ray et al., 2020; Bureau of Reclamation, 2021d). The Water Utility Climate Alliance advises municipal water providers, to address uncertainty by considering a wide range of plausible future climate conditions (WUCA, 2010). In some areas, the impacts of wildfires on water supply resiliency are being considered (Martin, 2016). Many North American Indigenous Peoples are engaged in climate change adaptation planning although these efforts may be hampered by the complicated legal and administrative setting in which they must operate (Norton-Smith et al., 2016a; McNeeley, 2017).

Recent climate extremes have heightened governmental attention to climate change impacts (e.g., (California Natural Resources Agency et al., 2020). Droughts have exposed shortcomings in water management and governance (Gray et al., 2015; Xiao et al., 2017b; Lopez-Perez et al., 2018) spurring legislation and administrative changes to improve groundwater regulation and documentation of water rights (California Department of Food and Agriculture, 2017; Miller, 2017; Lund et al., 2018; Hanak et al., 2019).Water allocation policies are being reassessed to enhance equity, sustainability and flexibility through shortage sharing agreements, improved groundwater regulation and voluntary water transfers. Developments include an interstate drought management agreement for the Colorado River (US Law, 2019), and agreements between the US and Mexico to provide pulse flows to benefit the ecology of the Colorado River Delta (Pitt and Kendy, 2017). State-wide water planning in Colorado has emphasized building drought resilience (e.g. by facilitating temporary water transfers) (Colorado State Government, 2015; Yates et al., 2015). At local scales there have been innovations in cooperative watershed protection and water resource planning (Cantú, 2016). Indigenous Peoples are playing an increasing role in identifying equitable and resilient options for adaptation by contributing their knowledge and voicing their perspectives on the importance of healthy water bodies for human and environmental well-being (Norton-Smith et al., 2016a; Water and Tribes Initiative, 2020). Collaboration between stakeholders, policymakers and scientists is increasingly common in water resources adaptation planning and assessment.

Examples of adaptation include increasing adoption of water-saving irrigation methods in California (Cooley, 2016), experimentation with using flood waters to enhance groundwater recharge (Kocis and Dahlke, 2017; California Department of Water Resources, 2018), and agricultural land management programs, including developing riparian buffers to protect water quality (14.5.4) (Mehdi et al., 2015) (Schoeneberger et al., 2017). Indigenous Peoples are building upon traditional practices to adapt to the effects of climate change, for example by working jointly to recharge local aquifers (Basel et al., 2020).

Water right laws, interstate compacts and international treaties regarding transboundary water shape the context for climate change adaptation, but the possibility of long-term climate change typically was not contemplated at their inception. Gaps in coverage and vaguely defined terms can lead to tensions and disputes, especially in areas facing increased aridity, creating difficulties for adaptation. For example, unregulated pumping of groundwater for irrigation during short-term droughts can serve as an adaptation to acute conditions, (14.5.4) but if persisting long-term, can deplete finite groundwater resources and dewater hydrologically connected rivers. Such outcomes have engendered bitter and costly interstate conflicts in the US, some reaching the US Supreme Court including *Texas v New Mexico* (Rio Grande) and *Florida v. Georgia* (Apalachicola-Chattahoochee-Flint).

Trans-boundary rivers that exemplify the need to address climate impacts include the Colorado (Gerlak et al., 2013), Columbia (Cosens et al., 2016), and Rio Grande/Rio Bravo (Mumme, 1999; Mumme, 2016; Garrick et al., 2018; Payne, 2020). Drought emergencies can open opportunities for progress on collaborative adaptive governance, but such windows may quickly close when wetter conditions return (Sullivan, (2019).

Water serves a wide variety of environmental functions and human uses as it moves through North America's river basins, so the impacts of climate change are expected to be widespread and multifaceted. This increases the importance of collaborative adaptation efforts that are equitable, transparent and give voice to differing values, perspectives, and entitlements across a broad socioeconomic spectrum of urban and rural, Indigenous and non-Indigenous participants (Miller et al., 2016; Cosens et al., 2018). Adaptation planning may be hampered by conflicting interests, jurisdictional boundaries, and inherent interconnections between actions and impacts at different points throughout a watershed or river basin. Differential power relationships, decision-making authority and access to information also can interfere with effective adaptive governance, while equitable processes for decision-making bolstered by reliable shared information can help to overcome those impediments (Cosens et al., 2016; Arnold et al., 2017; Cosens et al., 2018; Porter and Birdi, 2018).

Across North America, there are growing signs of progress toward adaptive water governance and implementation of climate-resilient, and ecosystem-based, water management solutions (Colorado River Basin Stakeholders, 2015). California's approach to groundwater sustainability regulation intends to foster such collaborative problem-solving by giving local Groundwater Sustainability Agencies the authority to design locally appropriate plans to meet state-defined sustainability goals (State of California, 2014; Miller, 2017). As evidenced by the US interstate disputes, the greatest difficulties arise in cases where stark upstream-downstream differences in interests leave little room for mutual benefit. Severe aridification may test the limits of adaptive capacity.

Research on water diplomacy recommends broadening negotiations beyond a narrow focus on zero-sum issues, like rigid water allocations, to embrace a more diverse set of shared interests including the need for flexibility to respond to changing conditions. A process for ongoing inclusive engagement of a watershed's stakeholders in mutual social, policy and science learning is important. Such mutual learning can build trust and establish a common platform of credible information for co-creation of adaptation solutions. In addition, better understanding of the policy positions and constraints of others can help stakeholders to identify workable solutions to contentious water management issues (Payne, 2020; Wilder et al., 2020). Cooperation between Mexico and the US on mapping and assessment of transboundary aquifers is a product of such ongoing engagement (Callegary et al., 2018; Sanchez et al., 2018). Other examples of the benefits of sustained engagement are provided by a set of co-management arrangements between state, federal and Indigenous authorities on water management for fishery restoration in the US Pacific Northwest (Tsatsaros et al., 2018), and Indigenous involvement in multi-level co-management of water resources in Canada's Northwest Territories (Latta, 2018).

14.5.4 Food, Fibre, and Other Ecosystem Products

14.5.4.1 Observed Impacts and Projected Risks: Agriculture, livestock, and forestry

Climate change has affected crops across North America through changes in growing seasons and regions, extreme heat, precipitation, water stress, and soil quality (Table 14.1, 5.4.1; Figure 5.3) (Mann and Gleick, 2015; Galloza et al., 2017; Otkin et al., 2018). These changes directly influence crop productivity, quality and market price (*high confidence*) (Kistner et al., 2018; Reyes and Elias, 2019). Effects of historical climate change on maize, soybean, barley and wheat crop yields vary from strong increases to strong decreases (e.g. >-0.5 to >+0.5 t ha-1yr-1 for maize) within North America's agroecological regions, even for the same crop (Ray et al., 2019). Across North America, climate change has generally reduced agricultural productivity by 12.5% since 1961, with progressively greater losses moving south from Canada to Mexico (Ortiz-Bobea et al., 2021), yet responses are highly differential across regions and crops. Some crop loss events are partially attributed to climate change (*high confidence*) such as the 2012 Midwest and Great Plains drought, which cost agriculture USD$30B (Smith and Matthews, 2015; Rupp et al., 2017). Aridity is extending northward, altering crop suitability ranges (Fig 14.4); up to 50% of distributional shifts in growing regions for US crops between 1970-2010 may be related to climate change (Lant et al., 2016; Cho and McCarl, 2017). Irrigation is expanding to areas formerly largely dependent on rainfall (Wang et al., 2018b).

Without adaptation, climate change is projected to reduce overall yields of important North American crops (e.g., wheat, maize, soybeans) (*high confidence*) (Chen et al., 2017; Levis et al., 2018) (Tables SM14.3-4). For example, projected heat stress (RCP8.5) reduced midcentury (2040–2069) maize and cotton yields by 12-15% of historical yields (1950–2005), with the US-SW suffering the largest impacts (Elias et al., 2018) (Table SM14.5). Warming and heat extremes will delay or prevent chill accumulation, affecting perennial crop development (e.g. fruit set failure), yield (e.g., walnuts, pistachios, stone fruit), and quality (e.g. grapes) (*medium confidence*) (Parker et al., 2020). Warming will alter the length of growing seasons of cold-season crops (e.g., broccoli, lettuce) and will shift suitability ranges of warm-season California crops (e.g., tomatoes) (*medium confidence*) (Marklein et al., 2020). Increasing atmospheric CO_2 will enhance yields yet reduce nutrient content of many crops (*high confidence*); a CO2 concentration of 541 ppm (seen by 2050 in RCP 8.5) would reduce per capita nutrient availability in North American diets by 2.5–4.0% (Beach et al., 2019). Crop pest and pathogen outbreaks are expected to worsen under climate change (*high confidence*) (Deutsch et al., 2018; Wolfe et al., 2018; Zhang et al., 2019a).

Climate change is anticipated to cause declines in livestock production across North America (*high confidence;* Table 14.4 & SM14.6) (Havstad et al., 2018; Murray-Tortarolo et al., 2018); increases in extreme temperature raise the risk of livestock heat stress, disease, and pest impacts (Rojas-Downing et al., 2017). Projected aridification reduces forage production in the Southwest US and Northern Mexico (*high confidence*) (Polley et al., 2013; Reeves et al., 2014; Cooley, 2016; Bradford et al., 2020) and transforms grasslands to woody shrublands (Briske et al., 2015; Murray-Tortarolo et al., 2018), while warmer and wetter conditions in the northern regions (CA-PR, US-NW, US-NP) may enhance rangeland production by extending growing seasons (*high confidence*) (Hufkens et al., 2016; Derner et al., 2018; Zhang et al., 2019a). Increased CO_2 will enhance production (*medium confidence*), but reduce forage quality (*high confidence*) in US-NP and US-NW (Table SM14.6) (Derner et al., 2018).

Climate change impacts on forests (14.5.1, Box 14.2) may affect timber production by altering tree species distributions, productivity, and wildfire and insect disturbances (*medium confidence*). Southern or drier locations may shift from forests to other vegetation types, whereas higher latitude areas may experience forest expansion (Brecka et al., 2018). Tree species composition is projected to change with climate change (Wang et al., 2015; Bose et al., 2017). Tree growth may increase or decrease from changes in temperature or moisture depending on location, with lower growth expected from warming in water-limited areas (Littell et al., 2010). Increased productivity associated with more favourable climate conditions is projected for boreal forests (Brecka et al., 2018), although in some regions, growth will reverse and decline with additional warming (D'Orangeville et al., 2018; Chaste et al., 2019). As a result of these changes, timber yields in North America may increase in the future (Beach et al., 2015; EPA, 2015a) or decrease (Boulanger et al., 2014; McKenney et al., 2016; D'Orangeville et al., 2018; Thorne et al., 2018; Chaste et al., 2019) depending on location and mechanisms included. Wildfires and insect outbreaks are projected to increase with future climate change, thereby limiting biomass (Gauthier et al., 2015; Bentz et al., 2019; Chaste et al., 2019).

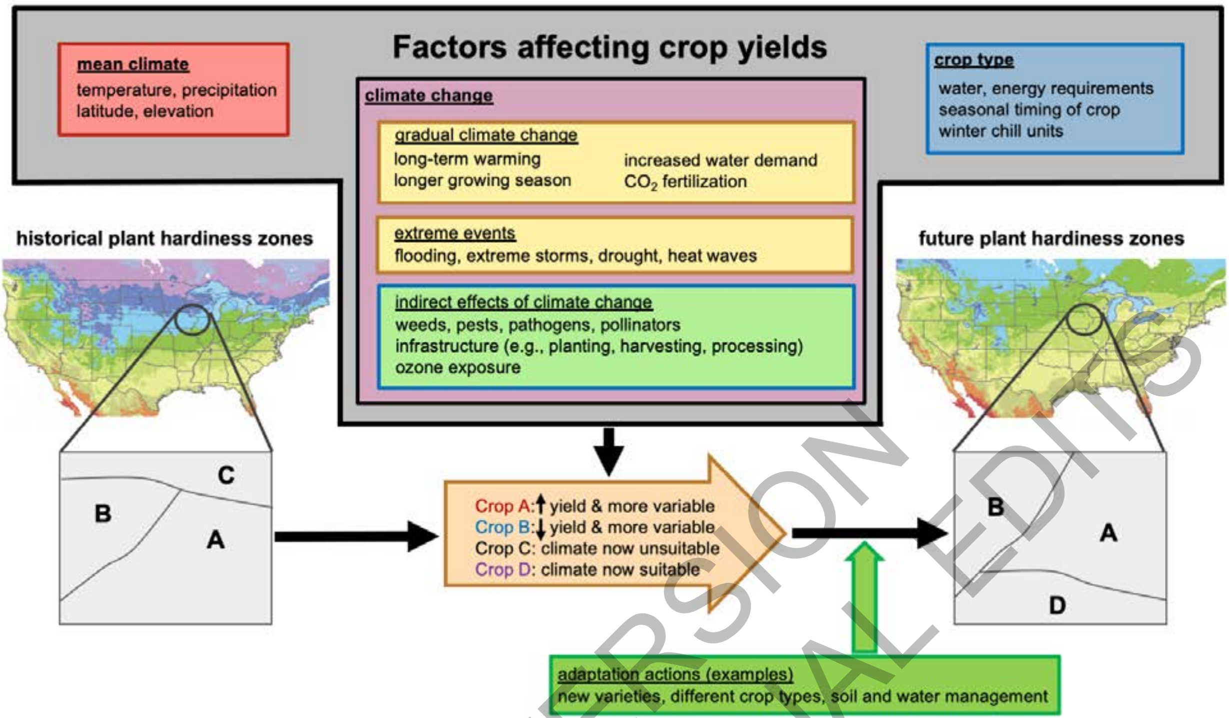


Figure 14.5: Crop responses to climate change will depend on existing mean climate, the type of climate change, and characteristics of crop types. Hypothesized responses for Crop Types A, B, C, and D include changing crop yields or changing crop area. Adaptation actions may alter hypothesized responses; maps from Matthews et al. (2019)

14.5.4.2 Observed Impacts and Projected Risks: Fisheries and Aquaculture

Climate impacts outlined in Section 14.5.2 have induced yield losses for multiple subsistence, recreational, and commercial fisheries (*very high confidence*) and contributed to commercial fishery closures across North America (Figure 14.6, Table SM14.7, 14.5.1, 14.5.3) (Lynn et al., 2014; Barbeaux et al., 2020; Fisher et al., 2021). Climate-driven declines in productivity are widespread (*high confidence*) (Figure 14.6), although a few increases are observed in northern regions (*medium confidence*) (Cunningham et al., 2018; Crozier et al., 2019; Zhang et al., 2019b). Redistribution of species has increased travel distance to fishing grounds, shifted stocks across regulatory and international boundaries, and increased interactions with protected species (*very high confidence*) (Cross-Chapter Box MOVING PLATE in Chapter 5) (14.5.2) (Morley et al., 2018; Free et al., 2019; IPCC, 2019c; Rogers et al., 2019; Stevenson and Lauth, 2019; Young et al., 2019) (Figure 14.6, Table SM14.7). Climate shocks have reduced yield and increased instability in fishery revenue (*high confidence*) (Fisher et al., 2021).

Declines in yield and poleward stock redistributions (avg. ~20.6 km decade^{-1}) are expected to continue under climate change, and increase in magnitude with atmospheric carbon (*high confidence*) (Table 14.4) (Hare et al., 2016; Pecl et al., 2017; Rheuban et al., 2017; Morley et al., 2018; Smale et al., 2019a; Szuwalski et al., 2021). For example, without adaptation, end of century losses of Bering sea pollock yield (relative to persistence scenarios) is *likely* to reach 50% under moderate (RCP4.5) and 80% under low (RCP8.5) mitigation scenarios, respectively (Holsman et al., 2020). Expanding HABs, pathogens, and altered ocean chemistry (OA and dissolved oxygen) will reduce yields and increase closures of fisheries along all North American coasts (*medium confidence*) (14.5.2) (Deutsch et al., 2015a; Ekstrom et al., 2015; Seung et al., 2015; Punt et al., 2016; Howard et al., 2020). For fisheries that represent 56% of current US fishing revenue, projected annual net losses under high emission scenarios (RCP 8.5; 2021-2100) may reach double that of low emission scenarios (RCP2.6) (Moore et al., 2021).

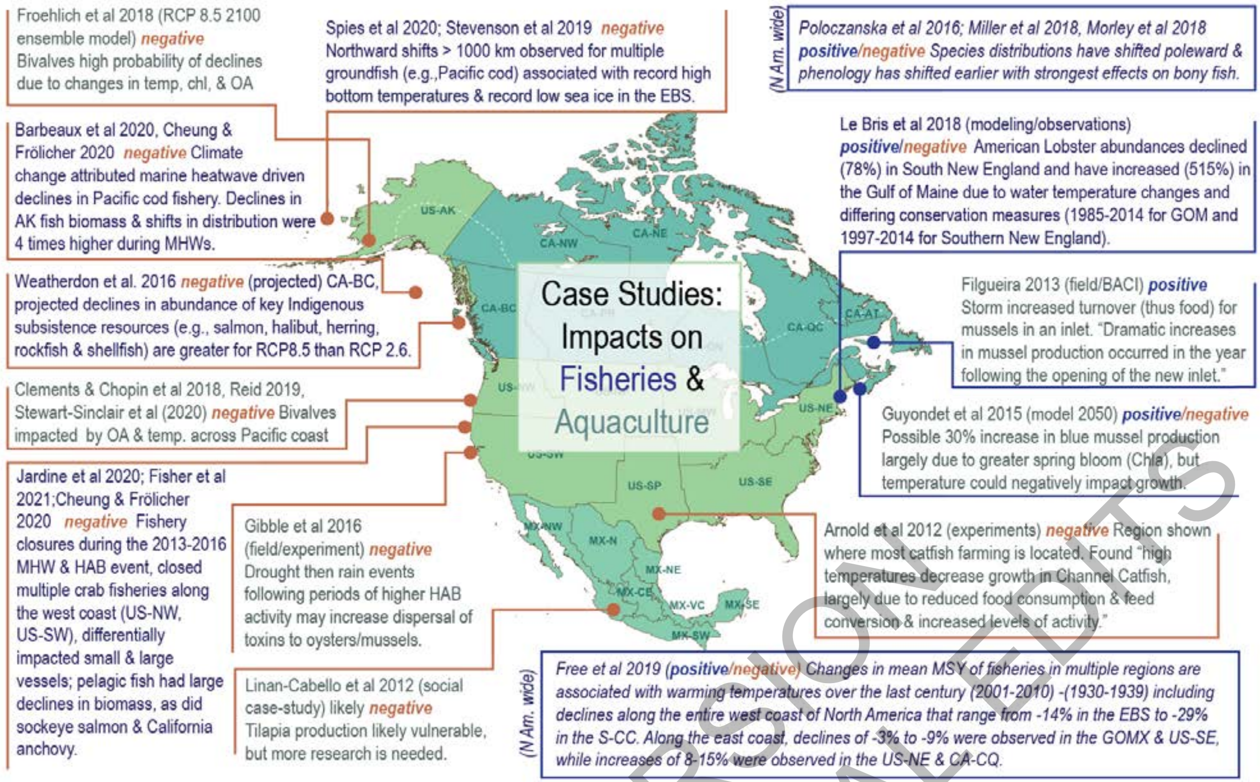


Figure 14.6: Climate change impacts on North American fisheries and aquaculture

Warming waters and OA have impacted aquaculture production in North America (*high confidence*) (Figure 14.6) (Clements and Chopin, 2017; Reid et al., 2019; Stewart-Sinclair et al., 2020). Under climate change (RCP8.5), declines in marine finfish and bivalve aquaculture become *likely* by mid-century (Froehlich et al., 2018; Stewart-Sinclair et al., 2020). Adaptation is possible but uncertain (Bitter et al., 2019; Fitzer et al., 2019; Reid et al., 2019), especially with increasing extreme events. Nature-based aquaculture solutions (e.g., conservation aquaculture, restorative aquaculture) could aid carbon mitigation and local-level adaptation, especially for seaweed and bivalve culture (Box 14.7) (Froehlich et al., 2017; Froehlich et al., 2019; Reid et al., 2019; Theuerkauf et al., 2019).

Table 14.4: Observed and projected impacts to food and fibre resources.

Climate Driver	Observed Change[1]	Reference	Projected change	Reference
Agriculture and livestock (Tables SM14.2-5)				
Extreme events	Estimates of yield reduction from heat stress for both maize and cotton indicate that historically, US-SW heat stress reduced cotton yield by 26% and maize yield by 18% compared to potential yield. Extreme heat was associated with increased crop failure in MX-CE, US-SW; Hailstorm increased frequency observed in MX coinciding with the most vulnerable stage or flowering period of maize; extreme precipitation damages to soil, increased erosion, and reduced crop yields observed in MX and US-MW	(Altieri and Nicholls, 2009; Mastachi-Loza et al., 2016; Elias et al., 2018; Kistner et al., 2018; Reyes and Elias, 2019)	Projected heat stress (RCP8.5) reduces midcentury (2040–2069) maize and cotton yields by 12-15% of historical yields (1950–2005) with largest impacts in US-SW additional drought-related stress in US-MW could reduce maize and soybean yields by ~5% and ~10%, respectively, by late century under RCP 4.5 ; warming and extreme heat (>35%) will delay (or prevent) chill accumulation, impacting perennial crop development, yields, and quality (US-SW). Increases in extreme temperature raise the risk of livestock heat stress, disease, and pest impacts.	(Jin et al.; Rojas-Downing et al., 2017; Elias et al., 2018; Parker et al., 2020)
Mean growing season precipitation decline, mean temperature increase, drought	Across the US Great Plains (US-SP, US-NP) between 1968-2013 climate change induced 3.55%, -0.55%, and 0.94% change in yield for (irrigated and non-irrigated) maize, sorghum and soybeans (respectively); Droughts and increasing temperatures reduced soil fertility in MX and contributed to soil erosion and degradation and suitability loss of 18-22%; Experimental and simulated reductions in water supply of 25-50% result in similar magnitude declines in yield for multiple food and forage crops (e.g., wheat, maize)	(Frisvold and Konyar, 2012; Leskovar et al., 2012; Aladenola and Madramootoo, 2014; Galloza et al., 2017; Havstad et al., 2018; Kukal and Irmak, 2018)	Warming alters the length of growing seasons of cold-season crops and shifts suitability ranges of warm-season California crops; aridification reduces forage production US-SW, MX-N; warming is associated with reduced livestock growth and fertility, increased pathogens in US-SE, US-SP, US-MW, US-NE, and reduced milk production in US-MW.	(St-Pierre et al., 2003; Polley et al., 2013; Key and Sneeringer, 2014; Reeves et al., 2014; Cooley, 2016; Hristov et al., 2018; Ortiz-Colón et al., 2018; Bowling et al.; Bradford et al., 2020; Marklein et al., 2020) (Hufkens et al., 2016; Derner et al., 2018; Zhang et al., 2019b)
Multiple drivers	Climate change reduced total factor productivity of agriculture and livestock in North America by 12.5% (ranging from approx. -35% to +8%) between 2016-2015; losses have been greatest in Mexico (-30% to -25% Figure5), and lowest in Canada (>0%);Reduced yield in MX, US; increased weed, pest pressure in US-NE, US-MW, US-NP, US-NW	(Garruña-Hernández et al.; Loreto et al.; Wolfe et al., 2018; Torres Castillo et al., 2020; Ortiz-Bobea et al., 2021)	Projected declines in yield and changes of in suitability ranges for maize (-18%-+5%), sorghum (-16 to +12%), and wheat (-38 to -15%) in MX (RCP 4.5, 8.5; 2040-2099); northward shifts in the suitable area for 6 crops from the central US (2100); Warming accompanied by increased CO_2 may benefit crop production of small grains in southern Canada up to 3 ºC GWL, although benefits decline after 2.5ºC GWL. Increased CO_2 enhances production but reduces forage quality US-NP,US-NW. Without adaptation, 2ºC GWL	(Calderón-García et al.; Herrera-Pantoja and Hiscock; Lant et al., 2016; Chen et al., 2017; Montiel-González et al.; Reyer et al.; Derner et al., 2018; Deutsch et al., 2018; Levis et al., 2018; López-Blanco et al.; Murray-Tortarolo et al.; Wolfe et al., 2018; Gomez Diaz et al.; Qian et al.; Zhang et al., 2019b; Arce Romero et al.)

			increased insect-caused production losses ~36% and~44% for maize and wheat, respectively.	
Aquaculture and fisheries (Tables SM14.6, SM14.8)				
Extreme events	MHW and HAB event of 2014-2016 resulted in multiple fishery closures along the west coast (US-NW, US-SW); disparate impacts observed between small and large vessels with greatest impacts on small vessel revenue and fishery participation; impacts were highest for ports in the CC-N and least for fishing communities with diverse livelihoods and harvest portfolios; In the EBS, GOA, and N-CC, declines in fish biomass and shifts in distribution were 4 times higher and greater during MHWs than that of general warming over the same period; pelagic fish showed largest decrease in biomass (7%), as did Sockeye salmon and California anchovy; Increased risk to hatcheries and low lying pond systems from severe storms. Extreme heat is associated with reduced productivity of aquaculture species.	(Handisyde et al., 2017; Food Agriculture Organization of the United Nations; Froehlich et al., 2019; Reid et al., 2019; Bertrand et al., 2020; Cheung and Frölicher, 2020; Jardine et al., 2020; Sippel et al., 2020; Fisher et al., 2021)	Projected doubling of MHW impact levels by 2050 amongst the most important fisheries species (over previous assessments that focus only on long-term climate change)	(Cheung and Frölicher, 2020)
Multiple drivers	Climate shocks reduce catch, revenue and county-level wages and employment among commercial harvesters in US-NE; climate variability 1996 - 2017 is responsible for a 16% (95% CI: 10% to 22%) decline in county-level fishing employment in New England; impacts mediated by local biology and institutions; Seafood is an important source of nutrients and protein for Indigenous Peoples in CA-BC; polices that incorporate nutrition in fisheries management are limited in North America	(Marushka et al., 2019; Oremus, 2019) (14.5.6 Health)	Declines in North American catch potential of flatfish are projected under RCP8.5 for the EBS, GOA, GOMX, US-SE, and US-NE; declines in productivity projected for multiple species in MX, with largest declines in productivity (>35%) for abalone and pacific sardine; Impacts are greatest for artisanal species ; projected declines in fish community biomass for all North American coasts except US-SW and the Canadian Arctic; declines are greater under RCP8.5 than RCP2.6. Modest increases (up to 10%) in landings of CA-QC and CA-AT surf clams and shrimp are projected under RCP2.6 by 2100 while declines in snow crab up to 16% are expected (RCP2.6,8.5); Mussel landings projected to increase 21%., while declines in shellfish and lobster landings (2090) are twice as high under RCP 8.5 (42%-54%) as RCP 2.6.	(Weatherdon et al., 2016; Cheung, 2018; Carozza et al., 2019; Cisneros-Mata et al.; Reum et al., 2019; Tai et al., 2019; Mendenhall et al., 2020; Wilson et al., 2020)

			Shellfish, snow crab landings projected to decline in CA-QC and CA-QT; declines under RCP 8.5 are double that of RCP 2.6; Climate change reduces EBS blue king crab recovery in simulations; Relative to US and CA, MX has strongest benefits in net catch under RCP2.6 relative to RCP8.5 (>30% increase in catch); increases of 70% in catch potential projected for the Canadian Arctic (CA-NE,CA-NW) under RCP 8.5 (versus minimal changes under RCP2.6); high resolution and size spectrum models project declines in groundfish catch and biomass in S-EBS; shifting transboundary stocks may increase challenges.	
Ocean and lake acidification	OA reduced maximum sustainable yield, catch and profits of EBS Tanner crab in simulations; survival of larval and juvenile red king crab (RKC) in the lab decreased 97-100% with decreasing pH;No appreciable effects of pH on larval growth of walleye pollock in the lab (Hurst, 2013); Mixed evidence of impacts of changes in pH on freshwater or saltwater finfish aquaculture; OA reduced growth, calcification, attachment and increased mortality in calcifying molluscs and seaweeds in US, CA; OA may benefit non-calcifying seaweeds.	(Long et al., 2013a; Seung et al., 2015; Punt et al., 2016; Clements and Chopin; Handisyde et al., 2017; Swiney et al., 2017; Food Agriculture Organization of the United Nations; Froehlich et al.; Reid et al., 2019; Stewart-Sinclair et al.)	Projected declines for some shellfisheries and flatfish due to OA and temperature; OA conditions under RCP 8.5 reach critical risk thresholds for mollusc harvests earlier in northern regions than southern areas; OA risk to shellfisheries is highest in N-CC;OA caused 1% additional decline in Arctic cod populations by 2100 under RCP8.5;OA influences management reference points of Northern Rock sole. OA and temperature reduce probability of recovery in simulations of EBS blue king crab.	(Ekstrom et al., 2015; Reum et al., 2019; Steiner et al., 2019; Wilson et al., 2020; Punt et al., 2021)
Mean temperature increase	Species distributions have shifted poleward and phenology has shifted earlier with strongest effects on bony fish. Warming over the last century (2001-2010) - (1930-1939) is associated with declines in MSY along the entire west coast of North America that range from -14% in the EBS to -29% in the CC-S. Along the east coast, declines of -3% to -9% were observed in the GOMX and US-SE, while increased of 8-15% were observed in the US-NE and CA-CQ. Mixed positive and negative growth and mortality responses for aquaculture species in North America; Juvenile red king crab survival decreases as temperatures increase in lab experiments . American Lobster abundances	(Poloczanska et al., 2016; McCoy et al., 2017; Swiney et al., 2017; Le Bris et al., 2018; Miller et al., 2018; Food Agriculture Organization of the United Nations; Free et al., 2019; Froehlich et al.; Reid et al., 2019; Weiskerger et al., 2019; Bertrand et al., 2020; Le et al., 2020)	By end of century, North America fish biomass, catch potential and revenue are ~9% higher in RCP 2.6 than RCP 8.5 and differences are greatest for US fisheries (relative to CA, MX; Projected poleward redistributions (reported ranges of 10.3 to 39.1 km decade^{-1}) and to depth decrease access to shellfisheries in CA-QC and subsistence species in CA-BC (-28% by 2100), with impacts increasing N to S and under RCP 8.5 as compared to RCP 2.6.; Climate change (RCP8.5) is projected to shift the relative % of catch and profits for US - Canada transboundary stocks under RCP8.5 (but not RCP2.6). Projected decreases in biomass of historically large fisheries US-NA and CA-QC, and US-AK	(Weatherdon et al., 2016; Cheung, 2018; Froehlich et al., 2018; Morley et al., 2018; Greenan et al., 2019b; Steiner et al., 2019; Sumaila et al., 2019; Bryndum-Buchholz et al., 2020; Holsman et al., 2020; Palacios-Abrantes et al., 2020; Reum et al., 2020; Sumaila and Zwaag, 2020; Whitehouse and Aydin, 2020; Wilson et al., 2020)

declined (78%) in South New England and have increased (515%) in the Gulf of Maine due to water temperature changes and differing conservation measures (between 1985 and 2014 for GOM and 1997 and 2014 for Southern New England).	and important subsistence species in CA-WA and CA-BC, while some increases in the North Atlantic; Declines are greater under RCP 8.5 relative to RCP 2.6; in EBS (US-AK) community biomass, catches, and mean body size decreased by 36%, 61%, and 38%, respectively under RCP 8.5 (2100). Climate change causes projected declines in global marine aquaculture production under RCP 8.5 with impacts greater for bivalve than finfish and with significant disparities among regions in direction and magnitude of changes; greatest declines for finfish aquaculture expected in Northern regions (GOA, CA-BC, CA-CQ), and large declines for bivalve production (declines of 20-100%) for Canada. Declines become more probable by 2050-2070.

14.5.4.3 Food and Fibre Adaptation: Cross Cutting Themes

Across food and fibre systems, climate resilience is enhanced through diversifying income and harvest portfolios and increasing local biodiversity and functional redundancy (*high confidence*) (Messier et al., 2019; Rogers et al., 2019; Young et al., 2019; Aquilué et al., 2020; Fisher et al., 2021). Ecosystem-based practices and sustainable intensification (increasing yields while minimizing resource demand and ecosystem impacts) (Cassman and Grassini; Rockström et al., 2021) will help the sector meet food production demands under climate change (*medium confidence*), but effectiveness generally declines and is less certain after 2050 in scenarios without carbon mitigation (*high confidence*) (Bermeo et al., 2014; Gaines et al., 2018; Costello et al., 2020; Free et al., 2020; Holsman et al., 2020). Across the sector, successful adaptation is underpinned by approaches that meaningfully consider the coupled social-ecological networks around food and fibre production and value Indigenous Knowledge (*very high confidence*) (Box 14.1) (FAO, 2018; Steele et al., 2018; Calliari et al.). Integrated modeling, participatory planning and inclusive decision making promote effective and equitable adaptation responses (*very high confidence*) (Figure 14.7, 14.7) (Toledo-Hernández et al., 2017; Eakin et al., 2018; Monterosso and Conde, 2018; Alexander et al., 2019; Hodgson and Halpern, 2019; Holsman et al., 2019; Samhouri et al., 2019; Barbeaux et al., 2020; Hollowed et al., 2020), while a paucity of high resolution and locally tailored climate change information remains a barrier to adaptation (Ekstrom et al., 2015; Donatti et al., 2017; Young et al., 2019).

Figure 14.7: Adaptation in North American food sectors modified from Cottrell et al. (2019).

14.5.4.4 Food and Fibre Adaptation: Agriculture, Livestock, and Forestry

Land management and horticulture approaches that preserve and improve soil structure and organic matter can reduce erosion (*high confidence*) (Section 14.5.1, 3) (Lal et al., 2011; Bisbis et al., 2018), and preserving biodiversity and water, changing planting dates, and double cropping are effective climate adaptation strategies (Bisbis et al., 2018; Hernandez-Ochoa et al., 2018; Monterroso-Rivas et al., 2018; Wolfe et al., 2018). Traditional agriculture inherently includes climate adaptive practices that enhance biodiversity, soil quality and agricultural production (e.g., multiple cultivars, heat-tolerant heritage cattle breeds) (Bermeo et al.; Gomez-Aiza et al., 2017; Ortiz-Colón et al., 2018). Agroecology and agroforestry (Box 14.7) in North America has expanded from (but not replaced) traditional and rural practices in Mexico (Metcalfe et al., 2020a) as a sustainable and climate-resilient alternative to industrial agriculture (Schoeneberger et al., 2017) that increases productivity (by 6-65% depending on the crop), enhances microclimatesand provides co-benefits for GHG mitigation (Abbas et al., 2017; Cardinael et al., 2017; Schoeneberger et al., 2017; Snapp et al., 2021). Irrigation is an effective adaptation strategy in key agricultural areas (Miller, 2017; Lund et al., 2018) and could stabilize food security in rain-fed regions (e.g., southeastern Mexico) (Spring, 2014); water allocation must balance multiple needs and rights (*medium confidence*) (14.5.3) (Brown et al., 2015b; Levis et al., 2018; Gomez Diaz et al., 2019). Heritage livestock breeds, changing species, and precision ranching technology may promote ranch and rangelands resilience (Zhao et al., 2013). In loblolly pine plantations in the southern US, effective adaptation includes reducing tree density and, less effectively, shifting to slash pine (Susaeta et al., 2014). Salvage logging following forest disturbances (e.g., insect outbreaks) can increase timber harvest (Bogdanski et al., 2011; USDA Forst Service, 2011; Han et al., 2018; Morris et al., 2018a).

14.5.4.5 Food and Fibre Adaptation: Fisheries and Aquaculture

Proactive and ecosystem-based management increases climate resilience in fisheries (*high confidence*) but effectiveness after 2050 may be limited without global carbon mitigation (*medium confidence*) (Gaichas et al., 2017; Gaines et al., 2018; Kritzer et al., 2019; Barbeaux et al., 2020; Free et al., 2020; Holsman et al., 2020). Flexibility (e.g., mobility, diverse incomes or harvest portfolios) underpins climate resilience across regions, management policies, and fisheries, although small-scale fisheries have less scope for adaptation (Aguilera et al., 2015; Young et al., 2019). Climate-informed and dynamic management (Hazen et al., 2018) improves modeled fishery performance (*medium confidence*) (see section 14.5.2) (Froehlich et al., 2017; Tommasi et al., 2017a; Tommasi et al., 2017b; Karp et al., 2019; Barbeaux et al., 2020), yet planning and policies that directly incorporate climate change information remain limited (Skern-Mauritzen et al., 2015; Marshall et al., 2019b). Expanding aquaculture across North America will *likely* address deficits in nutritional and protein yields (Gentry et al., 2019; Costello et al., 2020), yet aquaculture initiatives have largely progressed without explicitly considering climate impacts (FAO, 2018; Froehlich et al., 2019) and critical elements for climate adaptation (e.g., climate-informed zoning, monitoring, insurance) are not widely implemented (Liñan-Cabello et al.; FAO, 2018 ; Stewart-Sinclair et al., 2020). Climate-informed and standardized aquaculture governance, and increased coordination with fishery and coastal management, is needed for climate resilience (*high confidence*) (Brugère et al., 2019; Froehlich et al., 2019; Free et al., 2020; Galparsoro et al., 2020).

14.5.5 Cities, Settlements and Infrastructure

Cities are complex social-ecological systems with large populations, concentrated wealth, ageing infrastructure, reliance on extrinsic and increasingly stressed natural systems, social inequality, differential institutional capacities, and impervious, heat-retaining surfaces (Maxwell et al., 2018a; Schell et al., 2020). These factors interact with location (e.g., proximity to coast, in a flood plain) to create city-specific vulnerabilities to climate change and requirements for resilience initiatives (Mercer Clarke et al., 2016). Cities are home to diverse cultural and social communities, including large Indigenous populations, who can be uniquely affected by climate change yet who bring valuable IK and leadership to urban adaptation efforts (Statistics Canada, 2020; Brown et al., 2021). The rural and remote settlements of North America also experience similar hazards and risks, but due to different factors such as geographic isolation, dependence on local food resources, and socioeconomic conditions (Kearney and Bell, 2019; Vodden and Cunsolo, 2021).

14.5.5.1 Observed Impacts

14.5.5.1.1 Rising temperatures and extreme heat

Extreme heat events are affecting natural assets and built infrastructure as well as individuals in cities and rural settlements across North America (*high confidence*) (Maria Raquel et al., 2016; Amec Foster Wheeler Environment and Infrastructure, 2017; Howell and Brady, 2019; Martinich and Crimmins, 2019). Key urban infrastructure systems (e.g., services in buildings, energy distribution) are interdependent and susceptible to cascading impacts (e.g., electricity supply disruption during a heat wave compromising another system like water delivery, high-rise cooling) (Brown et al., 2021). Urban social inequality and systemic racism has led to disproportionately higher exposure to urban heat island effects in low-income and minority neighbourhoods in US cities, due in part, to less green space and tree cover to offset heat retained in the built environment (Hoffman et al., 2020; Schell et al., 2020; Hsu et al., 2021). In the rural context, extreme heat contributes to migration out of small communities (e.g., cases reported in Mexico (Nawrotzki et al., 2015a)). Extreme heat events pose a significant risk to residents of small towns across North America due to limited resources to address heat impacts and attendant increased morbidity and mortality (McDonald et al., 2016; Guo et al., 2018; D'ulisse, 2019) (See 14.5.6.1).

Hot and dry conditions increase risk of wildfires close to human settlements through collateral impacts on properties, economic activity and human health (Box 14.2, 14.5.6.3). These environmental conditions also stress natural assets (e.g., urban forests, wetlands, household gardens, green walls) and performance of green infrastructure leading to higher operation and maintenance costs (*high confidence*) (Kabisch et al., 2017; Terton, 2017).

14.5.5.1.2 Storms and flooding

Short-duration, high-intensity rainfall and other extreme events (e.g., hurricanes, atmospheric river events) create significant flooding risks and impacts for cities in North America and negatively affect the lives, livelihoods, economic activities, infrastructure, and access to services (*high confidence*) (Amec Foster Wheeler Environment and Infrastructure, 2017; Curry et al., 2019). In 2016, US flooding events caused 126 fatalities and US$11B (2016) in damages (NOAA, 2019). In Canada, flooding accounts for 40% of the costs associated with weather-related disasters recorded since 1970 (Canadian Institute for Climate Choices, 2020); the most costly event was the 2013 Calgary flood (*CA-PR*) (CAD$1.8B in catastrophic insurance losses and CAD$6B in direct costs such as uninsured losses) (Office of the Auditor General of Canada, 2016). Mexico City is seasonally impacted by high-intensity rainfall events that generate local flooding (de Alba and Castillo, 2014). Rural and remote settlements are also threatened by floods; Indigenous lands in Canada are disproportionately exposed to flooding, with almost 22 % of residential properties at risk of a 100-year flood (Thistlethwaite et al., 2020a; Yumagulova, 2020).

Wind storms and hurricanes are significant climate hazards for North American cities and settlements, affecting urban forests, electricity distribution and service delivery, and damaging buildings and transportation infrastructure (Amec Foster Wheeler Environment and Infrastructure, 2017; British Columbia Hydro, 2019; Smith, 2020), with enduring impacts on small villages due to lost livelihoods and limited recovery capacity (e.g., Rio Lagartos and Las Coloradas in Mexico (*MX-SE*) after Hurricane Isidore) (Audefroy and Cabrera Sánchez, 2017). The Pacific coast of Mexico is also experiencing hurricanes such as Patricia (Category IV) in 2015 and Newton (Category I) in 2016 (CONAGUA, 2015; CONAGUA, 2016); hurricane Patricia affected 56 municipalities in the states of Colima, Nayarit and Jalisco (*MX-CE, MX-NW*) (Calleja-Reina, 2016).

14.5.5.1.3 Sea level rise

SLR interacts with shoreline erosion, storm surge and wave action, saline intrusion, and coastal flooding to directly threaten coastal cities and small communities in North America with impacts to public and private buildings and infrastructure, port and transportation facilities, water resources (*high confidence*) (NOAA National Weather Service, 2017; Boretti, 2019), and cultural heritage sites (Dawson et al., 2020) (Box 14.4). SLR is creating conditions where considerable financial investments are needed and, in many cases, are being raised to address adaptation needs (Fatorić and Seekamp, 2017; Hinkel et al., 2018; Greenan et al., 2019a) (see Box 14.4, CCP6). Across North America, high population density and concentrated development along the coast generates exposure to SLR impacts.

14.5.5.2 Projected Impacts and Risks

Evidence since the AR5 highlights increased risk to quality of life in cities and rural communities as a result of exposure to intensifying climate change hazards, and the compounding and interacting effects of climate and non-climate factors (*medium confidence*).

14.5.5.2.1 Rising temperatures and extreme heat

Extreme heat events are projected to increase in frequency and intensity across North America in the coming decades (14.2.2, Figure 14.2(F),(G)). Inland urban areas in southern and eastern US are susceptible to urban heat island effects, particularly the Midwest/Great Lakes regions (Krayenhoff et al., 2018) and Mexico City and many other cities in Mexico (Vargas and Magaña, 2020). Climate change (RCP8.5) interacting with urban form, development and systemic racism (Schell et al., 2020; Hsu et al., 2021), could worsen risks from extreme heat in North American cities, especially where there is limited adaptation *(high confidence*) (Krayenhoff et al., 2018). Impacts from extreme heat will be exacerbated when multiple hazards occur simultaneously (e.g., heat waves concurrent with droughts) (Mora et al., 2018; Zscheischler et al., 2018). Extreme heat events increase energy demand for space cooling in buildings, especially during peak demand periods and heat waves (IEA, 2018a). This can decrease cooling efficiency, increase emissions of GHG from electricity generation, increase refrigerant loads and associated emissions, and negatively affect air quality (IEA, 2018a). Major electrical grid failure (i.e., "blackouts") have increased across the US, and will continue to be particularly dangerous for human health when they coincide with extreme heat events (Stone et al., 2021). Efforts to increase resilience of the infrastructure that cities rely on are increasing (Climate-Safe Infrastructure Working Group, 2018)

Warmer and/or drier conditions may reduce water supply reliability for cities and small communities that rely on surface water sources fed by rain or snowmelt runoff (e.g., Victoria and Vancouver, Canada (*CA-BC*) (Metro Vancouver, 2016; Vadeboncoeur, 2016; Islam et al., 2017); San Pedro, Hermosillo and Los Pargas, Aguascalientes, México (*MX-NW, MX-CE*) (Vadeboncoeur, 2016; Soto-Montes-de-Oca and Alfie-Cohen, 2019); New York City, (*US-NE*) (N. Y. C. Department of Environmental Protection, 2014) and Washington State (*US-NW*) (Fosu et al., 2017) (see 14.5.3.2).

14.5.5.2.2 Storms and flooding

Annual and winter precipitation is expected to increase for most of Canada (14.2, Figure 14.2(D), (E)) and will increase flooding in cities and settlements (Bonsal et al., 2019) (*high confidence*). Although there is more geographical variation across the continental US (e.g., between high-latitude and subtropical zones), extreme precipitation events are projected to increase in frequency and intensity with impacts on flood hazards (Easterling et al., 2017) (14.5.3.2). Winter (snow and ice) storms are expected to increase in northern North America and decrease in southern North America under RCP 8.5 (Jeong and Sushama, 2018b). Projected increases in wind-driven rain exposure is an emerging consideration for moisture-resilient design and management of buildings, especially in western and northern Canada (Jeong and Cannon, 2020).

14.5.5.2.3 Sea level rise

In the US, many people are projected to be at risk of flooding from SLR (*high confidence*) (Box 14.4). A projected SLR of 0.9m by 2100 could place 4.2 million people at risk of inundation in US coastal counties, whereas a 1.8-m SLR exposes 13.1 million people (Hauer et al., 2016). In California, under an extreme 2-m SLR by 2100, US$150B (2010) of property or more than 6% of the state's GDP and 600,000 people could be affected by flooding (Barnard et al., 2019). A 1-m SLR would inundate 42% of the Albemarle-Pamlico Peninsula in North Carolina and incur property losses of up to US$14B (2016) (Bhattachan et al., 2018). In nine southeast US states, a 1-m SLR would result in the loss of more than13,000 recorded historical and archaeological sites with over 1,000 eligible for inclusion in the National Register for Historic Places (Anderson et al., 2017). SLR raises groundwater levels by impeding drainage and enhancing runoff during rain events (Hoover et al., 2017); coastal flooding enhances saltwater intrusion affecting drinking water supply in settlements (e.g., coast of Texas) (Anderson and Al-Thani, 2016).

In Canada, SLR is expected to increase the frequency and magnitude of extreme high water-level events (Greenan et al., 2019a) and to create widespread impacts on natural and human systems *(high confidence*) (Lemmen et al., 2016) (Box 14.4). Although coastal sensitivity is high in the Arctic, Canada's more populated regions are also sensitive to the impacts of SLR (Manson et al., 2019). The Mi'kmaq community of Lennox Island First Nation is exploring relocation options because of erosion from SLR (Savard et al., 2016).

In Mexico, crucial coastal tourism cities such as Cancun, Isla Mujeres, Playa del Carmen, Puerto Morelos and Cozumel (*MX-SE*) are at risk of SLR with an estimated economic impact of US$1.4 –2.3B (Ruiz-Ramírez et al., 2019) (14.5.7.1.12). Negative effects of the "coastal squeeze" phenomena (generated by SLR, land subsidence, sediment deficit, and current urbanization processes) have been documented on tourist destinations along the coasts of Mexican Gulf of Mexico and Mexican Caribbean. Zoning, limiting urbanization along the coastline, and using nature-base solutions (Box 14.7) are alternatives that could be applied to improve the adaptation of these destinations (Martínez et al., 2014; Salgado and Luisa Martinez, 2017; Lithgow et al., 2019).

Rural low-lying coastal areas are at risk from SLR where natural barriers or shoreline infrastructure are deteriorating and this interacts with remoteness, resource-dependent economies, and socioeconomic challenges to adaptive capacity (Bhattachan et al., 2018; Manson et al., 2019). The Northeast Atlantic region of North America (*CA-AT, US-NE*) is exposed to high risk by combined effects of land subsidence and climate-driven SLR (Lemmen et al., 2016; Sweet et al., 2017; Fleming et al., 2018; Greenan et al., 2018) (Box 14.4).

14.5.5.3 Adaptation

In North American cities, present-day adaptation responses extend beyond the traditional focus on infrastructure to include measures aimed to protect people, property, and ecosystems (*medium confidence*). Barriers to adaptation include challenges related to the local physical and environmental setting, effects of colonialism and racism, socioeconomic attributes of the population, institutional frameworks, and competing interests of city stakeholders (*medium confidence*). Current scale of adaptation is generally not commensurate with reducing risks from projected climatic hazards, although resources exist that provide guidance and examples of effective adaptation *(medium confidence*). Some remote Canadian communities have demonstrated strengths (e.g., strong social networks) that support resilience to climate change (Kipp et al., 2020; Vodden and Cunsolo, 2021). In some US cities with political resistance to action on climate change, adaptation measures focused on addressing extreme events (rather than climate change impacts) were able to make progress (Hamin et al., 2014). Enhanced public awareness of the risks from extreme events associated with climate change is important for motivating adaptation (Howe et al., 2019) (14.3) and developing a climate change agenda (Aragón-Durand, 2020).

Community-level planning tailors adaptation responses and disaster preparedness to the local context but misalignment of policies within and between levels of government can prevent implementation (Oulahen et al., 2018). Coordination, planning, and national support are needed to provide sufficient financial resources to implement climate-resilient policies and infrastructure (USGCRP, 2018) (see 14.7.3).

Public health measures to address extreme heat events are more common across North America, with a focus on vulnerable populations (e.g., City of Toronto, 2019) and innovative approaches for reaching at-risk populations with an overarching intent of prevention (*medium confidence*) (Guilbault et al., 2016) (14.4.6.1). The heatwave plan for Montreal includes visits to vulnerable populations, cooling shelters, monitoring of heat-related illness, and extended hours for public pools (Lesnikowski et al., 2017); efforts have reduced heat wave-related mortalities (Benmarhnia et al., 2016).

Other adaptation responses to reduce temperature effects include modifying structures (roofs, engineered materials) and the urban landscape through green infrastructure (e.g., urban trees, wetlands, green roofs), which increases climate resilience and quality of life by reducing urban heat effects, while additionally improving air quality, capturing stormwater, and delivering other co-benefits to the community (e.g., access to food, connection to nature, social connectivity) (Ballinas and Barradas, 2016; Emilsson and Sang, 2017; Kabisch et al., 2017; Krayenhoff et al., 2018; Petrovic et al., 2019; Schell et al., 2020) (Box 14.7) (*high confidence*). Green infrastructure can be flexible and cost-effective (Ballinas and Barradas, 2016; Emilsson and Sang, 2017; Kabisch et al., 2017). Initiatives can be “bottom-up” community-led adaptation with support from municipal governments, (e.g., East Harlem, New York City) (Petrovic et al., 2019). Valuing municipal natural assets (e.g., assigning economic value to cooling from urban forests or stormwater retention by urban wetlands) is becoming increasingly common in Canada and the US (Wamsler, 2015; Roberts et al., 2017a; Municipal Natural Assets Initiative, 2018). Guidance assists municipalities to identify, value, and account for natural assets in their financial planning and asset management programs (O'Neil and Cairns, 2017) and consider future climate (Municipal Natural Assets Initiative, 2018).

Meeting increasing demand for indoor space cooling with equitable access, requires new approaches to providing cooling (e.g., equipment efficiencies, refrigerants with lower global warming potential) and electricity production and transmission innovation (Shah et al., 2015; IEA, 2018a). While energy efficiency and building code standards are not directly established by local governments, they can encourage behaviour change via incentives (e.g., rebates on efficient equipment) or disincentives (e.g., more onerous permit approvals).

Experiences with droughts, heat waves and other weather extremes has led many municipal water managers to accept the importance of building resilience to the risks of future water shortages and costs posed by climate change (Metro Vancouver, 2016; Misra et al., 2021; WUCA, 2021). In the US SW, water utilities have introduced demand-management programs to encourage water conservation (e.g., tiered pricing, incentives for water-efficient appliances and fixtures, and rewards for replacing water-guzzling lawns with water-thrifty native vegetation) (Luthy et al., 2020; Baker, 2021) (14.5.3.3). Water providers also have increased their adaptive capacity by diversifying water sources (Hanak et al., 2015).

Adaptation to the risks of wildland-urban interface fire is underway (Kovacs et al., 2020) (Box 14.2) but the scope of adaptation required to sufficiently minimize wildfire risks for cities and settlements across North America has not been assessed (*medium confidence*). Leadership at the local level is increasingly supported by federal resources that provide guidance on hazard and exposure assessment, property protection, community resilience and emergency planning (National Research Council of Canada, 2021).

Cities and settlements in North America can be susceptible to multiple flooding hazards (i.e., coastal SLR, pluvial, fluvial); each presents unique adaptation challenges that can be addressed through structural (e.g., armouring coastlines, reservoirs, levees, floodgates; New York City commuter tunnels) and non-structural approaches (e.g., land use planning and zoning, expanding green infrastructure; Chetumal, Mexico) (Hardoy et al., 2014) (*high confidence*). Green infrastructure practices (Box 14.7) (e.g., open space preservation, floodplain restoration, urban forestry, de-channelization of streams) can reduce urban flooding, erosion, and harmful runoff (Kovacs et al., 2014; Angel et al., 2018b; Government of Canada, 2021c). Structural approaches have limitations and require trade-offs that could be addressed with a focus on socio-ecological solutions and stronger institutional coordination (e.g., flood risk management in Mexico City) (Aragón-Durand, 2020). In response to high intensity rainfall events, Mexico City invested in stormwater infrastructure, although additional benefits could have been realized if water supply needs had been incorporated (de Alba and Castillo, 2014). Some programs exist to facilitate stormwater and wastewater infrastructure updating to accommodate increased precipitation across North America. The US federal Clean Water State Revolving Fund, provides low-interest loans for states to upgrade infrastructure for climate change, with US$42B provided since 1987 (ASCE, 2019). In Canada, local governments are important leaders in managing engineered and green infrastructure decisions, incentivizing property-level flood protection, and ensuring service delivery (Government of Canada, 2021c). The civil engineering profession is playing an active role in facilitating an understanding of risks and prioritization of adaptation investments in communities (Tye and Giovannettone, 2021).The high concentration of valuable assets in cities requires mechanisms to facilitate replacement of assets including use of existing and proposed insurance mechanisms (14.7) *(medium confidence*).

Adaptation planning and implementation to address SLR and coastal flooding has been initiated across cities and settlements in North America but varies in preparedness (*high confidence*) (Box 14.4). Efforts are supported by SLR design guidelines. In Canada, the Government of British Columbia provided SLR projections for 2050 (i.e., +0.5m) and 2100 (i.e., +1m) in order to initiate community vulnerability and risk assessment, and adaptation planning (The Arlington Group Planning + Architecture Inc et al., 2013). Based on recent hurricane impacts in Yucatan, Mexico, recommendations to enhance the rules governing the Mexican Recovery Program included incorporating local and Indigenous knowledge when rebuilding houses and other structures on coasts (Audefroy and Cabrera Sánchez, 2017). Where adaptation in-place is insufficient, planned retreat is being considered as an sustainable option for reducing future risks (Saunders-Hastings et al., 2020).

[START BOX 14.4 HERE]

Box 14.4: Sea Level Rise Risks and Adaptation Responses for Selected North American Cities and Settlements

Approximately 95 million Americans lived in coastal communities in 2017 (US Census Bureau, 2019) and in 2013, Canada had roughly 6.5 million coastal residents (Lemmen et al., 2016), while Mexico had 19 million people living in coastal municipalities in 2015 (Azuz-Adeath et al., 2018). Sea level rise around North American coastlines (Figure Box14.4.1) is projected to be greatest along the coasts of Atlantic Canada, northern Gulf of Mexico for the US, and the Pacific coast of Mexico (IPCC, In Press). Sections 14.5.2.1, 14.5.5.1.3, 14.5.5.2.3 describe SLR impacts. Status of adaptation to SLR by local governments is variable (see Table Box 14.4.1, where progress is indicated by colour coding) and ranges from financed implementation to preliminary/preparatory/scoping studies and workshops. Adaptation planning and implementation to address SLR and coastal flooding have been initiated across many cities and settlements in North America but preparedness varies (*high confidence*).

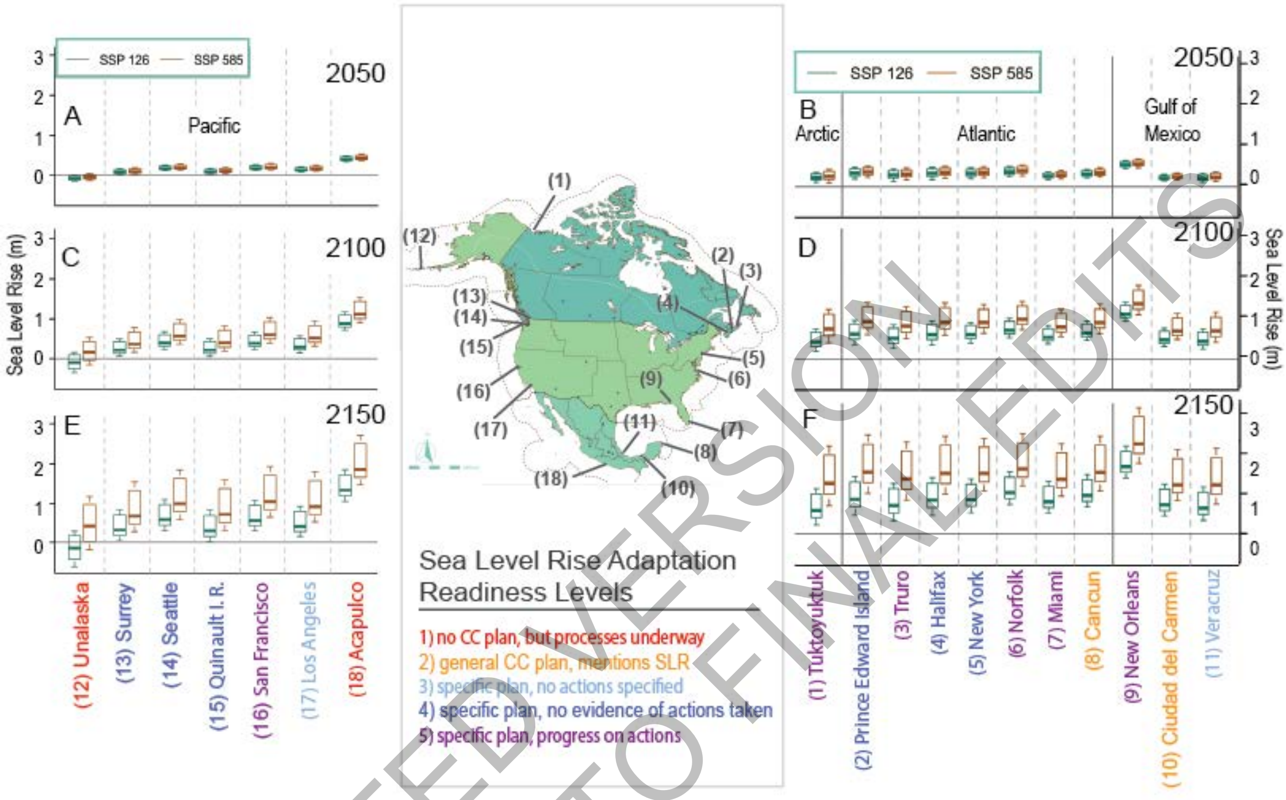


Figure Box 14.4.1: Sea Level Rise (SLR) projections for 2050, 2100 and 2150 for selected North American cities. Projections changes are relative to 2005, which is the central year for the 1994-2014 reference period. Horizontal lines in the boxes represent the median projection, boxes represent 25th to 75th percentile and whiskers the 10th to 90th percentile of SLR projections from all CMIP6 models as well as other lines of evidence (see Table 9.7 in WGI.9 for more details). Two SLR scenarios are provided for lower (SSP 126) and higher emissions (SSP 585), and are consistent with WGI AR6 Interactive Atlas. Numbers and colors (see Table Box14.4.1 for detailed readiness definitions) on the map and in the projections represent sites and status of SLR adaptation progress. Information supporting SLR adaptation status is summarized in Table Box14.4.1.

Table Box14.4.1. Status of adaptation actions associated with locations on SLR map, colour-coded according to level of SLR preparedness through Adaptation (as discoverable on government websites): No climate change adaptation action plan but processes underway such as workshops, studies, vulnerability assessments (red), General Climate Change Adaptation Action Plan which mentions SLR as a risk/issue/impact but no concrete actions developed (orange), Specific Plan for SLR but does not include specific actions (light blue), Specific Plan for SLR with concrete actions identified but no evidence of actions taken to date (med blue), and Specific Plan for SLR with evidence of progress on taking actions including allocating funding for projects (purple).

Ocean Basin	Site #	Area/City	Exposure (not exhaustive)	Does the area/city have an Adaptation Plan for SLR? If so, are they taking actions to implement it? (Status)
Arctic	1	Tuktoyuktuk, CA	Infrastructure, municipal services, transportation, homes, 900 people	Tuktoyaktuk Coastal Erosion Study completed March 2019. Additional investments in both planning and actual adaptation measures have occurred. Limited financial resources remain a barrier. (Government of Canada, 2020)

Atlantic	2	Prince Edward Island with Lennox Island, CA	PEI: residential, industrial and commercial infrastructure. Lennox Island: 10 out of 79 homes, causeway to the island, sacred grounds, sewage treatment systems	Prince Edward Island government released a five year climate change action plan in 2018 which includes both adaptation and mitigation (Prince Edward Island Government, 2018). Biennial progress reports were issued (Prince Edward Island Government, 2019). The Mi'kmaq community of Lennox Island First Nation has explored relocation options (Daigle et al., 2015).
	3	Truro, CA	A regional centre of 12,000 residents, which has been vulnerable to repeated floods for decades.	Town of Truro, County of Colchester and Millbrook First Nations commissioned a flood risk study 2014–2017 (CBCL, 2017; Sherren et al., 2019) triggered by the 2012 flooding. Outcome was Truro-Onslow dyke project -- a voluntary retreat with realignment of dyke infrastructure and habitat restoration by conversion of agricultural land into salt marsh habitat (Saunders-Hastings et al., 2020).
	4	Halifax, CA	Transportation causeways and bridges, marine facilities, municipal infrastructure.	HalifACT 2050 is a comprehensive plan adopted as of 2020 by the Halifax regional council which includes reducing GHGs and adapting to climate change including a coastal preparedness section 5.2.9. (Halifax Regional Council, 2020)
	5	New York, US	20 million people at risk by 2050; 40% of water treatment plans will be compromised by flooding, 60% of power plants will need to be relocated, transportation systems will need to be upgraded to avoid flooding	New York City has developed many adaptation plans for sustaining NYC in light of SLR and other climate hazards/impacts, especially since Hurricane Sandy affected the city in 2012. It is unclear how much of the planning has moved forward into implementation (NYC, 2013; New York City, 2015; NYC Mayor's Office of Resiliency, 2020).
	6	Norfolk, US	Homes, massive US naval base, shipyards, active waterfront, and deep water ports	City of Norfolk published a very specific Coastal Resilience Strategy in 2014. Capital improvement projects highlighted in this strategy have been funded (City of Norfolk Virginia, 2014). Plan for protecting Naval base and shipyard not evident.
	7	Miami, US	Homes, port, transportation infrastructure, tourism (hotels, restaurants, beaches)	Miami Dade County released a specific SLR Strategy in 2021. Actions in the plan include elevating roads and other infrastructure, designing ways to accommodate more water in and around buildings, building on higher ground and expanding waterfront parks and canals. The plan includes a map with current and planned adaptation projects in the county (Miami-Dade County, 2021).
	8	Cancun, MX	Tourism infrastructure (hotels, restaurants, beaches), homes, markets, service industry, transportation.	2013 Climate Change plan assigns adaptation in general to different government levels. No evidence of specific adaptation plan for SLR (Government of Quintana Roo, 2013)
Gulf of Mexico	9	New Orleans, US	Entire city, especially low-lying, low-income areas, is vulnerable as evidenced by Hurricane Katrina in 2005.	City of New Orleans adaptation is incorporated in the broader Louisiana coastal climate change adaptation plan (CPRA, 2023). The process includes very specific projects with updates on risk based implementation.
	10	Ciudad del Carmen, MX	Freshwater access, 11,000 homes, aquaculture	The Campeche State Climate Change plan was released in 2013 (Government of Campeche, 2013). The plan does not include any specific recommended actions to adapt to SLR in Cuidad del Carmen. Flood risk maps for Ciudad del Carmen were created in 2011 (Audefroy, 2019).

	11	Veracruz, MX	Freshwater access, sewage treatment systems, electrical and petrochemical industries	State of Veracruz published a Climate Change plan in 2008 (Government of Veracruz, 2008). Plan includes specific tables of actions needed to monitor and adapt to SLR. World Bank funded coastal adaptation in Veracruz focused on mangroves to dissipate storm surge but no investments in infrastructure to mitigate SLR.
Pacific	12	Unalaska, US	Loss of cultural resources, salinization of rivers/lakes,	Climate Change Adaptation and Vulnerability Assessment Workshops have been held with discussion of coastal erosion. SLR not viewed as important as impacts from sea ice and permafrost loss (Poe et al., 2016).
	13	Surrey (Greater Vancouver Area),CA	Disruption in flow of goods in/out of Port of Vancouver, communication facilities, road, rail and air transportation infrastructure, businesses and agriculture.	Surrey has a Coastal Flood Adaptation Strategy (CFAS) approved by Council (City of Surrey, 2019) with 46 actions (policy and program, local area infrastructure). Some local area infrastructure improvements received capital funding.
	14	Seattle, US	Low-lying areas, near-shore habitats, stormwater drains, roads, homes, businesses, socially vulnerable communities.	Seattle released a Climate Change Response Plan in 2017 which includes general approaches including development of risk maps for SLR which are also available online (City of Seattle, 2017).
	15	Quinault Indian Reservation (Tahola), US	650 residents and buildings.	Quinault Indian Reservation has a plan to move Tahola to higher ground, one half mile from the existing village (EPA, 2021).
	16	San Francisco, US	37,200 residents, 17,200 businesses and 167,300 jobs are vulnerable to inundation by 2100 at upper bounds of SLR, mostly along the bay side of the city.	SF has an active, SLR planning process as well as an iterative Sea Level Rise Action Plan (City of San Francisco, 2016), planning tools and iterative assessment (City and County of San Francisco, 2020).The process specifically addresses wastewater, water, transportation, power, public safety, open space, port, neighborhoods and changing shoreline.
	17	Los Angeles, US	Power plants, wastewater treatment plants, Port of Los Angeles, beaches, tourism	Los Angeles has commissioned a projected SLR impact report but not an action plan. The Port of Los Angeles is particularly vulnerable and, as of 2019, has a SLR Adaptation Plan (Newbold et al., 2019).
	18	Acapulco, MX	Tourism infrastructure (hotels, restaurants beaches), homes, markets, service industry, transportation.	No climate change plan exists although the Mexican Tourism Sector conducted a climate change vulnerability assessment covering Acapulco (Guerrero, 2017).

[END BOX 14.4 HERE]

14.5.6 Health and Wellbeing

Research examining climate change impacts on human health in North America has increased substantially since AR5 (Harper et al., 2021a). Using a systematic approach (Harper et al., 2021b), the assessment focused on advancements since AR5.

14.5.6.1 Heat-Related Mortality and Morbidity

High temperatures currently increase mortality and morbidity in North America (*very high confidence*), with impacts that vary by age, gender, location, and socioeconomic factors (*very high confidence*). Observed increases in heat-related mortality have been attributed to climate change in North America (Vicedo-Cabrera et al., 2021). Temperature effects on health vary based on how unusual the temperature is for that time and location (*medium evidence, high agreement*), highlighting the important role that temperature extremes and variability play in mortality and morbidity (Li et al., 2013; Lee et al., 2014; Barreca et al., 2016; Allen and Sheridan, 2018). Adaptation has played an important role in reducing observed heat-related deaths (Vicedo-Cabrera et al., 2018b).

Rising temperatures are projected to increase heat-related mortality across emission scenarios this century in North America (*very high confidence*), although the magnitude of increase varies geographically (Isaksen et al., 2014; Petkova et al., 2014; Wu et al., 2014; Weinberger et al., 2017; Anderson et al., 2018a; Limaye et al., 2018; Marsha et al., 2018; Morefield et al., 2018). The elderly (Isaksen et al., 2014; Limaye et al., 2018) and urban areas (Limaye et al., 2018) are projected to experience the greatest increase in heat-related mortality this century. Warming temperatures are also projected to increase heat-related morbidity (*medium confidence*). For instance, the incidence and treatment costs of asthma attributed to warmer temperatures are projected to increase in Texas by 2040-2050 (A1B) (McDonald et al., 2015).

While heat-related mortality is projected to increase across emissions scenarios and shared socio-economic pathways, fewer deaths are projected under both lower emissions scenarios and higher adaptation scenarios in North America (*very high confidence*). Heat-related mortality was projected to be 50% less under RCP4.5 compared to RCP8.5 in the US for SSP3 and SSP5 (Wu et al., 2014; Marsha et al., 2018) (Table 14.5).

Table 14.5: A summary of adaptation options for different health outcomes in North America.

Health outcome	Adaptation Options
Heat-related mortality and morbidity	Future temperature-related health impacts can be reduced by adaptation measures (Petkova et al., 2014; Wu et al., 2014; Mills et al., 2015b; Kingsley et al., 2016; Anderson et al., 2018b; Marsha et al., 2018; Morefield et al., 2018), including more effective warning and response systems and building designs, enhanced pollution controls, urban planning strategies, and resilient health infrastructure (*very high confidence*) (Figure Box 14.7.1).
Wildfire-relate mortality	Air quality indices are correlated with many respiratory conditions (Yao et al., 2013; Hutchinson et al., 2018), suggesting that providing air quality information to the public could reduce smoke-related health impacts (Yao et al., 2013; Rappold et al., 2017). Enhanced coordination between the health sector and fire suppression agencies can also reduce the health impacts of wildfire smoke via improving communication, weather forecasting, mapping, fire shelters, and coordinated decision making (Withen, 2015), including transnational and cross-jurisdictional actions.
Vectorborne disease	Prevention of vectorborne disease currently involves surveillance, reducing environmental risks, and promoting individual behaviours to reduce human-vector contact. Top ranked Canadian West Nile interventions include individual protection (i.e., window screens, wearing lightly coloured clothing), and regional management and mosquito-targeting interventions (i.e., larvicides, vaccination of animal reservoirs, modification of human-made larval sites) (Hongoh et al., 2016).
Waterborne disease	Climate change is projected to increase waterborne disease risks (*medium confidence*), particularly in areas with aging water and wastewater infrastructure in North America (*high confidence*). In Wisconsin, US, precipitation changes are projected to increase gastrointestinal illness in children this century (A1B, A2, B1) (Uejio et al., 2017). Slight reductions in precipitation-associated gastrointestinal illness is projected if water treatment infrastructure is upgraded slowly over time; however, if water treatment infrastructure is installed more rapidly, large decreases in precipitation-associated gastrointestinal illness incidence are projected (Uejio et al., 2017), highlighting the benefits of rapidly implementing adaptation actions.
Foodborne disease	Food safety programs play important roles in reducing the risk of climate-related foodborne disease (*high confidence*). Integrated health surveillance, more stringent refrigeration temperature controls to limit pathogen growth, targeted communication to public and food sector, and enhanced coordination between health and food sectors can reduce risk (Hueffer et al., 2013; Jones et al., 2013; Fillion et al., 2014; Doyle et al.,

	2015). In Mexico, the projected risk of Vibrio parahaemolyticus in oysters was 11 times higher in a high emissions scenario compared to a low emissions scenario by the end of the century; however, this risk could be substantially lowered with adaptation measures, including improving temperature control (Ortiz-Jiménez, 2018).
Mental health	Effectiveness of individual and/or group therapy, and place-specific mental health infrastructure, to treat mental health challenges is well-proven; yet, there is limited evidence evaluating these interventions within the context of climate change (e.g. Tschakert et al., 2017; Young et al., 2017b; Cunsolo and Ellis, 2018).

14.5.6.2 Cold-Related Mortality

Winter season mortality rates are generally high in high income regions such as North America, with most of that mortality due to cardiovascular diseases (Ebi and Mills, 2013). It is important to differentiate between mortality related to cold temperatures and mortality due to other factors that vary with season (Ebi and Mills, 2013; Ebi, 2015). Warmer temperatures do not always equate to lower winter mortality: many cold-related deaths do not occur during the coldest times of year or in the coldest places (*high confidence*) but occur during the beginning or end of the winter season (Barnett et al., 2012; Lee et al., 2014; Schwartz et al., 2015; Sarofim et al., 2016b; Smith and Sheridan, 2019). Warmer US cities generally experience more mortality from extreme cold events and cold temperatures than colder cities in the US and Canada (Lee et al., 2014; Gasparrini et al., 2015; Schwartz et al., 2015; Wang et al., 2016; Smith and Sheridan, 2019). While mortality rates linked to direct cold-exposure (e.g. hypothermia, falls, and fractures) is generally low, the relatively higher mortality during milder temperatures is thought to be largely due to respiratory infections and cardiovascular impacts (Lee et al., 2014; Gasparrini et al., 2015), which, although correlate with temperature, may not be caused by cold temperatures (Ebi and Mills, 2013; Ebi, 2015; Sarofim et al., 2016a). When separating the effects of cold temperatures from the effects of the winter season, one study found cold temperature did not drive mortality and suggested that winter season excess mortality was due to seasonal factors other than temperature (e.g. influenza, seasonal gatherings) (Kinney et al., 2015).

Mortality attributed to cold temperatures has increased in the US and remained stable in Canada from 1985-2012 despite increasing winter temperatures (Vicedo-Cabrera et al., 2018b). Some attenuation in cold-related mortality in Mexico and warmer US states is projected under climate change, but less so in colder climates in north-eastern US and Canada, with statistically insignificant trends in some regions and increasing cold-related mortality in other regions (Li et al., 2013; Mills et al., 2015b; Schwartz et al., 2015; Sarofim et al., 2016a; Wang et al., 2016; Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018a; Lee et al., 2019). These reductions in cold-mortality are generally considered relatively small.

Observed and projected trends in winter mortality highlight that non-climate factors may have a greater role in driving winter mortality than cold temperature, and that these deaths are expected to occur with or without climate change (Ebi and Mills, 2013; Ebi, 2015; Sarofim et al., 2016a). This challenges the assumption that warmer winters due to climate change would dramatically lower winter season mortality (*medium evidence, medium agreement*).

14.5.6.3 Wildfire-Related Morbidity

Smoke from intensified wildfire activity in North America is associated with respiratory distress (*very high confidence*), and persists long distances from the wildfire and beyond the initial high-exposure time period (Hutchinson et al., 2018)(Box 14.2). Exposure to wildfire smoke increases hospital admissions (McLean et al., 2015; Alman et al., 2016; Reid et al., 2016; Yao et al., 2016; Rojas-Downing et al., 2017). Increased wildfire smoke from climate change is projected to result in more respiratory hospital admissions in the Western US by 2046-2051 (A1B) (Liu et al., 2016; Rojas-Downing et al., 2017).

The magnitude of health risks varies by age (Le et al., 2014; Reid et al., 2016; Liu et al., 2017a; Liu et al., 2017b), gender (Delfino et al., 2009; Rojas-Downing et al., 2017), socio-economic conditions (Henderson et al., 2011; Rappold et al., 2012; Reid et al., 2016), and underlying medical conditions (Liu et al., 2015). The intersectionality of these subgroups plays an important role in health-related vulnerability to wildfire smoke.

Among the elderly in the western US, risks of respiratory admissions from wildfire smoke was significantly higher for African American women in lower-education counties (Liu et al., 2017b). For Indigenous Peoples, medical visits for respiratory distress, heart disease, and headaches increased during a wildfire in California (Lee et al., 2009). In Northern Canada, Indigenous livelihoods were disrupted during a wildfire, which negatively impacted mental, emotional, and physical health (Dodd et al., 2018a; Howard et al., 2021).

14.5.6.4 Vectorborne Disease

Climate change creates conditions that enable earlier seasonal activity and general northern expansion of ticks (Ogden et al., 2014), increasing human exposure to tickborne diseases in North America (*very high confidence*). Lyme disease incidence and geographic extent has already increased in Canada and the US (Eisen et al., 2016), which has been associated with climate change (Ogden et al., 2014), including warmer temperature (Cheng et al., 2017; Lin et al., 2019). Climate change is projected to increase disease spread into new geographic regions, lengthen the season of disease transmission, and increase tickborne disease risk in North America across emissions scenarios throughout this century (*very high confidence*), with regional variability (Roy-Dufresne et al., 2013; Feria-Arroyo et al., 2014; Monaghan et al., 2015; Robinson et al., 2015; McPherson et al., 2017). Chagas disease is transmitted by triatomines, and most of the Mexican population (88.9%) already reside in areas with at least one infected vector species in both rural and urban populations (Carmona-Castro et al., 2018). Chagas has already extended its range into the southern US, and the triatomines' niche is projected to expand northward this century (Garza et al., 2014; Carmona-Castro et al., 2018) in both rural and urban areas (Carmona-Castro et al., 2018).

Climate change is projected to impact the distribution, abundance, and infection rates of mosquitoes in North America (*high confidence*), which will increase risk of mosquito-borne diseases including West Nile Virus, chikungunya, and dengue (*medium confidence*). The geographic distribution of West Nile virus is projected to expand in North America this century (A1B) (Harrigan et al., 2014). In the US and Canada, mosquitoes are projected to emerge earlier in the year and remain active longer into the fall; however, mosquito population dynamics vary by location with northern locations projected to have an increased vector abundance, and currently hot areas may become too hot, thus negatively affecting mosquito survival (A2, A1B, B1) (Chen et al., 2013; Morin and Comrie, 2013; Brown et al., 2015a).

Local transmission of chikungunya virus has emerged in Mexico and the US since AR5, and areas suitable for transmission are projected to expand (RCP4.5, RCP8.5) (Tjaden et al., 2017). Although chikungunya virus is not currently in Canada, climate change is projected to make southern British Columbia suitable for virus transmission this century, particularly under RCP8.5 (Ng et al., 2017).

The dengue mosquito vector is well-established in Mexico and southeastern US. In northwestern Mexico, incidence of dengue cases is associated with minimum monthly temperature (Diaz-Castro et al., 2017), and the geographic range of the vector in the US is restricted, in part, by low temperatures. Thus, a northward range expansion is projected; however, future dengue risk also depends on built environments and competition with other mosquito species (Colón-González et al., 2013a; Eisen and Moore, 2013). Climate change is projected to increase the geographic range and extend the seasonal activity of the dengue vector in the southern US by 2045-2065 (A1B); however, transmission is projected to be limited by low winter temperatures in the mainland US, potentially preventing its permanent establishment (Butterworth et al., 2017). In Mexico, increased dengue cases are projected this century (A1B, A2, B1) (Colón-González et al., 2013b).

14.5.6.5 Waterborne Disease

Heavy precipitation events are associated with contaminated drinking water and waterborne disease in North America (*high confidence*). Acute gastrointestinal illnesses increase with many hydro-climatological variables, including precipitation, streamflow, and snowmelt (Harper et al., 2011; Wade et al., 2014; Galway et al., 2015). Extreme precipitation is associated with *Campylobacter* and *Salmonella* infections in the US, particularly in counties characterized by farms and private well water (Soneja et al., 2016). In Canada, human *Giardia* infections are associated with increased temperature, precipitation, pathogen presence in livestock manure, and river water level and flow (Brunn et al., 2019). Land-use patterns and aquafer-types are associated with waterborne disease, and ecological zones with higher waterborne rates are projected to expand in range by 2080 in Canada (Brubacher et al., 2020).

In North America, stormwater and water treatment infrastructure play important roles in reducing waterborne disease risk during precipitation events (*high confidence*). In the US, heavy precipitation events are associated with higher rates of childhood gastrointestinal illness in municipalities with untreated drinking water, but not in municipalities with treated drinking water (Uejio et al., 2014). In Mexico, disparities in access to treated water are a key determinant of under age-5 morbidity (Jiménez-Moleón and Gómez-Albores, 2011; Romero-Lankao et al., 2014a). In remote communities in Alaska and Northern Canada, challenges in water service provision and maintenance can increase risk of waterborne disease during high impact weather events (Harper et al., 2011; Bressler and Hennessy, 2018; Harper et al., 2020). In older sections of many North American cities sewage treatment plant capacity is exceeded by overflow of combined sanitary and storm sewer systems during heavy precipitation events, resulting in bypass of untreated and microbiologically contaminated wastewater discharge into drinking water sources (Jagai et al., 2017; Olds et al., 2018; Staley et al., 2018). These sewer overflow events are associated with increased gastrointestinal illness across age groups (Jagai et al., 2017).

14.5.6.6 Foodborne Disease

Warmer air temperature, changes in precipitation, extreme weather events, and ocean warming can increase microbial pathogen loads in food (*very high confidence*). Indeed, temperature and extreme weather are top factors influencing food safety in Canada (Charlebois and Summan, 2015). Outbreaks of *Vibrio parahaemolyticus* have been associated with the consumption of raw oysters harvested from higher-than-usual ocean temperatures in Canada and Alaska (McLaughlin et al., 2005; Taylor et al., 2018). Warmer air temperature increases *Campylobacter*, *Salmonella*, and *E. coli* prevalence in Canadian meat products (Smith et al., 2019), higher microbial load in American produce (Ward et al., 2015), and increased *Campylobacter* spp., pathogenic *E. coli*, and *Salmonella* spp. infections in humans (Akil et al., 2014; Valcour et al., 2016; Uejio, 2017).

Climate change is projected to increase food safety risks (*medium confidence*); however, the actual burden of foodborne disease will depend on the efficacy of public health interventions (*high confidence*). Increased ciguatera fish poisoning is associated with increased SSTs and tropical storm frequency, and this risk is projected to increase this century (Gingold et al., 2014). *Campylobacter* infection in humans due to food contamination from flies is projected to increase this century in Canada (Cousins et al., 2019), and increased housefly populations are projected this century in Mexico (Meraz Jimenez et al., 2019). Climate change may also lead to new emerging foodborne disease risks. For instance, *V. cholerae* is a pathogen previously restricted to tropical regions; however, due to warming ocean temperatures, its detection has significantly increased along Canadian coasts (Banerjee et al., 2018).

Climate change is projected to increase human foodborne exposure to chemical contaminants (*medium confidence*). Increases in SST have been associated with greater accumulation of mercury in seafood, marine mammals, and fish (Ziska et al., 2016). This particularly increases food safety risks in the Arctic, with methylmercury and polychlorinated biphenyl (PCB) concentrations in high trophic animals projected to increase under high emission scenarios by 2100 (Alava et al., 2017; Alava et al., 2018).

Climate-related foodborne disease risks vary temporally, and are influenced, in part, by food availability, accessibility, preparation, and preferences (*medium confidence*). For example, seafood risks are more pronounced in coastal regions due to high seafood consumption (Radke et al., 2015). In Alaska and Northern Canada, where locally harvested foods are critical to diet, climate change may introduce new pathogens to local food sources through wildlife range changes, warming temperatures affecting safe fermentation and drying preparation methods, and food temperature control in belowground cold storage in or near permafrost (King and Furgal, 2014; Harper et al., 2015; Rapinski et al., 2018).

14.5.6.7 Nutrition

Agricultural productivity declines due to climate change (14.5.4) are projected to lower caloric availability and increase the prevalence of underweight people and climate-related deaths in North America by 2050

(IMPAACT) (Springmann et al., 2016a; Springmann et al., 2016b; Springmann et al., 2018); however, this lower caloric availability could also reduce obesity, which could result in deaths avoided (Springmann et al., 2016a; Springmann et al., 2016b). The climate-related deaths per capita due to reduced fruit and vegetable consumption is projected to exceed the mortality due to reduced caloric intake in North America by 2050, particularly in Canada and US (Springmann et al., 2016a; Springmann et al., 2016b). These climate change projections underscore the importance of focusing on nutritional security in North America, instead of only considering caloric intake.

Shifting to a more sustainable diet can have adaptation and mitigation co-benefits while simultaneously improving health outcomes for North Americans. Transitioning to more plant-based diets is projected to reduce climate-related deaths in Canada, US, and Mexico by 2050 (Springmann et al., 2016a; Springmann et al., 2016b), while simultaneously reducing food-related GHG emissions per capita in North America by 2050 (Springmann et al., 2018).

Nutrition impacts will not be experienced uniformly within countries (Shannon et al., 2015; Zeuli et al., 2018). In Alaska and Canada, Indigenous knowledge has documented how climate change has already impacted locally harvested foods and challenged nutrition security (Lynn et al., 2013; Petrasek MacDonald et al., 2013; Harper et al., 2015; Hupp et al., 2015; Bunce et al., 2016) (CCP6). For First Nations coastal communities in western Canada, decreased access to traditionally harvested seafood is projected to reduce nutritional status by 2050 (RCP2.5, RCP8.5), with higher nutritional impacts for men and older adults (Marushka et al., 2019). Substitution of seafood with non-traditional foods (i.e., chicken, canned tuna) would not replace the projected nutrients lost (Marushka et al., 2019), challenging assumptions that market food substitutions could be effective adaptation strategies for Indigenous Peoples.

14.5.6.8 Mental Health and Wellness

Climate change has had, and will continue to have, negative impacts on mental health in North America (*high confidence*) (Figure 14.8). Climate change impacts mental health through multiple direct and indirect pathways stemming from extreme weather events, slower, cumulative events, and vicarious or anticipatory events (Cunsolo Willox et al., 2013; Cunsolo Willox et al., 2014; Durkalec et al., 2015; Yusa et al., 2015; Schwartz et al., 2017; Trombley et al., 2017; Burke et al., 2018b; Cunsolo and Ellis, 2018; Dodd et al., 2018b; Hayes et al., 2018; Middleton et al., 2020b). Climate change disruptions to infrastructure, underlying determinants of health, and changing place attachment are also stressors on mental health (Vida et al., 2012; Cunsolo Willox et al., 2013; Burke et al., 2018b; Obradovich et al., 2018).

In North America, climate change has been linked to strong emotional reactions; depression and generalized anxiety; ecological grief and loss; increased drug and alcohol usage, family stress, and domestic violence; increased suicide and suicide ideation; and loss of cultural knowledge, and place-based identities and connections (Cunsolo Willox et al., 2013; Durkalec et al., 2015; Harper et al., 2015; Fernández-Arteaga et al., 2016; Schwartz et al., 2017; Trombley et al., 2017; Burke et al., 2018b; Cunsolo and Ellis, 2018; Clayton, 2020; Dumont et al., 2020).

Suicide is projected to increase in Mexico and the US by 2050 due to rising temperatures (RCP8.5) (Burke et al., 2018b) (*limited evidence*). Literature on climate change and mental health in North America is increasing; however, few population-level quantitative studies exist, although are increasing (e.g. Burke et al., 2018b; Kim et al., 2019; Dumont et al., 2020; Middleton et al., 2021).

Figure 14.8: Pathways through which climate change impacts mental health risk in North America.

14.5.7 Tourism and Recreation

Tourism is one of the largest and fastest growing industries in North America, contributing USD$2.5 trillion to North Americas' GDP in 2019 (WTTC, 2018; Duro and Turrión-Prats, 2019). The US is the world's largest tourism economy (USD$1839 billion contribution to global GDP in 2019), Mexico is ranked 9th (USD$196 billion) and Canada 13th (USD$108 billion) (WTTC, 2018). The tourism industry is both impacted by climate change and significantly contributes to it through the emission of GHGs from travel and activities (Becken and Hay, 2007). By 2060 under RCP8.5 Canada and the US are projected to benefit from climate-induced changes in tourism expenditures of up to 92% and 21% respectively, whereas Mexico could experience a 25% decrease (OECD, 2015; Scott et al., 2019a).

14.5.7.1 Observed Impacts and Projected Risks of Climate Change

14.5.7.1.1 Alpine and Nordic skiing, snowmobiling and other winter sports

Winter tourism activities with hard limits to adaptation, particularly those that occur at sea level where less precipitation is expected to fall as snow (i.e., Nordic skiing, snowmobiling, snowshoeing), are at the highest risk from climate change and may experience irreversible impacts well before 2°C of warming above pre-industrial levels (*high confidence*) (Figure 14.9). During record warm winters, alpine ski resorts in eastern Canada experienced reductions in ski season lengths of between 11 and 17 days (Rutty et al., 2017) and resorts in the US Northeast (*US-NE*) experienced decreased skier visits by 11.6% and reductions in operational profits of 33% amounting to US$40-52 million (Dawson et al., 2009). Even with advanced snowmaking as an adaptation to warmer temperatures, average ski season lengths are projected to decrease 8% (RCP2.6, 2050s) to 73% (RCP8.5, 2080s) in Ontario, Canada (*CA-ON*) (Scott et al., 2019b), 12% (RCP4.5, 2050s) to 22% (RCP8.5, 2080s) in Quebec, Canada (*CA-QC*), and 13% (RCP 4.5, 2050s) to 45% (RCP 8.5, 2080s) in the US Northeast (*US-NE*) (Wobus et al., 2017; Scott et al., 2020). Season length for snowmobiling and cross-country skiing is projected to decrease more dramatically (*high confidence*) by from 80% (RCP4.5) to 100% (RCP 8.5) by mid-century (Wobus et al., 2017) (also see CCP5). The number of outdoor skating-days may decrease by 34% in Toronto and Montreal and 19% in Calgary by 2090 under RCP8.5 (Robertson et al., 2015). The skating season length for the Rideau Canal in Ottawa, Canada, a UNESCO heritage site attracting 1.3 million visitors annually, may decrease by 3.8±2.0 days per decade with later opening dates of 2.6±1.5 days per decade (Jahanandish and Alireza, 2019).

14.5.7.1.2 Beach, coral reef, and protected areas tourism

Sea level rise, increased storm surge, wave action, algae blooms, extreme air temperatures, and changes in wind and precipitation patterns threaten coastal tourism infrastructure, submerge beaches, erode walking paths on coasts, and impact destination attractiveness, tourism demand, and recreation economies (*very high confidence*). Warm weather tourism activities, including beach tourism, snorkelling, and national park visitation will have more time to implement adaptation strategies to reduce climate risks as significant and widespread impacts are not expected until 3 to 4°C of warming (Fig 14.9) (Rutty and Scott, 2015; Atzori et al., 2018; Santos-Lacueva et al., 2018; Duro and Turrión-Prats, 2019). Thirty percent of hotels along the Gulf of Mexico and Caribbean Sea are exposed to flooding and 66% are located on eroding beaches (Lithgow et al., 2019). Coral reef cover in Akumal Bay, Mexico decreased by 79% between 2011 and 2014 (Gil et al., 2015; Manuel-navarrete and Pelling, 2015). The recreation value of coral reef tourism in Florida, Puerto Rico, and Hawai'i is expected to decrease by 90% by mid-century under RCP8.5 (EPA, 2017) (14.4.2). Wildfires and insect outbreaks have contributed to reduced desirability for tourism across forest and mountain regions (Bawa, 2017; Hestetune et al., 2018; White et al., 2020). Visitors to Utah's National Parks declined 0.5 to 1.5% during wildfire years between 1993 to 2015, resulting in US$2.7 to 4.5 million in lost revenue (Kim and Jakus, 2019) (see Box 14.2). Trees damaged by insects have caused campground and hiking trail closures in the western US and Alaska (Arnberger et al., 2018). SLR, flooding, coastal erosion, changing air and sea temperatures, changing humidity, and extreme weather events are putting cultural heritage sites at risks (Fatorić and Seekamp, 2017; Hollesen et al., 2018; Tetu et al., 2019).

14.5.7.1.3 Arctic tourism

Cruise and yacht tourism in the North American Arctic increased rapidly over the past decade as changes in sea ice has expanded open water areas and season length (Johnston et al., 2016; Pizzolato et al., 2016; Dawson et al., 2018). The risk of a major accident or incident among Arctic-going yachts and some expedition passenger vessels is very high relative to other ships (*high confidence*) due to the combined increases in mobile ice, especially along the Northwest Passage (Barber et al., 2018a; Howell and Brady, 2019; Copland et al., 2021; Lemmen et al., 2021), limited regulation for private yachts (Dawson et al., 2014; Dawson et al., 2017), the propensity for cruise ships to travel into newly ice-free and poorly charted areas, and the increasing number of non-ice strengthened vessels operating in the region (Dawson et al., 2018;

Copland et al., 2019; Copland et al., 2021). Compounding risks include a lack of hydrographic charting and the lack of emergency response infrastructure (e.g., spill response, search and rescue, salvage) (Amap, 2017). Tourism demand for polar bear viewing in Churchill, Manitoba, Canada may change due to climate-related declines in polar bear health (Gil et al., 2015; Manuel-navarrete and Pelling, 2015), but may be offset by 'Last Chance Tourism' (LCT), a niche tourism market of individuals who explicitly seek to visit vanishing landscapes and/or disappearing flora and fauna (Lemelin et al., 2010).The ethics of promoting LCT has been questioned considering that more visitation to sensitive sites increases local impacts as well as travel-related emissions (Groulx et al., 2016; Groulx et al., 2019).

14.5.7.2 Emerging Responses and Adaptation

Compared to other economic sectors (see section 14.5.8), the tourism industry has high adaptive capacity (*high confidence*) (Figure 14.9). Investments in climate-resilient infrastructure within Canadian National Parks have increased visitation rates during the shoulder seasons (Fisichelli et al., 2015; Lemieux et al., 2017; Wilkins et al., 2018), regional collaboration among US and Canadian park agencies has enhanced adaptive capacity through integrated planning and management (Lemieux et al., 2015), and technological advancements have reduced the vulnerability of alpine winter sports from warming temperatures (e.g., snowmaking, refrigerated surfaces, chemical additives) (Rutty and Scott, 2015; Scott et al., 2019b; Scott et al., 2020). Snowmaking as an adaptation strategy affects mitigation efforts by increasing the need for energy and fuel (Scott et al., 2019b).

Tourists are also highly adaptable and, depending on their levels of place attachment, location loyalty, and socio-demographics, are *very likely* to substitute the timing or location of their travel activity based on climate and climatic-driven environmental changes (Rutty and Scott, 2015; Atzori et al., 2018). Lemieux (2017) found that if the state of the Athabasca Glacier (CA-PR, Figure14.1) were to change negatively as a result of climate change, 83% would travel elsewhere, and if large infrastructure was built as an adaptive measure for viewing receding glaciers at Jasper National Park, 40% of tourists would no longer visit.

Hard and soft limits to adaptation exist in the tourism sector (Manuel-navarrete and Pelling, 2015). For example, machine-made snow without the use of environmentally harmful chemical additives that are banned in most jurisdictions, can only be made efficiently in temperatures below -2 °C, but projections indicate warming temperatures above this threshold (Wobus et al., 2017; Scott et al., 2019a). Multi-jurisdictional adaptation planning for parks and protected areas in the US has been hindered by a lack of funding, communication, and funding trade-offs that could be remedied through coordination (Lemieux et al., 2015). Social inequalities generated by the tourism development process must also be considered by climate-related interventions to avoid the perpetuation of inequalities that may exist, particularly in less developed regions and rapidly developing regions. For example, New developments in Hawai'i, Florida, Quebec, and popular resort areas in Mexico have led to social inequalities through increased property taxes leading to the marginalization of local residents away from these areas in favour of wealthy tourists (Manuel-navarrete and Pelling, 2015) (also see 14.5.9).

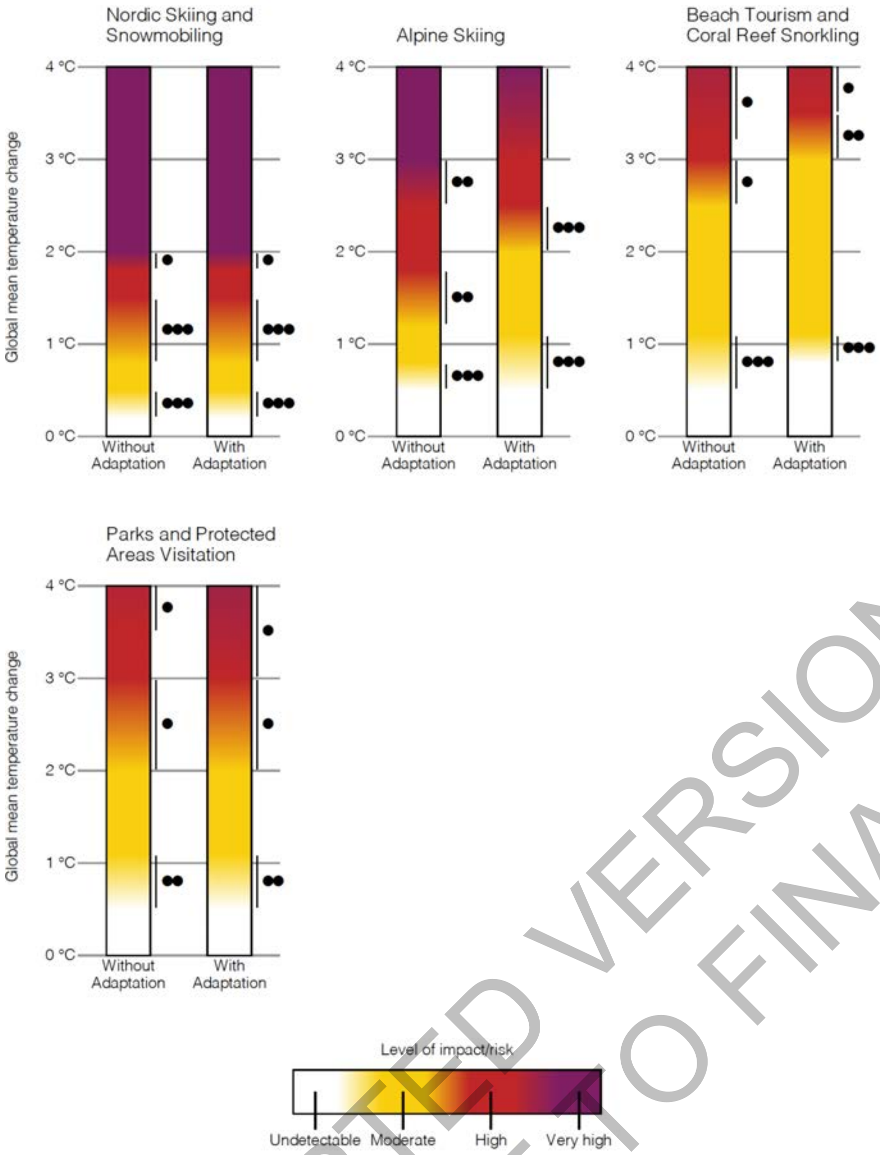


Figure 14.9: Burning ember of the relative risks to select tourism activities in North America with and without adaptation as a function of global mean surface temperature increase since pre-industrial times. Risks to tourism activities include: 1) season length reductions from warming temperatures for Nordic skiing and snowmobiling, 2) season length reductions from warming temperatures and precipitation changes for alpine skiing, 3) visitor experience changes as a result of warming surface and ocean temperatures for beach tourism and degrading coral reef systems for snorkelling, 4) visitor experience changes related to warming temperatures and changing landscape aesthetic for Parks and Protected Areas. Risks assessed cover all of North America (3, 4), or are specific to certain regions (1, 2). The supporting literature and methods are provided in Supplementary Materials (SM14.4).

14.5.8 Economic Activities and Sectors in North America

Economic sectors highly reliant on climate, such as agriculture, tourism, fisheries, and forestry, have higher levels of exposure and sensitivity (*high confidence)* and greater overall risk to climate change compared to other economic sectors such as mining, construction, and manufacturing (*medium confidence*). However, the cascading nature of climate impacts related to trade (Box 14.5), labour productivity (14.5.8.1.5), and infrastructure (14.5.8.1.2) means that there is no economic sector in North America that will be unaffected by climate change *(very high confidence*) (Figure 14.10). For Canada, this assessment is further supported by the Canadian Climate Assessment (Lemmen et al., 2021). The combined economies of Canada, Mexico and the US represented ~28% of the global GDP in 2019, with the US accounting for almost 90% of the total activity for North America (World Bank, 2020a). The risks posed at different GWLs for any given economic activity or sector are presented in Figure 14.10. By combining expert judgement with a systematic review of the literature for each sector, the information in this Figure represents a broader synthesis, especially for sectors with a smaller literature base and at higher GWLs. The assessment of the risks of climate change on tourism (14.5.7) and the interactions between sectors through trade (Box 14.5) are discussed separately.

14.5.8.1 Observed Impacts and Projected Risks of Climate Change

14.5.8.1.1 Agriculture, fisheries, and forestry

The wide range of observed and projected impacts of climate hazards on food and fibre in North America are documented in 14.5.4 (also see Chapter 5). Agriculture (USNW - corn and soybeans), fisheries (cod and pollock), and forestry (Boreal Forest timber yield) are expected to experience substantial and widespread risks by 2°C of global warming above pre-industrial (*medium to high confidence)* (Figure 14.10). Economic models generally show economic losses in the agricultural sector across North America, especially at higher GWL (14.5.4) (EPA, 2017; Boyd and Markandya, 2021), although the effects in local economies, especially rural areas of the US that are highly dependent on agriculture, will be substantial even at lower GWLs (Gowda et al., 2018). Full evaluations of climate risks for forestry and fisheries are presented in 14.5.1, 14.5.4 (also see 14.6), respectively.

14.5.8.1.2 Transportation

Transportation infrastructure, including roads, bridges, rail, air, sea, and pipelines, are highly vulnerable to rising temperatures, SLR, weather extremes, changing ice conditions, permafrost degradation, and flooding (*high confidence*), resulting in damage, disruption to operations, unsafe conditions, and supply-chain impacts (Board and Council, 2008; Natural Resources Conservation Service; Andrey and Palko, 2017; Jacobs et al., 2018; Lemmen et al., 2021) (Box 14.5). In the Mexican states of Veracruz, Tabasco, San Luis Potosí, Chiapas and Oaxaca, 105,000 infrastructure sites, mostly major connecting roads, were found to be at risk of flooding from tropical storms (De la Peña et al. 2018). Low water levels in the Great Lakes has severely impacted US grain transport (Attavanich et al., 2013). High intensity rain events destroyed 1,000km of roads and washed out hundreds of bridges and culverts in 2013 resulting in an estimated CAD$6 billion (2013 dollars) in damages and recovery costs in Alberta, Canada (*CA-PR*) (Palko and Lemmen, 2017). In 2019, the rail line from Winnipeg to Churchill Manitoba, which is the only ground transportation to the community and to Canada's only deep-water Arctic port, was reopened after being closed for over two years due to the cumulative effects of flooding, permafrost degradation, and political challenges (Lin et al., 2020). In the US, the number of heat-related train delays has increased (Bruzek et al., 2013; Chinowsky et al., 2019) and by the end of the century may cause economic losses of US$25 to 45 billion (RCP4.5) or US$35 to 60 billion (RCP8.5) (Chinowsky et al., 2019). Sea ice reduction in the North American Arctic has led to a rapid increase in ship traffic (Huntington et al., 2015; Phillips, 2016; Pizzolato et al., 2016; Huntington et al., 2021b; Li et al., 2021) with cascading risks related to invasive species introduction, accident rates, black carbon emissions, underwater noise pollution for marine mammals, and risks to subsistence harvesting activities in Indigenous communities. (Ware et al., 2014; Council of Canadian Academies, 2016, Huntington, 2021; Verna et al., 2016; Chan et al., 2019)

14.5.8.1.3 Energy, oil and gas, and mining

Climate change is increasing the demand for electric power for cooling and threatens existing power supply (*high confidence*) (see 14.5.5). Increased energy demand often occurs during peak energy usage and especially during heat waves (Cruz and Krausmann, 2013; Leong and Donner, 2015). Cooling represented 74% of peak electricity demand in Philadelphia on a particularly hot day in July 2011 (Waite et al., 2017; IEA, 2018b). In Canada, warming temperatures are expected to reduce demand for heating by 18 - 33% and increase demand for cooling by 14 - 126% by 2070 compared to 1959-89 and 1998-2014 baseline periods, respectively (Berardi and Jafarpur, 2020). The effects on hydropower are uneven across the region with the potential for increases in capacity in Canada but declines of over 20% in Mexico (RCP4.5 and RCP8.5) (Turner et al., 2017). Electricity demand in the US is projected to increase by 5.3 % per degree C rise in temperature (Hsiang et al., 2017). Energy infrastructure, such as drilling platforms, refineries and pipelines and evacuation routes are also increasingly vulnerable to higher sea levels, hurricanes, storm surges, mobile multi-year sea ice, erosion, inland flooding, wildfires, and other climate-related changes (Zamuda et al., 2018).

Operational efficiency and human safety at mining and energy production sites is expected to be adversely affected by increases in extreme events (Section 14.2), including storms, heavy rains, riverine flooding, and wildfires (*high confidence*). General remoteness of many mining sites (especially in the North American

Arctic) exacerbates risks related to emergency responses to extreme events such as wildfire (*medium confidence*). The 2016 Fort McMurray wildfire in Alberta Canada forced the evacuation of 88,000 people and the shutdown of mine operations. Damages were minimal because companies had undertaken proactive FireSmart interventions specifically developed for the industry (Council of Canadian Academies, 2019) (see Box 14.1). Onshore oil field production in Tabasco, Mexico, which accounts for 16% of the country's daily output, was interrupted by extensive flooding (Cruz and Krausmann, 2013). Two-thirds of mine operators globally, including major operators in North America, have experienced production challenges related to water shortages and flooding (Carbon Disclosure Project, 2013).Water availability stress due to climate change is lower in Canada than in the US and Mexico and mines in Canada may be less exposed to this risk (World Resourcs Institute, 2012), with some exceptions, i.e., water-intensive oil sands mining in the Athabasca River basin in Canada (Leong and Donner, 2016) (also see 14.5.3).Warming temperatures also has the potential to alter the nature, characteristics and quality of mineral resources such as kaolin or limestone (Phillips, 2016).

14.5.8.1.4 Construction

In the US, construction workers comprise 6% of the total workforce but accounted for 36% of all occupational heat-related deaths from 1992-2016 (Dong et al., 2019). It is expected that total labour hours among outdoor construction workers will decrease by 0.53 (+/- 0.01)% per °C based on existing warming trends (Hsiang et al., 2017) also see (EPA, 2017). Risks are expected to be exacerbated as SLR and storm surge expands the risk zone for coastal flooding exposing more property to inundation and enhancing construction demand (EPA, 2017) (Box 14.4, section 14.5.5.1.3). Meeting existing and projected demand for water in affected regions could also require building new desalination plants. Texas has constructed over 44 desalination plants across the state because of a lack of freshwater to meet potable water demand and due to climate driven droughts (Kloesel et al., 2018b). Other infrastructure damaged by floods and SLR will need to be reassessed and perhaps relocated away from the coast. Relocation requires availability of land that frequently does not exist within urban areas (Lithogow, 2019). Some US tribes and Indigenous groups in Canada lack the financial resources to build climate-resilient infrastructure such as housing and sewage treatment facilities to assure clean drinking water (Martínez et al., 2014; Salgado and Luisa Martinez, 2017; Lithgow et al., 2019).

Permafrost thaw in northern North America will result in increased construction and reconstruction needs (*medium confidence*) related to direct damage to buildings, roads, airport runways and other critical infrastructure including decreased bearing capacities of building and pipeline foundations, damage to road surfaces, and deterioration of reservoirs and impoundments used for wastewater and mine tailings containment (Pendakur, 2017; Meredith et al., 2019). Ice roads have become less safe due to warming, pavement damage has increased related to seasonal thaw/freeze cycles, and there have been interruptions in airport operations, water and sewage service, and school operations in the Canadian territories of Yukon and Nunavut (Canadian Western and Eastern Arctic – (*CA-WA* and *CA-EA*), fig 14.1) (Council of Canadian Academies, 2019). By the end of the century, the economic impact of projected reconstruction of Alaska's public infrastructure due to climate change (mainly from permafrost thaw) is estimated to range from USD$4.2B (RCP4.5) to USD$5.5B (RCP8.5) (Melvin et al., 2017; Markon et al., 2018).

14.5.8.1.5 Manufacturing

Twelve million Americans (Bureau of Labor Statistics, 2015), 1.5 million Canadians (Statistics Canada, 2020) and 9 million Mexicans (Statistics Mexico, 2021) are employed in manufacturing. The southeast US and Texas have the highest manufacturing output, with 34% of total US output ($700 billion per year). The impact of climate change on manufacturing varies greatly by region. Vulnerability of the sector to climate change stems from exposure of workers to increasing temperatures and humidity, exposure of facilities to SLR and flooding, and changes in water supply and quality required in many manufacturing processes (Lall et al., 2018).

14.5.8.1.6 Labour Productivity

Climate change is negatively affecting working conditions and labour productivity in North America (*medium confidence*) (Section 14.5.6.1 and Box 14.5). Working conditions in temperatures above a Heat Index of 85ºF (29.4ºC) are correlated with potentially hazardous health conditions (Tustin et al., 2018) and for every ºC increase in temperature, labour productivity is estimated to be reduced by 0.11% for low risk workers and 0.53% for high risk workers (i.e., construction, mining, agriculture and manufacturing) (Hsiang et al., 2017). By mid-century (RCP8.5), temperature increase, changing water availability and SLR, are projected to result in a 0.6% drop in labour productivity in auto, timber, textile and chemical manufacturing in the Southeast and Texas regions (Kinniburgh et al., 2015; Hsiang et al.). Labour productivity in the US automobile industry decreases by 8% for every six or more days of consecutive unusually hot weather (above 90ºF/32.2ºC) (Cachon et al., 2012). Thirty percent of California workers are employed in high-risk industries, such as agriculture, with exposure to high temperature leading to loss in productivity (Rogers et al., 2015). Under RCP8.5 increases in extreme temperatures, labour productivity in the US is projected to decrease, costing US$190 billion in lost wages by 2090 (EPA, 2017; Kjellstrom et al., 2019)(also see (Gubernot et al., 2014; Kiefer et al., 2016; Carter et al., 2018).

14.5.8.2 Current and Potential Adaptation

Adaptation options are highly diverse and sector-specific (EPA, 2017). Regardless of economic sector, companies that implement effective and rapid response options that address climate change stressors will have a competitive advantage (Gasbarro et al., 2016, Lemmen, 2021). Most companies focus on short-term risk management and consequently short-term adaptation is often favoured over long-term approaches particularly in the private sector, which will be ineffective for climate change risk reduction over the long term (Gasbarro et al., 2016).

Investment and coordination of climate services (forecasting) can support many economic sectors across North America. In 2017, 15% of S&P 500 companies publicly disclosed an effect on earnings from weather events, reflecting a growing trend (Williams et al., 2018).Existing US federal-sponsored planning tools provide guidance to states and to plan for SLR and flooding with large threats to commercial sectors (US Department of Transportation, 2015). The NOAA Coastal Services Center SLR and coastal inundation viewer (https://coast.noaa.gov/digitalcoast/tools/slr.html), the Army Corps of Engineers Sea Level Change Curve simulator, and Climate Central's interactive portal (Ocean at the Door) all provide access to visualizations of future sea level rise that are available to US coastal cities and towns for commercial planning purposes. Similar resources are being developed and are available for Canada including Canada's Climate Atlas (https://climateatlas.ca/).

Adaptation options for transportation and related infrastructure include engineering and technological solutions, as well as innovative policy, planning, management, and maintenance approaches (Natural Resources Conservation Service, 2008; Jacobs et al., 2018). For northern transportation, new technologies and infrastructure adaptations can be employed to facilitate heat extraction (e.g. air convection embankments, heat drains, thermosyphons, high albedo surfacing, gentle embankment slopes) (McGregor et al., 2010b; United Nations, 2020) Adaptation options for roads include changing pavement mixes to be more tolerant to heat or frost heaving, expanding drainage capacity, reducing flood risks, enhancing travel advisories and alerts, elevating or relocating new infrastructure where feasible and changing infrastructure design requirements to include climate change considerations or to introduce new flood event thresholds (Natural Resources Conservation Service, 2008; EPA, 2017; Pendakur, 2017). Railroads are testing temperature sensors on rail tracks to provide early warning of buckling. Sensors that signal when tracks are approaching dangerous temperatures may help to avoid accidents (Hodge et al., 2014; Chinowsky et al., 2019).

Adapting building codes more uniformly to changing climate conditions such as SLR, storms, winds and wildfires reduces risk (Olsen, 2015; Maxwell et al., 2018b). North America has not, on the whole, adapted its building code regulations to consider the dynamic challenges of climate change, although some specific efforts have been made, including the addition of requirements for wildfire within California's building codes and Canada's Climate-resilient building and core public infrastructure initiative, which involves updating building codes and standards to improve climate resiliency (Lacasse et al., 2020) (Box 14.4). To enhance safety, some outdoor workers have been fitted with heat sensors to analyse/assess how warming may affect productivity and well-being (Runkle et al., 2019). Other options include raising public roads and seawalls, initiating buy-outs of property owners in flood-risk areas, and improving storm water drainage. Adopting approaches like the International Future Living Institute's Living Building Challenge (LBC) may inform future regulatory processes (Eisenberg, 2016). The LBC (https://living-future.org/basics/) has seven thematic areas that inform building design, although only a subset of those are relevant for climate change including water, energy, and materials considerations.

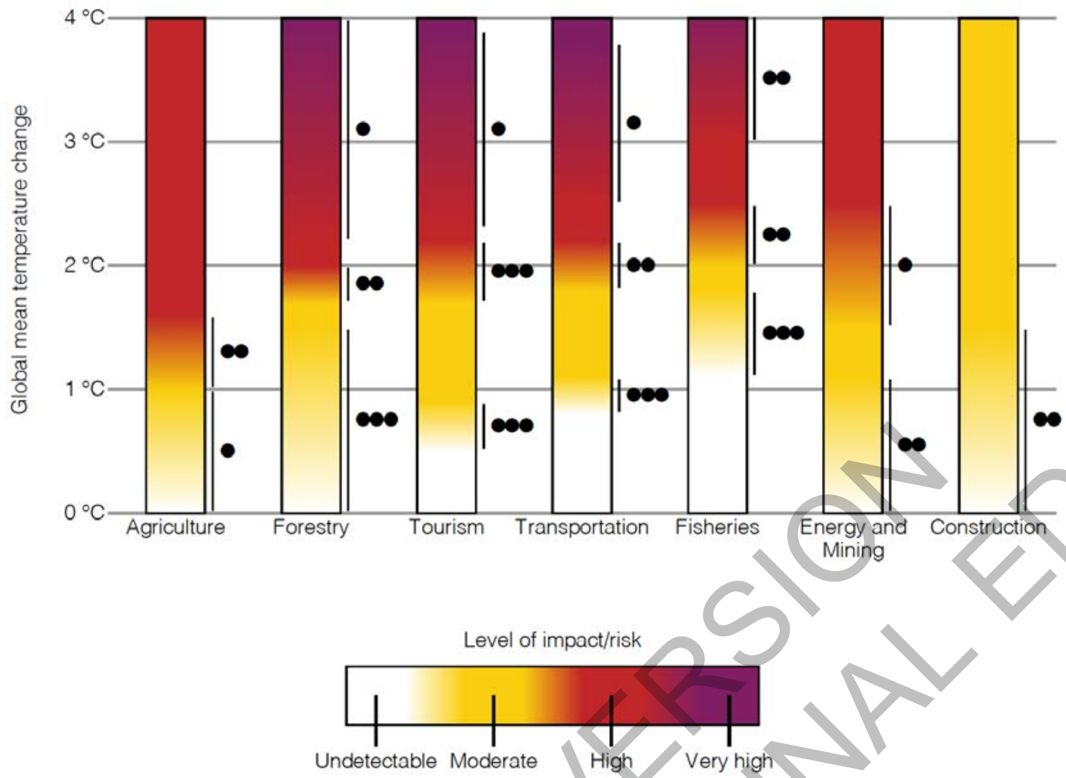


Figure 14.10: Burning Ember of the relative risks to economic sectors in North America as a function of projected global mean surface temperature increase since pre-industrial times. Impacts on economic sectors include: 1) changing crop yield leading to economic loss for agriculture, 2) changes in the quality and quantity of timber yields, 3) reductions in season length and economic viability for tourism activities, 4) increased maintenance and reconstruction costs to transportation infrastructure, 5) changes in fisheries catch, 6) reduced productivity in mining and energy operations, 6) reduced labour productivity in outdoor construction, and 7) increased maintenance and reconstruction costs to transportation systems. Risks to economic sectors and activities were sometimes assessed across all of North America (3, 4), within specific regions (1, 2), and for specific crops or species (1 - corn and soybean, 2 – cod and pollock). The supporting literature and methods are provided in Supplementary Material (SM14.4).

[START BOX 14.5 HERE]

Box 14.5: Climate Change Impacts on Trade Affecting North America

In North America, trade - defined as the sum of export and import of goods and services - is valued at $1.3 trillion USD annually (2019 dollars) and represents 30% of North American GDP. Variations within the region are notable; Mexico relies on trade for 80% of its GDP and Canada for 66% (World Bank, 2020a). Canada and the US traded over USD$55.2 billion worth of products related to the agriculture industry between 2015 and 2018 (Government of Canada, 2019). Canada, the US and Mexico have the longest running trade pacts globally and these agreements have played a major role in supporting economic and social development in the region (see (Frankel and Rose, 2005; Eaton et al., 2016; World Bank, 2020b). However, recent changes to the North American Free Trade agreement do not clearly address climate change (Lucatello, 2019).

Climate risks may create shocks to the trade system by damaging infrastructure and disrupting supply-chains in North America (*medium confidence*). Sea level rise, flooding, permafrost thaw, landslides, and increased frequency and magnitude of extreme weather events are projected to impact transportation infrastructure which will pose challenges to the movement of goods, especially in coastal areas (Lantuit et al., 2012; Doré et al., 2016; Hjort et al., 2018; Koks et al., 2019; Lemmen et al., 2021). Maritime ports are at the greatest risk from climate hazards (Messner et al., 2013; Slack and Comtois, 2016), followed by roads, rail, and airports (Anarde et al., 2017). Due to the trans-national nature of trade, extreme weather disruptions in one region are likely to lead to cascading effects in other regions *(high confidence*) (Lemmen et al., 2021). For example, climate change will have negative impacts for global food and energy trade where reductions in crop production and fish stocks in some regions could cause food and fish price spikes elsewhere (Beaugrand et al., 2015; Lam et al., 2016; Shukla, 2019) (also see 14.5.4, Figure 14.10, and 5.11.8).

Climate change impacts may alter current trade practices and patterns with implications for regional economic development in North America, especially in the Arctic (*medium confidence*). Climate change is causing modal-shifts in cargo shipping. For example, lower water levels in lakes and rivers (e.g., Mackenzie River, Mississippi River) impact freight transport and may cause a shift from marine transport to more GHG-intensive rail, road, or air transport (Koetse and Rietveld, 2009; Du et al., 2017; Pendakur, 2017). Sea ice change is creating new Arctic marine trade corridors (Melia et al., 2016; Pizzolato et al., 2016; Ng et al., 2018; Bennett et al., 2020; Mudryk et al.), including shorter and potentially more economical routes such as the Northwest Passages (see CCP6, Box 6.1). Warming temperatures have also reduced the season length for ice roads, which are heavily relied upon to service remote communities and remote industries including forestry and mining (Pendakur, 2017) (see *14.5.8.1.2)*.

Effective and equitable trade policies can act as important adaptation strategies (*medium confidence*). Higher temperatures have had no direct effect on developed countries' exports, but have significantly reduced growth in exports among developing countries, which in turn can increase the price of goods that developed countries then import (Costinot et al., 2016; Constant and Davin, 2019). Schenker (2013) estimated that the climate impacts on trade from developing to developed countries could be responsible for 16.4% of the total expected cost of climate change in the US in 2100 and thus, North America would benefit from increased investment in effective and equitable trade policies and adaptation in developing regions. Under an RCP8.5 scenario (~2.6 to 4.8 degree C warming) and within current trade integration, climate change could lead to up to 55 million undernourished people by 2050; these projections decrease by 64% (20 million people) with the introduction of reduced trade tariffs and the lessening of institutional and infrastructure barriers (Janssens et al., 2020). Although most studies focus on global food security (agriculture), it is likely that the same challenges exist for other commodities and manufactured goods.

[END BOX 14.5 HERE]

[START BOX 14.6 HERE]

Box 14.6: The Costs and Economic Consequences of Climate Change in North America

Observed Impacts

Extreme weather events, including hurricanes, droughts, and flooding, and wildfires, have been partly attributed to anthropogenic climate change (e.g., Rupp et al., 2015; Emanuel, 2017); attribution table in Chapter 16) (*high confidence*). Direct, indirect and non-market economic damages from extreme events have increased in some parts of North America (*high confidence*). The number of extreme events with inflation-adjusted damages totalling more than US$1B has risen in the US over the past decades (NOAA, 2020; Smith, 2020), and similar increases have been observed in Canada (Boyd and Markandya, 2021). Factors other than climate change, including increases in exposure and the value of the assets at risk, also explain increasing damage amounts (Freeman and Ashley, 2017; Vano et al., 2018). Climate change explains a portion of long-term increases in economic damages of hurricanes (*limited evidence, low agreement*). Studies of US hurricanes since 1900 have found increasing economic losses that are consistent with an influence from climate change (Estrada et al., 2015; Grinsted et al., 2019), although another study finds no increase (Weinkle et al., 2018).

Formal attribution of economic damages from individual extreme events to anthropogenic climate change has been limited, but climate change could account for a substantial fraction of the damages (*limited evidence, medium agreement*). Two recent studies have shown approaches for how damages may be attributed for individual events in the US. Assuming a direct proportionality between attributable risk of the event to the attributable economic damages, one study suggested that 30-75% of the direct damages from Hurricane Harvey was caused by climate change, with a best estimate of US$67B out of an estimated US$90B total of attributable damages (Frame et al., 2020). Another study modeled the component of the flooding from Hurricane Sandy due to rising SLR and mapped that to coastal damages. That study estimated that US$8.1 billion (13% of the total) was attributable to the climate influence on SLR (Strauss et al., 2021).

The effect of climate change has been identified in aggregate measures of economic performance, such as GDP, in North America and globally (*medium confidence*)*,* although the magnitude of these changes is difficult to constrain (*medium confidence).* Climate change has been observed to affect national GDP level and economic growth (*low confidence*). The extent to which climate has affected GDP may be challenging to identify statistically (Cross-Working Group Box ECONOMIC in Chapter 16). Observed GDP effects are generally slightly negative in the US, higher and negative for Mexico, and the directionality of the effects in Canada varies by study and modeling approach (Burke et al., 2015; Colacito et al., 2018; Kahn et al., 2019).

Projected Risks

Projections of market and non-market economic damages demonstrate the substantial economic risks of climate impacts associated with high temperature pathways (RCP8.5) (*high confidence*). Since AR5, a wide range of estimates of the costs of climate change have been developed for the US (EPA, 2015a; Houser et al., 2015; EPA, 2017; Hsiang et al., 2017; Martinich and Crimmins, 2019), with ongoing processes to update national estimates for Canada and Mexico (Semarnat, 2009; NRTEE, 2011; Estrada et al., 2013; Sawyer et al., 2020). While the magnitude of the estimates depend on approach and assumptions in the methods and expectations of future socioeconomic conditions, these studies show substantial projected economic damages across North America by the end of the century, especially for warming greater than 4ºC (*high evidence, high agreement*). Whether these damages translate into GDP effects is not clear for Canada. Some modeling approaches show modest GDP increases in 2050 and 2100, while others suggest modest decreases although it is anticipated that the economic effects for Canada will be large and negative (Boyd and Markandya, 2021). Large costs and risks, such as those associated with extreme events such as wildfires (Hope et al., 2016) and the increased need for infrastructure replacement (Neumann et al., 2015; Maxwell et al., 2018a) will have compounding effects in the markets by disrupting economic activities (Box 14.5).

Market and non-market risks and costs will not be experienced equally across countries, sectors and regions in North America (*high confidence*). For the US, reductions in mortality, energy expenditures and improvements in agricultural yields are projected to result in net gains in the North and Pacific Northwest whereas in the South, higher heat-related mortality, increases in energy expenditures, SLR and storm surge are projected to result in economic losses by the end of century (Hsiang et al., 2017). No region in the US is expected to avoid some level of adverse effects (EPA, 2017; Martinich and Crimmins, 2019) (*medium evidence, high agreement*). Economic models generally show losses in the agricultural sector across North America, especially at higher GWL (Boyd and Markandya, 2021, EPA 2017). Some models show large gains in parts of Canada, although these models do not capture the full range of climate hazards including change in precipitation or extreme events (Boyd and Markandya, 2021).

Economics of Adaptation Opportunities

Economic analysis can help reveal where the avoided economic damages are greater than the costs of adaptation, improving decision-making for adaptation planning and efforts in North America (*high confidence*). Detailed assessment of total needs and costs of climate adaptation are limited (Sussman et al., 2014), but estimates suggest that the costs are large (*low evidence, high agreement*). Cost-benefit and other economic analyses that incorporate damage estimates are expanding for adaptation decision-making (Li et al., 2014), especially for technical options in areas with high exposure such as coastal areas in Mexico (Haer et al., 2018) and Alaskan infrastructure (Melvin et al., 2017). Cost-benefit analysis has also been applied to coordinating planning across jurisdictions in North America for SLR and flood control (Adeel et al., 2020). Adaptation costs in the US are lower on RCP4.5 compared to RCP8.5 emission pathways (Martinich and Crimmins, 2019). Adaptation, however, cannot be based solely on the cost benefit analysis due to the high level of uncertainty related to climate risks (Cross-Chapter Box DEEP in Chapter 17).

Improving projections of future economic risk and damages facilitates the development of tools that can be used for economic analysis of climate policies (*high confidence*). Monetized estimates of the damages from climate change have been developed and refined since AR5, motivated in part by efforts to estimate the Social Cost of Carbon (SCC) (National Academies of Sciences, 2017). Support for these efforts and the use of SCC in regulatory analysis of mitigation and adaptation efforts have been pledged across the national and sub-national governments of Canada, the US and Mexico. Harmonizing SCC and consistent use can further enhance coordination of mitigation and adaptation decision-making (Auffhammer, 2018; Aldy et al., 2021).Using these damages estimates can also inform other policy and tools that improve the consideration of climate impacts in markets and decision-making (Report of the Climate-Related Market Risk Subcommittee, 2020).

[END BOX 14.6 HERE]

14.5.9 Livelihoods

Exposure and vulnerability to climate hazards have varied across North America by region and by population (*high confidence*). These differences have been often underpinned by social and economic inequalities and have been observed between households, social groups, rural and urban communities, and Indigenous Peoples (*high confidence*). These vulnerabilities have also been observed to contribute to maladaptation (*medium confidence*) (14.5.9.1). Social and economic trends and development will determine near-term impacts on livelihoods from projected climate hazards; livelihoods will also adapt to the risks and opportunities (*high confidence*) (14.5.9.2). Actions to enhance the livelihoods of the most vulnerable social groups in North America will lessen the impacts of climate hazards on them (*high confidence*) (14.5.9.3).

14.5.9.1 Observed Impacts

Livelihoods are 'the resources used and the activities undertaken in order to live. Livelihoods are usually determined by the entitlements and assets to which people have access' (IPCC, 2018) (8.1.1). While often understood as subsistence or traditional ways of life (Oswal, 1991), livelihoods are often conceptualized more broadly as encompassing the economic, cultural, and social capitals or assets, capabilities, and activities that individuals, households, and social groups use as the means to make a living (DFID, 1999; Obrist et al., 2010).

Past and current patterns of development in North America have propagated and perpetuated vulnerabilities that have created differential impacts on livelihoods from climate hazards (*high confidence*). Predatory and extractive economies have underpinned economic activity in North America historically and currently. While generating substantial wealth, these patterns have also driven social and economic inequality (*medium evidence, high agreement*) (Jasanof, 2010; Shove, 2010; Klinsky et al., 2016; Robinson and Shine, 2018). Patterns of development that reinforce these structures remain a large contributor to current social-environmental risks and have affected all kinds of contemporary livelihoods (Cannon and Müller-Mahn, 2010; Koch et al., 2019) (also, see Chapter 18).

Climate impacts have damaged livelihoods across North America, especially those of marginalized people (*high confidence*) and deepened inequalities for these groups (*medium confidence*). Across North America, climate change has affected livelihoods with larger effects on individuals, households and communities that are already more vulnerable due to a range of pre-existing social and environmental stressors (Olsson et al., 2014; Hickel, 2017; Koch et al., 2019) such as Indigenous Peoples, urban ethnic minorities, and immigrants (Guyot et al., 2006; Gronlund, 2014; Klinenberg, 2015). These impacts have also contributed to a deepening of inequalities for marginalized groups (Audefroy and Cabrera Sánchez, 2017; García et al., 2018) (*medium evidence, high agreement*). As climate hazards further degrade their livelihoods, these groups have faced additional challenges to avoiding or escaping poverty (Ruiz Meza, 2014). Furthermore, these groups have needed to use their more limited resources to manage present challenges, restricting their future capacities to adapt (Tolentino-Arévalo et al., 2019). Climate impacts have also affected the livelihoods of the middle classes (Domínguez et al., 2020) who have become more vulnerable due to changes in their social and economic security (Garza-Lopez et al., 2018). Gender has also been recognized as a determinant of differential vulnerability with implications for women's livelihoods (Cross-Chapter Box GENDER in Chapter 18).

Migration and mobility have been an important part of livelihoods in North America (*high confidence*). Movement across North America has been reinforced by social, cultural and economic ties (Box 14.5). For example, middle class retirees from Canada and the US engage from temporary, seasonal to permanent migration to the warmer climates of the Southern US and Mexico, often benefiting from the lower cost of living (Domínguez et al., 2018). Temporary or semi-permanent labor migration, generally followed by remittances, has been an important part of livelihoods for rural areas in Mexico (*high confidence*) and has been employed as a response to climate hazards (*low evidence*). Drought in rural areas which are highly dependent on subsistence agriculture have observed migration to urban areas in Mexico (Nawrotzki et al., 2017). Evidence of international migration in response to climate hazards is sparse with difficulties in identifying a climate signal due to the multi-causal nature of migration decision-making (Cross-Chapter Box MIGRATE in Chapter 7). There is limited evidence of extreme weather events or climate hazards on migration from Mexico to the United States (Nawrotzki et al., 2015b; Nawrotzki et al., 2015c; Nawrotzki et al., 2016; Murray-Tortarolo and Salgado, 2021).

Pre-existing social vulnerabilities have also led to forced displacement from extreme weather events (*low confidence*). In the US, compounding effects of SLR and storm surge interacted with pre-existing social vulnerabilities of local communities to generate large-scale displacement after the effects of Hurricane Katrina on New Orleans in 2005 (Jessoe et al., 2018). The processes of relocation and recovery in New Orleans was further shaped by vulnerability where out-migration was more likely to be minorities and economically disadvantaged while the recovery was predominantly in neighborhoods that were wealthier prior to the disaster (Fussell et al., 2014; Fussell, 2015). Newer evidence from Hurricane Maria in Puerto Rico in 2017 has shown an initial spike in displacement with slower recovery with more vulnerable communities returning at higher rates (DeWaard et al., 2020); however, overall out-migration trends have been consistent with long-term economic migration (Santos-Lozada et al., 2020). Interactions of slower onset climate hazards with displacement, such as observed in Shishmaref, Alaska, have revealed the challenges in attribution of migration to climate as it intersects with socioeconomic conditions and lived experiences (Marino and Lazrus, 2015).

Maladaptation has also been occurring in livelihoods, especially as it relates to agricultural practices that are less resilient to climate hazards and competition for land use (*limited evidence, high agreement*). Focusing on examples in Mexico (see 14.5.4.3 for US and Canada examples), for some Mexican Indigenous Peoples, the replacement of ancestral farming practices with technological adaptations like transgenic crops has reduced their resilience by making them more dependent on external inputs and more expensive supplies while increasing putting their health at risk with herbicide and insecticide use (Mercer et al., 2012). Existing power structures have also interacted with climate hazards to generate maladaptive outcomes (Quintana, 2013). Mennonite communities in the northern state of Chihuahua, Mexico have pursued commercial agricultural markets that lead them to shift to transgenic crops and to overexploit local groundwater resources in a region experiencing multi-year droughts. These actions have led to conflict with other local farming groups with less economic capital to access groundwater (Quintana, 2013). Climate mitigation measures may also have adverse effects on local livelihoods with implications for adaptive capacity. The Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) mitigation program has been highlighted as a trade-off between an international/national carbon mitigation strategy and the ability of some Mexican rural communities to improve their food security (Barbier, 2014) (5.6.3.3).

14.5.9.2 Projected Risks

Livelihoods will evolve as a result of both challenges presented directly or indirectly from climate impacts as well as socioeconomic changes and technological developments (*high confidence*). Livelihoods, however, can be undermined by many of the projected climate risks with the impacts depending on adaptive capacity and adaptation limits (*high confidence*) (8.4.5.1). Real areas in Mexico and the southern US with agriculture-based livelihoods and projected reduction in precipitation will be adversely affected (Esperon-Rodriguez et al., 2016) (14.5.4). Outdoor workers in rural and urban areas will be exposed to higher health risks from higher temperatures and heatwaves (14.5.8). Reduced livelihoods will also be associated with adverse mental health effects (14.5.6.8).

Future climate hazards will deepen patterns of social inequality as vulnerable groups may also experience intersecting impacts that adversely affect their livelihoods (*medium confidence)*. Health, in particular, will be a key intersection as marginalized and disadvantaged groups often have poorer health status and hold occupations that may involve higher exposure to climate hazards. African Americans are expected to experience the largest impacts on their health status due to differential exposure and vulnerability to climate hazards (Marsha et al., 2016) (Section 14.5.6).

Displacement, migration and resettlement will increase along higher emission pathways (*medium confidence*). Combining projections of SLR and population scenarios for the US, Haer et al. (2013) and Hauer et al. (2016) have estimated the magnitude of the population at risk in coastal communities, numbering in the millions. In the near-term, where climate hazards influence out-migration, it will mostly augment existing patterns as migration is strongly influenced by existing social networks (7.3.2). Planned relocation and resettlements will reduce the exposure to climate hazards for the involved populations but could adversely affect their livelihoods in the absence of supportive programs (Jantarasami et al., 2018a) (7.3.2), since livelihood outcomes strongly depend on socioeconomic conditions.

14.5.9.3 Adaptation

Climate hazards undermine adaptation by damaging livelihoods (*high confidence*). Many actions that enhance and promote resilient livelihoods can have substantial benefit for adaptation to climate hazards (*medium confidence*). Livelihoods in the context of climate change are characterized by adjustments that then feedback into the assets that comprise a livelihood. Social capital - in the form of household and community cohesion - facilitates the development of adaptation strategies to the impacts of climate change in rural and urban communities at the household level and for small groups (Barbier, 2014; Nawrotzki et al., 2015b; Nawrotzki et al., 2015c). Cultural capital, especially in the form of local knowledge and Indigenous knowledge, can guide adaptation practices in North America (Akpinar Ferrand and Cecunjanin, 2014), preserving Indigenous cultures and enhancing future adaptation and resilience (Pearce et al., 2012 2015; Audefroy and Cabrera Sánchez, 2017) (Box 14.1). In Mexico, rain-water harvesting (practiced by some Mayan communities) and the use of local-traditional varieties of maize have assisted in the adaptation to climate impacts and promoted food security (Akpinar Ferrand and Cecunjanin, 2014; Hellin et al., 2014). Funding and support for these social adaptation strategies have been uneven (Barbier, 2014; Romeo-Lankao et al., 2014). The legacy of colonialism and historical patterns of development will continue to shape the adaptation responses and resiliency of Indigenous Peoples (Todd, 2015; Davis and Todd, 2017; Whyte, 2017; Cameron et al., 2019).

Migration is a common adaptation strategy to maintain and diversify people's livelihoods and will continue to play an important role when households manage climate and social risks (*high confidence)* (7.4.3). In the near-term, actions that enhance in-situ adaptive capacities as well as fostering safe and orderly migration can result in synergies for both adaptation and development (Cross-Chapter Box MIGRATE in Chapter 7). Populations that experience less mobility or cannot engage in voluntary migration as an adaptation may need additional support to adapt to climate hazards, for example northern communities that are at risk of climatic events (Hamilton et al., 2016). Policies associated with the transition from high GHG intensive extractive industries, sometimes referred to as "just transitions", may also support in-situ livelihoods if they also aim to address and redress existing inequalities to reduce vulnerabilities (McCauley, 2018); however, these policies could result in maladaptation if they create new inequalities or generate other environmental damages.

14.5.10 Violence, Crime, and Security

Elevated rates of various types of crime have been associated with higher temperatures in the US and Mexico (*medium confidence based on limited evidence and high agreement*) (14.5.10.1). If social relationships prevailing now and in the recent past continue, projections show future crime rates in the US and Mexico increasing with increasing temperatures (*low confidence*) (14.5.10.2). Degradation of human security and conflicts exacerbated by climate change—even outside of North America—will increase the demand for humanitarian assistance, foreign aid and resettlement (*medium confidence*) (14.5.10.2).

14.5.10.1 Observed Impacts

14.5.10.1.1 Violence and crime in the past and present

Crime, including violent crime, has been associated with higher temperatures in the US (*medium confidence*). Studies of crime statistics in the US have revealed a relationship between temperature and a range of violent crimes including aggravated assaults, rapes, and homicides; effects for property crimes are weaker (Ranson, 2014; Houser et al., 2015; Heilmann and Kahn, 2019; Mares and Moffett, 2019) (*limited evidence, medium agreement*). These effects have been observed in US urban centres (Hsiang et al., 2013; Mares, 2013; Ranson, 2014; Schinasi and Hamra, 2017; Heilmann and Kahn, 2019) and more generally across the US (Mares and Moffett, 2019). Differential effects have also been observed within urban areas. Observed higher rates of domestic and intimate partner violence during periods of high heat in less affluent neighbours in Los Angeles have been associated with disparities in access to air conditioning and greenery (Heilmann et al., 2021). By contrast, (Lynch et al., 2020a) found no significant correlation between annual homicide rate and annual temperature for New York City (Lynch et al., 2020b). For Mexico, (Burke et al., 2018a) found temperature linkages with intergroup killings by drug-trafficking organizations, homicides, and suicides. No linkages between temperature and crime have been reported for Canada. Differences in spatial and temporal aggregation of the crime statistics as well as in the measure of climate change or variability explain some of the differences between studies. Several causal pathways can explain these relationships (Miles-Novelo and Anderson, 2019; Lynch et al., 2020b). The dominant theory is that weather changes result in changes in behavioural patterns that lead to more opportunities for crimes. For example, studies that disaggregate by month often report significant positive associations between temperature anomalies and violent crime (especially aggravated assaults, rapes, and homicides), particularly in the cold season (Harp and Karnauskas, 2018; Mares and Moffett, 2019)). Smaller increases in crime during positive warm-season temperature anomalies may be due to people seeking shelter in cooler indoor spaces, decreasing crimes of opportunity (Gamble and Hess, 2012) (7.2.7).

The archaeological record has been used to infer linkages between climatic variability and social process, including violence (inferred with *medium confidence*). Past North American societies have been exposed to greater climatic variability than is documented in the instrumental record. Because future climatic conditions are likely to exceed those known for the recent past (Cross-Chapter Box PALEO in Chapter 1), the North American archaeological record can illuminate possible relationships between climate variability and violence that cannot be observed in the present record. In the upland US Southwest between A.D. 600 and 1280, one study found that violence significantly increased as climatically-controlled maize production decreased and interannual variability increased (Kohler et al., 2014) (*low evidence, high agreement*); massive emigration from the northern Southwest in the last half of the AD 1200s is connected with though not completely explained by climatic variability (Scheffer et al., 2021). In the central and southern Maya lowlands, following centuries of increasing populations and attempts to produce more maize (Roman et al., 2018), episodes of drought and/or increased summer temperatures in the 9th and 10th centuries AD (Dunning et al., 2012; Kennett et al., 2012) accompanied increased conflicts and social disintegration including collapse of long-lived dynasties, cessation of monumental inscriptions (Carleton et al., 2017) and emigration (*medium evidence, medium agreement*). Such findings reinforce research on contemporary societies that climate-induced farming shortfalls in regions dependent on agriculture may induce or exacerbate conflict, especially in interaction with unfavourable demographic, political, and socioeconomic factors (e.g. (Koubi, 2019))(*medium evidence, medium agreement*) (7.2.7.).

14.5.10.1.2 Security

Climate change poses risks to peace (16.5.2.3.8) that could affect North America (*medium confidence*). Military and security communities are adapting their planning, operations and infrastructure to current impacts of climate change in North America and globally (*medium agreement, medium evidence)*. Arctic nations are renewing their military capacity and expanding their constabulary presence around their existing boundaries (Choi, 2020). There is increasing awareness that climate change causes weather patterns and extreme events that directly harm military installations and readiness through infrastructure damage, loss of utilities, and loss of operational capability (Duffy-Anderson et al., 2019). Transboundary disputes and competition over resources such as fish (Østhagen, 2020) are a concern in the changing Arctic and increases in military and constabulary operations are being observed (Jönsson et al., 2012; Smith et al., 2018; Eyzaguirre et al., 2021).

14.5.10.2 Projected Risks

14.5.10.2.1 Violence and Crime

Projections of future crime derived from the empirical relationships between temperature and crime in the US show the potential for increased criminality under RCP8.5 compared to RCP4.5 (*low confidence*). For RCP8.5, holding all socioeconomic conditions at 2015 levels, violent crime could increase 0.6 –2.1% by mid-century and 1.9 –4.5% by late-century (Houser et al., 2015). The rise in property crime is projected to be smaller as property crime flattens at higher temperatures (Hsiang et al., 2013). Using relationships between crime and monthly temperatures established for five US regions by Harp and Karnauskas (2018), Harp and Karnauskas (2020) project 18,800 additional violent crimes annually beyond 2014 levels by the end of the 21st century under 1.5ºC warming, rising to 48,200 under 4ºC warming. Aggregating data by states weighted by population density, (Mares and Moffett, 2019) project an average annual increase of 0.94% across seven categories of violent and property crime for each anomalous ºC warming (an average annual increase of about 100,000 crimes). Changing socioeconomic conditions in the future may either reduce or exacerbate the projected contemporaneous relationship between temperature anomalies and crime (Agnew, 2011; Lynch et al., 2020b) whereas adaptation could weaken these relationships.

14.5.10.2.2 Defense and Security

Climate change will affect ecosystems (16.5.2.3), living standards (16.5.2.3.4), health (16.5.2.3.5), and food security (16.5.2.3.6) globally and these changes may exacerbate violence and political instability (*medium confidence)* with implications for national security in North America (*medium confidence*). Climate variability, hazards, and trends to date have played a role in exacerbating conflict, but the influence of climate appears to be minor and more uncertain than the roles of low socioeconomic development, low state capability and high intergroup inequality (Mach et al., 2019). More profound impacts from climate change on weather and seasons as well as changing socioeconomic conditions could lead to patterns of violence that cannot be predicted by projecting relationships between current climate and violence into the future (14.6.3) (Mach et al., 2019). If global levels of violence increase, there will be increased demand for international efforts, including disaster aid and humanitarian efforts (Eyzaguirre et al., 2021). Climate change and geopolitical goals interact in the Arctic (Smith et al., 2018). New transportation corridors and the potential access to natural resources could lead to competition for access to and control over the region (Estrada, 2021) (CCP6.2.6; Box CCP6.1; FAQ CCP6.2). Governance structures exist to manage geopolitical manoeuvring and to protect the human security of Arctic populations (14.5.10.3; 7.2.7.1).

14.5.10.3 Adaptation Options

14.5.10.3.1 Violence and Crime

Co-benefits from adaptation options include improving the liveability of and quality of life in cities, reducing socioeconomic vulnerability and exposure to locally higher temperatures (*medium confidence*). Urban settings in the US have disproportionately higher exposure to urban heat island effects in low-income and minority neighbourhoods in US cities (14.5.5.1). Co-benefits from adaptation responses in the urban landscape can reduce socioeconomic vulnerabilities and exposure to higher temperatures (14.5.5.3). Evaluation of adaptation efforts to reduce crime rates that have been associated with temperature are limited. In LA, a link has been inferred between violence and older buildings that may lack air conditioning (Heilmann et al., 2021). By contrast, access to air conditioning did not appear to lessen crime rates in Mexico (Baysan et al., 2019).

14.5.10.3.2 Defence and Security

Existing environmental and international agreements that consider climate risks can contribute to cooperation (*medium confidence*). Strengthening and empowering existing environmental and diplomatic avenues (e.g., the Arctic Council and international agreements such as the United Nations Convention on the Law of the Sea, and various subnational actors and agreements (CCP6.3.2)) to incorporate risks from climate impacts could enhance cooperative avenues for defusing conflict (Huebert et al., 2012). Improving the consideration of climate risks in efforts to expand economies and trade (Box 14.5), and improvements in peace-keeping (7.4.4) (Barnett, 2018) could also reduce future conflict risks.

14.6 Key Risks

Ten key risks from climate change were identified for North American based on definitions and assessment approaches outlined in Chapter 16, which were extended to include the development of a risk database and analysis that included expert evaluation of interactions between climate hazards and sectors (Figure 14.11, SM14.3).

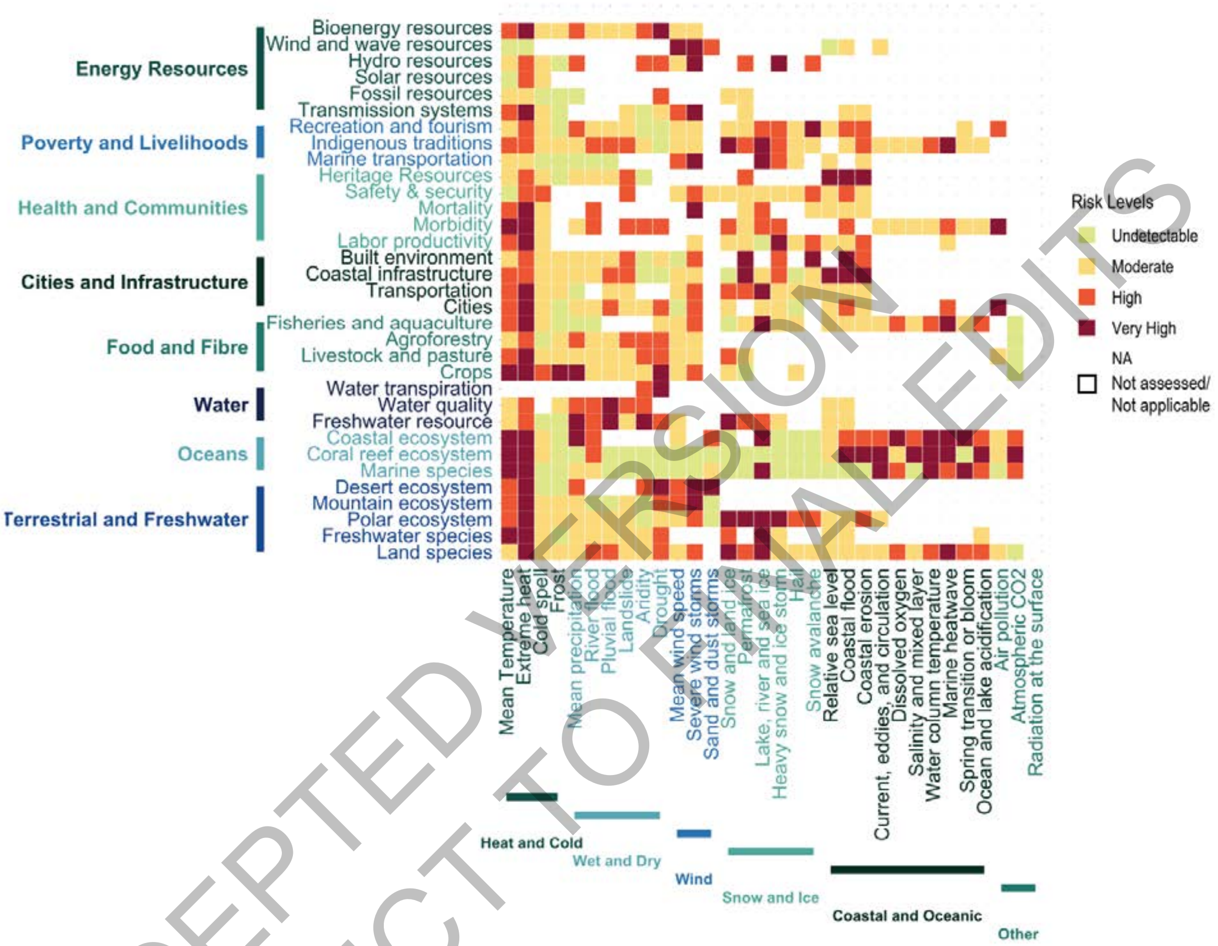


Figure 14.11: Rapid assessment of relative risk by sector (y axis) and climate hazard (x-axis) for North America based on an assessment of asset-specific vulnerability and exposure across climate hazards (see SM14.3 for methodological details). For each unique combination, the hazard by sector risk was ranked as very high (very high risk and *high confidence*), high (significant impacts and risk, *high to medium confidence*), medium (impacts are detectable and attributable to climate change, *medium confidence*), low or not detected (risk is low or not detectable). Blank cells are those where the assessment was not applicable or not conducted. Risks identified through the rapid assessment were further evaluated in the chapter assessments (see corresponding sector text for full assessment of risk and impacts).

14.6.1 Key Risks of Climate Change for North America

In North America, divergent perceptions regarding the attribution and implications of climate change pose a key risk to adaptation mainstreaming (KR1). This lack of adequate adaptation in turn amplifies threats to human life and safety from intensifying extreme events, fires, and storms (KR2). Climate change hazards pose risks to economic and social well-being (KR3), marine social-ecological systems (KR4), unique terrestrial ecosystems and their services (KR5), freshwater services (KR6), physical and mental health (KR7), food and nutritional security (KR8), and commerce and trade (KR9). Cumulatively, these risks interact to imperil the quality of life for North American communities, cities, and towns (KR10).

14.6.2 Key Risks across Sectors in North America

KR1: In the public and policy domains, divergent perceptions of anthropogenic climate change pose a risk of inaction on adaptation efforts to reduce exposure and socioeconomic vulnerability

Complex factors including individual beliefs, ideology, worldview, partisan identity, as well as societal context influence how the public, as well as professional groups, communities, and policy makers, perceive and understand climate change (14.3.3; 14.3.4) (*high confidence*). While there is expert scientific consensus on anthropogenic climate change, rhetoric, misinformation and politicization of science have contributed to misperceptions (*high confidence)*, polarization on the severity of impacts and risks to society, indecision, and delayed action (14.3.1) (*high confidence*). In North America, this impedes adaptation efforts (14.3.4) and inflates climate risks (*high confidence*).

KR2: Risk to life, safety, and property from intensifying extreme events

Human life and safety across North America and especially along the coasts of Mexico, the Hawaiian Islands, Gulf of Mexico, Atlantic Canada and southeastern US will be placed at risk from SLR and severe storms and hurricanes, even at 1.5ºC GWL (*very high confidence*) (14.5.2,14.5.5, Box 14.4). Warming, heatwaves, and increases in wildfire activity in many regions of North America pose risks to air quality, health, lives, and property (Box 14.2). More extreme precipitation and flooding pose a risk to human morbidity, mortality, and safety in fluvial flood zones and areas downstream of levees, dams, and flood culverts. Increasing intensity of storm events poses a risk of landslides, erosion, and flooding in shoreline and urban communities, especially high bank areas along exposed coasts, in Arctic and temperate areas where winter sea ice has diminished, and in low-lying coastal areas where SLR and storm surge often overwhelm existing natural coastal features and engineered structures (14.5.5, Box 14.4).

KR3: Cumulative damages from climate hazards pose a substantial risk to economic well-being and shared prosperity

Climate change impacts are projected to cause large market and non-market damages (*high confidence*). By end-of-century under higher GWL scenarios (>4°C), these damages are expected to reach several tens of billions of dollars/annually in Canada and hundreds of billions/annually in the United States. Losses in labour productivity and wages, and damages to coastal properties will be especially large; however, all sectors in the US and most sectors in Canada are projected to see substantial relative damages on high emission pathways by mid to end-of-century compared to lower emission pathways. Economic sectors with hard limits to adaptation (i.e., winter tourism) or that are highly affected by climate variability (i.e., agriculture and fisheries) will be at more risk at lower temperatures than other economic sectors (14.5.7; 14.5.8). Strategic implementation of adaptation strategies coupled with lower emissions scenarios result in multi-billion-dollar reductions in economic damages (14.5.8, Box 14.6).

KR4: Risk of degradation of marine and coastal ecosystems, including loss of biodiversity, function, and related services with cascading effects for communities and livelihoods

Ocean warming will increase the frequency and intensity of marine heatwaves (MHWs, Box 14.3), accelerate unprecedented rates of sea ice loss, and alter ocean circulation, chemistry, and nutrient cycling in ways that profoundly impact marine productivity, biodiversity, and foodwebs (*very high confidence*) (Section 14.5.2). Collectively these impacts pose a risk to nearshore ecological and human systems (*high confidence*), increasing the probability of phenological mismatches, large-scale redistribution of species, and species population declines (14.5.4) with cascading impacts that strain cultural and economic systems reliant on marine productivity across North America (*high confidence*). Nearshore areas of Chesapeake Bay (US) and Akimiski Island, mid-western James Bay and the coasts in the Pacific ranging from of the Gulf of Alaska through Baja Peninsula have a high proportion of species near their upper thermal limit, and are areas of particularly climate change risk.

KR5: Risk to major terrestrial ecosystems leading to disruptions of species, ecosystems and their services

Major risks to terrestrial ecosystems across North America, such as semi-arid landscapes, rangelands, boreal and temperate forests, and Arctic tundra, include significant ecosystem transformations and shifts in species abundances and ranges and major vegetation types (e.g., transitions from forests to grasslands), with cascading implications for regional biodiversity (*very high confidence*). Warming increases the risk of permafrost thaw with propagating impacts on species and communities in the Canadian and US Arctic (*high confidence*; Ch. 6). Forest disturbances, including wildfire, drought, insects, and pathogens are expected to increase with warming, acting synergistically to raise the prevalence of tree mortality and ecosystem transformation (*medium confidence*; 14.5.1). These changes will reduce services provided by terrestrial ecosystems, including timber yields and carbon sequestration (*medium confidence*).

KR6: Risk to freshwater resources with consequences for ecosystems, reduced surface water availability for irrigated agriculture and other human uses.

Droughts and earlier snowmelt runoff will increase water scarcity during the summer peak water demand period especially in regions with extensive irrigated agriculture, leading to economic losses and increased pressures on groundwater as a substitute for diminished surface water supplies (*medium to high confidence*; 14.5.3). Streams in North America are expected to continue to warm, with important ramifications for aquatic ecosystems (*high confidence*), reducing habitat for salmon and trout species that are economically and culturally important (14.5.1). Warming and drying coupled with other stressors (e.g., pollutants, nutrients, and invasive species) pose a risk to ecosystem structure and function in lakes, streams and reservoirs across many parts of North America (*high confidence*) (14.5.1, 14.5.3). Warming, increases in heavy rainfall and nutrient loading pose risks for water quality and harmful algal blooms (*medium to high confidence*; 14.5.3).

KR7: Risk to human health and wellbeing, including mental health.

Heat-related human mortality is projected to increase in North America as a result of climate change and aging populations, poverty, chronic diseases and inadequate public health systems (*very high confidence*) (14.5.6.1). Gradual changes to temperature and precipitation are impacting urban ecosystems and creating ecosystem regime changes resulting in the poleward expansion among insects that bring risks related to vector-borne diseases such as West Nile virus and Lyme disease (*high confidence*) (14.5.6). Climate change is expected to lead to wide-ranging mental health challenges related to an increase in the psychological burdens of climate change (*high confidence*), particularly for individuals with existing mental health conditions, live in severely impacted areas, or who are reliant on climate for livelihoods and cultural well-being (e.g., Indigenous Peoples and farmers) (14.5.6.8).

KR8: Risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries, and aquaculture productivity and access

Cascading and interacting impacts of climate change threatens food systems and food and nutritional security for many North Americans, especially those already experiencing food and nutritional scarcity, women and children with high nutritional needs, and Indigenous Peoples reliant on subsistence resources *(high confidence*) (14.5.6). In agricultural regions experiencing aridification and where water scarcity precludes substantial expansion of irrigation, warming and extreme heat pose a risk to food and forage crop and livestock production (14.5.4) (*high confidence*). Ocean warming and marine heatwaves will continue to disrupt commercial capture fisheries through species redistribution and changes to yield (*high confidence)* and warming waters and OA will increasingly impact aquaculture production (*high confidence*) (14.5.4). Interactions between competing aspects of human security (e.g., food, energy, and water) will be exacerbated by climate change (*high confidence*) (Sections 14.5.3, 43).

KR9: Risks to major infrastructure supporting commerce and trade with implications for sustainable economic development, regional connections, and livelihoods

Climate change and extreme events are expected to increase risks to the North America economy via infrastructure damage and deterioration (*high confidence*), disruption to operations, unsafe conditions for workers (*medium confidence)*, and interruptions to international and interregional supply chains (*medium confidence*) (14.5.8, Box 14.5). These climatic impacts will have cascading implications for local livelihoods, sustainable economic development pathways, regional connectivity and will reinforce pre-existing social inequities (*medium confidence*). Infrastructure damage will also disrupt economic activities, including manufacturing, tourism, fisheries, natural resource extraction, and energy production (*high confidence*) (14.5.8).

KR10: Risk to the quality of life in North American communities, cities, and towns

In major North American cities and settlements, vulnerability to climate change has increased and is projected to continue to rise (*medium confidence*) (14.5.5). Concentrated populations with unequal adaptive capacities, exposure of valuable assets, ageing infrastructure, differing degrees of institutional capacity and effectiveness will underpin climate hazards (14.5.5). Coastal, riverine, and urban flooding displacing communities and coastal ecosystems (14.5.5.2) will become a dominant risk to urban centres (*high confidence*), will cause disruptions to transportation and trade infrastructure (14.5.8); large wildfires endangering lives, livelihoods, property and key infrastructure, and economic activities and contributing to compromised air quality and municipal water contamination (14.5.6, Box 14.2).

14.6.3 Cumulative risk, tipping points, thresholds and limits

Across North America, climate change poses a risk to social-ecological systems increasingly destabilized by compounding climate impacts and non-climate pressures (*high confidence*) (14.5.1-3) that erode the connectivity and redundancy underpinning system resilience (14.5.1-5) (Xiao et al., 2017a; Koven et al., 2020; Malhi et al., 2020; Turner et al., 2020). Accelerating climate change and increasingly severe hazards and shocks may induce abrupt changes or push systems, people, and species to critical points--i.e., tipping points, where a small additional change causes a disproportionately large response, triggering feedbacks that lock systems into novel regimes (Scheffer et al., 2001; Scheffer, 2010; Anderies et al., 2013; Lenton, 2013; Iglesias and Whitlock, 2020; Lenton, 2020a). Climate change tipping points can compound and amplify climate impacts and risk, induce disparate climate burdens and benefits across human and ecological systems, and irreversibly restructure ecosystems and livelihoods (e.g., species extinctions, fisheries collapse, community managed relocation) (Lynham et al., 2017). Examples of systems with potential tipping points in North America include permafrost and sea-ice loss triggering transformation of ecological and human systems (including substantial shipping opportunities) in the Arctic that are permanent and irreversible except on geological timescales, and which are potentially underway (*high agreement, low evidence*) (14.6.2, Box 14.3, CCP6), mid-latitude forest ecosystems at low to middle elevations in western North America where wildfire and cumulative climate and non-climate pressures may restructure forests and succession in ways that promote transition to new vegetation types (Section 14.5.1), and agricultural communities in northern Mexico and the SW United States where aridification and drought may interact with water resource policies, economic opportunities and pressures, and farm practices to induce either adaptation (via changes in irrigation practices), or farm abandonment, land-use transformation, and livelihood changes (due to heat stress, soil deterioration, or reduced economic viability) (14.5.3, 14.5.4, CCP 6) (Yumashev et al., 2019; Turner et al., 2020; Heinze et al., 2021).

Identification of critical thresholds, elements, and connections within a system may also help identify potential positive tipping points, i.e., focal components or processes in a system where a relatively small investment or intervention can induce a large benefit and enable self-reinforcing transformative adaptation (14.7, Ch 17) (Tàbara et al., 2018; Lenton, 2020b; Otto et al., 2020). Under low mitigation scenarios, compounding risks and higher carbon emission scenarios increase the potential that amplifying feedback loops and fatal synergies across sectors could lead to existential threats to the socio-ecological systems of North America (*medium confidence*). Societal collapse has been linked to shifts in climate regimes, especially when societies have lost resilience due to slowly mounting socio-ecological challenges; while other studies reveal that social continuity and flexibility enable historical climate resilience and prosperity under changing environments (Lenton et al., 2019; Otto et al., 2020; Degroot et al., 2021; Richards et al., 2021) (FAQ 14.2).

Accounting for tipping points, interactions, and reinforcing dynamics among ecological, social, and climate processes is necessary for comprehensive analyses of climate change risk, cost, and urgency, as well as effective adaptation design and implementation (14.7) (Cai et al., 2015; Steffen and et al., 2018; Lenton et al.; Narita et al., 2020; Dietz et al., 2021). Multiple lines of evidence across sectors assessed in this chapter suggest that after mid-century and without carbon mitigation, climate-driven changes to ecological and social boundary conditions may rapidly push many systems into disequilibrium (*medium confidence*), emphasizing the importance of prioritizing adaptation actions with co-benefits for mitigation (14.5.4, Box 14.3). Reducing climate hazards through mitigation and removing catalysts of system instability through adaptation measures that increase system resilience (e.g., ecosystem restoration) will help reduce the risk that systems move across a tipping point from a desirable to an alternate or undesirable state (14.5.4, 14.7, Box 14.3) (Narita et al., 2020; Turner et al., 2020; Heinze et al., 2021).

[START FAQ 14.2 HERE]

FAQ 14.2: What can we learn from the North American past about adapting to climate change?

The archaeology and history of Indigenous Peoples and Euroamerican farmers show that climate variability can have severe impacts on livelihoods, food security, and personal safety. Traditional societies developed numerous methods to cope with variability, but have always expanded to the limits of what those adaptations permit. Current knowledge and technology can buffer societies from many negative effects of climate change already experienced but will be severely challenged by the novel conditions we are now creating.

People came into North America more than 15,000 years ago and have experienced both massive and minor shifts in climate ever since. At the end of the last very cold phase of the most recent Ice Age, about 11,500 years ago, temperatures rose extremely rapidly—as much as 10ºC (18ºF) in a decade in some regions. This undoubtedly contributed to the extinction of large mammals like mammoths and mastodons that people hunted alongside many other resources (see Cross-Chapter Box PALEO in Chapter 1). There were so few people on the land though, and other resources were so abundant, that the long-standing human means of coping with climate variability—switching foods and moving on—were sufficient.

Following the end of the Ice Age, populations across North America grew for the next few thousand years, at a rate that increased once people began to domesticate corn (maize), beans, and squash (the "Three Sisters") as well as other crops. However, more people meant less mobility, and farmers are also more invested in their fields and remaining in place than foragers are to hunting grounds. Other means of coping with vulnerability to food shortage caused by climate variability included some continued hunting and gathering of wild resources, planting fields in multiple locations and with different crops, storage in good years, and exchange with neighbours and neighbouring groups.

According to archaeological evidence, however, these adaptation strategies were not always sufficient during times of climate-induced stress. Human remains showing the effects of malnutrition are fairly common, and conflict caused in part by climate-induced shortfalls in farming has left traces that include fortified sites, sites placed in defensible locations, and trauma to human bone. Larger and more hierarchical groups emerged, first in Mesoamerica and then in the US Southwest, Midwest, and Southeast. These groups offered the possibility of buffering poor production in one area with surplus from another, but they also tended to increase inequality within their borders and often attempted to expand at the expense of their neighbours, introducing new sources of potential conflict. Dense hierarchical societies also arose in other areas such as the Northwest coast where agriculture was not practiced but resources such as salmon and roots were abundant and either relatively constant or storable.

These societies were not immune to climate hazards despite their greater population and more formal organization. Archaeological evidence strongly suggests that drought, or growing conditions that were too hot or cold, contributed to the decline of groups ranging from Classic period Maya states in Mesoamerica, to the somewhat less hierarchical societies of Chaco in the US Southwest and Cahokia in the US Midwest (Figure FAQ14.2.1). The usual pattern seems to be that climatic variability compounded social and environmental problems that were already challenging these societies.

If societies in North America prior to the Euroamerican colonization were vulnerable to climate variability, surely the more recent and technologically advanced societies of North America were at lower risk? The 20th Century Dust Bowl created in the US and Canadian prairies suggests otherwise. Severe drought conditions throughout the 1930s—which to make matters worse peaked during the Great Depression—did not cause either the US or Canada to collapse. But both countries suffered massive economic losses, regional loss of topsoil, and regional human strife (including loss of crops, income, and farms) leading to migration. Yet anthropogenic global climate change was of little or no consequence in the 1930s. While farming practices made climate stress worse, the climate variability itself was either completely, or mostly within the envelope of historical climate variability that earlier human societies had experienced.

Indigenous Peoples and Euroamerican farmers and ranchers have a long history of mostly successful adaptation to changing weather patterns. The wisdom held by Indigenous families and communities includes deep knowledge of how plants, animals, and atmospheric conditions provide early-warning signals of approaching weather shifts, and stories about how past communities have tried to cope with climate-related resource shortfalls. Long-standing community-level management of resources also helps prevent shortfalls, and institutions such as kin groups, church groups, clubs, and local governments (which exist in communities of both Euroamericans and Indigenous Peoples, in different forms) can be powerful aids in ameliorating shortfalls and resolving conflict.

Still, Indigenous knowledge, and traditional knowledge among Euroamerican farming communities, provide guidelines for how to cope with *traditional* problems. Contemporary governmental restrictions (such as legal water rights allocations, international borders and tribal lands boundaries) have limited the adaptive capacity that Indigenous societies developed over the centuries. Now human-caused climate forcing, if not mitigated by reducing heat-trapping greenhouse gases, is expected to produce climates in North America that have no local analogs in human history even as it destroys heritage sites that are sources of knowledge about paleoclimates and the diverse ways of coping with them that past people have discovered. Just as past peoples often *avoided* local climate change by moving on, in a world where mobility options are severely limited a lesson from archaeology and history is that we should use our hard-won knowledge of the causes of climate change to avoid creating futures with no past analogs to provide useful guidance.

Figure FAQ 14.2.1: Examples of areas where past climate variability has contributed to crises. Climatic variability is mostly likely to lead to crisis when it is accompanied by social, demographic, and political conditions or environmental mismanagement that compound climatic impacts on societies.

[END FAQ 14.2 HERE]

[START FAQ 14.3 HERE]

FAQ 14.3: What impacts do changes in the North American Arctic have within and outside the region?

The North American Arctic is warming at nearly three times the global average, creating a cascading web of local, regional, and global impacts within and beyond polar regions. Changes in the Arctic not only effect global ocean circulation and climate regulation, but also facilitate new Arctic transportation routes and support transboundary resources with geopolitical, environmental, and cultural implications as conditions change.

Rapid warming and extreme temperatures in the Arctic is leading to unprecedented seasonal sea ice loss, permafrost thaw, and increasing ocean temperatures. Cascading from these biophysical changes are cultural, socio-economic and political consequences that are widespread and largely unprecedented in human history.

Changes in sea ice create safety hazards for Indigenous Peoples and northerners who rely on frozen seas and rivers for transportation between remote communities and to subsistence hunting areas. Thawing permafrost, especially that of ice rich permafrost, creates challenges and costs for a region with low population density and a small tax base to support major infrastructure investments. Warmer ocean temperatures induce large-scale distributional shifts and reduced productivity and access to the largest North America fisheries. Ice-associated marine mammals, such as Polar bears, seals, and walrus, have declined precipitously with decreasing sea ice in the Bering Sea, and widespread ecosystem changes from fish through birds and marine mammal species have altered the system with uncertain outcomes for these productive ice-driven ecosystems. Newly ice-free shipping routes are increasing regional and geopolitical tensions and may facilitate novel threats like the spread of invasive species and safety hazards to local hunters and fishers. The local and regional impacts of climate change in the North American Arctic are profound and span social, cultural, health, economic, and political imperatives.

Although the region is remote, changes in the Arctic impact the rest of the world. The Arctic serves as a regulator of global climate and other ecological processes through large-scale patterns related to air and ocean circulation. These vitally important processes are nearing points beyond which rapid and irreversible (on the scale of multiple human generations) changes are possible. The magnitude of cascading changes over the next two centuries includes regional warming and temperature extremes, permafrost declines, and sea ice loss beyond that experienced in human existence. This includes macro-scale risks related to sea level rise from the melting of glaciers and thermal expansion of oceans. Changes in the Arctic are more pronounced than elsewhere and portend climate change impacts in other areas of the globe.

Adaptation in the Arctic is underway and lessons learned on what works and what is effective and feasible to implement can provide global insights. Successful adaptation in the North American Arctic region has been attributed, in part, to the explicit and meaningful inclusion of Indigenous Knowledge and Indigenous self-determination, and diverse perspectives in decision making processes, strong local leadership, co-management approaches, technological investment in integrated climate modeling and projections, and multilateral cooperation.

[END FAQ 14.3 HERE]

14.7 Adaptation in North America

14.7.1 Overview of Observed Adaptation in North America

Climate adaptation efforts have increased across all North American regions and sectors (*high confidence*). Support for and implementation of adaptation policies, plans and measures have not been equal across the public and private sectors, regions or varying levels of governance (*high confidence*) (Table 14.7). To date, reactive (coping-based) and incremental adaptations have helped North Americans avoid greater damages from observed climate impacts (*medium confidence*). There is increasing agreement that worsening impacts and expanding risk conditions may exceed current adaptation capacities by mid-century under high emissions scenarios (RCP8.5) (*medium confidence*).

14.7.1.1 Individuals and Households

Across North America, individuals and households have taken action to reduce climate-influenced risks (*high confidence).* These autonomous adaptations comprise the majority of the observed responses in the peer-reviewed literature (Berrang-Ford and et al., Accepted). The increased use of cooling systems (which could be maladaptive unless there are innovations (14.5.5.3)) (Barreca et al., 2016), creating defensible space around homes in wildfire-prone areas (Box 14.2), and the modification or redesign of housing structures along coasts (Koerth et al., 2017) are important household responses to existing risks. Although these actions have played a role in reducing risks, the capacity to undertake such actions is not uniform across individuals in North America and has exacerbated existing social inequities, especially in coastal areas (Keenan et al., 2018; de Koning and Filatova, 2020). Additionally, these adaptation activities often are taken without consideration of the impact on mitigation efforts (Kates et al., 2012; Fedele et al., 2019; Shi and Moser, 2021).

14.7.1.2 Local and Sub-National Governments

A majority of local jurisdictions in North America have undertaken some level of adaptation; these efforts largely focused on planning and less on implementation (*high confidence*). Some sub-national governments, namely States and Provinces, have engaged in advanced adaptation planning efforts (*high confidence*). Indigenous Peoples in North America have undertaken substantial activities (14.4, Box 14.1).

Many cities across North America have undertaken adaptation planning (Hughes, 2015; Reich et al., 2016; Moser et al., 2017; Auditors General, 2018; McMillan et al., 2019) (14.5) with some financing adaptation implementation, for example, in the case of SLR (Box 14.4). Adaptation actions commonly implemented in cities include climate-informed building codes, enacting energy conservation measures, modifying zoning, and increasing green infrastructure (see 14.5.5.3; Box 14.7) (Binder et al., 2015; Maxwell et al., 2018a; Moss et al., 2019; Brown et al., 2021). The majority of cities have formed practitioner networks to share information (ICLEI Canada, 2016; Vogel et al., 2016; C40 Cities, 2018) and supporting learning and collaboration through regional collaborations that include utility managers and the private sector (Fünfgeld, 2015; Moser et al., 2017).

In Canada, the Map of Adaptation Actions Canada (https://changingclimate.ca/case-studies/) presents over 200 adaptation case studies addressing a variety of climate-related impacts (Warren and Lulham, 2021). The City of Saskatoon, in developing its Climate Action Plan (which includes a Corporate Climate Adaptation Strategy), engaged with local businesses, NGOs, residents and experts to identify potential risks (and benefits) requiring action (City of Saskatoon, 2019). Similarly, the City of Surrey specifically used community outreach programs to develop its Coastal Flood Adaptation Strategy (CFAS) through a value-based planning approach (City of Surrey, 2019). Municipal asset management, local services and community well-being were key considerations for the City of Selkirk, Manitoba when developing an adaptation strategy as well as ensuring a budgeting process that supports implementation (City of Selkirk, 2019). As of 2019, eight of thirteen Canadian provinces and territories have high-level climate adaptation strategies. The scope of these efforts vary by jurisdiction as a review conducted by federal and provincial auditors in Canada identified several deficiencies related to a lack of detailed implementation plans, obligated funding, and specific timelines (Auditors General, 2018).

Progress in Mexico on adaptation implementation at the local level has been extensive (INECC and Semarnat, 2018). Activities include executing programs for relocating infrastructure in high-risk zones in priority tourist sites, incorporating adaptation criteria in public investment projects that involve construction and infrastructure management, water management, application of climate adaptation norms for the construction of tourist buildings in coastal zones, and improving the security of key water, communication, and transportation infrastructure (14.5.5, 14.5.7, 14.5.8). Additionally, local capacity and protocol to respond to extreme weather events as a function of climate change have been integrated more regularly into community-based hazard mitigation plans. States and municipalities in Mexico must have climate policies that are consistent with the guidelines of national strategies (see 14.7.1.5) and state-level programs on climate change, in addition to other state and municipal laws. As a result, these entities have developed and implemented early warning systems designed to protect the population from climate-related risks, such as strong storms and hurricanes (INECC and Semarnat, 2018).

Implementation of adaptation initiatives and specific actions in US cities has increased in the approximately five years between the 3rd US National Climate Assessment (NCA3) (Melillo et al., 2014) and the 4th Assessment (NCA4), and adaptation responses have been observed widely (Lempert et al., 2018). ICLEI-USA provides numerous resources for adaptation planning and implementation for cities, Indigenous Peoples, and Regional Governments (https://icleiusa.org/). The Georgetown Center for Climate maintains a comprehensive resource for tracking adaptation progress for States (https://www.georgetownclimate.org/adaptation/plans.html). As of 2021, 18 US states have completed climate adaptation plans, and six states have plans underway as of the time of this report (Georgetown Climate Center, 2021). California, in particular, has adopted sustained climate assessment to allow for more rapid iterations on adaptation planning (Bedsworth et al., 2018; Miao, 2019). Across all US states, however, adaptation activities do not have readily accessible budgets, such that levels of funding cannot be assessed directly (Gilmore and St. Clair, 2018).

14.7.1.3 National/Multi-National Governance

The federal government of each North American country has developed policies and actions that promote climate adaptation (Figure 14.12). Recognizing the cultural, economic and social networks that span North America, the federal governments have also committed to engagement on adaptation and resilience across borders and through cooperation on domestic adaptation efforts (The White House, 2016). Each country also outlines their respective adaptation efforts through submissions under the UN Framework Convention on Climate Change (UNFCCC), including their Nationally Determined Contributions (NDCs) under the Paris Agreement. The federal governments also support adaptation efforts in other countries through international climate negotiations as well as related agreements, such as the Sendai Framework for Disaster Risk Reduction and efforts to support the achievement of the Sustainable Development Goals (SDGs).

Mexico's 2020 update to its first NDC communicated extensive adaptation efforts (Government of Mexico, 2020). The measures outlined in this document highlight the importance of co-benefits for adaptation efforts as they relate to the SDGs and to support mitigation commitments. Ecosystem- and nature-based solutions (Box 14.7) are the basis for much of the synergies between adaptation and mitigation efforts. These plans are supported by domestic legislation through the General Law on Climate Change, which includes the Climate Change Adaptation Process (CCAP). CCAP provides a holistic systems-approach for identifying instruments and institutional arrangements for adaptation implementation (Semarnat and INECC, 2015; INECC and Semarnat, 2018). This approach includes guidance for planning (e.g., the Climate Change Mid-Century Strategy, the Special Climate Change Program 2014–2018 (PECC)) and formalizes its adaptation commitments to the Paris Agreement.

In Canada, the Federal Adaptation Policy Framework (Government of Canada, 2011) guides domestic action to develop adaptation knowledge, build adaptive capacity, and mainstream adaptation into federal policy, in support of the Pan-Canadian Framework on Clean Growth and Climate Change (Government of Canada, 2016), which included specific adaptation measures and investments to build resilience. In August 2021, the government initiated a National Adaptation Strategy with development anticipated through 2022. Additionally, the government facilitates efforts and funds research, capacity building, and information sharing across sectors and amongst government departments (Government of Canada, 2021a). The Canadian Centre for Climate Services provides access to climate data, tools, and information (https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services.html). In Canada's revised NDC, near-term commitments to protecting land and oceans and efforts related to sustainable and resilient energy systems are highlighted as examples of co-benefits between climate change adaptation and mitigation (Government of Canada, 2021b).

The US has experienced substantial revisions to its climate policy and its international engagement since AR5 with implications still unclear (Bomberg, 2021). Since AR5 and until early 2020, many congressionally mandated federal efforts (Beavers et al., 2016; Parris et al., 2016; Rockman et al., 2016; Caffrey and Hoffman, 2018) faced programmatic challenges, but most continued to provide research and capacity development to support adaptation implementation across the US. Importantly, the US government sustained the national climate assessments (Lempert et al., 2018). Recently, the administration has re-engaged with the Paris Agreement and the US has submitted an NDC (Government of the United State of America, 2021); however, adaptation was not directly addressed. Subsequent Executive orders mandate adaptation planning at the federal level (e.g., USEO 13754; USEO 14008). As of the time of this report, the US climate policy landscape is rapidly evolving, including major legislative initiatives (e.g., Green New Deal (Boyle et al., 2021).

14.7.1.4 Private Sector, Including Companies, NGOs, Professional Organisations, Academic Institutions, and Communities of Practice

The private sector comprises a diverse set of actors who influence, interact with and support adaptation efforts, generally through shared governance with the public sector. The weight of evidence points to the benefits of these collaborations and the importance of voluntary code-making and self-regulation (17.4.2.1.6). In North America, non-governmental organisations (NGO) and professional organisations have been important agents of change in the adaptation field (Bennett and Grannis, 2017; Stults and Meerow, 2017). Efforts included supporting community-based resilience efforts, network-building, web-based guidance and resources, case studies, workshops and other services to support adaptation action (e.g., vulnerability assessments, scenario-based planning).

Market and financial mechanisms have provided important buffering capacity against climate shocks in North America. Insurance products are being developed to meet emerging climate risks, especially related to availability and pricing of flood insurance in Canada (Thistlethwaite, 2017; Davies, 2020) and the United States (Kousky et al., 2021). Some existing US flood insurance products provided through joint public and private arrangements has led to rebuilding in flood-prone locations (Zellmer and Klein, 2016). The price of these products may limit their uptake in low income neighbourhoods (Cannon et al., 2020).

Professional organisations have participated in the development and adoption of measures to integrate climate resilience into the built environment. This includes new designs, guidelines, codes, standards, and specifications, in addition to infrastructure inventories that incorporate evaluation of vulnerabilities and identification of priority at-risk areas (Amec Foster Wheeler Environment and Infrastructure, 2017; ASCE, 2018a). These efforts are supported by provincial/state and federal initiatives (e.g., Canada's Climate Lens (Infrastructure Canada, 2018), and California's Climate-Safe Infrastructure Working Group (Climate-Safe Infrastructure Working Group, 2018)). Infrastructure Canada has undertaken Canada-wide initiatives to improve infrastructure resilience to climate change (https://www.infrastructure.gc.ca/plan/crbcpi-irccipb-eng.html). The Standards Council of Canada (SCC) established the Northern Infrastructure Standardization Initiative (NISI) (https://www.scc.ca/en/nisi) engaging stakeholders including Indigenous Peoples to develop standards specific for addressing climate change impacts on northern infrastructure design, planning and management, and community development (Standards Council of Canada, 2020).

Professional organisations in the US (e.g., National Medical Association, American Institute of Architects, Association of Metropolitan Water Agencies, Water Utility Climate Alliance, American Society of Adaptation Professionals, etc.) have engaged with their members particularly through training about urban adaptation (Stults and Meerow, 2017). The private sector and citizens (Klein et al., 2018) have been involved in the management of increasing flood risk, such as the adoption of property-level flood protection (Thistlethwaite and Henstra, 2018; Valois et al., 2019), implementing FireSmart Canada and Firewise USA guidance (Box 14.2). In Canada, Engineers Canada developed the PIEVC Protocol to provide guidance for professionals in engineering and geoscience (https://www.pievc.ca/).

Research-based institutions have accelerated the development of web-based tools for visualizing and exploring climate information, in addition to furthering the scholarship on adaptation. In the US, joint university, foundation, and government programs have contributed to advancing the field with products such as oceanographic and fishery climate forecasting tools (14.5.2), in addition to methods for evaluating water resource plans under uncertainty about future mean and extreme conditions (ASCE, 2018a; Ray et al., 2020). Some regional research centres focus on stakeholder engagement in addition to research; these include the National and Regional Climate Adaptation Science Center Network of the US Geological Survey (https://www.usgs.gov/ecosystems/climate-adaptation-science-centers), the US Department of Agriculture's Climate Hub Network (https://www.climatehubs.usda.gov/), and the Climate Program Office of NOAA (https://cpo.noaa.gov/) includes the Regional Integrated Science Assessment Network (https://cpo.noaa.gov/Meet-the-Divisions/Climate-and-Societal-Interactions/RISA/About-RISA) to support delivery of climate services. So-called "networks of networks," consisting of NGOs, state and city government programs, have provided an alternative to federal support. For example, the Science for Adaptation Network (SCAN) formed subsequent to dismantling the Federal Advisory group to the US National Climate Assessment (Moss et al., 2019).

14.7.2 The Solution Space

14.7.2.1 Incremental Adaptation, Barriers and Limits

Adaptation actions to moderate the effects of climate impacts are well-documented in North America and have buffered much of the past and currently observed climate impacts (e.g. Lempert et al., 2018; Lemmen et al., 2021). While it is challenging to catalogue adaptation activities as many are not published or are not necessarily undertaken with climate adaptation as the primary rationale (1.3.2.2), most of the activities identified by sector in this Chapter have been primarily incremental adaptation measures (*medium evidence*, *high agreement*). Many actions are extensions of existing practices for managing climate variability and there is broad agreement that worsening future conditions will exceed the capacity of many of these efforts (Kates et al.; Termeer et al., 2017; Fazey et al., 2018; Fedele et al.; Shi and Moser, 2021).

Progress in adaptation planning and implementation between regions in North America is uneven (Bierbaum et al., 2013; Moser et al., 2017; Auditors General, 2018; INECC and Semarnat, 2018; Shi and Moser, 2021) (Table 14.6, Box 14.7). At the local level (cities) in the US, commitment of elected officials, financial resources and awareness of climate change hazards and risks have been identified as driving the variation in climate adaptation (Shi et al., 2015). Adaptation programs have come under budgetary and political pressures that limit continuity of efforts (Moss et al., 2019). Implementation of adaptation has also faced challenges due to institutional arrangements, constraints, and gaps that prevent different levels of government, social organizations and academia to act in an integrated and timely way to consider biodiversity, agriculture and water systems (i.e., Box 14.7) (Bourne et al., 2016; Nalau et al., 2018).

Table 14.6: Adaptation trends and progress across sectors. Adaptation progress consists of assessment (A), planning (P), implementation of strategies (I), and evaluation of efficacy (E). L=low, M=moderate, H=high.

			Adaptation progress				Limits	
Sector	Strategies	Cases	A	P	I	E	Soft	Hard
Terrestrial Eco-Systems (14.5.1.1)	Broad use of tools such as scenario planning, structured decision making, and adaptation planning frameworks	Planning for climate refugia in the Sierra Nevada of California, USA (Morelli et al., 2016)	H	H	L-M	L	Management agency internal policies may prevent the flexibility required for implementation of adaptation strategies	Some species may face local extirpation or even extinction if adaptive capacity is overwhelmed
Oceans (14.5.2)	Proactive and rapid management approaches to minimize impacts of increasingly frequent entanglements of protected species, caused by climate-driven changes in prey and fishery activities	Dynamic closure areas to reduce loggerhead turtle bycatch in Hawaiian shallow-set longline fisheries (Howell et al., 2015; Lewison et al., 2015), blue whale ship-strike risk in near-real time (Hazen et al., 2017; Abrahms et al., 2019a), and bycatch of multiple top predator species in a West Coast drift gillnet fishery (Hazen et al., 2018).	H	H	M	M	Lack of coordination and planning at multiple scales as species redistribute across fishery areas, marine protected zones, and international and jurisdictional boundaries	Marine species mortality events
Freshwater Resources (14.5.3)	Forecasting and warning of harmful algal blooms (HABs) that affect water quality	Reduced human exposure to the increased risk of toxins from HABs in the Great Lakes	M	L-M	L-M	L-M	Financial resources required to enhance water treatment facilities to deal with HABs; technological innovation to improve treatment and removal of HABs; closure of recreational water use	Severe human health effects; mortality of aquatic species

Water Availability (14.5.3)	Water allocation policies reassessed to enhance equity, sustainability and flexibility in times of shortage through sharing agreements, improved groundwater regulation and voluntary water transfers	US Colorado River interstate shortage sharing agreement	H	H	M	L-M	Complex legal and administrative challenges, heightening lengthy disputes and costly interstate legal battles	Depletion of finite groundwater resources and reduced flow in hydrologically connected rivers
Food & Fibre (14.5.4)	Improved climate resilience through increasing income and harvest/crop portfolio diversification	Fishing communities in the US-SW and US-NE through nature-based aquaculture solutions (Messier et al., 2019; Rogers et al., 2019; Young et al., 2019; Fisher et al., 2021)	H	H	M-H	M	Lack of high resolution and locally tailored climate change information	Collapse of fisheries and loss of crops due to excessive warming and extreme events
Cities & Infrastructure (14.5.5)	Consideration of the value of green infrastructure and natural assets to meet a range of adaptation needs related to flooding, extreme urban heat, SLR, drought	Municipal Natural Assets Initiative (MNAI) assists Canadian municipalities to integrate natural assets in financial planning and asset management programs and consider projected climate changes (Municipal Natural Assets Initiative, 2018)	H	H	M	L-M	Organizations' willingness to take on solutions that are emergent and less tested; capacity for municipalities to undertake the development and assessment this new infrastructure	Rate and magnitude of climate changes exceed capacity of natural/green infrastructure to cope
Health & Communities (14.5.5, 14.5.6)	Access to green spaces, cooler infrastructure, and cooling stations	The heatwave plan for Montreal includes visits to vulnerable populations, cooling shelters, monitoring of heat-related illness, and extended hours for public pools (Lesnikowski et al., 2017)	H	H	L-M	L-M	Lack of effective warning and response systems, ability to reach at-risk populations, building designs, enhanced pollution controls, urban planning strategies, and affordable, resilient health infrastructure	Extreme increase heat-related mortality and morbidity
Tourism & recreation (14.5.7)	Diversification of winter-focused recreation and tourism opportunities	Investments in climate-resilient infrastructure within Canadian National Parks have increased visitation rates during the shoulder seasons (Fisichelli et al., 2015; Lemieux et al., 2017; Wilkins et al., 2018)	H	H	M	L	Social inequalities generated by the tourism development process not considered, such as increased property taxes leading to the marginalization of local residents in favour of wealthy tourists	Lack of precipitation that falls as snow particularly in lower elevation areas
Commerce & transportation (14.5.8)	Improved engineering and technological	For roads, changing pavement mixes to be more tolerant to	H	H	M	L	Lack of financial resources to build climate-resilient	Extreme events may cause

	solutions, in addition to innovative policy, planning, management, and maintenance approaches enhance climate resilience for transportation & related commerce	heat or frost heaving, expanding drainage capacity, reducing flood risks, enhancing travel advisories and alerts, elevating or relocating new infrastructure where feasible and changing infrastructure design requirements (Natural Resources Conservation Service, 2008; EPA, 2017; Pendakur, 2017).		infrastructure, particularly in marginalized communities	significant and irreversible impacts on the transportation sector with major implications for supply-chains and global trade

Adaptive capacity in the face of climate risks and impacts has not been equal across North American communities (Sarkodie and Strezov, 2019). Lack of representation, health inequities, and economic constraints adversely affect the capacity to respond to change and further exacerbate marginalization. For example, within many water basins in Canada and the US, planning processes are often hampered by conflicting interests, asymmetric information and differential power (ICLEI Canada, 2016; Nordgren et al., 2016; Woodruff and Stults, 2016).

The absence of evidence about the current effectiveness of proposed adaptation actions to guide future actions and investments presents a serious risk to North America, especially at higher global warming levels (GWLs) (*medium confidence*). Evaluating the limits to adaptation and the effectiveness of adaptation actions is hindered by a lack of monitoring and evaluation (Auditors General, 2018; Dilling et al., 2019; Berrang-Ford and et al., Accepted). Incremental, passive adaptations are often characterized by *soft limits* due to differing access to resources and by perceptions and tolerance of risk (Moser, 2010; Dow et al., 2013). At current warming levels, socio-ecological systems have been reaching limits to adaptation in regions with high exposure and high sensitivity (*medium confidence*). However, the implications for adaptation are unclear as soft adaptation limits are mutable and change with evolving knowledge, values, interests, and perspectives involved in decision making (Adger et al., 2009; Moser et al., 2017). *Hard* limits have been identified for some natural systems, such as species extinctions (14.5.1.3, Table 14.2, 14.5.2.1).

Adaptation actions in one place or sector can have adverse side effects elsewhere (*medium confidence*). For example, increased use of groundwater for irrigation in response to aridification can reduce baseflows into rivers with adverse impacts on stream ecology and water availability for communities far downstream (14.5.3). Additionally, across multiple sectors in North America, adaptation actions have tended to be sector-specific rather than integrating across systems (Gao and Bryan, 2017; Fulton et al., 2019), despite the increasing awareness of cascading impacts and interdependencies (Zimmerman and Faris, 2010; C40 Cities and AECOM, 2017) and risks from possible ecological and social thresholds that have been identified under higher GWL (14.6.3). For example, the water, energy and food nexus in North America has highlighted that food, water, and energy security depend on transportation infrastructure (Romero-Lankao et al., 2018) (14.5.8.1.2).

14.7.2.2 Adaptation Through Participatory and Robust Decision-Making, Indicators and Sustained Assessments

In response to some of the challenges presented in 14.7.2.1, substantial progress has been made in the North American context on the development of climate services, indicators, sustained assessments, and participatory and stakeholder-driven robust decision-making (*medium confidence*) (Fazey et al.; Fedele et al., 2019; Moss et al., 2019; Boon et al., 2021; Werners et al., 2021).

Decision-making related to adaptation policies, plans and projects has become more formalized, emphasizing participatory governance and co-production of knowledge. Canada has improved capacity with its Canadian Expert Panel on Climate Change Adaptation and Resilience Results (EPCCARR) and the recent National Adaptation Plan (14.7.1.5), with the development of a series of indicators to measure progress on adaptation (EPCCAR, 2018; Government of Canada, 2021a). In the US, indicators have been developed to communicate climate risks and guide adaptation efforts from Federal (Kenney et al., 2020) to more regional initiatives (Kenney and Gerst, 2021). These climate indicators have been used to support user-driven assessments and to articulate adaptation goals (Moss et al., 2019; Kenney et al., 2020). However, these frameworks have not sufficiently incorporated monitoring and evaluation into adaptation plans (Lempert et al., 2018; Kenney et al., 2020). Tools and services to facilitate risk assessment and action planning have been made available through federal government climate service efforts and guidance for their use has been developed (Vano et al., 2018). However, these products have been characterized as insufficiently developed to allow all adaptation practitioners to use these services (Meerow and Mitchell, 2017).

Throughout North America, co-development (or co-production) of adaptation efforts among stakeholders who share common climate vulnerabilities or risk levels (e.g., individuals, groups, communities, businesses or institutions) has been a core attribute of adaptation planning (Mees et al., 2016) and ranges across many sectors (e.g., Box 14.1, 14.5.2.2, 14.5.3.3, 14.5.4.3). Participatory efforts and robust decision-making have also been observed; some integrated watershed planning processes have high degrees of sustained stakeholder involvement (14.5.3.3) (FAQ 14.4; (Harris-Lovett et al., 2015; Cantú, 2016)).

14.7.2.3 Transformational Adaptation and Climate Resilience

Climate change and its projected impacts pose a substantial risk to North America as a region as well as to sectors, communities, and individuals (14.6.2). Incorporating different values and knowledge systems, consideration of equity and justice as core objectives, and addressing underlying vulnerabilities are principles that can guide transformational adaptation and resilience (*medium confidence*).

Approaches that advance adaptation within the existing contexts (finances, institutions, processes) have been increasingly promoted by governments to mainstream climate risk into all considerations (Rosenzweig and Solecki, 2014; Van der Brugge and Roosjen, 2015; Boon et al.; Shi and Moser, 2021). Policies and programs that build upon existing approaches that have inherent climate resilience including Indigenous knowledge-based land and resource management (14.5.4), co-management of agriculture and freshwater resources (Section 14.5.3), nature-based solutions (Box 14.7), links between health and equity, and ecosystem-based management (Section 14.5.2, 14.5.3, 14.5.4) have advanced sustainable and equitable climate resilience. Implementing the recommendations in the ASCE committee's report on adaptation to a changing climate (2018a) and Canada's Infrastructure and Buildings Working Group report has been identified as an opportunity to improve social equity by ensuring the resilience of infrastructure and the services it provides, through adoption of standards and good asset management practices (Amec Foster Wheeler Environment and Infrastructure, 2017; ASCE, 2018a).

Long-term policy signals to incentivize ongoing, scalable adaptation action that is coordinated with mitigation efforts will increase actions and avoid potential maladaptive investment (Moser, 2018; Shi & Moser 2021). Using SDG goals and the NDCs as a framework for inclusive and coordinated partnership and vertical integration across sub-national, national and regional planning can promote climate resilient development (CRD) (18.1.3). Coordination of policies and responses have been identified as supporting longer-term, transformational adaptation and minimizing risk (Termeer et al., 2017; Fazey et al., 2018). New approaches for enabling and incentivizing transformative adaptation in North America are rapidly emerging (Colloff et al. 2017, Fedel et al. 2019, Werners et al. 2021). Evaluation of the feasibility of evolving adaptation strategies is only in the early stages, but recent work has provided the foundation for assessing these considerations (Chapter 16, Table 14.7).

Table 14.7: Simplified example for transitioning from incremental to transformative adaptation approaches to support future climate-resilient sustainable development. Modified from IPCC SR1.5 adaptation feasibility assessment for Land

and Ecosystem Transitions (IPCC, 2018). Feasibility Dimensions (can be barriers and/or enablers): Economic (EC), Technological (TEC), Institutional (INST), Socio-cultural (SOC), Environmental/Ecological (ENV), Geophysical (GEO) (Chapter 16).

		Adaptation Approaches			Mitigation	Feasibility Dimensions	
Hazard	Response	Incremental	Transformational	Evidence/ Agreement	Co-benefits	Barriers	Enablers
Extreme storms causing severe flooding and erosion	Integrated Ecosystem and Watershed management	Restoration of stream corridors to incorporate environmental flows; continuing to build hardened surfaces and stream diversions in urban areas to accommodate infrequent yet extreme storm events	Restoration of streambanks and beds to stabilize and slow flows; use drought-tolerant plantings and shade trees to reduce evaporation rates; incorporate impervious surfaces in urban settings in combination with designating wide buffer area within floodplains to accommodate increased frequency of extreme events; integrate equity & justice considerations	*Medium*	Conservation of soil and increased opportunity for carbon sequestration	Sectors working in silos, inadequate financing, inability to identify shared goals (EC, INST, SOC, GEO)	Develop coordinated suite of adaptation efforts, co-produced among stakeholders and across sectors (INST, SOC, ENV)

Differing values, perspectives, interests, and needs of relevant actors (Dittrich et al., 2016) through participatory processes, such as co-production of knowledge (Meadow et al., 2015; Wall et al., 2017), have been incorporated through the Resilience Dialogues (http://www.resiliencedialogues.org/), and the development of guidance on climate scenarios (Chaumont, 2014). Framing of adaptation goals strongly determines beneficiaries of resultant policies and underscores the importance of a plurality of perspectives in adaptation governance (Cochran et al., 2013; Plummer, 2013; Allison and Bassett, 2015; Raymond-Yakoubian and Daniel, 2018). Sustained engagement through iterative knowledge development, learning, and negotiation has been identified as core for addressing climate risks (Kates et al.; Seijger et al., 2014). Interdisciplinary and inclusive adaptation programs that embrace and plan for conflict and resolution, and address inequalities have been part of broadening the opportunities for engagement (Cantú, 2016; Termeer et al., 2017; Parlee and Wiber, 2018; Sterner et al., 2019; Haasnoot et al., 2020).

Equity and justice in climate adaptation have been identified as providing a foundation for resilience in natural, social, and built systems (Cochran et al., 2013; Reckien et al., 2017; Schell et al., 2020). This approach recognizes that social vulnerability undermines efforts to increase adaptive capacity and that adaptation may also entrench existing social inequities, such as marginalization of communities of colour, gender discrimination, legacy effects of colonisation, and gentrification of coastal communities (Schell et al., 2020; Thomas, 2020). Thus, identifying systemic racism and effects colonialism within and across institutions has also been identified as part of achieving more just and equitable adaptation (Shi & Moser 2021). Acknowledgment and incorporation of Indigenous knowledge in adaptation planning and implementation also recognizes Indigenous sovereignty issues and the importance of the equitable role of Indigenous self-determination in governance and planning (Raymond-Yakoubian and Daniel, 2018) (Box 14.1; 14.4).

Strategies have been emerging to facilitate progress by including specific guidance on tools for financing and funding climate change adaptation infrastructure (Berry and Danielson, 2015; Chen et al., 2016; Zerbe, 2019). This includes facilitating transitions between incremental and transformational efforts to facilitate CRD (Chapter 18, the Five Transitions) (Fig. 14.12).

The extent to which resilient infrastructure contributes to social justice and equity has also been taken into consideration (Climate-Safe Infrastructure Working Group, 2018; Doorn, 2019). Proactive actions focused on small towns and rural areas—including the interdependencies between cities and surrounding areas—increases the potential that small and medium cities can build adaptive capacity at a pace that is commensurate with present and future risks (Moss et al., 2019; Vodden and Cunsolo, 2021). This coordination also creates greater opportunity for translation of knowledge into practice and assessing knowledge in the context that it is to be applied to improve decision-making across scales (Enquist et al., 2017; Moss et al., 2019).

Figure 14.12: Conceptual diagram of the key elements for expanding the adaptation solution space and implementing climate-resilient development (Chapter 18). Figure adapted from Shi & Moser (2021).

[START BOX 14.7 HERE]

Box 14.7: Nature-based Solutions to Support Adaptation to Climate Change

Nature-based Solutions (NbS) are "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2016). NbS in the context of climate change, or Nature-based Adaptation (NbA; Box 1.3), can jointly address multiple social-ecological issues related to climate change hazards, impacts, adaptation and mitigation (Figure Box14.7.1, Cross-Chapter Box NATURAL in Chapter 2). Successful NbA draws from existing adaptation approaches (Borsje et al., 2011; Temmerman et al., 2013; Law et al., 2018; Reguero et al., 2018; Buotte et al., 2019) and is applied across ecological and human systems (Table Box 14.7.1; Figure Box14.7.1; *high confidence*).

Through a capacity to evolve to keep pace with climate change, these approaches can impart self-sustaining and cost-efficient long-term protection in addition to serving as biodiverse, carbon sinks (Scyphers et al., 2011; Cheong et al., 2013; Temmerman et al., 2013; Rodriguez et al., 2014; Herr and Landis, 2016; Sasmito et al., 2016; Reguero et al., 2018). NbA is generally less expensive and strengthens over time, as compared with built infrastructure which erodes with time (*medium confidence*) (Narayan et al., 2016; Smith et al., 2017; Sutton-Grier et al., 2018). Analysis of the impacts of Hurricane Sandy determined that communities located behind wetlands experienced 20% less damage (Narayan et al., 2016). Coral reefs are providing $544M per year (Beck et al., 2018a) and mangroves $22USDB in property protection for coastal communities in the US and Mexico (Beck et al., 2018b). By 2030, flooding from changes in storms, SLR (based on RCP8.5) and increases in built infrastructure in the US Gulf Coast may result in net economic losses of up to US$176 billion, of which US$50 billion could be avoided through implementation of nature-based measures including wetland and oyster reef restoration and other green infrastructure (Box 14.4, 14.5.2) (EPA, 2015b; Reguero et al., 2018).

Innovative approaches in Canada (Borsje et al., 2011; Spalding et al., 2014; Soto-Navarro et al., 2020) and the US (Law et al., 2018; Buotte et al., 2019; Soto-Navarro et al., 2020) have led to social and environmental co-benefits and could address both future climate risk and long-standing social injustices (Hobbie and Grimm, 2020; Schell et al., 2020; Cousins, 2021). Effective NbA requires a well-coordinated suite of adaptation efforts (e.g., assessment, planning, funding, implementation, and evaluation) that is co-produced among stakeholders and across sectors (*high confidence*) (Millar and Stephenson, 2015; Kabisch et al., 2016; Dilling et al., 2019; Morecroft et al., 2019; Lavorel et al., 2020). Evaluating the efficacy of NbA may become more tractable with more uniform guidelines for implementation (Scarano, 2017; Malhi et al., 2020; Seddon et al., 2020), and coordination in scaling-up local-level NbA measures is likely to facilitate long-term success (Gao and Bryan, 2017).

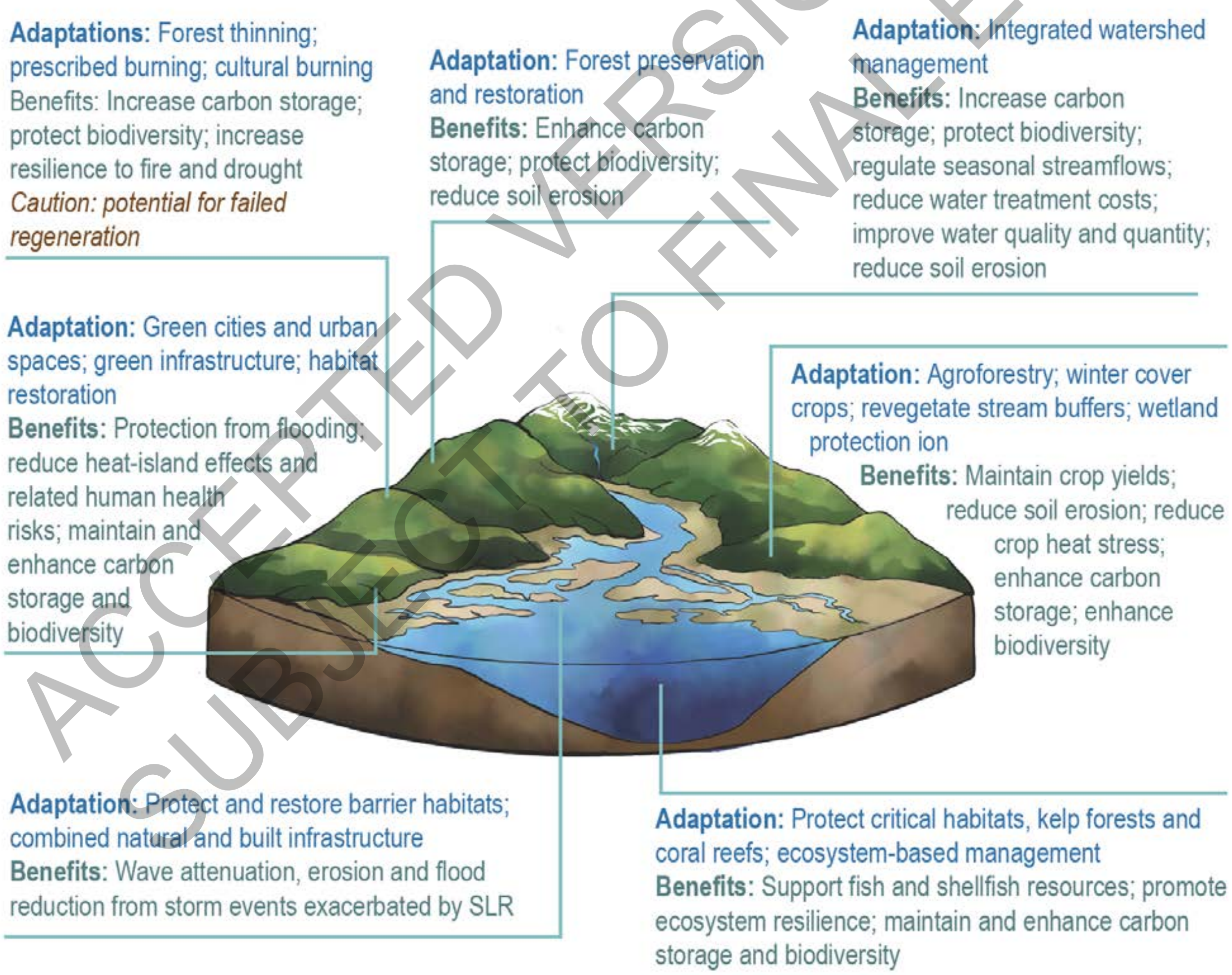


Figure Box14.7.1: Climate hazards protection services provided by nature-based solutions.

Table Box 14.7.1: Nature-based adaptation in North America.

Sector	NbS Actions	Benefits	References

Coasts	Conservation and restoration of barrier habitats, salt marshes, mangroves, coral and oyster reefs, sand dunes, and river deltas; combined natural and built infrastructure, e.g., oyster reef in front of breakwall	Wave attenuation; erosion and flood reduction from storm events exacerbated by SLR; novel, created habitats, connectivity; recreation, quality of life	(Borsje et al., 2011; Scyphers et al., 2011; Cheong et al., 2013; Pinsky et al., 2013a; Temmerman et al., 2013; Ferrario et al., 2014; Möller et al., 2014; Rodriguez et al., 2014; Spalding et al., 2014; Yates et al.; EPA, 2015b; Grenier et al., 2015; Brandon et al., 2016; Herr and Landis, 2016; Narayan et al., 2016; Sasmito et al., 2016; Ward et al., 2016; Aerts et al., 2018; Beck et al., 2018a; Morris et al., 2018b; Moudrak et al.; Reguero et al., 2018; Sutton-Grier et al., 2018)
	Watershed approaches such as protecting and restoring forests and wetlands in coastal watersheds, adopting stream buffers in agricultural areas (see agriculture below)	Create a less flashy/variable hydrology; reduce sediment, nutrient, hazardous chemical input to coastal waters and reduce eutrophication and other water quality impairments, notably in in deep waters where fish seek refuge from rising sea surface temperatures	(Deutsch et al., 2015b) Boesch 2019,CENR 2010
Aquaculture	Controlled culture of fish, bivalves, corals and other marine species	Enhance, restore and reduce pressure on wild species and ecosystems; Restore threatened species such as coral reef species. Store carbon.	(Froehlich et al., 2017; Reid et al., 2019; Theuerkauf et al., 2019)
Agriculture	Re-vegetate stream buffer zones; plant winter cover crops; wetland protection and restoration; agroforestry	Self-sustaining and cost-efficient long-term protection from soil erosion; maintain and enhance crop yields; enhance carbon sinks; enhance biodiversity; reduce nutrient input to coasts	(CENR, 2010; Boesch; Seddon et al., 2020)
Urban Areas	Replace impervious surfaces with permeable pavement, green space, parks, wetlands and green infrastructure, e.g., stormwater ponds, bioswales, rain gardens, green roofs; community gardens, urban forests; restore natural habitats;	Reduce urban heat-island effects, air pollution; self-sustaining and cost-efficient long-term protection from flooding, erosion, SLR; enhance carbon sequestration biodiversity, habitat and connectivity; improved quality of life, human health benefits	(Hobbie and Grimm, 2020; Brown et al., 2021)

Terrestrial	Forest conservation based on productivity and vulnerability to drought and fire; longer harvest rotations	Increase carbon storage and biodiversity	(Law et al., 2018; Buotte et al., 2020; Soto-Navarro et al., 2020; Mori et al., 2021)
	Forest thinning; prescribed burning; cultural burning	Reduce wildfire risk and severity; increase forest resilience to fire; reduce forest drought stress; increase carbon storage	(Box 14.2 and citations therein)
	Protecting and restoring natural forests	Regulate stream flow; reduce soil erosion; protect and enhance biodiversity	(Lawler et al., 2020; Seddon et al., 2020)
	Beaver (*Castor canadensis*) reintroduction	Regulate seasonal stream flow	(McKelvey and Buotte, 2018; Vose et al., 2018)
Freshwater	Forests to Faucets and other watershed restoration projects for stream & drinking water protection	Improve water quality; reduced drinking water treatment costs; increase and regulate streamflow	(Gartner et al., 2017; Claggett and Morgan, 2018; Price and Heberling, 2018)

[END BOX 14.7 HERE]

[START FAQ 14.4 HERE]

FAQ 14.4: What are some effective strategies for adapting to climate change that have been implemented across North America, and are there limits to our ability to adapt successfully to future change?

Climate adaptation is happening across North America. These efforts are differential across sectors, scale and scope. Without more integrative and equitable approaches across broad scales, known as transformational adaptation, the continent may face limits to the future effectiveness of adaptation actions.

Across North America, progress in introducing climate adaptation is steady, but incremental. Adaptation is typically limited to planning, while implementation is often hindered by “soft” limits, such as access to financial resources, disparate access to information and decision-making tools, the existence of antiquated policies and management frameworks, lack of incentives, and highly variable political perceptions of the urgency of climate change.

Cities and other state and local entities are taking the lead in adaptation efforts, particularly in terms of mainstreaming the use of many approaches to adaptation. These approaches include a suite of efforts ranging from assessment of impacts and vulnerability (relative to individuals, communities, jurisdictions, economic sectors, natural resources, etc.), planning processes, implementation of identified strategies, and evaluation of the effectiveness of these strategies. Other institutions (e.g., non-governmental organizations, professional societies, private engineering and architecture businesses) also are making significant progress in the adaptation arena, particularly at local to regional levels.

The water management and utilities sectors have made significant progress toward implementation of adaptation strategies using broad-based participatory planning approaches. Consideration of climate change is now folded into some ongoing watershed-wide planning efforts. An example is provided by the One-Water-One-Watershed (OWOW) approach followed by the Santa Ana Watershed Project Authority (SAWPA) in southern California. SAWPA is a Joint Powers Authority comprising five regional water districts that provide drinking water to more than 6 million people as well as industrial and irrigation water across the 2,400-square-mile watershed. The OWOW perspective focuses on integrated planning for multi-benefit projects and explicit consideration of the impacts of any planning option across the entire watershed.

Planning is supported by stakeholder-driven advisory bodies organized along themes that consider a full suite of technical, political, environmental and social considerations. SAWPA provides member agencies with decision-support tools and assistance to implement water conservation policies and pricing regimes, and one member agency is an industry leader on potable water recycling.

The marine and coastal fisheries sector also has shown considerable progress in climate adaptation planning, particularly in terms of assessing impacts and vulnerability of fisheries. Along the Pacific Northwest coast of the US and Alaska, seasonal and sub-seasonal forecasts of ocean conditions exacerbated by warming (e.g., O_2, pH, temperature, sea ice extent) already have informed fisheries and aquaculture management. Similarly, forecasts and warnings have reduced human exposure to the increased risk of toxins from harmful algal blooms in the Gulf of Mexico, the Great Lakes, California, Florida, Texas and the Gulf of Maine.

Professional organizations and insurance play an important part in mainstreaming climate adaptation. Government and private sector initiatives can help address adaptation effort through building design guidelines and engineering standards, as well as insurance tools that reflects the damages from climate impacts. Through the identification of climate risks and proactive adaptation planning, the private sector can contribute to reducing risks throughout North America by securing operations, supply chains, and markets.

Indigenous Peoples and rural community efforts across the continent show great potential for enhancing and accelerating adaptation efforts particularly when integrated with western-based natural resource management practices, such as cultural burning, traditional forest "tending" that reduces build-up of fuels (in addition to prescribed fire and mechanical thinning). In the agricultural sector, examples include planting and cultivation of culturally significant plants, as a traditional practice of soil conservation, in addition to food crops or in lieu of synthetic or mechanical soil treatments.

Future changes in climate (e.g., more intense heat waves, catastrophic wildfire and post-fire erosion, sea level rise and forced relocations) could exceed the current capacity of human and natural systems to successfully adapt (or "hard limits"). The inclusion and equitable contribution of Indigenous Peoples and rural communities in decision-making and governance processes—including recognition of the interdependencies between cities and surrounding areas—increases the likelihood of building adaptive capacity at a pace that is commensurate with present and future climate change risks.

Large-scale, equitable transformational adaptation likely will be required to respond to the growing rate and magnitude of changes before crossing tipping points where hard limits exist, beyond which adaptation may no longer be possible. Increasingly, there are calls for accelerating and scaling up adaptation efforts, in addition to aligning policies and regulatory legislation at multiple levels of government. Improved processes for adaptation decision-making, governance, and coordination, across sectors and jurisdictions, could enhance North America's capacity to adapt to rapid climatic change. These actions include a focused societal shift, across governments, institutions, and trans-national boundaries, from primarily technological approaches to nature-based solutions that help foster changes in perception of risk and, ultimately, human behaviour.

[END FAQ 14.4 HERE]

References

Abate, R. S. and E. A. Kronk, 2013: *Climate change and Indigenous peoples: The search for legal remedies*. Edward Elgar Publishing, Cheltenham, UK, and Northampton, MA, USA.

Abatzoglou, J. T. et al., 2021: Increasing Synchronous Fire Danger in Forests of the Western United States. *Geophysical Research Letters*, **48**(2), e2020GL091377, doi:https://doi.org/10.1029/2020GL091377.

Abatzoglou, J. T. et al., 2020: Population exposure to pre-emptive de-energization aimed at averting wildfires in Northern California. *Environmental Research Letters*, **15**(9), doi:10.1088/1748-9326/aba135.

Abatzoglou, J. T. and A. P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. U. S. A.*, **113**(42), 11770-11775, doi:10.1073/pnas.1607171113.

Abbas, F. et al., 2017: Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. *Environmental Science and Pollution Research*, **24**(12), 11177-11191, doi:10.1007/s11356-017-8687-0.

Abrahms, B. et al., 2019a: Memory and resource tracking drive blue whale migrations. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(12), 5582-5587, doi:10.1073/pnas.1819031116.

Abrahms, B. et al., 2019b: Dynamic ensemble models to predict distributions and anthropogenic risk exposure for highly mobile species. *Divers. Distrib.*, **116**, 5582, doi:10.1111/ddi.12940.

Abram, N. et al., 2019: Framing and Context of the Report. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [P^rtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. AlegrÌa, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.

Adams, A. et al., 2021: *Climate change and human health in Montana: a special report of the Montana Climate Assessment*. Montana State University, Institute on Ecosystems, Center for American Indian and Rural Health Equity, Bozeman, MT, 216 pp.

Adeel, Z. et al., 2020: Developing a Comprehensive Methodology for Evaluating Economic Impacts of Floods in Canada, Mexico and the United States. *International Journal of Disaster Risk Reduction*, 101861.

Adger, W. N. et al., 2009: Are there social limits to adaptation to climate change? *Climatic Change*, **93**(3-4), 335-354, doi:10.1007/s10584-008-9520-z.

Aerts, J. et al., 2018: Pathways to resilience: adapting to sea level rise in Los Angeles. *Ann N Y Acad Sci*, **1427**(1), 1-90, doi:10.1111/nyas.13917.

Affiliated Tribes of Northwest Indians, 2020: *American Indian Communities in the Contiguous United States: Unmet infrastructure needs and the recommended pathway to address a fundamental threat to lives, livelihoods, and cultures*.

AFN, 2020: *National climate gathering report: Driving Change, leading solutions*. Assembly of First Nations, Ottawa.

AghaKouchak, A. et al., 2015: Water and climate: Recognize anthropogenic drought. *Nature*, **524**(7566), 409-411, doi:10.1038/524409a.

Agnew, R., 2011: Dire forecast: A theoretical model of the impact of climate change on crime. *Theoretical Criminology*, **16**(1), 21-42, doi:10.1177/1362480611416843.

Aguilera, S. E. et al., 2015: Managing Small-Scale Commercial Fisheries for Adaptive Capacity: Insights from Dynamic Social-Ecological Drivers of Change in Monterey Bay. *PLOS ONE*, **10**(3), e0118992, doi:10.1371/journal.pone.0118992.

Aitken, S. N. and M. C. Whitlock, 2013: Assisted Gene Flow to Facilitate Local Adaptation to Climate Change. *Annual Review of Ecology, Evolution, and Systematics*, **44**(1), 367-388, doi:10.1146/annurev-ecolsys-110512-135747.

Akil, L., A. Ahmad and R. S. Reddy, 2014: Effects of climate change on Salmonella infections. *Foodborne Pathogens and Disease*, **11**(12), 974-980, doi:10.1089/fpd.2014.1802.

Aklin, M. and J. Urpelainen, 2014: Perceptions of scientific dissent undermine public support for environmental policy. *Environ. Sci. Policy*, **38**, 173-177, doi:10.1016/j.envsci.2013.10.006.

Akpinar Ferrand, E. and F. Cecunjanin, 2014: Potential of rainwater harvesting in the thirsty world: A survey of ancient and traditional rainwater harvesting applications. *Geography compass*, **8**(6).

Aladenola, O. and C. Madramootoo, 2014: Response of greenhouse-grown bell pepper (Capsicum annuum L.) to variable irrigation. *Canadian Journal of Plant Science*, **94**(2), 303-310, doi:10.4141/cjps2013-048.

Alam, M. J., J. L. Goodall, B. D. Bowes and E. H. Girvetz, 2017: The Impact of Projected Climate Change Scenarios on Nitrogen Yield at a Regional Scale for the Contiguous United States. *JAWRA Journal of the American Water Resources Association*, **53**(4), 854-870, doi:10.1111/1752-1688.12537.

Alava, J. J., W. W. L. Cheung, P. S. Ross and U. R. Sumaila, 2017: Climate change–contaminant interactions in marine food webs: Toward a conceptual framework. *Global Change Biology*, **23**(10), 3984-4001, doi:10.1111/gcb.13667.

Alava, J. J., A. M. Cisneros-Montemayor, U. R. Sumaila and W. W. L. Cheung, 2018: Projected amplification of food web bioaccumulation of MeHg and PCBs under climate change in the Northeastern Pacific. *Sci Rep*, **8**(1), 13460, doi:10.1038/s41598-018-31824-5.

Aldy, J. E., M. J. Kotchen, R. N. Stavins and J. H. Stock, 2021: Keep climate policy focused on the social cost of carbon. *Science*, **373**(6557), 850-852, doi:10.1126/science.abi7813.

Alexander, C. et al., 2011: Linking Indigenous and scientific knowledge of climate change. *BioScience*, **61**(6), 477-484, doi:10.1525/bio.2011.61.6.10.

Alexander, K. A., A. J. A. Hobday, C. A. Cvitanovic and E. A. Ogier, 2019: Progress in integrating natural and social science in marine ecosystem-based management research. 71-83.
Alexeev, V. A., C. D. Arp, B. M. Jones and L. Cai, 2016: Arctic sea ice decline contributes to thinning lake ice trend in northern Alaska. *Environmental Research Letters*, **11**(7), 074022, doi:10.1088/1748-9326/11/7/074022.
Alfie, M. and G. M. Cruz-Bello, 2021: *Living with risk: climate change and vulnerability. Community perceptions in peri-urban areas of La Paz City, Mexico*. Available at: http://ilitia.cua.uam.mx:8080/jspui/bitstream/123456789/362/1/Living with risk.pdf.
Alfred, T., 2009: Colonialism and state dependency. *Journal of Aboriginal Health*, **5**(2), 42-60.
Alfred, T., 2015: Cultural strength: Restoring the place of Indigenous knowledge in practice and policy. *Australian Aboriginal Studies*, **1**, 3-11.
Alfred, T. and J. Corntassel, 2005: Being Indigenous: Resurgences against contemporary colonialism. *Government and Opposition*, **40**(4), 597-614, doi:10.1111/j.1477-7053.2005.00166.x.
Allaire, M., H. W. Wu and U. Lall, 2018: National trends in drinking water quality violations. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(9), 2078-2083, doi:10.1073/pnas.1719805115.
Allen, C. D., D. D. Breshears and N. G. McDowell, 2015: On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, **6**(8), art129, doi:10.1890/es15-00203.1.
Allen, M. J. and S. C. Sheridan, 2018: Mortality risks during extreme temperature events (ETEs) using a distributed lag non-linear model. *International Journal of Biometeorology*, **62**(1), 57-67, doi:10.1007/s00484-015-1117-4.
Allison, E. H. and H. R. Bassett, 2015: Climate change in the oceans: Human impacts and responses. *Science*, **350**(6262), 778-782, doi:10.1126/science.aac8721.
Alman, B. L. et al., 2016: The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: A case crossover study. *Environmental Health*, **15**(1), 1-9, doi:10.1186/s12940-016-0146-8.
Altieri, A. H. and K. B. Gedan, 2015: Climate change and dead zones. *Glob. Chang. Biol.*, **21**(4), 1395-1406, doi:10.1111/gcb.12754.
Altieri, M. A. and C. I. Nicholls, 2009: Cambio climático y agricultura campesina: impactos y respuestas adaptativas. *LEISA revista de agroecología*, **24**(4), 5-8.
Amap, 2017: *Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay-Davis Strait Region*. 1-19 pp.
Amec Foster Wheeler Environment and Infrastructure, 2017: *National infrastructure and buildings climate change adaptation state of play report*. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjZ3Ij42uDyAhXMop4KHRuRDgwQFnoECAUQAQ&url=https%3A%2F%2Fengineerscanada.ca%2Fsites%2Fdefault%2Ffiles%2Fibwg_sop_2017.pdf&usg=AOvVaw3m4_iWRCO8opw9Nhv9P49f.
Anarde, K. A. et al., 2017: Impacts of hurricane storm surge on infrastructure vulnerability for an evolving coastal landscape. *Natural Hazards Review*, **19**(1), 4017020-4017020.
Anderegg, W. R., J. W. Prall, J. Harold and S. H. Schneider, 2010: Expert credibility in climate change. *Proceedings of the National Academy of Sciences*, **107**(27), 12107-12109.
Anderies, J. M., S. R. Carpenter, W. Steffen and J. Rockström, 2013: The topology of non-linear global carbon dynamics: from tipping points to planetary boundaries. *Environmental Research Letters*, **8**(4), 044048-044048, doi:10.1088/1748-9326/8/4/044048.
Anderson, C. R. et al., 2019: Scaling up from regional case studies to a global harmful algal bloom observing system. *Frontiers in Marine Science*, **6**, 250.
Anderson, D. G. et al., 2017: Sea-level rise and archaeological site destruction: An example from the southeastern United States using DINAA (Digital Index of North American Archaeology). *PLoS ONE*, **12**(11), 1-25, doi:10.1371/journal.pone.0188142.
Anderson, F. and N. Al-Thani, 2016: Effect of sea level rise and groundwater withdrawal on seawater intrusion in the Gulf Coast Aquifer: Implications for agriculture. *Journal of Geoscience and Environment Protection*, **04**(04), 116-124, doi:10.4236/gep.2016.44015.
Anderson, G. B., K. W. Oleson, B. Jones and R. D. Peng, 2018a: Classifying heatwaves: developing health-based models to predict high-mortality versus moderate United States heatwaves. *CLIMATIC CHANGE*, **146**(3-4, SI), 439-453, doi:10.1007/s10584-016-1776-0.
Anderson, G. B., K. W. Oleson, B. Jones and R. D. Peng, 2018b: Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities. *Climatic Change*, **146**(3-4), 455-470, doi:10.1007/s10584-016-1779-x.
Andrey, J. and K. Palko, 2017: Introduction. In: *Climate risks and adaptation practices for the Canadian transportation sector 2016* [Palko, K. and D. S. Lemmen (eds.)]. Government of Canada, Ottawa, ON, pp. 2-10.
Angel, J. et al., 2018a: Midwest. In: *Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 872-940.
Angel, J. et al., 2018b: Midwest. [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 872-940.
Aquilué, N. et al., 2020: Evaluating forest resilience to global threats using functional response traits and network properties. *Ecological Applications*, **30**(5), 1-14, doi:10.1002/eap.2095.

Arafeh-Dalmau, N. et al., 2019: Extreme Marine Heatwaves Alter Kelp Forest Community Near Its Equatorward Distribution Limit. *Frontiers in Marine Science*, **6**(499), doi:10.3389/fmars.2019.00499.
Aragón-Durand, F., 2020: Resilience of Mexico City Megalopolis to climate change. [Michael, B., J. Twigg, A. Allen and C. Wamsler (eds.)]. Routledge.
Arbuckle, M. B., 2017: The interaction of religion, political ideology, and concern about climate change in the United States. *Soc. Nat. Resour.*, **30**(2), 177-194.
Arce Romero, A. et al., 2020: Crop yield simulations in Mexican agriculture for climate change adaptation. *2020*, **33**(3), 17, doi:10.20937/atm.52430.
Archer, S. R. et al., 2017: Woody Plant Encroachment: Causes and Consequences. *Rangeland Systems*, 25-84, doi:10.1007/978-3-319-46709-2_2.
Arnberger, A. et al., 2018: Visitor preferences for visual changes in bark beetle-impacted forest recreation settings in the United States and Germany. *Environmental Management*, **61**(2), 209-223.
Arnold, C. A., H. Gosnell, M. H. Benson and R. K. Craig, 2017: Cross-interdisciplinary insights into adaptive governance and resilience. *Ecol. Soc.*, **22**(4), doi:10.5751/es-09734-220414.
Arsenault, R., 2021: Water insecurity in Ontario First Nations: An exploratory study on past interventions and the need for Indigenous Water Governance. *Water*, **13**(5), 717, doi:10.3390/w13050717.
ASCE, 2018a: *Climate-Resilient Infrastructure: Adaptive Design and Risk Management* [Bilal, M. A. (ed.)]. Engineers, A. S. o. C., Reston, VA. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwih14yZ8-DyAhXJxZ4KHdQFDQ0QFnoECAIQAQ&url=https%3A%2F%2Fwww.techstreet.com%2Fproducts%2Fpreview%2F2025997&usg=AOvVaw1bG0UB95MvM4-KF5o8Llln.
ASCE (ed.), 2018b: *Climate-Resilient Infrastructure: Adaptive Design and Risk Management*, ASCE Manuals and Reports on Engineering Practice No. 140, American Society of Civil Engineers, Reston VA, 311 pp. ISBN ISBN 9780784415191.
ASCE, 2019: Congress introduces legislation on the clean water state revolving fund. Available at: https://www.infrastructurereportcard.org/congress-introduces-legislation-clean-water-state-revolving-fund/.
ASCE, 2021: *A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure: American Society of Civil Engineers*. Available at: https://infrastructurereportcard.org/wp-content/uploads/2020/12/National_IRC_2021-report.pdf.
Attavanich, W. et al., 2013: Effects of climate change on US grain transport. *Nat. Clim. Chang.*, **3**(7), 638-643, doi:10.1038/nclimate1892.
Atzori, R., A. Fyall and G. Miller, 2018: Tourist responses to climate change: Potential impacts and adaptation in Florida's coastal destinations. *Tourism Management*, **69**, 12-22, doi:10.1016/J.TOURMAN.2018.05.005.
Audefroy, J. F. and B. N. Cabrera Sánchez, 2017: Integrating local knowledge for climate change adaptation in Yucatan, Mexico. *International Journal of Sustainable Built Environment*, **6**, 228-237.
Auditors General, 2018: *Perspectives on climate change action in Canada*. Office of the Auditors General, Canada, O. o. t. A. G. o., 49 pp. Available at: https://www.oag-bvg.gc.ca/internet/English/parl_otp_201803_e_42883.html.
Auffhammer, M., 2018: Quantifying economic damages from climate change. *Journal of Economic Perspectives*, **32**(4), 33-52.
Azócar, G. et al., 2021: Climate change perception, vulnerability, and readiness: inter-country variability and emerging patterns in Latin America. *Journal of Environmental Studies and Sciences*, **11**(1), 23-36, doi:10.1007/s13412-020-00639-0.
Azuz-Adeath, I., E. Rivera-Arriaga and H. Alonso-Peinada, 2018: Current Demographic Conditions and Future Scenarios in Mexico´s Coastal Zone. *Journal of Integrated Coastal Zone Management*, **19**(2), 85-112.
Bachelet, M., 2019: Global update at the 42nd session of the Human Rights Council, Opening statement by UN High Commissioner for Human Rights Michelle Bachelet.
Bad River Band of Lake Superior Tribe of Chippewa Indians and Abt Associates Inc., 2016: *Bad River Reservation: Seventh generation climate change monitoring plan*.
Baeza, A. et al., 2018: Biophysical, infrastructural and social heterogeneities explain spatial distribution of waterborne gastrointestinal disease burden in Mexico City. *Environmental Research Letters*, **13**(6), doi:10.1088/1748-9326/aac17c.
Bai, Y. N., A. Fernald, V. Tidwell and T. Gunda, 2019: Reduced and Earlier Snowmelt Runoff Impacts Traditional Irrigation Systems. *Journal of Contemporary Water Research & Education*, **168**(1), 10-28, doi:10.1111/j.1936-704X.2019.03318.x.
Bain, D. M. and T. L. Acker, 2018: Hydropower Impacts on Electrical System Production Costs in the Southwest United States. *Energies*, **11**(2), doi:10.3390/en11020368.
Baker, J. E., 2021: Subsidies for Succulents: Evaluating the Las Vegas Cash-for-Grass Rebate Program. *Journal of the Association of Environmental and Resource Economists*, **8**(3), 475-508, doi:10.1086/712429.
Ball, G., P. Regier and R. González-Pinzón, 2021: Wildfires increasingly impact western US fluvial networks. *Nat Commun* **12**, doi:https://doi.org/10.1038/s41467-021-22747-3.
Ballard, M. and S. Thompson, 2013: Flooding hope and livelihoods: Lake St. Martin First Nation. *Canadian Journal of Nonprofit and Social Economy Research*, **4**(1), 43-65, doi:10.22230/ cjnser.2013v4n1a129.

Ballard, T. C., E. Sinha and A. M. Michalak, 2019: Long-Term Changes in Precipitation and Temperature Have Already Impacted Nitrogen Loading. *Environmental Science & Technology*, **53**(9), 5080-5090, doi:10.1021/acs.est.8b06898.
Ballew, M. T. et al., 2019: Climate Change in the American Mind: Data, Tools, and Trends. *Environment: Science and Policy for Sustainable Development*, **61**(3), 4-18.
Ballew, M. T. et al., 2020: Does socioeconomic status moderate the political divide on climate change? The roles of education, income, and individualism. *Global environmental change*, **60**, 102024.
Ballinas, M. and V. L. Barradas, 2016: The Urban Tree as a Tool to Mitigate the Urban Heat Island in Mexico City: A Simple Phenomenological Model. *Journal of environmental quality*, **45**(1), 157-166, doi:10.2134/jeq2015.01.0056.
Bamford, E. et al., 2020: *NIDIS Tribal Drought Engagement Strategy 2021–2025: For the Missouri River Basin and Midwest Drought Early Warning Systems (DEWS)*. NOAA NIDIS.
Banerjee, S. K., R. Rutley and J. Bussey, 2018: Diversity and dynamics of the Canadian coastal Vibrio community: An emerging trend detected in the temperate regions. *Journal of Bacteriology*, **200**(15), 1-4, doi:10.1128/JB.00787-17.
Barbaras, A. M., 2014: Indigenous territoriality in contemporary Mexico. *Chungará: Revista de Antropología Chilena*, **46**(3), 437-452.
Barbeaux, S. J., K. Holsman and S. Zador, 2020: Marine Heatwave Stress Test of Ecosystem-Based Fisheries Management in the Gulf of Alaska Pacific Cod Fishery. *Frontiers in Marine Science*, **7**(August), 1-21, doi:10.3389/fmars.2020.00703.
Barber, D. G. et al., 2018a: Increasing mobility of high Arctic Sea ice increases marine hazards off the east coast of Newfoundland. *Geophysical Research Letters*, **45**, 2370-2379.
Barber, Q. E. et al., 2018b: Potential impacts of climate change on the habitat of boreal woodland caribou. *Ecosphere*, **9**(10), e02472.
Barbier, E. B., 2014: Climate change mitigation policies and poverty. *WIREs Clim Change*, **5**, 483-491.
Barnard, P. L. et al., 2019: Dynamic flood modeling essential to assess the coastal impacts of climate change. *Sci Rep*, **9**(1), 1-13, doi:10.1038/s41598-019-40742-z.
Barnett, A. G., S. Hajat, A. Gasparrini and J. Rocklöv, 2012: Cold and heat waves in the United States. *Environmental Research*, **112**, 218-224, doi:10.1016/j.envres.2011.12.010.
Barnett, J., 2018: Global environmental change I: Climate resilient peace? *Progress in Human Geography*, **43**(5), 927-936, doi:10.1177/0309132518798077.
Barreca, A. et al., 2016: Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century. *Journal of Political Economy*, **124**(1), 105-159, doi:10.1086/684582.
Barreiro, J., 1999: Global warming, climate change and native lands issue. *Native Americas: Hemispheric journal of Indigenous Issues*, **XVI Fall/W**.
Barrera-Bassols, N. and V. M. Toledo, 2005: Ethnoecology of the Yucatec Maya: Symbolism, knowledge and management of natural resources. *Journal of Latin American Geography*, **4**(1), 9-41, doi:10.1353/lag.2005.0021.
Bartos, M. D. and M. V. Chester, 2015: Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change*, **5**(8), 748-752, doi:10.1038/nclimate2648.
Basel, B. et al., 2020: Bee mietii rak rkabni nis (The people know how to seed water): A Zapotec experience in adapting to water scarcity and drought. *Climate and Development*, 1-15, doi:10.1080/17565529.2020.1855100.
Battiste, M. A. and J. Y. Henderson, 2000: *Protecting Indigenous Knowledge and Heritage: A Global Challenge*. UBC Press, Purich Publishing, 324-324 pp. ISBN 9781895830156.
Bauer, S. et al., 2015: Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. *PLoS ONE*, **10**(3), 1-25, doi:10.1371/journal.pone.0120016.
Bawa, R. S., 2017: Effects of wildfire on the value of recreation in western North America. *Journal of Sustainable Forestry*, **36**(1), 1-17, doi:10.1080/10549811.2016.1233503.
Baysan, C. et al., 2019: Economic and Non-Economic Factors in Violence: Evidence from Organized Crime, Suicides and Climate in Mexico. doi:10.1016/j.jebo.2019.10.021.
Beach, R. H. et al., 2015: Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*, **10**(9), 095004, doi:10.1088/1748-9326/10/9/095004.
Beach, R. H. et al., 2019: Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. *The Lancet Planetary Health*, **3**(7), e307-e317, doi:10.1016/s2542-5196(19)30094-4.
Beaugrand, G. et al., 2015: Future vulnerability of marine biodiversity compared with contemporary and past changes. *Nature Climate Change*, **5**(7), 695-695.
Beavers, R. L., U. S. N. P. Service, C. A. Schupp and M. A. Caffrey, 2016: RESOURCE MANAGEMENT OF COASTAL PARKS: ADAPTATION STRATEGIES IN AN ERA OF CLIMATE CHANGE. doi:10.1130/abs/2016am-282514.
Beck, M. W. et al., 2018a: The global flood protection savings provided by coral reefs. *Nature Communications*, **9**(1), 2186, doi:10.1038/s41467-018-04568-z.
Beck, M. W. et al., 2018b: *The global value of mangroves for risk reduction. Summary Report.*, The Nature Conservancy, Conservancy, T. N., Berlin, 12 pp.

Becken, S. and J. Hay, 2007: *Tourism and Climate Change (Risks and Opportunities)*. Channel View Publications North York, ON. ISBN 9781845410674.
Bedsworth, L. et al., 2018: Statewide Summary Report. California's Fourth Climate Change Assessment. *publication no. SUMCCCA4--2018--013*.
Behe, C., R. Daniel and J. Raymond-Yakoubian, 2018: Understanding the Arctic through a co-production of knowledge.
Bell, J., M. Brubaker, K. Graves and J. Berner, 2010: *Climate change and mental health: uncertainty and vulnerability for Alaska Natives*.
Beltaos, S. and B. C. Burrell, 2015: Hydroclimatic aspects of ice jam flooding near Perth-Andover, New Brunswick. *Canadian Journal of Civil Engineering*, **42**(9), 686-695, doi:10.1139/cjce-2014-0372.
Bendixsen, D. P., S. W. Hallgren and A. E. Frazier, 2015: Stress factors associated with forest decline in xeric oak forests of south-central United States. *Forest Ecology and Management*, **347**, 40-48, doi:10.1016/j.foreco.2015.03.015.
Benmarhnia, T. et al., 2016: A difference-in-differences approach to assess the effect of a heat action plan on heat-related mortality, and differences in effectiveness according to sex, age, and socioeconomic status (Montreal, Quebec). *Environ. Health Perspect.*, **124**(11), 1694-1699, doi:10.1289/EHP203.
Bennett, A. and J. Grannis, 2017: *Lessons in Regional Resilience: Case Studies on Regional Climate Collaboratives*. Georgetown Climate Center, Washington, DC.
Bennett, M. M. et al., 2020: The opening of the Transpolar Sea Route: Logistical, geopolitical, environmental, and socioeconomic impacts. *Marine Policy*,(August), doi:10.1016/j.marpol.2020.104178.
Bennett, T. M. B. et al., 2014: Indigenous Peoples, lands, and resources. In: *Climate change impacts in the United States: The Third National Climate Assessment* [Melillo, J., T. C. Richmond and G. W. Yohe (eds.)]. U.S. Global Change Research Program, pp. 297-317.
Bentz, B. J. et al., 2019: Ips typographus and Dendroctonus ponderosae Models Project Thermal Suitability for Intra- and Inter-Continental Establishment in a Changing Climate. *Frontiers in Forests and Global Change*, **2**(March), doi:10.3389/ffgc.2019.00001.
Berardi, U. and P. Jafarpur, 2020: Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renewable and Sustainable Energy Reviews*, **121**, 109681, doi:https://doi.org/10.1016/j.rser.2019.109681.
Bering Sea Elders Advisory Group and Alaska Marine Conservation Council, 2011: *The Northern Bering Sea: Our way of life*. Available at: https://eloka-arctic.org/communities/media/files/AMCC_BeringSeaElders-northern-bering-sea-report-04-01-12.pdf.
Bering Sea Elders Group, 2016: Northern Bering Sea and Bering Strait: Ecosystem and climate change.
Bermeo, A., S. Couturier and M. G. Pizaña, 2014: Conservation of traditional smallholder cultivation systems in indigenous territories: Mapping land availability for milpa cultivation in the Huasteca Poblana, Mexico. *Applied Geography*, **53**, 299-310, doi:10.1016/j.apgeog.2014.06.003.
Berrang-Ford, L. and et al., Accepted: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*.
Berry, J. and L. Danielson, 2015: *Paying for urban infrastructure adaptation in Canada: An analysis of existing and potential economic instruments for local governments*. Simon Fraser University.
Bertrand, A. et al., 2020: *El Niño Southern Oscillation (ENSO) effects on fisheries and aquaculture*. FAO, Rome. ISBN 978-92-5-132327-4.
Bhattachan, A. et al., 2018: Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. *Environmental Science and Policy*, **90**(October), 122-134, doi:10.1016/j.envsci.2018.10.006.
BIA, 2021: *National Climate Assessment: Indigenous Peoples Resilience Actions*. Bureau of Indian Affairs.
Bianucci, L. et al., 2016: Ocean biogeochemical models as management tools: a case study for Atlantic wolffish and declining oxygen. *ICES Journal of Marine Science: Journal du Conseil*, **73**(2), 263-274, doi:10.1093/icesjms/fsv220.
Bierbaum, R. et al., 2013: A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change*, **18**(3), 361-406.
Billiot, S. et al., 2020a: *Pillar 9: Make U.S. Communities more resilient to the impacts of climate change in review of the 2020 Congressional Action Plan on the climate crisis*.
Billiot, S. et al., 2020b: *Pillar 7: Improve public health and manage climate risks to health infrastructure in Tribal review of the 2020 Congressional Action Plan on the climate crisis*.
Binder, S. B., C. K. Baker and J. P. Barile, 2015: Rebuild or relocate? Resilience and postdisaster decision-making after Hurricane Sandy. *American Journal of Community Psychology*, **56**(1-2), 180-196, doi:10.1007/s10464-015-9727-x.
Bisbis, M. B., N. Gruda and M. Blanke, 2018: Potential impacts of climate change on vegetable production and product quality--A review. *J. Clean. Prod.*, **170**, 1602-1620.
Bitter, M. C., L. Kapsenberg, J. P. Gattuso and C. A. Pfister, 2019: Standing genetic variation fuels rapid adaptation to ocean acidification. *Nature Communications*, **10**(1), 1-10, doi:10.1038/s41467-019-13767-1.
Bladon, K. D., M. B. Emelko, U. Silins and M. Stone, 2014: Wildfire and the future of water supply. *Environ. Sci. Technol.*, **48**(16), 8936-8943, doi:10.1021/es500130g.

Board, T. R. and N. R. Council, 2008: *Potential Impacts of Climate Change on U.S. Transportation: Special Report 290*. The National Academies Press, Washington, DC, 296 pp.
Boesch, D. F., 2019: Barriers and Bridges in Abating Coastal Eutrophication. *Frontiers in Marine Science*, **6**(123), doi:10.3389/fmars.2019.00123.
Bogdanski, B., L. Sun, B. Peter and B. Stennes, 2011: *Markets for forest products following a large disturbance: Opportunities and challenges from the mountain pine beetle outbreak in western Canada*. Information Report, Centre, T. P. F., Victoria, BC, 78 pp. Available at: https://www.researchgate.net/profile/Bryan-Bogdanski/publication/264040371_Markets_for_forest_products_following_a_large_disturbance_opportunities_and_challenges_from_the_mountain_pine_beetle_outbreak_in_western_Canada/links/54887b5b0cf2ef3447909bfe/Markets-for-forest-products-following-a-large-disturbance-opportunities-and-challenges-from-the-mountain-pine-beetle-outbreak-in-western-Canada.pdf?_sg%5B0%5D=aZeI4sS7IK-g8FNWZiuRyv-LvHNjd9-UPHso-Z1PsDrER_wSw3AjyQ4uMhPEKaKu4XmjV-Y8zYA7BOTNeqHZbA.su52m_s1ZNUvyr2k.
Bolsen, T., J. Druckman and F. Cook, 2015: Citizens', Scientists', and Policy Advisors' Beliefs about Global Warming. *Ann. Am. Acad. Pol. Soc. Sci.*, **658**(1), 271-295, doi:10.1177/0002716214558393.
Bolsen, T. and J. N. Druckman, 2018: Do partisanship and politicization undermine the impact of a scientific consensus message about climate change? *Group Process. Intergroup Relat.*, **21**(3), 389-402, doi:10.1177/1368430217737855.
Bolsen, T., R. Palm and J. T. Kingsland, 2019: Counteracting Climate Science Politicization With Effective Frames and Imagery. *Sci. Commun.*, **41**(2), 147-171, doi:10.1177/1075547019834565.
Bolsen, T. and M. A. Shapiro, 2018: The US News Media, Polarization on Climate Change, and Pathways to Effective Communication. *Environmental Communication*, **12**(2), 149-163, doi:10.1080/17524032.2017.1397039.
Bomberg, E., 2021: The environmental legacy of President Trump. *Policy Studies*, 1-18, doi:10.1080/01442872.2021.1922660.
Bonsal, B., Z. Liu, E. Wheaton and R. Stewart, 2020: Historical and Projected Changes to the Stages and Other Characteristics of Severe Canadian Prairie Droughts. *Water*, **12**(12), doi:10.3390/w12123370.
Bonsal, B. R. et al., 2019: Chapter 6. Changes in freshwater availability across Canada. Government of Canada Ottawa, Ontario, 261–342 pp.
Boon, E., H. Goosen, F. van Veldhoven and R. Swart, 2021: Does Transformational Adaptation Require a Transformation of Climate Services? *Frontiers in Climate*, **3**(2), doi:10.3389/fclim.2021.615291.
Boretti, A., 2019: A realistic expectation of sea level rise in the Mexican Caribbean. *Journal of Ocean Engineering and Science*, **4**(4), 379-386, doi:https://doi.org/10.1016/j.joes.2019.06.003.
Borish, D., Accepted: Relationships between Rangifer and Indigenous well-being in the North American Arctic and Subarctic: What we know, what we don't know, and what we need to know. *Arctic*, **75**(1).
Borrows, J., 2002: *Recovering Canada: The resurgence of Indigenous law*. University of Toronto Press, Toronto.
Borrows, J., 2010a: *Canada's Indigenous constitution*. University of Toronto Press, Toronto.
Borrows, J., 2010b: *Drawing out law: A spirit's guide*. University of Toronto Press, Toronto.
Borrows, J., 2016: *Freedom and Indigenous constitutionalism*. University of Toronto Press, Toronto.
Borsje, B. W. et al., 2011: How ecological engineering can serve in coastal protection. *Ecol. Eng.*, **37**(2), 113-122, doi:10.1016/j.ecoleng.2010.11.027.
Bose, A. K., A. Weiskittel and R. G. Wagner, 2017: A three decade assessment of climate-associated changes in forest composition across the north-eastern USA. *Journal of Applied Ecology*, **54**(6), 1592-1604, doi:10.1111/1365-2664.12917.
Boulanger, Y., S. Gauthier and P. J. Burton, 2014: A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. *Canadian Journal of Forest Research*, **44**(4), 365-376, doi:10.1139/cjfr-2013-0372.
Bourne, A. et al., 2016: A Socio-Ecological Approach for Identifying and Contextualising Spatial Ecosystem-Based Adaptation Priorities at the Sub-National Level. *PLOS ONE*, **11**(5), e0155235, doi:10.1371/journal.pone.0155235.
Bowling, L. C. et al., 2020: Agricultural impacts of climate change in Indiana and potential adaptations. *Climatic Change*, **163**(4), 2005-2027, doi:10.1007/s10584-020-02934-9.
Box, J. E. et al., 2019: Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, **14**(4), 045010, doi:10.1088/1748-9326/aafc1b.
Boyd, R. and A. Markandya, 2021: Costs and Benefits of Climate Change Impacts and Adaptation. In: *Canada in a Changing Climate* [Warren, F. J. and N. Lulham (eds.)], pp. 345-487.
Boykoff, M. T. and J. M. Boykoff, 2004: Balance as bias: Global warming and the US prestige press. *Global environmental change*, **14**(2), 125-136.
Boykoff, M. T. and J. M. Boykoff, 2007: Climate change and journalistic norms: A case-study of US mass-media coverage. *Geoforum*, **38**(6), 1190-1204.
Boyle, A. D. et al., 2021: Green New Deal proposals: Comparing emerging transformational climate policies at multiple scales. *Energy Research & Social Science*, **81**, 102259, doi:https://doi.org/10.1016/j.erss.2021.102259.
Bradford, J. B. and D. M. Bell, 2017: A window of opportunity for climate-change adaptation: easing tree mortality by reducing forest basal area. *Frontiers in Ecology and the Environment*, **15**(1), 11-17, doi:10.1002/fee.1445.
Bradford, J. B., D. R. Schlaepfer, W. K. Lauenroth and K. A. Palmquist, 2020: Robust ecological drought projections for drylands in the 21st century. *Global Change Biology*, **26**(7), 3906-3919, doi:10.1111/gcb.15075.

Brandon, C. M., J. D. Woodruff, P. M. Orton and J. P. Donnelly, 2016: Evidence for elevated coastal vulnerability following large-scale historical oyster bed harvesting. *Earth Surface Processes and Landforms*, **41**(8), 1136-1143, doi:10.1002/esp.3931.
Brecka, A. F. J., C. Shahi and H. Y. H. Chen, 2018: Climate change impacts on boreal forest timber supply. *Forest Policy and Economics*, **92**, 11-21, doi:10.1016/j.forpol.2018.03.010.
Breckheimer, I. K. et al., 2020: Crowd-sourced data reveal social–ecological mismatches in phenology driven by climate. *Frontiers in Ecology and the Environment*, **18**(2), 76-82, doi:10.1002/fee.2142.
Breitburg, D. et al., 2018: Declining oxygen in the global ocean and coastal waters. *Science*, **359**(6371), doi:10.1126/science.aam7240.
Bressler, J. M. and T. W. Hennessy, 2018: Results of an Arctic Council survey on water and sanitation services in the Arctic. *International Journal of Circumpolar Health*, **77**(1), 1421368, doi:10.1080/22423982.2017.1421368.
Briske, D. D. et al., 2015: Climate-change adaptation on rangelands: linking regional exposure with diverse adaptive capacity. *Frontiers in Ecology and the Environment*, **13**(5), 249-256, doi:10.1890/140266.
British Columbia Hydro, 2019: *Storm report: The most damaging storm in BC Hydro's history*. Available at: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/news-and-features/report-most-damaging-storm-bc-hydro-history-january-2019.pdf.
Bronen, R., J. K. Maldonado, E. Marino and P. Hardison, 2018: Climate change and displacement: Challenges and needs to address an imminent reality. In: *Challenging the prevailing paradigm of displacement and resettlement: Risks, impoverishment, legacies, solutions* [Cernea, M. M. and J. K. Maldonado (eds.)]. Routledge, pp. 252-272.
Brosch, T., 2021: Affect and emotions as drivers of climate change perception and action: a review. *Current Opinion in Behavioral Sciences*, **42**, 15-21, doi:https://doi.org/10.1016/j.cobeha.2021.02.001.
Brown, C., E. Jackson, D. Harford and D. Bristow, 2021: Cities and towns. [Warren, F. J. and N. Lulham (eds.)]. Government of Canada, Ottawa, ON, pp. 26-102.
Brown, H. E. et al., 2015a: Projection of climate change influences on US West Nile virus vectors. *Earth Interactions*, **19**(18), 1-18, doi:10.1175/EI-D-15-0008.1.
Brown, M. E. et al., 2015b: *Climate Change, Global Food Security, and the U.S. Food System*. Washington, DC. Available at: https://www.usda.gov/oce/climate_change/FoodSecurity2015Assessment/FullAssessment.pdf.
Brown, M. R. et al., 2019a: Significant PTSD and other mental health effects present 18 months after the Fort Mcmurray wildfire: findings from 3,070 grades 7–12 students. *Frontiers in psychiatry*, **10**, 623.
Brown, T. C., V. Mahat and J. A. Ramirez, 2019b: Adaptation to Future Water Shortages in the United States Caused by Population Growth and Climate Change. *Earths Future*, **7**(3), 219-234, doi:10.1029/2018ef001091.
Brubacher, J. et al., 2020: Associations of five food- and water-borne diseases with ecological zone, land use and aquifer type in a changing climate. *Science of the Total Environment*, **728**, 138808, doi:10.1016/j.scitotenv.2020.138808.
Brubaker, M. et al., 2014: *Climate change in Wainwright, Alaska: Strategies for community health*. ANTHC Center for Climate and Health. Available at: https://anthc.org/wp-content/uploads/2016/01/CCH_AR_062014_Climate-Change-in-Wainwright.pdf.
Brugère, C., J. Aguilar-Manjarrez, M. C. M. Beveridge and D. Soto, 2019: The ecosystem approach to aquaculture 10 years on – a critical review and consideration of its future role in blue growth. *Reviews in Aquaculture*, **11**(3), 493-514, doi:10.1111/raq.12242.
Brulle, R. J., 2014: Institutionalizing delay: foundation funding and the creation of US climate change counter-movement organizations. *Climatic change*, **122**(4), 681-694.
Brulle, R. J., 2018: The climate lobby: a sectoral analysis of lobbying spending on climate change in the USA, 2000 to 2016. *Climatic change*, **149**(3), 289-303.
Brulle, R. J., J. Carmichael and J. C. Jenkins, 2012: Shifting public opinion on climate change: an empirical assessment of factors influencing concern over climate change in the US, 2002–2010. *Climatic change*, **114**(2), 169-188.
Brunn, A., D. N. Fisman, J. M. Sargeant and A. L. Greer, 2019: The influence of climate and livestock reservoirs on human cases of Giardiasis. *EcoHealth*, **16**, 116-127, doi:10.1007/s10393-018-1385-7.
Bruno, J. F. et al., 2018: Publisher Correction: Climate change threatens the world's marine protected areas. *Nature Climate Change*, **8**(8), 751-751, doi:10.1038/s41558-018-0202-1.
Bruzek, R., L. Biess and L. Al-Nazer, 2013: Development of Rail Temperature Predictions to Minimize Risk of Track Buckle Derailments. *2013 Joint Rail Conference*, doi:10.1115/jrc2013-2451.
Bryndum-Buchholz, A. et al., 2020: Climate-change impacts and fisheries management challenges in the North Atlantic Ocean. *Marine Ecology Progress Series*, **648**, 1-17, doi:10.3354/meps13438.
Bullerjahn, G. S. et al., 2016: Global solutions to regional problems: Collecting global expertise to address the problem of harmful cyanobacterial blooms. A Lake Erie case study. *Harmful Algae*, **54**, 223-238, doi:10.1016/j.hal.2016.01.003.
Bunce, A. et al., 2016: Vulnerability and adaptive capacity of Inuit women to climate change: a case study from Iqaluit, Nunavut. *Natural Hazards*, **83**, 1419-1419, doi:10.1007/s11069-016-2398-6.
Buotte, P. C., B. E. Law, W. J. Ripple and L. T. Berner, 2020: Carbon sequestration and biodiversity co-benefits of preserving forests in the western United States. *Ecological Applications*, **30**(2), doi:10.1002/eap.2039.
Buotte, P. C. et al., 2019: Near-future forest vulnerability to drought and fire varies across the western United States. *Global change biology*, **25**(1), 290-303.

Bureau of Labor Statistics, 2019: Manufacturing: NAICS 31-33 Workforce Statistics, US department of Labor. Available at: https://www.bls.gov/iag/tgs/iag31-33.htm - workforce.
Bureau of Reclamation, 2021a: *Columbia River Basin SECURE Water Act Section 9503(c) Report to Congress*. US Bureau of Reclamation.
Bureau of Reclamation, 2021b: *Rio Grande Basin SECURE Water Act Section 9503(c) Report to Congress*. US Bureau of Reclamation, Interior, U. S. D. o., 52 pp.
Bureau of Reclamation, 2021c: *Sacramento and San Joaquin River Basins SECURE Water Act Section 9503(c) Report to Congress*. U.S. Bureau of Reclamation, Interior, U. S. D. o. t.
Bureau of Reclamation, 2021d: *Water Reliability in the West -2021 SECURE Water Act Report. Prepared for the United States Congress*. U.S. Bureau of Reclamation, Water Resources and Planning Office, Interior, U. S. D. o., Denver, CO, 60 pp.
Burgess, D. O., 2017: *Mass balance of ice caps in the Queen Elisabeth Islands, Arctic Canada: 2014-2015*, **8223**, Geological Survey of Canada, Geological Survey of Canada,, Open File, 38 pp.
Burke, M. et al., 2018a: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8**(8), 723-729, doi:10.1038/s41558-018-0222-x.
Burke, M. et al., 2018b: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8**, 723-729, doi:10.1038/s41558-018-0222-x.
Burke, M., S. M. Hsiang and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**(7577), 235-239, doi:10.1038/nature15725.
Burkett, M., R. Verchik and D. Flores, 2017: *Reaching higher ground: Avenues to secure and manage new land for communities displaced by climate change*. Center for Progressive Reform. Available at: https://cpr-assets.s3.amazonaws.com/documents/ReachingHigherGround_1703.pdf.
Bush, E. and D. S. Lemmen, 2019: *Canada's Changing Climate Report* [Bush, E. and D. S. Lemmen (eds.)]. Government of Canada, Ottawa, Ontario, Canada. Available at: https://changingclimate.ca/CCCR2019/.
Butterworth, M. K., C. W. Morin and A. C. Comrie, 2017: An analysis of the potential impact of climate change on dengue transmission in the southeastern United States. *Environmental Health Perspectives*, **125**(4), 579-585, doi:10.1289/EHP218.
C40 Cities, Climate Leadership Group, About C40. Available at: http://www.c40cities.org/about.
C40 Cities and AECOM, 2017: *C40 infrastructure interdependencies and climate risks report*. 26-26 pp. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiAm-zkrNjsAhUEITQIHRyRCHgQFjABegQIBBAC&url=https%3A%2F%2Funfccc.int%2Fsites%2Fdefault%2Ffiles%2Freport_c40_interdependencies_.pdf&usg=AOvVaw0XIWzEBxmRX8QD2IILzvuy.
Cachon, G. P., S. Gallino and M. Olivares, 2012: Severe weather and automobile assembly productivity. *Columbia Business School Research Paper*,(12/37).
Cadieux, P. et al., 2020: Projected effects of climate change on boreal bird community accentuated by anthropogenic disturbances in western boreal forest, Canada. *Diversity and Distributions*, **26**(6), 668-682, doi:https://doi.org/10.1111/ddi.13057.
Caffrey, R. L. B. and C. H. Hoffman, 2018: Sea Level Rise and Storm Surge Projections for the National Park Service.
Cai, Y. et al., 2015: Environmental tipping points significantly affect the cost−benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112**(15), 4606-4611, doi:10.1073/pnas.1503890112.
Cajete, G., 1999: *Native science: Natural laws of interdependence*. Clear Light Publishers, Sana Fe.
Calderón-García, J. O., A. I. Monterroso-Rivas and J. D. Gómez-Díaz, 2015: Cambio climático en el Centro de México: impacto en la producción de cebada (Hordeum vulgare) en Tlaxcala. *Ra Ximhai*, **11**(5), 37-46.
California Department of Food and Agriculture, 2017: *California Agricultural Production Statistics*. Available at: https://www.cdfa.ca.gov/statistics/ (accessed 2004/2/19).
California Department of Water Resources, 2018: *FLOOD-MAR White Paper: Using Flood Water for Managed Aquifer Recharge to Support Sustainable Water Resources*, Resources, D. o. W., 56 pp.
California Department of Water Resources, 2019: *Climate Action Plan, Phase 3: Climate Change Vulnerability Assessment*, Resources, D. o. W., 153 pp. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Climate-Action-Plan/Files/CAP-III-Vulnerability-Assessment.pdf?la=en&hash=7DF13A5B51C4B4FA808166C596F7EAE67ED58AC5.
California Natural Resources Agency, California Environmental Protection Agency and California Department of Food and Agriculture, 2020: 2020 Water Resilience Portfolio July 2020- in Response to Executive Order N-10-19. State of California, Sacramento, CA, 148 pp.
California State Water Resources Control Board, 2021: *Drinking Water Needs Assessment*. California Environmental Protection Agency, 332 pp. Available at: https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/needs/2021_needs_assessment.pdf.
Callegary, J. B. et al., 2018: Findings and lessons learned from the assessment of the Mexico-United States transboundary San Pedro and Santa Cruz aquifers: The utility of social science in applied hydrologic research. *Journal of Hydrology-Regional Studies*, **20**, 60-73, doi:10.1016/j.ejrh.2018.08.002.
Calleja-Reina, M. (ed.), La comunicación institucional en la gestión de crisis: Cómo minimizar los riesgos del huracán Patricia (México). I Congreso Internacional Comunicación y Pensamiento. Comunicracia y Desarrollo Social.

Calliari, E., M. Michetti, L. Farnia and E. Ramieri, 2019: A network approach for moving from planning to implementation in climate change adaptation: Evidence from southern Mexico. *Environmental Science & Policy*, **93**, 146-157, doi:10.1016/j.envsci.2018.11.025.
Callison, C., 2015: *How climate change comes to matter: The communal life of facts*. Duke University Press, Durham, NC.
Camacho-Villa, T. C. et al., 2021: Mayan traditional knowledge on weather forecasting: Who contributes to whom in coping with climate change? *Frontiers in Sustainable Food Systems*, **5**, 618453, doi:10.3389/fsufs.2021.618453.
Cameron, L., D. Courchene, S. Ijaz and I. Mauro, 2019: The Turtle Lodge: sustainable self-determination in practice. *AlterNative: An International Journal of Indigenous Peoples*, **15**(1), 13-21, doi:10.1177/1177180119828075.
Campo Caap, 2018: *Campo climate adaptation action plan*. Available at: https://documentcloud.adobe.com/link/track?uri=urn%3Aaaid%3Ascds%3AUS%3Aded4a635-d313-45b0-b65b-3f7c87a60201 - pageNum=1.
Canadian Council of Forest Ministers, 2016: *Canadian Wildland Fire Strategy. A 10-Year Review and Renewed Call to Action*. Wildland Fire Management Group, CCFM, Canada, N. R., Ottawa, ON. Available at: http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/37108.pdf.
Canadian Institute for Climate Choices, 2020: *Tip of the iceberg*. Available at: https://climatechoices.ca/wp-content/uploads/2020/12/Tip-of-the-Iceberg-_-CoCC_-Institute_-Full.pdf.
Cannon, C., K. F. Gotham, K. Lauve-Moon and B. Powers, 2020: The climate change double whammy: Flood damage and the determinants of flood insurance coverage, the case of post-Katrina New Orleans. *Climate Risk Management*, **27**, 100210.
Cannon, T. and D. Müller-Mahn, 2010: Vulnerability, Resilience and Development Discourses in Context of Climate Change. **55**.
Cantú, C., 2016: Responses of Southern California's Urban Water Sector to Changing Stresses and Increased Uncertainty: Innovative Approaches. In: *Water Policy and Planning in a Variable and Changing Climate* [Miller, K. A., A. F. Hamlet, D. S. Kenney and K. T. Redmond (eds.)]. CRC Press - Taylor & Francis Group, Boca Raton, FL, pp. 276-288. ISBN 9781482227970.
Carbon Disclosure Project, 2013: *Metals & Mining: a sector under water pressure. Analysis for institutional investors of critical issues facing the industry*. London, United Kingdom. Available at: https://www.cdp.net/es/reports/downloads/897.
Cardinael, R. et al., 2017: Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France. *Agriculture, Ecosystems and Environment*, **236**, 243-255, doi:10.1016/j.agee.2016.12.011.
Carleton, W. C., D. Campbell and M. Collard, 2017: Increasing temperature exacerbated Classic Maya conflict over the long term. *Quat. Sci. Rev.*, **163**, 209-218, doi:10.1016/j.quascirev.2017.02.022.
Carlisle, D. M. et al., 2019: *Flow modification in the Nation's streams and rivers: U.S. Geological Survey Circular 1461* 75 pp. Available at: https://doi.org/10.3133/cir1461.
Carmona-Castro, O., D. A. Moo-Llanes and J. M. Ramsey, 2018: Impact of climate change on vector transmission of *Trypanosoma cruzi* (Chagas, 1909) in North America. *Medical and Veterinary Entomology*, **32**(1), 84-101, doi:10.1111/mve.12269.
Carozza, D. A., D. Bianchi and E. D. Galbraith, 2019: Metabolic impacts of climate change on marine ecosystems: Implications for fish communities and fisheries. *Global Ecology and Biogeography*, **28**(2), 158-169, doi:10.1111/geb.12832.
Carroll, C., S. A. Parks, S. Z. Dobrowski and D. R. Roberts, 2018: Climatic, topographic, and anthropogenic factors determine connectivity between current and future climate analogs in North America. *Glob. Chang. Biol.*, **24**(11), 5318-5331, doi:10.1111/gcb.14373.
Carter, L. et al., 2018: *Chapter 19: Southeast* [Reidmiller, D. R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock and B. C. Stewart (eds.)]. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II U.S. Global Change Research Program, Washington, DC, USA, 734-808 pp. Available at: http://dx.doi.org/10.7930/nca4.2018.ch19.
Cassman, K. G. and P. Grassini, 2020: A global perspective on sustainable intensification research. *Nature Sustainability*, **3**(4), 262-268, doi:10.1038/s41893-020-0507-8.
Castro, J. A. G. and S. L. R. De Robles, 2019: Climate change and flood risk: vulnerability assessment in an urban poor community in Mexico. *Environment and Urbanization*, **31**(1), 75-92, doi:10.1177/0956247819827850.
Cavanaugh, K. C. et al., 2014: Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. *Proc. Natl. Acad. Sci. U. S. A.*, **111**(2), 723-727, doi:10.1073/pnas.1315800111.
Cavole, L. M. et al., 2016: Biological impacts of the 2013--2015 warm-water anomaly in the Northeast Pacific: Winners, losers, and the future. *Oceanography*, **29**(2), 273-285.
CBCL, 2017: *Truro Flood Risk Study*. CBCL Limited Consulting Engineers, Halifax. Available at: https://www.cens.org/flood.
CENR, 2010: *Scientific Assessment of Hypoxia in U.S. Coastal Waters*. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology, Washington, D.C., 164 pp. Available at: https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/hypoxia-report.pdf.

Chan, F. T. et al., 2019: Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. *Global Change Biology*, **25**(1), 25-38, doi:10.1111/gcb.14469.
Chapra, S. C. et al., 2017: Climate change impacts on harmful algal blooms in US Freshwaters: a screening-level assessment. *Environ. Sci. Technol.*, **51**(16), 8933-8943.
Charlebois, S. and A. Summan, 2015: Determinants of future microbial food safety in Canada for risk communication. *Journal of Food Safety*, **35**(3), 303-317, doi:10.1111/jfs.12172.
Chasco, B. E. et al., 2017: Competing tradeoffs between increasing marine mammal predation and fisheries harvest of Chinook salmon. *Sci. Rep.*, **7**(1), 15439, doi:10.1038/s41598-017-14984-8.
Chaste, E. et al., 2019: Increases in heat-induced tree mortality could drive reductions of biomass resources in Canada's managed boreal forest. *Landsc. Ecol.*, **34**(2), 403-426, doi:10.1007/s10980-019-00780-4.
Chaumont, D., 2014: A guidebook on climate scenarios: Using climate information to guide adaptation research and decisions. *Ouranos, Canada*.
Chavarria, S. B. and D. S. Gutzler, 2018: Observed Changes in Climate and Streamflow in the Upper Rio Grande Basin. *Journal of the American Water Resources Association*, **54**(3), 644-659, doi:10.1111/1752-1688.12640.
Chen, C. et al., 2016: Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. *Environ. Sci. Policy*, **66**, 403-419, doi:10.1016/j.envsci.2016.05.007.
Chen, C. C. et al., 2013: Climate change and West Nile Virus in a highly endemic region of North America. *International Journal of Environmental Research and Public Health*, **10**(7), 3052-3071, doi:10.3390/ijerph10073052.
Chen, T. H., X. Li, J. Zhao and K. Zhang, 2017: Impacts of cold weather on all-cause and cause-specific mortality in Texas, 1990–2011. *Environmental Pollution*, **225**, 244-251, doi:10.1016/j.envpol.2017.03.022.
Chen, Y. et al., 2021: Future increases in Arctic lightning and fire risk for permafrost carbon. *Nature Climate Change*, 1-7.
Cheng, A. et al., 2017: Analyzing the potential risk of climate change on Lyme disease in Eastern Ontario, Canada using time series remotely sensed temperature data and tick population modelling. *Remote Sensing*, **9**(6), 609, doi:10.3390/rs9060609.
Cheong, S.-M. et al., 2013: Coastal adaptation with ecological engineering. *Nature Climate Change*, **3**(9), 787-791, doi:10.1038/nclimate1854.
Cherry, N. and W. Haynes, 2017: Effects of the Fort McMurray wildfires on the health of evacuated workers: follow-up of 2 cohorts. *CMAJ open*, **5**(3), E638.
Cheung, W. W. and T. L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Sci Rep*, **10**(1), 1-10.
Cheung, W. W. L., 2018: The future of fishes and fisheries in the changing oceans. *Journal of Fish Biology*, **92**(3), 790-803, doi:10.1111/jfb.13558.
Chief, K., A. Meadow and K. Whyte, 2016: Engaging southwestern tribes in sustainable water resources topics and management. *Water*, **8**(8), 350-350, doi:10.3390/w8080350.
Chinn, S., P. S. Hart and S. Soroka, 2020: Politicization and Polarization in Climate Change News Content, 1985-2017. *Science Communication*, **42**(1), 112-129.
Chinowsky, P. et al., 2019: Impacts of climate change on operation of the US rail network. *Transport Policy*, **75**, 183-191, doi:10.1016/j.tranpol.2017.05.007.
Chisholm Hatfield, S. et al., 2018: Indian time: time, seasonality, and culture in Traditional Ecological Knowledge of climate change. *Ecological Processes*, **7**(1), 25, doi:10.1186/s13717-018-0136-6.
Cho, S. J. and B. A. McCarl, 2017: Climate change influences on crop mix shifts in the United States. *Sci Rep*, **7**, 40845-40845.
Choi, T., 2020: Maritime Militarization in the Arctic: Identifying Civil-Military Dependencies. In: *Arctic Yearbook 2020* [Heininen, L., H. Exner-Pirot and J. Barnes (eds.)]. Arctic Portal, Akureyri, Iceland, pp. 60-78.
Christianson, A. C., T. K. McGee and N. Whitefish Lake First, 2019a: Wildfire evacuation experiences of band members of Whitefish Lake First Nation 459, Alberta, Canada. *Natural Hazards*, **98**, 9-29, doi:10.1007/s11069-018-3556-9.
Christianson, K. R., B. M. Johnson, M. B. Hooten and J. J. Roberts, 2019b: Estimating lake–climate responses from sparse data: An application to high elevation lakes. *Limnology and Oceanography*, **64**(3), 1371-1385, doi:10.1002/lno.11121.
Chryst, B. et al., 2018: Global warming's "Six Americas Short Survey": Audience segmentation of climate change views using a four question instrument. *Environmental Communication*, **12**(8), 1109-1122.
Cinner, J. E. et al., 2016: Bright spots among the world's coral reefs. *Nature*, **535**(7612), 416-419, doi:10.1038/nature18607.
Cisneros-Mata, M. A. et al., 2019: Fisheries governance in the face of climate change: Assessment of policy reform implications for Mexican fisheries. *PLoS ONE*, **14**(10), 1-19, doi:10.1371/journal.pone.0222317.
City of Norfolk Virginia, 2014: *Coastal Resilience Strategy*. Virginia, C. o. N., Norfolk, VA, 14 pp. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiyrpW-7tzyAhWEt54KHQ6rAgoQFnoECAMQAQ&url=https%3A%2F%2Fwww.norfolk.gov%2FDocumentCenter%2FView%2F16292%2FCoastal-Resilience-Strategy-Report-to-Residents-%3FbidId%3D&usg=AOvVaw2vmS8Wnb2cdPxNIquFCp6r.

City of San Francisco, 2016: *San Francisco Sea Level Rise Action Plan*. Francisco, C. a. C. o. S., San Francisco, CA, 100 pp. Available at: https://sfplanning.s3.amazonaws.com/default/files/plans-and-programs/planning-for-the-city/sea-level-rise/160309_SLRAP_Final_ED.pdf.
City of Saskatoon, 2019: *Corporate climate adaptation strategy. Local actions: Saskatoon's Adaptation Strategy (Part Two)*. Available at: https://www.saskatoon.ca/sites/default/files/images/local_actions_report-ccas-disclaimer.pdf.
City of Seattle, 2017: *Preparing for Climate Change*. Environment, S. O. i. o. S., Seattle, WA, 82 pp. Available at: https://www.seattle.gov/Documents/Departments/Environment/ClimateChange/SEAClimatePreparedness_August2017.pdf
City of Selkirk, 2019: *Climate adaptation stra*. Available at: https://www.myselkirk.ca/wp-content/uploads/2019/07/Climate-Change-Adaptation-Strategy-Final-May2019.pdf.
City of Surrey, 2019: *Coastal Flood Adaptation Strategy*. Available at: https://www.surrey.ca/sites/default/files/media/documents/CFASFinalReportNov2019.pdf
City of Toronto, 2019: *Hot weather response framework*. 12 pp. Available at: https://www.toronto.ca/wp-content/uploads/2019/05/9030-2019-HWR-Framework-updated-05-22-19.AODA_.pdf.
Claggett, S. and R. Morgan, 2018: USFS Looks to the Future in Upcoming Forests to Faucets Analysis. *Journal American Water Works Association*, **110**(7), 41-47, doi:10.1002/awwa.1114.
Clamen, M. and D. Macfarlane, 2018: Plan 2014: The historical evolution of Lake Ontario–St. Lawrence River regulation. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, **43**(4), 416-431.
Claret, M. et al., 2018: Rapid coastal deoxygenation due to ocean circulation shift in the NW Atlantic. *Nat. Clim. Chang.*, **8**(10), 866-872, doi:10.1038/s41558-018-0263-1.
Clayton, S., 2020: Climate anxiety: Psychological responses to climate change. *Journal of Anxiety Disorders*, **74**, 102263, doi:10.1016/j.janxdis.2020.102263.
Clements, J. C. and T. Chopin, 2017: Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. *Reviews in Aquaculture*, **9**(4), 326-341, doi:10.1111/raq.12140.
Climate-Safe Infrastructure Working Group, 2018: *Paying it forward: The path toward climate-safe infrastructure in California*. Available at: http://resources.ca.gov/docs/climate/ab2800/AB2800_Climate-SafeInfrastructure_FinalWithAppendices.pdf.
Cochran, P. et al., 2013: Indigenous frameworks for observing and responding to climate change in Alaska. *CLIMATIC CHANGE*, **120**(3, SI), 557-557, doi:10.1007/s10584-013-0735-2.
Coffey, R. et al., 2019: A review of water quality responses to air temperature and precipitation changes 2: nutrients, algal blooms, sediment, pathogens. *JAWRA Journal of the American Water Resources Association*, **55**(4), 844-868.
Cohen, S., G. Koshida and L. Mortsch, 2015: Climate and water availability indicators in Canada: Challenges and a way forward. Part III–Future scenarios. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, **40**(2), 160-172.
Cohen, W. B. et al., 2016: Forest disturbance across the conterminous United States from 1985–2012: the emerging dominance of forest decline. *Forest Ecology and Management*, **360**, 242-252.
Colacito, R., B. Hoffmann, T. Phan and T. Sablik, 2018: The Impact of Higher Temperatures on Economic Growth. *Federal Reserve Bank of Richmond Economic Brief*,(August), 5.
Collins, T. W. and B. Bolin, 2009: Situating hazard vulnerability: people's negotiations with wildfire environments in the US Southwest. *Environmental Management*, **44**(3), 441-455.
Cologna, V. and M. Siegrist, 2020: The role of trust for climate change mitigation and adaptation behaviour: A meta-analysis. *Journal of Environmental Psychology*, **69**, 101428, doi:https://doi.org/10.1016/j.jenvp.2020.101428.
Colombi, B. J., 2012: Salmon and the adaptive capacity of Nimiipuu (Nez Perce) culture to cope with change. *American Indian Quarterly*, **36**(1), 75-97, doi:10.5250/amerindiquar.36.1.0075.
Colón-González, F. J., C. Fezzi, I. R. Lake and P. R. Hunter, 2013a: The Effects of Weather and Climate Change on Dengue. *PLoS Neglected Tropical Diseases*, **7**(11), e2503-e2503, doi:10.1371/journal.pntd.0002503.
Colón-González, F. J., C. Fezzi, I. R. Lake and P. R. Hunter, 2013b: The effects of weather and climate change on dengue. *PLoS Neglected Tropical Diseases*, **7**(11), e2503, doi:10.1371/journal.pntd.0002503.
Colorado River Basin Stakeholders, 2015: Colorado River Basin Stakeholders Moving Forward to Address Challenges Identified in the Colorado River Basin Water Supply and Demand Study, Phase 1 Report. Bureau of Reclamation, Washington, D. C., 452 pp. pp.
Colorado State Government, 2015: *Colorado's Water Plan*. Government, C. S., 567 pp. Available at: https://www.colorado.gov/pacific/sites/default/files/CWP2016.pdf.
Colorado Water Conservation Board, 2020: Alternative Transfer Methods in Colorado -- Status Update, Framework for Continued Support, and Recommendations for CWCB Action, Denver, CO, 87 pp. pp.
CONAGUA, 2015: *Reseña del huracán "Patricia" del Oceano Pacífico*, Comisión Nacional del Agua, S. M. N., Comisión Nacional del Agua, Servicio Metereológico Nacional. Available at: https://smn.conagua.gob.mx/es/ciclones-tropicales/informacion-historica.
CONAGUA, 2016: *Huracán "Newton" del Oceano Pacífico*, Comisión Nacional del Agua, S. M. N., Comisión Nacional del Agua, Servicio Metereológico Nacional. Available at: https://smn.conagua.gob.mx/es/ciclones-tropicales/informacion-historica.

Confederated Tribes of the Umatilla Indian Reservation, 2016: *Umatilla Indian Reservation hazard mitigation plan*. Available at: https://ctuir.org/media/xydmr1pt/ctuir-hazard-mitigation-plan-part-a.pdf.
Constant, K. and M. Davin, 2019: *Unequal Vulnerability to Climate Change and the Transmission of Adverse Effects Through International Trade*. vol. 74, 727-759 pp. ISBN 0123456789.
Coogan, S. C., F.-N. Robinne, P. Jain and M. D. Flannigan, 2019: Scientists' warning on wildfire—a Canadian perspective. *Canadian Journal of Forest Research*, **49**(9), 1015-1023.
Cook, B. I., T. R. Ault and J. E. Smerdon, 2015: Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Sci Adv*, **1**(1), e1400082, doi:10.1126/sciadv.1400082.
Cook, J. and S. Lewandowsky, 2016: Rational irrationality: Modeling climate change belief polarization using Bayesian networks. *Topics in cognitive science*, **8**(1), 160-179.
Cook, J., S. Lewandowsky and U. K. Ecker, 2017: Neutralizing misinformation through inoculation: Exposing misleading argumentation techniques reduces their influence. *PloS one*, **12**(5), e0175799.
Cook, J. et al., 2013: Quantifying the consensus on anthropogenic global warming in the scientific literature. *Environmental Research Letters*, **8**(2), 024024, doi:10.1088/1748-9326/8/2/024024.
Cook, J. et al., 2016: Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters*, **11**(4), 048002.
Cooley, C., 2021: *List of Tribal hazard mitigation plans and hazards included*. Institute for Tribal Environmental Professionals, Northern Arizona University.
Cooley, H., 2016: California's Irrigated Agriculture and Innovations in Adapting to Water Scarcity. In: *Water Policy and Planning in a Variable and Changing Climate* [Miller, K. A., A. F. Hamlet, D. S. Kenney and K. T. Redmond (eds.)]. CRC Press - Taylor & Francis Group, Boca Raton, FL, pp. 261-274.
Cooley, S. R. et al., 2015: An Integrated Assessment Model for Helping the United States Sea Scallop (Placopecten magellanicus) Fishery Plan Ahead for Ocean Acidification and Warming. *PLOS ONE*, **10**(5), e0124145, doi:10.1371/journal.pone.0124145.
Coop, J. D. et al., 2020: Wildfire-Driven Forest Conversion in Western North American Landscapes. *BioScience*, **70**(8), 659-673, doi:10.1093/biosci/biaa061.
Cooper, M. G., A. W. Nolin and M. Safeeq, 2016: Testing the recent snow drought as an analog for climate warming sensitivity of Cascades snowpacks. *Environ. Res. Lett.*, **11**(8), doi:10.1088/1748-9326/11/8/084009.
Copland, L., J. Dawson and A. Cook, 2019: *Impacts of Climate Change on Navigational Choke Points for Ships Operating in the Canadian Arctic*. Innovation and Policy Branch of Transport Canada, Ottawa, ON. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwidqoSAs-TsAhVzOX0KHU7xAHwQFjAAegQIBRAC&url=https%3A%2F%2Ftcdocs.ingeniumcanada.org%2Fsites%2Fdefault%2Ffiles%2F2020-03%2FImpacts of Climate Change on Navigational Choke Points for Ships Operating in the Canadian Arctic - full report.pdf&usg=AOvVaw1w-d9_upLgjVlP1up1il3J.
Copland, L. et al., 2021: Changes in shipping navigability in the Canadian Arctic between 1972 and 2016. *FACETS*, **6**, 1069-1087, doi:10.1139/facets-2020-0096.
Corkeron, P. et al., 2018: The recovery of North Atlantic right whales, Eubalaena glacialis, has been constrained by human-caused mortality. *R Soc Open Sci*, **5**(11), 180892, doi:10.1098/rsos.180892.
Corner, A. et al., 2015: How do young people engage with climate change? The role of knowledge, values, message framing, and trusted communicators. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(5), 523-534.
Corntassel, J. and C. Bryce, 2012: Practicing sustainable self-determination: Indigenous approaches to cultural restoration and revitalization. *Brown Journal of World Affairs*, **18**(2), 151-162.
Corona-Jimenez, M. A., 2018: Knowledge, perception and readiness to face the climate change in a growing population, the returning migrants. *Estudios sociales. Revista de alimentación contemporánea y desarrollo regiona*, **28**(2), 1-28, doi: https://doi.org/10.24836/es.v28i52.578
Cosens, B., A. Fremier, N. Bankes and J. Abatzoglou, 2016: The Columbia River Treaty and the Dynamics of Transboundary Water Negotiations in a Changing Environment: How Might Climate Change Alter the Game? In: *Water Policy and Planning in a Variable and Changing Climate* [Miller, K. A., A. F. Hamlet, D. S. Kenney and K. T. Redmond (eds.)]. CRC Press, Taylor and Francis Group, Boca Raton, FL, pp. 185-206. ISBN 9781482227970.
Cosens, B. A., L. Gunderson and B. C. Chaffin, 2018: Introduction to the Special Feature Practicing Panarchy: Assessing legal flexibility, ecological resilience, and adaptive governance in regional water systems experiencing rapid environmental change. *Ecol. Soc.*, **23**(1), doi:10.5751/es-09524-230104.
Costello, C. et al., 2020: The future of food from the sea. *Nature*,(June), doi:10.1038/s41586-020-2616-y.
Costinot, A., D. Donaldson and C. Smith, 2016: Evolving comparative advantage and the impact of climate change in agricultural markets: evidence from 1.7 million fields around the world. *J Polit Econ*, **124**(1), 205-248.
Cottrell, R. S. et al., 2019: Food production shocks across land and sea. *Nature Sustainability*, **2**(2), 130-137, doi:10.1038/s41893-018-0210-1.
Coulthard, G. S., 2014: *Red skin, white masks: Rejecting the colonial politics of recognition*. University of Minnesota Press, Minneapolis.
Council of Canadian Academies, 2016: *Commercial Marine Shipping Accidents: Understanding The Risks In Canada, Workshop Report.* . Ottawa (ON), Canada.

Council of Canadian Academies, 2019: *Canada's Top Climate Change Risks*. The Expert Panel on Climate Change Risks and Adaptation Potential, Council of Canadian Academies, Ottawa (ON), Canada.
Cousins, J. J., 2021: Justice in nature-based solutions: Research and pathways. *Ecological Economics*, **180**, 106874, doi:https://doi.org/10.1016/j.ecolecon.2020.106874.
Cousins, M., J. M. Sargeant, D. Fisman and A. L. Greer, 2019: Modelling the transmission dynamics of *Campylobacter* in Ontario, Canada, assuming house flies, *Musca domestica*, are a mechanical vector of disease transmission. *Royal Society Open Science*, **6**(2), 181394, doi:10.1098/rsos.181394.
Cozzetto, K. et al., 2013a: Climate change impacts on the water resources of American Indians and Alaska Natives in the U.S. *Climatic Change*, **120**(3), 569-584, doi:10.1007/s10584-013-0852-y.
Cozzetto, K. et al., 2013b: Climate change impacts on the water resources of American Indians and Alaska Natives in the US. *Climatic Change*, **120**(3), 569-584, doi:10.1007/s10584-013-0852-y.
Cozzetto, K., C. Cooley and A. Taylor, 2021a: Drinking water infrastructure. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 142-158.
Cozzetto, K., D. Marks-Marino and Status of Tribes Climate Change Working Group, 2021b: Executive summary. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ.
CPRA, 2021: 2023 Coastal Master Plan. Available at: https://coastal.la.gov/our-plan/2023-coastal-master-plan/.
Craft, A., 2014: Living treaties, breathing research. *Canadian Journal of Women and the Law*, **26**(1), 1-22, doi:10.3138/cjwl.26.1.1.
Crausbay, S. D. et al., 2020: Unfamiliar Territory: Emerging Themes for Ecological Drought Research and Management. *One Earth*, **3**(3), 337-353.
Crausbay, S. D. et al., 2017: Defining Ecological Drought for the Twenty-First Century. *Bull. Am. Meteorol. Soc.*, **98**(12), 2543-2550, doi:10.1175/BAMS-D-16-0292.1.
Cross, S. F., M. Flaherty and A. Byrne, 2016: *Diversification of Aquaculture in North America*. FAO, Rome, Italy. Available at: https://www.researchgate.net/profile/Malcolm_Beveridge/publication/320546704_Planning_for_aquaculture_diversification_the_importance_of_climate_change_and_other_drivers/links/59eb0d72a6fdccef8b08eee0/Planning-for-aquaculture-diversification-the-importance-of-climate-change-and-other-drivers.pdf - page=103.
Crozier, L. G. et al., 2021: Climate change threatens Chinook salmon throughout their life cycle. *Communications biology*, **4**(1), 1-14.
Crozier, L. G. et al., 2019: Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. *PloS one*, **14**(7), e0217711.
Cruz, A. M. and E. Krausmann, 2013: Vulnerability of the oil and gas sector to climate change and extreme weather events. 41-53, doi:10.1007/s10584-013-0891-4.
Cui, Y. F., D. Q. Cheng and D. V. Chan, 2019: Investigation of Post-Fire Debris Flows in Montecito. *ISPRS Int. Geo-Inf.*, **8**(1), 18, doi:10.3390/ijgi8010005.
Cunningham, C. J., P. A. H. Westley and M. D. Adkison, 2018: Signals of large scale climate drivers, hatchery enhancement, and marine factors in Yukon River Chinook salmon survival revealed with a Bayesian life history model. *Glob. Chang. Biol.*, doi:10.1111/gcb.14315.
Cunningham Kain, M., Á. E. Pop Ac and U. N. Permanent Forum on Indigenous Issues Secretariat, 2013: Study on the knowledge, history and contemporary social circumstances of indigenous peoples are embedded in the curricula of education systems. United Nations, New York, 19 pp.
Cunsolo, A. and N. R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8**(4), 275-281, doi:10.1038/s41558-018-0092-2.
Cunsolo, A. et al., 2020: Ecological grief and anxiety: the start of a healthy response to climate change? *Lancet Planetary Health*, **4**(7), E261-E263, doi:10.1016/S2542-5196(20)30144-3.
Cunsolo Willox, A. et al., 2013: Climate change and mental health: An exploratory case study from Rigolet, Nunatsiavut, Canada. *Climatic Change*, **121**(2), 255-270, doi:10.1007/s10584-013-0875-4.
Cunsolo Willox, A. et al., 2014: Examining relationships between climate change and mental health in the Circumpolar North. *Regional Environmental Change*, **15**, 169-182, doi:10.1007/s10113-014-0630-z.
Cunsolo Willox, A. et al., 2015: Examining relationships between climate change and mental health in the Circumpolar North. *Regional Environmental Change*, **15**(1), 169-182, doi:10.1007/s10113-014-0630-z.
Curley, A., 2019: Unsettling Indian Water Settlements: The Little Colorado River, the San Juan River, and Colonial Enclosures. *Antipode*, **0**, 1-19, doi:10.1111/anti.12535.
Curry, C. L., S. U. Islam, F. W. Zwiers and S. J. Déry, 2019: Atmospheric Rivers Increase Future Flood Risk in Western Canada's Largest Pacific River. *Geophysical Research Letters*, **46**(3), 1651-1661, doi:10.1029/2018GL080720.
D'Orangeville, L. et al., 2016: Northeastern North America as a potential refugium for boreal forests in a warming climate. *Science*, **352**(6292), 1452-1455, doi:10.1126/science.aaf4951.
D'Orangeville, L. et al., 2018: Beneficial effects of climate warming on boreal tree growth may be transitory. *Nature Communications*, **9**(1), doi:10.1038/s41467-018-05705-4.

D'ulisse, N., 2019: It's hot today, eh? Montreal's 2018 heat wave from Urgences-santé's perspective. *Prehospital and Disaster Medicine*, **34**(s1), s29-s29, doi:10.1017/S1049023X19000773.
Dahlke, F. T., S. Wohlrab, M. Butzin and H.-O. Pörtner, 2020: Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, **369**(6499), 65-70.
Daigle, R., S. O'Carroll, L. Young and P. Paul, 2015: *Impacts of Climate Change and Sea Level Rise on the Mi'kmaq Communities of the Bras d'Or Lakes*. Resources, U. k. I. o. N., 88 pp. Available at: http://www.dev.uinr.ca/wp-content/uploads/2015/07/Climate-Change-2015-Report-WEB-COMPRESSED-1.pdf.
Daigle, R. J., 2006: *Impacts of sea-level rise and climate change on the coastal zone of southeastern New Brunswick*. Environment Canada, Ottawa, ON, 644 pp. Available at: https://publications.gc.ca/site/eng/9.667859/publication.html.
Davenport, F. V. B., Marshall Diffenbaugh, Noah S., 2021: Contribution of historical precipitation change to US flood damages. *PNAS (Proceedings of the National Academy of Sciences)*, **118**(4), doi:10.1073/pnas.2017524118.
Davies, I. P., R. D. Haugo, J. C. Robertson and P. S. Levin, 2018: The unequal vulnerability of communities of color to wildfire. *PLoS one*, **13**(11), e0205825.
Davies, J. B., 2020: Reforming Canada's Disaster Assistance Programs. *Canadian Public Policy*, **46**(2), 187-197.
Davies, K. T. A. and S. W. Brillant, 2019: Mass human-caused mortality spurs federal action to protect endangered North Atlantic right whales in Canada. *Mar. Policy*, **104**, 157-162, doi:10.1016/j.marpol.2019.02.019.
Davis, H. and Z. Todd, 2017: On the Importance of a Date, or Decolonizing the Anthropocene. *ACME: An International E-Journal for Critical Geographies*, **16**(4).
Davis, K. T. et al., 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proc. Natl. Acad. Sci. U. S. A.*, **116**(13), 6193-6198, doi:10.1073/pnas.1815107116.
Dawson, J., M. Johnston and E. Stewart, 2017: The unintended consequences of regulatory complexity: The case of cruise tourism in Arctic Canada. *Marine Policy*, **76**, 71-78, doi:10.1016/j.marpol.2016.11.002.
Dawson, J., M. E. Johnston and E. J. Stewart, 2014: Ocean & Coastal Management Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change. *Ocean Coast. Manage.*, **89**, 88-99, doi:10.1016/j.ocecoaman.2013.12.005.
Dawson, J. et al., 2018: Temporal and spatial patterns of ship traffic in the Canadian arctic from 1990 to 2015. *Arctic*, **71**(1), doi:10.14430/arctic4698.
Dawson, J., D. Scott and G. McBoyle, 2009: Climate change analogue analysis of ski tourism in the northeastern USA. *Climate Research*, **39**(1), 1-9, doi:10.3354/cr00793.
Dawson, T. et al., 2020: Coastal heritage, global climate change, public engagement, and citizen science. *Proceedings of the National Academy of Sciences*, **117**(15), 8280-8286.
de Alba, F. and O. Castillo, 2014: "Después del desastre... Viene la informalidad" Una reflexión sobre las inundaciones en la metrópolis de Mexico. *Revista de Direito da Cidade*, **6**.
de Koning, K. and T. Filatova, 2020: Repetitive floods intensify outmigration and climate gentrification in coastal cities. *Environmental Research Letters*, **15**(3), 034008, doi:10.1088/1748-9326/ab6668.
DeBeer, C. M., H. S. Wheater, S. K. Carey and K. P. Chun, 2016: Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a review and synthesis. *Hydrology and Earth System Sciences*, **20**(4), 1573-1598, doi:10.5194/hess-20-1573-2016.
Degroot, D. et al., 2021: Towards a rigorous understanding of societal responses to climate change. *Nature*, **591**(7851), 539-550, doi:10.1038/s41586-021-03190-2.
Delfino, R. et al., 2009: The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. *Occupational and Environmental Medicine*, **66**(3), 189-197, doi:10.1136/oem.2008.041376.
Derksen, C. et al., 2019: Chapter 5: Changes in snow, ice, and permafrost across Canada. In: *Canada's Changing Climate Report* [Bush, E. and D. S. Lemmen (eds.)]. Government of Canada, Ottawa, Ontario, pp. 194-260.
Derner, J. et al., 2018: Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. *Climatic Change*, **146**(1-2), 19-32, doi:10.1007/s10584-017-2029-6.
Dettinger, M., B. Udall and A. Georgakakos, 2015: Western water and climate change. *Ecological Applications*, **25**(8(December 2015)), 2069-2093.
Deutsch, C. et al., 2015a: Climate change tightens a metabolic constraint on marine habitats. *Science*, **348**(6239), 1132-1136, doi:10.1126/science.aaa1605.
Deutsch, C. et al., 2015b: Climate change tightens a metabolic constraint on marine habitats. *Science*, **348**(6239), 1132, doi:10.1126/science.aaa1605.
Deutsch, C. A. et al., 2018: Increase in crop losses to insect pests in a warming climate. *Science*, **361**(6405), 916-919, doi:10.1126/science.aat3466.
DeWaard, J., J. E. Johnson and S. D. Whitaker, 2020: Out-migration from and return migration to Puerto Rico after Hurricane Maria: evidence from the consumer credit panel. *Population and Environment*, **42**(1), 28-42, doi:10.1007/s11111-020-00339-5.
Dezutter, T. et al., 2019: Mismatch between microalgae and herbivorous copepods due to the record sea ice minimum extent of 2012 and the late sea ice break-up of 2013 in the Beaufort Sea. *Prog. Oceanogr.*, **173**, 66-77, doi:10.1016/j.pocean.2019.02.008.
DFID, Sustainable Livelihoods Guidance Sheets Available at: http://www.ennonline.net/resources/667

Diaz, H., M. Hurlbert and J. Warren (eds.), 2016: *Vulnerability and Adaptation to Drought: The Canadian Prairies and South America*, Energy, ecology, and the environment series, University of Calgary Press, Calgary, Alberta, 388 pp.

Diaz-Castro, S., M. Moreno-Legorreta, A. Ortega-Rubio and V. Serrano-Pinto, 2017: Relation between dengue and climate trends in the northwest of Mexico. *Tropical Biomedicine*, **34**(1), 157-165.

Dibike, Y. et al., 2012: Simulation of North American lake-ice cover characteristics under contemporary and future climate conditions. *International Journal of Climatology*, **32**(5), 695-709, doi:10.1002/joc.2300.

Dibike, Y., T. Prowse, B. Bonsal and H. O'Neil, 2017: Implications of future climate on water availability in the western Canadian river basins. *International Journal of Climatology*, **37**(7), 3247-3263, doi:10.1002/joc.4912.

Dietz, S., J. Rising, T. Stoerk and G. Wagner, 2021: Economic impacts of tipping points in the climate system. *Proceedings of the National Academy of Sciences*, **118**(34), e2103081118, doi:10.1073/pnas.2103081118.

Dilling, L. et al., 2019: Is adaptation success a flawed concept? *Nature Climate Change*, **9**(8), 572-574.

Ding, D. et al., 2011: Support for climate policy and societal action are linked to perceptions about scientific agreement. *Nature Climate Change*, **1**(9), 462.

Ding, Q. et al., 2017: Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. *Nat. Clim. Chang.*, **7**, 289, doi:10.1038/nclimate3241.

Dittmer, K., 2013: Changing streamflow on Columbia basin tribal lands—climate change and salmon. *Climatic Change*, **120**(3), 627-627, doi:10.1007/s10584-013-0745-0.

Dittrich, R., A. Wreford and D. Moran, 2016: A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecol. Econ.*, **122**, 79-89.

Dobrowski, S. Z. et al., 2015: Forest structure and species traits mediate projected recruitment declines in western US tree species. *Global Ecology and Biogeography*, **24**(8), 917-927, doi:10.1111/geb.12302.

Dodd, W. et al., 2018a: The summer of smoke: ecosocial and health impacts of a record wildfire season in the Northwest Territories, Canada. *The Lancet Global Health*, **6**(S30), doi:10.1016/S2214-109X(18)30159-1.

Dodd, W. et al., 2018b: Lived experience of a record wildfire season in the Northwest Territories, Canada. *Canadian Journal of Public Health*, **109**(3), 327-337, doi:10.17269/s41997-018-0070-5.

Dodson, M., 2007: UNPFII E/C.19/2007/10 Report on Indigenous Traditional Knowledge.

Doll, J. E., B. Petersen and C. Bode, 2017: Skeptical but adapting: What Midwestern farmers say about climate change. *Weather, Climate, and Society*, **9**(4), 739-751.

Domínguez, M., F. Cabranes, J. Pacheco and J. Argáez, 2020: Resiliencia social en contextos urbanos de vulnerabilidad. El caso de los grupos sin seguridad social en la ciudad de Mérida. In: *Expresiones de la segregación residencial y de la pobreza en contextos urbanos y metropolitanos* [Aguilar, A. and I. Escamilla (eds.)]. MAPorrua and UNAM, México. ISBN 978-607-524-349-8.

Domínguez, M., M. Rubiales and J. Bayona, 2018: Inmigración de calidad de vida y partial exit: un estudio a partir de los casos de Mérida (México) y Barcelona (España). *Revista Colombiana de Sociología*, **41**(1), 177-202.

Donatti, C. I. et al., 2017: What information do policy makers need to develop climate adaptation plans for smallholder farmers? The case of Central America and Mexico. *Climatic Change*, **141**(1), 107-121, doi:10.1007/s10584-016-1787-x.

Donatuto, J. et al., 2021: Health & Wellbeing. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 159-173.

Donatuto, J. et al., 2020: The story of 13 moons: Developing an environmental health and sustainability curriculum founded on Indigenous first foods and technologies. *Sustainability*, **12**(21), 8913, doi:10.3390/su12218913.

Doney, S. C. et al., 2007: Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. *Proc. Natl. Acad. Sci. U. S. A.*, **104**(37), 14580-14585, doi:10.1073/pnas.0702218104.

Dong, X. S. et al., 2019: Heat-related deaths among construction workers in the United States. *American Journal of Industrial Medicine*, **62**(12), 1047-1057, doi:10.1002/ajim.23024.

Donnelly, J. P. et al., 2020: Climate and human water use diminish wetland networks supporting continental waterbird migration. *Global change biology*, **26**(4), 2042-2059.

Donovan, V. M., C. L. Wonkka and D. Twidwell, 2017: Surging wildfire activity in a grassland biome. *Geophysical Research Letters*, **44**(12), 5986-5993, doi:10.1002/2017gl072901.

Doolittle, A. A., 2010: The politics of Indigeneity: Indigenous strategies for inclusion in climate change negotiations. *Conservation and Society*, **8**(4), 286-291, doi:10.4103/0972-4923.78142.

Doorn, N., 2019: How can resilient infrastructures contribute to social justice? Preface to the Special Issue of Sustainable and Resilient Infrastructure on resilient infrastructures and social justice. *Sustainable and Resilient Infrastructure*, 1-4, doi:10.1080/23789689.2019.1574515.

Doran, P. T. and M. K. Zimmerman, 2009: Examining the scientific consensus on climate change. *Eos, Transactions American Geophysical Union*, **90**(3), 22-23.

Doré, G., F. Niu and H. Brooks, 2016: Adaptation Methods for Transportation Infrastructure Built on Degrading Permafrost. *Permafrost and Periglacial Processes*, **27**(4), 352-364, doi:10.1002/ppp.1919.

Dove, N. C. et al., 2020: High-severity wildfire leads to multi-decadal impacts on soil biogeochemistry in mixed-conifer forests. *Ecological Applications*, e02072.

Dow, K. et al., 2013: Limits to adaptation. *Nature Climate Change*, **3**(4), 305-307, doi:10.1038/nclimate1847.

Doyle, J. T. et al., 2018: Challenges and opportunities for tribal waters: Addressing disparities in safe public drinking water on the crow reservation in Montana, USA. *International Journal of Environmental Research and Public Health*, **15**(4), 567, doi:10.3390/ijerph15040567.
Doyle, J. T., M. H. Redsteer and M. J. Eggers, 2013: Exploring effects of climate change on Northern Plains American Indian health. *Climatic Change*, **120**, 643-655, doi:10.1007/s10584-013-0799-z.
Doyle, M. P. et al., 2015: The food industry's current and future role in preventing microbial foodborne illness within the United States. *Clinical Infectious Diseases*, **61**(2), 252-259, doi:10.1093/cid/civ253.
Drews, S. and J. C. Van den Bergh, 2016: What explains public support for climate policies? A review of empirical and experimental studies. *Clim. Policy*, **16**(7), 855-876.
Druckman, J. N. and M. C. McGrath, 2019: The evidence for motivated reasoning in climate change preference formation. *Nat. Clim. Chang.*, **9**(2), 111-119, doi:10.1038/s41558-018-0360-1.
Du, Q., A. M. Kim and Y. Zheng, 2017: Modeling multimodal freight transportation scenarios in Northern Canada under climate change impacts. *Research in Transportation Business and Management*, **23**, 86-96, doi:10.1016/j.rtbm.2017.02.002.
Dudley, R. W. et al., 2017: Trends in snowmelt-related streamflow timing in the conterminous United States. *Journal of Hydrology*, **547**, 208-221, doi:10.1016/j.jhydrol.2017.01.051.
Duffy-Anderson, J. T. et al., 2019: Responses of the Northern Bering Sea and Southeastern Bering Sea Pelagic Ecosystems Following Record-Breaking Low Winter Sea Ice. *Geophysical Research Letters*, doi:10.1029/2019gl083396.
Dumont, C. et al., 2020: Climate change and risk of completed suicide. *Journal of Nervous and Mental Disease*, **208**(7), 559-565, doi:10.1097/NMD.0000000000001162.
Dunlap, R. E., A. M. McCright and J. H. Yarosh, 2016: The political divide on climate change: Partisan polarization widens in the US. *Environment: Science and Policy for Sustainable Development*, **58**(5), 4-23.
Dunn, D. C., S. M. Maxwell, A. M. Boustany and P. N. Halpin, 2016: Dynamic ocean management increases the efficiency and efficacy of fisheries management. *Proc. Natl. Acad. Sci. U. S. A.*, **113**(3), 668-673, doi:10.1073/pnas.1513626113.
Dunning, N. P., T. P. Beach and S. Luzzadder-Beach, 2012: Kax and kol: collapse and resilience in lowland Maya civilization. *Proc. Natl. Acad. Sci. U. S. A.*, **109**(10), 3652-3657, doi:10.1073/pnas.1114838109.
Duran-Encalada, J. A., A. Paucar-Caceres, E. Bandala and G. Wright, 2017: The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region. *European Journal of Operational Research*, **256**(2), 567-581.
Durkalec, A., C. Furgal, M. W. Skinner and T. Sheldon, 2015: Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community. *Social Science & Medicine*, **136-137**, 17-26, doi:10.1016/j.socscimed.2015.04.026.
Duro, J. A. and J. Turrión-Prats, 2019: Tourism seasonality worldwide. *Tourism Management Perspectives*, **31**, 38-53, doi:10.1016/J.TMP.2019.03.010.
Eakin, H. et al., 2018: Agricultural change and resilience: Agricultural policy, climate trends and market integration in the Mexican maize system. *Anthropocene*, **23**, 43-52, doi:10.1016/j.ancene.2018.08.002.
Easterling, D. R. et al., 2017: Precipitation change in the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Vol I* [Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart and T. K. Maycock (eds.)]. U.S. Global Change Research Program, Washington DC, USA, pp. 207-230.
Eaton, J., S. Kortum, B. Neiman and J. Romalis, 2016: Trade and the Global Recession. *American Economic Review*, **106**(11), 3401-3438, doi:10.1257/aer.20101557.
Ebi, K. L., 2015: Greater understanding is needed of whether warmer and shorter winters associated with climate change could reduce winter mortality. *Environmental Research Letters*, **10**(11), 111002, doi:10.1088/1748-9326/10/11/111002.
Ebi, K. L. and D. Mills, 2013: Winter mortality in a warming climate: A reassessment. *Wiley Interdisciplinary Reviews: Climate Change*, **4**(3), 203-212, doi:10.1002/wcc.211.
Edwin, S. G. and N. Mölders, 2018: Particulate matter exposure of rural interior communities as observed by the First Tribal Air Quality Network in the Yukon Flat. *Journal of Environmental Protection*, **9**, 1425-1448, doi:10.4236/jep.2018.913088.
Eisen, L. and C. G. Moore, 2013: Aedes (Stegomyia) aegypti in the continental United States: A vector at the cool margin of its geographic range. *Journal of Medical Entomology*, **50**(3), 467-478, doi:10.1603/ME12245.
Eisen, R. J., L. Eisen, N. H. Ogden and C. B. Beard, 2016: Linkages of weather and climate With Ixodes scapularis and Ixodes pacificus (Acari: Ixodidae), enzootic transmission of Borrelia burgdorferi, and Lyme Disease in North America. *Journal of Medical Entomology*, **53**(2), 250-261, doi:10.1093/jme/tjv199.
Eisenberg, D. A., 2016: Transforming building regulatory systems to address climate change. *Building Research & Information*, **44**(5-6), 468-473, doi:10.1080/09613218.2016.1126943.
Ekstrom, J. A. et al., 2015: Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change*, **5**(3), 207-214, doi:10.1038/nclimate2508.
Elias, E. et al., 2018: Vulnerability of field crops to midcentury temperature changes and yield effects in the Southwestern USA. *Climatic Change*, **148**(3), 403-417, doi:10.1007/s10584-017-2108-8.

Emanuel, K., 2017: Assessing the present and future probability of Hurricane Harvey's rainfall. *Proc. Natl. Acad. Sci. U. S. A.*, **114**(48), 12681-12684, doi:10.1073/pnas.1716222114.
Emanuel, R. E., 2019: Water in the Lumbee world: A river and its people in a time of change. *Environmental History*, **24**(1), 25-51, doi:10.1093/envhis/emy129.
Emilsson, T. and Å. O. Sang, 2017: Impacts of climate change on urban areas and nature-based solutions for adaptation. Springer Open, London, UK, pp. 15-28.
Enquist, C. A. F. et al., 2017: Foundations of translational ecology. *Frontiers in Ecology and the Environment*, **15**(10), 541-550, doi:10.1002/fee.1733.
EPA, 2015a: *Climate Change in the United States: Benefits of Global Action*. US Environmental Protection Agency, Washington, DC. Available at: https:// www.epa.gov/sites/production/files/2015-07/ documents/epa816r13006.pdf (accessed 04/03/19).
EPA, 2015b: *Flood Loss Avoidance Benefits of Green Infrastructure for Stormwater Management*. Agency, U. S. E. P., Washington, DC, 195 pp. Available at: https://www.epa.gov/sites/default/files/2016-05/documents/flood-avoidance-green-infrastructure-12-14-2015.pdf
EPA, 2017: *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment*. United States Environmental Protection Agency, O. o. A. P., EPA, 271 pp.
EPA, 2021: Quinault Indian Nation Plans for Relocation. Available at: https://www.epa.gov/arc-x/quinault-indian-nation-plans-relocation.
EPCCAR, 2018: *Measuring Progress on Adaptation and Climate Resilience: Recommendations to the Government of Canada*. Environment and Climate Change Canada, Ottawa, ON, 188-188 pp.
Escalante-Sandoval, C. and P. Nuñez-Garcia, 2017: Meteorological drought features in northern and northwestern parts of Mexico under different climate change scenarios. *Journal of Arid Land*, **9**(1), 65-75, doi:10.1007/s40333-016-0022-y.
Esperon-Rodriguez, M., M. Bonifacio-Bautista and V. L. Barradas, 2016: Socio-economic vulnerability to climate change in the central mountainous region of eastern Mexico. *Ambio*, **45**(2), 146-160, doi:10.1007/s13280-015-0690-4.
Estrada, A. G., 2021: Climate Change and Great Power Competition in the Arctic. In: *Security in the Global Commons and Beyond* [Ramirez, J. M. and B. Bauza-Abril (eds.)]. Springer International Publishing, pp. 33-50. ISBN 978-3-030-67972-9.
Estrada, F., W. J. W. Botzen and R. S. J. Tol, 2015: Economic losses from US hurricanes consistent with an influence from climate change. *Nature Geoscience*, **8**(11), 880-884, doi:10.1038/ngeo2560.
Estrada, F., E. Papyrakis, R. S. J. Tol and C. Gay-Garcia, 2013: The economics of climate change in Mexico: implications for national/regional policy. *Climate Policy*, **13**(6), 738-750, doi:10.1080/14693062.2013.813806.
Etchart, L., 2017: The role of Indigenous Peoples in combating climate change. *Palgrave Communications*, **3**, 17085, doi:10.1057/palcomms.2017.85.
Eyzaguirre, J. et al., 2021: International Dimensions. In: *Canada in a Changing Climate: National Issues Report,* [Warren, D. A. and N. Lulham (eds.)]. Government of Canada, Ottawa, ON, pp. 623-734.
FAO, 2018: *The State of World Fisheries and Aquaculture: Meeting the sustainable development goals*. Food and Agriculture Organization of the United Nations, Rome, Italy.
FAQI, 2019: *2019 climate change report*. Femmes Autochtones du Québec Inc./Quebec Native Women Inc., Kahnawake, QC, 28-28 pp.
Farrell, J., 2016a: Corporate funding and ideological polarization about climate change. *Proceedings of the National Academy of Sciences*, **113**(1), 92-97.
Farrell, J., 2016b: Network structure and influence of the climate change counter-movement. *Nature Climate Change*, **6**(4), 370-374.
Fasullo, J. T. and R. S. Nerem, 2018: Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future. *Proc. Natl. Acad. Sci. U. S. A.*, **115**(51), 12944-12949, doi:10.1073/pnas.1813233115.
Fatorić, S. and E. Seekamp, 2017: Are cultural heritage and resources threatened by climate change? A systematic literature review. *Climatic Change*, **142**(1-2), 227-254, doi:10.1007/s10584-017-1929-9.
Fatorić, S. and E. Seekamp, 2019: Knowledge co-production in climate adaptation planning of archaeological sites. *Journal of Coastal Conservation*, **23**(3), 689-698.
Fayazi, M., I.-A. Bisson and E. Nicholas, 2020: Barriers to climate change adaptation in indigenous communities: A case study on the mohawk community of Kanesatake, Canada. *International Journal of Disaster Risk Reduction*, **49**, 101750, doi:10.1016/j.ijdrr.2020.101750.
Fazey, I. et al., 2018: Ten essentials for action-oriented and second order energy transitions, transformations and climate change research. *Energy Research & Social Science*, **40**, 54-70.
Fedele, G. et al., 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116-125, doi:https://doi.org/10.1016/j.envsci.2019.07.001.
Fell, S. C., J. L. Carrivick and L. E. Brown, 2017: The Multitrophic Effects of Climate Change and Glacier Retreat in Mountain Rivers. *Bioscience*, **67**(10), 897-911, doi:10.1093/biosci/bix107.
FEMA, 2016: *South Carolina Dam Failure Assessment and Advisement. FEMA P-1801*, Agency, F. E. M., Washington, D.C., 64 pp. Available at: https://www.fema.gov/media-library/assets/ documents/129760.

FEMA, 2019: *The National Dam Safety Program: Biennial Report to the United States Congress, Fiscal Years 2016–2017*. Security, U. S. D. o. H. Available at: https://www.fema.gov/sites/default/files/2020-08/national-dam-safety_biennial-report-2016-2017.pdf.
Feng, Z. et al., 2016: More frequent intense and long-lived storms dominate the springtime trend in central US rainfall. *Nat. Commun.*, **7**, doi:10.1038/ncomms13429.
Ferguson, J. and M. Weaselboy, 2020: Indigenous sustainable relations: considering land in language and language in land. *Current Opinion in Environmental Sustainability*, **43**, 1-7, doi:10.1016/j.cosust.2019.11.006.
Feria-Arroyo, T. P. et al., 2014: Implications of climate change on the distribution of the tick vector Ixodes scapularis and risk for Lyme disease in the Texas-Mexico transboundary region. *Parasites & Vectors*, **7**, 199-199, doi:10.1186/1756-3305-7-199.
Fernández-Arteaga, V. et al., 2016: Association between completed suicide and environmental temperature in a Mexican population, using the Knowledge Discovery in Database approach. *Computer Methods and Programs in Biomedicine*, **135**, 219-224, doi:10.1016/j.cmpb.2016.08.002.
Ferrario, F. et al., 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat. Commun.*, **5**, 3794, doi:10.1038/ncomms4794.
Filbee-Dexter, K., C. J. Feehan and R. E. Scheibling, 2016: Large-scale degradation of a kelp ecosystem in an ocean warming hotspot. *Marine Ecology Progress Series*, **543**, 141-152, doi:10.3354/meps11554.
Fillion, M. et al., 2014: Development of a strategic plan for food security and safety in the Inuvialuit Settlement Region, Canada. *International Journal of Circumpolar Health*, **73**, 25091, doi:10.3402/ijch.v73.25091.
Finney, D. L. et al., 2018: A projected decrease in lightning under climate change. *Nature Climate Change*, **8**(3), 210-213, doi:10.1038/s41558-018-0072-6.
Firesmart Canada, 2018: *Firesmart Begins at home. FireSmart Home Development Guide*. 17 pp. Available at: https://www.firesmartcanada.ca/mdocs-posts/firesmart-home-development-guide/.
Fisher, M. C. et al., 2021: Climate shock effects and mediation in fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, **118**(2), 1-8, doi:10.1073/pnas.2014379117.
Fisichelli, N. A., G. W. Schuurman, W. B. Monahan and P. S. Ziesler, 2015: Protected Area Tourism in a Changing Climate: Will Visitation at US National Parks Warm Up or Overheat? *PLoS One*, **10**(6), e0128226, doi:10.1371/journal.pone.0128226.
Fitzer, S. C. et al., 2019: Selectively bred oysters can alter their biomineralization pathways, promoting resilience to environmental acidification. *Glob. Chang. Biol.*, doi:10.1111/gcb.14818.
Fleming, E. et al., 2018: Coastal effects. [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunke, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 322-352.
Fleming, S. W. and H. E. Dahlke, 2014: Modulation of linear and nonlinear hydroclimatic dynamics by mountain glaciers in Canada and Norway: Results from information-theoretic polynomial selection. *Canadian Water Resources Journal*, **39**(3), 324-341, doi:10.1080/07011784.2014.974308.
Foley, M. M. et al., 2013: Improving Ocean Management through the Use of Ecological Principles and Integrated Ecosystem Assessments. *Bioscience*, **63**(8), 619-631, doi:10.1525/bio.2013.63.8.5.
Food Agriculture Organization of the United Nations, F., 2019: *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options. FAO FISHERIES AND AQUACULTURE TECHNICAL PAPER 627*. Food & Agriculture Org., 654 pp. ISBN 9789251306079.
Ford, J. D., 2012: Indigenous health and climate change. *American Journal of Public Health*, **102**(7), 1260-1266, doi:10.2105/AJPH.2012.300752.
Ford, J. D. et al., 2016: Including Indigenous knowledge and experience in IPCC assessment reports. *Nature Climate Change*, **6**, 349-353, doi:10.1038/nclimate2954.
Ford, J. D., G. McDowell and J. Jones, 2014: The state of climate change adaptation in the Arctic. *Environmental Research Letters*, **9**(10), 104005, doi:10.1088/1748-9326/9/10/104005.
Ford, J. D., B. Smit and J. Wandel, 2006: Vulnerability to climate change in the Arctic: A case study from Arctic Bay, Canada. *Global Environmental Change*, **16**(2), 145-160, doi:10.1016/j.gloenvcha.2005.11.007.
Foster, L. M. et al., 2016: Energy budget increases reduce mean streamflow more than snow–rain transitions: using integrated modeling to isolate climate change impacts on Rocky Mountain hydrology. *Environmental Research Letters*, **11**(4), 044015, doi:10.1088/1748-9326/11/4/044015.
Fosu, B. O., S. Y. Simon Wang and J.-H. Yoon, 2017: The 2014/15 Snowpack Drought in Washington State and its Climate Forcing. *Bulletin of the American Meteorological Society*, **97**(12), S19-S24, doi:10.1175/BAMS-D-16-0154.1.
Foulon, E. and A. N. Rousseau, 2019: Surface Water Quantity for Drinking Water during Low Flows - Sensitivity Assessment Solely from Climate Data. *Water Resources Management*, **33**(1), 369-385, doi:10.1007/s11269-018-2107-1.
Frame, D. J., M. F. Wehner, I. Noy and S. M. Rosier, 2020: The economic costs of Hurricane Harvey attributable to climate change. *Climatic Change*.
Frankel, J. A. and A. K. Rose, 2005: Is Trade Good or Bad for the Environment? Sorting Out the Causality. *The Review of Economics and Statistics*, **87**(1), 85-91, doi:10.1162/0034653053327577.

Franks, J. S., D. R. Johnson and D. S. Ko, 2016: Pelagic sargassum in the tropical North Atlantic. *Gulf Caribb. Res.*, **27**(1), SC6-SC11.
Frans, C. et al., 2018: Glacier Recession and the Response of Summer Streamflow in the Pacific Northwest United States, 1960–2099. *Water Resources Research*, **54**(9), 6202-6225.
Frederikse, T. et al., 2020: The causes of sea-level rise since 1900. *Nature*, **584**(7821), 393-397, doi:10.1038/s41586-020-2591-3.
Free, C. M. et al., 2020: Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *Plos one*, **15**(3), e0224347.
Free, C. M. et al., 2019: Impacts of historical warming on marine fisheries production. **983**(March), 979-983, doi:10.1126/science.aau1758.
Friedlingstein, P. et al., 2020: Global Carbon Budget 2020. *Earth Syst. Sci. Data*, **12**(4), 3269-3340, doi:10.5194/essd-12-3269-2020.
Frieler, K. et al., 2013: Limiting global warming to 2C is unlikely to save most coral reefs. *Nature Climate Change*, **3**(2), 165-170, doi:10.1038/nclimate1674.
Frisvold, G. B. and K. Konyar, 2012: Less water: How will agriculture in Southern Mountain states adapt? *Water Resources Research*, **48**(5), 1-15, doi:10.1029/2011WR011057.
Froehlich, H. E., J. C. Afflerbach, M. Frazier and B. S. Halpern, 2019: Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. *Curr. Biol.*, doi:10.1016/j.cub.2019.07.041.
Froehlich, H. E., T. E. Essington and P. S. McDonald, 2017: When does hypoxia affect management performance of a fishery? A management strategy evaluation of Dungeness crab (Metacarcinus magister) fisheries in Hood Canal, Washington, USA. *Can. J. Fish. Aquat. Sci.*, **74**(6), 922-932.
Froehlich, H. E., R. R. Gentry and B. S. Halpern, 2018: Global change in marine aquaculture production potential under climate change. *Nat Ecol Evol*, **2**(11), 1745-1750, doi:10.1038/s41559-018-0669-1.
Froehlich, H. E. et al., 2015: Spatial and temporal variation in nearshore macrofaunal community structure in a seasonally hypoxic estuary. *Marine Ecology Progress Series*, **520**, 67-83, doi:10.3354/meps11105.
Frölicher, T. L., E. M. Fischer and N. Gruber, 2018: Marine heatwaves under global warming. *Nature*, **560**(7718), 360-364, doi:10.1038/s41586-018-0383-9.
Fulton, E. A. et al., 2019: Ecosystems say good management pays off. *Fish and Fisheries*, **20**(1), 66-96, doi:10.1111/faf.12324.
Fünfgeld, H., 2015: Facilitating local climate change adaptation through transnational municipal networks. *Current Opinion in Environmental Sustainability*, **12**, 67-73, doi:10.1016/j.cosust.2014.10.011.
Fussell, E., 2015: The long-term recovery of New Orleans' population after Hurricane Katrina. *American Behavioral Scientist*, **59**(10), 1231-1245.
Fussell, E., K. J. Curtis and J. DeWaard, 2014: Recovery migration to the City of New Orleans after Hurricane Katrina: a migration systems approach. *Population and environment*, **35**(3), 305-322.
Fyfe, J. C. et al., 2017: Large near-term projected snowpack loss over the western United States. *Nat. Commun.*, **8**, doi:10.1038/ncomms14996.
Gabbert, W., 2004: *Becoming Maya: Ethnicity and social inequality in Yucatan since 1500*. University of Arizona Press, Tucson.
Gaichas, S. K. et al., 2017: Combining stock, multispecies, and ecosystem level fishery objectives within an operational management procedure: Simulations to start the conversation. *ICES Journal of Marine Science*, **74**(2), 552-565, doi:10.1093/icesjms/fsw119.
Gaines, S. D. et al., 2018: Improved fisheries management could offset many negative effects of climate change. *Science advances*, **4**(8), eaao1378.
Galappaththi, E. K., J. D. Ford, E. M. Bennett and F. Berkes, 2019: Climate change and community fisheries in the arctic: A case study from Pangnirtung, Canada. *Journal of Environmental Management*, **250**(September), 109534-109534, doi:10.1016/j.jenvman.2019.109534.
Galloza, M. S., A. Lopez-Santos and S. Martinez-Santiago, 2017: Predicting land at risk from wind erosion using an index-based framework under a climate change scenario in Durango, Mexico. *Environmental Earth Sciences*, **76**(16), doi:10.1007/s12665-017-6751-1.
Galparsoro, I. et al., 2020: Global stakeholder vision for ecosystem-based marine aquaculture expansion from coastal to offshore areas. *Reviews in Aquaculture*, **n/a**(n/a), doi:10.1111/raq.12422.
Galway, L. P., 2019: Perceptions of climate change in Thunder Bay, Ontario: towards a place-based understanding. *Local Environ.*, **24**(1), 68-88.
Galway, L. P. et al., 2015: Hydroclimatic variables and acute gastro-intestinal illness in British Columbia, Canada: A time series analysis. *Water Resources Research*, **51**(2), 885-895, doi:10.1002/2014WR015519.
Gamble, J. L. et al., 2016: Populations of concern. In: *The impacts of climate change on human health in the United States: A scientific assessment*. U.S. Global Change Research Program, Washington, DC, pp. 247-286.
Gamble, J. L. and J. J. Hess, 2012: Temperature and violent crime in Dallas, Texas: relationships and implications of climate change. *West. J. Emerg. Med.*, **13**(3), 239-246, doi:10.5811/westjem.2012.3.11746.
Gampe, D. et al., 2021: Increasing impact of warm droughts on northern ecosystem productivity over recent decades. *Nature Climate Change*, doi:10.1038/s41558-021-01112-8.

Gao, L. and B. A. Bryan, 2017: Finding pathways to national-scale land-sector sustainability. *Nature*, **544**, 217-225, doi:10.1038/nature21694.
García, M., S. Adame and R. Sánchez Rodríguez, 2018: Vulnerabilidad urbana por ciclones tropicales el caso de dos ciudades del estado de Yucatán. In: *Riesgo de desastres en México: Eventos hidrometeorológicos y climáticos* [Rodríguez, J., C. Welsh, M. L. Romo and A. Travieso (eds.)]. REDESCLIM and IMTA.
Garrick, D. E., E. Schlager, L. De Stefano and S. Villamayor-Tomas, 2018: Managing the Cascading Risks of Droughts: Institutional Adaptation in Transboundary River Basins. *Earths Future*, **6**(6), 809-827, doi:10.1002/2018ef000823.
Garruña-Hernández, R. et al., 2012: Changes in flowering and fruiting of Habanero pepper in response to higher temperature and CO2. *Journal of Food, Agriculture & Environment*, **10**(3-4), 802-808.
Gartner, T. et al., 2017: Protecting Drinking Water at the Source: Lessons From US Watershed Investment Programs. *Journal American Water Works Association*, **109**(4), 30-41, doi:10.5942/jawwa.2017.109.0049.
Garza, M. et al., 2014: Projected future distributions of vectors of *Trypanosoma cruzi* in North America under climate change scenarios. *PLOS Neglected Tropical Diseases*, **8**(5), e2818, doi:10.1371/journal.pntd.0002818.
Garza-Lopez, M. et al., 2018: MODIFICATION OF THE HABITAT FOR Lysiloma latisiliquum (L.) Benth. (TZALAM) FOR CLIMATE CHANGE. *Revista Fitotecnia Mexicana*, **41**(2), 127-135.
Gasbarro, F., F. Rizzi and M. Frey, 2016: Adaptation Measures of Energy and Utility Companies to Cope with Water Scarcity Induced by Climate Change. *Bus. Strateg. Environ.*, **25**(1), 54-72, doi:10.1002/bse.1857.
Gasparrini, A. et al., 2015: Mortality risk attributable to high and low ambient temperature: A multicountry observational study. *The Lancet*, **386**(9991), 369-375, doi:10.1016/S0140-6736(14)62114-0.
Gasparrini, A. et al., 2017: Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health*, **1**(9), e360-e367, doi:10.1016/S2542-5196(17)30156-0.
Gattuso, J.-P. et al., 2018: Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. *Frontiers in Marine Science*, **5**, doi:10.3389/fmars.2018.00337.
Gattuso, J. P. et al., 2015: OCEANOGRAPHY. Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science*, **349**(6243), aac4722, doi:10.1126/science.aac4722.
Gaughen, S., S. Bliss, J. Mauck and T. Romero, 2021: Cultural resources. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 210-221.
Gauthier, S. et al., 2015: Vulnerability of timber supply to projected changes in fire regime in Canada's managed forests. *Canadian Journal of Forest Research*, **45**(11), 1439-1447, doi:10.1139/cjfr-2015-0079.
Gauthier, S. et al., 2014: *Tracking climate change effects: Potential indicators for Canada's forests and forest sector*. Natural Resources Canada, Canadian Forest Service, Ottawa, Ontario, 86 pp.
Gearheard, S. F. et al., 2013: *The meaning of ice: People and sea ice in three Arctic communities*. International Polar Institute Press, Hanover, NH, 366 pp.
Gentry, R. R. et al., 2019: Exploring the potential for marine aquaculture to contribute to ecosystem services. *Reviews in Aquaculture*, **0**(0), doi:10.1111/raq.12328.
Georgetown Climate Center, 2021: State Adaptation Progress Tracker. Available at: https://www.georgetownclimate.org/adaptation/plans.html.
Gerlak, A. K., F. Zamora-Arroyo and H. P. Kahler, 2013: A Delta in Repair: Restoration, Binational Cooperation, and the Future of the Colorado River Delta. *Environment*, **55**(3), 29-39, doi:10.1080/00139157.2013.785865.
Gershunov, A. et al., 2019: Precipitation regime change in Western North America: The role of Atmospheric Rivers. *Sci Rep*, **9**, 11, doi:10.1038/s41598-019-46169-w.
Gibert, J. P., 2019: Temperature directly and indirectly influences food web structure. *Sci. Rep.*, **9**(1), 5312, doi:10.1038/s41598-019-41783-0.
Giddens, A., 2015: The politics of climate change. *Policy & Politics*, **43**(2), 155-162.
Giersch, J. J. et al., 2017: Climate-induced glacier and snow loss imperils alpine stream insects. *Glob. Chang. Biol.*, **23**(7), 2577-2589, doi:10.1111/gcb.13565.
Gil, M. A. et al., 2015: Rapid tourism growth and declining coral reefs in Akumal , Mexico. *Mar. Biol.*, **162**, 2225-2233, doi:10.1007/s00227-015-2748-z.
Gillett, N. P., A. J. Weaver, F. W. Zwiers and M. D. Flannigan, 2004: Detecting the effect of climate change on Canadian forest fires. *Geophysical Research Letters*, **31**(18), doi:10.1029/2004gl020876.
Gilmore, E. A. and T. St. Clair, 2018: Budgeting for climate change: obstacles and opportunities at the US state level. *Clim. Policy*, **18**(6), 729-741.
Gingold, D. B., M. J. Strickland and J. J. Hess, 2014: Ciguatera fish poisoning and climate change: Analysis of National Poison Center data in the United States, 2001-2011. *Environmental Health Perspectives*, **122**(6), 580-586, doi:10.1289/ehp.1307196.
Gledhill, D. et al., 2015: Ocean and Coastal Acidification off New England and Nova Scotia. *Oceanography*, **25**(2), 182-197, doi:10.5670/oceanog.2015.41.
Gobler, C. J., 2020: Climate change and harmful algal blooms: Insights and perspective. *Harmful Algae*, **91**, 101731, doi:10.1016/j.hal.2019.101731.

Gobler, C. J. et al., 2017: Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proc. Natl. Acad. Sci. U. S. A.*, **114**(19), 4975-4980, doi:10.1073/pnas.1619575114.
Goldberg, M. H. et al., 2020: Identifying the most important predictors of support for climate policy in the United States. *Behavioural Public Policy*, 1-23, doi:doi:10.1017/bpp.2020.39.
Gomez Diaz, J. D. et al., 2019: Soil moisture regimes in Mexico in a global 1.5°C warming scenario. *International Journal of Climate Change Strategies and Management*, **11**(4), 465-482, doi:10.1108/IJCCSM-08-2018-0062.
Gomez-Aiza, L. et al., 2017: Can wildlife management units reduce land use/land cover change and climate change vulnerability? Conditions to encourage this capacity in Mexican municipalities. *Land Use Policy*, **64**, 317-326, doi:10.1016/j.landusepol.2017.03.004.
Gonzalez, P. et al., 2018: Southwest. In: *Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 1101-1184.
Government of Alberta, 2016: *Home again : recovery after the Wood Buffalo wildfire*. 43 pp. Available at: https://open.alberta.ca/publications/9781460131350.
Government of Campeche, 2013: *Programa estatal de accion ante el Cambio Climatico*. Campeche, G. o., Campeche, MX, 133 pp. Available at: http://www.ccpy.gob.mx/pdf/agenda-campeche/programa-estatal-cambio-climatico/PECCCampeche.pdf.
Government of Canada, 2011: *Federal Adaptation Policy Framework*. Canada, E., Gatineau, QC. Available at: https://publications.gc.ca/collections/collection_2016/eccc/M4-133-2016-eng.pdf.
Government of Canada, 2016: Pan-Canadian framework on clean growth and climate change. Canada's plan to address climate change and grow the economy.
Government of Canada, 2019: Trade data online. International trade data and market intelligence.
Government of Canada, 2020: Hamlet of Tuktoyaktuk: Climate Change and Coastal Erosion. Available at: https://www.canada.ca/en/crown-indigenous-relations-northern-affairs/news/2020/07/hamlet-of-tuktoyaktuk-climate-change-and-coastal-erosion.html.
Government of Canada, 2021a: *Adapting to the Impacts of Climate Change in Canada: an update on the National Adaptation Strategy*. Canada, E. a. C. C., Gatineau QC, 17 pp. Available at: https://www.canada.ca/content/dam/eccc/documents/pdf/reports/report-update-national-adaptation-strategy.pdf.
Government of Canada, 2021b: *Canada's 2021 Nationally determined Contribution Under the Paris Agreement*. 42 pp. Available at: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Canada%20First/Canada's%20Enhanced%20NDC%20Submission1_FINAL%20EN.pdf.
Government of Canada, Infrastructure in Ontario. Available at: https://www.infrastructure.gc.ca/plan/prog-proj-on-eng.html.
Government of Mexico, 2020: *Nationally Determined Contributions. 2020 Update*. Resources, M. o. E. a. N., 42 pp. Available at: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Mexico%20First/NDC-Eng-Dec30.pdf.
Government of Quintana Roo, 2013: *Programa Estatal de Accion ante el Cambio Climatico*. 116 pp. Available at: https://cambioclimatico.gob.mx/wp-content/uploads/2018/11/Documento-4-Programa-Estatal-de-Acci%C3%B3n-Quintana-Roo-PEACCQROO-2013.pdf.
Government of the United State of America, 2021: *The United State of America National Determined Contribution. Reducing Greenhouse Gases in the United States; A 2030 Emissions Target*. Washington, DC, 24 pp. Available at: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/United%20States%20of%20America%20First/United%20States%20NDC%20April%2021%202021%20Final.pdf.
Government of Veracruz, 2008: *Programa Veracruzano ante el Cambio Climático*. 194 pp. Available at: https://drive.google.com/file/d/0B87bmmJLaLIgU3pqVnhkMEFJbWc/edit?usp=sharing.
Gowda, P. et al., 2018: Agriculture and Rural Communities. In: *Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. Global Change Research Program, Washington, DC, USA, pp. 391-437.
Gräns, A. et al., 2014: Aerobic scope fails to explain the detrimental effects on growth resulting from warming and elevated CO2 in Atlantic halibut. *Journal of Experimental Biology*, **217**(5), 711-717.
Gray et al., 2015: *Allocating California's Water: Directions for Reform*. California, P. P. I. o., San Francisco, CA. Available at: https://www.ppic.org/content/pubs/report/R_1115BGR.pdf.
Green, D. and G. Raygorodetsky, 2010: Indigenous knowledge of a changing climate. *Climatic Change*, **100**(2), 239-242, doi:10.1007/s10584-010-9804-y.
Greenan, B. J. W. et al., 2019a: *Changes in oceans surrounding Canada* [Bush, E. and D. S. Lemmen (eds.)]. Canada's Changing Climate Report, Government of Canada, Ottawa, Ontario, 343-423 pp. Available at: https://changingclimate.ca/site/assets/uploads/sites/2/2018/12/CCCR-Chapter7-ChangesInOceansSurroundingCanada.pdf.
Greenan, B. J. W. et al., 2018: Changes in oceans surrounding Canada; Chapter 7. [Bush, E. and D. S. Lemmen (eds.)]. Government of Canada, Ottawa, ON, pp. 343-423.

Greenan, B. J. W. et al., 2019b: Climate Change Vulnerability of American Lobster Fishing Communities in Atlantic Canada. *Frontiers in Marine Science*, **6**(September), 1-18, doi:10.3389/fmars.2019.00579.
Grenier, C. M., S. K. Grossman and J. S. Barber, 2015: *Swinomish Olympia Oyster Monitoring Plan*. Swinomish Indian Tribal Commnity, Commnity, S. I. T., La Conner, WA, 21 pp. Available at: https://creoi.org/wp-system/wp-content/uploads/2016/02/swin_cr_2015_04_greineretaloystermonitoring.pdf.
Griffith, A. W. and C. J. Gobler, 2019: Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. *Harmful Algae*, doi:10.1016/j.hal.2019.03.008.
Grinsted, A., P. Ditlevsen and J. H. Christensen, 2019: Normalized US hurricane damage estimates using area of total destruction, 1900-2018. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(48), 23942-23946, doi:10.1073/pnas.1912277116.
Gronlund, C., 2014: Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. *Current epidemiology reports*, **1**(3).
Grossman, Z., 2008: Indigenous Nations' responses to climate change. *American Indian Culture and Research Journal*, **32**(3), 5-27, doi:10.17953/aicr.32.3.n561082k204ul53g.
Groulx, M., K. Boluk, C. J. Lemieux and J. Dawson, 2019: Place stewardship among last chance tourists. *Annals of Tourism Research*, doi:10.1016/j.annals.2019.01.008.
Groulx, M. et al., 2016: Motivations to engage in last chance tourism in the Churchill Wildlife Management Area and Wapusk National Park: the role of place identity and nature relatedness. *J. Sustainable Tour.*, **24**, doi:10.1080/09669582.2015.1134556.
Guay, C., M. Minville and M. Braun, 2015: A global portrait of hydrological changes at the 2050 horizon for the province of Québec. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, **40**(3), 285-302.
Gubernot, D. M., G. B. Anderson and K. L. Hunting, 2014: The epidemiology of occupational heat exposure in the United States: a review of the literature and assessment of research needs in a changing climate. *International journal of biometeorology*, **58**(8), 1779-1788, doi:10.1007/s00484-013-0752-x.
Guerrero, G. o., 2017: *VULNERABILIDAD DEL DESTINO TURÍSTICO ACAPULCO*. A.C., A. N. D. I. Y. D., Cuernavaca, MX, 31 pp. Available at: https://www.gob.mx/cms/uploads/attachment/file/249041/SECCION-II.-ACAPULCO.pdf
Guilbault, S., P. Kovacs and P. Berry, 2016: *Cities adapt to extreme heat: Celebrating local leadership*. Available at: https://www.iclr.org/images/Cities_Adapt_to_Extreme_Heat_online.compressed.pdf.
Guiterman, C. H. et al., 2018: Long-Term Persistence and Fire Resilience of Oak Shrubfields in Dry Conifer Forests of Northern New Mexico. *Ecosystems*, **21**(5), 943-959, doi:10.1007/s10021-017-0192-2.
Guo, Y. et al., 2018: Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLoS Med.*, **15**(7), 1-17, doi:10.1371/journal.pmed.1002629.
Gutiérrez, J. M. et al., In Press: *Atlas* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U. Available at: http://interactive-atlas.ipcc.ch/.
Guyot, M. et al., 2006: Local observations of climate change and impacts on traditional food security in two northern aboriginal communities. *International Journal of Circumpolar Health*, **65**(5).
Haasnoot, M. et al., 2020: Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, **20**(2), 37, doi:10.1007/s10113-020-01623-8.
Haer, T. et al., 2018: Coastal and river flood risk analyses for guiding economically optimal flood adaptation policies: a country-scale study for Mexico. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **376**(2121), doi:10.1098/rsta.2017.0329.
Haer, T., E. Kalnay, M. Kearney and H. Moll, 2013: Relative sea-level rise and the conterminous United States: Consequences of potential land inundation in terms of population at risk and GDP loss. *Global Environmental Change*, **23**(6), 1627-1636, doi:10.1016/j.gloenvcha.2013.09.005.
Haffey, C. et al., 2018: Limits to Ponderosa Pine Regeneration following Large High-Severity Forest Fires in the United States Southwest. *Fire Ecology*, **14**(1), 143-163, doi:10.4996/fireecology.140114316.
Hagerman, S. M. and R. Pelai, 2018: Responding to climate change in forest management: two decades of recommendations. *Frontiers in Ecology and the Environment*, **16**(10), 579-587, doi:https://doi.org/10.1002/fee.1974.
Haguma, D. et al., 2014: Optimal hydropower generation under climate change conditions for a northern water resources system. *Water resources management*, **28**(13), 4631-4644.
Halifax Regional Council, 2020: HalifACT: Acting on Climate Together. Available at: https://www.halifax.ca/about-halifax/energy-environment/halifact-2050-acting-climate-together.
Halofsky, J. E., D. L. Peterson and B. J. Harvey, 2020: Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, **16**(1), 4.
Hamilton, L. C. et al., 2016: Climigration? Population and climate change in Arctic Alaska. *Population and environment*, **38**(2), 115-133.

Hamin, E. M., N. Gurran and A. M. Emlinger, 2014: Barriers to municipal climate adaptation: Examples from coastal Massachusetts smaller cities and towns. *J. Am. Plann. Assoc.*, **80**(2), 110-122, doi:10.1080/01944363.2014.949590.
Han, H. et al., 2018: Productivity and costs of two beetle-kill salvage harvesting methods in Northern Colorado. *Forests*, **9**(9), doi:10.3390/f9090572.
Hanak, E. et al., 2019: *Water and the Future of the San Joaquin Valley*. Public Policy Institute of California (PPIC), 100 pp. Available at: https://www.ppic.org/wp-content/uploads/water-and-the-future-of-the-san-joaquin-valley-february-2019.pdf (accessed 2019/3/15).
Hanak, E. et al., 2015: *What if California's drought continues?*, 1-20 pp. Available at: http://www.ppic.org/content/pubs/report/R_815EHR.pdf.
Handisyde, N., T. C. Telfer and L. G. Ross, 2017: Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish and Fisheries*, **18**(3), 466-488, doi:10.1111/faf.12186.
Hanes, C. C. et al., 2019: Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, **49**(3), 256-269, doi:10.1139/cjfr-2018-0293.
Hanrahan, M. et al., 2014: Exploring water insecurity in a Northern Indigenous community in Canada: The "never-ending job" of the Southern Inuit of Black Tickle, Labrador. *Arctic Anthropology*, **51**(2), 9-22.
Happer, C. and G. Philo, 2013: The Role of the Media in the Construction of Public Belief and Social Change. *Journal of Social and Political Psychology*, **1**(1), 321-336, doi:10.5964/jspp.v1i1.96.
Hardoy, J., I. Hernandez, J. A. Pacheco and G. Sierra, 2014: Institutionalizing climate change adaptation at municipal and state level in Chetumal and Quintana Roo, Mexico. *Environment and Urbanization*, **26**(1), 69-85, doi:10.1177/0956247813519053.
Hare, J. A. et al., 2016: A Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U.S. Continental Shelf. *PLoS One*, **11**(2), e0146756, doi:10.1371/journal.pone.0146756.
Harp, R. D. and K. B. Karnauskas, 2018: The Influence of Interannual Climate Variability on Regional Violent Crime Rates in the United States. *GeoHealth*, **2**(11), 356-369.
Harp, R. D. and K. B. Karnauskas, 2020: Global warming to increase violent crime in the United States. *Environ. Res. Lett.*, **15**(3), 034039, doi:10.1088/1748-9326/ab6b37.
Harper, S. L. et al., 2021a: Trends and gaps in climate change and health research in North America. *Environmental Research*, **199**, 111205, doi:10.1016/j.envres.2021.111205.
Harper, S. L. et al., 2021b: Climate change and health in North America: literature review protocol. *Systematic Reviews*, **10**, 3, doi:10.1186/s13643-020-01543-y.
Harper, S. L. et al., 2015: Climate-sensitive health priorities in Nunatsiavut, Canada. *BMC Public Health*, **15**, 605-605, doi:10.1186/s12889-015-1874-3.
Harper, S. L. et al., 2011: Weather, water quality and infectious gastrointestinal illness in two Inuit communities in Nunatsiavut, Canada: Potential implications for climate change. *EcoHealth*, **8**(1), 93-108, doi:10.1007/s10393-011-0690-1.
Harper, S. L., C. Wright, S. Masina and S. Coggins, 2020: Climate change, water, and human health research in the Arctic. *Water Security*, **10**, 100062, doi:10.1016/j.wasec.2020.100062.
Harpold, A., M. Dettinger and S. Rajagopal, 2017: Defining snow drought and why it matters. **98**, doi:10.1029/2017eo068775.
Harrigan, R. J., H. A. Thomassen, W. Buermann and T. B. Smith, 2014: A continental risk assessment of West Nile virus under climate change. *Global Change Biology*, **20**, 2417-2425, doi:10.1111/gcb.12534.
Harrington, J., 2006: Climate change, human rights, and the right to be cold. *Fordham Environmental Law Review*, **18**, 513-535.
Harris-Lovett, S. R. et al., 2015: Beyond User Acceptance: A Legitimacy Framework for Potable Water Reuse in California. *Environmental Science & Technology*, **49**(13), 7552-7561, doi:10.1021/acs.est.5b00504.
Hauer, M. E., J. M. Evans and D. R. Mishra, 2016: Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, **6**(7), 691-695, doi:10.1038/nclimate2961.
Hauser, D. D. W., K. L. Laidre and H. L. Stern, 2018: Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. *Proceedings of the National Academy of Sciences*, **115**(29), 7617-7622, doi:10.1073/pnas.1803543115.
Havstad, K. M. et al., 2018: Vulnerabilities of Southwestern U.S. Rangeland-based animal agriculture to climate change. *Climatic Change*, **148**(3), 371-386, doi:10.1007/s10584-016-1834-7.
Hayes, K. et al., 2018: Climate change and mental health: Risks, impacts and priority actions. *International Journal of Mental Health Systems*, **12**, 28, doi:10.1186/s13033-018-0210-6.
Haynes, K. M., R. F. Connon and W. L. Quinton, 2018: Permafrost thaw induced drying of wetlands at Scotty Creek, NWT, Canada. *Environmental Research Letters*, **13**, 114001, doi:10.1088/1748-9326/aae46c.
Hazen, E. L. et al., 2019: Marine top predators as climate and ecosystem sentinels. *Frontiers in Ecology and the Environment,* 1**7(**10), doi:10.1002/fee.2125.
Hazen, E. L. et al., 2013: Predicted habitat shifts of Pacific top predators in a changing climate. *Nat. Clim. Chang.*, **3**(3), 234-238, doi:10.1038/nclimate1686.
Hazen, E. L. et al., 2017: WhaleWatch: a dynamic management tool for predicting blue whale density in the California Current. *J. Appl. Ecol.*, **54**(5), 1415-1428, doi:10.1111/1365-2664.12820.

Hazen, E. L. et al., 2018: A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Sci Adv*, **4**(5), eaar3001, doi:10.1126/sciadv.aar3001.
Heilmann, K. and M. E. Kahn, 2019: *The Urban Crime and Heat Gradient in High and Low Poverty Areas* Paper, N. W. Available at: https://ssrn.com/abstract=3406479
Heilmann, K., M. E. Kahn and C. K. Tang, 2021: The urban crime and heat gradient in high and low poverty areas. *Journal of Public Economics*, **197**, 104408, doi:https://doi.org/10.1016/j.jpubeco.2021.104408.
Heinze, C. et al., 2021: The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences*, **118**(9), e2008478118, doi:10.1073/pnas.2008478118.
Hellin, J., M. R. Bellon and S. J. Hearne, 2014: Maize Landraces and Adaptation to Climate Change in Mexico. *Journal of Crop Improvement*, **28**(4), 484-501, doi:10.1080/15427528.2014.921800.
Helmer, E. H. et al., 2019: Neotropical cloud forests and páramo to contract and dry from declines in cloud immersion and frost. *PLOS ONE*, **14**(4), e0213155, doi:10.1371/journal.pone.0213155.
Henderson, S. B., M. Brauer, Y. C. Macnab and S. M. Kennedy, 2011: Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort. *Environmental Health Perspectives*, **119**(9), 1266-1271, doi:10.1289/ehp.1002288.
Hepler, M. and E. A. Kronk Warner, 2019: Learning from Tribal innovations: Lessons in climate change adaptation. *Environmental Law Reporter News & Analysis*, **49**(12), 11130-11149.
Hermann, A. J. et al., 2019: Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsz043.
Hernandez-Ochoa, I. M. et al., 2018: Climate change impact on Mexico wheat production. *Agricultural and Forest Meteorology*, **263**, 373-387, doi:https://doi.org/10.1016/j.agrformet.2018.09.008.
Herr, D. and E. Landis, 2016: *Coastal blue carbon ecosystems. Opportunities for Nationally Determined Contributions. Policy Brief.*, IUCN & TNC, Gland, Switzerland; Washington. DC, 28 pp. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj7vZaMp6nyAhXIop4KHc8WBfcQFnoECAIQAQ&url=https%3A%2F%2Fwww.nature.org%2Fcontent%2Fdam%2Ftnc%2Fnature%2Fen%2Fdocuments%2FBC_NDCs_FINAL.pdf&usg=AOvVaw2eCzacDePJuC9_v4XbnRTe.
Herrera-Pantoja, M. and K. M. Hiscock, 2015: Projected impacts of climate change on water availability indicators in a semi-arid region of central Mexico. *Environmental Science & Policy*, **54**, 81-89, doi:https://doi.org/10.1016/j.envsci.2015.06.020.
Hestetune, A. et al., 2018: Research note: Climate change and the demand for summer tourism on Minnesota's North Shore. *Journal of Outdoor Recreation and Tourism*, **24**(February), 21-25, doi:10.1016/j.jort.2018.10.003.
Hicke, J. A., B. Xu, A. J. Meddens and J. M. Egan, 2020: Characterizing recent bark beetle-caused tree mortality in the western United States from aerial surveys. *Forest Ecology and Management*, **475**, 118402.
Hickel, J., 2017: *The Divide: A Brief Guide to Global Inequality and its Solutions*.
Hill, R. et al., 2020: Working with Indigenous, local and scientific knowledge in assessments of nature and nature's linkages with people. *Current Opinion in Environmental Sustainability*, **43**, 8-20, doi:10.1016/j.cosust.2019.12.006.
Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8**(7), 570-578, doi:10.1038/s41558-018-0176-z.
Hjort, J. et al., 2018: Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature communications*, **9**(1), 5147-5147.
Hmielowski, J. D. et al., 2014: An attack on science? Media use, trust in scientists, and perceptions of global warming. *Public Understanding of Science*, **23**(7), 866-883, doi:10.1177/0963662513480091.
Ho, M. et al., 2017: The future role of dams in the United States of America. *Water Resources Research*, **53**(2), 982-998, doi:10.1002/2016wr019905.
Hobbie, S. E. and N. B. Grimm, 2020: Nature-based approaches to managing climate change impacts in cities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190124, doi:doi:10.1098/rstb.2019.0124.
Hobday, A. J. et al., 2016: A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, **141**, 227-238, doi:10.1016/j.pocean.2015.12.014.
Hodge, V. J., S. O'Keefe, M. Weeks and A. Moulds, 2014: Wireless sensor networks for condition monitoring in the railway industry: A survey. *IEEE Transactions on Intelligent Transportation Systems*, **16**(3), 1088-1106.
Hodgson, E. E. and B. S. Halpern, 2019: Investigating cumulative effects across ecological scales. *Conservation Biology*, **33**(1), 22-32, doi:10.1111/cobi.13125.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5ºC global warming on natural and human systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.
Hoegh-Guldberg, O. et al., 2019a: The human imperative of stabilizing global climate change at 1.5°C. *Science*, **365**(6459), eaaw6974, doi:10.1126/science.aaw6974.

Hoegh-Guldberg, O., L. Pendleton and A. Kaup, 2019b: People and the changing nature of coral reefs. *Regional Studies in Marine Science*, **30**, 100699-100699, doi:10.1016/j.rsma.2019.100699.
Hoffman, J. S., V. Shandas and N. Pendleton, 2020: The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas. *Climate*, **8**(1), doi:10.3390/cli8010012.
Hoh Indian Tribe, 2016: *2015 Hoh River Coho Salmon Fishery Disaster for the Hoh Indian Tribe*. Available at: https://media.fisheries.noaa.gov/dam-migration/75_washington_coho_pink_salmon_request_hoh_noaa-sf.pdf.
Holbrook, N. J. et al., 2019: A global assessment of marine heatwaves and their drivers. *Nature Communications*, **10**(1), 2624, doi:10.1038/s41467-019-10206-z.
Hollesen, J. et al., 2018: Climate change and the deteriorating archaeological and environmental archives of the Arctic. *Antiquity*, **92**(363), 573-586, doi:10.15184/aqy.2018.8.
Hollowed, A. B. et al., 2020: Integrated Modeling to Evaluate Climate Change Impacts on Coupled Social-Ecological Systems in Alaska. *Frontiers in Marine Science*, **6**, 775-775.
Holsman, K. et al., 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11**(1), 1-10.
Holsman, K. K. et al., 2019: Towards climate resiliency in fisheries management. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsz031.
Holsman, K. K., M. D. Scheuerell, E. Buhle and R. Emmett, 2012: Interacting effects of translocation, artificial propagation, and environmental conditions on the marine survival of Chinook salmon from the Columbia River, Washington, U.S.A. *Conservation biology : the journal of the Society for Conservation Biology*, **26**(5), 912-922, doi:10.1111/j.1523-1739.2012.01895.x.
Hongoh, V. et al., 2016: Assessing interventions to manage West Nile virus using multi-criteria decision analysis with risk scenarios. *PLoS ONE*, **11**(8), e160651, doi:10.1371/journal.pone.0160651.
Hoover, D. J., K. O. Odigie, P. W. Swarzenski and P. Barnard, 2017: Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA. *Journal of Hydrology: Regional Studies*, **11**, 234-249, doi:10.1016/j.ejrh.2015.12.055.
Hope, E. S. et al., 2016: Wildfire Suppression Costs for Canada under a Changing Climate. *PLOS ONE*, **11**(8), e0157425, doi:10.1371/journal.pone.0157425.
Hori, Y. et al., 2018a: Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic Change*, **148**(1), 109-122, doi:10.1007/S10584-018-2178-2.
Hori, Y., W. A. Gough, B. Tam and L. J. S. Tsuji, 2018b: Community vulnerability to changes in the winter road viability and longevity in the western James Bay region of Ontario's Far North. *Regional Environmental Change*, **18**(6), 1753-1763, doi:10.1007/S10113-018-1310-1.
Hornsey, M. J. and K. S. Fielding, 2020: Understanding (and Reducing) Inaction on Climate Change. *Social Issues and Policy Review*, **14**(1), 3-35, doi:https://doi.org/10.1111/sipr.12058.
Hornsey, M. J., E. A. Harris, P. G. Bain and K. S. Fielding, 2016: Meta-analyses of the determinants and outcomes of belief in climate change. *Nature Climate Change*, **6**(6), 622-626.
Hornsey, M. J., E. A. Harris and K. S. Fielding, 2018: Relationships among conspiratorial beliefs, conservatism and climate scepticism across nations. *Nat. Clim. Chang.*, **8**(7), 614.
Houser, S. et al., 2001: Native Peoples and Native Homelands. In: *Climate change impacts on the United States: The potential consequences of climate variability and change. Foundation report* [National Assessment Synthesis Team (ed.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 612-612.
Houser, T. et al., 2015: *Economic risks of climate change: an American prospectus*. Columbia University Press. ISBN 023153955X.
Howard, C. et al., 2021: SOS! Summer of Smoke: a retrospective cohort study examining the cardiorespiratory impacts of a severe and prolonged wildfire season in Canada's high subarctic. *BMJ Open*, **11**(2), e037029, doi:10.1136/bmjopen-2020-037029.
Howard, E. M. et al., 2020: Climate-driven aerobic habitat loss in the California Current System. *Science Advances*, **6**(20), 1-12, doi:10.1126/sciadv.aay3188.
Howe, P. D., J. R. Marlon, X. Wang and A. Leiserowitz, 2019: Public perceptions of the health risks of extreme heat across US states, counties, and neighborhoods. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*, **116**(14), 6743-6743, doi:10.1073/pnas.1813145116.
Howe, P. D., M. Mildenberger, J. R. Marlon and A. Leiserowitz, 2015: Geographic variation in opinions on climate change at state and local scales in the USA. *Nat. Clim. Chang.*, **5**(6), 596.
Howell, E. A. et al., 2015: Enhancing the TurtleWatch product for leatherback sea turtles, a dynamic habitat model for ecosystem-based management. *Fish. Oceanogr.*, **24**(1), 57-68.
Howell, S. E. L. and M. Brady, 2019: The dynamic response of sea ice to warming in the Canadian Arctic Archipelago. *Geophysical Research Letters*, **46**, 13119-13125.
Hristov, A. N. et al., 2018: Climate change effects on livestock in the Northeast US and strategies for adaptation. *Climatic Change*, **146**(1-2), 33-45, doi:10.1007/s10584-017-2023-z.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356**(6345), 1362-1369.
Hsiang, S. M., M. Burke and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341**(6151), 1235367, doi:10.1126/science.1235367.

Hsu, A., G. Sheriff, T. Chakraborty and D. Manya, 2021: Disproportionate exposure to urban heat island intensity across major US cities. *Nature Communications*, **12**(1), 2721, doi:10.1038/s41467-021-22799-5.

Hu, F. S. et al., 2015: Arctic tundra fires: natural variability and responses to climate change. *Frontiers in Ecology and the Environment*, **13**(7), 369-377, doi:10.1890/150063.

Huang, K. et al., 2018: Enhanced peak growth of global vegetation and its key mechanisms. *Nat Ecol Evol*, **2**(12), 1897-1905, doi:10.1038/s41559-018-0714-0.

Huang, X. Y., D. L. Swain and A. D. Hall, 2020: Future precipitation increase from very high resolution ensemble downscaling of extreme atmospheric river storms in California. *Science Advances*, **6**(29), doi:10.1126/sciadv.aba1323.

Huebert, R., H. Exner-Pirot, A. Lajeunesse and J. Gulledge, 2012: Climate change & international security: The Arctic as a bellwether. Arlington, VA: Center for Climate and Energy Solutions.

Hueffer, K., A. J. Parkinson, R. Gerlach and J. Berner, 2013: Zoonotic infections in Alaska: Disease prevalence, potential impact of climate change and recommended actions for earlier disease detection, research, prevention and control. *International Journal of Circumpolar Health*, **72**, 19562, doi:10.3402/ijch.v72i0.19562.

Hufkens, K. et al., 2016: Productivity of North American grasslands is increased under future climate scenarios despite rising aridity. *Nature Climate Change*, **6**(7), 710-714, doi:10.1038/nclimate2942.

Hughes, S., 2015: A meta-analysis of urban climate change adaptation planning in the US. *Urban Climate*, **14**(Part 1), 17-29.

Hughes, T. P. et al., 2018: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, **359**(6371), 80-83, doi:10.1126/science.aan8048.

Huisman, J. et al., 2018: Cyanobacterial blooms. *Nat. Rev. Microbiol.*, **16**(8), 471-483, doi:10.1038/s41579-018-0040-1.

Huisman, N. L. H., A. J. Huisman and K. G. Karthikeyan, 2017: Seasonal and animal farm size influences on in-stream phosphorus transport in an agricultural watershed. *Nutr. Cycling Agroecosyst.*, **109**(1), 29-42, doi:10.1007/s10705-017-9866-6.

Huntington, H. P. et al., 2015: Vessels, risks, and rules: Planning for safe shipping in Bering Strait. *Mar. Policy*, **51**, 119-127, doi:10.1016/j.marpol.2014.07.027.

Huntington, H. P. et al., 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10**(4), 342-348, doi:10.1038/s41558-020-0695-2.

Huntington, H. P. et al., 2021a: "We never get stuck:" A collaborative analysis of change and coastal community subsistence practices in the Northern Bering and Chukchi Seas, Alaska. *Arctic*, **74**(2), 113-126, doi:10.14430/arctic72446.

Huntington, H. P. et al., 2021b: Societal implications of a changing Arctic Ocean. *Ambio*, doi:10.1007/s13280-021-01601-2.

Hupp, J., M. Brubaker, K. Wilkinson and J. Williamson, 2015: How are your berries? Perspectives of Alaska's environmental managers on trends in wild berry abundance. *International Journal of Circumpolar Health*, **74**(1), 28704, doi:10.3402/ijch.v74.28878.

Hurst, T. P. et al., 2019: Elevated CO alters behavior, growth, and lipid composition of Pacific cod larvae. *Mar. Environ. Res.*, **145**, 52-65, doi:10.1016/j.marenvres.2019.02.004.

Hurst, T. P. et al., 2012: Resiliency of juvenile walleye pollock to projected levels of ocean acidification. *Aquatic Biology*, **17**(3), 247-259, doi:10.3354/ab00483.

Hurteau, M. D., G. W. Koch and B. A. Hungate, 2008: Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. *Frontiers in Ecology and the Environment*, **6**(doi:10.1890/070187).

Hurteau, M. D., S. Liang, A. L. Westerling and C. Wiedinmyer, 2019: Vegetation-fire feedback reduces projected area burned under climate change. *Sci Rep*, **9**(1), 2838, doi:10.1038/s41598-019-39284-1.

Hutchinson, J. A. et al., 2018: The San Diego 2007 wildfires and Medi-Cal emergency department presentations, inpatient hospitalizations, and outpatient visits: An observational study of smoke exposure periods and a bidirectional case-crossover analysis. *PLoS Medicine*, **15**(7), e1002601, doi:10.1371/journal.pmed.1002601.

Hyrenbach, K. D., K. A. Forney and P. K. Dayton, 2000: Marine protected areas and ocean basin management. *Aquat. Conserv.*, **10**(6), 437-458.

IBC, 2020: *2020 Facts of the Property and Casualty Insurance Industry in Canada*. IBC, Toronto, Canada, 75 pp.

IBWC, 2017: *Report of Transboundary Bypass Flows into the Tijuana River* [Team, M. B. T. and W. Q. Workgroup (eds.)]. Available at: https://www.ibwc.gov/Files/Report_Trans_Bypass_Flows_Tijuana_033117.pdf.

ICC Alaska, 2020: *Food sovereignty and self-governance: Inuit role in managing Arctic marine resources*. Alaska, I. C. C., Anchorage, AK. Available at: https://www.inuitcircumpolar.com/project/food-sovereignty-and-self-governance-inuit-role-in-managing-arctic-marine-resources/.

ICC Canada, 2008: *The sea ice is our highway: an Inuit perspective on transportation in the Arctic, a contribution by ICC to the Arctic Council's Arctic Marine Shipping Assessment*. Canada, I. C. C. Available at: https://www.inuitcircumpolar.com/project/the-sea-ice-is-our-highway-an-inuit-perspective-on-transportation-in-the-arctic/.

ICLEI Canada, 2016: *Making strides on community adaptation in Canada*. Available at: http://icleicanada.org/images/Making_Strides_on_Community_Adaptation_Final.pdf.

IEA, 2018a: *The Future of Cooling, IEA, Paris* Available at: https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf.

IEA, 2018b: The Future of Cooling, IEA, Paris
Iglesias, V. and C. Whitlock, 2020: If the trees burn, is the forest lost? Past dynamics in temperate forests help inform management strategies. *Philos Trans R Soc Lond B Biol Sci*, **375**(20190115), doi:10.1098/rstb.2019.0115.
Ijaz, S., 2019: *4th Onjisay Aki gathering of Elders, youth & scientists on climate change*. Turtle Lodge Central House of Knowledge, Sagkeeng First Nation, MB.
Indigenous Climate Action, E. Deranger, J. Gobby and R. Sinclair, 2021: Decolonizing climate policy in Canada: Report from Phase One.
INECC and Semarnat, 2018: *Sexta Comunicación Nacional y Segundo Informe Bienal de Actualización ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático*.
International Joint Commission (IJC), 2018: *Climate Change Guidance Framework for IJC Boards: A Highlights Report 2018*. Available at: https://ijc.org/sites/default/files/2019-03/IJC_IWI_Board_Climate_Change_Highlights_Report_2018.pdf.
IPBES, 2018: *The IPBES regional assessment report on biodiversity and ecosystem services for the Americas* [Rice, J. (ed.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F. (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R. (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp. ISBN 9781107058163.
IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V. (ed.)]. In press pp. ISBN 9789291691517.
IPCC, 2019a: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
IPCC, 2019b: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O. (ed.)]. In press pp.
IPCC, 2019c: *Special Report on the Ocean and Cryosphere in a Changing Climate*.
IPCC, In Press: *Climate Change 2021: The Physical Science Basis, the Working Group I contribution to the Sixth Assesment Report* [[Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. IPCC, Press, C. U.
Irby, I. et al., 2015: Challenges associated with modeling low-oxygen waters in Chesapeake Bay: a multiple model comparison. *Biogeosciences Discussions*, **12**(24).
Isaak, D. J. et al., 2018: Global Warming of Salmon and Trout Rivers in the Northwestern U.S.: Road to Ruin or Path Through Purgatory? *Transactions of the American Fisheries Society*, **147**(3), 566-587, doi:10.1002/tafs.10059.
Isaak, D. J. et al., 2016: Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. *Proc. Natl. Acad. Sci. U. S. A.*, **113**(16), 4374-4379, doi:10.1073/pnas.1522429113.
Isaksen, T. B., M. Yost, E. Hom and R. Fenske, 2014: Projected health impacts of heat events in Washington State associated with climate change. *Reviews on Environmental Health*, **29**(1-2), 119-123, doi:10.1515/reveh-2014-0029.
Islam, S. U., S. J. Déry and A. T. Werner, 2017: Future Climate Change Impacts on Snow and Water Resources of the Fraser River Basin, British Columbia. *Journal of Hydrometeorology*, **18**(2), 473-496, doi:10.1175/JHM-D-16-0012.1.
ITK, 2019: *National Inuit climate change strategy*. Kanatami, I. T., 48 pp. Available at: https://www.itk.ca/wp-content/uploads/2019/06/ITK_Climate-Change-Strategy_English.pdf.
Ito, T. et al., 2019: Mechanisms of Low-Frequency Oxygen Variability in the North Pacific. *Global Biogeochem. Cycles*, **33**(2), 110-124.
IUCN, 2016: *Resolution 6.069: Defining Nature-based solutions*. WCC-2016-Res-069, IUCN, Gland, Switzerland, 2 pp. Available at: https://www.iucn.org/sites/dev/files/content/documents/wcc_2016_res_069_en.pdf.
Jacobs, J. M. et al., 2018: *Chapter 12: Transportation* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II U.S. Global Change Research Program, Washington, D.C., USA, 470-511 pp.
Jagai, J. S. et al., 2017: Sanitary sewer overflows and emergency room visits for gastrointestinal illness: Analysis of Massachusetts data, 2006-2007. *Environmental Health Perspectives*, **125**(11), 117007, doi:10.1289/EHP3143.
Jahanandish, N. A. and Alireza, 2019: "Is climate change impacting Rideau Canal Skateway, the world's longest skating rink? *Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards*, **98**(1), 91-101.

Jamestown S'klallam Tribe, 2016: *2015 Puget Sound Coho Fishery Disaster for the Jamestown S'klallam Tribe*. Available at: https://media.fisheries.noaa.gov/dam-migration/68_puget_coho_request_jamestown_noaa-sf.pdf.
Janssens, C. et al., 2020: Through International Trade. *Nature Climate Change*, **10**(September).
Jantarasami, L. C. et al., 2018a: Tribes and Indigenous Peoples. In: *Impacts, Risks and Adaptation in the United States: Fourth National Climate Assessment* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, D.C., U.S.A., pp. 572-603.
Jantarasami, L. C. et al., 2018b: Tribes and Indigenous Peoples. In: *Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 572-603.
Jardine, S. L., M. C. Fisher, S. K. Moore and J. F. Samhouri, 2020: Inequality in the Economic Impacts from Climate Shocks in Fisheries: The Case of Harmful Algal Blooms. *Ecological Economics*, **176**(April), 106691-106691, doi:10.1016/j.ecolecon.2020.106691.
Jasanof, S., 2010: A New Climate for Society. *Theory, Culture & Society*, 233-253.
Javeline, D. et al., 2015: Expert opinion on extinction risk and climate change adaptation for biodiversity. *Elementa: Science of the Anthropocene*, **3**, 000057, doi:10.12952/journal.elementa.000057.
Jeong, D. I. and L. Sushama, 2018a: Rain-on-snow events over North America based on two Canadian regional climate models. *Climate Dynamics*, **50**(1-2), 303-316, doi:10.1007/s00382-017-3609-x.
Jeong, I. D. and A. J. Cannon, 2020: Projected changes to risk of wind-driven rain on buildings in Canada under +0.5 °C to +3.5 °C global warming above the recent period. *Climate Risk Management*, **30**, 100261, doi:https://doi.org/10.1016/j.crm.2020.100261.
Jeong, I. D. and L. Sushama, 2018b: Rain-on-snow events over North America based on two Canadian regional climate models. *Climate Dynamics*, **50**(1-2), 303-316, doi:10.1007/s00382-017-3609-x.
Jessoe, K., D. T. Manning and J. E. Taylor, 2018: Climate Change and Labour Allocation in Rural Mexico: Evidence from Annual Fluctuations in Weather. *Econ J*, **128**(608), 230-261, doi:10.1111/ecoj.12448.
Jewett, L. and A. Romanou, 2017: Ch. 13: Ocean Acidification and Other Ocean Changes. Climate Science Special Report: Fourth National Climate Assessment, Volume I. doi:10.7930/j0qv3jqb.
Jiménez-Moleón, M. C. and M. A. Gómez-Albores, 2011: Waterborne diseases in the state of Mexico, Mexico (2000-2005). *Journal of Water and Health*, **9**(1), 200-207, doi:10.2166/wh.2010.149.
Jin, Z. et al., 2017: The combined and separate impacts of climate extremes on the current and future US rainfed maize and soybean production under elevated CO2. *Global Change Biology*, **23**(7), 2687-2704, doi:https://doi.org/10.1111/gcb.13617.
Johnson, H. E. et al., 2018: Human development and climate affect hibernation in a large carnivore with implications for human-carnivore conflicts. *Journal of Applied Ecology*, **55**(2), 663-672, doi:10.1111/1365-2664.13021.
Johnson, R. K. and K. Almlof, 2016: Adapting boreal streams to climate change: effects of riparian vegetation on water temperature and biological assemblages. *Freshw. Sci.*, **35**(3), 984-997, doi:10.1086/687837.
Johnston, L. M. and M. D. Flannigan, 2018: Mapping Canadian wildland fire interface areas. *International Journal of Wildland Fire*, **27**(1), 1-14, doi:https://doi.org/10.1071/WF16221.
Johnston, L. M. et al., 2020: Wildland fire risk research in Canada. *Environmental Reviews*, **28**(2), 164-186.
Johnston, M., J. Dawson, E. De Souza and E. J. Stewart, 2016: Management challenges for the fastest growing marine shipping sector in Arctic Canada: pleasure crafts. *Polar Rec.*, doi:10.1017/S0032247416000565.
Jones, C. et al., 2021: Actionable science and collaborative climate planning. In: *Status of Tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 46–55.
Jones, E. H. et al., 2013: *Vibrio* infections and surveillance in Maryland, 2002-2008. *Public Health Reports*, **128**(6), 537-545, doi:10.1177/003335491312800613.
Jones, L. A. et al., 2019a: Coupling of palaeontological and neontological reef coral data improves forecasts of biodiversity responses under global climatic change. *R Soc Open Sci*, **6**(4), 182111, doi:10.1098/rsos.182111.
Jones, M. C. et al., 2020: High sensitivity of Bering Sea winter sea ice to winter insolation and carbon dioxide over the last 5500 years. *Science Advances*, **6**(36), eaaz9588, doi:10.1126/sciadv.aaz9588.
Jones, S. M. and D. S. Gutzler, 2016: Spatial and Seasonal Variations in Aridification across Southwest North America. *Journal of Climate*, **29**(12), 4637-4649, doi:10.1175/jcli-d-14-00852.1.
Jones, T. et al., 2019b: Unusual mortality of Tufted puffins (Fratercula cirrhata) in the eastern Bering Sea. *PLoS One*, **14**(5), e0216532, doi:10.1371/journal.pone.0216532.
Jönsson, A. M. et al., 2012: Guess the impact of Ips typographus—An ecosystem modelling approach for simulating spruce bark beetle outbreaks. *Agricultural and Forest Meteorology*, **166-167**, 188-200, doi:10.1016/j.agrformet.2012.07.012.
Jost, G., R. D. Moore, B. Menounos and R. Wheate, 2012: Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada. *Hydrology and Earth System Sciences*, **16**(3), 849-860, doi:10.5194/hess-16-849-2012.

Juday, G. P., C. Alix and T. A. Grant, 2015: Spatial coherence and change of opposite white spruce temperature sensitivities on floodplains in Alaska confirms early-stage boreal biome shift. *Forest Ecology and Management*, **350**, 46-61, doi:10.1016/j.foreco.2015.04.016.
Kabisch, N. et al., 2016: Nature-based solutions to climate change mitigation and adaptation in urban areas perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, **21**(2).
Kabisch, N., H. Korn, J. Stadler and A. Bonn, 2017: *Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice*. Springer Open, 337-337 pp. ISBN 9783319560915.
Kahn, M. et al., 2019: Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis. doi:10.3386/w26167.
Kane, J. M., J. Morgan Varner, M. R. Metz and P. J. van Mantgem, 2017: Characterizing interactions between fire and other disturbances and their impacts on tree mortality in western U.S. Forests. *Forest Ecology and Management*, **405**, 188-199, doi:10.1016/j.foreco.2017.09.037.
Kaplan, M. B., T. A. Mooney, D. C. McCorkle and A. L. Cohen, 2013: Adverse effects of ocean acidification on early development of squid (Doryteuthis pealeii). *PLoS One*, **8**(5), e63714, doi:10.1371/journal.pone.0063714.
Kappes, M. A. et al., 2010: Hawaiian albatrosses track interannual variability of marine habitats in the North Pacific. *Prog. Oceanogr.*, **86**(1), 246-260, doi:10.1016/j.pocean.2010.04.012.
Karp, M. A. et al., 2019: Accounting for shifting distributions and changing productivity in the development of scientific advice for fishery management. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsz048.
Kates, R. W., W. R. Travis and T. J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences*, **109**(19), 7156-7161, doi:10.1073/pnas.1115521109.
Kean, J. W. et al., 2019: Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: Opportunities and challenges for post-wildfire risk assessment. *Geosphere*, **15**(4), 1140-1163, doi:10.1130/ges02048.1.
Kearney, G. D. and R. A. Bell, 2019: Perceptions of Global Warming Among the Poorest Counties in the Southeastern United States. *J. Public Health Manag. Pract.*, **25**(2), 107-112, doi:10.1097/PHH.0000000000000720.
Keeley, A. T. H. et al., 2018: New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters*, **13**(7), 073002, doi:10.1088/1748-9326/aacb85.
Keenan, J. M., T. Hill and A. Gumber, 2018: Climate gentrification: from theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters*, **13**(5), 054001, doi:10.1088/1748-9326/aabb32.
Kennett, D. J. et al., 2012: Development and disintegration of Maya political systems in response to climate change. *Science*, **338**(6108), 788-791, doi:10.1126/science.1226299.
Kenney, M. A. and M. D. Gerst, 2021: Synthesis of Indicators, Datasets, and Frameworks Available to Establish Resilience and Adaptation Indicators: Case Study of Chesapeake Bay Region, USA. *Current Climate Change Reports*, **7**(2), 35-44, doi:10.1007/s40641-021-00170-6.
Kenney, M. A., A. C. Janetos and M. D. Gerst, 2020: A framework for national climate indicators. *Clim. Change*, **163**(4), 1705-1718.
Kent, L. L. Y. et al., 2017: Climate drives fire synchrony but local factors control fire regime change in northern Mexico. *Ecosphere*, **8**(3), 13, doi:10.1002/ecs2.1709.
Kermoal, N. and I. Altamirano-Jiménez, 2016: *Living on the Land: Indigenous Women's Understanding of Place*. AU Press, Edmonton, Alberta.
Kevins, A. and S. N. Soroka, 2018: Growing apart? Partisan sorting in Canada, 1992–2015. *Canadian Journal of Political Science/Revue canadienne de science politique*, **51**(1), 103-133.
Key, N. and S. Sneeringer, 2014: Potential Effects of Climate Change on the Productivity of U.S. Dairies. *American Journal of Agricultural Economics*, **96**(4), 1136-1156, doi:10.1093/ajae/aau002.
Khalafzai, M.-A. K., T. K. McGee and B. Parlee, 2019: Flooding in the James Bay region of Northern Ontario, Canada: Learning from traditional knowledge of Kashechewan First Nation. *International Journal of Disaster Risk Reduction*, **36**, 101100, doi:10.1016/j.ijdrr.2019.101100.
Khan, A., A. Charles and D. Armitage, 2018: Place-based or sector-based adaptation? A case study of municipal and fishery policy integration. *Climate Policy*, **18**(1), 14-23, doi:10.1080/14693062.2016.1228520.
Kiefer, M. et al., 2016: Worker health and safety and climate change in the Americas: issues and research needs. *REVISTA PANAMERICANA DE SALUD PUBLICA-PAN AMERICAN JOURNAL OF PUBLIC HEALTH*, **40**(3), 192-197.
Kim, M. K. and P. M. Jakus, 2019: Wildfire, national park visitation, and changes in regional economic activity. *Journal of Outdoor Recreation and Tourism*, **26**(February 2018), 34-42, doi:10.1016/j.jort.2019.03.007.
Kim, Y. et al., 2019: Suicide and ambient temperature: A multi-country multi-city study. *Environmental Health Perspectives*, **127**(11), 117007-117007, doi:10.1289/EHP4898.
King, N. et al., 2019: How do Canadian media report climate change impacts on health? A newspaper review. *Climatic Change*, **152**(3-4), 581-596.
King, U. and C. Furgal, 2014: Is hunting still healthy? Understanding the interrelationships between Indigenous participation in land-based practices and human-environmental health. *International Journal of Environmental Research and Public Health*, **11**(6), 5751-5782, doi:10.3390/ijerph110605751.

Kingsley, S. L. et al., 2016: Current and projected heat-related morbidity and mortality in Rhode Island. *Environmental Health Perspectives*, **124**(4), 460-467, doi:10.1289/ehp.1408826.
Kinney, P. L. et al., 2015: Winter season mortality: will climate warming bring benefits? *Environmental Research Letters*, **10**, 064016-064016, doi:10.1088/1748-9326/10/6/064016.
Kinniburgh, F., M. G. Simonton and C. Allouch, 2015: Come Heat and High Water: Climate Risk in the Southeastern US and Texas. *Risky Business Project*, 87.
Kipp, A. et al., 2020: At-a-glance Climate change impacts on health and wellbeing in rural and remote regions across Canada: A synthesis of the literature. **39**(4), 122-126.
Kirchmeier-Young, M. C. et al., 2019: Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earth's Future*, **7**(1), 2-10, doi:10.1029/2018ef001050.
Kistner, E. et al., 2018: Vulnerability of specialty crops to short-term climatic variability and adaptation strategies in the Midwestern USA. *Climatic Change*, **146**(1-2), 145-158, doi:10.1007/s10584-017-2066-1.
Kitzberger, T., D. A. Falk, A. L. Westerling and T. W. Swetnam, 2017: Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. *PloS one*, **12**(12), e0188486.
Kjellstrom, T. et al., 2019: *Working on a warmer planet: The effect of heat stress on productivity and decent work*. International Labour Office, Office, I. L., Geneva, 98 pp. Available at: https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_711919.pdf.
Klein, J. et al., 2018: The role of the private sector and citizens in urban climate change adaptation: Evidence from a global assessment of large cities. *Global environmental change*, **53**, 127-136.
Klinenberg, E., 2015: *Heat wave: A social autopsy of disaster in Chicago*. University of Chicago Press.
Klinsky, S., T. Roberts, S. Huq and C. Okereke, 2016: Why equity is fundamental in climate change policy research. *Global environmental change*, doi:10.1016/j.gloenvcha.2016.08.002.
Kloesel, K. et al., 2018a: Southern Great Plains. In: *Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 987-1035.
Kloesel, K. et al., 2018b: Chapter 23: Southern Great Plains. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, D.C., U.S.A., pp. 987-1035.
Klotzbach, P. J., S. G. Bowen, R. Pielke and M. Bell, 2018: CONTINENTAL US HURRICANE LANDFALL FREQUENCY AND ASSOCIATED DAMAGE Observations and Future Risks. *Bulletin of the American Meteorological Society*, **99**(7), 1359-+, doi:10.1175/bams-d-17-0184.1.
Knutson, C. L., M. J. Hayes and M. D. Svoboda, 2007: Case study of Tribal drought planning: The Hualapai Tribe. *Natural Hazards Review*, **8**(4), 125-131, doi:10.1061/(asce)1527-6988(2007)8:4(125).
Koch, A., C. Brierley, M. M. Maslin and S. L. Lewis, 2019: Earth system impacts of the European arrival and Great Dying in the Americas after 1492. *Quaternary Science Reviews*, **2007**, 13-36.
Kocis, T. N. and H. E. Dahlke, 2017: Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California. *Environmental Research Letters*, **12**(8), 084009, doi:10.1088/1748-9326/aa7b1b.
Koerth, J., A. T. Vafeidis and J. Hinkel, 2017: Household-Level Coastal Adaptation and Its Drivers: A Systematic Case Study Review. *Risk Analysis*, **37**(4), 629-646, doi:10.1111/risa.12663.
Koetse, M. J. and P. Rietveld, 2009: The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment*, **14**(3), 205-221, doi:10.1016/j.trd.2008.12.004.
Kohler, T. A. et al., 2014: The Better Angels of Their Nature: Declining Conflict Through Time Among Prehispanic Farmers of the Pueblo Southwest. *Am. Antiq.*, **79**, 444-464.
Koks, E. E. et al., 2019: A global multi-hazard risk analysis of road and railway infrastructure assets. *Nature Communications*, **10**(1), 2677, doi:10.1038/s41467-019-10442-3.
Kolden, C. A., 2019: We're not doing enough prescribed fire in the Western United States to mitigate wildfire risk. *Fire*, **2**(2), 30.
Kolesar, S. E., K. A. Rose and D. L. Breitburg, 2017: Hypoxia Effects Within an Intra-guild Predation Food Web of Mnemiopsis leidyi Ctenophores, Larval Fish, and Copepods. *Modeling Coastal Hypoxia*, 279-317, doi:10.1007/978-3-319-54571-4_11.
Kootenai Culture Committee, 2015: The traditional worldview of the Kootenai people. *Montana: The Magazine of Western History*, **65**(3), 47-73.
Kossin, J. P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558**(7708), 104-+, doi:10.1038/s41586-018-0158-3.
Kossin, J. P. et al., 2017: Ch. 9: Extreme Storms. Climate Science Special Report: Fourth National Climate Assessment, Volume I. doi:10.7930/j07s7kxx.
Koubi, V., 2019: Climate Change and Conflict. *Annual Review of Political Science*, **22**(1), 343-360, doi:10.1146/annurev-polisci-050317-070830.

Kousky, C., H. Kunreuther, S. Xian and N. Lin, 2021: Adapting our Flood Risk Policies to Changing Conditions. *Risk Analysis*, **n/a**(n/a), doi:https://doi.org/10.1111/risa.13692.
Kovach, R. P. et al., 2019: An Integrated Framework for Ecological Drought across Riverscapes of North America. *BioScience*, **69**(6), 418-431, doi:10.1093/biosci/biz040.
Kovachis, N. et al., 2017: Ice-jam flood delineation: Challenges and research needs. *Canadian Water Resources Journal*, **42**(3), 258-268, doi:10.1080/07011784.2017.1294998.
Kovacs, P., S. Guilbault, E. Lambert and R. Kovacs, 2020: *Cities adapt to extreme wildfires: Celebrating local leadership*. Available at: https://www.iclr.org/wp-content/uploads/2020/12/Cities-Adapt-to-Extreme-WILDFIRES_Final_Dec19.pdf.
Kovacs, P., S. Guilbault and D. Sandink, 2014: *Cities adapt to extreme rainfall: Celebrating local leadership*. Institute for Catastrophic Loss Reduction, Toronto, 104-104 pp.
Koven, C. D. et al., 2020: Benchmarking and parameter sensitivity of physiological and vegetation dynamics using the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) at Barro Colorado Island, Panama. *Biogeosciences*, **17**(11), 3017-3044, doi:10.5194/bg-17-3017-2020.
Krayenhoff, E. S. et al., 2018: Diurnal interaction between urban expansion, climate change and adaptation in US cities. *Nat. Clim. Chang.*, **8**(12), 1097-1103, doi:10.1038/s41558-018-0320-9.
Kritzer, J. P., C. Costello, T. Mangin and S. L. Smith, 2019: Responsive harvest control rules provide inherent resilience to adverse effects of climate change and scientific uncertainty. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsz038.
Kronik, J. and D. Verner, 2010: *Indigenous Peoples and climate change in Latin America and the Caribbean*. World Bank Publications, Washington.
Kronk Warner, E. A. and R. S. Abate, 2013: International and domestic law dimensions of climate justice for Arctic Indigenous People. *Revue Generale de Droit*, **43**, 113-150, doi:10.7202/1021212ar.
Kukal, M. S. and S. Irmak, 2018: Climate-Driven Crop Yield and Yield Variability and Climate Change Impacts on the U.S. Great Plains Agricultural Production. *Sci Rep*, **8**(1), 1-18, doi:10.1038/s41598-018-21848-2.
Kunkel, K. E. and S. M. Champion, 2019: An Assessment of Rainfall from Hurricanes Harvey and Florence Relative to Other Extremely Wet Storms in the United States. *Geophysical Research Letters*, **46**(22), 13500-13506, doi:10.1029/2019gl085034.
Kunkel, K. E. et al., 2020: Precipitation Extremes: Trends and Relationships with Average Precipitation and Precipitable Water in the Contiguous United States. *Journal of Applied Meteorology and Climatology*, **59**(1), 125-142, doi:10.1175/jamc-d-19-0185.1.
Kunkel, K. E. et al., 2016: Trends and Extremes in Northern Hemisphere Snow Characteristics. *Current Climate Change Reports*, **2**(2), 65-73, doi:10.1007/s40641-016-0036-8.
Kytomaa, H. K. et al., 2019: An integrated method for quantifying and managing extreme weather risks and liabilities for industrial infrastructure and operations. *Process Saf. Prog.*, 11, doi:10.1002/prs.12087.
La Jolla Band of Luiseno Indians, 2019: *Adaptation Plan*. Available at: https://drive.google.com/file/d/1NVEfYOMUMdQcaFBATFT-Lq8eVThqW_Oj/view.
Lacasse, M. A., A. Gaur and T. V. Moore, 2020: Durability and Climate Change—Implications for Service Life Prediction and the Maintainability of Buildings. *Buildings*, **10**(3), 53.
Lachapelle, E., C. P. Borick and B. Rabe, 2012: Public Attitudes toward Climate Science and Climate Policy in Federal Systems: Canada and the United States Compared 1. *Review of Policy Research*, **29**(3), 334-357.
Lake, F. K., 2021: Indigenous fire stewardship: Federal/Tribal partnerships for wildland fire research and management. *Fire Management Today*, **79**(1), 30-39.
Lal, R. et al., 2011: Management to mitigate and adapt to climate change. *Journal of Soil and Water Conservation*, **66**(4), 276-282, doi:10.2489/jswc.66.4.276.
Lall, U. et al., 2018: Water. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, doi:10.7930/nca4.2018.ch3.
Lam, V. W. Y., W. W. L. Cheung and U. R. Sumaila, 2016: Marine capture fisheries in the Arctic: winners or losers under climate change and ocean acidification? *Fish and Fisheries*, **17**(2), 335-357, doi:10.1111/faf.12106.
Lane, D. R. et al., 2013: Quantifying and valuing potential climate change impacts on coral reefs in the United States: comparison of two scenarios. *PLoS One*, **8**(12), e82579, doi:10.1371/journal.pone.0082579.
Lant, C., T. J. Stoebner, J. T. Schoof and B. Crabb, 2016: The effect of climate change on rural land cover patterns in the Central United States. *Climatic Change*, **138**(3-4), 585-602, doi:10.1007/s10584-016-1738-6.
Lantuit, H. et al., 2012: The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines. *Estuaries and Coasts*, **35**(2), 383-400, doi:10.1007/s12237-010-9362-6.
Larrauri, P. C. and U. Lall, 2019: *Assessing the exposure of critical infrastructure and other assets to the climate induced failure of aging dams in the U.S. Final Report for the Global Risk Institute*. Columbia Water Center, Columbia University. Available at: https://globalriskinstitute.org/publications/assessing-the-hazard-and-exposure-of-dams-in-the-u-s/.
Latta, A., 2018: Indigenous Rights and Multilevel Governance: Learning From the Northwest Territories Water Stewardship Strategy. *International Indigenous Policy Journal*, **9**(2), doi:10.18584/iipj.2018.9.2.4.

Latulippe, N. and N. Klenk, 2020: Making room and moving over: knowledge co-production, Indigenous knowledge sovereignty and the politics of global environmental change decision-making. *Current Opinion in Environmental Sustainability*, **42**, 7-14, doi:10.1016/j.cosust.2019.10.010.
Laufkötter, C., J. Zscheischler and T. L. Frölicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science (New York, N.Y.)*, **369**(6511), 1621-1625, doi:10.1126/science.aba0690.
Lavorel, S., B. Locatelli, M. J. Colloff and E. Bruley, 2020: Co-producing ecosystem services for adapting to climate change. *Philos. Trans. R. Soc. B-Biol. Sci.*, **375**(1794), doi:10.1098/rstb.2019.0119.
Law, B. E. et al., 2018: Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences*, **115**(14), 3663-3668, doi:10.1073/pnas.1720064115.
Lawler, J. J. et al., 2020: Planning for climate change through additions to a national protected area network: implications for cost and configuration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190117, doi:doi:10.1098/rstb.2019.0117.
Le Bris, A. et al., 2018: Climate vulnerability and resilience in the most valuable North American fishery. *Proc. Natl. Acad. Sci. U. S. A.*, **115**(8), 1831-1836, doi:10.1073/pnas.1711122115.
Le, G. E. et al., 2014: Canadian forest fires and the effects of long-range transboundary air pollution on hospitalizations among the elderly. *ISPRS Int. Geo-Inf.*, **3**(2), 713-731, doi:10.3390/ijgi3020713.
Le, M. H., K. V. Dinh, M. V. Nguyen and I. Rønnestad, 2020: Combined effects of a simulated marine heatwave and an algal toxin on a tropical marine aquaculture fish cobia (Rachycentron canadum). *Aquaculture Research*, **51**(6), 2535-2544, doi:10.1111/are.14596.
Leblond, M., M.-H. St-Laurent and S. D. Côté, 2016: Caribou, water, and ice–fine-scale movements of a migratory arctic ungulate in the context of climate change. *Movement ecology*, **4**(1), 14.
Lee, J. Y. et al., 2019: Predicted temperature-increase-induced global health burden and its regional variability. *Environment International*, **131**, 105027-105027, doi:10.1016/j.envint.2019.105027.
Lee, M. et al., 2014: Acclimatization across space and time in the effects of temperature on mortality: A time-series analysis. *Environmental Health*, **13**, 89, doi:10.1186/1476-069X-13-89.
Lee, T.-S. et al., 2009: Risk factors associated with clinic visits during the 1999 forest fires near the Hoopa Valley Indian Reservation, California, USA. *International Journal of Environmental Health Research*, **19**(5), 315-327, doi:10.1080/09603120802712750.
Leiserowitz, A. A., 2005: American risk perceptions: Is climate change dangerous? *Risk Analysis: An International Journal*, **25**(6), 1433-1442.
Lemelin, H. et al., 2010: Last-chance tourism: the boom, doom, and gloom of visiting vanishing destinations. *Curr. Issues Tourism*, **13**, 477-493.
Lemieux, C. J. et al., 2017: "The End of the Ice Age?": Disappearing World Heritage and the Climate Change Communication Imperative. *Environmental Communication*, doi:10.1080/17524032.2017.1400454.
Lemieux, C. J., J. Thompson, D. S. Slocombe and R. Schuster, 2015: Climate change collaboration among natural resource management agencies: lessons learned from two US regions. *Journal of Environmental Planning and Management*, **58**(4), 654-677, doi:10.1080/09640568.2013.876392.
Lemmen, D. et al., 2021: Sector Impacts and Adaptation. In: *Canada in a changing climate* [Warren, F. and N. Lulham (eds.)]. Government of Canada, Ottawa, ON, pp. 488-570.
Lemmen, D. S., F. J. Warren, T. S. James and C. S. L. Mercer Clarke, 2016: *Canada's marine coasts in a changing climate*. **53**, 1689-1699 pp. Available at: www.adaptation.nrcan.gc.ca.
Lempert, R. J. et al., 2018: Chapter 28: Reducing Risks Through Adaptation Actions. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, D.C., U.S.A., pp. 1309-1345.
Lenton, T. M., 2013: Environmental tipping points. *Annual Review of Environment and Resources* **38**, 1-29, doi:10.1146/annurev-environ-102511-084654.
Lenton, T. M., 2020a: Tipping positive change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190123, doi:doi:10.1098/rstb.2019.0123.
Lenton, T. M., 2020b: Tipping positive change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 0-2, doi:10.1098/rstb.2019.0123.
Lenton, T. M. et al., 2019: Climate tipping points — too risky to bet against. *Nature*, **575**(7784), 592-595, doi:10.1038/d41586-019-03595-0.
Leong, D. and S. Donner, 2016: Future Water Supply and Demand Management Options in the Athabasca Oil Sands. *River Research and Applications*, **32**(9), 1853-1861, doi:10.1002/rra.3033.
Leong, D. N. S. and S. D. Donner, 2015: Climate change impacts on streamflow availability for the Athabasca Oil sands. *Climatic Change*, 651-663.
Leskovar, D. I., S. Agehara, K. Yoo and N. Pascual-Seva, 2012: Crop Coefficient-based Deficit Irrigation and Planting Density for Onion: Growth, Yield, and Bulb Quality. *HortScience*, **47**(1), 31-37, doi:10.21273/HORTSCI.47.1.31.
Lesnikowski, A. et al., 2017: What does the Paris Agreement mean for adaptation? *Climate Policy*, **17**(7), 825-831, doi:10.1080/14693062.2016.1248889.
Levin, P. S. et al., 2014: Guidance for implementation of integrated ecosystem assessments: a US perspective. *ICES J. Mar. Sci.*, **71**(5), 1198-1204, doi:10.1093/icesjms/fst112.

Levis, S. et al., 2018: CLMcrop yields and water requirements: avoided impacts by choosing RCP 4.5 over 8.5. *Climatic Change*, **146**(3-4), 501-515, doi:10.1007/s10584-016-1654-9.
Leviston, Z., J. Price and B. Bishop, 2014: Imagining climate change: The role of implicit associations and affective psychological distancing in climate change responses. *Eur. J. Soc. Psychol.*, **44**(5), 441-454, doi:10.1002/ejsp.2050.
Lewandowsky, S. et al., 2019: Influence and seepage: An evidence-resistant minority can affect public opinion and scientific belief formation. *Cognition*, **188**, 124-139.
Lewison, R. et al., 2015: Dynamic Ocean Management: Identifying the Critical Ingredients of Dynamic Approaches to Ocean Resource Management. *Bioscience*, **65**(5), 486-498, doi:10.1093/biosci/biv018.
Li, D. et al., 2017: How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters*, **44**(12), 6163-6172, doi:10.1002/2017gl073551.
Li, J., M. Mullan and J. Helgeson, 2014: Improving the practice of economic analysis of climate change adaptation. *Journal of Benefit-Cost Analysis*, **5**(3), 445-467.
Li, M. et al., 2016: What drives interannual variability of hypoxia in Chesapeake Bay: Climate forcing versus nutrient loading? *Geophysical Research Letters*, **43**(5), 2127-2134, doi:10.1002/2015gl067334.
Li, T., R. M. Horton and P. L. Kinney, 2013: Projections of seasonal patterns in temperature-related deaths for Manhattan, New York. *Nature Climate Change*, **3**(8), 717-721, doi:10.1038/nclimate1902.
Li, X. et al., 2021: Arctic shipping guidance from the CMIP6 ensemble on operational and infrastructural timescales. *Climatic Change*, **167**(1), 23, doi:10.1007/s10584-021-03172-3.
Limaye, V. S. et al., 2018: Climate change and heat-related excess mortality in the eastern USA. *EcoHealth*, **15**(3), 485-496, doi:10.1007/s10393-018-1363-0.
Lin, S. et al., 2019: The effects of multiyear and seasonal weather factors on incidence of Lyme disease and its vector in New York State. *Science of the Total Environment*, **665**, 1182-1188, doi:10.1016/j.scitotenv.2019.02.123.
Lin, Y., A. K. Y. Ng and M. Afenyo, 2020: Chapter 13 - Climate change, a double-edged sword: The case of Churchill on the Northwest Passage. In: *Maritime Transport and Regional Sustainability* [Ng, A. K. Y., J. Monios and C. Jiang (eds.)]. Elsevier, pp. 223-235. ISBN 978-0-12-819134-7.
Liñan-Cabello, M. A., A. L. Quintanilla-Montoya, C. Sepúlveda-Quiroz and O. D. Cervantes-Rosas, 2016: AnthropogenicSusceptibility to environmental variability of the aquaculture sector in the State of Colima, Mexico: case study. *Lat. Am. J. Aquat. Res.*, **44**(3), 649-656, doi:10.3856/vol44-issue3-fulltext-24.
Lipton, D. et al., 2018: Ecosystems, Ecosystem Services, and Biodiversity. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 268-321.
Lithgow, D. et al., 2019: Exploring the co-occurrence between coastal squeeze and coastal tourism in a changing climate and its consequences. *Tourism Management*, **74**, 43-54, doi:10.1016/j.tourman.2019.02.005.
Littell, J. S., D. McKenzie, D. L. Peterson and A. L. Westerling, 2009: Climate and wildfire area burned in western U. S. ecoprovinces, 1916-2003. *Ecological Applications*, **19**(4), 1003-1021.
Littell, J. S., D. McKenzie, H. Y. Wan and S. A. Cushman, 2018: Climate Change and Future Wildfire in the Western United States: An Ecological Approach to Nonstationarity. *Earths Future*, **6**(8), 1097-1111, doi:10.1029/2018ef000878.
Littell, J. S. et al., 2010: Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change*, **102**(1), 129-158, doi:10.1007/s10584-010-9858-x.
Littlefield, C. E., M. Krosby, J. L. Michalak and J. J. Lawler, 2019: Connectivity for species on the move: supporting climate-driven range shifts. *Frontiers in Ecology and the Environment*, **17**(5), 270-278, doi:10.1002/fee.2043.
Liu, J. C. et al., 2016: Future respiratory hospital admissions from wildfire smoke under climate change in the Western US. *Environmental Research Letters*, **11**(12), 124018, doi:10.1088/1748-9326/11/12/124018.
Liu, J. C. et al., 2015: A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environmental Research*, **136**, 120-132, doi:10.1016/j.envres.2014.10.015.
Liu, J. C. et al., 2017a: Wildfire-specific fine particular matter and risk of hospital admissions in urban and rural counties. *Epidemiology*, **28**(1), 77-85, doi:10.1097/EDE.0000000000000556.
Liu, J. C. et al., 2017b: Who among the elderly is most vulnerable to exposure to and health risks of fine particulate matter from wildfire smoke? *American Journal of Epidemiology*, **186**(6), 730-735, doi:10.1093/aje/kwx141.
Lluch-Cota, S. E. et al., 2010: Changing climate in the Gulf of California. *Progress in Oceanography*, **87**(1-4), 114-126, doi:10.1016/j.pocean.2010.09.007.
Loehman, R., W. Flatley, L. Holsinger and A. Thode, 2018: Can Land Management Buffer Impacts of Climate Changes and Altered Fire Regimes on Ecosystems of the Southwestern United States? *Forests*, **9**(4), 192, doi:10.3390/f9040192.
Loehman, R. A., R. E. Keane and L. M. Holsinger, 2020: Simulation Modeling of Complex Climate, Wildfire, and Vegetation Dynamics to Address Wicked Problems in Land Management. *Frontiers in Forests and Global Change*, **3**(3), doi:10.3389/ffgc.2020.00003.
Long, J. W., F. K. Lake, R. W. Goode and B. M. Burnette, 2020a: How traditional tribal perspectives influence ecosystem restoration. *Ecopsychology*, **12**(2), 71-82, doi:10.1089/eco.2019.0055.

Long, J. W., F. K. Lake, R. W. Goode and B. M. Burnette, 2020b: How Traditional Tribal Perspectives Influence Ecosystem Restoration. *Ecopsychology*.
Long, W., K. M. Swiney and R. J. Foy, 2013a: Effects of ocean acidification on the embryos and larvae of red king crab, Paralithodes camtschaticus. *Marine Pollution Bulletin*, **69**(1-2), 38-47, doi:10.1016/j.marpolbul.2013.01.011.
Long, W. C. et al., 2013b: Effects of ocean acidification on juvenile red king crab (Paralithodes camtschaticus) and Tanner crab (Chionoecetes bairdi) growth, condition, calcification, and survival. *PLoS One*, **8**(4), e60959, doi:10.1371/journal.pone.0060959.
López-Blanco, J. et al., 2018: Land suitability levels for rainfed maize under current conditions and climate change projections in Mexico. *Outlook Agric.*, **47**(3), 181-191, doi:10.1177/0030727018794973.
Lopez-Perez, M., F. I. Arreguin-Cortes and O. F. Ibanez, 2018: National Drought Policy in Mexico: A Paradigm Change from Reactive to Proactive Management. In: *Drought and Water Crises: Integrating Science, Management, and Policy, 2nd Edition* [Pulwarty, D. A. W. and S. Roger (eds.)]. CRC Press, Boca Raton, FL, pp. 409-429.
Loredo, S. A. et al., 2019: Spatial and temporal diving behavior of non-breeding common murres during two summers of contrasting ocean conditions. *J. Exp. Mar. Bio. Ecol.*, **517**, 13-24, doi:10.1016/j.jembe.2019.05.009.
Loreto, D., M. Esperón-Rodríguez and V. L. Barradas, 2017: The climatic-environmental significance, status and socioeconomic perspective of the grown-shade coffee agroecosystems in the central mountain region of Veracruz, Mexico. *Investigaciones Geograficas*, **2017**(92), 87-100, doi:10.14350/rig.51876.
Louis, R. P., 2007: Can you hear us now? Voices from the margin: Using Indigenous methodologies in geographic research. *Geographical Research*, **45**(2), 130-139, doi:10.1111/j.1745-5871.2007.00443.x.
Low, M., 2020: The Deh Cho Aboriginal Aquatic Resources and Oceans Management program-linking indigenous peoples and academic researchers for monitoring of aquatic resources in a region of rapid permafrost loss. Vol. 2020 ed., pp. B123-101.
Lubetkin, K. C., A. L. Westerling and L. M. Kueppers, 2017: Climate and landscape drive the pace and pattern of conifer encroachment into subalpine meadows. *Ecological Applications*, **27**(6), 1876-1887, doi:10.1002/eap.1574.
Lucatello, S., 2019: *Del TLCAN al T-MEC : la dimensión olvidada del medio ambiente en América del Norte*. Instituto de Investigaciones Dr. José María Luis Mora : siglo xxi :Anthropos Editorial. ISBN 978-607-03-1043-0 ISSN.
Lund, J., J. Medellin-Azuara, J. Durand and K. Stone, 2018: Lessons from California's 2012–2016 drought. *Journal of Water Resources Planning and Management*, **144**(10), doi:10.1061/(asce)wr.1943-5452.0000984.
Luthy, R. G., J. M. Wolfand and J. L. Bradshaw, 2020: Urban Water Revolution: Sustainable Water Futures for California Cities. *Journal of Environmental Engineering*, **146**(7), doi:10.1061/(asce)ee.1943-7870.0001715.
Lynch, A. J. et al., 2016: Climate Change Effects on North American Inland Fish Populations and Assemblages. *Fisheries*, **41**(7), 346-361, doi:10.1080/03632415.2016.1186016.
Lynch, M. J., P. B. Stretesky and M. A. Long, 2020a: Climate Change, Temperature, and Homicide: A Tale of Two Cities, 1895–2015. *Wea. Climate Soc.*, **12**(1), 171-181, doi:10.1175/WCAS-D-19-0068.1.
Lynch, M. J., P. B. Stretesky, M. A. Long and K. L. Barrett, 2020b: The Climate Change-Temperature-Crime Hypothesis: Evidence from a Sample of 15 Large US Cities, 2002 to 2015. *International Journal of Offender Therapy and Comparative Criminology*, 0306624X20969934, doi:10.1177/0306624X20969934.
Lynham, J. et al., 2017: Costly stakeholder participation creates inertia in marine ecosystems. *Marine Policy*, **76**(October 2015), 122-129, doi:10.1016/j.marpol.2016.11.011.
Lynn, K. et al., 2013: The impacts of climate change on tribal traditional foods. In: *Climate Change and Indigenous Peoples in the United States* [Maldonado, J. K., B. Colombi and R. Pandya (eds.)]. Springer, Cham, pp. 37-48.
Lynn, K. et al., 2014: The impacts of climate change on tribal traditional foods. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions* [Maldonado, J. K., B. Colombi and R. Pandya (eds.)]. Springer International Publishing, Cham, pp. 37-48. ISBN 9783319052663.
Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, doi:10.1038/s41586-019-1300-6.
Mach, K. J., D. Mastrandrea, T. E. Bilir and C. B. Field, 2016: Understanding and responding to danger from climate change: the role of key risks in the IPCC AR5. *Climatic Change*, **136**, 427-444, doi:10.1007/s10584-016-1645-x.
Mach, K. J., M. D. Mastrandrea, P. T. Freeman and C. B. Field, 2017: Unleashing expert judgment in assessment. *Global Environmental Change*, **44**, 1-14, doi:https://doi.org/10.1016/j.gloenvcha.2017.02.005.
Mahoney, K., J. Lukas and M. Mueller, 2018: *Colorado-New Mexico Regional Extreme Precipitation Study Summary Report Volume VI Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety*. Colorado Division of Water Resources and New Mexico Office of the State Engineer, 57 pp. Available at: https://wwa.colorado.edu/publications/reports/co-nm-reps_summary.pdf.
Maibach, E. W., A. Leiserowitz, C. Roser-Renouf and C. Mertz, 2011: Identifying like-minded audiences for global warming public engagement campaigns: An audience segmentation analysis and tool development. *PloS one*, **6**(3), e17571.
Maldonado, J. et al., 2021: Protection-in-place and community-led relocation. In: *Status of Tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ.
Maldonado, J. et al., 2017: The Story of Rising Voices: Facilitating collaboration between indigenous and western ways of knowing. In: *Responses to disasters and climate change: Understanding vulnerability and fostering resilience* [Companion, M. and M. S. Chaiken (eds.)]. CRC Press, pp. 15-26. ISBN 9781498760966.

Maldonado, J. K. et al., 2016: Engagement with indigenous peoples and honoring traditional knowledge systems. *Climatic Change*, **135**(1), 111-126, doi:10.1007/s10584-015-1535-7.
Maldonado, J. K., B. Colombi and R. Pandya, 2013: Climate change and Indigenous Peoples in the United States: Impacts, experiences and actions. *Climatic Change*, **120**, 601-614.
Malhi, Y. et al., 2020: Climate change and ecosystems: threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190104, doi:doi:10.1098/rstb.2019.0104.
Mamuji, A. A. and J. L. Rozdilsky, 2018: Wildfire as an increasingly common natural disaster facing Canada: understanding the 2016 Fort McMurray wildfire. *Natural Hazards*, 1-18.
Mann, M. E. and P. H. Gleick, 2015: Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(13), 3858-3859, doi:10.1073/pnas.1503667112.
Manson, G. K., N. J. Couture and T. S. James, 2019: *CanCoast 2.0: Data and indices to describe the sensitivity of Canada's*. Available at: G.K. Manson, N.J. Couture, and T.S. James.
Manuel-navarrete, D. and M. Pelling, 2015: Subjectivity and the politics of transformation in response to development and environmental change. *Glob. Environ. Change*, **35**, 558-569, doi:10.1016/j.gloenvcha.2015.08.012.
Mares, D., 2013: Climate change and levels of violence in socially disadvantaged neighborhood groups. *J. Urban Health*, **90**(4), 768-783, doi:10.1007/s11524-013-9791-1.
Mares, D. M. and K. W. Moffett, 2019: Climate Change and Crime Revisited: An Exploration of Monthly Temperature Anomalies and UCR Crime Data. *Environ. Behav.*, **51**(5), 502-529, doi:10.1177/0013916518781197.
Maria Raquel, C. d. S., F. A. Montalto and M. I. Palmer, 2016: Potential climate change impacts on green infrastructure vegetation. *Urban Forestry and Urban Greening*, **20**, 128-139, doi:10.1016/j.ufug.2016.08.014.
Marin, P. G., C. Julio, R. T. Dante Arturo and V. N. Daniel Jose, 2018: Drought and Spatiotemporal Variability of Forest Fires Across Mexico. *Chin. Geogr. Sci.*, **28**(1), 25-37, doi:10.1007/s11769-017-0928-0.
Marino, E. and H. Lazrus, 2015: Migration or Forced Displacement?: The Complex Choices of Climate Change and Disaster Migrants in Shishmaref, Alaska and Nanumea, Tuvalu. *Human Organization*, **74**(4), 341-350, doi:10.17730/0018-7259-74.4.341.
Marklein, A., E. Elias, P. Nico and K. Steenwerth, 2020: Projected temperature increases may require shifts in the growing season of cool-season crops and the growing locations of warm-season crops. *Science of the Total Environment*, **746**, 140918-140918, doi:10.1016/j.scitotenv.2020.140918.
Markon, C. et al., 2018: Alaska. [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 1185-1241.
Marks-Block, T., F. K. Lake and L. M. Curran, 2019: Effects of understory fire management treatments on California Hazelnut, an ecocultural resource of the Karuk and Yurok Indians in the Pacific Northwest. *Forest Ecology and Management*, **450**, 117517, doi:https://doi.org/10.1016/j.foreco.2019.117517.
Marks-Marino, D., 2019: *The Samish Indian Nation*. Climate Change Program, Institute for Tribal Environmental Professionals, Northern Arizona University.
Marks-Marino, D., 2020a: *Blue Lake Rancheria*. Climate Change Program, Institute for Tribal Environmental Professionals, Northern Arizona University.
Marks-Marino, D., 2020b: *Quapaw Nation*. Climate Change Program, Institute for Tribal Environmental Professionals, Northern Arizona University.
Marks-Marino, D., 2021: *The Seminole Tribe of Florida*. Available at: https://www7.nau.edu/itep/main/tcc/Tribes/gc_seminole.
Marsha, A. et al., 2016: Influences af climatic and population changes on health-related mortality in Houston, Texas, USA. *Climatic Change*.
Marsha, A. et al., 2018: Influences of climatic and population changes on heat-related mortality in Houston, Texas, USA. *Climatic Change*, **146**(3-4), 471-485, doi:10.1007/s10584-016-1775-1.
Marshall, A. M., J. T. Abatzoglou, T. E. Link and C. J. Tennant, 2019a: Projected changes in interannual variability of peak snowpack amount and timing in the Western United States. *Geophys. Res. Lett.*, doi:10.1029/2019GL083770.
Marshall, K. N. et al., 2019b: Inclusion of ecosystem information in US fish stock assessments suggests progress toward ecosystem-based fisheries management. *ICES Journal of Marine Science*, **76**(1), 1-9, doi:10.1093/icesjms/fsy152.
Marshall, K. N. et al., 2018: Ecosystem-Based Fisheries Management for Social–Ecological Systems: Renewing the Focus in the United States with Next Generation Fishery Ecosystem Plans. *Conservation Letters*, **11**(1), e12367, doi:10.1111/conl.12367.
Martin, C. et al., 2020a: Change rippling through our waters and culture. *Journal of Contemporary Water Research & Education*, **169**(1), 61-78, doi:10.1111/j.1936-704X.2020.03332.x.
Martin, D. A., 2016: At the nexus of fire, water and society. *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, **371**(1696), doi:10.1098/rstb.2015.0172.
Martin, J. T. et al., 2020b: Increased drought severity tracks warming in the United States' largest river basin. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(21), 11328-11336, doi:10.1073/pnas.1916208117.

Martínez, M. L., G. Mendoza-González, R. Silva-Casarín and E. Mendoza-Baldwin, 2014: Land use changes and sea level rise may induce a "coastal squeeze" on the coasts of Veracruz, Mexico. *Global Environmental Change*, **29**, 180-188, doi:10.1016/j.gloenvcha.2014.09.009.
Martinez-Austria, P. and E. Bandala, 2017: Temperature and Heat-Related Mortality Trends in the Sonoran and Mojave Desert Region. *Atmosphere*, **8**(12), 53, doi:10.3390/atmos8030053.
Martinez-Austria, P. F., E. R. Bandala and C. Patino-Gomez, 2016: Temperature and heat wave trends in northwest Mexico. *PHYSICS AND CHEMISTRY OF THE EARTH*, **91**, 20-26, doi:10.1016/j.pce.2015.07.005.
Martinez-Austria, P. F., A. V. Hidalgo and C. Patino-Gomez, 2019: Dynamic modelling of the climate change impact in the Conchos River basin water management. *Tecnologia Y Ciencias Del Agua*, **10**(1), 207-233, doi:10.24850/j-tyca-2019-01-08.
Martinich, J. and A. Crimmins, 2019: Climate damages and adaptation potential across diverse sectors of the United States. *Nat. Clim. Chang.*, **9**, 397-404, doi:10.1038/s41558-019-0444-6.
Marushka, L. et al., 2019: Potential impacts of climate-related decline of seafood harvest on nutritional status of coastal First Nations in British Columbia, Canada. *PLoS One*, **14**(2), e0211473, doi:10.1371/journal.pone.0211473.
Mase, A. S., B. M. Gramig and L. S. Prokopy, 2017: Climate change beliefs, risk perceptions, and adaptation behavior among Midwestern US crop farmers. *Climate Risk Management*, **15**, 8-17.
Mashpee Wampanoag, T., 2019: *Mashpee Wampanoag Tribe multi-hazard mitigation plan*. Available at: https://static1.squarespace.com/static/59ca33c0f09ca4a9c58455a9/t/5da7612ed2d7bf603d826b25/1571250511773/Draft+Mashpee+Wampanoag+Tribe+Multi-Hazard+Mitigation+Plan_191014.pdf.
Masood, S., T. M. Van Zuiden, A. R. Rodgers and S. Sharma, 2017: An uncertain future for woodland caribou (Rangifer tarandus caribou): The impact of climate change on winter distribution in Ontario. *Rangifer*, **37**(1), doi:10.7557/2.37.1.4103.
Mastachi-Loza, C. A. et al., 2016: Regional analysis of climate variability at three time scales and its effect on rainfed maize production in the Upper Lerma River Basin, Mexico. *Agriculture, Ecosystems & Environment*, **225**, 1-11, doi:https://doi.org/10.1016/j.agee.2016.03.041.
Mathis, J. T., J. N. Cross, W. Evans and S. C. Doney, 2015: Ocean Acidification in the Surface Waters of the Pacific-Arctic Boundary Regions. *Oceanography*, **28**(2), 122-135.
Matthews, S. N., L. R. Iverson, M. P. Peters and A. M. Prasad, 2019: *Assessing potential climate change pressures across the conterminous United States: mapping plant hardiness zones, heat zones, growing degree days, and cumulative drought severity throughout this century*. U.S. Department of Agriculture, Forest Service, Northern Research Station, U.S. Department of Agriculture, F. S., Northern Research Station, Newtown Square, PA, 31 pp. Available at: https://doi.org/10.2737/NRS-RMAP-9.
Maxwell, K. et al., 2018a: Built environment, urban systems, and cities. *In: Reidmiller, DR; Avery, CW; Easterling, DR; Kunkel, KE; Lewis, KLM; Maycock, TK; Stewart, BC, eds. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Washington, DC: US Global Change Research Program. pp. 438–478.*, 438-478, doi:doi: 10.7930/NCA4.2018.CH11.
Maxwell, K. et al., 2018b: Built environment, urban systems, and cities. *In: Reidmiller, DR; Avery, CW; Easterling, DR; Kunkel, KE; Lewis, KLM; Maycock, TK; Stewart, BC, eds. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Washington, DC: US Global Change Research Program. pp. 438–478.*, **2**, 438-478.
Maxwell, S. M. et al., 2015: Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. *Marine Policy*, **58**, 42-50, doi:10.1016/j.marpol.2015.03.014.
Mayer, A. and E. K. Smith, 2019: Unstoppable climate change? The influence of fatalistic beliefs about climate change on behavioural change and willingness to pay cross-nationally. *Climate Policy*, **19**(4), 511-523.
Maynard, N. G., 2014: *Native Peoples - Native homelands climate change workshop II - Final report: An Indigenous response to climate change. November 18-21, 2009*. Prior Lake, Minnesota, 132 pp.
Mayor, S. J. et al., 2017: Increasing phenological asynchrony between spring green-up and arrival of migratory birds. *Sci. Rep.*, **7**(1), 1902, doi:10.1038/s41598-017-02045-z.
McCabe, G. J. et al., 2017: Evidence that Recent Warming is Reducing Upper Colorado River Flows. *Earth Interactions*, **21**, doi:10.1175/ei-d-17-0007.1.
McCabe, R. M. et al., 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophys. Res. Lett.*, **43**(19), 10366-10376, doi:10.1002/2016GL070023.
McClain, L., 2021: Confluence for climate education: Aaniiih Nakoda College addresses our changing environment. *Tribal College Journal of American Indian Higher Education*, **32**(3).
McCoy, D. et al., 2017: Large-scale climatic effects on traditional Hawaiian fishpond aquaculture. *PLOS ONE*, **12**(11), e0187951-e0187951, doi:10.1371/journal.pone.0187951.
McCrary, R. R. and L. O. Mearns, 2019: Quantifying and Diagnosing Sources of Uncertainty in Midcentury Changes in North American Snowpack from NARCCAP. *Journal of Hydrometeorology*, **20**(11), 2229-2252, doi:10.1175/jhm-d-18-0248.1.
McCright, A. M. and R. E. Dunlap, 2011: The politicization of climate change and polarization in the American public's views of global warming, 2001–2010. *The Sociological Quarterly*, **52**(2), 155-194.
McDonald, R. et al., 2016: *Planting healthy air: A global analysis of the role of urban trees in addressing particulate matter pollution and extreme heat*. 95-95 pp. Available at: https://global.nature.org/content/healthyair.

McDonald, Y. J., S. E. Grineski, T. W. Collins and Y.-A. Kim, 2015: A scalable climate health justice assessment model. *Social Science & Medicine*, **133**, 242-252, doi:10.1016/j.socscimed.2014.10.032.
McGee, T. K., 2019: Preparedness and experiences of evacuees from the 2016 Fort McMurray Horse River wildfire. *Fire*, **2**(1), 13.
McGregor, D., 2014: Traditional knowledge and water governance: The ethic of responsibility. *AlterNative*, **10**(5), 493-507.
McGregor, D., W. Bayha and D. Simmons, 2010a: "Our responsibility to keep the land alive": Voices of Northern Indigenous researchers. *Pimatisiwin: A Journal of Aboriginal and Indigenous Community Health*, **8**(1), 101-124.
McGregor, R. et al., 2010b: *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions*. Canada, T. A. o., Ottawa, ON, 177 pp. Available at: https://trid.trb.org/view/925691.
McIntyre, P. J. et al., 2015: Twentieth-century shifts in forest structure in California: Denser forests, smaller trees, and increased dominance of oaks. *Proc. Natl. Acad. Sci. U. S. A.*, **112**(5), 1458-1463, doi:10.1073/pnas.1410186112.
McKelvey, K. S. and P. C. Buotte, 2018: Effects of Climate Change on Wildlife in the Northern Rockies. In: *Climate Change and Rocky Mountain Ecosystems* [Halofsky, J. E. and D. L. Peterson (eds.)]. Springer International Publishing, Cham, pp. 143-167. ISBN 978-3-319-56928-4.
McKenney, D. et al., 2016: *Canada's Timber Supply: Current Status and Future Prospects under a Changing Climate*. Natural Resources Canada, Canadian Forest Service, Information report GLC-X-15, 75 pp.
McLaughlin, J. B. et al., 2005: Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *New England Journal of Medicine*, **353**(14), 1463-1470, doi:10.1056/NEJMoa051594.
McLean, K. E., J. Yao and S. B. Henderson, 2015: An evaluation of the British Columbia asthma monitoring system (BCAMS) and PM2.5 exposure metrics during the 2014 forest fire season. *International Journal of Environmental Research and Public Health*, **12**(6), 6710-6724, doi:10.3390/ijerph120606710.
McMillan, T. et al., 2019: *Local adaptation in Canada: Survey report*. Available at: http://ok-cear.sites.olt.ubc.ca/files/2019/06/Local-Adaptation-in-Canada-Full-web.-1.pdf.
McNeeley, S. M., 2017: Sustainable Climate Change Adaptation in Indian Country. *Weather Climate and Society*, **9**(3), 392-403, doi:10.1175/wcas-d-16-0121.1.
McNeeley, S. M. and M. D. Shulski, 2011: Anatomy of a closing window: Vulnerability to changing seasonality in Interior Alaska. *Global Environmental Change*, **21**(2), 464-473, doi:10.1016/j.gloenvcha.2011.02.003.
McPherson, M. et al., 2017: Expansion of the Lyme disease vector Ixodes Scapularis in Canada inferred from CMIP5 climate projections. *Environmental Health Perspectives*, **125**(5), 057008-057008, doi:10.1289/EHP57.
McWethy, D. B. et al., 2019: Rethinking resilience to wildfire. *Nature Sustainability*, **2**(9), 797-804.
Meadow, A. M. et al., 2015: Moving toward the deliberate coproduction of climate science knowledge. *Weather, Climate, and Society*, **7**(2), 179-191.
Meadow, A. M., S. LeRoy, J. Weiss and L. Keith, 2018: *Climate profile for the city of Flagstaff, Arizona*. Available at: https://climas.arizona.edu/sites/default/files/pdfclimate-profile.pdf.
Meakin, S. and T. Kurtvits, 2009: *Assessing the impacts of climate change on food security in the Canadian Arctic*. GRID-Adrenal, 46 pp. Available at: https://www.grida.no/publications/146.
Medellin-Azuara, J. et al., 2015: Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA. *Hydrogeol. J.*, **23**(6), 1205-1216, doi:10.1007/s10040-015-1283-9.
Meehl, G. A., C. Tebaldi and D. Adams-Smith, 2016: US daily temperature records past, present, and future. *Proc. Natl. Acad. Sci. U. S. A.*, **113**(49), 13977-13982, doi:10.1073/pnas.1606117113.
Meerow, S. and C. L. Mitchell, 2017: Weathering the storm: The politics of urban climate change adaptation planning. *Environment and Planning A*, **49**(11), 2619-2627, doi:10.1177/0308518X17735225.
Mees, H. et al., 2016: Coproducing flood risk management through citizen involvement: Insights from cross-country comparison in Europe. *Ecol. Soc.*, **21**(3), doi:10.5751/ES-08500-210307.
Mehdi, B. et al., 2015: Simulated impacts of climate change and agricultural land use change on surface water quality with and without adaptation management strategies. *Agriculture, Ecosystems & Environment*, **213**, 47-60.
Meixner, T. et al., 2016: Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, **534**, 124-138, doi:10.1016/j.jhydrol.2015.12.027.
Mekonnen, Z. A., R. F. Grant and C. Schwalm, 2017: Carbon sources and sinks of North America as affected by major drought events during the past 30 years. *Agricultural and Forest Meteorology*, **244-245**, 42-56, doi:10.1016/j.agrformet.2017.05.006.
Melia, N., K. Haines and E. Hawkins, 2016: Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters*, **43**(18), 9720-9728, doi:10.1002/2016gl069315.
Melillo, J. M., T. T. C. Richmond and G. W. Yohe, 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. US Global Change Research Program, Program, U. G. C. R., Washington, DC, 841 pp.
Melis, T. et al., 2016: Using Large-Scale Flow Experiments to Rehabilitate Colorado River Ecosystem Function in Grand Canyon: Basis for an Adaptive Climate-Resilient Strategy. *Water Policy and Planning in a Variable and Changing Climate*, 315-345, doi:10.1201/b19534-21.
Melvin, A. M. et al., 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences*, **114**(2), E122-E131.

Mendenhall, E. et al., 2020: Climate change increases the risk of fisheries conflict. *Marine Policy*, **117**(March), 103954-103954, doi:10.1016/j.marpol.2020.103954.
Meraz Jimenez, A. d. J. et al., 2019: Potential distribution of Musca domestica in Jesus Maria Municipality, Aguascalientes, Mexico, based on climate change scenarios. *Revista Mexicana De Ciencias Pecuarias*, **10**(1), 14-29, doi:10.22319/rmcp.v10i1.4241.
Mercer Clarke, C. S. L., P. Manuel and F. J. Warren, 2016: The coastal challenge. [Lemmen, D. S., F. J. Warren, T. S. James and C. S. L. Mercer Clarke (eds.)]. Government of Canada, Ottawa, Ontario, pp. 69-98.
Mercer, K. L., H. R. Perales and J. D. Wainwright, 2012: Climate change and the transgenic adaptation strategy: Smallholder livelihoods, climate justice, and maize landraces in Mexico. *Global Environmental Change*, **22**(2), 495-504, doi:10.1016/j.gloenvcha.2012.01.003.
Merculieff, L. et al., 2017: *Arctic traditional knowledge and wisdom: Changes in the North American Arctic, perspectives from Arctic Athabascan Council, Aleut International Association, Gwich'in Council International, and published accounts*. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjcw7Co2PTyAhWqFTQIHYKbCqsQFnoECAQQAQ&url=https%3A%2F%2Fwww.caff.is%2Fmonitoring-series%2F412-arctic-traditional-knowledge-and-wisdom-changes-in-the-north-american-arctic%2Fdownload&usg=AOvVaw0ufqookgH19G50Yo2soge1.
Meredith, M. et al., 2019: Polar Regions. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. IPCC.
Messier, C. et al., 2019: The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, **6**(1), doi:10.1186/s40663-019-0166-2.
Messner, S., L. Moran, G. Reub and J. Campbell, 2013: Climate change and sea level rise impacts at ports and a consistent methodology to evaluate vulnerability and risk. *WIT Transactions on Ecology and the Environment*, **169**, 141-153, doi:10.2495/CP130131.
Metcalfe, S. E. et al., 2020a: Community perception, adaptation and resilience to extreme weather in the Yucatan Peninsula, Mexico. *Regional Environmental Change 2020 20:1*, **20**(1), 1-15, doi:10.1007/S10113-020-01586-W.
Metcalfe, S. E. et al., 2020b: Community perception, adaptation and resilience to extreme weather in the Yucatan Peninsula, Mexico. *Regional Environmental Change*, **20**(1), 1-15, doi:10.1007/S10113-020-01586-W.
Metro Vancouver, 2016: *Climate projections for Metro Vancouver*. Available at: http://www.metrovancouver.org/services/air-quality/AirQualityPublications/ClimateProjectionsForMetroVancouver.pdf.
Meyer-Gutbrod, E. L., C. H. Greene and K. T. A. Davies, 2018: Marine species range shifts necessitate advanced policy planning: The case of the North Atlantic right whale. *Oceanography*, **31**(2), 19-23.
Meza-Matty, I. A. et al., 2021: Daily, seasonal, and annual variability of temperature in streams inhabited by the endemic San Pedro Martir trout (Oncorhynchus mykiss nelsoni), in Baja California, Mexico, and the predicted temperature for the years 2025 and 2050. *Journal of Limnology*, **80**(2), doi:10.4081/jlimnol.2021.2001.
Miami-Dade County, 2021: *Miami-Dade Conty Sea Level Rise Strategy*. County, M.-D., Miami, FL. Available at: https://mdc.maps.arcgis.com/sharing/rest/content/items/b1a93c86abb548f99f712df2dac6d670/data.
Miao, Q., 2019: What affects government planning for climate change adaptation: Evidence from the U.S. states. *Environmental Policy and Governance*, **29**(5), 376-394, doi:10.1002/eet.1866.
Michalak, A. M., 2016: Study role of climate change in extreme threats to water quality. *Nature*, **535**(7612), 349-350, doi:10.1038/535349a.
Michalak, A. M. et al., 2013: Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences*, **110**(16), 6448-6452, doi:10.1073/pnas.1216006110.
Middleton, J. et al., 2020a: "We're people of the snow:" Weather, climate change, and Inuit mental wellness. *Social Science & Medicine*, **262**, 113137, doi:10.1016/j.socscimed.2020.113137.
Middleton, J. et al., 2020b: Indigenous mental health in a changing climate: A systematic scoping review of the global literature. *Environmental Research Letters*, **15**(5), 053001-053001, doi:10.1088/1748-9326/ab68a9.
Middleton, J. et al., 2021: Temperature and place associations with Inuit mental health in the context of climate change. *Environmental Research*, **198**, 111166-111166, doi:10.1016/j.envres.2021.111166.
Mildenberger, M. et al., 2016: The distribution of climate change public opinion in Canada. *PLoS One*, **11**(8), e0159774.
Mildenberger, M., M. Lubell and M. Hummel, 2019: Personalized risk messaging can reduce climate concerns. *Glob. Environ. Change*, **55**(Complete), 15-24, doi:10.1016/j.gloenvcha.2019.01.002.
Miles-Novelo, A. and C. A. Anderson, 2019: Climate Change and Psychology: Effects of Rapid Global Warming on Violence and Aggression. *Current Climate Change Reports*, **5**(1), 36-46.
Millar, C. I. and N. L. Stephenson, 2015: Temperate forest health in an era of emerging megadisturbance. *Science*, **349**(6250), 823-826, doi:10.1126/science.aaa9933.

Miller, A. E., T. L. Wilson, R. L. Sherriff and J. Walton, 2017: Warming drives a front of white spruce establishment near western treeline, Alaska. *Global Change Biology*, **23**(12), 5509-5522, doi:https://doi.org/10.1111/gcb.13814.
Miller, D. D. et al., 2018: Adaptation strategies to climate change in marine systems. *Glob. Chang. Biol.*, **24**(1), e1-e14, doi:10.1111/gcb.13829.
Miller, K. A., 2017: Extreme Drought and California's Water Economy: Challenges and Opportunities for Building Resilience. In: *Building a Climate Resilient Economy and Society – Challenges and Opportunities* [Ninan, K. N. and M. Inoue (eds.)]. Edward Elgar. , Northampton, MA, USA, pp. 164-182. ISBN ISBN: 978 1 78536 844 8.
Miller, K. A., A. F. Hamlet, D. S. Kenney and K. T. Redmond, 2016: *Water Policy and Planning in a Variable and Changing Climate*. CRC Press, 434 pp. ISBN 9781482227987.
Mills, D. et al., 2015a: Quantifying and monetizing potential climate change policy impacts on terrestrial ecosystem carbon storage and wildfires in the United States. *Climatic Change*, **131**(1), 163-178, doi:10.1007/s10584-014-1118-z.
Mills, D. et al., 2015b: Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States. *Climatic Change*, **131**(1), 83-95, doi:10.1007/s10584-014-1154-8.
Mills, L. S. et al., 2018: Winter color polymorphisms identify global hot spots for evolutionary rescue from climate change. *Science*, **359**(6379), 1033-1036, doi:10.1126/science.aan8097.
Mills, L. S. et al., 2013: Camouflage mismatch in seasonal coat color due to decreased snow duration. *Proc. Natl. Acad. Sci. U. S. A.*, **110**(18), 7360-7365, doi:10.1073/pnas.1222724110.
Milly, P. C. D. et al., 2015: On Critiques of "Stationarity is Dead: Whither Water Management?". *Water Resources Research*, **51**(9), 7785-7789, doi:10.1002/2015wr017408.
Milly, P. C. D. and K. A. Dunne, 2020: Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, **367**(6483), 1252-+, doi:10.1126/science.aay9187.
Mioduszewski, J. R. et al., 2019: Past and future interannual variability in Arctic sea ice in coupled climate models. *The Cryosphere*, **13**(1), 113-124, doi:10.5194/tc-13-113-2019.
Misra, V. et al., 2021: The Florida Water and Climate Alliance (FloridaWCA): Developing a Stakeholder-Scientist Partnership to Create Actionable Science in Climate Adaptation and Water Resource Management. *Bulletin of the American Meteorological Society*, **102**(2), E367-E382, doi:10.1175/bams-d-19-0302.1.
Molina-Martínez, A. et al., 2016: Changes in butterfly distributions and species assemblages on a Neotropical mountain range in response to global warming and anthropogenic land use. *Diversity and Distributions*, **22**(11), 1085-1098, doi:10.1111/ddi.12473.
Molina-Navarro, E. et al., 2016: Hydrological modeling and climate change impacts in an agricultural semiarid region. Case study: Guadalupe River basin, Mexico. *Agricultural Water Management*, **175**, 29-42, doi:10.1016/j.agwat.2015.10.029.
Möller, I. et al., 2014: Wave attenuation over coastal salt marshes under storm surge conditions. *Nat. Geosci.*, **7**, 727, doi:10.1038/ngeo2251.
Molnar, M. et al., 2021: Ecosystem Services; Chapter 5. In: *Canada in a Changing Climate* [Warren, F. J. and N. Lulham (eds.)]. Government of Canada, Ottawa, ON, pp. 264-344.
Monaghan, A. J. et al., 2015: Climate change influences on the annual onset of Lyme disease in the United States. *Ticks and Tick-borne Diseases*, **6**(5), 615-622, doi:10.1016/j.ttbdis.2015.05.005.
Monterosso, A. and C. Conde, 2018: Adaptive capacity: identifying the challenges faced by municipalities addressing climate change in Mexico. *Climate and Development*, **10**(8), 729-741, doi:10.1080/17565529.2017.1372264.
Monterroso-Rivas, A. I. et al., 2018: Multi-temporal assessment of vulnerability to climate change: insights from the agricultural sector in Mexico. *Climatic Change*, **147**(3-4), 457-473, doi:10.1007/s10584-018-2157-7.
Montiel-González, I., S. Martínez-Santiago, A. López Santos and G. García Herrera, 2017: Climate change impact on rainfed agriculture in Aguascalientes, Mexico for the near future (2015-2039). *Revista Chapingo Serie Zonas Áridas*, **16**(1), 1-13, doi:10.5154/r.rchsza.2017.01.001.
Moore, C. et al., 2021: Estimating the economic impacts of climate change on 16 major US fisheries. *Climate Change Economics*, **12**(1), doi:10.1142/S2010007821500020.
Moore, S. E. and K. J. Kuletz, 2019: Marine birds and mammals as ecosystem sentinels in and near Distributed Biological Observatory regions: An abbreviated review of published accounts and recommendations for integration to ocean observatories. *Deep Sea Res. Part 2 Top. Stud. Oceanogr.*, **162**, 211-217.
Mora, C. et al., 2018: Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nat. Clim. Chang.*, **8**(12), 1062-1071, doi:10.1038/s41558-018-0315-6.
Morales, K. et al., 2021: *Emerging topics* [Marks-Marino, D. (ed.)]. Status of tribes and climate change report, Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, 277-295 pp. Available at: https://drive.google.com/file/d/11uwJpvcUkJNdaCGZAPdguYe35R4KXm1d/view?usp=sharing.
Morecroft, M. D. et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366**(6471).
Morefield, P. E. et al., 2018: Heat-related health impacts under scenarios of climate and population change. *International Journal of Environmental Research and Public Health*, **15**(11), 2438-2438, doi:10.3390/ijerph15112438.
Moreira, F. et al., 2020: Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters*, **15**(1), 011001, doi:10.1088/1748-9326/ab541e.

Morelli, T. L. et al., 2016: Managing Climate Change Refugia for Climate Adaptation. *PLoS One*, **11**(8), e0159909, doi:10.1371/journal.pone.0159909.
Mori, A. S. et al., 2021: Biodiversity–productivity relationships are key to nature-based climate solutions. *Nature Climate Change*, **11**(6), 543-550, doi:10.1038/s41558-021-01062-1.
Morin, C. W. and A. C. Comrie, 2013: Regional and seasonal response of a West Nile virus vector to climate change. *Proceedings of the National Academy of Sciences*, **110**(39), 15620-15625, doi:10.1073/pnas.1307135110.
Morley, J. W. et al., 2018: Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLoS ONE*, **13**(5), 1-28, doi:10.1371/journal.pone.0196127.
Morris, J. L. et al., 2018a: Bark beetles as agents of change in social–ecological systems. *Frontiers in Ecology and the Environment*, **16**, S34-S43, doi:10.1002/fee.1754.
Morris, R. L., T. M. Konlechner, M. Ghisalberti and Stephen E. Swearer, 2018b: From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Global Change Biology*, **24**(5), 1827-1842, doi:10.1111/gcb.14063.
Morton, L. W., G. Roesch-McNally and A. Wilke, 2017: Upper Midwest farmer perceptions: Too much uncertainty about impacts of climate change to justify changing current agricultural practices. *Journal of Soil and Water Conservation*, **72**(3), 215-225.
Mortsch, L., S. Cohen and G. Koshida, 2015: Climate and water availability indicators in Canada: Challenges and a way forward. Part II–Historic trends. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, **40**(2), 146-159.
Moser, J. C., B. A. Fitzgibbon and K. D. Klepzig, 2005: The Mexican pine beetle, *Dendroctonus mexicanus*: First record in the United States and co-occurrence with the southern pine beetle— *Dendroctonus frontalis* (Coleoptera: Scolytidae or Curculionidae: Scolytidae). *Entomological News*, **116**(4), 235-243.
Moser, K. A. et al., 2019: Mountain lakes: Eyes on global environmental change. *Global and Planetary Change*, **178**, 77-95, doi:10.1016/j.gloplacha.2019.04.001.
Moser, S. C., 2010: Communicating climate change: history, challenges, process and future directions. *WIREs Climate Change*, **1**(1), 31-53, doi:10.1002/wcc.11.
Moser, S. C., J. Coffee and A. Seville, 2017: *Rising to the challenge together: A Review and Critical Assessment of the State of the US Climate Adaptation Field* The Kresge Foundation, Foundation, T. K., 106 pp. Available at: https://kresge.org/content/rising-challenge-together.
Moss, R. H. et al., 2019: Evaluating Knowledge to Support Climate Action: A Framework for Sustained Assessment. *Weather, Climate, and Society*, **11**(3), 465–487, doi:https://doi.org/10.1175/WCAS-D-18-0134.1.
Mote, P. W. et al., 2018: Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science*, **1**(1), doi:10.1038/s41612-018-0012-1.
Mottershead, K. D., T. K. McGee and A. Christianson, 2020: Evacuating a First Nation Due to Wildfire Smoke: The Case of Dene Tha' First Nation. *International Journal of Disaster Risk Science*, **11**(3), 274-286, doi:10.1007/s13753-020-00281-y.
Moudrak, N., B. Feltmate, H. Venema and H. Osman, 2018: *Combating Canada's Rising Flood Costs: Natural infrastructure is an underutilized option*. Intact Centre on Climate Adaptation University of Waterloo, Canada, I. B. o., Waterloo, 68 pp. Available at: http://assets.ibc.ca/Documents/Resources/IBC-Natural-Infrastructure-Report-2018.pdf
Muckleshoot Tribal Council, 2021: *2017 and 2019 Green River/Duwamish River Commercial Fisheries Disaster for Muckleshoot Indian Tribe*. Available at: https://s3.amazonaws.com/media.fisheries.noaa.gov/2020-10/70891_Muckleshoot.pdf?null.
Mudryk, l. et al., 2021: Impact of 1°, 2°, and 4°C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change*, **11**, 673-679.
Mudryk, L. R. et al., 2018: Canadian snow and sea ice: historical trends and projections. *The Cryosphere*, **12**(4), 1157-1176, doi:10.5194/tc-12-1157-2018.
Mueter, F. J., N. A. Bond, J. N. Ianelli and A. B. Hollowed, 2011: Expected declines in recruitment of walleye pollock (Theragra chalcogramma) in the eastern Bering Sea under future climate change. *ICES Journal of Marine Science*, **68**(6), 1284-1296, doi:10.1093/icesjms/fsr022.
Muhlfeld, C. C. et al., 2014: Invasive hybridization in a threatened species is accelerated by climate change. *Nature Climate Change*, **4**(7), 620.
Mumme, S. P., 1999: Managing acute water scarcity on the US-Mexico border: Institutional issues raised by the 1990's drought. *Natural Resources Journal*, **39**(1), 149-166.
Mumme, S. P., 2016: Scarcity and Power in US-Mexico Transboundary Water Governance: Has the Architecture Changed since NAFTA? *Globalizations*, **13**(6), 702-718, doi:10.1080/14747731.2015.1129710.
Municipal Natural Assets Initiative, 2018: *Primer on natural asset management*. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiQkf_-2fTyAhXKJDQIHWvbDIEQFnoECAQQAQ&url=https%3A%2F%2Fmnai.ca%2Fmedia%2F2018%2F01%2FFCMPrimer_Jan1_2018.pdf&usg=AOvVaw0caGvTGr70T3Z2vIWOmGvv.
Munson, S. M., J. B. Bradford and K. R. Hultine, 2020: An Integrative Ecological Drought Framework to Span Plant Stress to Ecosystem Transformation. *Ecosystems*, 1-16.

Murphy, K. W. and A. W. Ellis, 2019: An analysis of past and present megadrought impacts on a modern water resource system. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **64**(1), 45-65, doi:10.1080/02626667.2019.1571274.
Murray-Tortarolo, G. N., V. J. Jaramillo and J. Larsen, 2018: Food security and climate change: the case of rainfed maize production in Mexico. *Agric. For. Meteorol.*, **253-254**, 124-131, doi:10.1016/j.agrformet.2018.02.011.
Murray-Tortarolo, G. N. and M. M. Salgado, 2021: Drought as a driver of Mexico-US migration. *Climatic Change*, **164**(3), 48, doi:10.1007/s10584-021-03030-2.
Mustonen, T., 2005: *Stories of the raven—Snowchange 2005 conference report Anchorage Alaska*. Snowchange Cooperative. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiG_9OU2vTyAhUSNn0KHa0DDnAQFnoECAQQAQ&url=http%3A%2F%2Fwww.snowchange.org%2Fpages%2Fwp-content%2Fuploads%2F2011%2F04%2FStoriesOfTheRaven_06NF.pdf&usg=AOvVaw0w5sr-CBO1FXnVTpBILWvs.
Myers-Smith, I. H. et al., 2019: Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change. *Ecological Monographs*, **89**(2), e01351, doi:10.1002/ecm.1351.
N. Y. C. Department of Environmental Protection, 2014: *One New York City: One Water*. Available at: https://www1.nyc.gov/assets/dep/downloads/pdf/climate-resiliency/one-nyc-one-water.pdf.
Nakashima, D., J. Rubis and I. Krupnik, 2018: *Indigenous knowledge for climate change assessment and adaptation*. Cambridge University Press, Cambridge.
Nalau, J., S. Becken and B. Mackey, 2018: Ecosystem-based Adaptation: A review of the constraints. *Environmental Science & Policy*, **89**, 357-364, doi:10.1016/j.envsci.2018.08.014.
Napolean, V., 2012: Thinking about Indigenous legal orders. In: *Dialogues on human rights and legal pluralism* [Provost, R. and C. Sheppard (eds.)]. Springer, Dordrecht, pp. 229-245.
Narayan, S. et al., 2016: The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLoS One*, **11**(5), e0154735, doi:10.1371/journal.pone.0154735.
Narita, D., H.-O. Poertner and K. Rehdanz, 2020: Accounting for risk transitions of ocean ecosystems under climate change: an economic justification for more ambitious policy responses. *Climatic Change*, **162**(1), 1-11, doi:10.1007/s10584-020-02763-w.
National Academies of Sciences, 2017: *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. National Academies Press, 280 pp. ISBN 9780309454230.
National Academies of Sciences, 2019: *A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs*. National Academies Press, 258 pp. ISBN 9780309485388.
National Fire Protection Association, 2013: *Community Wildfire Safety Through Regulation. A Best Practices Guide for Planners and Regulators*. National Fire Protection Association (NFPA), 25 pp. Available at: https://www.nfpa.org/-/media/Files/Public-Education/By-topic/Wildland/WildfireBestPracticesGuide.ashx?la=en.
National Research Council, 2002: *Riparian areas: functions and strategies for management*. National Academies Press, Press, T. N. A., Wahsington, D.C. Available at: https://doi.org/10.17226/10327.
National Research Council of Canada, 2021: *National guide for wildland-urban-interface fires: Guidance on hazard and exposure assessment, property protection, community resilience and emergency planning to minimize the impact of wildland-urban interface fires*. ISBN 9780660363080.
National Tribal Air Association, 2021: *Status of Tribal Air Report 2021*. Available at: https://secureservercdn.net/198.71.233.47/7vv.611.myftpupload.com/wp-content/uploads/2021/05/2021-NTAA-Status-of-Tribal-Air-Report.pdf.
Natural Resources Canada, 2018: *The State of Canada's Forests: Annual Report*. Canada, N. R., Ottawa, 80 pp. Available at: https://cfs.nrcan.gc.ca/publications/download-pdf/39336.
Natural Resources Canada, 2021: Cost of wildland fire protection, Natural Resources Canada. Available at: https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/forest-change-indicators/cost-fire-protection/17783.
Natural Resources Conservation Service, 2008: U.S. General Soil Map (STATSGO2), United States Department of Agriculture. Available at: http://soildatamart.nrcs.usda.gov.
Návar, J., 2015: Hydro-climatic variability and perturbations in Mexico's north-western temperate forests. *Ecohydrology*, **8**(6), 1065-1072, doi:10.1002/eco.1564.
Navarro-Espinoza, S. et al., 2021: Effects of Untreated Drinking Water at Three Indigenous Yaqui Towns in Mexico: Insights from a Murine Model. *International Journal of Environmental Research and Public Health*, **18**(2), doi:10.3390/ijerph18020805.
Navarro-Estupinan, J. et al., 2018: Observed trends and future projections of extreme heat events in Sonora, Mexico. *INTERNATIONAL JOURNAL OF CLIMATOLOGY*, **38**(14), 5168-5181, doi:10.1002/joc.5719.
Nawrotzki, R. J., J. DeWaard, M. Bakhtsiyarava and J. T. Ha, 2017: Climate shocks and rural-urban migration in Mexico: exploring nonlinearities and thresholds. *Climatic Change*, **140**(2), 243-258, doi:10.1007/s10584-016-1849-0.
Nawrotzki, R. J., L. M. Hunter, D. M. Runfola and F. Riosmena, 2015a: Climate change as a migration driver from rural and urban Mexico. *Environmental Research Letters*, **10**(11), 114023, doi:10.1088/1748-9326/10/11/114023.

Nawrotzki, R. J., L. M. Hunter, D. M. Runfola and F. Riosmena, 2015b: Climate Change as Migration Driver from Rural and Urban Mexico. *Environ. Res. Lett.*, **10**(11), doi:10.1088/1748-9326/10/11/114023.
Nawrotzki, R. J., F. Riosmena, L. M. Hunter and D. M. Runfola, 2015c: Amplification or suppression: Social networks and climate change-migration association in rural Mexico. *Global Environmental Change*, **35**, 463-474.
Nawrotzki, R. J., D. M. Runfola, L. M. Hunter and F. Riosmena, 2016: Domestic and International Climate Migration from Rural Mexico. *Human Ecology*, **44**(6), 687-699, doi:10.1007/s10745-016-9859-0.
Nelson, M. K. and D. Shilling, 2018: *Traditional ecological knowledge: Learning from Indigenous practices for environmental sustainability*. Cambridge University Press, New York, NY, US. ISBN 9781108552998.
Neumann, J. E. et al., 2015: Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, **131**(1), 97-109.
New York City, 2015: New York City Panel on Climate Change 2015 Report Executive Summary. *Annals of the New York Academy of Sciences*, **1336**(1), 9-17, doi:https://doi.org/10.1111/nyas.12591.
Newbold, A. F. et al., 2019: Port of Los Angeles Sea Level Rise Adaptation Plan. In: *Ports 2019*, pp. 89-100.
Ng, A. K. Y. et al., 2018: Implications of climate change for shipping: Opening the Arctic seas. *Wiley Interdisciplinary Reviews: Climate Change*, **9**(2), e507-e507, doi:10.1002/wcc.507.
Ng, V. et al., 2017: Assessment of the probability of autochthonous transmission of chikungunya virus in Canada under recent and projected climate change. *Environmental Health Perspectives*, **125**(6), 067001, doi:10.1289/EHP669.
Nicholls, R. J. et al., 2018: Stabilization of global temperature at 1.5 C and 2.0 C: implications for coastal areas. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160448.
Nielsen-Gammon, J. W. et al., 2020: Unprecedented Drought Challenges for Texas Water Resources in a Changing Climate: What Do Researchers and Stakeholders Need to Know? *Earths Future*, **8**(8), doi:10.1029/2020ef001552.
NIFC, 2021: Suppression Costs, National Interagency Fire Center. Available at: https://www.nifc.gov/fire-information/statistics/suppression-costs.
NOAA, 2021: Coral Reef Watch, NOAA. Available at: https://coralreefwatch.noaa.gov/satellite/analyses_guidance/global_coral_bleaching_2014-17_status.php.
NOAA, 2019: US billion-dollar weather and climate disasters. *Disaster Prevention and Management: An International Journal*, **15**(4).
NOAA, US billion-dollar weather and climate disasters, National Centers for Environmental Information. Available at: https://www.ncdc.noaa.gov/billions.
NOAA National Weather Service, 2017: *Summary of natural hazard statistics for 2016 in the United States*. NOAA, 6 pp. Available at: https://www.weather.gov/media/hazstat/sum16.pdf
Nolan, C. et al., 2018: Past and future global transformation of terrestrial ecosystems under climate change. **361**(6405), 920-923, doi:10.1126/science.aan5360 %J Science.
Nordgren, J., M. Stults and S. Meerow, 2016: Supporting local climate change adaptation: Where we are and where we need to go. *Environ. Sci. Policy*, **66**, 344-352, doi:10.1016/j.envsci.2016.05.006.
Norgaard, K. M. and W. Tripp, 2019: *Karuk Climate Adaptation Plan*. Karul Tribe. Available at: https://karuktribeclimatechangeprojects.files.wordpress.com/2019/08/final-karuk-climate-adaptation-plan_july2019.pdf.
Norton-Smith, K. et al., 2016a: *Climate change and indigenous peoples: a synthesis of current impacts and experiences*. U.S. Department of Agriculture, F. S. P. N. R. S., Portland, OR, 136 pp.
Norton-Smith, K. et al., 2016b: *Climate change and Indigenous Peoples: A synthesis of current impacts and experiences.* . U.S. Department of Agriculture, Portland, OR, US, 136 pp. Available at: https://www.fs.fed.us/pnw/pubs/pnw_gtr944.pdf.
NRTEE, 2011: *Paying the Price: The Economic Impacts of Climate Change for Canada*. Economy, N. R. T. o. t. E. a. t., Ottawa, Ontario, Canada, 168 pp. Available at: http://nrt-trn.ca/wp-content/uploads/2011/09/paying-the-price.pdf.
Nursey-Bray, M., R. Palmer, T. F. Smith and P. Rist, 2019: Old ways for new days: Australian Indigenous peoples and climate change. *Local Environment*, **24**(5), 473-486, doi:10.1080/13549839.2019.1590325.
NYC, 2013: *A Stronger, More Resilient New York*. York, T. C. o. N., NY, NY, 445 pp. Available at: http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Lo_res.pdf.
NYC Mayor's Office of Resiliency, 2020: *Climate Resiliency Design Guidelines*. NYC Mayor's Office of Resiliency, NY, NY, 72 pp. Available at: https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v4-0.pdf.
Nyland, K. E. et al., 2017: Traditional Iñupiat ice cellars (SIĠḶUAQ) in Barrow, Alaska: Characteristics, temperature monitoring, and distribution. *Geographical Review*, **107**(1), 143-158, doi:10.1111/j.1931-0846.2016.12204.x.
O'Neil, S. J. and S. Cairns, 2017: *Defining and scoping municipal natural assets*. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiY4Zfv3PTyAhUIFjQIHZ7qAkMQFnoECAQQAQ&url=https%3A%2F%2Fwww.assetmanagementbc.ca%2Fwp-content%2Fuploads%2Fdefiningscopingmunicipalnaturalcapital-final-15mar2017.pdf&usg=AOvVaw33tgp0TYhy8HHQaPuqjYB4.
O'Reilly, C. M. et al., 2015: Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, **42**(24), 10,773-710,781, doi:10.1002/2015gl066235.

O'Connor, R. C. et al., 2020: Small-scale water deficits after wildfires create long-lasting ecological impacts. *Environmental Research Letters*, **15**(4), 044001, doi:10.1088/1748-9326/ab79e4.
Obradovich, N., R. Migliorini, M. P. Paulus and I. Rahwan, 2018: Empirical evidence of mental health risks posed by climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(43), 10953-10958, doi:10.1073/pnas.1801528115.
Obrist, B., C. Pfeiffer and R. Henley, 2010: Multi-layered social resilience: a new approach in mitigation research. *Progress in Development Studies*, **10**(4), 283-293.
OECD, 2015: *The Economic Consequences of Climate Change*.
Office of the Auditor General of Canada, 2016: *Spring 2016: Reports of the Commissioner of the Environment and Sustainable Development, Report 2: Mitigating the impacts of Severe Weather Events*. 24-24 pp. Available at: https://www.oag-bvg.gc.ca/internet/English/parl_cesd_201605_02_e_41381.html.
Ogden, N. H. et al., 2014: Estimated effects of projected climate change on the basic reproductive number of the Lyme disease vector Ixodes scapularis. *Environmental Health Perspectives*, **122**(6), 631-638, doi:10.1289/ehp.1307799.
Olds, H. T. et al., 2018: High levels of sewage contamination released from urban areas after storm events: A quantitative survey with sewage specific bacterial indicators. *PLoS Medicine*, **15**(7), e1002614, doi:10.1371/journal.pmed.1002614.
Olsen, R., 2015: *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate*. American Society of Civil Engineers, Reston, VA, 93 pp. ISBN 9780784479193.
Olsson, L. et al., 2014: Livelihoods and poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793-832.
Oneida Nation Pre-Disaster Mitigation Plan Steering Committee and Bay-Lake Regional Planning Commission, 2016: *Oneida Nation - 2015-20 Pre-Disaster Mitigation Plan*. Available at: https://baylakerpc.org/application/files/7915/2830/1159/oneida_nation_haz_plan_update_final.pdf.
Oremus, K. L., 2019: Climate variability reduces employment in New England fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(52), 26444-26449, doi:10.1073/pnas.1820154116.
Oreskes, N., 2004: The scientific consensus on climate change. *Science*, **306**(5702), 1686-1686.
Oreskes, N. and E. M. Conway, 2011: *Merchants of doubt: How a handful of scientists obscured the truth on issues from tobacco smoke to global warming*. Bloomsbury Publishing USA. ISBN 1608193942.
Ortega-Gaucin, D., J. D. Bartolon and H. V. C. Bahena, 2018: Drought Vulnerability Indices in Mexico. *Water*, **10**(11), doi:10.3390/w10111671.
Ortiz-Bobea, A. et al., 2021: Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change*, **11**(4), 306-312, doi:10.1038/s41558-021-01000-1.
Ortiz-Colón, G. et al., 2018: Assessing climate vulnerabilities and adaptive strategies for resilient beef and dairy operations in the tropics. *Climatic Change*, **146**(1-2), 47-58, doi:10.1007/s10584-017-2110-1.
Ortiz-Jiménez, M. A., 2018: Quantitative evaluation of the risk of Vibrio parahaemolyticus through consumption of raw oysters (Crassostrea corteziensis) in Tepic, Mexico, under the RCP2.6 and RCP8.5 climate scenarios at different time horizons. *Food Research International*, **111**, 111-119, doi:10.1016/j.foodres.2018.05.012.
Østhagen, 2020: Fish, Not Oil, at the Heart of (Future) Arctic Resource Conflicts. In: *Arctic Yearbook 2020* [Heininen, L., H. Exner-Pirot and J. Barnes (eds.)]. Arctic Portal, Akureyri, Iceland, pp. 43-59.
Oswal, U., 1991: *Estrategias de supervivencia en la Ciudad de México*. Universidad Nacional Autónoma de México, Mexico City.
Otkin, J. A. et al., 2018: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, **99**(5), 911-919, doi:10.1175/BAMS-D-17-0149.1.
Otto, I. M. et al., 2020: Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(5), 2354-2365, doi:10.1073/pnas.1900577117.
Oulahen, G. et al., 2018: Barriers and Drivers of Planning for Climate Change Adaptation across Three Levels of Government in Canada. *Planning Theory & Practice*, **19**(3), 405-421, doi:10.1080/14649357.2018.1481993.
Overpeck, J. T. and B. Udall, 2020: Climate change and the aridification of North America COMMENT. *Proceedings of the National Academy of Sciences of the United States of America*, **117**(22), 11856-11858, doi:10.1073/pnas.2006323117.
Palacios-Abrantes, J., U. R. Sumaila and W. W. L. Cheung, 2020: Challenges to transboundary fisheries management in North America under climate change. *Ecology and Society*, **25**(4), art41-art41, doi:10.5751/ES-11743-250441.
Palaiologou, P. et al., 2019: Social vulnerability to large wildfires in the western USA. *Landscape and Urban Planning*, **189**, 99-116.
Palko, K. and D. S. Lemmen, 2017: *Climate risks and adaptation practices for the Canadian transportation sector 2016*. Canada, G. o. Available at: https://trid.trb.org/view/1483889.
Paredes-Tavares, J. et al., 2018: Impacts of Climate Change on the Irrigation Districts of the Rio Bravo Basin. *Water*, **10**(3).

Parisien, M.-A. et al., 2020: Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nature Communications*, **11**(1), 1-9.
Parker, A. and Z. Grossman, 2012: *Asserting native resilience: Pacific rim Indigenous nations face the climate change*. Oregon State University Press, Corbalis, OR, US.
Parker, L. E., A. J. McElrone, S. M. Ostoja and E. J. Forrestel, 2020: Extreme heat effects on perennial crops and strategies for sustaining future production. *Plant Science*, **295**, 110397, doi:https://doi.org/10.1016/j.plantsci.2019.110397.
Parks, S. A. and J. T. Abatzoglou, 2020: Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, **47**(22), e2020GL089858.
Parks, S. A., S. Z. Dobrowski, J. D. Shaw and C. Miller, 2019: Living on the edge: trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere*, **10**(3), 17, doi:10.1002/ecs2.2651.
Parlee, B. L., E. Goddard, Ł. K. é. D. F. Nation and M. Smith, 2014: Tracking change: Traditional knowledge and monitoring of wildlife health in Northern Canada. *Human Dimensions of Wildlife*, **19**(1), 47-61, doi:10.1080/10871209.2013.825823.
Parlee, C. and M. Wiber, 2018: Using conflict over risk management in the marine environment to strengthen measures of governance. *Ecol. Soc.*, **23**(4), doi:10.5751/ES-10334-230405.
Parris, A. S. et al., 2016: *Climate in context: science and society partnering for adaptation*. John Wiley & Sons. ISBN 1118474791.
Partain, J. L., Jr. et al., 2017: An Assessment of the Role of Anthropogenic Climate Change in the Alaska Fire Season of 2015. *Bulletin of the American Meteorological Society*, **97**(12), S14-S18, doi:10.1175/bams-d-16-0149.1.
Patrick, R., 2018: Adapting to climate change through source water protection: Case studies from Alberta and Saskatchewan, Canada. *International Indigenous Policy Journal*, **9**(3), doi:10.18584/iipj.2018.9.3.1.
Patricola, C. M. and M. F. Wehner, 2018: Anthropogenic influences on major tropical cyclone events. *Nature*, **563**(7731), 339-346, doi:10.1038/s41586-018-0673-2.
Paul, M. J., R. Coffey, J. Stamp and T. Johnson, 2019a: A Review of Water Quality Responses to Air Temperature and Precipitation Changes 1: Flow, Water Temperature, Saltwater Intrusion. *JAWRA Journal of the American Water Resources Association*, **55**(4), 824-843.
Paul, S., D. Ghebreyesus and H. O. Sharif, 2019b: Brief Communication: Analysis of the Fatalities and Socio-Economic Impacts Caused by Hurricane Florence. *GEOSCIENCES*, **9**(2), doi:10.3390/geosciences9020058.
Pauloo, R. A. et al., 2020: Domestic well vulnerability to drought duration and unsustainable groundwater management in California's Central Valley. *Environmental Research Letters*, **15**(4), doi:10.1088/1748-9326/ab6f10.
Payne, T. R., 2020: IN (NOT SO) DEEP WATER: THE TEXAS–NEW MEXICO WATER WAR AND THE UNWORKABLE PROVISIONS OF THE RIO GRANDE COMPACT. *Texas Tech Law Review*, **52**, 669-703, doi:https://dx.doi.org/10.2139/ssrn.3327529.
Peacock, M. B. et al., 2018: Blurred lines: Multiple freshwater and marine algal toxins at the land-sea interface of San Francisco Bay, California. *Harmful Algae*, **73**, 138-147, doi:10.1016/j.hal.2018.02.005.
Pearce, T., J. D. Ford, A. Caron and B. P. Kudlak, 2012: Climate change adaptation planning in remote, resource-dependent communities: an Arctic example. *Regional Environ. Change*, **12**(4), 825-837, doi:10.1007/s10113-012-0297-2.
Pearce, W., S. Niederer, S. M. Özkula and N. Sánchez Querubín, 2019: The social media life of climate change: Platforms, publics, and future imaginaries. *WIREs Climate Change*, **10**(2), e569, doi:https://doi.org/10.1002/wcc.569.
Pearson, A. R., M. T. Ballew, S. Naiman and J. P. Schuldt, 2017: *Race, class, gender and climate change communication*. Oxford research encyclopedia of climate science, Press, O. U., 26 pp. Available at: https://oxfordre.com/climatescience/view/10.1093/acrefore/9780190228620.001.0001/acrefore-9780190228620-e-412.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355**(6332), doi:10.1126/science.aai9214.
Pedrozo Acuña, A., 2012: *Impactos del incremento en el nivel medio del mar en la zona costera del estado de Campeche, México*. 90 pp. Available at: https://play.google.com/store/books/details?id=P4N9oAEACAAJ
https://books.google.com/books/about/Impactos_del_incremento_en_el_nivel_medi.html?hl=&id=P4N9oAEACAAJ.
Pendakur, K., 2017: *Northern Territories* [Palko, K. and D. S. Lemmen (eds.)]. Climate risks and adaptation practices for the Canadian transportation sector, Government of Canada, Ottawa, ON, 27-64 pp. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiNg7P73vTyAhVbHzQIHe3MB4MQFnoECAIQAQ&url=https%3A%2F%2Fwww.nrcan.gc.ca%2Fsites%2Fwww.nrcan.gc.ca%2Ffiles%2Fearthsciences%2Fpdf%2Fassess%2F2016%2FChapter-3e.pdf&usg=AOvVaw1THBkF7993TvZu5ReWKRyV.
Pershing, A. et al., 2018: Chapter 9 : Oceans and Marine Resources. Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II. doi:10.7930/nca4.2018.ch9.
Peterson St-Laurent, G., L. E. Oakes, M. Cross and S. Hagerman, 2021: R–R–T (resistance–resilience–transformation) typology reveals differential conservation approaches across ecosystems and time. *Communications Biology*, **4**(1), 39, doi:10.1038/s42003-020-01556-2.

Petkova, E. P. et al., 2014: Heat-related mortality in a warming climate: Projections for 12 U.S. cities. *International Journal of Environmental Research and Public Health*, **11**(11), 11371-11383, doi:10.3390/ijerph111111371.
Petrasek MacDonald, J. et al., 2013: A necessary voice: Climate change and lived experiences of youth in Rigolet, Nunatsiavut, Canada. *Global Environmental Change*, **23**(1), 360-371, doi:10.1016/j.gloenvcha.2012.07.010.
Petrovic, N., T. Simpson, B. Orlove and B. Dowd-Uribe, 2019: Environmental and social dimensions of community gardens in East Harlem. *Landscape and Urban Planning*, **183**(October 2018), 36-49, doi:10.1016/j.landurbplan.2018.10.009.
Pfeiffer, J. M. and E. Huerta Ortiz, 2007: Invasive plants impact California native plants used in traditional basketry. *Journal of California Native Plant Society*, **35**(1), 7-13.
Pfeiffer, J. M. and R. A. Voeks, 2008: Biological invasions and biocultural diversity: Linking ecological and cultural systems. *Environmental Conservation*, **35**(4), 281-293, doi:10.1017/S0376892908005146.
Phelps, M., 2019: Increasing eDNA capabilities with CRISPR technology for real-time monitoring of ecosystem biodiversity. *Molecular Ecology Resources*, **19**(5), 1103-1105, doi:https://doi.org/10.1111/1755-0998.13084.
Phillips, J., 2016: Climate change and surface mining : A review of environment-human interactions & their spatial dynamics. *Appl. Geogr.*, **74**, 95-108, doi:10.1016/j.apgeog.2016.07.001.
Piatt, J. F. et al., 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. *PloS one*, **15**(1), e0226087.
Pierotti, R. and D. Wildcat, 2000: Traditional ecological knowledge: The third alternative (commentary). *Ecological Applications*, **10**(5), 1333-1340, doi:10.2307/2641289.
Pinsky, M. L. and D. Byler, 2015: Fishing, fast growth and climate variability increase the risk of collapse. *Proceedings of the Royal Society B: Biological Sciences*, **282**(1813), 1-9, doi:10.1098/rspb.2015.1053.
Pinsky, M. L., G. Guannel and K. K. Arkema, 2013a: Quantifying wave attenuation to inform coastal habitat conservation. *Ecosphere*, **4**(8), art95, doi:10.1890/es13-00080.1.
Pinsky, M. L. et al., 2018: Preparing ocean governance for species on the move. *Science*, **360**(6394), 1189-1191, doi:10.1126/science.aat2360.
Pinsky, M. L. et al., 2013b: Marine taxa track local climate velocities. *Science*, **341**(6151), 1239-1242, doi:10.1126/science.1239352.
Pitt, J. and E. Kendy, 2017: Shaping the 2014 Colorado River Delta pulse flow: Rapid environmental flow design for ecological outcomes and scientific learning. *Ecological Engineering*, **106**, 704-714, doi:10.1016/j.ecoleng.2016.12.002.
Pizzolato, L. et al., 2016: The influence of declining sea ice on shipping activity in the Canadian Arctic. *Geophys. Res. Lett.*, **43**, 12,146-112,154, doi:10.1002/2016GL071489.
Plummer, R., 2013: Can Adaptive Comanagement Help to Address the Challenges of Climate Change Adaptation? *Ecology and Society*, **18**(4), doi:10.5751/es-05699-180402.
Podschwit, H. and A. Cullen, 2020: Patterns and trends in simultaneous wildfire activity in the United States from 1984 to 2015. *International Journal of Wildland Fire*.
Podur, J. and M. Wotton, 2010: Will climate change overwhelm fire management capacity? *Ecological modelling*, **221**(9), 1301-1309.
Poe, A., T. Van Pelt and J. Littell, 2016: *The Aleutian-Bering Climate Vulnerability Assessment. Final Report.*, Cooperative, A. a. B. S. I. L. C., Anchorage, AK, 151 pp. Available at: https://www.sciencebase.gov/catalog/item/5a554be9e4b01e7be242bf0b.
Poesch, M. S. et al., 2016: Climate Change Impacts on Freshwater Fishes: A Canadian Perspective. *Fisheries*, **41**(7), 385-391, doi:10.1080/03632415.2016.1180285.
Poff, N. L., 2019: A river that flows free connects up in 4D. *Nature*, **569**(7755), 201-202, doi:10.1038/d41586-019-01393-2.
Polley, H. W. et al., 2013: Climate Change and North American Rangelands: Trends, Projections, and Implications. *Rangeland Ecology & Management*, **66**(5), 493-511, doi:10.2111/rem-d-12-00068.1.
Poloczanska, E. S. et al., 2016: Responses of Marine Organisms to Climate Change across Oceans. *Front. Mar. Sci.*, **3**, 515, doi:10.3389/fmars.2016.00062.
Polovina, J. J., J. P. Dunne, P. A. Woodworth and E. A. Howell, 2011: Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES J. Mar. Sci.*, **68**(6), 986-995, doi:10.1093/icesjms/fsq198.
Pomara, L. Y., O. E. LeDee, K. J. Martin and B. Zuckerberg, 2014: Demographic consequences of climate change and land cover help explain a history of extirpations and range contraction in a declining snake species. *Global Change Biology*, **20**(7), 2087-2099, doi:10.1111/gcb.12510.
Port Gamble S'klallam Tribe, 2016: *2015 Puget Sound Coho Fishery Disaster for the Port S'Klallam Tribe*. Available at: https://media.fisheries.noaa.gov/dam-migration/68_puget_coho_request_portgamble_noaa-sf.pdf.
Port Gamble S'klallam Tribe, 2020: *2019 Frasier River Sockeye and 2019 Puget Sound Coho and Chum Fishery Disasters for the Port Gamble S'Klallam Tribe*. Available at: https://s3.amazonaws.com/media.fisheries.noaa.gov/2020-10/PortGamble_combined.pdf?null.
Port Gamble S'klallam Tribe, 2021: *2020 Fraser River Sockeye Fishery and Puget Sound Fall Chum Disaster for the Port Gamble S'Klallam Tribe*. Available at: https://s3.amazonaws.com/media.fisheries.noaa.gov/2020-10/PortGamble_combined.pdf?null.

Porter, J. J. and K. Birdi, 2018: 22 reasons why collaborations fail: Lessons from water innovation research. *Environ. Sci. Policy*, **89**, 100-108, doi:10.1016/j.envsci.2018.07.004.
Poushter, J. and C. Huang, 2019: *Climate Change Still Seen as the Top Global Threat, but Cyberattacks a Rising Concern*. Pew Research Center. Available at: https://www.pewresearch.org/global/2019/02/10/climate-change-still-seen-as-the-top-global-threat-but-cyberattacks-a-rising-concern/.
Powless, B., 2012: An Indigenous movement to confront climate change. *Globalizations*, **9**(3), 411-424.
Preece, E. P. et al., 2021: Prevalence and persistence of microcystin in shoreline lake sediments and porewater, and associated potential for human health risk. *Chemosphere*, **272**, 129581, doi:10.1016/j.chemosphere.2021.129581.
Prein, A. F. et al., 2016: Running dry: The US Southwest's drift into a drier climate state. *Geophysical Research Letters*, **43**(3), 1272-1279, doi:10.1002/2015gl066727.
Prein, A. F. et al., 2017a: Increased rainfall volume from future convective storms in the US. *Nat. Clim. Chang.*, **7**(12), 880-+, doi:10.1038/s41558-017-0007-7.
Prein, A. F. et al., 2017b: The future intensification of hourly precipitation extremes. *Nature Climate Change*, **7**(1), 48-+, doi:10.1038/nclimate3168.
Preston, D. L. et al., 2016: Climate regulates alpine lake ice cover phenology and aquatic ecosystem structure. *Geophysical Research Letters*, **43**(10), 5353-5360, doi:10.1002/2016gl069036.
Price, J. I. and M. T. Heberling, 2018: The Effects of Source Water Quality on Drinking Water Treatment Costs: A Review and Synthesis of Empirical Literature. *Ecological Economics*, **151**, 195-209, doi:10.1016/j.ecolecon.2018.04.014.
Prober, S. M. et al., 2019: Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. *Ecological Monographs*, **89**(1), e01333, doi:https://doi.org/10.1002/ecm.1333.
Punt, A. E. et al., 2021: Evaluating the impact of climate and demographic variation on future prospects for fish stocks: An application for northern rock sole in Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, **189-190**, 104951-104951, doi:10.1016/j.dsr2.2021.104951.
Punt, A. E. et al., 2016: Effects of long-term exposure to ocean acidification conditions on future southern Tanner crab (Chionoecetes bairdi) fisheries management. *ICES Journal of Marine Science: Journal du Conseil*, **73**(3), 849-864, doi:10.1093/icesjms/fsv205.
Puyallup Tribe of Indians, 2016: *Climate Change Impact Assessment and Adaptation Options*. A collaboration of the Puyallup Tribe of Indians and Cascadia Consulting Group. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiJ4OPL3_TyAhXtHjQIHY69AXgQFnoECAQQAQ&url=http%3A%2F%2Fwww.puyallup-tribe.com%2FtempFiles%2FPuyallupClimateChangeImpactAssessment_2016_FINAL_pages.pdf&usg=AOvVaw20wRMSPV0rqGbpAw2HgILN.
Qian, B. et al., 2019: Climate change impacts on Canadian yields of spring wheat, canola and maize for global warming levels of 1.5 °c, 2.0 °c, 2.5 °c and 3.0 °c. *Environmental Research Letters*, **14**(7), doi:10.1088/1748-9326/ab17fb.
Quinault Indian Nation, 2017: *Taholah Village Relocation Master Plan*. Available at: http://www.quinaultindiannation.com/planning/FINAL_Taholah_Relocation_Plan.pdf.
Quintana, V., 2013: Nuevo orden alimentario y disputa por el agua en el norte de México. *Apuntes*, **XL**(73), 175-202.
Quinton, W. et al., 2019: A synthesis of three decades of hydrological research at Scotty Creek, NWT, Canada. *Hydrology and Earth System Sciences*, **23**(4), 2015-2039, doi:10.5194/hess-23-2015-2019.
Quispe, M. E. C. and UNPFII, 2015: *Study on the treatment of traditional knowledge in the framework of the United Nations Declaration on the Rights of Indigenous Peoples and the post-2015 development agenda*. United Nations Permanent Forum on Indigenous Issues, New York, NY, US. Available at: https://digitallibrary.un.org/record/788550.
Radke, E. G., A. Reich and J. G. Morris, 2015: Epidemiology of ciguatera in Florida. *American Journal of Tropical Medicine and Hygiene*, **93**(2), 425-432, doi:10.4269/ajtmh.14-0400.
Radonic, L., 2017: Through the aqueduct and the courts: An analysis of the human right to water and indigenous water rights in Northwestern Mexico. *Geoforum*, **84**, 151-159, doi:10.1016/j.geoforum.2017.06.014.
Rakocinski, C. F. and D. P. Menke, 2016: Seasonal hypoxia regulates macrobenthic function and structure in the Mississippi Bight. *Mar. Pollut. Bull.*, **105**(1), 299-309, doi:10.1016/j.marpolbul.2016.02.006.
Ranasinghe, R. et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Ranson, M., 2014: *Crime, Weather, and Climate Change*. Harvard Kennedy School M-RCBG Associate Working Paper Series Available at: http://dx.doi.org/10.2139/ssrn.2111377.
Rapinski, M. et al., 2018: Inuit perception of marine organisms: From folk classification to food harvest. *Journal of Ethnobiology*, **38**(3), 333-355, doi:10.2993/0278-0771-38.3.333.
Rappold, A. G. et al., 2012: Cardio-respiratory outcomes associated with exposure to wildfire smoke are modified by measures of community health. *Environmental Health*, **11**, 71, doi:10.1186/1476-069X-11-71.
Rappold, A. G. et al., 2017: Community vulnerability to health impacts of wildland fire smoke exposure. *Environmental Science and Technology*, **51**(12), 6674-6682, doi:10.1021/acs.est.6b06200.

Ray, D. K. et al., 2019: Climate change has likely already affected global food production. *PLoS One*, **14**(5), e0217148-e0217148, doi:10.1371/journal.pone.0217148
10.1371/journal.pone.0217148. eCollection 2019.

Ray, P. et al., 2020: Vulnerability and risk: climate change and water supply from California's Central Valley water system. *Climatic Change*, **161**(1), 177-199, doi:10.1007/s10584-020-02655-z.

Raymond-Yakoubian, J. and R. Daniel, 2018: An Indigenous approach to ocean planning and policy in the Bering Strait region of Alaska. **97**(September), 101-108, doi:10.1016/j.marpol.2018.08.028.

Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: An urban perspective. *Environ. Urban.*, **29**(1), 159-182, doi:10.1177/0956247816677778.

Record, N. et al., 2019: Rapid Climate-Driven Circulation Changes Threaten Conservation of Endangered North Atlantic Right Whales. *Oceanography*, **32**(2), doi:10.5670/oceanog.2019.201.

Redmond, L. E., 2018: Alpine limnology of the Rocky Mountains of Canada and the USA in the context of environmental change. *Environmental Reviews*, **26**(3), 231-238, doi:10.1139/er-2017-0046.

Redsteer, M. H., K. B. Kelley, H. Francis and D. Block, 2013: Increasing vulnerability of the Navajo people to drought and climate change in the southwestern United States: Accounts from Tribal Elders. In: *Indigenous Knowledge for Climate Change Assessment and Adaptation*. Cambridge University Press, Cambridge, pp. 171-187.

Redsteer, M. H., K. B. Kelley, F. Harris and D. Block, 2018: Accounts from tribal elders: Increasing vulnerability of the Navajo people to drought and climate change in the southwestern United States. In: *Indigenous knowledge for climate change assessment and adaptation* [Nakashima, D. and J. T. Rubius (eds.)]. Cambridge University Press, Cambridge, UK, pp. 171-187.

Reeves, M. C., A. L. Moreno, K. E. Bagne and S. W. Running, 2014: Estimating climate change effects on net primary production of rangelands in the United States. *Climatic Change*, **126**(3-4), 429-442, doi:10.1007/s10584-014-1235-8.

Regional Municipality of Wood Buffalo, 2016: *RMWB 2016 Wildfire Recovery Plan*. Available at: http://asset.rmwb.ca/files/RMWB-2016-Wildfire-Recovery-Plan.pdf.

Reguero, B. G. et al., 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS One*, **13**(4), e0192132, doi:10.1371/journal.pone.0192132.

Reich, R. M., J. E. Lundquist and K. Hughes, 2016: Host-environment mismatches associated with subalpine fir decline in Colorado. *Journal of Forestry Research*, **27**(5), 1177-1189, doi:10.1007/s11676-016-0234-1.

Reid, C. E. et al., 2016: Differential respiratory health effects from the 2008 northern California wildfires: A spatiotemporal approach. *Environmental Research*, **150**, 227-235, doi:10.1016/j.envres.2016.06.012.

Reid, G. K. et al., 2019: Climate change and aquaculture: considering adaptation potential. *Aquaculture Environment Interactions*, **11**, 603-624.

Reo, N. J. and L. A. Ogden, 2018: Anishnaabe Aki: an Indigenous perspective on the global threat of invasive species. *Sustainability Science*, **13**(5), 1443-1452, doi:10.1007/s11625-018-0571-4.

Report of the Climate-Related Market Risk Subcommittee, M. R. A. C. o. t. U. C. F. T. C., 2020: Managing Climate Risk in the U.S. Financial System. https://www.cftc.gov/sites/default/files/2020-09/9-9-20%20Report%20of%20the%20Subcommittee%20on%20Climate-Related%20Market%20Risk%20-%20Managing%20Climate%20Risk%20in%20the%20U.S.%20Financial%20System%20for%20posting.pdf?utm_source=Resources+for+the+Future&utm_campaign=446310f72b-EMAIL_CAMPAIGN_2020_09_25_07_06&utm_medium=email&utm_term=0_e896179bd7-446310f72b-100217617.

Resiere, D. et al., 2018: Sargassum seaweed on Caribbean islands: an international public health concern. *The Lancet*, **392**(10165), 2691, doi:10.1016/S0140-6736(18)32777-6.

Reum, J. C. P. et al., 2020: Ensemble Projections of Future Climate Change Impacts on the Eastern Bering Sea Food Web Using a Multispecies Size Spectrum Model. *Frontiers in Marine Science*, **7**(March), 1-17, doi:10.3389/fmars.2020.00124.

Reum, J. C. P. et al., 2019: Species-specific ontogenetic diet shifts attenuate trophic cascades and lengthen food chains in exploited ecosystems. *Oikos*, 1-14, doi:10.1111/oik.05630.

Reyer, C. P. O. et al., 2017: Climate change impacts in Latin America and the Caribbean and their implications for development. *Regional Environmental Change*, **17**(6), 1601-1621, doi:10.1007/s10113-015-0854-6.

Reyes, J. J. and E. Elias, 2019: Spatio-temporal variation of crop loss in the United States from 2001 to 2016. *Environmental Research Letters*, **14**(7), 074017-074017, doi:10.1088/1748-9326/ab1ac9.

Rheuban, J. E., M. T. Kavanaugh and S. C. Doney, 2017: Implications of Future Northwest Atlantic Bottom Temperatures on the American Lobster (Homarus americanus) Fishery. *Journal of Geophysical Research: Oceans*, **122**(12), 9387-9398, doi:10.1002/2017jc012949.

Richards, C. E., R. C. Lupton and J. M. Allwood, 2021: Re-framing the threat of global warming: an empirical causal loop diagram of climate change, food insecurity and societal collapse. *Climatic Change*, **164**(3), 49, doi:10.1007/s10584-021-02957-w.

Richter, B., E. Powell, T. Lystash and M. Faggert, 2016: Protection and Restoration of Freshwater Ecosystems. *Water Policy and Planning in a Variable and Changing Climate*, 81-105, doi:10.1201/b19534-8.

Riley, R. et al., 2011: *Oklahoma inter-tribal meeting on climate variability and change. Meeting summary report*. National Weather Centre, Norman, OK. Available at: http://www.southernclimate.org/publications/Oklahoma_Intertribal_Climate_Change_Meeting.pdf.
Rioja-Rodríguez, H., M. L. Quezada-Jiménez, P. Zúñiga-Bello and M. Hurtado-Díaz, 2018: Climate change and potential health effects in Mexican children. *Annals of Global Health*, **84**(2), 281-284, doi:10.29024/aogh.915.
Risser, M. D. and M. F. Wehner, 2017: Attributable Human-Induced Changes in the Likelihood and Magnitude of the Observed Extreme Precipitation during Hurricane Harvey. *Geophys. Res. Lett.*, **44**(24), 12457-12464, doi:10.1002/2017gl075888.
Ristroph, E. B., 2019: Avoiding maladaptations to flooding and erosion: A case study of Alaska Native Villages. *Ocean and Coastal Law Journal*, **24**(2), 110-135.
Ritchie, H. and M. Roser, 2020: CO_2 and Greenhouse Gas Emissions. OurWorldInData.org.
Ritzman, J. et al., 2018: Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae*, **80**, 35-45, doi:10.1016/j.hal.2018.09.002.
RMJOC, R. M. J. O. C., 2020: *Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies: Second Edition (RMJOC-II) Part II: Columbia River Reservoir Regulation and Operations -- Modeling and Analyses* River Management Joint Operating Committee., Portland, OR. Available at: https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/9936/rec/7.
Roberts, C. M. et al., 2017a: Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences*, **114**(24), 6167-6175, doi:10.1073/pnas.1701262114.
Roberts, J. J., K. D. Fausch, T. S. Schmidt and D. M. Walters, 2017b: Thermal regimes of Rocky Mountain lakes warm with climate change. *PLoS One*, **12**(7), e0179498, doi:10.1371/journal.pone.0179498.
Robertson, C., R. McLeman and H. Lawrence, 2015: Winters too warm to skate? Citizen-science reported variability in availability of outdoor skating in Canada. *Canadian Geographer*, **59**(4), 383-390, doi:10.1111/cag.12225.
Robinne, F.-N., D. W. Hallema, K. D. Bladon and J. M. Buttle, 2020: Wildfire impacts on hydrologic ecosystem services in North American high-latitude forests: A scoping review. *Journal of Hydrology*, **581**, 124360.
Robinson, M. and T. Shine, 2018: *Achieving a climate justice pathway to 1.5 °C. Vol. 8.*
Robinson, R. A. et al., 2009: Travelling through a warming world: climate change and migratory species. *Endanger. Species Res.*, **7**, 87-99, doi:10.3354/esr00095.
Robinson, S. J. et al., 2015: Disease risk in a dynamic environment: the spread of tick-borne pathogens in Minnesota, USA. *EcoHealth*, **12**(1), 152-163, doi:10.1007/s10393-014-0979-y.
Robison, J. et al., 2018: Indigenous Water Justice. *Lewis & Clark Law Review*, **22**(3), 80.
Rockman, M. et al., 2016: *Cultural Resources Climate Change Strategy*. National Park Service, U.S. Department of the Interior, 51 pp. Available at: https://market.android.com/details?id=book-dSUpuwEACAAJ
https://books.google.com/books/about/Cultural_Resources_Climate_Change_Strate.html?hl=&id=dSUpuwEACAAJ.
Rockström, J. et al., 2021: Royal Swedish Academy of Sciences Sustainable intensification of agriculture for human prosperity and global sustainability Published by : Springer on behalf of Royal Swedish Academy of Sciences Stable URL : https://www.jstor.org/stable/45147911 Sustainable intensification of agriculture for human prosperity and global sustainability.
Rodman, K. C. et al., 2020: A changing climate is snuffing out post-fire recovery in montane forests. *Global Ecology and Biogeography*, **29**, 2039-2051, doi:10.1111/geb.13174.
Rodriguez, A. B. et al., 2014: Oyster reefs can outpace sea-level rise. *Nat. Clim. Chang.*, **4**, 493, doi:10.1038/nclimate2216.
Rogers, J., J. Barba and F. Kinniburgh, 2015: *FROM BOOM TO BUST?CLIMATE RISK IN THE GOLDEN STATE*. Risky Business Project, Project, R. B., 70 pp. Available at: https://riskybusiness.org/site/assets/uploads/2015/09/California-Report-WEB-3-30-15.pdf.
Rogers, L. A. et al., 2019: Shifting habitats expose fishing communities to risk under climate change. *Nature Climate Change*, **9**(7), 512-516, doi:10.1038/s41558-019-0503-z.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163, doi:10.1016/j.crm.2017.02.001.
Roman, S., E. Palmer and M. Brede, 2018: The Dynamics of Human–Environment Interactions in the Collapse of the Classic Maya. *Ecological Economics*, **146**, 312-324, doi:https://doi.org/10.1016/j.ecolecon.2017.11.007.
Romeo-Lankao, P. et al., 2014: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B; Regional Aspects Contribution of Working Group II to the Fiftth Assessment Report of the Intergovernmmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, United Kingdom and New York, NY, USA, pp. 1439-1498.
Romero-Lankao, P., A. Bruns and V. Wiegleb, 2018: From risk to WEF security in the city: The influence of interdependent infrastructural systems. *Environ. Sci. Policy*, doi:10.1016/j.envsci.2018.01.004.
Romero-Lankao, P. et al., 2014a: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439-1498.

Romero-Lankao, P. et al., 2014b: North America. [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439-1498.

Romps, D. M., J. T. Seeley, D. Vollaro and J. Molinari, 2014: Climate change. Projected increase in lightning strikes in the United States due to global warming. *Science*, **346**(6211), 851-854, doi:10.1126/science.1259100.

Rosenzweig, C. and W. Solecki, 2014: Hurricane Sandy and adaptation pathways in New York: lessons from a first responder city. *Glob. Environ. Change*, **28**, 395–408, doi:10.1016/j.gloenvcha.2014.05.003.

Rosol, R., S. Powell-Hellyer and H. M. Chan, 2016: Impacts of decline harvest of country food on nutrient intake among Inuit in Arctic Canada: impact of climate change and possible adaptation plan. *International Journal of Circumpolar Health*, **75**, 31127, doi:10.3402/ijch.v75.31127.

Ross, A. D., S. M. Rouse and W. Mobley, 2019: Polarization of Climate Change Beliefs: The Role of the Millennial Generation Identity. *Social Science Quarterly*, **100**(7), 2625-2640.

Roy-Dufresne, E. et al., 2013: Poleward expansion of the white-footed mouse (*Peromyscus leucopus*) under climate change: Implications for the spread of Lyme disease. *PLoS ONE*, **8**(11), e80724, doi:10.1371/journal.pone.0080724.

Ruiz Meza, L., 2014: Adaptive capacity of small-scale coffe farmers to climate change impacts in the Soconusco region of Chiapas, Mexico. *Climate and Development*, **7**(2), 100-109, doi:10.1080/17565529.2014.900472.

Ruiz-Ramírez, J. D., J. I. Euán-Ávila and V. H. Rivera-Monroy, 2019: Vulnerability of coastal resort cities to mean sea level rise in the Mexican Caribbean. *Coast. Manage.*, **47**(1), 23-43, doi:10.1080/08920753.2019.1525260.

Runkle, J. D. et al., 2019: Evaluation of wearable sensors for physiologic monitoring of individually experienced temperatures in outdoor workers in southeastern U.S. *Environ. Int.*, **129**, 229-238, doi:10.1016/j.envint.2019.05.026.

Rupp, D. E. et al., 2015: Anthropogenic influence on the changing likelihood of an exceptionally warm summer in Texas, 2011. *Geophysical Research Letters*, **42**(7), 2392-2400.

Rupp, D. E. et al., 2017: Influence of the Ocean and Greenhouse Gases on Severe Drought Likelihood in the Central United States in 2012. *Journal of Climate*, **30**(5), 1789-1806, doi:10.1175/jcli-d-16-0294.1.

Russo, T. A. and U. Lall, 2017: Depletion and response of deep groundwater to climate-induced pumping variability. *Nature Geoscience*, **10**(2), 105-+, doi:10.1038/ngeo2883.

Rutty, M. and D. Scott, 2015: Bioclimatic comfort and the thermal perceptions and preferences of beach tourists. *International Journal of Biometeorology*, **59**(1), 37-45, doi:10.1007/s00484-014-0820-x.

Rutty, M. et al., 2017: Using ski industry response to climatic variability to assess climate change risk : An analogue study in Eastern Canada. *Tourism Manage.*, **58**, 196-204, doi:10.1016/j.tourman.2016.10.020.

Ryan, K. C., A. T. Jones, C. L. Koerner and K. M. Lee, 2012: *Wildland fire in ecosystems: effects of fire on cultural resources and archaeology*. Service, U. F., Fort Collins, CO. Available at: http://dx.doi.org/10.2737/rmrs-gtr-42.

Rykaczewski, R. R. et al., 2015: Poleward displacement of coastal upwelling-favorable winds in the ocean's eastern boundary currents through the 21st century. *Geophysical Research Letters*, **42**(15), 6424-6431, doi:10.1002/2015gl064694.

Sakakibara, C., 2010: Kiavallakkikput agviq (into the whaling cycle): Cetaceousness and climate change among the Iñupiat of Arctic Alaska. *Annals of the Association of American Geographers*, **100**(4), 1003-1012.

Salgado, K. and M. Luisa Martinez, 2017: Is ecosystem-based coastal defense a realistic alternative? Exploring the evidence. *Journal of Coastal Conservation*, **21**(6), 837-848, doi:10.1007/s11852-017-0545-1.

Samhouri, J. F. et al., 2019: An ecosystem-based risk assessment for California fisheries co-developed by scientists , managers , and stakeholders. *Biol. Conserv.*, **231**(December 2018), 103-121, doi:10.1016/j.biocon.2018.12.027.

Sanchez, R., L. Rodriguez and C. Tortajada, 2018: Transboundary aquifers between Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, Mexico, and Texas, USA: Identification and categorization. *Journal of Hydrology-Regional Studies*, **20**, 74-102, doi:10.1016/j.ejrh.2018.04.004.

Sánchez-Cortés, M. S. and E. L. Chavero, 2011: Indigenous perception of changes in climate variability and its relationship with agriculture in a Zoque community of Chiapas, Mexico. *Climatic Change*, **107**(3), 363-389, doi:10.1007/S10584-010-9972-9.

Sanford, E. et al., 2019: Widespread shifts in the coastal biota of northern California during the 2014-2016 marine heatwaves. *Sci. Rep.*, **9**(1), 4216, doi:10.1038/s41598-019-40784-3.

Sankey, J. B. et al., 2017: Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, **44**(17), 8884-8892, doi:10.1002/2017gl073979.

Santos-Lacueva, R., S. A. Clavé and Ò. Saladié, 2018: Case Study Mexico: Riviera Maya - how is the Riviera Maya tourism industry dealing with climate change? An overview of non-climatic stressors that determine the destination's vulnerability to climate change. In: *Global climate change and coastal tourism: recognizing problems, managing solutions and future expectations* [Jones, A. and M. Phillips (eds.)]. CAB International, Online. ISBN 9781780648439.

Santos-Lozada, A. R., M. Kaneshiro, C. McCarter and M. Marazzi-Santiago, 2020: Puerto Rico exodus: long-term economic headwinds prove stronger than Hurricane Maria. *Population and Environment*, **42**(1), 43-56, doi:10.1007/s11111-020-00355-5.
Sarkodie, S. A. and V. Strezov, 2019: Economic, social and governance adaptation readiness for mitigation of climate change vulnerability: Evidence from 192 countries. *Science of The Total Environment*, **656**, 150-164, doi:https://doi.org/10.1016/j.scitotenv.2018.11.349.
Sarofim, M. C. et al., 2016a: *Temperature-realated death and illness*. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, U.S. Global Change Research Program, Washington, DC, 43-68 pp. Available at: http://dx.doi.org/doi:10.7930/J00P0WXS.
Sarofim, M. C. et al., 2016b: Temperature-related death and illness. U.S. Global Change Research Program, Washington, DC, pp. 43-68.
Saros, J. E. et al., 2010: Melting Alpine glaciers enrich high-elevation lakes with reactive nitrogen. *Environ. Sci. Technol.*, **44**(13), 4891-4896, doi:10.1021/es100147j.
Sasmito, S. D., D. Murdiyarso, D. A. Friess and S. Kurnianto, 2016: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecol. Manage.*, **24**(2), 263-278, doi:10.1007/s11273-015-9466-7.
Sato, M. et al., 2016: Impacts of moderate hypoxia on fish and zooplankton prey distributions in a coastal fjord. *Marine Ecology Progress Series*, **560**, 57-72, doi:10.3354/meps11910.
Sauchyn, D., D. Davidson and M. Johnston, 2020: Prairie Provinces. In: *Canada in a changing climate: Regional perspectives report* [Warren, F. J., N. Lulham and D. S. Lemmen (eds.)]. Government of Canada, Ottawa, ON, Canada, pp. 39-46.
Saunders-Hastings, P., M. Bernard and B. Doberstein, 2020: *Planned Retreat Approaches to Support Resilience to Climate Change in Canada* Natural Resources Canada Canada, N. R., Ottawa, Canada, 66 pp. Available at: https://gevityinc.com/sites/default/files/documents/gid_328323.pdf.
Savard, J. P., D. van Proosdij and S. O'Carroll, 2016: *Perspectives on Canada's East Coast region* [Lemmen, D. S., F. J. Warren, T. S. James and C. S. L. Mercer Clarke (eds.)]. Canada's Marine Coasts in a changing climate, Government of Canada, Canada, G. o., Ottawa, ON, 99-152 pp. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj4heeagtjsAhV9FTQIHRW9CicQFjAAegQIAhAC&url=https%3A%2F%2Fwww.nrcan.gc.ca%2Fsites%2Fwww.nrcan.gc.ca%2Ffiles%2Fearthsciences%2Fpdf%2Fassess%2F2016%2FCoastal_Assessment_Chapter4_EastCoastRegion.pdf&usg=AOvVaw3ue1hNG7w8ZvBpkEWgvmi3.
Savo, V. et al., 2016: Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change*, **6**(5), 462-473, doi:10.1038/nclimate2958.
Sawatzky, A. et al., 2021: "It depends…": Inuit-led identification and interpretation of land-based observations for climate change adaptation in Nunatsiavut, Labrador. *Regional Environmental Change*, **21**, 54, doi:10.1007/s10113-021-01772-4.
Sawyer, D., R. Ness, D. Clark and D. Beugin, 2020: *Tip of the Iceberg: Navigating the Known and Unknown Costs of Climate Change for Canada*. Canadian Institute for Climate Choice, 52 pp. Available at: https://climatechoices.ca/wp-content/uploads/2020/12/Tip-of-the-Iceberg-_-CoCC_-Institute_-Full.pdf
Scarano, F. R., 2017: Ecosystem-based adaptation to climate change: concept, scalability and a role for conservation science. *Perspectives in Ecology and Conservation*, **15**(2), 65-73, doi:https://doi.org/10.1016/j.pecon.2017.05.003.
Scheffer, M., 2010: Complex systems: Foreseeing tipping points. *Nature*, **467**(7314), 411-412, doi:10.1038/467411a.
Scheffer, M. et al., 2001: Catastrophic shifts in ecosystems. *Nature*, **413**(6856), 591-596, doi:10.1038/35098000.
Scheffer, M. et al., 2021: Loss of resilience preceded transformations of pre-Hispanic Pueblo societies. *Proceedings of the National Academy of Sciences*, **118**(18), e2024397118, doi:10.1073/pnas.2024397118.
Schell, C. J. et al., 2020: The ecological and evolutionary consequences of systemic racism in urban environments. *Science (New York, N.Y.)*, **369**(6510), doi:10.1126/science.aay4497.
Schenker, O., 2013: Exchanging goods and damages: the role of trade on the distribution of climate change costs. *Environ Resour Econ*, **54**, 261-282.
Schinasi, L. H. and G. B. Hamra, 2017: A Time Series Analysis of Associations between Daily Temperature and Crime Events in Philadelphia, Pennsylvania. *J. Urban Health*, **94**(6), 892-900, doi:10.1007/s11524-017-0181-y.
Schlinger, C. et al., 2021: Water. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 98-141.
Schmidt, A., A. Ivanova and M. S. Schäfer, 2013: Media attention for climate change around the world: A comparative analysis of newspaper coverage in 27 countries. *Global Environmental Change*, **23**(5), 1233-1248, doi:10.1016/j.gloenvcha.2013.07.020.
Schoen, E. R. et al., 2017: Future of Pacific Salmon in the Face of Environmental Change: Lessons from One of the World's Remaining Productive Salmon Regions. *Fisheries*, **42**(10), 538-553, doi:10.1080/03632415.2017.1374251.
Schoeneberger, M. M., G. Bentrup and T. Patel-Weynand, eds, 2017: *Agroforestry: Enhancing resiliency in U.S. agricultural landscapes under changing conditions*. U.S. Department of Agriculture, Forest Service, Washington, DC, 228 pp. Available at: https://www.fs.fed.us/research/publications/gtr/gtr_wo96.pdf.

Schoenefeld, J. J. and M. R. McCauley, 2016: Local is not always better: the impact of climate information on values, behavior and policy support. *Journal of Environmental Studies and Sciences*, **6**(4), 724-732, doi:10.1007/s13412-015-0288-y.
Schoennagel, T. et al., 2017: Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences*, **114**(18), 4582-4590.
Schwalm, C. R. et al., 2017: Global patterns of drought recovery. *Nature*, **548**(7666), 202-205, doi:10.1038/nature23021.
Schwartz, J. D. et al., 2015: Projections of temperature-attributable premature deaths in 209 U.S. cities using a cluster-based Poisson approach. *Environmental Health*, **14**, 85-85, doi:10.1186/s12940-015-0071-2.
Schwartz, M. W. et al., 2012: Managed Relocation: Integrating the Scientific, Regulatory, and Ethical Challenges. *BioScience*, **62**(8), 732-743, doi:10.1525/bio.2012.62.8.6.
Schwartz, R. M. et al., 2017: Longitudinal impact of Hurricane Sandy exposure on mental health symptoms. *International Journal of Environmental Research and Public Health*, **14**(9), 957, doi:10.3390/ijerph14090957.
Schweiger, A. J., K. R. Wood and J. Zhang, 2019: Arctic Sea Ice Volume Variability over 1901–2010: A Model-Based Reconstruction. *Journal of Climate*, **32**(15), 4731-4752, doi:10.1175/jcli-d-19-0008.1.
Scott, D., C. M. Hall and S. Gössling, 2019a: Global tourism vulnerability to climate change. *Annals of Tourism Research*, **77**, 49-61, doi:https://doi.org/10.1016/j.annals.2019.05.007.
Scott, D., R. Steiger, N. Knowles and Y. Gang, 2020: Regional ski tourism risk to climate change: An inter-comparison of Eastern Canada and US Northeast markets. *Journal of SUstainable Tourism*, **28**(4), 568-586.
Scott, D. et al., 2019b: The differential futures of ski tourism in Ontario (Canada) under climate change: the limits of snowmaking adaptation. *Current Issues in Tourism*, 1327-1342.
Scott, J., A. Wagner and G. Winter, 2017: *Metlakatla Indian Community climate change adaptation plan*.
Scyphers, S. B., S. P. Powers, K. L. Heck, Jr. and D. Byron, 2011: Oyster Reefs as Natural Breakwaters Mitigate Shoreline Loss and Facilitate Fisheries. *PLOS ONE*, **6**(8), e22396, doi:10.1371/journal.pone.0022396.
Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190120, doi:doi:10.1098/rstb.2019.0120.
Seidl, R. et al., 2017: Forest disturbances under climate change. *Nature Climate Change*, **7**(6), 395-402, doi:10.1038/nclimate3303.
Seijger, C., J. van Tatenhove, G. Dewulf and H. S. Otter, 2014: Responding to coastal problems: Interactive knowledge development in a US nature restoration project. *Ocean Coast. Manag.*, **89**, 29-38.
Semarnat, 2009: *The economics of climate change in Mexico: Synopsis*. Secretaria de Medio Ambiente y Recursos Naturales y Secretaria de Hacienda y Credito Publico, Mexico City.
Semarnat, 2014: *Programa Especial de Cambio Climático 2014 – 2018 (PECC)*. Secretaria de Medio Ambiente y Recursos Naturales y Secretaria de Hacienda y Credito Publico, Mexico City.
Semarnat and INECC, 2015: *Elementos Mínimos para la Elaboración de los Programas de Cambio Climático de las Entidades Federativas S. d. M. A. y. R. N. (SEMARNAT)*. Available at: http://www.inecc.gob.mx/descargas/cclimatico/2015_elem_minims_prog_cc_efederativas.pdf.
SEMARNAT and INECC, 2018: *México Sexta Comunicación Nacional y Segundo Informe Bienal de Actualización ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático*.
Sena, P. K., 2014: *UNPFII E/C.19/2014/2 Study to examine challenges in the African region to protecting traditional knowledge, genetic resources and folklore*. United Nations, New York, NY, US. Available at: https://undocs.org/E/C.19/2014/2.
Sena, P. K. and UNPFII, 2013: *Study on resilience, traditional knowledge and capacity-building for pastoralist communities in Africa*. United Nations Permanent Forum on Indigenous Issues, New York, NY, US. Available at: https://digitallibrary.un.org/record/743819.
Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Settee, P., 2020: The impact of climate Change on Indigenous food sovereignty. In: *Indigenous food systems: Concepts, cases, and conversations* [Settee, P. and S. Shukla (eds.)]. Canadian Scholars, Toronto, ON, Canada.
Seung, C. K. et al., 2015: Economic impacts of changes in an Alaska crab fishery from ocean acidification. *Climate Change Economics*, **06**(04), 1550017-1550017, doi:10.1142/S2010007815500177.
Shah, N., M. Wei, V. Letschert and A. Phadke, 2015: *Benefits of leapfrogging to superefficiency and low global warming potential refrigerants in room air conditioning*. Available at: https://eta-publications.lbl.gov/sites/default/files/lbnl-1003671.pdf.
Shannon, K. L., B. F. Kim, S. E. McKenzie and R. S. Lawrence, 2015: Food system policy, public health, and human rights in the United States. *Annual Review of Public Health*, **36**, 151-173, doi:10.1146/annurev-publhealth-031914-122621.
Sharma, S. et al., 2019: Widespread loss of lake ice around the Northern Hemisphere in a warming world. *Nature Climate Change*, **9**(3), 227-231, doi:10.1038/s41558-018-0393-5.

Sharp, F., 2019: *Quinault Indian Nation Testimony. United States House of Representatives Committee on Natural Resources Subcommittee on Water, Oceans, and Wildlife Legislative Hearing on H.R. 335, H.R. 729, H.R. 2185, H.R.3115, H.R. 3237, H.R. 3510, H.R. 3541, H.R. 3596*. Available at: https://www.congress.gov/116/meeting/house/109853/witnesses/HHRG-116-II13-Wstate-SharpF-20190725.pdf.

Sherren, K. et al., 2019: Coastal infrastructure realignment and salt marsh restoration in Nova Scotia, Canada. In: *Responding to Rising Seas: OECD Country Approaches to Tackling Coastal Risk*. OECD Publishing, Paris, France, pp. 111-135.

Sherry, J., T. Neale, T. K. McGee and M. Sharpe, 2019: Rethinking the maps: a case study of knowledge incorporation in Canadian wildfire risk management and planning. *Journal of environmental management*, **234**, 494-502.

Shi, L., E. Chu and J. Debats, 2015: Explaining Progress in Climate Adaptation Planning Across 156 U.S. Municipalities. *Journal of the American Planning Association*, **81**(3), 191-202, doi:10.1080/01944363.2015.1074526.

Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372**(6549), eabc8054, doi:10.1126/science.abc8054.

Shinbrot, X. A. et al., 2019: Smallholder farmer adoption of climate-related adaptation strategies: The importance of vulnerability context, livelihood assets, and climate perceptions. *Environmental Management*, **63**(5), 583-595, doi:10.1007/s00267-019-01152-z.

Shove, E., 2010: Social Theory and Climate Change. *Theory, Culture & Society*, **27**, 277-288.

Shukla, P. R., J. Skea E. Calvo Buendia V. Masson-Delmotte H. O. Pörtner D. C. Roberts P. Zhai R. Slade S. Connors R. van Diemen M. Ferrat E. Haughey S. Luz S. Neogi M. Pathak J. Petzold J. Portugal Pereira Vyas E. Huntley K. Kissick M., 2019: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Siddon, E. and S. Zador, 2017: *Ecosystem Considerations 2017 Status of the Eastern Bering Sea Marine Ecosystem*. Repository, N. I. Available at: https://repository.library.noaa.gov/view/noaa/19464.

Siddon, E. C. et al., 2013: Spatial match-mismatch between juvenile fish and prey provides a mechanism for recruitment variability across contrasting climate conditions in the eastern Bering Sea. *PLoS One*, **8**(12), e84526, doi:10.1371/journal.pone.0084526.

Siedlecki, S. A. et al., 2015: Seasonal and interannual oxygen variability on the Washington and Oregon continental shelves. *J. Geophys. Res. C: Oceans*, **120**(2), 608-633, doi:10.1002/2014JC010254.

Siedlecki, S. A. et al., 2016: Experiments with Seasonal Forecasts of ocean conditions for the Northern region of the California Current upwelling system. *Sci. Rep.*, **6**, 27203, doi:10.1038/srep27203.

Sigler, M. F. et al., 2014: Spring and fall phytoplankton blooms in a productive subarctic ecosystem, the eastern Bering Sea, during 1995–2011. *Deep Sea Research Part II: Topical Studies in Oceanography*, **109**, 71-83, doi:10.1016/j.dsr2.2013.12.007.

Simpson, L. B., 2011: *Dancing on our turtle's back: Stories of Nishnaabeg re-creation, resurgence and a new emergence*. ARP Books, Winnipeg.

Sinha, E., A. M. Michalak and V. Balaji, 2017: Eutrophication will increase during the 21st century as a result of precipitation changes. *Science*, **357**(6349), 405-408, doi:10.1126/science.aan2409.

Sioui, M., 2019: Drought in the Yucatan: Maya perspectives on tradition, change, and adaptation. In: *Drought challenges: Policy options for developing countries* [Mapedza, E., D. Tsegai, M. Bruntrup and R. McLeman (eds.)]. Elsevier Science, Netherlands, pp. 67-75.

Sioui, M., 2020: *Indigenous geographies in the Yucatan: Learning from the responsibility-based Maya environmental ethos*. Springer Nature, Switzerland.

Sioui, M. and R. McLeman, 2014: Asserting Mino Pimàdiziwin on Unceded Algonquin Territory: Experiences of a Canadian "non-status" First Nation in re-establishing its traditional land ethic. *AlterNative*, **10**(4), 354-375, doi:10.1177/117718011401000404.

Sippel, S. et al., 2020: Climate change now detectable from any single day of weather at global scale. *Nature Climate Change*, **10**(1), 35-41, doi:10.1038/s41558-019-0666-7.

Skern-Mauritzen, M. et al., 2015: Ecosystem processes are rarely included in tactical fisheries management. *Fish and Fisheries*, 165-175, doi:10.1111/faf.12111.

Slack, B. and C. Comtois, 2016: Inland river ports. Routledge, pp. 141-157.

Smale, D. A. et al., 2019a: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9**(4), 306-312, doi:10.1038/s41558-019-0412-1.

Smale, D. A. et al., 2019b: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9**(4), 306-312, doi:10.1038/s41558-019-0412-1.

Smith, A., 2020: *2010-2019: A landmark decade of U.S. billion-dollar weather and climate disasters*. Information, N. N. C. f. E., 15 pp. Available at: https://www.climate.gov/news-features/blogs/beyond-data/2010-2019-landmark-decade-us-billion-dollar-weather-and-climate; accessed 12 May 2020.

Smith, A. B. and J. L. Matthews, 2015: Quantifying uncertainty and variable sensitivity within the US billion-dollar weather and climate disaster cost estimates. *Natural Hazards*, **77**(3), 1829-1851, doi:10.1007/s11069-015-1678-x.

Smith, A. M. et al., 2016a: The science of firescapes: achieving fire-resilient communities. *Bioscience*, **66**(2), 130-146.

Smith, B. A. et al., 2019: Seasonality and zoonotic foodborne pathogens in Canada: relationships between climate and *Campylobacter*, *E . coli* and *Salmonella* in meat products. *Epidemiology and Infection*, **147**, e190, doi:10.1017/s0950268819000797.
Smith, C. S. et al., 2017: Hurricane damage along natural and hardened estuarine shorelines: Using homeowner experiences to promote nature-based coastal protection. *Marine Policy*, **81**, 350-358, doi:https://doi.org/10.1016/j.marpol.2017.04.013.
Smith, E. T. and S. C. Sheridan, 2019: The influence of extreme cold events on mortality in the United States. *Science of the Total Environment*, **647**, 342-351, doi:10.1016/j.scitotenv.2018.07.466.
Smith, H. G. et al., 2011: Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology*, **396**(1-2), 170-192, doi:10.1016/j.jhydrol.2010.10.043.
Smith, J. B. et al., 2018: *Chapter 16: Climate Effects on U.S. International Interests* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II, U.S. Global Change Research Program, Washington, D.C., USA, 604-637 pp. Available at: http://dx.doi.org/10.7930/nca4.2018.ch16.
Smith, W. K. et al., 2016b: Large divergence of satellite and Earth system model estimates of global terrestrial CO2 fertilization. *Nature Climate Change*, **6**(3), 306-310, doi:10.1038/nclimate2879.
Snapp, S. et al., 2021: *Agroecology and climate change rapid evidence review: Performance of agroecological approaches in low- and middle- income countries*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) CGIAR Research Program on Climate Change, A. a. F. S. C., Wageningen, the Netherlands. Available at: https://ccafs.cgiar.org/resources/publications/agroecology-and-climate-change-rapid-evidence-review-performance.
Solander, K. C. et al., 2018: Interactions between Climate Change and Complex Topography Drive Observed Streamflow Changes in the Colorado River Basin. *Journal of Hydrometeorology*, **19**(10), 1637-1650, doi:10.1175/jhm-d-18-0012.1.
Soneja, S. et al., 2016: Exposure to extreme heat and precipitation events associated with increased risk of hospitalization for asthma in Maryland, U.S.A. *Environmental Health*, **15**, 57, doi:10.1186/s12940-016-0142-z.
Soto-Montes-de-Oca, G. and M. Alfie-Cohen, 2019: Impact of climate change in Mexican peri-urban areas with risk of drought. *Journal of Arid Environments*, **162**, 74-88, doi:https://doi.org/10.1016/j.jaridenv.2018.10.006.
Soto-Navarro, C. et al., 2020: Mapping co-benefits for carbon storage and biodiversity to inform conservation policy and action. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190128, doi:doi:10.1098/rstb.2019.0128.
Spalding, M. D. et al., 2014: Coastal ecosystems: a critical element of risk reduction. *Conservation Letters*, **7**(3), 293-301.
Spies, I. et al., 2020: Genetic evidence of a northward range expansion in the eastern Bering Sea stock of Pacific cod. *Evolutionary Applications*, **13**(2), 362-375, doi:10.1111/eva.12874.
Spies, T., R. Scheller and J. Bolte, 2018: Adaptation in fire-prone landscapes: interactions of policies, management, wildfire, and social networks in Oregon, USA. *Ecology and Society*, **23**(2).
Spring, Ú., 2014: Water security and national water law in Mexico. *Earth Perspectives*, **1**(1), 7, doi:10.1186/2194-6434-1-7.
Springmann, M., H. C. J. Godfray, M. Rayner and P. Scarborough, 2016a: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, **113**(15), 4146-4151, doi:10.1073/pnas.1523119113.
Springmann, M. et al., 2016b: Global and regional health effects of future food production under climate change: a modelling study. *The Lancet*, **387**(10031), 1937-1946, doi:10.1016/S0140-6736(15)01156-3.
Springmann, M. et al., 2018: Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *The Lancet Planetary Health*, **2**(10), e451-e461, doi:10.1016/S2542-5196(18)30206-7.
Sproles, E. A., T. R. Roth and A. W. Nolin, 2016: Future Snow? A Spatial-Probabilistic Assessment of the Extraordinarily Low Snowpacks of 2014 and 2015 in the Oregon Cascades. *The Cryosphere Discussions*, 1-21, doi:10.5194/tc-2016-66.
St-Pierre, N. R., B. Cobanov and G. Schnitkey, 2003: Economic Losses from Heat Stress by US Livestock Industries¹. *Journal of Dairy Science*, **86**, E52-E77, doi:10.3168/jds.S0022-0302(03)74040-5.
St. Regis Mohawk Tribe, 2013: Climate Change Adaptation Plan for Akwesasne.
STACCWG, 2021: *Status of Tribes and Climate Change Working Group. Status of Tribes and Climate Change Report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ.
Staley, Z. R. et al., 2018: Fecal source tracking and eDNA profiling in an urban creek following an extreme rain event. *Sci Rep*, **8**, 14390, doi:10.1038/s41598-018-32680-z.
Standards Council of Canada, 2020: *Building a climate resilient future with northern standards*. Canada, G. o., 3 pp. Available at: https://www.scc.ca/en/system/files/publications/SCC_NISI_Brochure_EN.pdf.
Stanley, R. R. E. et al., 2018: A climate-associated multispecies cryptic cline in the northwest Atlantic. *Science Advances*, **4**(3), eaaq0929-eaaq0929, doi:10.1126/sciadv.aaq0929.

Star, J. et al., 2016: Supporting adaptation decisions through scenario planning: Enabling the effective use of multiple methods. *Climate Risk Management*, **13**, 88-94.
State of Alaska, 2020: *State of Alaska Federal Fishery Disaster Requests – Alaska Kuskokwim River and Salmon Fisheries, 2020*. Available at: https://media.fisheries.noaa.gov/2021-05/03.08.21 Gina Raimondo AK Federal Fishery Disaster Request Ltr.pdf.
State of California, 2014: Sustainable Groundwater Management Act, AB 1739, SB 1319 and SB 1168. Available at: http://groundwater.ca.gov/legislation.cfm.
Statistics Canada. Available at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1410002201.
Statistics Mexico. Available at: https://datareportal.com/reports/digital-2021-mexico.
Steele, C. et al., 2018: Cascading impacts of climate change on southwestern US cropland agriculture. *Climatic Change*, **148**(3), 437-450, doi:10.1007/s10584-018-2220-4.
Steffen, W. and et al., 2018: Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, **in review**, 1-45, doi:10.1073/pnas.1810141115.
Stein, B. A. et al., 2013: Preparing for and managing change: climate adaptation for biodiversity and ecosystems. *Frontiers in Ecology and the Environment*, **11**(9), 502-510, doi:https://doi.org/10.1890/120277.
Steiner, N. S. et al., 2019: Impacts of the changing ocean-sea ice system on the key forage fish arctic cod (Boreogadus saida) and subsistence fisheries in the Western Canadian arctic-evaluating linked climate, ecosystem and economic (CEE) models. *Frontiers in Marine Science*, **6**(APR), doi:10.3389/fmars.2019.00179.
Stephens, S. L. et al., 2014: Temperate and boreal forest mega-fires: Characteristics and challenges. *Frontiers in Ecology and the Environment*, **12**, 115-122.
Stephenson, N. L. et al., 2019: Which trees die during drought? The key role of insect host-tree selection. *Journal of Ecology*, **107**(5), 2383-2401, doi:10.1111/1365-2745.13176.
Sterner, T. et al., 2019: Policy design for the Anthropocene. *Nature Sustainability*, **2**(January), doi:10.1038/s41893-018-0194-x.
Stevens-Rumann, C. S. et al., 2018: Evidence for declining forest resilience to wildfires under climate change. *Ecol. Lett.*, **21**(2), 243-252, doi:10.1111/ele.12889.
Stevens-Rumann, C. S. and P. Morgan, 2019: Tree regeneration following wildfires in the western US: a review. *Fire Ecology*, **15**, 17, doi:10.1186/s42408-019-0032-1.
Stevenson, D. E. and R. R. Lauth, 2019: Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. *Polar Biol.*, **42**(2), 407-421, doi:10.1007/s00300-018-2431-1.
Stevenson, K. T. et al., 2015: How emotion trumps logic in climate change risk perception: exploring the affective heuristic among wildlife science students. *Hum. Dimensions Wildl.*, **20**(6), 501-513.
Stewart, I. T., J. Rogers and A. Graham, 2020: Water security under severe drought and climate change: Disparate impacts of the recent severe drought on environmental flows and water supplies in Central California. *Journal of Hydrology X*, **7**, 100054, doi:10.1016/j.hydroa.2020.100054.
Stewart, J. A. E. et al., 2021: Effects of postfire climate and seed availability on postfire conifer regeneration. *Ecological Applications*, **31**(3), e02280, doi:https://doi.org/10.1002/eap.2280.
Stewart-Sinclair, P. J., K. S. Last, B. L. Payne and T. A. Wilding, 2020: A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecology and Evolution*, **10**(7), 3518-3534, doi:10.1002/ece3.6149.
Stock, C. A. et al., 2017: Reconciling fisheries catch and ocean productivity. *Proceedings of the National Academy of Sciences*, 201610238, doi:10.1073/pnas.1610238114.
Stone, B. et al., 2021: Compound Climate and Infrastructure Events: How Electrical Grid Failure Alters Heat Wave Risk. *Environmental Science & Technology*, **55**(10), 6957-6964, doi:10.1021/acs.est.1c00024.
Storlazzi, C. D. et al., 2019: Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction. *Open-File Report*, doi:10.3133/ofr20191027.
Stortini, C. H., N. L. Shackell, P. Tyedmers and K. Beazley, 2015: Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada. *ICES Journal of Marine Science*, **72**(6), 1731-1743, doi:10.1093/icesjms/fsv022.
Strauss, B. H. et al., 2021: Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. *Nature Communications*, **12**(1), 2720, doi:10.1038/s41467-021-22838-1.
Strong, A. L. et al., 2014: Ocean Acidification 2.0: Managing our Changing Coastal Ocean Chemistry. *BioScience*, **64**(7), 581-592, doi:10.1093/biosci/biu072.
Stults, M. and S. Meerow, 2017: *Professional societies and climate change: An analysis of how urban-focused professional societies are integrating climate change into their member engagement activities*. Foundation, T. K., 36 pp. Available at: http://kresge.org/sites/default/files/library/env1007-psreport-0117_revised_11917.pdf.
Sullivan, A., D. D. White and M. Hanemann, 2019: Designing collaborative governance: Insights from the drought contingency planning process for the lower Colorado River basin. *Environ. Sci. Policy*, **91**, 39-49, doi:10.1016/j.envsci.2018.10.011.
Sully, S. et al., 2019: A global analysis of coral bleaching over the past two decades. *Nature communications*, **10**(1), 1-5.
Sumaila, U. R. et al., 2019: *Benefits of the Paris Agreement to ocean life, economies, and people*. Available at: http://advances.sciencemag.org/.

Sumaila, U. R. and D. L. V. Zwaag, 2020: Canada and transboundary fisheries management in changing oceans: Taking stock, future scenarios. *Ecology and Society*, **25**(4), 1-4, doi:10.5751/ES-12209-250444.
Supran, G. and N. Oreskes, 2017: Assessing ExxonMobil's climate change communications (1977–2014). *Environmental Research Letters*, **12**(8), 084019.
Suryan, R. M. et al., 2021: Ecosystem response persists after a prolonged marine heatwave. *Sci Rep*, **11**(1), 6235, doi:10.1038/s41598-021-83818-5.
Susaeta, A., D. R. Carter and D. C. Adams, 2014: Impacts of Climate Change on Economics of Forestry and Adaptation Strategies in the Southern United States. *Journal of Agricultural and Applied Economics*, **46**(2), 257-272, doi:10.1017/s1074070800000778.
Sussman, F. et al., 2014: Climate change adaptation cost in the US: what do we know? *Climate Policy*, **14**(2), 242-282.
Sutton-Grier, A. E. et al., 2018: Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts. *Sustainability*, **10**(2), 523.
Sweet, W. et al., 2014: *Sea Level Rise and Nuisance Flood Frequency Changes around the United States*. US Department of Commerce, Silver Spring, MD, 66 pp. Available at: https://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf.
Sweet, W. V. et al., 2017: Ch. 12: Sea Level Rise. Climate Science Special Report: Fourth National Climate Assessment, Volume I. doi:10.7930/j0vm49f2.
Swiney, K. M., W. Christopher Long and R. J. Foy, 2017: Decreased pH and increased temperatures affect young-of-the-year red king crab (Paralithodes camtschaticus). *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsw251.
Swinomish Indian Tribe Community, 2010: *Swinomish climate change initiative: climate adaptation action plan*. La Conner, WA. Available at: https://www.swinomish-climate.com/swinomish-climate-change-initiative.
Sydeman, W. J., E. Poloczanska, T. E. Reed and S. A. Thompson, 2015: Climate change and marine vertebrates. *Science*, **350**(6262), 772-777, doi:10.1126/science.aac9874.
Syphard, A. D., J. E. Keeley, A. H. Pfaff and K. Ferschweiler, 2017: Human presence diminishes the importance of climate in driving fire activity across the United States. *Proceedings of the National Academy of Sciences*, **114**(52), 13750-13755, doi:10.1073/pnas.1713885114.
Szuwalski, C. et al., 2021: Climate change and the future productivity and distribution of crab in the Bering Sea. *ICES Journal of Marine Science*, **78**(2), 502-515, doi:10.1093/icesjms/fsaa140.
Tàbara, D. J. et al., 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, **31**, 120-129, doi:https://doi.org/10.1016/j.cosust.2018.01.012.
Tai, T. C. et al., 2019: Evaluating present and future potential of arctic fisheries in Canada. *Marine Policy*, **108**(August), 103637-103637, doi:10.1016/j.marpol.2019.103637.
Tam, B. Y. et al., 2019: CMIP5 drought projections in Canada based on the Standardized Precipitation Evapotranspiration Index. *Canadian Water Resources Journal*, **44**(1), 90-107, doi:10.1080/07011784.2018.1537812.
Tan, X. et al., 2019: Dynamic and thermodynamic changes conducive to the increased occurrence of extreme spring fire weather over western Canada under possible anthropogenic climate change. *Agricultural and Forest Meteorology*, **265**, 269-279, doi:https://doi.org/10.1016/j.agrformet.2018.11.026.
Tape, K. D. et al., 2016: Range Expansion of Moose in Arctic Alaska Linked to Warming and Increased Shrub Habitat. *PLoS One*, **11**(4), e0152636, doi:10.1371/journal.pone.0152636.
Taranu, Z. E. et al., 2015: Acceleration of cyanobacterial dominance in north temperate-subarctic lakes during the Anthropocene. *Ecology Letters*, **18**(4), 375-384, doi:https://doi.org/10.1111/ele.12420.
Taylor, M. et al., 2018: Outbreak of Vibrio parahaemolyticus associated with consumption of raw oysters in Canada, 2015. *Foodborne Pathogens and Disease*, **15**(9), 554-559, doi:10.1089/fpd.2017.2415.
Tellman, B. et al., 2018: Adaptive pathways and coupled infrastructure: seven centuries of adaptation to water risk and the production of vulnerability in Mexico City. *Ecology and Society*, **23**(1), doi:10.5751/es-09712-230101.
Temmerman, S. et al., 2013: Ecosystem-based coastal defence in the face of global change. *Nature*, **504**(7478), 79-83, doi:10.1038/nature12859.
Termeer, C. J. A. M., A. Dewulf and G. R. Biesbroek, 2017: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management*, **60**(4), 558-576, doi:10.1080/09640568.2016.1168288.
Termini, O. and S. E. Kalafatis, 2021: The Paradox of Public Trust Shaping Local Climate Change Adaptation. *Atmosphere*, **12**(2), 241.
Terton, A., 2017: *Building a climate-resilient city: Urban ecosystems*. International Institute for Sustainable Development, Development, I. I. f. S., Winnipeg, Canada, 10 pp. Available at: http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-climate-resilient-city-urban-ecosystems.pdf.
Tetu, P. L., L. F., P. S. and J. Dawson, 2019: 'Sovereignty' over submerged cultural heritage in the Canadian Arctic waters: case study from the Franklin expedition wrecks (1845-48. *Polar Geography*.
The Arlington Group Planning + Architecture Inc, Tetra Tech Company, Jardine Consulting and Sustainability Solutions Group, 2013: *Sea level rise adaptation primer: A toolkit to build adaptive capacity on Canada's South Coasts*. 191-191 pp. Available at: http://www.env.gov.bc.ca/cas/adaptation/pdf/SLR-Primer.pdf.

The Geneva Association et al., 2020: *Flood Risk Management in Canada: Building flood resilience in a changing climate*. The Geneva Association, Economics, T. G. A. I. A. f. t. S. o. I., Zurich, 66 pp. Available at: https://www.genevaassociation.org/sites/default/files/research-topics-document-type/pdf_public/frm_canada_web.pdf.
The White House, 2016: FACT SHEET: United States Key Deliverables for the 2016 North American Leaders' Summit. Office of the Press Secretary.
Theuerkauf, S. J. et al., 2019: A global spatial analysis reveals where marine aquaculture can benefit nature and people. *PLoS ONE*, **14**(10), 1-29, doi:10.1371/journal.pone.0222282.
Thistlethwaite, J., 2017: The emergence of flood insurance in Canada: Navigating institutional uncertainty. *Risk Anal.*, **37**(4), 744-755, doi:10.1111/risa.12659.
Thistlethwaite, J. and D. Henstra, 2018: Protection for those who need it most: Sustainable property insurance in high-risk areas.(134).
Thistlethwaite, J. et al., 2018: Application of re/insurance models to estimate increases in flood risk due to climate change. *Geoenvironmental Disasters*, **5**(8), 13, doi:https://doi. org/10.1186/s40677-018-0101-9.
Thistlethwaite, J., A. Minano, D. Henstra and D. Scott, 2020a: *Indigenous Reserve Lands in Canada Face High Flood Risk*.
Thistlethwaite, J., A. Minano, D. Henstra and D. Scott, 2020b: *Indigenous reserve lands in Canada face high flood risk. Policy Brief No. 159*. Centre for International Governance Innovation, Waterloo, ON, Canada. Available at: https://www.cigionline.org/publications/indigenous-reserve-lands-canada-face-high-flood-risk.
Thomas, C. D., 2020: The development of Anthropocene biotas. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190113, doi:doi:10.1098/rstb.2019.0113.
Thompson, L. M. et al., 2021: Responding to Ecosystem Transformation: Resist, Accept, or Direct? *FISHERIES*, **46**(1), 8-21, doi:10.1002/fsh.10506.
Thompson, S., M. Ballard and D. Martin, 2014: Lake St. Martin First Nation community members' experiences of induced displacement: 'We're like refugees'. *Refuge*, **29**(2), 75-86, doi:10.25071/1920-7336.38168.
Thorne, J. H. et al., 2018: Climate change vulnerability assessment of forests in the Southwest USA. *Climatic Change*, **148**(3), 387-402, doi:10.1007/s10584-017-2010-4.
Thurman, L. L. et al., 2020: Persist in place or shift in space? Evaluating the adaptive capacity of species to climate change. *Frontiers in Ecology and the Environment*.
Tjaden, N. B. et al., 2017: Modelling the effects of global climate change on Chikungunya transmission in the 21 st century. *Sci Rep*, **7**, 3813, doi:10.1038/s41598-017-03566-3.
Tlingit and C. Haida, 2019: *Central Council of the Tlingit & Haida Indian Tribes of Alaska Climate Change Adaptation Plan*. Available at: http://www.ccthita.org/services/community/environmental/documents/T&HClimateChangeAdaptationPlan.pdf.
Todd, Z., 2015: Indigenizing the Anthropocene. *Art in the Anthropocene: Encounters among aesthetics, politics, environments and epistemologies*, 241-254.
Toledo, V. M., 2013: The biocultural paradigm ecological crisis, modernity and traditional cultures. *Sociedad y Ambiente*, **1**(1), 50-60.
Toledo-Hernández, M., T. C. Wanger and T. Tscharntke, 2017: Neglected pollinators: Can enhanced pollination services improve cocoa yields? A review. *Agriculture, Ecosystems & Environment*, **247**(July), 137-148, doi:10.1016/j.agee.2017.05.021.
Tolentino-Arévalo, O., M. Markantoni, A. Espinoza-Tenorio and M. Mesa-Jurado, 2019: Drivers of Adaptive Capacity to Climate Change in Coastal Fishing Communities of Tabasco. In: *Vaiability and sustainability of small-scale fisheries in Latin America and The Caribbean* [Salas, S. (ed.)]. Springer International Publishing AG.
Tom, G., C. Begay and R. Yazzie, 2018: *Climate adaptation plan for the Navajo Nation*. Available at: https://www.nndfw.org/docs/Climate%20Change%20Adaptation%20Plan.pdf.
Tommasi, D. et al., 2017a: Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. *Prog. Oceanogr.*, **152**, 15-49, doi:10.1016/j.pocean.2016.12.011.
Tommasi, D. et al., 2017b: Improved management of small pelagic fisheries through seasonal climate prediction. *Ecol. Appl.*, **27**(2), 378-388, doi:10.1002/eap.1458.
Torres Castillo, N. E. et al., 2020: Impact of climate change and early development of coffee rust – An overview of control strategies to preserve organic cultivars in Mexico. *Science of the Total Environment*, **738**, doi:10.1016/j.scitotenv.2020.140225.
Trainer, V. L. et al., 2019: Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae*, doi:10.1016/j.hal.2019.03.009.
Treen, K. M. d. I., H. T. P. Williams and S. J. O'Neill, 2020: Online misinformation about climate change. *WIREs Climate Change*, **11**(5), e665, doi:https://doi.org/10.1002/wcc.665.
Trenberth, K. E. et al., 2018: Hurricane Harvey Links to Ocean Heat Content and Climate Change Adaptation. *Earths Future*, **6**(5), 730-744, doi:10.1029/2018ef000825.
Treuer, G., K. Broad and R. Meyer, 2018: Using simulations to forecast homeowner response to sea level rise in South Florida: Will they stay or will they go? *Global Environmental Change*, **48**, 108-118, doi:https://doi.org/10.1016/j.gloenvcha.2017.10.008.

Tribal Adaptation Menu Team, 2019: *Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal climate adaptation menu*. Odanah, Wisconsin, 54 pp.
Tribal Climate Adaptation Guidebook Writing Team, M. Dalton, S. Chisholm Hatfield and A. S. Petersen, 2018: Tribal Climate Adaptation Guidebook. [Dalton, M., S. Chisholm Hatfield and A. S. Petersen (eds.)], Corvallis, OR.
Trombley, J., S. Chalupka and L. Anderko, 2017: Climate change and mental health. *American Journal of Nursing*, **117**(4), 44-52, doi:10.1097/01.NAJ.0000515232.51795.fa.
Trosper, R. L., 2002: Northwest coast indigenous institutions that supported resilience and sustainability. *Ecological Economics*, **41**(2), 329-344, doi:10.1016/S0921-8009(02)00041-1.
Trtanj, J. et al., 2016: Chapter 6: Climate impacts on water-related illness. Global Change Research Program, Washington DC, pp. 157-188.
Tsatsaros, J. H. et al., 2018: Indigenous Water Governance in Australia: Comparisons with the United States and Canada. *Water*, **10**(11), doi:10.3390/w10111639.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(5), e476, doi:10.1002/wcc.476.
Tuhiwai Smith, L., 2021: *Decolonizing Methodologies: Research and Indigenous Peoples*. Zed Books, London, UK.
Turner, M. G., K. H. Braziunas, W. D. Hansen and B. J. Harvey, 2019a: Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proceedings of the National Academy of Sciences*, **116**(23), 11319-11328, doi:10.1073/pnas.1902841116.
Turner, M. G. et al., 2020: Climate change, ecosystems and abrupt change: science priorities. *Philos. Trans. R. Soc. B-Biol. Sci.*, **375**(1794), doi:10.1098/rstb.2019.0105.
Turner, N. J. and H. Clifton, 2009: “It's so different today”: Climate change and indigenous lifeways in British Columbia, Canada. *Global Environmental Change*, **19**(2), 180-190, doi:https://doi.org/10.1016/j.gloenvcha.2009.01.005.
Turner, S. W. D. et al., 2017: Climate impacts on hydropower and consequences for global electricity supply investment needs. *Energy*, **141**, 2081-2090, doi:https://doi.org/10.1016/j.energy.2017.11.089.
Turner, S. W. D. et al., 2019b: Compound climate events transform electrical power shortfall risk in the Pacific Northwest. *Nature Communications*, **10**, doi:10.1038/s41467-018-07894-4.
Tustin, A. W. et al., 2018: Evaluation of Occupational Exposure Limits for Heat Stress in Outdoor Workers - United States, 2011-2016. *MMWR Morb Mortal Wkly Rep*, **67**(26), 733-737, doi:10.15585/mmwr.mm6726a1.
Tye, M. R. and J. P. Giovannettone, 2021: *The Impacts of Future Weather and Climate Extremes on United States' Infrastructure: Assessing and Prioritizing Adaptation Actions*. ASCE (American Society of Civil Engineers), Reston, VA. ISBN 978-0-7844-1586-3.
Tymstra, C., B. J. Stocks, X. Cai and M. D. Flannigan, 2020: Wildfire management in Canada: Review, challenges and opportunities. *Progress in Disaster Science*, **5**, 100045.
Uejio, C. K., 2017: Temperature influences on Salmonella infections across the continental United States. *Annals of the American Association of Geographers*, **107**(3), 751-764, doi:10.1080/24694452.2016.1261681.
Uejio, C. K., M. Christenson, C. Moran and M. Gorelick, 2017: Drinking-water treatment, climate change, and childhood gastrointestinal illness projections for northern Wisconsin (USA) communities drinking untreated groundwater. *Hydrogeology Journal*, **25**(4), 969-979, doi:10.1007/s10040-016-1521-9.
Uejio, C. K. et al., 2014: Drinking water systems, hydrology, and childhood gastrointestinal illness in central and northern Wisconsin. *American Journal of Public Health*, **104**(4), 639-646, doi:10.2105/AJPH.2013.301659.
Ullrich, P. A. et al., 2018: California's Drought of the Future: A Midcentury Recreation of the Exceptional Conditions of 2012-2017. *Earths Future*, **6**(11), 1568-1587, doi:10.1029/2018ef001007.
UNGA, 2007: *G.A. Res. 61/295 of 13 September 2007, Preamble and Article 31 – United Nations General Assembly. (2017, September 11). A/HRC/36/46 Report of the Special Rapporteur on the rights of Indigenous Peoples.* . United Nations General Assembly. Available at: https://undocs.org/A/HRC/36/46
UNGA, 2015: *Promotion and protection of the rights of indigenous peoples with respect to their cultural heritage Study by the Expert Mechanism on the Rights of Indigenous Peoples, UN Document A/HRC/30/53, 2015 – The Expert Mechanism on the Rights of Indigenous Peoples. Promotion and protection of the rights of Indigenous peoples with respect to their cultural heritage: report*. United Nations General Assembly. Available at: https://undocs.org/A/HRC/30/53.
UNGA, 2017: *A/HRC/36/46 Report of the Special Rapporteur on the rights of indigenous peoples*. United Nations General Assembly. Available at: https://undocs.org/A/HRC/36/46.
UNGA, 2018: *EMRIP Study on Free, prior and informed consent: a human rights-based approach Study of the Expert Mechanism on the Rights of Indigenous Peoples, UN Document A/HRC/39/62, 2018 – The Expert Mechanism on the Rights of Indigenous Peoples. Free, prior and informed consent: report*. United Nations General Assembly. Available at: https://undocs.org/A/HRC/39/62.
United Nations, 2019: World Population Prospects 2019: Data Booklet. *Statistical Papers - United Nations (Ser. A), Population and Vital Statistics Report*, doi:10.18356/3e9d869f-en.
United Nations, 2020: *Climate Change Impacts and Adaptation for Transport Networks and Nodes*. Nations, U., Geneva, 216 pp. Available at: https://www.mdpi.com/2075-5309/10/3/53/htm.
US Census Bureau, 2019: *Coastline America*. Commerce, U. D. o., 1 pp. Available at: https://www.census.gov/content/dam/Census/library/visualizations/2019/demo/coastline-america.pdf

US Department of Transportation, 2015: *Gulf Coast Study, Phase Two Case Study*. Federal Highway Administration, Administration, F. H., Washington, D.C, 4 pp. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/gulf_coast_study/gcsph2.pdf.
US Law, 2019: Colorado River Drought Contingency Plan Authorization Act.
USDA Forst Service, 2011: *Economic use of beetle-killed trees*. Laboratory, F. P., 10 pp. Available at: https://www.fpl.fs.fed.us/documnts/statusreports/fpl-status-reports-201110-BeetleKilledTrees.pdf.
USEO 13754, Executive Order on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis. Briefing Room.
USEO 14008, *Executive Order on Tackling the Climate Crisis at Home and Abroad*, Room, B., Washington, D.C. Available at: https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/.
USEPA, 2018: *The danger of wildland fire smoke to public health*. United States Environmental Protection Agency.
USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* U.S. Global Change Research Program, Washington, DC, USA, 470 pp.
USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp.
USGCRP, 2019: *The Climate Report: National Climate Assessment-Impacts, Risks, and Adaptation in the United States*. 272 pp. ISBN 9781612198026.
Ute Mountain Ute Tribe and Wood Environment Infrastructure Solutions Inc, 2019: *Ute Mountain Ute Tribal hazard mitigation plan*. Available at: https://drive.google.com/file/d/131KDOsAuswejNKcjgX4iWRe-eHSobXMV/view.
Vadeboncoeur, N., 2016: Perspectives on Canada’s West Coast region. [Lemmen, D. S., F. J. Warren, T. S. James and C. S. L. M. Clarke (eds.)]. Government of Canada, Ottawa, ON, pp. 297-252.
Valcour, J. E. et al., 2016: A descriptive analysis of the spatio-temporal distribution of enteric diseases in New Brunswick, Canada. *BMC Public Health*, **16**, 204, doi:10.1186/s12889-016-2779-5.
Valois, P. et al., 2019: Development and validation of five behavioral indices of flood adaptation. *BMC Public Health*, **19**(1), 1-17, doi:10.1186/s12889-019-6564-0.
Van der Brugge, R. and R. Roosjen, 2015: An institutional and socio-cultural perspective on the on the adaptation pathways approach. *J Water Clim Change*, **6**(4), 743–758, doi:10.2166/wcc.2015.001.
van der Linden, S., A. Leiserowitz and E. Maibach, 2019: The gateway belief model: A large-scale replication. *Journal of Environmental Psychology*, **62**, 49-58.
van der Linden, S., A. Leiserowitz, S. Rosenthal and E. Maibach, 2017: Inoculating the public against misinformation about climate change. *Global Challenges*, **1**(2), 1600008.
van der Linden, S. L., A. A. Leiserowitz, G. D. Feinberg and E. W. Maibach, 2015: The scientific consensus on climate change as a gateway belief: Experimental evidence. *PLoS One*, **10**(2), e0118489.
van der Wiel, K. et al., 2017: Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrology and Earth System Sciences*, **21**(2), 897-921, doi:10.5194/hess-21-897-2017.
van Hooidonk, R. et al., 2016: Local-scale projections of coral reef futures and implications of the Paris Agreement. *Sci Rep*, **6**(1), doi:10.1038/srep39666.
van Mantgem, P. J. et al., 2018: Pre-fire drought and competition mediate post-fire conifer mortality in western U.S. National Parks. *Ecological Applications*, **28**(7), 1730-1739, doi:10.1002/eap.1778.
van Oldenborgh, G. J. et al., 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12**(12), 124009, doi:10.1088/1748-9326/aa9ef2.
van Putten, I. E. et al., 2015: Empirical evidence for different cognitive effects in explaining the attribution of marine range shifts to climate change. *ICES Journal of Marine Science*, **73**(5), 1306-1318, doi:10.1093/icesjms/fsv192.
Vanderslice, J., 2011: Drinking water infrastructure and environmental disparities: Evidence and methodological considerations. *American Journal of Public Health*, **101**(S1), S109-S114, doi:10.2105/AJPH.2011.300189.
Vano, J. A. et al., 2018: DOs and DON'Ts for using climate change information for water resource planning and management: guidelines for study design. *Climate Services*, **12**, 1-13, doi:https://doi.org/10.1016/j.cliser.2018.07.002.
Vano, J. A. et al., 2019: HYDROCLIMATIC EXTREMES AS CHALLENGES FOR THE WATER MANAGEMENT COMMUNITY: LESSONS FROM OROVILLE DAM AND HURRICANE HARVEY. *Bull. Am. Meteorol. Soc.*, **100**(1), S9-S14, doi:10.1175/bams-d-18-0219.1.
Vargas, N. and V. Magaña, 2020: Climatic risk in the Mexico city metropolitan area due to urbanization. *Urban Climate*, **33**, 100644, doi:https://doi.org/10.1016/j.uclim.2020.100644.
Verna, D. et al., 2016: Ballast-borne marine invasive species : exploring the risk to coastal Alaska , Ballast-borne marine invasive species : exploring the risk to coastal Alaska , USA. doi:10.3391/mbi.2016.7.2.08.
Vernon, M. J., R. L. Sherriff, P. van Mantgem and J. M. Kane, 2018: Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. *Forest Ecology and Management*, **422**, 190-198, doi:10.1016/j.foreco.2018.03.043.
Vicedo-Cabrera, A. M. et al., 2018a: Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. *Climatic Change*, **150**, 391-402, doi:10.1007/s10584-018-2274-3.

Vicedo-Cabrera, A. M. et al., 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11**(6), 492-500, doi:10.1038/s41558-021-01058-x.
Vicedo-Cabrera, A. M. et al., 2018b: A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. *Environment International*, **111**, 239-246, doi:10.1016/j.envint.2017.11.006.
Vida, S., M. Durocher, T. B. M. J. Ouarda and P. Gosselin, 2012: Relationship between ambient temperature and humidity and visits to mental health Emergency Departments in Québec. *Psychiatric Services*, **63**(11), 1150-1153, doi:10.1176/appi.ps.201100485.
Villarreal, M. L. et al., 2019: Distant neighbors: recent wildfire patterns of the Madrean Sky Islands of southwestern United States and northwestern Mexico. *Fire Ecology*, **15**(1), 2.
Vodden, K. and A. Cunsolo, 2021: Rural and remote communities. In: *Canada in a Changing Climate: National Issues Report* [Warren, F. J. and N. Lulham (eds.)]. Government of Canada, Ottawa, ON, pp. 103-184.
Vogel, J., E. McNie and D. Behar, 2016: Co-producing actionable science for water utilities. *Climate Services*, **2**(3), 10.
Voggesser, G. et al., 2013: Cultural impacts to tribes from climate change influences on forests. *Climatic Change*, **120**(3), 615-626, doi:10.1007/s10584-013-0733-4.
Vose, J. M. et al., 2018: Forests. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 232-267.
Vose, R. S. et al., 2017: Ch. 6: Temperature Changes in the United States. Climate Science Special Report: Fourth National Climate Assessment, Volume I. doi:10.7930/j0n29v45.
Vousdoukas, M. I. et al., 2020: Sandy coastlines under threat of erosion. *Nature Climate Change*, **10**(3), 260-263, doi:10.1038/s41558-020-0697-0.
Wade, T. J., C. J. Lin, J. S. Jagai and E. D. Hilborn, 2014: Flooding and emergency room visits for gastrointestinal illness in Massachusetts: A case-crossover study. *PLoS ONE*, **9**(10), e110474-e110474, doi:10.1371/journal.pone.0110474.
Wahl, E. R., E. Zorita, V. Trouet and A. H. Taylor, 2019: Jet stream dynamics, hydroclimate, and fire in California from 1600 CE to present. *Proc. Natl. Acad. Sci. U. S. A.*, **116**(12), 5393-5398, doi:10.1073/pnas.1815292116.
Waite, M. et al., 2017: Global trends in urban electricity demands for cooling and heating. *Energy*, **127**, 786-802, doi:https://doi.org/10.1016/j.energy.2017.03.095.
Walker, X. J. et al., 2019: Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature*, **572**(7770), 520-523, doi:10.1038/s41586-019-1474-y.
Wall, D., 2017: *Tohono O'odham: Desert people in a changing environment*. Available at: https://www7.nau.edu/itep/main/tcc/Tribes/sw_toodham.
Wall, T. U., A. M. Meadow and A. Horganic, 2017: Developing Evaluation Indicators to Improve the Process of Coproducing Usable Climate Science. *Weather, Climate, and Society*, **9**(1), 95-107, doi:10.1175/WCAS-D-16-0008.1.
Wamsler, C., 2015: Mainstreaming ecosystem-based adaptation: Transformation toward sustainability in urban governance and planning. *Ecol. Soc.*, **20**(2), doi:10.5751/ES-07489-200230.
Wang, D. et al., 2021: Economic footprint of California wildfires in 2018. *Nature Sustainability*, **4**(3), 252-260, doi:10.1038/s41893-020-00646-7.
Wang, M. et al., 2019: The great Atlantic Sargassum belt. *Science*, **365**(6448), 83-87, doi:10.1126/science.aaw7912.
Wang, M. and J. E. Overland, 2015: Projected future duration of the sea-ice-free season in the Alaskan Arctic. *Prog. Oceanogr.*, **136**, 50-59, doi:10.1016/j.pocean.2015.01.001.
Wang, M., Q. Yang, J. E. Overland and P. Stabeno, 2018a: Sea-ice cover timing in the Pacific Arctic: The present and projections to mid-century by selected CMIP5 models. *Deep Sea Res. Part 2 Top. Stud. Oceanogr.*, **152**, 22-34, doi:10.1016/j.dsr2.2017.11.017.
Wang, S. L., R. Nehring and R. Mosheim, 2018b: Agricultural Productivity Growth in the United States: 1948-2015. *Amber Waves:The Economics of Food, Farming, Natural Resources, and Rural America*, **2018**(2).
Wang, W. J. et al., 2015: Importance of succession, harvest, and climate change in determining future composition in U.S. Central Hardwood Forests. *Ecosphere*, **6**(12), art277, doi:10.1890/es15-00238.1.
Wang, Y., L. Shi, A. Zanobetti and J. D. Schwartz, 2016: Estimating and projecting the effect of cold waves on mortality in 209 US cities. *Environment International*, **94**, 141-149, doi:10.1016/j.envint.2016.05.008.
Ward, M. et al., 2015: Associations between weather and microbial load on fresh produce prior to harvest. *Journal of Food Protection*, **78**(4), 849-854, doi:10.4315/0362-028x.jfp-14-381.
Ward, R. D., D. A. Friess, R. H. Day and R. A. Mackenzie, 2016: Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and Sustainability*, **2**(4), e01211, doi:10.1002/ehs2.1211.
Ware, C. et al., 2014: Climate change, non-indigenous species and shipping: assessing the risk of species introduction to a high-Arctic archipelago. *Diversity and Distributions*, **20**, 10-19, doi:10.1111/ddi.12117.
Warren, F. and N. Lulham, 2021: *Canada in a changing climate*. National Issues Report, Government of Canada, Canada, G. o., Ottawa, ON, 734 pp. Available at: https://changingclimate.ca/national-issues/.
Water and C. R. B. Tribes Initiative, 2020: *Toward a Sense of the Basin Designing a Collaborative Process to Develop the Next Set of Guidelines for the Colorado River System*. 68 pp. Available at: https://naturalresourcespolicy.org/docs/colorado-river-basin/basin-report-2020.pdf.

Water and C. R. B. Tribes Initiative, 2021: *Universal Access to Clean Water for Tribes in the Colorado River Basin*. 74 pp. Available at: http://www.naturalresourcespolicy.org/docs/water-tribes/wti-full-report-4.21.pdf.
Weatherdon, L. V. et al., 2016: Projected scenarios for coastal first nations' fisheries catch potential under climate change: Management challenges and opportunities. *PLoS ONE*, **11**(1), 1-28, doi:10.1371/journal.pone.0145285.
Webster, R. K. and T. Linton, 2013: Development and implementation of Sargassum Early Advisory System (SEAS). *Shore & Beach* **81**(3).
Wehner, M. F. et al., 2017: *Droughts, floods, and wildfires.* [Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart and T. K. Maycock (eds.)]. Climate Science Special Report: Fourth National Climate Assessment, Volume I, U.S. Global Change Research Program, Washington, D.C., USA, 231-256 pp.
Weijerman, M. et al., 2015a: How models can support ecosystem-based management of coral reefs. *Progress in Oceanography*, **138**, 559-570, doi:https://doi.org/10.1016/j.pocean.2014.12.017.
Weijerman, M. et al., 2015b: An integrated coral reef ecosystem model to support resource management under a changing climate. *PLoS ONE*, **10**(12), 1-23, doi:10.1371/journal.pone.0144165.
Weinberger, K. R. et al., 2017: Projected temperature-related deaths in ten large U.S. metropolitan areas under different climate change scenarios. *Environment International*, **107**, 196-204, doi:10.1016/j.envint.2017.07.006.
Weinkle, J. et al., 2018: Normalized hurricane damage in the continental United States 1900–2017. *Nature Sustainability*, **1**(12), 808-813, doi:10.1038/s41893-018-0165-2.
Weiskerger, C. J. et al., 2019: Impacts of a changing earth on microbial dynamics and human health risks in the continuum between beach water and sand. *WATER RESEARCH*, **162**, 456-456, doi:10.1016/j.watres.2019.07.006.
Weiskopf, S. R., O. E. Ledee and L. M. Thompson, 2019: Climate change effects on deer and moose in the midwest. *The Journal of Wildlife Management*, **83**(4), 769-781, doi:10.1002/jwmg.21649.
Weiskopf, S. R. et al., 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782, doi:https://doi.org/10.1016/j.scitotenv.2020.137782.
Wells, M. L. et al., 2015: Harmful algal blooms and climate change: Learning from the past and present to forecast the future. *Harmful Algae*, **49**, 68-93, doi:10.1016/j.hal.2015.07.009.
Werners, S. E. et al., 2021: Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, **116**, 266-275, doi:https://doi.org/10.1016/j.envsci.2020.11.003.
Wesche, S. D. and H. M. Chan, 2010: Adapting to the impacts of climate change on food security among Inuit in the western Canadian Arctic. *EcoHealth*, **7**(3), 361-373, doi:10.1007/s10393-010-0344-8.
Westerling, A. L., 2016: Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philos. Trans. R. Soc. B-Biol. Sci.*, **371**(1696), 10, doi:10.1098/rstb.2015.0178.
White, A. B., B. J. Moore, D. J. Gottas and P. J. Neiman, 2019: WINTER STORM CONDITIONS LEADING TO EXCESSIVE RUNOFF ABOVE CALIFORNIA'S OROVILLE DAM DURING JANUARY AND FEBRUARY 2017. *Bulletin of the American Meteorological Society*, **100**(1), 55-69, doi:10.1175/bams-d-18-0091.1.
White, E. M., T. R. Bergerson and E. T. Hinman, 2020: Research note: Quick assessment of recreation use and experience in the immediate aftermath of wildfire in a desert river canyon. *Journal of Outdoor Recreation and Tourism*, **29**(September 2019), doi:10.1016/j.jort.2019.100251.
Whitehouse, G. A. and K. Y. Aydin, 2020: Assessing the sensitivity of three Alaska marine food webs to perturbations: an example of Ecosim simulations using Rpath. *Ecological Modelling*, **429**(March), 109074-109074, doi:10.1016/j.ecolmodel.2020.109074.
Whyte, K., 2016: Is it colonial déjà vu?: Indigenous Peoples and climate injustice. In: *Humanities for the environment: Integrating knowledge, forging new constellations of practice* [Adamson, J., M. Davis and H. Huang (eds.)]. Earthscan Publications, pp. 88-104.
Whyte, K., 2017: Way beyond the lifeboat: An Indigenous allegory of climate justice. In: *Climate futures: Reimagining global climate justice* [Munshi, D., K.-K. Bhavnani, J. Foran and P. Kurian (eds.)], pp. 1-8.
Whyte, K. et al., 2021: Ecosystems & Biodiversity. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 56-80.
Wiecks, J. et al., 2021: Air. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 81-97.
Wiens, J. J., 2016: Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLoS Biol.*, **14**(12), e2001104, doi:10.1371/journal.pbio.2001104.
Wigtil, G. et al., 2016: Places where wildfire potential and social vulnerability coincide in the coterminous United States. *International journal of wildland fire*, **25**(8), 896-908.
Wildcat, D., 2013: Introduction: Climate change and Indigenous Peoples of the USA. *Climatic Change*, **120**(3), 509-515, doi:10.1007/s10584-013-0849-6.
Wilder, J. M. et al., 2017: Polar bear attacks on humans: Implications of a changing climate. *Wildlife Society Bulletin*, **41**(3), 537-547, doi:10.1002/wsb.783.
Wilder, M. O. et al., 2020: Hydrodiplomacy and adaptive governance at the US-Mexico border: 75 years of tradition and innovation in transboundary water management. *Environmental Science & Policy*, **112**, 189-202, doi:10.1016/j.envsci.2020.05.013.

Wilkins, E., S. de Urioste-Stone, A. Weiskittel and T. Gabe, 2018: Effects of Weather Conditions on Tourism Spending: Implications for Future Trends under Climate Change. *Journal of Travel Research*, **57**(8), 1042-1053, doi:10.1177/0047287517728591.
Williams, A. P. et al., 2019a: Observed Impacts of Anthropogenic Climate Change on Wildfire in California. *Earth's Future*, **0**(0), doi:10.1029/2019ef001210.
Williams, A. P. et al., 2013: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, **3**(3), 292-297, doi:10.1038/nclimate1693.
Williams, A. P. et al., 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368**(6488), 314-+, doi:10.1126/science.aaz9600.
Williams, C. A. et al., 2016: Disturbance and the carbon balance of US forests: A quantitative review of impacts from harvests, fires, insects, and droughts. *Global and Planetary Change*, **143**, 66-80, doi:10.1016/j.gloplacha.2016.06.002.
Williams, G. J. et al., 2019b: Coral reef ecology in the Anthropocene. *Functional Ecology*, **33**(6), 1014-1022.
Williams, H. T., J. R. McMurray, T. Kurz and F. H. Lambert, 2015: Network analysis reveals open forums and echo chambers in social media discussions of climate change. *Global Environmental Change*, **32**, 126-138.
Williams, J., M. T. Fergunson, M. Petkov and M. Wilkins, 2018: *The Effects of Weather Events on Corporate Earnings Are Gathering Force*. Ratings, S. P. G. and R. Economics, 23 pp. Available at: http://www.spglobal.com/ratingsdirect.
Williamson, C. E. et al., 2017: Climate change-induced increases in precipitation are reducing the potential for solar ultraviolet radiation to inactivate pathogens in surface waters. *Sci Rep*, **7**, 13033-13033, doi:10.1038/s41598-017-13392-2.
Wilson, J. R. et al., 2018: Adaptive comanagement to achieve climate-ready fisheries. *Conservation Letters*, **11**(6), e12452, doi:10.1111/conl.12452.
Wilson, R. R. et al., 2017: Relative influences of climate change and human activity on the onshore distribution of polar bears. *Biological Conservation*, **214**, 288-294, doi:10.1016/j.biocon.2017.08.005.
Wilson, T. J. et al., 2020: Potential socioeconomic impacts from ocean acidification and climate change effects on Atlantic Canadian fisheries. *PloS one*, **15**(1), e0226544.
Withen, P., 2015: Climate change and wildland firefighter health and safety. *New Solutions: A Journal of Environmental and Occupational Health Policy*, **24**(4), 577-584, doi:10.2190/NS.24.4.i.
Wobus, C. et al., 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*, **45**, 1-14.
Wobus, C. et al., 2019: Projecting Changes in Expected Annual Damages From Riverine Flooding in the United States. *Earths Future*, **7**(5), 516-527, doi:10.1029/2018ef001119.
Wolfe, D. W. et al., 2018: Unique challenges and opportunities for northeastern US crop production in a changing climate. *Climatic Change*, **146**(1-2), 231-245, doi:10.1007/s10584-017-2109-7.
Wong-Parodi, G. and I. Feygina, 2020: Understanding and countering the motivated roots of climate change denial. *Current Opinion in Environmental Sustainability*, **42**, 60-64.
Woo, S. H. L. et al., 2020: Air pollution from wildfires and human health vulnerability in Alaskan communities under climate change. *Environmental Research Letters*, **15**, 094019, doi:10.1088/1748-9326/ab9270.
Woodruff, S. C. and M. Stults, 2016: Numerous strategies but limited implementation guidance in US local adaptation plans. *Nat. Clim. Chang.*, **6**(August), doi:10.1038/nclimate3012.
World Bank, 2020: GDP. Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD.
World Bank, 2020: Trade Overview. Available at: https://www.worldbank.org/en/topic/trade/overview.
World Resourcs Institute, Aqueduct. Available at: https://www.wri.org/aqueduct.
Wotton, B., M. Flannigan and G. Marshall, 2017: Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environmental Research Letters*, **12**(9), 095003.
Wotton, B. M. and M. D. Flannigan, 1993: Length of the fire season in a changing climate. *The Forestry Chronicle*, **69**(2), 187-192.
Wright, M. et al., 2021: Seed production patterns of surviving Sierra Nevada conifers show minimal change following drought. *Forest Ecol. Manag.*, **480**(15).
WTTC, 2018: Travel & Tourism Power and Performance - September 2018. 1-23.
Wu, J. et al., 2014: Estimation and uncertainty analysis of impacts of future heat waves on mortality in the eastern United States. *Environmental Health Perspectives*, **122**, 10-16, doi:http://dx.doi.org/10.1289/ehp.1306670.
WUCA, 2010: *Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning. Report prepared for Water Utility Climate Alliance by Edward Means III, Maryline Laugier, Jennifer Daw, Marc Waage and Laurna Kaatz, January 2010*. Available at: http://www.wucaonline.org/assets/pdf/actions_whitepaper_012110.pdf.
WUCA, 2021: *Leading Practices in Climate Adaptation*. Prepared for the WUCA member agencies and adaptation community by the WUCA Leading Practices Committee and Aspen Global Change Institute. Available at: https://www.wucaonline.org/adaptation-in-practice/leading-practices.
Wuebbles, D. et al., 2014: CMIP5 Climate Model Analyses: Climate Extremes in the United States. *Bulletin of the American Meteorological Society*, **95**(4), 571-583, doi:10.1175/bams-d-12-00172.1.

Xiao, J. T. et al., 2017a: The formulations of site-scale processes affect landscape-scale forest change predictions: a comparison between LANDIS PRO and LANDIS-II forest landscape models. *Landsc. Ecol.*, **32**(7), 1347-1363, doi:10.1007/s10980-016-0442-2.
Xiao, M. et al., 2017b: How much groundwater did California's Central Valley lose during the 2012-2016 drought? *Geophysical Research Letters*, **44**(10), 4872-4879, doi:10.1002/2017gl073333.
Xiao, M., B. Udall and D. P. Lettenmaier, 2018: On the Causes of Declining Colorado River Streamflows. *Water Resources Research*, **54**(9), 6739-6756, doi:10.1029/2018wr023153.
Yang, Q. et al., 2019: How "The Blob" affected groundfish distributions in the Gulf of Alaska. *Fisheries Oceanography*, **28**(4), 434-453, doi:10.1111/fog.12422.
Yang, Z. et al., 2016: Nutrient reduction magnifies the impact of extreme weather on cyanobacterial bloom formation in large shallow Lake Taihu (China). *Water Res.*, **103**, 302-310, doi:10.1016/j.watres.2016.07.047.
Yao, J., M. Brauer and S. B. Henderson, 2013: Evaluation of a wildfire smoke forecasting system as a tool for public health protection. *Environmental Health Perspectives*, **121**(10), 1142-1147, doi:10.1289/ehp.1306768.
Yao, J., J. Eyamie and S. B. Henderson, 2016: Evaluation of a spatially resolved forest fire smoke model for population-based epidemiologic exposure assessment. *Journal of Exposure Science and Environmental Epidemiology*, **26**(3), 233-240, doi:10.1038/jes.2014.67.
Yates, D. N., K. A. Miller, R. L. Wilby and L. Kaatz, 2015: Decision-centric adaptation appraisal for water management across Colorado's Continental Divide. *Climate Risk Management*, **10**, 35-50, doi:10.1016/j.crm.2015.06.001.
Yates, K. K. et al., 2014: Diverse coral communities in mangrove habitats suggest a novel refuge from climate change. *Biogeosciences*, **11**(16), 4321-4337, doi:10.5194/bg-11-4321-2014.
Yellow Old Woman-Munro, D., L. Yumagulova and E. Dicken, 2021: *Unnatural disasters: Colonialism, climate displacement, and Indigenous sovereignty in Siksika Nation's disaster recovery efforts*. Canadian Institute for Climate Choices. Available at: https://climatechoices.ca/publications/unnatural-disasters/.
Young, D. J. N. et al., 2017a: Long-term climate and competition explain forest mortality patterns under extreme drought. *Ecol. Lett.*, **20**(1), 78-86, doi:10.1111/ele.12711.
Young, D. J. N. et al., 2017b: Long-term climate and competition explain forest mortality patterns under extreme drought. *Ecology Letters*, **20**, 78-86, doi:10.1111/ele.12711.
Young, T. et al., 2019: Adaptation strategies of coastal fishing communities as species shift poleward. *ICES Journal of Marine Science*, **76**(1), 93-103, doi:10.1093/icesjms/fsy140.
Yumagulova, L., 2020: Disrupting the riskscapes of inequities: A case study of planning for resilience in Canada's Metro Vancouver region. *Cambridge Journal of Regions, Economy and Society*,(October), 293-318, doi:10.1093/cjres/rsaa029.
Yumashev, D. et al., 2019: Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nature Communications*, **10**(1), 1-11, doi:10.1038/s41467-019-09863-x.
Yusa, A. et al., 2015: Climate change, drought and human health in Canada. *International Journal of Environmental Research and Public Health*, **12**(7), 8359-8412, doi:10.3390/ijerph120708359.
Zador, S. G., K. K. Holsman, K. Y. Aydin and S. K. Gaichas, 2017: Ecosystem considerations in Alaska: the value of qualitative assessments. *ICES J. Mar. Sci.*, **74**(1), 421-430, doi:10.1093/icesjms/fsw144.
Zaifman, J., D. Shan, A. Ay and A. G. Jimenez, 2017: Shifts in Bird Migration Timing in North American Long-Distance and Short-Distance Migrants Are Associated with Climate Change. *Int. J. Zool.*, **2017**, doi:10.1155/2017/6025646.
Zambrano, L. et al., 2021: Emergency Management. In: *Status of tribes and climate change report* [Marks-Marino, D. (ed.)]. Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ, pp. 222-240.
Zamora Saenz, I., 2018: *Percepciones sociales sobre el cambio climático en México*. Visor Ciudadano (57). Instituto Belisario Domínguez del Senado de la República. . Available at: http://bibliodigitalibd.senado.gob.mx/bitstream/handle/123456789/3888/VC_57.pdf?sequence=1&isAllowed=y.
Zamuda, C. et al., 2018: *Chapter 4: Energy Supply, Delivery, and Demand* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II, U.S. Global Change Research Program, Washington, D.C., USA, 174-201 pp. Available at: http://dx.doi.org/10.7930/nca4.2018.ch4.
Zanocco, C. et al., 2018: Place, proximity, and perceived harm: extreme weather events and views about climate change. *Climatic Change*, **149**(3-4), 349-365, doi:10.1007/s10584-018-2251-x.
Zellmer, S. B. and C. A. Klein, 2016: Floods as Unnatural Disasters: The Role of Law. In: *Water Policy and Planning in a Variable and Changing Climate* [Miller, K. A., A. F. Hamlet, D. S. Kenney and K. T. Redmond (eds.)]. CRC Press, Taylor and Francis Group, Boca Raton, FL, pp. 361-374. ISBN ISBN: 978-1-4822-2797-0.
Zemp, M. et al., 2019: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, **568**(7752), 382-386, doi:10.1038/s41586-019-1071-0.
Zerbe, J., 2019: *Update: Paying for Urban Infrastructure Adaptation in Canada: An Analysis of Current and Emerging Economic Instruments for Local Governments*. 74 pp. Available at: https://www.researchgate.net/profile/Johann-Zerbe/publication/336712724_Update_Paying_for_Urban_Infrastructure_Adaptation_in_Canada_An_Analysis_of_Current_and_Emerging_Economic_Instruments_for_Local_Governments/links/5dae6c974585155e27f7a9b0/Update-Paying-for-Urban-Infrastructure-Adaptation-in-Canada-An-Analysis-of-Current-and-Emerging-Economic-

Instruments-for-Local-Governments.pdf?_sg%5B0%5D=NuYrLrdIugBoFQUFpfJbzY2xPoQ4m5mc5O6eWJfusu-rLi_i_5laJ1hteRDZYp0kYbO8CdqiPGYG--puviRT7A.LQLlU9lycN_WCRH9ut8uIGlTHBMqkNxSHC2PnyyJxBjLTCpBhf5Dufz1Ron_47ZTDsnbpwquLNGOfFyKMkh2BQ&_sg%5B1%5D=zRfvWVYuZN3Q8ctjQ9f_y_8dU-KOZ11EnruHF4ylPqbcIxHG9nQPOxjLYQZ9vO2bDsijr2ymhRrkqAez1Whe66p8e2ZcXTwR4MSefAYI3T35.LQLlU9lycN_WCRH9ut8uIGlTHBMqkNxSHC2PnyyJxBjLTCpBhf5Dufz1Ron_47ZTDsnbpwquLNGOfFyKMkh2BQ&_iepl=.

Zeuli, K., A. Nijhuis, R. Macfarlane and T. Ridsdale, 2018: The impact of climate change on the food system in Toronto. *International Journal of Environmental Research and Public Health*, **15**(11), 2344-2344, doi:10.3390/ijerph15112344.

Zhang, T., Ü. Niinemets, J. Sheffield and J. W. Lichstein, 2018a: Shifts in tree functional composition amplify the response of forest biomass to climate. *Nature*, **556**(7699), 99-102, doi:10.1038/nature26152.

Zhang, W., G. Villarini, G. A. Vecchi and J. A. Smith, 2018b: Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. *Nature*, **563**(7731), 384-388, doi:10.1038/s41586-018-0676-z.

Zhang, X. et al., 2019a: *Changes in Temperature and Precipitation Across Canada* [Bush, E. and D. S. Lemmen (eds.)]. Canada's Changing Climate Report, Government of Canada, Ottawa, Ontario, 112-193 pp. Available at: https://changingclimate.ca/site/assets/uploads/sites/2/2018/12/CCCR-Chapter4-TemperatureAndPrecipitationAcrossCanada.pdf.

Zhang, X. et al., 2019b: On the variable effects of climate change on Pacific salmon. *Ecological Modelling*, **397**, 95-106, doi:10.1016/j.ecolmodel.2019.02.002.

Zhang, Y. et al., 2019c: Mortality risk and burden associated with temperature variability in China, United Kingdom and United States: comparative analysis of daily and hourly exposure metrics. *Environmental Research*, **179**(Part A), 108771-108771, doi:http://dx.doi.org/10.1016/j.envres.2019.108771.

Zhao, S. et al., 2013: Adjoint estimation of ozone climate penalties. *GEOPHYSICAL RESEARCH LETTERS*, **40**(20), 5559-5559, doi:10.1002/2013GL057623.

Zhao, Y. et al., 2015: Estimating heat stress from climate-based indicators: present-day biases and future spreads in the CMIP5 global climate model ensemble. *Environmental Research Letters*, **10**(8), 084013, doi:10.1088/1748-9326/10/8/084013.

Zhong, Y. F., M. Notaro and S. J. Vavrus, 2019: Spatially variable warming of the Laurentian Great Lakes: an interaction of bathymetry and climate. *Climate Dynamics*, **52**(9-10), 5833-5848, doi:10.1007/s00382-018-4481-z.

Zhu, Z. et al., 2016: Greening of the Earth and its drivers. *Nature Climate Change*, **6**(8), 791-795, doi:10.1038/nclimate3004.

Zimmerman, R. and C. Faris, 2010: New York City panel on climate change 2010 report, Chapter 4: Infrastructure impacts and adaptation. *Ann. N. Y. Acad. Sci.*, **1196**, 63-85.

Ziska, L. et al., 2016: Food safety, nutrition, and distribution. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, pp. 189-216.

Zscheischler, J. et al., 2018: Future climate risk from compound events. *Nature Climate Change*, **8**(6), 469-477, doi:10.1038/s41558-018-0156-3.

Zuniga-Vasquez, J. M., D. Cisneros-Gonzalez and M. Pompa-Garcia, 2019: Drought regulates the burned forest areas in Mexico: the case of 2011, a record year. *Geocarto Int.*, **34**(5), 560-573, doi:10.1080/10106049.2017.1415986.

Chapter 15: Small Islands

Coordinating Lead Authors: Michelle Mycoo (Trinidad and Tobago), Morgan Wairiu (Solomon Islands)

Lead Authors: Donovan Campbell (Jamaica), Virginie Duvat (France), Yimnang Golbuu (Palau), Shobha Maharaj (Germany/Trinidad and Tobago), Johanna Nalau (Australia/Finland), Patrick Nunn (Australia), John Pinnegar (United Kingdom), Olivia Warrick (New Zealand)

Contributing Authors: Giulia Anderson (USA/New Caledonia), Faye Abigail Cruz (Philippines), Eleanor Devenish-Nelson (United Kingdom), Kris Ebi (USA), Johanna Loehr (Germany), Roché Mahon (Trinidad and Tobago), Rebecca McNaught (Australia), Meg Parsons (New Zealand), Jeff Price (United Kingdom), Stacy-Ann Robinson (Jamaica), Adelle Thomas (Bahamas)

Review Editors: John Agard (Trinidad and Tobago), Mahmood Riyaz (Maldives)

Chapter Scientist: Giulia Anderson (USA/New Caledonia)

Date of Final Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Observed Impacts

A sense of urgency is prevalent among small islands in the combating of climate change and in adherence to the Paris Agreement to limit global warming to 1.5 °C above pre-industrial levels. Small islands are increasingly affected by increases in temperature, the growing impacts of tropical cyclones (TCs) , storm surges, droughts, changing precipitation patterns, sea-level rise (SLR), coral bleaching, and invasive species, all of which are already detectable across both natural and human systems (*very high confidence*[1]) {15.3.3.1, 15.3.3.2, 15.3.3.3, 15.3.4.1, 15.3.4.2, 15.3.4.3, 15.3.4.4, 15.3.4.5, 15.3.4.7}.

The observed impacts of climate change differ between urban and rural contexts, island types, and tropical and non-tropical islands (*high confidence*). Coastal cities and rural communities on small islands have been already impacted by sea-level rise, heavy precipitation events, tropical cyclones and storm surges. Climate change is also affecting settlements and infrastructure, health and wellbeing, water and food security, and economies and culture, especially through compound events (*high confidence*). As of 2017, an estimated 22 million people in the Caribbean live below 6 metres elevation and 50% of the Pacific's population lives within 10 km of the coast along with ≥50% of their infrastructure concentrated within 500 metres of the coast {15.3.4.1, 15.3.4.2, 15.3.4.3, 15.3.4.4, 15.3.4.5, 15.3.4.7}.

Tropical cyclones are severely impacting small islands (*high confidence*). The TC intensity and intensification rates at a global scale have increased in the past 40 years with intensity trends generally remaining positive. Intense TCs including categories 4 and 5 TCs have threatened human life and destroyed buildings and infrastructural assets in small islands in the Caribbean and the Pacific. Among 29 Caribbean islands, 22 were affected by at least one category 4 or 5 TC in 2017. TC Maria in 2017 destroyed nearly all of Dominica's infrastructure and losses amounted to over 225% of the annual GDP. Destruction from TC Winston in 2016 exceeded 20% of Fiji's current GDP. TC Pam devastated Vanuatu in 2015 and caused losses and damages to the agricultural sector valued at USD 56.5 million (64.1% of GDP). Coast-focused tourism is already extremely impacted by more intense TCs. {WGI 11.7.1, 12.4.7 15.2.1, 15.3.3.1, 15.3.3.3, 15.3.4.1, 15.3.4.2, 15,3.4.4, 15.3.4.5}.

Scientific evidence has confirmed that globally and in small islands tropical corals are presently at high risk (*high confidence*). Severe coral bleaching, together with declines in coral abundance have been observed in many small islands, especially those in the Pacific and Indian Oceans (*high confidence*). In the Pacific, median return time between two severe bleaching events has diminished steadily since 1980. The return time is now 6 years and often associated with the warm phase of ENSO events (*high confidence*). In Mid-2016, a new ENSO event occurred which reduced living coral cover by 75% in the Maldives {15.3.3.1.3, 15.3.4.8}.

Freshwater systems on small islands are exposed to dynamic climate impacts and are among the most threatened on the planet. An 11-36% reduction is estimated in the volume of fresh groundwater lens of the small atoll islands (area < 0.6 km^2) of the Maldives due to SLR. The El Niño related 2015-16 drought in Vanuatu led to reliance on small amounts of contaminated water left at the bottom of household tanks. A Caribbean high-resolution drought atlas spanning 1950–2016 indicates that the region-wide 2013–2016 drought was the most severe event during the multi-decadal period. In Puerto Rico, the island experienced 80 consecutive weeks of moderate drought, 48 weeks of severe drought and 33 weeks of extreme drought conditions between 2014 and 2016. Increasing trends in drought are apparent in the Caribbean although trends in the western Pacific are not statistically significant {15.3.3.2, 15.3.4.3}.

Small islands host significant levels of global terrestrial species diversity and endemism. Due to the large range of insular-related vulnerabilities, almost 50% of terrestrial species presently considered at risk of global extinction also occur on islands (*high confidence*)**.** Despite encompassing approximately two percent

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

of the Earth's terrestrial surface, oceanic and other high-endemicity islands are estimated to harbour substantial proportions of existing species including ~ 25% extant global flora, ~ 12% birds and ~10% mammals {15.3.3.3}.

Projected Impacts

Projected climate and ocean-related changes will significantly affect marine and terrestrial ecosystems and ecosystem services, which will in turn have cascading impacts across both natural and human systems (*high confidence*). Changes in wave climate superimposed on SLR will significantly increase coastal flooding (*high confidence*) and low-coastal and reef island erosion (*limited evidence, medium agreement*). The frequency, extent, duration, and consequences of coastal flooding will significantly increase from 2050 (*high confidence*), unless coastal and marine ecosystems are able to naturally adapt to SLR through vertical growth (*low confidence*). These changes are a major concern for small islands given that a high percentage of their population, infrastructure and economic assets are located in the low elevation coastal zone of below 10 metres elevation {15.3.3.1.1, 15.3.3.1.2, 15.3.3.1.3, 15.3.3.1.4}.

Projected changes in the wave climate superimposed on SLR will rapidly increase flooding in small islands, despite highly contrasting exposure profiles between ocean sub-regions (*high confidence*). A 5-10 cm additional SLR (expected for ~2030–2050) will double flooding frequency in much of the Indian Ocean and Tropical Pacific, while TCs will remain the main driver of (rarer) flooding in the Caribbean Sea and Southern Tropical Pacific. Some Pacific atoll islands will *likely*[2] undergo annual wave-driven flooding over their entire surface from the 2060s–2070s to 2090s under RCP8.5, although future reef growth may delay the onset of flooding (*limited evidence, low agreement*) {15.3.3.1.1}.

Modelling of both temperature and ocean acidification effects under future climate scenarios (RCP 4.5 and RCP 8.5) suggest that some small islands will experience severe coral bleaching on an annual basis before 2040 (*medium confidence*). Above 1.5°C, globally inclusive of small islands, it is projected there will be further loss of 70–90% of reef-building corals, with 99% of corals being lost under warming of 2°C or more above the pre-industrial period. Intact coral reefs, seagrass meadows and mangroves provide a variety of ecosystem services that are important to island communities (*high confidence*). These include provisioning services regulating services, cultural services and those that support community resilience (*high confidence)*. If coastal ecosystems are degraded and lost, then the benefits they provide cannot be easily replaced (*medium confidence*) {15.3.3.1.3, 15.3.3.1.4}.

Projected changes in aridity are expected to impose freshwater stress on many small islands, especially SIDS *(high confidence*). It is estimated that with a warming of 1.5°C or less, freshwater stress on small islands would be 25% less as compared to 2.0°C. While some island regions are projected to experience substantial freshwater decline, an opposite trend is observed for some western Pacific and northern Indian Ocean islands. Drought risk projections for Caribbean SIDS aligned with observations from the Shared Socio-Economic Pathway (SSP) 2 scenario, indicate that a 1°C increase in temperature (from 1.7°C to 2.7°C) could result in a 60% increase in the number of people projected to experience a severe water resources stress from 2043–2071. In some Pacific atolls, freshwater resources could be significantly affected by a 0.40 m SLR. Similar impacts are anticipated for some Caribbean countries with worst-case scenario (RCP8.5) indicating a 0.5-m SLR by the mid-century (2046-2065) and 1-m SLR by the end-of-century (2081-2100). In SIDS with high projected population growth rates, they are expected to experience the most severe freshwater stress by 2030 under a 2°C warming threshold scenario {15.3.3.2}

The continued degradation and transformation of terrestrial and marine ecosystems of small islands due to human-dominated will amplify the vulnerability of island peoples to the impacts of climate change (*high confidence*). New studies highlight large population reductions with an extinction risk of 100% for endemic species within insular biodiversity hotspots including within the Caribbean, Pacific and

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

Suandaland regions by 2100 for > 3°C warming {15.3.3.3}. This is *likely* to decrease the provision of resources (e.g. potable water) to the millions of people living on small islands, resulting in impacts upon settlements and infrastructure, food and water security, health, economies, culture, and migration (*high confidence*) {15.3.3.2, 15.3.3.3, 15.3.4.1, 15.3.4.2, 15.4.3, 15.3.4.4, 15.3.4.5, 15.3.4.6, 15.3.4.7}.

Reef island and coastal area habitability in small islands is expected to decrease because of increased temperature, extreme sea levels and degradation of buffering ecosystems, which will increase human exposure to sea-related hazards (*high confidence*). Climate and non-climate drivers of reduced habitability are context specific. On small islands, coastal land loss attributable to higher sea level, increased extreme precipitation and wave impacts, and increased aridity have contributed to food and water insecurities that are *likely* to become more acute in many places (*high confidence*). In the Caribbean, additional warming by 0.2°–1.0°C, could lead to a predominantly drier region (5%–15% less rain than present-day), a greater occurrence of droughts along with associated impacts on agricultural production and yield in the region. Crop suitability modelling on several commercially important crops grown in Jamaica found that even an increase less than + 1.5 °C could result in a reduction in the range of crops that farmers may grow. Most Pacific Island Countries could experience ≥ 50% declines in maximum fish catch potential by 2100 relative to 1980–2000 under both an RCP 2.6 and RCP 8.5 scenario {15.3.4.3, 15.3.4.4}.

Future Risks

The reduced habitability of small islands is an overarching significant risk caused by a combination of several Key Risks facing most small islands even under a global temperature scenario of 1.5 degrees *(high confidence)*. These are loss of marine and coastal biodiversity and ecosystem services; submergence of reef islands); loss of terrestrial biodiversity and ecosystem services ; water insecurity ; destruction of settlements and infrastructure ; degradation of health and well-being ; economic decline and livelihood failure); and loss of cultural resources and heritage. Climate-related ocean changes, including those for slow onset events, and changes in extreme events are projected to cause and/or amplify Keys Risks in most small islands. Identification of Key Risks facilitates the selection of optimal context-specific adaptation options. Moreover, it can distil the benefits and/or disadvantages and long-term implications of choosing such options (*high confidence*) {15.3.4.9}.

The vulnerability of communities in small islands, especially those relying on coral reef systems for livelihoods, may exceed adaptation limits well before 2100 even for a low greenhouse gas emission pathway (*high confidence*). The impacts of climate change on vulnerable low-lying and coastal areas, present serious threats to the ability of land to support human life and livelihood's (*high confidence*). Climate-related migration is expected to increase, although the drivers and outcomes are highly context-specific and insufficient evidence exists to estimate numbers of climate-related migrants now and in the future (*medium evidence, high agreement*) {15.3.4.1, 15.3.4.6, CCB7-1}.

Small islands are already reporting loss and damage particularly from tropical cyclones and increases in sea-level rise *(high confidence)*. Despite the loss of human life and economic damage the methods and mechanisms to assess climate-induced loss and damage remain largely undeveloped for small islands. Further, there are no robust methodologies to infer attribution and such assessments are limited. A research gap on loss and damage includes how to assess the economic costs of loss and damage. Specific data on experienced loss and damage across socio-economic groups and demographics are needed. Monitoring and tracking slow onset events are equally important and require robust data {15.7, 15.8}.

Options, Limits and Opportunities of Adaptation

Some island communities are resilient with strong social safety nets and social capital that support responses and actions already occurring, but there is limited information on the effectiveness of the adaptation practices and the scale of needed action (*high confidence*). This is in part due to a need for a better understanding of the limits to adaptation and of what constitutes current resilience and/or successful adaptation in small island contexts. Greater insights into which drivers weaken local and indigenous resilience, together with recognition of the socio-political contexts within which communities operate, and the processes by which decisions are made, can assist in identifying opportunities at all scales to enhance climate adaptation and enable action towards climate resilient development pathways (*medium evidence, high agreement*) {15.6.1, 15.6.5, 15.7}.

In small islands, despite the existence of adaptation barriers several enablers can be used to improve adaptation outcomes and to build resilience (*high confidence*). These enablers include better governance and legal reforms; improving justice, equity and gender considerations; building human resource capacity; increased finance and risk transfer mechanisms; education and awareness programmes; increased access to climate information; adequately downscaled climate data and embedding Indigenous Knowledge and Local Knowledge (IKLK) as well as integrating cultural resources into decision-making (*high confidence*) {15.6.1 15.6.3, 15.6.4, 15.6.5}.

Small islands present the most urgent need for investment in capacity building and adaptation strategies (*high confidence*) but face barriers and constraints which hinder the implementation of adaptation responses. Barriers and constraints arise from governance arrangements, financial resources and human resource capacity. Additionally, institutional and legal systems are often inadequately prepared for managing adaptation strategies such as large-scale settlement relocation and other planned and/or autonomous responses to climate risks (*high confidence*). Adaptation strategies are already being implemented on some small islands although barriers are encountered including inadequate up-to-date and locally relevant information, limited availability of finance and technology, lack of integration of IKLK in adaptation strategies, and institutional constraints (*high confidence*) {15.5.3, 15.5.4, 15.6.3, 15.6.4, 15.6.5}.

For many small islands, adaptation actions are often incremental and do not match the scale of extreme or compounding events (*high confidence*). Much of the currently implemented adaptation measures remain small in scale (e.g., community-based adaptation projects), sectoral in focus and do not address the needed structural and system level adaptations to combat climate impacts and achieve long term sustainability of adaptation interventions. To address these shortcomings enablers are being integrated into National Adaptation Plans and Disaster Risk Reduction Plans (*high confidence*) {15.6.3}.

Although international climate finance has increased in magnitude small islands face challenges in accessing adaptation finance to cope with slow and rapid onset events (*high confidence*). In the Caribbean, 38% of flows were concessional loans and 62% were grants whereas in the Atlantic and Indian Oceans nearly 75% of the flows were in the form of concessional loans and 25% were grants. Solutions to these barriers are being explored and some small islands have started adopting enablers such as insurance and microfinance at both the national and local levels in responding to adaptation needs and to facilitate resiliency building. COVID-19 has caused, however, economic shock in many small islands which will limit adaptation, undermine the attainment of Sustainable Development Goals and slow down climate resilient development transitions {15.8.3}.

The unavailability of up-to-date baseline data and contrasting scenarios/temperature levels continue to impair the generation of local-to-regional observed and projected impacts for small islands, especially those that are developing nations (*high agreement*). Climate model data based on the most recent suite of scenarios (RCPs and especially SSPs) are still not widely available to primary modelling communities in most small island developing nations (*high agreement*). Coastal sites of small islands are not well-represented in global gridded population and elevation datasets, thereby making estimation of population exposure to SLR difficult. The lack of data continues to impede the development of robust impacts-based modelling output (e.g. for terrestrial biodiversity). Downscaling is pivotal for small islands due to their high diversity which makes generalisation invalid.

15.1 Introduction

This chapter examines the climate change impacts and projected risks faced by small islands, including the detection and attribution of observed impacts, the loss and damage they experience, and the enablers, limits and barriers to the implementation of adaptation options applicable to them. The implications of climate change impacts on the attainment of the Sustainable Development Goals (SDGs), the need for more climate-resilient development pathways based on a systems transitions approach, and how both of these intersect with future potential responses are assessed within the context of small island states.

The small islands covered in this chapter are located within the tropics of the southern, northern, and western Pacific Ocean, the central, eastern and western Indian Ocean, the Caribbean Sea, the eastern Atlantic off the coast of West Africa, and in the temperate Mediterranean Sea. In contrast to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), non-sovereign island states and territories dependent on continental states and islands of semi-autonomous, sub-national island jurisdictions are included in this chapter. Further, Small Island Developing States (SIDS) consisting of 39 small island and low-lying coastal developing states which belong to the Alliance of Small Island States (AOSIS) are covered in this assessment. Islands in the polar and sub-polar regions, North Atlantic Ocean, the Baltic Sea, the North Sea, the Black Sea and the Arctic Ocean are not included.

Small islands share similarities such as geographical remoteness, isolation, narrow resource bases, heavy dependency on external trade, vulnerability to exogenous economic shocks, economic volatility, and limited access to development finance. Many are biodiversity hotspots and experience a disproportionate impact of natural hazards associated with climate change. They are also diverse in physical and biophysical characteristics, economic systems, political/governance systems, and exhibit social and cultural differences. Adaptation responses vary among small islands because such diversity requires place-specific and culturally-specific adaptation responses.

The chapter is structured in accordance with the overall format of the AR6 Working Group II report (Figure 15.1). This section presents points of departure from AR5 and IPCC (Section 15.2). As shown in Figure 15.1, this is followed by an assessment of current and future risks that are expected to be experienced by small islands (Sections 15.3 and 15.4), what measures have been implemented (Section 15.5) and enablers, limits and barriers that are being encountered (Section 15.6). Section 15.7 deals with the SDGs, climate-resilient development pathways and potential future responses. The chapter ends with an identification of research gaps (Section 15.8).

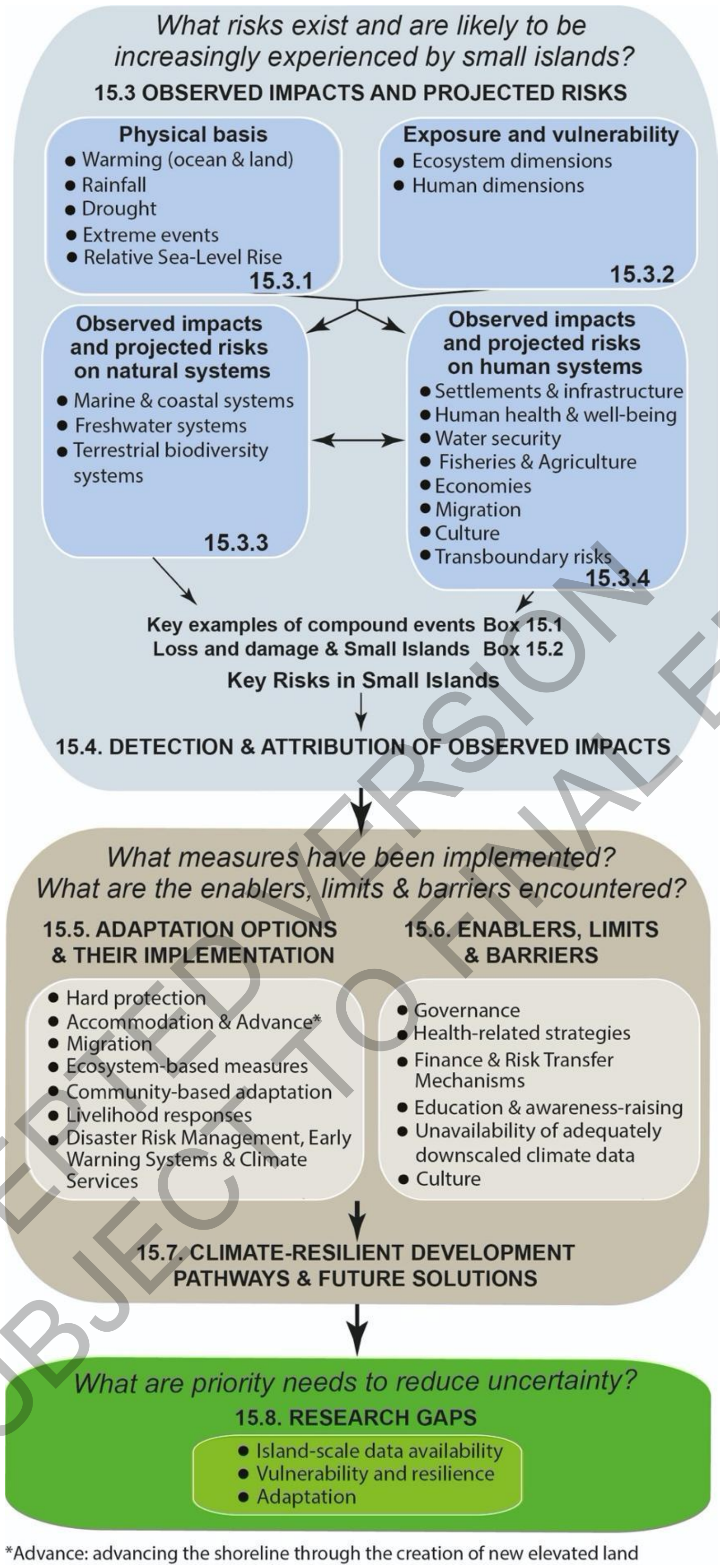


Figure 15.1: Schematic illustration of the interconnections of Chapter 15 themes, including on observed impacts and projected risks (Section 15.3) and on adaptation options and their implementation (Sections 15.5 and 15.6).

15.2 Points of Departure from AR5

Points of departure from AR5 are highlighted in this section in relation to exposure, vulnerability, impacts and risks (Section 15.2.1), and adaptation options (Section 15.2.2).

15.2.1 Points of Departure on Exposure, Vulnerability, Impacts and Risks

Scientific studies since AR5 confirm that global temperature will continue to increase even if greenhouse gas emissions are drastically reduced and will escalate the vulnerability, impacts and multiple interrelated risks experienced by small islands (*high confidence*) (IPCC, 2018). A greater sense of urgency in lowering global greenhouse gas emissions and a call for action now is resonating among small island states.

Post-AR5 new studies confirm observed impacts on the natural and human systems and indicate projected risks in both these systems over time. Over the past four decades, there was a significant increase in the probability of the global exceedances of tropical cyclones (TCs) of major intensity (Kossin et al., 2020), a trend confirmed by the occurrence of a growing number of intense TCs affecting the Atlantic and Pacific regions since AR5 (Magee et al., 2016; Bhatia et al., 2019; Knutson et al., 2019). Since AR5 also scientific evidence has confirmed that tropical corals are presently at high risk (*very high confidence*) and if global warming exceeds 1.5°C, known coral reef restoration options may be ineffective (IPCC, 2018). Even achieving emissions reduction targets consistent with the ambitious goal of 1.5°C of global warming under the Paris Agreement will result in the further loss of 70–90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2°C or more above the pre-industrial period (*high confidence*) (Hoegh-Guldberg et al., 2018).

Additionally, since the last assessment more robust scientific evidence exists on the impacts of sea level rise (SLR) and extreme sea level events (ESL) on small islands. Under Representative Concentration Pathways emission scenarios, RCP2.6, RCP4.5 and RCP8.5, many low-lying coastal areas at all latitudes, including small islands, will experience SLR and ESL events such as coastal storm surges and coastal flooding more frequently in the coming decades (Section 4.2.3.4.1; IPCC, 2019). SLR and ESL events will affect atoll islands and islands with higher elevations differently. New studies forecast that small islands are *likely* to experience some of the largest increases in endemic extinctions and may substantially contribute to future global biodiversity loss, as well as to impaired ecosystem functioning (Fortini et al., 2015; Vogiatzakis et al., 2016; Cramer et al., 2018). Scientific evidence points to large population reductions with an extinction risk of 100% for endemic species within insular biodiversity hotspots by 2100 (IPBES, 2018; Manes et al., 2021). An overarching concern since AR5 is the reduced habitability of small islands. Eight key risks affecting the habitability of small islands are identified in this assessment and these are covered in the pertinent sections of this chapter which assess adaptation responses.

15.2.2 Points of Departure on Adaptation

New knowledge of adaptation responses used in small islands has grown significantly since AR5. Strategies include hard protection, land reclamation and permanent relocation, with improved appreciation for when each strategy is relevant (IPCC, 2019). Evidence of migration as an adaptation response to climate change remains limited (Roland and Curtis, 2020). Understanding of ecosystem-based adaptation (EbA) has improved considerably but there is *medium agreement* regarding its benefits (Doswald et al., 2014; Nalau et al., 2018a) and *limited evidence and low agreement* on its economic efficiency and long-term effectiveness (Renaud et al., 2016; Oppenheimer et al., 2019).

Since the previous assessment, integration of Indigenous Knowledge and Local Knowledge (IKLK) into adaptation is recognized as a major benefit in preparing and recovering from TCs and EbA (Narayan et al., 2020). The roles of social capital, health-related adaptation strategies and livelihood responses are more fully understood (Nalau et al., 2018b; Nunn and Kumar, 2018; Abram et al., 2019; IPCC, 2019). Gender equity, climate justice, climate services, early warning systems, and disaster risk reduction (Vaughan and Dessai, 2014; Newth and Gunasekera, 2018), which were data gaps in AR5, have received more treatment, especially in the context of small islands. Stronger evidence confirms that education and awareness-raising enhance household and community adaptation (*high confidence*).

Knowledge has improved on limits to adaptation, including projected timeframes of limits for hard protection (*high confidence*) and EbA (*medium confidence*) (IPCC, 2019). There is also a better understanding that barriers and governance challenges vary by island and island groups (*high confidence*) and result in them having different adaptive capacities (IPCC, 2019). A major barrier to adaptation is limited information on the feasibility, outcomes and sustainability of adaptation responses in small islands. Moreover, limited time series data on monitoring and evaluation make evaluating the feasibility of adaptation responses difficult.

Adaptation financing for small islands has increased since AR5 although leveraging finance is a constraint and remains complex (Robinson and Dornan, 2017). Informal microfinancing has grown and risk transfer mechanisms are being explored although funding and access to insurance schemes is limited (Handmer and Nalau, 2019; Nunn and Kumar, 2019a; Petzold and Magnan, 2019). In small islands the methods and mechanisms to assess climate-induced loss or damage remain undeveloped (*medium confidence*) (Thomas and Benjamin, 2017; Handmer and Nalau, 2019).

Many small islands have experienced economic shock arising from COVID-19 and have had to re-direct investment previously targeting sustainable development (Sheller, 2020). Adaptation will be affected by economic contraction and indebtedness. Framing adaptation within climate-resilient development pathways (CRDPs) that emphasise systems transition and are implemented at scale may bolster small islands' resilience to multiple shocks like COVID-19.

15.3 Observed Impacts and Projected Risks of Climate Change

Compared to larger landmasses, many climate change driven impacts and risks are amplified for small islands. This is due largely to their boundedness (surrounded by ocean), their comparatively small land areas, and often their remoteness from more populated parts of the world, which restricts the global connectivity of islands. This is true on all types of islands (Figure 15.2).

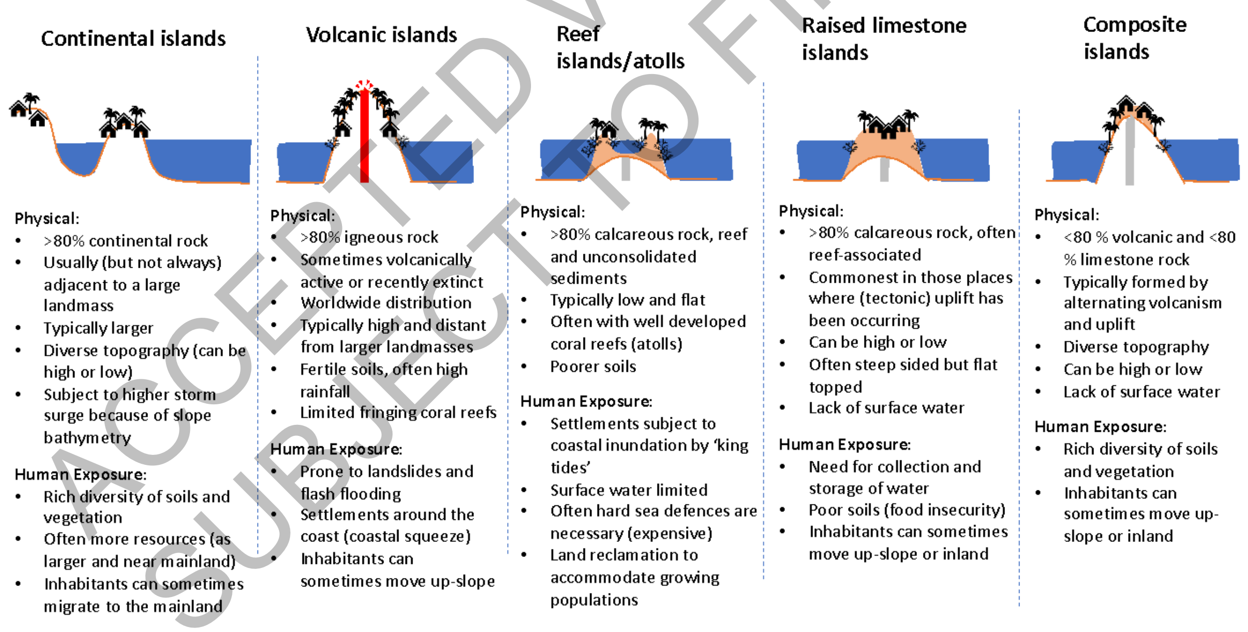


Figure 15.2: Classification of small island types - showing island characteristics and elements of human exposure (based on Nunn et al. (2016); Kumar et al. (2018)).

15.3.1 Synthesis of Observed and Projected Changes in the Physical Basis

There is increased evidence of warming in the small islands, particularly in the latter half of the 20th century (*high confidence*). The diversity of metrics and timescales used across studies makes it impossible to provide explicit comparisons, however Table 15.1 provides a summary of observed changes.

Table 15.1: Observed changes in basic climate metrics. RSLR: Relative Sea-Level Rise

Phenomenon	Location	Basic Trends	Specific Metric	Time period	Reference Literature
Air temp	West Pacific	Warmer	Increase in daily mean minimum temp by 0.14C/ decade	1951-2015	McGree et al. (2019)
Air temp	Caribbean	Warmer	Increase in daily minimum temp by 0.28C/ decade	1961-2010	Stephenson et al. (2014)
Air temp	Mediterranean	Warmer	Increase in annual mean surface temp 0.19-0.25C/ decade	1960-2005	Mariotti et al. (2015)
Land & Sea temp	Mediterranean	Warmer	Annual mean temperatures are now 1.54°C above the 1860-1890 level for land and sea		(MedECC, 2020)
Rainfall	Mediterranean	Drier	Decrease in annual mean precipitation by -0.6 mm/day/decade	1960-2005	Mariotti et al. (2015); Ducrocq et al. (2016)
Rainfall	Pacific Ocean	No clear pattern	No significant long-term trends in rainfall	1951-2015	McGree et al. (2019)
Rainfall	Indian Ocean	No clear pattern		1983-2015	Nguyen et al. (2018)
Rainfall	Caribbean	No clear pattern	No significant long-term trends in rainfall in the Caribbean over the 20th century	1901-2012	Jones et al. (2015)
Drought	Caribbean	Low confidence in the direction of change	Inconsistent between subregions and not statistically significant	1950-2016	Herrera and Ault (2017)
Drought	Pacific Ocean	Low confidence in the direction of change	Inconsistent between subregions and not statistically significant in the tropical Pacific. Significant decrease in Hawaii and sub-tropical South Pacific	1951-2015	McGree et al. (2016); McGree et al. (2019)
Tropical Cyclones	North Atlantic	Increase in intensity and decrease in frequency		1975-2009	Walsh et al. (2016)
Tropical Cyclones	Western North Pacific	Decreasing frequency	Decrease in frequency except over central North Pacific.	1977-2010	Walsh et al. (2016)
Tropical Cyclones	South Pacific	Increase in intensity and decrease in frequency		1989-2009	Walsh et al. (2016) Kuleshov et al. (2020)

Tropical Cyclones	Indian Ocean	No clear pattern	Poor data coverage	1961-2008	Tauvale and Tsuboki (2019); Kuleshov et al. (2020)
RSLR	East Caribbean	Greater than average	3-5mm/year	1993-2014	Becker et al. (2019)
RSLR	West/North Caribbean	Greater than average	2.5-3mm/year	1993-2014	Becker et al. (2019)
RSLR	Western Tropical Pacific	Greater than average	5-11mm/year	1993-2014	Becker et al. (2019)
RSLR	Mauritius/ Indian Ocean	Greater than average	4mm/year	1993-2014	Becker et al. (2019)
RSLR	Rodrigues/ Indian Ocean	Greater than average	6mm/year	1993-2014	Becker et al. (2019)

Some phenomena have no demonstrable trends in a region because of limited observed data, these include Tropical Cyclone (TC) frequency in the North-Eastern Pacific and Indian Oceans (Walsh et al., 2016); other phenomena are too variable to detect an overarching trend, including rainfall in regions where inter-annual and decadal variabilities such as the El Niño-Southern Oscillation, North Atlantic Oscillation, Pacific Decadal Variability, Atlantic Multidecadal Variability are dominant (Jones et al., 2015; McGree et al., 2019).

There are also marked regional variations in the rates of Sea Level Rise (SLR) (Merrifield and Maltrud, 2011; Palanisamy et al., 2012; Esteban et al., 2019) and Relative (that is, incorporating land movement) Sea-level Rise (RSLR). Various factors, including interannual and decadal sea level variations associated with low frequency modulation of ENSO and the Pacific Decadal Oscillation (PDO) and vertical land motion contribute to both relative sea-level variations and related uncertainties. Increased distant-source swell height from extra-tropical cyclones (ETCs) also contributes to Extreme Sea Levels (ESLs) (Mentaschi et al., 2017; Vitousek et al., 2017). Together, these stressors increase ESLs and their impacts, including coastal erosion and marine flooding and their impacts on both ecosystems and ecosystem services and human activities (Section 15.3.3.1 and Table 15.3).

Like observed impacts, projected impacts include some high confidence assessments, which are distributed across a diversity of models, timescales, and metrics. Generalised trends, and specific projections when available, are provided in Table 15.2. However, actual values and spatial distribution of precipitation changes remain uncertain as they are strongly model dependent (Paeth et al., 2017). Furthermore, the current capabilities of climate models, to adequately represent variability in climate drivers including ENSO, and the topography of small islands, limit confidence in these future changes (Cai et al., 2015a; Harter et al., 2015; Guilyardi et al., 2016).

Table 15.2: A small subset of projected changes in basic climate metric. Med=Mediterranean; NC=no change
[INSERT TABLE 15.2 HERE]

15.3.2 Trends in Exposure and Vulnerability

Most of the research that has been conducted on exposure and vulnerability from climate change demonstrates that factors including those that are geopolitical and political, environmental, socio-economic and cultural, together conspire to increase exposure and vulnerability of small islands (Box 15.1; Betzold, 2015; McCubbin et al., 2015; Duvat et al., 2017b; Otto et al., 2017; Weir et al., 2017; Taupo et al., 2018;

Barclay et al., 2019; Hay et al., 2019a; Ratter et al., 2019; Salmon et al., 2019; Bordner et al., 2020; Douglass and Cooper, 2020; Duvat et al., 2020a). Additional pressures on coastal and marine environments, including overexploitation of natural resources, may further exacerbate possible impacts in the future (Bell et al., 2013; Pinnegar et al., 2019; Siegel et al., 2019).

Furthermore, these factors exacerbate climate change induced problems such as coastal flooding and erosion faced by small islands. These impacts continue to worsen, which put small islands at increasingly higher risk to the impacts of climate change (Box 15.1). There are multiple stressors that affect the vulnerability of small islands to climate change (McNamara et al., 2019).

The problems of increasing exposure and vulnerability is most clearly seen in atoll islands. For example, in the capital of Tuvalu, economic stressors, food related stressors, and overcrowding make the islands much more vulnerable to climate impacts including changing precipitation patterns, ESLs, intense strong winds, warming SST and ocean acidification (McCubbin et al., 2015). Small islands, in trying to address the problem of limited land availability, put in place practices that lead to increasing exposure for island people. In Majuro, Marshall Islands (Ford, 2012), Tarawa, Kiribati (Biribo and Woodroffe, 2013; Duvat, 2013), and the Maldives Islands (Kench, 2012; Naylor, 2015; Duvat and Magnan, 2019b), population growth has led to land reclamation and the building of coastal protection structures, such as seawalls. Land reclamation and coastal protection structures negatively impact coastal and marine ecosystems, including reefs and mangroves, which compromise the protection services that they deliver to island communities through wave energy attenuation and sediment supply (Gracia et al., 2018; Curnick et al., 2019; Duvat and Magnan, 2019a) and may impact the long term sustainable adaptive planning of islands (Giardino et al., 2018). In addition, these construction activities disrupt natural coastal processes, thereby causing coastal erosion, which in turn increases the risk of flooding (Yamano et al., 2007; Duvat et al., 2017b) (Figure 15.3). This becomes a vicious cycle, with more land reclamation necessary to accommodate growing populations. Land reclamation requires stabilisation by protection structures, which then contributes to environmental degradation that increases the exposure and vulnerability of the communities living in these atolls (Duvat et al., 2017b).

Figure 15.3: Percentage of current population in selected small islands occupying vulnerable land (the number of people on land that may be exposed to coastal inundation—either by permanently falling below MHHW, or temporarily falling below the local annual flood height) in 2100 under an RCP4.5 scenario (adapted from Kulp and Strauss (2019) using the CoastalDEM_Perm_p50 model). Positions on the map are based on the capital city or largest town.

15.3.3 Observed Impacts and Projected Risks on Natural Systems

15.3.3.1 Impacts on Marine and Coastal Systems

15.3.3.1.1 Submergence and flooding of islands and coastal areas

Recent studies confirmed that observed ESL events causing extensive flooding generally resulted from compound effects, including the combination of SLR (Section 3.2.2.2 and Cross-Chapter Box SLR in Chapter 3) with ETCs, TCs and tropical depressions (WGI AR6 Sections 11.7.1 and 11.7.2), ENSO-related high-water levels associated with high or spring tide and/or local human disturbances amplifying impacts (*high confidence*). For example, the major floods that occurred in 1987 and 2007 in the Maldives involved the combination of distant-source swells and high spring tides and the settlement of reclaimed low-lying areas (Box 15.1; Wadey et al., 2017). In the Tuamotu atolls, French Polynesia, the 1996 and 2011 floods were due to the combination of distant-source swells causing lagoon filling and the obstruction of inter-islet channels by human-built structures (Canavesio, 2019). In 2011, the flooding of the lagoon-facing coast of Majuro Atoll, Marshall Islands, resulted from the combination of high sea levels occurring during La Niña conditions and seasonally high tides (Ford et al., 2018). Another example is the widespread flooding caused by distant TC Pam (2015) in Kiribati and Tuvalu, which was attributed to the strong swell generated, the long duration of the event and exceptionally high regional sea levels (Hoeke et al., 2021). On high tropical islands, major floods often occurred during TC events, due to the cumulative effects of storm surge and river flooding, the impacts of which were exacerbated by human-induced changes to natural processes in urban areas. This for example occurred in 2014 (TC Bejisa) in Reunion Island, France, in a harbour area favourable to water accumulation (Duvat et al., 2016); in 2015 (TC Pam) in Port Vila, Vanuatu, where urbanisation and human-induced changes to the river exacerbated flooding (Rey et al., 2017); and in 2017 (TC Irma) in Saint-Martin, Caribbean, where urbanisation had the same effect (Rey et al., 2019). Successive tropical depressions generating heavy rains were also involved in extensive flooding, for example in 2012 in Fiji (Kuleshov et al., 2014) and in 2014 in the Solomon Islands (Ha'apio et al., 2019).

Reconstructions of past storm surges and modelling studies assessing storm surge risk similarly highlighted high variations of risk along island coasts, due to variations in exposure, topography and bathymetry (*high confidence*). For example, the storm surge caused by TC Oli (2010) on the high volcanic island of Tubuai, French Polynesia, ranged from a few centimetres to 2.5 m, depending on coast exposure (Barriot et al., 2016). Investigating the contribution of reef characteristics to variations in wave-driven flooding on Roi-Namur Island, Kwajalein Atoll, Marshall Islands, (Quataert et al., 2015) found that the coasts fronted by narrow reefs with steep fore reef slopes and smoother reef flats are the most flood-prone. Modelling studies assessing storm surge risk in Fiji (McInnes et al., 2014) and Samoa (McInnes et al., 2016) confirmed the influence of coast exposure and water depth on risk distribution. In Apia, Samoa, Hoeke et al. (2015, p. 1117) found "differences in extreme sea levels in the order of 1 m at spatial scales of less than 1 km" and estimated (p. 1131) that a "1 m SLR relative to constant topography increases wave energy reaching the shore by up to 200% during storm surges." These studies reaffirmed the main control exerted by SLR on ESL events and associated storm surges compared to ENSO (*high confidence*). In Hawaii and the Caribbean, SLR is projected to exponentially increase flooding, with nearly every centimeter of SLR causing a doubling of the probability of flooding (Taherkhani et al., 2020). Simulations of SLR-induced flooding resulting from the combination of (i) direct marine flooding, (ii) flow reversal in drainage networks caused by extreme tide levels and (iii) the elevation of groundwater levels, at Honolulu, Hawaii, highlighted the major influence of this latter component (which is the most difficult to manage), as well as the increase of the proportion of triple-mechanism flooding as sea level rises (Habel et al., 2020). Where coral reefs buffer flooding through wave attenuation, flooding will be further aggravated by reef decline over time (Section 15.3.3.1.3).

Larger-scale studies confirmed that projected changes in the wave climate superimposed on SLR will rapidly increase flooding in small islands, despite highly contrasting exposure profiles between ocean sub-regions (*high confidence*) (Shope et al., 2016; Mentaschi et al., 2017; Shope et al., 2017; Vitousek et al., 2017; Morim et al., 2019). In particular, Vitousek et al. (2017) showed that even a 5-10 cm additional SLR (expected for ~2030–2050) will double flooding frequency in much of the Indian Ocean and Tropical Pacific, while TCs will remain the main driver of (rarer) flooding in the Caribbean Sea and Southern Tropical Pacific (Figure 15.3). Some Pacific atoll islands, which already experience major floods, will *likely* undergo annual wave-driven flooding over their entire surface from the 2060s–2070s (Storlazzi et al., 2018) to 2090s (Beetham et al., 2017) under RCP8.5, although future reef growth may delay the onset of flooding (*limited evidence, low agreement*) (Key Risk KR2 in Figure 15.5).

15.3.3.1.2 Reef island destabilisation and coastal erosion

Over the past three to five decades, shoreline changes were dominated by stability on reef islands and erosion on high islands; attribution of observed erosion to SLR and other climate change-related drivers is challenged by the complex interplay of multiple climatic, ecological and human drivers (*high confidence*). Since the 1950s-1970s, and even in regions exhibiting higher than global averaged SLR rates, atoll islands maintained their land area (*high confidence).* A literature review including 709 Indian and Pacific Oceans atoll islands showed that 73.1% of these islands were stable in area, while respectively 15.5% and 11.4% increased and decreased in area (Duvat, 2018). The rates of change did not correlate with SLR rates, suggesting that the impact of SLR on island land area was obscured by other climate drivers and human disturbances on some islands (*high confidence*) (Kench et al., 2015; McLean and Kench, 2015; Duvat, 2018). However, reef island disappearance and reduction in land area was clearly observed in New Caledonia and the Solomon Islands, and was attributed to the synergistic interactions of gradual SLR with stronger trade winds causing higher sea levels and local tectonics in the Solomon Islands (Albert et al., 2016; Garcin et al., 2016). Despite important knowledge gaps on coastal erosion in high tropical islands, recent studies confirmed increasing shoreline retreat and beach loss over the past decades, mainly due to TC and ETC waves and human disturbances (*high confidence*) (e.g., in the Caribbean region: Anguilla, Saint-Kitts, Nevis, Montserrat, Dominica and Grenada (Cambers, 2009; Reguero et al., 2018)), and Pacific (Hawaii (Romine and Fletcher, 2013); Tubuai, French Polynesia (Salmon et al., 2019)) and Indian Oceans (Anjouan, Comoros (Ratter et al., 2016)).

Despite storm-induced erosion prevailing along some shoreline sections, recent studies reaffirmed the contribution of TC and ETC waves to coastal and reef island vertical building through massive reef-to-island sediment transfer *(high confidence*). For example, TC Ophelia (1958) and Category 5 TC Fantala (2016), which respectively eroded the islands of Jaluit Atoll, Marshall Islands (Ford and Kench, 2016), and Farquhar Atoll, Seychelles (Duvat et al., 2017c), also contributed to island and beach expansion. Likewise, tropical depressions can have constructional effects, as reported on Fakarava Atoll, French Polynesia (Duvat et al., 2020b). On Saint-Martin/Sint Maarten and Saint-Barthélemy, the 2017 hurricanes, which caused marked shoreline retreat at most beach sites, also allowed beach formation and beach ridge development along some natural coasts (Duvat et al., 2019a; Pillet et al., 2019). Similarly, El Niño and La Niña were involved in rapid and highly contrasting shoreline changes (*high confidence*), including reef island accretion in the Ryukyu Islands, Japan (Kayanne et al., 2016), beach shifts on Maiana and Aranuka Atolls, Kiribati (Rankey, 2011), and beach erosion on Hawaii, USA (Barnard et al., 2015). These contrasting shoreline responses were respectively due to coral reef degradation from past bleaching events providing material to islands, wave directional shifts, and increased wave energy. The role of bleaching events in increasing short-term sediment generation in atoll contexts was confirmed by a study conducted on Gaafu Dhaalu Atoll, Maldives, which reported an increase of sediment production from ~0.5 kg CaCO3 m–2 yr^{-1} to ~3.7 kg CaCO3 m-2 yr^{-1} between 2016 (pre-bleaching) and 2019 (bleaching + 3 years) (Perry et al., 2020).

There is *high confidence* that accelerating SLR and increased wave height will affect the geomorphology of reef islands (Baldock et al., 2015; Costa et al., 2019; Tuck et al., 2019) and coastal systems on high islands (Grady et al., 2013; Barnard et al., 2015; Bindoff et al., 2019), and that the responses of these systems will highly depend on changes in boundary conditions (wave regime and direction, exposure to extreme events, impacts of ocean warming and acidification on supporting ecosystems, bathymetry and reef flat roughness) and the degree of disturbance of their natural dynamics by human activities (Smithers and Hoeke, 2014; McLean and Kench, 2015; Bheeroo et al., 2016; Ratter et al., 2016; Shope et al., 2016; Duvat et al., 2017a; Kench and Mann, 2017; Kench et al., 2018; Duvat et al., 2019a). Reef islands and beach and beach-dune systems that are not disturbed by human activities are respectively expected to migrate lagoonward (Webb and Kench, 2010; Albert et al., 2016; Beetham et al., 2017; Costa et al., 2019; Tuck et al., 2019) and landward (Bindoff et al., 2019), and to also experience increased erosion as well as changes in configuration, volume and elevation (Kench and Mann, 2017; Tuck et al., 2019) (Bramante et al., 2020; Kane and Fletcher, 2020). Small reef islands and narrow coastal systems affected by human disturbances will increasingly be at risk of disappearance due to SLR (KR2 in Figure 15.5), enhanced sediment loss caused by extreme events (Duvat et al., 2019a) and/or human activities (*high confidence*), as reported in Hawaii (Romine and Fletcher, 2013), Puerto Rico (Jackson et al., 2012), Sicily (Anfuso et al., 2012), and Takuu, Papua New Guinea (Mann and Westphal, 2014). SLR will also increase coastal erosion in the Mediterranean Sea, (e.g., in the Aegean Archipelago, Greece (Monioudi et al., 2017)), and Mallorca, Spain (Enríquez et al., 2017).

15.3.3.1.3 Impacts on marine and coastal ecosystems

Loss of marine and coastal biodiversity and ecosystem services is a Key Risk in small islands (see KR1 in Figure 15.5). Coral bleaching caused by elevated water temperatures is the most visible and widespread manifestation of a climate change impact on coastal ecosystems in most small islands but is far from being the only one (Section 3.4.2.1; Section 5.3.4; Spalding and Brown, 2015; Hoegh-Guldberg et al., 2017; IPCC, 2018; Bindoff et al., 2019; Sully et al., 2019). Severe coral bleaching, together with declines in coral abundance have been documented in many small islands, especially those in the Pacific and Indian Oceans,(e.g., Guam, Fiji, Palau, Vanuatu, Chagos, Comoros, Mauritius, Seychelles, and the Maldives (*high confidence*) (Box 15.1; Golbuu et al., 2007; Woesik et al., 2012; Perry and Morgan, 2017; Hughes et al., 2018). During severe bleaching events, not only do reefs lose a significant amount of live coral cover, but they also experience a decrease in growth potential, so reef erosion surpasses reef accretion (Perry and Morgan, 2017). Median return time between two severe bleaching events has diminished steadily since 1980 and is now only 6 years (e.g.,Hughes et al., 2017b; Hughes et al., 2018) and is often associated with warm phase of ENSO events (*high confidence*) (Lix et al., 2016). Modelling of both bleaching and ocean acidification effects under future climate scenarios suggested that some Pacific small islands (e.g., Nauru, Guam, Northern Marianas Islands) will experience conditions that cause severe bleaching on an annual basis before 2040 and that 90% of the world reefs are projected to experience conditions that result in severe bleaching annually by 2055 (*medium confidence*) (van Hooidonk et al., 2016). Models are currently predicting the large-scale loss of coral reefs by mid-century under even low-emissions scenarios. Even achieving emissions reduction targets consistent with the ambitious goal of 1.5°C of global warming under the Paris Agreement will result in the further loss of 70–90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2°C or more above the pre-industrial period (*high confidence*) (Hoegh-Guldberg et al., 2018).

Satellite data and local field studies at 3351 sites in 81 countries including small islands show that not all coral reefs are equally exposed to severe temperature stress events, and even similar coral reefs exposed to similar conditions show local and regional variation and species-specific responses (Sully et al., 2019). There is great variability in terms of sensitivity of corals to climate change, as also demonstrated in the Comoros Archipelago (Cowburn et al., 2018), in the Pacific (Fox et al., 2019; Mollica et al., 2019; Romero-Torres et al., 2020) and globally (Sully et al., 2019; McClanahan et al., 2020). It has been hypothesised that low-latitude tropical reefs bleached less than those in higher latitudes because: (i) of the geographical differences in species composition, (ii) of the higher genotypic diversity at low latitudes, and (iii) some corals were pre-adapted to thermal stress because of consistently warmer temperatures at low latitude prior to thermal stress events (Sully et al., 2019). However, latitudinal variation was not reported in other global surveys of coral bleaching occurrence (Donner et al., 2017; Hughes et al., 2017a; Hughes et al., 2017b; McClanahan et al., 2019). Ainsworth et al. (2016) and Ateweberhan et al. (2013) showed that coral bleaching can be mitigated by pre-exposure to elevated temperatures. Regionally, recovery is also highly variable. While some reefs in the Seychelles and Maldives were shown to recover to pre-disturbance levels of coral cover after previous bleaching events (Box 15.1; Pisapia et al., 2016; Koester et al., 2020), other reefs underwent seemingly permanent regime shifts toward domination by fleshy macro algae (Graham et al., 2015), or major declines in carbonate budgets, and thus the capacity of reefs to sustain vertical growth under rising sea levels (Perry and Morgan, 2017).

Despite their vital social and ecological value, substantial declines in seagrass communities have been documented in many small islands (Section 3.4.2.5; Arias-Ortiz et al., 2018; Kendrick et al., 2019; Brodie et al., 2020), including Fiji (Joseph et al., 2019), Reunion Island (Cuvillier et al., 2017), Bermuda, Cayman Islands, US Virgin Islands (Waycott et al., 2009), Kiribati (Brodie et al., 2020), Federated States of Micronesia, and Palau (Short et al., 2016), but attribution of such declines to climatic influences remains weak (*low confidence*). Impact of climate change on seagrasses goes beyond the loss of seagrass but includes acceleration of seagrass decomposition (Kelaher et al., 2018), palatability (Jimenez-Ramos et al., 2017) and the cumulative effect of warming and eutrophication (Ontoria et al., 2019). Seagrasses face a multitude of threats including physical disturbance and direct damage caused by rapidly growing human populations, declines in water quality, and coastal erosion (Short et al., 2016). Experimental studies have shown increased mortality, leaf necrosis, and respiration when seagrasses are exposed to higher-than-normal temperatures (Hernan et al., 2017). As such, seagrass meadows growing near the edge of their thermal tolerance are at risk from rising temperatures (Pedersen et al., 2016). In the Mediterranean, seagrass meadows are already showing signs of regression, which may have been aggravated by climate change (*high confidence*). Some studies suggest seagrasses have potential for acclimation and adaptation (Duarte et al., 2018; Ruiz et al., 2018; Beca-Carretero et al., 2020). Chefaoui et al. (2018) attempted to forecast the distribution of two seagrasses in the future, including around the islands of Cyprus, Malta, Sicily and the Balearic Islands. Under the worst-case scenario, *Posidonia oceanica* was projected to lose 75% of suitable habitat by 2050. Conversely, it has been suggested that seagrasses could actually benefit from an increase in anthropogenic carbon dioxide because of increased growth and photosynthesis (Hopley et al., 2007; Waycott et al., 2011; Sunday et al., 2016; Repolho et al., 2017). However, Collier et al. (2017) argued that when faced with increased heat waves, thermal stress will rarely be offset by the benefit of elevated CO_2 and therefore that the widespread belief that seagrasses will be a ‘winner’ under future climate change conditions seems unlikely *(low confidence*).

Since 2011, the Caribbean region has been experiencing unprecedented influxes of the pelagic seaweed *Sargassum*. These extraordinary sargassum ‘blooms’ have resulted in mass strandings of sargassum throughout the Lesser Antilles, with significant damage to coastal habitats, mortality of seagrass beds and associated corals (van Tussenbroek et al., 2017), as well as consequences for fisheries and tourism. Whether or not such events are related to long-term climate change remains unclear, however it has been suggested that the influx may be related to strong Amazon discharge, enhanced West African upwelling, together with rising seawater temperatures in the Atlantic (*low confidence*) (Oviatt et al., 2019; Wang et al., 2019). Since 2011, the Pacific atoll nation of Tuvalu has also been affected by algal blooms, the most recent being a large growth of *Sargassum* on the main atoll of Funafuti, and this phenomenon has been related to anthropogenic eutrophication and high seawater temperatures (De Ramon N’Yeurt and Iese, 2014).

Mangroves face serious risks from deforestation and unsustainable coastal development (Section 3.4.2.5; Gattuso et al., 2015). Large-scale die-offs around many small islands suggest that mangrove face increased risks from climate change (Sippo et al., 2018). Mangrove seaward edge retreat has been demonstrated in American Samoa and at Tikina Wai in Fiji, in Bermuda, West Papua, Grand Cayman and attributed to long-term SLR or tectonic subsidence (Ellison, 1993; Ellison, 2005; Gilman et al., 2007; Ellison and Strickland, 2015). Inundation-related mortality of mangroves could, in theory, be mitigated if mangrove substrates can “keep up” with rising sea level by accretion. Pacific Island studies using radionuclides (e.g., 210Pb, 137Cs) have suggested that most mangroves are keeping up with current rates of sea level rise (Alongi, 2008; MacKenzie et al., 2016), while surface elevation tables SETs suggest otherwise. Lovelock et al. (2015) reported that nearly 70% of the mangroves monitored with SETs are not keeping up with current SLR rates. If SLR exceeds 6 mm/yr, mangroves may be unable to maintain their elevation relative to sea level, a threshold likely to be surpassed in the next 30 years under high emission scenarios (Ellison, 1993; Saintilan et al., 2020). In these worst-case scenarios, flooding would result in tree, root, and rhizome death and an abrupt change in elevation through peat collapse (Krauss et al., 2010; Lang'at et al., 2014), creating a positive feedback loop between SLR and elevation loss. Geomorphology, hydrology, tidal range, and suspended sediments are important factors that will determine if mangroves will survive increased rates of SLR (Lovelock et al., 2015; Sasmito et al., 2015; Rogers et al., 2019). TCs can cause extensive damage to mangroves (Short et al., 2016). While immediate physical damage is often considerable, trees can sometimes recover by re-foliating, re-sprouting or regenerating (Kauffman and Cole, 2010). Examples of substantive mangrove recovery include the regrowth of trees in the Bay Islands of Honduras following Hurricane Mitch (October 1998) (Fickert, 2018) and in the Nicobar Islands, India, following the December 2004 Indian Ocean Tsunami (Nehru and Balasubramanian, 2018).

Sandy beaches are an important ecosystem in small islands, with high socio-economic as well as ecosystem services value (Ellison, 2018). Turtles and many seabirds nest just above the high-water mark on sandy beaches or among sand dunes, but TCs, rising seas, storm surges and heavy rainfall as well as inappropriate coastal development can erode beaches (Section 15.3.1.2) resulting in damage to nests and eggs (Fuentes et al., 2011). Beach-nesting turtle populations are projected to become threatened around many small islands as a result of future climate change (e.g., Bonaire - Netherlands Antilles (Fish et al., 2005), Bioko Island - Equatorial Guinea (Veelenturf et al., 2020), Cyprus (Varela et al., 2019), Raine Island – Australia (Pike et al., 2015)), although other populations such as those around the Cape Verde Islands are projected to remain relatively robust (Abella Perez et al., 2016). Turtles are also threatened by temperature rise around some small islands as warmer temperatures on nesting beaches can lead to an unbalanced sex-ratio in the population (e.g. St. Eustatius island, (Laloë et al., 2016)).

15.3.3.1.4 Marine and coastal ecosystem services

Intact coral reefs (Woodhead et al., 2019), seagrass meadows (Hejnowicz et al., 2015), and mangroves (UNEP, 2014b) (Friess, 2016) provide a variety of ecosystem services that are key to island communities, including provisioning services (e.g., timber, fisheries, aquaculture), regulating services (e.g., coastal protection, carbon storage, filtering of pollutants), cultural services (Pascua et al., 2017) as well as supporting community resilience (Förster et al., 2019). If coastal ecosystems are degraded and lost, then the benefits they provide are also lost (Oleson et al., 2018; Förster et al., 2019; Brodie et al., 2020). In small islands where the risk of loss to ecosystem services is high (Cross-Chapter Box DEEP in Chapter 17), many of these ecosystem services cannot be easily replaced (*medium confidence*). The beneficial role that coral reefs play in coastal protection through wave attenuation, and therefore enhancing climate resilience in small islands, has been extensively studied (e.g., Elliff and Silva, 2017; Harris et al., 2018; Reguero et al., 2018). Indeed, it has been demonstrated that in small islands (such as the Cayman Islands, Grenada, Bahamas) averted damages as a result of protecting intact coral reefs, can be considerable when expressed as a percentage of GDP (Beck et al., 2018). Ferrario et al. (2014) conducted a global meta-analysis including many small islands across the Atlantic, Pacific and Indian Oceans and found that coral reefs reduce wave height by an average of 84% (and wave energy by 97%) and that reef crests alone dissipate most of this energy. Based on another meta-analysis of 69 case studies worldwide (wave heights measured before and after the habitat), Narayan et al. (2016) observed that coral reefs, mangroves, and seagrass reduced wave height by 70%, 31% and 36%, respectively (Figure 15.4) and thus perform an essential role in protecting human lives and livelihoods (*high confidence*). Post-TC studies have provided additional evidence for the protection services offered by coastal ecosystems. On some Caribbean islands (e.g., Saint-Martin/Sint Maarten) where the dense indigenous vegetation belt was preserved, the vegetative structure buffered the waves of TCs Irma and José (2017), reducing the extent of marine inundation and shoreline retreat to a 30 m-wide coastal strip against values >160 m in deforested areas (Duvat et al., 2019a; Pillet et al., 2019). By contrast, the destruction of mangrove ecosystems, even a few trees around the fringes, can accelerate coastal erosion, as exemplified by observations in Micronesia (Krauss et al., 2010; Nunn et al., 2017a).

As corals, mangroves and seagrasses disappear, so do fish and other dependent organisms that directly benefit industries such as ecotourism and fisheries (*high confidence*) (Graham et al., 2015; Cinner et al., 2016). These impacts are sometimes exacerbated by catastrophic events such as tropical storms and marine heatwaves that destroy habitats and hence the resources upon which coastal fisheries depend (Sainsbury et al., 2018). There is *high confidence* that climate change impacts, together with local human disturbances, will continue to denude coastal and marine ecosystem services in many small islands with serious consequences for vulnerable communities (Elliff and Silva, 2017; Bindoff et al., 2019).

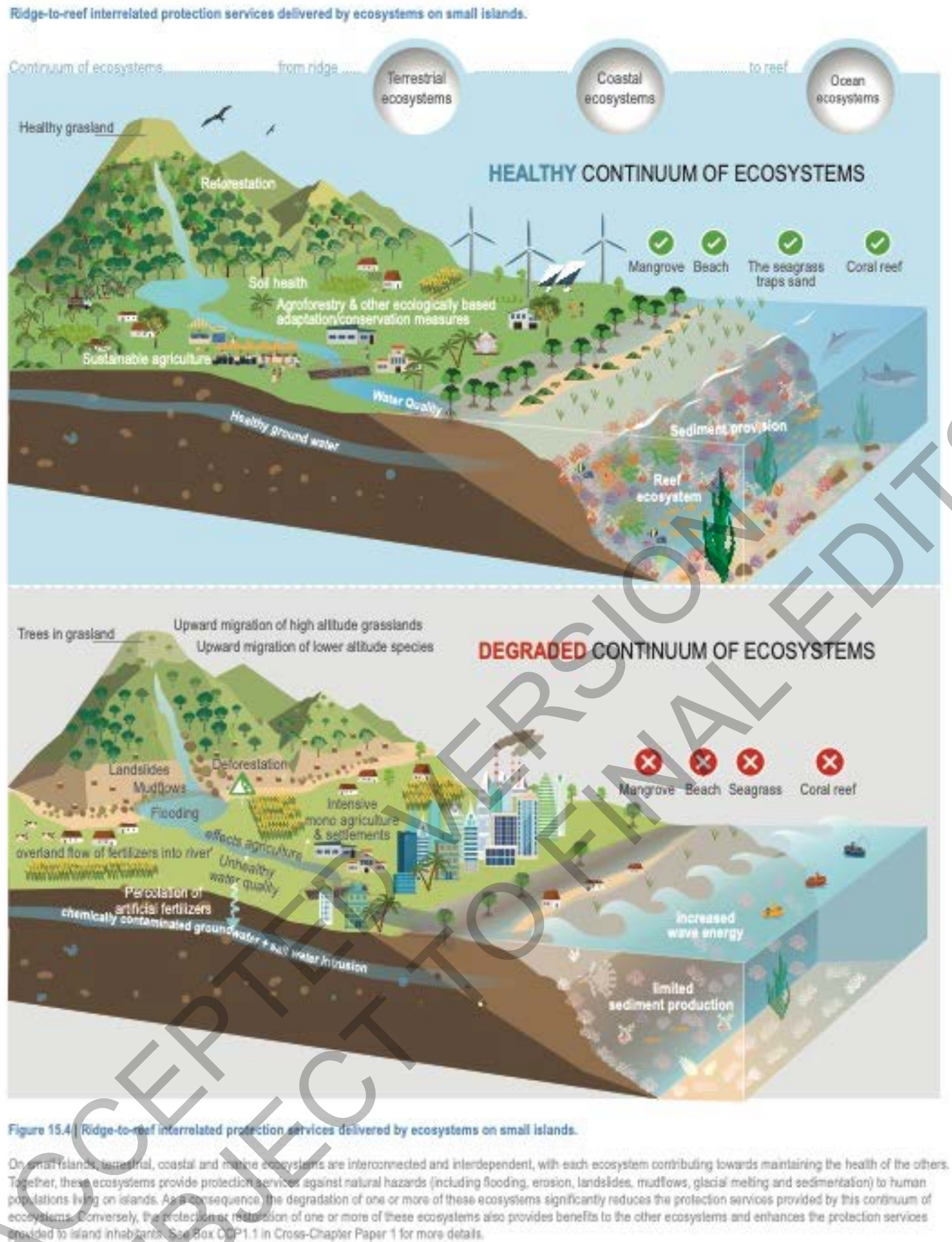


Figure 15.4: Ridge-to-reef interrelated protection services delivered by ecosystems on small islands. On small islands, terrestrial, coastal and marine ecosystems are interconnected and interdependent, with each ecosystem contributing towards maintaining the health of the others. Together, these ecosystems provide protection services against natural hazards (including flooding, erosion, landslides, mudflows, glacial melting and sedimentation) to human populations living on islands. As a consequence, the degradation of one or more of these ecosystems significantly reduces the protection services provided by this continuum of ecosystems. Conversely, the protection or restoration of one or more of these ecosystems also provides benefits to the other ecosystems and enhances the protection services provided to island inhabitants. See Box CCP1.1 for more details.

15.3.3.2 Impacts on Freshwater Systems

Freshwater systems on small islands are exposed to dynamic climate impacts and are considered to be among the most threatened on the planet (Key Risk 3 in Box 15.1; Settele et al., 2014; IPCC, 2018; Butchart et al., 2019). Hoegh-Guldberg et al. (2019) estimated that freshwater stress on small islands would be 25%

less with a warming of 1.5°C or less as compared to 2.0°C. While some island regions are projected to experience substantial freshwater decline, an opposite trend is observed for some western Pacific and northern Indian Ocean islands (Holding et al., 2016; Karnauskas et al., 2016). Island topography and ecophysiology influence water storage capacity and rainfall response potential (Dunn et al., 2018). On high volcanic and granitic islands, freshwater ecosystems are often closely connected with coastal spaces, and changes in freshwater supply from river systems have direct implications for salinity and sediment loads (*high confidence*) (Yang et al., 2015; Zahid et al., 2018). Climate impacts on streamflow patterns in tropical islands also create shifts in water supply for downstream users and habitat conditions for organisms supporting a wide range of ecosystem services (*high confidence*) (Strauch et al., 2015; Frazier and Brewington, 2019; Frauendorf et al., 2020).

Projected changes in aridity are expected to impose freshwater stress on many small islands, especially SIDS *(high confidence*).These changes are congruent with drought risk projections for Caribbean SIDS (Lehner et al., 2017; Taylor et al., 2018) and aligned with observations from the Shared Socio-Economic Pathway (SSP) 2 scenario, where a 1°C increase in temperature (from 1.7°C to 2.7°C) could result in a 60% increase in the number of people projected to experience a severe water resources stress from 2043–2071 (Schewe et al., 2014; Karnauskas et al., 2018). In the Mediterranean region, freshwater resources will decline 10–30% *(medium confidence)* (Koutroulis et al., 2016; Kumar et al., 2020). For example, analysis of annual and seasonal streamflow data on the island of Mallorca shows a decreasing trend during spring and summer, with a reduction of up to 17% in some basins (Garcia, 2017).

The influence of climate change spans several variables for atoll islands with multiple, interacting forces that exacerbate impacts on freshwater ecosystems (Connell, 2016), including groundwater and freshwater resources (Warix et al., 2017). Analysis of groundwater resources on Roi-Namur, in the Marshall Islands, reveals that the extent of salinisation of fresh groundwater lenses varies with the scale of the overwash (Gingerich et al., 2017). Alsumaiei and Bailey (2018) estimated an 11-36% reduction in the fresh groundwater lens volume of the small atoll islands (area < 0.6 km²) of the Maldives due to SLR. Small overwash events lead to saline conditions that last for up to 3 months (Oberle et al., 2017).

SLR undermines the long-term persistence of freshwater-dependent ecosystems on islands (Goodman et al., 2012) and is one of the greatest threats to the goods and services these environments provide (Box 16.1; Mitsch and Hernandez, 2013). Hoegh-Guldberg et al. (2019) posit that as sea level rises, managing the risk of salinisation of freshwater resources will become increasingly important. On Roi-Namur, Marshall Islands, Storlazzi et al. (2018) found that the availability of freshwater is impacted by the compounding effect of SLR and coastal flooding. In other Pacific atolls, Terry and Chui (2012) showed that freshwater resources could be significantly affected by a 0.40 m SLR. Similar impacts are anticipated for some Caribbean countries (Stennett-Brown et al., 2017). Such changes in SLR could increase salinity in estuarine and aquifer water, affecting ground and surface water resources for drinking and irrigation water (Mycoo, 2018a) across the region (*high confidence*). SLR also affects groundwater quality (Bailey et al., 2016), salinity (Gingerich et al., 2017), and water-table height (Masterson et al., 2014).

15.3.3.3 Impacts on Terrestrial Biodiversity Systems

Despite encompassing approximately two percent of the Earth's terrestrial surface, oceanic and other high-endemicity islands are estimated to harbour substantial proportions of existing species including ~ 25% extant global flora, ~ 12% birds and ~10% mammals (Alcover et al., 1998; Wetzel et al., 2013; Kumar and Tehrany, 2017). Islands also have higher densities of critically endangered species, hosting just under half of all species currently considered to be at risk of extinction (Spatz et al., 2017a; Spatz et al., 2017b), hence making the loss of terrestrial biodiversity and related ecosystem services a Key Risk (KR3) for small islands (Figure 15.5). Impacts from developing synergies between changing climate, natural and anthropogenic stressors on islands (Cross-Chapter Box DEEP in Chapter 17) could lead to disproportionate changes in global biodiversity. The most prominent drivers include: SLR, increasing intensities of extreme events (human activities — especially continuing/accelerating habitat destruction/degradation) and the introduction of invasive alien species (IAS) (Tershy et al., 2015). When coupled with characteristic small island traits such as spatial and other resource limitations, these synergies play a critical role towards increasing the vulnerability of these insular ecosystems (Box CCP1.1). This is likely to hinder the adaptation response of terrestrial biota ─ increasing the risk of biodiversity loss and in turn, impairing the resilience capacity of ecosystem functioning and services (*high confidence*) (Heller and Zavaleta, 2009; Ferreira et al., 2016; Vogiatzakis et al., 2016).

Current observations of insular species response to climate change generally report geographic range shifts/reductions for species and vegetation associations in addition to resulting impacts on local ecology (Virah-Sawmy et al., 2016; Koide et al., 2017; Maharaj et al., 2019). These include changes in plant/animal phenology and resulting community alterations such as for the common Mediterranean island species *Quercus ilex* (holly oak) and *Ficus carica* (common fig). Species have been shifting greater distances to access not only suitable climate conditions but also by association, suitable breeding conditions and seasonal food. Examples include: migratory birds such as *Coturnix coturnix* now having earlier spring arrival dates in the Mediterranean compared to six decades ago and the increased mortality of the iconic *Argyroxyphium sandwicense* (Hinahina) as result of warmer drier trends at Hawaiian high altitudes (Krushelnycky et al., 2012; Taylor and Kumar, 2016a; Vogiatzakis et al., 2016). There have also been die-offs of some species from temperature extremes (e.g., flying fox species: *Pteropus* species) within the Pacific islands (Taylor and Kumar, 2016a).

Recorded alterations of ecological interactions include increased competition, changes to migratory routes (Harter et al., 2015) and mismatches between species, such as increased pathogen attacks on Mediterranean forest species (Vogiatzakis et al., 2016). Also, in some areas of Madagascar there has been increased vulnerability to fire, due to the replacement of succulents by less fire resilient species (Virah-Sawmy et al., 2016). Further, the low functional redundancy of island ecosystems implies a comparatively higher proportion of keystone species than continents, many of them being endemics (Harter et al., 2015), with potentially unpredictable system consequences due to climate-induced ecological changes. For example, Caribbean land crabs have been observed to alter their food intake as a response to drying conditions (McGaw et al., 2019) and Aldabra giant land tortoises have reduced their activity in response to increasing temperature and decreasing precipitation (Falcon and Hansen, 2018); such changes in both these ecosystem engineers are of potential consequence for seed dispersal, among other ecological functions.

The majority of studies modelling geographical range changes of small island species, to even the most optimistic 21st century climate change scenarios imply a reduction in climate refugia (Table 15.3, Box CCP1.1). This is due to projected strong shifts, reductions or even complete losses of climatic niches resulting from inadequate geographic space for species to track suitable climate envelopes (*high confidence*) (e.g., Maharaj and New, 2013; Fortini et al., 2015; Struebig et al., 2015b). Because of the high proportion of global endemics hosted within small and especially isolated islands, the resulting increased extinction risk of such species (up to 100%) could lead to disproportionate losses in global biodiversity (m*edium to high confidence*) (Harter et al., 2015; Manes et al., 2021).

SLR has been projected to impact the terrestrial biodiversity of low-lying islands and coastal regions via large habitat losses both directly (e.g., submergence) and indirectly (e.g., salinity intrusion, salinisation of coastal wetlands and soil erosion) at even the 1m scenario (*medium to high confidence*). However, these impacts vary depending on the islands' topographical differences. In a study of SLR impacts on insular biodiversity hotspots, (Bellard et al., 2013a) reported that the Caribbean islands, Sundaland and the Philippines were projected to suffer the most habitat loss while the East Melanesian islands were projected to be lesser (but not minimally) affected. The most threatened of these, the Caribbean, was projected to have between 8.7% to 49.2% of its islands entirely submerged respectively from 1m to 6 m SLR (Bellard et al., 2013a). However, many current projection studies consider marine flooding directly and seldom incorporate other indirect impacts such as increased habitat losses from horizontal erosion loss, increased salinity levels, tidal ranges and extreme events. These projections are considered to be conservative, underestimating the extent of habitat loss to terrestrial biodiversity (Bellard et al., 2013b).

Marine flooding is expected to destroy habitats of coastal species, particularly range-restricted coastal and/or single-island endemics (many already listed as *at least* 'threatened' by the International Union for Conservation of Nature [IUCN]) within the limited terrain on atoll islands. These species have limited opportunities to accommodate such direct impacts of climate change apart from shifting further inland or to other neighbouring atolls which might have favourable habitat. However, fragmentation of habitat due to anthropogenic activity may hinder migration further inland, while shifting to neighbouring islands is not viable due to the water barrier between islands (*high confidence*) (Bellard et al., 2013b; Wetzel et al., 2013;

Kumar and Tehrany, 2017). Additionally, migratory birds, which use small islands (e.g. atolls) for stopovers or breeding/nesting sites, are projected to become impacted. Within the Mediterranean and Caribbean, significant losses to coastal wetlands - critical habitat for migratory birds has already been observed, with further significant habitat losses, redistribution and changes in quality being projected across island systems such as the Bahamas (Caribbean) and Sardinia (Mediterranean) (Vogiatzakis et al., 2016; Wolcott et al., 2018).

Indirect impacts of SLR may potentially result in equal or more biodiversity loss than direct impacts (*medium confidence*). Relocation of displaced coastal human populations and associated intensive agriculture and urban areas inland to natural habitat may result in greater biodiversity loss than direct impacts – especially on islands with large coastal populations and urban centres (Wetzel et al., 2012; Bellard et al., 2013b). Given the dense population of insular hotspots (~31.8% of existing humans within ~ 15.9% of inhabited global land area) and the fact that on many islands, large proportions of human populations live within coastal regions, it has been suggested that immense impacts from such relocations should be factored into projection and adaptation studies (Wetzel et al., 2012).

Tropical island natural habitats/systems are highly vulnerable to extreme weather events such as TCs, due to their small size, unique ecological systems and often low socio-economic capacity (*high confidence*) (Box 15.2; Goulding et al., 2016; Schütte et al., 2018). Growing evidence suggests high resilience of forest habitats (Keppel et al., 2014; Luke et al., 2017), especially within intact forest ecosystems to hurricanes and cyclones (Goulding et al., 2016). While initial damage can be high, relatively fast recovery rates have been reported for both floral and faunal components of these ecosystems (Cantrell et al., 2014; Shiels et al., 2014; Monoy et al., 2016; Richardson et al., 2018). Within the Caribbean in particular, high resilience of forest types has been associated with the *current* intensity and return rate of hurricanes over the last 150 years.

It should however be underscored that these relatively fast recovery rates are associated with the *present* intensity and return rate of TCs. They do not reflect the impacts of increasingly intense events such as Hurricane Dorian (2019), which resulted in almost complete inundation of several low-lying islands of the Bahamas from storm surges. Severe weather events also have indirect effects on islands' biodiversity — interacting synergistically with other stressors, such as increased invasion by non-native species and land use change. For example, TCs within Papua New Guinea resulted in the destruction of subsistence gardens, which led inhabitants to clear forest areas for new farming areas and for harvesting of timber resources to rebuild (Goulding et al., 2016).

The most recent projections suggest that TC intensity is predicted to increase as climate continues to change (Walsh et al., 2016; Kossin et al., 2017). There are too few studies available to suggest potential future response trends of these ecosystems to this increased intensity, however it seems plausible that present resilience capacities may be adversely impacted (*medium confidence*) (Marler, 2014). Further, the potential for stressors such as forest fragmentation/degradation or IAS combining with these increasingly intense events to cause precipitating ecosystem cascades is a real concern (Goulding et al., 2016).
Continued high rates of habitat loss and degradation have been reported for many small islands as natural habitats continue to be cleared to meet increasing demands upon natural resources from rising human populations, agriculture, urbanisation, unsustainable tourism, overgrazing and fires. This increases the vulnerability of ecosystems within especially oceanic islands — where isolation has given rise to high levels of endemism but simple biotic communities, with low functional redundancy (Box CCP1.1). There is *high confidence* that climate change may exacerbate the effects of this habitat loss upon the biodiversity of these islands as the climate refugia (Table 15.3) and the upslope shifts of range-restricted, dispersal-limited and poorly competitive species, confined within narrow latitudinal (and decreasing altitudinal) gradients, are increasingly challenged by fragmented and degraded landscapes (e.g., Struebig et al., 2015a; IPBES, 2019). Additionally, high-altitude ecosystems such as cloud forests which harbour high levels of endemism are projected to shrink due to increasing atmospheric temperature and competition from upward-shifting lowland species (Taylor and Kumar, 2016a). These may ultimately increase the risk of multiple extinctions, negatively impacting upon global biodiversity levels (*high confidence*) (Taylor and Kumar, 2016a; Portner et al., 2021).

Analyses of historical and current threats indicate that IAS and disease have been the primary drivers of insular extinctions in modern history (Bellard et al., 2016). Impacts of IAS on islands are projected to increase with time due to synergies between climate change and other traditional drivers such as increasing global trade, tourism, agricultural intensification, over exploitation and urbanisation (Bellard et al., 2014; Russell et al., 2017). Changing climate conditions may not necessarily increase the rate of IAS introductions but is expected to improve chances of IAS establishment via (i) altering IAS transport and introduction mechanisms, (ii) increasing the impacts and distributions of existing IAS and (iii) altering the effectiveness of existing control strategies (Hellmann et al., 2008; Russell et al., 2017). These are likely to enhance IAS impacts on islands including: restructuring of ecological communities leading to declines and extinctions/extirpations in flora and fauna, habitat degradation, declining ecosystem functioning, services and resilience, and in extreme cases, potential community homogenisation (*high confidence*) (Russell and Blackburn, 2017; IPBES, 2019). Given the high degree of endemicity within oceanic islands and their associated vulnerabilities, such exacerbation by changing climate pose a serious threat to decreasing global biodiversity (*medium to high confidence*) (van Kleunen et al., 2015).

Compared to continents, terrestrial IAS are disproportionately prevalent on islands (almost three-quarters of global species currently threatened by IAS and disease are found on islands) and also generate stronger impacts (e.g., within alpine ecosystems of high islands) than on continents (*high confidence)*(Bellard et al., 2014; Bellard et al., 2016; Frazier and Brewington, 2019). Russell and Blackburn (2017) suggested a correlation between small island size and increased numbers of IAS. SIDS within the Indian Ocean and in particular, the Pacific SIDS region were reported to have significantly more IAS **(***medium confidence*), while the Caribbean and Atlantic SIDS have fewer numbers but faster accumulation of IAS. Finally, while there have been developments in the eradication of IAS on islands (Jones et al., 2016), there is sparse evidence and hence assessment of the degree to which measures designed to prevent introduction and to manage invasion pathways and establishment have been successful.

Table 15.3: Percentage of selected islands classified as refugia for biodiversity at increasing levels of warming. While protected land is still 'protected' this table demonstrates the difficulty of protecting lands which might be 'more resilient' to climate change under increasing levels of warming and current land use practices. Derived from current and future projected distributions of ~130,000 terrestrial fungi, plants, invertebrates and vertebrates (Warren et al., 2018a). Refugia =areas remaining climatically suitable for >75% of the species modelled (Warren et al., 2018b). **Projections:** based on mean impacts from 21 CMIP5 climate model patterns (no dispersal) and elevationally downscaled to 1km under interpolated warming levels derived from RCP 2.6, 4.5, 6.0 and 8.0 (Warren et al., 2018a). First column-set = % island/island chain classified as a refugia based on ***climate alone*** ; second column-set = % natural land projected to be climate refugia — illustrating potential refugia 'space' already lost to habitat conversion. **Colour Key**: white > 50%; yellow = 30%-50%; red = 17%-30% and dark red <17% of land classified as refugia.

[INSERT TABLE 15.3 HERE]

15.3.4 Observed Impacts and Projected Risks on Human Systems

15.3.4.1 Island Settlements and Infrastructure

As a result of slow onset ocean and climate changes and changes in extreme events, settlements and infrastructure of small islands are at growing risk due to climate change in the absence of adaptation measures (*high confidence*). Ocean acidification and deoxygenation, increased ocean temperatures and relative sea level rise are impacting marine, coastal and terrestrial biodiversity and ecosystem services, making settlements more exposed and vulnerable to climate-related hazards. Changes in rainfall patterns such as heavy precipitation result in annual flood events that damage major assets and result in a loss of human life. Examples of settlements where this has occurred are Port of Spain (Mycoo, 2014b; Mycoo, 2018a) , Haiti (Weissenberger, 2018), Viti Levu (Brown et al., 2017; Singh-Peterson and Iranacolaivalu, 2018), urban areas of Fiji and Kiribati (McAneney et al., 2017; Cauchi et al., 2021), Male', Maldives (Wadey et al., 2017), and Mahé, in the Seychelles (Etongo, 2019).

The main settlements of small islands are located along the coast and with decades of high density coastal urban development, their population, buildings and infrastructure are currently exposed to multiple climate change-related hazards (Kumar and Taylor, 2015; Mycoo, 2017) and face key risks (*high confidence*) (KR5 in Figure 15.5). In many small islands, population is concentrated in the Low Elevation Coastal Zone (LECZ) which is defined as coastal areas below 10 metres elevation. Approximately 22 million in the

Caribbean live below 6 metres elevation (Cashman and Nagdee, 2017) and an estimated 90% of Pacific Islanders live within 5 km of the coast, if Papua New Guinea is excluded (Andrew et al., 2019). In the Solomon Islands and Vanuatu, over 60% of the population lives within 1 km of the coast (Andrew et al., 2019). Most Pacific islands have ≥50% of their infrastructure within 500 metres of the coast (Kumar and Taylor, 2015), and in Kiribati, Marshall Islands and Tuvalu, >95% of the infrastructure is located in the LECZ (Andrew et al., 2019) (Figure 15.3). Sustainable development challenges including insufficient land use planning and land use competition contribute to increased vulnerability of human settlements to climate change in small islands (Kelman, 2014)(Mycoo, 2021).

Categories 4 and 5 TCs are severely impacting settlements and infrastructure in small islands. TC Maria in 2017 destroyed nearly all of Dominica's infrastructure and losses per unit of GDP amounted to more than 225% of the annual GDP (Eckstein et al., 2018). Destruction from TC Winston in 2016 amounted to more than 20% of Fiji's current GDP (Cox et al., 2018). Additionally, living conditions in human settlements are changing due to storm surge which is already penetrating further inland compared with a few decades ago (IPCC, 2018 Section 3.4.4.3; Brown et al., 2018).

A growing percentage of the population in small islands lives in informal settlements which occupy marginal lands leading to increased population exposure and vulnerability to climate-related hazards (Mycoo and Donovan, 2017). Unplanned settlements have compounded flooding brought on by slow onset hazards such as coastal and riverine flooding and fast onset events such as TCs and storm surges (Butcher-Gollach, 2015; Chandra and Gaganis, 2016; Mycoo, 2017). Unsustainable land use practices and difficulties in enforcing land use zoning and building guidelines in informal settlements make them highly vulnerable to such events (Butcher-Gollach, 2015; Mecartney and Connell, 2017; Mycoo, 2017; Mycoo, 2018b; Trundle et al., 2018; Mycoo, 2021).

TC intensification in the future is *likely* to cause severe damage to human settlements and infrastructure in small islands. Additionally, SLR is expected to cause significant loss and damage (Martyr-Koller et al., 2021). Based on SLR projections, almost all port and harbour facilities in the Caribbean will suffer inundation in the future (Cashman and Nagdee, 2017). In Jamaica and St Lucia, SLR and ESLs are projected to be key risks to transport infrastructure at 1.5°C unless further adaptation is undertaken (Monioudi et al., 2018). Similar findings were reported for Samoa (Fakhruddin et al., 2015). Even islands of higher elevation are expected to be threatened, given the high amount of infrastructure located near to the coast, for example Fiji (Kumar and Taylor, 2015).

15.3.4.2 Human Health and Well-being

Small islands face disproportionate health risks associated with changes in temperature and precipitation, climate variability, and extremes (Cross-Chapter Box INTERREG in Chapter 16; Key Risk 4 in Section 15.3.9, Figure 15.5). Climate change is projected to increase the current burden of climate-related health risks (Weatherdon et al., 2016; Ebi et al., 2018; Schnitter et al., 2019). Health risks can arise from exposures to extreme weather and climate events, including heatwaves; changes in ecological systems associated with changing weather patterns that can result, for example, in more disease vectors, or in compromised safety and security of water and food; and exposures related to disruption of health systems, migration, and other factors (see Cross-Chapter Box ILLNESS in Chapter 2; McIver et al., 2016; Mycoo, 2018a; WHO, 2018).

Extreme weather and climate events, particularly TCs, floods, drought, and heat waves can cause injuries, infectious diseases, and deaths (Box 15.1; Schütte et al., 2018). For example, category 5 TC Winston hit Fiji on 20 February 2016. During the national state of emergency (7 March and 29 May 2016), the World Health Organization portable toolkit for an early warning alert and response system (EWARS in a Box) was deployed within 24 hours; it recorded 34,113 cases of the nine syndromes among 326,861 consultations in a population of about 900,000; 48% of cases were influenza-like illnesses, 30% were acute watery diarrhoea, and 13% were suspected cases of dengue. There also were 583 cases of Zika-like illness (1.7% of all cases) and two large outbreaks of viral conjunctivitis (total of 880 cases). During TC Maria in Puerto Rico, there were more deaths per 100,000 among individuals living in municipalities with the lowest socioeconomic development and for men 65 years of age or older (Santos-Burgoa et al., 2018); this excess risk persisted for at least a year after the event. The first human cases of leptospirosis in the U.S. Virgin Islands occurred in

2017 after TC Irma and Maria. TCs also can affect treatment and care for people with non-communicable diseases, including exacerbation or complications of illness and premature death (Ryan et al., 2015).

Heat-related mortality and risks of occupational heat stress in small island states are projected to increase with higher temperatures (Hoegh-Guldberg et al., 2018; Mendez-Lazaro et al., 2018). Higher temperatures also can affect the productivity of outdoor workers (Taylor et al., 2021). Climate change, urbanization, and air pollution are risk factors for the rise of allergic diseases in Asia and the (Pawankar et al., 2020).

Tropical and sub-tropical islands face risks from vector-borne diseases, such as malaria, dengue fever, and the Zika virus. El Niño events can increase the risk of diseases such as Zika virus by increasing biting rates, decreasing mosquito mortality rates, and shortening the time required for the virus to replicate within the mosquito (Caminade et al., 2017). By combining disease prediction models with climate indicators that are routinely monitored, alongside evaluation tools it is possible to generate probabilistic dengue outlooks in the Caribbean and early warning systems (Oritz et al., 2015; Lowe et al., 2018). Projections suggest that more individuals will become at risk of dengue fever by the 2030s and beyond because of an increasing abundance of mosquitos and larger geographic range (Ebi et al., 2018). Projected increases in mean temperature could double the dengue burden in New Caledonia by 2100 (Teurlai et al., 2015). In the Caribbean, Saharan dust transported across the Atlantic can interact with Caribbean seasonal climatic conditions to become respirable and contribute to asthma presentations at the emergency department (See Table 15.5; Akpinar-Elci et al., 2015).

Ciguatera fish poisoning (CFP) is a foodborne illness caused by toxic dinoflagellate algae that proliferate on degraded coral reefs and that can contaminate reef fish; symptoms can remain for a few weeks to months. CFP occurs in tropical and subtropical regions, primarily in the South Pacific and Caribbean, but wherever reef fish are consumed (Traylor and Singhal, 2020). In the Caribbean Sea, increasing ocean temperatures are expected to stabilize or slightly decrease the incidence of CFP because of shifts in species distribution of dinoflagellates associated with CFP (Kibler et al., 2015). CFP is endemic in the Cook Islands and French Polynesia, where incidence is associated with sea surface temperature anomalies (Zheng et al., 2020). In the Canary Islands, tropicalization trends due to climate change are expected to increase CFP occurrence in the future (Rodriguez et al., 2017). In addition, in the Caribbean, increased density of *Sargassum* algae, possibly due to ocean temperature impacts on ocean currents compounded by agricultural pollution, may lead to increased respiratory illnesses (Resiere et al., 2018; Resiere et al., 2019; Resiere et al., 2020).

Climate driven changes in the ability to access locally grown or harvested food, either through environmental degradation or changes in extreme event magnitude and/or frequency, can increase dependence on imported food and increase rates of malnutrition and non-communicable diseases (Springmann et al., 2016; WHO, 2018; Savage et al., 2019; Lieber et al., 2020). Projections suggest that local food accessibility could be reduced by 3.2% in the low- and middle-income countries of the Western Pacific (including the Philippines, Fiji, Papua New Guinea, Solomon Islands, and other Pacific islands) by 2050, with approximately 300,000 associated deaths possible (Springmann et al., 2016). A climate change-related 20% decline in coral reef fish production in some Pacific Island countries by 2050 could exacerbate the population growth-driven gap between volume of fish needed for nutritional security and fish available through sustained harvest (Bell et al., 2013; Cauchi et al., 2019; Savage et al., 2019)).

Heavy reliance on aquifers and rainwater harvesting in small islands, particularly atolls, coupled with overcrowding, population growth, and contamination increase the risk of waterborne disease (McIver et al., 2014; Strauch et al., 2014; McIver et al., 2016). For example, seasonal rainfall in Kiribati is associated with waterborne disease (such as diarrhea, cholera, and typhoid fever). Future projections indicate increases in the number of days of heavy rainfall by 2050, suggesting future increases in risk in heavily populated areas (McIver et al., 2014). Damage to water and sanitation services can cause infectious disease outbreaks, such as the cholera outbreak that occurred in Haiti following TC Matthew (Raila and Anderson, 2017; Hulland et al., 2019).

Evidence is emerging of the mental health impacts of climate change. Tuvaluans are experiencing distress because of the local environmental impacts caused or exacerbated by climate change, and by hearing about the potential future consequences of climate change (Gibson et al., 2020).

15.3.4.3 Water Security

Climate change impacts on freshwater systems frequently exacerbate existing pressure, especially in locations already experiencing water scarcity (Section 15.3.3.2 and Cross-Chapter Box INTERREG in Chapter 16; Schewe et al., 2014; Holding et al., 2016; Karnauskas et al., 2016), making Water Security a Key Risk (KR4 in Figure 15.5) in small islands. Small islands are usually environments where demand for resources related to socio-economic factors such as population growth, urbanisation and tourism already place increasing pressure on limited freshwater resources. In many small islands, water demand already exceeds supply. For example, in the Caribbean, Barbados is utilising close to 100% of its available water resources and St. Lucia has a water supply deficit of approximately 35% (Cashman, 2014). On many Mediterranean islands, water demand regularly outstrips supply as a result of low average precipitation coupled with increasing water demand from economic activities such as irrigated agriculture and tourism (Hof et al., 2014; Papadimitriou et al., 2019).

Population growth plays a strong role in projected future water stress (Schewe et al., 2014). Combining projected aridity change (fractional change compared to historical climatology) with population projections derived from SSP2, shows that the SIDS with high projected population growth rates are expected to experience the most severe freshwater stress by 2030 under a 2°C warming threshold scenario (Karnauskas et al., 2018). For several SIDS (e.g., Belize and Jamaica), increasing aridity change is a prominent exacerbating factor, but for others (e.g., the Solomon Islands and Comoros) population growth is the main factor. A 1°C increase in temperature (from 1.7°C to 2.7°C) could result in a 60% increase in the number of people projected to experience a severe water resources stress in 2043–2071 (Schewe et al., 2014; Karnauskas et al., 2018). Research on Jamaica concluded that the ability of rainwater harvesting to meet potable water needs between the 2030s and 2050s will be reduced based on predicted shorter intense showers and frequent dry spells (Aladenola et al., 2016).

The Caribbean and Pacific regions have historically been affected by severe droughts (Peters, 2015; FAO, 2016; Barkey and Bailey, 2017; Paeniu et al., 2017; Trotman et al., 2017; Anshuka et al., 2018) with significant physical impacts and negative socio-economic outcomes. Water quality is affected by drought as well as water availability. The El Niño related 2015-16 drought in Vanuatu led to reliance on small amounts of contaminated water left at the bottom of household tanks (Iese et al., 2021). The highest land disturbance percentages have coincided with major droughts in Cuba (de Beurs et al., 2019). Drought has been shown to have an impact on rainwater harvesting in the Pacific (Quigley et al., 2016) and Caribbean (Aladenola et al., 2016), especially in rural areas where connections to centralised public water supply have been difficult. Increasing trends in drought are apparent in the Caribbean (Herrera and Ault, 2017) although trends in the western Pacific are not statistically significant (McGree et al., 2016).

Areas where a freshwater lens is thinner are most likely to be impacted by multiple climate stressors, and these areas tend to be in coastal zones where populations are likely to be most concentrated (Holding et al., 2016). In Barbados, where groundwater is relied upon for food production, urban use, and environmental needs, higher food prices are expected in the future if informed land use management and integrated water resources policy implementation are not implemented to manage groundwater in the short term, even with modest climate change threats (Gohar et al., 2019).

15.3.4.4 Fisheries and Agriculture

Fisheries provide small islands with opportunities for economic development, revenues, food security and livelihoods (Bell et al., 2018). Ten Pacific Island countries and territories derive between 5% and >90% of all government revenue (except grants) from access fees paid by industrial tuna-fishing fleets, mainly from distant-water fishing nations (Bell et al., 2018; SPC, 2019). Under a high greenhouse gas emissions scenario (RCP 8.5), the total biomass of three tuna species in the waters of ten Pacific SIDS could decline by an average of 13% (range = −5% to −20%) due to a greater proportion of fish occurring in the high seas (Bell et al., 2021), meanwhile projected increases have been anticipated for Ascension Island and Saint Helena in the South Atlantic (Townhill et al., 2021). Additionally, seafood plays an important role in achieving food security in many islands. In the Pacific, fish protein is estimated to make up 50-90% of animal protein consumption in rural areas, and 40-80% in urban areas (Bell et al., 2009; Hanich et al., 2018) with similar values reported for some Indian Ocean and Caribbean islands (e.g. Maldives, Antigua and Barbuda). It has been suggested that island nations may need to retain more of their tuna catch rather than relying solely on coastal fisheries to achieve food security in the future (Cross-Chapter Box MOVING PLATE in Chapter 5; Bell et al., 2015; Bell et al., 2018). Furthermore, small island fisheries can be severely impacted by extreme events such as TCs, yet rapidly recovering pelagic fisheries can help to alleviate immediate food insecurity pressures in some circumstances, helping to build resilience (Pinnegar et al., 2019).

Observed impacts of climate change on fish and fisheries in small islands include declines in reef-associated species due to coral bleaching or cyclone damage (Robinson et al., 2019; Magel et al., 2020), oceanic-scale shifts in the distribution of large pelagic fish and hence their fisheries (Erauskin-Extramiana et al., 2019), changes to the size structure or breeding behaviour of species (e.g. (Asch et al., 2018)(Sections 3.3.3.2 and 3.4.3.1)). Many studies of future fisheries productivity in a changing climate suggest that yields will fall as a result of ocean productivity reductions, local species extinction and/or migration (Nurse, 2011; Asch et al., 2018; Robinson et al., 2019). Asch et al. (2018) provided future projections for biodiversity and fisheries maximum catch potential in Pacific Island countries and territories. These authors concluded that 9 of 17 Pacific Island entities (Cook Islands, Federated States of Micronesia, Guam, Kiribati, Marshall Islands, Niue, Papua New Guinea, Solomon Islands, and Tuvalu) could experience ≥ 50% declines in maximum catch potential by 2100 relative to 1980–2000 under both an RCP 2.6 and RCP 8.5 scenario (*medium confidence*). In Wallis and Futuna, maximum catch potential was projected to increase slightly (around 10%) by 2050, later declining by the year 2100. Similar projections have now been provided for all countries worldwide, including Pacific, Caribbean, Atlantic, Mediterranean and Indian Ocean small islands (Cheung et al., 2018). The small islands that show the largest anticipated decrease in fisheries maximum catch potential by the end of the century (according to an RCP4.5 and RCP 8.5 scenario) included the Federated States of Micronesia, Kiribati, Nauru, Palau, Tokelau, Tuvalu, São Tomé and Príncipe, whereas some other small islands such as Bermuda, Easter Island (Chile), and Pitcairn Islands (UK), might actually witness increases in fish catch potential (*medium confidence*) (Cheung et al., 2018). Monnereau et al. (2017)showed that for the fisheries sector, small island states are generally more vulnerable to climate change impacts compared to continental least developed countries or coastal states because of their increased reliance on fisheries, the exposure of coastal communities to potential climatic threats and their limited adaptive capacity.

Projected impacts of climate change on agriculture and fisheries pose serious threats to dependent human populations (Ren et al., 2018; Hoegh-Guldberg et al., 2019), making the risk caused to livelihoods a Key Risk in small islands (KR7 in Figure 15.5). On small islands, despite biophysical commonalities (e.g., size and isolation), differences in economic status and level of dependence on agriculture and fisheries produce dynamic climate impacts (Balzan et al., 2018). Climate change is impacting agricultural production in small islands through slow-onset stressors such as rising average temperatures, shifting rainfall patterns, sea level rise and extreme events like TCs. For example, TC Pam, a Category 5 cyclone, devastated Vanuatu in 2015 and caused losses and damages to the agriculture sector valued at USD 56.5 million (64.1% of GDP) (Nalau et al., 2017) and TC Winston Winston in 2016 resulted losses and damages on the agriculture sector in Fiji valued at USD 254.7 million (Iese et al., 2020). In 2017, total loss and damage associated with hurricane Maria (category 5) amounted to 224% of Dominica's 2016 GDP (Barclay et al., 2019). Losses and damage in agriculture often led to people eating imported processed foods affecting their diet and nutrition (Haynes et al., 2020).Small Islands' communities are also witnessing the indirect effects of the covid-19 pandemic on agricultural systems (Hickey and Unwin, 2020). However, the limited diversity of agriculture production and reduced household incomes are contributing to low diet diversity (Iese et al., 2020). Bell and Taylor (2015) assessed the effects of climate change on specific sectors of agriculture in the Pacific islands region and found that, by 2090, staple food crops of taro, sweet potato, and rice are expected to suffer from moderate to high impact. Among export crops, coffee is expected to sustain the most significant impact due largely to increased temperatures in the highland areas of Papua New Guinea – a high production area (Bell et al., 2016). Livestock is an important protein source in some small islands and is particularly vulnerable to changes in temperature through heat stress (Bell and Taylor, 2015; Lallo et al., 2018). With the concentration of island people along (often reef-fringed) coasts, there is a comparatively large dependence on nearshore marine foods and coastal agricultural systems (Ticktin et al., 2018).

In the Caribbean, additional warming by 0.2°–1.0°C, could lead to a predominantly drier region (5%–15% less rain than present-day), a greater occurrence of droughts (Taylor et al., 2018) along with associated impacts on agricultural production and yield in the region (Gamble et al., 2017; Hoegh-Guldberg et al., 2019; Nicolas et al., 2020). Crop suitability modeling on several commercially important crops grown in Jamaica found that even an increase less than + 1.5 °C could result in a reduction in the range of crops that farmers may grow (Rhiney et al., 2018).

Sugar yield in Fiji could decline by 2–14% under projected scenarios (McGree et al., 2020). Farmers in some small islands have utilised Indigenous knowledge systems built on local ontology to sharpen their sensitivity to environmental conditions (Shah et al., 2018). However, projected climate change across the Pacific could undermine climate-sensitive agricultural livelihoods and exacerbate food insecurity challenges (McCubbin et al., 2017; Campbell et al., 2021).

Projected climate impacts on island agroecosystem services could accentuate a myriad of social and ecological risks (Campbell, 2021). Without proactive farm management practices, the projected impacts of climate change on drought patterns is a major threat to cocoa pollination services (Arnold et al., 2018). Many tropical island agroforestry crops are completely dependent on insect pollination and it is therefore important to understand the climatic drivers of changing conditions related to pollinator abundance. Coastal agroforestry systems in small Pacific islands are vital to national food security but native biodiversity is rapidly declining (Ticktin et al., 2018). Biodiversity loss from traditional agroecosystems is a major threat to food and livelihoods security in SIDS (UNEP, 2014a). Additionally, while coastal-lowland salinisation and more-frequent flooding attributable to SLR have impacted coastal agriculture on some islands (Cruz and Andrade, 2017; Wairiu, 2017), stronger TCs can sometimes shock island terrestrial food production warranting reconfiguration (Mertz et al., 2010; Duvat et al., 2016; Chakrabarti et al., 2017). Calls to conserve associated environments and to make terrestrial food production on islands more resilient to climate-driven shocks underscore concern about future food security (Connell, 2013; de Scally, 2014). Implicit in the latter is reversing the decades-long loss of Indigenous knowledge about food production in many island societies and incorporating it into future strategies (Mercer et al., 2014b; Janif et al., 2016).

15.3.4.5 Economies

Small-island economies vary greatly in their nature, history/trends, and viability under a changed climate. As elsewhere, few small island economies are overseen by governments that are adequately prepared for the economic impacts of climate change over the next few decades (Connell, 2013; Hay, 2013). In particular, the lack of diversity that characterizes most small-island economies means they are especially vulnerable to global (climate-driven) shocks (Cross-Chapter Box DEEP in Chapter 17), be these the impacts of extreme events or more gradual longer-term change, which makes the maintenance of traditional mechanisms for coping with such shocks in many island societies all the more important (Granderson, 2017; Wilson and Forsyth, 2018; Nunn and Kumar, 2019b). As a result, the risk from climate change to economies constitutes a Key Risk (KR7 in Figure 15.5) in small islands.

Many island environments have been commercially exploited by external interests for much of their recent history. This is especially common for timber, the wholesale removal of forests, especially on tropical islands, exposing land to heavy rain that leads to denudation and increases lowland sedimentation (Wairiu, 2017; Eppinga and Pucko, 2018). Negative aspects of both processes will be exacerbated by climate change, demonstrating the practical need for reforestation in many island contexts (Thomson et al., 2016).Some small-island economies are sustained by extractive industries such as mining, creating dependencies that lead to their environmental impacts being downplayed (Tserkezis and Tsakanikas, 2016; Shepherd et al., 2018). It is important to address these impacts as they will add to negative impacts of climate change (Clifford et al., 2019).

Many small-island economies are sustained by tourism and have invested heavily in associated infrastructure and capacity building (Cannonier and Burke, 2018). Some rural island communities have become dependent on tourism to the point that it would be difficult to revert to subsistence living (Lasso and Dahles, 2018). Coast-focused (beach-sea) tourism in island contexts is already being impacted by beach erosion, elevated high SST causing coral bleaching, and associated marine-biodiversity loss, as well as more intense TCs (Tapsuwan and Rongrongmuang, 2015; Parsons et al., 2018; Wabnitz et al., 2018). The Covid-19 pandemic travel disruption significantly affected Caribbean islands tourism sector by reducing incomes that would have been used to enhance climate resilience (Sheller, 2020). Many tourism interests downplay the impacts and future risks from climate change (Shakeela and Becken, 2015), a position that may be borne out by sustained/rising demand for small island vacationing in some locales (Katircioglu et al., 2019). A way forward is for island tourism to emphasize its low-carbon and sustainable attributes, and to encourage smaller-scale eco-friendly holiday opportunities (Lee et al., 2018), in other words for island nations to embrace a 'blue economy' in line with SDG14 to conserve and utilise their oceans for sustainable futures (Hampton and Jeyacheya, 2020; Hassanali, 2020).

Given the high cost of imported goods, especially foodstuffs, larger island jurisdictions are striving to transform their economies to favour locally produced or locally constituted materials that employ local people and reduce their cost of living. The exposure of this component of island economies varies, yet manufacturing/commercial operations are usually found in the lowest-lying areas, often on reclaimed lands. This makes them especially vulnerable to rising sea level, part of a larger issue around the disproportionate exposure of infrastructure on small islands to climate change (Fakhruddin et al., 2015; Kumar and Taylor, 2015).

It is challenging to disentangle the role of climate change from that of globalisation and development in recent changes to human livelihoods on small islands, given that the latter have characterised many – especially SIDS – within the last few decades. However, recent climate change is clearly implicated in livelihood deterioration in many island contexts (Hernandez-Delgado, 2015; Nunn and Kumar, 2018). For example, livelihood impacts of climate-driven stressors (including shoreline/riverbank erosion, flooding and erratic rainfall) in three Mahishkhocha island-chars (river-mouth sand islands of Bangladesh) have been amplified by inadequate/misguided policy (Saha, 2017).The subordination of IKLK in favour of external adaptation strategies has accelerated livelihood decline in many island contexts (Wilson and Forsyth, 2018). Although economic and financial development has the potential to reduce environmental (and livelihood) degradation in SIDS (Seetanah et al., 2019), it is also clear that uneven development can steepen core-periphery disparities, especially in archipelagic contexts, resulting in deteriorating rural/peripheral livelihoods at the expense of improving urban ones (Wilson, 2013; Sofer, 2015) and increased rural-urban migration (Birk and Rasmussen, 2014; Connell, 2015).

15.3.4.6 Migration

Climate-related migration is considered to be a particular issue for small islands because changes in extreme events and slow-onset changes affect increasingly highly exposed and vulnerable low-lying coastal populations, therefore causing a threat to small island habitability (KR9 in Figure 15.5) (Storey and Hunter, 2010; Kumar and Taylor, 2015; Duvat et al., 2017b; Weir and Pittock, 2017; Hoegh-Guldberg et al., 2018; Mycoo, 2018a; Rasmussen et al., 2018). A typology of climate-related migration is provided in Cross-Chapter Box MIGRATE in Chapter 7. It is assumed that climate-related migration will increase in small islands, however, as is the case globally, the causes, form and outcomes are highly context specific. Types of climate-related migration occur across a continuum of agency from involuntary displacement at one end to voluntary movement to strategically reduce risks and planned resettlement at the other end (Section 15.5.1, also see Chapter 7; Birk and Rasmussen, 2014; Betzold, 2015; McNamara and Des Combes, 2015; Gharbaoui and Blocher, 2016; Stojanov et al., 2017; Weir, 2020).

Studies do not provide sufficiently robust evidence to attribute the various forms of migration to anthropogenic climate change directly on small islands or to accurately estimate the current number of climate-related migrants (see Chapter 7). Climate events and conditions strongly interact with other environmental stressors and economic, social, political and cultural reasons for migrating (*robust evidence, high agreement*) (Birk and Rasmussen, 2014; Campbell and Warrick, 2014; Laczko and Piguet, 2014; Marino and Lazrus, 2015; Connell, 2016; Weber, 2016b; Stojanov et al., 2017; Cashman and Yawson, 2019).

Despite difficulties with attribution, the literature establishes that climate variability and extreme events and broad environmental pressures have contributed to some degree to human mobility on small islands over time (*medium evidence, high agreement*) (Birk and Rasmussen, 2014; Campbell, 2014a; Campbell and Warrick, 2014; Donner, 2015; Kelman, 2015a; Connell, 2016; Stojanov et al., 2017; Barnett and McMichael, 2018; Martin et al., 2018) and these studies can provide analogues from which to inform climate-migration responses (Birk and Rasmussen, 2014; Kelman, 2015a; Connell, 2016).

Similarly, studies do not provide robust evidence to project how the full range of climate drivers may influence migration patterns on small islands into the future, although studies are emerging that estimate populations affected as a consequence of projected SLR. Rasmussen et al. (2018) estimated current populations of the world that are potentially subject to permanent inundation from projected local mean SLR associated with global mean surface temperature stabilisation targets of 1.5°C, 2.0°C, and 2.5°C occurring at 2100. For the affected land area and population, this analysis included a subset of 58 SIDS, as defined by the United Nations, for which the results are shown in Table 15.4.

Table 15.4: Global mean sea level rise (SLR) at 2100 projections and associated population of SIDS exposed to permanent inundation for global mean surface temperature stabilisation targets of 1.5°C, 2.0°C and 2.5°C. Rasmussen et al. (2018)

Stabilised Warming at 2100[a]	1.5°C		2.0°C		2.5°C	
Percentile	*50*	*5th–95th*	*50th*	*5th–95th*	*50th*	*5th–95th*
Global-mean SLR (cm) by percentile[b]	48	28–82	56	28–96	58	37–93
SIDS population exposure (thousands) by percentile[c]	400	300-560	420	300-640	430	320-630

Table Notes:
(a) Above pre-industrial level.
(b) Values are centimeters above 2000 current era baseline.
(c) Potentially affected population due to local mean SLR. Local mean SLR projections used for individual SIDS take account of variations from the global mean due to factors such as glacial isostatic adjustment, gravitational changes from ice melting, deltaic subsidence and tectonic movements.

The aggregate figures of population that could potentially be affected by permanent inundation shown in Table 15.4 and Figure 15.3 mask important differences in relative exposure between individual SIDS. Further, population affected by permanent inundation does not take into account the change in the frequency of ESL events and associated water-level attenuation (as per Vafeidis et al., 2019), nor does it account for adaptation measures that may alleviate impacts, future population growth, or the extent to which populations could adaptively migrate (Section 15.5.3). However, Rasmussen et al. (2018)'s analysis shows that comparatively small changes in mean sea level can result in large increases in the frequencies of ESL events and, hence, the risk of coastal flooding of inhabited land, suggesting many areas of SIDS may become uninhabitable well before the time of permanent inundation (see also studies referenced in Section 15.3.3.1.1). A similar conclusion is drawn by Kulp and Strauss (2019) who show that land area home to 10% or more of the population of many SIDS is at risk of chronic coastal flooding or permanent inundation by 2100.

Duvat et al. (2021a) employed an integrated systems approach to analyse future risk to habitability in atoll islands, taking into account changes in various ocean and atmospheric climate drivers and a moderate adaptation scenario (i.e., adaptation responses that remain similar in nature and magnitude to currently observed responses). They found that, compared to present-day risk, additional risk to habitability in Male, Maldives, and Fogafale, Tuvalu, is minimal under a low emissions scenario (RCP2.6) at 2050, although it may become moderate for Male and high for Fogafale by 2090. Under a worse case emissions scenario (RCP 8.5), future risk to habitability in these two urban islands may increase slightly in 2050, but may increase to moderate-to-high (for Male') and high-to-very high (for Fogafale) by 2090.

Even where settlement locations and livelihoods remain secure, an increase in health diseases, decrease in the availability of potable water, and increasing exposure to extreme events may reduce habitability (Section 15.3.4.9.2; Campbell and Warrick, 2014; Storlazzi et al., 2018). For example, the Fijian coastal community of Vunidogoloa made the decision to relocate in response to regular inundation during high tides. Raising houses on stilts and constructing a seawall failed to prevent regular flood damage to buildings and the entire community eventually relocated as a 'last resort' adaptation measure to a site within customary land. The availability of customary land for the new site was a key factor of success in this relocation example although this will not guarantee success in every case as relocation may expose communities to new risks (McNamara and Des Combes, 2015; Piggott-McKellar et al., 2019a).

15.3.4.7 Culture

Small island societies have developed IKLK based responses to living in dynamic environments susceptible to climate variability and extremes, which are based in broader systems of culture and heritage (*high confidence*) (Barnett and Campbell, 2010; Lazrus, 2015; Nunn et al., 2017b; Bryant-Tokalau, 2018b; Nalau et al., 2018b; Perkins and Krause, 2018). As expanded upon in Section 15.6.5 cultural resources are thought to play an important role in climate change adaptation on small islands through contributing to adaptive capacity and resilience (McMillen et al., 2014; Petzold and Ratter, 2015; Nunn et al., 2017b; Warrick et al., 2017; Falanruw, 2018; Mondragón, 2018; Neef et al., 2018; Parsons et al., 2018; Perkins and Krause, 2018; Hagedoorn et al., 2019; 2020a) (*robust evidence, medium agreement)*. Thus, loss of culture (KR8 in Figure 15.5) threatens adaptive capacity.

Some studies from the Pacific suggest that climate-migration linked to reduced habitability (Section 15.3.4.6) can have particularly severe cultural implications in a small island context where community solidarity and cohesion linked to place-based identity are important aspects of adaptive capacity (Hofmann, 2014; Lazrus, 2015; Warrick et al., 2017). In Federated States of Micronesia, land is owned through the matrilineal system and hence puts women in the centre of decision-making. The deterioration and loss of land (through saltwater intrusion, flooding, drought, erosion) not only can lead to economic deprivation but it also compromises cultural identities: "Where land signifies political, social, and economic well-being, becoming bereft of land cuts off an important thread of people's sense of belonging" (Hofmann, 2017, p. 82) particularly for Chuuk women. Land degradation and loss involves the "interruption to the matrilineal transmission of land" (Hofmann, 2017;p. 82), the loss of identities, relationships, and their customary authority.

The unquantifiable and highly localised cultural losses resulting from climate drivers are less researched and less acknowledged in policy than physical and economic losses (Karlsson and Hovelsrud, 2015; Thomas and Benjamin, 2018a). In the Bahamas, prolonged displacement of the entire population of Ragged Island following Hurricane Irma (2017) highlighted the cultural losses that can result from climate-induced displacement from ancestral homelands. Threats to identity, sense of place and community cohesion resulted from displacement, although all were important foundational features of the Islanders' self-initiated rehabilitation efforts and eventual return. Nonetheless, non-economic losses were not accounted for by policy addressing displacement (Thomas and Benjamin, 2018a). In the case of Monkey River Village in Belize, coastal erosion is threatening the community's cemetery. Residents place significant spiritual and emotional value on the cemetery which serves important community functions, and thus, threats to it are perceived to be serious and necessary to be taken into account in any planned response (Karlsson and Hovelsrud, 2015). A similar situation exists on Carriacou in the West Indies where culturally and historically significant archaeological sites are being lost due to coastal erosion caused by a combination of sand mining and extreme climate-ocean events exacerbated by SLR (Fitzpatrick et al., 2006).

Population and settlement concentration in coastal areas and high exposure to climate-driven coastal hazards on small islands mean that threats to tangible cultural heritage (archaeological sites, buildings, historic sites, UNESCO World Heritage Sites etc.) are high (Marzeion and Levermann, 2014; Reimann et al., 2018), although few studies examine this issue specifically in a small island context. On the island of Barbuda, archaeological sites containing important information on historical ecology and climatic shifts are at risk from coastal erosion and hurricanes. This loss of heritage represents identity loss, as "learning about the past is a crucial exploration of self that grounds and connects people to places" (Perdikaris et al., 2017)(p. 145). Loss and damage to heritage sites may also impact tourism and thus have significant economic impacts for narrow small island economies (Section 15.3.4.5).

15.3.4.8 Transboundary Risks/Issues

Inter-regional transboundary impacts are those generated by processes originating in another region or continent well beyond the borders of an individual archipelagic nation or small island. Intra-regional transboundary impacts originate from a within-region source (e.g., the Caribbean). Some transboundary processes may have positive effects on the receiving small island or nation, though most that are reported have negative impacts (Table 15.5).

Table 15.5: Summary of inter- and intra-regional transboundary risks and impacts on small islands
[INSERT TABLE 15.5 HERE]

[START BOX 15.1 HERE]

Box 15.1: Key Examples of Cumulative Impacts from Compound Events: Maldives Islands and Caribbean Region

Cumulative Impacts of the Compound Events of the 1998-2016 Period in the Maldives Islands

Between 1998 and 2016, the Maldives Islands were affected by three major climate events, including the 1997-1998 ENSO event, the 2007 flood event and the 2016 ENSO event, and by one tectonic event, the 2004 Indian Ocean Tsunami (Morri et al., 2015). These events illustrate the cumulative and cascading risks that a series of events may cause in reef-dependent atoll contexts (Figure Box15.1).

The 1997-1998 ENSO event was severe in the Maldives and as a result the living coral cover dropped to <10% (Bianchi et al., 2003). Recovery was still in progress in 2004 when the tsunami caused further (although not quantitatively assessed (Gischler and Kikinger, 2006)) damage to the reef ecosystem. Post-1998 recovery ultimately took 15 years, (i.e., longer than following the 1987 ENSO event, after which recovery had only taken a few years) and also longer than in the neighbouring undisturbed Chagos atolls, thereby suggesting the alteration of the recovery capacity of the reef ecosystem by human-induced reef degradation and climate change (Morri et al., 2015; Pisapia et al., 2017). Mid-2016, a new ENSO event occurred, which reduced living coral cover by 75% (Perry and Morgan, 2017). Future recovery of the reef ecosystem, which is critical to both current livelihoods and economic activities (especially diving-oriented tourism and fishing) and to long-term island persistence, will mainly depend first on the frequency and magnitude of future bleaching events, which are expected to increase due to ocean warming, and second on the highly variable effects of anthropogenic disturbances locally (Perry and Morgan, 2017; Pisapia et al., 2017; Duvat and Magnan, 2019b).

Additionally, the 2004 Indian Ocean tsunami (Magnan, 2006) and the 2007 flood (Wadey et al., 2017) caused damage totalling 62% of the country's GDP (Luetz, 2017). The tsunami also downgraded the Maldives (now a middle-income country) to the Least Developed Countries category and caused within-country migration, with 30,000 people (9.6% of the country's population) displaced (Republic of Maldives, 2009). These successive events, which had cumulative devastating effects on the reef ecosystem and cascading effects on health and well-being, livelihoods and economy, highlighted the risk posed by limited recovery time to the whole social-ecological system as well as the detrimental effect of local human disturbances on reef recovery.

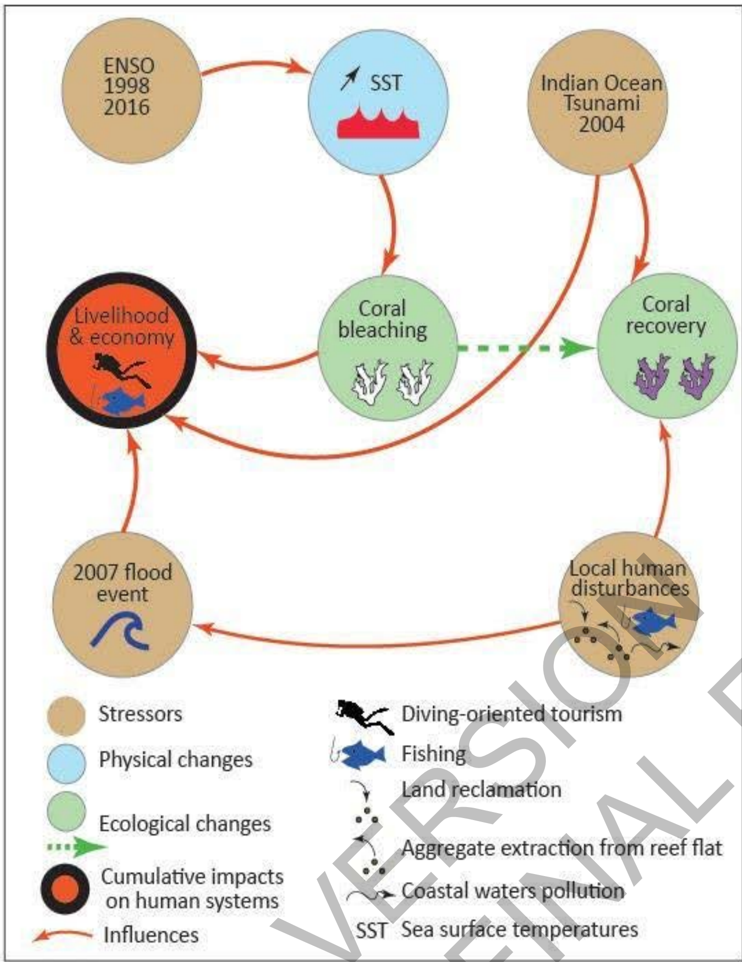


Figure Box15.1.1: Cascading and cumulative impacts of the compound events of the 1998-2016 period in the Maldives Islands.

Cumulative Impacts of the 2017 Hurricanes in the Caribbean Region

Among the 29 Caribbean SIDS, 22 were affected by at least one category 4 or 5 TC in 2017. These events highlighted how the pre-cyclone high exposure and vulnerability of these islands and their populations has caused a "cumulative community vulnerability" (Lichtveld, 2018, p. 28) that has amplified the impacts of these TCs, which will in turn increase the long-term vulnerability of affected islands. The exposure of these islands over their entire surface, combined with the concentration of people, and infrastructure, utilities and public services in flood-prone coastal areas, inadequate housing, limited access to healthy food and transportation, and unpreparedness explains widespread-to-total devastation (Shultz et al., 2018; Briones et al., 2019). The destruction of transport systems (Lopez-Candales et al., 2018) and island supply chains (Kim and Bui, 2019), which heavily depend on ports, roads, power and communications, made rescue logistically complex, explaining the lack of freshwater, food supplies, medications and fuel on some islands for several weeks after the event. This cumulative vulnerability caused "cascading public health consequences" (Shultz et al., 2018, p.9), including delayed (i.e., over the next year) mortality, physical injury during the clean-up and recovery phase, and increased the risk of chronic, vector-borne, contaminated water-related diseases, and mental sequelae (Kishore et al., 2018; Ferre et al., 2019).

The loss of mangroves (Branoff, 2018; Walcker et al., 2019; Taillie et al., 2020) and terrestrial forests (Eppinga and Pucko, 2018; Feng et al., 2018; Hu and Smith, 2018; Van Beusekom et al., 2018) exacerbated the cyclone-induced economic crisis. In the most affected islands, the destruction of buildings and outmigration generated a significant loss of tangible (e.g., museums) and intangible (e.g., traditional artistry) cultural heritage (Boger et al., 2019). Prolonged displacement of entire island populations (e.g., Ragged Island, the Bahamas; Barbuda) caused "non-economic loss and damage", including threats to health and well-being, and loss of culture, sense of place and agency (Thomas and Benjamin, 2019), which may further exacerbate the long-term vulnerability of concerned communities.

In early 2020, while island communities were still recovering from the 2017 hurricanes, the COVID-19 pandemic caused the closure of global transportation, with devastating socioeconomic impacts on tourism-dependent Caribbean economies (Sheller, 2020), illustrating how compounding crises increase island vulnerability to both climate and non-climate related events.

[END BOX 15.1 HERE]

[START BOX 15.2 HERE]

Box 15.2: Loss and Damage and Small Islands

Loss and damage has a range of conceptualizations (Section 1.4.4.2; Cross-Chapter Box LOSS in Chapter 17) and is a critical issue for many small islands, closely related to issues of climate justice (Section 15.7). Small islands are already experiencing an array of negative climate change impacts while climate risks are projected to increase as global average temperatures rise (Section 15.3, 16.2; Cross-Chapter Paper 2). Barriers and limits to adaptation also contribute to greater levels of both economic and non-economic loss and damage for small islands (Sections 15.6, 16.4).

For SIDS in particular, loss and damage has negative implications for sustainable development (Benjamin et al., 2018). The costs of loss and damage, particularly from extreme events, can deplete national capital reserves (Noy and Edmonds, 2019). Thomas and Benjamin (2017) show how loss and damage can lead to an 'unvirtuous cycle of climate-induced erosion of development and resilience'. In this cycle, addressing loss and damage strains limited national resources, diverting public funding and other resources to address negative climate impacts. This in turn reduces resources and capacities which could be allocated to adaptation, building resilience and sustainable development, thereby increasing vulnerability to climate change and leading to further loss and damage where the cycle begins again. The cascading and cumulative impacts of extreme events experienced in Pacific and Caribbean SIDS exemplify that this cycle may already be in effect.

In addition to the strain on national resources that loss and damage currently presents, credit ratings of SIDS have recently begun to include vulnerability to climate change, which may have negative impacts on their abilities to borrow external funds, attract foreign investment or access concessional financing (Buhr et al., 2018; Volz et al., 2020). Costs of addressing loss and damage may also affect the ability of SIDS to repay external debt, thus endangering eligibility for future access to funding (Baarsch and Kelman, 2016; Klomp, 2017; Shutter, 2020). These factors may place SIDS in situations where they face mounting costs of climate change with eroding capacities and resources to address loss and damage.

In the international policy arena, small islands - as part of Alliance of Small Island States (AOSIS) - have been strong advocates for including loss and damage in the United Nations Framework Convention on Climate Change (UNFCCC); highlighting the increasing and irreversible risks that climate change poses for islands in particular (Roberts and Huq, 2015; Adelman, 2016; Mace and Verheyen, 2016). AOSIS, along with other developing countries and groups, have advocated that there is a pressing need for finance and resources to address loss and damage as well as greater integration of loss and damage in the UNFCCC and the Paris Agreement, including in capacity building, technology and the global stocktake (Benjamin et al., 2018; Nand and Bardsley, 2020).

[END BOX 15.2 HERE]

15.3.4.9 Key Risks in Small Islands

15.3.4.9.1 Key Risk approach

This section builds on cross-chapter work led by Chapter 16 of the WGII AR6 Report aimed at identifying and assessing Key Risks across sectors and regions (Section 16.5 and Supplementary Material 16.A.2). Key Risks (KRs) are the risks of most pressing concern that are caused or exacerbated by climate change in a given region. A KR is defined as a 'potentially' severe risk, which can either be already severe or projected to become severe in the future, as a result of (i) changes in associated climate-related hazards and/or the exposure and/or vulnerability of natural and human systems to these hazards, and/or of (ii) the adverse consequences of adaptation or mitigation responses to the risk. In line with the guidelines used in the WGII AR6 Report, the identification of KRs in small islands is based on the chapter authors' expert judgment, using scientific literature and five types of criteria: (1) Importance of the affected system or dimension of the system, which is a value judgment left to readers to make; (2) Magnitude of adverse consequences, based on their pervasiveness, degree and irreversibility, and on the potential for impact thresholds and cascading effects across the system; (3) Likelihood of adverse consequences, although this probability is rarely quantifiable for small islands due to limited downscaled data at a small island level; (4) Temporal characteristics of the risk, including its period of emergence, persistence over time and trend; and (5) Ability to respond to the risk, with the severity of the risk being inversely proportional to this ability.

15.3.4.9.2 Key Risks in small islands

Slow onset climate and ocean changes, and changes in extreme events, are expected to cause and/or to amplify nine KRs in small islands, through both direct (e.g., decrease in rainfall will increase water insecurity) and indirect, that is, cascading effects: for example, loss of terrestrial biodiversity and ecosystem services will increase water insecurity, which will in turn cause the degradation of human health and well-being (Figure 15.5, Table 15.6 and Table 16.A.4 in Chapter 16 Supplementary Material).

These KRs include loss of marine and coastal biodiversity and ecosystem services (*high confidence*) (KR1; for details on KR coverage, see Section 15.3.3.1); submergence of reef islands (*low confidence*) (KR2; Section 15.3.3.1.1); loss of terrestrial biodiversity and ecosystem services (*high confidence*) (KR3; Section 15.3.3.3); water insecurity (*medium-high confidence*) (KR4; Section 15.3.4.3); destruction of settlements and infrastructure (*high confidence*) (KR5; Section 15.3.4.1); degradation of human health and well-being (*low confidence*) (KR6; section 15.3.4.2); economic decline and livelihood failure (*high confidence*) (KR7; Sections 15.3.4.4 and 15.3.4.5); and loss of cultural resources and heritage (*low confidence*) (KR8; Section 15.3.4.7).

Risk accumulation and amplification through cascading effects from ecosystems and ecosystem services to human systems will likely cause reduced habitability of some small islands (*high confidence*) identified as the overarching KR (KR9). Habitability is understood as the ability of these islands to support human life by providing protection from hazards which challenge human survival; by assuring adequate space, food and freshwater; and by providing economic opportunities, which contribute to health and well-being; recognizing that both supportive ecosystems and socio-cultural conditions (i.e. beliefs and values, institutions and governance arrangements, sense of community and attachment to place) play a critical role in habitability (Duvat et al., 2021a). The reduction of island habitability is expected to cause increased migration, along the above-mentioned involuntary displacement to planned resettlement spectrum (Section 15.3.4.6), which may eventually lead to population movements from exposed areas and depopulation of some islands. This risk is the highest for atoll nations, where some islands might become uninhabitable over this century (Section 15.3.4.6; Storlazzi et al., 2018; Duvat et al., 2021a). Despite a lack of literature assessing the risk of reduced habitability in non-atoll islands, the latter are also expected to experience decreased habitability, especially in their coastal areas.

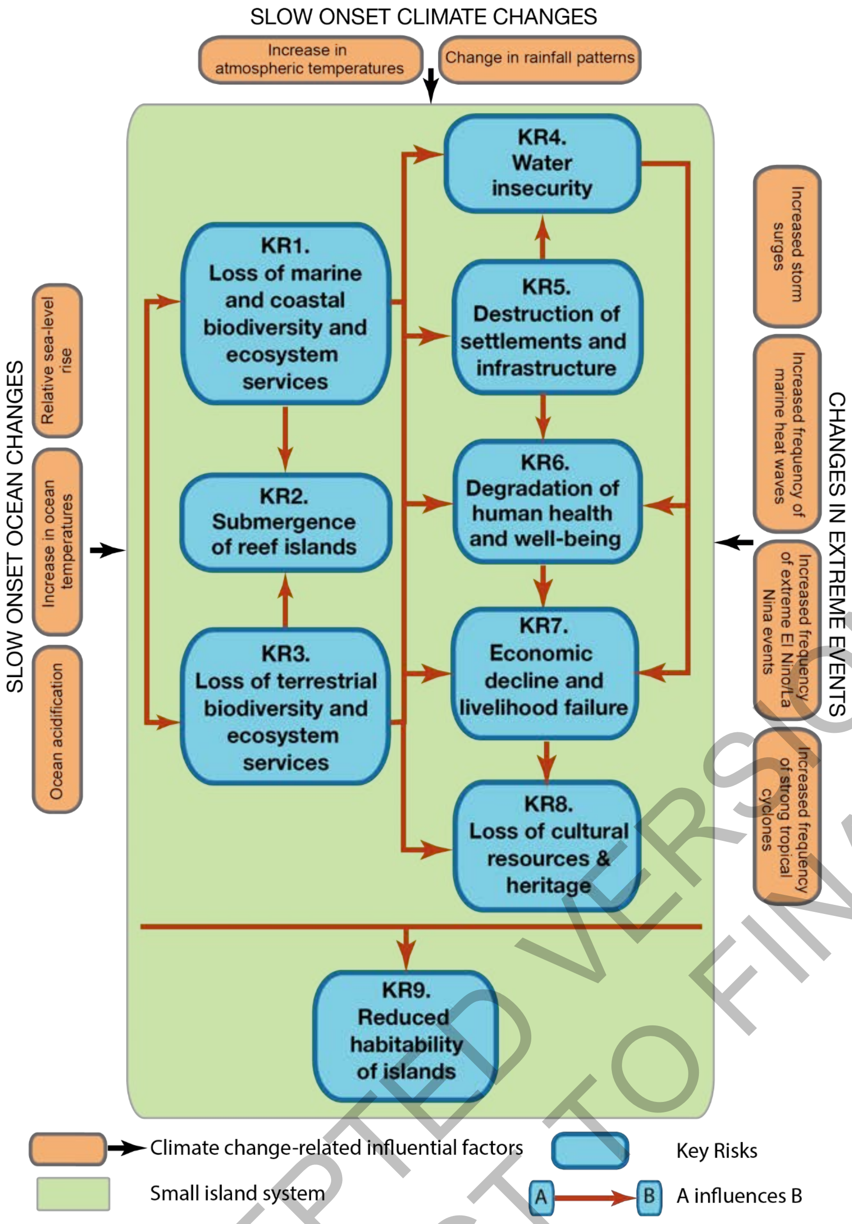


Figure 15.5: Key Risks in small islands. KR1 to 8 are interconnected as shown by arrows, which causes risk accumulation leading to reduced island habitability. The main interconnections are shown in this figure: for example, loss of marine and coastal and terrestrial biodiversity and ecosystem services (KR1 and KR3, respectively) are projected to cause the submergence of reef islands (KR2), water insecurity (KR4), destruction of settlements and infrastructure (KR5), degradation of human health and well-being (KR6), economic decline and livelihood failure (KR7), and loss of cultural resources and heritage (KR8). Importantly, Key Risks result from both direct effects (e.g. decrease in rainfall will increase water insecurity) and indirect effects (e.g. loss of terrestrial biodiversity and ecosystem services will increase water insecurity, which will in turn cause the degradation of human health and well-being).

15.4 Detection and Attribution of Observed Impacts of Climate Change on Small Islands

As highlighted in AR5, detection of climate change impacts on the fragile environments of small islands is challenging because of other non-climate drivers that affect small islands. Determination of attribution to incremental change of climate drivers is also challenging because of the natural climate variability. Therefore, there is limited scientific literature on observed impacts and attribution. A synthesis of findings on the impacts of climate change (Sections 15.3.3 and 15.3.4) shows that there is more information on impacts on ecosystems compared to human systems. There is *high confidence* in attribution to climate change of impacts on the coastal and marine as well as terrestrial ecosystems (Hansen and Cramer, 2015; Shope et al., 2016; van Hooidonk et al., 2016; Hoegh-Guldberg et al., 2017; Hughes et al., 2017b; Mentaschi et al., 2017; Shope et al., 2017; Vitousek et al., 2017; Wadey et al., 2017; Ford et al., 2018; Hughes et al., 2018; IPCC, 2018; Storlazzi et al., 2018; Bindoff et al., 2019) and *medium confidence* in attribution to climate change of impacts on livelihoods, economics and health (Figure 15.6; McIver et al., 2016; Eckstein et al., 2018; Santos-Burgoa et al., 2018; Schütte et al., 2018; WHO, 2018).

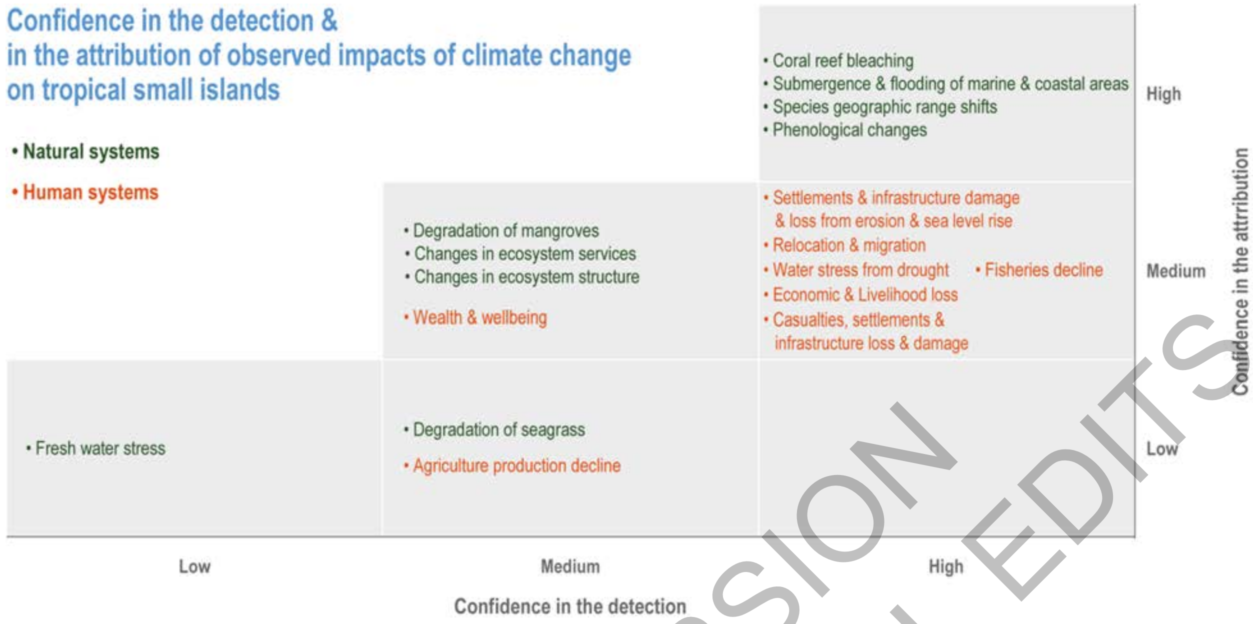


Figure 15.6: A comparison of the degree of confidence in the detection of observed impacts of climate change on tropical small islands with the degree of confidence in attribution to climate change drivers.

As Figure 15.6 shows there is *high confidence* that climate change causes changes in terrestrial ecosystems as well as coral reef bleaching through increases in sea surface temperature and submergence and flooding of coastal areas through sea level rise and increased wave height. With respect to casualties, settlements and infrastructure loss and damage, economic and livelihood loss, although confidence in detection is high, there is at present *medium confidence* in the attribution to climate change. *Medium confidence* in attribution frequently arises owing to the limited research available on small island environments.

15.5 Assessment of Adaptation Options and Their Implementation

Since AR5, small islands have experimented with new adaptation options, which has increased the lessons learnt from on-the-ground practices in these settings. Figure 15.7 shows some of the adaptation options that are being experimented with in small islands. This section covers most common adaptation actions and approaches across small islands and assesses the many constraints, enablers and limits to adaptation. Adaptation plays also a key role in climate resilient development and the insights emerging from small islands on this topic are discussed after the adaptation section.

15.5.1 Hard Protection

Seawalls have been a popular coastal protection measure on islands (Figure 15.7). An analysis of National Communications shows that 28% of coastal protection actions are seawalls, followed by breakwater structures and coastal protection units (Robinson, 2017a). Coastal protection infrastructure has been heavily invested, for example in the Caribbean region (Mycoo, 2014b) and Cuba (Mycoo, 2014a). A similar situation applies in many Indian Ocean islands, where coastal protection strategies are manifested by hard shoreline structures, many of which are proving challenging to maintain (Naylor, 2015; Betzold and Mohamed, 2017; Magnan and Duvat, 2018). In the Pacific the situation is different given that many islands have been occupied for millennia by indigenous communities with extant knowledge for coping with adversity (Granderson, 2017). The latter generally favours ‘soft’ shoreline structures for coastal protection although the building of seawalls has been rapid, especially in urban islands (Umeyama, 2012; Duvat, 2013; Magnan et al., 2018; Morris et al., 2018), and also in some rural islands (e.g., Tubuai, French Polynesia (Salmon et al., 2019)).

Many rural communities have uncritically emulated structures in urban contexts built and maintained with external finances. As a result, in many Pacific SIDS, seawalls have collapsed without additional funding available for repairs (Nunn and Kumar, 2018; Piggott-McKellar et al., 2020; Nunn et al., 2021). Similar cases have been recorded along the coast of Puerto Rico (Jackson et al., 2012) while on Indian Ocean islands (e.g., Seychelles), the shorelines are littered with broken seawalls and groynes (Duvat, 2009). In Samoa, seawalls close to Apia need constant investments to remain viable.

On small islands, another widespread issue with seawalls and other hard shoreline structures is that they invariably shift problems of shoreline erosion and lowland inundation elsewhere (Donner and Webber, 2014). Even surrounding entire islands with such structures, as has happened on Male' (Maldives), is not a long-term solution because of incidences of localised seawall collapse that can spread quickly if not addressed immediately (Naylor, 2015). Hard structures for coastal protection will become increasingly ineffective in the future, demonstrating the need for adaptation along most island coasts to become more transformative than has been the case over the past few decades. In the Bahamas, it has been suggested that coastal protection structures and strategies are implemented through "a rather piecemeal approach of single projects and small patches, partially resulting in maladaptation by further increasing processes of erosion" (Petzold et al., 2018)(p. 95). In the village of Lalomalava, Samoa, national adaptation funding was spent on erecting a seawall to protect the village, but the wall was not long enough to protect the whole village, leading some families and properties to face increasing impacts from large waves (Crichton and Esteban, 2018).

15.5.2 Accommodation and Advance as Strategies

In most small island contexts, the costs of adaptation through accommodation are prohibitive so that it has in most cases not been contemplated as a widespread option. However, accommodation measures such as the raising of dwellings and key infrastructure like coastal roads above ground level have been implemented to reduce the impacts of flooding in some islands (Figure 15.7). In the most populous islands of the Tuamotu atolls, French Polynesia, where between 48 and 98% of dwellings have already experienced flooding since the 1980s, elevated houses with floors built 1.5 m above ground level are subsidised by the Government as part of Risk Prevention Plans (Magnan et al., 2018). Despite this incentive, the opposition of the local authorities and population to these plans (which also include constraining setback guidelines) considerably limited implementation, hence elevated houses only represent 7% of the total housing stock. In the Philippines (Tubigon) and Indonesia (Jakarta area) residents have elevated their houses by building stilted houses or raising the floor using coral stones to face increased flooding (Jamero et al., 2017; Esteban et al., 2020). Also, in Puerto Rico houses have been raised to address flooding (Lopez-Marrero, 2010).

In some small island settings, land reclamation (i.e., land gain through infilling) has been implemented for decades to allow for infrastructure construction and to address land shortages arising from high population growth. For example, land reclamation in Port of Spain, the capital city of Trinidad, has long been used as a solution space to meet land for housing, industrial development and infrastructure provision (Mycoo, 2018b). Likewise, one third of the land area of Male', the capital island of the Maldives, results from land reclamation (Naylor, 2015). Land reclamation is also common in Pacific atoll countries and territories, where it occurs both in urban islands facing high population pressure, such as South Tarawa, Kiribati (Biribo and Woodroffe, 2013), Funafuti Atoll, Tuvalu (Onaka et al., 2017), and Rangiroa Atoll, French Polynesia (Duvat et al., 2019b), and in rural islands, e.g., Takapoto and Mataiva atolls, French Polynesia (Duvat et al., 2017b). In some cases, land reclamation has paved the way for land raising, which is increasingly considered to adapt to SLR in small islands contexts (Figure 15.7). For example, since the 1990s, the capital area of the Maldives has been expanded through the construction of a large new island, Hulhumale', which is still under construction and is built 60 cm higher than Male' to take into account SLR (Hinkel et al., 2018; Brown et al., 2020). More generally, in the Maldives, the 2004 Indian Ocean Tsunami has boosted island raising as part of the "safe island development programme" (Shaig, 2008). Recent studies suggest that land and island raising have some potential in small islands, especially in urban high-value areas where this can generate substantial revenues through the sale or lease of new land, and therefore leverage public adaptation finance (Bisaro et al., 2019).

15.5.3 Migration

Migration, including planned resettlement, is increasingly occurring in small islands to intentionally respond to or prepare for climate change impacts (Figure 15.7; Magnan et al., 2019). There is currently *limited evidence* and *low agreement* in the literature as to whether migration of various types is an effective strategy to adapt to localised impacts of climate change, as outcomes are highly context specific (Donner, 2015; McNamara et al., 2016; Hermann and Kempf, 2017; McMichael et al., 2019; Piggott-McKellar et al., 2019a; Tabe, 2019; Bertana, 2020; Weir, 2020).

In-situ adaptation options are frequently the preference of communities over resettlement (Jamero et al., 2017) and in many documented cases, relocation – both planned and autonomous – is an adaptation option of last resort due to high economic and socio-cultural cost (McNamara and Des Combes, 2015; Jamero et al., 2017; Crichton et al., 2020). In small islands, there is *medium evidence* and *high agreement* that the degree of migrant agency and choice in decisions about whether to move, where, when and how is an important determinant of success and therefore 'adaptiveness' (see Cross-Chapter Box MIGRATE in Chapter 7; McNamara and Des Combes, 2015; Hino et al., 2017; McMichael et al., 2019; Piggott-McKellar et al., 2019a; Bertana, 2020) . Two case studies of community relocation in Fiji (Denimanu and Vunidogoloa villages) recommend that participatory inclusion of all social groups in the relocation planning process, including in planning for livelihood sustainability in new locations, should be ensured in future planned community relocation to foster positive adaptive outcomes (Piggott-McKellar et al., 2019a).

There are few examples of highly 'successful' and therefore adaptive international resettlement or relocation in response to environmental pressures in history. For example, the experiences of Gilbertese resettled in the Solomon Islands highlight that tensions with host communities over land and resource rights and limited knowledge of new environments (such as where communities previously reliant on marine resources are resettled in high island locations) can create new vulnerabilities (Donner, 2015; Weber, 2016a; Tabe, 2019). Even where gradual international relocation is supported and planned through policy as in the case of Kiribati's "migration with dignity" strategy, strong cultural connection to land and uncertainty about life in receiving communities in Australia and New Zealand means that many remain opposed to indefinite or permanent migration (Allgood and McNamara, 2017; Hermann and Kempf, 2017). The same challenges could apply where domestic migration occurs between significantly different cultural, social and physical environments. However, planned migration for employment or education can reduce exposure in sending locations and spread risk through expanding economic opportunities and providing remittances, thus having inadvertent adaptation outcomes (Campbell, 2014a). Policies which support migration for employment by the most vulnerable - those that may wish to migrate but lack the resources to do so - may offer an adaptive strategy to environmental pressure, particularly where these incorporate adequate preparedness for life in host communities (Luetz, 2017; Curtain and Dornan, 2019; Drinkall et al., 2019). Research from the Maldives suggests that women and men do not possess equal capacities to use mobility as a strategy to adapt to climate change, with women less able to employ migration as an adaptation strategy due to gender roles, social expectations, economic structures, political laws and religious doctrines, and gender norms and cultural practices (Lama, 2018).

Forced relocation, involuntary displacement and low-agency migration (for example, due to low migrant financial resources, or limited participation in migration planning) is commonly associated with unsuccessful outcomes and can therefore be considered an impact of climate change rather than an adaptation strategy (Weber, 2016a; Thomas and Benjamin, 2017; Tabe, 2019). Resettlement of households, communities and larger island populations is increasingly discussed in the context of loss and damage when in-situ adaptation limits are thought to be reached. Limited data and research relating to adaptation limits, transformational adaptation, tolerable and intolerable risk levels in small islands, and limited ability to directly attribute climate change to migration decisions (in the context of both slow onset changes and extreme events) mean that policy applications are currently limited (Thomas and Benjamin, 2018b; Handmer and Nalau, 2019; Nand and Bardsley, 2020).

15.5.4 Ecosystem-based Measures

Small islands have focused increasingly on ecosystem-based adaptation (EbA) approaches and other Nature-Based Solutions that bring benefits both for the ecosystems and communities (Figure 15.7; Giffin et al., 2020). There is *robust evidence* on implementation of EbA approaches across small islands, yet *medium agreement* on the exact benefits of these activities (Mercer et al., 2012; Doswald et al., 2014; Nalau et al., 2018a) given the difficulties in quantifying benefits and the absence of monitoring and evaluation frameworks (Doswald et al., 2014). Traditionally, EbA activities, especially at national and regional scales, have predominantly focused on restoring or conserving coastal and marine ecosystems (e.g., coral reefs, mangrove forests and seagrass meadows), with less emphasis upon the services provided by natural inland forests (Mercer et al., 2012). Incorporation of forests is however increasing, in most cases as components of ridge to reef (Figure 15.4) (or DDR) projects (*limited to medium evidence*), and is geared towards integrated watershed management to establish downstream water security, erosion control and ultimately to protect the health of coral reef ecosystems (Förster et al., 2019).

Additionally, some islands are constructing climate-smart development plans such as improved management of existing and newly established protected areas, restoration of riparian zones, urban forests/trees, sub urban and peri urban home gardens, and improved agroforestry practices towards increasing resilience to changing climate conditions, wildfires as well as decreasing food insecurity (e.g., Pedersen et al., 2016; McLeod et al., 2019). Paired terrestrial and marine protected areas have shown that forest conservation and rehabilitation yield better outcomes for coral health as forests stabilize soils and prevent erosion and sequester groundwater pollutants (*limited to medium evidence, high agreement*) (Carlson et al., 2019). The success of protected areas is however undermined by weak governance due in part to limited financial resources which undermine management and the enforcement of regulations governing activity within them (Schleicher et al., 2019).

Since the 1990s, artificial reefs have been increasingly used in small islands to support reef restoration and reduce beach erosion, especially in the Caribbean region (e.g., Dominican Republic, Antigua, Grand Cayman, Grenada) and Indian Ocean (Maldives, Mauritius) (Fabian et al., 2013; Reguero et al., 2018). They have been more or less successful in reducing the destructive impacts of extreme events, depending on their technical characteristics and the local context. For example, while it resisted the waves generated by hurricanes Georges and Mitchell in 1998, the artificial reef (Reef Ball breakwater type) implemented at Gran Dominicus Resort, Dominican Republic, did not prevent significant beach erosion. In contrast, the coral reef restoration project implemented to "build a beach" on the resort island of Ihuru, North Male' Atoll, Maldives, was successful as it allowed beach expansion and prevented the erosive impacts of the 2004 Indian Ocean Tsunami on the beach (Fabian et al., 2013).

Over the past decades, beach nourishment has been implemented in small islands either to reduce beach erosion (e.g., in tourist areas), or to protect critical human assets (e.g., roads) that are highly exposed to storm waves. It has been increasingly used to maintain beaches in the islands of the Maldives (Shaig, 2011), and in Barbados (Mycoo, 2014b). However, islands have limited sand stocks and sediment extraction can aggravate risks and/or accelerate ecosystem degradation if implemented without the necessary precautions.

In designing and implementing EbA, IKLK have high relevance especially amongst Pacific small islands as many communities are remote and still rely on ecosystems for their livelihoods (Nalau et al., 2018b; Narayan et al., 2020). In Fiji, IKLK have informed EbA projects by identifying native species suitable to strengthen the coastal environment to reduce coastal erosion and flooding in the villages (Nalau et al., 2018b). Whole-of-island approaches, like Lomanu Gau in the Gau Island in Fiji, try to foster integrated management practices in small islands that are based on shared governance of resources, and understanding the interlinkages between sectors and ecosystems (Remling and Veitayaki, 2016). In the Caribbean, EbA approaches are somewhat absent in national and regional programmes and plans, yet at the local scale EbA strategies are used increasingly with implementation mostly led by NGOs (Mercer et al., 2012).

EbA approaches have many benefits but also face several challenges and limits. Biophysical limits can make some EbA and Nature-based Solutions ineffective: coral reefs are *unlikely* to withstand increased temperatures, reducing the effectiveness of coral reef based EbA options under higher temperature scenarios (Barkdull and Harris, 2018; Cornwall et al., 2021). Likewise, many other coastal and marine ecosystems, such as mangroves, face severe limitations with increasing sea levels and other climate impacts (Morris et al., 2018; Thomas et al., 2021).

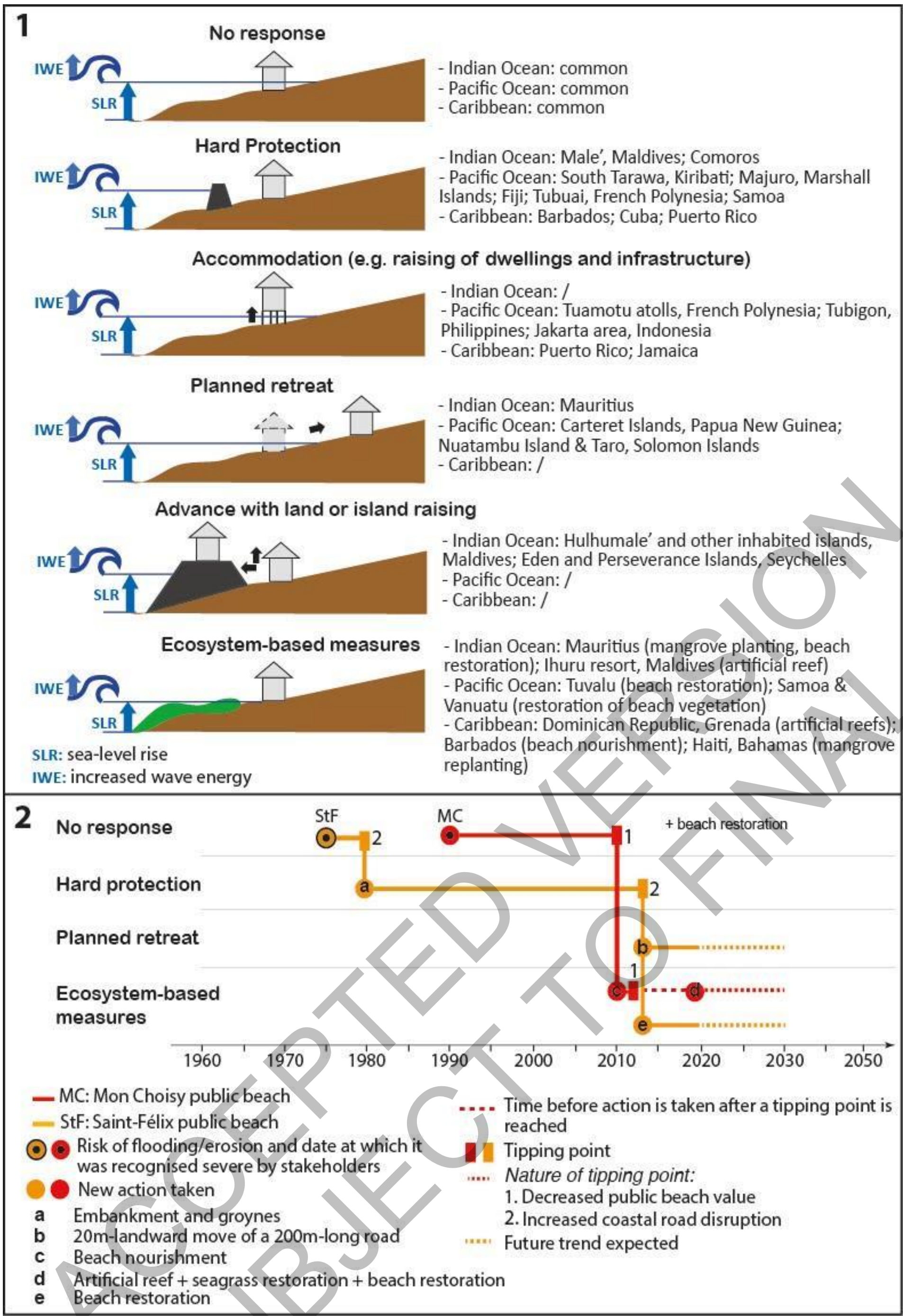


Figure 15.7: Adaptation measures implemented to reduce coastal risks in small islands. Panel 1 provides examples of implementation of different types of measures aimed at reducing coastal erosion and flooding. The measures include no response (no intervention, widespread in small islands), hard protection through the construction of engineering-based structures, accommodation through dwelling and infrastructure raising, planned retreat, advance (i.e. especially island raising) and ecosystem-based measures, in three small island regions, the Indian and Pacific Oceans and Caribbean. It highlights the prevalence of no response, hard protection and the increasing use of ecosystem-based measures. Based on the example of two beach sites in Mauritius (Mon Choisy in the north and Saint-Félix in the south), panel 2 shows that the measures used at a given coastal site evolve over time (e.g., from no response to hard protection, and then planned retreat and ecosystem-based measures) and that recent DRR (Saint-Félix) and adaptation (Mon Choisy) projects often combine several types of measures, including retreat and ecosystem-based measures (Duvat et al., 2020a). Together, panels 1 and 2 emphasize the diversity and increasing complexity of the measures implemented in small islands.

15.5.5 Community-based Adaptation

Community-based Adaptation (CBA) is best described as a "community-led process based on meaningful engagement and proactive involvement of local individuals and organisations" (Remling and Veitayaki, 2016)(p. 380). Enabling CBA projects to succeed relies on gaining a good understanding of the socio-political context within which the communities operate, including such key issues as land tenure arrangements and ownerships, gender, and decision-making processes that operate on the ground (Nunn, 2013; Buggy and McNamara, 2016; Crichton and Esteban, 2018; Delevaux et al., 2018; Nalau et al., 2018b; Parsons et al., 2018; McNamara et al., 2020; Piggott-McKellar et al., 2020).This also includes the broader and often more urgent development issues that impact on communities' wellbeing (Piggott-McKellar et al., 2020). Community-based projects demonstrate in the Pacific that communities' vulnerabilities, priorities and needs might be a better and more effective entry point for climate adaptation than framing projects solely around climate change (Remling and Veitayaki, 2016; Weir, 2020).This is supported by a recent review of 32 CBA initiatives in the Pacific where initiatives that were locally funded and implemented were more successful than those with external international funding (McNamara et al., 2020). Initiatives that integrated EbA and climate awareness raising also performed better (McNamara et al., 2020).

While CBA approaches to adaptation projects can increase community ownership and commitment to project implementation, these can also face challenges. In Pele Island, Vanuatu, implementation of CBA projects has experienced significant failures due to elite capture of project management, internal power dynamics within communities, and different priorities of communities living across the island that were supposed to be all responsible for implementing whole-of-island projects (Buggy and McNamara, 2016). Similarly, in Samoa, consultations with community leaders led to the misplacement of a revetment wall that increased flooding in the area against engineering advice (McGinn, 2020). Also, community-scale might not be always the best fit if the best scale to leverage adaptation is across catchment or whole-of-island scale (Buggy and McNamara, 2016; Remling and Veitayaki, 2016).

15.5.6 Livelihood Responses

Communities across small islands are adapting to the impacts of climate change across a range of livelihood activities. Coastal fishers have adapted by employing several activities ranging from diversification of livelihoods to changing fishing grounds and considering weather insurance (Blair and Momtaz, 2018; Lemahieu et al., 2018; Karlsson and McLean, 2020; Turner et al., 2020). In Antigua and Vanuatu, fishers have undertaken adaptation in response to increases in air and ocean temperature, increases in wind and changes in rainfall. In Antigua, adaptation strategies amongst coastal fishers have included investments in improved technologies and equipment, changing fishing grounds, and seeking better training and education (Blair and Momtaz, 2018). In Efate (Vanuatu) the majority (87%) of the fishermen used livelihood diversification as an adaptation strategy whereas 53% also searched for new fishing areas as a result of the changing conditions (Blair and Momtaz, 2018). In Southwest Madagascar, due to deteriorated reef conditions, coastal fishermen now go further offshore to catch fish or have adapted their fishing techniques, while others closer to the tourism markets, have opted for livelihood diversification (Lemahieu et al., 2018). Coastal fishers in the Dominican Republic have also diversified their livelihoods and use local knowledge in changing fishing practices and locations depending on environmental conditions (Karlsson and McLean, 2020). In the future, increased inland rainfall could for example provide new areas for inland aquaculture in the Solomon Islands as an adaptation strategy and also reduce pressure from coastal fishing (Dey et al., 2016).

In the agricultural sector in Jamaica, adaptation strategies include varying expenditure on inputs (e.g., fertilizers, chemicals, labour), diversifying cropping patterns, expanding or prioritising other cash crops (e.g., fruits and vegetables), engaging in small-scale livestock husbandry (Guido et al., 2018), and investing in irrigation technologies due to increased drought and infrequent rainfall (Popke et al., 2016). In many higher elevation islands within the Pacific, including Vanuatu and Fiji, communities continue to use to varying degrees traditional adaptive strategies designed to reduce their vulnerability to tropical cyclones. These include planting a diversity of different crops within household and communal gardens, locating gardens in different areas within their customary lands to ensure that not all crops are destroyed due to an extreme event, and the storage, and preservation of certain foodstuffs (so-called famine foods) (Campbell, 2014b; McMillen et al., 2014; Le Dé et al., 2018; Moncada and Bambrick, 2019).

Given changes in climatic conditions, in Puerto Rico women in the coffee industry are now forming their own "micro-clusters" of complementary activities, such as rebuilding of public spaces, running environmental education programmes for children, and opening new commercial enterprises (e.g., coffee shops, and food products) that do not rely on traditional coffee supply chains or government assistance (Borges-Méndez and Caron, 2019). Such alternative livelihood strategies parallel those undertaken by Pacific women working on various local-level climate change adaptation and environmental projects throughout small island nations of the Pacific. Women report testing and using adaptive strategies informed by IKLK, but which are being modified to suit the changing environmental conditions they are encountering and those projected in the future. This includes harvesting rainwater during droughts, planting native plants along coastlines to prevent erosion and flooding, developing plant nurseries, experimenting with growing salt-tolerant (taro) crops, and relocating crop cultivation inland (McLeod et al., 2018).

The tourism sector is increasingly a major source of cash-based livelihoods across small islands. Despite the high vulnerability and sensitivity of island tourism to climate change at a national scale (Scott et al., 2019), there is evidence from the South Pacific that local tourism operators' adaptive capacity is high due to socio-cultural factors. In Samoa, adaptive capacity consists of accommodation providers' social networks, resources, past experiences and understanding of environmental conditions, and remittances as a form of informal insurance (Parsons et al., 2017). The adaptive capacity of Tongan tour operators is strengthened by high climate change awareness, strong social networks and remittances as well as perceived high resilience against climate change (van der Veeken et al., 2016).

Evidence from Vanuatu shows that climate risk to tourism destinations is influenced by multiple, interconnected economic, socio-cultural, political, and environmental factors suggesting that holistic approaches are needed to reduce risk and avoid negative knock-on effects (Loehr, 2019). Tourism can strengthen mechanisms that reduce vulnerability and increase adaptive capacity of the wider destination, such as providing adaptation finance, investing in education and capacity building, and working with nature (Loehr, 2019).Examples include numerous EBA initiatives in the Caribbean including Marine Protected Areas in St. Lucia and Jamaica (Mycoo, 2018a). In Vanuatu, tourism businesses are engaged in establishing Marine Protected Areas to address multiple risks from climate change, population growth and development (Loehr et al., 2020). In the Seychelles, coral restoration programmes and mangrove reforestation are promoted through public-private partnerships, generating new opportunities for wetland-tourism livelihoods (Khan and Amelie, 2015).

The willingness of tourism businesses to finance adaptation measures varies. Islands have developed building codes which consider impacts from sea level rise but these are often not enforced enforced (Hess and Kelman, 2017). In cases where tourist resorts have been part of climate adaptation projects, such as funding for hard coastal protection infrastructure, the resort owners find that these diminish the aesthetics of the beach destination (Crichton and Esteban, 2018). Adaptation taxes and levies imposed on tourism can provide funding (Mycoo, 2018a) as The Environmental Protection and Tourism Improvement Fund Act, 2017 of British Virgin Islands shows (Smith, 2017). A lack of interaction between tourism and climate change decision makers is a commonly identified issue (Becken, 2019; Mahadew and Appadoo, 2019; Scott et al., 2019). A number of adaptation measures are recommended in the literature such as increasing climate change research, education and institutional capacities; product and market diversification away from coastal tourism to include terrestrial-based experiences and heritage tourism, and mainstreaming adaptation in tourism policies and vice versa (e.g., to include appropriate planning guidelines for tourism development, coastal setbacks and environmental impact assessments (Mycoo, 2018a; Becken et al., 2020) Thomas et al., 2020; van der Veeken et al., 2016).

15.5.7 Disaster Risk Management, Early Warning Systems and Climate Services

Disaster risk management (DRM) investments in small islands are commonly framed as reducing climate change-driven risk and contributing to sustainable development (Johnston, 2014; Mercer et al., 2014a; Kuruppu and Willie, 2015). Examples include strengthening the capacity of National Meteorological and Hydrological Services (NMHS) to deliver effective (WMO et al., 2018); nurturing community-based DRM to build social capital (Blackburn, 2014; McNaught et al., 2014; Gero et al., 2015; Handmer and Iveson, 2017; Chacowry et al., 2018; De Souza and Clarke, 2018; Currenti et al., 2019; Cvitanovic et al., 2019;

Hagedoorn et al., 2019), as well as processes that integrate IKLK with science (Hiwasaki et al., 2014; Carby, 2015; Bryant-Tokalau, 2018a; CANARI, 2019).

Many small islands, especially those with the highest risks and the least resources, remain highly challenged in building and sustaining integrated, people-centred, end-to-end early warning systems that are fully functional across the four interrelated components of EWS. Warning dissemination and communication, and disaster preparedness and response capacities are particular components of EWS requiring strengthening in SIDS (WMO, 2020). More recent assessments of early warning capabilities in the Caribbean highlight improvements in EWS for weather, water and climate over time (WMO et al., 2018; Mahon et al., 2019). However, progress has been uneven across hazards, governance levels and spatial and temporal scales, with more advanced development of some sub-systems and EWS pillars than others. Significant progress has been made in the area of detection, monitoring, analysis and forecasting of severe weather systems but there is a need to strengthen this area for other climate-related hazards such as wildfires, localised intense rainfall, floods, as well as heatwaves and droughts which become more important in a changing climate. Assessments also point to specific deficiencies including significant gaps in the area of disaster risk knowledge - particularly the development of risk assessments, the variable capacity for interpreting scientific warning products across states, as well as effective communication of warning messages to populations at risk (Lumbroso et al., 2016; WMO et al., 2018).

There is increasing recognition and commitment at global (Section 3.6.3.2.4; WMO, 2014; UN, 2015c; UN, 2015b; UN, 2015a), regional (CCCCC, 2012; CDEMA, 2014; SPC, 2016; SPREP, 2017; CIMH et al., 2019) and national levels (SPREP, 2016a; WMO, 2016a) of the importance of climate services in supporting adaptation decision making in small islands (*medium evidence, high agreement*). A number of SIDS-focused climate service programmes have emerged, especially in the Caribbean and Pacific (Group, 2015; Martin et al., 2015; SPREP, 2016b; WMO, 2016b; WMO, 2018a; WMO, 2018b) and at least one SIDS – Dominica - has been prioritised as a pilot implementation country under the Global Framework for Climate Services (WMO, 2016a). As is the case globally, climate services focused on decision-making at seasonal (3–6 month) timescales has thus far been the focus of investment in small islands. Less attention has been given to investments in and assessments of climate services for decision making at longer timescales (Vaughan et al., 2018).

Studies from the Caribbean (Dookie et al., 2019; Mahon et al., 2019) and Indian Ocean (Hermes et al., 2019), have found that NMHSs and regional intergovernmental bodies face capacity challenges in translation, transfer, and facilitation of the use of climate information to various end user groups. In many small island contexts a gap remains between investments in data quality and information services and uptake and use in risk reduction by policy and decision makers (Dookie et al., 2019). Bringing policy makers and users together to guide investments in climate information services is recommended, as is provision of dedicated resources to develop applicable tools and products that turn data and information services into risk reduction measures (Dookie et al., 2019; Haines, 2019).

Many of the outlined Key Risks (Section 15.3.4.9) can be addressed through the variety of adaptation options outlined in the previous sections in the context of small islands (Table 15.6, Supplementary Material 15.1). Whereas some of these adaptation options are widespread (e.g., hard protection, reforestation or the creation of MPAs), others (e.g. accommodation, health awareness raising and training) have been little experimented with to date in small island contexts. Although most of these adaptation options provide diversified co-benefits to small island communities, there is still *limited evidence* with regard to their effectiveness in reducing climate change impacts. While some of them respond directly to a Key Risk or a number of Key Risks (Table 15.6), others can be understood as overarching options that, for example, build adaptive capacity of communities and organizations and enable these actors to respond to a variety of Key Risks in an effective manner (see Supplementary Material 15.1).

Table 15.6: Adaptation options per Key Risk in small islands. This table summarizes risk-oriented adaptation options, their level of implementation, enablers and effectiveness in reducing exposure and vulnerability, co-benefits and disbenefits in small islands. For Key Risk 2 (submergence of reef islands), not included, adaptation options are the same as for Key Risk 5.

[INSERT TABLE 15.6 HERE]

15.6 Enablers, Limits and Barriers to Adaptation

Since AR5, more literature has emerged on barriers, limits and enablers to climate change adaptation across small islands. Here, we cover barriers, limits and enablers as they relate to key themes across small islands and adaptation.

15.6.1 Governance

Specific governance-related barriers for effective adaptation include: lack of coordination between government departments and sectors and limited policy integration (Scobie, 2016; Robinson, 2018b), lack of ownership of adaptation implementation in cases where communities or national governments have not been part of the adaptation decision process (Conway and Mustelin, 2014; Kuruppu and Willie, 2015; Prance, 2015; Nunn and Kumar, 2018; Parsons and Nalau, 2019), and difficulties in integrating IKLK in adaptation initiatives. Specific barriers to effective sustained adaptation in the Pacific include variable climate change awareness among decision-makers, and the preference for short-term responses rather than longer-term transformative ones (Nunn et al., 2014). These barriers also stem from donors' preferencing their own priorities that do not necessarily fit the country priorities or context (Conway and Mustelin, 2014; Kuruppu and Willie, 2015; Prance, 2015), which has led to increasing calls for effective community/cultural engagement in adaptation, especially through CBA and EbA (Nalau et al., 2018b). In cases where recovery efforts are framed as purely a matter of infrastructure other important aspects, such as livelihoods and gender, are more easily overlooked in adaptation (Turner et al., 2020).

In the Caribbean small islands such as Jamaica and St. Lucia, and also in the Pacific, barriers to mainstreaming adaptation include competing development priorities, the absence of planning frameworks or 'undetected' overlaps in existing frameworks, serious governance flaws linked to the prevalence of corruption and corrupt people in political and public life, and insufficient manpower and human resources, linked to countries' financial capacity (Robinson, 2018b). In addition, the lack of strong governance mechanisms for urban planning have contributed to urban sprawl and expansion that has increased the number of informal settlements, which together with population growth are driving Caribbean small islands to their limits (Enríquez-de-Salamanca, 2018; Mycoo, 2018a; Mycoo, 2018b). In the Pacific, only a few countries have embedded climate change adaptation in existing legislation despite the overall regional agreement to *A New Song for Coastal Fisheries - Pathways to Change: the Noumea Strategy*' to improve coastal fisheries management in a changing climate (Gourlie et al., 2018). Many climate change specific initiatives across small islands have a unidirectional focus on climate risks and shift limited resources away from other important development objectives (Baldacchino, 2018). Local level plans are often overlooked: for example, in Mauritius, local level climate adaptation plans are currently nearly non-existent while district councils have rarely been successful in even accessing international adaptation finance (Williams et al., 2020). In Samoa, several national level programs on adaptation have had difficulties in engaging with the local level even if the decision-making powers on actual land management sit within the communities (McGinn and Solofa, 2020).

Adaptation governance is also complicated further by the multitude of stakeholders involved, with differing agendas and priorities. In the Bahamas, private properties have significant say in how and what adaptation measures they decide to pursue and are not well regulated, with the tourism sector in particular dominated mainly by external investors (Petzold et al., 2018). Social organisations, such as the churches, that have significant influence in many Oceanic countries, are engaging in climate change discussions and governance. Many churches report, however, being constrained to act on climate adaptation due to lack of financial resources, low levels of professional knowledge on adaptation, and their members not perceiving climate change as an urgent risk (Rubow and Bird, 2016). Actors such as military services in the Indian and Pacific Oceans also control a high number of assets in vulnerable locations and will need to integrate climate information into adaptive planning in the future (Finucane and Keener, 2015).

Low technical capacity, and poor data availability and quality are reported as limiting adaptation in Caribbean small islands such as Dominica, and St. Vincent and the Grenadines (Smith and Rhiney, 2016; Robinson, 2018a) and Trinidad and Tobago (Mycoo, 2020). These factors are, however, secondary to the lack of finances, which is seen as a fundamental limit (Charan et al., 2017; Robinson, 2018a; Williams et al., 2020). This was also reported in the Seychelles, despite its success with innovative financing streams and being a leader in the Indian Ocean in this regard (Robinson, 2018a).

Limited regional cooperation across sub-national island jurisdictions (jurisdictions with semi-autonomous status) along with limited regional-scale climate information are also stymying action (Petzold and Magnan, 2019). This is a concern given the need for pooled governance in response to capacity constraints across small jurisdictions (Dornan, 2014; Kelman, 2018). There is also an insufficient understanding of the role of regional and international actors such as the Caribbean Community Climate Change Centre and the Global Environment Facility, respectively (Middelbeek et al., 2014). Sometimes external pressure and, for example, trans regional trade agreements are "useful for reducing unsustainable local socio-political arrangements" as seen in the Solomon Islands regarding fisheries management within the concept of Blue Economy (Keen et al., 2018, p. 338). Similarly, in Samoa, the World Bank's Pilot Program for Climate Resilience (PPCR) and Adaptation Fund's Enhancing Resilience of Samoa's Coastal Communities to Climate Change, illustrate successful examples of multi-level governance due to their programmatic and pragmatic approaches versus project-based approaches (McGinn and Solofa, 2020). Enabling factors in these programmes relate to strategic placements of funds and responsibilities in the relevant ministries, alignment with national priorities and pre-existing plans, pooling funding to fill existing finance gaps, and increased awareness across scales and departments of synergies and gaps between different initiatives (McGinn and Solofa, 2020). Initiatives such as the Pacific Adaptive Capacity Framework (Warrick et al., 2017) and regional strategies such as the Framework for the Disaster and Climate Resilient Development in the Pacific (FRDP) enable the localising of climate adaptation into cultural contexts in an integrated manner (SPC, 2016).

Countries including the Seychelles and Maldives have developed national climate change plans that recognize linkages to food security, health and disaster risk reduction, although these-face significant resourcing issues when it comes to implementation (Techera, 2018). National level plans, such as National Adaptation Plans of Action (NAPAs), increasingly could include local government engagement and have a stronger focus on urban centres and adaptation (Mycoo, 2018a). Building codes act as supportive enablers for adaptation governance: requiring more hurricane-resistant housing in the Caribbean, including incentives for informal settlements to build in a more resilient manner, can achieve multiple development and adaptation outcomes (Mycoo, 2018a). In Dominica, a Climate Resilience Executing Agency of Dominica (CREAD) established in 2019, aims to enable stronger climate resilience by bringing all sectors and services together for more effective coordination (Turner et al., 2020). Improvements in cross sectoral and cross agency coordination are creating opportunities for improved disaster preparedness and resilience measures in Vanuatu (Webb et al., 2015). A range of mechanisms also exists in the tourism industry: adaptation taxes and improved building regulations could reduce risk drastically for example in the Caribbean region (Mycoo, 2018a).

15.6.2 Health-Related Adaptation Strategies

The term 'health systems' refers to the organisation of people, institutions, and resources that work to protect and promote population health. The two components of health systems are public health and health care; adaptation is needed in both to develop climate-resilient health systems (WHO, 2015). Adaptation measures focus on each of the building blocks of health systems, including leadership and governance; a knowledgeable health workforce; health information systems; essential medical products and technologies; health service delivery; and financing. Many small island states have policies to manage climate-sensitive health risks, although Ministries of Health are largely unprepared to adapt to a changing climate because few programmes take climate change into account (McIver et al., 2016). Particularly vulnerable groups, such as Indigenous peoples, are often inadequately represented in adaptation planning processes and implementation, resulting in less effective interventions (Jones, 2019).

A range of climate-sensitive diseases pose threats to island communities. A vulnerability and adaptation assessment conducted in Dominica identified vector-, water- and food-borne diseases and food security as priority threats from climate change (Schnitter et al., 2019). Short-term adaptation options include strengthening solid waste management and enforcing current legislation; increasing public awareness; training health sector staff; improving the reliability and safety of water storage practices; improving climate change and health data collection methods and enhancing environmental monitoring; enhancing the integration of climate services into health decision-making; strengthening the organisational structure of emergency response; and ensuring sufficient resources and surge capacity. Longer-term adaptation options include developing early warning and response systems for climate-sensitive health risks; enhancing data collection and information flow; increasing the capacity of laboratory facilities; and developing emergency plans. For example, rainfall is the best environmental predictor of malaria in North Guadalcanal, Solomon Islands, leading to the development of an early warning tool that could increase resilience to climate change (Smith et al., 2017; Jeanne et al., 2018).

In small island states, water, sanitation, and hygiene infrastructure are particularly vulnerable to climate change, with impacts on the burden of diarrheal diseases. The resilience of types of sanitation infrastructure in urban and rural households in the Solomon Islands differ under scenarios of increased rainfall and flooding versus decreased rainfall and drought, reinforcing the centrality of taking the local context into account during adaptation decision-making (Fleming et al., 2019). Healthcare facilities, including hospitals, clinics, and community care centres, are vulnerable to extreme weather and climate events, such as flooding and TCs, and to climate-related outbreaks of infectious diseases that overwhelm their capacity to provide critical services (WHO, 2020). These facilities may lack functioning infrastructure and trained health workforce, and be predisposed to inadequate energy supplies, and water, sanitation, and waste management services. Adaptation is needed to build resilience and contribute to environmental sustainability.

Many major health care facilities in small island states are in exposed coastal areas and have limited ability to provide health services during disasters when services are most needed (WHO, 2018). For example, in Vanuatu, TC Pam in 2015 severely damaged two hospitals, 19 health care centres, and 50 healthcare dispensaries in 22 affected islands (Kim et al., 2015). A Smart Hospital Initiative in the Caribbean focuses on improving hospital resilience, strengthening structures and operations, and installing green technologies to reduce energy consumption and provide energy autonomy during extreme events and disasters (https://www.paho.org/en/health-emergencies/smart-hospitals).

15.6.3 Adaptation Finance and Risk Transfer Mechanisms

In the majority of small island developing states there is a high dependence on international financing to support adaptation to slow and rapid onset events (Robinson and Dornan, 2017; Petzold and Magnan, 2019). However, funds tend to be geared towards supporting sectoral-level adaptation initiatives for vulnerable natural resource sectors such as water, biodiversity and coastal zones (Kuruppu and Willie, 2015). Considering low income small islands such as Comoros, Haiti, and São Tomé and Príncipe, international modalities do little to address the root causes of vulnerability or to support system-wide transformations (Kuruppu and Willie, 2015). Although countries like Trinidad and Tobago have amassed oil wealth, the profits are not invested in a way that benefits environmental goals (Middelbeek et al., 2014). In Mauritius, a lack of financial resources for climate change adaptation has been recognised as a specific impediment in district council level (Williams et al., 2020).

Although small island jurisdictions have seen increased flows of adaptation finance through mostly top-town arrangements, they face large implementation difficulties (*medium evidence, high agreement*) (Weir and Pittock, 2017; Magnan and Duvat, 2018). There are growing concerns among policy- and decision-makers in small islands about the current levels and forms of adaptation finance, and about countries' experience with accessing it (Robinson and Dornan, 2017). In the Caribbean, 38% of flows were concessional loans and 62% were grants (Atteridge et al., 2017); the situation in the Atlantic and Indian Oceans is starkly different—nearly 75% of the flows were in the form of concessional loans and grants accounted for the remaining 25% (Canales et al., 2017). This raises questions about fairness and justice for small islands having to finance adaptation to climate impacts to which they have made a negligible contribution. In the Pacific, 86% of aid was delivered as project-based support (Atteridge and Canales, 2017), that can undermine the long-term sustainability of adaptation interventions (Conway and Mustelin, 2014; Remling and Veitayaki, 2016; Atteridge and Canales, 2017). Direct budget support was rare (Atteridge and Canales, 2017), signalling the importance of works such as Rambarran (2018) that support cross-regional lesson-learning by, for example, showcasing the experience of Seychelles with successfully devising innovative financing mechanisms for supporting adaptation and conservation goals, and reducing its public debt. Regional catastrophe risk insurance schemes however, such as Pacific Catastrophe Risk Insurance Company under the World Bank's Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) Program are trying to enable a regional effort in increasing accessibility to insurance (PCRAFI, 2017) as does the Caribbean Catastrophe Risk Insurance Facility, although these funds are still rather small compared to the needs across the countries (Handmer and Nalau, 2019).

Microfinance is increasingly viewed as a positive mechanism to improve access to climate adaptation funding (Di Falco and Sharma, 2018). In the Caribbean, a significant barrier in accessing climate finance relates to bureaucratic structures, which means that money intended for communities does not reach them (Mycoo, 2018a). Many adaptation projects even at the community level have upfront costs that need to be supported, especially in communities where there is little hard cash in use (Remling and Veitayaki, 2016). Despite such challenges, communities in the Pacific region have used "cashless adaptation" for a long time that involves trading of services and items as a form of Indigenous microfinance (Nunn and Kumar, 2019b). Social networks also function as a source of informal microfinance where extended family members send back remittances from overseas to their families and communities especially after disasters. In Samoa Indigenous tourism operators receive remittances from overseas family members (Crichton and Esteban, 2018; Parsons et al., 2018), with similar processes observed among atoll communities in the Solomon Islands (Birk and Rasmussen, 2014), Vanuatu (Handmer and Nalau, 2019) and Jamaica (Carby, 2017). However, the role of migration and remittances is still poorly understood; it is difficult to quantify the informal flows and understand the extent they support effective adaptation (*limited evidence, high agreement)* (Campbell, 2014a; Parsons et al., 2018; Handmer and Nalau, 2019).

In Old Harbour Bay, Jamaica's largest fishing village, a high number of community members engaged in the fishing industry, particularly vendors and scalers, do not own the material assets needed to fully benefit from these livelihood activities (Baptiste and Kinlocke, 2016). Developing a broader asset portfolio by increasing access to such assets via adaptation finance investments could reduce vulnerability across the community. This could function as an effective livelihood-based adaptation strategy for the most vulnerable such as women, who are part-time employed and in peripheral roles in the fishing industry (Baptiste and Kinlocke, 2016). In Belize and the Dominican Republic, many coastal fishers for example use informal credit from food stores or captains to enable them to withstand financial losses that are often incurred during bad weather and extreme events (Karlsson and McLean, 2020).

In Vanuatu, discussions are ongoing on increasing insurance availability for TCs and droughts, but standardisation of housing designs to get insurance can become difficult where the costs make it prohibitive and run counter to traditional building designs and materials (Baarsch and Kelman, 2016). Empirical evidence from Belize, Grenada, Jamaica and St. Lucia indicates that there are also other factors why people do not take insurance, including "the cost of premiums (44 %), lack of trust in insurance companies (27 %), having never considered insurance (26 %), a lack of need for insurance (25 %) and a lack of knowledge of insurance (22 %)" (Lashley and Warner, 2013, p. 108). Increasing trust could be addressed by seeking out domestic banks or credit unions with whom people are already engaging with, while also using social marketing campaigns to raise awareness of weather-related insurance to address knowledge gaps and lack of awareness of these tools (Lashley and Warner, 2013). In Dominica, many coastal fishers are suspicious of insurance schemes given past experiences of not being paid out on time or having to disclose catch data (Turner et al., 2020). Yet, insurance is not capable of addressing all kinds of loss and damage accruing from climate impacts and should be used as an adaptation strategy in combination with other strategies (Lashley and Warner, 2013).

Insurance cover is a critical question in small islands. For example, in Vanuatu, some companies do not "cover storm damage from the sea or high tides…which is not helpful for properties damaged by a tropical cyclone's storm surge" (Baarsch and Kelman, 2016)(p. 6). There is also limited access to insurance schemes due to lower demand in small markets (Petzold and Magnan, 2019) especially when many people do not have high cash-based incomes and likely cannot pay insurance premiums (Baarsch and Kelman, 2016). In Saint Lucia and Grenada (via the Caribbean Oceans and Aquaculture Sustainability Facility), discussions are ongoing with regard to national level parametric insurance, underpinned by financing from the US State Department, to help fishing communities recover more quickly following the passage of TCs in the future (Sainsbury et al., 2019; Turner et al., 2020). Likewise, (Reguero et al., 2020) have suggested a resilience insurance mechanism that could in theory reduce climate related losses and damages through investments in nature-based adaptation projects (e.g. coral reef restoration and potentially mangrove restoration).

15.6.4 Education and Awareness-Raising

A significant barrier to effective climate adaptation is the lack of education and awareness around climate change both among the general public, for example in the Bahamas (Petzold et al., 2018) and among decision-makers in the more remote rural communities (Nunn, 2013; Mycoo, 2015). Increasing knowledge on adaptation options and needs can increase adaptive capacity that is underpinned by "the ability of individuals to access, understand and apply the knowledge needed to inform their decision-making processes" (Cvitanovic et al., 2016 p. 54). This should however also be seen as a collective effort (Hayward et al., 2019).

Workshops and training are seen as crucial at the local scale to build communities' capacity to take action and to integrate climate change considerations to the broader development processes (Remling and Veitayaki, 2016), although purely workshop-based short-term capacity building in adaptation has been questioned (Conway and Mustelin, 2014; Lubell and Niles, 2019). More interactive community engagement strategies could include "participatory three-Dimensional modelling (P3DM), participatory video, development of photo journals, and civil society plans" (Beckford, 2018, p. 46) that enables broader engagement. In Fiji, Laje Rotuma youth EcoCamps have been used to engage younger Fijians to understand adaptation and increasing environmental stewardship with good outcomes (McNaught et al., 2014). In Palau, Camp Ebiil provides a culturally-based platform for younger generations to learn about nature and culture in an interactive camp (Singeo, 2011). Vanuatu's Volunteer Rainfall Observer Network in turn engages volunteers to record their rainfall observations, demonstrating the use of IKLK that can be integrated with contemporary weather forecasting (Chand et al., 2014). Likewise, initiatives such as ePOP Petites Ondes Participatives aim to develop a citizen network to share environmental information (e.g., via minivideos on smartphones). Across the Pacific, projects such as the European Union Pacific Technical Vocational Education and Training on Sustainable Energy and Climate Change Adaptation Project (EU PacTVET), have sought to increase capacity of Pacific islanders in disaster risk management and climate adaptation (Hemstock et al., 2018).

In Fiji, a study on adaptive behaviour and intention to invest in more adaptive portfolios found that the intent for adaptive behaviour increased with the supply of climate information (Di Falco and Sharma, 2018). In the Pacific, high performing CBA initiatives included climate awareness raising that equipped people with knowledge to understand occurring environmental changes and what to do (McNamara et al., 2020). Lack of information can increase community vulnerability. Remote Indigenous farming communities in St Vincent, in the Caribbean, for example have already observed decreased rainfall and increases in temperatures, but they have been largely excluded from agricultural training that includes information in how to improve agricultural strategies in times of climatic shocks and how to prepare for changing climatic conditions (Smith and Rhiney, 2016). In the Bahamas, cultural background, income and education levels impact the extent that people are aware of climate risks (Petzold et al., 2018) . In Dominica, access to information critical to fisheries is noted as a significant challenge, including data collection, its management and human resources in building capacity to process and use this information for evidence-based decision making (Turner et al., 2020).

The Caribbean Climate Online Risk and Adaptation tool has been developed to assist the tourism industry in producing "climate-sensitive developments" (Mackay and Spencer, 2017,p. 55). Though some authors conclude on the low climate awareness/understanding among small islanders (Middelbeek et al., 2014; Betzold, 2015; Petzold et al., 2018), others indicate that many Caribbean islanders are acutely aware of past storm events (i.e., social memory) and have a certain degree of self-reliance, which creates the capability to multi-task and cope with limited resources (Petzold and Magnan, 2019). There is, however, a disconnect between knowledge, attitudes and practices—knowledge sharing and learning need to be improved along with the take-up of an evidence-based decision-making approach (Lashley and Warner, 2013; Petzold et al., 2018; Saxena et al., 2018).

15.6.5 Culture

Culture can be defined as "material and non-material symbols that express collective meaning" (Adger et al., 2014, p. 762) and includes worldviews and values, how individuals and communities relate to their environment, and what they perceive to be at risk and in need of adaptation (McNaught et al., 2014; Nunn et al., 2014; Remling and Veitayaki, 2016; Nunn et al., 2017bGranderson, 2017; Neef et al., 2018; Oakes, 2019). In small islands, culture plays an important role in individual and community decision-making on adaptation both as an enabling factor and as a barrier (*robust evidence, high agreement*) (Nunn et al., 2017b; Parsons et al., 2017; Neef et al., 2018; Piggott-McKellar et al., 2020). The concept of *Vai Nui* as the interconnectedness of Pacific Islanders continues to support the collective agency to plan and undertake adaptation efforts in the region (Hayward et al., 2019). In Samoa, the principles of *Fa'asamoa* (the Samoan way of life) impacts on how decisions are made, including the role of the *aiga* (extended family) that is a web of local, national and transnational kinship networks (Parsons et al., 2018). Traditional village council structures and land stewardship enables an expanded range of coastal adaptation options in Samoa, including potential relocation, but at the same time may limit participation of all social groups in adaptation decision making (Crichton et al., 2020). In Dominica, in the aftermath of Hurricane Maria (2017), social capital in the form of transboundary nearby island networks enabled some communities to recover faster from the disaster including access to more livelihood opportunities and assets (Turner et al., 2020).

Yet, culture is often overlooked in adaptation policies and plans. For example, in the National Communications of 16 SIDS, only one country (Cook Islands) reported adaptation actions that addressed social issues, culture, and heritage (Robinson, 2018b). Externally-driven adaptation efforts in rural small-island communities that exclude community priorities, ignore or undervalue IKLK, and are based on secular western/global worldviews (Donner and Webber, 2014; Prance, 2015; McNamara et al., 2016; Nunn et al., 2017b; Schwebel, 2017; Mallin, 2018; Nunn and McNamara, 2019; Piggott-McKellar et al., 2019b) are often less successful (*high agreement, medium evidence*). The World Bank Kiribati Adaptation Program (KAP) for example builds mainly on western knowledge and science despite consultations with the Kiribati communities (Prance, 2015). Yet, in many contexts most land and knowledge is embedded in traditional governance and culture while adaptation plans and decisions are made elsewhere on how that land should be used and what knowledge is used (*high agreement*) (Nunn, 2013; Prance, 2015; Charan et al., 2017; Nalau et al., 2018a; Parsons et al., 2018; McGinn and Solofa, 2020).

In Kiribati, communities often use different timescales to evaluate the need for adaptation. I-Kiribati culture's core concept of time is short- and medium term (Prance, 2015), which should be considered in adaptation policy and planning processes especially at the household and community level (Donner and Webber, 2014). Key stakeholders, especially community leaders, should be included and empowered to help design and sustain adaptation (Baldacchino, 2018; Weiler et al., 2018). Focusing on values-as-relations (e.g., island communities' relationship with the environment and each other) could diversify the values considered in adaptation decision-making processes (Parsons and Nalau, 2019). Indeed, those Pacific islands with a more island-centric approach to climate adaptation tend to have overall more successful adaptation policies in place (Schwebel, 2017).

The cultural context and sources of knowledge are myriad and diverse in small islands. Community members often use both IKLK as well as western scientific-based weather forecasts to take actions to prepare for extreme weather events (Chand et al., 2014; Johnston, 2015; Janif et al., 2016; Granderson, 2017; Kelman et al., 2017), with specific examples from Niue, Tonga, Vanuatu and the Solomon Islands *(high agreement, high evidence)* (Chand et al., 2014; Chambers et al., 2017; Chambers et al., 2019). In Samoa, people keep particular areas reserved for disaster times such as TC seasons (Kuruppu and Willie, 2015) while in Vanuatu IKLK indicators for tropical cyclones include mango trees flowering early and turtles going further inland to lay their eggs (Chand et al., 2014). IKLK are however not evenly distributed within communities due to IKLK being traditional intellectual property of particular roles in the villages (e.g., weathermen in Vanuatu), and not available to other community members or external actors directly (Chand et al., 2014; Prance, 2015). In Tongoa Island, Vanuatu, communities are finding however that their IKLK-based seasonal calendars are out of sync given the changes in climatic conditions (Granderson, 2017) while erosion of IKLK remains a concern across most small island nations (Kuruppu and Willie, 2015; Granderson, 2017; Beckford, 2018).

Not all IKLK and other knowledge are necessarily helpful and IKLK can lead to maladaptation (Mercer et al., 2012; Beckford, 2018). Elders from the Chuuk State (Federated States of Micronesia, (Elders from Atafu Atoll, 2012), for instance, assign blame for changeable weather patterns, destructive typhoons, and loss of biodiversity to people's failure to maintain and employ their IKLK. Fatalism (belief that disasters are God's will) is still reported as a major cultural barrier to adaptation. In Maldives fatalism decreases direct adaptation action and influences perceptions of climate risks (Shakeela and Becken, 2015) while Indigenous communities in St Vincent do not prepare for hurricanes or climatic shocks for the same reason (Smith and Rhiney, 2016). In Oceania, Christianity and the church play an important role in how issues, such as climate change, are communicated and thought about (Rubow and Bird, 2016; Nunn et al., 2017b), including the Noah and flood story used as a justification that there is no need to worry about sea level rise (Rubow and Bird, 2016). New emerging forms of eco-theology (theology that connects humans with land, sea and sky) however situate climate change as part of environmental stewardship (Rubow and Bird, 2016) making churches active partners in caring for the environment.

Many studies also now demonstrate the value in considering multiple systems of knowledge through collaborative and co-production projects and strategies, which allow for culturally-situated knowledge, values, and practices to be positioned at the heart of sustainable climate change adaptation *(high agreement)* (Chambers et al., 2017; Plotz et al., 2017; Beckford, 2018; Malsale et al., 2018; Parsons et al., 2018; Suliman et al., 2019). In the Caribbean context, Beckford (2018) suggests the establishment of Caribbean Local and Traditional Knowledge Network, a shared regional platform makes IKLK more available for climate adaptation and community resilience projects where appropriate. Likewise, Indigenous research methodologies are emerging that introduce more culturally grounded concepts and methods into how research is conducted and decolonise mainstream research in the Pacific Islands (Suaalii-Sauni and Fulu-Aiolupotea, 2014).

Despite widespread international evidence that the impacts of climate change and disaster events often negatively affect women (and gender minorities) more than men (McSherry et al., 2014; Aipira et al., 2017; Gaillard et al., 2017), attention to gender equality as a concept is still only "embryonic in climate change adaptation in the Pacific" and although recognised in some policies and project designs, it is not well supported by on-the-ground actions or well monitored (Aipira et al., 2017, p. 237). Many Pacific small island climate change adaptation policies do not mainstream gender across the activities (Aipira et al., 2017), with women's groups being excluded from climate grants due to patriarchal formal and informal governance structures, lack of resources, lower access to educational and training schemes, and no track record (or receiving grants or meeting grant milestones) (McLeod et al., 2018). However, Pacific women identify several strategies that enable them to adapt to climate change more effectively. These include the recognition and support of women's IKLK by governments, researchers, and NGOs; increasing women's access to climate change funding and support from organisations to allow them to meet the requirements of international climate change grants; and specific education and training to women's groups to allow them to develop strategic action plans, mission statements, learn financial reporting requirements, as well as general leadership and institutional training (McLeod et al., 2018). Such and other measures could enable a broader representation and participation in adaptation processes despite cultural constraints (Table 15.7 on Enabling Conditions).

Table 15.7: Enabling Conditions and Factors for Adaptation in Small Islands
[INSERT TABLE 15.7 HERE]

15.7 Climate Resilient Development Pathways and Future Solutions in Small Islands

Synergies exist between climate resilient development pathways and implementation of SDGs in small islands because development decisions and outcomes are strengthened by consideration of climate and disaster risk (Robinson, 2017b; Hay et al., 2019a). However, monitoring progress of SDGs is challenging for small islands, in part due to large numbers of indicators and inadequate data. Literature on SDG implementation is generally lacking for small islands as is the integration of climate risk into infrastructure decisions.

Decisions that are optimal for adaptation may not be acceptable in the wider development context within which they operate. In the Pacific region, where 67% of infrastructure is located within 500 metres of coastline and commercial, public and industrial infrastructure are particularly vulnerable due to the location of urban centres (Kumar and Taylor, 2015). Yet the Parliamentary Complex in Samoa was redeveloped at the original site due to cultural and historical factors despite strong evidence of the need to relocate (Hay et al., 2019b).

Energy transitions in the Pacific islands demonstrate development synergies such as reduced dependency on volatile fossil fuel markets, increased resilience to weather related disasters and less need for investment in large scale centralised energy systems (Dornan, 2014; Cole and Banks, 2017; Weir, 2018; Weir and Kumar, 2020). However, high and rapid energy transition ambitions can lead to trade offs for rural electrification (Box 18.4; Dornan, 2014; Cole and Banks, 2017; Hills et al., 2018).

Tourism system transitions can enable the sector to contribute to climate resilient development pathways through managing climate risks and improving ecological, economic and social outcomes for small islands (*medium evidence, high agreement*) (Loehr, 2019; Mahadew and Appadoo, 2019; Loehr et al., 2020; Sheller, 2020).

There is a clear role for local governments to work closely with the informal private sector to achieve a 'trifecta' of climate change adaptation, economic development and disaster risk reduction, especially for women (McNamara et al., 2020). Yet, many cities and local governments in the Pacific region are severely resource constrained (Kelman, 2014; Kiddle et al., 2017; Keen and Connell, 2019; Nunn and McNamara, 2019).

Broader innovation in climate resilient development policy making has taken place in the Pacific (Hay et al., 2019a) and Caribbean (Mycoo, 2018a). The Pacific region is bringing together disaster risk management, low carbon growth and climate change adaptation with broader development efforts for the first time (SPC, 2016). Improvements in cross sectoral and cross agency coordination are creating opportunities for improved disaster preparedness and resilience measures in small islands (Webb et al., 2015; Nalau et al., 2016). Further integration between development priorities and risk management in national budgetary and development processes is necessary, as is continued investment in coordination mechanisms (Hay et al., 2019a).

Early research on the response to COVID-19 indicates that existing disaster response mechanisms in the Caribbean islands have assisted in rapid responses to COVID-19 (Hambleton et al., 2020). Many small islands are highly dependent on tourism for their economies and are facing worsening crises associated with climate-related disasters and more recently COVID-19 disruptions of travel (Sheller, 2020). The adaptive capacity and innovations demonstrated by SIDS during COVID-19, moving beyond dependence on ‘extractive’ international tourism, demonstrate the potential benefits of diversified and sustainable economies (and ecologies) for the enhanced resilience of both human and ecological communities (Sheller, 2020).

In the context of small islands, climate justice research is expanding beyond initial debates about nation-states responsibilities for the causes and responses to climate change, to demonstrate complex and dynamic intergenerational and multiscalar dilemmas of climate justice (Ferdinand, 2018; Sheller, 2018; Baptiste and Devonish, 2019; Look et al., 2019; Douglass and Cooper, 2020; Kotsinas, 2020; Sheller, 2020). In Caribbean SIDS, research highlights how intersecting external and internal socio-economic and political processes are allowing marginalised populations to become increasingly socially and economically disadvantaged and politically marginalised, which in turn heightens climate vulnerability and impedes sustainable development efforts (Baptiste and Devonish, 2019) (Moulton and Machado, 2019; Gahman and Thongs, 2020; Rhiney, 2020; Duvat et al., 2021b). Inequity extends to how development and disaster aid were coordinated and distributed within various nations after Hurricanes Irma, Maria and Harvey in 2017.

15.8 Research Gaps

Despite intensive study many knowledge gaps remain due to the complexity of biophysical and social interactions, and the local and regional diversity of small islands. Research and data gaps exist in four areas: island-scale data availability; ecosystem services data; vulnerability and resilience, and adaptation (Table 15.8).

Table 15.8: Research Gaps in Small Islands
[INSERT TABLE 15.8 HERE]

[START FAQ15.1 HERE]

FAQ 15.1: How is climate change affecting nature and human life on small islands, and will further climate change result in some small islands becoming uninhabitable for humans in the near future?

Climate change has already affected and will increasingly affect biodiversity, nature's benefits for people, settlements, infrastructure, livelihoods and economies on small islands. In the absence of ambitious human intervention to reduce emissions, climate change impacts are likely to make some small islands uninhabitable in the second part of the 21st century. By protecting and restoring nature in and around small islands as well as implementing anticipatory adaptation responses, humans can help reduce future risks to ecosystems and human lives on most small islands.

Observed changes – including increases in air and ocean temperatures, increases in storm surges, heavy rainfall events, and possibly more intense tropical cyclones - are already reducing the number and quality of ecosystem services, thereby causing the disruption of human livelihoods, damage to buildings and infrastructure, and loss of economic activities and cultural heritage on small islands. Widespread observed impacts include severe coral reef bleaching events, such as that associated with the 2015–16 El Niño season, the most damaging on record worldwide. Additionally, the 2017 Atlantic hurricane season was unusually characterised by sequential severe tropical cyclones that resulted in widespread cyclone-induced damage to ecosystems from the very interior of small islands to those of the ocean waters that surround them as well as damage to human settlements and economic activities within the whole Caribbean region. Although knowledge is limited regarding long term increases in tropical cyclone intensity, studies have shown that heavy rainfall and intense wind speed of individual tropical cyclones were increased by climate change. The combination of various climate events, such as tropical cyclones, extreme ocean waves, and El Niño or La Niña phases, with sea-level rise causes increased coastal flooding, especially on low-lying atoll islands of the Indian and Pacific Oceans.

The expected increased risk of such impacts under further climate change is significant. For example, some low-lying islands and areas may be extensively flooded at every high tide or during storms. As a result, their freshwater supplies and soils would be repeatedly contaminated by saltwater, with adverse cascading consequences for freshwater and terrestrial food supplies, biodiversity and ecosystems, and economic activities. It is unlikely that these locations would remain habitable unless such impacts are mitigated through reduction of heat-trapping greenhouse gas emissions or adaptation solutions that are acceptable for the populations of these islands. Acceptable adaptation options may be limited in these locations. Additionally, drought intensity may challenge freshwater security in some regions such as the Caribbean. Likewise, remote atoll islands where inhabitants rely on reef-derived food and other resources and that are at high risk of widespread coral reef degradation may become uninhabitable. Strategies to reduce risk may include substituting the consumption of vulnerable inshore reef resources by developing onshore aquaculture (fish farming), or promoting access to tuna and other pelagic fish, and/or importing food to meet nutritional needs. However, adoption of these strategies will depend on the acceptance of their local populations.

The intensity and timing of such impacts will be more severe under high warming futures compared to low warming futures accompanied by ambitious adaptation. Tailored, desirable and locally owned adaptation responses that incorporate both short- and long-term time horizons would certainly help to reduce future risks to nature and human life in small islands. Among the short-term measures frequently employed to address sea-level rise and flooding are seawalls. Long-term measures include ecosystem-based adaptation such as mangrove replanting, relocation of coastal villages to upland sites, creation of elevated land through reclamation, revised building codes as part of a broader disaster risk reduction strategy, shifting to alternative livelihoods and changes in farming and fishing practices.

[END FAQ15.1 HERE]

[START FAQ15.2 HERE]

FAQ 15.2: How have some small-island communities already adapted to climate change?

Faced with rising sea levels and storm surges along their coastal areas which have significantly threatened people's safety, buildings, infrastructure and livelihoods, Small Island communities have already embarked on the use of different adaptation strategies. These include reactive adaptation, which deals with short-term measures, and anticipatory adaptation, which takes action in advance to lessen climate change impacts in the long run. Reactive measures have proven not always to be effective. In contrast, anticipatory measures hold much promise for future adaptation.

The majority of people living on small islands occupy coasts, so the most widespread threats to people's livelihoods are those from sea-level rise, shoreline erosion, increased lowland flooding, and salinization of groundwater and soil. Humans can either adapt reactively or anticipate coming changes and prepare for them. Given the diversity of small islands across the world, and their capacities to adapt, there is no single solution that fits all contexts.

Coastal livelihoods in particular are already impacted by climate impacts. Coastal fishers have adapted to these changes in environmental conditions by diversifying livelihoods, expanding aquaculture production, considering weather insurance, building social networks to cope with reduced catches and availability during extreme storms, switching fishing grounds, and changing target species. Similarly, farmers have diversified livelihoods to more cash- and service-based activities such as tourism, changed plant species that thrive better in altered conditions, and shifted planting seasons according to changes in climate.

A typical reactive adaptation along small-island coasts involves the construction of hard impermeable structures such as seawalls to stop the encroachment of the sea. Yet such structures, especially along rural island coasts, often fail to prevent flooding during extreme sea levels or extreme-wave impacts, and can inadvertently damage nearshore ecosystems such as mangroves and beaches. In the Caribbean, Indian Ocean islands and some Pacific islands, there are numerous examples of coastal engineering structures that have been destroyed already or are in grave danger from the encroaching sea. In many instances, citizens and governments are unable to access external advice or funding, communities have built such structures without assistance or knowledge of expected future sea level rise.

In contrast, anticipatory adaptation, which anticipates expected future impacts and acts in advance, requires a longer-term view as well as some understanding of future climate-change impacts in particular contexts. Along small-island coasts, anticipatory adaptation typically involves recognising that sea level will continue rising and that problems currently experienced will be amplified in the future. One strategy for anticipatory adaptation in response to sea level rise and flooding is relocation, which is the movement of coastal communities away from vulnerable (coastal-fringe) locations to sites that are further inland. . Coastal setback policies have been applied to hotels in some islands such as Barbados. In coastal locations where the risks of rising sea level, flooding and erosion are very high and cannot effectively be reduced, 'retreat' from the shoreline is the only way to eliminate or reduce such risks.

Where relocation is successful, it is most commonly driven and funded by governments and non-government organisations, often within a specially designed policy framework. The Government of Fiji, for example, has introduced a relocation framework that specifically develops guidance on relocation processes, with several villages already having relocated. Evaluations to date recommend thorough cost-benefit analyses of relocation be undertaken before this strategy is pursued. Relocation is often viewed as a 'last resort' adaptation option because of high cost and because some socio-cultural aspects of life cannot be maintained in locations separated from customary land. The Bahamas relocated a community on Family Island from the shoreline to an inland location and the community of Boca de Cachón in the Dominican Republic was relocated to higher ground. The Navunievu community (Bua, Fiji) has mandated that every young adult building their family home in the village should do so upslope rather than on the regularly flooded coastal flat where the existing village is located. Over the next few decades, this will result in the gradual upslope migration of the community, an example of autonomous adaptation. Such creative community-grounded solutions hold great promise for future adaptation on small islands, where they are undertaken inclusively.

Anticipatory adaptation has been aligned with disaster risk reduction in some small islands. For example, Jamaica adopted such an approach in relocating three communities. Recognising that a proactive approach is needed, Jamaica developed a Resettlement Policy Framework aligned with the National Development Plan and based on vulnerability assessments of communities at risk of climate change and disaster risk. A resettlement action plan was developed for the Harbour Heights community using community engagement to design successful planned relocation. In some islands revised building codes are implemented as an anticipatory adaptation measure. As part of the build-back-better strategy hurricane resistant roofs are being built to cope with strong winds associated with tropical cyclones.

Ecosystem-based adaptation can be a low-cost anticipatory adaptation measure that is often used in small islands. It is referred to as a 'no-regret' or 'low-regret' strategy because it is low-costing, brings co-benefits and requires less maintenance in contrast to hard engineering structures. Ecosystem-based adaptation is used at different scales and in different sectors such as to protect fisheries, farming and tourism assets, and integrates various stakeholders from national to local governments and non-governmental agencies. Many islands have implemented ecosystem-based adaptation such as watershed management, mangrove replanting and other nature-based solutions to strengthen coastal foreshore areas that are subjected to coastal erosion and flooding caused by sea level rise and changing rainfall patterns. For example, mangroves have been planted on several cays in Belize and pandanus trees have been planted near the coastlines of the Marshall Islands. Agroforestry is another example of ecosystem-based adaptation. Planting trees and shrubs in combination with crops has been used to increase resilience of crops to droughts or excessive rainfall run-off. Case studies show that people living on islands benefit even further from using ecosystem-based adaptation. Their health improves as well as their food and water supply, while risks of disasters caused by extreme events are reduced.

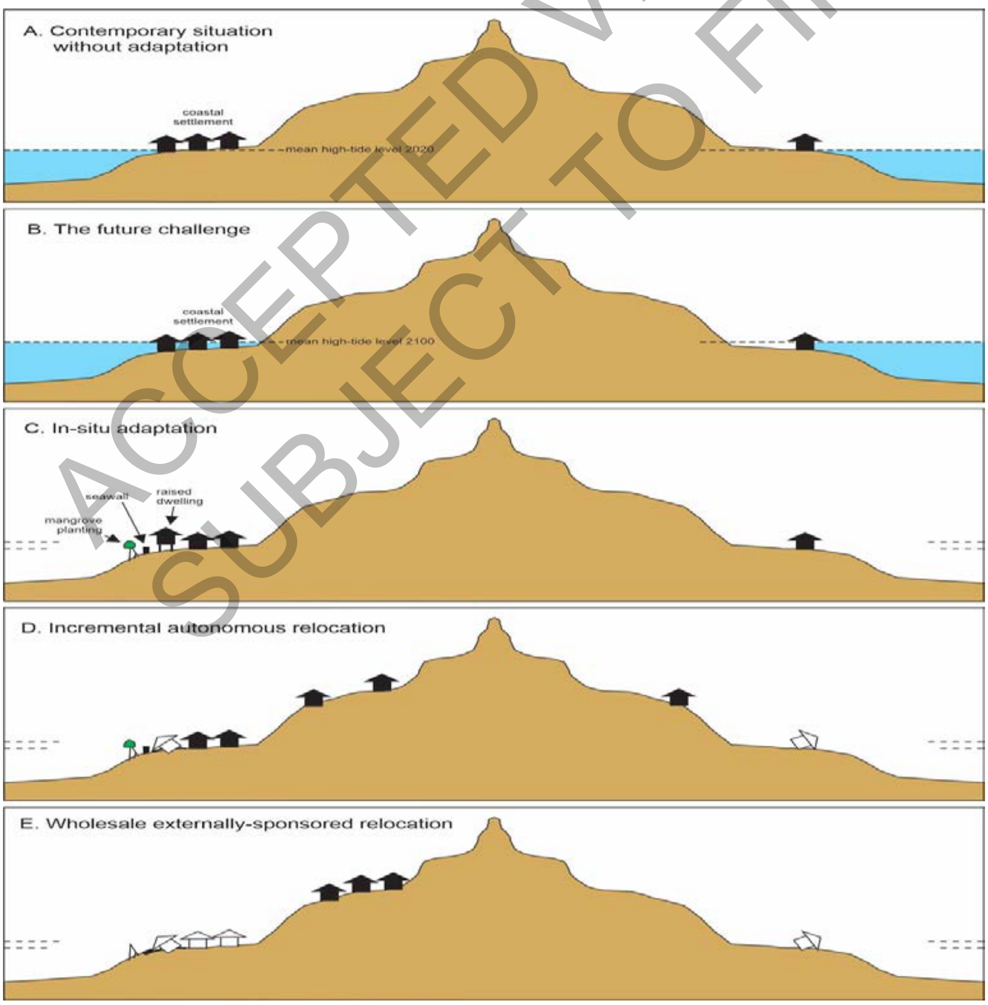


Figure FAQ15.2.1: Adaptation options for rural coastal communities in small islands
A – In many places today, coastal communities which have been established for hundreds of years are being more regularly inundated than ever before as a result of rising sea level. B – By the end of this century, sea level in such places may have risen one meter or more, making many such settlements (largely) uninhabitable, underscoring the need for effective (anticipatory) adaptation. C – One option is in-situ adaptation, popular because it is cheaper and less disruptive than other options; it is typically characterised by mangrove replanting, seawall construction and raising of dwellings. D – A second option is for communities to incrementally relocate upslope by building all new houses further inland. E – A third option is complete relocation of a vulnerable coastal community with external support upslope and inland.

[END FAQ15.2 HERE]

[START FAQ15.3 HERE]

FAQ 15.3: How will climate related changes affect the contributions of agriculture and fisheries to food security in small islands?

Agriculture and fisheries are heavily influenced by climate, which means a change in occurrence of tropical cyclones, air temperature, ocean temperature and/or rainfall can have considerable impacts on the production and availability of crops and seafood and therefore the health and welfare of island inhabitants. Projected impacts of climate change on agriculture and fisheries in some cases will enhance productivity, but in many cases could undermine food production, greatly exacerbating food insecurity challenges for human populations in small islands (also see Cross-Chapter Box MOVING PLATE in Chapter 5).

Small islands mostly depend on rain-fed agriculture, which is likely to be affected in various ways by climate change, including loss of agricultural land through floods and droughts, and contamination of freshwater and soil through salt-water intrusion, warming temperatures leading to stresses of crops, and extreme events such as cyclones. In some islands, crops that have been traditionally part of people's diet can no longer be cultivated due to such changes. For example, severe rainfall during planting seasons can damage seedlings, reduce growth and provide conditions that promote plant pests and diseases.

Changes in the frequency and severity of tropical cyclones or droughts will pose challenges for many islands. For example, more pronounced dry seasons, warmer temperatures, greater evaporation could cause plant stress reducing productivity and harvests. The impacts of drought may hinder insects and animals from pollinating crops, trees and other vegetative food sources on tropical islands. For instance, many agroforestry crops are completely dependent on insect pollination, and it is, therefore, important to monitor and recognize how climate change is affecting the number and productivity of these insects. Coastal agroforest systems in small islands are important to national food security but rely on biodiversity (e.g., insects for pollination services). Biodiversity loss from traditional agroecosystems has been identified as one of the most serious threats to food and livelihood security in islands. Ecosystem-based adaptation practices and diversification of crop varieties are possible solutions.

The continuous reduction of soil fertility as well as increasing incidences of pests, diseases, and invasive species contribute to the growing vulnerability of the agricultural systems on small islands. Higher temperatures could increase the presence of food or water borne diseases and the challenge of managing food safety. Changes in weather patterns can also disrupt food transportation and distribution systems on islands where indigenous communities are often located in remote areas.

Impacts of climate change on fisheries in small islands result from ocean temperature change, sea-level rise, extreme weather patterns such as cyclones, reducing ocean oxygen concentrations and ocean acidification. These combined pressures are leading to the widespread loss or damage to marine habitats such as coral reefs but also mangroves and seagrass beds and consequently of important fish species that depend on these habitats and are crucial both to the food security (a high proportion of dietary protein is derived from seafood) and incomes of island communities. Shifting ocean currents and warming waters are also changing the distribution of pelagic fish stocks, especially of open-water tuna, with further consequences for both local food security and national economies, where they are often highly dependent on income from fishing licenses (e.g., 98% of Gross Domestic Product in Tokelau, 66% of national income in Kiribati).

Climate change is projected to have profound effects on the future status and distribution of coastal and oceanic habitats, and consequently of the fish and invertebrates they support. High water temperature causes changes in the growth rate of fish species as well as the timing of spawning and migration patterns, with consequences for fisheries catch potential. Some small island countries and territories are projected to experience more than 50% declines in fishery catches by 2100. Other small islands such as Easter Island (Chile), Pitcairn Islands (UK), Bermuda, and Cabo Verde may actually witness increases in catch potential under certain climate scenarios. Food shortages are often apparent in small islands, following the passage of catastrophic tropical cyclones. Access to pelagic fisheries can help to alleviate immediate food insecurity pressures in some circumstances, whereas aquaculture (fish farming) is being viewed as a longer term means of diversifying incomes and enhancing resilience in many Caribbean and Pacific islands.

[END FAQ15.3 HERE]

Large Tables

Table 15.2: A small subset of projected changes in basic climate metric. Med=Mediterranean; NC=no change

Phenomenon	Location	General Trend	Metric	Specific projections 2040-2060		Specific projections 2080-2100		Comments	Reference
				RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5		
Air Temperature	Caribbean	Hotter, especially in the East	Monthly mean temperature compared to 1971-2000	NA	1.2C rise	1.6C rise	3.0C rise	Specific to Lesser Antilles	Bowden et al. (2020) Cantet et al. (2014)
	East Atlantic	Hotter	Average annual temperature compared to 1971-2000	1.5-2C rise	2.5C rise	NA	NA	Low-confidence, specific to Sao Tome and Principe	Chou et al. (2020)
	Med	Hotter, especially in summer	Average maximum daily temperature during summer compared to 1970-2000	1.6-1.9C rise	2-2.5C rise	NA	NA	Specific to Sicily, Crete and Cyprus	Varotsos et al. (2021)
	Pacific	Hotter	Average temperature compared to 1986-2005	0.5-1.5C rise	1.0-2.0C rise	1.0-2.0C rise	2.0-4.0C rise	Consistent in tropical lattitudes	Lough et al. (2016)
	Global small islands	Hotter	Heat index compared to 1986-2005	1C rise	1.5C rise	1.3C rise	2.8C rise	Equatorial, coastal and continental islands hotter than oceanic	Harter et al. (2015)
ENSO	Pacific	More frequent extreme events	Frequency compared to ~1900-1999	NA	NA	NA	100% more El Ninos, 73-100% more La Ninas	High natural variability limits statistical significance in related patterns	Cai et al., (2014); Cai et al. (2015b)
		Inconclusive change in variability	Amplitude change compared to 1979-2005	0.02C drop	0.01C rise	0.04C drop	0.04C rise	Specific projections are not statistically significant	Cai et al., (2018); Beobide-Arsuaga et al. (2021)
Precipitation	East Caribbean	Slightly wetter, more extreme seasonality	Total rainfall compared to wet/dry season compared to 1971-2001	NA	NA	5% rise/ 10% drop	8% rise/ 15% drop	Significant local variability	Cantet et al. (2014)
	West/ North Caribbean	Drier	Annual rainfall compared to 1986-2005; consecutive dry days compared to 1961-1990	NA	9% less rain	NA	Up to 327% more dry days	Specific to Puerto Rico and US Virgin Islands	Stennett-Brown et al. (2017); Bowden et al. (2020)

	East Atlantic	Inconclusive change	Monthly rainfall compared to 1971-2000	10-25mm rise	10-25mm drop	NA	NA	Low-confidence, specific to Sao Tome and Principe	Chou et al. (2020)
	West Pacific	Wetter, especially after mid-century	Annual average rainfall compared to 1971-2005	2% rise	6% rise	3% rise	8% rise	Low-confidence, specific to Borneo	Sa'adi et al. (2017)
	Central Pacific	Drier, more extreme seasonality	Total rainfall compared to 1975-2005	15% drop	20% drop	17% drop	30% drop	Low-confidence, specific to Hawaii	Timm et al. (2015)
	Southwest Indian Ocean	Drier during the wet season, especially south of 10S	Average change in daily rainfall compared to 1971-2000	NA	NA	NA	0.2 mm per day drop	Low confidence	Lazenby et al. (2018)
	Med	Drier, but highly varied	Annual mean precipitation compared to 1960-1990	70-100 mm drop	60-150 mm drop	NA	NA	Specific to Malta; no significant change in Sicily, Crete and Cyprus	Varotsos et al. (2021)
	Global small islands	Slightly wetter, highly variable	Mean annual precipitation compared to 1986-2005	<1% rise	<1% rise	1.8% rise	3.2% rise	Confidence limited by high standard deviation	Harter et al. (2015)
Tropical Cyclones	North Indian Ocean	More storms in the west, fewer in the east	Frequency compared to 1990-2013	NA	NA	NA	30-60% rise/ 20-40% drop	Specific to Arabian sea/ Bay of Bengal	Bell et al. (2020)
	South Indian Ocean	Fewer storms, fewer strong storms in east	Storm/category 4-5 frequency compared to 1979-2010	NA	NA	NA	20-40% drop/ 0-20% drop		Bell et al. (2019a)
	Northwest Pacific	Slightly more and stronger storms at increasingly high latitudes	Storm density compared to 1970-2000; poleward shift in annual mean of location of maximum intensity compared to 1980-2005	NA	NA	NA	15-40% rise; 0.2°	10-40N, 140-170E	Kossin et al. (2016); Chand et al. (2019)
	Southwest and low-latitude Pacific	Less frequent storms	Storm density compared to 1970-2000	NA	NA	NA	0-20% drop/ 20-30% drop	South/North Pacific up to 20N, 100-140E	Bell et al. (2019a) Chand et al. (2019)
	Northeast Pacific	Less frequent storms	Storm frequency compared to 1970-2016	NA	NA	NA	2-13% drop	No data for Southern Hemisphere	Bell et al. (2019b)
	Central North Pacific	More and stronger storms	Mean annual TC/category 4-5 composition	NA	NA	NA	31%/ 88% rise	Specific to Hawaii	Yoshida et al. (2017)

			compared to 1979-2010						
	Caribbean	Slightly fewer storms	Minor/major cyclones compared to 1984-2013	NA	12% drop/ NC	NA	NA	Specific to lesser Antilles	Cantet et al. (2021)
	East Atlantic	More storms and slightly more frequent intense storms	Storms per decade compared to 1979-2010	NA	NA	NA	0-3 rise	Specific to latitude >15N	Yoshida et al. (2017)
Extratropical cyclone	Med	Decreased frequency but increased intensity	Frequency of storms compared to 1986-2005	NC	NA	12% drop	NA		González-Alemán et al. (2019)

Table 15.3: Percentage of selected islands classified as refugia for biodiversity at increasing levels of warming. While protected land is still 'protected' this table demonstrates the difficulty of protecting lands which might be 'more resilient' to climate change under increasing levels of warming and current land use practices. Derived from current and future projected distributions of ~130,000 terrestrial fungi, plants, invertebrates and vertebrates (Warren et al., 2018a). Refugia =areas remaining climatically suitable for >75% of the species modelled (Warren et al., 2018b). **Projections:** based on mean impacts from 21 CMIP5 climate model patterns (no dispersal) and elevationally downscaled to 1km under interpolated warming levels derived from RCP 2.6, 4.5, 6.0 and 8.0 (Warren et al., 2018a). First column-set = % island/island chain classified as a refugia based on ***climate alone*** ; second column-set = % natural land projected to be climate refugia — illustrating potential refugia 'space' already lost to habitat conversion. **Colour Key**: white > 50%; yellow = 30%-50%; red = 17%-30% and dark red <17% of land classified as refugia.

Island(s)	Climate °C								Climate + Land Use °C							
	0.5	*1*	*1.5*	*2*	*2.5*	*3*	*3.5*	*4*	*0.5*	*1*	*1.5*	*2*	*2.5*	*3*	*3.5*	*4*
Aegean Islands	98	89	85	68	39	19	12	6	66	62	60	50	32	16	11	6
American Samoa	100	100	100	100	83	52	39	25	39	39	39	39	34	24	18	11
Andaman Nicobar	100	95	90	46	7	2	1	0	92	88	84	45	7	2	1	0
Balearic Islands	99	97	95	82	26	6	4	2	29	28	28	25	13	6	3	2
Bangka	100	100	97	3	1	0	0	0	20	20	19	1	0	0	0	0
Barbados	94	67	53	25	5	0	0	0	10	7	6	3	1	0	0	0
Borneo	98	92	89	60	25	14	10	6	67	62	60	43	24	13	10	6
Bougainville	92	81	77	62	39	28	24	19	87	77	74	58	37	27	23	18
British Indian Ocean Territory	100	100	94	0	0	0	0	0	47	47	47	0	0	0	0	0
Corsica	72	61	57	43	29	18	15	10	64	53	50	38	26	16	13	8
Crete	91	83	80	68	52	35	27	20	51	47	46	42	35	26	22	17
Cuba	97	94	92	69	14	4	3	1	48	46	45	36	10	4	3	1
Cyprus	53	51	49	44	32	20	14	8	48	46	44	37	24	14	9	6
Dominica	79	66	63	51	41	28	20	14	79	66	63	51	41	28	20	14
French Polynesia	100	100	100	100	100	81	68	54	38	38	38	38	38	32	28	23
Galapagos	91	82	79	67	50	27	18	13	93	88	86	74	54	33	21	14
Grenada	73	49	43	29	18	10	6	3	71	48	43	29	18	10	6	3
Guadeloupe	91	71	64	27	19	13	9	6	57	46	42	26	19	13	9	6
Guernsey	100	52	41	0	0	0	0	0	13	7	5	0	0	0	0	0
Hispaniola	77	60	54	35	22	15	12	9	55	43	40	28	19	13	11	8
Indonesia	95	87	81	54	28	17	14	11	60	55	51	36	23	15	12	10
Jamaica	77	65	61	47	31	17	10	5	64	54	51	40	27	15	9	4
Java	91	74	65	37	24	17	13	10	27	24	22	18	14	11	9	7
Kiribati	100	55	38	14	0	0	0	0	15	12	12	5	0	0	0	0

Madagascar	98	90	87	70	47	28	22	13	84	77	73	58	37	21	16	10
Maldives	100	38	1	0	0	0	0	0	16	0	0	0	0	0	0	0
Marajo	100	58	33	0	0	0	0	0	91	55	33	0	0	0	0	0
Marshall Islands	100	99	99	55	22	0	0	0	46	46	46	15	10	0	0	0
Mauritius	100	100	100	100	100	100	92	74	27	27	27	27	27	27	25	23
Micronesia	100	100	100	78	59	31	16	6	86	86	86	72	56	29	15	6
Montserrat	61	43	39	27	20	9	9	4	56	38	35	23	17	9	7	4
Nauru	100	100	97	0	0	0	0	0	11	11	11	0	0	0	0	0
New Caledonia	100	100	99	97	89	62	45	31	76	75	75	74	69	53	41	28
New Guinea	95	84	73	47	32	25	22	19	86	76	67	43	30	23	21	18
Northern Mariana Islands	100	100	99	95	58	29	19	11	49	49	49	46	35	22	16	9
Orinoco Delta	100	31	9	0	0	0	0	0	93	29	9	0	0	0	0	0
Palau	100	79	73	21	0	0	0	0	74	59	55	17	0	0	0	0
Palawan	86	70	64	36	21	12	9	6	55	47	44	31	20	12	9	6
Philippines	90	74	66	41	27	16	12	8	34	30	28	21	15	10	8	6
Prince Edward	100	100	100	100	100	97	9	0	35	35	35	35	35	33	2	0
Puerto Rico	84	66	59	41	25	15	11	7	63	52	49	36	24	14	11	7
Saint Lucia	77	50	45	29	14	6	3	1	72	50	45	29	14	6	3	1
Saint Vincent & the Grenadines	73	57	50	37	27	18	13	8	63	50	44	34	23	15	10	5
Samoa	100	100	100	99	89	67	56	46	34	34	34	34	31	24	22	20
Sardinia	95	87	83	65	34	16	10	5	41	38	37	31	22	12	8	4
Seychelles	100	100	98	83	57	25	16	9	25	25	25	22	18	8	6	5
Sicily	93	84	80	60	35	18	11	7	16	15	15	13	10	7	6	4
Singapore	100	100	100	98	9	0	0	0	14	14	14	13	3	0	0	0
Solomon Islands	93	79	74	48	28	15	10	6	92	78	73	48	28	15	10	6
Sri Lanka	98	94	89	64	23	11	7	5	47	46	44	36	16	7	5	4
Sulawesi	86	75	71	58	44	33	28	23	60	54	52	46	38	30	26	21
Sumatra	96	90	87	65	24	16	13	11	40	37	36	30	18	13	11	9
Sumba	98	90	86	70	49	23	11	4	36	33	31	26	18	9	4	2
Timor	92	84	80	66	48	30	22	15	11	10	9	8	7	5	4	3
Trinidad and Tobago	88	24	16	6	3	1	0	0	64	20	14	6	3	1	0	0
Tuvalu	100	100	100	34	0	0	0	0	3	3	3	0	0	0	0	0
Wallis and Futuna	100	100	100	65	32	11	3	0	35	35	35	33	21	7	1	0

Table 15.5: Summary of inter- and intra-regional transboundary risks and impacts on small islands

Transboundary Risks/Issues	**Small Island examples**	**Reference**
Large ocean waves from distant sources	Unusually large deep ocean swells generated from sources in the mid and high latitudes by extratropical cyclones (ETCs) cause considerable damage on the coasts of small islands thousands of kilometres away in the tropics. Impacts include inundation of settlements, infrastructure, and tourism facilities as well as coastal erosion. These waves can propagate to and influence reef islands in equatorial areas not usually exposed to high energy waves.	Hoeke et al. (2013); Smithers and Hoeke (2014); Shope et al. (2016); Canavesio (2019); Wandres et al. (2020) Jury (2018)

	Examples of extratropical swell waves causing flooding and inundation have been reported throughout the Pacific (French Polynesia, Fiji, Micronesia, the Marshall Islands, Kiribati, Papua New Guinea and the Solomon Islands). Modelling of future wave climates has been carried out for 25 tropical Pacific islands, and results suggests that December–February extreme wave heights will decrease for most islands by 2100 under both an RCP4.5 and RCP 8.5 scenario, although the frequency of the large winter wave events may increase around the Hawaiian Islands. In the Caribbean, northerly swells affecting the islands have been recognised as a significant coastal hazard. They cause considerable seasonal damage to beaches, marine ecosystems, and coastal infrastructure throughout the region.	
Transcontinental dust clouds and their impacts	The transport of airborne Saharan dust across the Atlantic into the Caribbean has been intensively studied. In the West African Sahel, where drought has been persistent since the mid-1960s, analysis has shown that there have been remarkable changes in dust emissions since the late 1940s. Variability in Sahel dust emissions may be related not only to droughts, but also to changes in the North Atlantic Oscillation (NAO), North Atlantic sea surface temperatures and the Atlantic Multidecadal Oscillation (AMO). The frequency of dust storms has been on the rise during the last decade. Forecasts suggest that their incidence will increase further. Transboundary movement of Saharan dust into the island regions of the Caribbean and the Mediterranean has been associated with human health problems including asthma cases in the Caribbean, cardiovascular morbidity in Cyprus, and pulmonary disease in the Cape Verde islands.	Prospero and Lamb (2003); Goudie (2014); Schweitzer et al. (2018); Goudie (2020) Middleton et al. (2008); Martins et al. (2009); Akpinar-Elci et al. (2015); Sakhamuri and Cummings (2019)
Influx of Sargassum from distant sources	Since 2011, the Caribbean region has witnessed unprecedented influxes of the pelagic seaweed Sargassum. These extraordinary sargassum 'blooms' have resulted in mass deposition of seaweed on beaches throughout the Lesser Antilles, with damage to coastal habitats, mortality of seagrass beds and associated corals, as well as consequences for fisheries and tourism. This recent phenomenon has been linked to climate change as well as the possible influence of nutrients from Amazon River floods and/or Sahara dust.	van Tussenbroek et al. (2017); Oviatt et al. (2019) Franks et al. (2016); Putman et al. (2018)
Large-scale changes in the distribution of fisheries resources	Ocean warming and other climatic phenomena (e.g., El Niño Southern Oscillation events and Indian Ocean Dipole) have been linked to observed oceanic shifts in tuna distribution with significant impacts on revenue for vulnerable small island states that depend on fisheries licences (e.g., 98% of national income in Tokelau, 66% of national income in Kiribati). The projected eastward redistribution of skipjack and yellowfin tuna due to climate change is expected to reduce the total tuna catch within the combined EEZs of the 10 Pacific Island Countries and territories (PICTs) where most purse-seine activity occurs by approximately 10% by 2050. Projected increases in tuna biomass have been anticipated for Ascension Island and Saint Helena in the South Atlantic.	Bell et al. (2018); SPC (2019); Oremus et al. (2020); Bell et al. (2021); Townhill et al. (2021)

Movement and impact of introduced and invasive species across boundaries	The spread of invasive alien species (IAS) is regarded as a significant transboundary threat to the health of biodiversity and ecosystems worldwide. The extent to which IAS (both animals and plants) successfully establish themselves at new locations in a changing climate will be dependent on many variables, but non-climate factors such as transmission pathways, suitability of the destination, ability to compete and adapt to new environments, and susceptibility to invasion of host ecosystems are deemed to be critical. Modelling studies have been used to project the future 'invisibility' of small island ecosystems subject to climate change and therefore to anticipate marine and terrestrial habitat degradation in the future. Evidence suggests that hurricanes may have hastened the spread of highly invasive Indo-Pacific lionfish (Pterois volitans) throughout the Caribbean in recent years. Two IAS, the Common Green Iguana (*Iguana iguana*) and Cuban Treefrog (*Osteopilus septentrionalis*) were reported in the Caribbean island of Dominica, following the passage of TC Maria in 2017. Observations 7 months after the hurricane, within close proximity to ports, suggest that these animals were stowaways on ships or within relief containers.	Russell et al., 2017) Vorsino et al. (2014); Taylor and Kumar (2016b) Johnston and Purkis (2015); van den Burg et al. (2020)
Spread of pests and pathogens within and between island regions	Increased climate instability has contributed to the emergence and spread of serious diseases carried by mosquitoes such as dengue, chikungunya and zika. The incidence and severity of mosquito-borne diseases have increased significantly in Pacific, Indian Ocean and Caribbean islands during the past 10 years, which calls for a better understanding of how climate change is shaping disease prevalence and transmission. Rising sea temperatures are thought to increase the frequency of disease outbreaks affecting reef-buildings. Of the range of bacterial, fungal and protozoan diseases known to affect stony corals, many have explicit links to temperature. Global projections suggest that disease is as likely to cause coral mortality as bleaching in the coming decades at many localities, with effects occurring earlier at sites in the Caribbean compared to the Pacific and Indian oceans. Model hindcasts suggest that climate-driven changes in sea surface temperature, as well as extreme heatwave events have all played a significant role in the spread of white-band disease throughout the Caribbean. Global food security is threatened by climate-related increases in crop pests and diseases. Black Sigatoka disease of bananas has recently completed its invasion of Latin American and Caribbean banana-growing areas. Infection risk has increased by a median of 44.2% across the Caribbean since the 1960s, due to increasing canopy wetness and improving temperature conditions for the pathogen.	Cao-Lormeau and Musso (2014); Caminade et al. (2017); Pecl et al. (2017); Filho et al. (2019) Maynard et al. (2015); Randall and van Woesik (2015) Bebber (2019)

Human migration and displacement	Currently there is limited empirical evidence that long-term climate change is driving transboundary human migration from islands, however following Hurricane Maria, Puerto Rico witnessed "depopulation" of 14% in only 2 years as a result of emigration to the US mainland.	Campbell (2014a); Melendez and Hinojosa (2017)
Transboundary risks to island food security. COVID-19 caused disruptions to food supply and disaster risk management operations	While SIDS are a diverse group of nations, most share such characteristics as limited land availability, insularity, susceptibility to natural hazards that make them particularly vulnerable to global environmental and economic change processes leading to regional food insecurity. The Pacific Islands Forum Secretariat (PIFS) has established a transboundary Framework for Action on Food Security, that promotes cooperation, investments, research and development, capacity-building, and adaptation to mitigate climate change threats.	Connell (2013) Islam and Kieu (2020); Sheller (2020)

Table 15.6: Adaptation options aimed at reducing Key Risks in small islands.

Key Risks	Risk-oriented adaptation options		Evidence and agreement	Implementation	Key enablers	Reduction of exposure and vulnerability	Co-benefits	Disbenefits
KR1. Loss of marine and coastal biodiversity and ecosystem services	EbA measures (15.4.4)	MPAs; paired terrestrial and MPAs	Medium evidence, low agreement with regard to climate change adaptation and benefits	Widespread across small islands, with climate resilience being a target of some MPAs	Strong governance and sufficient financial resources	Reduces the ecosystem exposure to human disturbances, increasing their resistance and resilience to climate events	For biodiversity, food supply, economics, human health and well-being	
		Active restoration of coastal and marine ecosystems	Limited evidence, low agreement with regard to long-term success	Mostly small-scale: replanting of mangroves, seagrasses and beach vegetation; transplantation of corals; beach nourishment	Funding: adaptation taxes and levies imposed on tourism; blue bonds; public-private partnerships	Reduces the vulnerability of natural ecosystems by increasing their resilience	Improved water quality; reduction in coastal erosion and flood risks; economic benefits	
	Hard protection (15.5.1)	Hard structures designed to enhance marine biodiversity	Medium evidence, medium agreement	Artificial reefs	Funding: adaptation and environmental taxes and levies, with limited evidence of direct reinvestment in conservation and management	Uncertainty on reduction of exposure and vulnerability of marine ecosystems; reduces the exposure of population and infrastructure to coastal risks	For food supply, economies (tourism), human health and well-being	
	Diversifying livelihoods (15.5.6)	Diversifying fisheries livelihoods (e.g. to aquaculture and tourism),	Limited to medium evidence,	Examples in the Caribbean region and in the	Improved governance and cooperation (e.g. through regional	Reduces exposure and vulnerability	Sustainably managed fisheries, improved food and	

		changing fishing grounds and/or target species	medium agreement	Pacific and Indian Oceans	strategies); weather insurance to enhance resilience	of livelihoods through the diversification of income and spreading of risks; targeting less offshore pelagic species reduces exposure of coastal habitats to overfishing	income security, greater economic and social resilience	
	Reef-to-ridge ecosystem management (Figure 15.4)	Improved land use as a driver of marine ecosystem health, including better management of forests, nutrients and waster water upland catchments	Limited evidence, medium agreement	Mostly in the Caribbean region and Pacific	Improved governance	Reduces the exposure of coral reefs to human degradation, increasing their resilience	Improved ecosystem protection services (e.g. against flooding, landslides and mudflows), biodiversity, human health and livelihoods	
KR3. Loss of terrestrial biodiversity and ecosystem services	Decreased deforestation (15.5.4)		Limited to medium evidence, high agreement	Mostly in the Caribbean region and Pacific	NDC, external and long-term funding, engagement of local landowners and resolution of land ownership issues, gender sensitive participation	For example, increase in forest extent, reduction in human exposure to natural disasters (hurricanes, landslides), improvement in vulnerability assessment scores	Increased connectivity between forest fragments, reduced erosion, improved water supply and quality, improved human health and sanitation, improved livelihoods and soil health; decreased poverty; supports global mitigation	

	Increased reforestation (native species) (15.5.4)	Towards habitat connectivity, heterogeneity and diversity	Medium evidence, high agreement	Relatively widespread, with examples in the Caribbean region and Pacific	NDC, funding, technical assistance, supply materials, provision of land, awareness raising, enforcement of policies, sense of shared responsibility, inclusion of Indigenous knowledge and local knowledge, social capital	Generally limited evidence, lack of long-term monitoring	Increased DRR; fewer floods and landslides; reduced erosion; increased human health and well-being; increased quality of ecosystem services; increased adaptive capacity; supports global mitigation	
	EbA (15.5.4)	Agroforestry and other silvicultural/agroecological practices (e.g. climate-smart agriculture)	Medium evidence, high agreement	Widespread in the Caribbean region and Pacific Ocean	NDC, shared access and benefit, local knowledge and training, farmers, private sector for developing technology, financing, data availability; political, institutional and socioeconomic conditions	Limited examples, some increases in adaptive capacity	Improved climate change awareness, increased well-being, improved gender equity, improved productivity and livelihoods	
	Watershed management/conservation (15.5.4)	Reforestation, slope revegetation	Medium evidence, high agreement	Widespread (e.g. in the Caribbean region and Pacific Ocean)	Less socially and politically acceptable than engineering solutions; communication and trust between stakeholders; sustainable financing mechanisms; island remoteness barrier to logistical implementation	Yes, through improved water security, reduced adaptation costs, reduced vulnerability to drought	DRD, improved climate change awareness, increased water security and quality, reduced run-off and sedimentation, increased well-being and financial stability	
	Ridge-to-reef ecosystem management (Figure 15.4)	Improved land use as a driver of terrestrial ecosystem health	Medium evidence, high agreement	See above	See above	Limited but slowly increasing evidence to date		

	Increasing the connectivity of Protected Areas (Pas) across elevation/climatic gradients to facilitate climate-driven redistribution of species (Figure 15.4)	Establishment of new PAs, forested migration corridors across elevation/climatic gradients, improving landscape connectivity by permanent protection of stepping stones	Very limited evidence, high agreement	Low degree of new implementations due to terrain limitations combined with competition from human land use needs; large variation in PA coverage among islands	Conservation of larger areas of forest habitat surrounding PAs, reforestation of degraded areas, increasing and enforcement of forest cover within PAs, policies towards the coordination of conservation actions/partnerships, incorporation of 'Other Effective area-based Conservation Measures' (OECMs)	Yes, especially if landscape connectivity is improved (migration corridors)	Improved water security, improved coastal ecosystem health, greater resiliency and recovery from wildfires, reduced pollution, DRR	May facilitate movement of Invasive Alien Species
	Eradication of Invasive Alien Species (IAS) (15.3.3.3)		Robust evidence, high agreement	Widespread (>700 islands)	Integration of changing climate conditions within ongoing prevention, control and eradication strategies, prevention via ongoing vigilance and biosecurity via quarantine, control and monitoring of incoming cargo and goods into islands	Yes, positive demographic and distributional responses of native species following eradication of IAS	Food security, protection of ecosystem health and services, increased livelihood security	A few native species harmed by eradication process
KR4. Water insecurity	Rainwater harvesting (15.3.4.3)		Robust h evidence, high agreement	Widespread across small islands (e.g. Jamaica, Barbuda, Solomon Islands)	Socio-cultural and financial	Yes	Biodiversity (watershed protection); health; economic (reduced dependence on public supply); food security	Dependent on mode of implementation. Nothing mentioned in the chapter.
	Desalination (15.6.1)		Limited evidence, high agreement	Relatively limited (e.g. Maldives)	Financial	Yes	Health; economic (reduced dependence on public supply)	Energy intensive (carbon footprint)

	Reforestation (15.5.4)		Medium evidence, high agreement	Examples reported in the Caribbean and Pacific (e.g. Fiji, Papua New Guinea)	Governance - whole-of-island approaches foster integrated management practices in small islands	Yes, through supporting wetland-oriented tourism	Economic (agroforestry); biodiversity (watershed restoration); food security; disaster risk reduction	Dependent on mode of implementation. Nothing mentioned in the chapter.
	Protected Area Management (terrestrial) (15.5.4)		Medium evidence, high agreement	Widespread across small islands (e.g. Samoa, Jamaica, Haiti, Grenada)	Financial/governance	Yes, through soil stabilization and sequestration of pollutants	Biodiversity (forest conservation); disaster risk reduction	
KR5. Destruction of settlements and infrastructure	Hard protection (15.5.1)		Medium agreement, limited evidence with regard to climate change adaptation and success	Widespread in both urban and rural areas of the Caribbean, Pacific and Indian Oceans	External funding; socio-cultural (meets the preference of the population); political-institutional (e.g. supported by business-as-usual approach of coastal risks); technical (requires materials and skills)	Reduces exposure in some places but not in others; increases vulnerability	Limited evidence of co-benefits	Beach loss; erosion acceleration; ecosystem degradation through material extraction; increased SLR impacts
	Accommodation (15.5.2)		Limited evidence with regard to climate change adaptation and success	Relatively limited	Technological, financial, institutional, sociocultural	Limited evidence to date	Maintains the functionalities of coastal systems and allows their maintenance through landward migration, under SLR	
	Advance with land raising and/or through the creation of artificial islands (15.5.2)		Limited evidence with regard to climate change adaptation (driven by population	Limited (e.g. Hulhumale', Maldives)	Technological, financial, institutional, sociocultural, high potential in urban (compared to rural) areas	Reduces population exposure where high standard as in Hulhumale', Maldives	Offers new land for economic development, generates revenues through sale or lease of land in urban areas	Widespread ecosystem destruction, increased negative impacts of SLR

			growth in the Maldives)					
	Migration including planned resettlement (15.5.3)		Limited evidence, low agreement with regard to climate change adaptation	Village-scale planned resettlement supported by government policy/legislation in the Pacific	Participatory inclusion of all social groups; financial (for small and remote communities); social-cultural connections; strong governance frameworks; enabling legislation; land availability or ownership; conditions in receiving locations; technical support	Reduced exposure locally; has created new vulnerabilities at some locations by bearing significant economic cost, impacting social capital and reducing access to services	New livelihood opportunities	Loss of cultural heritage, impacts on receiving communities
	EbA measures (15.4.4)		Medium agreement, medium evidence	Increasingly experienced; includes artificial reefs, beach nourishment and vegetation (including mangrove) restoration	Environmental/physical conditions; social acceptability; technical capacities (enhanced by external support); funding; inclusion in national adaptation policies	Limited evidence to date	Biodiversity strengthening; increased food supply; increased human health and well-being	
KR6. Health degradation	Increasing public awareness of health risks associated with climate change; providing training to health sector staff; improving reliability and safety of water storage practices (15.6.2)		Limited evidence	Few examples	Financial and human resources to implement options; early warning and response systems; integrating climate services into health decision-making systems; public uptake and buy in; improving health data collection systems	Primarily reduces vulnerability	Increased water security	

KR7. Economic decline and livelihood failure	Circular migration (15.5.3)		Limited evidence with regard to climate change adaptation (mostly driven by economic or social factors)	Examples in Tuvalu from outer to capital atoll and locations overseas	Labour and education opportunities in Funafuti, Tuvalu, and overseas	Yes on Namumea Atoll, Tuvalu	Job and education for migrants	
	Diversifying livelihoods (15.5.6)		Limited to medium evidence, low agreement	Observed in the Caribbean region and Pacific	Use of ndigenous knowledge and local knowledge and changing fishing areas; investment in technology and education	Yes in documented places (e.g. Antigua, Vanuatu, Madagascar, Dominican Republic)	Reduction of pressure on previous fishing areas	Greater catch putting increasing pressure on fish stock
	Improved technology & equipment/training (15.5.6)		Limited evidence, medium agreement	Examples in the Caribbean region and Pacific	Investments in technologies and education (e.g. irrigation technologies, growing salt-tolerant crops and relocating crop cultivation in Jamaica)	Yes in documented places	New technologies and education strengthening	
	Livestock husbandry (15.5.6)		Limited evidence	Limited (e.g. small-scale livestock husbandry in Jamaica)	Farm inputs and investments in technologies and education	No evidence to date. Limited examples of successful livestock husbandry only in Jamaica	Investments in farm inputs	
	Adaptive finance/education (15.5.6)		Limited evidence, medium agreement	Limited (e.g. in Puerto Rico, women engage in new	Tourism income; investment in education and capacity building;	Yes, reduces risk and avoids negative	Generates opportunities (e.g. for wetland tourism)	

				commercial enterprises that do not rely on traditional coffee supply chains or government assistance)	working with nature and EbA	knock-on effects		
	Product/Market diversification (15.5.6)	Diversity of crops, gardening in different areas, storage and preservation of foodstuffs, engagement of women in new commercial enterprises	Medium evidence, high agreement	Examples in the Caribbean region and Pacific	Availability of crops and land, new markets	Reduces vulnerability to tropical cyclones in Fiji and Vanuatu; new markets in Puerto Rico	Increases food security and improves nutrition; increases income security	
	Adaptation in tourism policies (15.5.6)		Limited evidence, high agreement	Limited (e.g. in the British Virgin Islands, policies like adaptation taxes and levies imposed on tourism can provide funding for adaptation measures)	Tourism regulations and policies that mainstream climate change adaptations; taxes and levies imposed on tourism	Limited evidence in reducing vulnerability		
KR8. Loss of cultural resources and heritage	Integrating Indigenous Knowledge and local knowledge (IKLK) with western science to provide integrated approaches to climate change (15.6.5)		Medium evidence, high agreement	Reported in the Pacific and Caribbean	Use of IKLK for preparing for disasters and understanding environmental change; social networks in sharing information and helping others; ecotheology increasing people's awareness of the environment	Yes, can reduce vulnerability when IK LK supports robust adaptation; No, can increase vulnerability if IKLK no longer provides	Can increase climate change information and its understanding in communities, and increase culturally appropriate climate adaptation	Reports from Vanuatu indicates that IK LK are at times inaccurate (eg seasonal calendars, biophysical weather indicators) due to climate change

						accurate information		
	Hard protection (15.5.5.1)		Medium agreement, limited evidence with regard to climate change adaptation and success	Widespread in protecting cultural sites and villages in both urban and rural areas of the Caribbean, Pacific and Indian Oceans	External funding; socio-cultural (generally meets the preference of the population); political-institutional (e.g. supported by business-as-usual approach of coastal risks); technical (requires materials and skills)	Reduces exposure in some places but not in others; increases vulnerability	Limited evidence of co-benefits	Beach loss; erosion acceleration; ecosystem degradation through material extraction; increased SLR impacts

Table 15.7: Enabling Conditions and Factors for Adaptation in Small Islands

Enabling Conditions and Factors for Adaptation		
Enabler	Example	Reference
Knowledge (Indigenous, Local, External)		
IKLK in developing adaptation strategies (soft protective structures; disaster preparedness)	Using IKLK in identifying Indigenous vegetation (e.g., ecosystem-based adaptation) to reduce erosion (Samoa, Vanuatu)	Crichton and Esteban (2018); Nalau et al. (2018b)
	Pacific storm prediction, disaster preparedness	Chand et al. (2014); Kuruppu and Willie (2015); Granderson (2017)
	Shared resource governance and understanding of linkages between sectors and ecosystems based on IKLK (e.g., Lomanu Gau village initiative (Fiji)	Remling and Veitayaki (2016)
Increased access to climate information	Increased access to climate information increasing individuals will and capacity to support/take adaptive actions (Fiji)	Di Falco and Sharma-Khushal (2019)
	Dissemination of adaptation skills and significance to youth (e.g., Ecocamps in Fiji)	McNaught et al. (2014)
Increased access to climate information (continued)	Pacific women's improved participation in adaptation processes via training, access to information and decision-making	McLeod et al. (2018)
	Improved climate data quality, management and associated observation, modelling and information services	Martin et al. (2015); Hermes et al. (2019)
	Caribbean: Improved climate data quality, management and associated observation, modelling and information services	Trotman et al. (2018)
	Provision of user-tailored products and services through knowledge co-production processes	SPREP (2016a)
Economy and Finance		
Economic diversification and shifting to CRDPs	Tourism system transitions/cooperation from tourism sector	Loehr (2019); Mahadew and Appadoo (2019); Loehr et al. (2020); Sheller (2020)
Finance models for adaptation	Innovative financing models that enable adaptation (e.g., Seychelles)	Rambarran (2018)
	Parametric fisheries insurance products to increase fishery resilience funded by Caribbean Catastrophe Risk Insurance Facility (Grenada and Saint Lucia)	CCRIF (2019)
Transregional trade agreements/associated pressure	Revised socio-political arrangements for better fisheries management (Solomon Islands)	Keen et al. (2018)
Economic viability via revenue from sale of new land	Maldives land raising on Hulhumale	Bisaro et al. (2019)
	"Safe island development programme" after 2004 Indian Ocean Tsunami in the Maldives	Shaig (2008)
Government subsidies	Tuamotu's government subsidy of raised houses	Magnan et al. (2018)
Co-investments and cooperation between agencies (donors, governments)	Tuvalu use of beach nourishment in collaboration with JICA	Onaka et al. (2017)
Diversification of livelihoods as basis for economic activity	Coastal fishers' diversification of livelihoods into the tourism sector (Vanuatu and Madagascar)	Blair and Momtaz (2018)

	Fishermen varying fishing practices and locations depending on environmental conditions (e.g., Dominican Republic)	Karlsson and McLean (2020)
Governance		
Changed governance arrangements resulting in improved coordination	Improved governance arrangements: Cross-sectoral and cross-agency coordination (e. g. Vanuatu)	Webb et al. (2015); Nalau et al. (2016)
Changed governance arrangements resulting in improved coordination (continued)	Agency explicitly tasked with coordinating sectors and services for climate resilience across government (Dominica)	Turner et al. (2020)
	Efficient and coordinated distribution of climate adaptation support across national projects and departments (e.g., Samoa)	McGinn and Solofa (2020)
New strict/explicit building codes	Caribbean infrastructure (esp. housing and hotels) now must be built to withstand strong hurricanes	Mycoo (2018a)
Localising climate adaptation plans, frameworks and policies	Pacific Adaptive Capacity Framework Framework for the Disaster and Climate Resilient Development in the Pacific (FRDP) Island-centric adaptation policy and planning	Warrick et al. (2017) SPC (2016) Schwebel (2017)
Social and cultural		
Social networks and capacity in disaster recovery	Support of social networks in hurricane recovery, access to livelihood opportunities (e.g., Dominica)	Turner et al. (2020)
	Increased Indigenous resilience and adaptive capacity via social networks and capital (e.g., Samoa)	Petzold and Ratter (2015); Parsons et al. (2018)
	Informal credit for fishermen at food stores during and after disasters (e.g., Belize and Dominican Republic)	Karlsson and McLean (2020)
Social networks and traditional familiarity with barter/microfinance	Community-level fundraising (e.g., Samoa, Solomons, Jamaica)	Birk and Rasmussen (2014); Carby (2017); Crichton and Esteban (2018); Parsons et al. (2018); Nunn and Kumar (2019a)
Maintenance of home community	Circular migration between Tuvalu and overseas	Marino and Lazrus (2015)
Empowerment of the migrating individuals	Relocations of villages (Fiji)	Marino and Lazrus 2015)

Table 15.8: Research Gaps in Small Islands

Research Gap	Elaboration
Unavailability of adequately downscaled climate data	There is a lack of oceanographic (e.g. tidal), meteorological, high resolution topographic and bathymetric data, as well as future sea-level and wave climate projections for most islands, which severely constrain modelling studies and therefore improved understanding of future coastal flooding, erosion, and rates of saline intrusion into aquifers (Giardino et al., 2018; Lal and Datta, 2019)
	There is a need for further developing context-specific numerical models, especially through the inclusion of sediment transport, production and delivery (Shope and Storlazzi, 2019), coastal and marine ecosystems' responses (Beetham et al., 2017), and various societal responses (e.g., engineering and ecosystem-based solutions (Giardino et al., 2018)) under different climate change and SLR scenarios.
	The complexity and specificities of small island environments and unavailability of robust baseline data considerably challenge modelling studies in small islands contexts, as reflected by the serious limitations of global modelling impact studies for these (Mentaschi et al., 2018; Vousdoukas et al., 2020).

	Data and model developments are therefore urgently needed to assess the future habitability or exploitability of the islands that are the most critical to small island countries and territories, and to help identify and promote appropriate (especially in technical terms) solutions.
	Adequately downscaled Regional Climate Model (RCM) data (sub-5 km^2) is also required to conduct modelling assessments for small island terrestrial ecosystems. This is particularly needed for islands with complex topography which could be important in providing much-needed climate refugia for the survival of narrow range species such as endemics (Balzan et al., 2018). Such spatial data could be used to maximize the potential of islands to deliver critical ecosystem services (Katovai et al., 2015; Balzan et al., 2018).
	Widely used WorldClim data may not be suitable when applied to the small island context (Box CCP1.1) Without such data, robust ecosystem based adaptation strategies such as climate-smart protected area planning and management under changing climate conditions cannot be developed.
	Thomas and Benjamin (2017) highlighted the lack of data as an area of concern related to assessing loss and damage at 1.5°C. Understanding loss and damage also requires more detail on island-specific losses and damages accruing from anthropogenic climate change impacts. At the moment, such assessments are limited, and most of the small islands have not yet documented these factors in their national adaptation plans or policies (Handmer and Nalau, 2019). There is a need for specific studies also on biophysical variables and species (e.g. impact of temperature rise on mangroves); long term impacts of ocean acidification on species, including relationship to disease outbreaks, and changing breeding grounds of marine species and impacts on fisheries and marine-based livelihoods; incorporating biophysical feedback and interconnectivity of environments into models; and more detailed datasets (e.g. bathymetry, coastal assets) (World Bank, 2016; McField, 2017; Wilson, 2017).
Vulnerability and Resilience	There is need for new research that investigates the variability of vulnerability within and between islands and states, typologies of best practice (Oculi and Stephenson, 2018), frequency of knowledge sharing among islands and regions (Foley, 2018), identification of regional framework mechanisms, and mapping the complex impact and hazard interactions at a regional scale (Duvat et al., 2017b; Neef et al., 2018; Scandurra et al., 2018; Thiault et al., 2018). Research needs to also examine resilience-building efforts within the four domains of islandness (boundedness, smallness, isolation, and littorality) to effectively capture subjective nuances associated with climate development efforts on islands (Kelman, 2018).
	Research gaps in place-based assessments of social service bundles coupled with policy actions (Balzan et al., 2018) highlight the need for new knowledge to strengthen communication, collaboration and networks between academia, donors, the private sector, community and government (Allahar and Brathwaite, 2016; Schipper et al., 2016) so as to improve understanding of vulnerability and resilience in small islands.
	A paucity of research exists currently on the vulnerability of island ecosystem services to climate change (Balzan et al., 2018). While there is rich scientific evidence on the pressures of habitat loss and degradation, impacts of natural hazards and invasive species, far less is known about the interactions of these factors with adaptive capacity and livelihood conditions on islands. In small island contexts, there is a specific need for assessing the effectiveness and cost of ecosystem - and community-based solutions where the latter have been implemented (Filho et al., 2020). The design of generic assessment methods and tools is required to allow for comparative analyses that will, in turn, provide useful guidance for the promotion of context-specific adaptation strategies (Blair and Momtaz, 2018). For many of the small islands, especially SIDS, the economic valuation of marine and coastal ecosystem services – coastal protection, fisheries, tourism - is of great importance, as well as the subsequent losses in these sectors and related livelihoods due to climate change impacts (Waite et al., 2014; Schuhmann and Mahon, 2015; World Bank, 2016; Layne, 2017; Duijndam et al., 2020). There are few integrated modelling studies to inform future habitability of differentiated small island types and how these models can inform decision support processes for ridge to reef stewardship (Povak et al., 2020). Existing studies (Rasmussen et al., 2018) have progressed knowledge since AR5, but island-specific analyses are required to robustly estimate the future ability of land to support life and livelihoods, taking into account multiple climate-drivers, future population exposure, and adaptation responses.
	More research is also needed in understanding how ecosystem benefits are modified under changing climate conditions and how these benefits can be quantified (Doswald et al., 2014). For example, many small islands lack comprehensive (and disaggregated) data related to food security which makes it challenging to attribute climate impacts on local food systems (Taylor et

	al., 2019). Balzan et al. (2018) highlight the importance of quantifying the role of biodiversity in delivering key ecosystem services and demonstrate how such data could provide insights on the interrelatedness of island ecosystems and transboundary service benefits.
Adaptation	In the last decade or so, there has been a significant increase in climate-related financing for small island states. However, monitoring and tracking of funding and metrics to evaluate overall impact are lacking (Boyd et al., 2017; Mallin, 2018). Research into adaptation costs could benefit from the inclusion of indirect effects of climate change such as psychological costs (Vincent and Cull, 2014; Gibson et al., 2019) but to date this research is missing. Greater effort could also be placed on quantifying the relationship between adaptation costs and adverse events (Adelman, 2016). There is also a need for overall land use planning guidelines in small coastal communities, including small islands (Major and Juhola, 2016). The usefulness and utility of insurance mechanisms for building resilience to climate hazards require up to date information on assets at risk (Tietze and van Anrooy, 2018) and further exploration of adaptation measures in small island contexts (Baarsch and Kelman, 2016). Additionally, the differences between theoretical adaptation practices and observed results from actual implementation, along with the integration of IKLK and external knowledge are currently not well understood (Mercer et al., 2014b; Kelman, 2015b; Saint Ville et al., 2015; Robinson and Gilfillan, 2016; Robinson, 2017b). Documenting experience-based knowledge of adaptation projects and programme implementation could fill important data gaps. At the project design stage, paucity of climate finance data is a barrier to accessing climate finance (Bhandary et al., 2021).
	Although studies examining the association between climate and weather extremes, events and conditions and mobility in small islands have increased since AR5 (Birk and Rasmussen, 2014; Kelman, 2015a; Connell, 2016; Stojanov et al., 2017; Barnett and McMichael, 2018), few studies robustly examine attribution of migration of small island populations, communities and individuals to anthropogenic climate change and other non-climate migration drivers. Biophysical, socio-economic and in-situ adaptation threshold that force small island populations to migrate remains under-explored (Barnett, 2017; Handmer and Nalau, 2019). The implications of forced and voluntary immobility (Allgood and McNamara, 2017; Farbotko, 2018; Suliman et al., 2019), the socio-economic, health, psychological and cultural outcomes of climate migrants, and gender dimensions of climate migration all remain under-researched.
	Limits to adaptation is still a largely under-researched topic globally (Nalau and Filho, 2018) and specifically in small island contexts, as are the linkages between adaptation limits, loss and damage and transformative adaptation (Thomas et al., 2020). In terms of projected risks and adaptation responses, further work is needed to improve knowledge of commonalities, differences, successes, and failures of natural and human adaptation responses (Kuruppu and Willie, 2015). One of the failings of current literature on limits to adaptation revolves largely on the use of barriers for sector-specific or small-scale scenarios, that provide an understanding only for that particular scenario and does not identify common constraints (Kuruppu and Willie, 2015). Research gaps on loss and damage include: how to assess the economic costs of loss and damage; mechanisms to develop robust policies in small island contexts; specific data on experienced loss and damage across socio-economic groups and demographics; monitoring and tracking of slow onset events (Thomas and Benjamin, 2017; Thomas et al., 2020) and the non-economic aspects including sense of place, health and community cohesion (Thomas and Benjamin, 2019).
	More studies are needed on the role that organisations (international, national and regional) play in adaptation efforts – their effectiveness at achieving desired outcomes, roles and accountability (Robinson and Gilfillan, 2016; Scobie, 2016; Mallin, 2018). It is also important that the impacts of socio-political relations inter-state are researched (Belmar et al., 2015) and more focus on climate justice (Baptiste and Devonish, 2019; Moulton and Machado, 2019; Gahman and Thongs, 2020) and gender are similarly needed (Mcleod et al., 2018). Given the high number of place-specific case studies in adaptation literature, more reviews are needed that synthesise key lessons and principles of adaptations in small island contexts from this knowledge. Further research is also needed to capture the lessons from COVID-19 response in small islands and how these could enable more robust adaptation and climate resilient development transitions as has been suggested at a broader scale by Schipper et al. (2020). There is also little to no information on impacts upon terrestrial and freshwater biodiversity from the relocation of coastal human populations inland due to SLR.

References

Abella Perez, E., A. Marco, S. Martins and L. A. Hawkes, 2016: Is this what a climate change-resilient population of marine turtles looks like? *Biological Conservation*, 193, 124-132, doi:10.1016/j.biocon.2015.11.023.

Abram, N. et al., 2019: Chapter 1: Framing and Context of the Report. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. Roberts, V. Masson-Delmotte, P. Zhai, Y. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)].

Adelman, S., 2016: Climate justice, loss and damage and compensation for small island developing states. *Journal of Human Rights and the Environment*, 7(1), 32-53, doi:10.4337/jhre.2016.01.02.

Adger, W. et al., 2014: Human security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.

Ainsworth, T. et al., 2016: Climate change disables coral bleaching protection on the Great Barrier Reef. *Science*, 352(6283), 338-342, doi:10.1126/science.aac7125.

Aipira, C., A. Kidd and K. Morioka, 2017: Climate Change Adaptation in Pacific Countries: Fostering Resilience through Gender Equality. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life* [Filho, W. L. (ed.)]. Springer, Germany.

Akpinar-Elci, M., F. Martin, J. Behr and R. Diaz, 2015: Saharan dust, climate variability, and asthma in Grenada, the Caribbean. *International Journal of Biometeorology*, 59(11), 1667-1671, doi:10.1007/s00484-015-0973-2.

Aladenola, O., A. Cashman and D. Brown, 2016: Impact of El Niño and Climate Change on Rainwater Harvesting in a Caribbean State. *Water Resources Management*, 30(10), 3459-3473, doi:10.1007/s11269-016-1362-2.

Albert, S. et al., 2016: Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environmental Research Letters*, 11(5), doi:10.1088/1748-9326/11/5/054011.

Alcover, J., A. Sans and M. Palmer, 1998: The extent of extinctions of mammals on islands. *Journal of Biogeography*, 25, 913-918, doi:10.1046/J.1365-2699.1998.00246.X.

Allahar, H. and C. Brathwaite, 2016: Business incubation as an instrument of innovation: the experience of South American and the Caribbean. *International Journal of Innovation*, 4(2), 71-85, doi:10.5585.iji.v4i2.107.

Allgood, L. and K. McNamara, 2017: Climate-induced migration: Exploring local perspectives in Kiribati. *Singapore Journal of Tropical Geography*, 38(3), 370-385, doi:10.1111/sjtg.12202.

Alongi, D. M., 2008: Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, 76(1), 1-13, doi:10.1016/j.ecss.2007.08.024.

Alsumaiei, A. and R. Bailey, 2018: Quantifying threats to groundwater resources in the Republic of Maldives Part I: Future rainfall patterns and sea-level rise. *Hydrological Processes*, 32(9), 1137-1153, doi:10.1002/hyp.11480.

Andrew, N. L. et al., 2019: Coastal proximity of populations in 22 Pacific Island Countries and Territories. *PLoS One*, 14(9), e0223249, doi:10.1371/journal.pone.0223249.

Anfuso, G., J. Martinez-del-Pozo and N. Rangel-Buitrago, 2012: Bad practice in erosion management: the Southern Sicily case study. In: *Pitfalls of shoreline destabilization: selected case studies* [Cooper, J. A. G. and O. H. Pilkey (eds.)]. Springer Science Business Media Netherlands.

Anshuka, A., F. Ogtrop and W. Vervoort, 2018: Drought Modelling in Small Island Developing States: A Case Study in Fiji. *Geophysical Research Abstracts*, 20.

Arias-Ortiz, A. et al., 2018: A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. *Nature Climate Change*, 8(4), 338-344, doi:10.1038/s41558-018-0096-y.

Arnold, S. et al., 2018: The significance of climate in the pollinator dynamics of a tropical agroforestry system. *Agriculture, Ecosystems & Environment*, 254, 1-9, doi:10.1016/j.agee.2017.11.013.

Asch, R. G., B. Erisman and E. Treml, 2018: Spawning aggregations act as a bottleneck influencing climate change impacts on a critically endangered reef fish. *Diversity and Distributions*, 24(12), 1712-1728, doi:10.1111/ddi.12809.

Ateweberhan, M. et al., 2013: Climate change impacts on coral reefs: synergies with local effects, possibilities for acclimation, and management implications. *Marine Pollution Bulletin*, 74(2), 526-539, doi:10.1016/j.marpolbul.2013.06.011.

Atteridge, A. and N. Canales, 2017: *Climate finance in the Pacific: an overview of flows to the region's Small Island Developing States. Working Paper No. 2017-04*. Stockholm Environmental Institute, Stockholm, Sweden.

Atteridge, A., N. Canales and G. Savvidou, 2017: *Climate finance in the Caribbean region's Small Island Developing States: Working paper No. 2017-08*. Stockholm Environment Institute.

Baarsch, F. and I. Kelman, 2016: Insurance Mechanisms for tropical cyclones and droughts in Pacific Small Island Developing States. *Jamba: Journal of Disaster Risk Studies*, 8(1), doi:10.4102/jamba.v8i1.288.

Bailey, R. et al., 2016: Assessing regional-scale spatio-temporal patterns of groundwater-surface water interactions using a coupled SWAT-MODFLOW model. *Hydrological Processes*, 30(23), doi:10.1002/hyp.10933.

Baldacchino, G., 2018: Seizing history: development and non-climate change in Small Island Developing States. *International Journal of Climate Change Strategies and Management*, 10(2), 217-228, doi:10.1108/ijccsm-02-2017-0037.
Baldock, T. et al., 2015: Impact of sea-level rise on cross-shore sediment transport on fetch-limited barrier reef island beaches under modal and cyclonic conditions. *Marine Pollution Bulletin*, 97(1-2), 188-198, doi:10.1016/j.marpolbul.2015.06.017.
Balzan, M., M. Potschin-Young and R. Haines-Young, 2018: Island ecosystem services: insights from a literature review on case-study island ecosystem services and future prospects. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 14(1), 71-90, doi:10.1080/21513732.2018.1439103.
Baptiste, A. and H. Devonish, 2019: The Manifestation of Climate Injustices: The Post-Hurricane Irma Conflicts Surrounding Barbuda's Communal Land Tenure. *Journal of Extreme Events*, 06(01), doi:10.1142/s2345737619400025.
Baptiste, A. and R. Kinlocke, 2016: We are not all the same!: Comparative climate change vulnerabilities among fishers in Old Harbour Bay, Jamaica. *Geoforum*, 73, 47-59, doi:10.1016/j.geoforum.2015.05.006.
Barclay, J. et al., 2019: Historical Trajectories of Disaster Risk in Dominica. *International Journal of Disaster Risk Science*, 10(2), 149-165, doi:10.1007/s13753-019-0215-z.
Barkdull, J. and P. G. Harris, 2018: Emerging responses to global climate change: ecosystem-based adaptation. *Global Change, Peace & Security*, 31(1), 19-37, doi:10.1080/14781158.2018.1475349.
Barkey, B. and R. Bailey, 2017: Estimating the Impact of Drought on Groundwater Resources of the Marshall Islands. *Water*, 9(1), doi:10.3390/w9010041.
Barnard, P. et al., 2015: Coastal vulnerability across the Pacific dominated by El Niño/Southern Oscillation. *Nature Geoscience*, 8(10), 801-807, doi:10.1038/ngeo2539.
Barnett, J., 2017: The dilemmas of normalising losses from climate change: Towards hope for Pacific atoll countries. *Asia Pacific Viewpoint*, 58(1), 3-13, doi:10.1111/apv.12153.
Barnett, J. and J. Campbell, 2010: *Climate Change and Small Island States: Power, Knowledge and the South Pacific*. Earthscan, London. ISBN 978-1-84407-494-5.
Barnett, J. and C. McMichael, 2018: The effects of climate change on the geography and timing of human mobility. *Population and Environment*, 39(4), 339-356, doi:10.1007/s11111-018-0295-5.
Barriot, J., J. Serafini, K. Maamaatuaiahutapu and L. Sichoix, 2016: The Island of Tubuai (French Polynesia) Landfall of Cyclone Oli on the 5th of February 2010. *Open Access Library Journal*, 3(e2615), doi:10.4236/oalib.1102615.
Bebber, D. P., 2019: Climate change effects on Black Sigatoka disease of banana. *Philosophical Transactions of the Royal Society B*, 374(1775), doi:10.1098/rstb.2018.0269.
Beca-Carretero, P. et al., 2020: Projected Rapid Habitat Expansion of Tropical Seagrass Species in the Mediterranean Sea as Climate Change Progresses. *Frontiers in Plant Science*, 11, 555376, doi:10.3389/fpls.2020.555376.
Beck, M. W. et al., 2018: The global flood protection savings provided by coral reefs. *Nature Communications*, 9(1), 2186, doi:10.1038/s41467-018-04568-z.
Becken, S., 2019: Decarbonising tourism: mission impossible? *Tourism Recreation Research*, 1-15, doi:10.1080/02508281.2019.1598042.
Becken, S., E. Whittlesea, J. Loehr and D. Scott, 2020: Tourism and climate change: evaluating the extent of policy integration. *Journal of Sustainable Tourism*, 28(10), 1603-1624, doi:10.1080/09669582.2020.1745217.
Becker, M., M. Karpytchev and F. Papa, 2019: Hotspots of Relative Sea Level Rise in the Tropics. In: *Tropical Extremes: Natural Variability and Trends* [Venugopal, V., J. Sukhatme, R. Murtugudde and R. Roca (eds.)]. Elsevier, pp. 203-262. ISBN 9780128092484.
Beckford, C., 2018: Climate change resiliency in Caribbean SIDS: building greater synergies between science and local and traditional knowledge. *Journal of Environmental Studies and Sciences*, 8(1), 42-50, doi:10.1007/s13412-017-0440-y.
Beetham, E., P. Kench and S. Popinet, 2017: Future Reef Growth Can Mitigate Physical Impacts of Sea-Level Rise on Atoll Islands. *Earth's Future*, 5(10), 1002-1014, doi:10.1002/2017ef000589.
Bell, J. et al., 2018: Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Marine Policy*, 88, 303-314, doi:10.1016/j.marpol.2017.05.019.
Bell, J. et al., 2013: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, 3(6), 591-599, doi:10.1038/nclimate1838.
Bell, J. and M. Taylor, 2015: *Building climate-resilient food systems for Pacific Islands*. WorldFish. Program Report: 2015-15, Penang, Malaysia.
Bell, J., M. Taylor, M. Amos and N. Andrew, 2016: *Climate change and Pacific Island food systems: the future of food, farming and fishing in the Pacific Islands under a changing climate*. Available at: https://cgspace.cgiar.org/rest/bitstreams/79049/retrieve.
Bell, J. D. et al., 2015: Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. *Marine Policy*, 51, 584-591, doi:10.1016/j.marpol.2014.10.005.
Bell, J. D. et al., 2009: Planning the use of fish for food security in the Pacific. *Marine Policy*, 33(1), 64-76, doi:10.1016/j.marpol.2008.04.002.
Bell, J. D. et al., 2021: Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, doi:10.1038/s41893-021-00745-z.

Bell, S. et al., 2019a: Projections of Southern Hemisphere Tropical Cyclone Track Density using CMIP5 models. *Climate Dynamics*, 52(9-10), 6065-6079, doi:10.1007/s00382-018-4497-4.
Bell, S. S. et al., 2019b: Eastern North Pacific tropical cyclone activity in historical and future CMIP5 experiments: assessment with a model-independent tracking scheme. *Climate Dynamics*, 53(7-8), 4841-4855, doi:10.1007/s00382-019-04830-0.
Bell, S. S. et al., 2020: North Indian Ocean tropical cyclone activity in CMIP5 experiments: Future projections using a model-independent detection and tracking scheme. *International Journal of Climatology*, 40(15), 6492-6505, doi:10.1002/joc.6594.
Bellard, C., C. Leclerc and F. Courchamp, 2013a: Impact of sea level rise on the 10 insular biodiversity hotspots. *Global Ecology and Biogeography*, 23(2), 203-212, doi:10.1111/geb.12093.
Bellard, C., C. Leclerc and F. Courchamp, 2013b: Potential impact of sea level rise on French islands worldwide. *Nature Conservation*, 5, 75-86, doi:10.3897/natureconservation.5.5533.
Bellard, C. et al., 2014: Vulnerability of biodiversity hotspots to global change. *Global Ecology and Biogeography*, 23(12), 1376-1386, doi:10.1111/geb.12228.
Bellard, C., C. P and T. Blackburn, 2016: Alien species as a driver of recent extinctions. *Biology Letters*, 12(20150623), doi:10.1098/rsbl.2015.0623.
Belmar, Y., K. McNamara and T. Morrison, 2015: Water security in small island developing states: the limited utility of evolving governance paradigms. *Wiley Interdisciplinary Reviews: Water*, 3(2), 181-193, doi:10.1002/wat2.1129.
Benjamin, L., A. Thomas and R. Haynes, 2018: An 'Islands' COP'? Loss and damage at COP23. *Review of European, Comparative & International Environmental Law*, 27(3), 332-340, doi:10.1111/reel.12255.
Beobide-Arsuaga, G., T. Bayr, A. Reintges and M. Latif, 2021: Uncertainty of ENSO-amplitude projections in CMIP5 and CMIP6 models. *Climate Dynamics*, 56(11-12), 3875-3888, doi:10.1007/s00382-021-05673-4.
Bertana, A., 2020: The role of power in community participation: Relocation as climate change adaptation in Fiji. *Environment and Planning C: Politics and Space*, 38(5), 902-919, doi:10.1177/2399654420909394.
Betzold, C., 2015: Adapting to climate change in small island developing states. *Climatic Change*, 133(3), 481-489, doi:10.1007/s10584-015-1408-0.
Betzold, C. and I. Mohamed, 2017: Seawalls as a response to coastal erosion and flooding: a case study from Grande Comore, Comoros (West Indian Ocean). *Regional Environmental Change*, 17(4), 1077-1087, doi:10.1007/s10113-016-1044-x.
Bhandary, R. R., K. S. Gallagher and F. Zhang, 2021: Climate finance policy in practice: a review of the evidence. *Climate Policy*, 21(4), 529-545, doi:10.1080/14693062.2020.1871313.
Bhatia, K. T. et al., 2019: Recent increases in tropical cyclone intensification rates. *Nature Communications*, 10(1), 635, doi:10.1038/s41467-019-08471-z.
Bheeroo, R., N. Chandrasekar, S. Kaliraj and N. Magesh, 2016: Shoreline change rate and erosion risk assessment along the Trou Aux Biches–Mont Choisy beach on the northwest coast of Mauritius using GIS-DSAS technique. *Environmental Earth Sciences*, 75(5), doi:10.1007/s12665-016-5311-4.
Bianchi, C. et al., 2003: Monitoring coral bleaching in the Maldives: lessons to be learned and a new hypotheses. *Oceanis*, 29(3-4), 325-354.
Bindoff, N. et al., 2019: Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on Ocean and Cryosphere in a Changing Climate* [Portner, H. O., D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)].
Biribo, N. and C. Woodroffe, 2013: Historical area and shoreline change of reef islands around Tarawa Atoll, Kiribati. *Sustainability Science*, 8(3), 345-362, doi:10.1007/s11625-013-0210-z.
Birk, T. and K. Rasmussen, 2014: Migration from atolls as climate change adaptation: Current practices, barriers and options in Solomon Islands. *Natural Resources Forum*, 38(1), 1-13, doi:10.1111/1477-8947.12038.
Bisaro, A. et al., 2019: Leveraging public adaptation finance through urban land reclamation: cases from Germany, the Netherlands and the Maldives. *Climatic Change*, 160(4), 671-689, doi:10.1007/s10584-019-02507-5.
Blackburn, S., 2014: The politics of scale and disaster risk governance: Barriers to decentralisation in Portland, Jamaica. *Geoforum*, 52, 101-112, doi:10.1016/j.geoforum.2013.12.013.
Blair, A. and S. Momtaz, 2018: Climate change perception and response: Case studies of Fishers from Antigua and Efate. *Ocean & Coastal Management*, 157, 86-94, doi:10.1016/j.ocecoaman.2018.02.015.
Boger, R., S. Perdikaris and I. Rivera-Collazo, 2019: Cultural heritage and local ecological knowledge under threat: Two Caribbean examples from Barbuda and Puerto Rico. *Journal of Anthropology and Archaeology*, 7(2), 1-14, doi:10.15640/jaa.v7n2a1.
Bordner, A. S., C. E. Ferguson and L. Ortolano, 2020: Colonial dynamics limit climate adaptation in Oceania: Perspectives from the Marshall Islands. *Global Environmental Change*, 61, doi:10.1016/j.gloenvcha.2020.102054.
Borges-Méndez, R. and C. Caron, 2019: Decolonizing Resilience: The Case of Reconstructing the Coffee Region of Puerto Rico After Hurricanes Irma and Maria. *Journal of Extreme Events*, 06(01), doi:10.1142/s2345737619400013.
Bowden, J. H. et al., 2020: High-resolution dynamically downscaled rainfall and temperature projections for ecological life zones within Puerto Rico and for the US Virgin Islands. *Int J Climatol*, 41(2), 1305-1327, doi:10.1002/joc.6810.

Boyd, E. et al., 2017: A typology of loss and damage perspectives. *Nature Climate Change*, 7(10), 723-729, doi:10.1038/NCLIMATE3389.
Bramante, J. F. et al., 2020: Sea Level Rise Will Drive Divergent Sediment Transport Patterns on Fore Reefs and Reef Flats, Potentially Causing Erosion on Atoll Islands. *Journal of Geophysical Research: Earth Surface*, 125(10), doi:10.1029/2019jf005446.
Branoff, B., 2018: Changes in mangrove tree mortality, forest canopy, and aboveground biomass accumulation rates following the 2017 hurricane season in Puerto Rico and the role of urbanization. *bioRxiv*, doi:10.1101/425140.
Briones, F., R. Vachon and M. Glantz, 2019: Local responses to disasters: recent lessons from zero-order responders. *Disaster Prevention and Management: An International Journal*, 28(1), 119-125, doi:10.1108/dpm-05-2018-0151.
Brodie, G. et al., 2020: Seagrass habitat in Tarawa Lagoon, Kiribati: Service benefits and links to national priority issues. *Marine Pollution Bulletin*, 155, doi:10.1016/j.marpolbul.2020.111099.
Brown, C. J. et al., 2017: Tracing the influence of land-use change on water quality and coral reefs using a Bayesian model. *Scientific Reports*, 7(1), 4740, doi:10.1038/s41598-017-05031-7.
Brown, S. et al., 2018: Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and 1.5C and 2.0C Rise in Global Temperatures to Year 2300. *Earth's Future*, 6, 583-600, doi:10.1002/2017EF000738.
Brown, S. et al., 2020: Land raising as a solution to sea-level rise: An analysis of coastal flooding on an artificial island in the Maldives. *Journal of Flood Risk Management*, 13(S1), doi:10.1111/jfr3.12567.
Bryant-Tokalau, J., 2018a: Handling Weather Disasters: The Resilience and Adaptive Capacity of Pacific Island Communities. In: *Indigenous Pacific Approaches to Climate Change: Pacific Island Countries* [Stewart, P. and A. Strathern (eds.)]. Palgrave Macmillan.
Bryant-Tokalau, J., 2018b: *Indigenous Pacific Approaches to Climate Change: Pacific Island Countries*. Palgrave Studies in Disaster Anthropology, Palgrave Macmillan.
Buggy, L. and K. McNamara, 2016: The need to reinterpret "community" for climate change adaptation: a case study of Pele Island, Vanuatu. *Climate and Development*, 8(3), 270-280, doi:10.1080/17565529.2015.1041445.
Buhr, B. et al., 2018: *Climate Change and the Cost of Capital in Developing Countries: Assessing the impact of climate risks on sovereign borrowing costs*. Imperial College Business School, SOAS University of London.
Butchart, S. et al., 2019: Chapter 3: Assessing progress towards meeting major international objectives related to nature and nature's contributions to people. In: *Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* [Brondizio, E., J. Settele, S. Diaz and H. Ngo (eds.)].
Butcher-Gollach, C., 2015: Planning, the urban poor and climate change in Small Island Developing States (SIDS): unmitigated disaster or inclusive adaptation? *International Development Planning Review*, 37(2), 225-248, doi:10.3828/idpr.2015.17.
Cai, W. et al., 2014: Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change*, 4(2), 111-116, doi:10.1038/NCLIMATE2100.
Cai, W. et al., 2015a: ENSO and greenhouse warming. *Nature Climate Change*, 5(9), 849-859, doi:10.1038/nclimate2743.
Cai, W. et al., 2018: Increased variability of eastern Pacific El Nino under greenhouse warming. *Nature*, 564(7735), 201-206, doi:10.1038/s41586-018-0776-9.
Cai, W. et al., 2015b: Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, 5(2), 132-137, doi:10.1038/nclimate2492.
Cambers, G., 2009: Caribbean beach changes and climate change adaptation. *Aquatic Ecosystem Health & Management*, 12(2), 168-176, doi:10.1080/14634980902907987.
Caminade, C. et al., 2017: Global risk model for vector-borne transmission of Zika virus reveals the role of El Nino 2015. *PNAS*, 114(1), 119-125, doi:10.1073/pnas.1700746114.
Campbell, D., 2021: Environmental change and the livelihood resilience of coffee farmers in Jamaica: A case study of the Cedar Valley farming region. *Journal of Rural Studies*, 81, 220-234, doi:10.1016/j.jrurstud.2020.10.027.
Campbell, D. et al., 2021: Wild Food Harvest, Food Security, and Biodiversity Conservation in Jamaica: A Case Study of the Millbank Farming Region. *Frontiers in Sustainable Food Systems*, 5, doi:10.3389/fsufs.2021.663863.
Campbell, J., 2014a: Climate change migration in the Pacific. *Contemporary Pacific*, 26(1), 1-29, doi:10.1353/cp.2014.0023.
Campbell, J., 2014b: Development, global change and traditional food security in Pacific Island countries. *Regional Environmental Change*, 15(7), 1313-1324, doi:10.1007/s10113-014-0697-6.
Campbell, J. and O. Warrick, 2014: *Climate Change and Migration Issues in the Pacific*. United Nations Economic and Social Commission for Asia and the Pacific, Fiji.
Canales, N., A. Atteridge and A. Sturesson, 2017: *Climate finance for the Indian Ocean and African Small Island Developing States: Working paper no. 2017-11*. Stockholm Environment Institute.
CANARI, 2020: Rising to the climate challenge: Coastal and marine resilience in the Caribbean, Barataria, Trinidad and Tobago. Available at: https://canari.org/wp-content/uploads/2020/08/CANARI-Coastal-Marine-Resilience-Issue-Paper.pdf.
Canavesio, R., 2019: Distant swells and their impacts on atolls and tropical coastlines. The example of submersions produced by lagoon water filling and flushing currents in French Polynesia during 1996 and 2011 mega swells. *Global and Planetary Change*, 177, 116-126, doi:10.1016/j.gloplacha.2019.03.018.

Cannonier, C. and M. Burke, 2018: The economic growth impact of tourism in Small Island Developing States—evidence from the Caribbean. *Tourism Economics*, 25(1), 85-108, doi:10.1177/1354816618792792.
Cantet, P., A. Belmadani, F. Chauvin and P. Palany, 2021: Projections of tropical cyclone rainfall over land with an Eulerian approach: case study of three islands in the West Indies. *International Journal of Climatology*, 41(51), E1164-1179, doi:10.1002/joc.6760.
Cantet, P., M. Déqué, P. Palany and J. Maridet, 2014: The importance of using a high-resolution model to study the climate change on small islands: the Lesser Antilles case. *Tellus A: Dynamic Meteorology and Oceanography*, 66(1), doi:10.3402/tellusa.v66.24065.
Cantrell, S. et al., 2014: Effects of a simulated hurricane disturbance on forest floor microbial communities. *Forest Ecology and Management*, 332, 22-31, doi:10.1016/j.foreco.2014.07.010.
Cao-Lormeau, V.-M. and D. Musso, 2014: Emerging arboviruses in the Pacific. *The Lancet*, 384(9954), 1571-1572, doi:10.1016/s0140-6736(14)61977-2.
Carby, B., 2015: Beyond the community: integrating local and scientific knowledge in the formal development approval process in Jamaica. *Environmental Hazards*, 14(3), 252-269, doi:10.1080/17477891.2015.1058740.
Carby, B., 2017: Integrating disaster risk reduction in national development planning: experience and challenges of Jamaica. *Environmental Hazards*, 17(3), 219-233, doi:10.1080/17477891.2017.1415864.
Carlson, R. R., S. A. Foo and G. P. Asner, 2019: Land Use Impacts on Coral Reef Health: A Ridge-to-Reef Perspective. *Frontiers in Marine Science*, 6, doi:10.3389/fmars.2019.00562.
Cashman, A., 2014: Water Security and Services in the Caribbean. *Water*, 6(5), 1187-1203, doi:10.3390/w6051187.
Cashman, A. and M. Nagdee, 2017: Impacts of Climate Change on Settlements and Infrastructure in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS). *Caribbean Marine Climate Change Report Card: Science Review 2017.*, 155-173.
Cashman, A. and D. Yawson, 2019: Water, Livelihoods, and Migration in SIDS: Climate Change and Future Prospects for Carriacou, West Indies. *Resources*, 8(4), doi:10.3390/resources8040174.
Cauchi, J. P., I. Correa-Velez and H. Bambrick, 2019: Climate change, food security and health in Kiribati: a narrative review of the literature. *Global Health Action*, 12(1), 1603683, doi:10.1080/16549716.2019.1603683.
Cauchi, J. P., S. Moncada, H. Bambrick and I. Correa-Velez, 2021: Coping with environmental hazards and shocks in Kiribati: Experiences of climate change by atoll communities in the Equatorial Pacific. *Environmental Development*, 37, doi:10.1016/j.envdev.2020.100549.
CCCCC, 2012: *Delivering Transformational Change: The Implementation Plan for the CARICOM 'Regional Framework for Achieving Development Resilient to Climate Change' (2011-2021)*. Available at: https://www.caribbeanclimate.bz/2009-2021-regional-planning-for-climate-compatible-development-in-the-region/.
CCRIF, 2019: Caribbean Countries to Benefit from Access to Insurance for the Fisheries Sector.
CDEMA, 2014: *Regional Comprehensive Disaster Management (CDM) Strategy and Results Framework 2014-2024.* . Barbados. Available at: www.cdema.org.
Chacowry, A., L. McEwen and K. Lynch, 2018: Recovery and resilience of communities in flood risk zones in a small island developing state: A case study from a suburban settlement of Port Louis, Mauritius. *International Journal of Disaster Risk Reduction*, 28, 826-838, doi:10.1016/j.ijdrr.2018.03.019.
Chakrabarti, P. et al., 2017: Alternate livelihood development for 'Aila' affected tribal people through aquaculture in Bali Island of the Sunderban, West Bengal, India. *Indian Journal of Fisheries*, 64, doi:10.21077/ijf.2017.64.special-issue.76186-03.
Chambers, L. et al., 2019: Traditional or contemporary weather and climate forecasts: reaching Pacific communities. *Regional Environmental Change*, doi:10.1007/s10113-019-01487-7.
Chambers, L. et al., 2017: A database for traditional knowledge of weather and climate in the Pacific. *Meteorological Applications*, 24(3), 491-502, doi:10.1002/met.1648.
Chand, S. et al., 2014: Indigenous Knowledge for Environmental Prediction in the Pacific Island Countries. *Weather, Climate, and Society*, 6(4), 445-450, doi:10.1175/wcas-d-13-00053.1.
Chand, S. S. et al., 2019: Western North Pacific Tropical Cyclone Tracks in CMIP5 Models: Statistical Assessment Using a Model-Independent Detection and Tracking Scheme. *Journal of Climate*, 32(21), 7191-7208, doi:10.1175/jcli-d-18-0785.1.
Chandra, A. and P. Gaganis, 2016: Deconstructing vulnerability and adaptation in a coastal river basin ecosystem: a participatory analysis of flood risk in Nadi, Fiji Islands. *Climate and Development*, 8(3), 256-269, doi:10.1080/17565529.2015.1016884.
Charan, D., M. Kaur and P. Singh, 2017: Customary Land and Climate Change Induced Relocation—A Case Study of Vunidogoloa Village, Vanua Levu, Fiji. In: *Climate Change Adaptation in Pacific Countries* [Filho, W. L. (ed.)]. Springer, Cham, Switzerland, pp. 19-33. ISBN 978-3-319-50093-5.
Chefaoui, R., C. Duarte and E. Serrao, 2018: Dramatic loss of seagrass habitat under projected climate change in the Mediterranean Sea. *Global Change Biology*, 24(10), 4919-4928, doi:10.1111/gcb.14401.
Cheung, W., J. Bruggeman and M. Butenschon, 2018: Chapter 4: Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century. In: *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T.

Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Oranization of the United Nations, Rome, Italy, pp. 63-86.
Chou, S. C. et al., 2020: Downscaling projections of climate change in Sao Tome and Principe Islands, Africa. *Climate Dynamics*, 54(9-10), 4021-4042, doi:10.1007/s00382-020-05212-7.
CIMH, CWWA, CARDI and CDEMA, 2019: Sectoral Early Warning Information Systems across Climate Timescales (EWISACTs) Roadmap and Plan of Action (RPA) 2020-2030. Available at: https://rcc.cimh.edu.bb/.
Cinner, J. et al., 2016: A framework for understanding climate change impacts on coral reef social–ecological systems. *Regional Environmental Change*, 16(4), 1133-1146, doi:10.1007/s10113-015-0832-z.
Clifford, M., S. Ali and K. Matsubae, 2019: Mining, land restoration and sustainable development in isolated islands: An industrial ecology perspective on extractive transitions on Nauru. *Ambio*, 48(4), 397-408, doi:10.1007/s13280-018-1075-2.
Cole, P. and G. Banks, 2017: Renewable energy programmes in the South Pacific – Are these a solution to dependency? *Energy Policy*, 110, 500-508, doi:10.1016/j.enpol.2017.08.048.
Collier, C. et al., 2017: Optimum Temperatures for Net Primary Productivity of Three Tropical Seagrass Species. *Frontiers in Plant Science*, 8, 1446, doi:10.3389/fpls.2017.01446.
Connell, J., 2013: *Islands at Risk? Environments, Economies, and Contemporary Change*. Edward Elgar, Cheltenham.
Connell, J., 2015: Vulnerable Islands: Climate Change, Tectonic Change, and Changing Livelihoods in the Western Pacific. *The Contemporary Pacific*, 27(1), 1-36.
Connell, J., 2016: Last days in the Carteret Islands? Climate change, livelihoods and migration on coral atolls. *Asia Pacific Viewpoint*, 57(1), 3-15, doi:10.1111/apv.12118.
Conway, D. and J. Mustelin, 2014: Strategies for improving adaptation practice in developing countries. *Nature Climate Change*, 4(5), 339-342, doi:10.1038/nclimate2199.
Cornwall, C. E. et al., 2021: Global declines in coral reef calcium carbonate production under ocean acidification and warming. *PNAS*, 118(21), doi:10.1073/pnas.2015265118.
Costa, M., E. Macedo and E. Siegle, 2019: Wave refraction and reef island stability under rising sea level. *Global and Planetary Change*, 172, 256-267, doi:10.1016/j.gloplacha.2018.10.015.
Cowburn, B., M. Samoilys and D. Obura, 2018: The current status of coral reefs and their vulnerability to climate change and multiple human stresses in the Comoros Archipelago, Western Indian Ocean. *Marine Pollution Bulletin*, 133, 956-969, doi:10.1016/j.marpolbul.2018.04.065.
Cox, J. et al., 2018: Disaster, Divine Judgment, and Original Sin: Christian Interpretations of Tropical Cyclone Winston and Climate Change in Fiji. *The Contemporary Pacific*, 30(2), 380-410, doi:10.1353/cp.2018.0032.
Cramer, W. et al., 2018: Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, 8(11), 972-980, doi:10.1038/s41558-018-0299-2.
Crichton, R. and M. Esteban, 2018: Limits to Coastal Adaptation in Samoa: Insights and Experiences. In: *Limits to Climate Change Adaptation* [Filho, W. L. and J. Nalau (eds.)]. Springer, Cham, Switzerland, pp. 283-300. ISBN 978-3-319-64598-8.
Crichton, R. N., M. Esteban and M. Onuki, 2020: Understanding the preferences of rural communities for adaptation to 21st-century sea-level rise: A case study from the Samoan islands. *Climate Risk Management*, 30, doi:10.1016/j.crm.2020.100254.
Cruz, J. and C. Andrade, 2017: Groundwater salinization in Graciosa and Pico islands (Azores archipelago, Portugal): processes and impacts. *Journal of Hydrology: Regional Studies*, 12, 69-87, doi:10.1016/j.ejrh.2017.04.003.
Curnick, D. et al., 2019: The value of small mangrove patches. *Science*, 363(6424), doi:10.1126/science.aaw0809.
Currenti, R. et al., 2019: Adaptation to Climate Change in an Interior Pacific Island Village: a Case Study of Nawairuku, Ra, Fiji. *Human Ecology*, 47(1), 65-80, doi:10.1007/s10745-019-0049-8.
Curtain, R. and M. Dornan, 2019: *A pressure release valve? Migration and climate change in Kiribati, Nauru and Tuvalu*. Australian National University.
Cuvillier, A. et al., 2017: Causes of seasonal and decadal variability in a tropical seagrass seascape (Reunion Island, south western Indian Ocean). *Estuarine, Coastal and Shelf Science*, 184, 90-101, doi:10.1016/j.ecss.2016.10.046.
Cvitanovic, C. et al., 2016: Linking adaptation science to action to build food secure Pacific Island communities. *Climate Risk Management*, 11, 53-62, doi:10.1016/j.crm.2016.01.003.
Cvitanovic, C. et al., 2019: Maximising the benefits of participatory climate adaptation research by understanding and managing the associated challenges and risks. *Environmental Science & Policy*, 94, 20-31, doi:10.1016/j.envsci.2018.12.028.
de Beurs, K., N. McThompson, B. Owsley and G. Henebry, 2019: Hurricane damage detection on four major Caribbean islands. *Remote Sensing of Environment*, 229, 1-13, doi:10.1016/j.rse.2019.04.028.
De Ramon N'Yeurt, A. and V. Iese, 2014: The proliferating brown alga Sargassum polycystum in Tuvalu, South Pacific: assessment of the bloom and applications to local agriculture and sustainable energy. *Journal of Applied Phycology*, 27(5), 2037-2045, doi:10.1007/s10811-014-0435-y.
de Scally, F., 2014: Evaluation of storm surge risk: A case study from Rarotonga, Cook Islands. *International Journal of Disaster Risk Reduction*, 7, 9-27, doi:10.1016/j.ijdrr.2013.12.002.
De Souza, R. and J. Clarke, 2018: Chapter 11: Advancing Coastal Climate Resilience: Inclusive Data and Decision-Making for Small Island Communities. In: *Resilience: The Science of Adpatation to Climate Change* [Zommers, Z. and K. Alverson (eds.)]. Elsevier, pp. 143-150.

Delevaux, J. M. S. et al., 2018: A linked land-sea modeling framework to inform ridge-to-reef management in high oceanic islands. *PLoS One*, 13(3), e0193230, doi:10.1371/journal.pone.0193230.
Dey, M. et al., 2016: Economic impact of climate change and climate change adaptation strategies for fisheries sector in Solomon Islands: Implication for food security. *Marine Policy*, 67, 171-178, doi:10.1016/j.marpol.2016.01.004.
Di Falco, S. and S. Sharma, 2018: Investing in Climate Change Adaptation: Motivations and Green Incentives in the Fiji Islands. *Ecological Economics*, 154, 394-408, doi:10.1016/j.ecolecon.2018.08.015.
Di Falco, S. and S. Sharma-Khushal, 2019: Cognitive drivers, and the effect of information on climate change adaptive behaviour in Fiji Islands. *Environmental Science & Policy*, 92, 245-254, doi:10.1016/j.envsci.2018.11.019.
Donner, S., 2015: The legacy of migration in response to climate stress: learning from the Gilbertese resettlement in the Solomon Islands. *Natural Resources Forum*, 39(3-4), 191-201, doi:10.1111/1477-8947.12082.
Donner, S. and S. Webber, 2014: Obstacles to climate change adaptation decisions: a case study of sea-level rise and coastal protection measures in Kiribati. *Sustainability Science*, 9(3), 331-345, doi:10.1007/s11625-014-0242-z.
Donner, S. D., G. J. M. Rickbeil and S. F. Heron, 2017: A new, high-resolution global mass coral bleaching database. *PLoS One*, 12(4), e0175490, doi:10.1371/journal.pone.0175490.
Dookie, D., M. Enenkel and J. Spence, 2019: From science to science-based: Using state-of-the-art climate information to strengthen DRR in Small Island States. In: *Strengthening disaster resilience in small states: Commonwealth perspectives* [Khonje, W. and T. Mitchell (eds.)]. Commonwealth Secretariat, London, UK, pp. 13-41.
Dornan, M., 2014: Access to Electricity in Small Island Developing States of the Pacific: Issues and Challenges. *Renewable and Sustainable Energy Reviews*, 31, 726-735, doi:10.1016/j.rser.2013.12.037.
Doswald, N. et al., 2014: Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, 6(2), 185-201, doi:10.1080/17565529.2013.867247.
Douglass, K. and J. Cooper, 2020: Archaeology, environmental justice, and climate change on islands of the Caribbean and southwestern Indian Ocean. *PNAS*, 117(15), 8254-8262, doi:10.1073/pnas.1914211117.
Drinkall, S. et al., 2019: Migration with Dignity: A case study on the livelihood transitions of Micronesians to Portland and Salem, Oregon. *Journal of Disaster Research*, 14(9), 1267-1276, doi:10.20965/jdr.2019.p1267.
Duarte, B. et al., 2018: Climate Change Impacts on Seagrass Meadows and Macroalgal Forests: An Integrative Perspective on Acclimation and Adaptation Potential. *Frontiers in Marine Science*, 5, doi:10.3389/fmars.2018.00190.
Ducrocq, V., P. Drobinski, S. Gualdi and P. Raimbault, 2016: Sub-chapter 1.2.1: The water cycle in the Mediterranean. In: *The Mediterranean region under climate change: A scientific update*. IRD Editions, Marseille, France. ISBN 9782709922203.
Duijndam, S. et al., 2020: Valuing a Caribbean coastal lagoon using the choice experiment method: The case of the Simpson Bay Lagoon, Saint Martin. *Journal for Nature Conservation*, 56, doi:10.1016/j.jnc.2020.125845.
Dunn, D. et al., 2018: A strategy for the conservation of biodiversity on mid-ocean ridges from deep-sea mining. *Science Advances*, 4, doi:10.1126/sciadv.aar4313.
Duvat, V., 2009: Beach erosion management in Small Island Developing States: Indian Ocean case studies. In: *Coastal Processes*, pp. 149-160, doi:10.2495/cp090141.
Duvat, V., 2013: Coastal protection structures in Tarawa Atoll, Republic of Kiribati. *Sustainability Science*, 8(3), 363-379, doi:10.1007/s11625-013-0205-9.
Duvat, V., A. Anisimov and A. Magnan, 2020a: Assessment of coastal risk reduction and adaptation-labelled responses in Mauritius Island (Indian Ocean). *Regional Environmental Change*, 20(110), doi:10.1007/s10113-020-01699-2.
Duvat, V. and A. Magnan, 2019a: Rapid human-driven undermining of atoll island capacity to adjust to ocean climate-related pressures. *Scientific Reports*, 9(15129), doi:10.1038/s41598-019-51468-3.
Duvat, V. et al., 2016: Assessing the impacts of and resilience to Tropical Cyclone Bejisa, Reunion Island (Indian Ocean). *Natural Hazards*, 83(1), 601-640, doi:10.1007/s11069-016-2338-5.
Duvat, V. et al., 2017a: Trajectories of exposure and vulnerability of small islands to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, 8(6), doi:10.1002/wcc.478.
Duvat, V. and A. K. Magnan, 2019b: Lessons learnt from coastal risks governance on Reunion Island, Indian Ocean, France. In: *Facing Hydrometeorological extremes events: a governance issue* [La Jeunesse, I. and C. Larrue (eds.)]. Wiley-Blackwell. ISBN 978-1-119-38354-3.
Duvat, V. et al., 2019a: High human influence on beach response to tropical cyclones in small islands: Saint-Martin Island, Lesser Antilles. *Geomorphology*, 325, 70-91, doi:10.1016/j.geomorph.2018.09.029.
Duvat, V. et al., 2020b: Contribution of moderate climate events to atoll island building (Fakarava Atoll, French Polynesia). *Geomorphology*, 354(107057), doi:10.1016/j.geomorph.2020.107057.
Duvat, V., B. Salvat and C. Salmon, 2017b: Drivers of shoreline change in atoll reef islands of the Tuamotu Archipelago, French Polynesia. *Global and Planetary Change*, 158, 134-154, doi:10.1016/j.gloplacha.2017.09.016.
Duvat, V., N. Volto and C. Salmon, 2017c: Impacts of category 5 tropical cyclone Fantala (April 2016) on Farquhar Atoll, Seychelles Islands, Indian Ocean. *Geomorphology*, 298, 41-62, doi:10.1016/j.geomorph.2017.09.022.
Duvat, V. K. E., 2018: A global assessment of atoll island planform changes over the past decades. *Wiley Interdisciplinary Reviews: Climate Change*, 10(1), doi:10.1002/wcc.557.
Duvat, V. K. E. et al., 2021a: Risks to future atoll habitability from climate-driven environmental changes. *WIREs Climate Change*, doi:10.1002/wcc.700.

Duvat, V. K. E. et al., 2019b: Taking control of human-induced destabilisation of atoll islands: lessons learnt from the Tuamotu Archipelago, French Polynesia. *Sustainability Science*, doi:10.1007/s11625-019-00722-8.
Duvat, V. K. E. et al., 2021b: Understanding interlinkages between long-term trajectory of exposure and vulnerability, path dependency and cascading impacts of disasters in Saint-Martin (Caribbean). *Global Environmental Change*, 67, doi:10.1016/j.gloenvcha.2021.102236.
Ebi, K. et al., 2018: Health risks of warming of 1.5 °C, 2 °C, and higher, above pre-industrial temperatures. *Environmental Research Letters*, 13(6), doi:10.1088/1748-9326/aac4bd.
Eckstein, D., M. Hutfils and M. Winges, 2018: *Who Suffers Most from Extreme Weather Events? Weather-related Loss Events in 2017 and 1998 to 2017*. Germanwatch, Germany.
Elders from Atafu Atoll, 2012: *Echoes at Fishermen's Rock: Traditional Tokelau fishing* [Hooper, A. and I. Tinielu (eds.)]. Knowledges of Nature 4, UNESCO, Paris, 120 pp.
Elliff, C. and I. Silva, 2017: Coral reefs as the first line of defense: Shoreline protection in face of climate change. *Marine Environment Research*, 127, 148-154, doi:10.1016/j.marenvres.2017.03.007.
Ellison, J., 1993: Mangrove Retreat with Rising Sea-level, Bermuda. *Estuarine, Coastal and Shelf Science*, 37, 75-87, doi:10.1006/ecss.1993.1042.
Ellison, J., 2005: Holocene palynology and sea-level change in two estuaries in Southern Irian Jaya. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 220(3-4), 291-309, doi:10.1016/j.palaeo.2005.01.008.
Ellison, J. and P. Strickland, 2015: Establishing relative sea level trends where a coast lacks a long term tide gauge. *Mitigation and Adaptation Strategies for Global Change*, 20(7), 1211-1227, doi:10.1007/s11027-013-9534-3.
Ellison, J. C., 2018: Pacific Island Beaches: Values, Threats and Rehabilitation. In: *Beach Management Tools - Concepts, Methodologies and Case Studies* [Botero, C., O. Cervantes and C. Finkl (eds.)]. Springer, Cham, Switzerland, pp. 679-700. ISBN 978-3-319-58303-7.
Enríquez, A. et al., 2017: Changes in beach shoreline due to sea level rise and waves under climate change scenarios: application to the Balearic Islands (western Mediterranean). *Natural Hazards and Earth System Sciences*, 17(7), 1075-1089, doi:10.5194/nhess-17-1075-2017.
Enríquez-de-Salamanca, Á., 2018: Vulnerability reduction and adaptation to climate change through watershed management in St. Vincent and the Grenadines. *GeoJournal*, 84(4), 1107-1119, doi:10.1007/s10708-018-9914-z.
Eppinga, M. and C. Pucko, 2018: The impact of hurricanse Irma and Maria on the forest ecosystems of Saba and St. Eustatius, north Caribbean. *Biotropica*, 50(5), 723-728, doi:10.1111/btp.12600.
Erauskin-Extramiana, M. et al., 2019: Large-scale distribution of tuna species in a warming ocean. *Global Change Biology*, 25(6), 2043-2060, doi:10.1111/gcb.14630.
Esteban, M. et al., 2019: Adaptation to sea level rise on low coral islands: Lessons from recent events. *Ocean & Coastal Management*, 168, 35-40, doi:10.1016/j.ocecoaman.2018.10.031.
Esteban, M. et al., 2020: Adaptation to sea level rise: Learning from present examples of land subsidence. *Ocean & Coastal Management*, 189, doi:10.1016/j.ocecoaman.2019.104852.
Etongo, D., 2019: Climate Change Adaptation in Seychelles: Actors, Actions, Barriers, Strategies for Improvement. *Seychelles Research Journal*, 1(2), 43-66.
Fabian, R., M. Beck and D. Potts, 2013: *Reef Restoration for Coastal Defense: A Review*. University of California, Santa Cruz, USA.
Fakhruddin, S., M. Babel and A. Kawasaki, 2015: Assessing the vulnerability of infrastructure to climate change on the Islands of Samoa. *Natural Hazards and Earth System Sciences*, 15(6), 1343-1356, doi:10.5194/nhess-15-1343-2015.
Falanruw, M., 2018: Canaries of Civilization: Small Island Vulnerability, Past Adaptations and Sea-Level Rise. In: *Indigenous Knowledge for Climate Change Assessment and Adaptation* [Nakashima, D., I. Krupnik and J. Rubis (eds.)]. Cambridge University Press, UNESCO, Cambridge, pp. 247-253. ISBN 9781316481066.
Falcon, W. and D. Hansen, 2018: Island rewilding with giant tortoises in an era of climate change. *Philosophical Transactions Royal Society B*, 373(1761), doi:10.1098/rstb.2017.0442.
FAO, 2016: *Drought characteristics and management in the Caribbean*. FAO Water Reports, 42, FAO, Rome.
Farbotko, C., 2018: Voluntary immobility: indigenous voices in the Pacific. *Forced Migration Reviews*, 57, 81-83.
Feng, Y. et al., 2018: Rapid remote sensing assessment of impacts from Hurricane Maria on forests of Puerto Rico. *PeerJ Preprints*, doi:10.7287/peerj.preprints.26597v1.
Ferdinand, M., 2018: Subnational climate justice for the French Outre-mer: postcolonial politics and geography of an epistemic shift. *Island Studies Journal*, 13(1), 119-134, doi:10.24043/isj.49.
Ferrario, F. et al., 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, 5, 3794, doi:10.1038/ncomms4794.
Ferre, I. et al., 2019: Hurricane Maria's Impact on Punta Santiago, Puerto Rico: Community Needs and Mental Health Assessment Six Months Postimpact. *Disaster Medicine and Public Health Preparedness*, 13(1), 18-23, doi:10.1017/dmp.2018.103.
Ferreira, M. et al., 2016: Effects of climate change on the distribution of indigenous species in oceanic islands (Azores). *Climatic Change*, 138(3-4), 603-615, doi:10.1007/s10584-016-1754-6.
Fickert, T., 2018: Better Resilient than Resistant—Regeneration Dynamics of Storm-Disturbed Mangrove Forests on the Bay Island of Guanaja (Honduras) during the First Two Decades after Hurricane Mitch (October 1998). *Diversity*, 10(1), doi:10.3390/d10010008.

Filho, W. L. et al., 2020: Reviewing the role of ecosystems services in the sustainability of the urban environment: A multi-country analysis. *Journal of Cleaner Production*, 262, doi:10.1016/j.jclepro.2020.121338.
Filho, W. L. et al., 2019: Climate Change, Health and Mosquito-Borne Diseases: Trends and Implications to the Pacific Region. *International Journal of Environmental Research and Public Health*, 16(24), doi:10.3390/ijerph16245114.
Finucane, M. L. and V. W. Keener, 2015: Understanding the climate-sensitive decisions and information needs of island communities. *Journal of the Indian Ocean Region*, 11(1), 110-120, doi:10.1080/19480881.2015.1021181.
Fish, M. R. et al., 2005: Predicting the Impact of Sea-Level Rise on Caribbean Sea Turtle Nesting Habitat. *Conservation Biology*, 19(2), 482-491, doi:10.1111/j.1523-1739.2005.00146.x.
Fitzpatrick, S. M., M. Kappers and Q. Kaye, 2006: Coastal Erosion and Site Destruction on Carriacou, West Indies. *Journal of Field Archaeology*, 31(3), 251-262, doi:10.1179/009346906791071954.
Fleming, L. et al., 2019: Urban and rural sanitation in the Solomon Islands: How resilient are these to extreme weather events? *Science of the Total Environment*, 683, 331-340, doi:10.1016/j.scitotenv.2019.05.253.
Foley, A., 2018: Climate impact assessment and "islandness". *International Journal of Climate Change Strategies and Management*, 10(2), 289-302, doi:10.1108/ijccsm-06-2017-0142.
Ford, M., 2012: Shoreline Changes on an Urban Atoll in the Central Pacific Ocean: Majuro Atoll, Marshall Islands. *Journal of Coastal Research*, 28, 11-22, doi:10.2112/jcoastres-d-11-00008.1.
Ford, M. and P. Kench, 2016: Spatiotemporal variability of typhoon impacts and relaxation intervals on Jaluit Atoll, Marshall Islands. *Geology*, 44(2), 159-162, doi:10.1130/g37402.1.
Ford, M., M. Merrifield and J. Becker, 2018: Inundation of a low-lying urban atoll island: Majuro, Marshall Islands. *Natural Hazards*, 91(3), 1273-1297, doi:10.1007/s11069-018-3183-5.
Förster, J., E. McLeod, M. Bruton-Adams and H. Wittmer, 2019: Climate Change Impacts on Small Island States: Ecosystem Services Risks and Opportunities. In: *Atlas of Ecosystem Services* [Schroter, M. (ed.)], pp. 353-359. ISBN 978-3-319-96228-3.
Fortini, L. et al., 2015: Large-Scale Range Collapse of Hawaiian Forest Birds under Climate Change and the Need for 21st Century Conservation Options [corrected]. *PLoS One*, 10(10), e0140389, doi:10.1371/journal.pone.0140389.
Fox, M. D. et al., 2019: Limited coral mortality following acute thermal stress and widespread bleaching on Palmyra Atoll, central Pacific. *Coral Reefs*, 38(4), 701-712, doi:10.1007/s00338-019-01796-7.
Franks, J. S., D. R. Johnson and D. S. Ko, 2016: Pelagic Sargassum in the Tropical North Atlantic. *Gulf and Caribbean Research*, 27(1), doi:10.18785/gcr.2701.08.
Frauendorf, T. C. et al., 2020: Using a space-for-time substitution approach to predict the effects of climate change on nutrient cycling in tropical island stream ecosystems. *Limnology and Oceanography*, 65(12), 3114-3127, doi:10.1002/lno.11577.
Frazier, A. and L. Brewington, 2019: Current Changes in Alpine Ecosystems of Pacific Islands. *Encyclopedia of the World's Biomes*, 607-619, doi:10.1016/B978-0-12-409548-9.11881-0.
Friess, D., 2016: Ecosystem Services and Disservices of Mangrove Forests: Insights from Historical Colonial Observations. *Forests*, 7(183), doi:10.3390/f7090183.
Fuentes, M. M. P. B., C. J. Limpus and M. Hamann, 2011: Vulnerability of sea turtle nesting grounds to climate change. *Global Change Biology*, 17(1), 140-153, doi:10.1111/j.1365-2486.2010.02192.x.
Gahman, L. and G. Thongs, 2020: Development justice, a proposal: Reckoning with disaster, catastrophe, and climate change in the Caribbean. *Transactions of the Institute of British Geographers*, doi:10.1111/tran.12369.
Gaillard, J. et al., 2017: Beyond men and women: a critical perspective on gender and disaster. *Disasters*, 41(3), 429-447, doi:10.1111/disa.12209.
Gamble, D., D. Burrell, J. Popke and S. Curtis, 2017: Contextual analysis of dynamic drought perception among small farmers in Jamaica. *Climate Research*, 74(2), 109-120, doi:10.3354/cr01490.
Garcin, M. et al., 2016: Lagoon islets as indicators of recent environmental changes in the South Pacific – The New Caledonian example. *Continental Shelf Research*, 122, 120-140, doi:10.1016/j.csr.2016.03.025.
Gattuso, J. et al., 2015: Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science*, 349(6243), aac4722, doi:10.1126/science.aac4722.
Gero, A. et al., 2015: Disasters and climate change in the Pacific: adaptive capacity of humanitarian response organizations. *Climate and Development*, 7(1), 35-46, doi:10.1080/17565529.2014.899888.
Gharbaoui, D. and J. Blocher, 2016: The Reason Land Matters: Relocation as Adaptation to Climate Change in Fiji Islands. In: *Migration, Risk Management and Climate Change: Evidence and Policy Responses* [Milan, A., B. Schraven, K. Warner and N. Cascone (eds.)]. Springer, Cham, pp. 149-173. ISBN 978-3-319-42920-5.
Giardino, A., K. Nederhoff and M. Vousdoukas, 2018: Coastal hazard risk assessment for small islands: assessing the impact of climate change and disaster reduction measures on Ebeye (Marshall Islands). *Regional Environmental Change*, 18(8), 2237-2248, doi:10.1007/s10113-018-1353-3.
Gibson, K., N. Haslam and I. Kaplan, 2019: Distressing encounters in the context of climate change: Idioms of distress, determinants, and responses to distress in Tuvalu. *Transcultural Psychiatry*, 56(4), 667-696, doi:10.1177/1363461519847057.
Gibson, K. E., J. Barnett, N. Haslam and I. Kaplan, 2020: The mental health impacts of climate change: Findings from a Pacific Island atoll nation. *Journal of Anxiety Disorders*, 73, doi:10.1016/j.janxdis.2020.102237.

Giffin, A. et al., 2020: Marine and coastal ecosystem-based adaptation in Asia and Oceania: review of approaches and integration with marine spatial planning. *Pacific Conservation Biology*, doi:10.1071/pc20025.
Gilman, E., J. Ellison, I. Sauni and S. Tuaumu, 2007: Trends in surface elevations of American Samoa mangroves. *Wetlands Ecology and Management*, 15(5), 391-404, doi:10.1007/s11273-007-9038-6.
Gingerich, S., C. Voss and A. Johnson, 2017: Seawater-flooding events and impact on freshwater lenses of low-lying islands: Controlling factors, basic management and mitigation. *Journal of Hydrology*, 551, 676-688, doi:10.1016/j.jhydrol.2017.03.001.
Gischler, E. and R. Kikinger, 2006: Effects of the tsunami of 26 December 2004 on Rasdhoo and Northern Ari Atolls, Maldives. *Atoll Research Bulletin*, 561.
Gohar, A., A. Cashman and F. Ward, 2019: Managing food and water security in Small Island States: New evidence from economic modelling of climate stressed groundwater resources. *Journal of Hydrology*, 569, 239-251, doi:10.1016/j.jhydrol.2018.12.008.
Golbuu, Y. et al., 2007: Palau's coral reefs show differential habitat recovery following the 1998-bleaching event. *Coral Reefs*, 26(2), 319-332, doi:10.1007/s00338-007-0200-7.
González-Alemán, J. J. et al., 2019: Potential Increase in Hazard From Mediterranean Hurricane Activity With Global Warming. *Geophysical Research Letters*, 46(3), 1754-1764, doi:10.1029/2018gl081253.
Goodman, J. et al., 2012: Differential response to soil salinity in endangered key tree cactus: implications for survival in a changing climate. *PLoS One*, 7(3), e32528, doi:10.1371/journal.pone.0032528.
Goudie, A. S., 2014: Desert dust and human health disorders. *Environmental International*, 63, 101-113, doi:10.1016/j.envint.2013.10.011.
Goudie, A. S., 2020: Dust storms and human health. In: *Extreme Weather Events and Human Health: International Case Studies* [Akhtar, R. (ed.)]. Springer, Switzerland. ISBN 978-3-030-23772-1.
Goulding, W., P. Moss and C. McAlpine, 2016: Cascading effects of cyclones on the biodiversity of Southwest Pacific islands. *Biological Conservation*, 193, 143-152, doi:10.1016/j.biocon.2015.11.022.
Gourlie, D. et al., 2018: Performing "A New Song": Suggested Considerations for Drafting Effective Coastal Fisheries Legislation Under Climate Change. *Marine Policy*, 88, 342-349, doi:10.1016/j.marpol.2017.06.012.
Gracia, A., N. Rangel-Buitrago, J. A. Oakley and A. T. Williams, 2018: Use of ecosystems in coastal erosion management. *Ocean & Coastal Management*, 156, 277-289, doi:10.1016/j.ocecoaman.2017.07.009.
Grady, A. et al., 2013: The influence of sea level rise and changes in fringing reef morphology on gradients in alongshore sediment transport. *Geophysical Research Letters*, 40(12), 3096-3101, doi:10.1002/grl.50577.
Graham, N. et al., 2015: Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature*, 518(7537), 94-97, doi:10.1038/nature14140.
Granderson, A., 2017: The Role of Traditional Knowledge in Building Adaptive Capacity for Climate Change: Perspectives from Vanuatu. *Weather, Climate, and Society*, 9(3), 545-561, doi:10.1175/wcas-d-16-0094.1.
Group, W. B., 2015: CIF Pilot Program for Climate Resilience.
Guido, Z. et al., 2018: The stresses and dynamics of smallholder coffee systems in Jamaica's Blue Mountains: a case for the potential role of climate services. *Climatic Change*, 147(1-2), 253-266, doi:10.1007/s10584-017-2125-7.
Guilyardi, E. et al., 2016: Fourth CLIVAR Workshop on the Evaluation of ENSO Processes in Climate Models: ENSO in a Changing Climate. *Bulletin of the American Meteorological Society*, 97(5), 817-820, doi:10.1175/bams-d-15-00287.1.
Ha'apio, M. O., R. Gonzalez and M. Wairiu, 2019: Is there any chance for the poor to cope with extreme environmental events? Two case studies in the Solomon Islands. *World Development*, 122, 514-524, doi:10.1016/j.worlddev.2019.06.023.
Habel, S., C. H. Fletcher, T. R. Anderson and P. R. Thompson, 2020: Sea-Level Rise Induced Multi-Mechanism Flooding and Contribution to Urban Infrastructure Failure. *Scientific Reports*, 10(1), 3796, doi:10.1038/s41598-020-60762-4.
Hagedoorn, L. et al., 2019: Community-based adaptation to climate change in small island developing states: an analysis of the role of social capital. *Climate and Development*, 1-12, doi:10.1080/17565529.2018.1562869.
Haines, S., 2019: Managing expectations: articulating expertise in climate services for agriculture in Belize. *Climate Change*, 157, 43-59, doi:10.1007/s10584-018-2357-1.
Hambleton, I. R., S. M. Jeyaseelan and M. M. Murphy, 2020: COVID-19 in the Caribbean small island developing states: lessons learnt from extreme weather events. *The Lancet Global Health*, 8(9), e1114-e1115, doi:10.1016/s2214-109x(20)30291-6.
Hampton, M. P. and J. Jeyacheya, 2020: Tourism-Dependent Small Islands, Inclusive Growth, and the Blue Economy. *One Earth*, 2(1), 8-10, doi:10.1016/j.oneear.2019.12.017.
Handmer, J. and H. Iveson, 2017: Cyclone Pam in Vanuatu: learning from the low death toll. *Australian Journal of Emergency Management*, 32(2), 60-65.
Handmer, J. and J. Nalau, 2019: Understanding Loss and Damage in Pacific Small Island Developing States. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* [Mechler, R., L. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, pp. 365-381. ISBN 978-3-319-72025-8.
Hanich, Q. et al., 2018: Small-scale fisheries under climate change in the Pacific Islands region. *Marine Policy*, 88, 279-284, doi:10.1016/j.marpol.2017.11.011.

Hansen, G. and W. Cramer, 2015: Global distribution of observed climate change impacts. *Nature Climate Change*, 5(3), 182-185, doi:10.1038/nclimate2529.
Harris, D. et al., 2018: Coral reef structural complexity provides important coastal protection from waves under rising sea levels. *Science Advances*, 4, doi:eaao4350.
Harter, D. et al., 2015: Impacts of global climate change on the floras of oceanic islands – Projections, implications and current knowledge. *Perspectives in Plant Ecology, Evolution and Systematics*, 17(2), 160-183, doi:10.1016/j.ppees.2015.01.003.
Hassanali, K., 2020: CARICOM and the blue economy – Multiple understandings and their implications for global engagement. *Marine Policy*, 120, doi:10.1016/j.marpol.2020.104137.
Hay, J., 2013: Small island developing states: coastal systems, global change and sustainability. *Sustainability Science*, 8(3), 309-326, doi:10.1007/s11625-013-0214-8.
Hay, J., V. Duvat and A. K. Magnan, 2019a: Trends in Vulnerability to Climate-related Hazards in the Pacific: Research, Understanding and Implications. In: *The Oxford Handbook of Planning for Climate Change Hazards* [Pfeffer, T., J. Smith and K. Ebi (eds.)]. Oxford University Press, New York.
Hay, J., P. Hartley and J. Roop, 2019b: Climate risk assessments and management options for redevelopment of the Parliamentary Complex in Samoa, South Pacific. *Weather and Climate Extremes*, 25, doi:10.1016/j.wace.2019.100214.
Haynes, E. et al., 2020: Food Sources and Dietary Quality in Small Island Developing States: Development of Methods and Policy Relevant Novel Survey Data from the Pacific and Caribbean. *Nutrients*, 12(11), doi:10.3390/nu12113350.
Hayward, B., D. H. Salili, L. L. Tupuana'i and J. Tualamali'i, 2019: It's not "too late": Learning from Pacific Small Island Developing States in a warming world. *WIREs Climate Change*, 11(1), doi:10.1002/wcc.612.
Hejnowicz, A., H. Kennedy, M. Rudd and M. Huxham, 2015: Harnessing the climate mitigation, conservation and poverty alleviation potential of seagrasses: prospects for developing blue carbon initiatives and payment for ecosystem service programmes. *Frontiers in Marine Science*, 2(32), doi:10.3389/fmars.2015.00032.
Heller, N. and E. Zavaleta, 2009: Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, 142(1), 14-32, doi:10.1016/j.biocon.2008.10.006.
Hellmann, J., J. Byers, B. Bierwagen and J. Dukes, 2008: Five potential consequences of climate change for invasive species. *Conservation Biology*, 22(3), 534-543, doi:10.1111/j.1523-1739.2008.00951.x.
Hemstock, S. et al., 2018: Professionalizing the "resilience" sector in the Pacific Islands Region: Formal education for capacity building. In: *A Critical Approach to Climate Change Adaptation: Discourses, Policies and Practices*. Routledge Advances in Climate Change Research, Routledge, UK. ISBN 978-1-13-805629-9.
Hermann, E. and W. Kempf, 2017: Climate Change and the Imagining of Migration: Emerging Discourses on Kiribati's Land Purchase in Fiji. *The Contemporary Pacific*, 29(2), 231-263, doi:10.1353/cp.2017.0030.
Hermes, J. et al., 2019: A Sustained Ocean Observing System in the Indian Ocean for Climate Related Scientific Knowledge and Societal Needs. *Frontiers in Marine Science*, 6, doi:10.3389/fmars.2019.00355.
Hernan, G. et al., 2017: Future warmer seas: increased stress and susceptibility to grazing in seedlings of a marine habitat-forming species. *Global Change Biology*, 23(11), 4530-4543, doi:10.1111/gcb.13768.
Hernandez-Delgado, E., 2015: The emerging threats of climate change on tropical coastal ecosystem services, public health, local economies and livelihood sustainability of small islands: Cumulative impacts and synergies. *Marine Pollution Bulletin*, 101(1), 5-28, doi:10.1016/j.marpolbul.2015.09.018.
Herrera, D. and T. Ault, 2017: Insights from a New High-Resolution Drought Atlas for the Caribbean Spanning 1950–2016. *Journal of Climate*, 30(19), 7801-7825, doi:10.1175/jcli-d-16-0838.1.
Hess, J. and I. Kelman, 2017: Tourism Industry Financing of Climate Change Adaptation: Exploring the Potential in Small Island Developing States. *Climate, Disaster and Development Journal*, 2(2), 34-45, doi:10.18783/cddj.v002.i02.a04.
Hickey, G. M. and N. Unwin, 2020: Addressing the triple burden of malnutrition in the time of COVID-19 and climate change in Small Island Developing States: what role for improved local food production? *Food Security*, 1-5, doi:10.1007/s12571-020-01066-3.
Hills, J., E. Michalena and K. Chalvatzis, 2018: Innovative Technology in the Pacific: Building Resilience for Vulnerable Communities. *Technological Forecasting and Social Change*, 129, 16-26, doi:10.1016/j.techfore.2018.01.008.
Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, 8(7), 570-578, doi:10.1038/s41558-018-0176-z.
Hino, M., C. Field and K. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, 7(5), 364-370, doi:10.1038/nclimate3252.
Hiwasaki, L., E. Luna, Syamsidik and R. Shaw, 2014: Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. *International Journal of Disaster Risk Reduction*, 10, 15-27, doi:10.1016/j.ijdrr.2014.07.007.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P.

Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Pan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)].

Hoegh-Guldberg, O. et al., 2019: The human imperative of stabilizing global climate change at 1.5°C. *Science*, 365(6459), doi:10.1126/science.aaw6974.

Hoegh-Guldberg, O., E. Poloczanska, W. Skirving and S. Dove, 2017: Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science*, 4, doi:10.3389/fmars.2017.00158.

Hoeke, R., K. McInnes and J. O'Grady, 2015: Wind and Wave Setup Contributions to Extreme Sea Levels at a Tropical High Island: A Stochastic Cyclone Simulation Study for Apia, Samoa. *Journal of Marine Science and Engineering*, 3(3), 1117-1135, doi:10.3390/jmse3031117.

Hoeke, R. K., H. Damlamian, J. Aucan and M. Wandres, 2021: Severe Flooding in the Atoll Nations of Tuvalu and Kiribati Triggered by a Distant Tropical Cyclone Pam. *Frontiers in Marine Science*, 7, doi:10.3389/fmars.2020.539646.

Hoeke, R. K. et al., 2013: Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change*, 108, 128-138, doi:10.1016/j.gloplacha.2013.06.006.

Hof, A., M. Blazquez-Salom, M. Colom and A. Periz, 2014: Chapter 9: Challenges and Solutions for Urban-Tourist Water Supply on Mediterranean Tourist Islands: The Case of Majorca, Spain. In: *The Global Water System in the Anthropocene* [Bhaduri, A., J. Bogardi, J. Leentvaar and S. Marx (eds.)]. Springer, Charm.

Hofmann, R., 2014: Culturecide in changing Micronesian climates? About the unintenionality of climate change. *The International Journal of Human Rights*, 18(3), 336-349, doi:10.1080/13642987.2014.914707.

Hofmann, R., 2017: Experiencing environmental dynamics in Chuuk, Micronesia. In: *Environmental Transformations and Cultural Responses: Ontologies, Discourses, and Practices in Oceania* [Durr, E. and A. Pascht (eds.)]. Palgrave Macmillan, pp. 75-102.

Holding, S. et al., 2016: Groundwater vulnerability on small islands. *Nature Climate Change*, 6(12), 1100-1103, doi:10.1038/nclimate3128.

Hopley, D., S. Smithers and K. Parnell, 2007: *Geomorphology of the Great Barrier Reef: Development, Diversity and Change*. Cambridge University Press, Cambridge, UK. ISBN 9780511535543.

Hu, T. and R. Smith, 2018: The Impact of Hurricane Maria on the Vegetation of Dominica and Puerto Rico Using Multispectral Remote Sensing. *Remote Sensing*, 10(6), doi:10.3390/rs10060827.

Hughes, T. et al., 2018: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, 359(6371), 80-83, doi:10.1126/science.aan8048.

Hughes, T. et al., 2017a: Coral reefs in the Anthropocene. *Nature*, 546(7656), 82-90, doi:10.1038/nature22901.

Hughes, T. et al., 2017b: Global warming and recurrent mass bleaching of corals. *Nature*, 543(7645), 373-377, doi:10.1038/nature21707.

Hulland, E. et al., 2019: Increase in Reported Cholera Cases in Haiti Following Hurricane Matthew: An Interrupted Time Series Model. *American Journal of Tropical Medicine and Hygiene*, 100(2), 368-373, doi:10.4269/ajtmh.17-0964.

Iese, V. et al., 2020: Agriculture Under a Changing Climate. In: *Climate Change and Impacts in the Pacific* [Kumar, L. (ed.)]. Springer, Cham, Cham, Switzerland, pp. 323-358. ISBN 978-3-030-32877-1.

Iese, V. et al., 2021: Historical and future drought impacts in the Pacific islands and atolls. *Climatic Change*, 166(1-2), doi:10.1007/s10584-021-03112-1.

IPBES, 2018: *The IPBES assessment report on land degradation and restoration* [Montanarella, L., R. Scholes and A. Brainich (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

IPBES, 2019: *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* [Díaz, S., J. Settele, B. E.S., H. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. Brauman, S. Butchart, K. Chan, L. Garibaldi, K. Ichii, J. Liu, S. Subramanian, G. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. Shin, I. Visseren-Hamakers, K. Willis and C. Zayas (eds.)]. IPBES Secretariat, Bonn, Germany, 56 pp.

IPCC, 2018: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the globalresponse to the threat of climate change, sustainable development, and efforts to eradicate poverty.* [Masson-Delmotte, V., P. Zhai, H. O. Portner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Pean, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)].

IPCC, 2019: *Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. Roberts, V. Masson-Delmotte, P. Zhai, Y. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)].

Islam, M. S. and E. Kieu, 2020: Tackling Regional Climate Change Impacts and Food Security Issues: A Critical Analysis across ASEAN, PIF, and SAARC. *Sustainability*, 12(3), doi:10.3390/su12030883.

Jackson, C., D. Bush and W. Neal, 2012: Documenting beach loss in front of seawalls in Puerto Rico: pitfalls of engineering a small Island nation shore. In: *Pitfalls of Shoreline Stabilization* [Cooper, J. A. G. and O. H. Pilkey (eds.)]. Springer, Netherlands.
Jamero, M. L. et al., 2017: Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change*, 7(8), 581-586, doi:10.1038/nclimate3344.
Janif, S. et al., 2016: Value of traditional oral narratives in building climate-change resilience: insights from rural communities in Fiji. *Ecology and Society*, 21(2), doi:10.5751/ES-08100-210207.
Jeanne, I. et al., 2018: Mapping a Plasmodium transmission spatial suitability index in Solomon Islands: a malaria monitoring and control tool. *Malaria Journal*, 17(1), 381, doi:10.1186/s12936-018-2521-0.
Jimenez-Ramos, R. et al., 2017: Global and local disturbances interact to modify seagrass palatability. *PLoS One*, 12(8), e0183256, doi:10.1371/journal.pone.0183256.
Johnston, I., 2014: Disaster management and climate change adaptation: a remote island perspective. *Disaster Prevention and Management*, 23(2), 123-137, doi:10.1108/dpm-06-2013-0096.
Johnston, I., 2015: Traditional warning signs of cyclones on remote islands in Fiji and Tonga. *Environmental Hazards*, 14(3), 210-223, doi:10.1080/17477891.2015.1046156.
Johnston, M. W. and S. J. Purkis, 2015: Hurricanes accelerated the Florida-Bahamas lionfish invasion. *Global Change Biology*, 21(6), 2249-2260, doi:10.1111/gcb.12874.
Jones, H. et al., 2016: Invasive mammal eradication on islands results in substantial conservation gains. *PNAS*, 113(15), 4033-4038, doi:10.1073/pnas.1521179113.
Jones, P. et al., 2015: Long-term trends in precipitation and temperature across the Caribbean. *International Journal of Climatology*, 36(9), 3314-3333, doi:10.1002/joc.4557.
Jones, R., 2019: Climate change and Indigenous Health Promotion. *Global Health Promotion*, 26(3_suppl), 73-81, doi:10.1177/1757975919829713.
Joseph, L. et al., 2019: Implications of Seagrass Ecosystem Degradation on Marine Resources and People's Livelihood: A Case Study from Komave Village, Fiji. *Asian Journal of Fisheries and Aquatic Research*, 2(3), 1-13, doi:10.9734/AJFAR/2018/v2i330011.
Jury, M. R., 2018: Characteristics and Meteorology of Atlantic Swells Reaching the Caribbean. *Journal of Coastal Research*, 342, 400-412, doi:10.2112/jcoastres-d-17-00029.1.
Kane, H. H. and C. H. Fletcher, 2020: Rethinking Reef Island Stability in Relation to Anthropogenic Sea Level Rise. *Earth's Future*, 8(10), doi:10.1029/2020ef001525.
Karlsson, M. and G. Hovelsrud, 2015: Local collective action: Adaptation to coastal erosion in the Monkey River Village, Belize. *Global Environmental Change*, 32, 96-107, doi:10.1016/j.gloenvcha.2015.03.002.
Karlsson, M. and E. McLean, 2020: Caribbean Small-Scale Fishers' Strategies for Extreme Weather Events: Lessons for Adaptive Capacity from the Dominican Republic and Belize. *Coastal Management*, 48(5), 456-480, doi:10.1080/08920753.2020.1795971.
Karnauskas, K., J. Donnelly and K. Anchukaitis, 2016: Future freshwater stress for island populations. *Nature Climate Change*, 6(7), 720-725, doi:10.1038/nclimate2987.
Karnauskas, K., C. Schleussner, J. Donnelly and K. Anchukaitis, 2018: Freshwater stress on small island developing states: population projections and aridity changes at 1.5 and 2 °C. *Regional Environmental Change*, 18(8), 2273-2282, doi:10.1007/s10113-018-1331-9.
Katircioglu, S., M. Cizreliogullari and S. Katircioglu, 2019: Estimating the role of climate changes on international tourist flows: evidence from Mediterranean Island States. *Environmental Science and Pollution Research*, 26(14), 14393-14399, doi:10.1007/s11356-019-04750-w.
Katovai, E., D. D. Katovai, W. Edwards and W. F. Laurance, 2015: Forest Structure, Plant Diversity and Local Endemism in a Highly Varied New Guinea Landscape. *Tropical Conservation Science*, 8(2), 284-300, doi:10.1177/194008291500800202.
Kauffman, J. B. and T. G. Cole, 2010: Micronesian Mangrove Forest Structure and Tree Responses to a Severe Typhoon. *Wetlands*, 30(6), 1077-1084, doi:10.1007/s13157-010-0114-y.
Kayanne, H. et al., 2016: Eco-geomorphic processes that maintain a small coral reef island: Ballast Island in the Ryukyu Islands, Japan. *Geomorphology*, 271, 84-93, doi:10.1016/j.geomorph.2016.07.021.
Keen, M. and J. Connell, 2019: Regionalism and Resilience? Meeting Urban Challenges in Pacific Island States. *Urban Policy and Research*, 37(3), 324-337, doi:10.1080/08111146.2019.1626710.
Keen, M., A. Schwarz and L. Wini-Simeon, 2018: Towards defining the Blue Economy: Practical lessons from pacific ocean governance. *Marine Policy*, 88, 333-341, doi:10.1016/j.marpol.2017.03.002.
Kelaher, B., M. Coleman and M. Bishop, 2018: Ocean warming, but not acidification, accelerates seagrass decomposition under near-future climate scenarios. *Marine Ecology Progress Series*, 605, 103-110, doi:10.3354/meps12762
Kelman, I., 2014: No change from climate change: vulnerability and small island developing states. *The Geographical Journal*, 180(2), 120-129, doi:10.1111/geoj.12019.
Kelman, I., 2015a: Difficult decisions: Migration from Small Island Developing States under climate change. *Earth's Future*, 3(4), 133-142, doi:10.1002/2014ef000278.
Kelman, I., 2015b: Disaster Risk Governance for Pacific Island Communities. *The Asia-Pacific Journal*, 13(48).

Kelman, I., 2018: Islandness within climate change narratives of small island developing states (SIDS). *Island Studies Journal*, 13(1), 149-166, doi:10.24043/isj.52.
Kelman, I. et al., 2017: Here and now: perceptions of Indian Ocean islanders on the climate change and migration nexus. *Geografiska Annaler: Series B, Human Geography*, 99(3), 284-303, doi:10.1080/04353684.2017.1353888.
Kench, P., 2012: Compromising Reef Island Shoreline Dynamics: Legacies of the Engineering Paradigm in the Maldives. In: *Pitfalls of Shoreline Stabilization: Selected Case Studies* [Cooper, J. and O. Pilkey (eds.)]. Springer, Cham, Switzerland, pp. 165-186. ISBN 978-94-007-4122-5.
Kench, P., M. Ford and S. Owen, 2018: Patterns of island change and persistence offer alternate adaptation pathways for atoll nations. *Nature Communications*, 9(1), 605, doi:10.1038/s41467-018-02954-1.
Kench, P. and T. Mann, 2017: Reef Island Evolution and Dynamics: Insights from the Indian and Pacific Oceans and Perspectives for the Spermonde Archipelago. *Frontiers in Marine Science*, 4, doi:10.3389/fmars.2017.00145.
Kench, P. et al., 2015: Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll. *Geology*, 43(6), 515-518, doi:10.1130/g36555.1.
Kendrick, G. A. et al., 2019: A Systematic Review of How Multiple Stressors From an Extreme Event Drove Ecosystem-Wide Loss of Resilience in an Iconic Seagrass Community. *Frontiers in Marine Science*, 6, doi:10.3389/fmars.2019.00455.
Keppel, G., C. Morrison, J. Meyer and H. Boehmer, 2014: Isolated and vulnerable: the history and future of Pacific Island terrestrial biodiversity. *Pacific Conservation Biology*, 20(2).
Khan, A. and V. Amelie, 2015: Assessing climate change readiness in Seychelles: implications for ecosystem-based adaptation mainstreaming and marine spatial planning. *Regional Environmental Change*, 15(4), 721-733, doi:10.1007/s10113-014-0662-4.
Kibler, S. et al., 2015: Effects of ocean warming on growth and distribution of dinoflagellates associated with ciguatera fish poisoning in the Caribbean. *Ecological Modelling*, 316, 194-210, doi:10.1016/j.ecolmodel.2015.08.020.
Kiddle, G. et al., 2017: Unpacking the Pacific Urban Agenda: Resilience Challenges and Opportunities. *Sustainability*, 9(10), doi:10.3390/su9101878.
Kim, K. and L. Bui, 2019: Learning from Hurricane Maria: Island ports and supply chain resilience. *International Journal of Disaster Risk Reduction*, 39(101244), doi:10.1016/j.ijdrr.2019.101244.
Kim, R., A. Costello and D. Campbell-Lendrum, 2015: Climate change and health in Pacific island states. *Bulletin from the World Health Organization*, 93(12), 819, doi:10.2471/BLT.15.166199.
Kishore, N. et al., 2018: Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine*, 379(2), 162-170, doi:10.1056/NEJMsa1803972.
Klomp, J., 2017: Flooded with debt. *Journal of International Money and Finance*, 73, 93-103, doi:10.1016/j.jimonfin.2017.01.006.
Knutson, T. et al., 2019: Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution. *Bulletin of the American Meteorological Society*, 100(10), 1987-2007, doi:10.1175/bams-d-18-0189.1.
Koester, A. et al., 2020: Early trajectories of benthic coral reef communities following the 2015/16 coral bleaching event at remote Aldabra Atoll, Seychelles. *Sci Rep*, 10(1), 17034, doi:10.1038/s41598-020-74077-x.
Koide, D. et al., 2017: An upward elevation shift of native and non-native vascular plants over 40 years on the island of Hawai'i. *Journal of Vegetation Science*, 28(5), 939-950, doi:10.1111/jvs.12549.
Kossin, J., K. Emanuel and S. Camargo, 2016: Past and Projected Changes in Western North Pacific Tropical Cyclone Exposure. *Journal of Climate*, 29(16), 5725-5739, doi:10.1175/jcli-d-16-0076.1.
Kossin, J., K. Knapp, T. Olander and C. Velden, 2020: Global increase in major tropical cyclone exceedance probability over the past four decades. *PNAS*, 117(22), 11975-11980, doi:10.1073/pnas.2021573117.
Kossin, J. P. et al., 2017: Extreme Storms. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume 1* [Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. Stewart and T. Maycock (eds.)]. U.S. Global Change Research Program, Washington D.C., USA, pp. 257-276.
Kotsinas, M., 2020: Climate (In)justice: An Intersectional Feminist Analysis of Disaster Management in Antigua and Barbuda in the Aftermath of Hurricane Irma. *Politikon: The IAPSS Journal of Political Science*, 47, 7-35, doi:10.22151/politikon.47.1.
Koutroulis, A. et al., 2016: Cross sectoral impacts on water availability at +2 °C and +3 °C for east Mediterranean island states: The case of Crete. *Journal of Hydrology*, 532, 16-28, doi:10.1016/j.jhydrol.2015.11.015.
Krauss, K. W. et al., 2010: Surface Elevation Change and Susceptibility of Different Mangrove Zones to Sea-Level Rise on Pacific High Islands of Micronesia. *Ecosystems*, 13(1), 129-143, doi:10.1007/s10021-009-9307-8.
Krushelnycky, P. D. et al., 2012: Climate-associated population declines reverse recovery and threaten future of an iconic high-elevation plant. *Global Change Biology*, 19(3), 911-922, doi:10.1111/gcb.12111.
Kuleshov, Y., P. Gregory, A. B. Watkins and R. J. B. Fawcett, 2020: Tropical cyclone early warnings for the regions of the Southern Hemisphere: strengthening resilience to tropical cyclones in small island developing states and least developed countries. *Natural Hazards*, 104(2), 1295-1313, doi:10.1007/s11069-020-04214-2.
Kuleshov, Y. et al., 2014: Extreme Weather and Climate Events and Their Impacts on Island Countries in the Western Pacific: Cyclones, Floods and Droughts. *Atmospheric and Climate Sciences*, 04(05), 803-818, doi:10.4236/acs.2014.45071.
Kulp, S. and B. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, 10(4844), doi:10.1038/s41467-019-12808-z.

Kumar, L. et al., 2018: An indicative index of physical susceptibility of small islands to coastal erosion induced by climate change: an application to the Pacific islands. *Geomatics, Natural Hazards and Risk*, 9(1), 691-702, doi:10.1080/19475705.2018.1455749.

Kumar, L. et al., 2020: *Climate Change and Impacts in the Pacific*, 1 ed. [Kumar, L. (ed.)]. Springer, Berlin, 557 pp.

Kumar, L. and S. Taylor, 2015: Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change*, 5(11), 992-996, doi:10.1038/nclimate2702.

Kumar, L. and M. Tehrany, 2017: Climate change impacts on the threatened terrestrial vertebrates of the Pacific Islands. *Scientific Reports*, 7(5030), doi:10.1038/s41598-017-05034-4.

Kuruppu, N. and R. Willie, 2015: Barriers to reducing climate enhanced disaster risks in Least Developed Country-Small Islands through anticipatory adaptation. *Weather and Climate Extremes*, 7, 72-83, doi:10.1016/j.wace.2014.06.001.

Laczko, F. and E. Piguet, 2014: Regional Perspectives on Migration, the Environment and Climate Change. In: *People on the Move in a Changing Climate: The regional impact of environmental change on migration* [Piguet, E. and F. Laczko (eds.)]. Springer, Cham, Switzerland.

Lal, A. and B. Datta, 2019: Multi-objective groundwater management strategy under uncertainties for sustainable control of saltwater intrusion: Solution for an island country in the South Pacific. *Journal of Environmental Management*, 234, 115-130, doi:10.1016/j.jenvman.2018.12.054.

Lallo, C. H. O. et al., 2018: Characterizing heat stress on livestock using the temperature humidity index (THI)—prospects for a warmer Caribbean. *Regional Environmental Change*, 18(8), 2329-2340, doi:10.1007/s10113-018-1359-x.

Laloë, J.-O., N. Esteban, J. Berkel and G. C. Hays, 2016: Sand temperatures for nesting sea turtles in the Caribbean: Implications for hatchling sex ratios in the face of climate change. *Journal of Experimental Marine Biology and Ecology*, 474, 92-99, doi:10.1016/j.jembe.2015.09.015.

Lama, P., 2018: Gendered consequences of mobility for adaptation in small island developing states: case studies from Maafushi and Kudafari in the Maldives. *Island Studies Journal*, 13(2), 111-128, doi:10.24043/isj.64.

Lang'at, J. K. et al., 2014: Rapid losses of surface elevation following tree girdling and cutting in tropical mangroves. *PLoS One*, 9(9), e107868, doi:10.1371/journal.pone.0107868.

Lashley, J. and K. Warner, 2013: Evidence of demand for microinsurance for coping and adaptation to weather extremes in the Caribbean. *Climatic Change*, 133(1), 101-112, doi:10.1007/s10584-013-0922-1.

Lasso, A. and H. Dahles, 2018: Are tourism livelihoods sustainable? Tourism development and economic transformation on Komodo Island, Indonesia. *Asia Pacific Journal of Tourism Research*, 23(5), 473-485, doi:10.1080/10941665.2018.1467939.

Layne, D., 2017: Impacts of Climate Change on Tourism in the Coastal and Marine Enviornments of Caribbean Small Island Developing States (SIDS). In: *Caribbean Marine Climate Change Report Card: Science Review 2017.* [Buckley, P., B. Townhill, U. Trotz, K. Nichols, P. Murray, C. Clarke-Samuels, A. Gordon and M. Taylor (eds.)].

Lazenby, M. J., M. C. Todd, R. Chadwick and Y. Wang, 2018: Future Precipitation Projections over Central and Southern Africa and the Adjacent Indian Ocean: What Causes the Changes and the Uncertainty? *Journal of Climate*, 31(12), 4807-4826, doi:10.1175/jcli-d-17-0311.1.

Lazrus, H., 2015: Risk Perception and Climate Adaptation in Tuvalu: A Combined Cultural Theory and Traditional Knowledge Approach. *Human Organization*, 74(1), doi:10.17730/humo.74.1.q0667716284749m8.

Le Dé, L., T. Rey, F. Leone and D. Gilbert, 2018: Sustainable livelihoods and effectiveness of disaster responses: a case study of tropical cyclone Pam in Vanuatu. *Natural Hazards*, 91(3), 1203-1221, doi:10.1007/s11069-018-3174-6.

Lee, S., S. Wu and A. Li, 2018: Low-carbon tourism of small islands responding to climate change. *World Leisure Journal*, 60(3), 235-245, doi:10.1080/16078055.2018.1496530.

Lehner, F. et al., 2017: Projected drought risk in 1.5°C and 2°C warmer climates. *Geophysical Research Letters*, 44(14), 7419-7428, doi:10.1002/2017gl074117.

Lemahieu, A. et al., 2018: Local perceptions of environmental changes in fishing communities of southwest Madagascar. *Ocean & Coastal Management*, 163, 209-221, doi:10.1016/j.ocecoaman.2018.06.012.

Lichtveld, M., 2018: Disasters Through the Lens of Disparities: Elevate Community Resilience as an Essential Public Health Service. *American Journal of Public Health*, 108(1), 28-30, doi:10.2105/AJPH.2017.304193.

Lieber, M. et al., 2020: A systematic review and meta-analysis assessing the impact of droughts, flooding, and climate variability on malnutrition. *Global Public Health*, 1-15, doi:10.1080/17441692.2020.1860247.

Lix, J. K. et al., 2016: Differential bleaching of corals based on El Nino type and intensity in the Andaman Sea, southeast Bay of Bengal. *Environmental Monitoring and Assessment*, 188(3), 175, doi:10.1007/s10661-016-5176-8.

Loehr, J., 2019: The Vanuatu Tourism Adaptation System: a holistic approach to reducing climate risk. *Journal of Sustainable Tourism*, 28(4), 515-534, doi:10.1080/09669582.2019.1683185.

Loehr, J., S. Becken, J. Nalau and B. Mackey, 2020: Exploring the multiple benefits of ecosystem-based adaptation for climate risks and destination well-being. *Journal of Hospitality & Tourism Research*, doi:0.1177/1096348020944438.

Look, C., E. Friedman and G. Godbout, 2019: The Resilience of Land Tenure Regimes During Hurricane Irma: How Colonial Legacies Impact Disaster Response and Recovery in Antigua and Barbuda. *Journal of Extreme Events*, 06(01), doi:10.1142/s2345737619400049.

Lopez-Candales, A., D. F. Hernandez-Suarez, A. D. Osterman-Pla and J. G. Conde-Santiago, 2018: A Reminder From the Devastation Hurricane Maria Left Behind. *Cureus*, 10(1), e2038, doi:10.7759/cureus.2038.

Lopez-Marrero, T., 2010: An integrative approach to study and promote natural hazards adaptive capacity: a case study of two flood-prone communities in Puerto Rico. *Geographical Journal*, 176(2), 150-163, doi:10.1111/j.1475-4959.2010.00353.x.

Lough, J. M. et al., 2016: Observed and projected changes in surface climate of tropical Pacific Islands. In: *Vulnerability of Pacific Island agriculture and forestry to climate change* [Taylor, M., A. McGregor and B. Dawson (eds.)]. Pacific Community, pp. 47-101.

Lovelock, C. E. et al., 2015: The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, 526(7574), 559-563, doi:10.1038/nature15538.

Lowe, R. et al., 2018: Nonlinear and delayed impacts of climate on dengue risk in Barbados: A modelling study. *PLoS Medicine*, 15(7), e1002613, doi:10.1371/journal.pmed.1002613.

Lubell, M. and M. Niles, 2019: The limits of capacity building. *Nature Climate Change*, 9(8), 578-579, doi:10.1038/s41558-019-0541-6.

Luetz, J., 2017: Chapter 3: Climate change and migration in the Maldives: Some lessons for policy makers. In: *Climate Change Adaptation in Pacific Countries: Fostering resilience and improving the quality of life* [Filho, W. L. (ed.)]. Springer, Cham. ISBN 978-3-319-50093-5.

Luke, S. H. et al., 2017: The effects of catchment and riparian forest quality on stream environmental conditions across a tropical rainforest and oil palm landscape in Malaysian Borneo. *Ecohydrology*, 10(4), e1827, doi:10.1002/eco.1827.

Lumbroso, D., E. Brown and N. Ranger, 2016: Stakeholders' perceptions of the overall effectiveness of early warning systems and risk assessments for weather-related hazards in Africa, the Caribbean and South Asia. *Natural Hazards*, 84(3), 2121-2144, doi:10.1007/s11069-016-2537-0.

Mace, M. J. and R. Verheyen, 2016: Loss, Damage and Responsibility after COP21: All Options Open for the Paris Agreement. *Review of European, Comparative & International Environmental Law*, 25(2), 197-214, doi:10.1111/reel.12172.

Mackay, E. and A. Spencer, 2017: The future of Caribbean tourism: competition and climate change implications. *Worldwide Hospitality and Tourism Themes*, 9(1), 44-59, doi:10.1108/whatt-11-2016-0069.

MacKenzie, R. A. et al., 2016: Sedimentation and belowground carbon accumulation rates in mangrove forests that differ in diversity and land use: a tale of two mangroves. *Wetlands Ecology and Management*, 24(2), 245-261, doi:10.1007/s11273-016-9481-3.

Magee, A. D., D. C. Verdon-Kidd, A. S. Kiem and S. A. Royle, 2016: Tropical cyclone perceptions, impacts and adaptation in the Southwest Pacific: an urban perspective from Fiji, Vanuatu and Tonga. *Natural Hazards and Earth System Sciences*, 16(5), 1091-1105, doi:10.5194/nhess-16-1091-2016.

Magel, J., S. Dimoff and J. K. Baum, 2020: Direct and indirect effects of climate change-amplified pulse heat stress events on coral reef fish communities. *Ecological Applications*, 30(6), doi:10.1002/eap.2124.

Magnan, A., 2006: L'evacuation des populations aux Maldives apres le tsunami du 26 decembre 2004. *Mappemonde*, 84(4).

Magnan, A. and V. Duvat, 2018: Unavoidable solutions for coastal adaptation in Reunion Island (Indian Ocean). *Environmental Science & Policy*, 89, 393-400, doi:10.1016/j.envsci.2018.09.002.

Magnan, A. K. et al., 2019: Cross Chapter Box 9: Low Lying Islands and Coasts. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. Roberts, V. Masson-Delmotte, P. Zhai, Y. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)].

Magnan, Alexandre K. et al., 2018: Atoll population exposure to marine inundation: the example of the Tuamotu Archipelago (Rangiroa and Tikehau atolls), French Polynesia. *VertigO*, 18(3), doi:10.4000/vertigo.23607.

Mahadew, R. and K. Appadoo, 2019: Tourism and climate change in Mauritius: assessing the adpatation and mitigation plans and prospects. *Tourism Review*, doi:10.1108/TR-12-2017-0203.

Maharaj, S. et al., 2019: Assessing protected area effectiveness within the Caribbean under changing climate conditions: A case study of the small island, Trinidad. *Land Use Policy*, 81, 185-193, doi:10.1016/j.landusepol.2018.09.030.

Maharaj, S. and M. New, 2013: Modelling individual and collective species responses to climate change within Small Island States. *Biological Conservation*, 167, 283-291, doi:10.1016/j.biocon.2013.08.027.

Mahon, R. et al., 2019: Fit for purpose? Transforming National Meteorological and Hydrological T Services into National Climate Service Centers. *Climate Services*, 13, 14-23, doi:10.1016/j.cliser.2019.01.002.

Major, D. C. and S. Juhola, 2016: Guidance for Climate Change Adaptation in Small Coastal Towns and Cities: A New Challenge. *Journal of Urban Planning and Development*, 142(4), doi:10.1061/(asce)up.1943-5444.0000356.

Mallin, M., 2018: From sea-level rise to seabed grabbing: The political economy of climate change in Kiribati. *Marine Policy*, 97, 244-252, doi:10.1016/j.marpol.2018.04.021.

Malsale, P. et al., 2018: Protocols and Partnerships for Engaging Pacific Island Communities in the Collection and Use of Traditional Climate Knowledge. *Bulletin of the American Meteorological Society*, 99(12), 2471-2489, doi:10.1175/bams-d-17-0163.1.

Manes, S. et al., 2021: Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, 257, doi:10.1016/j.biocon.2021.109070.

Mann, T. and H. Westphal, 2014: Assessing Long-Term Changes in the Beach Width of Reef Islands Based on Temporally Fragmented Remote Sensing Data. *Remote Sensing*, 6(8), 6961-6987, doi:10.3390/rs6086961.
Marino, E. and H. Lazrus, 2015: Migration or Forced Displacement?: The Complex Choices of Climate Change and Disaster Migrants in Shishmaref, Alaska and Nanumea, Tuvalu. *Human Organization*, 74(4), 341-350, doi:10.17730/0018-7259-74.4.341.
Mariotti, A., Y. Pan, N. Zeng and A. Alessandri, 2015: Long-term climate change in the Mediterranean region in the midst of decadal variability. *Climate Dynamics*, 44(5-6), 1437-1456, doi:10.1007/s00382-015-2487-3.
Marler, T., 2014: Pacific island tropical cyclones are more frequent and globally relevant, yet less studied. *Frontiers in Environmental Science*, 2, doi:10.3389/fenvs.2014.00042.
Martin, D. et al., 2015: Development and implementation of a climate data management system for western Pacific small island developing states. *Meteorological Applications*, 22(2), 273-287, doi:10.1002/met.1461.
Martin, P., P. Nunn, J. Leon and N. Tindale, 2018: Responding to multiple climate-linked stressors in a remote island context: The example of Yadua Island, Fiji. *Climate Risk Management*, 21, 7-15, doi:10.1016/j.crm.2018.04.003.
Martins, P. et al., 2009: Under-report and underdiagnosis of chronic respiratory diseases in an African country. *Allergy*, 64(7), 1061-1067, doi:10.1111/j.1398-9995.2009.01956.x.
Martyr-Koller, R. et al., 2021: Loss and damage implications of sea-level rise on Small Island Developing States. *Current Opinion in Environmental Sustainability*, 50, 245-259, doi:10.1016/j.cosust.2021.05.001.
Marzeion, B. and A. Levermann, 2014: Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environmental Research Letters*, 9(3), doi:10.1088/1748-9326/9/3/034001.
Masterson, J. et al., 2014: Effects of sea-level rise on barrier island groundwater system dynamics - ecohydrological implications. *Ecohydrology*, 7(3), 1064-1071, doi:10.1002/eco.1442.
Maynard, J. et al., 2015: Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nature Climate Change*, 5(7), 688-694, doi:10.1038/nclimate2625.
McAneney, J., R. van den Honert and S. Yeo, 2017: Stationarity of major flood frequencies and heights on the Ba River, Fiji, over a 122-year record. *International Journal of Climatology*, 37, 171-178, doi:10.1002/joc.4989.
McClanahan, T. R. et al., 2019: Temperature patterns and mechanisms influencing coral bleaching during the 2016 El Niño. *Nature Climate Change*, 9(11), 845-851, doi:10.1038/s41558-019-0576-8.
McClanahan, T. R. et al., 2020: Large geographic variability in the resistance of corals to thermal stress. *Global Ecology and Biogeography*, 29(12), 2229-2247, doi:10.1111/geb.13191.
McCubbin, S., T. Pearce, J. Ford and B. Smit, 2017: Social-ecological change and implications for food security in Funafuti, Tuvalu. *Ecology and Society*, 22(1), doi:10.5751/es-09129-220153.
McCubbin, S., B. Smit and T. Pearce, 2015: Where does climate fit? Vulnerability to climate change in the context of multiple stressors in Funafuti, Tuvalu. *Global Environmental Change*, 30, 43-55, doi:10.1016/j.gloenvcha.2014.10.007.
McField, M., 2017: Impacts of Climate Change on Coral in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS). *Caribbean Marine Climate Change Report Card: Science Review 2017.*, 52-59.
McGaw, I. J., T. E. Van Leeuwen, R. H. Trehern and A. E. Bates, 2019: Changes in precipitation may alter food preference in an ecosystem engineer, the black land crab, Gecarcinus ruricola. *PeerJ*, 7, e6818, doi:10.7717/peerj.6818.
McGinn, A. and A. Solofa, 2020: Chapter 12: Mutli-level governance of climate change adaptation: A case study of country-wide adaptation projects in Samoa. In: *Managing Climate Change Adaptation in the Pacific Region* [Filho, W. L. (ed.)]. Springer International, pp. 231-253.
McGree, S. et al., 2019: Recent Changes in Mean and Extreme Temperature and Precipitation in the Western Pacific Islands. *Journal of Climate*, 32(16), 4919-4941, doi:10.1175/jcli-d-18-0748.1.
McGree, S., S. Schreider and Y. Kuleshov, 2016: Trends and Variability in Droughts in the Pacific Islands and Northeast Australia. *Journal of Climate*, 29(23), 8377-8397, doi:10.1175/jcli-d-16-0332.1.
McGree, S., S. Schreider, Y. Kuleshov and B. Prakash, 2020: On the use of mean and extreme climate indices to predict sugar yield in western Fiji. *Weather and Climate Extremes*, 29, doi:10.1016/j.wace.2020.100271.
McInnes, K. et al., 2016: Application of a synthetic cyclone method for assessment of tropical cyclone storm tides in Samoa. *Natural Hazards*, 80(1), 425-444, doi:10.1007/s11069-015-1975-4.
McInnes, K. et al., 2014: Quantifying storm tide risk in Fiji due to climate variability and change. *Global and Planetary Change*, 116, 115-129, doi:10.1016/j.gloplacha.2014.02.004.
McIver, L. et al., 2016: Health Impacts of Climate Change in Pacific Island Countries: A Regional Assessment of Vulnerabilities and Adaptation Priorities. *Environmental Health Perspectives*, 124(11), 1707-1714, doi:10.1289/ehp.1509756.
McIver, L. et al., 2014: Assessment of the health impacts of climate change in Kiribati. *International Journal of Environmental Research and Public Health*, 11(5), 5224-5240, doi:10.3390/ijerph110505224.
McLean, R. and P. Kench, 2015: Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdisciplinary Reviews: Climate Change*, 6(5), 445-463, doi:10.1002/wcc.350.
McLeod, E. et al., 2018: Raising the voices of Pacific Island women to inform climate adaptation policies. *Marine Policy*, 93, 178-185, doi:10.1016/j.marpol.2018.03.011.
McLeod, E. et al., 2019: Lessons From the Pacific Islands – Adapting to Climate Change by Supporting Social and Ecological Resilience. *Frontiers in Marine Science*, 6, doi:10.3389/fmars.2019.00289.

McMichael, A., M. Katonivualiku and T. Powell, 2019: Planned relocation and everyday agency in low-lying coastal villages in Fiji. *Geography Journal*, 185, 325-337, doi:10.1111/geoj.12312.
McMillen, H. L. et al., 2014: Small islands, valuable insights: systems of customary resource use and resilience to climate change in the Pacific. *Ecology and Society*, 19(4), doi:10.5751/es-06937-190444.
McNamara, K., R. Bronen, N. Fernando and S. Klepp, 2016: The complex decision-making of climate-induced relocation: adaptation and loss and damage. *Climate Policy*, doi:10.1080/14693062.2016.1248886.
McNamara, K. and H. Des Combes, 2015: Planning for Community Relocations Due to Climate Change in Fiji. *International Journal of Disaster Risk Science*, 6(3), 315-319, doi:10.1007/s13753-015-0065-2.
McNamara, K. E. et al., 2019: What is shaping vulnerability to climate change? The case of Laamu Atoll, Maldives. *Island Studies Journal*, 14(1), 81-100, doi:10.24043/isj.67.
McNamara, K. E. et al., 2020: An assessment of community-based adaptation initiatives in the Pacific Islands. *Nature Climate Change*, 10(7), 628-639, doi:10.1038/s41558-020-0813-1.
McNaught, R., O. Warrick and A. Cooper, 2014: Communicating climate change for adaptation in rural communities: a Pacific study. *Regional Environmental Change*, 14(4), 1491-1503, doi:10.1007/s10113-014-0592-1.
McSherry, A., E. J. Manalastas, J. C. Gaillard and S. N. M. Dalisay, 2014: From Deviant to Bakla, Strong to Stronger: Mainstreaming Sexual and Gender Minorities into Disaster Risk Reduction in the Philippines. *Forum for Development Studies*, 42(1), 27-40, doi:10.1080/08039410.2014.952330.
Mecartney, S. and J. Connell, 2017: Urban Melanesia: The Challenges of Managing Land, Modernity and Tradition. In: *Kastom, property and ideology* [McDonnell, S., M. Allen and C. Filer (eds.)]. Australian National University Press, pp. 57-84. ISBN 9781760461058.
MedECC, 2020: Summary for Policymakers. In: *Climate and Environmental Change in the Mediterranean basin—Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 34.
Melendez, E. and J. Hinojosa, 2017: *Estimates of Post-Hurricane Maria Exodus from Puerto Rico*. Center for Puerto Rican Studies, Hunter College.
Mendez-Lazaro, P. et al., 2018: A heat vulnerability index to improve urban public health management in San Juan, Puerto Rico. *International Journal of Biometeorology*, 62(5), 709-722, doi:10.1007/s00484-017-1319-z.
Mentaschi, L. et al., 2017: Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophysical Research Letters*, 44, 2416-2426, doi:10.1002/2016GL072488.
Mentaschi, L. et al., 2018: Global long-term observations of coastal erosion and accretion. *Scientific Reports*, 8(1), 12876, doi:10.1038/s41598-018-30904-w.
Mercer, J., I. Kelman, B. Alfthan and T. Kurvits, 2012: Ecosystem-Based Adaptation to Climate Change in Caribbean Small Island Developing States: Integrating Local and External Knowledge. *Sustainability*, 4(8), 1908-1932, doi:10.3390/su4081908.
Mercer, J. et al., 2014a: Nation-building policies in Timor-Leste: disaster risk reduction, including climate change adaptation. *Disasters*, 38(4), 690-718, doi:10.1111/disa.12082.
Mercer, J., T. Kurvits, I. Kelman and S. Mavrogenis, 2014b: Ecosystem-Based Adaptation for Food Security in the AIMS SIDS: Integrating External and Local Knowledge. *Sustainability*, 6(9), 5566-5597, doi:10.3390/su6095566.
Merrifield, M. and M. Maltrud, 2011: Regional sea level trends due to a Pacific trade wind intensification. *Geophysical Research Letters*, 38(21), n/a-n/a, doi:10.1029/2011gl049576.
Mertz, O. et al., 2010: Sustainable land use in Tikopia: Food production and consumption in an isolated agricultural system. *Singapore Journal of Tropical Geography*, 31(1), 10-26, doi:10.1111/j.1467-9493.2010.00389.x.
Middelbeek, L., K. Kolle and H. Verrest, 2014: Built to last? Local climate change adaptation and governance in the Caribbean – The case of an informal urban settlement in Trinidad and Tobago. *Urban Climate*, 8, 138-154, doi:10.1016/j.uclim.2013.12.003.
Middleton, N. et al., 2008: A 10-year time-series analysis of respiratory and cardiovascular morbidity in Nicosia, Cyprus: the effect of short-term changes in air pollution and dust storms. *Environmental Health*, 7, 39, doi:10.1186/1476-069X-7-39.
Mitsch, W. and M. Hernandez, 2013: Landscape and climate change threats to wetlands of North and Central America. *Aquatic Sciences*, 75(1), 133-149, doi:10.1007/s00027-012-0262-7.
Mollica, N. R. et al., 2019: Skeletal records of bleaching reveal different thermal thresholds of Pacific coral reef assemblages. *Coral Reefs*, 38(4), 743-757, doi:10.1007/s00338-019-01803-x.
Moncada, S. and H. Bambrick, 2019: Extreme weather events in Small Island Developing States: barriers to climate change adaptation among coastal communities in a remote island of Fiji. In: *Dealing with climate change on small islands: Towards effective and sustainable adaptation* [Klock, C. and M. Fink (eds.)]. Gottingen University Press, Germany, pp. 217-247. ISBN 978-3-86395-435-2.
Mondragón, C., 2018: Forest, Reef and Sea-Level Rise in North Vanuatu: Seasonal Environmental Practices and Climate Fluctuations in Island Melanesia. In: *Indigenous Knowledge for Climate Change Assessment and Adaptation* [Nakashima, D., I. Krupnik and J. Rubis (eds.)]. Cambridge University Press, Cambridge, pp. 23-40. ISBN 9781316481066.
Monioudi, I. N. et al., 2017: Assessment of island beach erosion due to sea level rise: the case of the Aegean archipelago (Eastern Mediterranean). *Natural Hazards and Earth System Sciences*, 17(3), 449-466, doi:10.5194/nhess-17-449-2017.

Monioudi, I. N. et al., 2018: Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. *Regional Environmental Change*, 18(8), 2211-2225, doi:10.1007/s10113-018-1360-4.

Monnereau, I. et al., 2017: The impact of methodological choices on the outcome of national-level climate change vulnerability assessments: An example from the global fisheries sector. *Fish and Fisheries*, 18(4), 717-731, doi:10.1111/faf.12199.

Monoy, C. et al., 2016: Temporal Changes in Tree Species and Trait Composition in a Cyclone-prone Pacific Dipterocarp Forest. *Ecosystems*, 19(6), 1013-1022, doi:10.1007/s10021-016-9983-0.

Morim, J. et al., 2019: Robustness and uncertainties in global multivariate wind-wave climate projections. *Nature Climate Change*, 9(9), 711-718, doi:10.1038/s41558-019-0542-5.

Morri, C. et al., 2015: Through bleaching and tsunami: Coral reef recovery in the Maldives. *Marine Pollution Bulletin*, 98(1-2), 188-200, doi:10.1016/j.marpolbul.2015.06.050.

Morris, R., T. Konlechner, M. Ghisalberti and S. Swearer, 2018: From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Global Change Biology*, 24(5), 1827-1842, doi:10.1111/gcb.14063.

Moulton, A. A. and M. R. Machado, 2019: Bouncing Forward After Irma and Maria: Acknowledging Colonialism, Problematizing Resilience and Thinking Climate Justice. *Journal of Extreme Events*, 06(01), doi:10.1142/s2345737619400037.

Mycoo, M., 2014a: Autonomous household responses and urban governance capacity building for climate change adaptation: Georgetown, Guyana. *Urban Climate*, 9, 134-154, doi:10.1016/j.uclim.2014.07.009.

Mycoo, M., 2014b: Sustainable tourism, climate change and sea level rise adaptation policies in Barbados. *Natural Resources Forum*, 38(1), 47-57, doi:10.1111/1477-8947.12033.

Mycoo, M., 2015: Communicating climate change in rural coastal communities. *International Journal of Climate Change Strategies and Management*, 7(1), 58-75, doi:10.1108/ijccsm-04-2013-0042.

Mycoo, M., 2017: A Caribbean New Urban Agenda post-Habitat III: Closing the gaps. *Habitat International*, 69, 68-77, doi:10.1016/j.habitatint.2017.09.001.

Mycoo, M., 2018a: Beyond 1.5 °C: vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional Environmental Change*, 18(8), 2341-2353, doi:10.1007/s10113-017-1248-8.

Mycoo, M., 2018b: Urban sustainability in Caribbean Small Island Developing States: a conceptual framework for urban planning using a case study of Trinidad. *International Development Planning Review*, 40(2), 143-174, doi:10.3828/idpr.2018.8.

Mycoo, M., 2020: Environmental governance in small island developing states: Challenges and opportunities for transformation using a Trinidad and Tobago case study. In: *Handbook of Governance in Small States.* [Briguglio, L., J. Byron, S. Moncada and W. Veenendaal (eds.)]. Routledge, London, UK. ISBN 9780429061356.

Mycoo, M., 2021: Vulnerabilities to Climate Change and Enhancing Resilience in Caribbean Small Island Developing States: A Spatial Planning Framework. In: *Small Island Developing States: vulnerability and resilience under climate change* [Moncada, S., L. Briguglio, H. Bambrick, I. Kelman, C. Iorns and L. Nurse (eds.)]. Springer, Cham, Switzerland.

Mycoo, M. and M. Donovan, 2017: *A Blue Urban Agenda: Adapting to Cliamte Change in the Coastal Cities of Caribbean and Pacific Small Island Developing States*. IBD, Washington, D.C. ISBN 978-1-59782-293-1.

Nalau, J., S. Becken and B. Mackey, 2018a: Ecosystem-based Adaptation: A review of the constraints. *Environmental Science & Policy*, 89, 357-364, doi:10.1016/j.envsci.2018.08.014.

Nalau, J. et al., 2018b: The Role of Indigenous and Traditional Knowledge in Ecosystem-Based Adaptation: A Review of the Literature and Case Studies from the Pacific Islands. *Weather, Climate, and Society*, 10(4), 851-865, doi:10.1175/wcas-d-18-0032.1.

Nalau, J. and W. L. Filho, 2018: Introduction: Limits to Adaptation. In: *Limits to Climate Change Adaptation* [Filho, W. and J. Nalau (eds.)]. Springer, Cham.

Nalau, J., J. Handmer and M. Dalesa, 2017: The role and capacity of government in climate crises: TC Pam in Vanuatu. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life* [Filho, W. L. (ed.)]. Springer, Berlin, pp. 151-161.

Nalau, J. et al., 2016: The practice of integrating adaptation and disaster risk reduction in the south-west Pacific. *Climate and Development*, 8(4), 365-375, doi:10.1080/17565529.2015.1064809.

Nand, M. M. and D. K. Bardsley, 2020: Climate change loss and damage policy implications for Pacific Island Countries. *Local Environment*, 25(9), 725-740, doi:10.1080/13549839.2020.1825357.

Narayan, S. et al., 2016: The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLoS One*, 11(5), e0154735, doi:10.1371/journal.pone.0154735.

Narayan, S. et al., 2020: Local adaptation responses to coastal hazards in small island communities: insights from 4 Pacific nations. *Environmental Science & Policy*, 104, 199-207, doi:10.1016/j.envsci.2019.11.006.

Naylor, A., 2015: Island morphology, reef resources, and development paths in the Maldives. *Progress in Physical Geography*, 39(6), 728-749, doi:10.1177/0309133315598269.

Neef, A. et al., 2018: Climate adaptation strategies in Fiji: The role of social norms and cultural values. *World Development*, 107, 125-137, doi:10.1016/j.worlddev.2018.02.029.

Nehru, P. and P. Balasubramanian, 2018: Mangrove species diversity and composition in the successional habitats of Nicobar Islands, India: A post-tsunami and subsidence scenario. *Forest Ecology and Management*, 427, 70-77, doi:10.1016/j.foreco.2018.05.063.
Newth, D. and D. Gunasekera, 2018: Projected Changes in Wet-Bulb Globe Temperature under Alternative Climate Scenarios. *Atmosphere*, 9(5), doi:10.3390/atmos9050187.
Nguyen, P. et al., 2018: Global Precipitation Trends across Spatial Scales Using Satellite Observations. *Bulletin of the American Meteorological Society*, 99(4), 689-697, doi:10.1175/bams-d-17-0065.1.
Nicolas, F. et al., 2020: Assessing the Potential Impact of Climate Change on Rice Yield in the Artibonite Valley of Haiti Using the CSM-CERES-Rice Model. *Transactions of the ASABE*, 63(5), 1385-1400, doi:10.13031/trans.13868.
Noy, I. and C. Edmonds, 2019: Increasing fiscal resilience to disasters in the Pacific. *Natural Hazards*, 97(3), 1375-1393, doi:10.1007/s11069-019-03719-9.
Nunn, P., 2013: The end of the Pacific? Effects of sea level rise on Pacific Island livelihoods. *Singapore Journal of Tropical Geography*, 34(2), 143-171, doi:10.1111/sjtg.12021.
Nunn, P., W. Aalbersberg, S. Lata and M. Gwilliam, 2014: Beyond the core: community governance for climate-change adaptation in peripheral parts of Pacific Island Countries. *Regional Environmental Change*, 14(1), 221-235, doi:10.1007/s10113-013-0486-7.
Nunn, P., A. Kohler and R. Kumar, 2017a: Identifying and assessing evidence for recent shoreline change attributable to uncommonly rapid sea-level rise in Pohnpei, Federated States of Micronesia, Northwest Pacific Ocean. *Journal of Coastal Conservation*, 21(6), 719-730, doi:10.1007/s11852-017-0531-7.
Nunn, P. and R. Kumar, 2018: Understanding climate-human interactions in Small Island Developing States (SIDS). *International Journal of Climate Change Strategies and Management*, 10(2), 245-271, doi:10.1108/ijccsm-01-2017-0012.
Nunn, P. and R. Kumar, 2019a: Measuring Peripherality as a Proxy for Autonomous Community Coping Capacity: A Case Study from Bua Province, Fiji Islands, for Improving Climate Change Adaptation. *Social Sciences*, 8(8), doi:10.3390/socsci8080225.
Nunn, P., J. Runman, M. Falanruw and R. Kumar, 2017b: Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. *Regional Environmental Change*, 17(4), 959-971, doi:10.1007/s10113-016-0950-2.
Nunn, P. D., C. Klöck and V. Duvat, 2021: Seawalls as maladaptations along island coasts. *Ocean & Coastal Management*, 205, doi:10.1016/j.ocecoaman.2021.105554.
Nunn, P. D., L. Kumar, I. Eliot and R. F. McLean, 2016: Classifying Pacific islands. *Geoscience Letters*, 3(1), doi:10.1186/s40562-016-0041-8.
Nunn, P. D. and R. Kumar, 2019b: Cashless Adaptation to Climate Change: Unwelcome yet Unavoidable? *One Earth*, 1(1), 31-34, doi:10.1016/j.oneear.2019.08.004.
Nunn, P. D. and K. E. McNamara, 2019: Failing adaptation in island contexts: the growing need for transformational change. In: *Dealing with climate change on small islands: Towards effective and sustainable adaptation*, pp. 19-44. ISBN 978-3-86395-435-2.
Nurse, L., 2011: The implications of global climate change for fisheries management in the Caribbean. *Climate and Development*, 3(3), 228-241, doi:10.1080/17565529.2011.603195.
Oakes, R., 2019: Culture, climate change and mobility decisions in Pacific Small Island Developing States. *Population and Environment*, 40(4), 480-503, doi:10.1007/s11111-019-00321-w.
Oberle, F., P. Swarzenski and C. Storlazzi, 2017: Atoll Groundwater Movement and Its Response to Climatic and Sea-Level Fluctuations. *Water*, 9(650), doi:10.3390/w9090650.
Oculi, N. and S. Stephenson, 2018: Conceptualizing climate vulnerability: Understanding the negotiating strategies of Small Island Developing States. *Environmental Science & Policy*, 85, 72-80, doi:10.1016/j.envsci.2018.03.025.
Oleson, K. L. L. et al., 2018: Charting progress towards system-scale ecosystem service valuation in islands. *Environmental Conservation*, 45(03), 212-226, doi:10.1017/s0376892918000140.
Onaka, S. et al., 2017: Effectiveness of Gravel Beach Nourishment on Pacific Island. *Asian and Pacific Coastas*, 651-662, doi:10.1142/9789813233812_0059.
Ontoria, Y. et al., 2019: Interactive effects of global warming and eutrophication on a fast-growing Mediterranean seagrass. *Marine Environmental Research*, 145, 27-38, doi:10.1016/j.marenvres.2019.02.002.
Oppenheimer, M. et al., 2019: Chapter 4: Seal level rise and implications for low lying islands, coasts and communities. In: *IPCC Special Report on Ocean and Cryosphere* [Portner, H. O., D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)].
Oremus, K. L. et al., 2020: Governance challenges for tropical nations losing fish species due to climate change. *Nature Sustainability*, 3(4), 277-280, doi:10.1038/s41893-020-0476-y.
Oritz, P. et al., 2015: Spatial Models for Prediction and Early Warning of Aedes aegypti Proliferation from Data on Climate Change and Variability in Cuba. *MEDICC Review*, 17(2), 20-28.
Otto, I. et al., 2017: Social vulnerability to climate change: a review of concepts and evidence. *Regional Environmental Change*, 17(6), 1651-1662, doi:10.1007/s10113-017-1105-9.

Oviatt, C. A., K. Huizenga, C. S. Rogers and W. J. Miller, 2019: What nutrient sources support anomalous growth and the recent sargassum mass stranding on Caribbean beaches? A review. *Marine Pollution Bulletin*, 145, 517-525, doi:10.1016/j.marpolbul.2019.06.049.
Paeniu, L., E. Holland, C. Miller and G. Anderson, 2017: Rainfall Trends, Drought Frequency and La Niña in Tuvalu: A Small Equatorial Island State in the Pacific Ocean. *Journal of Environmental & Analytical Toxicology*, 07(05), doi:10.4172/2161-0525.1000501.
Paeth, H. et al., 2017: Quantifying the evidence of climate change in the light of uncertainty exemplified by the Mediterranean hot spot region. *Global and Planetary Change*, 151, 144-151, doi:10.1016/j.gloplacha.2016.03.003.
Palanisamy, H. et al., 2012: Regional sea level change and variability in the Caribbean sea since 1950. *Journal of Geodetic Science*, 2(2), 125-133, doi:10.2478/v10156-011-0029-4.
Papadimitriou, L. et al., 2019: Developing a water strategy for sustainable irrigated agriculture in Mediterranean island communities – Insights from Malta. *Outlook on Agriculture*, 48(2), 143-151, doi:10.1177/0030727019841060.
Parsons, M., C. Brown, J. Nalau and K. Fisher, 2018: Assessing adaptive capacity and adaptation: insights from Samoan tourism operators. *Climate and Development*, 10(7), 644-663, doi:10.1080/17565529.2017.1410082.
Parsons, M. and J. Nalau, 2019: Adaptation policy and planning in Pacific small island developing states. In: *Research Handbook on Climate Change Adaptation Policy* [Keskitalo, C. and B. Preston (eds.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 273-290.
Parsons, M., J. Nalau and K. Fisher, 2017: Alternative Perspectives on Sustainability: Indigenous Knowledge and Methodologies. *Challenges in Sustainability*, 5(1), doi:10.12924/cis2017.05010007.
Pascua, P. a. et al., 2017: Beyond services: A process and framework to incorporate cultural, genealogical, place-based, and indigenous relationships in ecosystem service assessments. *Ecosystem Services*, 26, 465-475, doi:10.1016/j.ecoser.2017.03.012.
Pawankar, R. et al., 2020: Asia Pacific Association of Allergy Asthma and Clinical Immunology White Paper 2020 on climate change, air pollution, and biodiversity in Asia-Pacific and impact on allergic diseases. *Asia Pacific Allergy*, 10(1), e11, doi:10.5415/apallergy.2020.10.e11.
PCRAFI, 2017: *PCRAFI Program Phase II: Furthering Disaster Risk Finance in the Pacific*. SPC, Pacific Islands Forum Secretariat, World Bank Group. Available at: https://www.financialprotectionforum.org/publication/pcrafi-program-phase-ii-furthering-disaster-risk-finance-in-the-pacific.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355(6332), doi:10.1126/science.aai9214.
Pedersen, O. et al., 2016: Heat stress of two tropical seagrass species during low tides - impact on underwater net photosynthesis, dark respiration and diel in situ internal aeration. *New Phytologist*, 210(4), 1207-1218, doi:10.1111/nph.13900.
Perdikaris, S. et al., 2017: Cultural heritage under threat: the effects of climate change on the small island of Barbuda, Lesser Antilles. In: *Public Archaeology and Climate Change* [Dawson, T., C. Nimura, E. Lopez-Romero and M. Daire (eds.)]. Oxbow Books, Oxford, pp. 138-148. ISBN 9781785707070.
Perkins, R. and S. Krause, 2018: Adapting to climate change impacts in Yap State, Federated States of Micronesia: the importance of environmental conditions and intangible cultural heritage. *Island Studies Journal*, 13(1), 65-78, doi:10.24043/isj.51.
Perry, C. and K. Morgan, 2017: Bleaching drives collapse in reef carbonate budgets and reef growth potential on southern Maldives reefs. *Scientific Reports*, 7, 40581, doi:10.1038/srep40581.
Perry, C., K. Morgan, I. Lange and R. Yarlett, 2020: Bleaching-driven reef community shifts drive pulses of increased reef sediment generation. *Royal Society Open Science*, 7(192153), doi:10.1098/rsos.19215310.6084/m9.figshare.c.
Peters, E., 2015: The 2009/2010 Caribbean drought: a case study. *Disasters*, 39(4), 738-761, doi:10.1111/disa.12123.
Petzold, J. and A. Magnan, 2019: Climate change: thinking small islands beyond Small Island Developing States (SIDS). *Climatic Change*, 152(1), 145-165, doi:10.1007/s10584-018-2363-3.
Petzold, J. and B. Ratter, 2015: Climate change adaptation under a social capital approach – An analytical framework for small islands. *Ocean & Coastal Management*, 112, 36-43, doi:10.1016/j.ocecoaman.2015.05.003.
Petzold, J., B. Ratter and A. Holdschlag, 2018: Competing knowledge systems and adaptability to sea-level rise in The Bahamas. *Area*, 50(1), 91-100, doi:10.1111/area.12355.
Piggott-McKellar, A., K. McNamara, P. Nunn and S. Sekinini, 2019a: Moving People in a Changing Climate: Lessons from Two Case Studies in Fiji. *Social Sciences*, 8(133), doi:10.3390/socsci8050133.
Piggott-McKellar, A., K. McNamara, P. Nunn and J. Watson, 2019b: What are the barriers to successful community-based climate change adaptation? A review of grey literature. *Local Environment*, 24(4), 374-390, doi:10.1080/13549839.2019.1580688.
Piggott-McKellar, A., P. Nunn, K. McNamara and S. Sekinini, 2020: Dam(n) Seawalls: A case of climate change maladaptation in Fiji. In: *Managing Climate Change Adaptation in the Pacific Region* [Filho, W. L. (ed.)]. Springer International, pp. 69-84.
Pike, D. A., E. A. Roznik and I. Bell, 2015: Nest inundation from sea-level rise threatens sea turtle population viability. *Royal Society Open Science*, 2(7), 150127, doi:10.1098/rsos.150127.
Pillet, V. et al., 2019: Assessing the impacts of shoreline hardening on beach response to hurricanes: Saint-Barthelemy, Lesser Antilles. *Ocean and Coastal Management*, 174, 71-91, doi:10.1016/j.ocecoaman.2019.03.021.

Pinnegar, J. et al., 2019: Assessing vulnerability and adaptive capacity of the fisheries sector in Dominica: long-term climate change and catastrophic hurricanes. *ICES Joural of Marine Science*, 76(5), 1353-1367, doi:10.1093/icesjms/fsz052.

Pisapia, C. et al., 2016: Coral recovery in the central Maldives archipelago since the last major mass-bleaching, in 1998. *Scientific Reports*, 6, 34720, doi:10.1038/srep34720.

Pisapia, C., A. El Kateb, P. Hallock and S. Spezzaferri, 2017: Assessing coral reef health in the North Ari Atoll (Maldives) using the FoRAM Index. *Marine Micropaleontology*, 133, 50-57, doi:10.1016/j.marmicro.2017.06.001.

Plotz, R., L. Chambers and C. Finn, 2017: The Best of Both Worlds: A Decision-Making Framework for Combining Traditional and Contemporary Forecast Systems. *Journal of Applied Meteorology and Climatology*, 56(8), 2377-2392, doi:10.1175/jamc-d-17-0012.1.

Popke, J., S. Curtis and D. Gamble, 2016: A social justice framing of climate change discourse and policy: Adaptation, resilience and vulnerability in a Jamaican agricultural landscape. *Geoforum*, 73, 70-80, doi:10.1016/j.geoforum.2014.11.003.

Portner, H. O. et al., 2021: IPBES-IPCC co-sponsored workshop report on biodiversity and climate change. doi:10.5281/zenodo.4782538.

Povak, N. A. et al., 2020: A decision support tool for the conservation of tropical forest and nearshore environments on Babeldaob Island, Palau. *Forest Ecology and Management*, 476, doi:10.1016/j.foreco.2020.118480.

Prance, F., 2015: Chapter 7: Indigenous ontologies and developmentalism. In: *Environmental Change and the World's Futures: Ecologies, Ontologies and Mythologies* [Marshall, J. and I. Connor (eds.)]. Routledge, London, UK.

Prospero, J. and P. Lamb, 2003: African Droughts and Dust Transport to the Caribbean: Climate Change Implications. *Science*, 302(5647), 1024-1027.

Putman, N. F. et al., 2018: Simulating transport pathways of pelagic Sargassum from the Equatorial Atlantic into the Caribbean Sea. *Progress in Oceanography*, 165, 205-214, doi:10.1016/j.pocean.2018.06.009.

Quataert, E. et al., 2015: The influence of coral reefs on wave-driven flooding of tropical coastlines. *Geophysical Research Letters*, 42, 6407-6415, doi:10.1002/.

Quigley, N., S. Beavis and I. White, 2016: Rainwater harvesting augmentation of domestic water supply in Honiara, Solomon Islands. *Australian Journal of Water Resources*, 20(1), 65-77, doi:10.1080/13241583.2016.1173314.

Raila, E. and D. Anderson, 2017: Healthcare waste management during disasters and its effects on climate change: Lessons from 2010 earthquake and cholera tragedies in Haiti. *Waste Management & Research*, 35(3), 236-245, doi:10.1177/0734242X16682312.

Rambarran, J., 2018: Debt for Climate Swaps: Lessons for Caribbean SIDS from the Seychelles' Experience. *University of the West Indies*, 67(2).

Randall, C. J. and R. van Woesik, 2015: Contemporary white-band disease in Caribbean corals driven by climate change. *Nature Climate Change*, 5(4), 375-379, doi:10.1038/nclimate2530.

Rasmussen, D. et al., 2018: Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd centuries. *Environmental Research Letters*, 13(3), doi:10.1088/1748-9326/aaac87.

Ratter, B., J. Petzold and K. Sinane, 2016: Considering the locals: coastal construction and destruction in times of climate change on Anjouan, Comoros. *Natural Resources Forum*, 40(3), 112-126, doi:10.1111/1477-8947.12102.

Ratter, B. M. W., A. Hennig and A. Zahid, 2019: Challenges for shared responsibility - Political and social framing of coastal protection transformation in the Maldives. *Die Erde*, 150(3), 169-183, doi:10.12854/erde-2019-426.

Reguero, B. et al., 2018: Coral reefs for coastal protection: A new methodological approach and engineering case study in Grenada. *Journal of Environmental Management*, 210, 146-161, doi:10.1016/j.jenvman.2018.01.024.

Reguero, B. G. et al., 2020: Financing coastal resilience by combining nature-based risk reduction with insurance. *Ecological Economics*, 169, doi:10.1016/j.ecolecon.2019.106487.

Reimann, L. et al., 2018: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications*, 9(1), 4161, doi:10.1038/s41467-018-06645-9.

Remling, E. and J. Veitayaki, 2016: Community-based action in Fiji's Gau Island: a model for the Pacific? *International Journal of Climate Change Strategies and Management*, 8(3), 375-398, doi:10.1108/ijccsm-07-2015-0101.

Ren, X., Y. Lu, B. O'Neill and M. Weitzel, 2018: Economic and biophysical impacts on agriculture under 1.5 °C and 2 °C warming. *Environmental Research Letters*, 13(11), doi:10.1088/1748-9326/aae6a9.

Renaud, F.G. et al., 2016: *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice*. Advances in Natural and Technological Hazards Research, Springer International, Cham.

Repolho, T. et al., 2017: Seagrass ecophysiological performance under ocean warming and acidification. *Scientific Reports*, 7, 41443, doi:10.1038/srep41443.

Republic of Maldives, 2009: *Maldives - 4 years after the tsunami: Progress and remaining gaps*, Planning, M. o. F. a. T.-D. o. N., Maldives.

Resiere, D. et al., 2020: Sargassum seaweed health menace in the Caribbean: clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding. *Clin Toxicol (Phila)*, 59(3), 215-223, doi:10.1080/15563650.2020.1789162.

Resiere, D., H. Mehdaoui, R. Neviere and B. Megarbane, 2019: Sargassum invasion in the Caribbean: the role of medical and scientific cooperation. *Rev Panam Salud Publica*, 43, e52, doi:10.26633/RPSP.2019.52.

Resiere, D. et al., 2018: Sargassum seaweed on Caribbean islands: an international public health concern. *The Lancet*, 392(10165), doi:10.1016/s0140-6736(18)32777-6.
Rey, T., L. Le De, F. Leone and D. Gilbert, 2017: An integrative approach to understand vulnerability and resilience post-disaster: The 2015 cyclone Pam in urban Vanuatu as a case study. *Disaster Prevention and Management: An International Journal*, 26(3), 259-275, doi:10.1108/dpm-07-2016-0137.
Rey, T. et al., 2019: Coastal Processes and Influence on Damage to Urban Structures during Hurricane Irma (St-Martin & St-Barthélemy, French West Indies). *Journal of Marine Science and Engineering*, 7(215), doi:10.3390/jmse7070215.
Rhiney, K., 2020: Dispossession, disaster capitalism and the post-hurricane context in the Caribbean. *Political Geography*, 78, doi:10.1016/j.polgeo.2020.102171.
Rhiney, K., A. Eitzinger, A. Farrell and S. Prager, 2018: Assessing the implications of a 1.5 °C temperature limit for the Jamaican agriculture sector. *Regional Environmental Change*, 18(8), 2313-2327, doi:10.1007/s10113-018-1409-4.
Richardson, B., M. Richardson and G. González, 2018: Responses of Two Litter-Based Invertebrate Communities to Changes in Canopy Cover in a Forest Subject to Hurricanes. *Forests*, 9(6), doi:10.3390/f9060309.
Roberts, E. and S. Huq, 2015: Coming full circle: the history of loss and damage under the UNFCCC. *International Journal of Global Warming*, 8(2), 141-157.
Robinson, J. P. W., S. K. Wilson, S. Jennings and N. A. J. Graham, 2019: Thermal stress induces persistently altered coral reef fish assemblages. *Global Change Biology*, 25(8), 2739-2750, doi:10.1111/gcb.14704.
Robinson, S., 2017a: Climate change adaptation trends in small island developing states. *Mitigation and Adaptation Strategies for Global Change*, 22(4), 669-691, doi:10.1007/s11027-015-9693-5.
Robinson, S., 2017b: Mainstreaming climate change adaptation in small island developing states. *Climate and Development*, 11(1), 47-59, doi:10.1080/17565529.2017.1410086.
Robinson, S., 2018a: Adapting to climate change at the national level in Caribbean small island developing state. *Island Studies Journal*, 13(1), 79-100, doi:10.24043/isj.59.
Robinson, S., 2018b: Climate change adaptation in small island developing states: Insights and lessons from a meta-paradigmatic study. *Environmental Science & Policy*, 85, 172-181, doi:10.1016/j.envsci.2018.03.030.
Robinson, S. and M. Dornan, 2017: International financing for climate change adaptation in small island developing states. *Regional Environmental Change*, 17(4), 1103-1115.
Robinson, S. and D. Gilfillan, 2016: Regional organisations and climate change adaptation in small island developing states. *Regional Environmental Change*, 17(4), 989-1004, doi:10.1007/s10113-016-0991-6.
Rodriguez, F. et al., 2017: "Canary Islands (NE Atlantic) as a biodiversity 'hotspot' of Gambierdiscus: Implications for future trends of ciguatera in the area". *Harmful Algae*, 67, 131-143, doi:10.1016/j.hal.2017.06.009.
Rogers, K. et al., 2019: Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. *Nature*, 567(7746), 91-95, doi:10.1038/s41586-019-0951-7.
Roland, H. B. and K. J. Curtis, 2020: The differential influence of geographic isolation on environmental migration: a study of internal migration amidst degrading conditions in the central Pacific. *Population and Environment*, 42(2), 161-182, doi:10.1007/s11111-020-00357-3.
Romero-Torres, M. et al., 2020: Coral reef resilience to thermal stress in the Eastern Tropical Pacific. *Global Change Biology*, 26(7), 3880-3890, doi:10.1111/gcb.15126.
Romine, B. and C. Fletcher, 2013: A Summary of Historical Shoreline Changes on Beaches of Kauai, Oahu, and Maui, Hawaii. *Journal of Coastal Research*, 288, 605-614, doi:10.2112/jcoastres-d-11-00202.1.
Rubow, C. and C. Bird, 2016: Eco-theological Responses to Climate Change in Oceania. *Worldviews*, 20(2), 150-168, doi:10.1163/15685357-02002003.
Ruiz, J. M. et al., 2018: Experimental evidence of warming-induced flowering in the Mediterranean seagrass Posidonia oceanica. *Marine Pollution Bulletin*, 134, 49-54, doi:10.1016/j.marpolbul.2017.10.037.
Russell, J. and T. Blackburn, 2017: Invasive Alien Species: Denialism, Disagreement, Definitions, and Dialogue. *Trends in Ecology and Evolution*, 32(5), 312-314, doi:10.1016/j.tree.2017.02.005.
Russell, J., J. Meyer, N. Holmes and S. Pagad, 2017: Invasive alien species on islands: impacts, distribution, interactions and management. *Environmental Conservation*, 44(4), 359-370, doi:10.1017/s0376892917000297.
Ryan, B. et al., 2015: Identifying and Describing the Impact of Cyclone, Storm and Flood Related Disasters on Treatment Management, Care and Exacerbations of Non-communicable Diseases and the Implications for Public Health. *PLoS Currents Disasters*, 7, doi:10.1371/currents.dis.62e9286d152de04799644dcca47d9288.
Sa'adi, Z., S. Shahid, E.-S. Chung and T. b. Ismail, 2017: Projection of spatial and temporal changes of rainfall in Sarawak of Borneo Island using statistical downscaling of CMIP5 models. *Atmospheric Research*, 197, 446-460, doi:10.1016/j.atmosres.2017.08.002.
Saha, C., 2017: Dynamics of climatic and anthropogenic stressors in risking island-char livelihoods: a case of northwestern Bangladesh. *Asian Geographer*, 34(2), 107-129, doi:10.1080/10225706.2017.1354770.
Sainsbury, N. et al., 2018: Changing storminess and global capture fisheries. *Nature Climate Change*, 8(8), 655-659, doi:10.1038/s41558-018-0206-x.
Sainsbury, N. C. et al., 2019: The challenges of extending climate risk insurance to fisheries. *Nature Climate Change*, 9(12), 896-897, doi:10.1038/s41558-019-0645-z.

Saint Ville, A., G. Hickey and L. Phillip, 2015: Addressing food and nutrition insecurity in the Caribbean through domestic smallholder farming system innovation. *Regional Environmental Change*, 15(7), 1325-1339, doi:10.1007/s10113-015-0770-9.
Saintilan, N. et al., 2020: Thresholds of mangrove survival under rapid sea level rise. *Science*, 368, 1118-1121, doi:10.1126/science.aba2656.
Sakhamuri, S. and S. Cummings, 2019: Increasing trans-Atlantic intrusion of Sahara dust: a cause of concern? *The Lancet Planetary Health*, 3(6), e242-e243, doi:10.1016/s2542-5196(19)30088-9.
Salmon, C., V. Duvat and V. Laurent, 2019: Human- and climate-driven shoreline changes on a remote mountainous tropical Pacific Island: Tubuai, French Polynesia. *Anthropocene*, 25, doi:10.1016/j.ancene.2019.100191.
Santos-Burgoa, C. et al., 2018: Differential and persistent risk of excess mortality from Hurricane Maria in Puerto Rico: a time-series analysis. *The Lancet Planetary Health*, 2(11), e478-e488, doi:10.1016/s2542-5196(18)30209-2.
Sasmito, S. D., D. Murdiyarso, D. A. Friess and S. Kurnianto, 2015: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management*, 24(2), 263-278, doi:10.1007/s11273-015-9466-7.
Savage, A., L. McIver and L. Schubert, 2019: Review: the nexus of climate change, food and nutrition security and diet-related non-communicable diseases in Pacific Island Countries and Territories. *Climate and Development*, 12(2), 120-133, doi:10.1080/17565529.2019.1605284.
Saxena, A., K. Qui and S. Robinson, 2018: Knowledge, attitudes and practices of climate adaptation actors towards resilience and transformation in a 1.5°C world. *Environmental Science & Policy*, 80, 152-159, doi:10.1016/j.envsci.2017.11.001.
Scandurra, G., A. Romano, M. Ronghi and A. Carfora, 2018: On the vulnerability of Small Island Developing States: A dynamic analysis. *Ecological Indicators*, 84, 382-392, doi:10.1016/j.ecolind.2017.09.016.
Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proc Natl Acad Sci U S A*, 111(9), 3245-3250, doi:10.1073/pnas.1222460110.
Schipper, E. et al., 2016: Linking disaster risk reduction, climate change and development. *International Journal of Disaster Resilience in the Built Environment*, 7(2), 216-228, doi:10.1108/ijdrbe-03-2015-0014.
Schipper, E. L. F. et al., 2020: Turbulent transformation: abrupt societal disruption and climate resilient development. *Climate and Development*, 13(6), 467-474, doi:10.1080/17565529.2020.1799738.
Schleicher, J., C. A. Peres and N. Leader-Williams, 2019: Conservation performance of tropical protected areas: How important is management? *Conservation Letters*, 12(5), doi:10.1111/conl.12650.
Schnitter, R. et al., 2019: An Assessment of Climate Change and Health Vulnerability and Adaptation in Dominica. *International Journal of Environmental Research and Public Health*, 16(1), doi:10.3390/ijerph16010070.
Schuhmann, P. W. and R. Mahon, 2015: The valuation of marine ecosystem goods and services in the Caribbean: A literature review and framework for future valuation efforts. *Ecosystem Services*, 11, 56-66, doi:10.1016/j.ecoser.2014.07.013.
Schütte, S. et al., 2018: Connecting planetary health, climate change, and migration. *The Lancet Planetary Health*, 2(2), e58-e59, doi:10.1016/s2542-5196(18)30004-4.
Schwebel, M. B., 2017: Gathering at the AOSIS: perceived cooperation among Pacific Small Island States. *International Environmental Agreements: Politics, Law and Economics*, 18(2), 215-228, doi:10.1007/s10784-017-9379-4.
Schweitzer, M. D. et al., 2018: Lung health in era of climate change and dust storms. *Environmental Research*, 163, 36-42, doi:10.1016/j.envres.2018.02.001.
Scobie, M., 2016: Policy coherence in climate governance in Caribbean Small Island Developing States. *Environmental Science & Policy*, 58, 16-28, doi:10.1016/j.envsci.2015.12.008.
Scott, D., C. Hall and S. Gössling, 2019: Global tourism vulnerability to climate change. *Annals of Tourism Research*, 77, 49-61, doi:10.1016/j.annals.2019.05.007.
Seetanah, B. et al., 2019: Impact of Economic and Financial Development on Environmental Degradation: Evidence from Small Island Developing States (SIDS). *Emerging Markets Finance and Trade*, 55(2), 308-322, doi:10.1080/1540496x.2018.1519696.
Settele, J. et al., 2014: Terrestrial and Inland Water Systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, United Kingdom, pp. 271-360. ISBN 9781107415379.
Shah, S., A. Moroca and J. Bhat, 2018: Neo-traditional approaches for ensuring food security in Fiji Islands. *Environmental Development*, 28, 83-100, doi:10.1016/j.envdev.2018.11.001.
Shaig, A., 2008: Settlement planning for natural hazard resilience in small island states: the population and development consolidation approach. James Cook University, Australia.
Shaig, A., 2011: *Survey of Climate Change Adaptation Measure in Maldives*, Ministry of Housing and Environment and United Nationals Development Programme, Maldives.

Shakeela, A. and S. Becken, 2015: Understanding tourism leaders' perceptions of risks from climate change: an assessment of policy-making processes in the Maldives using the social amplification of risk framework (SARF). *Journal of Sustainable Tourism*, 23(1), 65-84, doi:10.1080/09669582.2014.918135.
Sheller, M., 2018: Caribbean Reconstruction and Climate Justice: Transnational Insurgent Intellectual Networks and Post-Hurricane Transformation. *Journal of Extreme Events*, 5(4), 1840001, doi:10.1142/S2345737618400018.
Sheller, M., 2020: Reconstructing tourism in the Caribbean: connecting pandemic recovery, climate resilience and sustainable tourism through mobility justice. *Journal of Sustainable Tourism*, 1-14, doi:10.1080/09669582.2020.1791141.
Shepherd, T., I. Rumengan and A. Sahami, 2018: Post-depositional behaviour of mercury and arsenic in submarine mine tailings deposited in Buyat Bay, North Sulawesi, Indonesia. *Marine Environmental Research*, 137, 88-97, doi:10.1016/j.marenvres.2018.02.028.
Shiels, A., G. González and M. Willig, 2014: Responses to canopy loss and debris deposition in a tropical forest ecosystem: Synthesis from an experimental manipulation simulating effects of hurricane disturbance. *Forest Ecology and Management*, 332, 124-133, doi:10.1016/j.foreco.2014.08.005.
Shope, J. and C. Storlazzi, 2019: Assessing Morphologic Controls on Atoll Island Alongshore Sediment Transport Gradients Due to Future Sea-Level Rise. *Frontiers in Marine Science*, 6, doi:10.3389/fmars.2019.00245.
Shope, J., C. Storlazzi, L. Erikson and C. Hegermiller, 2016: Changes to extreme wave climates of islands within the Western Tropical Pacific throughout the 21st century under RCP 4.5 and RCP 8.5, with implications for island vulnerability and sustainability. *Global and Planetary Change*, 141, 25-38, doi:10.1016/j.gloplacha.2016.03.009.
Shope, J., C. Storlazzi and R. Hoeke, 2017: Projected atoll shoreline and run-up changes in response to sea-level rise and varying large wave conditions at Wake and Midway Atolls, Northwestern Hawaiian Islands. *Geomorphology*, 295, 537-550, doi:10.1016/j.geomorph.2017.08.002.
Short, F. et al., 2016: Impacts of climate change on submerged and emergent wetland plants. *Aquatic Botany*, 135, 3-17, doi:10.1016/j.aquabot.2016.06.006.
Shultz, J. M. et al., 2018: Hurricane Risks, Health Consequences, and Response Challenges for Small island Based Populations: Observations from the 2017 Atlantic Hurricane Season. *Disaster Medicine and Public Health Preparedness*, 13(1), 5-17, doi:10.1017/dmp.2018.28.
Shutter, A., 2020: Barbados Sovereign Debt Restructuring 2018-2019—Like the island, small but perfectly formed. *Capital Markets Law Journal*, 15(2), 250-257, doi:10.1093/cmlj/kmaa006.
Siegel, K. J. et al., 2019: Sovereign states in the Caribbean have lower social-ecological vulnerability to coral bleaching than overseas territories. *Proc Biol Sci*, 286(1897), 20182365, doi:10.1098/rspb.2018.2365.
Singeo, A., 2011: *Teaching Indigenous Knowledge towards Environmental Conservation: A Case Study of Camp Ebiil in Palau*. EIU Best Practices, 22, Asia Pacific Centre of Education for International Understanding, Seoul, South Korea, 47 pp.
Singh-Peterson, L. and M. Iranacolaivalu, 2018: Barriers to market for subsistence farmers in Fiji – A gendered perspective. *Journal of Rural Studies*, 60, 11-20, doi:10.1016/j.jrurstud.2018.03.001.
Sippo, J. Z. et al., 2018: Mangrove mortality in a changing climate: An overview. *Estuarine, Coastal and Shelf Science*, 215, 241-249, doi:10.1016/j.ecss.2018.10.011.
Smith, J. et al., 2017: Malaria early warning tool: linking inter-annual climate and malaria variability in northern Guadalcanal, Solomon Islands. *Malaria Journal*, 16(1), 472, doi:10.1186/s12936-017-2120-5.
Smith, R. and K. Rhiney, 2016: Climate (in)justice, vulnerability and livelihoods in the Caribbean: The case of the indigenous Caribs in northeastern St. Vincent. *Geoforum*, 73, 22-31, doi:10.1016/j.geoforum.2015.11.008.
Smith, S., Environmental Levy Takes Effect September 1, Government of the British Virgin Islands, British Virgin Islands. Available at: https://www.bvitourism.com/news/environmental-levy-takes-effect-september-1.
Smithers, S. and R. Hoeke, 2014: Geomorphological impacts of high-latitude storm waves on low-latitude reef islands — Observations of the December 2008 event on Nukutoa, Takuu, Papua New Guinea. *Geomorphology*, 222, 106-121, doi:10.1016/j.geomorph.2014.03.042.
Sofer, M., 2015: Kadavu Island: adaptation and stagnation in the Fijian periphery. *Miscellanea Geographica*, 19(2), 14-20, doi:10.1515/mgrsd-2015-0006.
Spalding, M. and B. Brown, 2015: Warm-water coral reefs and climate change. *Science*, 350(6262), 769-771, doi:10.1126/science.aad0349.
Spatz, D. et al., 2017a: Globally threatened vertebrates on islands with invasive species. *Science Advances*, 3(e1603080), doi:10.1126/sciadv.1603080.
Spatz, D. R. et al., 2017b: Managing Invasive Mammals to Conserve Globally Threatened Seabirds in a Changing Climate. *Conservation Letters*, 10(6), 736-747, doi:10.1111/conl.12373.
SPC, 2016: *Framework for Resilient Development in the Pacific: An Integrated Approach to Address Climate Change and Disaster Risk Management (FRDP) 2017-2030*.
SPC, 2019: *Policy Brief: Implications of climate-driven redistribution of tuna for Pacific Island economies*. Pacific Community, Noumea, New Caledonia, 4 pp.
SPREP, 2016a: *Pacific Islands Meteorological Services in Action : a compendium of climate services case studies*. SPREP, Samoa.
SPREP, 2016b: *Vanuatu Framework for Climate Services* [Tait, A. and G. Macara (eds.)]. National Institute of Water and Atmospheric Research, New Zealand.

SPREP, 2017: Pacific Roadmap for Strengthening Climate Services 2017-2026.
Springmann, M. et al., 2016: Global and regional health effects of future food production under climate change: a modelling study. *The Lancet*, 387(10031), 1937-1946, doi:10.1016/s0140-6736(15)01156-3.
Stennett-Brown, R., J. Jones, T. Stephenson and M. Taylor, 2017: Future Caribbean temperature and rainfall extremes from statistical downscaling. *International Journal of Climatology*, 37(14), 4828-4845, doi:10.1002/joc.5126.
Stephenson, T. et al., 2014: Changes in extreme temperature and percipitation in the Caribbean region, 1961-2010. *International Journal of Climatology*, 34, 2957-2971, doi:10.1002/joc.3889.
Stojanov, R. et al., 2017: Local perceptions of climate change impacts and migration patterns in Malé, Maldives. *The Geographical Journal*, 183(4), 370-385, doi:10.1111/geoj.12177.
Storey, D. and S. Hunter, 2010: Kiribati: an environmental 'perfect storm'. *Australian Geographer*, 41(2), 167-181, doi:10.1080/00049181003742294.
Storlazzi, C. et al., 2018: Most atolls will be uninhabitable by the mid-21st century because of seal-level rise exacerbating wave-driven flooding. *Science Advances*, 4, eaap9741, doi:10.1126/sciadv.aap9741.
Strauch, A. M. et al., 2014: Climate change and land use drivers of fecal bacteria in tropical hawaiian rivers. *Journal of Environmental Quality*, 43(4), 1475-1483, doi:10.2134/jeq2014.01.0025.
Strauch, A. M., R. A. MacKenzie, C. P. Giardina and G. L. Bruland, 2015: Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system. *Journal of Hydrology*, 523, 160-169, doi:10.1016/j.jhydrol.2015.01.045.
Struebig, M. et al., 2015a: Targeted conservation to safeguard a biodiversity hotspot from climate and land-cover change. *Current Biology*, 25(3), 372-378, doi:10.1016/j.cub.2014.11.067.
Struebig, M. J. et al., 2015b: Anticipated climate and land-cover changes reveal refuge areas for Borneo's orang-utans. *Global Change Biology*, 21(8), 2891-2904, doi:10.1111/gcb.12814.
Suaalii-Sauni, T. and S. Fulu-Aiolupotea, 2014: Decolonising Pacific research, building Pacific research communities and developing Pacific research tools: The case of the talanoa and the faafaletui in Samoa. *Asia Pacific Viewpoint*, 55(3), 331-344, doi:10.1111/apv.12061.
Suliman, S. et al., 2019: Indigenous (im)mobilities in the Anthropocene. *Mobilities*, 14(3), 298-318, doi:10.1080/17450101.2019.1601828.
Sully, S. et al., 2019: A global analysis of coral bleaching over the past two decades. *Nature Communications*, 10(1), 1264, doi:10.1038/s41467-019-09238-2.
Sunday, J. M. et al., 2016: Ocean acidification can mediate biodiversity shifts by changing biogenic habitat. *Nature Climate Change*, 7(1), 81-85, doi:10.1038/nclimate3161.
Tabe, T., 2019: Climate Change Migration and Displacement: Learning from Past Relocations in the Pacific. *Social Sciences*, 8(218), doi:10.3390/socsci8070218.
Taherkhani, M. et al., 2020: Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, 10(1), 6466, doi:10.1038/s41598-020-62188-4.
Taillie, P. et al., 2020: Widespread mangrove damage resulting from the 2017 Atlantic mega hurricane season. *Environmental Research Letters*, 15(064010), doi:10.1088/1748-9326/ab82cf.
Tapsuwan, S. and W. Rongrongmuang, 2015: Climate change perception of the dive tourism industry in Koh Tao island, Thailand. *Journal of Outdoor Recreation and Tourism*, 11, 58-63, doi:10.1016/j.jort.2015.06.005.
Taupo, T., H. Cuffe and I. Noy, 2018: Household vulnerability on the frontline of climate change: the Pacific atoll nation of Tuvalu. *Environmental Economics and Policy Studies*, 20(4), 705-739, doi:10.1007/s10018-018-0212-2.
Tauvale, L. and K. Tsuboki, 2019: Characteristics of Tropical Cyclones in the Southwest Pacific. *Journal of the Meteorological Society of Japan. Ser. II*, 97(3), 711-731, doi:10.2151/jmsj.2019-042.
Taylor, A. and K. Kumar, 2016a: Global Climate Change Impacts on Pacific Islands Terrestrial Biodiversity: a review. *Tropical Conservation Science*, 9(1), 203-223, doi:10.1177/194008291600900111.
Taylor, M. et al., 2018: Future Caribbean Climates in a World of Rising Temperatures: The 1.5 vs 2.0 Dilemma. *Journal of Climate*, 31(7), 2907-2926, doi:10.1175/jcli-d-17-0074.1.
Taylor, N. A. S., J. Y. Lee, S. Kim and S. R. Notley, 2021: Physiological interactions with personal-protective clothing, physically demanding work and global warming: An Asia-Pacific perspective. *Journal of Thermal Biology*, 97, 102858, doi:10.1016/j.jtherbio.2021.102858.
Taylor, S. and L. Kumar, 2016b: Will climate change impact the potential distribution of a native vine (Merremia peltata) which is behaving invasively in the Pacific region? *Ecology and Evolution*, 6(3), 742-754, doi:10.1002/ece3.1915.
Taylor, S. F. W., M. J. Roberts, B. Milligan and R. Ncwadi, 2019: Measurement and implications of marine food security in the Western Indian Ocean: an impending crisis? *Food Security*, 11(6), 1395-1415, doi:10.1007/s12571-019-00971-6.
Techera, E., 2018: Supporting blue economy agenda: fisheries, food security and climate change in the Indian Ocean. *Journal of the Indian Ocean Region*, 14(1), 7-27, doi:10.1080/19480881.2017.1420579.
Terry, J. and T. Chui, 2012: Evaluating the fate of freshwater lenses on atoll islands after eustatic sea-level rise and cyclone-driven inundation: A modelling approach. *Global and Planetary Change*, 88-89, 76-84, doi:10.1016/j.gloplacha.2012.03.008.
Tershy, B. et al., 2015: The Importance of Islands for the Protection of Biological and Linguistic Diversity. *BioScience*, 65(6), doi:10.1093/biosci/biv031.

Teurlai, M. et al., 2015: Socio-economic and Climate Factors Associated with Dengue Fever Spatial Heterogeneity: A Worked Example in New Caledonia. *PLoS Neglected Tropical Diseases*, 9(12), e0004211, doi:10.1371/journal.pntd.0004211.
Thiault, L. et al., 2018: Mapping social-ecological vulnerability to inform local decision making. *Conservation Biology*, 32(2), 447-456, doi:10.1111/cobi.12989.
Thomas, A. and L. Benjamin, 2017: Management of loss and damage in small island developing states: implications for a 1.5 °C or warmer world. *Regional Environmental Change*, 18(8), 2369-2378, doi:10.1007/s10113-017-1184-7.
Thomas, A. and L. Benjamin, 2018a: Perceptions of climate change risk in The Bahamas. *Journal of Environmental Studies and Sciences*, 8(1), 63-72, doi:10.1007/s13412-017-0429-6.
Thomas, A. and L. Benjamin, 2018b: Policies and mechanisms to address climate-induced migration and displacement in Pacific and Caribbean small island developing states. *International Journal of Climate Change Strategies and Management*, 10(1), T86-104, doi:10.1108/IJCCSM-03-2017-0055.
Thomas, A. and L. Benjamin, 2019: Non-economic loss and damage: lessons from displacement in the Caribbean. *Climate Policy*, 1-14, doi:10.1080/14693062.2019.1640105.
Thomas, A., O. Serdeczny and P. Pringle, 2020: Loss and damage research for the global stocktake. *Nature Climate Change*, 10(8), 700-700, doi:10.1038/s41558-020-0807-z.
Thomas, A. et al., 2021: Global evidence of constraints and limits to human adaptation. *Regional Environmental Change*, 21(3), doi:10.1007/s10113-021-01808-9.
Thomson, L., R. Thaman and F. Anna, 2016: Chapter 8: Native forests, plantation forests and trees outside forests: their vulnerability and roles in mitigating and building resilience to climate Change. In: *Vulnerability of Pacific Agriculture and Forestry to Climate Change* [Taylor, M., A. McGregor and B. Dawson (eds.)]. Secretariat of the Pacific Community, New Caledonia, pp. 383-446.
Ticktin, T. et al., 2018: Linkages between measures of biodiversity and community resilience in Pacific Island agroforests. *Conservation Biology*, 32(5), 1085-1095, doi:10.1111/cobi.13152.
Tietze, U. and R. van Anrooy, 2018: *Assessment of insurance needs and opportunities in the Caribbean fisheries sector*. FAO FIsheries and Aquaculture Circular No. 1175, Food and Agriculture Organization of the United Nations, Rome, Italy, 62 pp.
Timm, E., T. Giambelluca and H. Diaz, 2015: Statistical downscaling of rainfall changes in Hawai'i based on the CMIP5 global model projections. *Journal of Geophysical Research: Atmospheres*, 120, 92-112, doi:10.1002/2014JD022059.
Townhill, B. L. et al., 2021: Climate Change Impacts on Atlantic Oceanic Island Tuna Fisheries. *Frontiers in Marine Science*, 8, doi:10.3389/fmars.2021.634280.
Traylor, J. and M. Singhal, 2020: Ciguatera Toxicity. In: *StatPearls [Internet]*. StatPearls Publishing.
Trotman, A. et al., 2017: Chapter 20: Drought Risk Management in the Caribbean Community: Early Warning Information and Other Risk Reduction Considerations. In: *Drought and Water Crises: Integrating science, management, and policy* [Wilhite, D. and R. Pulwarty (eds.)]. Taylor and Francis Group, Boca Raton.
Trotman, A. et al., 2018: Strengthening Climate Services for the Health Sector in the Caribbean. *World Meteorological Organization Bulletin*, 67(2).
Trundle, A., B. Barth and D. McEvoy, 2018: Leveraging endogenous climate resilience: urban adpatation in Pacific Small Island Developing States. *Environment and Urbanization*, 31(1), 53-74, doi:10.1177/0956247818816654.
Tserkezis, E. and A. Tsakanikas, 2016: The economic impact of mining activity on the Greek island of Milos: An unusual neighbor. *The Extractive Industries and Society*, 3(1), 129-140, doi:10.1016/j.exis.2015.10.007.
Tuck, M., P. Kench, M. Ford and G. Masselink, 2019: Physical modelling of the response of reef islands to sea level rise. *Geology*, 47(9), doi:10.1130/G46362.1.
Turner, R., P. McConney and I. Monnereau, 2020: Climate Change Adaptation and Extreme Weather in the Small-Scale Fisheries of Dominica. *Coastal Management*, 48(5), 436-455, doi:10.1080/08920753.2020.1795970.
Umeyama, M., 2012: Shore Protection against Sea Level Rise and Tropical Cyclones in Small Island States. *Natural Hazards Review*, 13(2), 106-116, doi:10.1061/(asce)nh.1527-6996.0000052.
UN, 2015a: *Paris Agreement*. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
UN, 2015b: *Sendai Framework for Disaster Risk Reduction 2015-2030.* Available at: https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf.
UN, 2015c: *Transforming our world: the 2030 Agenda for Sustainable Development.* Available at: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.
UNEP, 2014a: *Emerging issues for Small Island Developing States. Results of the UNEP/UN DESA Foresight Process*. United Nations Environment Programme, Nairobi, Kenya.
UNEP, 2014b: *The importance of mangroves to people: A call to action* [van Bochove, J., E. Sullivan and T. Nakamura (eds.)]. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge. ISBN 978-92-807-3397-6.
Vafeidis, A. et al., 2019: Water-level attenuation in global-scale assessments of exposure to coastal flooding: a sensitivity analysis. *Natural Hazards and Earth System Sciences*, 19(5), 973-984, doi:10.5194/nhess-19-973-2019.
Van Beusekom, A. et al., 2018: Hurricane Maria in the U.S. Caribbean: Disturbance Forces, Variation of Effects, and Implications for Future Storms. *Remote Sensing*, 10(9), doi:10.3390/rs10091386.

van den Burg, M. P., J. L. K. Brisbane and C. R. Knapp, 2020: Post-hurricane relief facilitates invasion and establishment of two invasive alien vertebrate species in the Commonwealth of Dominica, West Indies. *Biological Invasions*, 22(2), 195-203, doi:10.1007/s10530-019-02107-5.
van der Veeken, S. et al., 2016: Tourism destinations' vulnerability to climate change: Nature-based tourism in Vava'u, the Kingdom of Tonga. *Tourism and Hospitality Research*, 16(1), 50-71, doi:10.1177/1467358415611068.
van Hooidonk, R. et al., 2016: Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific Reports*, 6, 39666, doi:10.1038/srep39666.
van Kleunen, M. et al., 2015: Global exchange and accumulation of non-native plants. *Nature*, 525(7567), 100-103, doi:10.1038/nature14910.
van Tussenbroek, B. et al., 2017: Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities. *Marine Pollution Bulletin*, 122(1-2), 272-281, doi:10.1016/j.marpolbul.2017.06.057.
Varela, M. et al., 2019: Assessing climate change associated sea level rise impacts on sea turtle nesting beaches using drones, photogrammetry and a novel GPS system. *Global Change Biology*, 25(2), 753-762, doi:10.1111/gcb.14526.
Varotsos, K. V. et al., 2021: Near future climate change projections with implications for the agricultural sector of three major Mediterranean islands. *Regional Environmental Change*, 21(1), doi:10.1007/s10113-020-01736-0.
Vaughan, C. and S. Dessai, 2014: Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. *WIREs Climate Change*, 5(5), 587-603, doi:10.1002/wcc.290.
Vaughan, C., S. Dessi and C. Hewitt, 2018: Surveying Climate Services: What Can We Learn from a Bird's-Eye View? *Weather, Climate, and Society*, 10, 373-395, doi:10.1175/WCAS-D-17-0030.1.
Veelenturf, C. A., E. M. Sinclair, F. V. Paladino and S. Honarvar, 2020: Predicting the impacts of sea level rise in sea turtle nesting habitat on Bioko Island, Equatorial Guinea. *PLoS One*, 15(7), e0222251, doi:10.1371/journal.pone.0222251.
Vincent, K. and T. Cull, 2014: Using Indicators to Assess Climate Change and Vulnerabilities: Are There Lessons to Lear from Emerging Loss and Damage Debates? *Geography Compass*, 8(1), 1-12, doi:10.1111/gec3.12105.
Virah-Sawmy, M. et al., 2016: A landscape vulnerability framework for identifying integrated conservation and adaptation pathways to climate change: the case of Madagascar's spiny forest. *Landscape Ecology*, 31(3), 637-654, doi:10.1007/s10980-015-0269-2.
Vitousek, S. et al., 2017: Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, 7(1), 1399, doi:10.1038/s41598-017-01362-7.
Vogiatzakis, I., A. Mannion and D. Sarris, 2016: Mediterranean island biodiversity and climate change: the last 10,000 years and the future. *Biodiversity and Conservation*, 25(13), 2597-2627, doi:10.1007/s10531-016-1204-9.
Volz, U. et al., 2020: *Climate Change and Sovereign Risk*. SOAS University of London, Asian Development Bank Institute, World Wide Fund for Nature Singapore, Four Twenty Seven, London, UK.
Vorsino, A. E. et al., 2014: Modeling Hawaiian ecosystem degradation due to invasive plants under current and future climates. *PLoS One*, 9(5), e95427, doi:10.1371/journal.pone.0095427.
Vousdoukas, M. et al., 2020: Sandy coastlines under threat of erosion. *Nature Climate Change*, 10, 260-263, doi:10.1038/s41558-020-0697-0.
Wabnitz, C., A. Cisneros-Montemayor, Q. Hanich and Y. Ota, 2018: Ecotourism, climate change and reef fish consumption in Palau: Benefits, trade-offs and adaptation strategies. *Marine Policy*, 88, 323-332, doi:10.1016/j.marpol.2017.07.022.
Wadey, M., S. Brown, R. Nicholls and I. Haigh, 2017: Coastal flooding in the Maldives: an assessment of historic events and their implications. *Natural Hazards*, 89(1), 131-159, doi:10.1007/s11069-017-2957-5.
Wairiu, M., 2017: Land degradation and sustainable land management practices in Pacific Island Countries. *Regional Environmental Change*, 17(4), 1053-1064, doi:10.1007/s10113-016-1041-0.
Waite, R., L. Burke and E. Gray, 2014: *Coastal Capital: Ecosystem Valuation for Decision Making in the Caribbean*. World Resources Institute, Washington, D.C. Available at: http://www.wri.org/coastal-capital.
Walcker, R. et al., 2019: Damages caused by hurricane irma in the human-degraded mangroves of Saint Martin (Caribbean). *Scientific Reports*, 9(18971), doi:10.1038/s41598-019-55393-3.
Walsh, K. et al., 2016: Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews-Climate Change*, 7(1), 65-89, doi:doi:10.1002/wcc.371.
Wandres, M. et al., 2020: Distant-Source Swells Cause Coastal Inundation on Fiji's Coral Coast. *Frontiers in Marine Science*, 7, doi:10.3389/fmars.2020.00546.
Wang, M. et al., 2019: The great Atlantic Sargassum belt. *Science*, 365, 83-87, doi:10.1126/science.aaw7912.
Warix, S., L. Rademacher and M. Stege, 2017: Groundwater Resource Vulnerability to Climate Change: Outer Atolls of the Republic of the Marshall Islands.
Warren, R. et al., 2018a: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5C rather than 2C. *Science*, 360, 791-795, doi:10.1126/science.aar3646.
Warren, R. et al., 2018b: The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Climatic Change*, 147(3-4), 395-409, doi:10.1007/s10584-018-2158-6.
Warrick, O. et al., 2017: The 'Pacific Adaptive Capacity Analysis Framework': guiding the assessment of adaptive capacity in Pacific island communities. *Regional Environmental Change*, 17(4), 1039-1051, doi:10.1007/s10113-016-1036-x.

Waycott, M. et al., 2009: Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *PNAS*, 106(30), 12377-12381, doi:10.1073/pnas.0905620106.
Waycott, M. et al., 2011: Chapter 6: Vulnerability of mangroves, sesagrasses and intertidal flats in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change.* [Bell, J., J. E. Johnson and A. J. Hobday (eds.)]. Secretariat of the Pacific Community, pp. 297-368.
Weatherdon, L. et al., 2016: Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. *Frontiers in Marine Science*, 3(48), doi:10.3389/fmars.2016.00048.
Webb, A. and P. Kench, 2010: The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change*, 72(3), 234-246, doi:10.1016/j.gloplacha.2010.05.003.
Webb, J. et al., 2015: Tools for CBA: Lessons from NGO Collaboration in Vanuatu. *Coastal Management*, 43(4), 407-423, doi:10.1080/08920753.2015.1046807.
Weber, E., 2016a: Only a pawn in their games? Environmental (?) migration in Kiribati - past, present and future. *Die Erde*, 147(2), 153-164, doi:10.12854/erde-147-11.
Weber, E., 2016b: Trade agreements, labour mobility and climate change in the Pacific Islands. *Regional Environmental Change*, 17(4), 1089-1101, doi:10.1007/s10113-016-1047-7.
Weiler, F., C. Klöck and M. Dornan, 2018: Vulnerability, good governance, or donor interests? The allocation of aid for climate change adaptation. *World Development*, 104, 65-77, doi:10.1016/j.worlddev.2017.11.001.
Weir, T., 2018: Renewable energy in the Pacific Islands: Its role and status. *Renewable and Sustainable Energy Reviews*, 94, 762-771, doi:10.1016/j.rser.2018.05.069.
Weir, T., 2020: Adaptation in Small Islands: Research Themes and Gaps. In: *Managing Cliamte Change Adaptation in the Pacific Region* [Filho, W. L. (ed.)]. Springer, Cham, pp. 45-67.
Weir, T., L. Dovey and D. Orcherton, 2017: Social and cultural issues raised by climate change in Pacific Island countries: an overview. *Regional Environmental Change*, 17(4), 1017-1028, doi:10.1007/s10113-016-1012-5.
Weir, T. and M. Kumar, 2020: Renewable energy can enhance resilience of small islands. *Natural Hazards*, 1-7, doi:10.1007/s11069-020-04266-4.
Weir, T. and J. Pittock, 2017: Human dimensions of environmental change in small island developing states: some common themes. *Regional Environmental Change*, 17(4), 949-958, doi:10.1007/s10113-017-1135-3.
Weissenberger, S., 2018: Haïti: vulnérabilité, résilience et changements climatiques. *Haiti Perspectives*, 6(3), 19-26.
Wetzel, F., H. Beissmann, D. Penn and W. Jetz, 2013: Vulnerability of terrestrial island vertebrates to projected sea-level rise. *Global Change Biology*, 19(7), 2058-2070, doi:10.1111/gcb.12185.
Wetzel, F., W. Kissling, H. Beissmann and D. Penn, 2012: Future climate change driven sea-level rise: secondary consequences from human displacement for island biodiversity. *Global Change Biology*, 18(9), 2707-2719, doi:10.1111/j.1365-2486.2012.02736.x.
WHO, 2015: *Operational framework for building climate resilient health systems*. World Health Organization, Geneva.
WHO, 2018: *Climate change and health in small island developing nations: a WHO special initiative*. World Health Organizations, Geneva.
WHO, 2020: *WHO Guidance for Climate-Resilient and Environmentally Sustainable Health Care Facilities*. Wold Health Organization, Geneva.
Williams, D., S. Rosendo, O. Sadasing and L. Celliers, 2020: Identifying local governance capacity needs for implementing climate change adaptation in Mauritius. *Climate Policy*, 20(5), 548-562, doi:10.1080/14693062.2020.1745743.
Wilson, A. and C. Forsyth, 2018: Restoring near-shore marine ecosystems to enhance climate security for island ocean states: Aligning international processes and local practices. *Marine Policy*, 93, 284-294, doi:10.1016/j.marpol.2018.01.018.
Wilson, K., 2013: Wan laki aelan? Diverse development strategies on Aniwa, Vanuatu. *Asia Pacific Viewpoint*, 54(2), 246-263, doi:10.1111/apv.12012.
Wilson, R., 2017: Impacts of Climate Change on Mangrove Ecosystems in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS). *Caribbean Marine Climate Change Report Card: Science Review 2017.*, 61-82.
WMO, 2014: *Implementation Plan of the Global Framework for Climate Services*. Switzerland.
WMO, 2019: Global Framework for Climate Services (GFCS) Implementation in Dominica. Available at: https://gfcs.wmo.int.
WMO, 2019: Programme for building regional climate capacity in the Caribbean. Available at: https://public.wmo.int/en/projects/program-building-regional-climate-capacity-caribbean.
WMO, 2019: Implementing the Global Framework for Climate Services at Regional and National Scales. Available at: https://public.wmo.int/en/projects/implementing-global-framework-climate-services-gfcs-regional-and-national-scales.
WMO, 2019: Multi-Hazard Early Warning Systems (MHEWS). Available at: https://www.wmo.int/pages/prog/drr/projects/Thematic/MHEWS/MHEWS_en.html.
WMO, 2020: *2020 State of Climate Services: Risk Information and Early Warning Systems*. Available at: https://library.wmo.int/doc_num.php?explnum_id=10385.

WMO, UNDRR and WB, 2018: *Caribbean 2017 Hurricane Season: an evidence-based assessment of the Early Warning System*. WMO, Switzerland. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/2018_wmo_crews-caribbean-report_en.pdf.

Woesik, R. et al., 2012: Climate-change refugia in the sheltered bays of Palau: analogs of future reefs. *Ecology and Evolution*, 2(10), 2474-2484, doi:10.1002/ece3.363.

Wolcott, D., D. Donner, D. Brown and C. Ribic, 2018: Kirtland's Warbler Winter Habitat Changes Across the Bahamian Archipelago in Response to Future Climate-condition Scenarios. *Caribbean Naturalist*, 49, 1-20.

Woodhead, A. et al., 2019: Coral reef ecosystem services in the Anthropocene. *Functional Ecology*, 33, doi:10.1111/1365-2435.13331.

World Bank, 2016: *Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs.*, Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES), World Bank, Washington, D.C.

Yamano, H. et al., 2007: Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. *Global and Planetary Change*, 57(3-4), 407-416, doi:10.1016/j.gloplacha.2007.02.007.

Yang, Z., T. Wang, N. Voisin and A. Copping, 2015: Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuarine, Coastal and Shelf Science*, 156, 19-30, doi:10.1016/j.ecss.2014.08.015.

Yoshida, K. et al., 2017: Future Changes in Tropical Cyclone Activity in High-Resolution Large-Ensemble Simulations. *Geophysical Research Letters*, 44(19), 9910-9917, doi:10.1002/2017gl075058.

Zahid, A. et al., 2018: Chapter 32: Model Impact of Climate Change on the Groundwater Flow and Salinity Encroachment in the Coastal Areas of Bangladesh. In: *Groundwater of South Asia* [Mukherjee, A. (ed.)]. Springer Hydrogeography, pp. 545-568. ISBN 978-981-10-3888-4.

Zheng, L. et al., 2020: Modeling the time-lag effect of sea surface temperatures on ciguatera poisoning in the South Pacific: Implications for surveillance and response. *Toxicon*, 182, 21-29, doi:10.1016/j.toxicon.2020.05.001.

Chapter 16: Key Risks Across Sectors and Regions

Coordinating Lead Authors: Brian O'Neill (USA), Maarten van Aalst (The Netherlands), Zelina Zaiton Ibrahim (Malaysia)

Lead Authors: Lea Berrang Ford (United Kingdom/Canada), Suruchi Bhadwal (India), Halvard Buhaug (Norway), Delavane Diaz (USA), Katja Frieler (Germany), Matthias Garschagen (Germany), Alexandre Magnan (France), Guy Midgley (South Africa), Alisher Mirzabaev (Uzbekistan/Germany), Adelle Thomas (Bahamas), Rachel Warren (United Kingdom)

Contributing Authors: Sharina Abdul Halim (Malaysia), Idowu Ajibade (Nigeria/Canada/USA), Philip Antwi-Agyei (Ghana), Richard Betts (United Kingdom), Rachel Bezner Kerr (USA), Joern Birkmann (Germany), Martina Angela Caretta (USA), Tamma Carleton (USA), Connor Cavanagh (Ireland/Norway), Winston Chow (Singapore), Gueladio Cisse (Mauritania/ Switzerland/France), Andrew Constable (Australia), Mark Costello (New Zealand), Jackie Dawson (Canada), Richard Dawson (United Kingdom), Simon Donner (Canada), Sybren Drijfhout (The Netherlands), Virginie K.E. Duvat (France), Kristie Ebi (USA), Tamsin Edwards (United Kingdom), Francois Engelbrecht (South Africa), Alexandra Paige Fischer (USA), Isabel Fletcher (United Kingdom), James Ford (United Kingdom), Eranga Galappaththi (Sri Lanka/Canada), Francois Gemenne (Belgium), Patrick Gonzalez (USA), Neal Haddaway (Sweden/Germany/United Kingdom), Isabel Hagen (Switzerland), Stephane Hallegatte (France/USA), Toshihiro Hasegawa (Japan), Masahiro Hashizume (Japan), Cullen Hendrix (USA), Kevin Hennessy (Australia), Tom Hertel (USA), Jeremy Hess (USA), Helene Hewitt (United Kingdom), Kirstin Holsman (USA), Veronika Huber (Germany/Spain), Christian Huggel (Switzerland), Bramka Jafino (Indonesia/The Netherlands), Kripa Jagannathan (Canada/India/USA), Rhosanna Jenkins (United Kingdom), Chris Jones (United Kingdom), Vhalinavho Khavhagali (South Africa), Elco Koks (The Netherlands), Gerhard Krinner (France), Judy Lawrence (New Zealand), Gonéri Le Cozannet (France), Alexandra Lesnikowski (Canada), Karen Levy (USA), Tabea Lissner (Germany), Rachel Lowe (United Kingdom), Simone Lucatello (Mexico), Yong Luo (China), Brendan Mackey (Australia), Shobha Maharaj (Germany/Trinidad and Tobago), Custodio Matavel (Mozambique/Germany), Timon McPhearson (USA), Veruska Muccione (Switzerland), Aditi Mukherji (India), Didacus Namanya (Uganda), Gerald Nelson (USA), David Obura (Kenya), Jean Ometto (Brazil), Friederike Otto (United Kingdom/Germany), Camille Parmesan (United Kingdom/USA), Patricia Pinho (Brazil/United Kingdom), Franziska Piontek (Germany), Prajal Pradhan (Nepal/Germany), Jeff Price (United Kingdom), Joacim Rocklov (Sweden), Steven Rose (USA), Alexander Ruane (USA), Daniela Schmidt (Germany/United Kingdom), Alcade Segnon (Republic of Benin), Sonia Seneviratne (Switzerland), Olivia Serdeczny (Poland/Germany), Mohammad Aminur Rahman Shah (Bangladesh/United Kingdom), Yuanyuan Shang (China/Australia), Roopam Shukla (India/Germany), AR Siders (USA), Nicholas P. Simpson (Zimbabwe/South Africa), Chandi Singh (India), Asha Sitati (Kenya), Tom Spencer (United Kingdom), Nicola Stevens (South Africa), Emily Theokritoff (Germany), Maria Cristina Tirado-von der Pahlen (Spain/USA), Christopher Trisos (South Africa), Nicola Ulibarri (USA), Mariana Vale (Brazil), Krispa Vasant (India), Ana Vicedo-Carbrera (Spain/Switzerland), Colette Wabnitz (Canada), Anita Wreford (New Zealand), Gary Yohe (USA), Carol Zavaleta (Peru), Xuebin Zhang (Canada), Zhibin Zhang (China)

Review Editors: Tong Jiang (China), Michael Oppenheimer (USA)

Chapter Scientist: Rhosanna Jenkins (United Kingdom)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Introduction and framing

This chapter synthesizes observed climate change impacts (16.2), adaptation-related responses (16.3), limits to adaptation (16.4), and the key risks identified across sectors and regions (16.5). We consider how these risks accrue with increasing global average temperature; how they depend on future development and adaptation efforts; and what this implies for the Sustainable Development Goals and the five main Reasons for Concern about climate change (16.6).

Observed impacts

The impacts of changes in climate-related systems have been identified in a wide range of natural, human, and managed systems (*very high confidence*[1]). Compared to the last IPCC AR5 there is more evidence for impacts of long-term changes in climate-related systems (including the atmosphere, ocean and cryosphere) on socio-economic indicators and *high confidence* in the sensitivity of societies to weather conditions. There is also stronger evidence for impacts of long-term climate change on ecosystems, including the observed widespread mortality of warm water corals, far reaching shifts in phenology in marine and terrestrial ecosystems and the expansion of tropical species into the ranges of temperate species, and boreal species moving into Arctic regions (*high confidence*). {16.2.3, 16.2.3.1}

Increased rainfall intensity associated with tropical cyclones and rising sea levels have contributed to observed damages in local coastal systems (*medium confidence*). However, while the impact is expected to be widespread, formal attribution of damages to long term changes in the climate-related systems is still limited by restricted knowledge about changes in exposure and vulnerability and the missing quantification of the contribution of sea level rise to the extent of flooded areas. {16.2.3.3}

Due to complex interactions with socio-economic conditions, evidence on the impact of long-term climate change on crop prices and malnutrition is largely lacking while the sensitivity of malnutrition to weather conditions has become more evident in some regions, particularly Africa (*medium to high confidence*). A negative impact of long-term climate change on crop yields has been identified in some regions (e.g., wheat yields in Europe) (*medium confidence*) while studies are still inconsistent in other regions. {16.2.3.4}

Climate change has increased observed heat-related mortality (*medium confidence*) and contributed to the observed latitudinal or altitudinal range expansion of vector- borne diseases into previously colder areas (*medium to high confidence*) while evidence on the impact of long-term climate change on water-borne diseases is largely lacking. Overall, there is extensive observational evidence that extreme ambient temperatures increase human mortality (*high confidence*) and that the occurrence of water- and vector-borne diseases is sensitive to weather conditions (*high confidence*). {16.2.3.5, 16.2.3.6, 16.2.3.7}

Extreme weather events not only cause substantial direct economic damage (*high confidence*), but also reduce economic growth in the short-term (year of, and year after event) (*high confidence*) as well as in the long-term (up to 15 years after the event) (*medium confidence*), with more severe impacts in developing than in industrialized economies (*high confidence*). Evidence has increased for all of these conclusions; however, evidence for impacts of long-term climate change is still limited. {16.2.3.7}

Climate variability and extremes are associated with increased prevalence of conflict, with more consistent evidence for low-intensity organized violence than for major armed conflict (*medium confidence*). Compared to other socio-economic drivers, the link is relatively weak (*medium confidence*) and conditional on high population size, low socioeconomic development, high political marginalization, and high agricultural dependence (*medium confidence*). Literature also suggests a larger climate-related influence

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

on the dynamics of conflict than on the likelihood of initial conflict outbreak (*low confidence*). There is insufficient evidence at present to attribute armed conflict to climate change. {16.2.3.8}

There is high confidence that anthropogenic climate forcing has had an impact on internal displacement, given the observed impact of anthropogenic climate forcing on the occurrence of weather extremes (*high confidence*, Table SM16.21) and the strong contribution of weather extremes to observed displacement (*high confidence*). However, the link between long-term changes in the climate-related systems has not been demonstrated systematically and so far there is no attribution of observed trends in displacement to long-term changes in the climate-related systems. Links between weather fluctuations (including extreme events) and human mobility are complex and conditional on socio-economic situations; e.g., poor populations may more often be involuntarily displaced or 'trapped' and not be able to migrate. {16.2.3.9}

Observed adaptation in ecosystems

While species are increasingly responding to climate change, these responses may not be adaptive or sufficient to cope with the rate of climate changes (*high confidence*). Responses have been documented in a range of species, including for example changes in the timing of breeding and migration. It is unclear whether these responses reflect long-term evolutionary adaptation or short-term coping mechanisms. Existing assessments indicate that some species' responses will be insufficient to avert extinction. {16.3.1}

Observed adaptation-related responses in human systems

Responses across all sectors and regions reported in the scientific literature are dominated by minor modifications to usual practices or measures for dealing with extreme weather events, whilst evidence of transformative adaptation in human systems is low (*high confidence*). Responses have accelerated in both developed and developing regions since AR5, with some examples of regression. Despite this, there is negligible evidence in the scientific literature documenting responses that are simultaneously widespread, rapid, and that challenge norms and adaptation limits. {16.3.2.3}

There is negligible evidence that existing responses are adequate to reduce climate risk (*high confidence*). There is some evidence of global vulnerability reduction, particularly for mortality and economic losses due to flood risk and extreme heat. (16.3.2.4) Evidence on the effectiveness of specific adaptations remains limited. There is negligible robust evidence to assess the overall adequacy of the global adaptation response to address the scale of climate risk. No studies have systematically assessed the adequacy and effectiveness of adaptation at a global scale, across nations or sectors, or for different levels of warming. {16.3.2.3}

Adaptation responses are showing co-benefits, for mitigation and other societal goals (*high confidence*). There is increasing evidence of co-benefits of adaptation responses. Co-benefits are most frequently linked to changes in agricultural practices (e.g., conservation agriculture), land use management (e.g., agroforestry), building technologies (e.g., building efficiency standards), and urban design (e.g., walkable neighbourhoods). {16.3.2.3}

Evidence of maladaptation is increasing (*high confidence*), i.e. adaptation that increases climate risk or creates new risks in other systems or for other actors. Globally, maladaptation has been reported most frequently in the context of agriculture and migration in the global south. {16.3.2.6}

Limits to adaptation across natural and human systems

There is increasing evidence on limits to adaptation which result from the interaction of adaptation constraints and can be differentiated into soft and hard limits (*high confidence*). Soft limits may change over time as additional adaptation options become available. Hard limits will not change over time as no additional adaptive actions are possible. Evidence focuses on constraints that may lead to limits at some point of the adaptation process, with less information on how limits may be related to different levels of socio-economic or climatic change (*high confidence*). {16.4.1, 16.4.2, 16.4.3}

Limits to adaptation have been identified for terrestrial and aquatic species and ecosystems, coastal communities, water security, agricultural production, and human health and heat (*high confidence*). Beginning at 1.5°C, autonomous and evolutionary adaptation responses by terrestrial and aquatic species and ecosystems face hard limits, resulting in biodiversity decline, species extinction and loss of related livelihoods (*high confidence*). Beginning at 3°C, hard limits are projected for water management measures, leading to decreased water quality and availability, negative impacts on health and wellbeing, economic losses in water and energy dependent sectors and potential migration of communities (*medium confidence*). Adaptation to address risks of heat stress, heat mortality and reduced capacities for outdoor work for humans face soft and hard limits across regions beginning at 1.5°C, and are particularly relevant for regions with warm climates (*high confidence*). {16.4.2, 16.4.3}

Soft limits are currently being experienced by individuals and households along the coast and by small-scale farmers (*medium confidence*). As sea levels rise and extreme events intensify, coastal communities face soft limits due to financial, institutional and socio-economic constraints reducing the efficacy of coastal protection and accommodation approaches and resulting in loss of life and economic damages (*medium confidence*). {16.4.2, 16.4.3}

Hard limits for coastal communities reliant on nature-based coastal protection will be experienced beginning at 1.5°C (*medium confidence*). Soft and hard limits for agricultural production are related to water availability and the uptake and effectiveness of climate-resilient crops which are constrained by socio-economic and political challenges (*medium confidence*). {16.4.2, 16.4.3}

Across regions and sectors, the most significant determinants of soft limits are financial, governance, institutional and policy constraints (*high confidence*). The ability of actors to overcome these socio-economic constraints largely influence whether additional adaptation is able to be implemented and prevent soft limits from becoming hard. While the rate, extent and timing of climate hazards largely determine hard limits of biophysical systems, these factors appear to be less influential in determining soft limits for human systems (*medium confidence*). {16.4.2, 16.4.3}

Financial constraints are important determinants of limits to adaptation, particularly in low-to-middle income countries (*high confidence*). Impacts of climate change may increase financial constraints (*high confidence*) and contribute to soft limits to adaptation being reached (*medium confidence*). Global and regional evidence shows that climate impacts may limit the availability of financial resources, stunt national economic growth, result in higher levels of losses and damages and thereby increase financial constraints. {16.4.3.2, 16.4.3.3}

Key risks across climate and development pathways

Regional and sectoral chapters of this report identified over 130 Key Risks (KRs) that could become severe under particular conditions of climate hazards, exposure, and vulnerability. These key risk are represented in eight so-called Representative Key Risks (RKRs) clusters of key risks relating to low-lying coastal systems; terrestrial and ocean ecosystems; critical physical infrastructure, networks and services; living standards; human health; food security; water security; and peace and mobility (*high confidence*). A key risk is defined as a potentially 'severe' risk, i.e. that is relevant to the interpretation of dangerous anthropogenic interference (DAI) with the climate system. Key risks cover scales from the local to the global, are especially prominent in particular regions or systems, and are particularly large for vulnerable subgroups, especially low-income populations, and already at-risk ecosystems (*high confidence*). The conditions under which RKRs would become severe have been assessed along levels for warming, exposure/vulnerability, and adaptation: for warming, high refers to climate outcomes consistent with RCP8.5 or higher, low refers to climate outcomes consistent with RCP2.6 or lower, and medium refers to intermediary climate scenarios; exposure/vulnerability levels are relative to the range of future conditions considered in the literature; for adaptation, high refers to near maximum potential and low refers to the continuation of today's trends. (6.5.2.1, 16.5.2.2, Table SM16.4).

For most Representative Key Risks (RKRs), potentially global and systemically pervasive risks become severe in the case of high warming, combined with high exposure/vulnerability, low adaptation, or both (*high confidence*). Under these conditions there would be severe and pervasive risks to

critical infrastructure and to human health from heat-related mortality (*high confidence*), to low-lying coastal areas, aggregate economic output, and livelihoods (all *medium confidence*), of armed conflict (*low confidence),* and to various aspects of food security (with different levels of confidence). Severe risks interact through cascading effects, potentially causing amplification of RKRs over the course of this century (*low evidence, high agreement*). {16.5.2.3, 16.5.2.4, 16.5.4, Figure 16.10}
For some RKRs, potentially global and systemically pervasive risks would become severe even with medium to low warming (i.e. 1.5-2°C) if exposure/vulnerability is high and/or adaptation is low (*medium to high confidence*). Under these conditions there would be severe and pervasive risks associated with water scarcity and water-related disasters (*high confidence*), poverty, involuntary mobility, and insular ecosystems and biodiversity hotspots (all *medium confidence*). {16.5.2.3, 16.5.2.4}

All potentially severe risks that apply to particular sectors or groups of people at more specific regional and local levels require high exposure/vulnerability or low adaptation (or both), but do not necessarily require high warming (*high confidence*). Under these conditions there would be severe, specific risks to low-lying coastal systems, to people and economies from critical infrastructure disruption, economic output in developing countries, livelihoods in climate-sensitive sectors, waterborne diseases especially in children in low- and middle-income countries, water-related impacts on traditional ways of life, and involuntary mobility for example in small islands and low-lying coastal areas (*medium to high confidence*). {16.5.2.3, 16.5.2.4}

Some severe impacts are already occurring (*high confidence*) and will occur in many more systems before mid-century (*medium confidence*). Tropical and polar low-lying coastal human communities are experiencing severe impacts today (*high confidence*), and abrupt ecological changes resulting from mass population-level mortality are already observed following climate extreme events. Some systems will experience severe risks before the end of the century (*medium confidence*), for example critical infrastructure affected by extreme events (*medium confidence*). Food security for millions of people, particularly low-income populations, also faces significant risks with moderate to high warming or high vulnerability, with a growing challenge by 2050 in terms of providing nutritious and affordable diets (*high confidence*). {16.5.2.3, 16.5.3}

In specific systems already marked by high exposure and vulnerability, high adaptation efforts will not be sufficient to prevent severe risks from occurring under high warming (*low evidence, medium agreement*). This is particularly the case for some ecosystems and water-related risks (from water scarcity and to indigenous and traditional cultures and ways of life). {16.5.2.3, 16.5.2.4, 16.5.3}

Interconnectedness and globalization establish pathways for the transmission of climate-related risks across sectors and borders, for instance through trade, finance, food, and ecosystems (*high confidence*). Examples include semiconductors, global investments, major food crops like wheat, maize and soybean, and transboundary fish stocks. There are knowledge gaps on the need for, effectiveness of, and limits to adaptation to such interregional risks {Cross-Chapter Box INTERREG in this Chapter}

Key risks increase the challenges in achieving global sustainability goals (*high confidence*). The greatest challenges will be from risks to water (RKR-G), living standards (RKR-D), coastal socio-ecological systems (RKR-A) and peace and human mobility (RKR-H). The most relevant goals are Zero hunger (SDG2), Sustainable cities and communities (SDG11), Life below water (SDG14), Decent work and economic growth (SDG8), and No poverty (SDG1). Priority areas for regions are indicated by the intersection of hazards, risks and challenges, where, in the near term, challenges to SDGs indicate probable systemic vulnerabilities and issues in responding to climatic hazards. (*high confidence*) {16.6.1}

The scale and nature of climate risks is partly determined by the responses to climate change, not only in how they reduce risk, but also how they may create other risks (sometimes inadvertently, and sometimes to others than those who implement the response, in other places, or later in time).

Solar Radiation Modification (SRM) approaches have potential to offset warming and ameliorate other climate hazards, but their potential to reduce risk or introduce novel risks to people and ecosystems is not well understood (*high confidence*). SRM effects on climate hazards are highly dependent on deployment scenarios and substantial residual climate change or overcompensating change would occur at regional scales and seasonal timescales (*high confidence*). Due in part to limited research, there is low confidence in projected benefits or risks to crop yields, economies, human health, or ecosystems. Large negative impacts are projected from rapid warming for a sudden and sustained termination of SRM in a high-CO2 scenario. SRM would not stop CO2 from increasing in the atmosphere or reduce resulting ocean acidification under continued anthropogenic emissions (*high confidence*). There is high agreement in the literature that for addressing climate change risks SRM is, at best, a supplement to achieving sustained net zero or net negative CO2 emission levels globally. Co-evolution of SRM governance and research provides a chance for responsibly developing SRM technologies with broader public participation and political legitimacy, guarding against potential risks and harms relevant across a full range of scenarios. [Cross-Working Group Box SRM}

Recent global estimates of the economic cost of climate impacts exhibit significant spread and generally increase with global average temperature, as well as vary by other drivers, such as income, population and composition of the economy (*high confidence*). The wide variation across disparate methodologies does not allow a robust range of damage estimates to be identified with confidence, though the spread of estimates increases with warming in all methodologies, indicating higher risk (in terms of economic costs) at higher temperatures (*high confidence*). Reconciling methodological variance is a priority for facilitating use of different lines of evidence; however, that some new estimates are higher than the AR5 range indicates that global aggregate economic impacts could be higher than previously assessed (low confidence due to the lack of robustness and comparability across methodologies). {Cross-Working Group Box ECONOMIC in Chapter 16}

Reasons for Concern across scales

The five major Reasons for Concern (RFCs), describing risks associated with (1) unique and threatened systems, (2) extreme weather events, (3) distribution of impacts, (4) global aggregate impacts, and (5) large-scale singular events, were updated using expert elicitation. RFC risk levels were assessed with no or low adaptation, but limits to adaptation are a factor in the identification of very high risk levels.

Compared to AR5 and SR15, risks increase to high and very high levels at lower global warming levels for all five RFCs (*high confidence*), and transition ranges are assigned with greater confidence. Transitions from high to very high risk emerge in all five RFCs, compared to just two RFCs in AR5 (*high confidence*). {16.6.3, Figure 16.15}

- For unique and threatened systems (RFC1), as before, levels of risk at a given level of warming are higher than for the other RFCs. Risks are already (at current warming of 1.1ºC) in the transition from moderate to high (*very high confidence*), compared to moderate in AR5 and SR15, based on observed and modelled impacts. The transition to very high risk occurs between 1.2ºC and 2.0ºC warming *(high confidence)*. {16.6.3.1}

- For risks from extremes (RFC2), the transition to high risk is between 1.0ºC and 1.5ºC (high confidence) and to very high risk (new in AR6) between 1.8 and 2.5ºC (*medium confidence*). {16.6.3.2}

- For risks disproportionately affecting particularly vulnerable societies and socio-ecological systems, including disadvantaged people and communities in countries at all levels of development (RFC3), current risk is moderate (*high confidence*) and the transition to high risk is between 1.5–2.0ºC warming (*medium confidence)*. The transition to very high risk occurs at between 2.0–3.5ºC warming (*medium confidence*). {16.6.3.3}

- The risk of global aggregate impacts, including monetary damages, lives affected, species lost or ecosystem degradation at a global scale (RFC4), has begun to transition to moderate risk (*medium confidence*), with a transition to high risk between 1.5–2.5ºC (*medium confidence*) and to very high risk (new in AR6) at between 2.5 and 4.5ºC (*low confidence*). {16.6.3.4}

- Present-day risks associated with large-scale singular events (sometimes called tipping points or critical thresholds) (RFC5) are already moderate (*high confidence*), with a transition to high risk between

1.5–2.5ºC (*medium confidence*) and to very high risk (new in AR6) between 2.5–4ºC (*low confidence*). {16.6.3.5}

Limiting global warming to 1.5ºC would ensure risk levels remain moderate for RFC3, RFC4 and RFC5 (*medium confidence*) but risk for RFC2 would have transitioned to a high risk at 1.5ºC and RFC1 would be well into the transition to very high risk (*high confidence*). Remaining below 2ºC warming (but above 1.5ºC) would imply that risk for RFC3 through 5 would be transitioning to high, and risk for RFC1 and RFC2 would be transitioning to very high (*high confidence*). By 2.5ºC warming, RFC1 will be in very high risk (*high confidence*) and all other RFCs will have begun their transitions to very high risk (medium confidence for RFC2 and RFC3, low confidence for RFC4 and RFC5).

RFC1, RFC2 and RFC5 include risks that are irreversible, such as species extinction, coral reef degradation, loss of cultural heritage, or loss of a small island due to sea level rise. Once such risks materialise, as is expected at very high risk levels, the impacts would persist even if global temperatures would subsequently decline to levels associated with lower levels of risk in an 'overshooting' scenario (*high confidence*). {16.6.3}

16.1 Introduction and Framing

16.1.1 Objective of the Chapter

Anthropogenic climate change poses risks to many human and ecological systems. These risks are increasingly visible in our day-to-day lives, including a growing number of disasters that already bear a fingerprint of climate change. There is increasing concern about how these risks will shape the future of our planet – our ecosystems, our well-being and development opportunities. Policy makers are asking what is known about the risks, and what can be done about them. Many people and especially youth around the world are calling for urgency, ambition and action. Companies are wondering how to manage new threats to their bottom line, or how to grasp new opportunities. On top of this growing concern about climate change, the COVID-19 pandemic has exposed vulnerabilities to shocks, significantly aggravated climate-related risks, and posed new questions about how to achieve a green, resilient and inclusive recovery (see Cross-Chapter Box COVID in Chapter 7).

The three synthesis chapters of this report (16, 17 and 18) aim to address these concerns. They synthesize information from across all thematic and regional Chapters of the Working Group (WGII) Sixth Assessment Report (AR6) and the recent IPCC Special Reports on Global Warming of 1.5ºC, on Climate Change and Land, and on Ocean and Cryosphere in a Changing Climate (SR15, SRCCL and SROCC), but also include an independent assessment of the literature, especially literature that cuts across sectors and regions.

Chapter 16 lays the groundwork by synthesizing the state of knowledge on the observed impacts of climate change (Section 16.2) and ongoing adaptation responses (Section 16.3), the limits to adaptation (Section 16.4), and the key risks we should be concerned about, how these risks evolve with global temperature change, and also how they depend on future development and adaptation efforts (Sections 16.5 and 16.6). It thus brings together elements that were assessed in different chapters in previous assessments, especially the Third, Fourth and Fifth Assessment Reports (TAR, AR4, and AR5, respectively). Background on specific methodological aspects of this chapter is provided in Supplementary Material..

The strong link between risks, adaptation and development connects this chapter closely to Chapters 17 and 18. Chapter 17 assesses decision-making: what do we know about the ways to manage risks in a warming climate (including in the context of the key risks and limits to adaptation identified in this chapter)? Chapter 18 puts all of this information into the perspective of climate-resilient development pathways: how can we achieve sustainable development given the additional challenges posed by climate change?

16.1.2 Risk Framing

In the IPCC AR6, 'risk' is defined as the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species (Chapter 1 this volume, SR15). The AR6 definition explicitly notes that 'risks can arise from potential impacts of climate change as well as human responses to climate change.'

The main risks assessed here relate to the potential *impacts* of climate change. In recent years, the growing visibility of current climate impacts has resulted in a stronger focus on understanding and managing such risk across timescales, rather than just for the longer-term future. Examples include the rapid growth in attribution of specific extreme weather events, the use of scientific evidence of climate change impacts in legal cases, the context of the Paris Agreement's Article 8 on 'averting, minimizing and addressing loss and damage' associated with climate change, but also the stronger links between adaptation and disaster risk reduction, including early warning systems, wider discussions on how to build resilience in the face of a more volatile climate, and attention for limits to adaptation that are already being reached.

Of course the scale of these risks is also determined by the *responses* to climate change, mainly in how they reduce risk, but also how they may create risks (sometimes inadvertently, and sometimes to others than those who implement the response, in other places, or later in time). Our focus is on adaptation responses, given that mitigation is covered in WGIII AR6, but we acknowledge certain important interactions, such as biomass-production as an alternative to fossil fuels which can compete with food production and thus aggravate adaptation challenges. Given that solar radiation modification (SRM) could also be considered a response with significant implications for climate risks across scales, this chapter also includes Cross-Working Group Box SRM.

This assessment focuses primarily on *adverse* consequences of climate change. However, climate change also has *positive* implications (benefits and opportunities) for certain people and systems, although there are gaps in the literature on these positive effects. Some risks assessed in this chapter are actually about a balance between positive and negative effects of climate change (and of response options, especially adaptation). In those contexts, we assess the combined effect of both, aiming to identify not only the aggregate impacts (the balance between positive and negative effects) but also the distributional aspects (winners and losers). A more comprehensive discussion of the decision-making related to such trade-offs in relation to adaptation is provided in Chapter 17.

This chapter's assessment takes a global perspective, although many risks and responses materialise at the local or national scale. We use case studies to illustrate the ways these risks aggregate across scales, again with particular concern for distributional aspects.

16.1.3 Storyline of the Chapter, and What's New Compared to Previous Assessments

Figure 16.1 illustrates the elements covered by the chapter, which can be summarised as four key questions.

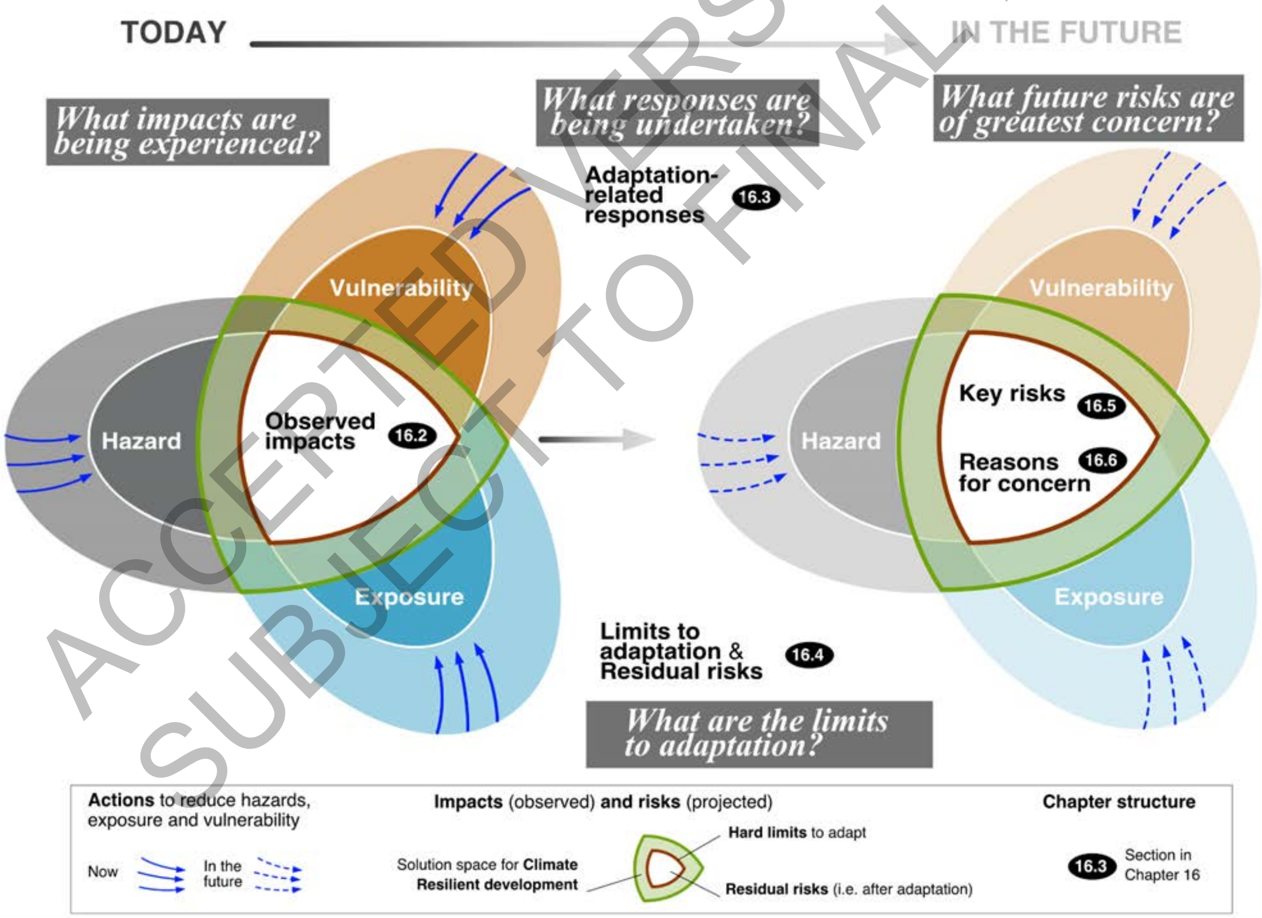


Figure 16.1. Illustrative storyline of the chapter highlighting the central questions addressed in the various sections, going from realized risks (observed impacts) to future risks (key risks and reasons for concern), informed by adaptation-related responses and the limits to adaptation. The pink arrows illustrate actions to reduce hazard, exposure and vulnerability, which shape risks over time. Accordingly, the green areas at the centre of the propeller diagrams indicate the ability for such solutions to reduce risk, up to certain adaptation limits, leaving the white residual risk (or observed impacts) in the centre. The shading of the right-hand side propeller diagram compared to the non-shaded one on the left reflects some degree of uncertainty about future risks. The figure builds on the conceptual framework of risk-adaptation-relationships used in SROCC (Garschagen et al., 2019).

16.1.3.1 What Impacts are Being Experienced?

This assessment of climate related impacts that are already taking place is covered in Section 16.2, which aims to differentiate between observed changes in climate hazards (also called 'climate impact drivers' in IPCC Working Group I) and the exposure and vulnerability of human and ecological systems.

Observed impacts of climate change were synthesized in the TAR, AR4 and AR5. The TAR found that recent regional climate changes had already affected many physical and biological systems, with preliminary indications that some human systems had been affected, primarily through floods and droughts. AR4 found *likely*[2] discernible impacts on many physical and biological systems, and more limited evidence for impacts on human environments. AR5 devoted a separate chapter to observed impacts, which found growing evidence of impacts on human and ecological systems on all continents and across oceans (Cramer et al., 2014).

Section 16.2 reports on the expanded literature since then, generally reflecting a growing and more certain impact of climate change on humans and ecological systems.

16.1.3.2 What Responses are Being Undertaken?

Section 16.3 provides, for the first time, a comprehensive synthesis of observed adaptation-related responses to the rising risks.

Such adaptation responses were first covered in the TAR, and further developed in the AR4 and AR5. For instance, AR5 Chapter 15 notes that adaptation to climate change was transitioning from a phase of awareness to the construction of actual strategies and plans in societies (Mimura et al., 2014) but did not include a comprehensive mapping of responses.

Based on such a comprehensive mapping, Section 16.3 finds growing evidence of adaptation-related responses, although these are dominated by minor modifications to usual practices or measures for dealing with extreme weather events, and there is limited evidence for the extent to which they reduce climate risk.

16.1.3.3 What are the Limits to Adaptation?

The literature on limits to adaptation, which is covered in Section 16.4, has strongly evolved since AR5, including links to discussions on Loss and Damage in the UNFCCC. While the SPM of AR4 noted that there was no clear picture of the limits to adaptation, or the cost, AR5 Chapter 16 (Klein et al., 2014) reported increasing insights emerging from the interactions between climate change and biophysical and socioeconomic constraints, and highlighted the fact that limits could be both hard and soft. It also noted that residual losses and damages will occur from climate change despite adaptation and mitigation action. However, AR5 Chapter 16 still found that the empirical evidence needed to identify limits to adaptation of specific sectors, regions, ecosystems, or species that can be avoided with different GHG mitigation pathways was lacking.

Section 16.4 provides a more comprehensive assessment of limits to adaptation, highlighting again that limits to adaptation are not fixed, but are properties of dynamic socio-ecological systems. They are shaped not only by the magnitude of the climate hazards (e.g., the amount of sea level rise in low lying coasts and islands), and the exposure and vulnerability to those hazards (e.g., people and assets in those areas), but also by physical, infrastructural and social tolerance thresholds and adaptation choices of actors in societies (e.g., the decision to migrate from locations strongly impacted by climate change). The evolution of such socio-

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

economic systems over time, including their interaction with the changing physical climate, determines the evolution of limits to adaptation.

16.1.3.4 What Future Risks are of Greatest Concern?

The fourth and final element of the chapter is the question about the risks we face, and which ones we should be most concerned about. This is addressed in Section 16.5 and 16.6.

Section 16.5.1 presents a full discussion of 'key risks', synthesized from across all chapters, defined as those risks that are potentially severe and therefore especially relevant to the interpretation of 'dangerous anthropogenic interference with the climate system' in the terminology of UNFCCC Article 2.

In 2015 the Paris Agreement established the goal of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. However, assessment of key risks across a range of future warming levels remains a high priority for several reasons: (1) understanding risks at higher levels of warming can help prepare for them, should efforts to limit warming be unsuccessful (UNEP, 2017); (2) understanding risks at higher levels can inform the benefits of limiting warming to lower levels; (3) in addition, there is continued debate about whether warming limits should be at or rather somewhere below 2ºC (in particular at 1.5ºC); and (4) there is a more explicit recognition that key risks can result not only from increased warming, but also from changes in the exposure and vulnerability of society, and from a lack of ambitious adaptation efforts. So relatively limited warming does not automatically imply that key risks will not occur. In assessing key risks, we have applied four criteria: magnitude of adverse consequences, likelihood of adverse consequences, temporal characteristics of the risk, and ability to respond. Of course, this is an aggregated approach to what is dangerous; it should be noted that in practice, 'dangerous' will occur at a myriad of temperature levels depending on who or what is at risk (and their circumstances), geographic scale and time scale.

A new element is that we particularly look at a set of eight 'representative key risks' that exemplify the underlying set of key risks identified in the earlier chapters: risk to the integrity of low-lying coastal socio-ecological systems, risk to terrestrial and ocean ecosystems, risk to critical physical infrastructure and networks, risk to living standards (including economic impacts, poverty and inequality), risk to human health, risk to food security, risk to water security, and risk to peace and mobility (Section 16.5.2.3). Another increased focus relates to the issue of compound risks. This includes risks associated with compound hazards (WGI AR6 Chapter 11, Seneviratne et al., 2021), but also implications for future risk when repeated impacts erode vulnerability, as well as through transboundary effects (including effects both from one system to a neighbouring one, as well as from one system to a distant one), also discussed in the cross-chapter box on interregional risks and adaptation (Cross-Chapter Box INTEREG in this Chapter).

Section 16.6 maps the representative key risks in Section 16.5 to the Sustainable Development Goals, noting both direct and indirect implications for Climate Resilient Development as assessed in Chapter 18.

Finally, section 16.6 presents an updated assessment of the so-called 'Reasons for Concern' (RFC): risks related to unique and threatened systems, extreme events, distribution of impacts, aggregate impacts (including the cross-chapter box on the global economic impacts of climate change and the social cost of carbon, Cross-Working Group Box ECONOMIC) and the risk of irreversible and abrupt transitions.

The AR4 and AR5 each also evaluated the most important climate risks, framed firstly in terms of the state of knowledge relevant to Article 2 of the UNFCCC. The TAR first synthesized this knowledge in five RFCs. AR4 identified a set of 'key vulnerabilities', and provided an update of the RFCs. AR5 further refined a new risk framework developed in SREX, and used it to assess 'key risks' and provide another update of the overarching Reasons for Concern, drawing as well on Cramer et al. (2014) assessment of observed changes.

Our risk assessment also further builds on risk assessments from the Special Reports that are part of the AR6 cycle, i.e. SR15; SRCCL, and SROCC. While since AR4 the RFC assessment framework has remained largely consistent, refinements in methodology have included the consideration of different risks, the role of adaptation, use of confidence statements, more formalized protocols and standardized metrics (Zommers et al., 2020). In subsequent assessment cycles, the risk level at a given temperature has generally increased, reflecting accumulating scientific evidence (Zommers et al., 2020).

16.1.4 Drivers of Exposure and Vulnerability

While this chapter focuses on climate-related impacts, risks and responses, these all take place against a backdrop of trends in exposure and vulnerability driven by demographics, socio-economic development (including inequalities) and ecosystem degradation. Other global trends that are shaping climate risks include technological innovation, shifts in global power relations, and resource scarcity (Retief et al., 2016). Note that these global trends may *increase* but also *reduce* exposure and/or vulnerability, for instance when growing incomes, savings and social protection systems increase resilience in the face of shocks and stresses. Drivers and future trends in vulnerability and exposure – next to climate-induced changes in natural hazards – therefore need to be considered in comprehensive risk assessments and eventually adaptation solutions, but empirical research suggests that they remain to be underemphasized in current national adaptation planning (Garschagen et al., 2021a).

While these risk drivers are often listed separately, they are often closely interconnected, including between human and ecological systems, and increasingly also through climate risks and responses (e.g., Simpson et al., 2021). Climate impacts increasingly affect these drivers, and may compete with financial resources that could otherwise be applied for development, mitigation, adaptation and resilience building, also affecting inequalities (e.g., Taconet et al., 2020).

16.1.4.1 Demographics

Population growth (or decline) can result in increasing (or decreasing) pressure on natural resources (e.g., soils, water and fish stocks) (IPBES, 2019), and can result in the expansion of densely populated areas (Cardona et al., 2012; Day et al., 2016). A majority of the population in the coming decades will be in urban areas. While urbanization can have many benefits that reduce vulnerability, such as employment opportunities and increased income, better access to healthcare and education, and improved infrastructure, unsustainable urbanisation patterns can create challenges for resource availability, exacerbate pollution levels (Rode et al., 2015), and increase exposure to some risks. For example, ~10% of the global population live in Low Elevation Coastal Zones (in 2000; areas <10 m of elevation) (McGranahan et al., 2007; Neumann et al., 2015), which is expected to increase by 5% to 13.6% by 2100 depending on the population scenario (Neumann et al., 2015; Jones and O’Neill, 2016). Building assets and infrastructure in naturally risk-prone areas are also projected to increase (Magnan et al., 2019), which may also lead to environmental degradation that can further aggravate risk, e.g., destruction of wetlands that buffer against floods (Schuerch et al., 2018; Oppenheimer et al., 2019). Demographic trends, coupled with changes in income, can also result in increasing demands for land, food, water and energy, and therefore to major changes in land use and cover change (Arneth, 2019). The observed and projected population decline in some rural areas also has implications for vulnerability and exposure. In addition, demographic changes such as aging may increase vulnerability to some climate hazards, including heat stress (Byers et al., 2018; Rohat et al., 2019a; Rohat et al., 2019b).

16.1.4.2 Biodiversity and Ecosystems

Rapidly accelerating trends in human impacts on global ecosystems and biodiversity, especially in the past 5 decades, have resulted precipitous declines in the numbers of many wild species on land and in the ocean, transformation of the terrestrial land surface for agricultural production, and the pervasive spread of alien and invasive species (IPBES, 2019). As a result, the capacity of ecosystems to support human society is thought to be coming under threat. For instance, the fraction of all primary production being appropriated for human use has doubled over the course of the 20th Century (to about 25% in 2005), although it has grown at a slower rate than human population (Krausmann et al., 2013). Future projections significantly depend on bioenergy production, signalling one of the feedbacks between responses to climate change and climate risks.

16.1.4.3 Poverty Trends and Socioeconomic Inequalities Within and Across Societies

Poverty contributes to exposure and vulnerability by limiting access of individuals, households and communities to economic resources and restraining adaptive capacities (e.g., for food and energy supply, or for financing adaptation responses) (Hallegatte and Rozenberg, 2017). Over the past decades, until the COVID-19 pandemic, global poverty rates have declined rapidly. Between 1981 and 2015, the share of global population living in extreme poverty (under the international poverty line of US$1.90 per day) declined from 42% to 10%, leaving 736 million people in extreme poverty, concentrated in South Asia and Sub-Saharan Africa (World Bank, 2018). This general reduction in poverty across the world is accompanied by a decrease in vulnerability to many types of climate change impacts (*medium confidence*). However, the COVID-19 pandemic has significantly increased extreme poverty by about 100 million people in 2020, with disproportionate economic impacts on the poorest, most fragile and smaller countries (World Bank, 2021) and significant implications for vulnerability to climate change (see also Cross-Chapter Box COVID in Chapter 7).

The majority of the population in poverty are smallholder farmers and pastoralists, whose livelihoods critically depend on climate-sensitive natural ecosystems, e.g., through semi-subsistence agriculture where food consumption is primarily dependent on households' own food production (Mbow et al., 2019). A significant share of this population is affected by armed conflict, which deters economic development and growth and increases local dependence on subsistence agriculture (Serneels and Verpoorten, 2015; Braithwaite et al., 2016; Tollefsen, 2017), and aggravating humanitarian challenges (e.g., ICRC, 2020). Extreme weather events, particularly droughts, can result in poverty traps keeping people poor or making them poorer, resulting in widening inequalities within and across countries.

Climate risks are also strongly related to other inequalities, often but not always intersecting with poverty. AR5 found with very high confidence that differences in vulnerability and exposure arise from multidimensional inequalities, often produced by uneven development processes. These inequalities relate to geographic location, as well as economic, political and socio-cultural aspects, such as wealth, education, race/ethnicity, religion, gender, age, class/caste, disability, and health status (Oppenheimer et al., 2014). Since AR5, a number of studies have confirmed and refined this assessment, especially also regarding socio-economic inequality and poverty (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017; Pelling and Garschagen, 2019; Hallegatte et al., 2020). Poor people more often live in exposed areas such as wastelands or riverbanks (Garschagen and Romero-Lankao, 2015; Winsemius et al., 2018). Also, poor people lose more of their total wealth to climatic hazards, receive less post-shock support from their often-times equally poor social networks, and are often not covered by social protection schemes (Leichenko and Silva, 2014; Hallegatte et al., 2016). Countries with high inequality tend to have above-average levels of exposure and vulnerability to climate hazards (BEH UNU-EHS, 2016). Many socio-economic models used in climate research have been found to have a limited ability to capture and represent the poor at a larger scale (Rao et al., 2019; Rufat et al., 2019). However, an analysis of 92 countries found that relative income losses and other climate change impacts were disproportionately high among the poorest (Hallegatte and Rozenberg, 2017, see Section 16.2.6). There have also been advances in detecting and attributing the impacts of climate change and vulnerability at household scale and specifically on women's agency and adaptive capacity (Rao et al., 2019). The distribution of impacts and responses (adaptation and mitigation) affects inequality, not just between countries, but also within countries (e.g., Tol, 2020) and between different people within societies. Distribution has so far largely been thought of in a geographical sense, but identifying those most at risk requires an additional focus on the social distribution of impacts, responses, as well as of resilience, as influenced for instance by differential social protection coverage (Tenzing, 2020).

Many climate responses interact with all of these global risk drivers. Some raise additional equity concerns about marginalising those most vulnerable and exacerbating social conflicts (Oppenheimer et al., 2019), leading to wider questions about the governance of climate risks (and impacts) across scales. Hence, our assessment of impacts, responses, and risks is complemented by the assessment of governance and the enabling environment for risk management in Chapter 17, and of climate-resilient development in Chapter 18.

16.2 Synthesis of Observed Impacts

This section synthesizes the observed impacts of changes in climate-related systems (see Section 16.2.1) on different natural, human, and managed systems (outlined in Chapters 2-8) and regions (outlined in Chapters 9-15). To stay as specific as possible given the required level of aggregation, we decided in favour of a summary along specific prominent indicators such as 'crop yields' or 'areas burned by wildfires' instead of an assessment across broad categories such as 'food production' which could include a broad range of measures ranging from climate induced changes in growing seasons to growing seasons to impacts on livestock and fisheries etc. or 'wildfires' which could also cover impacts on the frequency, intensity, timing, or emissions and health impacts of wildfires. However, this decision for specificity certainly implies a decision against comprehensiveness. In addition, the level of specificity has to be adjusted given the literature basis which is quite broad regarding crop yields but still limited and less harmonized regarding indicators when it comes to e.g., conflicts. A broader discussion can be found in the sectoral or regional chapters that all cover 'observed impacts' individually. Section 16.2.1 provides key definitions, followed by recent advances in available methods and data for climate impact attribution (Section 16.2.2), and the assessment of observed impacts (Section 16.2.3). It is important to note that the assessment is primarily based on peer-reviewed literature, i.e. it is limited to the regions and phenomena for which such studies are available. So 'no assessment' in a certain region does not apply the considered type of impact did not occur in this region.

16.2.1 Definitions

The section adopts the general definition of **detection** as 'demonstration that a considered system has changed without providing reasons for the change' and **attribution** as identifying the causes of the observed change or a specific event (see Glossary).

Based on these general definitions and following the approach applied in WGII AR5 Chapter 18 (Cramer et al., 2014), we define an **observed impact** as the difference between the observed state of a **natural, human, or managed system** and a counterfactual baseline that characterizes the system's state in the absence of changes in the **climate-related systems** defined here as climate system including the ocean and the cryosphere as physical or chemical systems.

The difference between the observed and the counterfactual baseline state is considered the change in the natural, human, or managed system that is attributed to the changes in the climate-related systems (**impact attribution**).The counterfactual baseline may be stationary or may change over time, for example due to direct human influences such as changes in land use patterns, agricultural or water management affecting exposure and vulnerability to climate related hazards (see Section 16.2.3 for methods on how to construct the counterfactual).

In line with the AR5 definition, 'changes in climate-related systems' here refer to any long-term trend, irrespective of the underlying causes; thus, an observed impact is not necessarily an observed impact of anthropogenic climate forcing. For example, in this section sea level rise is defined as relative sea level rise measured against a land-based reference frame (tide gauge measurements), meaning that it is driven not only by thermal expansion and loss of land ice influenced by anthropogenic climate forcing, but also by vertical land movements. As attribution of coastal damages to sea level rise does not distinguish between these components it does not imply attribution to anthropogenic forcing. Where the literature does allow attribution of changes in natural, human or managed systems to anthropogenic climate forcing ('joint attribution', Rosenzweig et al., 2007), this is highlighted in the assessment. Often the attribution of changes in the natural, human or managed systems to anthropogenic forcing can be done in a two-step approach where i) an observed change in a climate-related system is attributed to anthropogenic climate forcing ('climate attribution') and ii) changes in natural, human, or managed systems are attributed to this change in the climate-related system ('impact attribution').

For climate attribution the main challenge is the separation of externally human forced changes in the climate-related systems from their internal variability while for impact attribution it often is the separation of the effects of other external forcings (i.e., direct human influences or natural disturbances) from the impacts of the changes in the climate-related systems. Direct influences not related to changes in the climate-related systems could e.g., be pollution and land use changes amplifying biodiversity losses, intensification of fishing reducing fish stocks, and increasing protection reducing losses due to river floods. The direct human or natural influences may counter the impacts of climate change (e.g., climate change may have reduced flood hazards but exposure may have increased as people have moved to flood-prone areas, resulting in no change in observed damages). Given the definition of impact attribution, that means that there may be an observed impact of climate change without the detection of a change in the natural, human or managed system. This is different from 'climate attribution' where detection and attribution are consecutive steps.

Changes in climate related systems can certainly also affect natural, human and managed systems through indirect effects on land use, pollution or exposure. However, these indirect effects are barely addressed in existing studies.

In addition to impact attribution, there is research on the identification of natural, human, or managed systems' response to short-term (typically daily, monthly or annual) weather fluctuations or individual *extreme weather events*. As different from impact attribution we separately define:

'Identification of weather sensitivity' refers to the attribution of the response of a system to fluctuations in weather and short-term changes in the climate-related systems including individual *extreme weather events* (e.g., a heatwave or storm surge).

Typical questions addressed include: 'How much of the observed variability of crop yields is due to variations in weather conditions compared to contributions from management changes?' (e.g., Ray et al., 2015; Müller et al., 2017) and 'Can weather fluctuations explain part of the observed variability in annual national economic growth rates?' (e.g., Burke et al., 2015). Identification of weather sensitivity may also address the effects of individual *climate extremes*, for example asking, 'Was the observed outbreak of cholera triggered by an associated flood event?' (e.g., Rinaldo et al., 2012; Moore et al., 2017b). It is important to note that sensitivity could be described in diverse ways and that for example the fraction of the observed variability in a system explained by weather variability differs from the strength of the systems' response to a specific change in a weather variable. Nevertheless, all these different measures are integrated in the 'identification of weather sensitivity' assessment where 'sensitivity' should not be considered a quantitative one dimensional mathematical measure.

In this chapter we explicitly distinguish between assessment statements related to 'climate attribution' (listed in Table SM16.21), 'impact attribution' (listed in Table SM16.22), and 'identification of weather sensitivity' (listed in Table SM16.23). The identification of 'weather sensitivity' does not necessarily imply that there also is an impact of long-term climate change on the considered system. However, if the probability or intensity of an *extreme weather event* has increased due to anthropogenic forcing ('climate attribution') (NASEM, 2016; WGI AR6 Chapter 11 Seneviratne et al., 2021) and the event is also identified as an important driver of an observed fluctuation in a natural, human or managed system ('identification of weather sensitivity'), then the observed fluctuation is considered (partly) attributed to long-term climate change ('impact attribution') and even to anthropogenic forcing.

16.2.2 Methods and Data for Impact Attribution Including Recent Advances

By definition the counterfactual baseline required for impact attribution cannot be observed. However, it may be approximated by impact model simulations forced by a stationary climate e.g. derived by de-trending the observed climate (Diffenbaugh et al., 2017; Mengel et al., 2021) while other relevant drivers (e.g., land use changes or application of pesticides) of changes in the system of interest (e.g., a bird population) evolve according to historical conditions. To attribute to anthropogenic climate forcing, the anthropogenic trends in climate are estimated from a range of different climate models and subtracted from the observed climate e.g., Abatzoglou and Williams (2016) for changes in the extent of forest fires or Diffenbaugh and Burke (2019) for effects on economic inequality) or the 'no anthropogenic climate forcing' baseline is directly derived from a large ensemble of climate model simulations not accounting for anthropogenic forcings e.g., Kirchmeier-Young et al. (2019b) for the extent of forest fires). In any case it has to be demonstrated that the applied impact models are able to explain the observed changes in natural, human or managed systems by e.g., reproducing the observations when forced by observed changes in climate-related systems and other relevant drivers.

In a situation where an influence of other direct human drivers can be excluded (e.g., by restriction to remote areas not affected by direct human interventions), the 'no climate-change' baseline can also be approximated by data from early observational periods with no or minor levels of climate change. In particular, the contribution of climate change to the observed changes in ecosystems is often also determined by a 'multiple lines of evidence' approach where the baseline is not formally quantified but the observed changes are identified as a signal of climate change compared to a no-climate change situation based on process understanding from e.g. paleo data and laboratory or field experiments in combination with individual long term observational records and the large scale spatial or temporal pattern of observed changes that can hardly be explained by alternative drivers (Parmesan et al., 2013).

To date, explicit accounting for direct human or natural influences is often hampered by an incomplete understanding of the processes and limited observational data. There are, however, first studies demonstrating the potential of detailed process-based or empirical modelling that explicitly account for known variations in direct human or natural drivers and separate their effects from the ones induced by changes in the climate-related systems. Examples are Butler et al. (2018) for the separation of growing season adjustments from within growing season climate effects on US crop yields; Wang and Hijmans (2019), separating effects of shifts in land use from climate effects; Jongman et al. (2015); Formetta and Feyen (2019), and Tanoue et al. (2016) for the separation of changes in exposure and vulnerability from climate effects on river floods; Kirchmeier-Young et al. (2019b) for wildfire attribution; Venter et al. (2018) for the attribution of ecosystem structural changes to climate change versus other disturbances.

There also has been significant progress in the compilation of fragmented and distributed observational data (e.g., Cohen et al. (2018) for phenological ecosystem changes, Poloczanska et al. (2013) for distributional shifts in marine ecosystems, the new global fire atlas (Andela et al., 2019) including information about individual fire size, duration, speed and direction), as well as regional downscaling (e.g., Ray et al. (2015)) allowing for the identification of an overall picture of the impacts of progressing climate change. Given the ever increasing body of literature on observed changes in natural, human, and managed systems there also is a first machine learning approach for an automated identification for relevant literature that could complement or support expert assessments as the one provided here (Callaghan et al., 2021).

16.2.3 Observed Impacts

In this section we synthesize observed impacts across a range of ecosystems, sectors, and regions. Figure 16.2 summarizes the attribution of observed (regional) changes in natural, human or managed systems (orange symbols and confidence ratings), the quantification of weather sensitivity of those systems (blue symbols and confidence ratings), and the attribution of underlying changes in the climate-related systems to anthropogenic forcing (grey symbols and confidence ratings). The Figure can be read as a summary and Table of content for the underlying Tables 16.B.1 on climate attribution, 16.B.2 on impact attribution, and 16.B.3 on identification of weather sensitivity that provide the more detailed explanations behind each regional or global assessment, including all references. The synthesis was generated in collaboration with 'detection and attribution contact persons' from the individual chapters that each includes its own assessment of observed impacts, and contributing authors on individual topics. The synthesis of 'climate attribution' studies in Table SM16.21 was particularly informed by the WGI assessment.

If Figure 16.2 only provides an assessment of attributed impacts on a given system (e.g., Phenology shifts in terrestrial ecosystems) but does not include an associated 'identification of weather sensitivity' that does not mean that the system is not sensitive to weather fluctuations. The focus of our assessment was on 'impacts attribution' and we only provide an assessment of 'weather sensitivities' if the literature has turned out to provide only limited evidence on impacts of long-term climate change but rather addressed the system's responses to short term weather fluctuations.

16.2.3.1 Ecosystems

The collapse or transformation of ecosystems is one of the most abrupt potential tipping points associated with climate change. Climate change has started to induce such tipping points with the first examples including mass mortality in coral reef ecosystems (e.g., Donner et al., 2017; Hughes et al., 2018; Hughes et al., 2019) (*high confidence*), and changes in vegetation cover triggered by wildfires with climate change suppressing the recovery of the former cover (Tepley et al., 2017; Davis et al., 2019) (*low confidence* because of the still limited number of studies). Another example of an abrupt change in an ecosystem triggered by a climate extreme is the shift from kelp- to urchin-dominated communities along parts of the Western North America coast due a marine heatwave (Rogers-Bennett and Catton, 2019; McPherson et al., 2021, see 'Marine ecosystems - Kelp forest', Table SM16.22) where anthropogenic climate forcing has been shown to have increased the probability for an event of that duration by at least a factor of 33 (Laufkötter et al., 2020). Many terrestrial ecosystems on all continents show evidence of significant structural transformation, including woody thickening and 'greening' in more water-limited ecosystems, with a significant role played by rising atmospheric CO2 fertilization in these trends (*high confidence*) (Fang et al., 2017; Stevens et al., 2017; Burrell et al., 2020). Climate change is identified as a major driver of increases in burned areas in the Western US (*high confidence,* see 'Terrestrial ecosystems - Burned areas', Table SM16.22).

There is also a clear footprint of climate change on species distribution, with appreciable proportions of tropical species expanding into the ranges of temperate species, and boreal species moving into Arctic regions (*high confidence*, see 'Marine ecosystems - Range reduction and shift' and 'Terrestrial ecosystems - Range reduction and shift', Table SM16.22). Climate change has also shifted the phenology of animals and plants on land and in the ocean (*high confidence*, see 'Marine ecosystems - Phenology shift' and 'Terrestrial ecosystems - Phenology shifts', Table SM16.22). Both processes have led to emerging hybridisation, competition, temporal or spatial mismatches in predator-prey, guest-host relationships, and invasion of alien plant pests or pathogens (Edwards and Richardson, 2004; Bebber et al., 2013; Parmesan et al., 2013; Millon et al., 2014; Thackeray et al., 2016).

16.2.3.2 Water Distribution - River Flooding and Reduction in Water Availability

Observed trends in high river flows strongly vary across regions but also with the considered time period (Gudmundsson et al., 2019; Gudmundsson et al., 2021) as influenced by climate oscillations such as the El Niño–Southern Oscillation (Ward et al., 2014). On global scale the spatial pattern of observed trends is largely explained by observed changes in climate conditions as demonstrated by multi-model hydrological simulations forced by observed weather while the considered direct human influences only play a minor role on global scale (Gudmundsson et al., 2021, see 'Water distribution - Flood hazards', Table SM16.22). The annual total number of reported fatalities from flooding shows a positive trend (1.5% per year from 1960-2013, Tanoue et al., 2016) which appears to be primarily driven by changes in exposure dampened by a reduction in vulnerability while climate induced increases in affected areas only show a weak positive trend on global scale (see 'Water distribution - Flood induced fatalities', Table SM16.22). However, the signal of climate change in flood induced fatalities may be lost in the regional aggregation where effects of increasing and decreasing hazards may cancel out. Thus, a climate driven increase in flood induced damages becomes detectable in continental subregions with increasing discharge while the signal of climate change may not be detectable without disaggregation (Sauer et al., 2021, see 'Water distribution: Flood-induced economic damages', Table 16.2), see 'Water distribution: Flood-induced economic damages', Table 16.2). Compared to river floods the analysis of impacts of long-term changes in the climate related systems on the reduction in water availability is much more fragmented and reduced to individual case studies regarding associated societal impacts (see 'Water distribution - Reductions in water availability + induced damages and fatalities', Table SM16.22). At the same time weather fluctuations have led to reductions in water availability with severe societal consequences and high numbers of drought-induced fatalities and damages in particular in Africa and Asia (see 'Water distribution - Reductions in water availability + induced damages and fatalities, Table SM16.23) and impacts on malnutrition (see 'Food system - Malnutrition, Table SM16.23). Although anthropogenic climate forcing has increased droughts' intensity or probability in many regions of the world (*medium confidence*), ('Atmosphere - Droughts, Table SM16.21), the existing knowledge has not yet been systematically linked to attribute long-term trends in malnutrition, fatalities, and damages induced by reduced water availability to anthropogenic climate forcing or long-term climate change. For impacts of individual attributable drought events see Table 4.5 of Chapter 4 and 'Water distribution - Reductions in water availability + induced damages and fatalities, Table SM16.23.

16.2.3.3 Coastal Systems

With their enormous destructive power tropical cyclones represent a major risk for coastal systems (see 'Coastal systems - Damages', Table SM16.23). Despite its relevance, confidence in the influence of anthropogenic climate forcing on the strength and occurrence probability of tropical storms themselves is still low (see 'Coastal systems: Tropical cyclones', Table SM16.21). However, anthropogenic climate forcing has become the dominant driver of sea level rise (*high confidence*) (see 'Coastal systems - Mean and extreme sea levels', Table SM16.21) and has increased the risk of coastal flooding, including inundation induced by tropical cyclones. In addition, anthropogenic climate forcing has increased the amount of rainfall associated with tropical cyclones (*high confidence)* (Risser and Wehner, 2017; Van Oldenborgh et al., 2017; Wang et al., 2018) for hurricane Harvey in 2017 (Patricola and Wehner, 2018) and for hurricanes Katrina in 2005, Irma in 2017, and Maria in 2017 (see 'Atmosphere - Heavy precipitation', Table SM16.21). Assuming that the extreme rainfall is a major driver of the total damages induced by the tropical cyclone, the contribution of anthropogenic climate forcing to the occurrence probability of the observed rainfall (fraction of attributable risk) can also be considered the fraction of attributable risk of the hurricane-induced damages or fatalities (Frame et al., 2020; Clarke et al., 2021, see 'Coastal systems - Damages', Table SM16.22). However, first studies do not only quantify the change in occurrence probabilities but translate the actual change in climate-related systems into the additional area affected by flooding in a process-based way (Strauss et al. (2021), contribution of anthropogenic SLR to damages induced by hurricane Sandy; Wehner and Sampson (2021), contribution increased precipitation to damages induced by hurricane Harvey) and attribute a considerable part of the observed damage to anthropogenic climate forcing. In addition, disruption of local economic activity in Annapolis, Maryland and loss of areas and settlements in Micronesia and Solomon Islands have been attributed to relative sea level rise (Nunn et al., 2017; Albert et al., 2018; Hino et al., 2019) while permafrost thawing and sea ice retreat are additional drivers of observed coastal damages in Alaska (Albert et al., 2016; Smith and Sattineni, 2016; Fang et al., 2017).

16.2.3.4 Food System

Crop yields respond to weather variations but also to increasing atmospheric CO_2, changes in management (e.g., fertilizer input, changes in varieties), diseases, and pests. However, the weather signal is clearly detectable in national and subnational annual yield statistics in main production regions (see 'Food system - Crop yields', Table SM16.23). Over the last decades crop yields have increased nearly everywhere mainly due to technological progress (e.g., Lobell and Field, 2007 (global); Butler et al., 2018 (US); Hoffman et al., 2018 (Sub-Saharan Africa); Agnolucci and De Lipsis, 2019 (Europe)) with only minor areas not experiencing improvements in maize, wheat, rice, and soy yields. However meanwhile, stagnation or decline in yields is also observed on parts of the harvested areas (*high confidence*) (~20% to 40% of harvested areas of maize, wheat, rice and soy with wheat being most affected) (Ray et al., 2012; Iizumi et al., 2018). Evidence on the contribution of climate change to recent trends is still limited (see 'Food system - Crop yields', Table SM16.22). Current global-scale process-based simulations forced by simulated historical and pre-industrial climate miss an evaluation to what degree simulations reproduce observed yields (Iizumi et al., 2018). Global scale empirical approaches do not explicitly account for extreme weather events but growing season average temperatures and precipitation (e.g., Lobell et al., 2011; Ray et al., 2019). In addition, studies are constrained by only fragmented information about changes in agricultural management such as growing season adjustments. Some of these limitations have be overcome in regional studies indicating a climate induced increase (28% of observed trend since 1981) in maize yields in the US (Butler et al., 2018 based on a detailed accounting of impacts of extreme temperatures and growing season adjustments) and a climate induced decrease in millet and sorghum yields (10–20% for millet and 5–15% for sorghum in 2000-2009 compared to pre-industrial conditions) in Africa and a negative effect of historical climate change on potential wheat yields (27% reduction from 1990 to 2015) in Australia (Hochman et al., 2017; Sultan et al., 2019) based on detailed process-based modelling including a dedicated evaluation against observed yield fluctuations). However, these findings need additional support by independent studies while results are relatively convergent that climate change has been an important driver of the recent declines in wheat yields in Europe (*medium confidence*) (Moore and Lobell, 2015; Agnolucci and De Lipsis, 2019; Ray et al., 2019).

Due to complex interactions with socio-economic conditions, climate-induced trends in crop yields and production do not directly transmit to crop prices, availability of food, or nutrition status. This complexity, in addition to the limited availability of long-term data, has so far impeded the detection and attribution of a long-term impact of climate change on associated food security indicators. However, in a few cases, observed crop prices (e.g., domestic grain price in Russia and Africa, Götz et al., 2016; Mawejje, 2016;

Baffes et al., 2019) are shown to be sensitive to fluctuations in local weather through its impact on production (see 'Food system - Food prices', Table SM16.23). In addition, there is growing evidence that *climate extremes* (in particular droughts) have led to malnutrition (in particular stunting of children) in the historical period (*medium confidence*, see 'Food system - Malnutrition', Table SM16.23) but without an attribution of changes to long-term climate change.

16.2.3.5 Temperature-related Mortality

There is nearly universal evidence that non-optimal ambient temperatures increase mortality (*high confidence)*, with notable heterogeneity only in the shape of the temperature-mortality relationship across geographical regions but often sharply growing relative risks at the outer 5% of the local historical temperature distributions (Gasparrini et al., 2015; Guo et al., 2018; Carleton et al., 2020; Zhao et al., 2021, see 'Other societal impacts - Heat-related mortality', Table SM16.23). Significant advances have been made since AR5 regarding the study of temperature-related excess mortality in previously under-researched regions, such as developing countries and (sub-)tropical climates e.g. Africa (South-East Asia: Dang et al., 2016; Ingole et al., 2017; Mazdiyasni et al., 2017; Wichmann, 2017; e.g., Scovronick et al., 2018; Alahmad et al., 2019; the Middle East: Gholampour et al., 2019; and Latin America: Péres et al., 2020). Progress has also been made with regard to temporal changes in temperature-related excess mortality and underlying population vulnerability over time. Heat-attributable mortality fractions have declined over time in most countries due to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioural changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change (see 'Other societal impacts - Heat-related mortality', Table SM16.22, De'Donato et al., 2015; Arbuthnott et al., 2016; Vicedo-Cabrera et al., 2018a). Important exceptions exist, e.g., where unprecedented heat waves have occurred recently. No conclusive evidence emerges regarding recent temporal trends in excess mortality attributable to cold exposure (Vicedo-Cabrera et al., 2018b). Quantitative detection and attribution studies of temperature-related mortality are still rare. One study (Vicedo-Cabrera et al.), using data from 43 countries, found that 37% (range 20.5–76.3%) of average warm-season heat-related mortality during recent decades can be attributed to anthropogenic climate change (*medium confidence*, see 'Other societal impacts - Heat-related mortality', Table SM16.22). Studying excess mortality associated with past heat waves, such as the 2003 or 2018 events in Europe, even higher proportions of deaths attributable to anthropogenic climate change have been reported for France and the UK (Mitchell et al., 2016; Clarke et al., 2021). Formal attribution studies encompassing cold-related mortality are quasi non-existent. The very few studies from Europe and Australia (Christidis et al., 2010; Åström et al., 2013; Bennett et al., 2014) find weak impacts of climate change on cold-associated excess mortality, with contradictory outcomes both towards higher and lower risks (*low confidence*, see 'Other societal impacts - Heat-related mortality', Table SM16.22).

16.2.3.6 Water-borne Diseases

Infectious diseases with water-associated transmission pathways constitute a large burden of disease globally. Since AR5 the evidence has strengthened that waterborne diseases, and especially gastrointestinal infections, are highly to moderately sensitive to weather variability (*medium confidence*, see 'Water distribution - Water-borne diseases', Table SM16.23). Increased temperature and high precipitation, with associated flooding events, have been shown to generally increase the risk of diarrhoeal diseases. There are however a number of studies that describe important exceptions and modifications to this general observation. While high temperatures favour bacterial diarrhoeal diseases, virally transmitted diarrhoea is on the contrary mostly associated with low temperatures (Carlton et al., 2016; Chua et al., 2021). Socio-economic determinants, such as the existence of single household water supplies (Herrador et al., 2015) or combined sewer overflows (Jagai et al., 2017), have been shown to critically increase the risk of gastrointestinal infections linked to heavy rainfall in high-income countries. Also, for both low- and high-income countries it has been found that gastrointestinal diseases increase following a heavy rainfall event only if preceded by a dry period (Carlton et al., 2014; Setty et al., 2018). Yet, so far there is no consistent evidence on the role of droughts in favouring waterborne disease transmission (Levy et al., 2016). As exemplified by the large cholera outbreak following the 2010 earthquake in Haiti, the existence of functioning sanitation systems is critical for preventing waterborne disease outbreaks, while climatic factors (especially rainfall) are important in driving the transmission dynamics once the outbreak has started (Rinaldo et al., 2012). Other socio-economic factors, such as human mobility and water management project (e.g., dam constructions) also modify the strength of the association between climatic factors and waterborne diseases, as shown by recent studies in Africa (Perez-Saez et al., 2015; Finger et al., 2016).

Whereas the weather sensitivity of waterborne diseases is well-established for all world regions (see 'Water distribution - Water-borne diseases', Table SM16.23), studies attempting to attribute recent trends in waterborne disease to climate change are non-existent, except for investigations on the distribution of marine *Vibrio* bacteria and associated disease outbreaks in the coastal North Atlantic and the Baltic Sea regions (Baker-Austin et al., 2013; Baker-Austin et al., 2016; Vezzulli et al., 2016; Ebi et al., 2017). These investigations provide evidence that increases in sea surface temperatures over recent decades as well as during recent summer heat waves are linked to increased concentrations of *Vibrio* bacteria in coastal waters and an associated rise in environmentally acquired *Vibrio* infections in humans.

16.2.3.7 Vector-borne Diseases

Vector-borne diseases constitute a large burden of infectious diseases worldwide and are highly sensitive to fluctuations of weather conditions including extreme events. Thus, both extreme rainfall and droughts have increased infections (*high confidence,* see documentation of cases in 'Other societal impacts - Vector-borne diseases', Table SM16.23). For example, in Sudan, anomalous high rainfall increased *Anopheles* mosquito breeding sites, leading to malaria outbreaks (Elsanousi et al., 2018) while in Barbados and Brazil, drought conditions in urban areas have enhanced dengue incidence due to changes in water storage behaviour creating breeding sites for *Aedes* mosquitoes around human dwellings (Lowe et al., 2018; Lowe et al., 2021)). In the Caribbean and Pacific island nations, weather extremes, such as storms and flooding have led to outbreaks of dengue due to disruption to water and sanitation services, leading to increased exposure to *Aedes* mosquito breeding sites (Descloux et al., 2012; Sharp et al., 2014; Uwishema et al., 2021). In South and Central America, and Asia, dengue incidence has been shown to sensitive to variations in temperature and the monsoon season in addition to variations induced by urbanization and population mobility (*high confidence* (South and Central America)*; medium confidence* (Asia); see 'Other societal impacts - Vector-borne diseases', Table SM16.23).

The attribution of changes in disease incidence to long-term climate change is often limited by relatively short reporting periods often only covering 10-15 years. Most studies then attribute trends in the occurrence of vector-borne diseases to the trends in climate across the same observational period and do not refer to an early 'no climate change' baseline climate. This means that they also capture trends induced by longer term climate oscillations. Nevertheless, we list them in Table SM16.22 on 'impact attribution' to clearly distinguish them from the analysis of interannual fluctuations. The overall consistency of their findings across regions and time windows indicates that climate change is an important driver of the observed latitudinal or altitudinal range expansions of vector-borne diseases into previously colder areas (*medium to high confidence,* see 'Other societal impacts - Vector-borne diseases', Table SM16.22). In highland areas of Africa and South America, epidemic outbreaks of malaria have become more frequent due to warming trends that allow *Anopheles* mosquitoes to persist at higher elevations (Pascual et al., 2006; Siraj et al., 2014). In the US, ticks that transmit Lyme disease have expanded their range northwards due to warmer temperatures (*high confidence*, (Kugeler et al., 2015; McPherson et al., 2017; Lin et al., 2019; Couper et al., 2020, see 'Other societal impacts - Vector-borne diseases', Table SM16.22). In Southern Europe, climate suitability for *Aedes* mosquitoes, which transmit dengue and chikungunya, and *Culex* mosquitoes, which transmit West Nile virus, has also increased and contributed to unprecedented outbreaks including the 2018 West Nile fever outbreak (*medium confidence*) (Medlock et al., 2013; Paz et al., 2013; Roiz et al., 2015; ECDC, 2018, see 'Other societal impacts - Vector-borne diseases', Table SM16.22).

16.2.3.8 Economic Impacts

Since the AR5, there has been significant progress regarding the identification of economic responses to weather fluctuations: Evidence has increased that *extreme weather events* such as tropical cyclones, droughts, and severe fluvial floods have not only caused substantial immediate direct economic damage (*high confidence*, see 'Coastal Systems - Damages, Table SM16.23, 'Water distribution - Reductions in water availability + induced damages and fatalities, Table SM16.23, and 'Water distribution - Flood-induced economic damages, Table SM16.22), but have also reduced economic growth in the short-term (year of, and year after event) (Strobl, 2011; Strobl, 2012; Fomby et al., 2013; Felbermayr and Gröschl, 2014, Loyaza et al. 2012) (*high confidence*) as well as long-term (up to 10-15 years after event) (*medium confidence*) (Hsiang and Jina, 2014; Berlemann and Wenzel, 2016; Berlemann and Wenzel, 2018; Krichene et al., 2020; Tanoue et al., 2020, see 'Other societal impacts - Macroeconomic output', Table SM16.23). Short- and long-term reductions of economic growth by *extreme weather events* affect both, developing and industrialized countries, but have been shown to be more severe in developing than in industrialized economies thereby increasing inequality between countries (*high confidence*, see 'Other societal impacts - Between country inequality', Table SM16.23). Further, *extreme weather events* have increased within-country inequality since poorer people are more exposed and suffer relatively higher well-being losses than richer parts of the population (*medium confidence*, see 'Other societal impacts - Between country inequality', Table SM16.23). Going beyond *extreme weather events*, economic production depends non-linearly on temperature fluctuations: below a certain threshold temperature, economic production increases with temperature whereas it decreases above a certain threshold temperature (*high confidence*) (Burke et al., 2015; Pretis et al., 2018; Kalkuhl and Wenz, 2020; Kotz et al., 2021).

So far, there are few individual studies attributing observed economic damages to long term climate change except for damages induced by river flooding, droughts, and tropical cyclones (see 'Coastal systems - Damages', 'Water distribution - Flood induced damages', and 'Water distribution - Reduction in water availability + induced damages and fatalities', Table SM16.22) *extremes* to anthropogenic forcing. In addition, the empirical findings on the sensitivity of macroeconomic development to weather fluctuations and *extreme weather events* have been used to estimate the cumulative effect of historical warming on long term economic development (see 'Other societal impacts - Macroeconomic output', Table SM16.22): anthropogenic climate change is estimated to have reduced GDP growth over the last 50 years with substantially larger negative effects on developing countries and in some cases positive effects on colder industrialized countries (*low confidence*) (Diffenbaugh and Burke, 2019). Globally, between-country inequality has decreased over the last 50 years. Climate change is estimated to have substantially slowed down this trend, i.e., increased inequality compared to a counterfactual no climate change baseline (*low confidence*) (Diffenbaugh and Burke, 2019). On a regional level, decreasing rainfall trends in Sub-Saharan Africa (SSA) may have increased the GDP per capita gap between SSA and other developing countries (*low confidence*) (Barrios et al., 2010). Overall, more research is needed on the impact channels through which *extreme weather events* and weather variability can hinder economic development, especially in the long-term.

16.2.3.9 Social Conflict

There are few studies directly attributing changes in conflict risk to climate change in the modern era (van Weezel, 2020), preventing a confident assessment of the effect of long-term changes in the climate-related systems on armed conflict (see 'Other societal impacts - Social conflict', Table SM16.22). However, a sizeable literature links the prevalence of armed conflict within countries to within- and between-year variations in rainfall, temperature or drought exposure; often via reduced-form econometric analysis or statistical models that control for important non-climatic factors, such as agricultural dependence, level of economic development, state capacity, and ethnopolitical marginalization (see 'Other societal impacts - Social conflict' in Table SM16.23). Overall, there is more consistent evidence that climate variability has influenced low-intensity organized violence than major civil wars (Detges, 2017; Nordkvelle et al., 2017; Linke et al., 2018). Likewise, there is more consistent evidence that climate variability has affected dynamics of conflict, such as continuation, severity, and frequency of violent conflict events, than the likelihood of initial conflict outbreak (Yeeles, 2015; Eastin, 2016; Von Uexkull et al., 2016, Section 7.2.7). Moreover, research suggests with *medium confidence* (*medium evidence*, *medium agreement*) that weather effects on armed conflict have been most prominent in contexts marked by a large population, low socioeconomic development, high political marginalization, and high agricultural dependence (Theisen, 2017; Koubi, 2019; Buhaug et al., 2020; Ide et al., 2020).

Some studies also seek to evaluate potential indirect links between climate and weather anomalies and prevalence of armed conflict via food price shocks or forced migration. While there is *robust evidence* that the likelihood of social unrest in the developing world generally increases in response to rapid growth in food prices (Bellemare, 2015; Rudolfsen, 2018), the magnitude of the climate effect on unrest via food prices is less well established (Martin-Shields and Stojetz, 2019). Similarly, research shows with *high confidence* that climate variability and extremes have affected human mobility (see 'Other societal impacts -

Displacement and migration', Table SM16.23), but there is low agreement and limited evidence that weather-induced migration has increased the likelihood of armed conflict (Section 7.2, Brzoska and Fröhlich, 2016; Kelley et al., 2017; Selby et al., 2017; Abel, 2019). Research on weather-related effects on interstate security generally conclude that periods of transboundary water scarcity are more likely to facilitate increased international cooperation than conflict (Bernauer and Böhmelt, 2020).

In general, the historical influence of climate on conflict is judged to be small when compared to dominant conflict drivers (Mach et al., 2019). Much of this research is limited to (parts of) Sub-Saharan Africa, which raises some concerns about selection bias and generalizability of results (Adams et al., 2018).

16.2.3.10 Displacement and Migration

Given the complexity of human migration processes and decisions (e.g., Boas et al., 2019, Cattaneo et al., 2019) and the paucity of long-term, reliable and internally consistent observational data on displacement (IDMC, 2019; IDMC, 2020) and migration (Laczko, 2016) the contribution of long-term changes in climate related systems to observed human displacement or migration patterns has not been quantified so far, except for individual examples for displacement induced by inland flooding where the heavy precipitation has been attributed to anthropogenic climate forcing and coastal flooding (see 'Other societal impacts - Displacement and migration', Table SM16.22; CCP2).

However, new evidence has emerged since the AR5 that further documents widespread effects of weather fluctuations and extreme events on migration (see 'Other societal impacts- Displacement and migration' in Table SM16.23). Numerous studies find significant links between temperature or precipitation anomalies, or *extreme weather events* such as storms or floods, and internal as well as international migration (Coniglio and Pesce, 2015; Cattaneo and Peri, 2016; Nawrotzki and DeWaard, 2016; Beine and Parsons, 2017for international migration; and IDMC, 2019 for internal displacement). Internal displacement of millions of people every year is triggered by natural hazards, mainly floods and storms (IDMC, 2019). The effects of weather fluctuations and extremes on migration are considered more important for temporary mobility and displacement than permanent migration, and more influential on short-distance movement, including urbanization, than international migration (McLeman, 2014; Hauer et al., 2020; Hoffmann et al., 2020, Section 7.2.6). Importantly, these links are conditional on the socio-economic situation in the origin; e.g., poor populations may be 'trapped' and not be able to migrate in the face of adverse climate or weather conditions (Black et al., 2013; Adams, 2016). Many studies have also explored the channels through which climate or weather influence migration, and have identified incomes in the agricultural sector as one of the main channels (Nawrotzki et al., 2015; Viswanathan and Kavi Kumar, 2015; Cai et al., 2016a). In particular, declines in agricultural incomes and employment due to changed weather variability may foster increased rural-urban movement; and the resulting pressures on urban wages in turn fosters international migration (Marchiori et al., 2012; Maurel and Tuccio, 2016). Another possible but controversial channel is violent conflict, which may be fostered (though not exclusively caused) by adverse climate conditions such as drought, and in turn lead to people seeking refugee status, although evidence of such an indirect effect is weak (Brzoska and Fröhlich, 2016; Abel et al., 2019; Schutte et al., 2021).

16.2.3.11 Case study on climate change and the outbreak of the Syrian civil war

Separating between climatic and non-climatic factors in impact attribution is often challenging, as highlighted by the debate surrounding the causes of the Syrian civil war. During the years 2006–2010, the Fertile Crescent region in Eastern Mediterranean and Western Asia was hit by the worst drought on meteorological record, compounding a consistent drying of the region over the past half century (Trigo et al., 2010; Hoerling et al., 2012; Mathbout et al., 2018, SR15 BOX 3.2). The magnitude of the multiyear drought is estimated to have become two to three times more likely as a result of increased CO_2 forcing (Kelley et al., 2015). The drought had a devastating impact on agricultural production in the northeast of Syria. In 2007–2008 alone, average crop yields dropped by 32% in irrigated areas and as much as 79% in rain-fed areas (De Châtel, 2014), and herders in the northeast lost around 85% of their livestock (Werrell et al., 2015). Successive years with little or no income eventually forced people to leave their farms in great numbers and seek employment in less affected parts of the country, adding to existing pressures on housing, labour market, and public goods provision (Gleick, 2014; Kelley et al., 2015). In March 2011, by which time the

'Arab Spring' uprisings had gained momentum and spread across much of the region, anti-regime protests broke out in Syria, first in the southern city of Dara'a and then in Damascus and throughout the country.

Yet, the attribution of the Syrian civil war to climate change has triggered a heated debate. A number of studies argue that the principal drivers of the drought-induced economic collapse were political rather than environmental in nature, shaped by adverse economic reforms and unsustainable agricultural policies, promoting water-intensive irrigation schemes for cotton cultivation and implementing abrupt subsidy cuts at the peak of the drought, implying that many poor farmers no longer could afford fertilizers or fuel to power irrigation pumps (Barnes, 2009; De Châtel, 2014; Eklund and Thompson, 2017; Selby et al., 2017). Thus, the 2006–10 drought did not precipitate similar devastating socioeconomic impacts on agrarian communities across the borders in Turkey, Iraq or Jordan, although environmental conditions were comparable (Trigo et al., 2010; Eklund and Thompson, 2017; Feitelson and Tubi, 2017).

However, the relevant attribution question is not whether the same drought would produce the same consequences under different political and socio-economic conditions but rather, given the same political and socio-economic context, how would the outcomes have differed in the absence of the climate event? Research still provides very limited insights into whether and how the escalation process would have evolved differently in a counterfactual no-climate change world.

Thus, the role of the drought in augmenting pre-existing internal migration, and the role of the distress migration in accentuating demographic, economic, and social pressures in receiving areas, remain contested. Estimates of the number of people who abandoned their farms in response to the drought range from less than 40–60,000 families (Selby et al., 2017) to more than 1.5 million displaced (Gleick, 2014). However, the numbers have to be seen in the context of prevailing population growth, significant rural-urban migration, and the preceding inflow of around 1.5 million refugees from neighbouring Iraq (De Châtel, 2014; Hoffmann, 2016). In addition, research suggests that the migrants played a peripheral role in the initial social mobilization in March 2011 (Fröhlich, 2016).

While it is undisputed that the drought caused direct economic losses, its overall additional impact on the Syrian economy, relative to other prevalent drivers of economic misery, including rampant unemployment, increasing inequalities, declining rural productivity, and loss of oil revenues (Aïta, 2009; Landis, 2012; De Châtel, 2014; Selby, 2019) has not been quantified.

In addition, the protesters' demands centred around contentious political rather than economic issues, including release of political prisoners, ending of torture and indiscriminate violence by security forces, and abolishment of the near 50-year old state of emergency (Selby et al., 2017; Ash and Obradovich, 2020). The mobilization in Syria in the spring of 2011 also made explicit references to events across the Middle East and North African region. Analyses of regional and social media and networks show high level of interaction across the Arab world, and the initial Syrian uprising adopted a mobilization model and rhetorical frames similar to those developed in Tunisia and Egypt (Leenders, 2013; 2014). However, the Syrian uprising stands out in how it was met with overwhelming violent force by the police and security forces, which changed the character of the resistance and opened up for militarization of non-state actors that further escalated the conflict (Heydemann, 2013; Leenders, 2013; Bramsen, 2020).

In summary, the drought itself is shown to be attributable to greenhouse gas emissions. The agricultural losses and internal migration from rural to urban areas can be directly linked to the drought and in this way are partly attributable to greenhouse gas emissions, although there are no studies comparing the observed losses and number of people displaced to a counterfactual situation of a weaker drought in a 'no climate change' situation. Current research does not provide enough evidence to attribute the civil war to climate change. In contrast, it is likely that social uprisings would have occurred even without the drought.

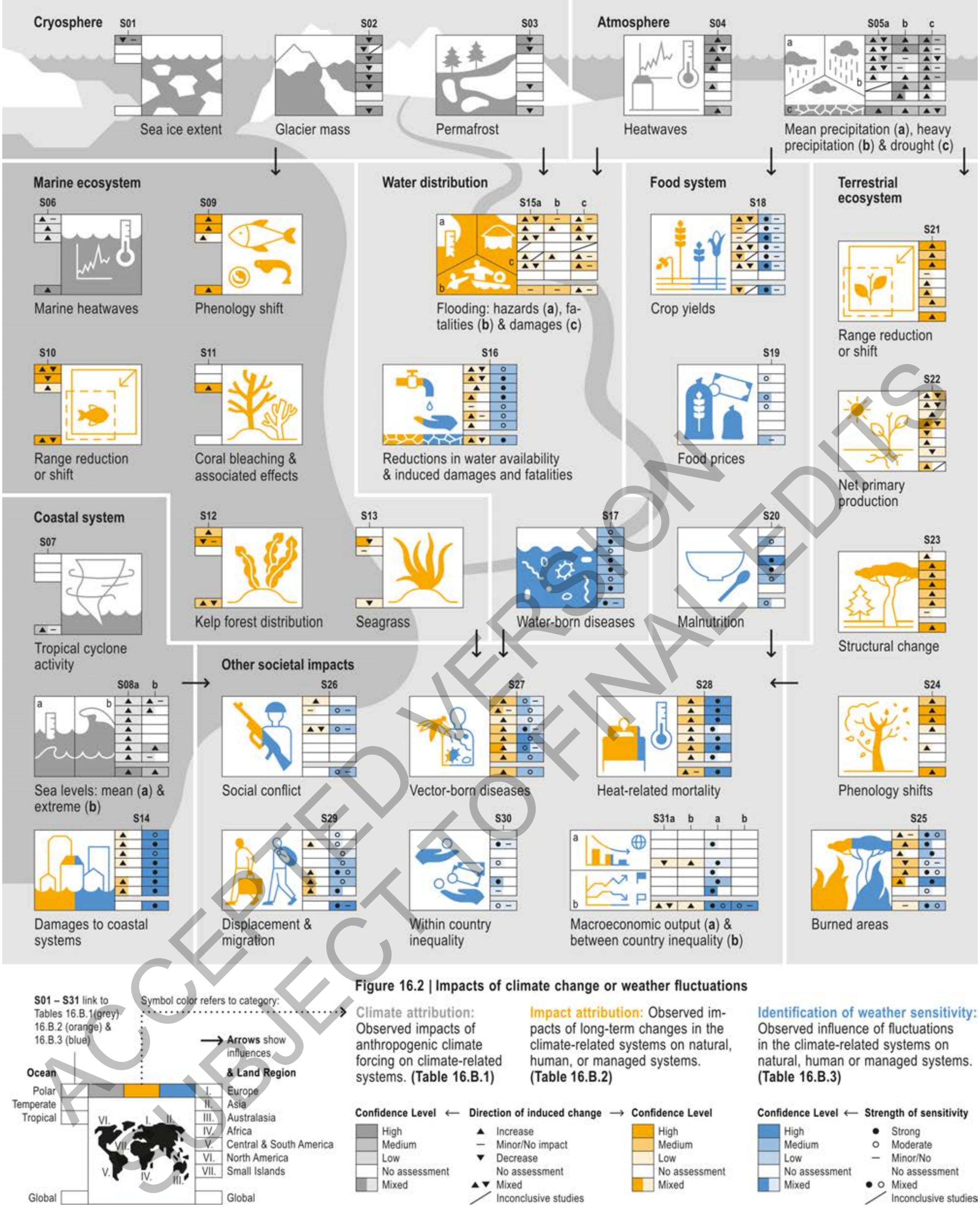


Figure 16.2: Impact of Climate Change or Weather Fluctuations.

16.3 Synthesis of Observed Adaptation-related Responses

A new development since AR5, is there is now growing evidence assessing progress on adaptation across sectors, geographies and spatial scales. Uncertainty persists around what defines adaptation and how to measure it (Cross-Chapter Box FEASIB in Chapter 18, UNEP, 2021). As a result, most literature synthesizing responses are based on documented or reported adaptations only, and are thus subject to substantial reporting bias.

We document implemented adaptation-related responses that could directly reduce risk. Adaptation *as a process* is more broadly covered in Chapter 17 (Section 17.4.2), including risk management, decision-making, planning, feasibility (see Cross-Chapter Box FEASIB in Chapter 18), legislation and learning. Here, we focus on a subset of adaptation activities: adaptation-related responses of species, ecosystems, and human societies that have been implemented, observed, and could directly reduce risk. We consider all adaptation-related responses to assumed, perceived, or expected climate risk, regardless of whether or not impacts or risks have been formally attributed to climate change.

We use the term 'adaptation-related responses', recognising that not all responses reduce risk. While 'adaptation' implies risk reduction, we use the broader term 'responses' to reflect that responses may decrease risk, but in some cases may increase risk.

It is not currently possible to conduct a comprehensive global assessment of effectiveness, adequacy, or the contribution of adaptation-related responses to changing risk due to an absence of robust empirical literature. This constrains assessment of adaptation progress and gaps in the context of over-shoot scenarios. Given limited evidence to inform comprehensive global assessment of effectiveness and adequacy, we assess evidence that adaptation responses in human systems indicate transformational change. Chapter 17 considers adaptation planning and governance, including adaptation solutions, success, and feasibility assessment (Cross-Chapter Box FEASIB in Chapter 18), discussed further in Box 16.1 (also see Cross-Chapter Box PROGRESS in Chapter 17).

In natural ecosystems or species, detectable changes can be considered as 'impact' or 'response'. The distinction between 'observed impacts' (16.2) and 'observed responses' (16.3) is not always clear. For example, autonomous distributional shifts in wild species induced by increasing temperatures (an observed impact) may reduce risk to the species (an autonomous adaptation response), but this process can be enhanced or supported by human intervention such as intentional changes in land use. Observed autonomous changes in natural ecosystems or species unsupported by human intervention are treated as impacts (see Section 16.2).

Adaptation-related responses are frequently motivated by a combination of climatic and non-climatic drivers, and interact with other transitions to affect risk. For societal responses, it is difficult to say whether they are triggered by observed or anticipated changes in climate, by non-climatic drivers, or a combination of all three. In the case of observed impacts, assessment typically focuses on detection and attribution *vis à vis* a counterfactual of no climate change. While there has been some effort to attribute reduced climate risk to adaptation-related responses (Toloo et al., 2013a; Toloo et al., 2013b; Hess et al., 2018; Weinberger et al., 2018), in many cases this has not been feasible given difficulties in defining adaptation and empirically disentangling the contribution of intersecting social transitions and changing risks. Literature on adaptation-related response frequently draws on theories-of-change to assess the likely contribution of adaptations to changes in risk, including maladaptation and co-benefits.

16.3.1 Adaptation-related Responses by Natural Systems

There is growing evidence of shifts in species distributions and ecosystem structure and functioning in response to climate change (Chapter 2). While many species are increasingly responding to climate change, there is limited evidence that these responses will be fully adaptive, and for many species the rate of response appears insufficient to keep pace with the rate of climate change under mid- and high-range emissions scenarios (*medium confidence*). There is relatively limited, but growing, empirical data to document adaptation of natural systems in the absence of human interventions. For example, Scheffers et al. (2016) reviewed climate responses across diverse species, reporting widespread and extensive observed changes in organisms (genetics, physiology, morphology), populations (phenology, abundance and dynamics), species (distributions), and ecosystems. A systematic review by Franks et al. (2014) synthesized evidence from 38 empirical studies of changes in terrestrial plant populations, finding evidence to support a mix of plastic and evolutionary responses. Boutin and Lane (2014) similarly reviewed adaptive responses in mammals, finding most species' responses due to phenotypic plasticity. Charmantier and Gienapp (2014) reviewed responses to climate change among birds, finding emerging evidence that birds from a range of taxa show advancement in their timing of migration and breeding in response to warming. Aragão et al.

(2018) reviewed adaptation responses in marine systems, including 12 studies of live marine mammals. They observed widespread evidence of shifting distributions and timing of biological events (Chapter 2, Chapter 3, and Cross-Chapter Paper 1 on Biodiversity Hotspots).

Some ecosystems and species' responses may be insufficient to keep pace with rates of climate change. It is difficult to distinguish whether adaptations are due to genotypic change or to phenotypic plasticity. Long-term natural adaptations will require the former, but the latter may provide short-term coping mechanisms to 'buy time' to respond to climate changes or lay foundations for evolutionary adaptation. There is mixed evidence regarding evolutionary versus plastic responses, with relatively limited evidence of longer-term evolutionary responses of species that can be associated with climate change. Similarly, it is difficult to assess whether responses are indeed potentially adaptive (e.g., coping, shifting, migrating) or simply reflective of impacts (e.g., stress, damage). Among mammal responses reviewed by Boutin and Lane (2014), for example, only 4 of 12 studies found some evidence that responses were adaptive. Even where adaptive responses are occurring, they may not be sufficient to keep pace with the rate of climate change. found, for example, that among the twelve studies in their review that directly assessed the sufficiency of responses to keep pace with the rate of climate change, eight concluded that responses would be insufficient to avert extinction.

16.3.2 Adaptation-related Responses by Human Systems

The literature that seeks to assess adaptation progress is growing at the global (Berrang-Ford et al., 2021a), regional (Bowen and Ebi, 2015; England et al., 2018; Robinson, 2018a; Wirehn, 2018; Olazabal et al., 2019; Thomas et al., 2019a; Biesbroek et al., 2020; Canosa et al., 2020; Robinson, 2020b), national (Hegger et al., 2017; Lesnikowski et al., 2019a; Lesnikowski et al., 2019b), and municipal (Araos et al., 2016; Reckien et al., 2018; Reckien et al., 2019; Lesnikowski et al., 2020; Singh et al., 2021) levels, using National Communications (Gagnon-Lebrun and Agrawala, 2007; Lesnikowski et al., 2015; Muchuru and Nhamo, 2017), local climate change action plans (Regmi et al., 2016b; Regmi et al., 2016a; Reckien et al., 2018; Reckien et al., 2019), adaptation project proposals, and reported adaptations in the peer reviewed literature. There remains persistent publication bias in the evidence base on adaptation given the difficulty of integrating diverse knowledge sources (see Section 16.3.3). To better assess how adaptation is occurring in human systems, we draw on this literature base and characterize evidence of adaptation across regions and sectors in terms of five key questions (Table 16.4, Ford et al., 2013; Biagini et al., 2014; Ford et al., 2015a; Bednar and Henstra, 2018; Reckien et al., 2018; Tompkins et al., 2018): What types of hazards are motivating adaptation-related responses? Who is responding? What types of responses are being documented? What evidence is available on adaptation effectiveness, adequacy, and risk reduction? To characterize evidence that adaptation responses indicate transformation, we use a typology based on four dimensions of climate adaptation: scope, depth, and speed, and consideration of limits to adaptation (Section 16.4, Termeer et al., 2017; Berrang-Ford et al., 2021a).

16.3.2.1 What Hazards are Motivating Adaptation-related Responses?

Drought and precipitation variability are the most prevalent hazards in the adaptation literature, particularly in the context of food and livelihood security. Adaptation frequently occurs in response to specific rapid or slow-onset physical events that can have adverse impacts on people. In some cases, people adapt in anticipation of climate change in general or to take advantage of new opportunities created by hazards (e.g., increased navigability due to melting sea ice). There is evidence that prior experience with hazards increases adaptation response (Barreca et al., 2015). Following drought and precipitation variability, the next specific hazards that are most frequently documented in the global adaptation literature are heat and flooding. Heat, while less salient, appears to be a driver of adaptation across all regions and sectors (Stone Jr et al., 2014; Hintz et al., 2018; Nunfam et al., 2018). Drought, extreme precipitation, and inland flooding are commonly reported in the context of water and sanitation (Bauer and Steurer, 2015; Lindsay, 2018; Kirchhoff and Watson, 2019; Hunter et al., 2020; Simpson et al., 2020). Flooding is frequently reported as a key hazard for adaptation in cities, followed by drought, precipitation variability, heat, and sea level rise (Broto and Bulkeley, 2013; Araos et al., 2016; Georgeson et al., 2016; Mees, 2017; Reckien et al., 2018; Hunter et al., 2020).

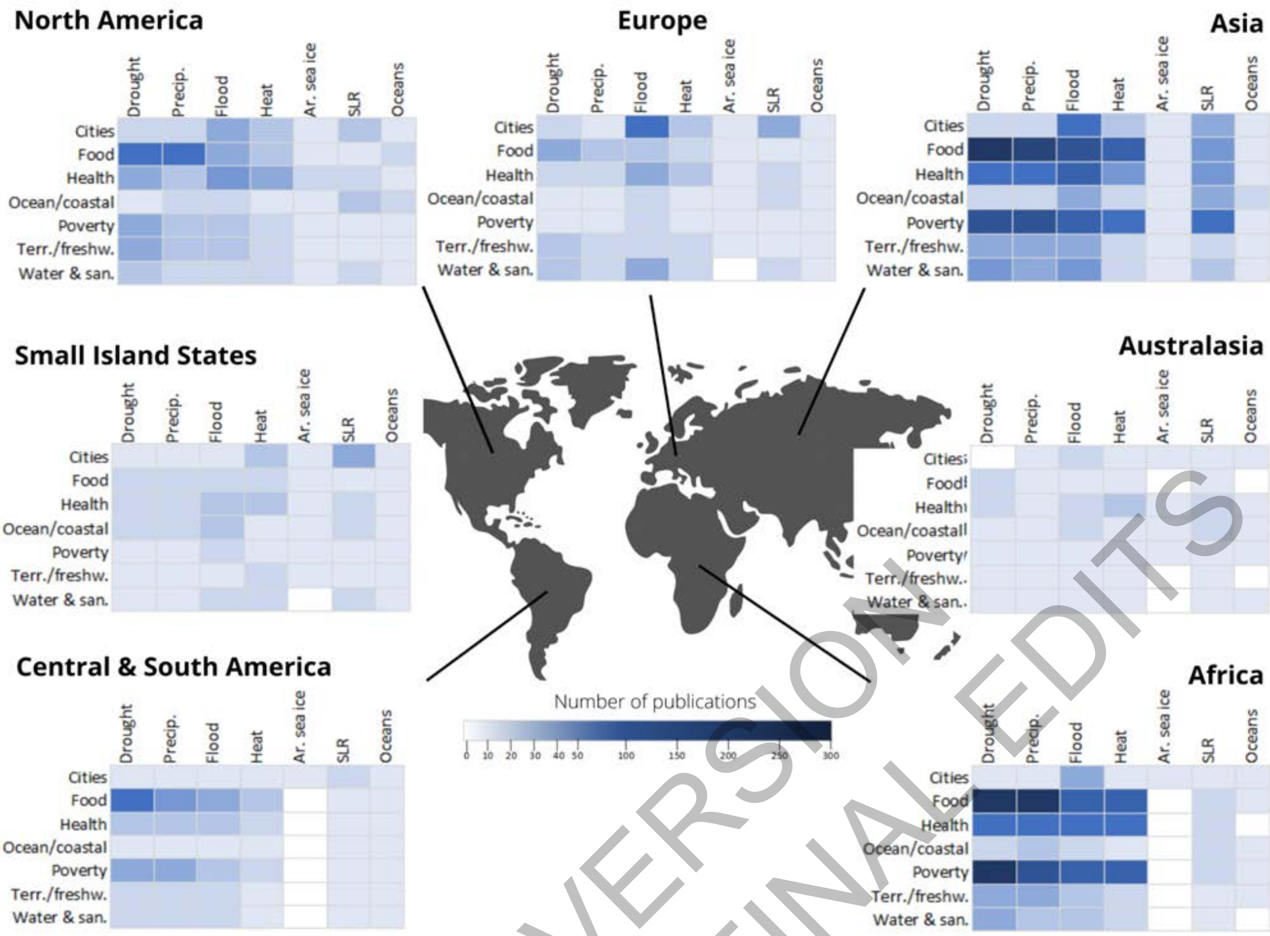


Figure 16.3: Salience of different types of hazards in the scientific literature on adaptation-related responses (i.e., responses that people undertake to reduce risk from climate change and associated hazards). Updated from a systematic review of 1,682 scientific publications (2013-2019) reporting on adaptation-related responses in human systems (Berrang-Ford et al., 2021a). Numbers in table reflect the number of publications reporting. Darker colours denote more extensive reporting on a hazard as a motivating factor for the response. Publications are counted in all relevant regions or sectors.

16.3.2.2 Who is Responding?

Individuals and households play a central role in adaptation globally. The most frequently reported actors engaged in adaptation-related responses in the scientific literature are individuals and households, particularly in the global south (Fig. 16.4). Regionally, household- and individual-level adaptation is documented most extensively in Africa and Asia, and to a lesser but still substantial extent in North America (Fig. 16.4).

National and local governments are also frequently engaged in reported adaptation across most regions. In Africa and Asia, reported adaptations have been primarily associated with individuals, households, national governments, NGOs, and international institutions, with more limited reporting of involvement from sub-national governments or the private sector (Ford et al., 2015a; Ford and King, 2015; Hunter et al., 2020). Engagement by sub-national governments in adaptation is more frequently documented in Europe and North America (Craft and Howlett, 2013; Craft et al., 2013; Bauer and Steurer, 2014; Lesnikowski et al., 2015; Shi et al., 2015; Austin et al., 2016). Reporting of private sector engagement is generally low. Civil society participation in adaptations is reported across all regions. Consistent with this, local governments are also widely reported in documented adaptation responses, particularly where municipal jurisdiction is high, including cities, infrastructure, water, and sanitation.

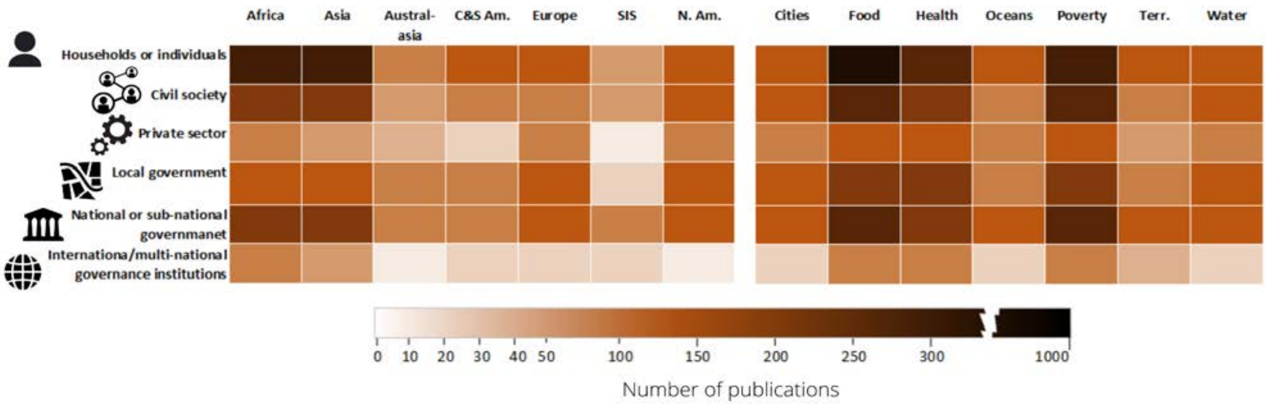


Figure 16.4: Who is responding, by geographic region and sector? Cell contents indicate the number of publications reporting engagement of each actor in adaptation-related responses. Darker colours denote a high number of publications. Based on a systematic review of 1,682 scientific publications (2013-2019) reporting on adaptation-related responses in human systems (Berrang-Ford et al., 2021a). SIS: Small Island States; Terr: Terrestrial and freshwater ecosystems.

16.3.2.3 What Types of Responses are Documented?

Behavioural change is the most common form of adaptation. The scientific literature presents extensive evidence of behavioural adaptation -- change in the strategies, practices, and actions that people, particularly individuals and households, undertake to reduce risk (Figure 16.5). This includes, for example, household measures to protect homes from flooding, protect crops from drought, relocation out of hazard zones, and shifting livelihood strategies (Porter et al., 2014). This is followed by adaptation via technological innovation and infrastructural development, nature-based adaptation (enhancing, protecting, or promoting ecosystem services), and institutional adaptation (enhancing multilevel governance or institutional capabilities). Behavioural adaptation is most frequently documented in Asia, Africa, and Small Island States, and in the agriculture, health, and development sectors. In the agricultural sector, households are adopting or changing to crops and livestock that are more adapted to drought, heat, moisture, pests, and salinity (Arku, 2013; Kattumuri et al., 2017; Wheeler and Marning, 2019). Studies in Africa and Asia have documented shifts in farming and animal husbandry practice (Arku, 2013; Garcia de Jalon et al., 2016; Gautier et al., 2016; Chengappa et al., 2017; Epule et al., 2017; Kattumuri et al., 2017; Abu and Reed, 2018; Asadu et al., 2018; Haeffner et al., 2018; Shaffril et al., 2018; Wiederkehr et al., 2018; Zinia and McShane, 2018; Currenti et al., 2019; Fischer, 2019a; Fischer, 2019b; Schofield and Gubbels, 2019; Sereenonchai and Arunrat, 2019; Wheeler and Marning, 2019; Mayanja et al., 2020). In Small Island Nations, studies have documented household flood protections measures such as raising elevation of homes and yards, creating flood barriers, improving drainage, moving belongings, and in some cases, relocating (Middelbeek et al., 2014; Currenti et al., 2019; Klock and Nunn, 2019).

The mix of adaptation response types differs across regions and sectors. Technological and infrastructural responses are widely reported in Europe, and globally in the context of cities and water and sanitation (Mees, 2017; Hintz et al., 2018). Responses to flood risk in Europe include the use of flood and climate resistant building materials, large scale flood management, and water storage and irrigation systems (van Hooff et al., 2015; Mees, 2017). Technological and infrastructural responses are also documented to some extent in agriculture, including for example breeding more climate resilient crops, precision farming and other high-tech solutions such as genetic modification (Makhado et al., 2014; Fisher et al., 2015; Costantini et al., 2020; Fraga et al., 2021; Grusson et al., 2021; Naulleau et al., 2021). While less common, institutional responses are more prominent in North America and Australasia as compared to other regions, and include zoning regulations, new building codes, new insurance schemes, and coordination mechanisms (Craft and Howlett, 2013; Craft et al., 2013; Parry, 2014; Ford et al., 2015b; Beiler et al., 2016; Lesnikowski et al., 2016; Labbe et al., 2017; Sterle and Singletary, 2017; Hu et al., 2018; Conevska et al., 2019). Institutional adaptations are more frequently reported in cites than other sectors. Institutional adaptation may be particularly subject to reporting bias, however, with many institutional responses likely to be reported in the grey literature (see Chapter 17). Nature-based solutions are less frequently reported, except in Africa, where they are relatively well-documented, and in the content of terrestrial systems where reports included species regeneration projects, wind breaks, erosion control, reforestation, and riparian zone management (Munji et al., 2014; Partey et al., 2017; Muthee et al., 2018).

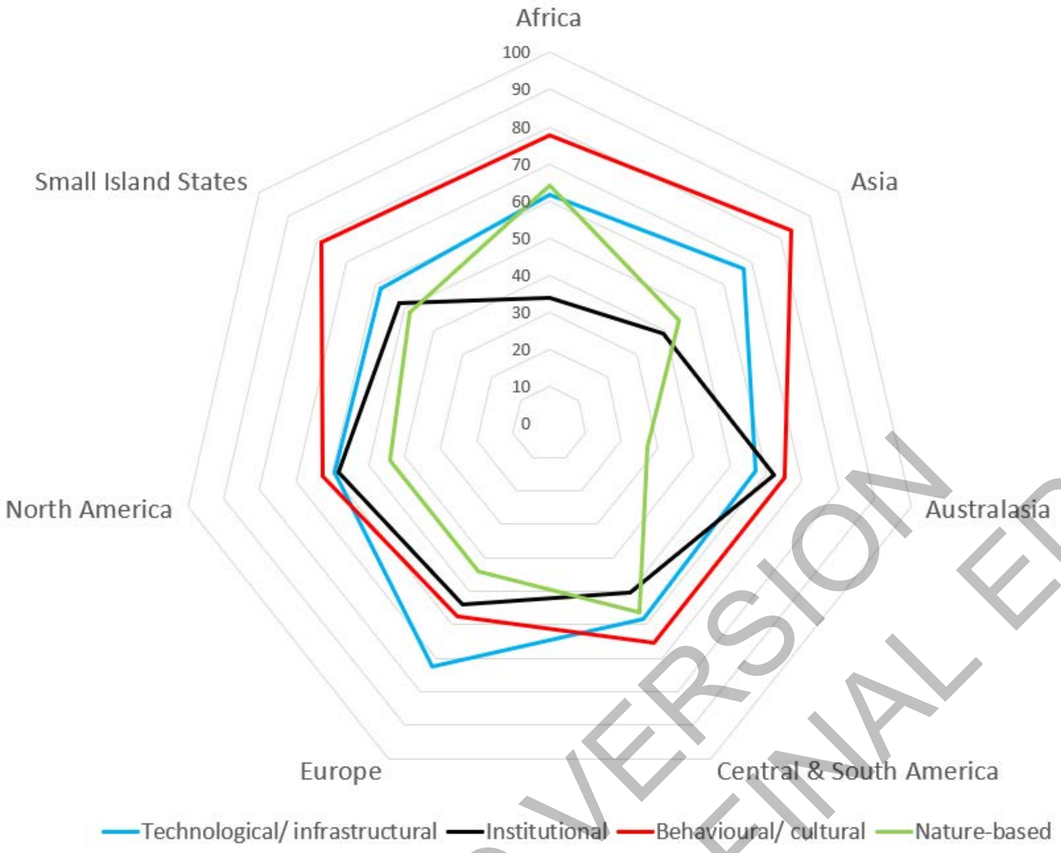


Figure 16.5: Type of adaptation responses by global region. Percentages reflect the number of articles mentioning each type of adaptation over the total number of articles for that region. Radar values do not total 100% per region since publications frequently report multiple types of adaptation; for example, construction of drainage systems (infrastructural), changing food storage practices by households (behavioural), and planting of tree cover in flood prone areas (nature-based) in response to flood risk to agricultural crops. Data updated and adapted from Berrang-Ford et al. (2021a), based on 1682 scientific publications reporting on adaptation-related responses in human systems.

Some but not all adaptation-related responses are engaging vulnerable populations in planning or implementation (*high confidence)* (Araos et al., 2021). Consideration of vulnerable populations is most frequently focused on low-income populations and women through the inclusion of informal or formal institutions or representatives in adaptation planning, or through targeted adaptations to reduce risk in these populations (*high confidence*). Consideration of vulnerable groups in adaptation responses are more frequently reported in the global south (*medium confidence*). Engagement in adaptation planning of vulnerable elderly, migrants, and ethnic minorities remains low across all global regions *(medium confidence)*. There is negligible literature on consideration of disabled peoples in planning and implementation of adaptation-related responses *(medium confidence)*.

16.3.2.4 Adaptation Effectiveness, Adequacy, and Risk Reduction

Despite a lack of systematic methods for assessing general adaptation effectiveness, there is some evidence of risk reduction for particular places and hazards, especially flood and heat vulnerability. There is some evidence of a reduction in global vulnerability, particularly for flood risk (Jongman et al., 2015; Tanoue et al., 2016; Miao, 2019) and extreme heat (Bobb et al., 2014; Boeckmann and Rohn, 2014; Gasparrini et al., 2015; Arbuthnott et al., 2016; Chung et al., 2017; Sheridan and Allen, 2018; Folkerts et al., 2020). Investment in flood protection, including building design and monitoring and forecasting, have reduced flood-related mortality over time and are cost-effective (Bouwer & Jonkman 2018; Ward et al. 2017).

Declining heat sensitivity, primarily reported in developed nations, has also been observed, and has been linked to air conditioning, reduced social vulnerability, and improved population health (Boeckmann and Rohn, 2014; Chung et al., 2017; Kinney, 2018; Sheridan and Allen, 2018). Formetta and Feyen (2019) demonstrate declining global all-cause mortality and economic loss due to extreme weather events over the past four decades, with the greatest reductions in low income countries, and with reductions correlated with wealth. Studies that correlate changes in mortality or economic losses with wealth indicators, to infer changes in vulnerability or exposure, lack direct empirical measures of vulnerability or exposure and are limited in their ability to assess how indirect effects of extreme events (e.g., morbidity, relocation, social disruption) may have changed or how changes may redistribute risk across populations.

There remain persistent difficulties in defining and measuring adaptation effectiveness and adequacy for many climate risks. No studies have systematically assessed the adequacy and effectiveness of adaptation at a global scale, across nations or sectors, or for different levels of warming. There has, however, been progress in operationalizing assessment of adaptation feasibility (Cross-Chapter Box FEASIB in Chapter 18). Effectiveness of adaptation-related responses reflects whether a particular response actually reduces climate risk, typically through reductions in vulnerability and exposure (Fig 1.7 in Section 1.4). Some adaptation-related responses may increase risk or create new risks (maladaptation) or have no or negligible impact on risk. Adequacy of adaptation-related responses refers to the extent to which responses are collectively sufficient to reduce the risks or impacts of climate change (Fig 1.7 in Section 1.4). A set of adaptation-related responses may, for example, result in reduced climate risk (effectiveness), but these reductions may be insufficient to offset the level of risk and avoid loss and damages. Feasibility reflects the degree to which climate responses are possible or desirable, and integrates consideration of potential effectiveness. A feasibility assessment drawing on these methods is presented in (Cross-Chapter Box FEASIB in Chapter 18).

Global adaptation is predominantly slow, siloed, and incremental with little evidence of transformative adaptation (*high confidence*). In the absence of a general method to assess the adequacy of adaptation actions, we assessed evidence for transformational adaptation documented in peer-reviewed publications identified by a global stock-taking initiative (Berrang-Ford et al., 2021b) and in other AR6 chapters (2-15) (see Supplemental Material, SM16.1 for details). 'Transformational adaptation' refers to the degree to which adaptations have been implemented widely (scope), reflect major shifts (depth), occur rapidly (speed), and challenge limits to adaptation (limits, Pelling et al., 2015; Few et al., 2017; Termeer et al., 2017, Table 16.1).

Table 16.1: Evidence of transformational adaptation assessed across four components (depth, scope, speed, and limits). Transformational adaptation does not imply adequacy or effectiveness of adaptation (low transformation may be sufficient for some climate risks, and high transformation may be insufficient to offset others). Nevertheless, these components provide a systematic framework for tracking adaptation progress and assessing the state of adaptation-related responses. The 'high' categories across each component reflect more transformative scenarios. Methods are described in Supplementary Material (SM16.1).

	Transformative potential of adaptation		
Dimensions	Low	Medium	High
Overall	Adaptation is largely sporadic and consists of small adjustments to business-as-usual. Coordination and mainstreaming are limited and fragmented.	Adaptation is expanding and increasingly coordinated, including wider implementation and multi-level coordination.	Adaptation is widespread and implemented at or very near its full potential across multiple dimensions.

Depth	Adaptations are largely expansions of existing practices, with minimal change in underlying values, assumptions, or norms.	Adaptations reflect a shift away from existing practices, norms, or structures to some extent.	Adaptations reflect entirely new practices involving deep structural reform, complete change in mindset, major shifts in perceptions or values, and changing institutional or behavioral norms.
Scope	Adaptations are largely localized and fragmented, with limited evidence of coordination or mainstreaming across sectors, jurisdictions, or levels of governance.	Adaptations affect wider geographic areas, multiple areas and sectors, or are mainstreamed and coordinated across multiple dimensions.	Adaptations are widespread and substantial, including most possible sectors, levels of governance, and actors.
Speed	Adaptations are implemented slowly.	Adaptations are implemented moderately quickly.	Change is considered rapid for a given context
Limits	Adaptations may approach but do not exceed or substantively challenge soft limits.	Adaptations may overcome some soft limits but do not challenge or approach hard limits.	Adaptations exceed many soft limits and approach or challenge hard limits.

Based on the literature, the overall transformative nature of adaptation across most global regions and sectors is low (*high confidence)* (Figure 16.6). Documented adaptations tend to involve minor modifications to usual practices taken to address extreme weather conditions (*high confidence*). For example, changing crop variety or timing of crop planting to address floods or droughts, new types of irrigation, pursuing supplementary livelihoods, and home elevations are widely reported but typically do not reflect radical or novel shifts in practice or values and are therefore considered low-depth (*high confidence*) (see Supplementary Material, SM16.1 for more examples). Adaptations documented in the literature are also frequently focused on a single sector or small geographic area (*high confidence*). Actions taken by individuals or households are generally small in scope (Hintz et al., 2018; Hlahla and Hill, 2018) unless they are widely adopted (e.g., by farmers across a region) or address numerous aspects of life. National policies are more likely to be broad in scope (Puthucherril et al., 2014), although they frequently focus on a single sector and are therefore still limited. The speed of adaptation is rarely noted explicitly, but the average speed documented in the literature is slow (*medium confidence*) (Cross-Chapter Box FEASIB in Chapter 18). Adaptation efforts frequently encounter either soft or hard limits (see Section 16.4), but there is limited evidence to suggest these limits are being challenged or overcome (*medium confidence*).

Few documented responses are simultaneously widespread, rapid, and novel (*high confidence*). Some examples exist, such as village relocations or creation of new multi-stakeholder resource governance systems (Schwan and Yu, 2018; McMichael and Katonivualiku, 2020), but these are rare. In general, adaptations that are broad in scope tend to be slow (*medium confidence*), suggesting that achieving high transformation in all four categories (depth, scope, speed, and limits) may be particularly challenging or even involve trade-offs.

Figure 16.6. Evidence of transformative adaptation by sector and region. Evidence of transformational adaptation does not imply effectiveness, equity, or adequacy. Evidence of transformative adaptation is assessed based on the scope, speed, depth, and ability to challenge limits of responses reported in the scientific literature (see Supplementary Material for methods). Studies relevant to multiple regions or sectors are included in assessment for each relevant sector/region.

16.3.2.5 Observed Maladaptation and Co-benefits

There is increasing reporting of maladaptation globally (Table 16.2, Section 17.5.1) (*high confidence*). Maladaptation has been particularly reported in the context of agricultural, forestry, and fisheries practices, migration in the global south, and some infrastructure based-interventions. Urban heat adaptations have been linked to maladaptation that increase health risks and/or energy consumption. Heat poses significant risks to the evolutionary tolerance levels of humans, animals, and crops (Asseng et al., 2021), and current adaptation interventions for reducing urban heat like cool or evaporation roofs and street trees may be insufficient to reduce heat-related vulnerabilities in some urban areas at higher levels of warming (Krayenhoff et al., 2018) (see also Section 16.4 on adaptation limits). There is evidence that autonomous adaptation by individuals and households can shift risk to others, with net increases in vulnerability. Intensification of pasture use as a coping response to climate-induced drought has been observed to increase risks to livestock reproduction and human life expectancy due to overgrazing, suggesting responses to pastoral vulnerability can cross tolerance limits for animals, humans, and food available for foraging (Suvdantsetseg et al., 2017).

Evidence on *realized* co-benefits of implemented adaptation responses with other priorities in the sustainable development goals is emerging among the areas of poverty reduction, food security, health and well-being, terrestrial and freshwater ecosystem services, sustainable cities and communities, energy security, work and economic growth, and mitigation (Table 16.2) (*high confidence*). Evidence on co-benefits of adaptation for mitigation is particularly strong, and is observed in various agricultural, forestry and land use management practices like agroforestry, climate smart agriculture and afforestation (Kremen and Miles, 2012; Christen and Dalgaard, 2013; Mbow et al., 2014; Locatelli et al., 2015; Suckall et al., 2015; Wichelns, 2016;

Kongsager, 2018; Debray et al., 2019; Loboguerrero et al., 2019; Morecroft et al., 2019; Chausson et al., 2020) as well as in the urban built environment (Perrotti and Stremke, 2020; Sharifi, 2020). Evidence on co-benefits of implemented responses for other SDG priority areas is less developed, however, in the areas of education, gender inequality and reduced inequalities, clean water and sanitation, industry, innovation and infrastructure, consumption and production, marine and coastal ecosystem protection, and peace, justice, and strong institutions. This indicates a gap between some assumed likely co-benefits of adaptation and empirical evidence on the realization of these co-benefits within the context of implemented adaptation responses (Berga, 2016; Froehlich et al., 2018; Gattuso et al., 2018; Morris et al., 2018; Chausson et al., 2020; Karlsson et al., 2020; Krauss and Osland, 2020).

Table 16.2: Observed examples of maladaptation and co-benefits from adaptation-related responses in human systems

Implemented adaptations	Observed maladaptation	References
Agricultural & forestry practices		
Intensified cultivation of marginal lands: clearing of virgin forests for farmland; frequent weeding; poorly-managed irrigation schemes; dependence on rainfed agriculture	Increased competition for resources such as water and nutrients; reduced soil fertility; invasive species; degraded environment; increased greenhouse gas emissions; reduced crops diversity and reduced harvest, thus increasing food insecurity in rural areas; accelerated illegal logging practices; increased vulnerability of herders and translated into poor health and working conditions (Mongolia)	Bele et al. (2014); D'haen et al. (2014); Chapman et al. (2016); Ifeanyi-obi et al. (2017); Suvdantsetseg et al. (2017); Villamayor-Tomas and Garcia-Lopez (2017); Afriyie et al. (2018); Ticehurst and Curtis (2018); Tran et al. (2018); Neset et al. (2019); Work et al. (2019); Yamba et al. (2019); Singh and Basu (2020)
Agroforestry systems	Higher water demand where trees were combined with crops and livestock; replaced native trees with non-indigenous trees; Reduced resilience of certain plants (e.g., cocoa); degraded soil and water quality and accelerated environmental degradation in Africa and Asia (Pakistan, Nepal, India, China, Philippines)	Nordhagen and Pascual (2013); D'haen et al. (2014); Hoang et al. (2014); Ruiz-Mallen et al. (2015); Kibet et al. (2016); Chengappa et al. (2017); Haji and Legesse (2017); Abdulai et al. (2018); Antwi-Agyei et al. (2018); Mersha and van Laerhoven (2018); Ullah et al. (2018); Krishnamurthy et al. (2019)
Agricultural transitions: Commercialization of common property; market-integration and sedentarisation of pastoralists; adoption and expansion of commercial crops	Soil degradation and high dependency on external inputs in South and Central America (El-Salvador, Guatemala, Honduras, Nicaragua, and Peru); dependency on foreign corporation seed systems; land enclosures. Adaptation that forced local farmers in Costa Rica to switch crops to commercially viable products (e.g., from rice to sugar cane) impoverished the land by removing nutrients and affecting food security for smallholder farmers.	Nordhagen and Pascual (2013); D'haen et al. (2014); Warner et al. (2015); Kibet et al. (2016); (Warner and Kuzdas, 2016); Haji and Legesse (2017); Antwi-Agyei et al. (2018); Mersha and van Laerhoven (2018); Krishnamurthy et al. (2019); Neset et al. (2019)
Proper, improper, and increased use of agrochemicals, pesticides, and fertilizers	Fertilizer and agrochemicals negatively affected soil quality and accelerated environmental degradation in several parts of Africa (Ghana, Nigeria) and Asia (Pakistan, Nepal, India, China, Philippines). In Europe (Sweden and Finland) there are concerns about the risk of pests and weeds developing immunity to pesticides, and drainage systems and rain transferred chemicals to other fields, thereby affecting arable land. In South and Central America (El-Salvador, Guatemala, Honduras, Nicaragua, and Peru) agrochemicals led to soil degradation, and high dependency on external input was reported. Loss of soil nutrients, increased GHG emissions (Sweden, Finland); high nitrate and phosphate concentration (Great Britain)	Postigo (2014); Rodriguez-Solorzano (2014); Fezzi et al. (2015); Sujakhu et al. (2016); Begum and Mahanta (2017); de Sousa et al. (2018); Tang et al. (2018); Yamba et al. (2019)

Tree planting	The lack of shaded trees increased vulnerability to landslides in areas where Robusta coffee was grown (Mexico); new tree species to cope with climate change increased sensitivity and displaced non-indigenous trees (India; Tanzania and Kenya); Cocoa planted under shade trees had higher mortality rate and more stress (Ghana); Eucalyptus trees planted to reduce soil erosion had high water demand (Pakistan); In certain urban areas, trees planted to provide shade damaged buildings during heavy storms.	Benito-Garzon et al. (2013); Hoang et al. (2014); Ruiz Meza (2015); Chengappa et al. (2017); Abdulai et al. (2018); Ullah et al. (2018)
Fisheries & water management		
Increased fishing activity	Fishery depletion and exacerbated negative trends in the ecosystem that threatened fishermen's subsistence	Goulden et al. (2013); Mazur et al. (2013); Rodriguez-Solorzano (2014); Pershing et al. (2016); Kanda et al. (2017); Kihila (2018); Pinsky et al. (2018)
Shrimp farming	A driver of deforestation of mangroves in Bangladesh; imposes external cost on paddy farmers; salinity levels are relatively higher in paddy plots closer to shrimp ponds. Coral mining increased vulnerability to flooding (in small islands in the Philippines)	Johnson et al. (2016); Jamero et al. (2017); Paprocki and Huq (2018); Sovacool (2018); Morshed et al. (2020)
Water irrigation infrastructure for agriculture; water desalination in response to water shortages	Increased land loss; redistributed risk among agrarian stakeholders; affected the rural poor (Cambodia; Costa Rica); uneven distribution of cost and benefits (US-Mexico border); Desalination plants to led disproportionately high cost for low income water users.	Barnett and O'Neill (2013); Olmstead (2014); Warner and Kuzdas (2016); Work et al. (2019)
Storage of large quantities of water in the home	Water rendered unsafe for drinking due contamination by fecal coliforms in Zimbabwe; drought-induced changes in water harvesting and storage increased breeding sites for mosquitoes (Australia); Water storage facilities and tanks provided ideal breeding conditions for mosquitoes and flies bringing both vectors and diseases closer to people (Ethiopia).	Boelee et al. (2013); Trewin et al. (2013); Kanda et al. (2017)
Increased number of farm dams for water storage; groundwater extraction and interbasin water transfers	Reduced river and ground water flow downstream; water grabs from shared surface or groundwater resources with poorly defined property rights shifted vulnerability to other groups and ecosystems (Cambodia; California): water extractions increased risks for the environment and food security, while transfers reduced hydropower generation and resulted in higher costs paid by electricity consumers and health impacts from air pollution caused by more electricity generation from natural gas (California); increase the concentration in hands of the more powerful large farmers (Argentina)	Mazur et al. (2013); Christian-Smith et al. (2015); (Hurlbert and Mussetta, 2016); Work et al.)
Built environment		

Seawalls and infrastructural development along coastlines	Coastal erosion, beach losses, changes in water current, and destruction of natural ecosystems in Asia, Australasia, Europe, and North America; increased or shifted erosion from protected to unprotected areas in Fiji, Marshall Islands, Nuie, Kiribati, Norway; failed or sped up flood waters and worsened conditions for riparian habitat and downstream residents; harmed nearby reefs and impeded autonomous adaptation practise that could be effective (Bangladesh).	Macintosh (2013); Maldonado et al. (2014); Porio (2014); Betzold (2015); Renaud et al. (2015); Gundersen et al. (2016); Sayers et al. (2018); Craig (2019); Javeline and Kijewski-Correa (2019); Loughran and Elliott (2019); Rahman and Hickey (2019); Piggott-McKellar et al. (2020); Simon et al. (2020) Dahl et al. (2017)
Smart or green luxury real estate development designed to reduce impacts from storm surges and erosion along coastal area; artificial islands.	Redistributed risk and vulnerability; displaced and diminished adaptive capacity of vulnerable groups, created new population of landless peasants; negatively affected neighbouring coastal areas and local ecology (Lagos, Miami, Hanoi, Jakarta, Manila; Maldives)	Caprotti et al. (2015); Magnan et al. (2016); Atteridge and Remling (2018); Ajibade (2019); Salim et al. (2019); Thomas and Warner (2019)
Subsidized insurance premiums for properties located in flood-prone areas, levees, dykes	Rebuilding in risky areas	Shearer et al. (2014); O'Hare et al. (2016); Craig (2019); Loughran and Elliott (2019)
Autonomous flood strategies such as sand bags, digging channels and sand walls around homes.	Sand bags used to reduce coastal erosion released plastics into the sea and led to loss of recreational value of beaches; sand walls shifted the flood impacts across space and time and were more detrimental to poor informal urban settlers (Dakar); caused erosion and degraded coastal lands (South Africa).	Schaer (2015); Wamsler and Brink (2015); (Chapman et al., 2016); Magnan et al. (2016); Mycoo (2018); Rahman and Hickey (2019)
Top-down technocratic adaptation with no consideration for ecosystem biodiversity, local adaptive capacity, and gender issues	Ignored the complexities of the landscapes and socio-ecological systems; constrained autonomous adaptation due to time and labour demands of public work; increased gender vulnerability; hamper women's water rights (South Africa); altered local gender norms (Ethiopia); led to a mismatch that undermine local-level processes that are vital to local adaptive capacity (Rwanda)	Cartwright et al. (2013); Goulden et al. (2013); Nordhagen and Pascual (2013); Carr and Thompson (2014); Nyamadzawo et al. (2015); Ruiz-Mallen et al. (2015); Djoudi et al. (2016); Gautier et al. (2016); Gundersen et al. (2016); Barnett and McMichael (2018); Kihila (2018); Mersha and van Laerhoven (2018); Clay and King (2019); Currenti et al. (2019); Yang et al. (2019)
Migration & relocation		
Out-migration or rural to urban migration in response to food insecurity and agricultural livelihood depreciation	Migration mostly undertaken by poorer household weakened local subsistence production capacity; disrupted family structures; reduced labour available for agricultural work; increased burden of responsibilities on women; fostered loss of solidarity within communities; increased divorce rates; exacerbated conflicts among different groups; increased pressure on urban housing and social services; expanded slum settlements around riparian and coastal areas including flood plains and swamplands (Ethiopia, Namibia, Benin, Botswana, Nigeria, Ghana, Kenya, Niger, Mail, Tanzania, Zimbabwe, South Africa, Morocco, Nepal, Pakistan, Bangladesh China, India, Australia, Nicaragua). Out-migration from small communities had devastating consequences on their fragile economies, thereby reducing community resilience in the long term (Australia).	Su et al. (2017);Aziz and Sadok (2015);Bhatta and Aggarwal (2016);Clay and King (2019); Elagib et al. (2017);Gao and Mills (2018); Kattumuri et al. (2017); Magnan et al. (2016); Ofoegbu et al. (2016); Rademacher-Schulz et al. (2014);Rademacher-Schulz et al. (2014);Wiederkehr et al. (2018); Yegbemey et al. (2017); Yila and Resurreccion (2013); Nizami et al. (2019); Mersha and Van Laerhoven (2016); Ojha et al. (2014); Radel et al. (2018); Gioli et al. (2014); Hooli (2016); Koubi et al. (2016)

Certain autonomous, forced, and planned relocation Temporary resettlement (India)	Expansion of informal settlements in cities (Solomon Islands); relocation to areas prone to landslide and soil erosion or insufficient housing (Fiji); disproportionate burden on vulnerable communities (China); temporary relocation created gender inequality associated with minimal privacy; poor access to private toilets; sexual harassment; reduced sleep; insufficient or food rationing; exploitation and abuse of children (India); inadequate funding and governance mechanism for community-based relocation caused loss of culture, economic decline and health concerns (Alaska); relocation of supply chain to reduce exposure to climate change resulted in adverse outcomes for communities along the supply chain.	Monnereau and Abraham (2013); Maldonado et al. (2014); Pritchard and Thielemans (2014); Averchenkova et al. (2016); Lei et al. (2017); Barnett and McMichael (2018); Currenti et al. (2019)
Implemented adaptations	Observed co-benefits	References
Agricultural practices		
Integrated agricultural practices (e.g., climate smart agriculture, urban and peri-urban agriculture and forestry; agroecology; silvopasture; soil desalinization; drainage improvement; integrated soil-crop system management; no tillage farming; rainwater harvesting; check dams)	Mitigation, especially carbon sequestration (but see (Sommer et al., 2018)); improved household equity regarding farming decisions, particularly inclusion of women; food security	Furman et al. (2014); Lwasa et al. (2014); Kibue et al. (2015); Nyasimi et al. (2017); Aryal et al. (2018); Han et al. (2018); Kakumanu et al. (2018); Sikka et al. (2018); Debray et al. (2019); Kerr et al. (2019); (Teklewold et al., 2019a); Teklewold et al. (2019b); Wang et al. (2020) Sommer et al. (2018)
Improved irrigation systems	Mitigation, especially avoided emissions; improved crop yields	Islam et al. (2020)
Conservation agriculture (e.g.crop diversification; soil conservation; cover cropping)	Mitigation, especially carbon sequestration; increased crop yields; food security; reduced heat and water stress; increased food security	Helling et al. (2015); Sapkota et al. (2015); Kimaro et al. (2016); Mainardi (2018); Asmare et al. (2019); Gonzalez-Sanchez et al. (2019)
Return to traditional farming practices	Mitigation, especially carbon sequestration	Pienkowski and Zbaraszewski (2019)
Place-specific practices & innovations: animal cross-breeding; direct crop seeding; site-specific nutrient management; irrigation innovations; use of riparian buffer strips;	Mitigation, especially carbon sequestration; improved crop yields; food security	Sushant (2013); Balaji et al. (2015); Helling et al. (2015); Jorgensen and Termansen (2016); Sen and Bond (2017); Wilkes et al. (2017); Kakumanu et al. (2018); Mainardi (2018); Sikka et al. (2018) Yadav et al. (2020)

use of green winter land; rice-rice system		
Land and water management		
Agroforestry	Mitigation, especially carbon sequestration; biodiversity and ecosystem conservation; improved food security; plant species diversification; diversification of household livelihoods; improved household incomes; improved access to forage material; energy access and reduced fuel wood gathering time and distance for women; soil and water conservation; aesthetic improvements in landscapes	Holler (2014); Suckall et al. (2015); Sharma et al. (2016); Nyasimi et al. (2017); Pandey et al. (2017); Schembergue et al. (2017); Ticktin et al. (2018); Debray et al. (2019); Jezeer et al. (2019); Krishnamurthy et al. (2019); Nyantakyi-Frimpong et al. (2019); Tschora and Cherubini (2020)
Afforestation and reforestation programs; Forest management practices (e.g., tree thinning)	Mitigation, especially carbon sequestration; biodiversity and ecosystem conservation; new employment opportunities; diversification of household livelihoods; increased household incomes; improved access to fuel wood; harvesting opportunities from enclosures	Holler (2014); Etongo et al. (2015); Diederichs and Roberts (2016); Acevedo-Osorio et al. (2017); Nyasimi et al. (2017); Krishnamurthy et al. (2019); Rahman et al. (2019) Wolde et al. (2016)
Ecosystem-based adaptations like mangrove restoration and natural coastal defences	Mitigation, especially carbon sequestration; habitat enhancement and protection for marine species; prevention of floor-related deaths, injuries, and damage; improved nutrition and income generation for local communities, improved water quality	Fedele et al. (2018) Roberts et al. (2012); Morris et al. (2019); (Jones et al., 2020)
Sustainable water management	Mitigation, especially avoided emissions; reduced water demand; increased awareness about impacts of water consumption; decreased incidence of fecaloral disease transmission; decreased use of drinking water for irrigation; reduced soil loss; increased groundwater retention; increased vegetation cover; increased food security and health and well-being; increased forage for livestock and amount of cultivated area; enhanced recreational areas	Spencer et al. (2017); Siraw et al. (2018); Stanczuk-Galwiaczek et al. (2018)
Return to traditional land management practices (e.g., the Ngitili system)	Mitigation, especially carbon sequestration; increased water availability for household and livestock use; increase in presence of edible and medicinal plants; regional economic growth; reduced land management conflicts; increased household income and access to education for children; improved access to wood fuel and reduced collection time for women; improved wildlife habitat.	Duguma et al. (2014)
REDD+ participation to maintain intact forest ecosystems	Mitigation, especially carbon sequestration; improved air quality; water and soil conservation; slowed rate of vector-borne disease; improved mental well-being associated with cultural continuity; clean water; nutritional and spiritual value of forest-derived foods; protection from violence related to natural resource extraction	McElwee et al. (2017); Spencer et al. (2017)
Urban planning and design		

Spatial planning – walkable neighbourhood design; strategic densification.	Mitigation, particularly avoided emissions; public health – increases in physical activity, reductions in air pollution and urban heat island effect	Beiler et al. (2016); Belanger et al. (2016)
Urban greening (e.g tree planting; construction of stormwater retention areas; construction of green roofs and cool roofs; provision of rainwater barrels; pervious pavement materials)	Mitigation, particularly avoided emissions; public health improvements – increases in physical activity, reductions in air and noise pollution, reduced urban heat island effect, improved mental health; urban flood risk management; water savings; energy savings	Samora-Arvela et al. (2017); Vahmani and Jones (2017); Newell et al. (2018); Alves et al. (2019); De la Sota et al. (2019)
Improved building efficiency standards	Mitigation, particularly avoided emissions; improved air quality; reduced urban heat island; improved natural indoor lighting	Barbosa et al. (2015); Koski and Siulagi (2016); Balaban and Puppim de Oliveira (2017); Landauer et al. (2019)
Use of local building materials	Mitigation, particularly avoided emissions	Lundgren-Kownacki et al. (2018)

16.3.3 Knowledge Gaps in Observed Responses

Many adaptation responses are not documented, and reporting bias is a key challenge for assessment of observed responses. Evidence of absence (i.e., where no adaptations are occurring) is different from absence of evidence (where responses are occurring but are not documented), with implications for understanding trends in global responses.

Adaptation is being reported differently across different sources of knowledge. The peer-reviewed literature, for example, has been primarily reporting reactive adaptation at the individual, household, and community levels, while the grey literature has been more mixed, reporting adaptation across governmental levels and civil society, with less focus on individuals and households (Ford et al., 2015a; Ford and King, 2015). Synthesis of impacts and responses within the private sector is particularly limited (Averchenkova et al., 2016; Minx et al., 2017), further suggesting that knowledge accumulation on climate responses has been particularly slow, and that more robust evidence synthesis is required to fill key knowledge gaps.

The potential for under-reporting is most acute in the context of minorities, remote and marginalized groups, who are often also be the most affected by the impacts of climate change and least able to respond to, or benefit from, the responses to, climate change (Araos et al., 2021). Deficits in reporting on impacts and responses are well-recognized in the global south, among vulnerable populations (e.g., women, socio-economically disadvantaged, indigenous, people living with disabilities), and within civil society (ibid.).

There is growing support for more comprehensive and systematic approaches to assess adaptation progress (Berrang-Ford et al., 2015; Ford et al., 2015a; Ford and King, 2015; Ford and Berrang-Ford, 2016; Biesbroek et al., 2018). Since AR5, there is increased recognition of the value of integrating diverse knowledge sources to fill knowledge gaps in observation of impacts and responses (Chapter 17; Cross-Chapter Box PROGRESS in Chapter 17). Van Bavel, for example, found that the involvement of local and diverse knowledge can improve the detection (*medium confidence*) and attribution (*medium confidence*) of health impacts, and improve the action (*high confidence*) (Van Bavel et al., 2020).

[START CROSS-CHAPTER BOX INTEREG HERE]

Cross-Chapter Box INTEREG: Inter-regional Flows of Risks and Responses to Risk

Authors: Birgit Bednar-Friedl (Austria, Chapter 13), Christopher Trisos (South Africa, Chapter 9), Laura Astigarraga (Uruguay, Chapter 12), Magnus Benzie (Sweden/United Kingdom), Aditi Mukherji (India, Chapter 4), Maarten Van Aalst (The Netherlands, Chapter 16)

Introduction

Our world today is characterized by a high degree of interconnectedness and globalization which establish pathways for the transmission of climate-related risks across sectors and borders (*high confidence*) (Challinor et al., 2018; Hedlund et al., 2018). While AR5 has pointed to this connection of risks across regions as 'cross-regional phenomena' (Hewitson et al., 2014), only a few countries so far have integrated interregional aspects into their climate change risks assessments (Liverman, 2016; Surminski et al., 2016; Adams et al., 2020) and adaptation is still framed as a predominantly national or local issue (Dzebo and Stripple, 2015; Benzie and Persson, 2019).

Interregional risks from climate change - also called cross-border, transboundary, transnational or indirect risks - are risks that are transmitted across borders (e.g., transboundary water use) and/or via teleconnections (e.g., supply chains, global food markets) (Moser and Hart, 2015). The risks can result from impacts, including compound or concurrent impacts, that cascade across several tiers, in ways that either diminish or escalate risk within international systems (Carter et al., 2021). Risk transmission may occur through trade and finance networks, flows of people (Cross-Chapter Box MIGRATE in Chapter 7), biophysical flows (natural resources such as water) and ecosystem connections. But not only risks are transmitted across borders and systems, but also the adaptation response may reduce risks at the origin of the risk, along the transmission channel or at the recipient of the risk (Carter et al., 2021). This Cross-Chapter Box discusses four interregional risk channels (trade, finance, food, and ecosystems) and how adaptation can govern these risks.

Figure Cross-Chapter Box INTEREG.1: Interregional climate risks: the example of the trade transmission channel, illustrated for the Thailand flood 2011 (Abe and Ye, 2013; Haraguchi and Lall, 2015; Carter et al., 2021)

Trade

Most commodities are traded on global markets and supply chains have become increasingly globalized. For instance, specialized industrial commodities like semi-conductors are geographically concentrated in a few countries (Challinor et al., 2017) (Liverman, 2016). When climatic events like flooding or heat affect the location of these extraction and production activities, economies are not only disrupted locally but also across borders and in distant countries (*high confidence*), as exemplified by the Thailand flood 2011 that led to a shortage of key inputs to the automotive and electronics industry not only in Thailand but also in Japan, Europe, and the USA (Figure Cross-Chapter Box INTEREG.1). For many industrialized countries like the United Kingdom, Japan, the USA and the European Union, there is increasing evidence that the trade impacts of climate change are significant and can have substantial domestic impacts (*medium confidence*) (Nakano, 2017; Willner et al., 2018, Section 13.9.1; Benzie and Persson, 2019; Knittel et al., 2020). Enhanced trade can transmit risks across borders and thereby amplify damages (Wenz and Levermann, 2016), but it can also increase resilience (Lim-Camacho et al., 2017; Willner et al., 2018).

Finance

Climate risks can also spread through global financial markets (Mandel et al., 2021). For the case of coastal and riverine flooding with low adaptation 2080 (RCP 8.5-SSP5), the financial system is projected to amplify direct losses by a factor of 2 (global average), but reach up to a factor of 10 for countries that are central financial hubs (Mandel et al., 2021, Figure 13.28). Indirect impacts may also arise through indirect effects on foreign direct investment, remittance flows, and official development assistance (Hedlund et al., 2018).

Food

The global supply of agricultural products is concentrated to a few main breadbaskets (Bren d'Amour et al., 2016; Gaupp et al., 2020, Chapter 5). For instance, Central and South America is one of the regions with the highest potential to increase food supplies to more densely populated regions in Asia, Middle East and Europe (Chapter 12). The exports of agricultural commodities (coffee, bananas, sugar, soybean, corn, sugarcane, beef livestock) have gained importance in the past two decades as international trade and globalization of markets have shaped the global agri-food system (Chapter 5).

The export of major food crops like wheat, maize and soybeans from many of the world's water scarce areas – Middle East, North Africa, parts of South Asia, North China Plains, south-west USA, Australia – to relatively water abundant parts of the world carries a high virtual water content (the net volume of water embedded in trade) (*high confidence*) (Hoekstra and Mekonnen, 2012; Dalin et al., 2017; Zhao et al., 2019, Chapter 4). Both importing and exporting countries are exposed to transboundary risk transmission through climate change impacts on distant water resources (Sartori et al., 2017; Zhao et al., 2019; Ercin et al., 2021). Climate change is projected to exacerbate risk and add new vulnerabilities for risk transmission (*medium confidence*). Rising atmospheric CO_2 concentration is projected to decrease water efficiency of growing maize and temperate cereal crops in parts of USA, East and Mediterranean Europe, South Africa, Argentina, Australia and South East Asia with important implications for future trade in food grains (Fader et al., 2010). By 2050 (SRES B2 scenario) virtual water importing countries in Africa and the Middle East may be exposed to imported water stress as they rely on imports of food grains from countries which have unsustainable water use (Sartori et al., 2017). Until 2100, virtual trade in irrigation water is projected to almost triple (for SSP2-RCP6.5 scenarios) and the direction of virtual water flows is projected to reverse with the currently exporting regions like South Asia becoming importers of virtual water (Graham et al., 2020). An additional 10-120% trade flow from water abundant regions to water scarce regions will be needed to sustain environmental flow requirements on a global scale by end of the century (Pastor et al., 2019). Exports of agricultural commodities contribute to deforestation, over-exploitation of natural resources and pollution, affecting the natural capital base and ecosystem services (Agarwala and Coyle, 2020; Rabin et al., 2020, Section 12.5.4).

Species and ecosystems

The spatial distributions of species on land and in the oceans are shifting due to climate change, with these changes projected to accelerate at higher levels of global warming (Pecl et al., 2017). These 'species on the move' have large effects on ecosystems and human well-being, and present challenges for governance (Pecl et al., 2017). For example, the number of transboundary fish stocks are projected to increase as key fisheries species are displaced by ocean warming (Pinsky et al., 2018). Conflict over shifting mackerel fisheries has already occurred between European countries (Spijkers and Boonstra, 2017), because few regulatory bodies have clear policies on shifting stocks; this leaves species open to unsustainable exploitation in new waters in the absence of regularly updated catch allocations to reflect changing stock distributions (Caddell, 2018).

Human health will also be affected as vector-borne diseases such as malaria and dengue shift geographic distributions (Caminade et al., 2014). There is also evidence that many warm-adapted invasive species, such as invasive freshwater cyanobacterium, have spread to higher latitudes due to climate change (Chapter 2).

Adaptation to interregional climate risks

Adaptation responses to reduce interregional risks can be implemented at a range of scales: at the point of the initial climate change impact (e.g. assistance for recovery after an extreme event, development of resilient infrastructure, climate-smart technologies for agriculture); at or along the pathway via which impacts are transmitted to the eventual recipient (e.g. trade diversification, re-routing of transport); in the recipient country (e.g. increasing storage to buffer supply disruptions), or by third parties (e.g. adaptation finance, technology transfer) (Bren d'Amour et al., 2016; Carter et al., 2021; Talebian et al., 2021). A knowledge gap exits on the need for, effectiveness of, and limits to adaptation under different socio-economic and land-use futures.

Due to regional and global interdependencies, climate resilience has a global, multi-level public good character (Banda, 2018). The benefits of adaptation are therefore shared beyond the places where adaptation is initially implemented. Conversely, adaptation may be successful at a local level whilst redistributing vulnerability elsewhere or even driving or exacerbating risks in other places (Atteridge and Remling, 2018). International cooperation is therefore needed to ensure that inter-regional effects are considered in adaptation and that adaptation efforts are coordinated to avoid maladaptation. However, regional and global scale governance of adaptation is only just beginning to emerge (Persson, 2019).

The UNFCCC Paris Agreement frames adaptation as a 'global challenge' (Article 7.2) and establishes the global goal on adaptation (Article 7.1), which provides space for dialogue between Parties on the global scale challenge of adaptation and the need for renewed political and financial investment in adaptation, including to address interregional effects (Benzie et al., 2018).

National Adaptation Plans (NAPs) can evolve to consider inter-regional effects as well as domestic ones (Liverman, 2016; Surminski et al., 2016; European Environment, 2020). Regional and international coordination of NAPs, coupled with building capacities and addressing existing knowledge gaps at the country level, can help to ensure that resources are oriented towards reducing interregional risks and building systemic resilience to climate change globally (Booth et al., 2020; Wijenayake et al., 2020).

Given the important role of private actors in managing interregional climate risks (Goldstein et al., 2019; Tenggren et al., 2019), efforts will be needed to align public and private strategies for managing interregional climate risks to avoid maladaptation and ensure just and equitable adaptation at different scales (Talebian et al., 2021).

[END CROSS-CHAPTER BOX INTEREG HERE]

A new development since AR5, there is now growing evidence assessing progress on adaptation across sectors, geographies and spatial scales. Uncertainty persists around what defines adaptation and how to measure it (Cross-Chapter Box FEASIB in Chapter 18, UNEP, 2021). As a result, most literature synthesizing responses are based on documented or reported adaptations only, and are thus subject to substantial reporting bias.

We document implemented adaptation-related responses that could directly reduce risk. Adaptation *as a process* is more broadly covered in Chapter 17 (Section 17.4.2), including risk management, decision-making, planning, feasibility (see Cross-Chapter Box FEASIB in Chapter 18), legislation and learning. Here, we focus on a subset of adaptation activities: adaptation-related responses of species, ecosystems, and human societies that have been implemented, observed, and could directly reduce risk. We consider all adaptation-related responses to assumed, perceived, or expected climate risk, regardless of whether or not impacts or risks have been formally attributed to climate change.

We use the term 'adaptation-related responses', recognising that not all responses reduce risk. While 'adaptation' implies risk reduction, we use the broader term 'responses' to reflect that responses may decrease risk, but in some cases may increase risk.

Given limited evidence to inform comprehensive global assessment of effectiveness and adequacy, we assess evidence that adaptation responses in human systems indicate transformational change. Chapter 17 considers adaptation planning and governance, including adaptation solutions, success, and feasibility assessment

(Cross-Chapter Box FEASIB in Chapter 18). It is not currently possible to conduct a comprehensive global assessment of effectiveness, adequacy, or the contribution of adaptation-related responses to changing risk due to an absence of robust empirical literature (discussed further in Cross-Chapter Box PROGRESS in Chapter 17).

In natural ecosystems or species, detectable changes can be considered as 'impact' or 'response'. The distinction between 'observed impacts' (16.2) and 'observed responses' (16.3) is not always clear. For example, autonomous distributional shifts in wild species induced by increasing temperatures (an observed impact) may reduce risk to the species (an autonomous adaptation response), but this process can be enhanced or supported by human intervention such as intentional changes in land use. Observed autonomous changes in natural ecosystems or species unsupported by human intervention are treated as impacts (see Section 16.2).

Adaptation-related responses are frequently motivated by a combination of climatic and non-climatic drivers, and interact with other transitions to affect risk. For societal responses, it is difficult to say whether they are triggered by observed or anticipated changes in climate, by non-climatic drivers, or as is the case in many societal responses, a combination of all three. In the case of impacts, assessment typically focuses on detection and attribution vis a vis a counterfactual of no climate change. While there has been some effort to attribute reduced climate risk to adaptation-related responses (Toloo et al., 2013a; Toloo et al., 2013b; Hess et al., 2018; Weinberger et al., 2018), in many cases this has not been feasible given difficulties in defining adaptation and empirically disentangling the contribution of intersecting social transitions and changing risks. Literature on adaptation-related response frequently draws on theories-of-change to assess the likely contribution of adaptations to changes in risk, including maladaptation and co-benefits.

16.4 Synthesis of Limits to Adaptation Across Natural and Human Systems

This section builds on previous IPCC Reports (i.e., AR5, SR15, SROCC, SRCCL) to advance concepts and emphasize remaining gaps in understanding about limits to adaptation. We provide case studies to illustrate these concepts and synthesize regional and sectoral limits to adaptation across natural and human systems that informs key risks (Section 16.5) and Reasons for Concern (Section 16.6). We also identify residual risks - risks that remain after efforts to reduce hazards, vulnerability, and/or exposure - associated with limits to adaptation.

16.4.1 Definitions and Conceptual Advances Since AR5

16.4.1.1 Limits to Adaptation since AR5

AR5 introduced the concept of limits to adaptation and provided a functional definition that has been used in subsequent Special Reports (SR15, SROCC, SRCCL) and is also used for AR6 (see also Chapter 1).

A limit is defined as the point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions (Klein et al., 2014). Tolerable risks are those where adaptation needed to keep risk within reasonable levels is possible, while intolerable risks are those where practicable or affordable adaptation options to avoid unreasonable risks are unavailable. This highlights that limits to adaptation are socially constructed and based on values that determine levels of reasonable or unreasonable risk as well as on available adaptation options, which vary greatly across and within societies.

Limits are categorized as being either 'soft' or 'hard'. Soft limits may change over time as additional adaptation options that are practicable or affordable become available. Hard limits will not change over time as no additional adaptive actions are possible. When a limit is exceeded, then intolerable risk may materialize and the actor's objectives or system's needs may be either abandoned or transformed (Figure Box16.1.1).

For human systems, soft and hard limits are largely distinguished by whether or not constraints to adaptation are able to be overcome. Constraints to adaptation (also called barriers) are factors that make it harder to plan and implement adaptation actions – such as limited financial resources, ineffective institutional arrangements or insufficient human capacity. Soft limits are mostly associated with human systems, due in part to the role of human agency in addressing constraints. For natural systems, the magnitude and rate of climate change and capacity of adaptation to such change largely determine the type of limit. Hard limits are largely associated with natural systems and are mostly due to inability to adapt to biophysical changes.

Using this understanding of limits, subsequent Special Reports have assessed relevant literature (Mechler et al., 2020). SR15 identifies several regions, sectors and ecosystems – including coral reefs, biodiversity, human health, coastal livelihoods, small island developing states, and the Arctic – that are projected to experience limits at either 1.5ºC or 2ºC. SRCCL states that land degradation due to climate change may result in limits to adaptation being reached in coastal regions and areas affected by thawing permafrost. SROCC details that risks of climate-related changes in the ocean and cryosphere may result in limits for ecosystems and vulnerable communities in coral reef environments, urban atoll islands and low-lying Arctic locations before the end of this century in case of high emissions scenarios.

A key area of advancement since AR5 is how incremental and transformational adaptation relate to limits to adaptation. Incremental adaptation maintains 'the essence and integrity of a system or process at a given scale' while transformational adaptation 'changes the fundamental attributes of a social-ecological system' (Matthews, 2018). Both incremental and transformational adaptation may expand the adaptive possibilities for a system, providing additional adaptation options after a system reaches a soft limit (Felgenhauer, 2015; Pelling et al., 2015; Termeer et al., 2017, see also Chapter 1 and 17; Alston et al., 2018; Panda, 2018; Mechler and Deubelli, 2021). However, it is critical to note that adaptation, whether incremental or transformational, must support securing an actor's objectives or system's needs from intolerable risks. Once objectives or needs have been abandoned or transformed, a limit to adaptation has occurred. However, objectives or needs may change over time as values of a society change (Taebi et al., 2020), thus adding further complexity to assessing limits to adaptation.

16.4.1.2 Residual risk since AR5

The term 'residual risk' was not assessed in detail in AR5 and was used interchangeably with other terms including 'residual impacts', 'residual loss and damage' and 'residual damage'. SR15 includes discussion of residual risks without an explicit definition and relates these to loss and damage and limits to adaptation, concluding that residual risks rise as global temperatures increase from 1.5°C to 2°C. SRCCL refers to residual risks arising from limits to adaptation related to land management. Such residual risk can emerge from irreversible forms of land degradation, such as coastal erosion when land completely disappears, collapse of infrastructure due to thawing of permafrost, and extreme forms of soil erosion. SROCC advanced the conceptualization of residual risk and integrated it within the risk framework, defining residual risk as the risk that remains after actions have been taken to reduce hazards, exposure and/or vulnerability. Residual risk is therefore generally higher where adaptation failure, insufficient adaptation or limits to adaptation occur. We use the SROCC definition of residual risk for our assessment in the following sections and identify residual risks that are associated with limits to adaptation.

[START BOX 16.1 HERE]

Box 16.1: Linking Adaptation Constraints, Soft and Hard Limits

McNamara et al. (2017) provides an example of community-scaled adaptation that highlights how constraints affect limits, the relationship between soft and hard limits, and the potential need to abandon or transform objectives. In Boigu Island, Australia, community members are already adapting to perceived climate change hazards - including sea level rise and coastal erosion - to secure their objective of sustaining livelihoods and way of life in their current location. Existing seawall and drainage systems provide inadequate protection from flooding during high tides, leading residents to elevate their houses to prevent damages. However, these adaptation measures have proved to be insufficient. Standing saltwater for extended periods of time after floods has resulted in losses and damages – including erosion of infrastructure, increased soil salinity, and heightened public health concerns. Additional adaptation efforts are constrained by scarcity of elevated land which inhibits movement of infrastructure within the community and lack of financial, technical and human assets to improve coastal protection measures.

These constraints are leading to a soft limit to adaptation – where risks would become unreasonable as sea levels continue to rise and practicable and affordable adaptation options are limited to currently available approaches. This soft limit could be overcome through addressing constraints and allowing further adaptation to take place, such as providing financial, technical and human resources for more effective coastal protection and drainage systems that would reduce flooding. However, if the effectiveness of these new adaptation measures decreases as sea levels rise further and if constraints are not able to be overcome, another soft limit may be reached. Eventually, if constraints are not addressed, no further adaptation measures are implemented and climate hazards intensify, the area could become uninhabitable. This would then be a hard limit for adaptation – there would be no adaptation options available that would allow the community to sustain livelihoods and way of life in its present location. This hard limit to adaptation may necessitate abandoning the objective of remaining in the community. The objective of the community may then transform to sustaining their livelihoods in a less vulnerable location which would necessitate relocation. However, such transformation of the community's objectives may be hindered by the expressed resistance of residents to migrate, due to their strong sense of place.

[END BOX 16.1 HERE]

16.4.2 Insights from Regions and Sectors about Limits to Adaptation

Here we provide example case studies to highlight constraints that may lead to soft limits, potential incremental and transformational adaptation options that may overcome soft limits, evidence of hard limits and residual risks.

16.4.2.1 Small Island Developing States (SIDS)

An expanding volume of empirical research highlights existing adaptation constraints that may lead to soft limits in SIDS. Investigation of national communications among 19 SIDS found that financial constraints, institutional challenges and poor resource endowments were the most-frequently reported as inhibiting adaptation for a range of climate impacts (Robinson, 2018b). Governance, financial and information constraints such as unclear property rights and lack of donor flexibility have led to hasty implementation of adaptation projects in Kiribati, whereas in Vanuatu and the Solomon Islands, limited awareness of rural adaptation needs and weak linkages between central governance and local communities have resulted in an urban bias in resource allocation (Kuruppu and Willie, 2015). Limited availability and use of information and technology also present constraints to adaptation – many SIDS suffer from lack of data and established routines to identify loss and damage, and the combination of poor monitoring of slow-onset changes and influence of non-climatic determinants of observed impacts challenges attribution (Thomas and Benjamin, 2018). The fact that climate information is often available only in the English language represents another common constraint for island communities (Betzold, 2015). Although indigenous and local knowledge systems can provide important experience-based input to adaptation policies (Miyan et al., 2017), socio-cultural values and traditions such as attachment to place, religious beliefs and traditions can also constrain adaptation in island communities, particularly for more transformational forms of adaptation (Ha'apio et al., 2018; Oakes, 2019).

Soft limits to adaptation for coastal flooding and erosion are already being experienced in Samoa due largely to financial, physical and technological constraints (Crichton and Esteban, 2018). While sea walls have been erected to minimize coastal erosion, these defences need regular upgrading and replacement as high swells, tropical cyclones and constant wave action erode their effectiveness. The high costs of installing, upgrading and enlarging such infrastructure has led to sea walls only being used in specific locations, leaving communities that are beyond the extent of these measures exposed to inundation and erosion. Native tree replanting has also been implemented but coastal flooding and erosion persist as large swells lead to high failure rates of replanting efforts. Across SIDS, adaptation to coastal flooding and erosion in particular is increasingly facing soft limits due to high costs, unavailability of technological options and limited physical space or environmental suitability for hard engineering or ecosystem-based approaches (Mackey and Ware, 2018; Nalau et al., 2018).

Retreat and relocation constitute transformative adaptation options, although evidence of permanent community-scale relocation in response to climate change remains limited at present (Kelman, 2015; McNamara and Des Combes, 2015). Material and emotional cost of emigration as well as loss of homeland, nationhood, and other intangible assets and values imply that relocation is generally considered a last resort (Jamero et al., 2017) and may mean abandoning objectives of remaining in existing locations, hence exceeding adaptation limits.

Hard limits in SIDS are mostly due to adaptation being unable to prevent intolerable risks from escalating climate hazards such as sea-level rise and related risks of flooding and surges, severe tropical cyclones, and contamination of groundwater. Emerging evidence suggests that shortage of water and land degradation have already contributed to migration of multiple island communities in the Pacific (Handmer and Nalau, 2019).

Residual risks for SIDS include loss of marine and terrestrial biodiversity and ecosystem services, increased food and water insecurity, destruction of settlements and infrastructure, loss of cultural resources and heritage, collapse of economies and livelihoods and reduced habitability of islands (Section 3.5.1, Section 15.3).

16.4.2.2 Agriculture in Asia

Lack of financial resources is found to be a significant constraint that contributes to soft limits to adaptation in agriculture across Asia. Although smallholder farmers are currently adapting to climate impacts, lack of finance and access to credit prevents upscaling of adaptive responses and has led to losses (Bauer, 2013; Patnaik and Narayanan, 2015; Bhatta and Aggarwal, 2016; Loria, 2016). Other constraints further contribute to soft limits including governance and associated institutional factors such as ineffective agricultural policies and organizational capacities (Tun Oo et al., 2017), information and technology challenges such as limited availability and access to technologies on the ground (Singh et al., 2018), socio-cultural factors such as the social acceptability of adaptation measures that are affected by gender (Huyer, 2016; Ravera et al., 2016), and limited human capacity (Masud et al., 2017). A wide range of pests and pathogens are predicted to become problematic to regional food crop production as average global temperatures rise (Deutsch et al., 2018) increasing crop loss across Asia for which farmers are already experiencing a variety of adaptation constraints including financial, economic and technological challenges (Sada et al., 2014; Tun Oo et al., 2017; Fahad and Wang, 2018). Extreme heat waves are projected in the densely populated agricultural regions of South Asia leading to increased risk of heat stress for farmers and resultant constraints on their ability to implement adaptive actions (Im et al., 2017). However, socio-economic constraints appear to have a higher influence on soft limits to adaptation in agriculture than biophysical constraints (Thomas et al., 2021). For example, an examination of farmers' adaptation to climate change in Turkey found that constraints related to access to climate information and access to credit will likely limit the yield benefits of incremental adaptation (Karapinar and Özertan, 2020). In Nepal, conservation policies restrict traditional grazing inside national parks, which promotes intensive agriculture and limits other cropping systems that have been implemented as climate change adaptation (Aryal et al., 2014).

In Bangladesh, small and landless farm households are already approaching soft limits in adapting to riverbank erosion (Alam et al., 2018). While wealthier farming households can implement a range of adaptation responses including changing planting times and cultivating different crops, poorer households have limited access to financial institutions and credit to implement such measures. Their adaptation responses of shifting to homestead gardening and animal rearing are insufficient to maintain their livelihoods and these households are more likely to engage in off-farm work or migrate.

(Palao et al., 2019) identify the possible need for transformational adaptation in Asian-Pacific agricultural practices due to changes in biophysical parameters as global average temperatures rise. In this context, transformational adaptation would consist of changing farming locations to different provinces or different elevations for the production of specific crops or introducing new farming systems. Nearly 50% of maize in the region along with 18% of potato and 8% of rice crops would need to either be shifted in location or use new cropping systems, with the most significant transformation being needed in China, India, Myanmar and the Philippines. For maize suitability by 2030, seven provinces in the east and northeast of China are projected to experience over 50% reduction in suitability and two northern states in India may experience

70% reduction in suitability. Cassava and sweet potato may play a critical role in food resilience in these areas, as these crops are more resilient to climate change (Prain and Naziri, 2019).

In terms of hard limits, the rate and extent of climate change is critical as agriculture is climate-dependent and sensitive to changes in climate parameters. Poudel and Duex (2017) document that over 70% of the springs used as water sources in Nepalese mountain agricultural communities had a decreased flow and approximately 12% had dried up over the past decade. While there are some adaptation measures to address reduced water availability – e.g., the introduction of water-saving irrigation technology among Beijing farmers to alleviate water scarcity in metropolitan suburbs (Zhang et al., 2019) – these actions still depend on some level of water availability. If climate hazards intensify to the point where water supply cannot meet agricultural demands, hard limits to adaptation will occur.

Residual risks associated with agriculture in Asia include declines in fisheries, aquaculture and crop production, particularly in South and Southeast Asia (Section 10.3.5), increased food insecurity (Section 10.4.5), reductions of farmers' incomes by up to 25% (Section 10.4.5), loss of production areas (Section 10.4.5) and reduced physical work capacity for farmers - between 5-15% decline in south-southwest Asia and China under RCP8.5 (Section 5.12.4).

16.4.2.3 Livelihoods in Africa

For livelihoods dependent on small-scale rain-fed agriculture in Africa, climate hazards include floods and droughts. However, governance, financial and information/awareness/technology challenges are identified as the most significant constraints leading to soft limits, followed by social and human capacity constraints (Thomas et al., 2021). Finance and land tenure constraints restrict Ghanaian farmers when considering adaptation responses due to climate variability (Guodaar et al., 2017). Similarly, in East Africa, farmers with small pieces of land have limited economic profitability, making it difficult to invest in drought and/or flood management measures (Gbegbelegbe et al., 2018).

Increasing droughts and floods require costlier adaptation responses to reduce risks, such as using drought-tolerant species (Berhanu and Beyene, 2015) and coping strategies for flood-prone households (Schaer, 2015; Musyoki et al., 2016), resulting in soft limits for poorer households who cannot afford these responses. In Namibia weak governance and poor integration of information, such as disregarding knowledge of urban and rural residents in flood management strategies, has resulted in soft limits to adaptation, leading to temporary or permanent relocation of communities (Hooli, 2016). Shortage of land – namely high population pressure and small per capita land holding – leads to continuous cultivation and results in poor soil fertility. This low productivity is further aggravated by erratic rainfall causing soft limits as farmers cannot produce enough and must depend on food aid (Asfaw et al., 2019).

Relocation due to flooding is discussed as a transformation adaptation action taken in Botswana where the government decided to permanently relocate hundreds of residents to a nearby dryland area (Shinn et al., 2014). Some residents permanently relocated whereas others only temporarily relocated against the government's instructions. Such relocation processes must attend to micro-politics and risks of existing systemic issues of inequality and vulnerability.

In terms of hard limits, land scarcity poses a hard limit when implementing organic cotton production, an adaptation response supporting sustainable livelihoods (Kloos and Renaud, 2014).

Residual risks associated with livelihoods in Africa include poorer households becoming trapped in cycles of poverty (Section 9.9.3), increased rates of rural-urban migration (Section 9.8.4), decline of traditional livelihoods such as in agriculture (Section 9.9.3, Section 9.11.3.1) and fisheries (Section 9.11.1.2) and loss of traditional practices and cultural heritage (Section 9.9.2).

16.4.3 Regional and Sectoral Synthesis of Limits to Adaptation

16.4.3.1 Evidence on Limits to Adaptation

There is *high agreement* and *medium evidence* that there are limits to adaptation across regions and sectors. However, much of the available evidence focuses on constraints that may lead to limits at some point with little detailed information on how limits may be related to different levels of socio-economic or environmental change (*high confidence)*. Figure 16.7 assesses evidence on constraints and limits for broad categories of region and sector. Small Islands and Central and South America show most evidence of constraints being linked to adaptation limits across sectors while ocean and coastal ecosystems and health, wellbeing and communities show most evidence of constraints being linked to limits across regions (*medium confidence)*.

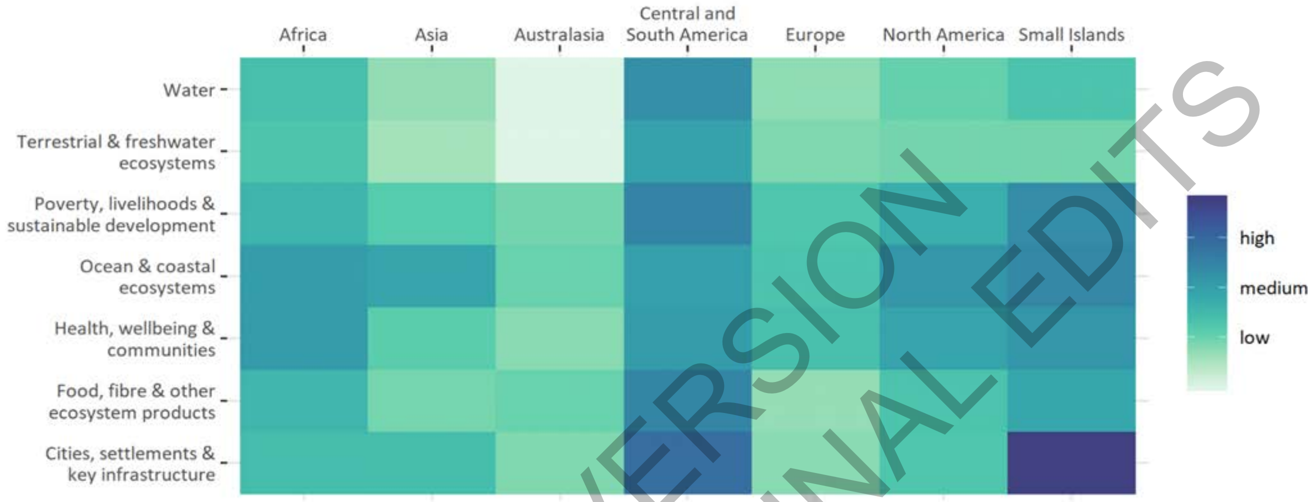


Figure 16.7 Evidence on constraints and limits to adaptation by region and sector. Data from (Thomas et al. 2021), based on 1682 scientific publications reporting on adaptation-related responses in human systems. See SM16.1 for methods. **Low evidence:** <20% of assessed literature has information on limits, literature mostly focuses on constraints to adaptation **Medium evidence:** between 20-40% of assessed literature has information on limits, literature provides some evidence of constraints being linked to limits **High evidence:** > 40% of assessed literature has information on limits, literature provides broad evidence of constraints being linked to limits

There are clusters of evidence with additional details on limits to adaptation, as detailed in Table 16.3. Evidence on limits to adaptation is largely focused on terrestrial and aquatic species and ecosystems, coastal communities, water security, agricultural production, and human health and heat *(high confidence)*.

Beginning at 1.5°C, autonomous and evolutionary adaptation responses by terrestrial and aquatic species and ecosystems face hard limits, resulting in biodiversity decline, species extinction and loss of related livelihoods *(high confidence)*. Interventionist adaptation strategies to reduce risks for species and ecosystems face soft limits due to governance, financial and knowledge constraints *(medium confidence).*

As sea levels rise and extreme events intensify, coastal communities face soft limits due to financial, institutional and socio-economic constraints reducing the efficacy of coastal protection and accommodation approaches and resulting in loss of life and economic damages (*medium confidence).* Hard limits for coastal communities reliant on nature based coastal protection will be experienced beginning at 1.5°C (*medium confidence)*.

Beginning at 3°C, hard limits are projected for water management measures, leading to decreased water quality and availability, negative impacts on health and wellbeing, economic losses in water and energy dependent sectors and potential migration of communities (*medium confidence*).

Soft and hard limits for agricultural production are related to water availability and the uptake and effectiveness of climate-resilient crops which is constrained by socio-economic and political challenges (*medium confidence).*

Adaptation measures to address risks of heat stress, heat mortality and reduced capacities for outdoor work for humans face soft and hard limits across regions beginning at 1.5°C and are particularly relevant for regions with warm climates *(high confidence)*.

Table 16.3: Adaptation limits and residual risks for select actors and systems. Asterisks indicate confidence level *=l*ow confidence*, **=*medium confidence*, ***=*high confidence, ****=very high confidence.*

Actor/system at risk	Adaptation limits	Residual risks
Terrestrial species in islands at risk to loss of habitat	**Hard:** autonomous adaptation unable to overcome loss of habitat and lack of physical space (***) (Box CCP1.1)	Biodiversity decline, local extinctions, half of all species currently considered to be at risk of extinction occur on islands (Box CCP 1.1)
Terrestrial species across Africa at risk to habitat changes	**Hard:** beyond 2°C many species will lack suitable climate conditions by 2100 despite migration and dispersal (***) (9.6.4.1)	9% of species face complete range loss (*) mountain-top endemics and species at poleward boundaries of African continent at risk of range loss due to disappearing cold climates (***) (9.6.4.1)
African aquatic organisms at risk to habitat changes	**Hard:** thermal changes above optimal physiological limits will reduce available habitats (9.6.2.4)	Greater risks of loss of endemic fish species than generalist fish species (9.6.2.4)
African coastal and marine ecosystems at risk to habitat changes	**Hard:** at 2°C bleaching of east African coral reefs (***) (9.6.2.3)	Over 90% of east African coral reefs destroyed at 2C (***) (9.6.2.3)
Coral reefs at risk to oceanic changes	**Hard:** coral restoration and management no longer effective after 2°C (***), enhanced coal and reef shading no longer effective after 3°C (**) (Figure 3.23)	Loss of more than 80% of healthy coral cover, loss of livelihoods dependent on coral reefs (***) (Figure 3.23, Table 8.7)
Cold-adapted species whose habitats are restricted to polar and high mountaintop areas at risk to loss of climate space	**Hard:** evolutionary responses unable to keep pace with the rate of climate change and degraded state of ecosystems (2.6.1, CCP 1.2.4.2)	Species extinctions in the case of species losing its climate space entirely on a regional or global scale (2.6.1, CCP 1.2.4.2)
Ecosystems in North America at risk to multiple climate hazards	**Soft:** governance constraints hinder implementation of adaptation strategies **Hard**: some species unable to adapt (Table 14.8)	-
Ecosystems and species at risk to multiple climate hazards	**Soft:** financial and knowledge constraints lead to limits for interventionist approaches such as translocation of species or ecosystem restoration **Hard:** some habitats unable to be effectively restored (2.6.6)	Species extinctions and changes, irreversible major biome shifts (2.6.6)
Coastal settlements in Australia and New Zealand at risk to sea level rise	**Soft and hard**: limits in the efficacy of coastal protection and accommodation approaches as sea levels rise and extreme events intensify (Box 11.5)	With 1-1.1m of sea level rise, value of coastal urban infrastructure at risk in Australia is A$164 to >226 billion while in NZ it is NZ$43 billion. Sea level rise will also result in significant cultural and archaeological sites disturbed and increasing flood risk and water insecurity with health and well-being impacts on Australia's small northern islands (Box 11.5)

Human settlements in coastal areas in the 1 in 100 year floodplain at risk to coastal flooding	**Soft**: socio-economic, institutional and financial constraints may lead to soft limits well in advance of technical limits of hard engineering measures (CCP 2.3.2, 2.3.4) **Hard:** Nature based measures (e.g. restoration of coral reefs, mangroves, marshes) reach hard limits beginning at 1.5°C of global warming. Retreat strategies reach hard limits as availability and affordability of land decreases (CCP 2.3.2.3, CCP 2.3.5)	at 3°C, globally up to 510 million people and up to US$12,739 billion in assets at risk by 2100 (CCP 2.2.1)
Communities in small islands at risk to freshwater shortages	**Hard**: domestic freshwater resources unable to recover from increased drought, sea level rise and decreased precipitation by 2030 (RCP8.5+ ice-sheet collapse), 2040 (RCP8.5) or 2060 (RCP4.5) (Box 4.2, 4.7.2)	Migration of communities due to water shortages with impacts on well-being, community cohesion, livelihoods and people-land relationships (Box 4.2)
Communities in North America at risk to poor water quality	**Soft**: financial and technological constraints lead to limits in ability to treat water for harmful algal blooms. (Table 14.8)	
Communities in Western and Central Europe at risk to water shortages	**Hard**: at 3°C, geophysical and technological limits reached in Southern Europe (13.10.3.3)	At 3°C, two thirds of the population of Southern Europe at risk to water security with significant economic losses in water and energy dependent sectors (**) (13.2.2, 13.6, 13.10.2.3)
Communities in Central and South America at risk to water shortages	**Soft**: improved water management as an adaptation strategy unable to overcome lack of trust and stakeholder flexibility, unequal power relations and reduced social learning. (12.5.3.4)	Increasing competition and conflict associated with high economic losses (**); glacier shrinkage leading to loss of related livelihoods and cultural values (12.5.3.1, Table 8.7)
Agricultural production in Europe at risk to heat and drought	**Soft**: above 3°C, unavailability of water will limit irrigation as an adaptation response (***) (13.5.1, 13.10.2.2)	At 3-4°C, yield losses for maize may reach up to 50% (**) (13.5.1, 13.10.2.2)
Crops at risk to temperature increase	**Soft**: socio-economic and political constraints limit uptake of climate-resilient crops (5.4.4.3) **Hard**: after 2°C, cultivar changes unable to offset global production losses (5.4.4.1)	Costs of adaptation and residual damages are US$63 billion at 1.5°C. US$80 billion at 2°C and US$128 billion at 3°C, with greater risks and damages in tropical and arid regions (5.4.4.1)
Human health in Europe at risk to heat	**Soft**: many adaptation measures will not be able to fully mitigate overheating in buildings with high levels of global warming (***) (13.6.2.3) **Hard:** above 3°C, people and health systems unable to adapt (***) (13.6.2.3, 13.7.2, 13.7.4, 13.10.2.1, 13.8)	At 1.5°C, 30,000 annual deaths due to extreme heat with up to 90,000 annual deaths at 3C in 2100 (***) (13.7.1) At 3°C, thermal comfort hours during summer will decrease by as much as 74% in locations in southern Europe (***) (13.6.1.5)
Human health at risk to heat	**Soft**: socio-economic constraints limit adaptation responses to extreme heat (7.4.2.6, Table 8.7)	Globally the impact of projected climate change on temperature-related mortality is expected to be a net increase under RCP4.5 to RCP8.5, even with adaptation, particularly for regions with warm climates (****) (7.3.1, Table 8.7)
South Asian settlements at risk to coastal flooding, drought, sea level rise and heatwaves	**Soft and hard**: At 4.5ºC, maximum temperature is expected to exceed survivability threshold across most of South Asia, particularly relevant for outdoor work (*) (Table 10.6)	At RCP4.5, 25-50% of population affected; at RCP8.5 more than 50% of population affected. At 4.5ºC of warming, increase in heat-related deaths of 12.7% in South Asia (*) (Table 10.6)

Tourism in Europe reliant on snow at risk to higher levels of warming	**Soft**: at 3°C, snowmaking as an adaptation measure limited by biophysical and financial constraints (***) (13.6.1.4, 13.6.2.3)	Damages in European tourism with larger losses in Southern Europe (***) (13.6.1.4)
Rapidly growing towns/cities and smaller cities at risk to range of climate hazards	**Soft**: governance and financial constraints lead to limits in ability to adapt (6.3, 6.4)	-

16.4.3.2 Constraints Leading to Limits to Adaptation

Across regions and sectors, a range of constraints (Figure 16.8) are identified as leading to limits to adaptation, particularly financial constraints and constraints related to governance, institutions and policy (*high confidence).* While individual constraints may appear straightforward to address, the combination of constraints interacting with each other leads to soft limits that are difficult to overcome (*high confidence*). The interplay of many different constraints that lead to limits makes it difficult to categorize limits beyond being either soft or hard.

Figure 16.8 Constraints associated with limits by region and sector. Data from (Thomas et al. 2021), based on 1682 scientific publications reporting on adaptation-related responses in human systems. See SM16.1 for methods. Constraints are categorized as: (1) Economic: existing livelihoods, economic structures, and economic mobility; (2) Social/cultural: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) Human capacity: individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, and skill development; (4) Governance, Institutions & Policy: existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements,

adaptive capacity, and absorption capacity; (5) Financial: lack of financial resources; (6) Information/Awareness/Technology: lack of awareness or access to information or technology; (7) Physical: presence of physical barriers; and (8) Biologic/climatic: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind. **Insufficient data:** there is not enough literature to support an assessment (less than 5 studies available); **Minor constraint:** <20% of assessed literature identifies this constraint; **Secondary constraint:** 20-50% of assessed literature identifies this constraint; **Primary constraint:** >50% of assessed literature identifies this constraint

Table 16.4: Key constraints associated with limits to adaptation for regions

Region	Key constraints associated with limits to adaptation
Africa	Financial constraints inhibit implementation of a variety of adaptation strategies including ecosystem-based adaptation (Section 9.11.4.2) and adoption of drought tolerant crops by farmers (Section 9.12.3). Information constraints (including limited climate science information), governance constraints (such as communication disconnects between national, district and community levels) and human capacity constraints (limited capacities to analyse threats and impacts) are identified as negatively affecting the implementation of adaptation policies (Section 9.13.1). Social/cultural constraints (social status, caste and gender) also affect adaptation in contexts with deep-rooted traditions (Section 9.12.4).
Asia	Governance, human capacity, financial and informational constraints commonly present barriers to urban adaptation (Section 10.4.6.5). Economic, governance, financial and informational constraints are related to both soft and hard limits to adaptation against a range of hazards in South Asia (Box 10.7), while in West Asia, physical constraints to heatwaves and drought have been associated with limits to adaptation (Box 10.7).
Australasia	A range of constraints, including governance, information and awareness, social/cultural, human capacity and financial have been identified as impeding adaptation action in the region (Section 11.7.2, Box 11.1). Evidence of limits to adaptation are primarily for ecosystems (Section 11.7.2, 11.6) although individuals and communities are also approaching soft limits due to social constraints (Chapter 11.7.2).
Central and South America	Financial, governance, knowledge, biophysical and social/cultural constraints identified as most significant for adaptation (Section 12.5, Table 12.3). Soft limits are largely related to governance constraints, while evidence of hard limits is related to biophysical constraints, such as glacier shrinking leading to loss of livelihoods and cultural values (Section 12.5.3.4).
Europe	Key constraints are identified as technical, biophysical, economic and social (Section 13.6.2.4). For cities, settlements and key infrastructure, technical socio-economic and environmental & regulatory constraints may lead to limits at a range of spatial scales (Figure 13.12) Biophysical constraints may lead to limits to the ability of water saving and water efficiency measures to prevent water insecurity under high warming scenarios (Section 13.2.2.2).
North America	Social/cultural, governance, financial, knowledge and biophysical constraints are identified as most significant for adaptation and leading to both soft and hard limits (Section 14.5.2.1, Section 14.6, Section 14.6.2.1, Table 14.8)
Small Islands	Financial, governance, information/awareness, technological, cultural and human capacity constraints are identified as affecting adaptation and leading to soft limits (Section 15.5.3, Section 15.5.4, Section 15.6.1, Section 15.6.3, Section 15.6.4). Differences between constraints and soft limits in the small island context is marginal, with policymakers in the Caribbean and Indian Oceans seeing these as synonymous (Section 15.6.1).

16.4.3.3 Climate Change Impacts, Financial Constraints and Limits to Adaptation

Across regions and sectors, financial constraints are identified as significant and contributing to limits to adaptation, particularly in low-to-middle income countries (*high confidence)* (Section 3.6.3, Section 4.7.2, Section 5.14.3, Section 6.4.5, Section 7.4.2, Section 8.4.5, Section 12.5.1, Section 12.5.2, Section 15.6.1, Section 15.6.3, Figure 16.8, Table 16.4, CCP2.4.2). Impacts of climate change may increase financial constraints (*high confidence*) and contribute to soft limits to adaptation being reached (*medium confidence*). Table 16.5 details climate impact observations that point to potentially substantial negative impacts on the availability of financial resources for different regions.

Table 16.5: Evidence of climate change impacts affecting availability of financial resources. Asterisks indicate confidence level *=*low confidence*, **=*medium confidence*, ***=*high confidence.*

Region	Evidence of climate change impacts affecting availability of financial resources
Africa	Negative consequences for economic growth and GDP growth rate from higher average temperatures and lower rainfall (***) (Section 9.9.1.1, Section 9.9.2, Section 9.9.3) Economic losses from damage to infrastructure in the energy, transport, water supply, communication services, housing, health, and education sectors (observed) (Section 9.7.2.2, Section 9.8.2)
Asia	High coastal damages due to sea level rise (China, India, Korea, Japan, Russia) (***) (Section 10.4.6.3.4) Decline in aquaculture production (Section 10.4.5.2.1) Loss of coastal ecosystem services (Bangladesh) (Section 5.9.3.2.4)
Australasia	Loss of wealth and negative impacts on GDP (Section 11.5.1.2, Section 11.5.2.2) High disaster costs (observed in Australia, NZ) (Section 11.5.2.1)
Central and South America	High costs of extreme events relative to GDP (observed in Guatemala, Belize) (Section 12.3.1.4) Decrease in growth of total GDP per capita and total income and labour income from one standard deviation in the intensity of a hurricane windstorm (Section 12.3.1.4)
Europe	Negative combined effect of multiple risks on economy for Europe in total (**) (Section 13.9.1, Section 13.10.2) Negative combined effect of multiple risks on economy for Southern Europe (***) (Section 13.9.1, Section 13.10.2) High economic costs in agriculture and construction following heat waves and flooding (Section 6.2.3.2, Section 7.4.2.2.1)
North America	Small but persistent negative economy wide effect on GDP (observed in the United States and Mexico) (**) (Box 14.5) Economic risks associated with high temperature scenarios (***) (Box 14.5) Small but persistent positive economy wide effect on GDP (observed in Canada) (**) (Box 14.5) Significant economic costs for urban, natural and ecosystem infrastructure (USA) (Section 6.2.5.9) High economic damages for a subset of sectors from high warming (southern and southeastern US) (Box 14.5) Adverse effects on municipal budgets due to costly liabilities, and disruption of financial markets (Box 14.5)
Small Islands	High economic costs relative to GDP from extreme events, particularly tropical cyclones (observed) (Section 15.3.4.1) Negative long-term implications of extreme events for state budgets (Section 8.2.1.4) Inundation of almost all port and harbour facilities (Caribbean) (Section 15.3.4.1)

At the national level, negative macroeconomic responses to climate change may limit the availability of financial resources, impede access to financial markets and stunt economic growth (*high confidence*). Economic growth has been shown to decline under higher temperatures (Burke et al., 2015; Kahn et al., 2019, Section 16.5.2.3.4) and following extreme events (Hsiang and Jina, 2014; IMF, 2017), particularly for medium- and low-income developing countries (Section 18.1). The most severe impacts of climate-related disasters on economic growth per capita have been observed in developing countries, although authors note a publication bias in the reporting of negative effects (Klomp and Valckx, 2014). Substantial immediate output losses and reduced economic growth due to extreme events have been observed both in the short- and long-term (Section 16.2.3). Estimates of the duration of negative effects of climate-related disasters differ, with some analyses suggesting that on average economies recover after two years (Klomp, 2016) and others finding negative effects of cyclones to persist 15 – 20 years following an event (Hsiang and Jina, 2014; IMF, 2017). Rising climate vulnerability has also been shown to increase the cost of debt (Kling et al., 2018). Rising climatic risks negatively affect developing countries' ability to access financial markets (Cevik and Jalles, 2020) and their disclosure may result in capital flight (Cross-Chapter Box FINANCE in Chapter 17). Overall, the direct and indirect economic effects of climate change represent a major risk to financial system stability (Section 11.5.2). These risks and effects may further limit the availability of financial resources needed to overcome constraints, in particular for developing countries.

Sectoral studies indicate that climate impacts will result in higher levels of losses and damages and decreases in income, thereby increasing financial constraints (*medium confidence)*. Yield losses for major agricultural crops are expected in nearly all world regions (Figure 5.7). Decreases in estimated marine fish catch potential and large economic impacts from ocean acidification are expected globally, leading to the risk of revenue loss (Section 5.8.3). Losses of primary productivity and farmed species of shellfish are expected in tropical and subtropical regions (Section 5.9.3.2.2). Economic losses have been observed in the power generation sector and transport infrastructure (Section 10.4.6.3.8), including economic losses from floods in urban areas (Section 4.2.4.5). However, some positive sectoral climate change impacts have been identified for the timber and forestry sector (Section 5.6.2), for primary productivity and farmed species of shellfish in high-latitude regions (Section 5.9.3.2.2) and agriculture in high-latitude regions (Section 5.4.1.1).

At the household or community level, climate impacts may increase financial constraints (*high confidence).* Impacts on agriculture and food prices could force between 3 to 16 million people into extreme poverty (Hallegatte and Rozenberg, 2017). Within-country inequality is expected to increase following extreme weather events (Section 16.2.3.6 and Chapter 8). Households affected by climate-related extreme events may be faced with continuous reconstruction efforts following extreme events (Adelekan and Fregene, 2015) or declines in critical livelihood resources in the agriculture, fisheries and tourism sectors (Forster et al., 2014, Section 3.5.1). Further erosion of livelihood security of vulnerable households creates the risk of poverty traps, particularly for rural and urban landless (Section 8.2.1, Section 8.3.3.1), for example in Malawi and Ethiopia (Section 9.9.3). Levels of labour productivity and economic outputs are projected to decrease as temperatures rise particularly in urban areas (Section 6.2.3.1). At the same time, higher utilities demand under higher urban temperatures exert additional economic stresses on urban residents and households. Substantial, negative impacts on the livelihoods of over 180 million people are expected from changes to African grassland productivity (Section 5.5.3.1). In Western Uzbekistan, farmers´ incomes are at risk of declining (Section 10.4.5.3). For Small Island Developing States, loss of livelihoods is expected due to negative climatic impacts on coastal environments and resources (Section 3.5.1). Negative effects on households from extreme events can also persist in the long-term and in multiple dimensions. Exposure to disasters during the first year of life significantly reduces the number of years of schooling, increases the chances of being unemployed as an adult and living in a multidimensionally poor household (González et al., 2021).

16.5 Key Risks Across Sectors and Regions

This section builds on the analogous chapter in AR5 (Oppenheimer et al., 2014) to refine the definition of climate-related key risks (KRs) and criteria for identifying them (16.5.1), and describe a broad range of key risks by sector and region as identified by the authors of WGII AR6 (Section 16.5.2, SM16.4). Based on this, eight clusters of key risks (i.e., Representative Key Risks, RKRs) are identified and assessed in terms of the conditions under which they would become severe. In addition, the section assesses variation in KRs and RKRs by the level of global average warming, socio-economic development pathways, and levels of adaptation, and illustrates the implications from resulting dynamics in all risk dimensions (hazard, exposure, vulnerability) along a case study of densely populated river deltas (Section 16.5.3). Last, interactions among RKRs are discussed (Section 16.5.4).

16.5.1 Defining Key Risks

A key risk is defined as a potentially severe risk and therefore especially relevant to the interpretation of dangerous anthropogenic interference (DAI) with the climate system, the prevention of which is the ultimate objective of the UNFCCC as stated in its Article 2 (Oppenheimer et al., 2014). Key risks are therefore a relevant lens for the interpretation of this policy framing. The severity of a risk is a context-specific judgment based on a number of criteria discussed below. KRs are 'potentially' severe because, while some could already reflect dangerous interference now, more typically they may become severe over time due to changes in the nature of hazards (or, more broadly, climatic impact-drivers (or, more broadly, climatic impact-drivers, IPCC, 2021a) and/or of the exposure/vulnerability of societies or ecosystems to those hazards. They also may become severe due to the adverse consequences of adaptation or mitigation responses to the risk (on the former see Section 17.5.1; the latter is not assessed separately here, except as it contributes to risks from climate hazards). Dangerous interferences in this chapter are considered over the course of the 21st century.

KRs may be defined for a wide variety of systems at a range of scales. The broadest definition is for the global human system or planetary ecological system, but KRs may also apply to regions, specific sectors or communities, or to parts of a system rather than to the system as a whole. For example, the population at the lower end of the wealth distribution is often impacted by climate change much more severely than the rest of the population (Leichenko and Silva, 2014; Hallegatte and Rozenberg, 2017; Hallegatte et al., 2017; Pelling and Garschagen, 2019).

KRs are determined not just by the nature of hazards, exposure, vulnerability, and response options, but also by values, which determine the importance of a risk. Importance is understood here as the degree of relevance to interpreting DAI at a given system's level or scale, and was an explicit criterion for identifying key vulnerabilities and risks in AR5 (Oppenheimer et al., 2014). Because values can vary across individuals, communities, or cultures, as well as over time, what constitutes a KR can vary widely from the perspective of each of these groups, or across individuals. For example, ecosystems providing indirect services and cultural assets such as historic buildings and archaeological sites may be considered very important to preserve by some people but not by others; and some types of infrastructure, such as a commuter rail, may be important to the well-being of some households but less so to others. Therefore, Chapter 16 authors do not make their own judgements about the importance of particular risks. Instead, we highlight importance as an overarching factor but identify and evaluate KRs based on four other criteria for what may be considered potentially severe.

Magnitude of adverse consequences. Magnitude measures the degree to which particular dimensions of a system are affected, should the risk materialize. Magnitude can include the size or extent of the system, the *pervasiveness of the consequences* across the system (geographically or in terms of affected population), as well as the *degree of consequences*. Consequences can be measured by a wide range of characteristics. For example, risks to food security can be measured as uncertain consequences for food consumption, access, or prices. The magnitude of these consequences would be the degree of change in these measures induced by climate change and accounting for the interaction with exposure and vulnerability. In addition to *pervasiveness* and *degree of change*, several other aspects can contribute to a judgement of magnitude, although they refer to concepts that are difficult to capture and highly context-specific:
Irreversibility of consequences. Consequences that are irreversible, at least over long timescales, would be considered a higher risk than those that are temporary. For example, changes to the prevailing ecosystem in a given location may not be reversible on the decade to century scale.
Potential for impact thresholds or tipping points. Higher risks are posed by the potential for exceeding a threshold beyond which the magnitude or rate of an impact substantially increases.
Potential for cascading effects beyond system boundaries. Higher risks are posed by those with the potential to generate downstream cascading effects to other ecosystems, sectors or population groups within the affected system and/or to another system, whether neighbouring or distant (Cross-Chapter Box INTEREG in this Chapter).

Likelihood of adverse consequences. A higher probability of high-magnitude consequences poses a larger risk a priori, whatever the scale considered. This probability may not be quantifiable, and it may be conditional on assumptions about the hazard, exposure, or vulnerability associated with the risk.

Temporal characteristics of the risk. Risks that occur sooner, or that increase more rapidly over time, present greater challenges to natural and societal adaptation. A persistent risk (due to the persistence of the hazard, exposure, and vulnerability) may also pose a higher threat than a temporary risk due, for example, to a short-term increase in the vulnerability of a population (e.g., due to conflict or an economic downturn).

Ability to respond to the risk. Risks are more severe if the affected ecosystems or societies have limited ability to reduce hazards (e.g., for human systems, through mitigation, ecosystem management and possibly solar radiation management); to reduce exposure or vulnerability through various human or ecological adaptation options; or to cope with or respond to the consequences, should they occur.

The relative influence of these different criteria is case-specific and left to author judgment in the identification of KRs (groups of authors in regional and sectoral chapters, see Supplementary Material Table SM16.10) and the assessment of representative key risks (author teams, see Supplementary Material Table SM16.10). But in general, the more criteria are met, the higher is the risk

16.5.2 Identification and Assessment of Key Risks and Representative Key Risks

16.5.2.1 Identification of Key Risks (KR)

The authors of the sectoral and regional chapters and Cross Chapter Papers of the WGII AR6 Report identified more than 130 key risks (Table SM16..4). Authors were asked to rely on the above definition and criteria to identify risks that could potentially become severe according to changes in the associated hazards, the study systems' exposure and/or vulnerability; and important adaptation strategies that could reduce these risks (see 16.B.2 for methodology). Wherever possible, identification is based on literature that includes projected future conditions for all three components of risk and adaptation. Where literature was insufficient, potential severity is based on current vulnerability and exposure to climate hazards and the expectation that hazards will increase in frequency and/or intensity in the future. This approach is more limited in that it does not consider future changes in exposure and vulnerability nor in adaptation, but has the benefit of being grounded in observed experience.

Table SM16.4 indicates that climate change presents a wide range of risks across scales, sectors and regions that could become severe under particular conditions of hazards, exposure, and vulnerability, which may or may not occur. Some illustrations of the extent and diversity of KRs are provided here, and more detailed assessment can be found in the Chapters referenced in the table.

Global scale KRs include threats to biodiversity in oceans, coastal regions, and on land, particularly in biodiversity hotspots, as well as other ecological risks such as geographic shifts in vegetation, tree mortality, reduction in populations, and reduction in growth (such as for shellfish). These ecological risks include cascading impacts on livelihoods and food security. Global-scale risks also include risks to people, property, and infrastructure from river flooding and extreme heat (particularly in urban areas), risks to fisheries (with implications for living standards and food security), and some health risks from food-borne diseases as well as psychopathologies.

Many KRs are especially prominent in particular regions or systems, or for particular subgroups of the population. For example, coastal systems and small islands are a nexus of many KRs, including those to ecosystems and their services, especially coral reefs; people (health, livelihoods); and assets, including infrastructure. Risks to socio-ecological systems in polar regions are also identified as KRs, as are ecological risks to the Amazon forest in South America and savannahs in Africa. For some regions risks from wildfire are of particular concern, including in Australasia and North America. Vector-borne diseases are a particular concern in Africa and Asia. Loss of cultural heritage is identified as a KR in Small Islands, Mountain Regions, Africa, Australasia, and North America.

For many risks, low-income populations are particularly vulnerable to KRs. Climate-related impacts on malnutrition and other forms of food insecurity will be larger for this group, along with small-holder farming households and indigenous communities reliant on agriculture, and for women, children, the elderly, and the socially isolated (Section 5.12). KRs in coastal communities are expected to affect low income populations more strongly, including through risks to livelihoods of those reliant on coastal fisheries. KRs related to health are generally higher for low income populations less likely to have adequate housing or access to infrastructure.

16.5.2.2 Identification of Representative Key Risks (RKR)

As in AR5 Oppenheimer et al. (2014), major clusters of KRs are further analysed, and here referred to as 'representative key risks' (RKRs). RKRs were defined in a three-step process (SM16.2.1). First, half of Chapter 16 authors independently mapped the KRs in Table SM16.4 to a set of candidate RKRs. Second, all Chapter 16 authors discussed the set of independent results and proposed a list of RKRs, considering scope and overlap. Third, this proposal was discussed with a consultative group of about twenty WGII AR6 authors from other chapters closely involved in the KR identification process, and a final list of 8 RKRs was identified (Table 16.6).

The RKRs are intended to capture the widest variety of KRs to human or ecological systems with a small number of categories that are easier to communicate and provide a manageable structure for further assessment. They expand the scope of some AR5 KR clusters (e.g., on coasts, health, food, and water) and add new ones (e.g., on peace and mobility). The RKRs encompass a diversity of types of systems, including an example of a geographically defined system (RKR-A on coastal regions), ecosystem well-being and integrity (RKR-B), a cross-cutting issue relevant to several outcomes of concern (RKR-C on critical infrastructure), and several topics focused directly on aspects of human well-being and security (RKR-D to RKR-H). This set of RKRs manages but does not eliminate overlap, instead providing alternative perspectives on underlying key risks that sometimes include complementary views on common risks. For example, the water security RKR highlights the many key risks mediated by water quantity or quality, which are sometimes manifested as risk to food security (RKR-F) or health (RKR-E).

Table 16.6: Climate-related representative key risks (RKRs). The scope of each RKR is further described in the assessments in Section 16.5.2.3. Relation to categories of overarching key risks identified in AR5 is provided for continuity.

Code	Representative Key Risk	Scope	Relation to AR5 overarching key risks for definitions, refer to (Oppenheimer et al., 2014)	Sub-section assessment
RKR-A	Risk to low-lying coastal socio-ecological systems	Risks to ecosystem services, people, livelihoods and key infrastructure in low-lying coastal areas, and associated with a wide range of hazards, including sea level changes, ocean warming and acidification, weather extremes (storms, cyclones), sea ice loss, etc.	Contains key risk (i), overlaps with key risks (iii) and (vii)	16.5.2.3.1
RKR-B	Risk to terrestrial and ocean ecosystems	Transformation of terrestrial and ocean/coastal ecosystems, including change in structure and/or functioning, and/or loss of biodiversity.	Contained in key risks (vii) and (viii)	16.5.2.3.2
RKR-C	Risks associated with critical physical infrastructure, networks and services	Systemic risks due to extreme events leading to the breakdown of physical infrastructure and networks providing critical goods and services.	Overlaps with key risk (iii)	16.5.2.3.3

RKR-D	Risk to living standards	Economic impacts across scales, including impacts on Gross Domestic Product (GDP), poverty, and livelihoods, as well as the exacerbating effects of impacts on socio-economic inequality between and within countries.	Broader version of key risk (ii)	16.5.2.3.4
RKR-E	Risk to human health	Human mortality and morbidity, including heat-related impacts and vector-borne and water-borne diseases.	Broader version of key risk (iv)	16.5.2.3.5
RKR-F	Risk to food security	Food insecurity and the breakdown of food systems due to climate change effects on land or ocean resources.	Overlaps with key risk (v)	16.5.2.3.6
RKR-G	Risk to water security	Risk from water related hazards (floods and droughts) and water quality deterioration. Focus on water scarcity, water-related disasters and risk to indigenous and traditional cultures and ways of life	Overlaps with key risk (iv)	16.5.2.3.7
RKR-H	Risks to peace and to human mobility	Risks to peace within and among societies from armed conflict as well as risks to low-agency human mobility within and across state borders, including the potential for involuntarily immobile populations.	New	16.5.2.3.8

16.5.2.3 Assessment of Representative Key Risks

Each RKR was assessed by a team of 4 to 9 members drawn from Chapter 16, other WGII AR6 chapters, and external contributing authors (16.B.3.1). The following subsections describe the scope of the category of risk (underlying KR considered) and the approach to defining 'severe' risks for each particular RKR. They also assess the conditions in terms of warming (more broadly, climatic impact-drivers; (Ranasinghe et al., 2021), exposure/vulnerability and adaptation under which the RKR would become severe. For each of these dimensions, RKR teams considered generic levels ranging from High to Medium and Low. For warming levels, in line with WG1 framing, High refers to climate outcomes consistent with RCP8.5 or higher, Low refers to climate outcomes consistent with RCP2.6 or lower, and Medium refers to intermediary climate scenarios. For reference, the full range of warming levels (across all climate models) associated with RCP8.5 for the 2081-2100 period is 3.0C to 6.2C; for RCP2.6 it is 0.9C to 2.3C; and for intermediate RCPs it is 1.8C to 3.6C (Cross-Chapter Box CLIMATE in Chapter 1). For Exposure-Vulnerability, levels are determined by the RKR teams relative to the range of future conditions considered in the literature, for example based on the Shared Socioeconomic Pathways (SSPs) in which future conditions based on SSPs 1 or 5 represent Low exposure or vulnerability and those based on SSPs 3 or 4 represent High exposure or vulnerability (O'Neill et al., 2014; van Vuuren and Carter, 2014). For Adaptation, two main levels have been considered: High refers to near maximum potential and Low refers to the continuation of today's trends. Despite being intertwined in reality, Exposure-Vulnerability and Adaptation conditions are distinguished to help understand their respective contributions to risk severity. Importantly, this assessment does not consider all risks, but only those that can be considered severe given the definition and criteria presented in Section 16.5.1. The assessment does not exclude the possibility that severe risks are already observed in some contexts, and considers projected risks through the end of this century.

Each RKR assessment followed a common set of guidelines (16.B.3) that included broad criteria for defining severity (Section 16.5.1), consideration of complex risks and interactions within and across RKRs, and consideration of risks across a range of scales, regions, and ecological and human development contexts. The specific definition of severity within each RKR was determined by the author teams of that assessment, applying different combinations of key risk criteria and metrics as judged appropriate in each case. Definitions are transparent and use common criteria, but are nonetheless based on the respective author team's judgment. Conclusions about severity and associated confidence statements are therefore conditional on those definitions.

Assessments are based on different types of evidence depending on the nature of the literature. In some cases, quantitative projections of potential impacts are available. In others and as for KR identification, the potential for severe risk is inferred from high levels of current vulnerability and the expectation that the relevant climate hazards (CIDs) will increase in frequency or intensity in the future.

16.5.2.3.1 Risk to the integrity of low-lying coastal socio-ecological systems (RKR-A)

RKR-A considers climate change-related risks to low-lying coasts including their physical, ecological and human components. Low-lying systems are those occupying land below 10 m of elevation that is contiguous and hydrologically connected to the sea (McGranahan et al., 2007). The assessment builds on Key Risks identified in chapters 3 and 15, Cross Chapter Paper 2 as well as in the SROCC (Magnan et al., 2019; Oppenheimer et al., 2019). It highlights risks to (i) natural coastal protection and habitats; (ii) lives, livelihoods, culture and well-being; and (iii) critical physical infrastructure; it therefore overlaps with several other RKRs (Fig. 16.10 and 16.11) but within a coastal focus. It encompasses all latitudes and considers multiple sources of climate hazards, including sea-level rise (SLR), ocean warming and acidification, permafrost thaw, and sea-ice loss and changes in weather extremes.

Severe risks to low-lying coasts involve irreversible long-term loss of land, critical ecosystem services, livelihoods, well-being or culture in relation to increasing combined drivers, including climate hazards and exposure and vulnerability conditions. The definition depends on the local context because of variation in the perception of tolerable risks and the limits to adaptation (Handmer and Nalau, 2019). Accordingly, a qualitative range of consequences is presented here, in place of a quantitative global severe risk threshold.

The literature suggests that severe risks generally occur at the nexus of high levels and rates of anthropogenic-driven change in climate hazards (16.2.3.2), concentrations of people and tangible and intangible assets, non-climate hazards such as sediment mining and ecosystem degradation (3.4.2.1), and the reaching of adaptation limits (16.4) (*medium evidence*, *high agreement*). In some Arctic communities and in communities reliant on warm-water coral reefs, even 1.5-2ºC warming will lead to severe risks from loss of ecosystem services (3.4.2.2; CCP6) (*high confidence)*. Loss of land is already underway globally due to accelerating coastal erosion and will be amplified by increased sea-level extremes and permanent flooding (*high confidence*; Oppenheimer et al. 2019, Ranasinghe et al. 2021). Observed impacts of and projected increases in high intensity extreme events (Ranasinghe et al. 2021) also provide evidence for severe risk to occur on livelihoods, infrastructure and well-being (Section 16.5.2.3.3) by mid-century (*high confidence*). Consequently, the combination of high warming, continued coastal development and low adaptation levels will challenge the habitability of many low-lying coastal communities in both developing and developed countries over the course of this century (*low evidence*, *high agreement*) (Duvat et al., 2021; Horton et al., 2021). In some contexts, climate risks are already considered severe (*medium evidence*, *medium agreement*), and in others, even lower warming will induce severe risks to habitability, which will not necessarily be offset by ambitious adaptation (*low evidence*, *medium agreement*).

(i) Natural coastal protection and habitats — Severe risks from the loss of shoreline protection from reductions in wave attenuation (Beck et al., 2018, Section 3.5.5.1; Section 3.5.4.5) and sediment delivery (3.4.2.5; 15.3.3) are already observed in some coastal systems (Section 16.2.3.1) and occur broadly even with 1.5ºC of global warming (Hoegh-Guldberg et al., 2018a; Bindoff et al., 2019, Section 3.4.2). These impacts are the consequence of warming and SLR on coastal ecosystems.

Warm-water coral reefs are at risk of widespread loss of structural complexity and reef accretion by 2050 under 1.5°C global warming (Section 3.4.2.1) (*high confidence*). Kelp forests may experience shifts in community structure (Arafeh-Dalmau et al., 2019; Rogers-Bennett and Catton, 2019; Smale, 2020; Smith et al., 2021) with >2°C of global warming especially at lower latitudes (Section 3.4.2.2) (*high confidence*). In addition, depending on the local tide and sediment conditions, SLR associated with >1.5°C of global warming (SSP1-2.6; 3.4.2.5) is sufficient to initiate shifts to alternate states in some seagrass and coastal wetland systems (van Belzen et al., 2017; El-Hacen et al., 2018, Section 3.4.2.5, Cross-Chapter Box SLR in Chapter 3), and submergence of some mangrove forests (3.4.2.5). A striking example of risks becoming severe at higher levels of warming is the one of coral islands with low elevation (Section 15.3.4, Box 15.1): the risk of loss of habitability transitions from Moderate-to-High under RCP2.6 for most island types (urban and rural) to High-to-Very High under RCP8.5 (Duvat et al., 2021), even under a high adaptation scenario

(Oppenheimer et al., 2019), partly due to declining sediment supply (Perry et al., 2018) and increased annual flooding (Giardino et al., 2018; Storlazzi et al., 2018).

More broadly, about 28,000 km2 of land have been lost globally since the 1980s due to anthropogenic factors (e.g., coastal structures, disruption of sediment fluxes) and coastal hazards (Mentaschi et al., 2018), and an additional loss of 6000-17,000 km2 is estimated by the end of the century due to coastal erosion alone associated with SLR in combination with other drivers (Hinkel et al., 2013).

(ii) Impacts to lives, livelihoods, culture and well-being — In the absence of effective adaptation, changing extreme and slow-onset hazards combined with anthropogenic drivers (e.g., increased population pressure at the coast between +5% and +13.6% by 2100 compared to today, Jones and O'Neill, 2016) will lead to loss of lives, livelihoods, health, well-being, and/or culture (McGregor et al., 2016; Pinnegar et al., 2019; Pugatch, 2019; Schneider and Asch, 2020; Thomas and Benjamin, 2020; McNamara et al., 2021) (*high confidence*). Catastrophic examples that may foreshadow the future include Hurricane Sandy in 2012 (Strauss et al., 2021)and super Typhoon Haiyan in 2013 (>6,000 deaths and inequities in access to safe housing; Trenberth et al. 2015) (6.2.2, 6.3.5.1). Although there is no unique definition of 'intolerable' loss, risks are generally expected to become severe over this century (Tschakert et al., 2017; Dannenberg et al., 2019; Tschakert et al., 2019). Globally, with High warming, 90 to 380 million more people will be exposed to annual flood levels by the mid- and end-century, respectively, compared to 250 million people today (Kulp and Strauss, 2019; Kirezci et al., 2020), with potential implications on forced displacement or migration (Oppenheimer et al., 2019; Wrathall et al., 2019; Hauer et al., 2020; Lincke and Hinkel, 2021, Section 16.5.2.3.9). Some of the largest fish-producing and fish-dependent ecoregions have already experienced losses of up to 35% in marine fisheries productivity due to warming (Free et al., 2019), and about 11% of the global population will face increasing nutritional risks if current trajectories continue (Golden et al., 2016). While difficult to measure, current climate-driven losses to (indigenous) knowledge, traditions (Tschakert et al., 2019; Pearson et al., 2021) and well-being (Ebi et al., 2017; Cunsolo and Ellis, 2018; Jaakkola et al., 2018) indicate such risk as already severe in some regions (*low evidence, medium agreement*), jeopardizing communities' realization of their rights to food, health and culture. In the Arctic, climate-driven changes to ice and weather regimes have substantially affected traditional coastal-based hunting and fishing activities (Fawcett et al., 2018; Galappaththi et al., 2019; Huntington et al., 2020; Nuttall, 2020, CCP6), and where permafrost thaw, SLR and coastal erosion are contributing to threatening cultural sites (Hollesen et al., 2018; Fenger-Nielsen et al., 2020).

(iii) Critical physical infrastructure — Severe risks are also illustrated through damages that lead to possibly long-lasting disruption of key services like transportation as well as energy generation and distribution in coastal areas (Section 16.5.2.3.3) under all RCPs (CCP2.2.3) and if no additional adaptation (*medium confidence*). Critical transport infrastructure is already suffering from structural failures in polar regions, for instance, due to permafrost thaw and increased erosion associated with ocean warming, storm surge flooding and loss of sea ice (Melvin et al., 2017; Fang et al., 2018, Section 14.5.2.8, Section 16.2.3.2, CCP6). One hundred airports are projected to be below mean sea-level in 2100 with 2°C of warming (i.e., 0.62 m SLR, Yesudian and Dawson, 2021), including in small islands (Monioudi et al., 2018; Storlazzi et al., 2018) and megacities. Projections show San Francisco International Airport, for instance, to be inundated by 2100 under the upper likely range of SLR in RCP8.5 (also considering subsidence trends, Shirzaei and Bürgmann, 2018). On the energy side, it is estimated that with 1.8m SLR, for example, four out of 13 US nuclear power plant facilities will become exposed to storm surges and three others will be surrounded or submerged by seawater (Jordaan et al., 2019; Jenkins et al., 2020).

16.5.2.3.2 Risk to terrestrial and ocean ecosystems (RKR-B)

This risk refers to transformations of terrestrial and ocean/coastal ecosystems that would include significant changes in structure and/or functioning, and/or loss of a substantial fraction of species richness (commonly used to indicate loss of biodiversity). These are sourced mainly from Chapters 2 and 3, CCP1, and reference the 1.5C report, Chapter 4 from WGII AR5, and Chapter 4 from WGII AR4 Reports.

Severe adverse impacts on biodiversity include significant risk of species extinction (e.g., loss of a substantial fraction (one tenth or more) of species from a local to global scale), mass population mortality (>50% of individuals or colonies killed), ecological disruption (order-of-magnitude increases or abrupt reductions of population numbers or biomass), shifts in ecosystem structure and function (order-of magnitude increases or abrupt decreases in cover and/or biomass of novel growth forms or functional types), and/or a socio-economically material increase in environmental risk (e.g., destruction by wildfire) or socio-economically material decline in goods and services (e.g., carbon stock losses, loss of grazing, loss of pollination). Metrics relevant to Sustainable Development Goals are also germane.

A substantial proportion of biodiversity is at risk of being lost below 2ºC of global warming (Chapter 2), due to range reductions and loss globally, with this risk amplified roughly three times in insular ecosystems and biodiversity hotspots, due to the increased vulnerability of endemic species (Manes et al., 2021). High latitude, high altitude, insular, freshwater, and coral reef ecosystems and biodiversity hotspots (Chapter 2, Cross-Chapter Paper 1 on Biodiversity Hotspots) are at appreciable risk of substantial biodiversity loss due to climate change even under Low warming (*high confidence*). These systems comprise a large fraction of unique and endemic biodiversity, with species impacts often exacerbated by multiple drivers of global change (Chapter 2, Chapter 3). Roughly one third of all known plant species are extremely rare, vulnerable to climate impacts, and clustered in areas of higher projected rates of anthropogenic climate change (Enquist et al., 2019). Much evidence shows increased risk of the loss of 10% or more of terrestrial biodiversity with increasing anthropogenic climate change (Urban, 2015; Smith et al., 2018) (*medium confidence*), *likely* with 2ºC warming above pre-industrial level (Chapter 2), with consequent degradation of terrestrial, freshwater, and ocean ecosystems (Oliver et al., 2015) and adverse impacts on ecosystem services (Pecl et al., 2017) and dependent human livelihoods (Dube et al., 2016). Adverse impacts on biodiversity may show lagged responses (Essl et al., 2015), and loss of a substantial fraction of species could occur abruptly, simultaneously across multiple taxa, below 4ºC of global warming (Trisos et al., 2020).

Mass population-level mortality (>50% of individuals or colonies killed) and resulting abrupt ecological changes can be caused by simple or compound climate extreme events, such as exceedance of upper thermal limits by vulnerable terrestrial species (Fey et al., 2015), who also note reduced mass mortality trends due to extreme low thermal events); marine heatwaves that can cause mortality, enhance invasive alien species establishment, and damage coastal ecological communities and small-scale fisheries (*high confidence*) (Section 3.4.2.7); and increased frequency and extent of wildfires that threaten populations dependent on habitat availability (like Koala Bears, Lam et al., 2020). Abrupt ecological changes are widespread and increasing in frequency (Turner et al., 2020), and include tree mortality due to insect infestation exacerbated by drought, and ecosystem transformation due to wildfire (Vogt et al., 2020). Freshwater ecosystems and their biodiversity are at high risk of biodiversity loss and turnover due to climate change (precipitation change and warming, including warming of water bodies), due to high sensitivity of processes and life histories to thermal conditions and water quality (Chapter 2) (*high confidence*). In marine systems, heatwaves cause damages in coastal systems, including extensive coral bleaching and mortality (very *high confidence*) (Section 3.4.2.1), mass mortality of invertebrate species (*low* to *high confidence*, depending on system) (Sections 3.4.2.2, Section 3.4.2.5, Section 3.4.4.1), and abrupt mortality of kelp-forest (*high confidence*) (Section 3.4.2.3) and seagrass-meadow habitat (*high confidence*) (Section 3.4.4.2). The biodiversity of polar seas shows strong impacts of climate change on phenological timing of plankton activity, Arctic fish species range contractions and species community change (Table 16.2) (*high confidence*). Extreme weather events and storm surges exacerbated by climate change have severe and sudden adverse impacts on coastal systems, including loss of seagrass meadows and mangrove forests (*high confidence*) (see Section 3.4.2.7, Section 3.4.2.8, Cross-Chapter Box EXTREMES in Chapter 2).

Ecological disruption (order-of-magnitude increases or abrupt reductions of population numbers or biomass) can occur due to unprecedented inter-species interactions with unpredictable outcomes in 'novel ecosystems' (Chapter 2) as species shift geographic ranges idiosyncratically in response to climatic drivers (Table 16.2). Idiosyncratic geographic shifts are now observed in an appreciable fraction of species studied (Chapter 2, Table 16.2). Commensal or parasitic diseases may infect immunologically naive hosts (e.g., chytrid fungus in amphibians). Atypical disturbance regimes may be enhanced, for example, with the spread of flammable plant species (e.g., du Toit et al., 2015), exacerbated by introduced species (e.g., Martin et al., 2015), thus significantly increasing risk of loss and damage to infrastructure and livelihoods, ecological degradation, and challenging existing management approaches.

Landscape- and larger-scale shifts in ecosystem structure and function (order-of magnitude increases or abrupt decreases in cover and/or biomass of novel growth forms or functional types) are occurring in non-equilibrium ecosystems (systems which exist in multiple states, often disturbance-controlled) in response to changing disturbance regime, climate and rising CO_2 (*high confidence*) Woody plant encroachment has been occurring in multiple ecosystems, including sub-tropical and tropical fire driven grassland and savanna systems, upland grassland systems, arid grasslands and shrublands (*high confidence*), leading to large scale biodiversity changes, albedo changes, and impacts on water delivery, grazing services and human livelihoods (*medium confidence*). Expansion of grasses (alien and native) into xeric shrublands is occurring causing increasing fire prevalence in previous fire free vegetation (CCP3). In tropical forests repeated droughts and recurrence of large-scale anthropogenic fires increase forest degradation, loss of biodiversity and ecosystem functioning (*high confidence*) (Anderson et al., 2018b; Longo et al., 2020). Accelerated growth rates and mortality of tropical trees is also adversely affecting tropical ecosystem functioning (McDowell et al., 2018; Aleixo et al., 2019). Projected changes in ecosystem functioning, such as via wildfire (Section 2.5.5.2), tree mortality (Section 2.5.5.3) and woody encroachment under climate change (Chapter 2) would alter hydrological processes, with adverse implications for water yields and water supplies (Sankey et al., 2017; Robinne et al., 2018; Rodrigues et al., 2019; Uzun et al., 2020).

The loss of a substantial fraction of biodiversity globally, abrupt impacts like significant local biodiversity loss and mass population mortality events, and ecological disruption due to novel species interactions have been observed or are projected at global warming levels below 2ºC (Chapter 2 Table 2.S.4, Cross Chapter Box: EXTREMES in Chapter 2, Section 2.4.4.3.1, Section 2.4.2.3.3) (*medium confidence*). Simple and compound impacts of extreme climate events are already causing significant loss and damage in vulnerable ecosystems, including through the facilitation of important global change drivers of ecological disruption and homogenisation like invasive species (*high confidence*). Severe impacts on human livelihoods and infrastructure, and valuable ecosystem services are all projected to accompany these changes. Adaptation potential for many of these risks is low due to the projected rate and magnitude of change, and to the requirement of significant amounts of land for terrestrial ecosystems (Hannah et al., 2020). Biodiversity conservation efforts may be hampered due to climate change impacts on the effectiveness of protected areas, with high sensitivity of effectiveness to forcing scenario (*medium confidence*). In addition, climate-related risks to ecosystems pose challenges to ecosystem-based adaptation responses (‘nature-based solutions’) (Section 2.1.3) (*medium confidence*).

16.5.2.3.3 Risk to critical physical infrastructure and networks (RKR-C)

RKR-C includes risks associated with the breakdown of physical infrastructure and networks which provide goods and services considered critical to the functioning of societies. It encompasses infrastructure systems for energy, water, transportation, telecommunications, health care and emergency response, as well as compound, cascading and cross-boundary risks resulting from infrastructure interdependencies (Birkmann et al., 2016; Fekete, 2019). Critical infrastructures such as transport or energy supply also play a central role in coping with climate risks, especially in acute disaster situations in which the services of transport infrastructure, communication technologies or electricity are particularly needed, despite the fact that these very systems are themselves exposed to disaster impacts (Garschagen et al., 2016; Pescaroli et al., 2018). The major hazards driving such risks are acute extreme events such as cyclones, floods, droughts or fires (*high confidence*), but cumulative and chronic hazards such as sea level rise (SLR) are also considered.

RKR-C is considered severe when the functioning of critical infrastructure cannot be secured and maintained against climate change impacts, resulting in the frequent and widespread breakdown of service delivery and eventually a significant rise of detrimental impacts on people (lives, livelihoods and well-being), the economy (including averted growth) or environment (disruption and loss of ecosystems) above historically observed levels. Severity in this RKR is assessed on two levels for (i) direct impacts of climate change on infrastructure assets and networks (e.g., amount of port infrastructure damaged or destroyed by SLR, flooding and storms) on which most of the literature focuses, as well as (ii) indirect and cascading downstream impacts to people, economy and environment (Markolf et al., 2019; Pyatkova et al., 2019; Chester et al., 2020), for which attribution is more difficult and uncertainties tend to be much higher. Overall, the literature with quantified assessments of climate change infrastructure risks remains to be less extensive than for many other risks, particularly with regards to assessments focusing on the Global South. While climate-related changes in hazards are widely considered in the literature, changes in future exposure and vulnerability conditions are often not treated explicitly. In addition, the severity of infrastructure risks also depends on future trends in the capacity to maintain, repair and rebuild infrastructure and adapt it to new hazard intensities (*medium evidence, high agreement*). These are mostly not quantified in a forward-looking manner in the literature; however, damage projections (see below) indicate a rapidly rising demand for investment, straining the financial capacity of countries (*medium evidence, high agreement*).

(i) Risks related to direct impacts on critical infrastructure would become severe with high warming, current infrastructure development regimes and minimal adaptation (*high confidence*), and in some contexts even with low warming, current vulnerability and no additional adaptation (*medium confidence*), with severity defined as infrastructure damage and required maintenance costs exceeding multiple times the current levels. Transport and energy infrastructure in coasts, polar systems and along rivers are projected to face a particularly steep rise in risk, resulting in severe risk even under medium warming (*high confidence*). Risk in relation to the increasing intensity and frequency of extreme events might become severe before the middle of the century (*medium confidence*). Damages from multiple climate hazards to transport, energy, industry and social infrastructure in Europe could increase tenfold by the 2080s, from 3.4 € billion annually to date, and 15-fold for transport infrastructure, under Medium warming (A1B, ~3°C by 2100) and with current adaptation levels, even if no further extension of the infrastructure in exposed areas is considered (Forzieri et al., 2018). Under High warming (RCP8.5) in 2100, the percent of roads in the United States that require rehabilitation due to high temperatures and precipitation is expected to increase to 23–33%, relative to 14% in 2100 when no climate change is considered (Mallick et al., 2018). Projections of climate-induced changes in exposure are an incomplete measure of risk but in the absence of other metrics can serve as a proxy for the potential for severe impacts. In the circumpolar Arctic, 14.8% of critical infrastructure assets would be affected by climate change under RCP8.5 by 2050, with lifecycle replacement costs projected to increase by 27.7% if infrastructure is to be preserved at current adaptation levels (Suter et al., 2019). Under RCP8.5, the number of ports under high risk will increase from 3.8% in the present day to 14.4% by 2100, as a result of increased coastal flooding and overtopping due to sea level rise, as well as the heat stress impacts of higher temperatures (Izaguirre et al., 2021). In the UK under High warming (4ºC), the number of clean and wastewater treatment sites located in the 1 in 75-year floodplain will increase by a third relative to today by the 2080s under current vulnerability and adaptation levels (Dawson et al., 2018). A global assessment of changing climate and water resources for electricity generation finds considerable reductions in usable hydropower and thermoelectric capacity by 2050 for a range of warming scenarios from Low to High, with absolute declines on average for most (61–74%) of the world's hydropower resources and monthly maximum reductions above 30% of usable capacity for over two-thirds of 1,427 thermoelectric power plants worldwide (Van Vliet et al., 2016). Many studies find large technical potential for coordinated adaptation-mitigation policies in the electricity sector to avoid a significant portion of projected climate change impacts (e.g., a two-thirds reduction, and in some cases fully offset) (Ciscar and Dowling, 2014; Van Vliet et al., 2016; Gerlak et al., 2018; Allen-Dumas et al., 2019).

(ii) Studies quantifying the indirect impacts of infrastructure failure on lives, livelihoods and economies are still rare but emerging, suggesting that risks would become severe in many contexts globally with high warming, current vulnerability and no additional adaptation (*medium confidence*). Severity in this context is defined as the potential to disrupt the lives, livelihoods and well-being of a significantly increased proportion of the population and to significantly forestall economic growth and development potential. Global risks to air travel from SLR, expressed in terms of expected annual route disruptions, could increase by a factor of between 17 and 69 by 2100 under the 1.5 ◦C and the 95th percentile value of the RCP8.5 SLR scenario, respectively (Yesudian and Dawson, 2021). By 2050, up to 185,000 airline passengers per year may be grounded due to extreme heat (48°C) if no additional adaptation is taken, roughly 23 times more than today (McKinsey Global Institute, 2020). In Africa, under RCP8.5 and without additional adaptation a 250% increase in disruption time of the transport network is expected by 2050 due to extreme temperatures, a 76% increase due to precipitation, and 1400% increase due to flooding (Cervigni et al., 2015). On the Dawlish railway section (UK), the number of days with line restrictions are set to increase by up to 1170%, to as many as 84–120 per year by 2100 due to 0.8m SLR with High warming (Dawson et al., 2016). Next to the limited number of projections or scenarios of indirect impacts, additional inferences from studies focusing on past and current impacts can be drawn. Already today, climate-related impacts on transport and energy infrastructure reach far beyond the direct impacts on physical infrastructure, triggering indirect impacts on, for example, health and income (*medium confidence*). A case study of future flood hazard in Europe found that the indirect impact of a power outage on the local economy is six to eight times greater than the direct flood damage and asset repair costs, due to the interruption of daily economic activity (Karagiannis et al., 2019). In low and middle-income countries, the annual costs from infrastructure disruptions reach up to 300 billion USD for firms and 90 billion USD for private households, with natural hazards such as floods being responsible for 10 to 70 % of these disruptions, depending on the sectors and regions (Hallegatte et al., 2019). Power outages triggered by floods or droughts have also been found to have substantial health implications, particularly amongst low-income populations (Klinger et al., 2014), and shown to impede disaster recovery efforts and severely disrupt local economies (Karagiannis et al., 2019; Nicolas et al., 2019). In addition, risks associated with infrastructure have the potential to become particularly severe when hazard-driven infrastructure disruptions undermine the capacity of emergency response in disaster situations (*low evidence, high agreement*). A study on the UK shows, for example, that even a small increase in minor road flooding leads to a disproportionately high disruption of the efficacy of emergency services (Yu et al., 2020). Similar risks have been found for rural areas, particularly in developing countries (Alegre et al., 2020).

16.5.2.3.4 Risk to living standards (RKR-D)

This RKR includes risks to (i) aggregate economic output at the global and national levels, (ii) poverty, and (iii) livelihoods, and their implications for economic inequality. It is informed by key risks identified by regional and sectoral chapters. Risks are potentially severe as measured by the magnitude of impacts in comparison to historical events or as inferred from the number of people currently vulnerable.

(i) Risks to aggregate economic output would become severe at the global scale with high warming and minimal adaptation (*medium confidence*), with severity defined as the potential for persistent annual economic losses due to climate change to match or exceed losses during the world's worst historical economic recessions. With historically observed levels of adaptation, warming of ~4ºC may cause a 10-23% decline in annual global GDP by 2100 relative to global GDP without warming, due to temperature impacts alone (Burke et al., 2015; Kahn et al., 2019; Kalkuhl and Wenz, 2020). These magnitudes exceed economic losses during the Great Recession (2008-2009, ~5% decline in global GDP, up to 15-18% in some countries) and the COVID-19 pandemic (2020, ~3% decline globally, up to 10% in some countries) (IMF, 2020; IMF, 2021). Unlike past recessions, climate change impacts would occur continuously in every year. However, smaller effects (1-8%) are found when using alternative methodologies (Diaz and Moore, 2017; Nordhaus and Moffat, 2017; Kompas et al., 2018; Kalkuhl and Wenz, 2020), assuming less warming (Kahn et al., 2019; Takakura et al., 2019), and assuming lower vulnerability and/or more adaptation (Diaz and Moore, 2017); this literature is comprehensively summarized in Cross-Working Group Chapter Box ECONOMIC. Impacts at high levels of warming are particularly uncertain, as all methodologies require extrapolation and insufficiently incorporate possible tipping elements in the climate system (Kopp et al., 2016).

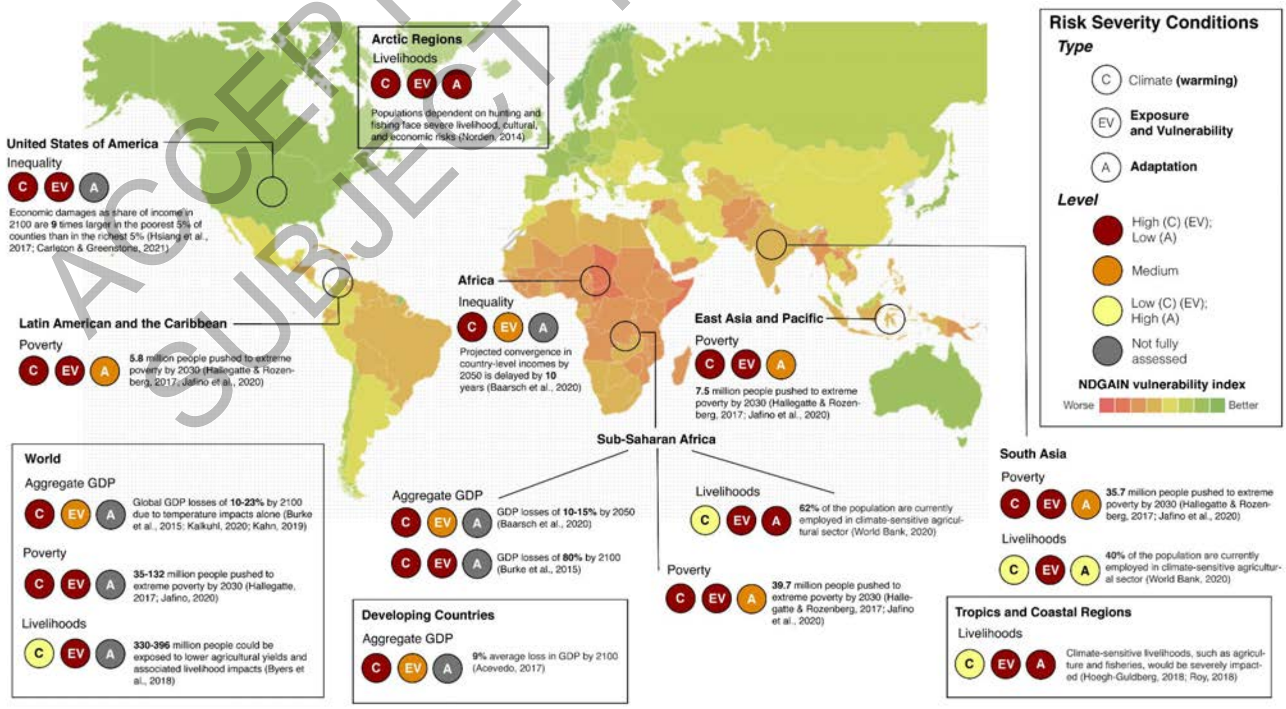


Figure 16.9. Illustrative examples from individual studies of risks to living standards and the conditions under which they could become severe. Selected studies are not representative of the literature, but provide examples of potentially

severe risks to aggregate economic output, poverty, and livelihoods. High, medium, and low levels of warming, exposure/vulnerability, and adaptation are defined as in Figure 16.10.

Annual economic output losses in developing countries could exceed the worst country-level losses during historical economic recessions (*medium confidence*). Assuming global warming of ~4ºC by 2100, historical adaptation levels, and high vulnerability, losses across sub-Saharan Africa may reach 12% of GDP by 2050 (Baarsch et al., 2020) and 80% by 2100 (Burke et al., 2015), and ~9% on average across developing countries by 2100 (Acevedo et al., 2017). The largest estimates are debated and depend on assumptions about development trends, adaptive capacity, and whether temperature impacts the level or growth rate of economic activity (Kalkuhl and Wenz, 2020). Severe risks are more likely in (typically hotter) developing countries because of nonlinearities in the relationship between economic damages and temperature (Burke et al., 2015; Acevedo et al., 2017). These risks are highest in scenarios and countries with: a large portion of the workforce employed in highly exposed industries (Acevedo et al., 2017); a high concentration of population and economic activity on coastlines (Hsiang and Jina, 2014; Acevedo et al., 2017); and an increase in the frequency or intensity of disasters triggered by natural hazards (Berlemann and Wenzel, 2018; Botzen et al., 2019). Whether baseline economic growth may help avoid severe future risks is highly uncertain (Dell et al., 2012; Burke et al., 2015; Acevedo et al., 2017; Deryugina and Hsiang, 2017).

(ii) Under medium warming pathways, climate change risks to poverty would become severe if vulnerability is high and adaptation is low (limited evidence, high agreement). We define poverty in terms of absolute consumption levels and define severity as tens to hundreds of millions of additional people in poverty relative to the number without change (globally) or an absolute increase in the number of people living in poverty compared to today (nationally or locally). This global impact is comparable to the effect of the 2007 food price shock (De Hoyos and Medvedev, 2009) and the 2020 COVID-19 pandemic (World Bank, 2020) and can be compared to about 700 million in poverty in 2017, down from 1.9 billion in 1990 (World Bank, 2020).

In a high-vulnerability development pathway, climate change in 2030 could push 35-132 million people into extreme poverty, in addition to the people already in poverty assuming climate is unchanged (disregarding impacts from natural variability; Hallegatte and Rozenberg, 2017; Jafino et al., 2020). In a low warming pathway, risks from mitigation costs could also be severe if no progressive redistribution from carbon pricing revenues is applied (Soergel et al., 2021). At the national level there is limited evidence of climate change causing an absolute increase in poverty (e.g., absolute increase of ~1-2%/yr through 2040, Montaud et al., 2017). Potentially severe risks to poverty are also supported by (1) the observed impacts of past disasters (Winsemius et al., 2018; Hallegatte et al., 2020; Rentschler and Melda, 2020) and previous crises such as food price shocks (Ivanic and Martin, 2008) or current diseases (WHO, 2018) on poor people and on poverty; (2) the expectation that these events will become more intense or frequent in some regions (WGI Chapter 12, Ranasinghe et al., 2021); and (3) population growth and the low adaptive and coping capacities of the poor (Leichenko and Silva, 2014; Huynh and Stringer, 2018; Thomas et al., 2020). This literature provides indirect evidence that climate change will keep many people poor and may cause more than tens of millions to fall into poverty (*low evidence, high agreement*).

(iii) Climate change poses severe risks to livelihoods at low levels of warming, high exposure/vulnerability, and low adaptation in climate-sensitive regions, ecosystems, and economic sectors (*high confidence*), where severity refers to the disruption of livelihoods for tens to hundreds of millions of additional people (Arnell and Lloyd-Hughes, 2014; Liu et al., 2018). More widespread severe risks would occur at high levels of warming (with high exposure/vulnerability and low adaptation) where there is additional potential for one or more social or ecological tipping points to be triggered (Cai et al., 2015; Cai et al., 2016b; Kopp et al., 2016; Steffen et al., 2018; Lenton et al., 2019), and for severe impacts on livelihoods to cascade from relatively more climate-sensitive to relatively less climate-sensitive sectors and regions (*medium confidence*) (Lawrence et al., 2020). Severity assessment is based on the current magnitude of exposure and vulnerability across multiple social and ecological systems, projected future exposure and vulnerability, and the rate at which hazard frequency or intensity is expected to increase (Otto et al., 2017; Roy et al., 2018; Li et al., 2019, Section 8.5). Without effective adaptation measures, regions with high dependence on climate-sensitive livelihoods – particularly agriculture and fisheries in the tropics and coastal regions – would be severely impacted even at low levels of warming (*high confidence*) (Hoegh-Guldberg et al., 2018b; Roy et al., 2018). For example, it is estimated that 330–396 million people could be exposed to lower agricultural yields and associated livelihood impacts at warming between 1.5 and 2ºC (Byers et al., 2018). Risks to the 200 million people with livelihoods derived from small-scale fisheries would also be severe, given sensitivity to ocean warming, acidification, and coral reef loss occurring beyond 1.5ºC (Cheung et al., 2018b; Froehlich et al., 2018; Free et al., 2019; Barnard et al., 2021). Livelihoods in highly exposed locations, such as small-island developing states, low-lying coastal areas, arid or semi-arid regions, the Arctic, and urban informal settlements or slums, are particularly vulnerable (Ford et al., 2015c; Hagenlocher et al., 2018; Ahmadalipour et al., 2019; Tamura et al., 2019). Within populations, the poor, women, children, the elderly, and indigenous populations are especially vulnerable due to a combination of factors including gendered divisions of paid and/or unpaid labour, as well as barriers in access to information, skills, services, or resources (Bose, 2017; Thomas et al., 2019b; Anderson and Singh, 2020; Adzawla and Baumüller, 2021)(*high confidence*). Future structural transformation could moderate risk severity by improving adaptive capacity, creating livelihoods in less climate-sensitive sectors, or by enabling sustainable migration to less climate-sensitive locations (Henderson et al., 2017; Roy et al., 2018). However, successful risk moderation would depend upon simultaneous avoidance of both climate change-related and mitigation-related (Doelman et al., 2019; Fujimori et al., 2019; Doelman et al., 2020) or maladaptation-related risks (Magnan et al., 2016; Benveniste et al., 2020; Schipper, 2020).

Climate change also could increase income inequality between countries (*high confidence*) as well as within them (*medium evidence, high agreement*) that result from and exacerbate impacts on aggregate economic activity, poverty, and livelihoods. Increasing inequality implies larger impacts on the least well-off, threatens their ability to respond to climate hazards, compromises basic principles of fairness and established global development goals, and potentially threatens the functioning of society and long-term progress (Roe and Siegel, 2011; Cingano, 2014; van der Weide and Milanovic, 2018). There is evidence that warming has slowed down the convergence in between-country income in recent decades (Diffenbaugh and Burke, 2019). Future impacts may halt or even reverse this trend during this century due to high sensitivity of developing economies (Burke et al., 2015; Pretis et al., 2018; Baarsch et al., 2020), although projections depend as much or more on future socioeconomic development pathways and mitigation policies as on warming levels (Takakura et al., 2019; Harding et al., 2020; Taconet et al., 2020). Within countries, studies that find adverse impacts on low-income groups imply an increase in inequality (Hallegatte and Rozenberg, 2017; Hsiang et al., 2017), although evidence for long-term climate impacts on within-country inequality at global scale remains limited.

16.5.2.3.5 Risk to human health (RKR-E)

This RKR includes (i) mortality from heat, and morbidity and mortality from (ii) vector-borne diseases and (iii) waterborne diseases. It builds on KRs identified primarily in Chapter 7 and health risks in regional chapters.

A severe risk to health is the potential for a widespread, substantial worsening of health conditions due to climate change. We measure severity in terms of the magnitude of mortality and morbidity. We consider a severe mortality impact to be a sustained increase in the crude mortality rate (CMR) of more than about 2-4 deaths per 10,000 people per year, or 2-5% over the current background rate. This range of increase is consistent with current mortality impacts with substantial global effects, including traffic fatalities (CMR of 1.6/10,000/yr, IHME) and the COVID-19 pandemic (4/10,000/yr, as of April, 2021, expressed as an annualized rate (Ritchie, Hannah et al., 2021). We use these global rates as thresholds in all cases, recognizing that they reflect substantial variation across regions and sub-populations (other points of comparison are included in Table SM16.13). Morbidity impacts are measured in numbers of disease cases or hospital admissions. We find that severe health impacts are projected to occur for particular sub-populations and regions where vulnerability is currently high and is assumed to persist into the future; we focus our assessment on these cases. In other cases, literature is either inadequate or does not support severe outcomes.

(i) Risks of heat-related mortality would become severe at global and regional scales with high levels of warming and vulnerability (*high confidence*). Under these conditions (SSP3-8.5), accounting for adaptation, heat mortality would increase the global CMR by up to 2-7/10,000/yr by 2100 (Carleton et al., 2020). For example, the US would experience a CMR increase of 2-4/10,000/yr by the end of the century (medium vulnerability without adaptation, and recent vulnerability with adaptation, respectively) (Weinberger et al., 2017; Shindell et al., 2020). Also assuming no adaptation and recent vulnerability, every population of the world would experience an increase of 2-10 percentage points in the proportion of deaths attributable to heat by the end of the century (RCP8.5). Harmful conditions for health are expected to increase in frequency and intensity over all land areas along with the rising temperatures in the coming decades (Pal and Eltahir, 2016; Russo et al., 2017; Ranasinghe et al., 2021; Saeed et al., 2021; Schwingshackl et al., 2021). Projections of exposure are an incomplete measure of risk but suggest the potential for severe impacts. For example, the percent of global population exposed to deadly heat stress would increase from today's 30% to 48-74% by the end of the century depending on level of warming and population distribution (Mora et al., 2017). Projected impacts are larger if exposure and/or vulnerability increases due to ageing of the population or increased inequality (Weinberger et al., 2017; Chen et al., 2020a; IPCC, 2021a) and with limited adaptation capacity (e.g., poor infrastructure, limited air conditioning, few medical and public health resources) (Table SM16.4) (Carleton et al., 2020). Higher risks are also expected in urban areas due to hazard amplification (i.e., urban heat island effect) and in highly dense settlements with other environmental hazards such as air pollution (Zhao et al., 2018; Sera et al., 2019).

(ii) Risks of vector-borne disease would become severe with high warming and current vulnerability, concentrated in children and in sensitive regions (*medium confidence*). Severity is defined by regionally substantial numbers of additional malaria deaths, disease cases, and episodic hospitalisation demands (for dengue).

With high warming, the CMR for malaria among children under the age of one year could increase by 5.2-10.1/10,000/yr in Africa under current vulnerability levels. This estimate assumes a net increase of 70-130 million more people exposed to potential disease transmission due to climate change in a high warming scenario (RCP8.5, end of century)(Caminade et al., 2014; Colón-González et al., 2018; Ryan et al., 2020), representing a 14-27% increase in the current population at risk (Ryan et al., 2020), and assumes children under 1 year of age are facing the same crude mortality in the future as for the African region today (Table SM16.13). The largest increase is observed in Eastern Africa, where the population exposed could nearly double by 2080 (Ryan et al., 2020) without accounting for population growth, driven mainly by changes among previously unexposed populations at higher altitude areas (Colón-González et al., 2018). Actual future disease burden of malaria will be highly sensitive to regional socio-economic development and the effectiveness of malaria intervention programs.

For dengue, with high warming and current levels of vulnerability there could be as many as a doubling of cases and hospital admissions per year globally, relative to today, driven by both warming and population growth. These estimates are derived by assuming similar relative incidence rates as today (Shepard et al., 2016) combined with projections of a more than doubling of the population exposed to potential disease transmission by the end of the century in a high warming scenario (RCP8.5), although much of this increase is driven by population growth (Colón-González et al., 2018; Monaghan et al., 2018; Messina et al., 2019). There are around 3 billion people exposed to dengue today.

(iii) Climate change would lead to severe risks of morbidity and mortality caused by waterborne diseases, particularly for diarrhoea in children in many lower- and middle-income countries (LMICs) and where vulnerability remains high (*medium confidence*). The global CMR for diarrhoea is 1.98 for all ages, but varies by region and age group, reaching as high as 53 for <1 year olds in Africa (Institute for Health Metrics and Evaluation (IHME), 2021) . In these vulnerable populations even a small percentage increase can lead to substantial additional morbidity and mortality. For example, assuming no change in vulnerability or population, an increase in diarrhoea mortality of only 5% over 2019 baseline rates would create a severe risk (CMR of 2.0) for children under the age of 1 in the WHO Africa (AFRO) region. This percent increase due to climate change is plausible since diarrhoea incidence increases of 7% (95% confidence interval 3-10%) are associated with a 1ºC increase in ambient temperature (WHO, 2014; Carlton et al., 2016), and diarrhoea is positively associated with heavy rainfall and flooding events (Levy et al., 2016), expected in some regions (WGI). Assuming vulnerability remains the same as today, mortality and morbidity rates would increase equivalently.

However, risks will be highly dependent on development trajectories, given that waterborne disease transmission is exacerbated by lack of clean drinking water and sanitation systems, inadequate food safety and hygiene conditions, lack of flood and drought protections, and interactions with other risks such as cholera outbreaks, food insecurity, and infrastructure damage. Climate change threatens the progress that has been made toward reducing the burden of diarrhea. For example, in Sub-Saharan Africa, while overall diarrhea rates are expected to continue to decline (GBD 2016 Diarrhoeal Disease Collaborators, 2018), warming in 2030 (relative to the late 20th century) is projected to lead to diarrheal deaths in children under 15 equivalent to a CMR increase of 0.56/10,000/yr (based on population projections for the region and age group (UN, 2020)) (WHO, 2014). In China, by 2030 climate change could delay progress toward reducing waterborne disease burden by 8-85 months (Hodges et al., 2014).This RKR includes (i) mortality from heat, and morbidity and mortality from (ii) vector-borne diseases and (iii) waterborne diseases. It builds on KRs identified primarily in Chapter 7 and health risks in regional chapters.

16.5.2.3.6 Risk to food security (RKR-F)

Climate change affects food security primarily through impacts on food production, including crops, livestock, and fisheries, as well as disruptions in food supply chains, linked to global warming, drought, flooding, precipitation variability and weather extremes (Myers et al., 2017; FAO et al., 2018; Mbow et al., 2019). This RKR builds on Key Risks identified primarily in the Food, Fibre, and other Ecosystem Products Chapter, some sectoral (Health), and regional (Africa, Australasia, Central and South America, North America) chapters, as well as SR15, SRCCL and SROCC.

The severity of the risk to food security is defined here using a combination of criteria including the magnitude and likelihood of adverse consequences, affecting 10s to 100s of millions of people, timing of the risk and ability to respond to the risk. In this assessment, we use the number of undernourished people as a proxy outcome of these dimensions and their multiple interactions.

Climate change will pose severe risks in terms of increasing the number of undernourished people, affecting tens to hundreds of million people under High vulnerability and High warming, particularly among low-income populations in developing countries (*high confidence*). Extreme weather events will increase risks of undernutrition even on a regional scale, via spikes in food price and reduced income (*high confidence*) (FAO et al., 2018, Hickey and Unwin, 2020; Mbow et al., 2019). The timing of these impacts and our ability to respond to them vary based on the level of GHG emissions and Shared Socioeconomic Pathways (SSP). Under a low vulnerability development pathway (SSP1), climate change starts posing a moderate risk to food security above 1ºC of global warming (i.e., impacts become detectable and attributable to climate-related factors), while beyond 2.5ºC the risk becomes high (widespread impacts on larger numbers or proportion of population or area, but with the potential to adapt or recover) (Hurlbert et al., 2019). Under high vulnerability-high warming scenario (i.e., SSP3-RCP6.0), up to 183 million additional people are projected to become undernourished in low income countries due to climate change by 2050 (Mbow et al., 2019). Climate-related changes in food availability and diet quality are estimated to result in a crude mortality rate of about 54 deaths per million people with about 2ºC warming by 2050 (SSP2, RCP8.5), most of them projected to occur in South and East Asia (67-231 deaths per million depending on the country) (Springmann et al., 2016). In a medium vulnerability-high warming scenario (SSP2, RCP6.0), Hasegawa et al. (2018) projects that the number of undernourished people increases by 24 million in 2050, compared to outcomes without climate change and accounting for the CO_2-fertilization effect. This number increases by around 78 million in a low warming scenario (RCP2.6) accounting for the impacts of both climate change and mitigation policies. Caveats to these modelling studies are that most models (crop models in particular) are designed for long-term change in climate but not suited to project the impacts of short-term extreme events. The inclusion of adaptation measures into modeling estimates remains selective and partial.

Climate change risks of micronutrient deficiency will become severe in high vulnerability development pathways and in the absence of societal adaptation, leading to hundreds of millions of additional people lacking key nutrients for atmospheric CO_2 levels above 500 ppm (*high confidence*) (Myers et al., 2017; Nelson et al., 2018; Mbow et al., 2019). For example, concentration of many micronutrients (e.g., phosphorus, potassium, calcium, sulphur, magnesium, iron, zinc, copper, and manganese) can decrease by 5-10% under atmospheric CO_2 concentrations of 690 ppm (3.5ºC warming). The decline in zinc content is projected to lead to an additional 150-220 million people affected by zinc deficiency with increases in existing deficiencies in more than 1 billion people (Myers et al., 2017). Similarly, decrease in protein and micronutrient content in rice due to a higher CO_2 concentration (568 to 590 ppm) can lead to 600 million people with rice as a staple at risk of micronutrient deficiency by 2050 (Zhu et al., 2018). Additionally, the impact on protein content of increased CO_2 concentration (> 500 ppm) can lead an additional 150 million people with protein deficiency by 2050 (within the total of 1.4 billion people with protein deficiency) in comparison to the scenario without increased CO_2 concentration (Medek et al., 2017).

16.5.2.3.7 Risk to water security (RKR-G)

Water security encompasses multiple dimensions: water for sanitation and hygiene, food production, economic activities, ecosystems, water-induced disasters, and use of water for cultural purposes (Chapter 4; Box 4.1; Section 4.6.1). Water security risks are a combination of water-related hazards such as floods, droughts, and water quality deterioration, and exposure of vulnerable groups exposed to too little, too much, or contaminated water. Reasons for these can include both environmental conditions and issues of safety and access influenced by effectiveness of water governance (Sadoff et al., 2020). These are manifest through loss of lives, property, livelihoods and culture, and impacts on human health and nutrition, ecosystems and water-related conflicts which in turn can drive forced human displacement.

This RKR focuses on three types of risks with the potential to become severe: those associated with water scarcity, those driven by water-related disasters, and those impacting indigenous and traditional cultures and ways of life. Risk to water security constitutes a potentially severe risk because climate change could impact the hydrologic cycle in ways that would lead to substantial consequences for the health, livelihoods, property, and cultures of large numbers of people. For those associated with water scarcity, 'severe' refers to magnitude (number of people in areas where water scarcity falls below recognised thresholds for adequate water supply per capita), along with the likelihood of unforeseen increases in water scarcity that outpace the ability to prepare for the increased risk by putting in place new large-scale infrastructure within the required timescale. For those associated with extreme events, 'severe' refers to magnitude (numbers of people affected, including deaths, physical health impacts including disease, mental health impacts, loss of livelihoods, loss of or damage to property) and timing (for example, events coinciding with other stresses, e.g., a pandemic occurring at a time when local infrastructures are weakened by an extreme weather event). Important water-related extreme events include river flooding caused by heavy and/or prolonged rainfall, glacial lake outburst floods, and droughts. For those impacting cultures, 'severe' refers to the loss of key aspects of traditional ways of life. This includes consequences of the above two key risks.

Risks associated with water scarcity have the potential to become severe based on projections of large numbers of people becoming exposed to low levels of water availability per person, where 'water availability' includes fresh water in the landscape, including soil moisture and streamflows, available for all uses including agriculture as a dominant sector. Approximately 1.6 billion people currently experience 'chronic' water scarcity, defined as the availability of less than 1000 m3 of renewable sources of fresh water per person per year (Gosling and Arnell, 2016). In this context, we define a severe outcome as an additional 1 billion people experiencing 'chronic' water scarcity, relating to all uses of water, representing an increase of a magnitude comparable with current levels. The global number of people experiencing chronic water scarcity is projected to increase by approximately 800 million to 3 billion for 2°C global warming, and up to approximately 4 billion for 4°C global warming, considering the effects of climate change alone, with present-day population (Gosling and Arnell, 2016). Severe outcomes are projected to occur even with no changes in exposure: present-day exposure is defined here as 'medium' since either an increase or decrease in exposure could be possible. Vulnerability is not quantified in the literature assessed here, so in this assessment it is considered that severe outcomes could occur with present-day levels of vulnerability, again defined here as 'medium'. Particularly severe outcomes (i.e., the high end of these ranges) are driven by regional patterns of climate change bringing severe reductions in precipitation and/or high levels of evapotranspiration in the most highly-populated regions, leading to very substantial reductions in water availability compared to demand. There is strong consensus across models that water scarcity is projected to increase across substantial parts of the world even though projections disagree on which specific areas would see this impact. Moreover, a projected decrease in water scarcity in some regions does not prevent the increase in water scarcity in other regions becoming severe. Hence there is *high confidence* that risks to water scarcity have the potential to become severe due to climate change. Consequences of water scarcity include potential competition and conflicts between water users (Vanham et al., 2018), damaging livelihoods, hindering socio-economic development, and reducing human well-being, for example through malnutrition resulting from inadequate water supplies leading to long-term health impacts such as child stunting (Cooper et al., 2019). The avoidance of these consequences at high levels of water scarcity would require transformational adaptations including large-scale interventions such as dams and water transfer infrastructure (Greve et al., 2018). Since these require many years or even decades for planning and construction, and are also costly and irreversible and can potentially lead to lock-in and maladaptation, the potential for inadequate policy decisions made in the context of high uncertainties in regional climate changes brings the risk of a shortfall in adaptation. Around 2050, at approximately 2°C global warming, the risk of a substantial adaptation shortfall and hence severe outcomes for water scarcity have a relatively high likelihood across large parts of the southern USA and Mexico, northern Africa, parts of the Middle-East, northern China, and southern Australia, as well as many parts of Northwest India and Pakistan (Greve et al., 2018).

Risks associated with water-related extreme events and disasters have the potential to become severe based on projections of large numbers of people or high values of assets being affected. The risks to people from disasters can often only be quantified in terms of the hazard and exposure (the number of people affected), rather than the full consequences such as number of deaths, injuries or other health outcomes, as these often depend on complex or unpredictable factors such the effectiveness of emergency and humanitarian responses or the access to healthcare. With approximately 50 million people per year currently affected by flooding (Alfieri et al., 2017), we define severe outcomes as more than 100 million people affected by flooding. At 2°C global warming, between approximately 50 million and 150 million people are projected to be affected by flooding, with figures rising to 110 million to 330 million at 4°C global warming. These projections assume present-day population and no additional adaptation, so no changes in exposure. Increased flood risk is projected by the WHO to lead to an additional 48,000 deaths of children under 5 years due to diarrhoea by 2030, with Sub-Saharan Africa impacted the most (WHO, 2014). Other consequences of floods that already occur include deaths by drowning, loss of access to fresh water, vector-borne diseases, mental health impacts, loss of livelihoods, and loss of or damage to property. Many of these consequences depend on the vulnerability of individuals, households or communities to flooding impacts, for example through the presence or absence of measures to safeguard health and livelihoods, such as through infrastructure services, insurance or community support. The risks associated with these consequences could increase if there were no local adaptations to counter the effect of increased levels of hazard by reducing exposure and/or vulnerability. Climate-related changes to extreme events that would lead to these severe outcomes: increased frequency and/or magnitude of river floods of flash floods due to heavy or long-lasting precipitation, rapid snowmelt, or catastrophic failure of glacial lake moraine dams. These climate conditions are projected to increase with global warming.

Risks to cultural uses of water can become severe if there are permanent loss of aspects of communities' cultures due to changes in water, including loss of areas of ice or snow with spiritual meanings, loss of culturally-important places of access to such places, and loss of culturally-important subsistence practices including by indigenous people (Chapter 4). This includes mountain regions where changes in the cryosphere are having profound impacts (CCP5). In these cases, severe outcomes would be defined locally rather than globally. Communities that lost a dominant environmental characteristic deeply associated with its cultural identity would be considered to be severely impacted. For example, due to the central role that travel on sea ice plays in the life of Inuit communities, providing freedom and mental wellbeing, loss of sea ice can be argued to represent environmental dispossession of these communities (Durkalec et al., 2015). Traditional ways of life are therefore threatened and resulting changes would be transformative rather than adaptive. Similarly, changes in streamflow affecting the availability of species for traditional hunting can also negatively impact indigenous communities (Norton-Smith et al.). Such changes are already being seen at current levels of warming, but studies remain somewhat limited in number, so this assessment is assigned *medium confidence* due to medium evidence and medium agreement. WG1 conclude that it is *virtually certain* that further warming will lead to further reductions in Northern Hemisphere snow cover and mass loss in individual glacier regions is projected to be between approximately 30% and 100% by 2100 under high-warming scenarios (Chapter 4). Streamflows are projected to change in most major river basins worldwide by several tens of percent at 4°C global warming (Chapter 4).

There is strong potential for increases in water scarcity, flooding, loss of snow and ice and changes in water bodies to lead to severe outcomes such as deaths from water-related diseases, drowning and starvation, long-term health impacts arising from malnutrition and diseases, loss of property, loss of existence or access to places of cultural significance, loss of livelihoods and loss of aspects of culture especially for indigenous people with traditional lifestyles. The numbers of people affected are projected to range from hundreds of millions to several billion, depending on the level of global warming and socio-economic futures. A key aspect of the risk is the high uncertainty in future regional precipitation changes in many regions of high vulnerability, including the potential for large and highly-impactful changes, for which it may not be possible to provide adaptation measures before they become needed, leading to a high likelihood of adaptation deficits.

16.5.2.3.8 Risks to peace and to human mobility (RKR-H)

This RKR includes risks to peace within and among societies from armed conflict as well as risks to human mobility, epitomized by involuntary migration and displacement within and across state borders and involuntary immobility. Breakdown of peace and the inability of people to choose to move or stay challenge core elements of human security (Adger et al., 2014). Risks to peace also inform the agency and viability of mobility decisions. However, evidence does not indicate that human mobility constitutes a general risk to peace.

Breakdown of peace, materialized as overt or covert violence across social and spatial scales, constitutes a key risk because of its potential to cause widespread loss of life, livelihood, and wellbeing. Such impacts are considered severe if they result in at least 1,000 excess battle-related deaths in a country in a year. This threshold is consistent with the conventional definition of war (Pettersson and Öberg, 2020). However, because armed conflict routinely causes significant material destruction, triggers mass displacement, threatens health and food security, and undermines economic activity and living standards (Baumann and Kuemmerle, 2016; FAO et al., 2017; de Waal, 2018), risks to peace can be considered severe also when conflict has cascading effects on other aspects of wellbeing and amplifies vulnerability to other RKRs. Beyond the magnitude of such impacts, the rapidity with which armed conflict can escalate and the challenges of ending violence once it has broken out imply potentially very limited time and ability to respond for populations at risk.

Mobility is a universal strategy for pursuing wellbeing and managing household risks (Section 7.2.6; Cross-Chapter Box MIGRATE in Chapter 7,UN, 2018) and, where it occurs in a safe and orderly fashion, can reduce social inequality and facilitate sustainable development (Franco Gavonel et al., 2021). Involuntary mobility constitutes a key risk because it implies reduced human agency with high potential for significant economic losses and non-material costs, an unequal gender burden, and amplified vulnerability to other RKRs (Schwerdtle et al., 2018; Adger et al., 2020; Maharjan et al., 2020; Piggott-McKellar et al., 2020). Climate change also may erode or overwhelm human capacity to use mobility as a coping strategy, producing involuntarily immobile populations (Adams, 2016). A severe impact is when a large share of an affected population is forcibly displaced or prevented from moving, relative to normal mobility patterns, at local to global scale. However, because mobility may be a favourable mechanism for reducing risk or an adverse outcome of risk, depending on the circumstances under which it occurs, it is not possible to specify a simple quantitative threshold for when impacts become severe.

Complex causal pathways and lack of long-term projection studies presently prevent making confident quantitative judgments about how risks to peace and human mobility will materialize in response to specific warming levels, development pathways, and adaptation scenarios. Literature concludes with medium confidence that risks to peace will increase with warming, with the largest impacts expected in weather-sensitive communities with low resilience to climate extremes and high prevalence of underlying risk factors (Theisen, 2017; Busby, 2018; Koubi, 2019; von Uexkull and Buhaug, 2021). However, climate-driven impacts on societies will depend critically on future political and socioeconomic development trajectories (limited evidence, high agreement), suggesting that risks due to climate change are relevant primarily for highly vulnerable populations and for pessimistic development scenarios. Overall risks to peace may decline despite warming if non-climatic determinants are reduced sufficiently in the future.

Regular human mobility will continue regardless of climate change but mobility-related risks will increase with warming, notably in densely populated hazard-prone regions, in small islands and low-lying coastal zones, and among populations with limited coping capacity (RKR-A; CCP2 2.2.2; Chapter 7) (*high confidence*). Such risks can become severe even with limited levels of warming for populations with low adaptive capacity and whose settlements and livelihoods are critically sensitive to environmental conditions (medium evidence, high agreement). Likewise, risk of involuntary immobility could become severe for highly vulnerable populations with limited resources, even with moderate levels of warming (limited evidence, high agreement). Critically, population growth and shifting exposure will interact with warming to shape these risks (Davis et al., 2018; Hauer et al., 2020; Robinson, 2020a). Although climate-driven human mobility generally does not increase risks to peace (*medium confidence*), armed conflict is a major driver of forced displacement (*high confidence*).

Expert elicitation estimates that 4°C warming above pre-industrial levels will have severe and widespread effects on armed conflict with 26% probability, assuming no change from present levels in non-climatic drivers (Mach et al., 2019). That judgment refers to impacts that exceed the threshold for severity considered here, suggesting that global warming of 4°C would produce severe risks to peace under present societal conditions (*low confidence*). Future risks to peace will remain strongly influenced by socioeconomic development (Hegre et al., 2016). A study of Sub-Saharan Africa that accounts for both temperature and socioeconomic changes, 2015–65, concludes that determinants other than rising temperatures, notably quality of governance, will remain most influential in shaping overall levels of violence even in the high-warming RCP8.5 scenario (Witmer et al., 2017).

A larger empirical literature offers indirect evidence that climate change may produce severe risks to peace within this century by demonstrating how climate variability and extremes affect contemporary conflict dynamics, especially in contexts marked by low economic development, high economic dependence on climate-sensitive activities, high or increasing social marginalization, and fragile governance (*medium confidence*) (Chapter 7.2.7; Chapter 16.2, Schleussner et al., 2016a; Von Uexkull et al., 2016; Busby, 2018; Harari and Ferrara, 2018; Ide et al., 2020; Scartozzi, 2020).

Climatic risks interact with economic, political, and social drivers to create risks to human mobility both directly (through the threat of physical harm and destruction of property and infrastructure) and indirectly (via adverse impacts on livelihood and wellbeing). Extreme weather events are leading causes of forced displacement (Cross-Chapter Box MIGRATE in Chapter 7, IDMC, 2020). Projected increases in the frequency and severity of extreme events (AR6 WGI Chapter 12, Ranasinghe et al., 2021) in combination with future population growth in hazard-prone regions (e.g., Merkens et al., 2016) suggest that risks to mobility will increase in response to future global warming (Robalino et al., 2015; Davis et al., 2018; Rigaud et al., 2018). For example, moving from RCP2.6 to RCP8.5 (entailing ~0.5°C additional global warming by 2050) is projected to increase internal migration by 2050 from 51 [31-72] million to 118 [92-143] million people across South Asia, Latin America, and Africa (Rigaud et al., 2018), although those estimates are principally comprised of migrants, whose decisions are also informed by non-climatic drivers, rather than involuntarily displaced people. Global levels of flood displacement are estimated to increase by 50% with each 1°C warming (Kam et al., 2021). Should future warming reduce adaptation options for vulnerable populations (Chapter 16.4), a consequence may be higher levels of involuntary migration and immobility (Grecequet et al., 2017; Otto et al., 2017). There is little evidence that climate-driven mobility negatively affects peace (Brzoska and Fröhlich, 2016; Burrows and Kinney, 2016; Freeman, 2017; Petrova, 2021).

There is high agreement that even moderate levels of future SLR will severely amplify involuntary migration and displacement in small islands and densely populated low-lying coastal areas in the absence of appropriate adaptive responses (*high confidence*) (Hauer, 2017; IPCC, 2019b; Hauer et al., 2020; McMichael et al., 2020, Section 15.3.4; Section 16.4). In some contexts climate change also may accelerate migration toward high-exposure coastal areas (Bell et al., 2021). Under a high emissions RCP8.5 scenario (global median 0.7m SLR by 2100), the number of people exposed to annual coastal flooding may more than double by 2100 compared to present numbers (Kulp and Strauss, 2019). In USA alone, SLR of 0.9 m could potentially put 4.2 million people at risk of inundation by the end of this century (Hauer, 2017). However, numbers of people exposed to SLR does not evenly translate to forcibly displaced populations (Hauer et al., 2020). Ascertaining how many people will move forcibly or as adaptive response to SLR is inherently challenging because of the complex and highly individual nature of migration decisions (Black et al., 2013; Boas et al., 2019; Piguet, 2019; Bell et al., 2021). Implications of climate change for risks to human mobility across borders are even harder to quantify and highly uncertain, due to unknown developments in legal and political conditions that govern international migration (McLeman, 2019; Wrathall et al., 2019).

16.5.2.4 Synthesis of the Assessment of Representative Key Risks

Figure 16.10 provides a synthesis of the RKRs and the conditions that lead to severe risks over the course of the 21st century, as assessed in Sections 16.5.2.3.1 to 16.5.2.3.8 (see Supplementary Table SM16.12 for further description). It identifies sets of conditions -- defined by levels of warming, exposure/vulnerability, and adaptation -- that would produce severe risk with a particular level of confidence. The risks are of two scopes: broadly applicable, meaning that the risks described by a particular KR or RKR would be severe pervasively and even globally; and specific, meaning that these risks would apply to particular areas, sectors, or groups of people.

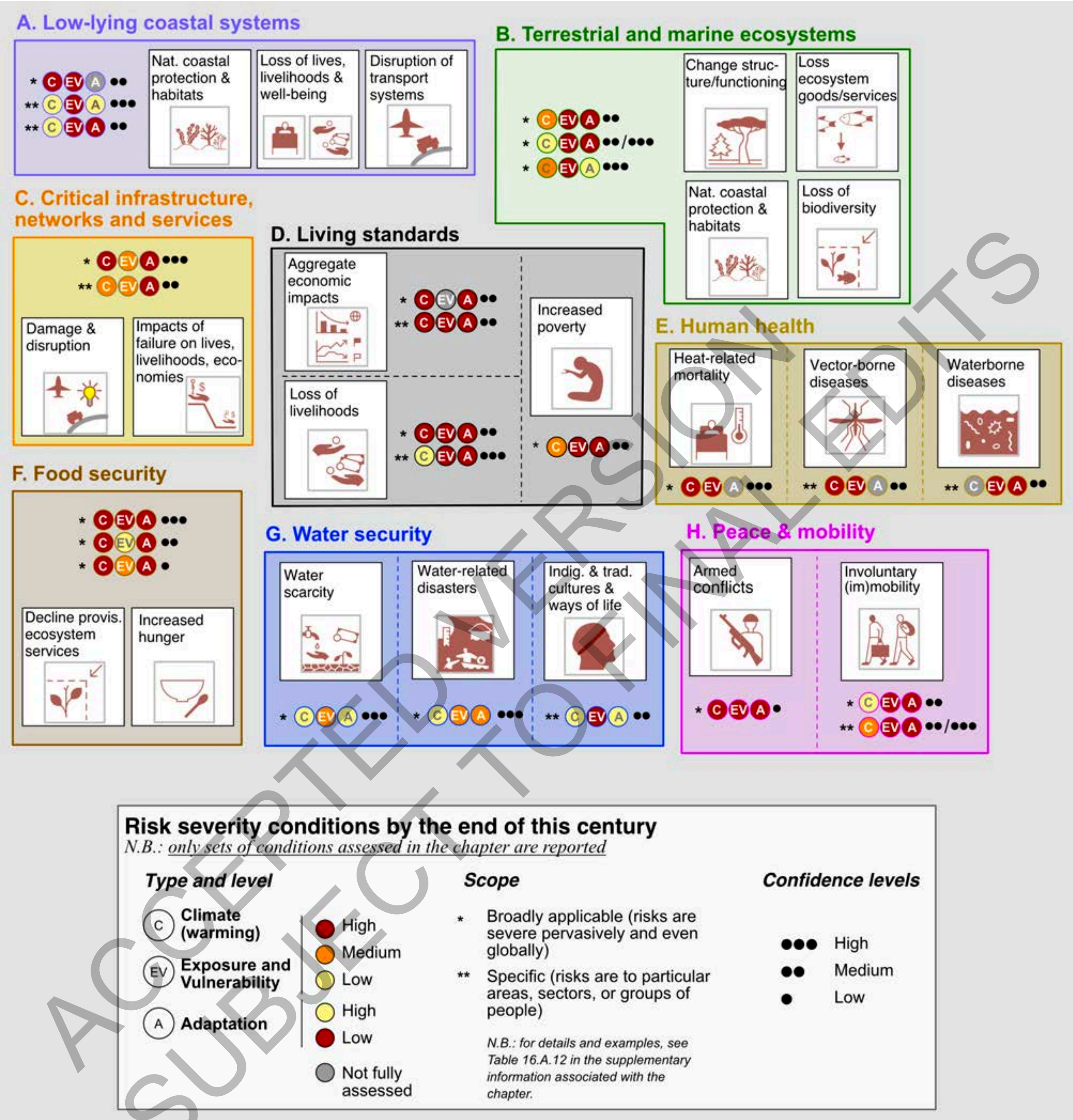


Figure 16.10: Synthesis of the severity conditions for Representative Key Risks by the end of this century. The figure does not aim to describe severity conditions exhaustively for each RKR, but rather to illustrate the risks highlighted in this report (Sections 16.5.2.3.1 to 16.5.2.3.8). Colored circles represent the levels of warming (climate), exposure/vulnerability, and adaptation that would lead to severe risks for particular key risks and RKRs. Each set of three circles represents a combination of conditions that would lead to severe risk with a particular level of confidence, indicated by the number of black dots to the right of the set, and for a particular scope, indicated by the number of stars to the left of the set. The two scopes are 'broadly applicable', meaning applicable pervasively and even globally, and 'specific', meaning applicable to particular areas, sectors, or groups of people. Details of confidence levels and scopes can be found in Section 16.5.2.3. In terms of severity condition levels (see Section 16.5.2.3), for warming levels (colored circles labeled 'C' in the figure), High refers to climate outcomes consistent with RCP8.5 or higher, Low refers to climate outcomes consistent with RCP2.6 or lower, and Medium refers to intermediary climate scenarios. Exposure-Vulnerability levels are determined by the RKR teams relative to the range of future conditions considered in the literature. For Adaptation, High refers to near maximum potential and Low refers to the continuation of today's trends.

Despite being intertwined in reality, Exposure-Vulnerability and Adaptation conditions are distinguished to help understand their respective contributions to risk severity.

Five main messages arise from this synthesis:

Severe risk is rarely driven by a single determinant (warming, exposure/vulnerability, adaptation), but rather by a combination of conditions that jointly produce the level of pervasiveness of consequences, irreversibility, thresholds, cascading effects, likelihood of consequences, temporal characteristics of risk and the systems' ability to respond (*medium* to *high confidence*). In other words, climate risk is not a matter of changing climatic impact drivers (CIDs) only, but of the confrontation between changing CIDs and changing socio-ecological conditions.

In most of the RKRs, severe risk for broadly applicable situations requires high levels of warming or exposure/vulnerability, or low adaptation. In many cases, it is associated with several of these conditions occurring simultaneously (e.g., high warming and high vulnerability). Examples include low-lying coastal areas (RKR-A; *medium confidence*), loss of livelihoods (RKR-D; *medium confidence*) or armed conflicts (RKR-H; *low confidence*).

High warming and exposure/vulnerability combined with low adaptation is however not necessarily required to lead to severe risk, and various other sets of conditions can lead to such an outcome. For example:
Without high levels of warming — This is especially the case for terrestrial and marine ecosystems (RKR-B) and water security (RKR-G) for which even medium to low levels of warming will generate severe risk, depending on the processes considered (e.g., mass population-level mortality and ecological disruption for ecosystems). This is also the case when more specific situations are considered, for example in the case of (in)voluntary mobility of vulnerable populations with limited resources (RKR-H), and for some critical infrastructure in already highly exposed and vulnerable contexts (RKR-C).
With high levels of adaptation — High levels of adaptation will not necessarily avoid severe risk, as is illustrated by the cases of coral-dependent and arctic coastal communities (RKR-A), some terrestrial and marine ecosystems (RKR-B), and water scarcity and the cultural uses of water (RKR-G).

All RKR assessments indicate that risks are higher in high vulnerability development pathways, and in some cases high vulnerability can occur in high income societies. Examples include the possibility of increasing coastal settlement and the location of critical infrastructure in highly exposed locations (RKR-A, RKR-C) including to floods (RKR-G) and risks to terrestrial and marine ecosystems (RKR-B). The assessment therefore show that depending on socioeconomic trends especially in terms of equity, social justice and income sustainability, as well as on the ability to shift towards more climate resilient economic and settlement systems (e.g., at the coast), higher income societies also are at serious risk of being substantially affected in the decades-to-century to come.

In terms of the time frames, most of the RKRs conclude that severe risks to many dimensions (ecosystems, health, etc.) are expected to occur by the end of the 21st century and across the globe. Some RKRs however highlight that severe risk could occur far earlier, e.g. as soon as a warming level of 1.5°C or 2°C is reached, which means potentially well before mid-century (IPCC, 2021a). In some cases, risks are already considered severe, for example after major climatic events such as tropical storms (RKR-A).

16.5.3 Variation of Key Risks Across Levels of Global Warming, Exposure and Vulnerability, and Adaptation

This section builds on Sections 16.5.1 and 16.5.2 as well as on additional literature to illustrate how consequences associated with KRs and RKRs are projected to vary with three types of determinants: global average warming level, as a proxy for associated changes in climate hazards (climatic impact-drivers, CIDs, Ranasinghe et al., 2021); socio-economic development pathway, as a means of capturing alternative future exposure and vulnerability conditions; and level of adaptation to reflect the extent to which successful adaptation is implemented. While these three dimensions are partly intertwined – e.g., warming and adaptation scenarios are constrained by development pathways (Chapter 18) – this section assesses the influence of each dimension separately (Section 16.5.3.2 to Section 16.5.3.4) to highlight how sensitivity varies across these dimensions for different KRs and RKRs. We then bring the dimensions together in an illustrative example (large deltas; Section 16.5.3.5).

16.5.3.1 Warming Level, Including Risks Avoided by Mitigation

Studies illustrating sensitivity to warming level typically do so by contrasting projected impacts for the same socioeconomic conditions but different climate pathways or temperature levels, often based on Representative Concentration Pathways (RCPs) (van Vuuren and Carter, 2014). We refer to future climate conditions either based on their global average warming level or as a 'high warming' scenario (based on RCP8.5), medium warming (RCP4.5 or RCP6.0), or low warming (RCP2.6 or 1.5ºC scenarios). Because some of these scenarios assume no or minimal mitigation (RCP8.5, RCP6.0) while others do (RCP4.5, RCP2.6), differences in outcomes between them reflect risks avoided by mitigation (assuming consistent socioeconomic assumptions).

Some ecological risks (Chapter 2) are particularly sensitive to warming. For example, warm-water coral reefs are already experiencing High risk levels and are expected to face Very High risks under 1.5ºC of global warming (Hoegh-Guldberg et al., 2018a; Bindoff et al., 2019). Some societal risks, such as human mortality due to extreme heat, also are sensitive to warming. A medium warming scenario (relative to high warming) reduces projected global average mortality due to heat from seven deaths per 10,000 people per year (7/10,000/yr) by 2100 to ~1/10,000/yr, assuming high vulnerability societal conditions (Carleton et al., 2020). At the national level, without considering adaptation, reductions in a broader measure of mortality are projected across a range of countries including Colombia, the Philippines, and several in Europe (Guo et al., 2018), and exposure of the US population to high mortality heatwaves is reduced by nearly half (Anderson et al., 2018a). Without considering changes in exposure or vulnerability, warming of 1.5-2ºC (compared to 4-5ºC) reduces global mortality impacts from an increase of 2.1-13.0% to 0.1-2.2% (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018a) and impacts in China from up to 4/10,000/yr (Weinberger et al., 2017) to 0.3-0.5/10,000/yr (Wang and Hijmans, 2019).

A low warming scenario (relative to high warming) reduces aggregate economic impacts from around 7% of global GDP to less than 1% (Takakura et al., 2019), and changes impacts on the number of people suffering from hunger from an increase (by 7-55 million) to a decrease (by up to 6 million) (Janssens et al., 2020). Low versus high warming also reduces the coastal population at risk of flooding due to SLR from tripling by 2100 (relative to today) to doubling (Kulp and Strauss, 2019, Section 16.5.2.3.2). The SROCC estimates that SLR risks are reduced from Moderate-to-High to Moderate for large tropical agricultural deltas and resource-rich megacities, and from High and Very high to Moderate-to-High for Arctic human communities and Urban atoll islands, respectively (Oppenheimer et al., 2019).

Higher levels of warming are projected to also generate higher income inequality between countries (e.g., Pretis et al., 2018; Takakura et al., 2019) as well as within them (Hallegatte et al., 2016) even though other drivers will be more important (Section 16.5.2.3.5). Similarly, climate and weather events are expected to play an increasing role in shaping risks to peace (*medium agreement*, *low evidence*) and migration (*high agreement*, *medium evidence*) in the future, but uncertainty is high due to complex causal pathways and non-climate factors likely dominate outcomes (Section 16.5.2.3.9). There is *high agreement* that future SLR will amplify levels of forced migration from small islands and low-lying coastal areas in the absence of appropriate adaptive responses (Oppenheimer et al., 2019).

A synthesis of risk assessments in the recent IPCC Special Reports (Magnan et al., 2021) concludes that an integrated measure of today's global climate risk level will increase by the end of this century by two- to four-fold under a low and high warming, respectively (based on aggregated scores developed in the study). An additional comparison of risk levels under +1.5 °C and +2 °C suggests that every additional 0.5 °C of global warming will increase the risk level by about a third.

16.5.3.2 Exposure and Vulnerability Trends

Development pathways describe plausible alternative futures of societal change and are critical to future risks because they affect outcomes of concern both through non-climate and climate-related channels (*very high confidence*).

Studies illustrating sensitivity to development pathways typically do so by contrasting projected impacts for the same climate pathway or temperature level but different levels of socioeconomic exposure and vulnerability, for example based on Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014; Van Vuuren et al., 2014). Or, they infer sensitivity to future development pathways based on differences in impacts across current populations with different levels of exposure or vulnerability. We refer to future conditions based on SSPs 1 or 5 as 'low exposure' or 'low vulnerability' conditions, and those based on SSPs 3 or 4 as 'high exposure' or 'high vulnerability' conditions (O'Neill et al., 2014; van Vuuren and Carter, 2014).

A wide range of climate change impacts depend strongly on development pathway (*high confidence*), A low (relative to high) exposure future, determined by limited population growth and urbanization, results in about 30% fewer people exposed to extreme heat globally (Jones et al., 2018b) and about 50% fewer in Africa (Rohat et al., 2019a), similar to the effect of a medium vs. high level of global warming. Low exposure conditions also reduce the fraction of the population in Europe at very high risk of heat stress from 39% to 11% (Rohat et al., 2019b). Demographic differences lead to a reduction in the global population exposed to mosquitos acting as viral disease vectors by more than half (Monaghan et al., 2018) and exposure to wildfire risk by nearly half (Knorr et al., 2016).

Studies are increasingly going beyond exposure to incorporate future vulnerability, finding that it is often the dominant determinant of risk (*high confidence*). A low (relative to high) vulnerability future reduces the risk to global poverty by an order of magnitude, robustly across approaches that account for macroeconomic growth, structural change in the economy, inequality, and access to infrastructure services (Hallegatte and Rozenberg, 2017), or for the exposure of vulnerable populations to multi-sector climate-related risks (Byers et al., 2018). A low (relative to high) vulnerability future also reduces the global mean number of temperature-attributable deaths in 2080-2095 due to enteric infections by an order of magnitude (from >80,000 to <7000; (Chua et al., 2021)). Low future socioeconomic vulnerability to flooding reduces global fatalities and economic losses by 69-96% (Jongman et al., 2015). Low vulnerability as measured by indicators including per capita GDP, education, governance, water demand, and storage potential reduces water insecurity by a factor of three (Koutroulis et al., 2019). A scenario with reduced barriers to trade reduces the number of people at risk of hunger due to climate change by 64% (Janssens et al., 2020). Structural transformation of the economy (shift of the workforce from highly exposed sectors such as agriculture and fishing to less exposed sectors such as services) lowers GDP impact projections by 25-30% in today's developing countries by 2100 (Acevedo et al., 2017).

The IPCC SRCCL supports the importance of societal conditions to climate-related risk (Hurlbert et al., 2019), concluding that risks of water scarcity in drylands (i.e., desertification), land degradation and food insecurity are close to High[3] beginning at 1.5ºC under high vulnerability conditions (SSP3), but remain close to Moderate up to slightly above 2ºC for low vulnerability conditions (SSP1). Specifically, risk of water scarcity in drylands (i.e., desertification) at 1.5ºC warming is reduced in low vulnerability (relative to high vulnerability) conditions from High to Medium. Similarly, under a 2ºC warming, risk is reduced from High to Moderate for food security and High to Moderate-to-High for land degradation.

While climate change will increase risk to society and ecosystems, future exposure and vulnerability conditions will also greatly impact outcomes of concern directly. Global economic damages to coastal assets from tropical cyclones are projected to increase by more than 300% due to coastal development alone, a much larger effect than projected climate change impacts through 2100 even in RCP8.5 (Gettelman et al., 2018). Similarly, global crop prices are more than three times more sensitive to alternative assumptions about changes in production technologies and demand than to alternative climate outcomes (Ren et al., 2016). Future water scarcity is driven mainly by both demographic change and socioeconomic changes affecting water demand and management. A measure of between-country inequality (Gini coefficient) would decline by more than 50% this century in low vulnerability conditions, but would double in a high vulnerability future (Crespo Cuaresma, 2017), outweighing the effect of climate (Taconet et al., 2020).

[3] The IPCC distinguishes between four qualitative risk levels, from Undetectable (risks that are undetected), to Moderate (detectable with at least medium confidence), High (significant and widespread) and Very high (very high probability of severe risks and significant irreversibility or persistence of impacts).

Similarly, the global prevalence of armed conflict will roughly double this century in a high vulnerability future, whereas it will drop by half in a low vulnerability future (Hegre et al., 2016). In Sub-Saharan Africa, assumptions about governance and political rights are estimated to be far more important to the future risk of violent conflict than climate change (Witmer et al., 2017).

16.5.3.3 Climate Adaptation Scenarios

One approach to understand adaptation benefits for risk reduction is to contrast projected impacts for the same climate and development conditions but different levels of adaptation. For example, global-scale coastal protection studies considering both RCPs and SSPs suggest that under a given RCP, the total flooded area may be reduced by 40% by using 1-m height dykes, compared to a no-adaptation baseline (Tamura et al., 2019). The global cost of SLR over the 21st century can be lowered by factor of two to four if local cost-benefit decisions consider migration an adaptation option, in addition to hard protection (Lincke and Hinkel, 2021). Under a low warming scenario, it is estimated that adaptation (i.e. changes in crop variety and planting dates) could reduce the total number of people at risk of hunger globally by about 4%, and by about 10% in a high warming scenario Hasegawa et al. (2014). Impacts on heat-related mortality would be cut from 10 to 7 deaths per 10,000 people per year in 2100 by adaptation actions beyond those assumed to be driven by income growth (Carleton et al., 2020). In a regional example, proactive adaptation efforts on infrastructure (especially roads, runways, buildings, and airports) in Alaska, USA, could reduce damage-related expenditure by 45% under medium or high warming (Melvin et al., 2017).

Another approach infers the potential future effectiveness of adaptation based on current sensitivity of impacts to interventions. For example, the future disease burden of malaria is likely to be highly dependent on the future development of health services, deployment of malaria programs and adaptation. Investments in water and sanitation infrastructure are also recognized to have the potential to reduce severe risks of waterborne disease, although these improvements likely need to provide transformative change (Cumming et al., 2019). The potential for severe risks may also be substantially reduced through the development of vaccines for specific enteric diseases (Riddle et al., 2018), although most current vaccines target viral pathogens, incidence for which tends to be inversely correlated with ambient temperature (Carlton et al., 2016). In addition, international migration as well as forced movement of people across borders will be influenced by developments in legal and political conditions (McLeman, 2019; Wrathall et al., 2019), but the fact that these developments are unknown strongly limits any forecasts on the magnitude of adaptation benefits (Section 16.5.2.3.9).

Last, there is growing concern that even ambitious adaptation efforts will not eliminate residual risks from climate change (Section 16.4.2). A synthesis of risk assessments in the recent IPCC Special Reports (Magnan et al., 2021) concludes that high societal adaptation is expected to reduce the aggregated score –the proxy used in the study– of global risk from anthropogenic climate change by about 40% under all RCPs by the end of the century, compared to risk levels projected without adaptation. It however also shows that even for the lowest warming scenario a residual risk one-third greater than today's risk level would still remain (with a doubling of today's aggregated score under the high emission scenario).

16.5.3.4 Illustration: Risk and Adaptation Pathways in Densely Populated and Agricultural Deltas

Large deltas, which are very dynamic risk hotspots of global importance and interest (Wigginton, 2015; Hill et al., 2020; Nicholls et al., 2020), serve well to illustrate how risk pathways develop over time, determined by climatic as well as non-climatic risk drivers as well as by adaptation. Deltas occupy less than 0.5% of the global land area but host over 5% of the global population (Dunn et al., 2019) and contribute major fractions of food production in many world regions (Kuenzer et al., 2020). Future risk in these areas is heavily driven by climate change but also greatly depends on past, current and future socio-economic changes which influence future trends in exposure, vulnerability and adaptive capacity of natural and human systems (*high confidence*) (Oppenheimer et al., 2019). From a risk perspective, trends over the past decades have been unfavourable for many deltas, as most of them have experienced a simultaneous intensification of hazards, rise in exposure and stagnation or only limited reduction in vulnerability, particularly in low income countries (*high confidence*) (Day et al., 2016; Tessler et al., 2016; Loucks, 2019; Oppenheimer et al., 2019; Hill et al., 2020).

16.5.3.4.1 Hazard trends in deltas

Deltas face multiple interacting hazards, many of which over the past decades have been intensified by local and regional anthropogenic developments (e.g., the construction of dams, groundwater extraction, or agricultural irrigation practices) and most of which are expected to be exacerbated by climate change (*high confidence*) (Giosan et al., 2014; Tessler et al., 2015; Tessler et al., 2016; Arto et al., 2019; Oppenheimer et al., 2019). The most important hazards include sea level rise (SLR), inundation, salinity intrusion, cyclones, storms and erosion, many of which occur in combination. The potential for flooding and inundation depends on the relative sea level rise (RSLR) which results from global and regional SLR as well as local subsidence within the deltas. Subsidence caused by natural and human drivers (mainly compaction and groundwater extraction) is currently the most important cause for RSLR in many deltas and can exceed the rate of climate-induced SLR by an order of magnitude (Oppenheimer et al., 2019). But in higher warming scenarios the relative importance of climate-driven SLR is expected to increase over time (Oppenheimer et al., 2019). In a global study covering 47 major deltas and assessing future trends of sediment delivery across four RCPs, three SSPs (1,2,3) and a projection of future dam construction, Dunn et al. (2019) find most deltas (33 out of the 47) will experience a mean decline of 38% in sediment flux by the end of the century when considering the average of the scenarios. Nienhuis et al. (2020) find in a global assessment that some deltas have gained land through increased sediment load (e.g., through deforestation), but recent land gains are unlikely to be sustained if SLR continues to accelerate. According to the latest assessments, it is *virtually certain* that global mean sea level will continue to rise over the 21st century, with sea level rise by 2100 *likely* to reach 0.28-0.55 m in a an SSP1-1.9 and 0.63-1.01 m in an SSP5-8.5 scenario relative to 1995-2014 (IPCC, 2021a). The combined effects of local subsidence and GMSL rise result in a significant increase in the potential for inundation of low-lying deltas across all RCPs, with some variation according to regional sea level change rates, without significant further adaptation measures (*very high confidence*).

In terms of salt-water intrusion and salinization, global comparative studies are still lacking but the general processes are well understood (e.g., White and Kaplan, 2017)) and research on individual deltas is on the rise. In the Mekong Delta of Vietnam, one of the main rice producing deltas globally, salinity intrusion has been observed to extend around 15 km inland during the rainy season and around 50 km during the dry season (Gugliotta et al., 2017), resulting in rice yield losses of up to 4 tons per hectare per year (Khat et al., 2018). SLR, along with the expansion of dams and dry season irrigation upstream, is expected to further increase the salinity intrusion into the delta. This creates additional risk for food production as rice and other crops might be pushed beyond their adaptation limits in terms of salt tolerance, potentially affecting many of the 282,000 agriculture-based livelihoods in the Mekong Delta and increasing the pressure for cost-intensive adaptation (Smajgl et al., 2015). Genua-Olmedo et al. (2016) find for the Ebro that in high scenario (RCP8.5, and SLR of almost 1m by 2100), SLR-induced salinity intrusion will lead to almost a doubling of salinity levels and a decrease of mean rice productivity by over 20% in a high SLR scenario with almost 1 meter of SLR by the end of the century.

16.5.3.4.2 Exposure trends in deltas

Next to the trends in hazards, future exposure of and in deltas is shaped particularly by the increase of population and infrastructure and the intensification of land use. Over the recent years, the population has been rising in major deltas, roughly along with overall national population trends (Szabo et al., 2016). In 2017, 339 million people lived in deltas with a high exposure to flooding, cyclones and other coastal hazards (Edmonds et al., 2020). Over 40% of the global population exposed to flooding from tropical cyclones lived in deltas, more than 90% of which in developing countries and emerging economies (ibid.). Looking into the future, population in low elevation coastal zones is expected to increase by 2050 across all SSPs with diverging developments in the second half of the century, and at the end of the century will reach well over 1 billion people in SSP3 (Jones and O'Neill, 2016; Merkens et al., 2016). A major part of this population is expected to reside in deltas with large cities or mega-urban agglomerations such as the Pearl River Delta, China. One of the first studies using the SSP-RCP framework on the delta scale suggests a strong increase in intensive agricultural land by the middle of the century in three SSPs (2, 3, 5) in the Volta Delta, Ghana, whilst the Mahanadi, India, and the Ganges-Brahmaputra-Meghna do not show a significant further increase (Kebede et al., 2018). Hence, the amount of population and infrastructure as well as agricultural land is expected to rise further under certain SSPs, further increasing the exposure to future climate hazards.

16.5.3.4.3 Vulnerability trends in deltas

Deltas are characterized by multifaceted vulnerabilities of their environment and human populations. Over 200 indicators are being used in the literature to characterize and analyse vulnerability in deltas, spanning social, ecological and economic aspects (Sebesvari et al., 2016). However, only a few studies model or dynamically assess trends in vulnerability, particularly for the future, at global scale, or take a comparative approach. But overall, a global trend assessment suggests that social vulnerability to climate hazards has been improving over the past years in all world regions hosting major deltas apart from Oceania, yet with emerging economies and developing countries in Africa showing less improvement than the Americas, Asia and Europe (Feldmeyer et al., 2017). An analysis of 48 major deltas finds that vulnerability therefore is a less dominant source of future increase in risk than exposure (Haasnoot et al., 2012). However, case study research from individual deltas suggests that delta populations, particularly those with agriculture-based livelihoods, have seen more limited vulnerability reduction due in particular to the impacts of environmental hazards, stress and disasters (*high confidence*). In the Mekong Delta, for instance, the strong economic growth since the beginning of Vietnam's reform process has not led to a reduction of vulnerability across the board for all socio-economic groups (Garschagen, 2015). Rather, issues such as widespread landlessness or continued poverty have maintained and, in some respect, increased social vulnerability.

16.5.4 RKR Interactions

Multiple feedbacks between individual risks exist that have the potential to create cascades (WEF, 2018; Weyer, 2019 p. 680; Simpson et al., 2021) and then to amplify systemic risks and impacts far beyond the level of individual RKRs (*medium confidence*). Scientific research however remains limited on whether such interactions would result in increasing or decreasing the initial impact(s), and hence risk severity across systems. Given the scope of this chapter on increasing risk severity, here we focus on assessing RKR interactions that lead to increasing risk. Drawing directly on RKR assessments (16.5.2.3.2 to 16.5.2.3.9), this section cites those assessments rather than primary literature. The arrows in Figure 16.11 are derived from a qualitative analysis by three authors of Chapter 16 of the material provided by chapters on KRs and RKR assessments (Section 16.5.2.3), and do not result from any systematic and quantitative approach as done in some recent studies (e.g., WEF, 2018; Yokohata et al., 2019).

Interactions at the RKR level (Figure 16.11, Panel A) – Climate change will combine with pre-existing socioeconomic and ecological conditions (grey blocks on the left hand-side of Panel A in Figure 16.10) to generate direct and second-order effects (black plain arrows) both on the structure and/or functioning of ecosystems (RKR-B) and on some natural processes such as the hydrologic cycle (RKR-G) for example. This then translates into implications not only for biodiversity, but also for natural resources that support livelihoods, which will in turn affect food security (especially food availability; RKR-F), water security (especially access to adequate quantities of acceptable quality water; RKR-G) and the living standards of already vulnerable groups and aggregate economic outputs at the global level (RKR-D). Climatic impact drivers (CID; IPCC, 2021a) will also directly affect infrastructure that are critical to ensure some basic conditions for economies to function (RKR-C), e.g., through transportation within and outside the country, energy production and international trade. Such disturbances to socioecological systems and economies pose climate-related risks to human health (RKR-E) as well as to peace and mobility (RKR-H). Indeed, while health is concerned with direct influence of climate change, e.g., through hotter air temperatures impacting morbidity and mortality or the spatial distribution of disease vectors such as mosquitos, it is also at risk of being stressed by direct and secondary climate impacts on living standards, food security and water security (RKR-D, RKR-F, RKR-G, respectively). Increased poverty, increased hunger and limited access to drinkable water are well-known drivers of poor health conditions. The role of impact cascades is even more prominent in the case of peace and mobility (RKR-H), even though the scientific literature does not conclude on any clear and direct climate influence on armed conflict and human migration. Rather, climate-induced degradation of natural resources that are vital for subsistence agriculture and fisheries, transformational and long-term consequences on livelihoods (e.g., new risks, increasing precarious living conditions, gendered inequity, etc.), as well as erosion of social capital due to exacerbated tension within and between communities, are considered among the main drivers of armed conflicts and forced displacement, therefore highlighting links with water security (RKR-G) and living standards (RKR-D), for example.

RKR assessments also suggest that some feedback effects are at work (arrows moving from the right to the left in Panel A) that contribute to the potentially long-lasting effects of climate risks. RKR-H assessment for example states that there is robust evidence that major armed conflicts routinely trigger mass displacement, threaten health and food security, and undermine economic activity and livelihoods, often with lasting negative consequences for living standards and socioeconomic development, therefore linking back to risks to living standards (RKR-D), human health (RKR-E) and food security (RKR-F).

Interactions at the KR level (Figure 16.11, Panel B) – Panel B illustrates risk connections at the Key Risk level (Section 16.5.2.1) and as described in RKR assessments (Section 16.5.2.3). To only take one example here, risk to livelihoods and economies is influenced by the loss of ecosystem services (RKR-B) and the loss or breakdown of critical infrastructures (RKR-C), as well as it influences risks to human lives and health (RKR-E), food and water security (RKR-F, RKR-G), poverty (RKR-D) and peace and mobility (RKR-H). As a third-order sequence, RKR assessments show that increased risk to peace and mobility affects lives and health as well as food security, which in turn threaten livelihoods and economies.

The above suggests that some vicious cycle effects play a central role in explaining impact processes. Cascading effects can indeed lead to cumulative risks that partly feed various drivers of the emergence of severe risks (Section 16.5.1), such as the acceleration of ecosystem degradation, or the reaching of thresholds and irreversible states in human systems at a decade-to-century time horizon (e.g., when permanent inundation questions the habitability of some low-lying coasts; RKR-A). The extent and duration of risk cascades are however expected to substantially vary depending on warming levels and development pathways, both separately (Section 16.5.3) and when combined (Section 16.6.1 and 16.6.2) (Fig. 16.10).

In addition, RKR assessments converge to suggest that regions that are already experiencing climate change impacts will experience severe impact cascades first (e.g., RKR-F), because they are in areas (i) that face development constraints and associated challenges such as poverty, inequity and social discrimination for example, and (ii) where climate change projections are the most intense for the next decades. That is especially a concern for Africa (RKR-F, RKR-G), Asia and Latin America (Chapters 9, 10 and 12). RKR-E concludes for example that the likelihood of severe risks to human health is especially high for highly susceptible populations, particularly the poor and otherwise marginalized. RKR assessments however emphasize that middle- and high-income regions are also to be considered at serious risk because climate change is accelerating at the global level (IPCC, 2021a), and because critical dimensions are exposed to severe risks such as major transportation (e.g., international airports) and energy (e.g., nuclear power plants) infrastructure for instance (RKR-C), and because of the interconnectedness of economies.

Finally, all RKR assessments suggest that enhanced adaptation has the potential to contain such feedback effects and cascading processes more broadly, and reduce the duration of the impacts on the system as a whole. There are however knowledge gaps on such a potential, as well as on the nature of impact cascades (positive, negative, neutral, mixed).

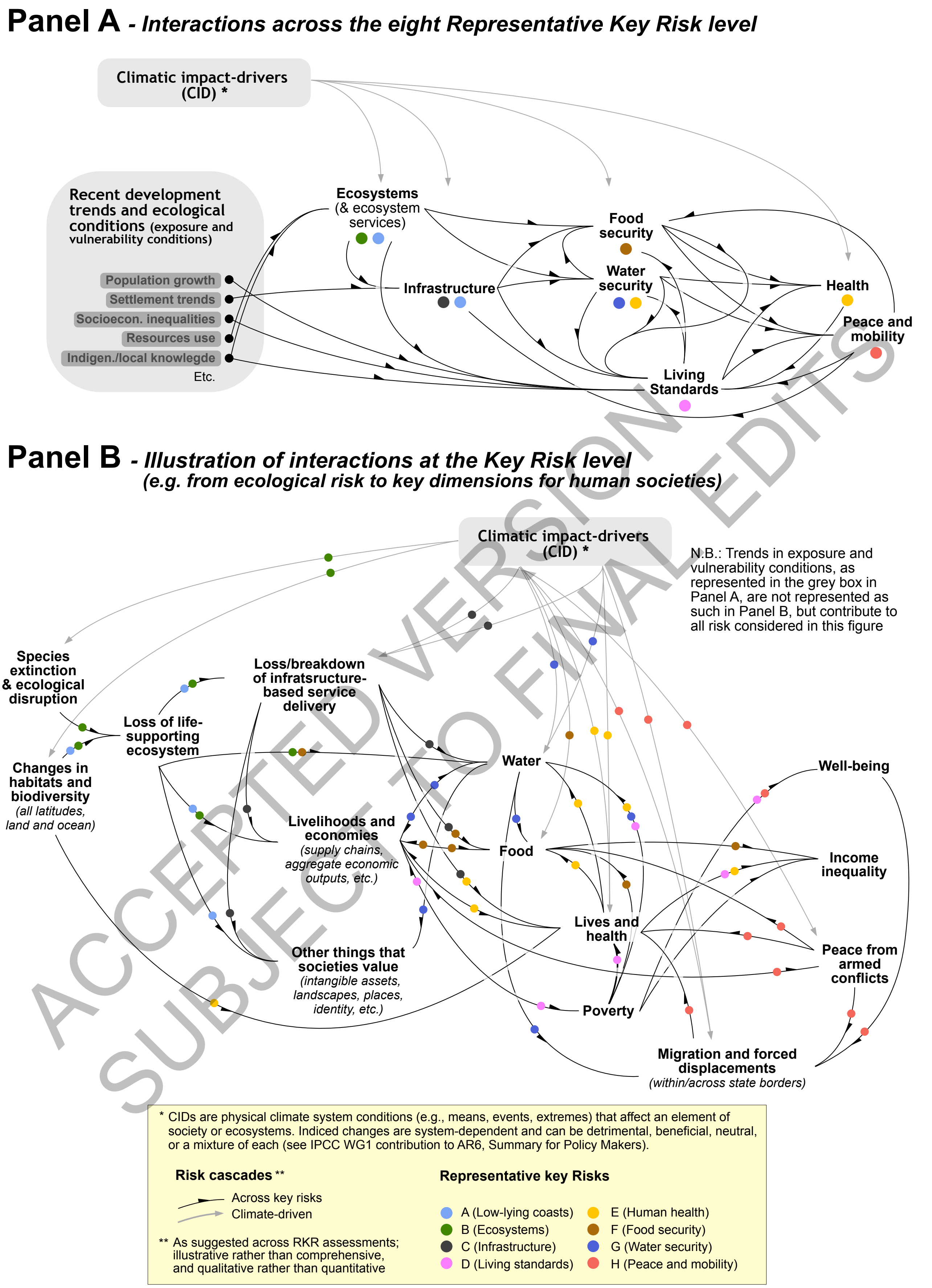


Figure 16.11: Illustration of some connections across key risks. Panel A describes all the cross-RKR risk cascades that are described in RKR assessments (Sections 16.5.2.3.2 to 16.5.2.3.9). Panel B builds on Section 16.5.2.2 and Table SM16.4 to provide an illustration of such interactions at the Key Risk level, e.g. from ecological risk to key dimensions

for human societies. The arrows are representative of interactions as qualitatively identified in this chapter; they do not result from any quantitative modelling exercise.

[START CROSS-WORKING GROUP BOX SRM HERE]

Cross-Working Group Box SRM: Solar Radiation Modification

Authors: Christopher H. Trisos (South Africa), Oliver Geden (Germany), Sonia I. Seneviratne (Switzerland), Masahiro Sugiyama (Japan), Maarten van Aalst (The Netherlands), Govindasamy Bala (India), Katharine J. Mach (USA), Veronika Ginzburg (Russia), Heleen de Coninck (The Netherlands), Anthony Patt (Switzerland)

Proposed Solar Radiation Modification Schemes

This cross-working group box assesses Solar Radiation Modification (SRM) proposals, their potential contribution to reducing or increasing climate risk, as well as other risks they may pose (categorised as risks from responses to climate change in the IPCC AR6 risk definition in 1.2.1.1), and related perception, ethics and governance questions.

SRM refers to proposals to increase the reflection of shortwave radiation (sunlight) back to space to counteract anthropogenic warming and some of its harmful impacts (de Coninck et al., 2018) (Cross-chapter Box 10; WG1 Chapter 4 and Chapter 5). A number of SRM options have been proposed, including: Stratospheric Aerosol Interventions (SAI), Marine Cloud Brightening (MCB), Ground-Based Albedo Modifications (GBAM), and Ocean Albedo Change (OAC). Although not strictly a form of SRM, Cirrus Cloud Thinning (CCT) has been proposed to cool the planet by increasing the escape of longwave thermal radiation to space and is included here for consistency with previous assessments (de Coninck et al., 2018). SAI is the most-researched proposal. Modeling studies show SRM could reduce surface temperatures and potentially ameliorate some climate change risks (with more confidence for SAI than other options), but SRM could also introduce a range of new risks.

There is high agreement in the literature that for addressing climate change risks SRM cannot be the main policy response to climate change and is, at best, a supplement to achieving sustained net zero or net negative CO_2 emission levels globally (de Coninck et al., 2018; MacMartin et al., 2018; Buck et al., 2020; National Academies of Sciences and Medicine, 2021b). SRM contrasts with climate change mitigation activities, such as emission reductions and CDR, as it introduces a 'mask' to the climate change problem by altering the Earth's radiation budget, rather than attempting to address the root cause of the problem, which is the increase in GHGs in the atmosphere. In addition, the effects of proposed SRM options would only last as long as a deployment is maintained— e.g. requiring ca. yearly injection of aerosols in the case of SAI as the lifetime of aerosols in the stratosphere is 1-3 years (Niemeier et al., 2011) or continuous spraying of sea salt in the case of MCB as the lifetime of sea salt aerosols in the atmosphere is only about 10 days—which contrasts with the long lifetime of CO_2 and its climate effects, with global warming resulting from CO_2 emissions *likely* remaining at a similar level for a hundred years or more (MacDougall et al., 2020) and long-term climate effects of emitted CO_2 remaining for several hundreds to thousands of years (Solomon et al., 2009).

Which scenarios?

The choice of SRM deployment scenarios and reference scenarios is crucial in assessment of SRM risks and its effectiveness in attenuating climate change risks (Keith and MacMartin, 2015; Honegger et al., 2021). Most climate model simulations have used scenarios with highly stylized large SRM forcing to fully counteract large amounts of warming in order to enhance the signal-to-noise ratio of climate responses to SRM (Kravitz et al., 2015; Sugiyama et al., 2018a; Tilmes et al., 2018; Krishna-Pillai et al., 2019).

The effects of SRM fundamentally depend on a variety of choices about deployment (Sugiyama et al., 2018b), including: its position in the portfolio of human responses to climate change (e.g., the magnitude of SRM used against the background radiative forcing), governance of research and potential deployment strategies, and technical details (latitude, materials, and season, among others, see WG1 Chapter 4.6.3.3). The plausibility of many SRM scenarios is highly contested and not all scenarios are equally plausible because of socio-political considerations (Talberg et al., 2018b), as with, for example, CDR (Fuss et al., 2014; Fuss et al., 2018). Development of scenarios and their selection in assessments should reflect a diverse set of societal values with public and stakeholder inputs (Sugiyama et al., 2018a; Low and Honegger, 2020), as depending on the focus of a limited climate model simulation, SRM could look grossly risky or highly beneficial(Pereira and al., 2021).

In the context of reaching the long-term global temperature goal of the Paris Agreement, there are different hypothetical scenarios of SRM deployment: early, substantial mitigation with no SRM, more limited or delayed mitigation with moderate SRM, unchecked emissions with total reliance on SRM, and regionally heterogeneous SRM. Each scenario presents different levels and distributions of SRM benefits, side effects, and risks. The more intense the SRM deployment, the larger is the likelihood for the risks of side effects and environmental risks (e.g., Heutel et al., 2018). Regional disparities in climate hazards may result from both regionally-deployed SRM options such as GBAM, and more globally uniform SRM such as SAI (Jones et al., 2018a; Seneviratne et al., 2018b). There is an emerging literature on smaller forcings of SAI to reduce global average warming, for instance, to hold global warming to 1.5°C or 2°C alongside ambitious conventional mitigation (Jones et al., 2018a; MacMartin et al., 2018), or bring down temperature after an overshoot (Tilmes et al., 2020). If emissions reductions and CDR are deemed insufficient, SRM may be seen by some as the only option left to ensure the achievement of the Paris Agreement's temperature goal by 2100.

Table Cross-Working Group Box SRM.1: SRM options and their potential climate and non-climate impacts
Description, potential climate impacts, potential impacts on human and natural systems, and termination effects of a number of SRM options: Stratospheric Aerosol Interventions (SAI), Marine Cloud Brightening (MCB), Ocean Albedo Change (OAC), Ground-Based Albedo Modifications (GBAM), and Cirrus Cloud Thinning (CCT).

SRM option	SAI	MCB	OAC	GBAM	CCT
Description	Injection of reflective aerosol particles directly into the stratosphere or a gas which then converts to aerosols that reflect sunlight	Spraying sea salt or other particles in marine clouds, making them more reflective	Increase surface albedo of the ocean (e.g., by creating microbubbles or placing reflective foam on the surface)	Whitening roofs, changes in land use management (e.g., no-till farming, bioengineering to make crop leaves more reflective), desert albedo enhancement, covering glaciers with reflective sheeting	Seeding to promote nucleation of cirrus clouds, reducing optical thickness and cloud lifetime to allow more outgoing longwave radiation to escape to space
Potential climate impacts *other than reduced warming*	Change precipitation and runoff pattern; reduced temperature and precipitation extremes; precipitation reduction in some monsoon regions; decrease in direct and increase in diffuse sunlight at surface; changes to stratospheric	Change in land-sea contrast in temperature and precipitation, regional precipitation and runoff changes	Change in land-sea contrast in temperature and precipitation, regional , precipitation and runoff changes.	Changes in regional precipitation pattern, regional extremes and regional circulation	Changes in temperature and precipitation pattern, altered regional water cycle, increase in sunlight reaching the surface

	dynamics and chemistry; potential delay in ozone hole recovery; changes in surface ozone and UV radiation				
Potential impacts on human and natural systems	Changes in crop yields, changes in land and ocean ecosystem productivity, acid rain (if using sulphate), reduced risk of heat stress to corals	Changes in regional ocean productivity, changes in crop yields, reduced heat stress for corals, changes in ecosystem productivity on land, sea salt deposition over land	Unresearched	Altered photosynthesis, carbon uptake and side effects on biodiversity	Altered photosynthesis and carbon uptake
Termination effects	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset.	GBAM can be maintained over several years without major termination effects because of its regional scale of application. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset.
References (also see main text of this box)	Tilmes et al. (2018) Simpson et al. (2019) Visioni et al. (2017)	Latham et al. (2012) Ahlm et al. (2017) Stjern et al. (2018)	Evans et al. (2010) Crook et al. (2015a)	Zhang et al. (2016); Field et al. (2018); Seneviratne et al. (2018a) Davin et al. (2014) Crook et al. (2015a)	Storelvmo and Herger (2014) Crook et al. (2015a) Jackson et al. (2016) Gasparini et al. (2020) Duan et al. (2020)

SRM risks to human and natural systems and potential for risk reduction

Since AR5, hundreds of climate modelling studies have simulated effects of SRM on climate hazards (Kravitz et al., 2015; Tilmes et al., 2018). Modelling studies have shown SRM has the potential to offset some effects of increasing GHGs on global and regional climate, including the increase in frequency and intensity of extremes of temperature and precipitation, melting of Arctic sea ice and mountain glaciers, weakening of Atlantic meridional overturning circulation, changes in frequency and intensity of tropical cyclones, and decrease in soil moisture (WG1, Chapter 4). However, while SRM may be effective in alleviating anthropogenic climate warming either locally or globally, it would not maintain the climate in a present-day state nor return the climate to a pre-industrial state (climate averaged over 1850-1900, See WG1 Chapter 1, Box 1.2) in all regions and in all seasons even when used to fully offset the global mean warming *(high confidence);* WG1 Chapter 4}. This is because the climate forcing and response to SRM options are different from the forcing and response to GHG increase. Because of these differences in climate forcing and response patterns, the regional and seasonal climates of a world with a global mean warming of 1.5 or 2°C achieved via SRM would be different from a world with similar global mean warming but achieved through mitigation MacMartin et al. JGR2019}. At the regional scale and seasonal timescale there could be considerable residual climate change and/or overcompensating change (e.g., more cooling, wetting or drying than just what's needed to offset warming, drying or wetting due to anthropogenic greenhouse gas emissions), and there is low confidence in understanding of the climate response to SRM at the regional scale (WG1, Chapter 4).

SAI implemented to partially offset warming (e.g., offsetting half of global warming) may have potential to ameliorate hazards in multiple regions and reduce negative residual change, such as drying compared to present-day climate, that are associated with fully offsetting global mean warming (Irvine and Keith, 2020), but may also increase flood and drought risk in Europe compared to unmitigated warming (Jones et al., 2021). Recent modelling studies suggest it is conceptually possible to meet multiple climate objectives through optimally designed SRM strategies (WG1, Chapter 4). Nevertheless, large uncertainties still exist for climate processes associated with SRM options (e.g. aerosol-cloud-radiation interaction) (WG1, Chapter 4) (Kravitz and MacMartin, 2020).

Compared with climate hazards, many fewer studies have examined SRM risks—the potential adverse consequences to people and ecosystems from the combination of climate hazards, exposure and vulnerability—or the potential for SRM to reduce risk (Curry et al., 2014; Irvine et al., 2017). Risk analyses have often used inputs from climate models forced with stylized representations of SRM, such as dimming the sun. Fewer have used inputs from climate models that explicitly simulated injection of gases or aerosols into the atmosphere, which include more complex cloud-radiative feedbacks. Most studies have used scenarios where SAI is deployed to hold average global temperature constant despite high emissions.

There is *low confidence* and large uncertainty in projected impacts of SRM on crop yields due in part to a limited number of studies. Because SRM would result in only a slight reduction in CO_2 concentrations relative to the emission scenario without SRM (Chapter 5, WG1), the CO_2 fertilization effect on plant productivity is nearly the same in emissions scenarios with and without SRM. Nevertheless, changes in climate due to SRM are likely to have some impacts on crop yields. A single study indicates MCB may reduce crop failure rates compared to climate change from a doubling of CO_2 pre-industrial concentrations (Parkes et al., 2015). Models suggest SAI cooling would reduce crop productivity at higher latitudes compared to a scenario without SRM by reducing the growing season length, but benefit crop productivity in lower latitudes by reducing heat stress (Pongratz et al., 2012; Xia et al., 2014; Zhan et al., 2019). Crop productivity is also projected to be reduced where SAI reduces rainfall relative to the scenario without SRM, including a case where reduced Asian summer monsoon rainfall causes a reduction in groundnut yields (Xia et al., 2014; Yang et al., 2016). SAI will increase the fraction of diffuse sunlight, which is projected to increase photosynthesis in forested canopy, but will reduce the direct and total available sunlight, which tends to reduce photosynthesis. As total sunlight is reduced, there is a net reduction in crop photosynthesis with the result that any benefits to crops from avoided heat stress may be offset by reduced photosynthesis, as indicated by a single statistical modeling study (Proctor et al., 2018). SAI would reduce average surface ozone concentration (Xia et al., 2017) mainly as a result of aerosol-induced reduction in stratospheric ozone in polar regions, resulting in reduced downward transport of ozone to the troposphere (Pitari et al., 2014; Tilmes et al., 2018). The reduction in stratospheric ozone also allows more UV radiation to reach the surface. The reduction in surface ozone, together with an increase in surface UV radiation, would have important implications for crop yields but there is *low confidence* in our understanding of the net impact.

Few studies have assessed potential SRM impacts on human health and wellbeing. SAI using sulfate aerosols is projected to deplete the ozone layer, increasing mortality from skin cancer, and SAI could increase particulate matter due to offsetting warming, reduced precipitation and deposition of SAI aerosols, which would increase mortality, but SAI also reduces surface-level ozone exposure, which would reduce mortality from air pollution, with net changes in mortality uncertain and depending on aerosol type and deployment scenario (Effiong and Neitzel, 2016; Eastham et al., 2018; Dai et al., 2020). However, these effects may be small compared to changes in risk from infectious disease (e.g., mosquito-borne illnesses) or food security due to SRM influences on climate (Carlson et al., 2020). Using volcanic eruptions as a natural analog, a sudden implementation of SAI that forced the ENSO system may increase risk of severe cholera outbreaks in Bengal (Trisos et al., 2018; Pinke et al., 2019). Considering only mean annual temperature and precipitation, SAI that stabilizes global temperature at its present-day level is projected to reduce income inequality between countries compared to the highest warming pathway (RCP8.5) (Harding et al., 2020). Some integrated assessment model scenarios have included SAI (Arino et al., 2016; Emmerling and Tavoni, 2018; Heutel et al., 2018; Helwegen et al., 2019; Rickels et al., 2020) showing the indirect costs and benefits to welfare dominate, since the direct economic cost of SAI itself is expected to be relatively low (Moriyama et al., 2017; Smith and Wagner, 2018). There is a general lack of research on the wide scope of potential risk or risk reduction to human health, wellbeing and sustainable development from SRM and on their distribution across countries and vulnerable groups (Carlson et al., 2020; Honegger et al., 2021).

SRM may also introduce novel risks for international collaboration and peace. Conflicting temperature preferences between countries may lead to counter-geoengineering measures such as deliberate release of warming agents or destruction of deployment equipment (Parker et al., 2018). Game-theoretic models and laboratory experiments indicate a powerful actor or group with a higher preference for SRM may use SAI to cool the planet beyond what is socially optimal, imposing welfare losses on others although this cooling does not necessarily imply excluded countries would be worse off relative to a world of unmitigated warming (Ricke et al., 2013; Weitzman, 2015; Abatayo et al., 2020). In this context counter-geoengineering may promote international cooperation or lead to large welfare losses (Heyen et al., 2019; Abatayo et al., 2020).

Cooling caused by SRM would increase the global land and ocean CO_2 sinks (*medium confidence*), but this would not stop CO_2 from increasing in the atmosphere or affect the resulting ocean acidification under continued anthropogenic emissions (*high confidence*) (WG1 Chapter 5).

Few studies have assessed potential SRM impacts on ecosystems. SAI and MCB may reduce risk of coral reef bleaching compared to global warming with no SAI (Latham et al., 2013; Kwiatkowski et al., 2015), but risks to marine life from ocean acidification would remain, because SRM proposals do not reduce elevated levels of anthropogenic atmospheric CO_2 concentrations. MCB could cause changes in marine net primary productivity by reducing light availability in deployment regions, with important fishing regions off the west coast of South America showing both large increases and decreases in productivity (Partanen et al., 2016; Keller, 2018).

There is large uncertainty in terrestrial ecosystem responses to SRM. By decoupling increases in atmospheric greenhouse gas concentrations and temperature, SAI could generate substantial impacts on large-scale biogeochemical cycles, with feedbacks to regional and global climate variability and change (Zarnetske et al., 2021). Compared to a high CO_2 world without SRM, global-scale SRM simulations indicate reducing heat stress in low latitudes would increase plant productivity, but cooling would also slow down the process of nitrogen mineralization which could decrease plant productivity (Glienke et al., 2015; Duan et al., 2020). In high latitude and polar regions SRM may limit vegetation growth compared to a high CO_2 world without SRM, but net primary productivity may still be higher than pre-industrial climate (Glienke et al., 2015). Tropical forests cycle more carbon and water than other terrestrial biomes but large areas of the tropics may tip between savanna and tropical forest depending on rainfall and fire (Beer et al., 2010; Staver et al., 2011). Thus, SAI-induced reductions in precipitation in Amazonia and central Africa are expected to change the biogeography of tropical ecosystems in ways different both from present-day climate and global warming without SAI (Simpson et al., 2019; Zarnetske et al., 2021). This would have potentially large consequences for ecosystem services (Chapter 2 and Chapter 9). When designing and evaluating SAI scenarios, biome-specific responses need to be considered if SAI approaches are to benefit rather than harm ecosystems. Regional precipitation change and sea salt deposition over land from MCB may increase or decrease primary productivity in tropical rainforests (Muri et al., 2015). SRM that fully offsets warming could reduce the dispersal velocity required for species to track shifting temperature niches whereas partially offsetting warming with SAI would not reduce this risk unless rates of warming were also reduced (Trisos et al., 2018; Dagon and Schrag, 2019). SAI may reduce high fire risk weather in Australia, Europe and parts of the Americas, compared to global warming without SAI (Burton et al., 2018). Yet SAI using sulfur injection could shift the spatial distribution of acid-induced aluminum soil toxicity into relatively undisturbed ecosystems in Europe and North America (Visioni et al., 2020). For the same amount of global mean cooling, SAI, MCB, and CCT would have different effects on gross and net primary productivity because of different spatial patterns of temperature, available sunlight, and hydrological cycle changes (Duan et al., 2020). Large-scale modification of land surfaces for GBAM may have strong trade-offs with biodiversity and other ecosystem services, including food security (Seneviratne et al., 2018a). Although existing studies indicate SRM will have widespread impacts on ecosystems, risks and potential for risk reduction for marine and terrestrial ecosystems and biodiversity remain largely unknown.

A sudden and sustained termination of SRM in a high CO_2 emissions scenario would cause rapid climate change (*high confidence*; WG1 Chapter 4). More scenario analysis is needed on the potential likelihood of sudden termination (Kosugi, 2013; Irvine and Keith, 2020). A gradual phase-out of SRM combined with emission reduction and CDR could avoid these termination effects (*medium confidence*) (MacMartin et al., 2014; Keith and MacMartin, 2015; Tilmes et al., 2016). Several studies find that large and extremely rapid warming and abrupt changes to the water cycle would occur within a decade if a sudden termination of SAI occurred (McCusker et al., 2014; Crook et al., 2015b). The size of this 'termination shock' is proportional to the amount of radiative forcing being masked by SAI. A sudden termination of SAI could place many thousands of species at risk of extinction, because the resulting rapid warming would be too fast for species to track the changing climate (Trisos et al., 2018).

Public perceptions of SRM

Studies on the public perception of SRM have used multiple methods: questionnaire surveys, workshops, and focus group interviews (Burns et al., 2016; Cummings et al., 2017). Most studies have been limited to Western societies with some exceptions. Studies have repeatedly found that respondents are largely unaware of SRM (Merk et al., 2015). In the context of this general lack of familiarity, the publics prefer carbon dioxide removal (CDR) to SRM (Pidgeon et al., 2012), are very cautious about SRM deployment because of potential environmental side effects and governance concerns, and mostly reject deployment for the foreseeable future. Studies also suggest conditional and reluctant support for research, including proposed field experiments, with conditions of proper governance (Sugiyama et al., 2020). Recent studies show that the perception varies with the intensity of deliberation (Merk et al., 2019), and that the public distinguishes different funding sources (Nelson et al., 2021). Limited studies for developing countries show a tendency for respondents to be more open to SRM (Visschers et al., 2017; Sugiyama et al., 2020), perhaps because they experience climate change more directly (Carr and Yung, 2018). In some Anglophone countries, a small portion of the public believes in chemtrail conspiracy theories, which are easily found in social media (Tingley and Wagner, 2017; Allgaier, 2019). Since researchers rarely distinguish different SRM options in engagement studies, there remains uncertainty in public perception.

Ethics

There is broad literature on ethical considerations around SRM, mainly stemming from philosophy or political theory, and mainly focused on SAI (Flegal et al., 2019). There is concern that publicly debating, researching and potentially deploying SAI could involve a 'moral hazard', with potential to obstruct ongoing and future mitigation efforts (Morrow, 2014; Baatz, 2016; McLaren, 2016), while empirical evidence is limited and mostly at the individual, not societal, level (Burns et al., 2016; Merk et al., 2016; Merk et al., 2019). There is low agreement whether research and outdoors experimentation will create a 'slippery slope' toward eventual deployment, leading to a lock-in to long-term SRM, or can be effectively regulated at a later stage to avoid undesirable outcomes (Hulme, 2014; Parker, 2014; Callies, 2019; McKinnon, 2019). Regarding potential deployment of SRM, procedural, distributive and recognitional conceptions of justice are being explored, (Svoboda and Irvine, 2014; Svoboda, 2017; Preston and Carr, 2018; Hourdequin, 2019). With the SRM research community's increasing focus on distributional impacts of SAI, researchers have started more explicitly considering inequality in participation and inclusion of vulnerable countries and marginalized social groups (Flegal and Gupta, 2018; Whyte, 2018; Táíwò and Talati, 2021), including considering stopping research (Stephens and Surprise, 2020; National Academies of Sciences and Medicine, 2021a). There is recognition that SRM research has been conducted predominantly by a relatively small number of experts in the Global North, and that more can be done to enable participation from diverse peoples and geographies in setting research agendas and research governance priorities, and undertaking research, with initial efforts to this effect (e.g., Rahman et al., 2018), noting unequal power relations in participation could influence SRM research governance and potential implications for policy (Whyte, 2018; Táíwò and Talati, 2021) (Winickoff et al., 2015; Frumhoff and Stephens, 2018; Biermann and Möller, 2019; McLaren and Corry, 2021; National Academies of Sciences and Medicine, 2021b)

Governance of research and of deployment

Currently, there is no dedicated, formal international SRM governance for research, development, demonstration, or deployment (see WG3 Chapter 14). Some multilateral agreements—such as the UN Convention on Biological Diversity or the Vienna Convention on the Protection of the Ozone Layer—indirectly and partially cover SRM, but none is comprehensive and the lack of robust and formal SRM governance poses risks (Ricke et al., 2013; Talberg et al., 2018a; Reynolds, 2019a). While governance objectives range broadly, from prohibition to enabling research and potentially deployment (Sugiyama et al., 2018b; Gupta et al., 2020), there is agreement that SRM governance should cover all interacting stages of research through to any potential, eventual deployment with rules, institutions, and norms (Reynolds, 2019b). Accordingly, governance arrangements are co-evolving with respective SRM technologies across the interacting stages of research, development, demonstration, and—potentially—deployment (Rayner et al., 2013; Parker, 2014; Parson, 2014). Stakeholders are developing governance already in outdoors research; for example, for MCB and OAC experiments on the Great Barrier Reef (McDonald et al., 2019). Co-evolution of governance and SRM research provides a chance for responsibly developing SRM technologies with broader public participation and political legitimacy, guarding against potential risks and harms relevant across a full range of scenarios, and ensuring that SRM is considered only as a part of a broader portfolio of responses to climate change (Stilgoe, 2015; Nicholson et al., 2018). For SAI, large-scale outdoor experiments even with low radiative forcing could be transboundary and those with deployment-scale radiative forcing may not be distinguished from deployment, such that (MacMartin and Kravitz, 2019) argue for continued reliance on modeling until a decision on whether and how to deploy is made, with modeling helping governance development. For further discussion of SRM governance see Chapter 14, WG3.

[END CROSS-WORKING GROUP BOX SRM HERE]

16.6 Reasons for Concern Across Scales

This section builds on Section 16.5 which identifies and assesses key risks (KRs) and representative key risks (RKRs), including conditions contributing to their severity (i.e., Figure 16.10), in two ways. First, we consider those risks in the context of the global goal for sustainable development which can be impacted, as expressed in the United Nations 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). This discussion supports further assessment in Chapter 18 on sustainable system transitions and climate resilient development pathways. Second, the potential global consequences are then elaborated in an updated assessment of five globally aggregated categories of risk, designated as Reasons for Concern (RFCs), that evaluates risk accrual by global warming level.

16.6.1 Key Risks and Sustainable Development

The United Nations 2030 Agenda for Sustainable Development, and the Sustainable Development Goals (SDGs) (UN, 2015), since 2015, have become an important vision for the United Nations member countries (Chimhowu, 2019) as well as for corporations to contribute towards sustainable growth (UNDP et al., 2016; Ike et al., 2019; van der Waal and Thijssens, 2020). Climate change risks, as embodied in the RKR and RFCs, can affect attainment of the SDGs and have consequences for lives and livelihoods (related to SDGs 1, 4, 8 and 9), health and well-being (related to SDGs 2, 3 and 6), ecosystems and species (related to SDGs 6, 14 and 15), economic (related to SDGs 1, 8 and 12), social and cultural assets (related to SDGs 5, 10, 11, 16 and 17), services including ecosystem services (related to SDGs 6, 7, 11, 12, 14 and 15), and infrastructure (related to SDGs 6, 7, 9, 11 and 12). This section assesses the level of linkages between key risks with sustainable development, in terms of the SDG targets and indicators. This informs on the key risks which are most relevant to consider with respect to the attainment of the SDGs.

16.6.1.1 Links Between Key Risks and SDGs

Within the AR6 cycle, the three IPCC Special Reports have all considered the relationships between climate change impacts and actions and the SDGs. SR15 discussed priorities for sustainable development in relation to climate adaptation efforts (Section 5.3.1, SR15); synergies and trade-offs of climate adaptation measures (Section 5.3.2, SR15); and the effect of adaptation pathways towards a 1.5ºC warmer world (Section 5.3.3 SR15). The SRCCL considered impacts of desertification on SDGs 1 (no poverty), 2 (zero hunger), 13 (climate), 15 (life on land), and 5 (gender) (IPCC, 2019a, Figure 3.9). Trade-offs and synergies between SDGs 2 (zero hunger) and 13 (climate action) at the global level were recognised (IPCC, 2019a, Section 5.6.6, Figure 5.16). Various integrated response options, interventions and investments were also evaluated within the SDG framework (IPCC, 2019a, Section 6.4.3). The SROCC (Chapter 5) concluded that climate change impacts on the ocean, overall, will negatively affect achieving the SDGs with 14 (life below water) being most relevant (Singh et al., 2019).

Many linkages between SDG 13 (climate action) and other SDGs have been identified *(very high confidence),* (Blanc, 2015; Kelman, 2015; Northrop et al., 2016; Hammill and Price-Kelly, 2017; ICSU, 2017; Mugambiwa and Tirivangasi, 2017; Dzebo et al., 2018; Major et al., 2018; Nilsson et al., 2018; Sanchez Rodriguez et al., 2018). In addition, interactions between different climate change actions and SDGs, and interactions among SDGs themselves, have also been assessed (Nilsson et al., 2016; IPCC, 2018; McCollum et al., 2018; Fuso-Nerini et al., 2019; IPCC, 2019b; Cernev and Fenner, 2020). The Cross-Chapter Box GENDER in Chapter 18 assessment indicates the importance of gender considerations in achieving success and benefits in adaptation efforts. Aligning climate change adaptation to the SDGs could bring potential co-benefits, increased efficiency in funding, and reduce the gap between adaptation planning and implementation (*very high confidence)* (IPCC, 2018; Sanchez Rodriguez et al., 2018; IPCC, 2019b; IPCC, 2019a).

Progress towards meeting the SDGs has been recognized to be able to reduce global disparities and support more climate resilient development pathways (IPCC WGII AR5, Chapter 13, p. 818; discussed further in Chapter 18). Nevertheless, we are still lagging in achieving the 2030 Goals (OECD, 2019; Sachs et al., 2021), and this affects societal vulnerability, readiness and risk response capacities (IPCC, 2019a, Chapters 6, 7, Chapters 6 and 8, this report). We assess the risk literature for linkages between key risks (grouped by RKRs) and the indicators of the SDGs (UN, 2015) using text analysis (details in Supplementary Material SM16.5) to identify the potential level of effect of different risks on the SDGs. Some 940 documents were analysed. The SDG status is associated with projected climate hazards, also called climatic impact-drivers (CID) (Ranasinghe et al., 2021) (panel a), and RKRs (panel c), summarising hazard and exposure with vulnerability aspects, as expressed by challenges in achieving the SDGs (panel d), on a regional level (Figure 16.12).

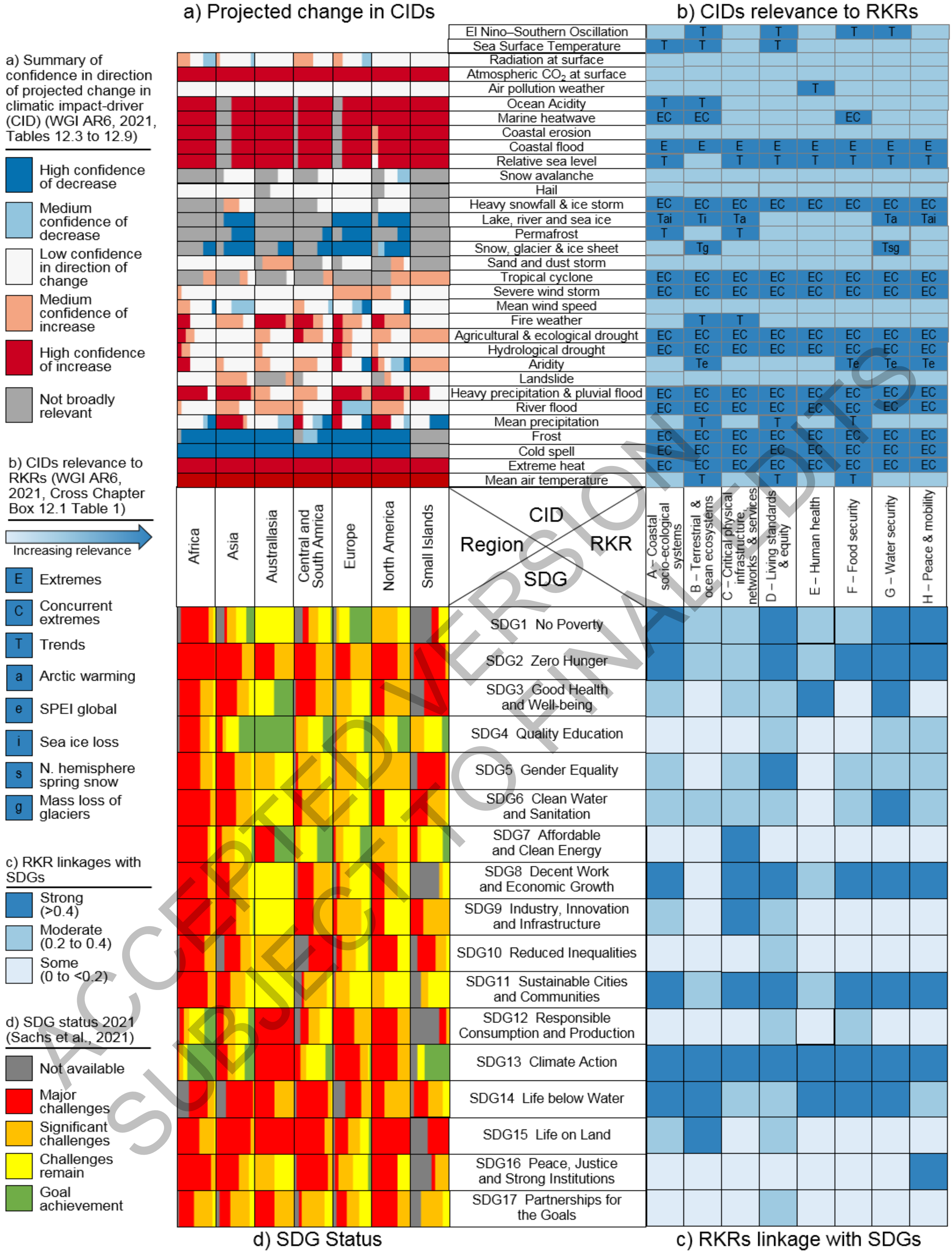


Figure 16.12: Linkages between the projected climatic impact-drivers (CIDs) by region, Sustainable Development Goals (SDGs) by region, and the Representative Key Risks (RKRs).

16.6.1.2 Results, Implications and Gaps

Linkages between the 17 SDGs and the eight RKRs (Figure 16.15 bottom left panel) are mapped to the regional SDG status (Figure 16.15 bottom right panel) and related to the climate hazards (CIDs) (Figure 16.15 top left panel). Interconnections between climate hazards (CIDs) and RKRs are complicated by the possibility of concurrent weather events, extremes and longer term trends. Risks are compounded by existing vulnerabilities (Iwama et al., 2016; Thomas et al., 2019b; Birkmann et al., 2021) and cascading consequences (Pescaroli and Alexander, 2015; Pescaroli and Alexander, 2018; Yokohata et al., 2019) (see for example Sections 3.4.3.5, 5.12, 6.2.6, 7.2.2.2) as well as interactions. The level of challenges faced in attaining the SDGs is one metric for assessing vulnerability and lack of capacity to manage risks (Cernev and Fenner, 2020). Other metrics are also available (Parker et al., 2019; Garschagen et al., 2021b; Birkmann et al., 2022). From Figure 16.12, aside from SDG13 (climate action), the strongest connections and risk challenges are with zero hunger (SDG2), sustainable cities and communities (SDG11), life below water (SDG14), decent work and economic growth (SDG8), no poverty (SDG1), clean water and sanitation (SDG6) and good health and well-being (SDG3) (*high confidence*). Other SDGs have strong linkages with specific RKRs, for example, terrestrial and marine ecosystems with Life on land (SDG15); infrastructure (RKR-C) with Industry, innovation and infrastructure (SDG9) and Affordable and clean energy (SDG7); living standards (RKR-D) with Gender equality (SDG5); and peace and mobility (RKR-H) with Peace, justice and strong institutions (SDG 16) (*high confidence*).

On a global scale, priority areas for regions can be evaluated from the intersection of climate hazards, risks and the level of challenges in SDG attainment (Moyer and Hedden, 2020; Sachs et al., 2021). The greatest linkages and effects on the SDGs will be due to risks to water (RKR-G), living standards (RKR-D), coastal socio-ecological systems (RKR-A) and Peace and human mobility (RKR-H) (*high confidence*) (details in Supplementary Material SM16.5).

In particular, coastal socio-ecological systems (RKR-A), living standards (RKR-D), food security (RKR-F), water security (RKR-G) and peace and mobility (RKR-H), have strong linkages with SDG 2 (zero hunger), for which there are significant to major challenges for all regions (*high confidence*). Almost all the RKRs are strongly linked to SDGs 8 (decent work and economic growth), and 11 (sustainable cities and communities) (*high confidence*), where regions such as Africa, Asia, and Central and South America face significant to major challenges in attaining targets. All regions also face major to significant challenges affecting SDGs 14 (life below water) and 15 (life on land), which relate to terrestrial and ocean ecosystems (RKR-B) (*high confidence*).

The analysis of RKR linkages to SDGs is also useful in identifying gaps and susceptibilities, especially for developing future climate resilient development targets. This aspect is discussed further in Chapter 18. Gaps may arise as SDG targets and indicators are not specifically focused on systems affected by climate change risks or impacts. For example, in the SRCCL Section 7.1.2 Hurlbert et al. (2019), noted the absence of an explicit goal for conserving fresh-water ecosystems and ecosystem services in the SDGs. Such gaps (Tasaki and Kameyama, 2015; Guppy et al., 2019) are inevitable as the current SDG targets and indicators focus on overall sustainable development. As another example, projected increases in frequency and intensity of hot temperature extremes are likely to result in increased heat-related illness and mortality, yet heat extremes are not called out as an SDG indicator under SDGs 3 (good health and well-being) nor 13 (climate action). The gaps on climate-related metrics for impacts on health are just beginning to be evaluated (Lloyd and Hales, 2019, see also Section 7.1.6). The current SDG 13 (climate action) targets also do not specifically track the possibility of differential impacts on society from disasters and extreme weather events (RFC2). For example, the first indicator (13.1.1.1), 'Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population', does not include any requirement for disaggregated data, unlike several other socio-economic and population SDG indicators, making it difficult to track the different effects that climate-related disasters are expected to have on men, women, and children across different segments of society, relevant for distributional impacts (RFC3) (see also Section 8.3, Cross-Chapter Box GENDER in Chapter 18). The risk consequences identified and discussed in each RKR (Section 16.5.2) provide useful entry points for identifying indicators and metrics for monitoring and evaluating specific impacts of key climate change risks. In addition, the sector and region chapters have considered various adaptation responses relevant to the SDGs (see for example, Sections 3.6, 4.7.5, 5.13.3, 8.2.1.6, 10.6.1, 13.11.4, 14.6.3) with relevant metrics for evaluation.

In summary, key risks, and the consequences arising from them, are directly linked to and will affect specific indicators of the SDGs *(high confidence).* They also will be indirectly linked to, and thus affect, the SDGs overall, due to the interactions between the key risks (Section 16.5) and between the SDGs themselves (*very high confidence*). These results support previous findings that climate change impacts pose a risk to achieving sustainability (Ansuategi et al., 2015; Chirambo, 2016; ICSU, 2017; Pradhan et al., 2017; Gomez-Echeverri, 2018; IPCC, 2018; IPCC, 2019b; IPCC, 2019a; Cernev and Fenner, 2020). Not all observed or expected consequences arising from the key risks are fully captured by the SDG indicators, and nor were they designed to be. Therefore, for monitoring and assessing the climate risk impacts, it is useful to consider specific, climate change impact indicators and metrics (Enenkel et al., 2020) to capture any realised impacts.

In the near term, the strength of connection between the RKRs and the SDGs, with respect to existing SDG challenges, indicate probable systemic vulnerabilities and issues in responding to climatic hazards (UN-IATFFD, 2019; Leal Filho et al., 2020; Weaver et al., 2020; Tiedemann et al., 2021) (*high confidence*). In the medium to long term (associated with global warming levels of between 2°C and 2.7°C under SSP2-45 scenario), if such vulnerabilities and challenges cannot be substantially reduced, the hazards and risks resulting from the projected climate hazards (CIDs) (Figure 16.12b, c) will further stress systems relevant for sustainable development, based on current experience of the COVID-19 pandemic (UN-IATFFD, 2021, see also Cross-Chapter Box COVID in Chapter 7; Section 8.2, Section 8.3) (*medium confidence, based on medium evidence, high agreement*).

The potential impacts of the various climate hazards, the occurrence of extreme events, and the projected trends of climate hazards, give rise to complex risks for ecological and human systems, which are compounded by the exposure, vulnerability and sustainability challenges faced in different regions of the world. The potential global consequences are elaborated in the next section which describes the framework and approach for the assessment of the five Reasons for Concern.

16.6.2 Framework and Approach for Assessment of RFCs and Relation to RKRs

The 'Reasons for Concern' (RFC) framework communicates scientific understanding about accrual of risk in relation to varying levels of warming for five broad categories: risk associated with (1) unique and threatened systems, (2) extreme weather events, (3) distribution of impacts, (4) global aggregate impacts, and (5) large-scale singular events (Smith et al., 2001; Mastrandrea and Schneider, 2004; Schneider and Mastrandrea, 2005). The RFC framework was first developed during the Third Assessment Report (Smith et al., 2001) along with a visual representation of these risks as 'burning embers' figures, and this assessment framework has been further developed and updated in subsequent IPCC reports including AR5 (IPCC, 2014; Oppenheimer et al., 2014) and the recent IPCC Special Reports (SR15 2018; SRCCL 2019; SROCC 2019).

Relationship between RKRs and RFCs

RFCs reflect risks aggregated globally that together inform the interpretation of dangerous anthropogenic interference with the climate system. The five RFC categories are maintained as previously defined for consistency with earlier assessments. Compared to the synthesis of risk across RKRs in Section 16.5, we note that the RKRs and RFCs are complementary methods that aggregate individual risks into different but interconnected categories (Figure 16.13).

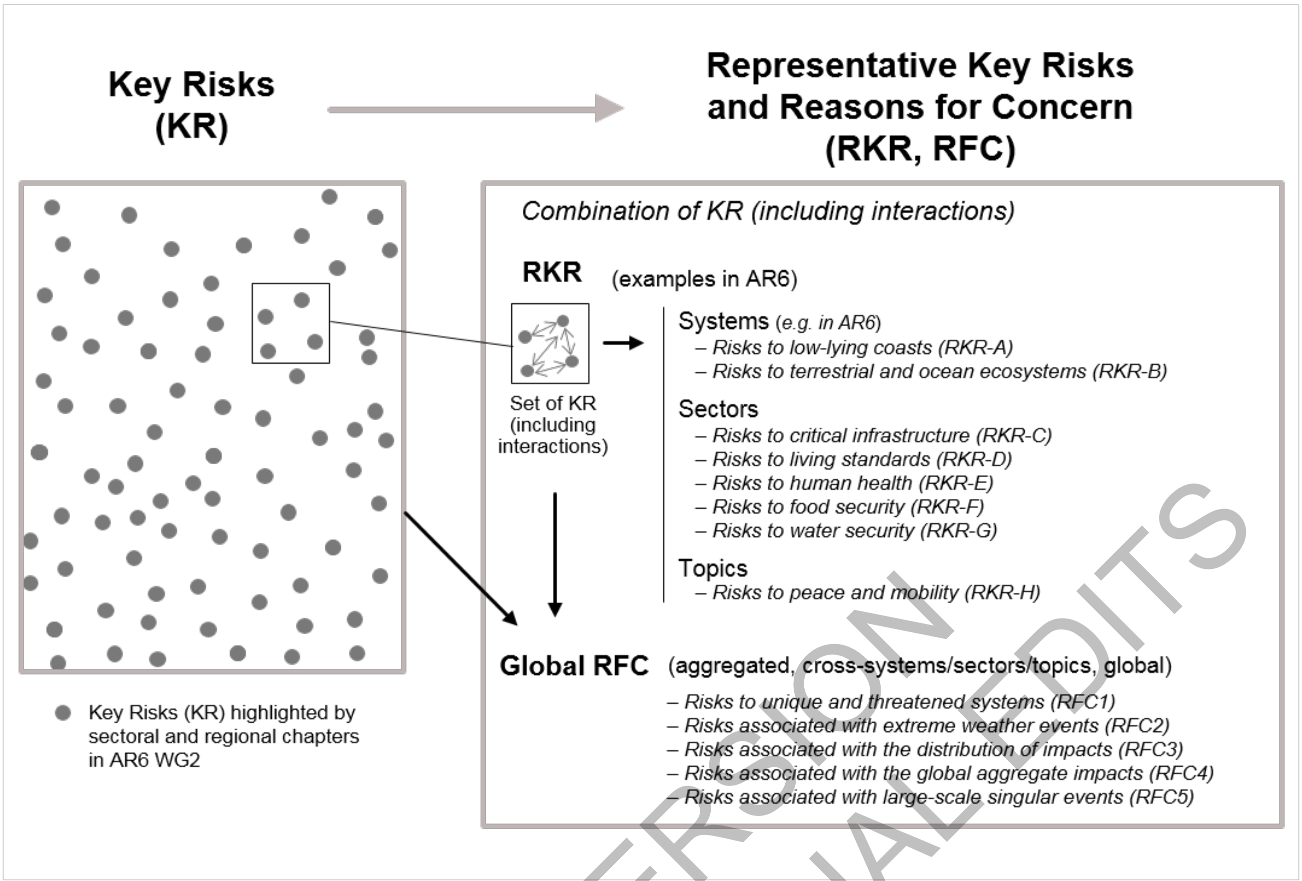


Figure 16.13 Interconnections between the Key Risks, Representative Key Risks and the Reasons for Concern

We draw important distinctions between RFC and RKR. First, RFCs assess risks that might be of global concern, while RKRs also include risks that may be of concern only locally or for specific population groups (Figure 16.13). RFCs focus on the full range of increasing risk, and locate transitions between four categories of risk: undetectable, moderate, high, and very high. RKRs focus on severe risks, and attempt to elaborate when/where severe impacts may occur. RKR assessments focus on the conditions under which some risks would become severe over the course of this century, while RFCs evaluate changes in risk levels against gradual increase in temperature levels. The RKR analysis used specific definitions of severity including quantified thresholds where possible, and this is distinct from the approach based on the combined elements of risk used in the RFC expert elicitation process. Severity as defined in the RKRs is associated with high or very high risk levels but does not align precisely with either of those categories, and a further difference arises from a more explicit emphasis on irreversibility and adaptation limits in the very high risk category in the RFCs. Thus RKR and RFC neither map directly to one another in terms of content, nor in terms of the response metric.

The treatment of vulnerability and adaptation is different in the RKR and RFC assessments. The RKR assessment considered specifically three alternative levels of vulnerability, whereas the RFC process did not explicitly differentiate risk by level of vulnerability. Therefore, the global warming levels at which the various RKR assessments identify risk of severe impacts are not directly comparable to risk transitions identified in the RFC assessments. In addition, RKRs consider implications of low vs. high adaptation in order to illustrate the potential role of ambitious adaptation efforts to limit risk severity; RFCs consider risks in a no/low adaptation scenario only, although there is some discussion of the potential role of adaptation in assessing the transition to very high risk. Last, both RKRs and RFCs focus on the 21st century scale, though recognizing risk will continue to increase after 2100, but treat this timing issue differently: RKRs assess severe risks over the course of this century and distinguish risks that are already severe, that will become severe by the mid-century, or that will become severe by the end of the century; while RFCs assess risk level irrespective of their timing, but according to different temperature levels.

Many of the elements of risk which contribute to RKRs also contribute to risk within one or more RFCs. In turn, elements of risk within some RFCs, such as extreme weather and changes in the earth system contribute to risk within one or more RKR. Hence RFCs may incorporate elements of many different RKRs, and vice versa. There are therefore common elements between some particular RKRs and RFCs: for example, risks to terrestrial and ocean ecosystems (RKR-B) contributes strongly to RFC1 (Unique and Threatened Systems) and RFC4 (Global Aggregate Impacts); while RFC2 (extreme weather events) has implications for all RKRs, including direct linkages with critical physical infrastructure, networks and services (RKR-C). Furthermore, risks emerging from the interaction of RKRs also contribute to the RFCs, but are only qualitatively described in Section 16.5.4. For example, the effects of risks to terrestrial and ocean ecosystems (RKR-A) affect living standards and equity (RKR-C), as does the associated decline in ecosystem services which then impacts livelihoods (RKR-D).

Elicitation Methodology

The method used to develop judgments on levels of risk builds on the approach described in WGII AR5 Chapter 19 (Oppenheimer et al., 2014) and outlined in more detail in (O'Neill et al., 2017), while integrating advances in the AR6 SRs including expert judgment (SRCCL, Zommers et al., 2020). We provide further details on the underlying judgements of risk level compared to previous assessments by indicating key risk criteria associated with each judgement: magnitude of adverse consequences, likelihood of adverse consequences, temporal profile of the risk, and ability to respond to the risk (Section 16.5.1). The definitions of risk levels used to make the expert judgements are presented in Table 16.7 (Section 16.5.1).

Table 16.7: Definition of Risk Levels for Reasons for Concern.

Level	Definition
Undetectable (White)	No associated impacts are detectable and attributable to climate change.
Moderate (Yellow)	Associated impacts are both detectable and attributable to climate change with at least medium confidence, also accounting for the other specific criteria for key risks.
High (Red)	Severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks.
Very High (Purple)	Very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.

A brief summary of the framework that was used to carry out the risk assessment, synthesis and expert elicitation is presented here and details are provided in Supplementary Material SM16.5. Expert judgements about the qualitatively defined levels of risk (i.e., undetectable, moderate, high, and very high) reached at various levels of global average warming are informed by evidence of observed impacts illustrated in Section 16.2 and variations in individual key risks under different scenarios of climate change, socioeconomics and adaptation effort in Section 16.5. We follow the methodological advances from SRCCL Chapter 7 (Hurlbert et al., 2019), which used an expert elicitation protocol for developing the burning embers (Zommers et al., 2020). Specifically, we used expert participants from within the AR6 author team and a protocol based on the modified Delphi technique (Mukherjee et al., 2015) and the Sheffield Elicitation Framework (Oakley and O'Hagan, 2010; Gosling, 2018). This approach (Figure 16.14) includes a two-round elicitation process with a first round of independent anonymous judgements about the global warming level at which risk levels transition from one to the next, and a final round of group discussion and deliberation to develop consensus. The results are then reported and additional references made to findings from other relevant chapters in this report, and reviewed by authors who had not participated in the elicitation as part of independent appraisal.

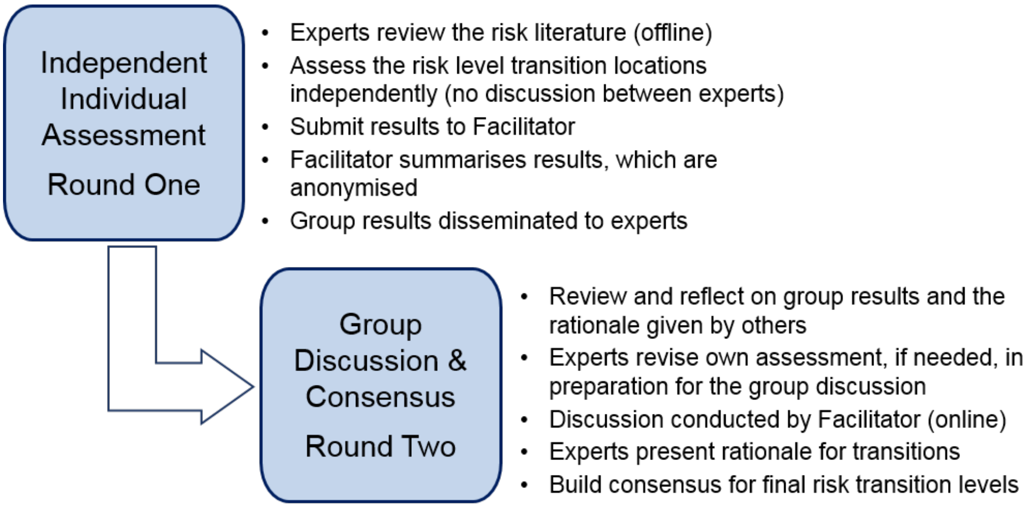


Figure 16.14 Expert elicitation approach for assessment of RFC risk level transitions. A more detailed description of the methodology used in this elicitation is provided in the Supplementary Material (SM16.5).

The resulting risk transition or 'ember' diagram illustrates the progression of socio-ecological risk from climate change as a function of global temperature change, taking into account the exposure and vulnerability of people and ecosystems, as assessed by literature-based expert judgment. Section 16.6.3 presents these diagrams for each Reason for Concern, providing information about the most important literature-based evidence that experts used to make their judgements. Similar assessments for selected individual KRs are discussed in Chapters 2, 7, 9, 12, 13, and 14.

Representation of Warming Levels
The RFC assessment reflects the latest understanding of warming reported in WGI AR6. Global surface temperature was 1.09 [0.95 to 1.20]ºC higher in 2011–2020 than 1850–1900, with stronger warming over land (1.59 [1.34 to 1.83]ºC) than over the ocean (0.88 [0.68 to 1.01]ºC) (WGI AR6 Cross Chapter Box 2.3 Table 1, Eyring et al. in Gulev et al., 2021). Warming levels are commonly reported and studied in the impacts literature using two scales of spatially averaged temperature rise, global surface air temperature (GSAT), commonly produced by General Circulation Models (GCMs) when projecting climate changes, and global mean surface temperature (GMST), commonly used in empirical studies. Both have the same reference point of pre-industrial of 1850–1900. The ember diagrams presented here use GSAT, which is consistent with most literature of projected risk (largely based on the output of climate models). To the extent that the embers also draw on the observed impacts literature using GMST, this potential variation is minimal as the average levels of GSAT and GMST have been shown to match closely (for further discussion on this see Cross-Chapter Box CLIMATE in Chapter 1). Hence the diagrams are presented with a single y-axis representing global temperature change, generally referring to global temperature rise irrespective of when it occurs: however, the majority of the literature assessed considers alternative levels of warming during the twenty-first century. For example, a warming level of 2ºC might occur in the 2050s, the 2080s, or in 2100 (see next section).

Furthermore, climate-related hazards associated with each of the RFCs are assessed in WGI AR6 Cross-Chapter Box 12.1 Table 1 (Tebaldi et al., 2021) which synthesizes information from various chapters of WGI on 35 such hazards according to global warming levels (GWLs) to inform understanding of their potential changes and associated risks with temperature levels in general.

Temporal dimension
When are the risks shown in the embers projected to occur? The issues associated with assessing transient risks are discussed in Chapter 3, SR15 (IPCC, 2018). Some of the literature, however, does explore the dynamics within human and natural systems (i.e., the way in which systems respond when a transient level of warming is first reached and then further, how they continue to develop if that transient level of warming is then maintained indefinitely). We note that this important factor is captured in the RFC assessment (and ember diagrams), since the timing of risk accrual is one of the criteria for the assessment of the level of risk (16.5.1). Risks that are known to evolve only over very long-time scales contribute less to the level of risk

than those which are known to occur rapidly. This is because sea level rise also depends on the dynamics of global warming, including the rate of change of radiative forcing, and time lags of several decades, including between atmospheric and ocean warming, and in reaching equilibrium sea level state (Oppenheimer et al., 2019; Fox-Kemper et al., 2021). However, longer-term risks that would arise if those transient temperatures were maintained are also included, and this is particularly important in RFC5 (large scale singular events). Note that risks that take place over a very long timescale are considered to be of lower concern than more imminent risks. However, changes of very large magnitude can still be very important even if far away in time, especially if these changes are irreversible (or reversible only on extremely long time scales) (see Section 16.5.1).

Although the embers do not indicate the decade in which certain risks are projected to occur, clearly this depends strongly on the level of mitigation action as well as the degree of adaptation. Hence, the ember diagram (Figure 16. 14) is shown alongside a graphic illustrating possible global temperature time series emerging from alternative future scenarios assessed by WGI AR6 which imply different levels of mitigation effort. For example, in a scenario with a high level of mitigation effort (SSP1-1.9) reaching net zero emissions in the 2050s, it is *extremely likely* that global warming remains below 2°C and more than 50% *likely* that it will remain below 1.6°C (AR6 WGI 4.3.1.1, Meinshausen et al., 2020). On the other hand, a level of 2°C warming is *extremely likely* to be exceeded during the 21st century under the three scenarios assessed by WGI AR6 in which greenhouse gas emissions do not fall below current levels before mid-century (i.e., SSP2-4.5, SSP3-7.0, SSP-8.5) (WGI AR6 4.3.1.1, Lee et al., 2021). WGI AR6 has assessed that 'global surface temperature averaged over 2081–2100 is *very likely* to be higher by 1.0°C–1.8°C under the lowest CO_2 emission scenario considered in this report (SSP1-1.9) and by 3.3°C–5.7°C under the highest CO_2 emission scenario (SSP5-8.5)'. However, almost all scenarios assessed by IPCC AR6 WGI reach 1.5°C global warming level in the early 2030s (WGI AR6 SPM, IPCC, 2021a).

Temperature overshoot

The concept of temperature overshoot, defined as 'exceedance of a specified global warming level followed by a decline to or below that level during a specified period of time' is a relevant consideration for this RFC risk assessment; however, the effect of overshoot has not explicitly been considered in the burning ember assessment due to the limited literature basis. However, despite the lack of directly assessed overshoot scenarios, the current literature provides several salient examples of irreversible changes that are projected to occur once global temperatures reach a particular level. For example, coral reefs are unable to survive repeated bleaching events that are too close together, leading to irreversible loss of the reefs even if bleaching were to cease (see Section 16.6.3.1 RFC1). Species extinction is irreversible, and Chapter 2 assesses that at ~1.6°C, >10% of species are projected to become endangered as compared with >20% at ~2.1°C (median) representing high and very high biodiversity risk, respectively *(medium confidence)* (Section 2.5.4). Similarly, WGI AR6 finds that 'Over the 21st century and beyond, abrupt and irreversible regional changes in the water cycle, including changes in seasonal precipitation, streamflow and aridity, cannot be excluded'. Thus, information about irreversibility provides information about the potential outcome of temperature overshoot scenarios. Other types of losses, such as loss of human or species life, are irreversible even if the loss process ceases in the future. The less resilient a system is, the more likely it is to suffer irreversible damage during a temperature overshoot; the more resilient it is, the more likely it is to be able to withstand the overshoot or recover afterwards. Very high levels of risk, as assessed here in the Reasons for Concern, are associated with a wide range of criteria for risk assessment including irreversibility. Whilst not all very high risks are irreversible, in general risks reaching a very high level include a component of irreversible risks that would persist during and after an overshooting of a given temperature level.

Risks associated with socioeconomic development, mitigation and mal-adaptation

The ember diagrams in Figure 16.14 capture only the risks arising from exposure of vulnerable socio-ecological systems to climatic hazards across a range of socioeconomic futures. They do not capture any risk component arising solely from changes in population or level of development. Importantly, they also do not capture additional risks that may arise from the human response to climate change, including climate change mitigation or unintended negative consequences of adaptation-related responses (i.e., maladaptation) (Section 17.5.1). Such risks are discussed in SRCCL Chapter 7, for example, adverse effects of the very large-scale use of land and water for primary bioenergy production on food production and biodiversity (Hurlbert et al., 2019). Contributions of mitigation or maladaptation to risk can be important, however, and are discussed further in the context of specific RFCs in Section 16.6.3. In general, such components of risk are difficult to quantify, and can be minimised by good design of climate change mitigation and adaptation. Thus, the effect is excluded from the ember diagrams to allow a more clear representation of the accrual of climate change risk with global warming.

Emergent Risk

AR5 Oppenheimer et al. (2014) defined 'emergent risk' as a risk that arises from the interaction of phenomena in a complex system. While emergent risk is a relevant consideration for this RFC risk assessment, this type of risk has not been explicitly accounted for in the burning ember assessment due to the limited literature basis. Unlike known or identified risks, emergent risks are characterized by the uncertainty of consequences and/or probabilities of occurrence. The International Risk Governance Council (IRGC) suggests three categories of emergent risks: 1) high uncertainty and a lack of knowledge about potential impacts and interactions with risk-absorbing systems; 2) increasing complexity, emergent interactions and systemic dependencies that can lead to non-linear impacts and surprises; and 3) changes in context (for example social and behavioural trends, organisational settings, regulations, natural environments) that may alter the nature, probability and magnitude of expected impacts. Feedback processes between climatic change, human interventions involving mitigation and adaptation actions, and processes in natural systems can be classified as emergent risks if they pose a threat to human security.

16.6.3 Global Reasons for Concern

In this section we present the results of the expert elicitation in the form of the burning embers diagram, alongside a description of the recent literature and scientific evidence for each of the RFCs in turn. The consensus transition values are illustrated in Figure 16.14, an updated version of the burning embers diagram that describes the additional risk due to climate change for each RFC when a temperature level is reached and then sustained or exceeded. (Table SM16.18 in Supplementary Material SM16.6 presents the consensus values of the transition range and median estimate in terms of global warming level by risk level for each of the five RFC embers). The shading of each ember provides a qualitative indication of the increase in risk with temperature, and we retain the color scheme employed in the most recent versions of this figure, where white, yellow, red, and purple indicate undetectable, moderate, high and very high additional risk, respectively. These transitions were assessed under conditions of low to no adaptation compared to today, in accordance with definitions provided in 16.3 (i.e., adaptation consists of fragmented, localized, incremental adjustments to existing practices), though the effect of adaptation on risk for individual RFCs and related literature is discussed further below.

The following subsections present the expert assessment and judgments made during the elicitation process to identify consensus transition values for each RFC. The description of these transitions is further extended with additional references to findings from underlying chapters in this report, and reviewed by Chapter 16 authors as part of independent appraisal. No changes were made to the transition values assessed through the expert elicitation.

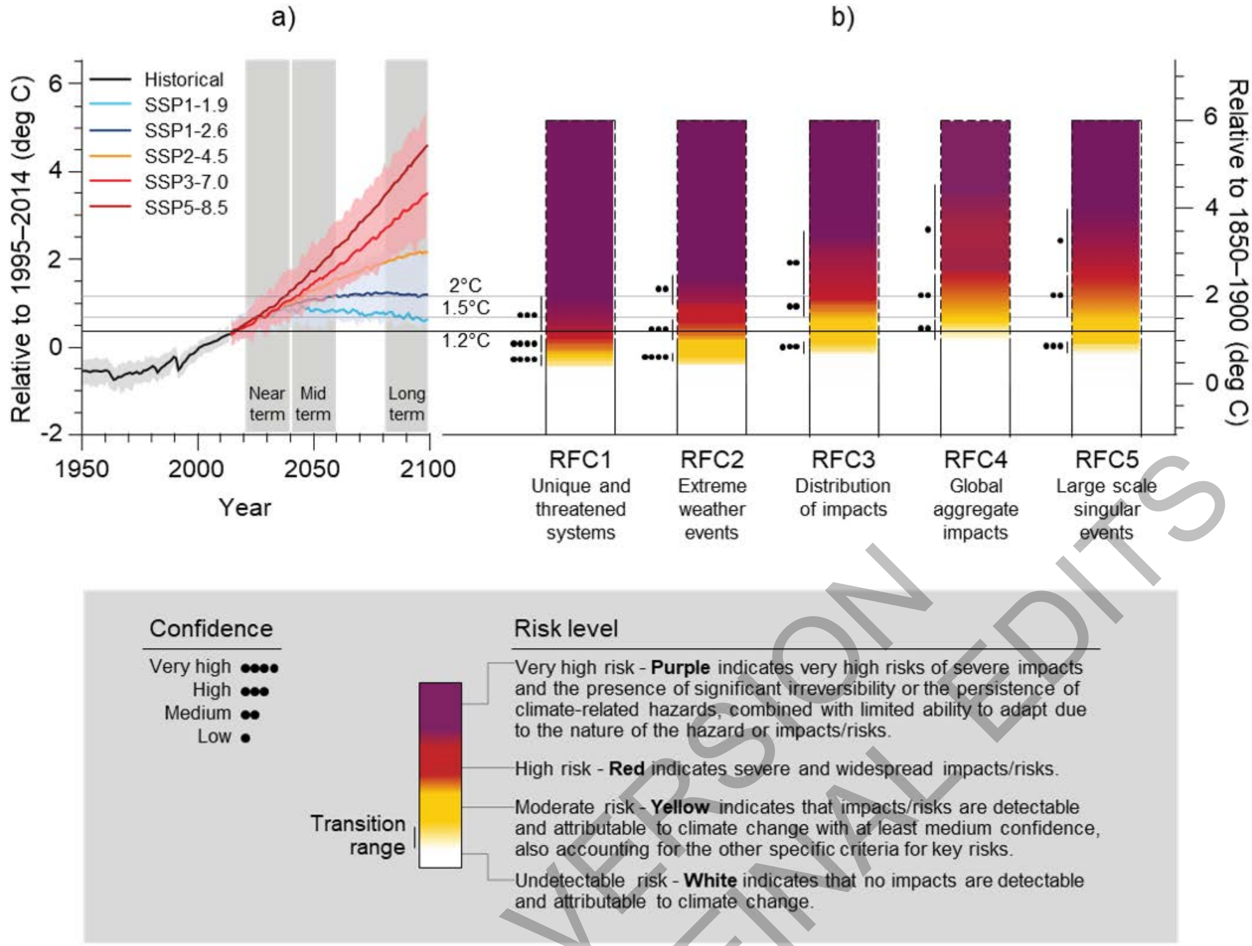


Figure 16.15: The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated by expert elicitation and reflecting new literature and scientific evidence since AR5 and SR15. (a) Global surface air temperature (GSAT), relative to 1995-2014 (left axis) and pre-industrial, 1850-1900 (right axis) (WGI AR6 Figure 4.2a, (Lee et al., 2021)). (b) Embers are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localized, incremental adjustments to existing practices). The horizontal line denotes the present global warming of 1.2°C (WMO, 2020) which is used to separate the observed, past impacts below the line from the future projected risks above it. **RFC1 Unique and threatened systems**: ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots. **RFC2 Extreme weather events**: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. **RFC3 Distribution of impacts**: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. **RFC4 Global aggregate impacts**: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. **RFC5 Large-scale singular events**: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GSAT. The levels of risk illustrated reflect the judgments of IPCC author experts from WGI and WGII.

16.6.3.1 Unique and Threatened Systems (RFC1)

This RFC addresses the potential for increased damage to or irreversible loss of a wide range of physical, biological, and human systems that are unique (i.e., restricted to relatively narrow geographical ranges and have high endemism or other distinctive properties) and are threatened by future changes in climate (Smith et al., 2001; Smith et al., 2009; Oppenheimer et al., 2014). The specific examples of such systems given in previous IPCC assessment reports has remained broadly consistent, with AR4 including 'coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots, small island states, and indigenous communities' (Smith 2009), AR5 including 'a wide range of physical, biological, and human systems that are restricted to relatively narrow geographical ranges' and 'are threatened by future changes in climate'

(Smith et al., 2001), while SR15 Chapter 3 included 'ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots'. In this cycle, we retain the definition used in SR15 as most explicit and inclusive of the previous definitions.

AR5 (Oppenheimer et al., 2014) assessed the transition from undetectable to moderate risk for RFC1 to lie below recent global temperatures (1986-2005, which at the time was considered to correspond to a global warming level of 0.6°C above pre-industrial levels; AR6 WGI now considers this time period of 1986-2005 to correspond to a global warming or approximately 0.7°C). At that time, there was at least *medium confidence* in attribution of a major role for climate change for impacts on at least one each of ecosystems, physical systems, and human systems within this RFC. SR15 Section 3.5.2.1 (Hoegh-Guldberg et al., 2018b), concurred with *high confidence* that the transition to moderate risk had already occurred before the time of writing.

The transitions here are informed by these assessments, along with the assessment in Chapter 2 on species high extinction risk and on ecosystem transitions. It also draws substantially from information in Cross-Chapter Paper 1 and Table SM16.22 on risks to unique and threatened biological systems. Some unique and threatened systems, such as coral reefs and sea-ice dependent ecosystems, were already showing attributable impacts with *high confidence* (see table 16.1, Cross-Chapter Paper 1 and Chapter 2) based on data collected in the mid to latter 20th century, when global warming of 0.5°C above pre-industrial levels had taken place, as noted already in AR3. In this AR6 assessment, the temperature range for the transition from undetectable to moderate risk is still located at a median value of 0.5°C above pre-industrial levels, with *very high confidence.* Since impacts were first detected in coral reef systems in the 1980s when warming of ~0.4°C of global warming had occurred (SR15 Chapter 3), this provides the temperature at which the transition begins. The September Arctic sea ice volume has declined by 55-65% between 1979 and 2010 (AR6 WGI, Schweiger et al., 2019) as global warming increased from around 0.36°C in 1979 to around 0.9°C in 2010. These provide evidence of a start to the transition from undetectable to moderate risk at 0.4°C above pre-industrial levels. Recent evidence of observed impacts on mountaintop ecosystems, sea ice dependent species, and of range shifts in multiple ecosystems during 1990-2000, which AR6 WGI now assesses as corresponding to a global warming of 0.69°C (see WGI AR6 Cross-Chapter Box 2.3, Figure 1, Gulev et al., 2021) provides evidence for an upper limit to this transition of 0.7°C with *very high confidence*. Overall, the transition is located at a median of 0.5°C with lower and upper limits of 0.4 and 0.7°C respectively with *very high confidence.*

AR5 assessed the transition from moderate to high risk to lie around 1°C above 1986–2005 levels (which corresponded at that time to 1.6°C above pre-industrial levels but has been reassessed by AR6 WGI to correspond to 1.7°C) to reflect projected 'increasing risk to unique and threatened systems, including Arctic sea ice and coral reefs, as well as threatened species as temperature increases over this range.' SR15 relocated the transition slightly from 1.6°C to 1.5°C, owing to increased literature projecting the effects of climate change upon Arctic sea ice and new literature assessing projected impacts of climate change on biodiversity at 1.5°C warming.

In this AR6 assessment, the transition from moderate to high is based on the high level of observed impacts, and the areas projected to begin undergoing major transformations by 1.5ºC (see CCP1, Chapter 2 and SR15). A substantial number of unique and threatened systems are assessed to be in a high risk state owing to the influence of anthropogenic climate change by the 2000-2010 period, when global warming had reached approximately 0.85ºC (range 0.7-1ºC) (see WGI AR6 Cross-Chapter Box 2.3, Gulev et al., 2021) using the 1995-2014 figure as a proxy for 2000-2010).

The most prominent example of a system assessed to be already in a high risk state is that of coral reefs, which are already degrading rapidly. Observed impacts on coral reefs increased significantly during 2014-2017 (Table 16.2, corresponding to a global warming of about 0.9ºC). This includes mass bleaching in the Indian Ocean in 1998, 2010, 2015 and 2016 when bleaching intensity exceeded 20% in surveyed locations in the western Indian Ocean, eastern Indian Ocean and western Indonesia. In the tropical Pacific Ocean, climate-driven mass bleaching was reported in all countries in the region, with most bleaching reports coinciding with 2014-2017 marine heatwaves. 50% of coral within shallow-water reefs of the northern and central two-thirds of the Great Barrier Reef were killed in 2015/16. Subsequent coral recruitment in 2018 was reduced to only 11% of the long-term average, representing an unprecedented shift in the ecology of the northern and middle sections of the reef system to a highly degraded state. A second key example are sea ice dependent systems in the Arctic. During August-October of 2010-2019, corresponding to a global warming of about 0.9°C, average Arctic sea-ice area has declined in area by 25% relative to 1979-1988 (*high confidence*, AR6 WGI, Figure 9.13). September Arctic sea ice volume has declined by about 72 % between 1979 and 2016, with the latter deemed a conservative estimate (AR6 WGI, Schweiger et al., 2019).

Other important examples of observed impacts on unique ecosystems that indicate that risks are already at a high level (Table SM16.22) include mass tree mortalities, now well recorded in multiple unique forest and woodland ecosystems around the world. Sections 2.4.3.3 and 2.4.5 report that between 1945 and 2007, drought-induced tree mortality (sometimes associated with insect damage and wildfire) has caused the mortality of up to 20% of trees in western North America, the African Sahel, and North Africa, linked to a warming of 0.3-0.9ºC above pre-industrial levels, and is implicated in more than 100 other cases of drought-induced tree mortality in Africa, Asia, Australia, Europe, and North and South America (*high confidence*). Species in biodiversity hotspots already show changes in response to climate change (CCP1, *high confidence*). Román-Palacios and Wiens (2020) attribute local extinctions of several taxonomic groups between the latter 20th century and 2003-2012, (corresponding to warming of less than 0.85ºC) to climate-change related temperature extremes for up to 44% (0-75%) of species. Widespread declines of up to 35% in the species richness of the unique pollinator group, bumble bees, between 1901 - 1974 and 2000 - 2014 are also attributed to climate change, via increasing exceedance of their thermal tolerance limits across Europe and North America (Soroye et al., 2020). The first extinctions attributed to climate change have been now detected with the present 1.2ºC warming including that of the Bramble Cays Melomys (*Melomys rubicola*), a sub-species of the lemuroid ringtail possum (*Hemibelideus lemuroides*), and golden toad (*Incilius periglenes*) (Chapter 2). An increasing frequency or unprecedented occurrence of mass animal mortality due to climate-change enhanced heat waves have also been observed in recent years on more than one continent, including temperature vulnerable terrestrial birds and mammals in South Africa and Australia (Ratnayake et al., 2019; McKechnie et al., 2021). There have also been 90% declines in sea ice dependent species such as sea lions and penguins in the Antarctic (Table 16.2). A strong effect of climate change on the observed contraction of ranges of polar fish species and strong expansion of ranges of arcto-boreal or boreal fish was observed between 2004 and 2012 Frainer et al. (2017). Even if current human driven habitat loss is excluded, many hotspots are projected to cease to be refugia (i.e., to remain climatically suitable for >75% of the species they contain which have been modelled), at 1.0-1.5ºC (Cross-Chapter Paper 1).

Based on observed and modelled impacts to unique and threatened systems, including in particular coral reefs, sea ice dependent systems, and biodiversity hotspots, AR6 assesses that the transition to high risks for RFC1 have already occurred at a median level of 0.9ºC, with a lower bound at 0.7ºC and an upper bound at the present day level of global warming of 1.2ºC (WMO, 2020) *(very high confidence)*.

Identification of the transition to very high risk is associated by definition with the reaching of limits to natural and/or societal adaptation. Adaptation which occurs naturally is already included in the risk assessment, but experts also discussed the effect of additional human-planned adaptation in reducing risk levels in RFC1. This additional adaptation could help species to survive *in situ* despite a changing climate (for example by reducing current anthropogenic stresses such as over harvesting), or facilitate the ability of species to shift geographic range in response to changes in climate, and the potential benefits of nature-based solutions and restoration (see Cross-Chapter Box NATURAL and Section 2.6.5.1 in Chapter 2).

When considering planned adaptation, the main option often considered in terrestrial ecosystems is the expansion of the protected area network, which is broadly beneficial in increasing the resilience of ecosystems to climate change (e.g., Hannah et al., 2020). However, this action is not effective if the unique and threatened systems in question reach a hard limit to adaptation (as in the case of the loss of Arctic summer sea ice, the submergence of a small island, the contraction and elimination of a species' climatic niche from a mountaintop, or the degradation of a coral reef) (Section 16.4). Furthermore, adaptation benefits deriving from restoration rapidly diminish with increasing temperature (Cross-Chapter Paper 1). One study quantifies how land management (in terms of protecting existing ecosystems or restoring lost ones) might reduce extinctions in biodiversity hotspots or globally significant terrestrial biodiversity areas more generally (Warren et al., 2018b). Whilst the latter suggests that substantial benefits can result globally in terrestrial systems, allowing less unique systems to persist at higher levels of warming but only under a high adaptation scenario in which globally applied terrestrial ecosystem restoration and protected area expansion takes place, this is less likely for many of the unique and threatened terrestrial systems which are more vulnerable than the globally significant biodiversity areas treated in that study (which excludes coral reefs and Arctic sea ice dependent systems). Such high levels of adaptation globally are likely infeasible owing to competition for land use with food production (Pörtner et al., 2021). Novel targeted adaptation interventions for coral reefs such as artificial upwelling and local radiation management show some promise for reducing the adverse effects of thermal stress and resulting coral bleaching Condie et al. (2021), but are far from implementation (Sawall et al., 2020; Kleypas et al., 2021). Larger benefits in this RFC could theoretically accrue only if adaptation action became ubiquitous and extensive, which experts considered infeasible at the scales required. Small island communities are confronted by socio-ecological limits to adaptation well before 2100, especially those reliant on coral reef systems for their livelihoods, even for a low emissions pathway (Chapter 3) (*high confidence*). At warming levels beyond 1.5°C, the potential to reach biophysical limits to adaptation due to limited water resources are reported for Small Islands (*medium confidence*) and unique systems dependent on glaciers and snowmelt (Chapter 4) (*medium confidence*).

AR5 assessed with *high confidence* that the transition from high to very high risks for RFC1 to lie around 2°C above 1986–2005 levels (then considered to correspond to 2.6°C above pre-industrial levels) to reflect the very high risk to species and ecosystems projected to occur beyond that level as well as limited ability to adapt to impacts on coral reef systems and in Arctic sea ice-dependent systems. Using the additional literature which became available on projected risks to Arctic sea ice, biodiversity and ecosystems at 1.5°C vs 2°C warming above pre-industrial levels, SR15 assessed that the transition from high to very high risks in RFC1 lay between 1.5°C and 2°C above pre-industrial levels.

In AR6, risks are considered to start to transition from high to very high risks above 1.2°C warming (present day, WMO, 2020), with a median value of 1.5°C, owing in particular to the observation of a present day onset of ecosystem degradation in coral reefs, which are projected in the SR15 report 'to decline by a further 70–90% at 1.5ºC (*very high confidence*)' . The literature for projected increases in risk to other unique and threatened systems and their limited ability to adapt above 2ºC warming is substantial and robust and the confidence level in very high risk remains high. At 2ºC, 18% of 34,000 insects are projected to lose >50% climatically determined geographic range, as compared with 6% at 1.5ºC (Warren et al., 2018a). The risk of species extinction increases with warming in all climate change projections, for all native species studied in biodiversity hotspots (Cross-Chapter Paper 1, *high confidence*), being roughly threefold greater for endemic than more widespread species for global warming of 3°C above pre industrial levels than 1.5°C) (Manes et al., 2021, Cross-Chapter Paper 1) (*medium confidence*). The Arctic is projected to be practically ice free in September in some years for global warming of between 1.5 and 2ºC (WGI AR6 Section 9.3.1.1, Fox-Kemper et al., 2021), undermining the persistence of ice dependent species such as polar bears, ringed seals and walrus (Meredith et al., 2019), and adversely affecting indigenous communities. Warming of 1.5ºC is also assessed (Chapter 3) to reduce the habitability of small islands, due to the combined impacts of several key risks *(high confidence)*. Hence the transition from high to very high risk in these systems is assessed to occur with *high confidence* beginning at 1.2ºC, passing through a median value of 1.5°C, and completing (i.e. reaching its upper bound) at 2ºC warming.

16.6.3.2 Extreme Weather Events (RFC2)

This RFC addresses the risks to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding (Hoegh-Guldberg et al., 2018b). Previous assessments of this RFC have focused mainly on changes to the hazard component of the risk, using the projected increase in hazard as an indicator of higher risk. However, in AR6 an expanding (although still smaller) body of evidence now allows also incorporation of the exposure and/or vulnerability components of risk and, to a limited extent, their trends.

AR5 identified a transition from undetectable to moderate risk below 'recent' temperatures (i.e., during 1986-2005, which then corresponded to a global warming of 0.6ºC above pre-industrial levels). SR15 Section 3.5.2.2 (Hoegh-Guldberg et al., 2018b), concluded that differences of 0.5ºC in global warming led to detectable changes in extreme weather and climate events on the global scale and for large regions. IPCC WGI AR6 Chapter 11 confirms this assessment and concludes that 'new evidence strengthens the conclusion from SR15 that even relatively small incremental increases in global warming (+0.5°C) cause statistically significant changes in extremes on the global scale and for large regions'. Substantial literature is available for comparisons at +1.5ºC vs +2ºC of global warming, but the conclusions are assessed to also apply at lower global warming levels and smaller increments of global warming given the identified linearity of regional responses of several extremes in relation to global warming(Seneviratne et al., 2016; Wartenburger et al., 2017; Tebaldi and Knutti, 2018) and the identification of emergence of global signals in climate extremes for global warming levels as small as 0.1°C (Seneviratne and Hauser, 2020, WGI AR6, Chapter 11, Figure 11.8; WGI Cross-Chapter Box 12.1). Further analyses are consistent with this assessment, based on model simulations (Fischer and Knutti, 2015; Schleussner et al., 2017; Kirchmeier-Young et al., 2019a; Seneviratne and Hauser, 2020) and observational evidence (Zwiers et al., 2011; Dunn et al., 2020). A global warming of +0.5ºC above pre-industrial conditions corresponds approximately to climate conditions in the 1980s (Chapter 2, Figure 2.11), a time frame at which detectable changes in some extremes were established at the global scale based on observations (Dunn et al., 2020). Heat-related mortality has also been assessed to have increased considerably because of climate change (Ebi et al., 2021; Vicedo-Cabrera et al., 2021). The onset, and also median location of the transitions of risk (Figure 16.15) from undetectable to moderate, is therefore considered to be 0.5ºC. Further strong new evidence shows that changes in extremes emerged during the 1990s and 2000s (Dunn et al., 2020) by which time +0.7ºC of global warming had taken place (IPCC SR15, Chapter 1; WGI AR6, Chapter 2). In AR5 Section 19.6.3.3 (Oppenheimer et al., 2014), a transition to moderate risk was assessed to have taken place at the then 'recent' global warming level of 0.6ºC, with high confidence. Owing to the increase in evidence, there is now *very high confidence* that the median value of the transition from undetectable to moderate risk is at 0.5ºC and led by heat extremes, with the lower estimate set at 0.5°C as well, and upper estimate at 0.7°C.

Further evidence of more recent observed changes in extreme weather and climate events, and their potential for associated adverse consequences across many aspects of society and ecosystems, has continued to accrue (WGI AR6 Chapter 11; WGI AR6 Chapter 12). Since a necessary condition for 'moderate' levels of risk is the detection and attribution of observed impacts, the following text provides an overview of some salient examples of this evidence. In particular, WGI AR6 Chapter 11 (Seneviratne et al., 2021) concludes that some recent hot extreme events that happened in the past decade (2010s) would have been *extremely unlikely* to occur without human influence on the climate system. Global warming in that decade reached approximately 1.09°C on average (IPCC WGI AR6 Chapter 2).

Assessment of a high level of risk requires a higher level of magnitude, severity and spatial extent of the risks. Events prior to that already had substantial impacts such as the 2003 European heatwave (IPCC SREX Chapter 9). Examples of impactful events in the early 2010s (at ca. 0.95°C of global warming, (WGI AR6 Chapter 2, Gulev et al., 2021) include the 2010 Russian heatwave (Barriopedro et al., 2011) and the 2010 Amazon drought (Lewis et al., 2011). Later impactful events include, among others, the 2013 heatwave in eastern China (Sun et al., 2014), the 2017 tropical cyclone Harvey (Risser and Wehner, 2017; Van Oldenborgh et al., 2017), and the 2018 concurrent north hemisphere heatwaves in Europe, North America and Asia (Vogel et al., 2019). Very recent events with severe and unprecedented impacts attributed to anthropogenic climate change indicate that thresholds to high risks may already have been crossed at recent levels of global warming (ca. 1.1°C-1.2°C) including the Siberian fires and the 2019 Australian bushfires that were linked to extreme heat and drought conditions (Van Oldenborgh et al., 2017) and extreme precipitation linked to increased storm activity in the US (Van Oldenborgh et al., 2017). Severe and unprecedented impacts occurred with current low levels of adaptation (16.2.3.4). The global-scale risk of wildfire considerably degrading ecosystems and increasing illnesses and death of people has been assessed to transition from undetectable to moderate over the range 0.6 to 0.9°C with *high confidence* (Chapter 2, Table 2.S.4, Figure 2.11).

In addition, long-term trends in various types of extremes are now detectable (WGI AR6 Chapter 11, Seneviratne et al., 2021). This includes increases in hot extremes over most land regions (*virtually certain*), increases in heavy precipitation at the global scale and over most regions with sufficient observations (*high confidence*), and increases in agricultural and ecological droughts in some regions (*medium confidence*) (WGI AR6 Chapter 11). There has also been overall a *likely* increase in the probability of compound events, such as an increase in concurrent heatwaves and droughts (*high confidence*) (WGI AR6 Chapter 11). There is *medium confidence* that weather conditions that promote wildfires (fire weather) have become more probable in southern Europe, northern Eurasia, the US, and Australia over the last century (WGI AR6 Chapter 11; SRCCL Chapter 2, Jolly et al., 2015; Abatzoglou and Williams, 2016). Furthermore, food security and livelihoods are being affected by short-term food shortages caused by climate extremes (5.12.1; Chapter 16, Food Security RKR) which have affected the productivity of all agricultural and fishery sectors (*high confidence*). The frequency of sudden food production losses has increased since at least mid-20th century on land and sea *(medium evidence, high agreement)*. Droughts, floods, and marine heatwaves contribute to reduced food availability and increased food prices, threatening food security, nutrition, and livelihoods of millions *(high confidence)*. Changes in sea surface temperatures drive simultaneous variation in climate extremes increasing the risk of multi-breadbasket failures (Cai et al., 2014; Perry et al., 2017). Droughts induced by the 2015-2016 El Niño, partially attributable to human influences (*medium confidence*), caused acute food insecurity in various regions, including eastern and southern Africa and the dry corridor of Central America (*high confidence*). Human-induced climate change warming also worsened the 2007 drought in southern Africa, causing food shortages, price spikes, and acute food insecurity in Lesotho (Verschuur et al., 2021). In the fisheries and aquaculture sector, marine heat waves are estimated to have doubled in frequency between 1982 and 2016, as well as increasing in intensity and length, with consequences for fish mortality (Ch 5) (Smale et al., 2019; Laufkötter et al., 2020). In the northeast Pacific, a recent 5-year warm period impacted the migration, distribution, and abundance of key fish resources (*high confidence*). At 1ºC warming the number of people affected by six categories of extreme events was found to have already increased by a factor of 2.3 relative to preindustrial (Lange et al., 2020).

The general picture is one of annual or more frequent occurrences of severe extremes with widespread impacts (as also reflected in section 16.2), and of multiple extremes, meeting the criteria for the 'severe and widespread' nature of risks that is required for classification at a 'high' level of risk. This is consistent with AR5 Chapter 19 (Oppenheimer et al., 2014), and gives *high confidence* that the lower threshold for entering high risks associated with extreme weather events is +1ºC, and that the best estimate is that this transition already occurred now that global warming has reached its present-day level of ca. 1.2ºC (WMO, 2020), slightly above the 1.09°C average conditions in the 2010s, i.e. 2011-2020 (IPCC WGI AR6 Chapter 2, Gulev et al., 2021).

A range of literature projects further substantial increases in several extreme event types with a global warming of +1.5ºC, notably hot extremes in most regions, heavy precipitation in several regions, and drought in some regions (IPCC SR15; WGI AR6 , Chapter 11). In particular, heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia (*high confidence*), North America (*medium* to *high confidence* depending on the region), and Europe (*medium confidence*). Also, more frequent and/or severe agricultural and ecological droughts are projected in a few regions in all continents except Asia, compared to 1850–1900 (*medium confidence*); increases in meteorological droughts are also projected in a few regions (*medium confidence*). Increases at 1.5°C of global warming are projected in marine heatwaves (Laufkötter et al., 2020) and the occurrence of fire weather (IPCC, 2019a). Heat-related mortality is assessed to increase from moderate to high levels of risk under about 1.5ºC warming under SSP3, a socioeconomic scenario with large challenges to adaptation (Ebi et al., 2021) especially in urban centres (Chapter 6). An additional 350 million people living in urban areas are estimated would be exposed to water scarcity from severe droughts at 1.5°C warming (Section 6.1; Section 6.2.2; CCP2 Coastal Cities). In summary, there is *high confidence* that the best estimate for the transition from moderate to high risk is 1.2°C of global warming, with 1°C as lower estimate and 1.5°C as upper estimate. The latter would be set to 1.3°C for an assessment at *medium confidence*.

As in RFC1, one of the criteria for identification of very high risks is limits to adaptation. Though the literature explicitly considering societal adaptation to extreme weather events is limited, there is evidence that investments in hydro-meteorological information, early warning systems and anticipatory forecast-based finance are a cost-effective way to prevent some of the most adverse effects of extreme events (Coughlan de Perez et al., 2016; Fakhruddin and Schick, 2019; Merz et al., 2020). Despite a lack of systematic methods for assessing general adaptation effectiveness, there is some evidence of risk reduction for particular places and hazards, especially flood and heat vulnerability (16.3.2.4) including investment in flood protection, building design and monitoring and forecasting, air conditioning, reduced social vulnerability, and improved population health. One study finds declining global mortality and economic loss due to extreme weather events over the past four decades Formetta and Feyen (2019) especially in low income countries. Using SSP2 as a proxy for expanded adaptation, Ebi et al. (2021) assesses that the transition to high risk for heat-related mortality increases to 1.8ºC (compared to 1.5ºC with less adaptation under SSP3). There is evidence of adaptation avoiding heat-related mortality at low levels of global warming, using early warning and response systems and sustainable alterations of the thermal environment at the individual, building, urban, and landscape levels (Jay et al., 2021). Despite the evidence that adaptation can reduce risks of heat stress, the impact of projected climate change on temperature-related mortality is expected to be a net increase under a wide range of climate change scenarios, even with adaptation (Ch 7, *high confidence).* Much of the adaptation literature focuses on coping with long-term gradual climate change and largely does not take into account the increased difficulty of adapting to climate extremes and general higher variability in climate that is projected to occur in the future. However, expanding and more coordinated adaptation, including wider implementation and multi-level coordination, has the potential to reduce the risks to crops from heatwaves at intermediate (but not high) levels of warming.(IPCC AR5 Ch7, Ahmed et al., 2018; Ahmed et al., 2019, Section 16.3.2.2; EEA, 2019; Raza et al., 2019; Tripathi and Sindhi, 2020).

The transition from high to very high risk for the RFC2 was not assessed in the AR5 or in SR15. Some new evidence suggests, however, that very high risks associated with weather and climate extremes would be reached at higher levels of global warming. In particular, changes in several hazards would be more widespread and pronounced at 2°C compared to 1.5°C global warming, including increases in multiple and concurrent extremes (IPCC WGI AR6 SPM; IPCC WGI AR6 Chapter 11, IPCC WGI AR6 Chapter 12). On average over land, high temperature events that would have occurred once in 50 years in the absence of anthropogenic climate change are projected to become 13.9 times more likely with 2ºC warming, and 39.2 times more likely with 4ºC warming (IPCC AR6 WGI SPM Figure 6, IPCC, 2021b) indicating a non-linear increase with warming. Ch 2 has assessed that risk of wildfire transitions from moderate to high over the range 1.5ºC to 2.5ºC warming (*medium confidence,* Table 2.S.4, Figure 2.11). The intensity of heavy precipitation events increase overall by about 7% for each additional degree of global warming (IPCC AR6 WGI SPM), while their frequency increases non-linearly. Events that would have occurred once every 10 years in a climate without human influence are projected to become 1.7 times more likely with 2ºC warming, and 2.7 times more likely with 4ºC warming (IPCC AR6 WGI SPM Figure 6). Several AR6 regions are projected to be affected by increases in agricultural and ecological droughts at 2°C of global warming, including W. North-America, C. North-America, N. Central-America, S. Central-America, Caribbean, N. South-America, N.E. South-America, South-American-Monsoon, S.W. South-America, S. South-America, West & Central-Europe, Mediterranean, W. Southern-Africa, E. Southern-Africa, Madagascar, E. Australia, and S. Australia (IPCC WGI AR6, Chapter 11, Seneviratne et al., 2021). This is a substantially larger number compared to projections at 1.5°C (IPCC WGI AR6, Chapter 11, Seneviratne et al., 2021). In these drying regions, events that would have occurred once every 10 years in a climate without human influence are projected to happen 2.4 times more frequently at 2°C of global warming (IPCC WGI AR6 SPM Figure 6). Urban land exposed to floods and droughts is very likely to have more than doubled between 2000 and 2030, and the risk of flooding accelerates after 2050 (Ch 4). At 2ºC of global warming, there are also significant projected increases in fluvial flood frequency and resultant risks associated with higher populations exposed to these flood risks (Alfieri et al., 2017; Dottori et al., 2018) projected.

Heat-related mortality is assessed to increase from high to very high by 3°C under SSP3, a socioeconomic scenario with large challenges to adaptation (Ebi et al., 2021). SRCCL assessed that very high risks would be reached in association with wildfire above 3ºC of global warming (IPCC, 2019a). Chapter 2 has assessed that risk of fire weather itself transitions from high to very high over the range 3ºC to 4.5ºC warming (*medium confidence,* Table 2.S.4, Figure 2.11). Matthews et al. (2017) show that at 1.5ºC of global warming, about 40% of all megacities would be affected at least 1 day per year with a heat index above 40.6ºC (i.e., with 40.6ºC 'feels-like' temperatures, accounting for moisture effects). This number would reach about 65% of megacities at 2.7ºC and close to 80% at 4ºC. In addition, there is evidence for a higher risk of concurrent heat extremes at different locations with increasing global warming (Vogel et al., 2019), meaning that several cities could be affected by deadly heatwaves simultaneously. Laufkötter et al. (2020) found that marine heatwave events would become annual to decadal events under 3ºC of global warming, with consequences for aquaculture (Chapter 5). Gaupp et al. (2019) conclude that risks of simultaneous crop failure across worldwide breadbasket regions, due to changes in maximum temperatures in the crop-growth relevant season or cumulative precipitation in relevant time frames, increase disproportionately between 1.5ºC and 2ºC of global warming. Populations exposed to extreme weather and climate events may consume inadequate or insufficient food, leading to malnutrition and increasing the risk of disease (Ch 5, *high confidence*). Hence, there is the potential for very high risks associated with changes in climate extremes for food security in the low adaptation case, already above 2ºC of global warming. Finally, studies suggest that regional thresholds for climate extremes could be reached at 2ºC of global warming, for instance in the

Mediterranean (Guiot and Cramer, 2016). Samaniego et al. (2018) conclude that soil moisture droughts in that region would become 2–3 times longer than at the end of the 20th century at 2ºC, and 3–4 times longer (125 days long per year) at 3ºC of global warming. There is clear evidence of very high risk at 3ºC global warming for wildfires, marine heatwaves, and heatwaves in megacities (the latter being set at 2.7ºC).

Based on the available evidence, we assess that there is *medium confidence* that the transition to very high risk would happen at a median value 2ºC of global warming, considering the increased risk for breadbasket failure and irreversible impacts associated with changes in extremes at this warming level (e.g. damages to ecosystems, health impacts, severe coastal storms), but that due to the disproportionate increases in risk between 1.5 and 2ºC this transition begins already at 1.8ºC. The higher range for this transition is set with *medium confidence* at 2.5ºC in this low/no adaptation scenario, owing to the further projected non-linear increases in risks associated with high temperature events above 2ºC (WGI AR6 Figure SPM.6,, IPCC, 2021b; Cross-Chapter Box12.1, Ranasinghe et al., 2021), and also the limits to adaptation associated with dealing with a rapid escalation of extreme weather events globally during this century; extreme events are particularly difficult to adapt to and thus more often exceed hard limits to adaptation, particularly in natural ecosystem settings (Section 16.4).

16.6.3.3 Distribution of Impacts (RFC3)

RFC3 reflects how key risks are distributed unevenly across regions and different population groups, due to the non-uniform spatial distributions of physical climate change hazards, exposure, and vulnerability across regions. It addresses how risks disproportionately affect particularly vulnerable societies and socio-ecological systems, including disadvantaged people and communities in countries at all levels of development. AR5 concluded that low-latitude and less developed areas generally face greater risk than higher latitude and more developed countries, including for food- and health-related risks. This conclusion remains valid and is now supported by greater evidence across a range of sectors and geographic regions.

Note that the assessment here is largely based on the national and regional distribution of impacts, rather than sub-national distribution or explicit consideration of vulnerable elements of society. Climate risks are also strongly related to inequalities, often but not always intersecting with poverty (16.1), geographic location, political and socio-cultural aspects. Thus, countries with high inequality tend to be more vulnerable, and more exposed, to climate hazards (16.1). Whilst the literature assessed here tends to be insufficiently granular to resolve local inequalities, it does confirm the AR5 finding that low-latitude and less developed areas generally face greater risk.

AR6 continues to highlight the uneven regional distribution of projected climate change risks. Biodiversity loss is projected to affect a greater number of regions with increasing warming, and to be highest in northern South America, southern Africa, most of Australia, and northern high latitudes (Section 2.5.1.3, *medium confidence)*. Climate change is projected to increase the number of people at risk of hunger in mid-century, concentrated in Sub-Saharan Africa, South Asia and Central America (Chapter 5, *high confidence*), increasing undernutrition, stunting, and related childhood mortality particularly in Africa and Asia and disproportionately affecting children and pregnant women (Chapter 7, *high confidence*) strongly mediated by socio-economic factors (Section 7.2.4.4, 7.3.1, *very high confidence*). Strong geographical differences in heat-related mortality are projected to emerge later this century, mainly driven by growth in regions with tropical and subtropical climates (Section 7.3.1, *very high confidence*)

In AR5 and SR15, the transition from undetectable to moderate risk was located below what were at the time 'recent' temperatures of between 0.5 to 0.8°C above pre-industrial levels, with medium to high confidence, based on evidence of distributional impacts on crop production and water resources. New literature has continued to confirm this transition has already taken place including more recent observed impacts for regions and groups within the food and water sectors, strongly linked to Representative Key Risks for Health, Water and Food Security (Section 16.2; 16.5; 5.4.1, 5.5.1, 5.8.1 and 5.12; Chapter 7).
In AR6, moderate risks have already been assessed to have occurred in Africa for economic growth and reduced inequality, biodiversity and ecosystems, mortality and morbidity due to heat extremes and infectious disease, and food production in fisheries and crop production (Figure 9.6). In Europe moderate risks to heat stress, mortality and morbidity have already been reached, as well as for water scarcity in some regions (Figure 13.30, Figure 13.33). In Australasia, moderate risks are assessed as present already for heat related

mortality risk as well as cascading effects on cities and settlements; and also very high risks already present in coral reef systems, and high risks to kelp forests and alpine biodiversity (Figure 11.7). In North America, moderate risks have already been reached for freshwater scarcity, water quality (Figure 14.4), agriculture, forestry, tourism, transport, energy & mining and construction (Figure 14.10).

For this assessment, the transition to moderate risk was assessed to have occurred between 0.7°C and 1.0°C of warming with *high confidence*, demonstrating that a moderate level of risk exists at present. The 0.2°C increase in this temperature range as compared with AR5 reflects the fact that AR6 WGI has assessed that the level of global warming reached by 1986-2005 was 0.52-0.82°C (as opposed to 0.55-0.67°C in previous assessments), and also reflects the opportunity for observations to be have made of the observed consequences of the additional rise in temperature that has taken place since the literature underpinning the AR5 assessment was published.

In AR5, the transition from moderate to high risk was assessed to occur between 1.6°C and 2.6°C above the pre-industrial levels with medium confidence. In SR15, new literature on projected risks allowed this range to be narrowed to 1.5–2°C. There is now substantial literature providing robust evidence of larger regional risks at 2°C warming than 1.5°C and in a range of systems, including crop production (with risks of simultaneous crop failure) (Thiault et al.; Gaupp et al., 2019), aquaculture and fisheries (Cheung et al., 2018b; Froehlich et al., 2018; Stewart-Sinclair et al., 2020), nutrition-related health (Springmann et al., 2016; Lloyd et al., 2018; Sulser et al., 2021), and exposure to stressors such as drought, floods (Alfieri et al., 2017; Hirabayashi et al., 2021) and extreme heat (Dosio et al., 2018; Harrington et al., 2018; Sun et al., 2019). One study (Gaupp et al., 2019) found that the risk of simultaneous crop failure in maize is estimated to increase from 6% to 40% at 1.5 °C relative to the historical baseline climate. In particular, further research on projected regional yield declines of wheat and maize between 1.5ºC and 2ºC, especially in Africa, has accrued Asseng et al. (2015), including in Ethiopia (Abera et al., 2018) with associated economic effects (Wang et al., 2019). Optimum maize production areas in E Asia are projected to reduce in area by 38% for global warming of 1.5–2.0°C (He et al., 2019). A study of Jamaica also estimated that warming of less than 1.5°C will have an overall negative impact on crop suitability and a general reduction in the range of crops, but above 1.5°C, irreversible changes to Jamaica's agriculture sector were projected (Rhiney et al., 2018).

Projections of increasing flood risk associated with global warming of 1.5 and 2°C continue to highlight regional disparities, with larger than average increases projected in Asia and Africa (Hirabayashi et al., 2021), including in China, India and Bangladesh (Alfieri et al., 2017). Similarly, nearly 80% of the 8-80 million additional people projected to be at risk of hunger owing to climate change are located in Africa and Asia (Springmann et al., 2016; Lloyd and Oreskes, 2018; Nelson et al., 2018). Schleussner et al. (2016b) analysed hotspots of multi-sectoral risks with 1.5°C and especially 2°C warming, highlighted projected crop yield reductions in West Africa, South-East Asia, as well as Central and northern South America; a reduction in water availability in the Mediterranean; and widespread bleaching of tropical coral reefs.

High risks to crop production are assessed to occur in Africa ~1.5-2ºC warming (Figure 9.6), to agriculture in North America for ~1.5ºC warming (Figure 14.10), and ~ 2.8ºC Europe (Figure 13.30). High risks of mortality and morbidity due to heat extremes and infectious disease are assessed to be reached in Africa with ~1.5ºC warming (Figure 9.6); heat stress, mortality and morbidity in Europe is assessed to reach a high level of risk at ~2ºC (Figure 13.30). Heat related mortality risk transitions to a high level by ~1.5-2ºC warming in Australasia while cascading effects on cities reach high risk with ~1.2ºC warming (Figure 11.7). Risks to water scarcity, forestry, tourism and transportation in N America are projected to reach high levels with ~2ºC warming (Figure 14.4, Figure 14.10).

Two complementary multi-sectoral analyses indicates that South Asia and Africa become hotspots of multi-sectoral climate change risk, largely due to changes in water related indicators which also affect crop production (Arnell et al., 2018; Byers et al., 2018). For instance, Byers et al. (2018) found that the doubling in global exposure to multi-sector risks that accrues as warming increases from 1.5 to 2°C is concentrated in Asian and African regions (especially East Africa), which together account for 85-95% of the global exposure.
Considering this evidence, for this assessment, the temperature range for the transition from moderate to high risk is located between 1.5°C to 2°C above pre-industrial levels, with *high confidence* in the lower

bound of 1.5°C, but *medium confidence* in the upper bound of 2°C, because simulation studies do not account for climate variability and therefore risks could be higher.

Very high risk implies limited ability to adapt. Adaptation potential not only differs across sectors and regions, but also occurs on different timescales depending on the nature and implementation level of the adaptation option under consideration and the system in which it is to be deployed. The costs of adaptation actions that would be needed to offset projected climate change impacts for major crop production are projected to rise once global warming reaches 1.5 °C (Iizumi et al., 2020). It has been estimated that the number of additional people at risk of hunger with 2.0 °C global warming could be reduced from 40 million to 30 million by raising the level of adaptation action (Baldos and Hertel, 2014) but beyond this level of warming residual impacts are projected to escalate (Iizumi et al., 2020). Chapter 5 assessed the potential of existing farm management practices to reduce yield losses, finding an average 8% loss reduction in mid-century and 11% by end-century (Section 5.4.4.1), which is insufficient to offset the negative impacts from climate change, particularly in currently warmer regions (5.4.3.2). The literature indicates that globally, crop production may be sustained below 2.0 °C warming with adaptation, but negative impacts will prevail at 2.0 °C warming and above in currently warm regions (Section 5.4.4.1). Importantly, residual damage (that which cannot be avoided despite adaptation) is projected to rise around 2.0 °C global warming (Iizumi et al., 2020). Evidence of constraints and limits for food, fiber and other ecosystem products for the different regions is evident for the various regions (16.4.3.1) indicating limited ability to adapt. Adaptation costs are also higher relative to GDP in low-income countries, for example for the building of sea-dikes (Brown et al., 2021).

In previous reports, the transition from high to very high risk for the distribution of impacts was not assessed due to limited available literature, but there is now sufficient evidence to do so. A range of literature quantifies the increasing regional probability of drought as compared to the present day, with projected increases in the area exposed to drought (Carrão et al., 2018; Pokhrel et al., 2021), as well as the duration (Naumann et al., 2018) and frequency of droughts with higher warming levels. Naumann et al. (2018) showed that, for drying areas, drought durations are projected to rise from 2 months/°C below 1.5 °C to 4.2 months/°C near 3°C warming. Most of Africa, Australia, southern Europe, southern and central United States, Central America, the Caribbean, north-west China, and parts of Southern America are projected to experience more frequent droughts. Adverse effects of climate change on food production are projected to become much more severe (Section 5.4.3.2) when global temperatures rise more than 2ºC globally but there are predicted to be much more negative impacts experienced sooner on food security in low- to mid-latitudes (Richardson et al., 2018a) (Sections 5.4.1). For instance, climate change by 2050 is projected to increase the number of people at risk of hunger by between 8 and 80 million with 2–3°C warming compared to no climate change conditions (Baldos and Hertel, 2014; Hasegawa et al., 2018; Nelson et al., 2018; Janssens et al., 2020). In addition to effects upon crop yield, agricultural labour productivity, and food access, and food-related health are projected to be negatively impacted by 2–3°C warming (Springmann et al., 2016; de Lima et al., 2021). Regionally, substantial regional disparity in risks to food production is projected to persist at these higher levels of warming. Risks for heat-related morbidity and mortality, ozone-related mortality, malaria, dengue, Lyme disease, and West Nile fever are projected to increase regionally and globally (Chapter 7) with potential infestation areas for disease-carrying vectors in multiple geographic regions that could be five times higher at 4ºC than at 2ºC (Liu-Helmersson et al., 2019).

Very high risks to crop production are assessed to occur in Africa above ~2.5ºC warming (Figure 9.6) and below 4ºC in Europe (Figure 13.30). Very high risks of mortality and morbidity due to heat extremes and infectious disease are assessed to occur in Africa with 2.5ºC warming (Figure 9.6); heat stress, mortality and morbidity in Europe is assessed to reach a very high level of risk at ~3.2ºC (Figure 13.30). Heat related mortality risk and cascading effects on cities both transitions to a very high level by ~2.5C warming in Australasia (Figure 11.7). Risks to water scarcity in N America are projected to reach very high levels with 3.5C warming (Figure 14.4). Hence this assessment concludes with *medium confidence* that a transition from high to very high risks, in terms of distribution of impacts, begins at 2ºC global warming, with a full transition to very high risks completed by 3.5ºC. However, it should be noted that many studies upon which this assessment has been based have not taken into account the impacts of extreme weather events and oscillations in sea surface temperatures hence risks at a given level of global warming might be underestimated in the literature.

16.6.3.4 Global Aggregate Impacts (RFC4)

This RFC considers impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale (Oppenheimer et al., 2014; O'Neill et al., 2017). RFC4 shares underlying key risk components with other RFCs (e.g., RFC1 and RFC2, see O'Neill et al., 2017) and thus draws on a similar literature as those assessments; however, this RFC focuses on impacts that reach levels of concern at the global level and also weighs the composite effect of risk elements ranging from economic to biodiversity.

In AR5 Section 19.6.3.5 (Oppenheimer et al., 2014), the transition from undetectable to moderate risk was assessed between 1.6 and 2.6ºC above pre-industrial levels (i.e., 1ºC and 2ºC above the 1986-2005 level) based on impacts to both Earth's biodiversity and the overall global economy with *medium confidence*. The risk transition between moderate and high risk was set around 3.6ºC above pre-industrial levels (i.e., 3ºC above the 1986-2005 level), based on literature finding extensive species vulnerability and biodiversity damage with associated loss of ecosystem goods and services at 3.5ºC (Foden et al., 2013; Warren et al., 2013). In SR15 Section 3.5.2.4 (Hoegh-Guldberg et al., 2018b), economic literature on potential socio-economic threshold events as well as empirical studies of global economic damages, combined with new evidence on biome shifts, extinction risk, species range loss (especially noting the integral role of insects in ecosystem function), and ecosystem degradation, were assessed and the upper bound of the transition to moderate risk was lowered to 1.5ºC warming above pre-industrial levels, and the transition from moderate and high risk was lowered to between 1.5ºC and 2.5ºC (*medium confidence*). The boundary between high risk and very high risk was not assessed in either of these reports because the temperature threshold was beyond the scope of the assessment in the case of SR15 and due to the limited literature available for this highest transition in AR5.

Since AR5, many new global estimates of the aggregate, economy-wide risks of climate change have been produced, though, as was the case in AR5, these continue to exhibit a low level of agreement, including for today's level of global warming, due primarily to differences in methods. Cross-Working Group Box ECONOMIC in this chapter includes a more thorough discussion of advancements and limitations of global economic impact estimates and methodologies, finding significant variation in estimates that increases with warming, indicating higher risk in terms of economic costs at higher temperatures (*high confidence*). Climate change has been found to exacerbate poverty through declines in agricultural productivity, changes in agricultural prices and extreme weather events (Hertel and Lobell, 2014; Hallegatte and Rozenberg, 2017). In terms of biodiversity risks, the literature indicates that losses in terrestrial and marine ecosystems increase substantially between 1.5ºC and 2ºC of warming (Hoegh-Guldberg et al., 2018b). Since SR15, further evidence of degradation of biodiversity and ecosystem services and ocean acidification at the global aggregate level has continued to accrue due to climate change (see Chapter 2).

For this RFC, the transition from undetectable to moderate risk to global aggregate impacts is assessed with *medium confidence* to occur between 1.0ºC (start of transition) and 1.5ºC (completion of transition) with a median judgment of transition at 1.3ºC, based on evidence of a combination of economic consequences, widespread impacts to climate-sensitive livelihoods, changes in biomes and loss of terrestrial and marine biodiversity. The start of the transition from undetectable to moderate risk is located at recent temperatures based on observed impacts to biodiversity (16.2.3.1). Experts noted aggregate impacts on biodiversity are detectable, with damages that have had global significance (e.g., drought, pine bark beetles, coral reef ecosystems). Consistent with the start of this transition at 1ºC, a similar elicitation conducted in Chapter 2 assessed that risks to biodiversity globally have already transitioned to a moderate level with 1ºC warming; whilst risks of widespread tree mortality are already moderate with 0.9ºC warming and finds that moderate risks of ecosystem structure change began with warming of 0.5ºC (Table 2.S.4, Figure 2.11). Human-induced warming has slowed growth of agricultural productivity over the past 50 years in mid- and low-latitudes (Chapter 5; Hurlbert et al., 2019). Although there is not yet strong evidence of attributable loss of life and livelihoods at the global level (16.5.2.3.4, 16.5.2.3.5), experts found that regional evidence of such observed impacts were still relevant to defining the beginning of the transition (e.g., Table SM16.22, Chapter 9). Informing the median value and upper bound of the transition to moderate risk, empirical studies and scenario analyses have found that regions with high dependence on climate-sensitive livelihoods like agriculture, fisheries and forestry would be severely impacted even at low levels of warming under conditions of low adaptation (RKR-D, Lobell et al., 2011; Hoegh-Guldberg et al., 2018b).

The transition to high risk is assessed with *medium confidence* to occur between 1.5ºC (start of transition) and 2.5ºC (completion of transition) with a median judgment of transition at 2.0ºC. Though economic estimates exhibit wide variation and low agreement at warming levels above 1.5ºC, many estimates are nonlinear with marginal economic impacts increasing with temperature (see Cross-Working Group Box ECONOMIC in this Chapter). At 1.5ºC warming, most aggregate global impacts to Gross Domestic Product are negative across different estimation methods, including bottom-up estimation (e.g., Takakura et al., 2019), meta-analysis (e.g., Howard and Sterner, 2017) and empirical estimations (e.g., Pretis et al., 2018; Kalkuhl and Wenz, 2020). At 2°C Watts et al. (2021) estimate a relative decrease in effective labour by 10%, which would have profound economic consequences. Byers et al. (2018) found that global exposure to multi-sector risks approximately doubles between 1.5°C and 2°C, whilst the percentage of the global population exposed to flooding is projected to rise by 24% with 1.5°C warming and by 30% with 2.0°C warning (Hirabayashi et al., 2021).

Section 16.5.2.3.4 (RKR-D, underlying key risk on poverty) reports that under medium warming pathways, climate change risks to poverty would become severe if vulnerability is high and adaptation is low (limited evidence, high agreement). At and beyond 1.5ºC, approximately 200 million people with livelihoods derived from small-scale fisheries would face severe risk, given sensitivity to ocean warming, acidification, and coral reef loss (Cheung et al., 2018a; Froehlich et al., 2018; Free et al., 2019). Warming between 1.5 and 2ºC could expose 330–396 million people to lower agricultural yields and associated livelihood impacts (Byers et al., 2018; Hoegh-Guldberg et al., 2018a), due to a high dependency of climate-sensitive livelihoods to agriculture globally (World Bank, 2020). Models project that climate change will increase the number of people at risk of hunger in 2050 by 8-80 million people globally, with the range depending on the level of warming (1.5–2.9ºC) and SSPs (Nelson et al., 2018; Mbow et al., 2019; Janssens et al., 2020). Higher atmospheric concentrations of carbon dioxide reduce the nutritional quality of wheat, rice, and other major crops, potentially affecting millions of people at a doubling of carbon dioxide relative to pre-industrial (*very high confidence*) (Section 7.3.1). Global ocean animal biomass is projected to decrease on average by 5% per 1°C increase, hence a 2.5C level of warming is associated with ~13% decline in ocean animal biomass, which would considerably reduce marine food provisioning, fisheries distribution and revenue value, with further consequences for ecosystem functioning (Chapter 5, *medium confidence*).

Losses in terrestrial and marine biodiversity increase substantially beyond 1.5ºC of warming (Hoegh-Guldberg et al., 2018b). Section 16.5.2.3.2 (RKR-B, risks to terrestrial and marine ecosystems) finds that substantial biodiversity loss globally, abrupt local ecosystem mortality impacts, and ecological species disruption are all projected at global warming levels below 3ºC, with insular systems and biodiversity hotspots at risk below 2ºC (*medium confidence*). Insects play a critical role in providing vital ecosystem services that underpin human systems, with major losses of their climatically determined geographic range at 2°C warming implying adverse effects on ecosystem functioning. Consistent with the transitions presented here, a similar burning ember developed in Chapter 2 assessed a transition from moderate to high risks globally for marine and terrestrial biodiversity (e.g., widespread death of trees, damages to ecosystems, and reduced provision of ecosystem services, and structural change, including biome shifts) beginning between 1.0 and 2.0ºC warming (Table 2.S.4, Figure 2.11).

Though explicit treatment of adaptation is limited in the RFC4 impacts literature (i.e., studies that compare risks for specific adaptation scenarios in terms of globally aggregated impacts with quantified findings), there is evidence of the potential for investments in improved hydro-meteorological information and early warning systems to avoid some of the most adverse social and economic impacts from extreme weather events in both developed and developing countries, with benefits at a globally significant level (Hallegatte, 2012). Studies of adaptation in the agriculture sector (e.g., changing crop variety, timing of crop planting, new types of irrigation, etc.) and infrastructure (e.g., coastal protection, hardening of critical infrastructure, flood and climate resistant building materials and water storage) show large potential benefits in terms of reduced impacts to lives and livelihoods (van Hooff et al., 2015; Mees, 2017). At higher warming levels, however, potential adaptations to address biodiversity loss are expected to be limited due to the projected rate and magnitude of change as well as the resources required (Hannah et al., 2020).

The transition to very high risks is assessed to occur between a range of 2.5–4.5ºC with *medium confidence* over the range, and *low confidence* assessed over a narrowed 'best estimate' range of 2.7–3.7ºC. The lower end of the range reflects the loss of an increasingly large fraction of biodiversity globally. Chapter 2 has assessed a transition from high to very high risks globally for biodiversity (marine and terrestrial) completing at ~2.5ºC warming, noting widespread death of trees, damages to ecosystems, and reduced provision of ecosystem services over the temperature range 2.5ºC–4.5ºC (Table 2.S.4, Figure 2.11); and similarly a transition from high to very high risks of ecosystem structure change (including biome shifts) between 3ºC and 5ºC warming (Table 2.S.4, Figure 2.11). A global study of 115,000 common species projects climatically determined geographic range losses of over 50% in 49% of insects, 44% of plants and 26% of vertebrates with global warming of 3.2ºC, implying an associated effect on provisional and regulating ecosystem services that support human wellbeing, including pollination and detrivory (Warren et al., 2018a). The risk of abrupt impacts on ecosystems as multiple species approach tolerance limits simultaneously is projected to threaten up to 15% of ecological communities with 4ºC of warming (Trisos et al., 2020). Under a 4ºC warming scenario, models project global annual damages associated with sea level rise of $31,000 billion per year in 2100 (Brown et al., 2021)

In terms of global economic impact, while an emerging economic literature is addressing many gaps and critiques of previous damage estimates for high warming (e.g., Jensen and Traeger, 2014; Burke et al., 2015; Lontzek et al., 2015; Moore and Diaz, 2015; Lemoine and Traeger, 2016; Moore et al., 2017a; Cai and Lontzek; Takakura et al., 2019, discussed further in Cross-Working Group Box ECONOMIC; Carleton et al., 2020; Méjean et al., 2020; Rode et al., 2021), there remains wide variation across disparate methodologies, though the spread of estimates increases with warming in all methodologies, indicating higher risk in terms of economic costs at higher temperatures (*high confidence*). Section 16.5.2.3.4 (RKR-D) finds that risks to aggregate economic output would become severe at the global scale at high warming (~4.4ºC) and minimal adaptation (*medium confidence*), defining severity as 'the potential for persistent annual economic losses due to climate change to match or exceed losses during the world's worst historical economic recessions'. Furthermore, climate change impacts on income inequality could compound risks to living standards (*high confidence*, 16.5.2.3.4). Chapter 4 finds that at 4°C, 4 billion people are projected to be exposed to physical water scarcity *(medium confidence)*.

[START CROSS-WORKING GROUP BOX ECONOMIC HERE]

Cross-Working Group Box ECONOMIC: Estimating Global Economic Impacts from Climate Change

Authors: Steven Rose (USA), Delavane Diaz (USA), Tamma Carleton (USA), Laurent Drouet (Italy), Celine Guivarch (France), Aurélie Méjean (France), Franziska Piontek (Germany)

This Cross-Working Group Box assesses literature estimating the potential global aggregate economic costs of climate change and the social cost of carbon (SCC), where the former are sometimes referred to as estimates of global 'climate damages' and the latter are estimates of the potential monetized impacts to society of an additional metric ton of carbon dioxide emitted to the atmosphere. These measures include the economic costs of climate change that could be felt in market sectors such as agriculture, energy services, labour productivity, and coastal resources, as well as non-market impacts such as other types of human health risks (including mortality effects) and ecosystems. Global economic impacts estimates can inform decisions about global climate management strategy, while SCC estimates can inform globally incremental emissions decisions. In practice, economic damage estimates have been used to explore economically efficient ('economically optimal') global emissions pathways (e.g.', Nordhaus and Moffat, 2017), while SCCs have been used to inform federal and state-level policy assessment in some countries (Greenstone et al., 2013; Rose and Bistline, 2016), but the type of SCC and application matter (Rose, 2017). This literature has been assessed in previous WGII reports (e.g.., Arent et al., 2014) and this box serves this need for this report. The assessment in this box was performed jointly across WGII and WGIII, building on the foundation of WGII AR6 Chapter 16's 'Risk to living standards' assessment (Section 16.5.2.3.4), which includes consideration of severe risks to global aggregate economic output, and WGIII AR6 Chapter 3's assessment of the benefits of mitigation. It also informs Chapter 16's global aggregate impacts Reason for Concern and supports Chapter 18's assessment of global emissions transitions, risk management, and climate-resilient development. In keeping with the broad risk framing presented in Chapter 1 of this report, other lines of evidence regarding climate risks, beyond monetary estimates, should be considered in decision-making, including key risks and Reasons for Concern.

Methods for estimating global economic costs of climate impacts

There are several broad approaches to estimating climate damages, including biophysical process models, structural economic models, statistical methods (also called empirical or econometric) and hybrid approaches, with each methodology having strengths and weaknesses. Process models simulate physical, natural science, and/or engineering processes and their response to climate variables, that are then monetized (e.g., Anthoff and Tol, 2014; Sieg et al., 2019; Narita et al., 2020). Process approaches have the advantage of being explicit and interpretable, though they can be computationally intensive; may omit relevant impact channels, interactions, and market dynamics affecting valuation; and, often lack a rigorous empirical basis for calibration (Fisher-Vanden et al.). Structural economic modelling represents climate impacts on inputs, production, household consumption, aggregate investment, and markets for economic sectors and regional economies (e.g., Reilly et al., 2007; Roson and Van der Mensbrugghe, 2012; Anthoff and Tol, 2014; Dellink et al., 2019; Takakura et al., 2019), often using computable general equilibrium (CGE) frameworks. Structural models can evaluate how market and non-market impacts might enter and transmit through economies, and adaptation responses within input and output markets, consumer and investment choices, and inter-regional trade (e.g., Darwin and Tol, 2001; Dellink et al., 2019; Takakura et al., 2019). Statistical methods estimate economic impacts in a given sector (e.g., Auffhammer, 2018) or in aggregate (e.g., Dell et al., 2014; Burke et al., 2015; Hsiang et al., 2017; Pretis et al., 2018; Kahn et al., 2019), inferred from observed changes in economic factors, weather, and climate, with responses and net results constrained by available data. Since AR5, hybrid approaches have taken different forms to integrate process, statistical and/or structural methods, and represent a potentially promising means of leveraging the strengths of different approaches (e.g., Moore and Diaz, 2015; and Hsiang et al., 2017; Moore et al., 2017a; Ricke et al., 2018; Yumashev et al., 2019; Chen et al., 2020b). There is also a small literature that uses expert elicitation to gather subjective assessments of climate risks and potential economic impacts (Nordhaus, 1994; IPCC, 2019a; Pindyck, 2019).

In addition to differences in methods, there are also differences in scope – geographic, sectoral, and temporal. Global estimates are frequently based on an aggregation of independent sector and/or regional modelling and estimates; however, there are examples of estimates from global modelling that simulate multiple types of climate impacts and their potential interactions within a single, coherent framework (e.g., Roson and Van der Mensbrugghe, 2012; Dellink et al., 2019; Takakura et al., 2019). Differences in scope also represent strengths and weaknesses between the methodologies, with narrower scope allowing for more detailed assessment, but missing potential interactions with the scope not covered (e.g., other geographic areas, sectors, markets, or periods of time).

Comprehensive economic estimates are challenging to produce for many reasons, including complex interactions among physical, natural, and social systems; pervasive climate, socio-economic, and system response uncertainties; and the heterogeneous nature of climate impacts that vary across space and time. Critiques and commentaries of global estimation methods (Pindyck, 2013; Stern, 2013; van den Bergh and Botzen, 2015; Cropper et al., 2017; Diaz and Moore, 2017; Pindyck, 2017; Rose et al., 2017; Stoerk et al., 2018; DeFries et al., 2019; Pezzey, 2019; Calel et al., 2020; Warner et al., 2020; EPRI, 2021; Grubb et al., 2021; Newell et al., 2021) include, among other things, concerns about statistical methods estimating weather but not climate relationships, making out-of-sample extrapolations, and model specification uncertainty, concerns about the observational grounding of structural modelling, overall concerns about the lack of adaptation consideration, as well as representation and evaluation of potential large-scale singular events such as ice sheet destabilisation or biodiversity destruction, some questioning the ability to generate robust estimates (i.e., estimates insensitive to reasonable alternative inputs and specifications), and general concerns about methodological details, transparency, and justification.

Additional methodological challenges to address (see, for instance, EPRI, 2021; Piontek et al., 2021) include how to capture and represent uncertainty and variability in potential damage responses for a given climate and societal condition, combine estimates from different methods and sources (including aggregating independent sectoral and regional results), assess sensitivity and evaluate robustness of estimates (including sensitivity to model specification), capture interactions and spillovers between regions and sectors, estimate societal welfare implications (versus GDP changes) of market and non-market impacts, consider distributional effects, represent micro and macro adaptation processes (and adaptation costs), specify nongradual damages and non-linearities, and improve understanding of potential long-run economic growth effects. Note that, the treatment of time preference, risk aversion, and equity considerations have important welfare implications for the aggregation of both potential economic impacts and climate change mitigation costs.

In addition to updated and new methods and estimates, newer literature has explored nongradual damages, such as climatic and socioeconomic tipping points (Lontzek et al., 2015; Méjean et al., 2020), potential damage to economic growth (e.g., Burke et al., 2015; Moore and Diaz, 2015), valuing uncertainty in potential damages (Jensen and Traeger, 2014; Lemoine and Traeger, 2016; Cai and Lontzek), and representing adaptation (Takakura et al., 2019; Carleton et al., 2020; Rode et al., 2021). Going forward, to help advance science and decisions, a key research priority is to understand and evaluate methodological strengths and weaknesses in damage estimation, and reconcile the differences affecting comparability in such a way that it informs use of the different lines of evidence. This will require greater transparency and assessment of details and assumptions in individual methods, communication and evaluation of alternatives for specifying or calibrating climate damage functional representations with respect to climate and non-climate drivers and potential non-linearities, including evaluating data sufficiency for levels within and beyond observations and for characterizing physical system dynamics, and evaluating the sensitivity of results to model specification and input parameter choices (Cropper et al., 2017). Improving the robustness of economic impact estimates is an active area of research. Below we describe the latest estimates.

Global estimates of the economic costs of climate impacts

Since AR5, many new estimates of the global economic costs of climate change have been produced. Figure Cross-Working Group Box ECONOMIC.1 shows a wide spread of estimates, with growing variance at higher levels of warming, both within and across methodology types (i.e., statistical, structural, or meta-analysis). Meta-analysis is used here to refer to studies that treat other studies' estimates as data points in an attempt to derive a synthesized functional form.

Global aggregate economic impact estimates (Figure Cross-Working Group Box ECONOMIC.1) are generally found to increase with global average temperature change, as well as vary by other drivers, such as income and population and the composition of the economy. Most estimates are nonlinear with higher marginal economic impacts at higher temperature, although some recover declining marginal economic impacts and functional forms cannot be determined for all studies. The drivers of non-linearity found in economic impact estimates, and the differences in non-linearity across estimates (e.g., convex versus concave, degree of curvature), are not well understood, with methodology construction, assumptions, and data all potential factors. Relative to AR5, there have been more estimates and greater variation in estimates, including some recent estimates significantly higher than the range reported in AR5. For most of the studies shown in Figure Cross-Working Group Box ECONOMIC.1, the visible variation within a study represents alternative socioeconomic projections and climate modelling, not economic impacts response uncertainty for a given socioeconomic and climate condition. Response uncertainty could be significant as indicated by some of the results shown in the figure (e.g., Burke et al., 2015; Rose et al., 2017), but methodological differences in how uncertainty is characterized (model specification, errors, and confidence intervals versus distributions of results) limits comparability and assessment. Note that modeling factors between global temperature change and the economic impact calculation, such as regional temperature pattern assumptions or assumed sea level rise dynamics, can also impact calculated estimates (e.g., Warren et al, 2021 PAGE09 estimates versus those in Rose et al, 2017, Chen et al, 2020 PAGE-ICE estimates versus Burke et al, 2015).

From Figure Cross-Working Group Box ECONOMIC.1, we find a large span of damage estimates, even without considering uncertainty/confidence in damage responses, including for today's level of warming (about 1˚C). There is also evidence that some regions benefit from low levels of warming, leading to net benefits globally at these temperatures. The size of the span of estimates grows with global warming level, with variation across statistical estimates larger than variation in structural estimates. The structural and meta analyses estimates appear to be in closer agreement, but that outcome is contingent on the meta analyses data considerations and approach. Meta analyses to date have not assessed the alternative methods and dealt with the lack of comparability between methods.

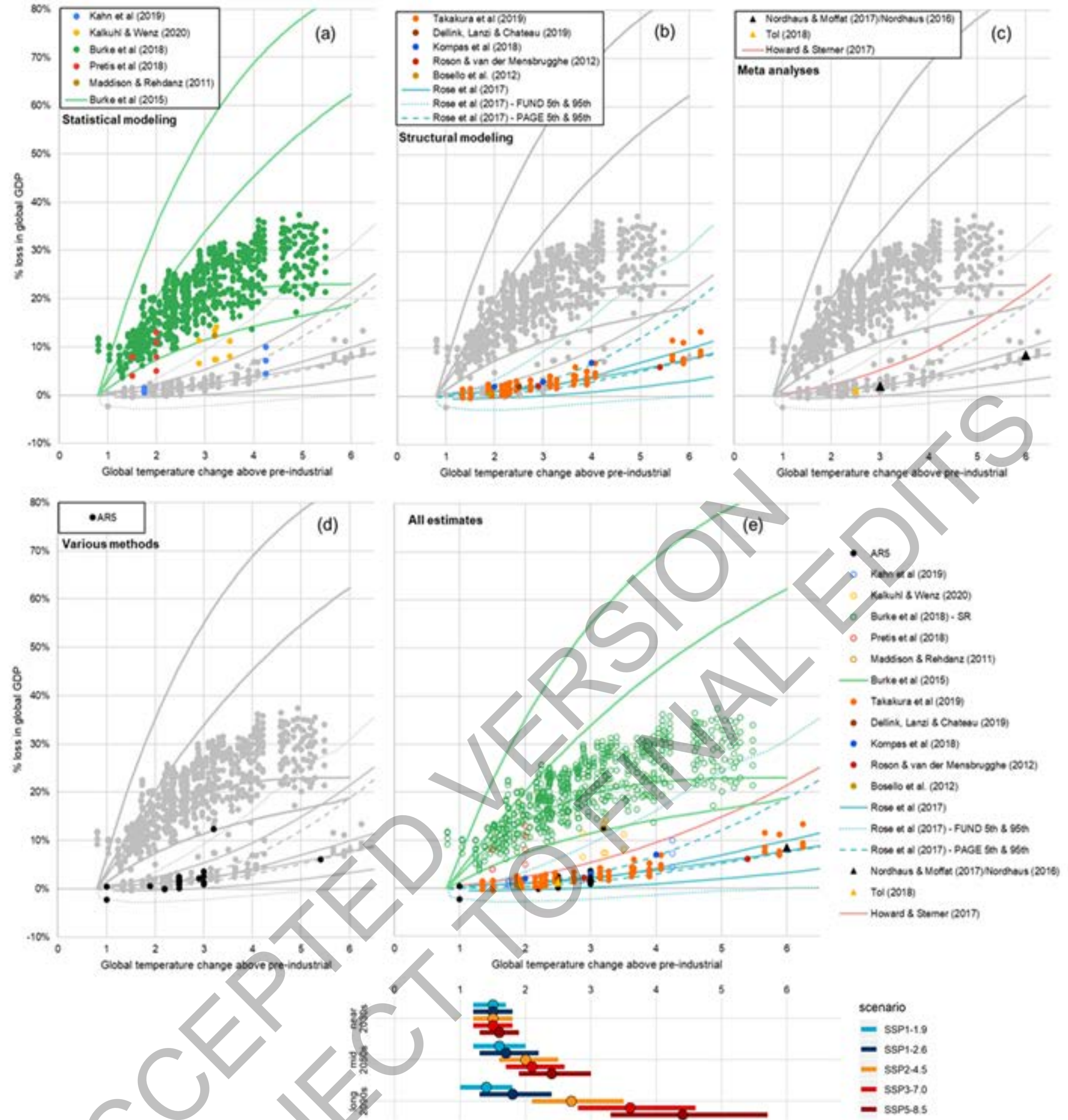


Figure Cross-Working Group Box ECONOMIC.1: Global aggregate economic impact estimates by global warming level (annual % global GDP loss relative to GDP without additional climate change). Top row panels present estimates by methodology type: (a) statistical modeling, (b) structural modeling, and (c) meta analyses, with all estimates from a paper in the same colour and estimates from methodologies other than that highlighted by the panel in grey for reference. Second row left panel (d) presents AR5 estimates. Second row right panel (e) presents all estimates in one figure, with the same colors as panels (a-d) using outlined dots for the statistical modelling estimates, solid dots for structural modelling estimates, and triangles for meta analysis estimates. In all panels, lines represent functions, with dashed and dotted lines 5th and 95th percentile functions from structural modelling. To avoid duplication, estimates from papers using the economic impacts estimates or model formulations already represented in the figure are not included (e.g., Diaz and Moore, 2017; Chen et al., 2020b; Glanemann et al., 2020; Warren et al., 2021). The exception is Burke et al. (2018), with the different estimates shown representing variation across climate scenarios for a given aggregate economic impacts specification from Burke et al. (2015) – the 'pooled, short run' statistical specification. Results shown for the latter are estimates with the author's different statistical model specifications (and a fixed climate scenario, SSP5). From top to bottom, the Burke et al. (2015) estimates are for the 'pooled, long run,' 'differentiated, long run,' 'pooled, short run' (authors' base case), and 'differentiated, short run' statistical specifications. For Howard and Sterner (2017), the authors' preferred function is shown. Overall, estimates shown in the figure can correspond to different future years, reflecting different socioeconomic conditions and climate pathways to a global warming level. Global average temperature change bars relative to the period 1850-1900 are shown below the economic cost estimates to provide context to potential future warming. Shown are the WGI AR6 assessed best estimates and 90% intervals for the illustrative emissions scenarios considered for the near term 2021-2040, mid-term 2041-2060, and long term 2081–2100.

Differences in methodology type and scope complicate comparison, assessment, and synthesis (Cropper et al., 2017; Diaz and Moore, 2017; EPRI, 2021; Piontek et al., 2021). In particular, structural economic modelling and empirical aggregate output modelling are fundamentally different, which has been identified as an issue affecting the comparability of results (Cropper et al., 2017). The different methodologies affect outcomes, with global aggregate estimates based on statistical methodologies typically higher than those from structural modelling (Figure Cross-Working Group Box ECONOMIC.1). This is, in part, due to the relationships in observational data captured by statistical modelling, assumed persistence of impacts in statistical modelling, broader adaptation responses in structural modelling, and differences in the representation of future societies and how they might evolve, respond, and interact. Within statistical modelling, results are also found to be very sensitive to the statistical model specification (e.g., Burke et al., 2015; Newell et al., 2021). Within structural modelling, differences in representations of biophysical changes and economic structural dynamics contribute to differences across structural estimates (e.g., Rose et al., 2017).

The wide range of estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates with confidence (high confidence). Evaluating and reconciling differences in methodologies is a research priority for facilitating use of the different lines of evidence (high confidence). However, the existence of higher estimates than AR5 indicate that global aggregate economic impacts could be higher than previously estimated (low confidence due to the lack of comparability across methodologies and robustness of estimates).

While Figure Cross-Working Group Box ECONOMIC.1 summarizes global aggregate estimates, the literature exhibits significant heterogeneity in regional economic impacts that are also sensitive to methodology, model specification, and societal assumptions (with, for instance, larger estimates due to the assumed size of society, but offsetting adaptive capacity improvements and adaptation responses). Regional results illustrate the potential for overall net benefits in more temperate regions at lower levels of warming with potential lower energy demand and comparative advantages in agricultural markets; however, at higher levels of warming net losses are estimated. In addition, economic impacts for poorer households and poorer countries represent a smaller share in aggregate quantifications expressed in GDP terms than their influence on well-being or welfare (Byers et al., 2018; Hallegatte et al., 2020).

Social cost of carbon methods and estimates

The global economic impact estimates discussed in the previous section serve as a key input into the calculation of the value of potential net damages caused by a marginal ton of carbon dioxide emissions, or the SCC. To compute an SCC, damage estimates are commonly combined in a multi-century modelling framework with socioeconomic and emissions projections, a physical model of the climate, including a sea-level rise component, and assumptions about the discount rate, with current frameworks having highly stylized representations of these components. Though we do not present quantitative estimates here, due to the challenge of comparability, for economic impacts methodologies (as discussed above) as well as other SCC estimation elements, large variations in SCC estimates are found in the literature assessed due to, among other things, differences in modelling component representations, input and parameter assumptions, considerations of uncertainty, and discounting, inflation, and emissions year (e.g., Tol, 2009; Tol, 2018; Pezzey, 2019; Iese et al., 2021). There are also different 'variants' of SCC estimates that differ conceptually, and in magnitude, depending on the reference condition for evaluating the impact of a marginal metric ton--is it being evaluated relative to a no-climate-policy baseline, an economically efficient pathway that weighs the benefits and costs of emissions mitigation, or a pathway based on a particular climate policy or goal such as 2°C or a concentration target (Rose et al., 2017)? The variant of SCC has implications for its applicability to different policy contexts (Rose and Bistline, 2016).

In addition to the economic impacts methodological challenges discussed above with respect to aggregate economic impact estimates, the additional components needed for SCC calculations give rise to a new set of technical issues and critiques, including incorporation of uncertainties in the components beyond climate damages, links between components, and discounting (van den Bergh and Botzen, 2015; Cropper et al., 2017; Diaz and Moore, 2017; Pindyck, 2017; Rose et al., 2017; EPRI, 2021). For component-specific discussions and assessment, see Cropper et al. (2017), Rose et al. (2017), and EPRI (2021).

Substantial progress has been made in recent years to better reflect complexities in the global economy, the climate system, and their interaction. For example, recent studies have explored damages to natural capital (Bastien-Olvera and Moore, 2021), the influence of imperfect substitutability between environmental services and market goods (Sterner and Persson, 2008; Weitzman, 2012; Drupp and Hänsel, 2021), the implications of heterogeneous climate change impacts across income groups (Dennig et al., 2015; EPRI, 2021; Errickson et al., 2021), the potential for persistent climate impacts to economic growth instead of effects on levels of economic output (Dietz and Stern, 2015; Moore and Diaz, 2015; Ricke et al., 2018; Kikstra et al., 2021; Newell et al., 2021), valuing the risks of climate tipping points (Cai and Lontzek, 2019; Rising et al., 2020), valuing uncertainty under risk aversion (Jensen and Traeger, 2014; Lemoine and Traeger, 2016), and modelling a distinction between intertemporal inequality aversion and risk aversion in the social welfare utility function (Crost and Traeger, 2013; Jensen and Traeger, 2014; Daniel et al., 2015). These new studies have, in general, raised estimates of the SCC (Crost and Traeger, 2013; Jensen and Traeger, 2014; Gerlagh and Michielsen, 2015; Moore and Diaz, 2015; Faulwasser et al., 2018; Guivarch and Pottier, 2018; Budolfson et al., 2019; Cai and Lontzek, 2019; Dietz and Venmans, 2019; Kalkuhl and Wenz, 2020), in some cases by an order of magnitude (Ricke et al., 2018). However, challenges persist in terms of moving from conceptual to practical application, such as pinning down parameter specifications, modelling specific mechanisms for impacts, and more fully representing adaptation.

Despite these scientific advances, SCC estimates vary widely in the literature. Technical issues with past and current modelling (e.g.', Pezzey, 2019; Pindyck, 2019; EPRI, 2021) and the challenge of comparability across methodologies imply that many estimates are not robust (*high confidence*). Also, as a result, the issue of directional bias of past estimates remains unsettled. Better representation of uncertainty in methods can improve robustness, while detailed methodology assessment and comparison will help define the relative biases of methods (*high confidence*).

Application to decision-making

The literature has also assessed the application of aggregate economic impact cost and SCC estimates (Rose and Bistline, 2016; Rose et al., 2017; Kaufman et al., 2020) and identified conceptual and technical issues that need to be considered when using results to inform policy decisions. These issues include: accounting for endogenous marginal benefits and socioeconomic conditions in evaluating policies with non-incremental global emissions implications; consistency in assumptions and treatment of uncertainty across benefit and cost calculations; fully accounting for the streams of both mitigation costs and benefits over time; avoiding inefficiently valuing or pricing emissions more than once across policies and jurisdictions; and accounting for emissions leakage to capture net climate implications. Furthermore, concerns about the robustness of estimates have led some to recommend considering alternatives, such as using marginal mitigation cost estimates based on modelling of policy goals instead of the SCC (e.g., Rose, 2012; Pezzey, 2019; Kaufman et al., 2020), although this comes with its own set of assumptions and technical challenges.

[END CROSS-WORKING GROUP BOX ECONOMIC HERE]

16.6.3.5 Large-scale Singular Events (RFC5)

This RFC, large-scale singular events (sometimes called tipping points or critical thresholds), considers abrupt, drastic, and sometimes irreversible changes in physical, ecological, or social systems in response to smooth variations in driving forces (accompanied by natural variability) (Oppenheimer et al., 2014; O'Neill et al., 2017). SR15 Section 3.5.2.5 presented four examples, including the cryosphere (West Antarctic ice sheet, Greenland ice sheet), thermohaline circulation (slowdown of the Atlantic Meridional Overturning

Circulation), the El Niño–Southern Oscillation (ENSO) as a global mode of climate variability, and the role of the Southern Ocean in the global carbon cycle (Hoegh-Guldberg et al., 2018b). Whilst most of the literature assessed here focuses on the resultant changes to climate-related hazards such as sea level rise, in this assessment evidence about the implications of accelerated sea level rise for human and natural systems is also considered. If sea level rise is accelerated by ice sheet melt, the associated impacts are projected to occur decades earlier than otherwise, directly affecting coastal systems including cities and settlements by the sea (CCP2) and wetlands (Chapter 2). The associated disruption to ports is projected to severely compromise global supply chains and maritime trade with local-global geo-political and economic consequences. In order to compensate for this acceleration, adaptation would need to occur much faster and at a much greater scale than otherwise, or indeed than has previously been observed (CCP2). The costs of accommodating port growth and adapting to sea level rise amount to USD22-768 billion before 2050 globally (medium evidence, high agreement) (see Section 2.1; Section 2.2; Cross-Chapter Box SLR in Chapter 3).

In AR5 Section 19.6.3.6 (Oppenheimer et al., 2014), the boundary between undetectable and moderate risk is set at levels between 0.6 and 1.6ºC above pre-industrial levels (i.e., 0ºC and 1ºC above the 1986-2005 level) with high confidence, based on emerging early warning signals of regime shifts in Arctic and warm water coral reef systems. The risk transition boundary between moderate and high risk was set between 1.6 and 3.6ºC above pre-industrial levels (i.e., 1ºC and 3ºC above the 1986-2005 level), with medium confidence based on projections of ice sheet loss, with faster increase between 1ºC and 2ºC than between 2ºC and 3ºC. The literature available at the time did not allow AR5 to assess the boundary between high and very high risk.

In SR15 Section 3.5.2.5 (Hoegh-Guldberg et al., 2018b), new assessments of the potential collapse of the West Antarctic ice sheet (WAIS) initiated by marine ice sheet instability (MISI) resulted in lowering the upper end of the transition from undetectable and moderate risk from 1.6ºC to 1ºC warming above pre-industrial levels, and lowering the upper end of the transition from moderate to high risk to 2.5ºC. Although SR15 did not produce embers beyond 2.5ºC, authors reported that the transition to very high risk was assessed at lying above 5ºC in light of growing literature on ice sheet contributions to sea level rise.

AR6 provides new evidence that relates to the location of the transition from undetectable to moderate risk. At the time of SR15, observations were suggesting that MISI might already be taking place in some parts of the WAIS while AR5 supported assessment of an additional MISI contribution to sea-level rise of several additional tenths of a metre over the next two centuries. Since SR15, new observations (WGI AR6 Section 9.4.2.1, Fox-Kemper et al., 2021) support the assessment of enhanced grounding line retreat and subsequent mass loss through basal melt in various parts of Antarctica, and year 2100 sea-level projections for the RCP8.5 scenario have increased by 10-12 cm owing to ice dynamics. However, the onset of MISI is driven by ocean warming in specific locations (ice cavities beneath floating ice shelves) and the relation between these ocean temperatures and global mean temperature is indirect and ambiguous. In addition, MISI implies a self-sustaining instability in the absence of further forcing. Because forcing is still increasing, it cannot be unambiguously assessed whether MISI is driving the observed retreat of grounding lines in the WAIS, or whether this retreat is a purely forced response (and would stop if the warming stops), or is just a manifestation of natural variability in upwelling of warmer waters on the Antarctic continental shelves and, as a result is just a temporary effect. Consistent with SROCC, AR6 states with *medium confidence* that sustained mass losses of several major glaciers in the Amundsen Sea Embayment (ASE) are compatible with the onset of MISI, but that whether unstable WAIS retreat already has begun or is imminent remains a critical uncertainty.

Whether associated with MISI or not, WGI AR6 (Fox-Kemper et al., 2021) now assesses with *very high confidence* that mass loss from both the Antarctic (whether associated with MISI or not) and Greenland Ice Sheets, is more than seven times higher over the period 2010-2016 than over the period 1992-1999 for Greenland and four times higher for the same time-intervals for Antarctica. Given their multi-century commitments to global sea level rise this reinforces the assessment of estimating the boundary between undetectable and moderate risks for ice sheets to lie between 0.7ºC (the level of global warming in the 1990s when melting began to accelerate) and 1ºC (as in SR15), with a median at 0.9ºC.

In the Amazon forest, increases in tree mortality and a decline in the carbon sink are already reported (Brienen et al., 2015; Hubau et al., 2020) and old-growth Amazon rainforest may have become a net carbon source for the period 2010-2019 (Qin et al., 2021). Estimates which include land-use emissions indicate the region may have become a net carbon source (Gatti et al., 2021). Fire activity is an important driver and both bigger fires (Lizundia-Loiola et al., 2020) and longer fire season (Jolly et al., 2015) have been reported in South America, although this is strongly linked to land-use and land-use change as well as climate (Kelley et al., 2021), and indeed land use change may be a stronger driver of potential loss of the Amazon forest than climate change. The risk of climate-change related loss of the Amazon forest is assessed already above 'undetectable' – but has only emerged over the last few years, when global warming had reached 1ºC, and is linked to land-use as well as GSAT levels. Chapter 2 has assessed ecosystem carbon loss from tipping points in tropical forest and loss of Arctic permafrost, and finds a transition to moderate risk over the range 0.6 to 0.9C (*medium confidence*). Specifically, WGII AR6 Table 2.S.4 finds that 'Primary tropical forest comprised a net source of carbon to the atmosphere, 2001-2019 (emissions 0.6 Gt y^{-1}, net 0.1 Gt y^{-1}) (Harris et al., 2021). Anthropogenic climate change has thawed Arctic permafrost (Guo et al., 2020), carbon emissions 1.7 ± 0.8 Gt y^{-1}, 2003-2017 (Natali et al., 2019)'. This also supports the upper limit for this transition lying at 1ºC.

The potential global loss of an entire ecosystem type, coral reefs, is also considered a large-scale singular event. In the 1990's when global warming was around 0.7ºC large scale coral reef bleaching also became apparent (16.2.3.1), also supporting the lower boundary for this transition in respect of coral reefs.

Overall, given the above evidence on ice sheets, Amazon forest, and coral reefs, the transition from undetectable to moderate risk is therefore assessed to occur between 0.7ºC and 1ºC warming with a median of 0.9ºC with *high confidence*.

The transition from moderate to high risk is informed by an assessment of risks at higher levels of warming than present. Nearly all climate models do show warmer temperatures around Antarctica in conjunction with rising global mean temperature and all ice sheet models do show sustained mass loss from the WAIS after temperature increase halts (thus implying MISI takes place) at various levels between 1.5ºC and 5ºC, and an increasing fraction of ice sheet models shows additional sustained mass loss from the East Antarctic Ice Sheet (EAIS) for peak warming between 2ºC and 4ºC, and all ice sheet models show mass loss for peak warming higher than 4ºC. Therefore, we assess an increasing link between MISI, WAIS collapse and Antarctic mass loss, for increasing temperature levels *(high confidence)*.

There is *high confidence* in the existence of threshold behaviour of the Greenland Ice Sheet in a warmer climate (WGI AR6 Ch 9, Fox-Kemper et al., 2021), however there is low agreement on the nature of the thresholds and the associated tipping points. Similarly the likelihood for accelerated and irreversible mass loss from Antarctica increases with increasing temperatures but thresholds cannot yet be unambiguously identified. By the year 2100, sea-level projections (AR6 WG1 SPM Fig SPM 8) now range from 0.57 m (0.37-0.85) for the SSP1-1.9 scenario to 1.35 m (1.02-1.89) for the SS5-8.5 scenario and become 1.99 m for the latter scenario (1.02-4.83) in case of low-likelihood, high-impact outcomes resulting from ice sheet instability, for which there is *limited evidence*. It should be noted that inclusion of such low-likelihood, high-impact outcomes dominated by not-well understood processes affecting ice dynamics on the large icecaps of Greenland, and in particular Antarctica, would also enhance the sea-level projections for other scenarios, but to a lesser extent for increasingly weaker forcing. No quantitative assessment of their effect in other scenarios than SSP5-8.5 yet exists as such simulations with ice-sheet models have not been carried out, or only in a very limited amount.

It should be noted that ice sheets may take many centuries to respond, implying that risk levels increase over time for the same warming level. Therefore we base judgments about risk transitions related to ice sheets primarily on their implications for 2000-year commitments to sea level rise from sustained mass loss from both ice sheets as projected by various ice sheet models, reaching 2.3-3.1 m at 1.5°C peak warming and 2-6 m at 2.0°C peak warming (WGI AR6 TS, Box TS.4 Figure 1, (Arias et al., 2021)). This is an important feature of the approach to this RFC (i.e., it is not primarily focused on implications for the next 100-200 years). In addition, since the AR5, there is new evidence about the Last Interglacial (LIG), when global mean temperature was about 0.5-1.5°C above the pre-industrial era. AR6 assesses that it is *virtually certain* that sea-level was higher than today at that time, *likely* by 5–10 m (*medium confidence*) (B.5.4 WGI AR6

SPM,(IPCC, 2021a)). Mid-Pliocene temperatures of 2.5°C (about 3 million years ago when global temperatures were 2.5°C–4°C higher) also provide evidence as an upper limit for the transition to high risk associated with long-term equilibrium sea-level rise of 5-25 m (WGI AR6 SPM B.5.4). In 2300 projected sea-level rise in an RCP8.5 or SSP5-8.5 scenario (consistent with a peak warming range of 4ºC-6ºC, varies between 1.7-6.8 and 2.2-5.9m respectively (WGI AR6 TS Box TS.4, Arias et al., 2021)), and when accounting for Marine Ice Cliff Instability taking place on Antarctica these numbers may increase to a range of 9.5-16.2 m (WGI AR6 TS Box TS.4, Arias et al., 2021)).

CMIP6 climate models project drying in the Amazon – especially in June-July-August, irrespective of future forcing scenario, but which increases with GSAT/higher scenarios (Lee et al., 2021). For higher GSAT levels Burton et al. (2021) explore different forcing scenarios and found, regardless of scenario, burned area increases markedly with GSAT. New understanding of the role of vegetation stomata will act to exacerbate this drying (Richardson et al., 2018b). A transition to high risk of savannization for the Amazon alone was assessed to lie between 1.5 and 3ºC with a median value at 2.0ºC. A mean temperature increase of 2ºC could reduce Arctic permafrost area ~15% by 2100 (Comyn-Platt et al., 2018). Chapter 2 has assessed ecosystem carbon loss from tipping points in tropical forest and loss of Arctic permafrost, and finds a transition from moderate to high risk over the range 1.5 to 3ºC with a median of 2ºC (*medium confidence,* Table 2.S.4, Figure 2.11). Its assessment of the transition from high to very high risk is located over the range 3ºC - 5ºC (*low confidence,* Table 2.S.4, Figure 2.11) based on the potential for Amazon forest dieback between 4-5ºC temperature increase above the pre-industrial period (Salazar and Nobre, 2010).

One of the criteria for locating a transition to very high risk is a limited ability to adapt. In natural systems limiting warming to 1.5°C rather than 2°C would enhance the ability of coastal wetlands to adapt naturally to sea level rise, since natural sedimentation rates more likely keep up with sea level rise (SR15, Hoegh-Guldberg 2018). In human systems, there is *medium confidence* that technical limits will be reached for hard protection to SLR beyond 2100 under high emissions scenarios, with limits associated with socio-economic and governance issues reached before 2100 (CCP2).

We therefore estimate the boundary between moderate and high risk to lie between 1.5ºC and 2.5ºC, with a median at 2.0ºC, with *medium confidence* based on projections for melting ice sheets and drying in the Amazon. We also estimate the boundary between high and very high risk to lie between 2.5ºC and 4ºC, but with *low confidence* due to uncertainties in the projections of sea level rise at higher levels of warming and differences between levels of warming at which very high risks were assessed in different systems.

16.6.4 Summary

The updated Reasons for Concern (RFC) show that transitions between levels of risk are now assessed to occur at lower levels of global warming than in previous assessments *(high confidence*), levels of confidence in assigning transitions have generally increased, evidence on the potential for adaptation to adequately address risks at different warming levels remains limited, and transitions from high to very high levels of risk have been assessed for all five RFCs, compared to just two RFCs in AR5, together showing how literature published since AR5 is informing us on our future climate risks.

- In particular, risks to unique and threatened systems (RFC1) are now assessed to be already at a high level today, as compared with a moderate level in previous assessments, and transition to a very high level is assessed to occur beginning at 1.2ºC, passing through a median value of 1.5°C, and completing the transition at 2.0ºC warming (*high confidence)*.

- Risks associated with extreme weather events (RFC2) are assessed to have begun to transition to a high level already when global warming reached 1ºC, with that transition projected to complete for a warming of 1.5ºC *(high confidence)*. Newly in AR6, a transition between high and very high levels of risk was assessed to lie at 2.0ºC warming for RFC2 (range 1.8- 2.5ºC).

- For risks associated with the distribution of impacts (RFC3), there is now *high confidence* that a transition to moderate risk has already occurred, and the transition to high risk is now projected to occur between 1.5–2.0ºC warming with *medium confidence*. Furthermore, a transition from high to very high risk is provided for the first time in this AR6 assessment, between 2.0–3.5ºC warming (*medium confidence*).

- Global aggregate impacts (RFC4) are assessed to have begun to transition to a moderate level already when global warming reached 1ºC, and are projected to transition to a high level with warming of 1.5 - 2.5ºC (median 2ºC) with *medium confidence.* An assessment of a transition to very high risk is provided for the first time in AR6, over the range 2.5 to 4.5ºC with *low confidence*.

- Risks associated with large-scale singular events are assessed to have already completed transitioning to moderate with 1ºC warming (*high confidence*), with a transition to high risk between 1.5–2.5ºC [median 2ºC] (*medium confidence*). An assessment of a transition to very high risk is provided for the first time in AR6, over the range 2.5–4.5ºC with *low confidence*.

In summary, risks to unique and threatened systems (RFC1) are higher at recent and projected levels of warming than assessed previously (*very high confidence)*; risks associated with extreme weather events (RFC2) are assessed comparably to AR5 and SR15 at recent and low levels of warming, but notably much higher at projected warming above 1.8°C (*medium confidence)*; risks associated with distribution of impacts (RFC3) and global aggregate impacts (RFC4) are similar to SR15 and higher than AR5 above 2°C (*medium confidence)*; and those associated with large-scale singular events (RFC5) are similar to SR15 and higher at both recent and projected warming than AR5 (*medium confidence)*.

Limiting global warming to 1.5ºC would ensure risk levels remain moderate for RFC3, RFC4 and RFC5 (*medium confidence*) but risk for RFC2 would have transitioned to a high risk at 1.5ºC and RFC1 would be well into the transition to very high risk (*high confidence*). Remaining below 2ºC warming (but above 1.5ºC) would imply that risk for RFC3 through 5 would be transitioning to high, and risk for RFC1 and RFC2 would be transitioning to very high (*high confidence*). By 2.5ºC warming, RFC1 will be in very high risk (*high confidence*) and all other RFCs will have begun their transitions to very high risk (*medium confidence* for RFC2 and RFC3, *low confidence* for RFC4 and RFC5*)*. These highest levels of risk are associated with an irreversible component, such that some impacts would persist even were global temperatures to subsequently decline in an 'overshooting' scenario.

Lack of evidence on the potential for adaptation to adequately reduce risk is a critical gap in our ability to assess global risk transitions at the RFC level, but not only. In some cases, such as RFC1, the widespread nature and rapid speed of the escalating risks, in combination with limited ability to adapt means that transitions to high risk may occur despite medium or even high levels of adaptation. Risks that are largely natural and not widely mediated by human vulnerability, are thus less likely to have risk transitions that shift under higher societal adaptation. Risk transitions that are mediated through human systems, such as distribution impacts, for example, are more likely to shift in response to adaptation as impacts are strongly mediated through vulnerability within human systems, but such a shift is difficult to quantify given knowledge gaps in the literature (Section 16.3). However, in some circumstances, expanded global adaptation could slow some of these transitions *(low confidence)*; in the case of RFC2, RFC3 and RFC4, the literature suggests that coordinated global adaptation could increase the global temperature at which risks transition from moderate to high, for example the prevention of mortality associated with heat stress within RFC2.

A higher level of adaptation, applied globally and effectively, could have larger benefits for several RFC, either postponing the onset of a high level of risk until a higher level of warming is reached (and allowing time for mitigation efforts) or allowing a system to survive a temporary overshoot of a lower temperature threshold. Adaptations are likely to have significant potential to reduce risks (Magnan et al., 2021) in particular for risks mediated through human systems. However, there is limited evidence available to assess the extent to which current or potential adaptations are or would be adequate in reducing climate risks at different levels of warming, and adaptation implications for risk transitions will be highly localized. Pathways and opportunities for risk management and adaptation actions with transformational potential are discussed in Chapter 17, together with enabling factors, governance frameworks, financing, success factors, and monitoring and evaluation discussed in Chapter 18, supporting sustainable system transitions and leading to options for climate resilient development pathways.

[START FAQ16.1 HERE]

FAQ16.1: What are key risks in relation to climate change?

A few clusters of key risks can be identified which have the potential to become particularly severe and pose significant challenges for adaptation worldwide. These risks, therefore, deserve special attention. They include risks to important resources such as food and water, risks to critical infrastructures, economies, health and peace, as well as risks to threatened ecosystems and coastal areas.

The IPCC defines key risks related to climate change as potentially severe risks that are relevant to the primary goal of the United Nations Framework Convention on Climate Change treaty to avoid 'dangerous human interference with the climate system', and whatever the scale considered (global to local). What constitutes 'dangerous' or 'severe' risks is partly a value judgment and can therefore vary widely across people, communities, or countries. However, the severity of risks also depends on criteria like the magnitude, irreversibility, timing, likelihood of the impacts they describe, as well as the adaptive capacity of the affected systems (species or societies). The Working Group II authors use these criteria in various ways to identify those risks that could become especially large in the future due to the interaction of physical changes to the climate system with vulnerable populations and ecosystems exposed to them. For example, some natural systems may be at risk of collapsing, as is the case for warm water coral reefs by mid-century, even if global warming is limited to +1.5°C. For human systems, severe risks can include increasing restriction of water resources that are already being observed; mortality or economic damages that are large compared to historical crises; or impacts on coastal systems from sea level rise and storms that could make some locations uninhabitable.

More than 130 key risks across sectors and regions have been identified by the chapters of this report, which have then been clustered into a set of 8 overarching risks, called representative key risks, which can occur from global to local scales but are of potential significance for a wide diversity of regions and systems globally. As shown in figure FAQ16.1, the representative key risks include risks to (1) low-lying coastal areas, (2) terrestrial and marine ecosystems, (3) critical infrastructures and networks, (4) living standards, (5) human health, (6) food security, (7) water security and (8) peace and mobility.

These representative key risks are expected to increase in the coming decades and will depend strongly not only on how much climate change occurs, but also on how the exposure and vulnerability of society changes, as well as on the extent to which adaptation efforts will be effective enough to substantially reduce the magnitude of severe risks. The report finds that risks are highest when high warming combines with development pathways with continued high levels of poverty and inequality, poor health systems, lack of capacity to invest in infrastructure, and other characteristics making societies highly vulnerable. Some regions already have high levels of exposure and vulnerability, such as in many developing countries as well as communities in small islands, Arctic areas and high mountains; in these regions, even low levels of warming will contribute to severe risks in the coming decades. Some risks in industrialized countries could also become severe over the course of this century, for example if climate change affects critical infrastructure such as transport hubs, power plants, or financial centres. In some cases such as coral reef environments and areas already severely affected by intense extreme events (e.g. recent typhoons or wildfires), for example, climate risks are already considered severe.

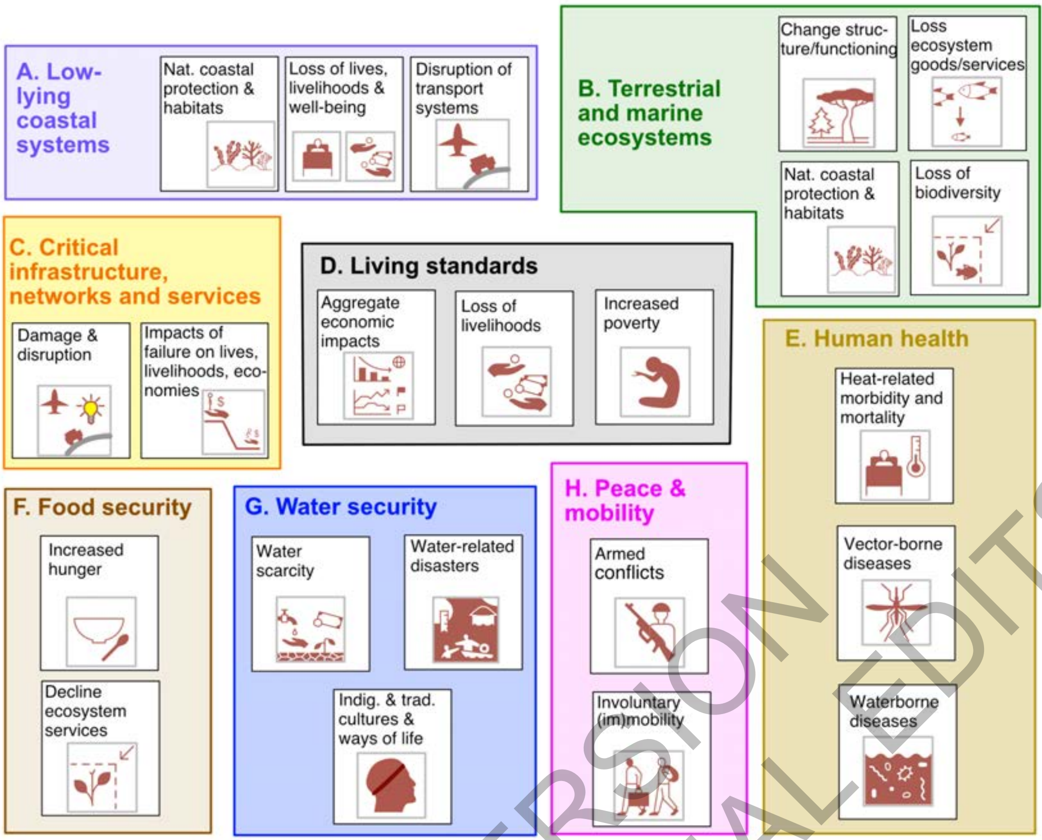


Figure FAQ16.1.1: Presentation of the 8 representative key risks assessed in this report (and their underlying main key risks).

[END FAQ16.1 HERE]

[START FAQ16.2 HERE]

FAQ16.2: How does adaptation help to manage key risks and what are its limits?

Adaptation helps to manage key risks by reducing vulnerability or exposure to climate hazards. However, constraining factors make it harder to plan or implement adaptation and result in adaptation limits beyond which risks cannot be prevented. Limits to adaptation are already being experienced, for instance by coastal communities, small-scale farmers and some natural systems.

Adaptation-related responses are actions that are taken with the intention of managing risks by reducing vulnerability or exposure to climate hazards. While mitigation responses aim to reduce greenhouse gas emissions and slow warming, adaptations respond to the impacts and risks that are unavoidable, either due to past emissions or failure to reduce emissions. However, while these responses intend to reduce risks, it is difficult to determine precise levels of risk reduction that can be attributed to adaptation. Changing levels of risk as well as other actions --such as economic development -- make it challenging to definitively connect specific levels of risk reduction with adaptation. Although it is not feasible to assess the adequacy of adaptation for risk reduction at global or regional levels, evidence from specific localized adaptation projects do show that adaptation-related responses reduce risk. Moreover, many adaptation measures offer near-term co-benefits related to mitigation and to sustainable development, including enhancing food security and reducing poverty.

Adaptation responses can occur in natural systems without the intervention of humans, such as species shifting their range, time of breeding, or migration behaviour. Humans can also assist adaptation in natural systems through, for example, conservation activities such as species regeneration projects or protecting ecosystem services. Other adaptation-related responses by humans aim to reduce risk by decreasing vulnerability and/or exposure of people to climate hazards. This includes infrastructural projects (e.g.

upgrading water systems to improve flood control), technological innovation (e.g. early warning systems for extreme events), behavioural change (e.g. shift to new crop types or livelihood strategies), cultural shifts (e.g. changing perspectives on urban greenspace, or increased recognition of Indigendous Knowledge and Local Knowledge), and institutional governance (e.g. adaptation planning, funding, and legislation).

While adaptation is important to reduce risk, adaptation cannot prevent all climate impacts from occurring. Adaptation has soft and hard limits, points at which adaptive actions are unable to prevent risks. Soft limits can change over time as additional adaptation options become available, while hard limits will not change as there are no additional adaptive actions that are possible. Soft limits occur largely due to constraints-- factors that make it harder to plan and implement adaptation, such as lack of financial resources or insufficient human capacity. Across regions and sectors, the most challenging constraints to adaptation are financial and those related to governance, institutions and policy measures. Limited funding and ineffective governance structures make it difficult to plan and implement adaptation-related responses which can lead to insufficient adaptation to prevent risks. Small-scale farmers and coastal communities are already facing soft limits to adaptation as measures that they have put in place are not enough to prevent loss. If constraints that are limiting adaptation are addressed, then additional adaptation can take place and these soft limits can be overcome. Evidence on limits to adaptation is largely focused on terrestrial and aquatic species and ecosystems, coastal communities, water security, agricultural production, and human health and heat.

Adaptation is critical for responding to unavoidable climate risks. Greater warming will mean more and more severe impacts requiring a high level of adaptation which may face greater constraints and reach soft and hard limits. At high levels of warming, it may not be possible to adapt to some severe impacts.

[END FAQ16.2 HERE]

[START FAQ16.3 HERE]

FAQ16.3: How do climate scientists differentiate between impacts of climate change and changes in natural or human systems that occur for other reasons?

We can already observe many impacts of climate change today. The large body of climatic impact data and research confirms this. To decide whether an observed change in a natural or human system is at least partly an impact of climate change we systematically compare the observed situation to a theoretical situation without observed levels of climate change. This is detection and attribution research.

Global mean temperature has already risen by more than 1°C and that also means that the impacts of climate change become more visible. Many natural and human systems are sensitive to weather conditions. Crop yields, river floods and associated damages, ecosystems such as coral reefs, or the extent of wildfires are affected by temperatures and precipitation changes. Other factors also come into play. So for example, crop yields around the world have increased over the last decades because of increasing fertilizer input, improved management and varieties. How do we detect the effect of climate change itself on these systems, when the other factors are excluded? This question is central for impact attribution. 'Impact of climate change' is defined as the difference between the observed state of the system (e.g., level of crop yields, damage induced by a river flood, coral bleaching) and the state of the system assuming the same observed levels of non-climate related drivers (e.g. fertilizer input, land use patterns, or settlement structures) but no climate change. So:
'Impact of climate change' is defined as the difference between the observed state of the system and the state of the system assuming the same observed levels of non-climate related drivers but no climate change. For example, we can compare the level of crop yields, damage induced by a river flood, and coral bleaching with differences in fertilizer input, land use patterns, or settlement structures, without climate change and with climate change occurring.

While this definition is quite clear, there certainly is the problem that in real life, we do not have a 'no climate change world' to compare with. We use model simulations where the influence of climate change can be eliminated to estimate what might have happened without climate change. In a situation where the influence of other non-climate related drivers is known to be minor (e.g., in very remote locations) the non-climate change situation can also be approximated by observation from an early period where climate change was still minor. Often a combination of different approaches increases our confidence in the quantification of the impact of climate change.

Impacts of climate change have been identified in a wide range of natural, human, and managed systems. For example, climate change is the major driver of observed widespread shifts in the timing of events in the annual cycle of marine and terrestrial species, the extent of areas burned by wildfires is increased by climate change in certain regions, it has increased heat-related mortality and had an impact on the expansion of vector-borne diseases.
In some other cases research has made considerable progress in identifying the sensitivity of certain processes to weather conditions without yet attributing observed changes to long-term climate change. Two examples of weather sensitivity without attribution are observed crop price fluctuations and waterborne diseases.

Finally it is important to note that 'attribution to climate change' does not necessarily mean 'attribution to anthropogenic climate change'. Instead, according to the IPCC definition, climate change means any long term change in the climate system no matter where it comes from.

[END FAQ16.3 HERE]

[START FAQ16.4 HERE]

FAQ16.4: What adaptation-related responses to climate change have already been observed, and do they help reduce climate risk?

Adaptation-related responses are the actions taken with the intention of managing risks by reducing vulnerability or exposure to climate hazards. Responses are increasing and expanding across global regions and sectors, although there is still a lot of opportunity for improvement. Examining the adequacy and effectiveness of the responses is important to guide, planning, implementation and expansion.

The most frequently reported adaptation-related responses are behavioural changes made by individuals and households in response to drought, flooding, and rainfall variability in Africa and Asia. Governments are increasingly undertaking planning, and implementing policy and legislation, including for example new zoning regulations and building codes, coordination mechanisms, disaster and emergency planning, or extension services to support farmer uptake of drought tolerant crops. Local governments are particularly active in adaptation-related responses, particularly in protecting infrastructure and services, such as water and sanitation. Across all regions, adaptation-related responses are strongly linked to food security, with poverty alleviation a key strategy in the Global South.

Overall, however, the extent of adaptation-related responses globally is low. On average, responses tend to be local, incremental, fragmented, and consistent with business-as-usual practices. There are no global regions or sectors where the overall adaptation-related response has been rapid, widespread, substantial, and has overcome or challenged key barriers. The extent of adaptation thus remains low globally, with significant potential for increased scope, depth, speed, and the challenging of adaptation limits. Examples of low extent adaptations include shifts by subsistence farmers in crop variety or timing, household flood barriers to protect houses and gardens, and harvesting of water for home and farm use. In contrast, high extent adaptation means that responses are widespread, coordinated, involve major shifts from normal practices, are rapid, and challenge existing constraints to adaptation. Examples of high extent adaptations include planned relocation of populations away from increasingly flood-prone areas, and widely implemented social support to communities to prevent migration or displacement due to climate hazards.

Increasing the extent of adaptation-related responses will require more widespread implementation and coordination, more novel and radical shifts from business-as-usual practices, more rapid transitions, and challenging or surmounting limits -- key barriers -- to adaptation. This might include, for example, best-practice programmes implemented in a few communities being expanded to a larger region or country, accelerated implementation of behaviours or regulatory frameworks, coordination mechanisms to support deep structural reform within and across governments, and strategic planning that challenges fundamental norms and underlying constraints to change.

We have very little information on whether existing adaptation-related responses that have already been implemented are reducing climate risks. There is evidence that risks due to extreme heat and flooding have declined, though it is not clear if these are due to specific adaptation-related responses or general and incremental socio-economic development. It is difficult to assess the effectiveness of adaptation-related responses, and even more difficult to know whether responses are adequate to adapt to rising climate risk. These remain unknown but important questions in guiding implementation and expansion of adaptation-related responses.

[END FAQ16.4 HERE]

[START FAQ16.5 HERE]

FAQ16.5: How does climate risk vary with temperature?

Climate risk is a complex issue and communicating and it is fraught with difficulties. Risk generally increases with global warming, though it depends on a combination of many factors such as exposure, vulnerability and response. To present scientific findings succinctly, a risk variation diagram can help visualize the relationship between warming level and risk. The diagram can be useful in communicating the change in risk with warming for different types of risk across sectors and regions, as well as for five categories of global aggregate risk called 'Reasons for Concern'.

A picture speaks a thousand words. The use of images to share ideas and information to convey scientific understanding is an inclusive approach for communicating complex ideas. A risk variation diagram is a simple way to present the risk levels that have been evaluated for any particular system. These diagrams take the form of bar charts where each bar represents a different category of risk. The traffic light colour system is used as a basis for doing the risks, making it universally understandable. These diagrams are known colloquially as 'burning ember' diagrams, and have been a cornerstone of IPCC assessments since the Third Assessment Report, and further developed and updated in subsequent reports. The fact that the diagrams are designed to be simple, intuitive, and easily understood with the caption alone, has contributed to their longstanding effectiveness. Here, in Figure FAQ16.5.1 below, we provide a simplified figure of this chapter's burning embers for five categories of global aggregate risk, called Reasons for Concern (RFC), which collectively synthesize how global risk changes with temperature. The diagram shows the levels of concern that scientists have about the consequences of climate change (for a specified risk category and scope), and how this relates to the level of temperature rise.

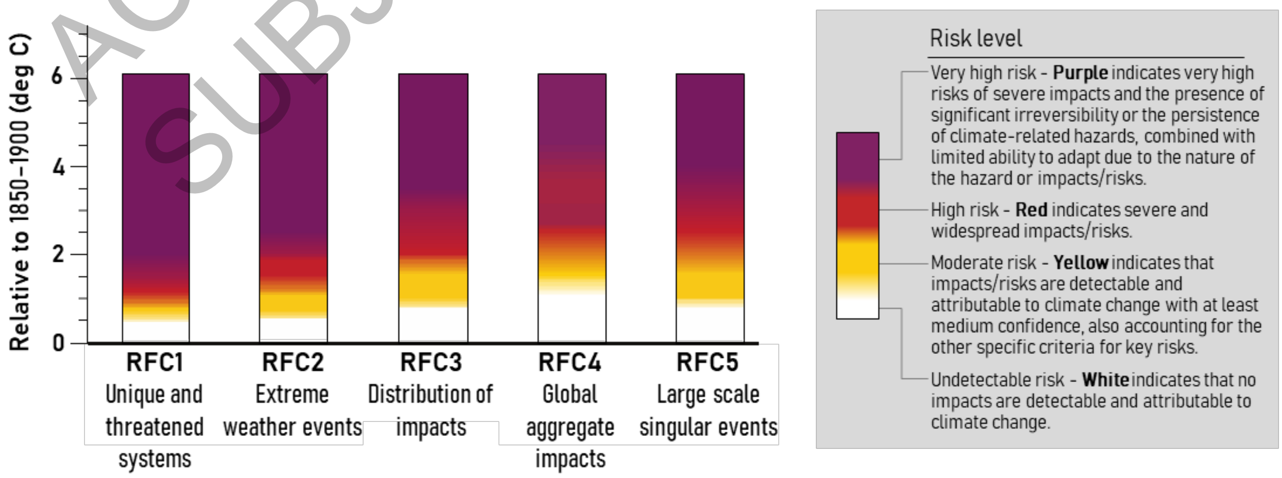


Figure FAQ16.5.1: Simplified presentation of the five Reasons for Concern burning ember diagrams as assessed in this report (adapted from Figure 16.15). The colours indicate the level of risk accrual with global warming for a low adaptation scenario. RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots. RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4 Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5 Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing.

In this diagram, the risk variation bars or embers are shown with temperature on the y-axis, and the base of the ember corresponds to a baseline temperature. Typically this baseline temperature is that before global warming started (i.e., average temperatures for the pre-industrial period of 1850 to 1900). This area of the ember appears white, which indicates no to negligible impacts due to climate change. Moving up the ember bar, changing colours show the increase in risk as the earth warms globally in terms of degrees Celsius – yellow for moderate risk, red for high risk, and purple for very high risk. Definitions of the risk levels are presented in Figure FAQ16.5.1 The risk transitions are informed by the latest literature and scientific evidence, and developed through consultation and development of consensus among experts. The bars depict an averaged assessment across the world which has the disadvantage of hiding regional variation. For example, some locations or regions could face high risk even when the global risk level is moderate.

When the embers for different risk categories are placed next to each other, it is possible to compare risk levels at different levels of global warming. For example, at 1ºC warming all embers appear yellow or white, so it is possible to say that keeping global warming below that particular temperature would help ensure risks remain moderate for all five categories of concern assessed. In contrast, at 2ºC warming, risk levels have transitioned to high for all categories assessed, and even reach a very high level of risk in the case of unique and threatened systems.

[END FAQ16.5 HERE]

[START FAQ16.6 HERE]

FAQ16.6: What is the role of extreme weather events in the risks we face from climate change?

Climate change has often been perceived as a slow and gradual process but by now it is abundantly clear that many of its impacts arise through shocks, such as extreme weather events. Many places are facing more frequent and intense extremes, and also more surprises. The impact of such shocks is shaped by exposure and vulnerability, where we live, and how we are prepared for and able to cope with shocks and surprises.

The rising risk of extreme events is one of the major reasons for concern about climate change. It is clear that this risk has already increased today. Many recent disasters already have a fingerprint of climate change.

There are large differences in such risks from country to country, place to place, and person to person. This is of course partly due to differences in hazards such as heatwaves, floods, droughts, storms, storm surges, etc., and the way those hazards are influenced by climate change. However, an even more important aspect is people's exposure and vulnerability: do these hazards occur in places where people live and work, and how badly do they affect people's lives and livelihoods? Some groups are especially vulnerable, for instance elderly in the case of heatwaves, or people with disabilities in the case of floods. In general, poor and marginalised people tend to be much more affected than rich people, partly because they have less reserves and support systems that help them to prepare for, cope with and recover from a shock. On the other hand, absolute economic losses are generally higher in richer places, simply because more assets are at risk there.

Many problems caused by extreme weather do not just appear because of one weather extreme, but due to a combination of several events. For instance, dryness may increase the risk of a subsequent heatwave. But the increased risk may also cascade through human systems, for instance when several consecutive disasters erode people's savings, or when a heatwave reduces the ability of power plants to produce electricity, which subsequently affects availability of electricity to turn on air conditioning to cope with the heat. Many shocks also have impacts beyond the place where they occur, for instance when a failed harvest affects food prices elsewhere. Climate risks can also be aggravated by other shocks, such as in the case of COVID-19, which not only had a direct health impact, but also affected livelihoods around the world and left many people much more vulnerable to weather extremes.

Understanding the risks we face can help in planning for the future. This may be a combination of short-term preparation, such as early warning systems, and longer-term strategies to reduce vulnerability, for instance through urban planning, as well as reducing greenhouse gases to avoid longer-term increases in risk. Many interventions to increase people's resilience are effective in the face of a range of shocks. For instance, social safety nets can help mitigate the impact of a drought on farmers' livelihoods, but also of the economic impacts of COVID-19.

Climate-related shocks are threats to society, but they can also offer opportunities for learning and change. Recent disasters can motivate action during a short window of opportunity when awareness of the risks is higher and policy attention is focused on solutions to adapt and reduce risk. However, those windows tend to be short, and attention is often directed at the event that was recently experienced, rather than resilience in the face of a wider range of risks.

[END FAQ 16.6 HERE]

References

Abatayo, A. L. et al., 2020: Solar geoengineering may lead to excessive cooling and high strategic uncertainty, 13393-13398 pp.

Abatzoglou, J. T. and A. P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, **113**(42), 11770-11775.

Abdulai, I. et al., 2018: Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. *GLOBAL CHANGE BIOLOGY*, **24**(1), 273-286, doi:10.1111/gcb.13885.

Abe, M. and L. Ye, 2013: Building Resilient Supply Chains against Natural Disasters: The Cases of Japan and Thailand. *Global Business Review*, **14**(4), 567-586, doi:10.1177/0972150913501606.

Abel, G. J., 2019: Estimates of Global Bilateral Migration Flows by Gender between 1960 and 2015. *International Migration Review*, **0**(0), doi:10.1111/imre.12327.

Abel, G. J., M. Brottrager, J. C. Cuaresma and R. Muttarak, 2019: Climate, conflict and forced migration. *Global Environmental Change*, **54**, 239-249.

Abera, K., O. Crespo, J. Seid and F. Mequanent, 2018: Simulating the impact of climate change on maize production in Ethiopia, East Africa. *Environmental Systems Research*, **7**(1), 1-12.

Abu, R. and M. G. Reed, 2018: Adaptation through bricolage: Indigenous responses to long-term social-ecological change in the Saskatchewan River Delta, Canada. *Canadian Geographer-Geographe Canadien*, **62**(4), 437-451, doi:10.1111/cag.12469.

Acevedo-Osorio, Á., A. A. Leiton, M. V. L. Durán and K. L. F. Quiroga, 2017: Sustentability and climate variability: Participatory agroecologycal actions to adaptation and socio-ecological reesilience in the colombian high-andean region. *Revista Luna Azul*, **44**, 6-26, doi:10.17151/luaz.2017.44.2.

Acevedo, S. et al., 2017: The Effects of Weather Shocks on Economic Activity: How Can Low-Income Countries Cope. *World Economic Outlook*.

Adams, C., T. Ide, J. Barnett and A. Detges, 2018: Sampling bias in climate–conflict research. *Nature Climate Change*, doi:10.1038/s41558-018-0068-2.

Adams, H., 2016: Why populations persist: mobility, place attachment and climate change. *Population and Environment*, **37**(4), 429-448, doi:10.1007/s11111-015-0246-3.

Adams, K. et al., 2020: *Climate-Resilient Trade and Production: The Transboundary Effects of Climate Change and Their Implications for EU Member States*. SEI, ODI, IDDRI.

Adelekan, I. and T. Fregene, 2015: Vulnerability of artisanal fishing communities to flood risks in coastal southwest Nigeria. *Climate and Development*, **7**(4), 322-338, doi:10.1080/17565529.2014.951011.

Adger, W. N. et al., 2020: Urbanization, Migration, and Adaptation to Climate Change. *One Earth*, **3**(4), 396-399, doi:10.1016/j.oneear.2020.09.016.

Adger, W. N. et al., 2014: Human Security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791. ISBN 9781107058071.

Adzawla, W. and H. Baumüller, 2021: Effects of livelihood diversification on gendered climate vulnerability in Northern Ghana. *Environment, Development and Sustainability*, **23**(1), 923-946, doi:10.1007/s10668-020-00614-3.

Afriyie, K., J. K. Ganle and E. Santos, 2018: 'The floods came and we lost everything': weather extremes and households' asset vulnerability and adaptation in rural Ghana. *Climate and Development*, **10**(3), 259-274, doi:10.1080/17565529.2017.1291403.

Agarwala, M. and D. Coyle, 2020: Natural capital in climate models. *Nature Sustainability*, doi:10.1038/s41893-020-00618-x.

Agnolucci, P. and V. De Lipsis, 2019: Long-run trend in agricultural yield and climatic factors in Europe. *Climatic Change*, 1-21.

Ahlm, L. et al., 2017: Marine cloud brightening–as effective without clouds. *Atmospheric Chemistry and Physics*, **17**(21), 13071-13087.

Ahmadalipour, A., H. Moradkhani and M. Kumar, 2019: Mortality risk from heat stress expected to hit poorest nations the hardest. *Climatic Change*, **152**(3), 569-579, doi:10.1007/s10584-018-2348-2.

Ahmed, F. et al., 2018: Tipping points in adaptation to urban flooding under climate change and urban growth: The case of the Dhaka megacity. *Land Use Policy*, **79**, 496-506.

Ahmed, I. et al., 2019: Climate change impacts and adaptation strategies for agronomic crops. In: *Climate change and agriculture*. IntechOpen, pp. 1-14.

Aïta, S., 2009: *Labour Markets Performance and Migration Flows in SYRIA*. Robert Schuman Centre for Advanced Studies.

Ajibade, I., 2019: Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. *Climatic Change*, **157**(2), 299-317, doi:10.1007/s10584-019-02535-1.

Alahmad, B., A. Shakarchi, M. Alseaidan and M. Fox, 2019: The effects of temperature on short-term mortality risk in Kuwait: A time-series analysis. *Environmental research*, **171**, 278-284.
Alam, G. M. M., K. Alam, S. Mushtaq and W. L. Filho, 2018: How do climate change and associated hazards impact on the resilience of riparian rural communities in Bangladesh? Policy implications for livelihood development. *Environmental Science & Policy*, **84**, 7-18, doi:10.1016/j.envsci.2018.02.012.
Albert, S. et al., 2018: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 C future. *Regional environmental change*, **18**(8), 2261-2272.
Albert, S. et al., 2016: Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environmental Research Letters*, **11**(5), 054011.
Alegre, X. E., Z. Stanton-Geddes, S. Aliyev and V. Bun, 2020: Analyzing Flooding Impacts on Rural Access to Hospitals and Other Critical Services in Rural Cambodia Using Geo-Spatial Information and Network Analysis. 25.
Aleixo, I. et al., 2019: Amazonian rainforest tree mortality driven by climate and functional traits. *Nature Climate Change*, **9**(5), 384-388, doi:10.1038/s41558-019-0458-0.
Alfieri, L. et al., 2017: Global projections of river flood risk in a warmer world: RIVER FLOOD RISK IN A WARMER WORLD. *Earth's Future*, **5**(2), 171-182, doi:10.1002/2016EF000485.
Allen-Dumas, M. R., G. L. Toole and V. C. Tidwell, 2019: An Interdisciplinary Approach to Assessing Vulnerability of US Midwest to Drought and Heat Waves. **17**(2), 5.
Allgaier, J., 2019: Science and environmental communication on YouTube: strategically distorted communications in online videos on climate change and climate engineering. *Frontiers in Communication*, **4**, 36.
Alston, M., J. Clarke and K. Whittenbury, 2018: Limits to adaptation: Reducing irrigation water in the Murray-Darling Basin dairy communities. *Journal of Rural Studies*, **58**, 93-102, doi:10.1016/j.jrurstud.2017.12.026.
Alves, A. et al., 2019: Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal Of Environmental Management*, **239**, 244-254, doi:10.1016/j.jenvman.2019.03.036.
Andela, N. et al., 2019: The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth System Science Data*, **11**, 529-552, doi:10.5194/essd-11-529-2019.
Anderson, G. B., K. W. Oleson, B. Jones and R. D. Peng, 2018a: Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities. *Climatic Change*, **146**(3), 455-470, doi:10.1007/s10584-016-1779-x.
Anderson, L. O. et al., 2018b: Vulnerability of Amazonian forests to repeated droughts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **373**(1760), 20170411, doi:10.1098/rstb.2017.0411.
Anderson, T. and H. Singh, 2020: Participatory methodologies enable communities to assess climate-induced loss and damage. *APN Science Bulletin*, **10**(1), doi:10.30852/sb.2020.1241.
Ansuategi, A. et al., 2015: *The impact of climate change on the achievement of the post-2015 sustainable development goals*. Climate and Development Knowledge Network (CDKN), 76 pp. (accessed 2020-09-16 14:59:27).
Anthoff, D. and R. Tol, 2014: FUND-Climate Framework for Uncertainty, Negotiation and Distribution. *Available at www. fund-model. org. Accessed October*, **26**, 2015.
Antwi-Agyei, P., A. J. Dougill, L. C. Stringer and S. N. A. Codjoe, 2018: Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Climate Risk Management*, **19**, 83-93, doi:10.1016/j.crm.2017.11.003.
Arafeh-Dalmau, N. et al., 2019: Extreme Marine Heatwaves Alter Kelp Forest Community Near Its Equatorward Distribution Limit. *Frontiers in Marine Science*, **6**, 499, doi:10.3389/fmars.2019.00499.
Aragão, L. E. O. C. et al., 2018: 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, **9**(1), 536, doi:10.1038/s41467-017-02771-y.
Araos, M. et al., 2016: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science & Policy*, **66**, 375-382, doi:10.1016/j.envsci.2016.06.009.
Araos, M., K. Jagannathan and e. al., 2021: The role of equity in adaptation: a systematic global review. *Nature Sustainability*, doi:10.2139/ssrn.3782859.
Arbuthnott, K., S. Hajat, C. Heaviside and S. Vardoulakis, 2016: Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. *Environmental Health*, **15**(1), doi:10.1186/s12940-016-0102-7.
Arent, D. J. et al., 2014: Key economic sectors and services. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.
Arias, P. A. et al., 2021: Technical Summary. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Arino, Y. et al., 2016: Estimating option values of solar radiation management assuming that climate sensitivity is uncertain. *Proc. Natl. Acad. Sci. U. S. A.*, **113**(21), 5886-5891, doi:10.1073/pnas.1520795113.

Arku, F. S., 2013: Local creativity for adapting to climate change among rural farmers in the semi-arid region of Ghana. *International Journal of Climate Change Strategies and Management*, **5**(4), 418-430, doi:10.1108/IJCCSM-08-2012-0049.
Arnell, N. W. and B. Lloyd-Hughes, 2014: The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Climatic Change*, **122**(1), 127-140, doi:10.1007/s10584-013-0948-4.
Arnell, N. W., J. A. Lowe, B. Lloyd-Hughes and T. J. Osborn, 2018: The impacts avoided with a 1.5 °C climate target: a global and regional assessment. *Climatic Change*, **147**(1), 61-76, doi:10.1007/s10584-017-2115-9.
Arneth, A., 2019: *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. IPPC.
Arto, I. et al., 2019: The socioeconomic future of deltas in a changing environment. *Science of The Total Environment*, **648**, 1284-1296, doi:10.1016/j.scitotenv.2018.08.139.
Aryal, J. P. et al., 2018: Adoption of multiple climate-smart agricultural practices in the Gangetic plains of Bihar, India. *International Journal of Climate Change Strategies and Management*, **10**(3), 407-427, doi:10.1108/IJCCSM-02-2017-0025.
Aryal, S., T. N. Maraseni and G. Cockfield, 2014: Sustainability of transhumance grazing systems under socio-economic threats in Langtang, Nepal. *Journal of Mountain Science*, **11**(4), 1023-1034, doi:10.1007/s11629-013-2684-7.
Asadu, A. N., R. Ozioko, I and M. U. Dimelu, 2018: Climate Change Information Source and Indigenous Adaptation Strategies of Cucumber Farmers in Enugu State, Nigeria. *Journal of Agricultural Extension*, **22**(2), 136-146, doi:10.4314/jae.v22i2.12.
Asfaw, A., B. Simane, A. Bantider and A. Hassen, 2019: Determinants in the adoption of climate change adaptation strategies: evidence from rainfed-dependent smallholder farmers in north-central Ethiopia (Woleka sub-basin). *Environment, Development and Sustainability*, **21**(5), 2535-2565.
Ash, K. and N. Obradovich, 2020: Climatic Stress, Internal Migration, and Syrian Civil War Onset. *Journal of Conflict Resolution*, **64**(1), 3-31, doi:10.1177/0022002719864140.
Asmare, F., H. Teklewold and A. Mekonnen, 2019: The effect of climate change adaptation strategy on farm households welfare in the Nile basin of Ethiopia Is there synergy or trade-offs? *International Journal of Climate Change Strategies and Management*, **11**(4), 518-535, doi:10.1108/IJCCSM-10-2017-0192.
Asseng, S. et al., 2015: Rising temperatures reduce global wheat production. *Nature climate change*, **5**(2), 143-147.
Asseng, S., D. Spaenkuch, I. M. Hernandez-Ochoa and J. Laporta, 2021: The upper temperature thresholds of life. *Lancet Planetary Health*, **5**(6), E378-E385.
Åström, D. O., B. Forsberg, K. L. Ebi and J. Rocklöv, 2013: Attributing mortality from extreme temperatures to climate change in Stockholm, Sweden. *Nature climate change*, **3**(12), 1050-1054.
Atteridge, A. and E. Remling, 2018: Is adaptation reducing vulnerability or redistributing it? *WIREs Climate Change*, **9**(1), e500, doi:10.1002/wcc.500.
Auffhammer, M., 2018: *Climate adaptive response estimation: Short and long run impacts of climate change on residential electricity and natural gas consumption using big data*. National Bureau of Economic Research.
Austin, S. E. et al., 2016: Public Health Adaptation to Climate Change in OECD Countries. *International Journal of Environmental Research and Public Health*, **13**(9), doi:10.3390/ijerph13090889.
Averchenkova, A. et al., 2016: Multinational and large national corporations and climate adaptation: are we asking the right questions? A review of current knowledge and a new research perspective. *Wiley Interdisciplinary Reviews-Climate Change*, **7**(4), 517-536, doi:10.1002/wcc.402.
Aziz, L. and W. Sadok, 2015: Strategies used by the saffron producers of Taliouine (Morocco) to adapt to climate change. *Revue De Geographie Alpine-Journal of Alpine Research*, **103**(2), doi:10.4000/rga.2902.
Baarsch, F. et al., 2020: The impact of climate change on incomes and convergence in Africa. *World Development*, **126**, 104699, doi:10.1016/j.worlddev.2019.104699.
Baatz, C., 2016: Can We Have It Both Ways? On Potential Trade-Offs Between Mitigation and Solar Radiation Management. *Environ. Values*, **25**(1), 29-49, doi:10.3197/096327115X14497392134847.
Baffes, J., V. Kshirsagar and D. Mitchell, 2019: What Drives Local Food Prices? Evidence from the Tanzanian Maize Market. *The World Bank Economic Review*, **33**(1), 160-184, doi:10.1093/wber/lhx008.
Baker-Austin, C. et al., 2016: Heat wave–associated vibriosis, Sweden and Finland, 2014. *Emerging infectious diseases*, **22**(7), 1216.
Baker-Austin, C. et al., 2013: Emerging Vibrio risk at high latitudes in response to ocean warming. *Nature Climate Change*, **3**(1), 73-77.
Balaban, O. and J. A. Puppim de Oliveira, 2017: Sustainable buildings for healthier cities: assessing the co-benefits of green buildings in Japan. *Journal of Cleaner Production*, **163**(S), S68-S78, doi:10.1016/j.jclepro.2016.01.086.
Balaji, V., S. Ganapuram and C. Devakumar, 2015: Communication and capacity building to advance adaptation strategies in agriculture in the context of climate change in India. *Decision*, **42**(2, SI), 147-158, doi:10.1007/s40622-015-0086-0.

Baldos, U. L. C. and T. W. Hertel, 2014: Global food security in 2050: the role of agricultural productivity and climate change. *Australian Journal of Agricultural and Resource Economics*, **58**(4), 554-570, doi:10.1111/1467-8489.12048.
Banda, M. L., 2018: *Global Adaptation Law: Optimizing Legal Design for Multi-Level Public Goods after the Paris Agreement*. Social Science Research Network, Rochester, NY. Available at: https://papers.ssrn.com/abstract=3134172
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3134172 (accessed 2020/11/04/15:55:44).
Barbosa, R., R. Vicente and R. Santos, 2015: Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon. *Building and Environment*, **92**, 440-451, doi:10.1016/j.buildenv.2015.05.019.
Barnard, P. L. et al., 2021: Multiple climate change-driven tipping points for coastal systems. *Scientific Reports*, **11**(1), 15560, doi:10.1038/s41598-021-94942-7.
Barnes, J., 2009: Managing the Waters of Baʿth Country: The Politics of Water Scarcity in Syria. *Geopolitics*, **14**(3), 510-530, doi:10.1080/14650040802694117.
Barnett, J. and C. McMichael, 2018: The effects of climate change on the geography and timing of human mobility. *POPULATION AND ENVIRONMENT*, **39**(4, SI), 339-356, doi:10.1007/s11111-018-0295-5.
Barnett, J. and S. J. O'Neill, 2013: Minimising the risk of maladaptation: a framework for analysis. In: *Climate Adaptation Futures*. Wiley, pp. 87-93.
Barreca, A. et al., 2015: Convergence in Adaptation to Climate Change: Evidence from High Temperatures and Mortality, 1900-2004. *American Economic Review*, **105**(5), 247-251, doi:10.1257/aer.p20151028.
Barriopedro, D. et al., 2011: The hot summer of 2010: redrawing the temperature record map of Europe. *Science*, **332**(6026), 220-224.
Barrios, S., L. Bertinelli and E. Strobl, 2010: Trends in rainfall and economic growth in Africa: A neglected cause of the african growth tragedy. *Review of Economics and Statistics*, **92**(2), 350-366, doi:10.1162/rest.2010.11212.
Bastien-Olvera, B. A. and F. C. Moore, 2021: Use and non-use value of nature and the social cost of carbon. *Nature Sustainability*, **4**(2), 101-108.
Bauer, A. and R. Steurer, 2014: Multi-level governance of climate change adaptation through regional partnerships in Canada and England. *GEOFORUM*, **51**, 121-129, doi:10.1016/j.geoforum.2013.10.006.
Bauer, A. and R. Steurer, 2015: National Adaptation Strategies, what else? Comparing adaptation mainstreaming in German and Dutch water management. *Regional Environmental Change*, **15**(2), 341-352, doi:10.1007/s10113-014-0655-3.
Bauer, K., 2013: Are preventive and coping measures enough to avoid loss and damage from flooding in Udayapur district, Nepal? *International Journal of Global Warming*, **5**(4), 433, doi:10.1504/IJGW.2013.057292.
Baumann, M. and T. Kuemmerle, 2016: The impacts of warfare and armed conflict on land systems. *Journal of Land Use Science*, **11**(6), 672-688, doi:10.1080/1747423X.2016.1241317.
Bebber, D. P., M. A. T. Ramotowski and S. J. Gurr, 2013: Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, **3**(11), 985-988, doi:10.1038/nclimate1990.
Beck, M. W. et al., 2018: The global flood protection savings provided by coral reefs. *Nature Communications*, **9**(1), 2186, doi:10.1038/s41467-018-04568-z.
Bednar, D. and D. Henstra, 2018: Applying a Typology of Governance Modes to Climate Change Adaptation. *POLITICS AND GOVERNANCE*, **6**(3), 147-158, doi:10.17645/pag.v6i3.1432.
Beer, C. et al., 2010: Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate, 834-838 pp.
Begum, A. and R. Mahanta, 2017: Adaptation to climate change and factors affecting it in Assam. *Indian Journal of Agricultural Economics*, **72**(3), 446-455.
BEH UNU-EHS, 2016: *World Risk Report*. United Nations University Institute for Environment and Human Security (UNU-EHS) Bündnis Entwicklung Hilft (BEH).
Beiler, M. O., L. Marroquin and S. McNeil, 2016: State-of-the-practice assessment of climate change adaptation practices across metropolitan planning organizations pre- and post-Hurricane Sandy. *TRANSPORTATION RESEARCH PART A-POLICY AND PRACTICE*, **88**, 163-174, doi:10.1016/j.tra.2016.04.003.
Beine, M. and C. R. Parsons, 2017: Climatic Factors as Determinants of International Migration: Redux. *CESifo Econ. Stud.*, **63**(4), 386-402, doi:10.1093/cesifo/ifx017.
Belanger, D. et al., 2016: A multilevel analysis to explain self-reported adverse health effects and adaptation to urban heat: a cross-sectional survey in the deprived areas of 9 Canadian cities. *BMC PUBLIC HEALTH*, **16**, doi:10.1186/s12889-016-2749-y.
Bele, M. Y., D. J. Sonwa and A. M. Tiani, 2014: Local Communities Vulnerability to Climate Change and Adaptation Strategies in Bukavu in DR Congo. *Journal Of Environment & Development*, **23**(3), 331-357, doi:10.1177/1070496514536395.
Bell, A. R. et al., 2021: Migration towards Bangladesh coastlines projected to increase with sea-level rise through 2100. *Environmental Research Letters*, **16**(2), 024045, doi:10.1088/1748-9326/abdc5b.
Bellemare, M. F., 2015: Rising Food Prices, Food Price Volatility, and Social Unrest. *American Journal of Agricultural Economics*, **97**(1), 1-21, doi:10.1093/ajae/aau038.

Benito-Garzon, M., H. D. Minh, N. Frascaria-Lacoste and J. Fernandez-Manjarres, 2013: Habitat Restoration and Climate Change: Dealing with Climate Variability, Incomplete Data, and Management Decisions with Tree Translocations. *Restoration Ecology*, **21**(5), 530-536, doi:10.1111/rec.12032.
Bennett, C. M., K. B. Dear and A. J. McMichael, 2014: Shifts in the seasonal distribution of deaths in Australia, 1968–2007. *International journal of biometeorology*, **58**(5), 835-842.
Benveniste, H., M. Oppenheimer and M. Fleurbaey, 2020: Effect of border policy on exposure and vulnerability to climate change. *Proceedings of the National Academy of Sciences*, **117**(43), 26692, doi:10.1073/pnas.2007597117.
Benzie, M. et al., 2018: *Meeting the global challenge of adaptation by addressing transboundary climate risk: A joint collaboration between SEI, IDDRI, and ODI*. Stockholm Environment Institute, Stockholm, Sweden, 10 pp. Available at: https://www.sei.org/publications/transboundary-climate-risk/.
Benzie, M. and Å. Persson, 2019: Governing borderless climate risks: moving beyond the territorial framing of adaptation. *International Environmental Agreements: Politics, Law and Economics*, **19**(4-5), 369-393, doi:10.1007/s10784-019-09441-y.
Berga, L., 2016: The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. *Engineering*, **2**(3), 313-318, doi:10.1016/j.eng.2016.03.004.
Berhanu, W. and F. Beyene, 2015: Climate Variability and Household Adaptation Strategies in Southern Ethiopia. *Sustainability*, **7**(6), 6353-6375, doi:10.3390/su7066353.
Berlemann, M. and D. Wenzel, 2016: Long-term Growth Effects of Natural Disasters. *Economics bulletin: EB*.
Berlemann, M. and D. Wenzel, 2018: Hurricanes, economic growth and transmission channels: Empirical evidence for countries on differing levels of development. *World Development*, **105**, 231-247.
Bernauer, T. and T. Böhmelt, 2020: International conflict and cooperation over freshwater resources. *Nature Sustainability*, 1-7.
Berrang-Ford, L., T. Pearce and J. D. Ford, 2015: Systematic review approaches for climate change adaptation research. *REGIONAL ENVIRONMENTAL CHANGE*, **15**(5, SI), 755-769, doi:10.1007/s10113-014-0708-7.
Berrang-Ford, L. et al., 2021a: Mapping evidence of human adaptation to climate change. *Nature Climate Change*, doi:10.21203/rs.3.rs-100873/v1.
Berrang-Ford, L. et al., 2021b: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, doi:10.21203/rs.3.rs-100873/v1.
Betzold, C., 2015: Adapting to climate change in small island developing states. *Climatic Change*, **133**(3), 481-489, doi:10.1007/s10584-015-1408-0.
Bhatta, G. D. and P. K. Aggarwal, 2016: Coping with weather adversity and adaptation to climatic variability: a cross-country study of smallholder farmers in South Asia. *Climate and Development*, **8**(2), 145-157, doi:10.1080/17565529.2015.1016883.
Biagini, B. et al., 2014: A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. *GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS*, **25**, 97-108, doi:10.1016/j.gloenvcha.2014.01.003.
Biermann, F. and I. Möller, 2019: Rich man's solution? Climate engineering discourses and the marginalization of the Global South. *International Environmental Agreements: Politics, Law and Economics*, **19**(2), 151-167.
Biesbroek, R., S. Badloe and I. N. Athanasiadis, 2020: Machine learning for research on climate change adaptation policy integration: an exploratory UK case study. *Regional Environmental Change*, **20**(3), doi:10.1007/s10113-020-01677-8.
Biesbroek, R. et al., 2018: Data, concepts and methods for large-n comparative climate change adaptation policy research: A systematic literature review. *WILEY INTERDISCIPLINARY REVIEWS-CLIMATE CHANGE*, **9**(6), doi:10.1002/wcc.548.
Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Birkmann, J. et al., 2021: Regional clusters of vulnerability show the need for transboundary cooperation. *Environmental Research Letters*.
Birkmann, J. et al., 2022: Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning. *Science of the Total Environment*, **803**, doi:10.1016/j.scitotenv.2021.150065.
Birkmann, J. et al., 2016: Extreme Events, Critical Infrastructures, Human Vulnerability and Strategic Planning: Emerging Research Issues. *Journal of Extreme Events*, **03**(04), 1650017, doi:10.1142/S2345737616500172.
Black, R. et al., 2013: Migration, immobility and displacement outcomes following extreme events. *Environmental Science & Policy*, **27**, S32-S43, doi:10.1016/j.envsci.2012.09.001.
Blanc, D. L., 2015: Towards integration at last? The sustainable development goals as a network of targets. *UN/DESA Working Papers*, **141**, 19.
Boas, I. et al., 2019: Climate migration myths. *Nature Climate Change*, **9**(12), 901-903.
Bobb, J. F., R. D. Peng, M. L. Bell and F. Dominici, 2014: Heat-Related Mortality and Adaptation to Heat in the United States. *ENVIRONMENTAL HEALTH PERSPECTIVES*, **122**(8), 811-816, doi:10.1289/ehp.1307392.

Boeckmann, M. and I. Rohn, 2014: Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. *BMC PUBLIC HEALTH*, **14**, doi:10.1186/1471-2458-14-1112.
Boelee, E. et al., 2013: Options for water storage and rainwater harvesting to improve health and resilience against climate change in Africa. *Regional Environmental Change*, **13**(3, SI), 509-519, doi:10.1007/s10113-012-0287-4.
Booth, L. et al., 2020: Simulating synergies between Climate Change Adaptation and Disaster Risk Reduction stakeholders to improve management of transboundary disasters in Europe. *International Journal of Disaster Risk Reduction*, **49**, 101668, doi:10.1016/j.ijdrr.2020.101668.
Bose, P., 2017: Climate adaptation: marginal populations in the vulnerable regions. *Climate and Development*, **9**(6), 575-578, doi:10.1080/17565529.2017.1318747.
Botzen, W. W., O. Deschenes and M. Sanders, 2019: The economic impacts of natural disasters: A review of models and empirical studies. *Review of Environmental Economics and Policy*, **13**(2), 167-188.
Boutin, S. and J. E. Lane, 2014: Climate change and mammals: evolutionary versus plastic responses. *EVOLUTIONARY APPLICATIONS*, **7**(1, SI), 29-41, doi:10.1111/eva.12121.
Bowen, K. J. and K. L. Ebi, 2015: Governing the health risks of climate change: towards multi-sector responses. *CURRENT OPINION IN ENVIRONMENTAL SUSTAINABILITY*, **12**, 80-85, doi:10.1016/j.cosust.2014.12.001.
Braithwaite, A., N. Dasandi and D. Hudson, 2016: Does poverty cause conflict? Isolating the causal origins of the conflict trap. *Conflict Management and Peace Science*, **33**(1), 45-66, doi:10.1177/0738894214559673.
Bramsen, I., 2020: From civil resistance to civil war: Nonstrategic mechanisms of militarization in the Syrian uprising. *Peace & Change*, **45**(2), 256-286.
Bren d'Amour, C. et al., 2016: Teleconnected food supply shocks. *Environmental Research Letters*, **11**(3), 035007, doi:10.1088/1748-9326/11/3/035007.
Brienen, R. J. W. et al., 2015: Long-term decline of the Amazon carbon sink. *Nature*, **519**(7543), 344-348, doi:10.1038/nature14283.
Broto, V. C. and H. Bulkeley, 2013: A survey of urban climate change experiments in 100 cities. *GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS*, **23**(1), 92-102, doi:10.1016/j.gloenvcha.2012.07.005.
Brown, S. et al., 2021: Global costs of protecting against sea-level rise at 1.5 to 4.0 °C. *Climatic Change*, **167**(1), 4, doi:10.1007/s10584-021-03130-z.
Brzoska, M. and C. Fröhlich, 2016: Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migration and Development*, **5**(2), 190-210.
Buck, H. J. et al., 2020: Evaluating the efficacy and equity of environmental stopgap measures. *Nature Sustainability*, **3**(7), 499-504, doi:10.1038/s41893-020-0497-6.
Budolfson, M. et al., 2019: Optimal climate policy and the future of world economic development. *The World Bank Economic Review*, **33**(1), 21-40.
Buhaug, H., M. Croicu, H. Fjelde and N. von Uexkull, 2020: A conditional model of local income shock and civil conflict. *The Journal of Politics*, doi:10.1086/709671.
Burke, M., W. M. Davis and N. S. Diffenbaugh, 2018: Large potential reduction in economic damages under UN mitigation targets. *Nature*, **557**(7706), 549-553, doi:10.1038/s41586-018-0071-9.
Burke, M., S. M. Hsiang and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**(7577), 235-239, doi:10.1038/nature15725.
Burns, E. T. et al., 2016: What do people think when they think about solar geoengineering? A review of empirical social science literature, and prospects for future research. *Earth's Future*, **4**(11), 536-542.
Burrell, A., J. Evans and M. De Kauwe, 2020: Anthropogenic climate change has driven over 5 million km 2 of drylands towards desertification. *Nature communications*, **11**(1), 1-11.
Burrows, K. and P. Kinney, 2016: Exploring the Climate Change, Migration and Conflict Nexus. *International Journal of Environmental Research and Public Health*, **13**(4), 443, doi:10.3390/ijerph13040443.
Burton, C., R. A. Betts, C. D. Jones and K. Williams, 2018: Will fire danger be reduced by using Solar Radiation Management to limit global warming to 1.5 C compared to 2.0 C? *Geophys. Res. Lett.*, **45**(8), 3644-3652.
Burton, C. et al., 2021: South American fires and their impacts on ecosystems increase with continued emissions. *Climate Resilience and Sustainability*, **n/a**(n/a), e8, doi:https://doi.org/10.1002/cli2.8.
Busby, J. W., 2018: Taking Stock: the Field of Climate and Security. *Current Climate Change Reports*, **4**(4), 338-346, doi:10.1007/s40641-018-0116-z.
Butler, E. E., N. D. Mueller and P. Huybers, 2018: Peculiarly pleasant weather for US maize. *Proceedings of the National Academy of Sciences*, **115**(47), 11935-11940, doi:10.1073/pnas.1808035115.
Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, **13**(5), 055012, doi:10.1088/1748-9326/aabf45.
Caddell, R., 2018: Precautionary Management and the Development of Future Fishing Opportunities: The International Regulation of New and Exploratory Fisheries. *Int. J. Mar. Coast. Law*, **33**(1), 199-260, doi:10.1163/15718085-13310013.
Cai, R., S. Feng, M. Oppenheimer and M. Pytlikova, 2016a: Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management*, **79**, 135-151.
Cai, W. et al., 2014: Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, **4**(2), 111-116, doi:10.1038/nclimate2100.

Cai, Y. et al., 2015: Environmental tipping points significantly affect the cost− benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112**(15), 4606-4611.
Cai, Y., T. M. Lenton and T. S. Lontzek, 2016b: Risk of multiple interacting tipping points should encourage rapid CO 2 emission reduction. *Nature Climate Change*, **6**(5), 520-525.
Cai, Y. and T. S. Lontzek, 2019: The social cost of carbon with economic and climate risks. *Journal of Political Economy*, **127**(6), 2684-2734.
Calel, R., S. C. Chapman, D. A. Stainforth and N. W. Watkins, 2020: Temperature variability implies greater economic damages from climate change. *Nature communications*, **11**(1), 1-5.
Callaghan, M. et al., 2021: Machine learning-based evidence and attribution mapping of 100,000 climate impact studies.
Callies, D. E., 2019: The Slippery Slope Argument against Geoengineering Research. *J. Appl. Philos.*, **36**(4), 675-687, doi:10.1111/japp.12345.
Caminade, C. et al., 2014: Impact of climate change on global malaria distribution. *Proceedings of the National Academy of Sciences*, **111**(9), 3286-3291.
Canosa, I., V et al., 2020: Progress in climate change adaptation in the Arctic. *ENVIRONMENTAL RESEARCH LETTERS*, **15**(9), doi:10.1088/1748-9326/ab9be1.
Caprotti, F., C. Springer and N. Harmer, 2015: 'Eco' For Whom? Envisioning Eco-urbanism in the Sino-Singapore Tianjin Eco-city, China. *International Journal of Urban and Regional Research*, **39**(3), 495-517, doi:10.1111/1468-2427.12233.
Cardona, O.-D. et al., 2012: Determinants of Risk: Exposure and Vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C. B., V. Barros, T. F. Stocker and Q. Dahe (eds.)]. Cambridge University Press, Cambridge, pp. 65-108. ISBN 978-1-139-17724-5.
Carleton, T. A. et al., 2020: *Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits*. National Bureau of Economic Research.
Carlson, C. J. et al., 2020: Solar geoengineering could redistribute malaria risk in developing countries. *medRxiv*.
Carlton, E. J. et al., 2014: Heavy rainfall events and diarrhea incidence: the role of social and environmental factors. *American journal of epidemiology*, **179**(3), 344-352.
Carlton, E. J. et al., 2016: A systematic review and meta-analysis of ambient temperature and diarrhoeal diseases. *International Journal of Epidemiology*, **45**(1), 117-130, doi:10.1093/ije/dyv296.
Carr, E. R. and M. C. Thompson, 2014: Gender and Climate Change Adaptation in Agrarian Settings: Current Thinking, New Directions, and Research Frontiers. *Geography Compass*, **8**(3), 182-197, doi:10.1111/gec3.12121.
Carr, W. A. and L. Yung, 2018: Perceptions of climate engineering in the South Pacific, Sub-Saharan Africa, and North American Arctic. *Clim. Change*, **147**(1-2), 119-132.
Carrão, H., G. Naumann and P. Barbosa, 2018: Global projections of drought hazard in a warming climate: a prime for disaster risk management. *Climate Dynamics*, **50**(5), 2137-2155, doi:10.1007/s00382-017-3740-8.
Carter, T. R. et al., 2021: A conceptual framework for cross-border impacts of climate change. *Global Environmental Change*, **69**, 102307, doi:10.1016/j.gloenvcha.2021.102307.
Cartwright, A. et al., 2013: Economics of climate change adaptation at the local scale under conditions of uncertainty and resource constraints: the case of Durban, South Africa. *ENVIRONMENT AND URBANIZATION*, **25**(1), 139-156, doi:10.1177/0956247813477814.
Cattaneo, C. et al., 2019: Human Migration in the Era of Climate Change. *Review of Environmental Economics and Policy*, **13**(2), 189-206, doi:10.1093/reep/rez008.
Cattaneo, C. and G. Peri, 2016: The migration response to increasing temperatures. *Journal of Development Economics*, **122**, 127-146.
Cernev, T. and R. Fenner, 2020: The importance of achieving foundational Sustainable Development Goals in reducing global risk. *Futures*, **115**, 102492, doi:10.1016/j.futures.2019.102492.
Cervigni, R., R. Liden, J. E. Neumann and K. M. Strzepek, 2015: *Enhancing the Climate Resilience of Africa's Infrastructure : The Power and Water Sectors*. World Bank Publications.
Cevik, S. and J. Jalles, 2020: *Feeling the Heat: Climate Shocks and Credit Ratings*.
Challinor, A. J., W. N. Adger and T. G. Benton, 2017: Climate risks across borders and scales. *Nature Climate Change*, **7**(9), 621-623, doi:10.1038/nclimate3380.
Challinor, A. J. et al., 2018: Transmission of climate risks across sectors and borders. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2121), 20170301, doi:10.1098/rsta.2017.0301.
Chapman, A. D. et al., 2016: Adaptation and development trade-offs: fluvial sediment deposition and the sustainability of rice-cropping in An Giang Province, Mekong Delta. *CLIMATIC CHANGE*, **137**(3-4), 593-608, doi:10.1007/s10584-016-1684-3.
Charmantier, A. and P. Gienapp, 2014: Climate change and timing of avian breeding and migration: evolutionary versus plastic changes. *EVOLUTIONARY APPLICATIONS*, **7**(1, SI), 15-28, doi:10.1111/eva.12126.
Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, **26**(11), 6134-6155, doi:10.1111/gcb.15310.

Chen, K., A. M. Vicedo-Cabrera and R. Dubrow, 2020a: Projections of Ambient Temperature-and Air Pollution-Related Mortality Burden Under Combined Climate Change and Population Aging Scenarios: a Review. *Current environmental health reports*, 1-13.
Chen, Y., A. Liu and X. Cheng, 2020b: Quantifying economic impacts of climate change under nine future emission scenarios within CMIP6. *Science of The Total Environment*, **703**, 134950.
Chengappa, P. G., C. M. Devika and C. S. Rudragouda, 2017: Climate variability and mitigation: perceptions and strategies adopted by traditional coffee growers in India. *CLIMATE AND DEVELOPMENT*, **9**(7), 593-604, doi:10.1080/17565529.2017.1318740.
Chester, M. V., B. S. Underwood and C. Samaras, 2020: Keeping infrastructure reliable under climate uncertainty. *Nature Climate Change*, **10**(6), 488-490, doi:10.1038/s41558-020-0741-0.
Cheung, W. W. L., J. Bruggeman and M. Butenschön, 2018a: Chapter 4: Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century. In: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations, Rome, pp. 63-86. ISBN 78-92-5-130607-9.
Cheung, W. W. L., M. C. Jones, G. Reygondeau and T. L. Frölicher, 2018b: Opportunities for climate-risk reduction through effective fisheries management. *Global Change Biology*, **24**(11), 5149-5163, doi:10.1111/gcb.14390.
Chimhowu, A. O., Hulme, D., Munro, L.T., 2019: The 'New' national development planning and global development goals: Processes and partnerships. *World Development*, **120**, 76-89, doi:10.1016/j.worlddev.2019.03.013.
Chirambo, D., 2016: Moving past the rhetoric: Policy considerations that can make Sino-African relations to improve Africa's climate change resilience and the attainment of the sustainable development goals. *Advances in Climate Change Research*, **7**(4), 253-263, doi:10.1016/j.accre.2016.11.002.
Christen, B. and T. Dalgaard, 2013: Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation. *Biomass & Bioenergy*, **55**, 53-67, doi:10.1016/j.biombioe.2012.09.053.
Christian-Smith, J., M. C. Levy and P. H. Gleick, 2015: Maladaptation to drought: a case report from California, USA. *SUSTAINABILITY SCIENCE*, **10**(3), 491-501, doi:10.1007/s11625-014-0269-1.
Christidis, N., G. C. Donaldson and P. A. Stott, 2010: Causes for the recent changes in cold-and heat-related mortality in England and Wales. *Climatic Change*, **102**(3-4), 539-553.
Chua, P. L. C. et al., 2021: Global projections of temperature-attributable mortality due to enteric infections: a modelling study. *The Lancet Planetary Health*, **5**(7), e436-e445, doi:10.1016/S2542-5196(21)00152-2.
Chung, Y. et al., 2017: Temporal Changes in Mortality Related to Extreme Temperatures for 15 Cities in Northeast Asia: Adaptation to Heat and Maladaptation to Cold. *AMERICAN JOURNAL OF EPIDEMIOLOGY*, **185**(10), 907-913, doi:10.1093/aje/kww199.
Cingano, F., 2014: *Trends in Income Inequality and its Impact on Economic Growth*. (accessed 2020-09-03 11:39:16).
Ciscar, J.-C. and P. Dowling, 2014: Integrated assessment of climate impacts and adaptation in the energy sector. *Energy Economics*, **46**, 531-538, doi:10.1016/j.eneco.2014.07.003.
Clarke, B. J., F. E. L. Otto and R. G. Jones, 2021: Inventories of extreme weather events and impacts: Implications for loss and damage from and adaptation to climate extremes, 100285 pp.
Clay, N. and B. King, 2019: Smallholders' uneven capacities to adapt to climate change amid Africa's `green revolution': Case study of Rwanda's crop intensification program. *WORLD DEVELOPMENT*, **116**, 1-14, doi:10.1016/j.worlddev.2018.11.022.
Cohen, J. M., M. J. Lajeunesse and J. R. Rohr, 2018: A global synthesis of animal phenological responses to climate change. *Nature Climate Change*, **8**(3), 224-228, doi:10.1038/s41558-018-0067-3.
Colón-González, F. J. et al., 2018: Limiting global-mean temperature increase to 1.5–2 °C could reduce the incidence and spatial spread of dengue fever in Latin America. *Proceedings of the National Academy of Sciences*, **115**(24), 6243-6248, doi:10.1073/pnas.1718945115.
Comyn-Platt, E. et al., 2018: Carbon budgets for 1.5 and 2 °C targets lowered by natural wetland and permafrost feedbacks. *Nature Geoscience*, **11**(8), 568-573, doi:10.1038/s41561-018-0174-9.
Condie, S. A. et al., 2021: Large-scale interventions may delay decline of the Great Barrier Reef. *Royal Society Open Science*, **8**(4), 201296, doi:doi:10.1098/rsos.201296.
Conevska, A., J. Ford, A. Lesnikowski and S. Harper, 2019: Adaptation financing for projects focused on food systems through the UNFCCC. *CLIMATE POLICY*, **19**(1), 43-58, doi:10.1080/14693062.2018.1466682.
Coniglio, N. D. and G. Pesce, 2015: Climate variability and international migration: An empirical analysis. *Environ. Dev. Econ.*, **20**(4), 434-468, doi:10.1017/S1355770X14000722.
Cooper, M. W. et al., 2019: Mapping the effects of drought on child stunting. *Proceedings of the National Academy of Sciences*, **116**(35), 17219-17224, doi:10.1073/pnas.1905228116.
Costantini, E. A. C. et al., 2020: Local adaptation strategies to increase or maintain soil organic carbon content under arable farming in Europe: Inspirational ideas for setting operational groups within the European innovation partnership. *JOURNAL OF RURAL STUDIES*, **79**, 102-115, doi:10.1016/j.jrurstud.2020.08.005.
Coughlan de Perez, E. et al., 2016: Action-based flood forecasting for triggering humanitarian action. *Hydrology and Earth System Sciences*, **20**(9), 3549-3560.

Couper, L. I., A. J. MacDonald and E. A. Mordecai, 2020: Impact of prior and projected climate change on US Lyme disease incidence. *bioRxiv*, 2020.2001.2031.929380, doi:10.1101/2020.01.31.929380.
Craft, J. and M. Howlett, 2013: Policy Capacity and the Ability to Adapt to Climate Change: Canadian and U.S. Case Studies. *REVIEW OF POLICY RESEARCH*, **30**(1, SI), 1-18, doi:10.1111/ropr.12000.
Craft, J., M. Howlett, M. Crawford and K. McNutt, 2013: Assessing Policy Capacity for Climate Change Adaptation: Governance Arrangements, Resource Deployments, and Analytical Skills in Canadian Infrastructure Policy Making. *REVIEW OF POLICY RESEARCH*, **30**(1, SI), 42-65, doi:10.1111/ropr.12002.
Craig, R. K., 2019: Coastal adaptation, government-subsidized insurance, and perverse incentives to stay. *CLIMATIC CHANGE*, **152**(2, SI), 215-226, doi:10.1007/s10584-018-2203-5.
Cramer, W. et al., 2014: Detection and Attribution of Observed Impacts. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 979-1037. ISBN 9781107058071.
Crespo Cuaresma, J., 2017: Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, **42**, 226-236, doi:10.1016/j.gloenvcha.2015.02.012.
Crichton, R. and M. Esteban, 2018: Limits to Coastal Adaptation in Samoa: Insights and Experiences. In: *Limits to Climate Change Adaptation* [Leal Filho, W. and J. Nalau (eds.)]. Springer International Publishing, Cham, pp. 283-300. ISBN 978-3-319-64598-8 978-3-319-64599-5.
Crook, J., L. Jackson, S. Osprey and P. Forster, 2015a: A comparison of temperature and precipitation responses to different Earth radiation management geoengineering schemes. *Journal of Geophysical Research: Atmospheres*, **120**(18), 9352-9373.
Crook, J. A., L. S. Jackson, S. M. Osprey and P. M. Forster, 2015b: A comparison of temperature and precipitation responses to different Earth radiation management geoengineering schemes. *J. Geophys. Res. D: Atmos.*, **120**(18), 9352-9373, doi:10.1002/2015JD023269.
Cropper, M. et al., 2017: Valuing climate damages: updating estimation of the social cost of carbon dioxide. *URL https://www. nap. edu/catalog/24651/valuing-climate-damagesupdating-estimation-of-the-social-cost-of.*
Crost, B. and C. P. Traeger, 2013: Optimal climate policy: uncertainty versus Monte Carlo. *Economics Letters*, **120**(3), 552-558.
Cumming, O. et al., 2019: The implications of three major new trials for the effect of water, sanitation and hygiene on childhood diarrhea and stunting: a consensus statement. *BMC Medicine*, **17**(1), 173, doi:10.1186/s12916-019-1410-x.
Cummings, C. L., S. H. Lin and B. D. Trump, 2017: Public perceptions of climate geoengineering: a systematic review of the literature. *Clim. Res.*, **73**(3), 247-264, doi:10.3354/cr01475.
Cunsolo, A. and N. R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8**(4), 275-281, doi:10.1038/s41558-018-0092-2.
Currenti, R. et al., 2019: Adaptation to Climate Change in an Interior Pacific Island Village: a Case Study of Nawairuku, Ra, Fiji. *HUMAN ECOLOGY*, **47**(1), 65-80, doi:10.1007/s10745-019-0049-8.
Curry, C. L. et al., 2014: A multimodel examination of climate extremes in an idealized geoengineering experiment. *J. Geophys. Res. D: Atmos.*, **119**(7), 3900-3923, doi:10.1002/2013JD020648.
D'haen, S. A. L., J. O. Nielsen and E. F. Lambin, 2014: Beyond local climate: rainfall variability as a determinant of household nonfarm activities in contemporary rural Burkina Faso. *CLIMATE AND DEVELOPMENT*, **6**(2), 144-165, doi:10.1080/17565529.2013.867246.
Dagon, K. and D. P. Schrag, 2019: Quantifying the effects of solar geoengineering on vegetation, 235-251 pp.
Dahl, K. A. et al., 2017: Effective inundation of continental United States communities with 21st century sea level rise. *Elementa: Science of the Anthropocene*, **5**.
Dai, Z., D. K. Weisenstein, F. N. Keutsch and D. W. Keith, 2020: Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering. *Communications Earth & Environment*, **1**(1), 1-9.
Dalin, C., Y. Wada, T. Kastner and M. J. Puma, 2017: Groundwater depletion embedded in international food trade. *Nature*, **543**(7647), 700-704, doi:10.1038/nature21403.
Dang, T. N. et al., 2016: Characterizing the relationship between temperature and mortality in tropical and subtropical cities: a distributed lag non-linear model analysis in Hue, Viet Nam, 2009–2013. *Global health action*, **9**(1), 28738.
Daniel, K. D., R. B. Litterman and G. Wagner, 2015: Applying Asset Pricing Theory to Calibrate the Price of Climate Risk: A Declining Optimal Price for Carbon Emissions. *Columbia Graduate School of Business working paper*.
Dannenberg, A. L., H. Frumkin, J. J. Hess and K. L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: public health implications. *Climatic Change*, **153**(1-2), 1-14, doi:10.1007/s10584-019-02382-0.
Darwin, R. F. and R. S. Tol, 2001: Estimates of the economic effects of sea level rise. *Environmental and Resource Economics*, **19**(2), 113-129.
Davin, E. L. et al., 2014: Preferential cooling of hot extremes from cropland albedo management. *Proceedings of the National Academy of Sciences*, **111**(27), 9757-9761.

Davis, K. F., A. Bhattachan, P. D'Odorico and S. Suweis, 2018: A universal model for predicting human migration under climate change: examining future sea level rise in Bangladesh. *Environmental Research Letters*, **13**(6), 064030, doi:10.1088/1748-9326/aac4d4.
Davis, K. T. et al., 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, **116**(13), 6193-6198, doi:10.1073/pnas.1815107116.
Dawson, D., J. Shaw and W. Roland Gehrels, 2016: Sea-level rise impacts on transport infrastructure: The notorious case of the coastal railway line at Dawlish, England. *Journal of Transport Geography*, **51**, 97-109, doi:10.1016/j.jtrangeo.2015.11.009.
Dawson, R. J. et al., 2018: A systems framework for national assessment of climate risks to infrastructure. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2121), 20170298, doi:10.1098/rsta.2017.0298.
Day, J. W. et al., 2016: Approaches to defining deltaic sustainability in the 21st century. *Estuarine, Coastal and Shelf Science*, **183**, 275-291, doi:10.1016/j.ecss.2016.06.018.
De Châtel, F., 2014: The role of drought and climate change in the Syrian uprising: Untangling the triggers of the revolution. *Middle Eastern Studies*, **50**(4), 521-535.
de Coninck, H. et al., 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
De Hoyos, R. E. and D. Medvedev, 2009: *Poverty effects of higher food prices: a global perspective*. The World Bank.
De la Sota, C., V. J. Ruffato-Ferreira, L. Ruiz-Garcia and S. Alvarez, 2019: Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain. *URBAN FORESTRY & URBAN GREENING*, **40**(SI), 145-151, doi:10.1016/j.ufug.2018.09.004.
de Lima, C. Z. et al., 2021: Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters*, **16**(4), 044020, doi:10.1088/1748-9326/abeb9f.
de Sousa, K. et al., 2018: How climate awareness influences farmers' adaptation decisions in Central America? *JOURNAL OF RURAL STUDIES*, **64**, 11-19, doi:10.1016/j.jrurstud.2018.09.018.
de Waal, A., 2018: The end of famine? Prospects for the elimination of mass starvation by political action. *Political Geography*, **62**, 184-195, doi:10.1016/j.polgeo.2017.09.004.
De'Donato, F. K. et al., 2015: Changes in the effect of heat on mortality in the last 20 years in nine European cities. Results from the PHASE project. *International journal of environmental research and public health*, **12**(12), 15567-15583.
Debray, V. et al., 2019: Agroecological practices for climate change adaptation in semiarid and subhumid Africa. *AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS*, **43**(4), 429-456, doi:10.1080/21683565.2018.1509166.
DeFries, R. S. et al., 2019: The missing economic risks in assessments of climate change impacts.
Dell, M., B. F. Jones and B. A. Olken, 2012: Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, **4**(3), 66-95, doi:10.1257/mac.4.3.66.
Dell, M., B. F. Jones and B. A. Olken, 2014: What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature*, **52**(3), 740-798.
Dellink, R., E. Lanzi and J. Chateau, 2019: The sectoral and regional economic consequences of climate change to 2060. *Environmental and Resource Economics*, **72**(2), 309-363.
Dennig, F. et al., 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112**(52), 15827-15832.
Deryugina, T. and S. Hsiang, 2017: *The marginal product of climate*. National Bureau of Economic Research.
Descloux, E. et al., 2012: Climate-Based Models for Understanding and Forecasting Dengue Epidemics, e1470 pp.
Detges, A., 2017: Droughts, state-citizen relations and support for political violence in Sub-Saharan Africa: A micro-level analysis. *Political Geography*, **61**, 88-98, doi:10.1016/j.polgeo.2017.07.005.
Deutsch, C. A. et al., 2018: Increase in crop losses to insect pests in a warming climate. *Science*, **361**(6405), 916-919, doi:10.1126/science.aat3466.
Diaz, D. and F. Moore, 2017: Quantifying the economic risks of climate change. *Nature Climate Change*, **7**(11), 774-782, doi:10.1038/nclimate3411.
Diederichs, N. and D. Roberts, 2016: Climate protection in mega-event greening: the 2010 FIFA World Cup and COP17/CMP7 experiences in Durban, South Africa. *CLIMATE AND DEVELOPMENT*, **8**(4), 376-384, doi:10.1080/17565529.2015.1085361.
Dietz, S. and N. Stern, 2015: Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, **125**(583), 574-620.
Dietz, S. and F. Venmans, 2019: Cumulative carbon emissions and economic policy: in search of general principles. *Journal of Environmental Economics and Management*, **96**, 108-129.

Diffenbaugh, N. S. and M. Burke, 2019: Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences*, **116**(20), 9808-9813.
Diffenbaugh, N. S. et al., 2017: Quantifying the influence of global warming on unprecedented extreme climate events. *Proceedings of the National Academy of Sciences*, **114**(19), 4881-4886.
Djoudi, H. et al., 2016: Beyond dichotomies: Gender and intersecting inequalities in climate change studies. *AMBIO*, **45**(3, SI), S248-S262, doi:10.1007/s13280-016-0825-2.
Doelman, J. C., E. Stehfest, A. Tabeau and H. van Meijl, 2019: Making the Paris agreement climate targets consistent with food security objectives. *Global Food Security*, **23**, 93-103, doi:10.1016/j.gfs.2019.04.003.
Doelman, J. C. et al., 2020: Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Global Change Biology*, **26**(3), 1576-1591, doi:10.1111/gcb.14887.
Donner, S. D., G. J. M. Rickbeil and S. F. Heron, 2017: A new, high-resolution global mass coral bleaching database. *PLOS ONE*, **12**(4), e0175490, doi:10.1371/journal.pone.0175490.
Dosio, A., L. Mentaschi, E. M. Fischer and K. Wyser, 2018: Extreme heat waves under 1.5 °C and 2 °C global warming. *Environmental Research Letters*, **13**(5), 054006, doi:10.1088/1748-9326/aab827.
Dottori, F. et al., 2018: Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, **8**(9), 781-786, doi:10.1038/s41558-018-0257-z.
Drupp, M. A. and M. C. Hänsel, 2021: Relative prices and climate policy: How the scarcity of nonmarket goods drives policy evaluation. *American Economic Journal: Economic Policy*, **13**(1), 168-201.
du Toit, J. C. O., T. G. O'Connor and L. Van den Berg, 2015: Photographic evidence of fire-induced shifts from dwarf-shrub- to grass-dominated vegetation in Nama-Karoo. *South African Journal of Botany*, **101**, 148-152, doi:10.1016/j.sajb.2015.06.002.
Duan, L., L. Cao, G. Bala and K. Caldeira, 2020: A Model-Based Investigation of Terrestrial Plant Carbon Uptake Response to Four Radiation Modification Approaches. *J. Geophys. Res. D: Atmos.*, **125**(9), 413, doi:10.1029/2019JD031883.
Dube, T., P. Moyo, M. Ncube and D. Nyathi, 2016: The Impact of Climate Change on Agro-Ecological Based Livelihoods in Africa: A Review. *Journal of Sustainable Development*, **9**(1), 256, doi:10.5539/jsd.v9n1p256.
Duguma, L. A., P. A. Minang and M. van Noordwijk, 2014: Climate Change Mitigation and Adaptation in the Land Use Sector: From Complementarity to Synergy. *ENVIRONMENTAL MANAGEMENT*, **54**(3), 420-432, doi:10.1007/s00267-014-0331-x.
Dunn, F. E. et al., 2019: Projections of declining fluvial sediment delivery to major deltas worldwide in response to climate change and anthropogenic stress. *Environmental Research Letters*, **14**(8), 084034, doi:10.1088/1748-9326/ab304e.
Dunn, R. J. et al., 2020: Development of an updated global land in situ-based data set of temperature and precipitation extremes: HadEX3. *Journal of Geophysical Research: Atmospheres*, **125**(16), e2019JD032263.
Durkalec, A., C. Furgal, M. W. Skinner and T. Sheldon, 2015: Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community. *Social Science & Medicine*, **136-137**, 17-26, doi:10.1016/j.socscimed.2015.04.026.
Duvat, V. K. E. et al., 2021: Risks to future atoll habitability from climate-driven environmental changes. *WIREs Climate Change*, doi:10.1002/wcc.700.
Dzebo, A., H. Janetschek, C. Brandi and G. Iacobuta, 2018: The Sustainable Development Goals viewed through a climate lens. 4.
Dzebo, A. and J. Stripple, 2015: Transnational adaptation governance: An emerging fourth era of adaptation. *Global Environmental Change*, **35**, 423-435, doi:10.1016/j.gloenvcha.2015.10.006.
Eastham, S. D., D. W. Keith and S. R. H. Barrett, 2018: Mortality tradeoff between air quality and skin cancer from changes in stratospheric ozone, 034035 pp.
Eastin, J., 2016: Fuel to the fire: Natural disasters and the duration of civil conflict. *International Interactions*, **42**(2), 322-349.
Ebi, K. L. et al., 2021: Burning embers: synthesis of the health risks of climate change. *Environmental Research Letters*, **16**(4), 044042, doi:10.1088/1748-9326/abeadd.
Ebi, K. L., N. H. Ogden, J. C. Semenza and A. Woodward, 2017: Detecting and attributing health burdens to climate change. *Environmental health perspectives*, **125**(8), 085004.
ECDC, 2021: West Nile virus transmission season 2018: Increase in cases, European Centre for Disease Prevention and Control. Available at: https://www.ecdc.europa.eu/en/west-nile-virus-transmission-season-2018-increase-cases.
Edmonds, D. A., R. L. Caldwell, E. S. Brondizio and S. M. O. Siani, 2020: Coastal flooding will disproportionately impact people on river deltas, 4741 pp.
Edwards, M. and A. J. Richardson, 2004: Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430**(7002), 881-884, doi:10.1038/nature02808.
EEA, 2019: *Climate change adaptation in the agriculture sector in Europe*. European Environment Agency, Copenhagen, Denmark. Available at: https://www.eea.europa.eu/publications/cc-adaptation-agriculture/at_download/file.
Effiong, U. and R. L. Neitzel, 2016: Assessing the direct occupational and public health impacts of solar radiation management with stratospheric aerosols. *Environmental Health*, **15**(1), 1-9.

Eklund, L. and D. Thompson, 2017: Differences in resource management affects drought vulnerability across the borders between Iraq, Syria, and Turkey. *Ecology and Society*, **22**(4), art9, doi:10.5751/ES-09179-220409.
El-Hacen, E.-H. M. et al., 2018: Evidence for 'critical slowing down' in seagrass: a stress gradient experiment at the southern limit of its range. *Scientific Reports*, **8**(1), 17263, doi:10.1038/s41598-018-34977-5.
Elagib, N. A., A. A. Musa and H. M. Sulieman (eds.), Socio-hydrological Framework of Farmer-Drought Feedback: Darfur as a Case Study. 2017, 461-479 pp. ISBN 978-3-319-51856-5 978-3-319-51855-8.
Elsanousi, Y. E. A., A. S. Elmahi, I. Pereira and M. Debacker, 2018: Impact of the 2013 floods on the incidence of malaria in Almanagil locality, Gezira State, Sudan. *PLoS currents*, **10**.
Emmerling, J. and M. Tavoni, 2018: Exploration of the interactions between mitigation and solar radiation management in cooperative and non-cooperative international governance settings. *Glob. Environ. Change*, **53**, 244-251, doi:10.1016/j.gloenvcha.2018.10.006.
Enenkel, M. et al., 2020: Why predict climate hazards if we need to understand impacts? Putting humans back into the drought equation. *Climatic Change*, 1-16.
England, M. I. et al., 2018: Climate change adaptation and cross-sectoral policy coherence in southern Africa. *REGIONAL ENVIRONMENTAL CHANGE*, **18**(7, SI), 2059-2071, doi:10.1007/s10113-018-1283-0.
Enquist, B. J. et al., 2019: The commonness of rarity: Global and future distribution of rarity across land plants. *Science advances*, **5**(11), eaaz0414.
EPRI, 2021: *Repairing the Social Cost of Carbon Framework: Immediate and One Year Steps for Scientifically Reliable Estimates and Use*. EPRI, Palo Alto, CA. Available at: https://www.epri.com/research/products/000000003002020523.
Epule, T. E., J. D. Ford, S. Lwasa and L. Lepage, 2017: Climate change adaptation in the Sahel. *Environmental Science and Policy*, **75**, 121-137, doi:10.1016/j.envsci.2017.05.018.
Ercin, E., T. I. E. Veldkamp and J. Hunink, 2021: Cross-border climate vulnerabilities of the European Union to drought. *Nature Communications*, **12**(1), 3322, doi:10.1038/s41467-021-23584-0.
Errickson, F. C. et al., 2021: Equity is more important for the social cost of methane than climate uncertainty. *Nature*, **592**(7855), 564-570.
Essl, F. et al., 2015: Delayed biodiversity change: no time to waste. *Trends in Ecology & Evolution*, **30**(7), 375-378, doi:10.1016/j.tree.2015.05.002.
Etongo, D., I. N. S. Djenontin, M. Kanninen and K. Fobissie, 2015: Smallholders' Tree Planting Activity in the Ziro Province, Southern Burkina Faso: Impacts on Livelihood and Policy Implications. *FORESTS*, **6**(8), 2655-2677, doi:10.3390/f6082655.
European Environment, A., 2020: *Monitoring and evaluation of national adaptation policies throughout the policy cycle*. Publications Office, LU.
Evans, J. et al., 2010: Can oceanic foams limit global warming? *Climate Research*, **42**(2), 155-160.
Fader, M. et al., 2010: Virtual water content of temperate cereals and maize: Present and potential future patterns. *Journal of Hydrology*, **384**(3), 218-231, doi:10.1016/j.jhydrol.2009.12.011.
Fahad, S. and J. Wang, 2018: Farmers' risk perception, vulnerability, and adaptation to climate change in rural Pakistan. *Land Use Policy*, **79**, 301-309, doi:10.1016/j.landusepol.2018.08.018.
Fakhruddin, B. S. and L. Schick, 2019: Benefits of economic assessment of cyclone early warning systems-A case study on Cyclone Evan in Samoa. *Progress in Disaster Science*, **2**, 100034.
Fang, X. et al., 2017: Isolating and quantifying the effects of climate and CO2 changes (1980–2014) on the net primary productivity in arid and semiarid China. *Forests*, **8**(3), 60.
Fang, Z., P. T. Freeman, C. B. Field and K. J. Mach, 2018: Reduced sea ice protection period increases storm exposure in Kivalina, Alaska. *Arctic Science*, **4**(4), 525-537, doi:10.1139/as-2017-0024.
FAO et al., 2017: *The State of Food Security and Nutrition in the World 2017*. FAO, Rome.
FAO et al., 2018: *The State of Food Security and Nutrition in the World: Building climate resilience for food security and nutrition.*, Food and Agriculture Organization of the United Nations, Rome. ISBN 978-92-5-130571-3.
Faulwasser, T., C. M. Kellett and S. R. Weller, 2018: MPC-DICE: An open-source Matlab implementation of receding horizon solutions to DICE. *IFAC-PapersOnLine*, **51**(5), 120-125.
Fawcett, D. et al., 2018: Inuit adaptability to changing environmental conditions over an 11-year period in Ulukhaktok, Northwest Territories. *Polar Record*, **54**(2), 119-132, doi:10.1017/S003224741800027X.
Fedele, G., B. Locatelli, H. Djoudi and M. J. Colloff, 2018: Reducing risks by transforming landscapes: Cross-scale effects of land-use changes on ecosystem services. *PLOS ONE*, **13**(4), doi:10.1371/journal.pone.0195895.
Feitelson, E. and A. Tubi, 2017: A main driver or an intermediate variable? Climate change, water and security in the Middle East. *Global Environmental Change*, **44**, 39-48, doi:10.1016/j.gloenvcha.2017.03.001.
Fekete, A., 2019: Critical infrastructure and flood resilience: Cascading effects beyond water. *Wiley Interdisciplinary Reviews-Water*, **6**(5), e1370, doi:10.1002/wat2.1370.
Felbermayr, G. and J. Gröschl, 2014: Naturally negative: The growth effects of natural disasters. *Journal of development economics*, **111**, 92-106.
Feldmeyer, D., J. Birkmann and T. Welle, 2017: Development of Human Vulnerability 2012–2017. *Journal of Extreme Events*, **04**(04), 1850005, doi:10.1142/S2345737618500057.
Felgenhauer, T., 2015: Addressing the limits to adaptation across four damage–response systems. *Environmental Science & Policy*, **50**, 214-224, doi:10.1016/j.envsci.2015.03.003.

Fenger-Nielsen, R. et al., 2020: Arctic archaeological sites threatened by climate change: A regional multi-threat assessment of sites in south-west Greenland. *Archaeometry*, arcm.12593, doi:10.1111/arcm.12593.
Few, R. et al., 2017: Transformation, adaptation and development: relating concepts to practice. *PALGRAVE COMMUNICATIONS*, **3**, doi:10.1057/palcomms.2017.92.
Fey, S. B. et al., 2015: Recent shifts in the occurrence, cause, and magnitude of animal mass mortality events. *Proceedings of the National Academy of Sciences*, **112**(4), 1083-1088, doi:10.1073/pnas.1414894112.
Fezzi, C., A. R. Harwood, A. A. Lovett and I. J. Bateman, 2015: The environmental impact of climate change adaptation on land use and water quality (vol 5, pg 255, 2015). *NATURE CLIMATE CHANGE*, **5**(3).
Field, L. et al., 2018: Increasing Arctic sea ice albedo using localized reversible geoengineering. *Earth's Future*, **6**(6), 882-901.
Finger, F. et al., 2016: Mobile phone data highlights the role of mass gatherings in the spreading of cholera outbreaks. *Proceedings of the National Academy of Sciences*, **113**(23), 6421-6426.
Fischer, A. P., 2019a: Adapting and coping with climate change in temperate forests. *GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS*, **54**, 160-171, doi:10.1016/j.gloenvcha.2018.10.011.
Fischer, A. P., 2019b: Characterizing behavioral adaptation to climate change in temperate forests. *LANDSCAPE AND URBAN PLANNING*, **188**, 72-79, doi:10.1016/j.landurbplan.2018.09.024.
Fischer, E. M. and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change*, **5**(6), 560-564.
Fisher-Vanden, K., D. Popp and I. S. Wing, 2014: Introduction to the special issue on climate adaptation: improving the connection between empirical research and integrated assessment models. *Energy Economics*, **46**, 495-499.
Fisher, M. et al., 2015: Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *CLIMATIC CHANGE*, **133**(2), 283-299, doi:10.1007/s10584-015-1459-2.
Flegal, J. A. and A. Gupta, 2018: Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity. *International Environmental Agreements: Politics, Law and Economics*, **18**(1), 45-61, doi:10.1007/s10784-017-9377-6.
Flegal, J. A., A.-M. Hubert, D. R. Morrow and J. B. Moreno-Cruz, 2019: Solar Geoengineering: Social Science, Legal, Ethical, and Economic Frameworks. *Annu. Rev. Environ. Resour.*, **44**(1), 399-423, doi:10.1146/annurev-environ-102017-030032.
Foden, W. B. et al., 2013: Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. *PloS one*, **8**(6), e65427.
Folkerts, M. A. et al., 2020: Long Term Adaptation to Heat Stress: Shifts in the Minimum Mortality Temperature in the Netherlands. *FRONTIERS IN PHYSIOLOGY*, **11**, doi:10.3389/fphys.2020.00225.
Fomby, T., Y. Ikeda and N. V. Loayza, 2013: The Growth Aftermath of Natural Disasters. *Journal of Applied Econometrics*, **28**(3), 412-434, doi:10.1002/jae.1273.
Ford, J. D. and L. Berrang-Ford, 2016: The 4Cs of adaptation tracking: consistency, comparability, comprehensiveness, coherency. *MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE*, **21**(6), 839-859, doi:10.1007/s11027-014-9627-7.
Ford, J. D. et al., 2015a: Adaptation tracking for a post-2015 climate agreement. *NATURE CLIMATE CHANGE*, **5**(11), 967-969, doi:10.1038/nclimate2744.
Ford, J. D. et al., 2015b: The status of climate change adaptation in Africa and Asia. *REGIONAL ENVIRONMENTAL CHANGE*, **15**(5, SI), 801-814, doi:10.1007/s10113-014-0648-2.
Ford, J. D. et al., 2013: How to Track Adaptation to Climate Change: A Typology of Approaches for National-Level Application. *ECOLOGY AND SOCIETY*, **18**(3), doi:10.5751/ES-05732-180340.
Ford, J. D. and D. King, 2015: Coverage and framing of climate change adaptation in the media: A review of influential North American newspapers during 1993-2013. *ENVIRONMENTAL SCIENCE & POLICY*, **48**, 137-146, doi:10.1016/j.envsci.2014.12.003.
Ford, J. D., G. McDowell and T. Pearce, 2015c: The adaptation challenge in the Arctic. *Nature Climate Change*, **5**(12), 1046-1053.
Formetta, G. and L. Feyen, 2019: Empirical evidence of declining global vulnerability to climate-related hazards. *Global Environmental Change*, **57**, 101920.
Forster, J., I. R. Lake, A. R. Watkinson and J. A. Gill, 2014: Marine dependent livelihoods and resilience to environmental change: A case study of Anguilla. *Marine Policy*, **45**, 204-212, doi:10.1016/j.marpol.2013.10.017.
Forzieri, G. et al., 2018: Escalating impacts of climate extremes on critical infrastructures in Europe. *Global Environmental Change-Human and Policy Dimensions*, **48**, 97-107, doi:10.1016/j.gloenvcha.2017.11.007.
Fox-Kemper, B. et al., 2021: Ocean, Cryosphere and Sea Level Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Fraga, H., M. Moriondo, L. Leolini and J. A. Santos, 2021: Mediterranean Olive Orchards under Climate Change: A Review of Future Impacts and Adaptation Strategies. *AGRONOMY-BASEL*, **11**(1), doi:10.3390/agronomy11010056.

Frainer, A. et al., 2017: Climate-driven changes in functional biogeography of Arctic marine fish communities. *Proceedings of the National Academy of Sciences*, **114**(46), 12202-12207, doi:10.1073/pnas.1706080114.
Frame, D. J., M. F. Wehner, I. Noy and S. M. Rosier, 2020: The economic costs of Hurricane Harvey attributable to climate change. *Climatic Change*, **160**(2), 271-281.
Franco Gavonel, M. et al., 2021: The migration-sustainability paradox: transformations in mobile worlds. *Current Opinion in Environmental Sustainability*, **49**, 98-109, doi:10.1016/j.cosust.2021.03.013.
Franks, S. J., J. J. Weber and S. N. Aitken, 2014: Evolutionary and plastic responses to climate change in terrestrial plant populations. *EVOLUTIONARY APPLICATIONS*, **7**(1, SI), 123-139, doi:10.1111/eva.12112.
Free, C. M. et al., 2019: Impacts of historical warming on marine fisheries production. *Science*, **363**(6430), 979-983, doi:10.1126/science.aau1758.
Freeman, L., 2017: Environmental Change, Migration, and Conflict in Africa: A Critical Examination of the Interconnections. *The Journal of Environment & Development*, **26**(4), 351-374, doi:10.1177/1070496517727325.
Froehlich, H. E., R. R. Gentry and B. S. Halpern, 2018: Global change in marine aquaculture production potential under climate change. *Nature Ecology & Evolution*, **2**(11), 1745-1750.
Fröhlich, C. J., 2016: Climate migrants as protestors? Dispelling misconceptions about global environmental change in pre-revolutionary Syria. *Contemporary Levant*, **1**(1), 38-50, doi:10.1080/20581831.2016.1149355.
Frumhoff, P. C. and J. C. Stephens, 2018: Towards legitimacy of the solar geoengineering research enterprise. *Philosophical transactions of the royal society A: mathematical, Physical and Engineering Sciences*, **376**(2119), 20160459.
Fujimori, S. et al., 2019: A multi-model assessment of food security implications of climate change mitigation. *Nature Sustainability*, **2**(5), 386-396, doi:10.1038/s41893-019-0286-2.
Furman, C., C. Roncoli, D. R. Nelson and G. Hoogenboom, 2014: Growing food, growing a movement: climate adaptation and civic agriculture in the southeastern United States. *AGRICULTURE AND HUMAN VALUES*, **31**(1), 69-82, doi:10.1007/s10460-013-9458-2.
Fuso-Nerini, F. et al., 2019: Connecting climate action with other Sustainable Development Goals. *Nature Sustainability*, **2**(8), 674-680, doi:10.1038/s41893-019-0334-y.
Fuss, S. et al., 2014: Betting on negative emissions, 850-853 pp.
Fuss, S. et al., 2018: Negative emissions—Part 2: Costs, potentials and side effects, 063002 pp.
Gagnon-Lebrun, F. and S. Agrawala, 2007: Implementing adaptation in developed countries: an analysis of progress and trends. *CLIMATE POLICY*, **7**(5), 392-408.
Galappaththi, E. K., J. D. Ford, E. M. Bennett and F. Berkes, 2019: Climate change and community fisheries in the arctic: A case study from Pangnirtung, Canada. *Journal of Environmental Management*, **250**, 109534, doi:10.1016/j.jenvman.2019.109534.
Gao, J. and B. F. Mills, 2018: Weather Shocks, Coping Strategies, and Consumption Dynamics in Rural Ethiopia. *WORLD DEVELOPMENT*, **101**, 268-283, doi:10.1016/j.worlddev.2017.09.002.
Garcia de Jalon, S., A. Iglesias and A. P. Barnes, 2016: Drivers of farm-level adaptation to climate change in Africa: an evaluation by a composite index of potential adoption. *MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE*, **21**(5), 779-798, doi:10.1007/s11027-014-9626-8.
Garschagen, M., 2015: Risky Change? Vietnam's Urban Flood Risk Governance between Climate Dynamics and Transformation. *Pacific Affairs*, **88**(3), 599-621, doi:10.5509/2015883599.
Garschagen, M. et al., 2019: Key concepts of risk, adaptation, resilience and transformation. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, pp. 87-90.
Garschagen, M. et al., 2021a: The consideration of future risk trends in national adaptation planning: conceptual gaps and empirical lessons. *Climate Risk Management*.
Garschagen, M., D. Doshi, J. Reith and M. Hagenlocher, 2021b: Global patterns of disaster and climate risk – An analysis of the consistency of leading index based assessments and their results *Climatic Change*.
Garschagen, M., M. Hagenlocher, second, R. Sabelfeld and Y. J. Lee, 2016: Infrastructure as a risk factor. In: *World Risk Report 2016: Focus on Logistics and Infrastructure*. Bündnis Entwicklung Hilft & United Nations University, pp. 14-22. ISBN 978-3-946785-02-6.
Garschagen, M. and P. Romero-Lankao, 2015: Exploring the relationships between urbanization trends and climate change vulnerability. *Climatic Change*, **133**(1), 37-52, doi:10.1007/s10584-013-0812-6.
Gasparini, B., Z. McGraw, T. Storelvmo and U. Lohmann, 2020: To what extent can cirrus cloud seeding counteract global warming? *Environmental Research Letters*, **15**(5), 054002.
Gasparrini, A. et al., 2015: Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet*, **386**(9991), 369-375, doi:10.1016/S0140-6736(14)62114-0.
Gasparrini, A. et al., 2017: Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health*, **1**(9), e360-e367.
Gatti, L. V. et al., 2021: Amazonia as a carbon source linked to deforestation and climate change. *Nature*, **595**(7867), 388-393, doi:10.1038/s41586-021-03629-6.
Gattuso, J.-P. et al., 2018: Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, **5**, 337.
Gaupp, F., J. Hall, S. Hochrainer-Stigler and S. Dadson, 2020: Changing risks of simultaneous global breadbasket failure. *Nature Climate Change*, **10**(1), 54-57, doi:10.1038/s41558-019-0600-z.

Gaupp, F., J. Hall, D. Mitchell and S. Dadson, 2019: Increasing risks of multiple breadbasket failure under 1.5 and 2 C global warming. *Agricultural Systems*, **175**, 34-45.
Gautier, D., D. Denis and B. Locatelli, 2016: Impacts of drought and responses of rural populations in West Africa: a systematic review. *WILEY INTERDISCIPLINARY REVIEWS-CLIMATE CHANGE*, **7**(5), 666-681, doi:10.1002/wcc.411.
Gbegbelegbe, S. et al., 2018: Smallholder farmers in eastern Africa and climate change: a review of risks and adaptation options with implications for future adaptation programmes. *CLIMATE AND DEVELOPMENT*, **10**(4), 289-306, doi:10.1080/17565529.2017.1374236.
Genua-Olmedo, A., C. Alcaraz, N. Caiola and C. Ibáñez, 2016: Sea level rise impacts on rice production: The Ebro Delta as an example. *Science of The Total Environment*, **571**, 1200-1210, doi:10.1016/j.scitotenv.2016.07.136.
Georgeson, L., M. Maslin, M. Poessinouw and S. Howard, 2016: Adaptation responses to climate change differ between global megacities. *NATURE CLIMATE CHANGE*, **6**(6), 584+, doi:10.1038/NCLIMATE2944.
Gerlagh, R. and T. O. Michielsen, 2015: Moving targets—cost-effective climate policy under scientific uncertainty. *Climatic change*, **132**(4), 519-529.
Gerlak, A. K. et al., 2018: Climate risk management and the electricity sector. *Climate Risk Management*, **19**, 12-22, doi:10.1016/j.crm.2017.12.003.
Gettelman, A. et al., 2018: Projections of future tropical cyclone damage with a high-resolution global climate model. *Climatic Change*, **146**(3-4), 575-585.
Gholampour, R., M. Darand and A. H. Halabian, 2019: Impacts of cold and hot temperatures on mortality rate in Isfahan, Iran. *Journal of Thermal Biology*, **86**, 102453.
Giardino, A., K. Nederhoff and M. Vousdoukas, 2018: Coastal hazard risk assessment for small islands: assessing the impact of climate change and disaster reduction measures on Ebeye (Marshall Islands). *Regional Environmental Change*, **18**(8), 2237-2248, doi:10.1007/s10113-018-1353-3.
Gioli, G., T. Khan, S. Bisht and J. Scheffran, 2014: Migration as an Adaptation Strategy and its Gendered Implications A Case Study From the Upper Indus Basin. *MOUNTAIN RESEARCH AND DEVELOPMENT*, **34**(3, SI), 255-265, doi:10.1659/MRD-JOURNAL-D-13-00089.1.
Giosan, L., J. Syvitski, S. Constantinescu and J. Day, 2014: Climate change: Protect the world's deltas. *Nature*, **516**(7529), 31-33, doi:10.1038/516031a.
Glanemann, N., S. N. Willner and A. Levermann, 2020: Paris Climate Agreement passes the cost-benefit test. *Nature communications*, **11**(1), 1-11.
Gleick, P. H., 2014: Water, Drought, Climate Change, and Conflict in Syria. *Weather, Climate, and Society*, **6**(3), 331-340, doi:10.1175/WCAS-D-13-00059.1.
Glienke, S., P. J. Irvine and M. G. Lawrence, 2015: The impact of geoengineering on vegetation in experiment G1 of the GeoMIP. *J. Geophys. Res. D: Atmos.*, **120**(19), 10-196.
Golden, C. D. et al., 2016: Nutrition: Fall in fish catch threatens human health. *Nature News*, **534**(7607), 317, doi:10.1038/534317a.
Goldstein, A., W. R. Turner, J. Gladstone and D. G. Hole, 2019: The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, **9**(1), 18-25, doi:10.1038/s41558-018-0340-5.
Gomez-Echeverri, L., 2018: Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs). *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160444.
Gonzalez-Sanchez, E. J. et al., 2019: Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. *SOIL & TILLAGE RESEARCH*, **190**, 22-30, doi:10.1016/j.still.2019.02.020.
González, F. A. I., M. E. Santos and S. London, 2021: Persistent effects of natural disasters on human development: quasi-experimental evidence for Argentina. *Environment, Development and Sustainability*, **23**(7), 10432-10454, doi:10.1007/s10668-020-01064-7.
Gosling, J. P., 2018: SHELF: The Sheffield Elicitation Framework. In: *Elicitation* [Dias, L. C., A. Morton and J. Quigley (eds.)]. Springer International Publishing, Cham, pp. 61-93. ISBN 978-3-319-65051-7 978-3-319-65052-4.
Gosling, S. N. and N. W. Arnell, 2016: A global assessment of the impact of climate change on water scarcity. *Climatic Change*, **134**(3), 371-385, doi:10.1007/s10584-013-0853-x.
Götz, L., I. Djuric and O. Nivievskyi, 2016: Regional price effects of extreme weather events and wheat export controls in Russia and Ukraine. *Journal of Agricultural Economics*, **67**(3), 741-763.
Goulden, M. C., W. N. Adger, E. H. Allison and D. Conway, 2013: Limits to Resilience from Livelihood Diversification and Social Capital in Lake Social-Ecological Systems. *ANNALS OF THE ASSOCIATION OF AMERICAN GEOGRAPHERS*, **103**(4), 906-924, doi:10.1080/00045608.2013.765771.
Graham, N. T. et al., 2020: Future changes in the trading of virtual water. *Nature Communications*, **11**(1), 1-7, doi:10.1038/s41467-020-17400-4.
Grecequet, M., J. DeWaard, J. J. Hellmann and G. J. Abel, 2017: Climate Vulnerability and Human Migration in Global Perspective. *Sustainability*, **9**(5), 720, doi:10.3390/su9050720.
Greenstone, M., E. Kopits and A. Wolverton, 2013: Developing a social cost of carbon for us regulatory analysis: A methodology and interpretation. **7**, 23-46, doi:10.1093/reep/res015.

Greve, P. et al., 2018: Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability*, **1**(9), 486-494, doi:10.1038/s41893-018-0134-9.
Grubb, M., C. Wieners and P. Yang, 2021: Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation. *Wiley Interdisciplinary Reviews: Climate Change*, **12**(3), e698.
Grusson, Y., I. Wesstrom and A. Joel, 2021: Impact of climate change on Swedish agriculture: Growing season rain deficit and irrigation need. *AGRICULTURAL WATER MANAGEMENT*, **251**, doi:10.1016/j.agwat.2021.106858.
Gudmundsson, L. et al., 2021: Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, **371**(6534), 1159-1162, doi:10.1126/science.aba3996.
Gudmundsson, L. et al., 2019: Observed trends in global indicators of mean and extreme streamflow. *Geophysical Research Letters*, **46**(2), 756-766.
Gugliotta, M. et al., 2017: Process regime, salinity, morphological, and sedimentary trends along the fluvial to marine transition zone of the mixed-energy Mekong River delta, Vietnam. *Continental Shelf Research*, **147**, 7-26, doi:10.1016/j.csr.2017.03.001.
Guiot, J. and W. Cramer, 2016: Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Science*, **354**(6311), 465-468.
Guivarch, C. and A. Pottier, 2018: Climate damage on production or on growth: what impact on the social cost of carbon? *Environmental Modeling & Assessment*, **23**(2), 117-130.
Gulev, S. K. et al., 2021: Changing State of the Climate System. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Gundersen, V., B. P. Kaltenborn and D. R. Williams, 2016: A bridge over troubled water: A contextual analysis of social vulnerability to climate change in a riverine landscape in south-east Norway. *NORSK GEOGRAFISK TIDSSKRIFT-NORWEGIAN JOURNAL OF GEOGRAPHY*, **70**(4), 216-229, doi:10.1080/00291951.2016.1194317.
Guo, D. et al., 2020: Attribution of historical near-surface permafrost degradation to anthropogenic greenhouse gas warming. *Environmental Research Letters*, **15**(8), 084040, doi:10.1088/1748-9326/ab926f.
Guo, Y. et al., 2018: Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLOS Medicine*, **15**(7), e1002629, doi:10.1371/journal.pmed.1002629.
Guodaar, L., A. Beni and P. Benebere, 2017: Using a mixed-method approach to explore the spatiality of adaptation practices of tomato farmers to climate variability in the Offinso North District, Ghana. *Cogent Social Sciences*, **3**(1), doi:10.1080/23311886.2016.1273747.
Guppy, L., P. Mehta and M. Qadir, 2019: Sustainable development goal 6: two gaps in the race for indicators. *Sustainability Science*, **14**(2), 501-513, doi:10.1007/s11625-018-0649-z.
Gupta, A. et al., 2020: Anticipatory governance of solar geoengineering: conflicting visions of the future and their links to governance proposals. *Curr Opin Environ Sustain*, **45**, 10-19, doi:10.1016/j.cosust.2020.06.004.
Ha'apio, M. O., M. Wairiu, R. Gonzalez and K. Morrison, 2018: Transformation of rural communities: lessons from a local self-initiative for building resilience in the Solomon Islands. *Local Environment*, **23**(3), 352-365.
Haasnoot, M. et al., 2012: Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change*, **115**(3-4), 795-819, doi:10.1007/s10584-012-0444-2.
Haeffner, M., J. A. Baggio and K. Galvin, 2018: Investigating environmental migration and other rural drought adaptation strategies in Baja California Sur, Mexico. *REGIONAL ENVIRONMENTAL CHANGE*, **18**(5, SI), 1495-1507, doi:10.1007/s10113-018-1281-2.
Hagenlocher, M., F. G. Renaud, S. Haas and Z. Sebesvari, 2018: Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards. *Science of The Total Environment*, **631-632**, 71-80, doi:10.1016/j.scitotenv.2018.03.013.
Haji, J. and B. Legesse, 2017: Impact of sedentarization program on the livelihood and food security of Ethiopian pastoralists. *JOURNAL OF ARID ENVIRONMENTS*, **136**, 45-53, doi:10.1016/j.jaridenv.2016.10.007.
Hallegatte, S., 2012: A cost effective solution to reduce disaster losses in developing countries: hydro-meteorological services, early warning, and evacuation. *World Bank policy research working paper*,(6058).
Hallegatte, S. et al., 2016: *Shock Waves: Managing the Impacts of Climate Change on Poverty*. The World Bank. ISBN 978-1-4648-0673-5 978-1-4648-0674-2.
Hallegatte, S., J. Rentschler and J. Rozenberg, 2019: *Lifelines: The Resilient Infrastructure Opportunity*. The World Bank. ISBN 978-1-4648-1430-3 978-1-4648-1431-0.
Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**(4), 250-256, doi:10.1038/nclimate3253.
Hallegatte, S., A. Vogt-Schilb, M. Bangalore and J. Rozenberg, 2017: Unbreakable. Building the Resilience of the Poor in the Face of Natural Disasters.
Hallegatte, S. et al., 2020: From Poverty to Disaster and Back: a Review of the Literature. *Economics of Disasters and Climate Change*, **4**(1), 223-247, doi:10.1007/s41885-020-00060-5.
Hammill, A. and H. Price-Kelly, 2017: Using NDCs, NAPs and the SDGs to Advance Climate-Resilient Development. *NDC Partnership*, 10.

Han, Q. et al., 2018: Phenological variation decreased carbon uptake in European forests during 1999–2013. *Forest Ecology and Management*, **427**, 45-51, doi:10.1016/j.foreco.2018.05.062.

Handmer, J. and J. Nalau, 2019: Understanding Loss and Damage in Pacific Small Island Developing States. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, pp. 365-381. ISBN 978-3-319-72026-5.

Hannah, L. et al., 2020: 30% land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography*.

Haraguchi, M. and U. Lall, 2015: Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making. *International Journal of Disaster Risk Reduction*, **14**, 256-272, doi:10.1016/j.ijdrr.2014.09.005.

Harari, M. and E. L. Ferrara, 2018: Conflict, Climate, and Cells: A Disaggregated Analysis. *The Review of Economics and Statistics*, **100**(4), 594-608, doi:10.1162/rest_a_00730.

Harding, A. R. et al., 2020: Climate econometric models indicate solar geoengineering would reduce inter-country income inequality. *Nat. Commun.*, **11**(1), 227, doi:10.1038/s41467-019-13957-x.

Harrington, L. J., D. Frame, A. D. King and F. E. L. Otto, 2018: How Uneven Are Changes to Impact-Relevant Climate Hazards in a 1.5 °C World and Beyond? *Geophysical Research Letters*, **45**(13), 6672-6680, doi:10.1029/2018GL078888.

Harris, N. L. et al., 2021: Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change*, **11**(3), 234-240, doi:10.1038/s41558-020-00976-6.

Hasegawa, T. et al., 2018: Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, **8**(8), 699-703, doi:10.1038/s41558-018-0230-x.

Hasegawa, T. et al., 2014: Climate Change Impact and Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. *Environmental Science & Technology*, **48**(1), 438-445, doi:10.1021/es4034149.

Hauer, M. E., 2017: Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change*, **7**, 321–325 doi:10.1038/nclimate3271.

Hauer, M. E. et al., 2020: Sea-level rise and human migration. *Nature Reviews Earth & Environment*, **1**(1), 28-39, doi:10.1038/s43017-019-0002-9.

He, Q., G. Zhou, X. Lü and M. Zhou, 2019: Climatic suitability and spatial distribution for summer maize cultivation in China at 1.5 and 2.0° C global warming. *Science Bulletin*, **64**(10), 690-697.

Hedlund, J., S. Fick, H. Carlsen and M. Benzie, 2018: Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk. *Global Environmental Change*, **52**, 75-85, doi:10.1016/j.gloenvcha.2018.04.006.

Hegger, D. L. T., H. L. P. Mees, P. P. J. Driessen and H. A. C. Runhaar, 2017: The Roles of Residents in Climate Adaptation: A systematic review in the case of the Netherlands. *ENVIRONMENTAL POLICY AND GOVERNANCE*, **27**(4), 336-350, doi:10.1002/eet.1766.

Hegre, H. et al., 2016: Forecasting civil conflict along the shared socioeconomic pathways. *Environmental Research Letters*, **11**(5), 054002, doi:10.1088/1748-9326/11/5/054002.

Helling, A. P., D. S. Conner, S. N. Heiss and L. S. Berlin, 2015: Economic Analysis of Climate Change Best Management Practices in Vermont Agriculture. *AGRICULTURE-BASEL*, **5**(3), 879-900, doi:10.3390/agriculture5030879.

Helwegen, K. G., C. E. Wieners, J. E. Frank and H. A. Dijkstra, 2019: Complementing CO₂ emission reduction by solar radiation management might strongly enhance future welfare, 453-472 pp.

Henderson, J. V., A. Storeygard and U. Deichmann, 2017: Has climate change driven urbanization in Africa? *Journal of development economics*, **124**, 60-82.

Herrador, B. R. G. et al., 2015: Analytical studies assessing the association between extreme precipitation or temperature and drinking water-related waterborne infections: a review. *Environmental Health*, **14**(1), 29.

Hertel, T. W. and D. B. Lobell, 2014: Agricultural adaptation to climate change in rich and poor countries: Current modeling practice and potential for empirical contributions. *Energy Economics*, **46**, 562-575, doi:10.1016/j.eneco.2014.04.014.

Hess, J. J. et al., 2018: Building Resilience to Climate Change: Pilot Evaluation of the Impact of India's First Heat Action Plan on All-Cause Mortality. *JOURNAL OF ENVIRONMENTAL AND PUBLIC HEALTH*, **2018**, doi:10.1155/2018/7973519.

Heutel, G., J. Moreno-Cruz and S. Shayegh, 2018: Solar geoengineering, uncertainty, and the price of carbon, 24-41 pp.

Hewitson, B. et al., 2014: Regional Context. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1133-1197. ISBN 9781107058163.

Heydemann, S., 2013: Tracking the 'Arab Spring': Syria and the Future of Authoritarianism. *Journal of Democracy*, **24**(4), 59-73, doi:10.1353/jod.2013.0067.

Heyen, D., J. Horton and J. Moreno-Cruz, 2019: Strategic implications of counter-geoengineering: Clash or cooperation? *Journal of Environmental Economics and Management*, **95**, 153-177.

Hill, C. et al., 2020: Hotspots of Present and Future Risk Within Deltas: Hazards, Exposure and Vulnerability. In: *Deltas in the Anthropocene* [Nicholls, R. J., W. N. Adger, C. W. Hutton and S. E. Hanson (eds.)]. Springer International Publishing, Cham, pp. 127-151. ISBN 978-3-030-23516-1 978-3-030-23517-8.

Hinkel, J., D. P. van Vuuren, R. J. Nicholls and R. J. T. Klein, 2013: The effects of adaptation and mitigation on coastal flood impacts during the 21st century. An application of the DIVA and IMAGE models. *Climatic Change*, **117**(4), 783-794, doi:10.1007/s10584-012-0564-8.

Hino, M. et al., 2019: High-tide flooding disrupts local economic activity. *Science Advances*, **5**(2), eaau2736, doi:10.1126/sciadv.aau2736.

Hintz, M. J., C. Luederitz, D. J. Lang and H. von Wehrden, 2018: Facing the heat: A systematic literature review exploring the transferability of solutions to cope with urban heat waves. *URBAN CLIMATE*, **24**, 714-727, doi:10.1016/j.uclim.2017.08.011.

Hirabayashi, Y. et al., 2021: Global exposure to flooding from the new CMIP6 climate model projections. *Scientific reports*, **11**(1), 3740, doi:10.1038/s41598-021-83279-w.

Hlahla, S. and T. R. Hill, 2018: Responses to Climate Variability in Urban Poor Communities in Pietermaritzburg, KwaZulu-Natal, South Africa. *SAGE OPEN*, **8**(3), doi:10.1177/2158244018800914.

Hoang, M. H. et al., 2014: Farmer portfolios, strategic diversity management and climate-change adaptation - implications for policy in Vietnam and Kenya. *CLIMATE AND DEVELOPMENT*, **6**(3), 216-225, doi:10.1080/17565529.2013.857588.

Hochman, Z., D. L. Gobbett and H. Horan, 2017: Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology*, **23**(5), 2071-2081.

Hodges, M. et al., 2014: Delays in reducing waterborne and water-related infectious diseases in China under climate change. *Nature climate change*, **4**(12), 1109-1115.

Hoegh-Guldberg, O. et al., 2018a: Cross-Chapter Box 6: Food Security. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.

Hoegh-Guldberg, O. et al., 2018b: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.

Hoekstra, A. Y. and M. M. Mekonnen, 2012: The water footprint of humanity. *Proceedings of the National Academy of Sciences*, **109**(9), 3232-3237, doi:10.1073/pnas.1109936109.

Hoerling, M. et al., 2012: On the Increased Frequency of Mediterranean Drought. *Journal of Climate*, **25**(6), 2146-2161, doi:10.1175/JCLI-D-11-00296.1.

Hoffman, A. L., A. R. Kemanian and C. E. Forest, 2018: Analysis of climate signals in the crop yield record of sub-Saharan Africa. *Global change biology*, **24**(1), 143-157.

Hoffmann, R. et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change*, **10**(10), 904-912, doi:10.1038/s41558-020-0898-6.

Hoffmann, S., 2016: INTERNATIONAL HUMANITARIAN AGENCIES AND IRAQI MIGRATION IN PRECONFLICT SYRIA. *International Journal of Middle East Studies*, **48**(2), 339-355, doi:10.1017/S0020743816000076.

Holler, J., 2014: Is Sustainable Adaptation Possible? Determinants of Adaptation on Mount Kilimanjaro. *PROFESSIONAL GEOGRAPHER*, **66**(4), 526-537, doi:10.1080/00330124.2014.922015.

Hollesen, J. et al., 2018: Climate change and the deteriorating archaeological and environmental archives of the Arctic. *Antiquity*, **92**(363), 573-586, doi:10.15184/aqy.2018.8.

Honegger, M., A. Michaelowa and J. Pan, 2021: Potential implications of solar radiation modification for achievement of the Sustainable Development Goals, 21 pp.

Hooli, L. J., 2016: Resilience of the poorest: coping strategies and indigenous knowledge of living with the floods in Northern Namibia. *REGIONAL ENVIRONMENTAL CHANGE*, **16**(3, SI), 695-707, doi:10.1007/s10113-015-0782-5.

Horton, R. M., A. de Sherbinin, D. Wrathall and M. Oppenheimer, 2021: Assessing human habitability and migration. *Science*, **372**(6548), 1279-1283, doi:10.1126/science.abi8603.

Hourdequin, M., 2019: Geoengineering justice: the role of recognition. *Science, Technology, & Human Values*, **44**(3), 448-477.

Howard, P. H. and T. Sterner, 2017: Few and not so far between: a meta-analysis of climate damage estimates. *Environmental and Resource Economics*, **68**(1), 197-225.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356**(6345), 1362-1369.
Hsiang, S. M. and A. S. Jina, 2014: *The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones*. National Bureau of Economic Research. Available at: http://www.nber.org/papers/w20352 (accessed 2019/09/26/).
Hu, Q. et al., 2018: An examination of midwestern US cities' preparedness for climate change and extreme hazards. *NATURAL HAZARDS*, **94**(2), 777-800, doi:10.1007/s11069-018-3420-y.
Hubau, W. et al., 2020: Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, **579**(7797), 80-87.
Hughes, T. P. et al., 2019: Global warming impairs stock–recruitment dynamics of corals. *Nature*, **568**, 387-390, doi:10.1038/s41586-019-1081-y.
Hughes, T. P., J. T. Kerry and T. Simpson, 2018: Large-scale bleaching of corals on the Great Barrier Reef. *Ecology*, **99**(2), 501, doi:10.1002/ecy.2092.
Hulme, M., 2014: *Can Science Fix Climate Change?: A Case Against Climate Engineering*. John Wiley & Sons, 144 pp. ISBN 9780745685267.
Hunter, N. B., M. A. North, D. C. Roberts and R. Slotow, 2020: A systematic map of responses to climate impacts in urban Africa. *ENVIRONMENTAL RESEARCH LETTERS*, **15**(10), doi:10.1088/1748-9326/ab9d00.
Huntington, H. P. et al., 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10**(4), 342-348, doi:10.1038/s41558-020-0695-2.
Hurlbert, M. et al., 2019: Risk management and decision making in relation to sustainable development. In: *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
Hurlbert, M. and P. Mussetta, 2016: Creating resilient water governance for irrigated producers in Mendoza, Argentina. *ENVIRONMENTAL SCIENCE & POLICY*, **58**, 83-94, doi:10.1016/j.envsci.2016.01.004.
Huyer, S., 2016: Closing the Gender Gap in Agriculture. *Gender, Technology and Development*, **20**(2), 105-116, doi:10.1177/0971852416643872.
Huynh, L. T. M. and L. C. Stringer, 2018: Multi-scale assessment of social vulnerability to climate change: An empirical study in coastal Vietnam. *Climate Risk Management*, **20**, 165-180.
ICRC, 2020: When rain turns to dust. Understanding and responding to the combined impact of armed conflicts and the climate and environment crisis on people's lives. ICRC, Geneva, 64 pp.
ICSU, 2017: *A guide to SDG interactions: from science to implementation*. International Council for Science (ICSU) (accessed 2019-04-05 08:25:52).
Ide, T., M. Brzoska, J. F. Donges and C.-F. Schleussner, 2020: Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk. *Global Environmental Change*, **62**, 102063, doi:10.1016/j.gloenvcha.2020.102063.
IDMC, 2019: *Global Report on Internal Displacement*. Internal Displacement Monitoring Centre, Norwegian Refugee Council (NRC). Available at: http://www.internal-displacement.org/sites/default/files/publications/documents/2019-IDMC-GRID.pdf.
IDMC, 2020: *Global Report on Internal Displacement 2020*. Internal Displacement Monitoring Centre, Geneva, Switzerland.
Iese, V. et al., 2021: Impacts of COVID-19 on agriculture and food systems in Pacific Island countries (PICs): Evidence from communities in Fiji and Solomon Islands. *Agricultural Systems*, **190**, 103099, doi:10.1016/j.agsy.2021.103099.
Ifeanyi-obi, C. C., A. O. Togun, R. Lamboll and S. Arokoyu, 2017: Socio-Economic Determinants of Cocoyam Farmer's Strategies for Climate Change Adaptation in Southeast Nigeria. *JOURNAL OF AGRICULTURAL EXTENSION*, **21**(2), 91-104, doi:10.4314/jae.v21i2.8.
Iizumi, T. et al., 2018: Uncertainties of potentials and recent changes in global yields of major crops resulting from census- and satellite-based yield datasets at multiple resolutions. *PLOS ONE*, **13**(9), e0203809, doi:10.1371/journal.pone.0203809.
Iizumi, T. et al., 2020: Climate change adaptation cost and residual damage to global crop production. *Climate Research*, **80**(3), 203-218.
Ike, M., J. D. Donovan, C. Topple and E. K. Masli, 2019: The process of selecting and prioritising corporate sustainability issues: Insights for achieving the Sustainable Development Goals. *Journal of Cleaner Production*, **236**, 117661, doi:10.1016/j.jclepro.2019.117661.
Im, E.-S., J. S. Pal and E. A. B. Eltahir, 2017: Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science Advances*, **3**(8), e1603322, doi:10.1126/sciadv.1603322.
IMF, 2017: *Seeking sustainable growth: short-term recovery, long-term challenges* [Währungsfonds, I. (ed.)]. World economic outlook, International Monetary Fund, Washington, DC, 284 pp. ISBN 978-1-4843-1249-0 978-1-4843-2114-0 978-1-4843-2112-6 978-1-4843-2111-9.
IMF, 2020: World Economic Outlook Update, June 2020. *International Monetary Fund (IMF): Washington*.
IMF, 2021: World Economic Outlook Update July 2021. International Monetary Fund.

Ingole, V. et al., 2017: Socioenvironmental factors associated with heat and cold-related mortality in Vadu HDSS, western India: a population-based case-crossover study. *International journal of biometeorology*, **61**(10), 1797-1804.
IPBES, 2019: *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*. 37 pp. Available at: https://www.ipbes.net/system/tdf/ipbes_7_10_add-1-_advance_0.pdf?file=1&type=node&id=35245.
IPCC, 2014: Summary for Policymakers. In: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing, T., R. K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, pp. 2-31.
IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V. (ed.)]. In press pp. ISBN 9789291691517.
IPCC, 2019a: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R. (ed.)]. In press pp.
IPCC, 2019b: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O. (ed.)]. In press pp.
IPCC, 2021a: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
IPCC, 2021b: *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Irvine, P. J. and D. W. Keith, 2020: Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards, 044011 pp.
Irvine, P. J. et al., 2017: Towards a comprehensive climate impacts assessment of solar geoengineering. *Earth's Future*, **5**(1), 93-106.
Islam, S. F.-u. et al., 2020: Mitigation of greenhouse gas emissions and reduced irrigation water use in rice production through water-saving irrigation scheduling, reduced tillage and fertiliser application strategies. *Science of the Total Environment*, **739**, 140215.
Ivanic, M. and W. Martin, 2008: *Implications of higher global food prices for poverty in low-income countries*. The World Bank.
Iwama, A. Y. et al., 2016: Risk, vulnerability and adaptation to climate change: An interdisciplinary approach. *Ambiente & Sociedade*, **19**, 93-116.
Izaguirre, C. et al., 2021: Climate change risk to global port operations. *Nature Climate Change*, **11**(1), 14-20.
Jaakkola, J. J. K., S. Juntunen and K. Näkkäläjärvi, 2018: The Holistic Effects of Climate Change on the Culture, Well-Being, and Health of the Saami, the Only Indigenous People in the European Union, 401-417 pp.
Jackson, L., J. Crook and P. Forster, 2016: An intensified hydrological cycle in the simulation of geoengineering by cirrus cloud thinning using ice crystal fall speed changes. *Journal of Geophysical Research: Atmospheres*, **121**(12), 6822-6840.
Jafino, B. A., B. Walsh, J. Rozenberg and S. Hallegatte, 2020: Revised Estimates of the Impact of Climate Change on Extreme Poverty by 2030.
Jagai, J. S. et al., 2017: Sanitary sewer overflows and emergency room visits for gastrointestinal illness: analysis of Massachusetts data, 2006–2007. *Environmental health perspectives*, **125**(11), 117007.
Jamero, M. L. et al., 2017: Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change*, **7**(8), 581-586, doi:10.1038/nclimate3344.
Janssens, C. et al., 2020: Global hunger and climate change adaptation through international trade. *Nature Climate Change*, **10**(9), 829-835.
Javeline, D. and T. Kijewski-Correa, 2019: Coastal homeowners in a changing climate. *CLIMATIC CHANGE*, **152**(2, SI), 259-274, doi:10.1007/s10584-018-2257-4.
Jay, O. et al., 2021: Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *The Lancet*, **398**(10301), 709-724, doi:10.1016/S0140-6736(21)01209-5.
Jenkins, L. M., R. Alvarez and S. M. Jordaan, 2020: Unmanaged climate risks to spent fuel from U.S. nuclear power plants: The case of sea-level rise. *Energy Policy*, **137**, 111106, doi:10.1016/j.enpol.2019.111106.
Jensen, S. and C. P. Traeger, 2014: Optimal climate change mitigation under long-term growth uncertainty: Stochastic integrated assessment and analytic findings. *European Economic Review*, **69**, 104-125.
Jezeer, R. E. et al., 2019: Influence of livelihood assets, experienced shocks and perceived risks on smallholder coffee farming practices in Peru *JOURNAL OF ENVIRONMENTAL MANAGEMENT*, **242**, 496-506, doi:10.1016/j.jenvman.2019.04.101.

Johnson, F. A. et al., 2016: Is shrimp farming a successful adaptation to salinity intrusion? A geospatial associative analysis of poverty in the populous Ganges-Brahmaputra-Meghna Delta of Bangladesh. *SUSTAINABILITY SCIENCE*, **11**(3), 423-439, doi:10.1007/s11625-016-0356-6.

Jolly, W. M. et al., 2015: Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, **6**(1), 1-11, doi:10.1038/ncomms8537.

Jones, A. et al., 2021: North Atlantic Oscillation response in GeoMIP experiments G6solar and G6sulfur: why detailed modelling is needed for understanding regional implications of solar radiation management. *Atmospheric Chemistry and Physics*, **21**(2), 1287-1304.

Jones, A. C. et al., 2018a: Regional Climate Impacts of Stabilizing Global Warming at 1.5 K Using Solar Geoengineering, 230-251 pp.

Jones, B. and B. C. O'Neill, 2016: Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environmental Research Letters*, **11**(8), 084003, doi:10.1088/1748-9326/11/8/084003.

Jones, B. et al., 2018b: Avoiding population exposure to heat-related extremes: demographic change vs climate change. *Climatic Change*, **146**(3), 423-437, doi:10.1007/s10584-017-2133-7.

Jones, H. P. et al., 2020: Global hotspots for coastal ecosystem-based adaptation. *PLOS ONE*, **15**(5), doi:10.1371/journal.pone.0233005.

Jongman, B. et al., 2015: Declining vulnerability to river floods and the global benefits of adaptation. *Proceedings of the National Academy of Sciences*, **112**(18), E2271-E2280.

Jordaan, S. M., A. Siddiqi, W. Kakenmaster and A. C. Hill, 2019: The Climate Vulnerabilities of Global Nuclear Power. *Global Environmental Politics*, **19**(4), 3-13, doi:10.1162/glep_a_00527.

Jorgensen, S. L. and M. Termansen, 2016: Linking climate change perceptions to adaptation and mitigation action. *CLIMATIC CHANGE*, **138**(1-2), 283-296, doi:10.1007/s10584-016-1718-x.

Kahn, M. et al., 2019: *Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis*. INTERNATIONAL MONETARY FUND. ISBN 978-1-5135-1459-8.

Kakumanu, K. R. et al., 2018: BUILDING FARM-LEVEL CAPACITIES IN IRRIGATION WATER MANAGEMENT TO ADAPT TO CLIMATE CHANGE. *IRRIGATION AND DRAINAGE*, **67**(1, SI), 43-54, doi:10.1002/ird.2143.

Kalkuhl, M. and L. Wenz, 2020: The impact of climate conditions on economic production. Evidence from a global panel of regions. *Journal of Environmental Economics and Management*, **103**, 102360.

Kam, P. M. et al., 2021: Global warming and population change both heighten future risk of human displacement due to river floods. *Environmental Research Letters*, **16**(4), 044026, doi:10.1088/1748-9326/abd26c.

Kanda, A., M. Murongazvombo and F. Ncube, 2017: Adapting household water use in rural Zimbabwe. *International Journal of Environmental Studies*, **74**(3), 471-485, doi:10.1080/00207233.2017.1319622.

Karagiannis, G. M. et al., 2019: Climate change and critical infrastructure – floods. 43.

Karapinar, B. and G. Özertan, 2020: Yield implications of date and cultivar adaptation to wheat phenological shifts: a survey of farmers in Turkey. *Climatic Change*, **158**(3-4), 453-472, doi:10.1007/s10584-019-02532-4.

Karlsson, M., E. Alfredsson and N. Westling, 2020: Climate policy co-benefits: a review. *Climate Policy*, **20**(3), 292-316, doi:10.1080/14693062.2020.1724070.

Kattumuri, R., D. Ravindranath and T. Esteves, 2017: Local adaptation strategies in semi-arid regions: study of two villages in Karnataka, India. *CLIMATE AND DEVELOPMENT*, **9**(1), 36-49, doi:10.1080/17565529.2015.1067179.

Kaufman, N. et al., 2020: A near-term to net zero alternative to the social cost of carbon for setting carbon prices. *Nature Climate Change*, 1-5.

Kebede, A. S. et al., 2018: Applying the global RCP–SSP–SPA scenario framework at sub-national scale: A multi-scale and participatory scenario approach. *Science of the Total Environment*, **635**, 659-672.

Keith, D. W. and D. G. MacMartin, 2015: A temporary, moderate and responsive scenario for solar geoengineering. *Nat. Clim. Chang.*, **5**(3), 201-206, doi:10.1038/nclimate2493.

Keller, D. P., 2018: Marine Climate Engineering. In: *Handbook on Marine Environment Protection : Science, Impacts and Sustainable Management* [Salomon, M. and T. Markus (eds.)]. Springer International Publishing, Cham, pp. 261-276. ISBN 9783319601564.

Kelley, C. et al., 2017: Commentary on the Syria case: Climate as a contributing factor. *Political Geography*, **60**(1), 245-247.

Kelley, C. P. et al., 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the national Academy of Sciences*, **112**(11), 3241-3246.

Kelley, D. I. et al., 2021: Technical note: Low meteorological influence found in 2019 Amazonia fires. *Biogeosciences*, **18**(3), 787-804, doi:10.5194/bg-18-787-2021.

Kelman, I., 2015: Difficult decisions: Migration from Small Island Developing States under climate change. *Earth's Future*, **3**(4), 133-142, doi:10.1002/2014EF000278.

Kerr, R. B. et al., 2019: Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *AGRICULTURE ECOSYSTEMS & ENVIRONMENT*, **279**, 109-121, doi:10.1016/j.agee.2019.04.004.

Khat, H. V., N. H. Dang and M. Yabe, 2018: Impact of salinity intrusion on rice productivity in the Vietnamese Mekong Delta. *Journal of the Faculty of Agriculture, Kyushu UniversityEconomics*, **63**(1), 6.

Kibet, S., M. Nyangito, L. MacOpiyo and D. Kenfack, 2016: Tracing innovation pathways in the management of natural and social capital on Laikipia Maasai Group Ranches, Kenya. *PASTORALISM-RESEARCH POLICY AND PRACTICE*, **6**, doi:10.1186/s13570-016-0063-z.

Kibue, G. W. et al., 2015: Assessment of climate change awareness and agronomic practices in an agricultural region of Henan Province, China. *ENVIRONMENT DEVELOPMENT AND SUSTAINABILITY*, **17**(3), 379-391, doi:10.1007/s10668-014-9546-5.

Kihila, J. M., 2018: Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review. *CLIMATE AND DEVELOPMENT*, **10**(5), 406-416, doi:10.1080/17565529.2017.1318739.

Kikstra, J. et al., 2021: The social cost of carbon dioxide under climate-economy feedbacks and temperature variability. *Preprint at https://www. researchgate. net/publication/350443280_The_social_cost_of_carbon_dioxide_under_climate-economy_feedbacks_and_temperature_variability*.

Kimaro, A. A. et al., 2016: Is conservation agriculture `climate-smart' for maize farmers in the highlands of Tanzania? *NUTRIENT CYCLING IN AGROECOSYSTEMS*, **105**(3, SI), 217-228, doi:10.1007/s10705-015-9711-8.

Kinney, P. L., 2018: Temporal trends in heat-related mortality: Implications for future projections. *Atmosphere*, **9**(10), doi:10.3390/atmos9100409.

Kirchhoff, C. J. and P. L. Watson, 2019: Are Wastewater Systems Adapting to Climate Change? *JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION*, **55**(4), 869-880, doi:10.1111/1752-1688.12748.

Kirchmeier-Young, M., H. Wan, X. Zhang and S. I. Seneviratne, 2019a: Importance of framing for extreme event attribution: The role of spatial and temporal scales. *Earth's Future*, **7**(10), 1192-1204.

Kirchmeier-Young, M. C. et al., 2019b: Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earth's Future*, **7**(7), 2-10.

Kirezci, E. et al., 2020: Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific Reports*, **10**(1), 11629, doi:10.1038/s41598-020-67736-6.

Klein, R. J. T. et al., 2014: Adaptation Opportunities, Constraints, and Limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943. ISBN 9781107058071.

Kleypas, J. et al., 2021: Designing a blueprint for coral reef survival. *Biological Conservation*, **257**, 109107, doi:10.1016/j.biocon.2021.109107.

Kling, G., Y. Lo, V. Murinde and U. Volz, 2018: Climate Vulnerability and the Cost of Debt. *SSRN Electronic Journal*, doi:10.2139/ssrn.3198093.

Klinger, C., O. Landeg and V. Murray, 2014: Power Outages, Extreme Events and Health: a Systematic Review of the Literature from 2011-2012. *PLoS Currents*, doi:10.1371/currents.dis.04eb1dc5e73dd1377e05a10e9edde673.

Klock, C. and P. D. Nunn, 2019: Adaptation to Climate Change in Small Island Developing States: A Systematic Literature Review of Academic Research. *JOURNAL OF ENVIRONMENT & DEVELOPMENT*, **28**(2), 196-218, doi:10.1177/1070496519835895.

Klomp, J., 2016: Economic development and natural disasters: A satellite data analysis. *Global Environmental Change*, **36**, 67-88, doi:10.1016/j.gloenvcha.2015.11.001.

Klomp, J. and K. Valckx, 2014: Natural disasters and economic growth: A meta-analysis. *Global Environmental Change*, **26**, 183-195, doi:10.1016/j.gloenvcha.2014.02.006.

Kloos, J. and F. G. Renaud, 2014: Organic Cotton Production as an Adaptation Option in North-West Benin. *Outlook on Agriculture*, **43**(2), 91-100, doi:10.5367/oa.2014.0166.

Knittel, N. et al., 2020: A global analysis of heat-related labour productivity losses under climate change—implications for Germany's foreign trade. *Climatic Change*, **160**(2), 251-269, doi:10.1007/s10584-020-02661-1.

Knorr, W., A. Arneth and L. Jiang, 2016: Demographic controls of future global fire risk. *Nature Climate Change*, **6**(8), 781-785.

Kompas, T., V. H. Pham and T. N. Che, 2018: The effects of climate change on GDP by country and the global economic gains from complying with the Paris climate accord. *Earth's Future*, **6**(8), 1153-1173.

Kongsager, R., 2018: Linking Climate Change Adaptation and Mitigation: A Review with Evidence from the Land-Use Sectors. *Land*, **7**(4), doi:10.3390/land7040158.

Kopp, R. E., R. L. Shwom, G. Wagner and J. Yuan, 2016: Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earth's Future*, **4**(8), 346-372.

Koski, C. and A. Siulagi, 2016: Environmental Harm or Natural Hazard? Problem Identification and Adaptation in US Municipal Climate Action Plans. *REVIEW OF POLICY RESEARCH*, **33**(3), 270-290, doi:10.1111/ropr.12173.

Kosugi, T., 2013: Fail-safe solar radiation management geoengineering. *Mitigation and Adaptation Strategies for Global Change*, **18**(8), 1141-1166.

Kotz, M. et al., 2021: Day-to-day temperature variability reduces economic growth, 319-325 pp.

Koubi, V., 2019: Climate Change and Conflict. *Annual Review of Political Science*, **22**(1), null, doi:10.1146/annurev-polisci-050317-070830.

Koubi, V., G. Spilker, L. Schaffer and T. Bohmelt, 2016: The role of environmental perceptions in migration decision-making: evidence from both migrants and non-migrants in five developing countries. *POPULATION AND ENVIRONMENT*, **38**(2), 134-163, doi:10.1007/s11111-016-0258-7.

Koutroulis, A. G. et al., 2019: Global water availability under high-end climate change: A vulnerability based assessment. *Global and Planetary Change*, **175**, 52-63, doi:10.1016/j.gloplacha.2019.01.013.

Krausmann, F. et al., 2013: Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences*, **110**(25), 10324, doi:10.1073/pnas.1211349110.

Krauss, K. W. and M. J. Osland, 2020: Tropical cyclones and the organization of mangrove forests: a review. *Annals of Botany*, **125**(2), 213-234, doi:10.1093/aob/mcz161.

Kravitz, B. and D. G. MacMartin, 2020: Uncertainty and the basis for confidence in solar geoengineering research, 64-75 pp.

Kravitz, B. et al., 2015: The geoengineering model intercomparison project phase 6 (GeoMIP6): Simulation design and preliminary results. *Geoscientific Model Development*, **8**(10), 3379-3392.

Krayenhoff, E. S. et al., 2018: Diurnal interaction between urban expansion, climate change and adaptation in US cities. *NATURE CLIMATE CHANGE*, **8**(12), 1097+, doi:10.1038/s41558-018-0320-9.

Kremen, C. and A. Miles, 2012: Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. *Ecology and Society*, **17**(4), doi:10.5751/es-05035-170440.

Krichene, H. et al., 2020: The Impacts of Tropical Cyclones and Fluvial Floods on Economic Growth–Empirical Evidence on Transmission Channels at Different Levels of Development. *Available at SSRN 3594081*.

Krishna-Pillai, S.-P. K. et al., 2019: Climate system response to stratospheric sulfate aerosols: sensitivity to altitude of aerosol layer. *Earth System Dynamics*, **10**(4), 885-900.

Krishnamurthy, L., P. Krishna Krishnamurthy, I. Rajagopal and A. Peralta Solares, 2019: Can agroforestry systems thrive in the drylands? Characteristics of successful agroforestry systems in the arid and semi-arid regions of Latin America. *AGROFORESTRY SYSTEMS*, **93**(2), 503-513, doi:10.1007/s10457-017-0143-0.

Kuenzer, C. et al., 2020: Profiling resilience and adaptation in mega deltas: A comparative assessment of the Mekong, Yellow, Yangtze, and Rhine deltas. *Ocean & Coastal Management*, **198**, 105362.

Kugeler, K. F., G. M. Farley, J. D. Forrester and P. S. Mead, 2015: Geographic Distribution and Expansion of Human Lyme Disease, United States.(1080-6059 (Electronic)).

Kulp, S. A. and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, **10**(1), 4844, doi:10.1038/s41467-019-12808-z.

Kuruppu, N. and R. Willie, 2015: Barriers to reducing climate enhanced disaster risks in Least Developed Country-Small Islands through anticipatory adaptation. *Weather and Climate Extremes*, **7**, 72-83, doi:10.1016/j.wace.2014.06.001.

Kwiatkowski, L. et al., 2015: Coral bleaching under unconventional scenarios of climate warming and ocean acidification. *Nat. Clim. Chang.*, **5**(8), 777-781, doi:10.1038/nclimate2655.

Labbe, J., J. D. Ford, M. Araos and M. Flynn, 2017: The government-led climate change adaptation landscape in Nunavut, Canada. *ENVIRONMENTAL REVIEWS*, **25**(1), 12-25, doi:10.1139/er-2016-0032.

Laczko, F., 2016: Improving Data on International Migration and Development: Towards a global action plan. *Improving Data on International Migration-towards Agenda*, **2030**, 1-12.

Lam, S. S., C. Waugh, W. Peng and C. Sonne, 2020: Wildfire puts koalas at risk of extinction. *Science*, **367**(6479), 750-750, doi:10.1126/science.aba8372.

Landauer, M., S. Juhola and J. Klein, 2019: The role of scale in integrating climate change adaptation and mitigation in cities. *JOURNAL OF ENVIRONMENTAL PLANNING AND MANAGEMENT*, **62**(5), 741-765, doi:10.1080/09640568.2018.1430022.

Landis, J., 2012: The Syrian Uprising of 2011: Why the Asad Regime Is Likely to Survive to 2013. *Middle East Policy*, **19**(1), 72-84, doi:10.1111/j.1475-4967.2012.00524.x.

Lange, S. et al., 2020: Projecting exposure to extreme climate impact events across six event categories and three spatial scales. *Earth's Future*, **8**(12), e2020EF001616.

Latham, J. et al., 2012: Marine cloud brightening. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **370**(1974), 4217-4262.

Latham, J. et al., 2013: Can marine cloud brightening reduce coral bleaching? *Atmos. Sci. Lett.*, **14**(4), 214-219, doi:10.1002/asl2.442.

Laufkötter, C., J. Zscheischler and T. L. Frölicher, 2020: High-impact marine heatwaves attributable to human-induced global warming. *Science*, **369**(6511), 1621-1625.

Lawrence, J., P. Blackett and N. A. Cradock-Henry, 2020: Cascading climate change impacts and implications. *Climate Risk Management*, **29**, 100234, doi:10.1016/j.crm.2020.100234.

Leal Filho, W. et al., 2020: *Partnerships for the Goals. Encyclopedia of the UN Sustainable Development Goals.*, Springer
Cham.

Lee, J. Y. et al., 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S.

Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Leenders, R., 2013: Social Movement Theory and the Onset of the Popular Uprising in Syria. *Arab Studies Quarterly*, **35**(3), 273, doi:10.13169/arabstudquar.35.3.0273.
Lei, Y. et al., 2017: Using government resettlement projects as a sustainable adaptation strategy for climate change. *Sustainability (Switzerland)*, **9**(8), doi:10.3390/su9081373.
Leichenko, R. and J. A. Silva, 2014: Climate change and poverty: vulnerability, impacts, and alleviation strategies: Climate change and poverty. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(4), 539-556, doi:10.1002/wcc.287.
Lemoine, D. and C. P. Traeger, 2016: Economics of tipping the climate dominoes. doi:10.1038/nclimate2902.
Lenton, T. M. et al., 2019: Climate tipping points—too risky to bet against. Nature Publishing Group.
Lesnikowski, A. et al., 2019a: Frontiers in data analytics for adaptation research: Topic modeling. *WILEY INTERDISCIPLINARY REVIEWS-CLIMATE CHANGE*, **10**(3), doi:10.1002/wcc.576.
Lesnikowski, A., R. Biesbroek, J. D. Ford and L. Berrang-Ford, 2020: Policy implementation styles and local governments: the case of climate change adaptation. *ENVIRONMENTAL POLITICS*, doi:10.1080/09644016.2020.1814045.
Lesnikowski, A. et al., 2016: National-level progress on adaptation. *NATURE CLIMATE CHANGE*, **6**(3), 261+, doi:10.1038/NCLIMATE2863.
Lesnikowski, A., J. D. Ford, R. Biesbroek and L. Berrang-Ford, 2019b: A policy mixes approach to conceptualizing and measuring climate change adaptation policy. *CLIMATIC CHANGE*, **156**(4), 447-469, doi:10.1007/s10584-019-02533-3.
Lesnikowski, A. C. et al., 2015: How are we adapting to climate change? A global assessment. *MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE*, **20**(2), 277-293, doi:10.1007/s11027-013-9491-x.
Levy, K., A. P. Woster, R. S. Goldstein and E. J. Carlton, 2016: Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. *Environmental Science & Technology*, **50**(10), 4905-4922, doi:10.1021/acs.est.5b06186.
Lewis, S. L. et al., 2011: The 2010 amazon drought. *Science*, **331**(6017), 554-554.
Li, Y. et al., 2019: Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Global Change Biology*, **25**(7), 2325-2337, doi:10.1111/gcb.14628.
Lim-Camacho, L. et al., 2017: Complex resource supply chains display higher resilience to simulated climate shocks. *Global Environmental Change*, **46**, 126-138, doi:10.1016/j.gloenvcha.2017.08.011.
Lin, S. et al., 2019: The effects of multiyear and seasonal weather factors on incidence of Lyme disease and its vector in New York State, 1182-1188 pp.
Lincke, D. and J. Hinkel, 2021: Coastal Migration due to 21st Century Sea-Level Rise. *Earth's Future*, **9**(5), e2020EF001965, doi:10.1029/2020EF001965.
Lindsay, A., 2018: Social learning as an adaptive measure to prepare for climate change impacts on water provision in Peru. *JOURNAL OF ENVIRONMENTAL STUDIES AND SCIENCES*, **8**(4), 477-487, doi:10.1007/s13412-017-0464-3.
Linke, A. M. et al., 2018: Drought, Local Institutional Contexts, and Support for Violence in Kenya. *Journal of Conflict Resolution*, **62**(7), 1544-1578, doi:10.1177/0022002717698018.
Liu-Helmersson, J., J. Rocklöv, M. Sewe and Å. Brännström, 2019: Climate change may enable Aedes aegypti infestation in major European cities by 2100. *Environmental research*, **172**, 693-699.
Liu, W. et al., 2018: Global drought and severe drought-affected populations in 1.5 and 2 °C warmer worlds. *Earth Syst. Dynam.*, **9**(1), 267-283, doi:10.5194/esd-9-267-2018.
Liverman, D., 2016: U.S. National climate assessment gaps and research needs: overview, the economy and the international context. *Climatic Change*, **135**(1), 173-186, doi:10.1007/s10584-015-1464-5.
Lizundia-Loiola, J., M. L. Pettinari and E. Chuvieco, 2020: Temporal Anomalies in Burned Area Trends: Satellite Estimations of the Amazonian 2019 Fire Crisis. *Remote Sensing*, **12**(1), doi:10.3390/rs12010151.
Lloyd, E. and N. Oreskes, 2018: Climate change attribution: When is it appropriate to accept new methods? *Earth's Future*, **1**(6(3)), 311-325.
Lloyd, S. J. et al., 2018: A Global-Level Model of the Potential Impacts of Climate Change on Child Stunting via Income and Food Price in 2030. *Environmental Health Perspectives*, **126**(9), 097007, doi:10.1289/EHP2916.
Lloyd, S. J. and S. Hales, 2019: *Challenges and gaps in assessing impacts of climate change on health in rural areas*. Expert Group Meeting on 'Eradicating Rural Poverty to Implement the 2030 Agenda for Sustainable Development', UN DESA EGM on 'Eradicating Rural Poverty to implement the 2030 Agenda for Sustainable Development, Addis Abba, Ethiopia, 33 pp. (accessed 2020-10-31).
Lobell, D. B. and C. B. Field, 2007: Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental research letters*, **2**(1), 014002.
Lobell, D. B., W. Schlenker and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333**(6042), 616-620.
Loboguerrero, A. M. et al., 2019: Food and Earth Systems: Priorities for Climate Change Adaptation and Mitigation for Agriculture and Food Systems. *Sustainability*, **11**(5), doi:10.3390/su11051372.

Locatelli, B., C. Pavageau, E. Pramova and M. Di Gregorio, 2015: Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs. *Wiley Interdisciplinary Reviews-Climate Change*, **6**(6), 585-598, doi:10.1002/wcc.357.

Longo, M. et al., Impacts of Degradation on Water, Energy, and Carbon Cycling of the Amazon Tropical Forests (accessed 2020-10-18 20:47:44).

Lontzek, T. S., Y. Cai, K. L. Judd and T. M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. 3-6, doi:10.1038/nclimate2570.

Loria, N., 2016: Farmers' Response and Adaptation Strategies to Climate Change in Low-Hills of Himachal Pradesh in India. *Nature Environment and Pollution Technology An International Quarterly Scientific Journal*, **15**(3), 895-901.

Loucks, D. P., 2019: Developed river deltas: are they sustainable? *Environmental Research Letters*, **14**(11), 113004, doi:10.1088/1748-9326/ab4165.

Loughran, K. and J. R. Elliott, 2019: Residential buyouts as environmental mobility: examining where homeowners move to illuminate social inequities in climate adaptation. *POPULATION AND ENVIRONMENT*, **41**(1), 52-70, doi:10.1007/s11111-019-00324-7.

Low, S. and M. Honegger, 2020: A Precautionary Assessment of Systemic Projections and Promises From Sunlight Reflection and Carbon Removal Modeling, risa.13565 pp.

Lowe, R. et al., 2018: Nonlinear and delayed impacts of climate on dengue risk in Barbados: A modelling study, e1002613 pp.

Lowe, R. et al., 2021: Combined effects of hydrometeorological hazards and urbanisation on dengue risk in Brazil: a spatiotemporal modelling study, e209-e219 pp.

Lundgren-Kownacki, K. et al., 2018: Climate change-induced heat risks for migrant populations working at brick kilns in India: a transdisciplinary approach. *INTERNATIONAL JOURNAL OF BIOMETEOROLOGY*, **62**(3), 347-358, doi:10.1007/s00484-017-1476-0.

Lwasa, S. et al., 2014: Urban and peri-urban agriculture and forestry: Transcending poverty alleviation to climate change mitigation and adaptation. *Urban Climate*, **7**, 92-106, doi:10.1016/j.uclim.2013.10.007.

Lynch, M., 2014: *The Arab uprisings explained: new contentious politics in the Middle East* [Lynch, M. (ed.)]. Columbia studies in Middle East politics, Columbia Univ. Press, New York, NY, 340 pp. ISBN 978-0-231-15885-5 978-0-231-15884-8 978-0-231-53749-0.

MacDougall, A. H. et al., 2020: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO₂, 2987-3016 pp.

Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-197, doi:10.1038/s41586-019-1300-6.

Macintosh, A., 2013: Coastal climate hazards and urban planning: how planning responses can lead to maladaptation. *MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE*, **18**(7), 1035-1055, doi:10.1007/s11027-012-9406-2.

Mackey, B. and D. Ware, 2018: Limits to Capital Works Adaptation in the Coastal Zones and Islands: Lessons for the Pacific. In: *Limits to Climate Change Adaptation* [Leal Filho, W. and J. Nalau (eds.)]. Springer International Publishing, Cham, pp. 301-323. ISBN 978-3-319-64598-8 978-3-319-64599-5.

MacMartin, D. G., K. Caldeira and D. W. Keith, 2014: Solar geoengineering to limit the rate of temperature change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **372**(2031), 20140134.

MacMartin, D. G. and B. Kravitz, 2019: Mission-driven research for stratospheric aerosol geoengineering. *Proceedings of the National Academy of Sciences*, **116**(4), 1089-1094.

MacMartin, D. G., K. L. Ricke and D. W. Keith, 2018: Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target, 20160454 pp.

Magnan, A. K. et al., 2019: Integrative Cross-Chapter Box on Low-Lying Islands and Coasts. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.

Magnan, A. K. et al., 2021: Global climate risk. *Nature Climate Change*, doi:10.1038/s41558-021-01156-w.

Magnan, A. K. et al., 2016: Addressing the risk of maladaptation to climate change. *WILEY INTERDISCIPLINARY REVIEWS-CLIMATE CHANGE*, **7**(5), 646-665, doi:10.1002/wcc.409.

Maharjan, A. et al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, **6**(1), 1-16, doi:10.1007/s40641-020-00153-z.

Mainardi, S., 2018: Location factors and spatial dependence in household perceptions and adaptations to climate change: A case in the upper Blue Nile Basin. *AGREKON*, **57**(1), 1-27, doi:10.1080/03031853.2017.1409128.

Major, D. C., M. Lehmann and J. Fitton, 2018: Linking the management of climate change adaptation in small coastal towns and cities to the Sustainable Development Goals. *Ocean & Coastal Management*, **163**, 205-208, doi:10.1016/j.ocecoaman.2018.06.010.

Makhado, R. A., A. T. Saidi and P. P. Tshikhudo, 2014: Optimising drought adaptation by small-scale farmers in southern Africa through integration of indigenous and technologically-driven practices. *African Journal of Science, Technology, Innovation and Development*, **6**(4), 265-273, doi:10.1080/20421338.2014.945391.

Maldonado, J. K. et al., 2014: The impact of climate change on tribal communities in the US: displacement, relocation, and human rights. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions* [Maldonado, J. K., B. Colombi and R. Pandya (eds.)]. Springer International Publishing, Cham, pp. 93-106. ISBN 978-3-319-05266-3.
Mallick, R. B. et al., 2018: Understanding the impact of climate change on pavements with CMIP5, system dynamics and simulation. *International Journal of Pavement Engineering*, **19**(8), 697-705, doi:10.1080/10298436.2016.1199880.
Mandel, A. et al., 2021: Risks on global financial stability induced by climate change: the case of flood risks. *Climatic Change*, **166**(1-2), 4, doi:10.1007/s10584-021-03092-2.
Manes, S. et al., 2021: Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, **257**, 109070.
Marchiori, L., J. F. Maystadt and I. Schumacher, 2012: The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management*, **63**(3), 355-374, doi:10.1016/j.jeem.2012.02.001.
Markolf, S. A. et al., 2019: Transportation resilience to climate change and extreme weather events - Beyond risk and robustness. *Transport Policy*, **74**, 174-186, doi:10.1016/j.tranpol.2018.11.003.
Martin-Shields, C. P. and W. Stojetz, 2019: Food security and conflict: Empirical challenges and future opportunities for research and policy making on food security and conflict. *World Development*, **119**, 150-164, doi:10.1016/j.worlddev.2018.07.011.
Martin, T. G. et al., 2015: Buffel grass and climate change: a framework for projecting invasive species distributions when data are scarce. *Biological Invasions*, **17**(11), 3197-3210, doi:10.1007/s10530-015-0945-9.
Mastrandrea, M. D. and S. H. Schneider, 2004: Probabilistic Integrated Assessment of 'Dangerous' Climate Change. *Science*, **304**(5670), 571-575, doi:10.1126/science.1094147.
Masud, M. M. et al., 2017: Adaptation barriers and strategies towards climate change: Challenges in the agricultural sector. *Journal of Cleaner Production*, **156**, 698-706, doi:10.1016/j.jclepro.2017.04.060.
Mathbout, S. et al., 2018: Spatial and temporal analysis of drought variability at several time scales in Syria during 1961–2012. *Atmospheric Research*, **200**, 153-168.
Matthews, J. B. R., 2018: Annex I: Glossary. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.
Matthews, T. K., R. L. Wilby and C. Murphy, 2017: Communicating the deadly consequences of global warming for human heat stress. *Proceedings of the National Academy of Sciences*, **114**(15), 3861-3866.
Maurel, M. and M. Tuccio, 2016: Climate Instability, Urbanisation and International Migration, 735-752 pp.
Mawejje, J., 2016: Food prices, energy and climate shocks in Uganda. *Agricultural and Food Economics*, **4**(1), doi:10.1186/s40100-016-0049-6.
Mayanja, M. N., C. Rubaire-Akiiki, J. Morton and J. D. Kabasa, 2020: Pastoral community coping and adaptation strategies to manage household food insecurity consequent to climatic hazards in the cattle corridor of Uganda. *CLIMATE AND DEVELOPMENT*, **12**(2), 110-119, doi:10.1080/17565529.2019.1605283.
Mazdiyasni, O. et al., 2017: Increasing probability of mortality during Indian heat waves. *Science Advances*, **3**(6), e1700066, doi:10.1126/sciadv.1700066.
Mazur, N., A. Curtis and M. Rogers, 2013: Do You See What I See? Rural Landholders' Belief in Climate Change. *SOCIETY & NATURAL RESOURCES*, **26**(1), 75-85, doi:10.1080/08941920.2012.686650.
Mbow, C. et al., 2019: Food Security. In: *An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
Mbow, C. et al., 2014: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability*, **6**, 8-14, doi:10.1016/j.cosust.2013.09.002.
McCollum, D. L. et al., 2018: Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters*, **13**(3), 033006, doi:10.1088/1748-9326/aaafe3.
McCusker, K. E., K. C. Armour, C. M. Bitz and D. S. Battisti, 2014: Rapid and extensive warming following cessation of solar radiation management. *Environ. Res. Lett.*, **9**(2), 024005, doi:10.1088/1748-9326/9/2/024005.
McDonald, J., J. McGee, K. Brent and W. Burns, 2019: Governing geoengineering research for the Great Barrier Reef. *Clim. Policy*, **19**(7), 801-811, doi:10.1080/14693062.2019.1592742.
McDowell, N. et al., 2018: Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, **219**(3), 851-869.
McElwee, P. et al., 2017: Using REDD plus Policy to Facilitate Climate Adaptation at the Local Level: Synergies and Challenges in Vietnam. *FORESTS*, **8**(1), doi:10.3390/f8010011.
McGranahan, G., D. Balk and B. Anderson, 2007: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, **19**(1), 17-37, doi:10.1177/0956247807076960.
McGregor, A., M. Taylor, R. M. Bourke and V. Lebot, 2016: Vulnerability of staple food crops to climate change. 79.
McKechnie, A. E., I. A. Rushworth, F. Myburgh and S. J. Cunningham, 2021: Mortality among birds and bats during an extreme heat event in eastern South Africa. *Austral Ecology*, **46**(4), 687-691, doi:10.1111/aec.13025.

McKinnon, C., 2019: Sleepwalking into lock-in? Avoiding wrongs to future people in the governance of solar radiation management research. *Environmental Politics*, **28**(3), 441-459.
McKinsey Global Institute, 2020: *Will infrastructure bend or break under climate stress*. Climate risk and response: Physical hazards and socioeconomic impacts, McKinsey Global Institute, 26 pp. (accessed 2021-08-23 07:29:13).
McLaren, D., 2016: Mitigation deterrence and the 'moral hazard' of solar radiation management. *Earth's Future*, **4**(12), 596-602.
McLaren, D. and O. Corry, 2021: The politics and governance of research into solar geoengineering. *Wiley Interdisciplinary Reviews: Climate Change*, **12**(3), e707.
McLeman, R., 2014: Climate and Human Migration Past Experiences, Future Challenges.
McLeman, R., 2019: International migration and climate adaptation in an era of hardening borders. *Nature Climate Change*, **9**(12), 911-918, doi:10.1038/s41558-019-0634-2.
McMichael, C., S. Dasgupta, S. Ayeb-Karlsson and I. Kelman, 2020: A review of estimating population exposure to sea-level rise and the relevance for migration. *Environmental Research Letters*, **15**(12), 123005, doi:10.1088/1748-9326/abb398.
McMichael, C. and M. Katonivualiku, 2020: Thick temporalities of planned relocation in Fiji. *GEOFORUM*, **108**, 286-294, doi:10.1016/j.geoforum.2019.06.012.
McNamara, K. E. and H. J. Des Combes, 2015: Planning for Community Relocations Due to Climate Change in Fiji. *International Journal of Disaster Risk Science*, **6**(3), 315-319, doi:10.1007/s13753-015-0065-2.
McNamara, K. E., R. Westoby and A. Chandra, 2021: Exploring climate-driven non-economic loss and damage in the Pacific Islands. *Current Opinion in Environmental Sustainability*, **50**, 1-11, doi:10.1016/j.cosust.2020.07.004.
McNamara, K. E., R. Westoby and S. G. Smithers, 2017: Identification of limits and barriers to climate change adaptation: case study of two islands in Torres Strait, Australia. *Geographical Research*, **55**(4), 438-455, doi:10.1111/1745-5871.12242.
McPherson, M. et al., 2017: Expansion of the Lyme Disease Vector Ixodes Scapularis in Canada Inferred from CMIP5 Climate Projections.(1552-9924 (Electronic)).
McPherson, M. L. et al., 2021: Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave, 298 pp.
Mechler, R. and T. M. Deubelli, 2021: Finance for Loss and Damage: a comprehensive risk analytical approach, 185-196 pp.
Mechler, R. et al., 2020: Loss and Damage and limits to adaptation: recent IPCC insights and implications for climate science and policy. *Sustainability Science*, **15**(4), 1245-1251, doi:10.1007/s11625-020-00807-9.
Medek, D., J. Schwartz and S. Myers, 2017: Estimated Effects of Future Atmospheric CO2 Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region. *Environmental Health Perspectives*, **125**(8), 087002, doi:10.1289/EHP41.
Medlock, J. M. et al., 2013: Driving forces for changes in geographical distribution of Ixodes ricinus ticks in Europe. *Parasites & Vectors*, **6**(1), 1, doi:10.1186/1756-3305-6-1.
Mees, H., 2017: Local governments in the driving seat? A comparative analysis of public and private responsibilities for adaptation to climate change in European and North-American cities. *JOURNAL OF ENVIRONMENTAL POLICY & PLANNING*, **19**(4), 374-390, doi:10.1080/1523908X.2016.1223540.
Meinshausen, M. et al., 2020: The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.*, **13**(8), 3571-3605, doi:10.5194/gmd-13-3571-2020.
Méjean, A., A. Pottier, M. Fleurbaey and S. Zuber, 2020: Catastrophic climate change, population ethics and intergenerational equity. *Climatic Change*, **163**(2), 873-890.
Melvin, A. M. et al., 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences*, **114**(2), E122-E131, doi:10.1073/pnas.1611056113.
Mengel, M., S. Treu, S. Lange and K. Frieler, 2021: ATTRICI v1.1 – counterfactual climate for impact attribution, 5269-5284 pp.
Mentaschi, L. et al., 2018: Global long-term observations of coastal erosion and accretion. *Scientific Reports*, **8**(1), 12876, doi:10.1038/s41598-018-30904-w.
Meredith, M. et al., 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Merk, C. et al., 2015: Exploring public perceptions of stratospheric sulfate injection. *Clim. Change*, **130**(2), 299-312.
Merk, C., G. Pönitzsch and K. Rehdanz, 2016: Knowledge about aerosol injection does not reduce individual mitigation efforts. *Environmental Research Letters*, **11**(5), 054009.
Merk, C., G. Pönitzsch and K. Rehdanz, 2019: Do climate engineering experts display moral-hazard behaviour? *Climate Policy*, **19**(2), 231-243.
Merkens, J.-L., L. Reimann, J. Hinkel and A. T. Vafeidis, 2016: Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, **145**, 57-66, doi:10.1016/j.gloplacha.2016.08.009.
Mersha, A. A. and F. Van Laerhoven, 2016: A gender approach to understanding the differentiated impact of barriers to adaptation: responses to climate change in rural Ethiopia. *Regional Environmental Change*, **16**(6), 1701-1713, doi:10.1007/s10113-015-0921-z.

Mersha, A. A. and F. van Laerhoven, 2018: The interplay between planned and autonomous adaptation in response to climate change: Insights from rural Ethiopia. *WORLD DEVELOPMENT*, **107**, 87-97, doi:10.1016/j.worlddev.2018.03.001.
Merz, B. et al., 2020: Impact forecasting to support emergency management of natural hazards. *Reviews of geophysics*, **58**(4), e2020RG000704.
Messina, J. P. et al., 2019: The current and future global distribution and population at risk of dengue. *Nature microbiology*, **4**(9), 1508-1515.
Miao, Q., 2019: Are We Adapting to Floods? Evidence from Global Flooding Fatalities. *Risk Analysis*, **39**(6), 1298-1313, doi:10.1111/risa.13245.
Middelbeek, L., K. Kolle and H. Verrest, 2014: Built to last? Local climate change adaptation and governance in the Caribbean - The case of an informal urban settlement in Trinidad and Tobago. *Urban Climate*, **8**, 138-154, doi:10.1016/j.uclim.2013.12.003.
Millon, A. et al., 2014: Dampening prey cycle overrides the impact of climate change on predator population dynamics: a long-term demographic study on tawny owls. *Global Change Biology*, **20**(6), 1770-1781, doi:10.1111/gcb.12546.
Mimura, N. et al., 2014: Adaptation Planning and Implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869-898. ISBN 9781107058071.
Minx, J. C. et al., 2017: Learning about climate change solutions in the IPCC and beyond. *Environmental Science & Policy*, **77**, 252-259, doi:10.1016/j.envsci.2017.05.014.
Mitchell, D. et al., 2016: Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environmental Research Letters*, **11**(7), 074006.
Miyan, M. A. et al., 2017: Barriers, needs and potential solutions to reducing vulnerability to global environment change for least developed countries in the Asia-Pacific Region. *APN Science Bulletin*, **7**(1), doi:10.30852/sb.2017.108.
Monaghan, A. J. et al., 2018: The potential impacts of 21st century climatic and population changes on human exposure to the virus vector mosquito Aedes aegypti. *Climatic change*, **146**(3-4), 487-500.
Monioudi, I. N. et al., 2018: Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. *Regional Environmental Change*, **18**(8), 2211-2225, doi:10.1007/s10113-018-1360-4.
Monnereau, I. and S. Abraham, 2013: Limits to autonomous adaptation in response to coastal erosion in Kosrae, Micronesia. *INTERNATIONAL JOURNAL OF GLOBAL WARMING*, **5**(4, SI), 416-432, doi:10.1504/IJGW.2013.057283.
Montaud, J.-M., N. Pecastaing and M. Tankari, 2017: Potential socio-economic implications of future climate change and variability for Nigerien agriculture: A countrywide dynamic CGE-Microsimulation analysis. *Economic Modelling*, **63**, 128-142, doi:10.1016/j.econmod.2017.02.005.
Moore, F. C., U. Baldos, T. Hertel and D. Diaz, 2017a: New science of climate change impacts on agriculture implies higher social cost of carbon. *Nature communications*, **8**(1), 1-9.
Moore, F. C. and D. B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, **5**(2), 127.
Moore, F. C. and D. B. Lobell, 2015: The fingerprint of climate trends on European crop yields. *Proceedings of the National Academy of Sciences*, **112**(9), 2670-2675, doi:10.1073/pnas.1409606112.
Moore, S. M. et al., 2017b: El Niño and the shifting geography of cholera in Africa. *Proceedings of the National Academy of Sciences*, **114**(17), 4436-4441.
Mora, C. et al., 2017: Global risk of deadly heat. *Nature Climate Change*, **7**(7), 501-506, doi:10.1038/nclimate3322.
Morecroft, M. D. et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *SCIENCE*, **366**(6471), 1329+, doi:10.1126/science.aaw9256.
Moriyama, R. et al., 2017: The cost of stratospheric climate engineering revisited. *Mitigation and Adaptation Strategies for Global Change*, **22**(8), 1207-1228.
Morris, R. L., T. M. Konlechner, M. Ghisalberti and S. E. Swearer, 2018: From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Global Change Biology*, **24**(5), 1827-1842, doi:10.1111/gcb.14063.
Morris, R. L. et al., 2019: Developing a nature-based coastal defence strategy for Australia. *AUSTRALIAN JOURNAL OF CIVIL ENGINEERING*, **17**(2), 167-176, doi:10.1080/14488353.2019.1661062.
Morrow, D. R., 2014: Ethical aspects of the mitigation obstruction argument against climate engineering research. *Philos. Trans. A Math. Phys. Eng. Sci.*, **372**(2031), doi:10.1098/rsta.2014.0062.
Morshed, M. M., M. S. Islam, H. Das Lohano and P. Shyamsundar, 2020: Production externalities of shrimp aquaculture on paddy farming in coastal Bangladesh. *AGRICULTURAL WATER MANAGEMENT*, **238**, doi:10.1016/j.agwat.2020.106213.

Moser, S. C. and J. A. F. Hart, 2015: The long arm of climate change: societal teleconnections and the future of climate change impacts studies. *Climatic Change*, **129**(1-2), 13-26, doi:10.1007/s10584-015-1328-z.
Moyer, J. D. and S. Hedden, 2020: Are we on the right path to achieve the sustainable development goals? *World Development*, **127**, 104749, doi:10.1016/j.worlddev.2019.104749.
Muchuru, S. and G. Nhamo, 2017: Climate change and the African livestock sector Emerging adaptation measures from UNFCCC national communications. *INTERNATIONAL JOURNAL OF CLIMATE CHANGE STRATEGIES AND MANAGEMENT*, **9**(2), 241-260, doi:10.1108/IJCCSM-07-2016-0093.
Mugambiwa, S. S. and H. M. Tirivangasi, 2017: Climate change: A threat towards achieving 'Sustainable Development Goal number two' (end hunger, achieve food security and improved nutrition and promote sustainable agriculture) in South Africa. *Jàmbá: Journal of Disaster Risk Studies*, **9**(1), doi:10.4102/jamba.v9i1.350.
Mukherjee, N. et al., 2015: The Delphi technique in ecology and biological conservation: applications and guidelines. *Methods in Ecology and Evolution*, **6**(9), 1097-1109, doi:10.1111/2041-210X.12387.
Müller, C. et al., 2017: Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications. *Geoscientific Model Development*, **10**(4), 1403-1422, doi:10.5194/gmd-10-1403-2017.
Munji, C. A., M. Y. Bele, M. E. Idinoba and D. J. Sonwa, 2014: Floods and mangrove forests, friends or foes? Perceptions of relationships and risks in Cameroon coastal mangroves. *ESTUARINE COASTAL AND SHELF SCIENCE*, **140**, 67-75, doi:10.1016/j.ecss.2013.11.017.
Muri, H., U. Niemeier and J. E. Kristjánsson, 2015: Tropical rainforest response to marine sky brightening climate engineering. *Geophys. Res. Lett.*, **42**(8), 2951-2960.
Musyoki, A., R. Thifhulufhelwi and F. M. Murungweni, 2016: The impact of and responses to flooding in Thulamela Municipality, Limpopo Province, South Africa. *Jàmbá: Journal of Disaster Risk Studies*, **8**(2), 10 pages, doi:10.4102/jamba.v8i2.166.
Muthee, K. W., C. Mbow, G. M. Macharia and W. Leal-Filho, 2018: Ecosystem services in adaptation projects in West Africa. *INTERNATIONAL JOURNAL OF CLIMATE CHANGE STRATEGIES AND MANAGEMENT*, **10**(4, SI), 533-550, doi:10.1108/IJCCSM-06-2017-0140.
Mycoo, M. A., 2018: Beyond 1.5 °C: vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional Environmental Change*, **18**(8), 2341-2353, doi:10.1007/s10113-017-1248-8.
Myers, S. S. et al., 2017: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annual Review of Public Health*, **38**(1), 259-277, doi:10.1146/annurev-publhealth-031816-044356.
Nakano, K., 2017: Screening of climatic impacts on a country's international supply chains: Japan as a case study. *Mitigation and Adaptation Strategies for Global Change*, **22**(4), 651-667, doi:10.1007/s11027-015-9692-6.
Nalau, J., S. Becken and B. Mackey, 2018: Ecosystem-based Adaptation: A review of the constraints. *Environmental Science & Policy*, **89**, 357-364, doi:10.1016/j.envsci.2018.08.014.
Narita, D., H.-O. Poertner and K. Rehdanz, 2020: Accounting for risk transitions of ocean ecosystems under climate change: an economic justification for more ambitious policy responses. *Climatic Change*, **162**(1), 1-11.
NASEM, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. The National Academies Press, National Academies of Sciences Medicine and Engineering, Washington, DC.
Natali, S. M. et al., 2019: Large loss of CO2 in winter observed across the northern permafrost region. *Nature Climate Change*, **9**(11), 852-857, doi:10.1038/s41558-019-0592-8.
National Academies of Sciences, E. and Medicine, 2021a: *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. The National Academies Press, Washington, DC, 328 pp. ISBN 978-0-309-67605-2.
National Academies of Sciences, E. and Medicine, 2021b: Reflecting sunlight: Recommendations for solar geoengineering research and research governance.
Naulleau, A., C. Gary, L. Prevot and L. Hossard, 2021: Evaluating Strategies for Adaptation to Climate Change in Grapevine Production-A Systematic Review. *FRONTIERS IN PLANT SCIENCE*, **11**, doi:10.3389/fpls.2020.607859.
Naumann, G. et al., 2018: Global Changes in Drought Conditions Under Different Levels of Warming. *Geophysical Research Letters*, **45**(7), 3285-3296, doi:10.1002/2017GL076521.
Nawrotzki, R. J. and J. DeWaard, 2016: Climate shocks and the timing of migration from Mexico. *Population and Environment*, **38**(1), 72-100, doi:10.1007/s11111-016-0255-x.
Nawrotzki, R. J., L. M. Hunter, D. M. Runfola and F. Riosmena, 2015: Climate change as a migration driver from rural and urban Mexico. *Environmental Research Letters*, **10**(11), 114023.
Nelson, G. et al., 2018: Income growth and climate change effects on global nutrition security to mid-century. *Nature Sustainability*, **1**(12), 773-781, doi:10.1038/s41893-018-0192-z.
Nelson, J. P., L. Kaplan and D. Tomblin, 2021: Assessing solar geoengineering research funders: Insights from two US public deliberations. *The Anthropocene Review*, **8**(1), 37-55.
Neset, T.-S. et al., 2019: Maladaptation in Nordic agriculture. *CLIMATE RISK MANAGEMENT*, **23**, 78-87, doi:10.1016/j.crm.2018.12.003.
Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. *PLOS ONE*, **10**(3), e0118571, doi:10.1371/journal.pone.0118571.

Newell, R., A. Dale and M. Roseland, 2018: Climate action co-benefits and integrated community planning: Uncovering the synergies and trade-offs. *International Journal of Climate Change: Impacts and Responses*, **10**(4), 1-23, doi:10.18848/1835-7156.
Newell, R. G., B. C. Prest and S. E. Sexton, 2021: The GDP-temperature relationship: implications for climate change damages. *Journal of Environmental Economics and Management*, **108**, 102445.
Nicholls, R. J., W. N. Adger, C. W. Hutton and S. E. Hanson, 2020: *Deltas in the Anthropocene*. Springer Nature.
Nicholson, S., S. Jinnah and A. Gillespie, 2018: Solar radiation management: a proposal for immediate polycentric governance. *Clim. Policy*, **18**(3), 322-334, doi:10.1080/14693062.2017.1400944.
Nicolas, C. et al., 2019: *Stronger Power: Improving Power Sector Resilience to Natural Hazards*. World Bank.
Niemeier, U., H. Schmidt and C. Timmreck, 2011: The dependency of geoengineered sulfate aerosol on the emission strategy, 189-194 pp.
Nienhuis, J. H. et al., 2020: Global-scale human impact on delta morphology has led to net land area gain. *Nature*, **577**(7791), 514-518, doi:10.1038/s41586-019-1905-9.
Nilsson, M. et al., 2018: Mapping interactions between the sustainable development goals: lessons learned and ways forward. *Sustainability science*, **13**(6), 1489-1503.
Nilsson, M., D. Griggs and M. Visbeck, 2016: Map the interactions between Sustainable Development Goals. 3.
Nizami, A., J. Ali and M. Zulfiqar, 2019: Climate change, hydro-meteorological hazards and adaptation for sustainable livelihood in Chitral Pakistan. *Sarhad Journal of Agriculture*, **35**(2), 432-441, doi:10.17582/journal.sja/2019/35.2.432.441.
Nordhagen, S. and U. Pascual, 2013: The Impact of Climate Shocks on Seed Purchase Decisions in Malawi: Implications for Climate Change Adaptation. *WORLD DEVELOPMENT*, **43**, 238-251, doi:10.1016/j.worlddev.2012.08.002.
Nordhaus, W. D., 1994: Expert opinion on climatic change.
Nordhaus, W. D. and A. Moffat, 2017: *A survey of global impacts of climate change: replication, survey methods, and a statistical analysis*. National Bureau of Economic Research.
Nordkvelle, J., S. A. Rustad and M. Salmivalli, 2017: Identifying the effect of climate variability on communal conflict through randomization. *Climatic Change*, **141**(4), 627-639, doi:10.1007/s10584-017-1914-3.
Northrop, E. et al., 2016: Examining the alignment between the intended nationally determined contributions and sustainable development goals. *World Resources Institute*.
Norton-Smith, K., K. Lynn, K. Chief and K. Cozzetto, Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences. 142.
Nunfam, V. F. et al., 2018: Social impacts of occupational heat stress and adaptation strategies of workers: A narrative synthesis of the literature. *SCIENCE OF THE TOTAL ENVIRONMENT*, **643**, 1542-1552, doi:10.1016/j.scitotenv.2018.06.255.
Nunn, P. D., A. Kohler and R. Kumar, 2017: Identifying and assessing evidence for recent shoreline change attributable to uncommonly rapid sea-level rise in Pohnpei, Federated States of Micronesia, Northwest Pacific Ocean. *Journal of Coastal Conservation*, **21**, 719-730, doi:10.1007/s11852-017-0531-7.
Nuttall, M., 2020: Water, ice, and climate change in northwest Greenland. *WIREs Water*, **7**(3), doi:10.1002/wat2.1433.
Nyamadzawo, G. et al., 2015: Optimizing dambo (seasonal wetland) cultivation for climate change adaptation and sustainable crop production in the smallholder farming areas of Zimbabwe. *INTERNATIONAL JOURNAL OF AGRICULTURAL SUSTAINABILITY*, **13**(1), 23-39, doi:10.1080/14735903.2013.863450.
Nyantakyi-Frimpong, H., P. Matous and M. E. Isaac, 2019: Smallholder farmers' social networks and resource-conserving agriculture in Ghana: a multicase comparison using exponential random graph models. *ECOLOGY AND SOCIETY*, **24**(1), doi:10.5751/ES-10623-240105.
Nyasimi, M. et al., 2017: Adoption and Dissemination Pathways for Climate-Smart Agriculture Technologies and Practices for Climate-Resilient Livelihoods in Lushoto, Northeast Tanzania. *CLIMATE*, **5**(3), doi:10.3390/cli5030063.
O'Hare, P., I. White and A. Connelly, 2016: Insurance as maladaptation: Resilience and the 'business as usual' paradox. *ENVIRONMENT AND PLANNING C-GOVERNMENT AND POLICY*, **34**(6), 1175-1193, doi:10.1177/0263774X15602022.
O'Neill, B. et al., 2014: A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic change*, **122**(3), 387-400.
O'Neill, B. et al., 2017: IPCC reasons for concern regarding climate change risks. *Nature Climate Change*, **7**(1), 28-37, doi:10.1038/nclimate3179.
Oakes, R., 2019: Culture, climate change and mobility decisions in Pacific Small Island Developing States. *Population and Environment*, **40**(4), 480-503, doi:10.1007/s11111-019-00321-w.
Oakley, J. and A. O'Hagan, 2010: *SHELF: the Sheffield elicitation framework (version 2.0)*. School of Mathematics and Statistics, University of Sheffield, UK. Available at: http://tonyohagan.co.uk/shelf/.
OECD, 2019: *Measuring Distance to the SDG Targets 2019: An Assessment of Where OECD Countries Stand,* . OECD Publishing, Paris.
Ofoegbu, C., P. W. Chirwa, J. Francis and F. D. Babalola, 2016: Assessing forest-based rural communities' adaptive capacity and coping strategies for climate variability and change: The case of Vhembe district in south Africa. *ENVIRONMENTAL DEVELOPMENT*, **18**, 36-51, doi:10.1016/j.envdev.2016.03.001.

Ojha, H. R. et al., 2014: Is South Asian Agriculture Adapting to Climate Change? Evidence from the Indo-Gangetic Plains. *AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS*, **38**(5), 505-531, doi:10.1080/21683565.2013.841607.
Olazabal, M. et al., 2019: A cross-scale worldwide analysis of coastal adaptation planning. *ENVIRONMENTAL RESEARCH LETTERS*, **14**(12), doi:10.1088/1748-9326/ab5532.
Oliver, T. H. et al., 2015: Declining resilience of ecosystem functions under biodiversity loss. *Nature Communications*, **6**(1), 10122, doi:10.1038/ncomms10122.
Olmstead, S. M., 2014: Climate change adaptation and water resource management: A review of the literature. *ENERGY ECONOMICS*, **46**(SI), 500-509, doi:10.1016/j.eneco.2013.09.005.
Oppenheimer, M. et al., 2014: Emergent Risks and Key Vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099. ISBN 9781107058071.
Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Otto, I. M. et al., 2017: Social vulnerability to climate change: a review of concepts and evidence. *Regional Environmental Change*, **17**(6), 1651-1662, doi:10.1007/s10113-017-1105-9.
Pal, J. S. and E. A. B. Eltahir, 2016: Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change*, **6**(2), 197-200, doi:10.1038/nclimate2833.
Palao, L. K., D. Naziri, J. G. Balanza and D. M. Campilan, 2019: *Transformational adaptation of key root and tuber crops in Asia: Assessing crop suitability amidst climate change by species distribution modelling*. International Potato Center (accessed 2020-10-14 01:08:35).
Panda, A., 2018: Transformational adaptation of agricultural systems to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **9**(4), e520, doi:10.1002/wcc.520.
Pandey, R. et al., 2017: Agroecology as a Climate Change Adaptation Strategy for Smallholders of Tehri-Garhwal in the Indian Himalayan Region. *SMALL-SCALE FORESTRY*, **16**(1), 53-63, doi:10.1007/s11842-016-9342-1.
Paprocki, K. and S. Huq, 2018: Shrimp and coastal adaptation: on the politics of climate justice. *CLIMATE AND DEVELOPMENT*, **10**(1), 1-3, doi:10.1080/17565529.2017.1301871.
Parker, A., 2014: Governing solar geoengineering research as it leaves the laboratory. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **372**(2031), 20140173.
Parker, A., J. B. Horton and D. W. Keith, 2018: Stopping Solar Geoengineering Through Technical Means: A Preliminary Assessment of Counter-Geoengineering, 1058-1065 pp.
Parker, L., C. Bourgoin, A. Martinez-Valle and P. Läderach, 2019: Vulnerability of the agricultural sector to climate change: The development of a pan-tropical Climate Risk Vulnerability Assessment to inform sub-national decision making. *PLOS ONE*, **14**(3), e0213641, doi:10.1371/journal.pone.0213641.
Parkes, B., A. Challinor and K. Nicklin, 2015: Crop failure rates in a geoengineered climate: impact of climate change and marine cloud brightening. *Environ. Res. Lett.*, **10**(8), 084003, doi:10.1088/1748-9326/10/8/084003.
Parmesan, C. et al., 2013: Beyond climate change attribution in conservation and ecological research. *Ecology Letters*, **16**(s1), 58-71, doi:10.1111/ele.12098.
Parry, J., 2014: The UK response to the challenge of climate change. *PROCEEDINGS OF THE INSTITUTION OF CIVIL ENGINEERS-MUNICIPAL ENGINEER*, **167**(2), 63-76, doi:10.1680/muen.13.00032.
Parson, E. A., 2014: Climate engineering in global climate governance: Implications for participation and linkage. *TEL*, **3**, 89.
Partanen, A.-I., D. P. Keller, H. Korhonen and H. D. Matthews, 2016: Impacts of sea spray geoengineering on ocean biogeochemistry. *Geophys. Res. Lett.*, **43**(14), 7600-7608.
Partey, S. T., R. B. Zougmore, M. Ouedraogo and N. V. Thevathasan, 2017: Why Promote Improved Fallows as a Climate-Smart Agroforestry Technology in Sub-Saharan Africa? *SUSTAINABILITY*, **9**(11), doi:10.3390/su9111887.
Pascual, M. et al., 2006: Malaria resurgence in the East African highlands: Temperature trends revisited. *Proceedings of the National Academy of Sciences*, **103**(15), 5829, doi:10.1073/pnas.0508929103.
Pastor, A. V. et al., 2019: The global nexus of food–trade–water sustaining environmental flows by 2050. *Nature Sustainability*, **2**(6), 499-507, doi:10.1038/s41893-019-0287-1.
Patnaik, U. and K. Narayanan, 2015: How effective are coping mechanisms in securing livelihoods against climatic aberrations?: Evidences from rural India. *International Journal of Climate Change Strategies and Management*, **7**(3), 359-374, doi:10.1108/IJCCSM-07-2014-0085.
Patricola, C. M. and M. F. Wehner, 2018: Anthropogenic influences on major tropical cyclone events. *Nature*, **563**(7731), 339-346.
Paz, S. et al., 2013: Permissive Summer Temperatures of the 2010 European West Nile Fever Upsurge. *PLOS ONE*, **8**(2), e56398, doi:10.1371/journal.pone.0056398.

Pearson, J., G. Jackson and K. E. McNamara, 2021: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, 205301962110054, doi:10.1177/20530196211005482.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355**(6332), eaai9214, doi:10.1126/science.aai9214.
Pelling, M. and M. Garschagen, 2019: Put equity first in climate adaptation. *Nature*, **569**(7756), 327-329, doi:10.1038/d41586-019-01497-9.
Pelling, M., K. O'Brien and D. Matyas, 2015: Adaptation and transformation. *Climatic Change*, **133**(1), 113-127, doi:10.1007/s10584-014-1303-0.
Pereira, L. and e. al., 2021: From Fairplay to Climate Wars: Making climate change scenarios more dynamic, creative and integrative. *Ecology and Society*.
Péres, W. E., A. F. Ribeiro, A. Russo and B. Nunes, 2020: The Association between Air Temperature and Mortality in Two Brazilian Health Regions. *Climate*, **8**(1), 16.
Perez-Saez, J. et al., 2015: A theoretical analysis of the geography of schistosomiasis in Burkina Faso highlights the roles of human mobility and water resources development in disease transmission. *PLoS Negl Trop Dis*, **9**(10), e0004127.
Perrotti, D. and S. Stremke, 2020: Can urban metabolism models advance green infrastructure planning? Insights from ecosystem services research. *Environment and Planning B-Urban Analytics and City Science*, **47**(4), 678-694, doi:10.1177/2399808318797131.
Perry, C. T. et al., 2018: Loss of coral reef growth capacity to track future increases in sea level. *Nature*, **558**(7710), 396-400, doi:10.1038/s41586-018-0194-z.
Perry, S. J., S. McGregor, A. S. Gupta and M. H. England, 2017: Future Changes to El Niño–Southern Oscillation Temperature and Precipitation Teleconnections. *Geophysical Research Letters*, **44**(20), 10,608-610,616, doi:10.1002/2017GL074509.
Pershing, A. J. et al., 2016: Response to Comments on 'Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery'. *SCIENCE*, **352**(6284), doi:10.1126/science.aae0463.
Persson, Å., 2019: Global adaptation governance: An emerging but contested domain. *WIREs Climate Change*, **10**(6), e618, doi:10.1002/wcc.618.
Pescaroli, G. and D. Alexander, 2015: A definition of cascading disasters and cascading effects: Going beyond the 'toppling dominos' metaphor. *Planet@ risk*, **3**(1), 58-67.
Pescaroli, G. and D. Alexander, 2018: Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework. *Risk Analysis*, **38**(11), 2245-2257, doi:10.1111/risa.13128.
Pescaroli, G., M. Nones, L. Galbusera and D. Alexander, 2018: Understanding and mitigating cascading crises in the global interconnected system. *International Journal of Disaster Risk Reduction*, **30**, 159-163, doi:10.1016/j.ijdrr.2018.07.004.
Petrova, K., 2021: Natural hazards, internal migration and protests in Bangladesh. *Journal of Peace Research*, **58**(1), 33-49, doi:10.1177/0022343320973741.
Pettersson, T. and M. Öberg, 2020: Organized violence, 1989–2019. *Journal of Peace Research*, **57**(4), 597-613, doi:10.1177/0022343320934986.
Pezzey, J. C., 2019: Why the social cost of carbon will always be disputed. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(1), e558.
Pidgeon, N. et al., 2012: Exploring early public responses to geoengineering. *Philos. Trans. A Math. Phys. Eng. Sci.*, **370**(1974), 4176-4196, doi:10.1098/rsta.2012.0099.
Pienkowski, D. and W. Zbaraszewski, 2019: THE CONCEPT OF CLIMATE RESILIENT ECONOMY FROM THE PERSPECTIVE OF LOCAL COMMUNITIES. *EKONOMIA I SRODOWISKO-ECONOMICS AND ENVIRONMENT*, **1**(68), 204-213.
Piggott-McKellar, A. E., P. D. Nunn, K. E. McNamara and S. T. Sekinini, 2020: *Dam(n) Seawalls: A Case of Climate Change Maladaptation in Fiji*. Climate Change Management, 69 pp.
Piguet, E., 2019: Climatic Statelessness: Risk Assessment and Policy Options. *Population and Development Review*, **45**(4), 865-883, doi:10.1111/padr.12295.
Pindyck, R. S., 2013: Climate Change Policy: What Do the Models Tell Us? **51**, 860-872, doi:10.1257/jel.51.3.860.
Pindyck, R. S., 2017: The use and misuse of models for climate policy. *Review of Environmental Economics and Policy*, **11**(1), 100-114.
Pindyck, R. S., 2019: The social cost of carbon revisited. *Journal of Environmental Economics and Management*, **94**, 140-160.
Pinke, Z., S. Pow and Z. Kern, 2019: Volcanic mega-eruptions may trigger major cholera outbreaks, 151-162 pp.
Pinnegar, J. K. et al., 2019: Assessing vulnerability and adaptive capacity of the fisheries sector in Dominica: long-term climate change and catastrophic hurricanes. *ICES Journal of Marine Science*, fsz052, doi:10.1093/icesjms/fsz052.
Pinsky, M. L. et al., 2018: Preparing ocean governance for species on the move. *Science*, **360**(6394), 1189-1191, doi:10.1126/science.aat2360.
Piontek, F. et al., 2021: Integrated perspective on translating biophysical to economic impacts of climate change. *Nature Climate Change*, 1-10.

Pitari, G. et al., 2014: Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, **119**(5), 2629-2653, doi:https://doi.org/10.1002/2013JD020566.
Pokhrel, Y. et al., 2021: Global terrestrial water storage and drought severity under climate change. *Nature Climate Change*, **11**(3), 226-233, doi:10.1038/s41558-020-00972-w.
Poloczanska, E. S. et al., 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3**, 919, doi:10.1038/nclimate1958
https://www.nature.com/articles/nclimate1958#supplementary-information.
Pongratz, J., D. B. Lobell, L. Cao and K. Caldeira, 2012: Crop yields in a geoengineered climate. *Nat. Clim. Chang.*, **2**(2), 101-105, doi:10.1038/nclimate1373.
Porio, E., 2014: Climate Change Vulnerability and Adaptation in Metro Manila Challenging Governance and Human Security of Urban Poor Communities. *ASIAN JOURNAL OF SOCIAL SCIENCE*, **42**(1-2), 75-102, doi:10.1163/15685314-04201006.
Porter, J. J., S. Dessai and E. L. Tompkins, 2014: What do we know about UK household adaptation to climate change? A systematic review. *Climatic Change*, **127**(2), 371-379, doi:10.1007/s10584-014-1252-7.
Pörtner, H. O. et al., 2021: *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change*. IPBES and IPCC.
Postigo, J. C., 2014: PERCEPTION AND RESILIENCE OF ANDEAN POPULATIONS FACING CLIMATE CHANGE. *JOURNAL OF ETHNOBIOLOGY*, **34**(3, SI), 383-400, doi:10.2993/0278-0771-34.3.383.
Poudel, D. D. and T. W. Duex, 2017: Vanishing Springs in Nepalese Mountains: Assessment of Water Sources, Farmers' Perceptions, and Climate Change Adaptation. *Mountain Research and Development*, **37**(1), 35, doi:10.1659/MRD-JOURNAL-D-16-00039.1.
Pradhan, P. et al., 2017: A Systematic Study of Sustainable Development Goal (SDG) Interactions. *Earth's Future*, **5**(11), 1169-1179, doi:10.1002/2017EF000632.
Prain, G. and D. Naziri, 2019: *The role of root and tuber crops in strengthening agri-food system resilience in Asia. A literature review and selective stakeholder assessment.*, International Potato Center (accessed 2020-10-14 01:11:39).
Preston, C. and W. Carr, 2018: Recognitional Justice, Climate Engineering, and the Care Approach. *Ethics, Policy & Environment*, **21**(3), 308-323, doi:10.1080/21550085.2018.1562527.
Pretis, F. et al., 2018: Uncertain impacts on economic growth when stabilizing global temperatures at 1.5°C or 2°C warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160460, doi:10.1098/rsta.2016.0460.
Pritchard, B. and R. Thielemans, 2014: 'Rising Waters Don't Lift All Boats': a sustainable livelihood analysis of recursive cycles of vulnerability and maladaptation to flood risk in rural Bihar, India. *Australian Geographer*, **45**(3), 325-339, doi:10.1080/00049182.2014.930001.
Proctor, J. et al., 2018: Estimating global agricultural effects of geoengineering using volcanic eruptions. *Nature*, **560**(7719), 480-483, doi:10.1038/s41586-018-0417-3.
Pugatch, T., 2019: Tropical storms and mortality under climate change. *World Development*, **117**, 172-182, doi:10.1016/j.worlddev.2019.01.009.
Puthucherril, T. G., S. Evans and M. Doelle, 2014: The role of the unfccc Regime in ensuring effective adaptation in developing countries: Lessons from Bangladesh. *Climate Law*, **4**(3-4), 327-352, doi:10.1163/18786561-00404007.
Pyatkova, K. et al., 2019: Assessing the knock-on effects of flooding on road transportation. *Journal of Environmental Management*, **244**, 48-60, doi:10.1016/j.jenvman.2019.05.013.
Qin, Y. et al., 2021: Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nature Climate Change*, **11**(5), 442-448, doi:10.1038/s41558-021-01026-5.
Rabin, S. S. et al., 2020: Impacts of future agricultural change on ecosystem service indicators. *Earth System Dynamics*, **11**(2), 357-376, doi:10.5194/esd-11-357-2020.
Radel, C., B. Schmook, L. Carte and S. Mardero, 2018: Toward a Political Ecology of Migration: Land, Labor Migration, and Climate Change in Northwestern Nicaragua. *WORLD DEVELOPMENT*, **108**, 263-273, doi:10.1016/j.worlddev.2017.04.023.
Rademacher-Schulz, C., B. Schraven and E. S. Mahama, 2014: Time matters: shifting seasonal migration in Northern Ghana in response to rainfall variability and food insecurity. *CLIMATE AND DEVELOPMENT*, **6**(1, SI), 46-52, doi:10.1080/17565529.2013.830955.
Rahman, A. A., P. Artaxo, A. Asrat and A. Parker, 2018: Developing countries must lead on solar geoengineering research. Nature publishing group.
Rahman, H. M. T. and G. M. Hickey, 2019: What Does Autonomous Adaptation to Climate Change Have to Teach Public Policy and Planning About Avoiding the Risks of Maladaptation in Bangladesh? *FRONTIERS IN ENVIRONMENTAL SCIENCE*, **7**, doi:10.3389/fenvs.2019.00002.
Rahman, S., M. S. Islam, M. N. H. Khan and M. Touhiduzzaman, 2019: Climate change adaptation and disaster risk reduction (DRR) through coastal afforestation in South-Central Coast of Bangladesh. *MANAGEMENT OF ENVIRONMENTAL QUALITY*, **30**(3), 498-517, doi:10.1108/MEQ-01-2018-0021.
Ranasinghe, R. et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the*

Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.
Rao, N. D., P. Sauer, M. Gidden and K. Riahi, 2019: Income inequality projections for the Shared Socioeconomic Pathways (SSPs). *Futures*, **105**, 27-39, doi:10.1016/j.futures.2018.07.001.
Ratnayake, H. U. et al., 2019: Forecasting wildlife die-offs from extreme heat events. *Animal Conservation*, **22**(4), 386-395, doi:10.1111/acv.12476.
Ravera, F., B. Martín-López, U. Pascual and A. Drucker, 2016: The diversity of gendered adaptation strategies to climate change of Indian farmers: A feminist intersectional approach. *Ambio*, **45**(S3), 335-351, doi:10.1007/s13280-016-0833-2.
Ray, D. K., J. S. Gerber, G. K. MacDonald and P. C. West, 2015: Climate variation explains a third of global crop yield variability. *Nature Communications*, **6**(1), 5989, doi:10.1038/ncomms6989.
Ray, D. K. et al., 2012: Recent patterns of crop yield growth and stagnation. *Nature Communications*, **3**(1), 1-7, doi:10.1038/ncomms2296.
Ray, D. K. et al., 2019: Climate change has likely already affected global food production. *PloS one*, **14**(5), e0217148.
Rayner, S. et al., 2013: The oxford principles. *Clim. Change*, **121**(3), 499-512.
Raza, A. et al., 2019: Impact of Climate Change on Crops Adaptation and Strategies to Tackle Its Outcome: A Review. *Plants*, **8**(2), doi:10.3390/plants8020034.
Reckien, D. et al., 2018: How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *JOURNAL OF CLEANER PRODUCTION*, **191**, 207-219, doi:10.1016/j.jclepro.2018.03.220.
Reckien, D. et al., 2019: Dedicated versus mainstreaming approaches in local climate plans in Europe. *RENEWABLE & SUSTAINABLE ENERGY REVIEWS*, **112**, 948-959, doi:10.1016/j.rser.2019.05.014.
Regmi, B. R., C. Star and W. Leal Filho, 2016a: Effectiveness of the Local Adaptation Plan of Action to support climate change adaptation in Nepal. *MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE*, **21**(3), 461-478, doi:10.1007/s11027-014-9610-3.
Regmi, B. R., C. Star and W. Leal Filho, 2016b: An overview of the opportunities and challenges of promoting climate change adaptation at the local level: a case study from a community adaptation planning in Nepal. *CLIMATIC CHANGE*, **138**(3-4), 537-550, doi:10.1007/s10584-016-1765-3.
Reilly, J. et al., 2007: Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone. *Energy Policy*, **35**(11), 5370-5383.
Ren, J., J. B. Campbell and Y. Shao, 2016: Spatial and temporal dimensions of agricultural land use changes, 2001–2012, East-Central Iowa. *Agricultural Systems*, **148**, 149-158.
Renaud, F. G. et al., 2015: Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta. *CLIMATIC CHANGE*, **133**(1), 69-84, doi:10.1007/s10584-014-1113-4.
Rentschler, J. and S. Melda, 2020: *People in Harm's Way : Flood Exposure and Poverty in 189 Countries*. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/34655.
Retief, F. et al., 2016: Global megatrends and their implications for environmental assessment practice. *Environmental Impact Assessment Review*, **61**, 52-60, doi:10.1016/j.eiar.2016.07.002.
Reynolds, J. L., 2019a: *The Governance of Solar Geoengineering: Managing Climate Change in the Anthropocene*. Cambridge University Press, 250 pp. ISBN 9781107161955.
Reynolds, J. L., 2019b: Solar geoengineering to reduce climate change: a review of governance proposals. *Proceedings of the Royal Society A*, **475**(2229), 20190255.
Rhiney, K., A. Eitzinger, A. D. Farrell and S. D. Prager, 2018: Assessing the implications of a 1.5 °C temperature limit for the Jamaican agriculture sector. *Regional Environmental Change*, **18**(8), 2313-2327, doi:10.1007/s10113-018-1409-4.
Richardson, K. J. et al., 2018a: Food security outcomes under a changing climate: impacts of mitigation and adaptation on vulnerability to food insecurity. *Climatic Change*, **147**(1), 327-341, doi:10.1007/s10584-018-2137-y.
Richardson, T. B. et al., 2018b: Carbon Dioxide Physiological Forcing Dominates Projected Eastern Amazonian Drying. *Geophysical Research Letters*, **45**(6), 2815-2825, doi:https://doi.org/10.1002/2017GL076520.
Ricke, K., L. Drouet, K. Caldeira and M. Tavoni, 2018: Country-level social cost of carbon. *Nature Climate Change*, **8**(10), 895-900.
Ricke, K. L., J. B. Moreno-Cruz and K. Caldeira, 2013: Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters*, **8**(1), 014021.
Rickels, W. et al., 2020: Who turns the global thermostat and by how much? *Energy Economics*, **91**, 104852.
Riddle, M. S., W. H. Chen, C. D. Kirkwood and C. A. MacLennan, 2018: Update on vaccines for enteric pathogens. *Clinical Microbiology and Infection*, **24**(10), 1039-1045, doi:10.1016/j.cmi.2018.06.023.
Rigaud, K. K. et al., 2018: *Groundswell: Preparing for Internal Climate Migration*. World Bank, Washington, DC. Available at: https://www.google.com/url?q=https://openknowledge.worldbank.org/bitstream/handle/10986/29461/WBG_ClimateChange_Final.pdf&sa=D&ust=1569585643138000&usg=AFQjCNHkSEpG_vTFA5JsgrR4F3mEZK8ELQ.

Rinaldo, A. et al., 2012: Reassessment of the 2010–2011 Haiti cholera outbreak and rainfall-driven multiseason projections. *Proceedings of the National Academy of Sciences*, **109**(17), 6602-6607.
Rising, J., S. Dietz, T. Stoerk and G. Wagner (eds.), Tipping Points in the Climate System and the Economics of Climate Change. EGU General Assembly Conference Abstracts, 2959 pp.
Risser, M. D. and M. F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44**(24), 12,457-412,464.
Robalino, J., J. Jimenez and A. Chacón, 2015: The Effect of Hydro-Meteorological Emergencies on Internal Migration. *World Development*, **67**, 438-448, doi:10.1016/j.worlddev.2014.10.031.
Roberts, D. et al., 2012: Exploring ecosystem-based adaptation in Durban, South Africa: 'learning-by-doing' at the local government coal face. *ENVIRONMENT AND URBANIZATION*, **24**(1), 167-195, doi:10.1177/0956247811431412.
Robinne, F.-N. et al., 2018: A spatial evaluation of global wildfire-water risks to human and natural systems. *Science of The Total Environment*, **610-611**, 1193-1206, doi:10.1016/j.scitotenv.2017.08.112.
Robinson, S.-a., 2018a: Adapting to climate change at the national level in Caribbean small island developing states. *Island Studies Journal*, **13**(1), 79-100, doi:10.24043/isj.59.
Robinson, S.-a., 2018b: Climate Change Adaptation Limits in Small Island Developing States. In: *Limits to Climate Change Adaptation* [Leal Filho, W. and J. Nalau (eds.)]. Springer International Publishing, Cham, pp. 263-281. ISBN 978-3-319-64599-5.
Robinson, S.-a., 2020a: Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. *WILEY INTERDISCIPLINARY REVIEWS-CLIMATE CHANGE*, **11**(4), doi:10.1002/wcc.653.
Robinson, S.-a., 2020b: A richness index for baselining climate change adaptations in small island developing states. *Environmental and Sustainability Indicators*, **8**, 100065, doi:10.1016/j.indic.2020.100065.
Rode, A. et al., 2021: Estimating a Social Cost of Carbon for Global Energy Consumption. *Nature*.
Rode, K. D., C. T. Robbins, L. Nelson and S. C. Amstrup, 2015: Can polar bears use terrestrial foods to offset lost ice-based hunting opportunities? *Frontiers in Ecology and the Environment*, **13**(3), 138-145, doi:10.1890/140202.
Rodrigues, E. L., C. M. Jacobi and J. E. C. Figueira, 2019: Wildfires and their impact on the water supply of a large neotropical metropolis: A simulation approach. *Science of The Total Environment*, **651**, 1261-1271, doi:10.1016/j.scitotenv.2018.09.289.
Rodriguez-Solorzano, C., 2014: Unintended outcomes of farmers' adaptation to climate variability: deforestation and conservation in Calakmul and Maya biosphere reserves. *ECOLOGY AND SOCIETY*, **19**(2), doi:10.5751/ES-06509-190253.
Roe, M. J. and J. I. Siegel, 2011: Political instability: Effects on financial development, roots in the severity of economic inequality. *Journal of Comparative Economics*, **39**(3), 279-309, doi:10.1016/j.jce.2011.02.001.
Rogers-Bennett, L. and C. A. Catton, 2019: Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, **9**(1), 15050, doi:10.1038/s41598-019-51114-y.
Rohat, G. et al., 2019a: Projections of Human Exposure to Dangerous Heat in African Cities Under Multiple Socioeconomic and Climate Scenarios. *Earth's Future*, 2018EF001020, doi:10.1029/2018EF001020.
Rohat, G. et al., 2019b: Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe. *Global and Planetary Change*, **172**, 45-59, doi:10.1016/j.gloplacha.2018.09.013.
Roiz, D. et al., 2015: Autochthonous Chikungunya Transmission and Extreme Climate Events in Southern France. *PLOS Neglected Tropical Diseases*, **9**(6), e0003854, doi:10.1371/journal.pntd.0003854.
Román-Palacios, C. and J. J. Wiens, 2020: Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences*, **117**(8), 4211-4217.
Rose, S., 2017: *Carbon Pricing and the Social Cost of Carbon*. EPRI, Palo Alto, CA. Available at: https://www.epri.com/research/products/000000003002011391.
Rose, S. and J. Bistline, 2016: Applying the social cost of carbon: technical considerations. *EPRI Report# 3002004659. Palo Alto, CA*.
Rose, S. K., 2012: The role of the social cost of carbon in policy. *Wiley Interdisciplinary Reviews: Climate Change*, **3**(2), 195-212.
Rose, S. K., D. B. Diaz and G. J. Blanford, 2017: Understanding the social cost of carbon: a model diagnostic and inter-comparison study. *Climate Change Economics*, **8**(02), 1750009.
Rosenzweig, C. et al., 2007: Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom. ISBN 9780521880107.
Roson, R. and D. Van der Mensbrugghe, 2012: Climate change and economic growth: impacts and interactions. *International Journal of Sustainable Economy*, **4**(3), 270-285.
Roy, J. et al., 2018: Sustainable development, poverty eradication and reducing inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O.

Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. In Press.
Rudolfsen, I., 2018: Food insecurity and domestic instability: a review of the literature. *Terrorism and Political Violence*, **0**(0), 1-28, doi:10.1080/09546553.2017.1418334.
Rufat, S., E. Tate, C. T. Emrich and F. Antolini, 2019: How Valid Are Social Vulnerability Models? *Annals of the American Association of Geographers*, **109**(4), 1131-1153, doi:10.1080/24694452.2018.1535887.
Ruiz-Mallen, I. et al., 2015: How do biosphere reserves influence local vulnerability and adaptation? Evidence from Latin America. *GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS*, **33**, 97-108, doi:10.1016/j.gloenvcha.2015.05.002.
Ruiz Meza, L. E., 2015: Adaptive capacity of small-scale coffee farmers to climate change impacts in the Soconusco region of Chiapas, Mexico. *CLIMATE AND DEVELOPMENT*, **7**(2), 100-109, doi:10.1080/17565529.2014.900472.
Russo, S., J. Sillmann and A. Sterl, 2017: Humid heat waves at different warming levels. *Scientific reports*, **7**(1), 1-7.
Ryan, S. J., C. A. Lippi and F. Zermoglio, 2020: Shifting transmission risk for malaria in Africa with climate change: a framework for planning and intervention. *Malaria Journal*, **19**, 1-14.
Sachs, J. et al., 2021: *Sustainable Development Report 2021*, 1 ed., Cambridge University Press. ISBN 978-1-00-910655-9 978-1-00-909891-5 978-1-00-910289-6.
Sada, R., A. Shrestha, A. Kumar Shukla and L. Anna Melsen, 2014: People's experience and facts of changing climate: impacts and responses. *International Journal of Climate Change Strategies and Management*, **6**(1), 47-62, doi:10.1108/IJCCSM-04-2013-0047.
Sadoff, C., D. Grey and E. Borgomeo, 2020: Water security. *Oxford Research Encyclopedia of Environmental Science*.
Saeed, F., C. F. Schleussner and M. Ashfaq, 2021: Deadly heat stress to become commonplace across South Asia already at 1.5 C of global warming. *Geophysical Research Letters*, **48**(7), e2020GL091191.
Salazar, L. F. and C. A. Nobre, 2010: Climate change and thresholds of biome shifts in Amazonia. *Geophysical Research Letters*, **37**(17), doi:10.1029/2010GL043538.
Salim, W., K. Bettinger and M. Fisher, 2019: Maladaptation on the Waterfront: Jakarta's Growth Coalition and the Great Garuda. *ENVIRONMENT AND URBANIZATION ASIA*, **10**(1), 63-80, doi:10.1177/0975425318821809.
Samaniego, L. et al., 2018: Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, **8**(5), 421-426.
Samora-Arvela, A. et al., 2017: GREEN INFRASTRUCTURE, CLIMATE CHANGE AND SPATIAL PLANNING: LEARNING LESSONS ACROSS BORDERS. *JOURNAL OF SPATIAL AND ORGANIZATIONAL DYNAMICS*, **5**(3), 176-188.
Sanchez Rodriguez, R., D. Ürge-Vorsatz and A. S. Barau, 2018: Sustainable Development Goals and climate change adaptation in cities. *Nature Climate Change*, **8**(3), 181-183, doi:10.1038/s41558-018-0098-9.
Sankey, J. B. et al., 2017: Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, **44**(17), 8884-8892, doi:10.1002/2017GL073979.
Sapkota, T. B. et al., 2015: Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains. *JOURNAL OF INTEGRATIVE AGRICULTURE*, **14**(8), 1524-1533, doi:10.1016/S2095-3119(15)61093-0.
Sartori, M., S. Schiavo, A. Fracasso and M. Riccaboni, 2017: Modeling the future evolution of the virtual water trade network: A combination of network and gravity models. *Advances in Water Resources*, **110**, 538-548, doi:10.1016/j.advwatres.2017.05.005.
Sauer, I. J. et al., 2021: Climate signals in river flood damages emerge under sound regional disaggregation. *Nature Communications*, **12**(1), 2128, doi:10.1038/s41467-021-22153-9.
Sawall, Y. et al., 2020: Discrete pulses of cooler deep water can decelerate coral bleaching during thermal stress: implications for artificial upwelling during heat stress events. *Frontiers in Marine Science*, **7**, 720.
Sayers, P., E. C. Penning-Rowsell and M. Horritt, 2018: Flood vulnerability, risk, and social disadvantage: current and future patterns in the UK. *REGIONAL ENVIRONMENTAL CHANGE*, **18**(2, SI), 339-352, doi:10.1007/s10113-017-1252-z.
Scartozzi, C. M., 2020: Reframing Climate-Induced Socio-Environmental Conflicts: A Systematic Review. *International Studies Review*,(viaa064), doi:10.1093/isr/viaa064.
Schaer, C., 2015: Condemned to live with one's feet in water?: A case study of community based strategies and urban maladaptation in flood prone Pikine/Dakar, Senegal. *International Journal of Climate Change Strategies and Management*, **7**(4), 534-551, doi:10.1108/IJCCSM-03-2014-0038.
Scheffers, B. R. et al., 2016: The broad footprint of climate change from genes to biomes to people. *SCIENCE*, **354**(6313), doi:10.1126/science.aaf7671.
Schembergue, A. et al., 2017: Sistemas agroflorestais como estrategia de adaptação aos desafios das mudanças climáticas no Brasil. *Revista de Economia e Sociologia Rural*, **55**(1), 9-30, doi:10.1590/1234-56781806-94790550101.
Schipper, E. L. F., 2020: Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, **3**(4), 409-414, doi:10.1016/j.oneear.2020.09.014.

Schleussner, C.-F., J. F. Donges, R. V. Donner and H. J. Schellnhuber, 2016a: Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proceedings of the National Academy of Sciences*, **113**(33), 9216-9221, doi:10.1073/pnas.1601611113.

Schleussner, C.-F., P. Pfleiderer and E. M. Fischer, 2017: In the observational record half a degree matters. *Nature Climate Change*, **7**(7), 460.

Schleussner, C. F. et al., 2016b: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth Syst. Dynam.*, **7**(2), 327-351, doi:10.5194/esd-7-327-2016.

Schneider, P. and F. Asch, 2020: Rice production and food security in Asian Mega deltas—A review on characteristics, vulnerabilities and agricultural adaptation options to cope with climate change. *Journal of Agronomy and Crop Science*, **206**(4), 491-503, doi:10.1111/jac.12415.

Schneider, S. H. and M. D. Mastrandrea, 2005: Probabilistic assessment of 'dangerous' climate change and emissions pathways. *Proceedings of the National Academy of Sciences of the United States of America*, **102**(44), 15728-15735, doi:10.1073/pnas.0506356102.

Schofield, D. and F. Gubbels, 2019: Informing notions of climate change adaptation: a case study of everyday gendered realities of climate change adaptation in an informal settlement in Dar es Salaam. *ENVIRONMENT AND URBANIZATION*, **31**(1), 93-114, doi:10.1177/0956247819830074.

Schuerch, M. et al., 2018: Future response of global coastal wetlands to sea-level rise. *Nature*, **561**(7722), 231-234, doi:10.1038/s41586-018-0476-5.

Schutte, S., J. Vestby, J. Carling and H. Buhaug, 2021: Climatic conditions are weak predictors of asylum migration. *Nature Communications*, **12**(1), 2067, doi:10.1038/s41467-021-22255-4.

Schwan, S. and X. Yu, 2018: Social protection as a strategy to address climate-induced migration. *INTERNATIONAL JOURNAL OF CLIMATE CHANGE STRATEGIES AND MANAGEMENT*, **10**(1, SI), 43-64, doi:10.1108/IJCCSM-01-2017-0019.

Schweiger, A. J., K. R. Wood and J. Zhang, 2019: Arctic Sea Ice Volume Variability over 1901?2010: A Model-Based Reconstruction. *Journal of Climate*, **32**(15), 4731-4752, doi:10.1175/jcli-d-19-0008.1.

Schwerdtle, P., K. Bowen and C. McMichael, 2018: The health impacts of climate-related migration. *BMC Medicine*, **16**(1), 1, doi:10.1186/s12916-017-0981-7.

Schwingshackl, C. et al., 2021: Heat Stress Indicators in CMIP6: Estimating Future Trends and Exceedances of Impact-Relevant Thresholds. *Earth's Future*, **9**(3), e2020EF001885.

Scovronick, N. et al., 2018: The association between ambient temperature and mortality in South Africa: A time-series analysis. *Environmental research*, **161**, 229-235.

Sebesvari, Z. et al., 2016: A review of vulnerability indicators for deltaic social–ecological systems. *Sustainability Science*, **11**(4), 575-590, doi:10.1007/s11625-016-0366-4.

Selby, J., 2019: Climate change and the Syrian civil war, Part II: The Jazira's agrarian crisis. *Geoforum*, **101**, 260-274, doi:10.1016/j.geoforum.2018.06.010.

Selby, J., O. S. Dahi, C. Fröhlich and M. Hulme, 2017: Climate change and the Syrian civil war revisited. *Political Geography*, **60**, 232-244.

Sen, L. T. H. and J. Bond, 2017: Agricultural adaptation to flood in lowland rice production areas of Central Vietnam: understanding the `regenerated rice' ratoon system. *CLIMATE AND DEVELOPMENT*, **9**(3), 274-285, doi:10.1080/17565529.2016.1149440.

Seneviratne, S. I. et al., 2016: Allowable CO 2 emissions based on regional and impact-related climate targets. *Nature*, **529**(7587), 477-483.

Seneviratne, S. I. and M. Hauser, 2020: Regional Climate Sensitivity of Climate Extremes in CMIP6 Versus CMIP5 Multimodel Ensembles. *Earth's future*, **8**(9), e2019EF001474.

Seneviratne, S. I. et al., 2018a: Land radiative management as contributor to regional-scale climate adaptation and mitigation. *Nat. Geosci.*, **11**(2), 88-96, doi:10.1038/s41561-017-0057-5.

Seneviratne, S. I. et al., 2018b: Land radiative management as contributor to regional-scale climate adaptation and mitigation, 88-96 pp.

Seneviratne, S. I. et al., 2021: Weather and Climate Extreme Events in a Changing Climate. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Sera, F. et al., 2019: How urban characteristics affect vulnerability to heat and cold: a multi-country analysis. *International journal of epidemiology*, **48**(4), 1101-1112.

Sereenonchai, S. and N. Arunrat, 2019: Fisher's Decisions to Adopt Adaptation Strategies and Expectations for Their Children to Pursue the Same Profession in Chumphon Province, Thailand. *CLIMATE*, **7**(2), doi:10.3390/cli7020034.

Serneels, P. and M. Verpoorten, 2015: The Impact of Armed Conflict on Economic Performance: Evidence from Rwanda. *Journal of Conflict Resolution*, **59**(4), 555-592, doi:10.1177/0022002713515409.

Setty, K. E. et al., 2018: Time series study of weather, water quality, and acute gastroenteritis at Water Safety Plan implementation sites in France and Spain. *Int J Hyg Environ Health*, **221**(4), 714-726, doi:10.1016/j.ijheh.2018.04.001.

Shaffril, H. A. M., S. E. Krauss and S. F. Samsuddin, 2018: A systematic review on Asian's farmers' adaptation practices towards climate change. *Science Of The Total Environment*, **644**, 683-695, doi:10.1016/j.scitotenv.2018.06.349.

Sharifi, A., 2020: Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. *Journal of Cleaner Production*, 122813.

Sharma, N. et al., 2016: Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development. *FOOD AND ENERGY SECURITY*, **5**(3), 165-183, doi:10.1002/fes3.87.

Sharp, T. M. et al., 2014: Characteristics of a Dengue Outbreak in a Remote Pacific Island Chain – Republic of the Marshall Islands, 2011–2012, e108445 pp.

Shearer, H., J. Dodson, E. Coiacetto and P. Taygfeld, 2014: Capacities of private developers in urban climate change adaptation. In: *Applied Studies in Climate Adaptation*, pp. 422-428.

Shepard, D. S., E. A. Undurraga, Y. A. Halasa and J. D. Stanaway, 2016: The global economic burden of dengue: a systematic analysis. *The Lancet infectious diseases*, **16**(8), 935-941.

Sheridan, S. C. and M. J. Allen, 2018: Temporal trends in human vulnerability to excessive heat. *ENVIRONMENTAL RESEARCH LETTERS*, **13**(4), doi:10.1088/1748-9326/aab214.

Shi, L., E. Chu and J. Debats, 2015: Explaining Progress in Climate Adaptation Planning Across 156 US Municipalities. *JOURNAL OF THE AMERICAN PLANNING ASSOCIATION*, **81**(3), 191-202, doi:10.1080/01944363.2015.1074526.

Shindell, D. et al., 2020: The effects of heat exposure on human mortality throughout the United States. *GeoHealth*, **4**(4), e2019GH000234.

Shinn, J. E., B. King, K. R. Young and K. A. Crews, 2014: Variable adaptations: Micro-politics of environmental displacement in the Okavango Delta, Botswana. *Geoforum*, **57**, 21-29, doi:10.1016/j.geoforum.2014.08.006.

Shirzaei, M. and R. Bürgmann, 2018: Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area. *Science Advances*, **4**(3), eaap9234, doi:10.1126/sciadv.aap9234.

Sieg, T., K. Vogel, B. Merz and H. Kreibich, 2019: Seamless estimation of hydrometeorological risk across spatial scales. *Earth's Future*, **7**(5), 574-581.

Sikka, A. K., A. Islam and K. V. Rao, 2018: CLIMATE-SMART LAND AND WATER MANAGEMENT FOR SUSTAINABLE AGRICULTURE. *IRRIGATION AND DRAINAGE*, **67**(1, SI), 72-81, doi:10.1002/ird.2162.

Simon, K., G. Diprose and A. C. Thomas, 2020: Community-led initiatives for climate adaptation and mitigation. *KOTUITUI-NEW ZEALAND JOURNAL OF SOCIAL SCIENCES ONLINE*, **15**(1), 93-105, doi:10.1080/1177083X.2019.1652659.

Simpson, I. R. et al., 2019: The Regional Hydroclimate Response to Stratospheric Sulfate Geoengineering and the Role of Stratospheric Heating, 12587-12616 pp.

Simpson, N. P. et al., 2021: A framework for complex climate change risk assessment. *One Earth*, **4**(4), 489-501, doi:10.1016/j.oneear.2021.03.005.

Simpson, N. P., C. D. Shearing and B. Dupont, 2020: Gated Adaptation during the Cape Town Drought: Mentalities, Transitions and Pathways to Partial Nodes of Water Security. *SOCIETY & NATURAL RESOURCES*, **33**(8), 1041-1049, doi:10.1080/08941920.2020.1712756.

Singh, C. and R. Basu, 2020: Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural–urban continuum in India. *The Geographical Journal*, **186**(1), 87-102, doi:10.1111/geoj.12328.

Singh, C., M. Madhavan, J. Arvind and A. Bazaz, 2021: Climate change adaptation in Indian cities: a review of existing actions and spaces for triple wins. *Urban Climate*.

Singh, G. G. et al., 2019: Climate impacts on the ocean are making the Sustainable Development Goals a moving target travelling away from us. *People and Nature*, **1**(3), 317-330, doi:10.1002/pan3.26.

Singh, N. P., B. Anand and M. A. Khan, 2018: Micro-level perception to climate change and adaptation issues: A prelude to mainstreaming climate adaptation into developmental landscape in India. *Natural Hazards*, **92**(3), 1287-1304, doi:10.1007/s11069-018-3250-y.

Siraj, A. S. et al., 2014: Altitudinal Changes in Malaria Incidence in Highlands of Ethiopia and Colombia. *Science*, **343**, 1154-1158, doi:10.1126/science.1244325.

Siraw, Z., M. A. Degefu and W. Bewket, 2018: The role of community-based watershed development in reducing farmers' vulnerability to climate change and variability in the northwestern highlands of Ethiopia. *LOCAL ENVIRONMENT*, **23**(12), 1190-1206, doi:10.1080/13549839.2018.1541344.

Smajgl, A. et al., 2015: Responding to rising sea levels in the Mekong Delta. *Nature Climate Change*, **5**(2), 167-174, doi:10.1038/nclimate2469.

Smale, D. A., 2020: Impacts of ocean warming on kelp forest ecosystems. *New Phytologist*, **225**(4), 1447-1454.

Smale, D. A. et al., 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9**(4), 306-312, doi:10.1038/s41558-019-0412-1.

Smith, J. B. et al., 2001: Vulnerability to climate change and reasons for concern: a synthesis. *Climate change*, 913-967.

Smith, J. B. et al., 2009: Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) 'Reasons for Concern'. *Proceedings of the national Academy of Sciences*, **106**(11), 4133-4137.

Smith, N. and A. Sattineni, 2016: Effect of erosion in Alaskan coastal villages. *52nd Associated Schools of Construction, Provo, Utah*.

Smith, P. et al., 2018: Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160456, doi:10.1098/rsta.2016.0456.

Smith, S. M. et al., 2021: Tropicalization and kelp loss shift trophic composition and lead to more winners than losers in fish communities. *Global Change Biology*, **27**(11), 2537-2548, doi:10.1111/gcb.15592.

Smith, W. and G. Wagner, 2018: Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environ. Res. Lett.*, **13**(12), 124001, doi:10.1088/1748-9326/aae98d.

Solomon, S., G.-K. Plattner, R. Knutti and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions, 1704-1709 pp.

Sommer, R., B. K. Paul, J. Mukalama and J. Kihara, 2018: Reducing losses but failing to sequester carbon in soils – the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. *Agriculture, Ecosystems & Environment*, **254**, 82-91, doi:10.1016/j.agee.2017.11.004.

Soroye, P., T. Newbold and J. Kerr, 2020: Climate change contributes to widespread declines among bumble bees across continents. *Science*, **367**(6478), 685-688.

Sovacool, B. K., 2018: Bamboo Beating Bandits: Conflict, Inequality, and Vulnerability in the Political Ecology of Climate Change Adaptation in Bangladesh. *WORLD DEVELOPMENT*, **102**, 183-194, doi:10.1016/j.worlddev.2017.10.014.

Spencer, B. et al., 2017: Case studies in co-benefits approaches to climate change mitigation and adaptation. *JOURNAL OF ENVIRONMENTAL PLANNING AND MANAGEMENT*, **60**(4), 647-667, doi:10.1080/09640568.2016.1168287.

Spijkers, J. and W. J. Boonstra, 2017: Environmental change and social conflict: the northeast Atlantic mackerel dispute. *Regional Environmental Change*, **17**(6), 1835-1851, doi:10.1007/s10113-017-1150-4.

Springmann, M. et al., 2016: Global and regional health effects of future food production under climate change: a modelling study. *The Lancet*, **387**(10031), 1937-1946, doi:10.1016/S0140-6736(15)01156-3.

Stanczuk-Galwiaczek, M., K. Sobolewska-Mikulska, H. Ritzema and J. M. van Loon-Steensma, 2018: Integration of water management and land consolidation in rural areas to adapt to climate change: Experiences from Poland and the Netherlands. *LAND USE POLICY*, **77**, 498-511, doi:10.1016/j.landusepol.2018.06.005.

Staver, A. C., S. Archibald and S. A. Levin, 2011: The Global Extent and Determinants of Savanna and Forest as Alternative Biome States, 230-232 pp.

Steffen, W. et al., 2018: Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, **115**(33), 8252, doi:10.1073/pnas.1810141115.

Stephens, J. C. and K. Surprise, 2020: The hidden injustices of advancing solar geoengineering research. *Global Sustainability*, **3**.

Sterle, K. and L. Singletary, 2017: Adapting to Variable Water Supply in the Truckee-Carson River System, Western USA. *WATER*, **9**(10), doi:10.3390/w9100768.

Stern, N., 2013: The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. **51**, 838-859, doi:10.1257/jel.51.3.838.

Sterner, T. and U. M. Persson, 2008: An even sterner review: Introducing relative prices into the discounting debate. **2**, 61-76, doi:10.1093/reep/rem024.

Stevens, N., C. E. R. Lehmann, B. P. Murphy and G. Durigan, 2017: Savanna woody encroachment is widespread across three continents. *Global Change Biology*, **23**(1), 235-244, doi:10.1111/gcb.13409.

Stewart-Sinclair, P. J., K. S. Last, B. L. Payne and T. A. Wilding, 2020: A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecology and Evolution*, **10**(7), 3518-3534, doi:10.1002/ece3.6149.

Stilgoe, J., 2015: *Experiment Earth: Responsible innovation in geoengineering*. Routledge, 240 pp. ISBN 9781317909149.

Stjern, C. W. et al., 2018: Response to marine cloud brightening in a multi-model ensemble. *Atmospheric Chemistry and Physics*, **18**(2), 621-634.

Stoerk, T., G. Wagner and R. E. Ward, 2018: Policy brief—Recommendations for improving the treatment of risk and uncertainty in economic estimates of climate impacts in the sixth Intergovernmental Panel on Climate Change assessment report. *Review of Environmental Economics and Policy*, **12**(2), 371-376.

Stone Jr, B. et al., 2014: Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three US Cities. *PLOS ONE*, **9**(6), e100852, doi:10.1371/journal.pone.0100852.

Storelvmo, T. and N. Herger, 2014: Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere. *Journal of Geophysical Research: Atmospheres*, **119**(5), 2375-2389.

Storlazzi, C. D. et al., 2018: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, **4**(4), eaap9741, doi:10.1126/sciadv.aap9741.

Strauss, B. et al., 2021: Economic Damages from Hurricane Sandy Attributable to Sea Level Rise Caused by Anthropogenic Climate Change. *Nature Communications*, **12**(1), 15.

Strobl, E., 2011: The economic growth impact of hurricanes: Evidence from U.S. coastal counties. *The Review of Economics and Statistics*, **93 (2)**, 575-589, doi:10.1162/REST_a_00082.

Strobl, E., 2012: The economic growth impact of natural disasters in developing countries: Evidence from hurricane strikes in the Central American and Caribbean regions. *Journal of Development Economics*, **97**(1), 130-141, doi:10.1016/j.jdeveco.2010.12.002.
Su, Y. et al., 2017: Gendered Responses to Drought in Yunnan Province, China. *MOUNTAIN RESEARCH AND DEVELOPMENT*, **37**(1), 24-34, doi:10.1659/MRD-JOURNAL-D-15-00041.1.
Suckall, N., L. C. Stringer and E. L. Tompkins, 2015: Presenting Triple-Wins? Assessing Projects That Deliver Adaptation, Mitigation and Development Co-benefits in Rural Sub-Saharan Africa. *AMBIO*, **44**(1), 34-41, doi:10.1007/s13280-014-0520-0.
Sugiyama, M. et al., 2018a: Next steps in geoengineering scenario research: limited deployment scenarios and beyond. *Clim. Policy*, **18**(6), 681-689, doi:10.1080/14693062.2017.1323721.
Sugiyama, M., S. Asayama and T. Kosugi, 2020: The North–South Divide on Public Perceptions of Stratospheric Aerosol Geoengineering?: A Survey in Six Asia-Pacific Countries. *Environmentalist*.
Sugiyama, M., A. Ishii, S. Asayama and T. Kosugi, 2018b: Solar Geoengineering Governance. In: *Oxford Research Encyclopedia of Climate Science*. oxfordre.com.
Sujakhu, N. M. et al., 2016: Farmers' Perceptions of and Adaptations to Changing Climate in the Melamchi Valley of Nepal. *MOUNTAIN RESEARCH AND DEVELOPMENT*, **36**(1), 15-30, doi:10.1659/MRD-JOURNAL-D-15-00032.1.
Sulser, T. B. et al., 2021: Disability-adjusted life years due to chronic and hidden hunger under food system evolution with climate change and adaptation to 2050. *The American Journal of Clinical Nutrition*, **114**(2), 550-563, doi:10.1093/ajcn/nqab101.
Sultan, B., D. Defrance and T. Iizumi, 2019: Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Scientific reports*, **9**(1), 1-15.
Sun, Q. et al., 2019: Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. *Environment International*, **128**, 125-136, doi:10.1016/j.envint.2019.04.025.
Sun, Y. et al., 2014: Rapid increase in the risk of extreme summer heat in Eastern China. *Nature Climate Change*, **4**(12), 1082-1085, doi:10.1038/nclimate2410.
Surminski, S. et al., 2016: *UK Climate Change Risk Assessment Evidence Report: Chapter 6, Business and Industry*. London.
Sushant, 2013: Impact of Climate Change in Eastern Madhya Pradesh, India. *TROPICAL CONSERVATION SCIENCE*, **6**(3, SI), 338-364, doi:10.1177/194008291300600304.
Suter, L., D. Streletskiy and N. Shiklomanov, 2019: Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic. *Polar Geography*, **42**(4), 267-286, doi:10.1080/1088937X.2019.1686082.
Suvdantsetseg, B. et al., 2017: Assessment of pastoral vulnerability and its impacts on socio-economy of herding community and formulation of adaptation options. *APN Science Bulletin*, **10**(1), doi:10.30852/sb.2020.1107.
Svoboda, T., 2017: *The ethics of climate engineering: solar radiation management and non-ideal justice*. Routledge. ISBN 1315468530.
Svoboda, T. and P. Irvine, 2014: Ethical and Technical Challenges in Compensating for Harm Due to Solar Radiation Management Geoengineering. *Ethics, Policy & Environment*, **17**(2), 157-174, doi:10.1080/21550085.2014.927962.
Szabo, S. et al., 2016: Population dynamics, delta vulnerability and environmental change: comparison of the Mekong, Ganges–Brahmaputra and Amazon delta regions. *Sustainability Science*, **11**(4), 539-554, doi:10.1007/s11625-016-0372-6.
Taconet, N., A. Méjean and C. Guivarch, 2020: Influence of climate change impacts and mitigation costs on inequality between countries. *Climatic Change*, doi:10.1007/s10584-019-02637-w.
Taebi, B., J. H. Kwakkel and C. Kermisch, 2020: Governing climate risks in the face of normative uncertainties. *WIREs Climate Change*, **11**(5), doi:10.1002/wcc.666.
Táíwò, O. O. and S. Talati, 2021: Who Are the Engineers? Solar Geoengineering Research and Justice. *Global Environmental Politics*, 1-7.
Takakura, J. y. et al., 2019: Dependence of economic impacts of climate change on anthropogenically directed pathways. *Nature Climate Change*, **9**(10), 737-741, doi:10.1038/s41558-019-0578-6.
Talberg, A., P. Christoff, S. Thomas and D. Karoly, 2018a: Geoengineering governance-by-default: an earth system governance perspective. *International Environmental Agreements: Politics, Law and Economics*, **18**(2), 229-253.
Talberg, A., S. Thomas, P. Christoff and D. Karoly, 2018b: How geoengineering scenarios frame assumptions and create expectations. *Sustainability Sci.*, **13**(4), 1093-1104.
Talebian, S. et al., 2021: Assessing future cross-border climate impacts using shared socioeconomic pathways. *Climate Risk Management*, **32**, 100311, doi:10.1016/j.crm.2021.100311.
Tamura, M., N. Kumano, M. Yotsukuri and H. Yokoki, 2019: Global assessment of the effectiveness of adaptation in coastal areas based on RCP/SSP scenarios. *Climatic Change*, **152**(3-4), 363-377, doi:10.1007/s10584-018-2356-2.
Tang, L. et al., 2018: Induce or reduce? The crowding-in effects of farmers' perceptions of climate risk on chemical use in China. *CLIMATE RISK MANAGEMENT*, **20**, 27-37, doi:10.1016/j.crm.2018.02.001.
Tanoue, M., Y. Hirabayashi and H. Ikeuchi, 2016: Global-scale river flood vulnerability in the last 50 years. *Scientific reports*, **6**, 36021.

Tanoue, M. et al., 2020: Estimation of direct and indirect economic losses caused by a flood with long-lasting inundation: Application to the 2011 Thailand flood. *Water Resources Research*, **56**(5), e2019WR026092.
Tasaki, T. and Y. Kameyama, 2015: Sustainability Indicators: Are We Measuring What We Ought to Measure? *Global Environmental Research*, **19**, 147-154.
Tebaldi, C. et al., 2021: Cross-Chapter Box 12.1: Projections by warming levels of hazards relevant to the assessment of Representative Key Risks and Reasons for Concern. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)].
Tebaldi, C. and R. Knutti, 2018: Evaluating the accuracy of climate change pattern emulation for low warming targets. *Environmental Research Letters*, **13**(5), 055006.
Teklewold, H., T. Gebrehiwot and M. Bezabih, 2019a: Climate smart agricultural practices and gender differentiated nutrition outcome: An empirical evidence from Ethiopia. *WORLD DEVELOPMENT*, **122**, 38-53, doi:10.1016/j.worlddev.2019.05.010.
Teklewold, H., A. Mekonnen and G. Kohlin, 2019b: Climate change adaptation: a study of multiple climate-smart practices in the Nile Basin of Ethiopia. *CLIMATE AND DEVELOPMENT*, **11**(2), 180-192, doi:10.1080/17565529.2018.1442801.
Tenggren, S. et al., 2019: Climate risk in a globalized world: empirical findings from supply chains in the Swedish manufacturing sector. *Journal of Environmental Planning and Management*, 18, doi:10.1080/09640568.2019.1660626.
Tenzing, J. D., 2020: Integrating social protection and climate change adaptation: A review. *WIREs Climate Change*, **11**(2), e626, doi:10.1002/wcc.626.
Tepley, A. J., J. R. Thompson, H. E. Epstein and K. J. Anderson-Teixeira, 2017: Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. *Global Change Biology*, **23**(10), 4117-4132, doi:10.1111/gcb.13704.
Termeer, C. J. A. M., A. Dewulf and G. R. Biesbroek, 2017: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *JOURNAL OF ENVIRONMENTAL PLANNING AND MANAGEMENT*, **60**(4), 558-576, doi:10.1080/09640568.2016.1168288.
Tessler, Z. D. et al., 2016: A global empirical typology of anthropogenic drivers of environmental change in deltas. *Sustainability Science*, **11**(4), 525-537, doi:10.1007/s11625-016-0357-5.
Tessler, Z. D. et al., 2015: Profiling risk and sustainability in coastal deltas of the world. *Science*, **349**(6248), 638-643, doi:10.1126/science.aab3574.
Thackeray, S. J. et al., 2016: Phenological sensitivity to climate across taxa and trophic levels. *Nature*, **535**(7611), 241-245, doi:10.1038/nature18608.
Theisen, O. M., 2017: Climate Change and Violence: Insights from Political Science. *Current Climate Change Reports*, **3**(4), 210-221, doi:10.1007/s40641-017-0079-5.
Thiault, L. A.-O. et al., Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries.(2375-2548 (Electronic)).
Thomas, A. et al., 2020: Climate Change and Small Island Developing States. *Annual Review of Environment and Resources*, **45**.
Thomas, A. and L. Benjamin, 2018: Management of loss and damage in small island developing states: implications for a 1.5 °C or warmer world. *Regional Environmental Change*, **18**(8), 2369-2378, doi:10.1007/s10113-017-1184-7.
Thomas, A. and L. Benjamin, 2020: Non-economic loss and damage: Lessons from displacement in the Caribbean. *Climate Policy*, **20**(6), 715-728.
Thomas, A. et al., 2019a: Climate change adaptation planning in practice: insights from the Caribbean. *REGIONAL ENVIRONMENTAL CHANGE*, **19**(7, SI), 2013-2025, doi:10.1007/s10113-019-01540-5.
Thomas, A. et al., 2021: Global evidence constraints and limits to human adaptation. *Regional Environmental Change*, **21**, doi:doi.org/10.1007/s10113-021-01808-9.
Thomas, K. et al., 2019b: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10**(2), e565, doi:10.1002/wcc.565.
Thomas, K. A. and B. P. Warner, 2019: Weaponizing vulnerability to climate change. *GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS*, **57**, doi:10.1016/j.gloenvcha.2019.101928.
Ticehurst, J. L. and A. L. Curtis, 2018: The intention of irrigators to adopt water use efficient measures: case studies in the north and south of the Murray-Darling Basin. *AUSTRALASIAN JOURNAL OF WATER RESOURCES*, **22**(2), 149-161, doi:10.1080/13241583.2018.1486267.
Ticktin, T. et al., 2018: Linkages between measures of biodiversity and community resilience in Pacific Island agroforests. *CONSERVATION BIOLOGY*, **32**(5), 1085-1095, doi:10.1111/cobi.13152.
Tiedemann, J. et al., 2021: *Meeting the Sustainable Development Goals in Small Developing States with Climate Vulnerabilities: Cost and Financing*. IMF Working Paper, International Monetary Fund, Washington, DC.
Tilmes, S. et al., 2020: Reaching 1.5 and 2.0 °C global surface temperature targets using stratospheric aerosol geoengineering, 579-601 pp.

Tilmes, S. et al., 2018: CESM1 (WACCM) stratospheric aerosol geoengineering large ensemble project. *Bull. Am. Meteorol. Soc.*, **99**(11), 2361-2371.
Tilmes, S., B. M. Sanderson and B. C. O'Neill, 2016: Climate impacts of geoengineering in a delayed mitigation scenario. *Geophysical Research Letters*, **43**(15), 8222-8229.
Tingley, D. and G. Wagner, 2017: Solar geoengineering and the chemtrails conspiracy on social media. *Palgrave Communications*, **3**(1), 1-7.
Tol, R. S., 2009: The economic effects of climate change. *Journal of economic perspectives*, **23**(2), 29-51.
Tol, R. S. J., 2018: The Economic Impacts of Climate Change. *Review of Environmental Economics and Policy*, **12**(1), 4-25, doi:10.1093/reep/rex027.
Tol, R. S. J., 2020: The distributional impact of climate change. *Annals of the New York Academy of Sciences*, doi:10.1111/nyas.14497.
Tollefsen, A. F., 2017: Experienced poverty and local conflict violence. *Conflict Management and Peace Science*, 0738894217741618, doi:10.1177/0738894217741618.
Toloo, G. et al., 2013a: Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. *INTERNATIONAL JOURNAL OF PUBLIC HEALTH*, **58**(5), 667-681, doi:10.1007/s00038-013-0465-2.
Toloo, G. S. et al., 2013b: Are heat warning systems effective? *ENVIRONMENTAL HEALTH*, **12**, doi:10.1186/1476-069X-12-27.
Tompkins, E. L., K. Vincent, R. J. Nicholls and N. Suckall, 2018: Documenting the state of adaptation for the global stocktake of the Paris Agreement. *Wiley Interdisciplinary Reviews-Climate Change*, **9**(5), e545, doi:10.1002/wcc.545.
Tran, D. D. et al., 2018: Questioning triple rice intensification on the Vietnamese mekong delta floodplains: An environmental and economic analysis of current land-use trends and alternatives. *Journal of Environmental Management*, **217**, 429-441, doi:10.1016/j.jenvman.2018.03.116.
Trewin, B. J., B. H. Kay, J. M. Darbro and T. P. Hurst, 2013: Increased container-breeding mosquito risk owing to drought-induced changes in water harvesting and storage in Brisbane, Australia. *International Health*, **5**(4), 251-258, doi:10.1093/inthealth/iht023.
Trigo, R. M., C. M. Gouveia and D. Barriopedro, 2010: The intense 2007–2009 drought in the Fertile Crescent: Impacts and associated atmospheric circulation. *Agricultural and Forest Meteorology*, **150**(9), 1245-1257, doi:10.1016/j.agrformet.2010.05.006.
Tripathi, A. K. and S. Sindhi, 2020: Droughts, Heatwaves and Agricultural Adaptation. *Review of Rural Affairs*, **55**(26-27).
Trisos, C. H. et al., 2018: Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. *Nat Ecol Evol*, **2**(3), 475-482, doi:10.1038/s41559-017-0431-0.
Trisos, C. H., C. Merow and A. L. Pigot, 2020: The projected timing of abrupt ecological disruption from climate change. *Nature*, **580**(7804), 496-501, doi:10.1038/s41586-020-2189-9.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(5), e476, doi:10.1002/wcc.476.
Tschakert, P. et al., 2019: One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change*, **55**, 58-72, doi:10.1016/j.gloenvcha.2018.11.006.
Tschora, H. and F. Cherubini, 2020: Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. *Global Ecology and Conservation*, **22**, doi:10.1016/j.gecco.2020.e00919.
Tun Oo, A., G. Van Huylenbroeck and S. Speelman, 2017: Determining factors for the application of climate change adaptation strategies among farmers in Magwe District, dry zone region of Myanmar. *International Journal of Climate Change Strategies and Management*, **9**(1), 36-55, doi:10.1108/IJCCSM-09-2015-0134.
Turner, M. G. et al., 2020: Climate change, ecosystems and abrupt change: science priorities. *Philosophical Transactions of the Royal Society B*, doi:10.1098/rstb.2019.0105.
Ullah, W. et al., 2018: Understanding climate change vulnerability, adaptation and risk perceptions at household level in Khyber Pakhtunkhwa, Pakistan. *INTERNATIONAL JOURNAL OF CLIMATE CHANGE STRATEGIES AND MANAGEMENT*, **10**(3), 359-378, doi:10.1108/IJCCSM-02-2017-0038.
UN-IATFFD, 2019: *Financing for Sustainable Development Report 2019*. United Nations, New York. Available at: https://developmentfinance.un.org/fsdr2019.
UN-IATFFD, 2021: *Financing for Sustainable Development Report 2021.*, United Nations, New York. Available at: https://developmentfinance.un.org/fsdr2021.
UN, 2015: *Transforming Our World: The 2030 Agenda for Sustainable Development*. Resolution, United Nations, New York, 35 pp.
UN, 2018: *Global Compact for Safe, Orderly and Regular Migration*. United Nations General Assembly. Available at: https://undocs.org/A/CONF.231/3.
UNDP, WEF, CCSI and SDSN, 2016: *Mapping_Mining_SDGs_An_Atlas_Executive_Summary_FINAL.pdf*. World Economic Forum, 74 pp. (accessed 2020-09-16 14:44:19).
UNEP, 2017: The Adaptation Gap Report 2017: Towards Global Assessment :: Our Planet.
UNEP, 2021: *The Adaptation Gap Report 2021*.
Urban, M. C., 2015: Accelerating extinction risk from climate change. *Science*, **348**(6234), 571-573, doi:10.1126/science.aaa4984.

Uwishema, O. et al., 2021: Dengue fever outbreak in Cook Island: A rising concern, efforts, challenges, and future recommendations, jmv.27223 pp.
Uzun, H. et al., 2020: Effect of prescribed fires on the export of dissolved organic matter, precursors of disinfection by-products, and water treatability. *Water Research*, **187**, 116385, doi:10.1016/j.watres.2020.116385.
Vahmani, P. and A. D. Jones, 2017: Water conservation benefits of urban heat mitigation. *Nature Communications*, **8**, doi:10.1038/s41467-017-01346-1.
Van Bavel, B. et al., 2020: Contributions of scale: What we stand to gain from including local communities and experts in climate and health monitoring and surveillance systems. *Environmental Research Letters*, **15**(8), doi:doi.org/10.1088/1748-9326/ab875e.
van Belzen, J. et al., 2017: Vegetation recovery in tidal marshes reveals critical slowing down under increased inundation. *Nature Communications*, **8**(1), 15811, doi:10.1038/ncomms15811.
van den Bergh, J. C. and W. Botzen, 2015: Monetary valuation of the social cost of CO2 emissions: a critical survey. *Ecological Economics*, **114**, 33-46.
van der Waal, J. W. H. and T. Thijssens, 2020: Corporate involvement in Sustainable Development Goals: Exploring the territory. *Journal of Cleaner Production*, **252**, 119625, doi:10.1016/j.jclepro.2019.119625.
van der Weide, R. and B. Milanovic, 2018: Inequality is Bad for Growth of the Poor (but Not for That of the Rich). *The World Bank Economic Review*, **32**(3), 507-530, doi:10.1093/wber/lhy023.
van Hooff, T., B. Blocken, J. L. M. Hensen and H. J. P. Timmermans, 2015: On the predicted effectiveness of climate adaptation measures for residential buildings (Reprinted from vol 82, pg 300-316, 2014). *BUILDING AND ENVIRONMENT*, **83**(SI), 142-158, doi:10.1016/j.buildenv.2014.10.006.
Van Oldenborgh, G. J. et al., 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12**(12), 124009.
Van Vliet, M. T., D. Wiberg, S. Leduc and K. Riahi, 2016: Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, **6**(4), 375-380.
van Vuuren, D. P. and T. R. Carter, 2014: Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. *Climatic Change*, **122**(3), 415-429, doi:10.1007/s10584-013-0974-2.
Van Vuuren, D. P. et al., 2014: A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change*, **122**(3), 373-386.
van Weezel, S., 2020: Local warming and violent armed conflict in Africa. *World Development*, **126**, 104708, doi:10.1016/j.worlddev.2019.104708.
Vanham, D. et al., 2018: Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 'Level of water stress'. *Science of The Total Environment*, **613-614**, 218-232, doi:10.1016/j.scitotenv.2017.09.056.
Venter, Z., M. Cramer and H.-J. Hawkins, 2018: Drivers of woody plant encroachment over Africa. *Nature communications*, **9**(1), 1-7.
Verschuur, J., S. Li, P. Wolski and F. E. L. Otto, 2021: Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. *Scientific Reports*, **11**(1), 3852, doi:10.1038/s41598-021-83375-x.
Vezzulli, L. et al., 2016: Climate influence on Vibrio and associated human diseases during the past half-century in the coastal North Atlantic. *Proceedings of the National Academy of Sciences*, **113**(34), E5062-E5071.
Vicedo-Cabrera, A. M. et al., 2018a: Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. *Climatic Change*, **150**(3), 391-402, doi:10.1007/s10584-018-2274-3.
Vicedo-Cabrera, A. M. et al., 2021: The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, **11**(6), 492-500, doi:10.1038/s41558-021-01058-x.
Vicedo-Cabrera, A. M. et al., 2018b: A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. *Environment international*, **111**, 239-246.
Villamayor-Tomas, S. and G. Garcia-Lopez, 2017: The influence of community-based resource management institutions on adaptation capacity: A large-n study of farmer responses to climate and global market disturbances. *GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS*, **47**, 153-166, doi:10.1016/j.gloenvcha.2017.10.002.
Visioni, D., G. Pitari and V. Aquila, 2017: Sulfate geoengineering: a review of the factors controlling the needed injection of sulfur dioxide. *Atmospheric Chemistry and Physics*, **17**(6), 3879-3889.
Visioni, D. et al., 2020: What goes up must come down: impacts of deposition in a sulfate geoengineering scenario. *Environ. Res. Lett.*, **15**(9), 094063, doi:10.1088/1748-9326/ab94eb.
Visschers, V. H. M., J. Shi, M. Siegrist and J. Arvai, 2017: Beliefs and values explain international differences in perception of solar radiation management: insights from a cross-country survey. *Clim. Change*, **142**(3-4), 531-544.
Viswanathan, B. and K. S. Kavi Kumar, 2015: Weather, agriculture and rural migration: evidence from state and district level migration in India. *Environment and Development Economics*, **20**(04), 469-492, doi:10.1017/S1355770X1500008X.
Vogel, M. M. et al., 2019: Concurrent 2018 hot extremes across Northern Hemisphere due to human-induced climate change. *Earth's future*, **7**(7), 692-703.

Vogt, J. T. et al., 2020: Interactions between weather-related disturbance and forest insects and diseases in the Southern United States. *Gen. Tech. Rep. SRS–255. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station.*, **255**, 1-37, doi:10.2737/SRS-GTR-255.
von Uexkull, N. and H. Buhaug, 2021: Security implications of climate change: A decade of scientific progress. *Journal of Peace Research*, **58**(1), 3-17, doi:10.1177/0022343320984210.
Von Uexkull, N., M. Croicu, H. Fjelde and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proceedings of the National Academy of Sciences*, **113**(44), 12391-12396.
Wamsler, C. and E. Brink, 2015: The role of individual adaptive practices for sustainable adaptation. *International Journal of Disaster Resilience in the Built Environment*, **6**(1), 6-29, doi:10.1108/IJDRBE-09-2014-0070.
Wang, H. and R. J. Hijmans, 2019: Climate change and geographic shifts in rice production in China. *Environmental Research Communications*, **1**(1), 011008, doi:10.1088/2515-7620/ab0856.
Wang, S. S. et al., 2018: Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. *Environmental Research Letters*, **13**(5), 054014.
Wang, X. et al., 2020: Cutting carbon footprints of vegetable production with integrated soil - crop system management: A case study of greenhouse pepper production. *Journal of Cleaner Production*, **254**, doi:10.1016/j.jclepro.2020.120158.
Wang, Y. et al., 2019: Tens of thousands additional deaths annually in cities of China between 1.5 °C and 2.0 °C warming. *Nature Communications*, **10**(1), 3376, doi:10.1038/s41467-019-11283-w.
Ward, P. J. et al., 2014: Strong influence of El Nino Southern Oscillation on flood risk around the world. *Proceedings of the National Academy of Sciences*, **111**, 15659-15664, doi:10.1073/pnas.1409822111.
Warner, B. P. and C. Kuzdas, 2016: Manufactured global-change risk pathways in industrial-based agrarian development. *Climate and Development*, **8**(5), 385-396, doi:10.1080/17565529.2015.1085359.
Warner, B. P., C. Kuzdas, M. G. Yglesias and D. L. Childers, 2015: Limits to adaptation to interacting global change risks among smallholder rice farmers in Northwest Costa Rica. *Global Environmental Change*, **30**, 101-112, doi:10.1016/j.gloenvcha.2014.11.002.
Warner, K., Z. Zommers and A. Wreford, 2020: The real economic dimensions of climate change. *Journal of Extreme Events*, **7**(03), 2131001.
Warren, R. et al., 2021: Global and regional aggregate damages associated with global warming of 1.5 to 4°C above pre-industrial levels.
Warren, R. et al., 2018a: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*, **360**(6390), 791-795, doi:10.1126/science.aar3646.
Warren, R. et al., 2018b: The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Climatic Change*, **147**(3), 395-409, doi:10.1007/s10584-018-2158-6.
Warren, R. et al., 2013: Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*, **3**(7), 678-682.
Wartenburger, R. et al., 2017: Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework. *Geoscientific Model Development*, **10**(9), 3609-3634.
Watts, N. et al., 2021: The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *The Lancet*, **397**(10269), 129-170, doi:10.1016/S0140-6736(20)32290-X.
Weaver, M., H. Tan and K. Crossan, 2020: Systems and Systemic Approaches for Attaining the SDGs Across Partnerships. In: *Partnerships for the Goals* [Leal Filho, W., A. M. Azul, L. Brandli, A. Lange Salvia and T. Wall (eds.)]. Springer International Publishing, Cham, pp. 1-14. ISBN 978-3-319-71067-9.
WEF, 2018: The Global Risks Report 2018. World Economic Forum (13th edition).
Wehner, M. and C. Sampson, 2021: Attributable human-induced changes in the magnitude of flooding in the Houston, Texas region during Hurricane Harvey. *Climatic Change*, **166**(1), 20, doi:10.1007/s10584-021-03114-z.
Weinberger, K. R. et al., 2017: Projected temperature-related deaths in ten large U.S. metropolitan areas under different climate change scenarios. *Environment International*, **107**, 196-204, doi:10.1016/j.envint.2017.07.006.
Weinberger, K. R., A. Zanobetti, J. Schwartz and G. A. Wellenius, 2018: Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities. *ENVIRONMENT INTERNATIONAL*, **116**, 30-38, doi:10.1016/j.envint.2018.03.028.
Weitzman, M. L., 2012: GHG targets as insurance against catastrophic climate damages. *Journal of Public Economic Theory*, **14**(2), 221-244.
Weitzman, M. L., 2015: A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering, 1049-1068 pp.
Wenz, L. and A. Levermann, 2016: Enhanced economic connectivity to foster heat stress–related losses. *Science Advances*, **2**(6), e1501026, doi:10.1126/sciadv.1501026.
Werrell, C. E., F. Femia and T. Sternberg, 2015: Did We See It Coming?: State Fragility, Climate Vulnerability, and the Uprisings in Syria and Egypt. *SAIS Review of International Affairs*, **35**(1), 29-46, doi:10.1353/sais.2015.0002.
Weyer, N. M., 2019: Annex I: Glossary. In: *Special Report on the Ocean and Cryosphere in a Changing Climate*.
Wheeler, S. A. and A. Marning, 2019: Turning water into wine: Exploring water security perceptions and adaptation behaviour amongst conventional, organic and biodynamic grape growers. *LAND USE POLICY*, **82**, 528-537, doi:10.1016/j.landusepol.2018.12.034.

White, E. and D. Kaplan, 2017: Restore or retreat? saltwater intrusion and water management in coastal wetlands, e01258 pp.
WHO, 2014: Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s.
WHO, 2018: *The state of food security and nutrition in the world 2018: building climate resilience for food security and nutrition*. Food & Agriculture Org., World Health Organization. ISBN 9251305714.
Whyte, K. P., 2018: Indigeneity in geoengineering discourses: Some considerations. *Ethics, Policy & Environment*, **21**(3), 289-307.
Wichelns, D., 2016: Managing Water and Soils to Achieve Adaptation and Reduce Methane Emissions and Arsenic Contamination in Asian Rice Production. *Water*, **8**(4), doi:10.3390/w8040141.
Wichmann, J., 2017: Heat effects of ambient apparent temperature on all-cause mortality in Cape Town, Durban and Johannesburg, South Africa: 2006–2010. *Science of the Total Environment*, **587**, 266-272.
Wiederkehr, C., M. Beckmann and K. Hermans, 2018: Environmental change, adaptation strategies and the relevance of migration in Sub-Saharan drylands. *ENVIRONMENTAL RESEARCH LETTERS*, **13**(11), doi:10.1088/1748-9326/aae6de.
Wigginton, N. S., 2015: Deltas are growing centers of risk. *Science*, **349**(6248), i-599, doi:10.1126/science.349.6248.598-i.
Wijenayake, V., D. Mombauer, P. M. Singh and M. Nadiruzzaman, 2020: Policy gaps and needs analysis for the implementation of NDCs on adaptation and loss and damage in Bangladesh, Nepal, and Sri Lanka. *APN Science Bulletin*, **10**(1), doi:10.30852/sb.2020.1283.
Wilkes, A. et al., 2017: Is cross-breeding with indigenous sheep breeds an option for climate-smart agriculture? *SMALL RUMINANT RESEARCH*, **147**, 83-88, doi:10.1016/j.smallrumres.2016.12.036.
Willner, S. N., C. Otto and A. Levermann, 2018: Global economic response to river floods. *Nature Climate Change*, **8**(7), 594-598, doi:10.1038/s41558-018-0173-2.
Winickoff, D. E., J. A. Flegal and A. Asrat, 2015: Engaging the Global South on climate engineering research. *Nature Climate Change*, **5**(7), 627-634.
Winsemius, H. C. et al., 2018: Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, **23**(3), 328-348, doi:10.1017/S1355770X17000444.
Wirehn, L., 2018: Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production. *LAND USE POLICY*, **77**, 63-74, doi:10.1016/j.landusepol.2018.04.059.
Witmer, F. D. et al., 2017: Subnational violent conflict forecasts for sub-Saharan Africa, 2015–65, using climate-sensitive models. *Journal of Peace Research*, **54**(2), 175-192, doi:10.1177/0022343316682064.
WMO, 2020: *State of the Global Climate 2020 PROVISIONAL REPORT*. World Meteorological Organization. Available at: https://library.wmo.int/doc_num.php?explnum_id=10444.
Wolde, B. et al., 2016: Determinants of enrollment in public incentive programs for forest management and their effect on future programs for woody bioenergy: evidence from Virginia and Texas. *Canadian Journal of Forest Research*, **46**(6), 775-782.
Work, C., V. Rong, D. Song and A. Scheidel, 2019: Maladaptation and development as usual? Investigating climate change mitigation and adaptation projects in Cambodia. *CLIMATE POLICY*, **19**(1), S47-S62, doi:10.1080/14693062.2018.1527677.
World Bank, Income share held by lowest 20%, data.worldbank.org.
World Bank, 2020: Employment in agriculture (% of total employment) (modeled ILO estimate) - World, Sub-Saharan Africa, South Asia, European Union, East Asia & Pacific, Latin America & Caribbean.
World Bank, 2021: *Global Economic Prospects, June 2021*. World Bank, Washington DC.
Wrathall, D. J. et al., 2019: Meeting the looming policy challenge of sea-level change and human migration. *Nature Climate Change*, **9**(12), 898-901, doi:10.1038/s41558-019-0640-4.
Xia, L., P. J. Nowack, S. Tilmes and A. Robock, 2017: Impacts of stratospheric sulfate geoengineering on tropospheric ozone. *Atmos. Chem. Phys.*, **17**(19), 11913-11928, doi:10.5194/acp-17-11913-2017.
Xia, L. et al., 2014: Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. D: Atmos.*, **119**(14), 8695-8711, doi:10.1002/2013JD020630.
Yadav, G. et al., 2020: A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers. *Computers in Industry*, **122**, 103280, doi:10.1016/j.compind.2020.103280.
Yamba, S., D. O. Appiah and L. P. Siaw, 2019: Smallholder farmers' perceptions and adaptive response to climate variability and climate change in southern rural Ghana. *COGENT SOCIAL SCIENCES*, **5**(1), doi:10.1080/23311886.2019.1646626.
Yang, H. et al., 2016: Potential negative consequences of geoengineering on crop production: A study of Indian groundnut. *Geophys. Res. Lett.*, **43**(22), 11786-11795, doi:10.1002/2016GL071209.
Yang, J., V. Owusu, E. Andriesse and A. D. Ablo, 2019: In-Situ Adaptation and Coastal Vulnerabilities in Ghana and Tanzania. *JOURNAL OF ENVIRONMENT & DEVELOPMENT*, **28**(3), 282-308, doi:10.1177/1070496519852992.

Yeeles, A., 2015: Weathering unrest: The ecology of urban social disturbances in Africa and Asia. *Journal of Peace Research*, **52**(2), 158-170.
Yegbemey, R. N., E. O. Yegbemey and J. A. Yabi, 2017: Sustainability analysis of observed climate change adaptation strategies in maize farming in Benin, West Africa. *OUTLOOK ON AGRICULTURE*, **46**(1), 20-27, doi:10.1177/0030727016689638.
Yesudian, A. N. and R. J. Dawson, 2021: Global analysis of sea level rise risk to airports. *Climate Risk Management*, **31**, 100266, doi:10.1016/j.crm.2020.100266.
Yila, J. O. and B. P. Resurreccion, 2013: Determinants of smallholder farmers' adaptation strategies to climate change in the semi arid Nguru Local Government Area, Northeastern Nigeria. *Management of Environmental Quality: An International Journal*, **24**(3), 341-364, doi:10.1108/14777831311322659.
Yokohata, T. et al., 2019: Visualizing the Interconnections Among Climate Risks. *Earth's Future*, **7**(2), 85-100, doi:10.1029/2018EF000945.
Yu, D. et al., 2020: Disruption of emergency response to vulnerable populations during floods. *Nature Sustainability*, 1-9, doi:10.1038/s41893-020-0516-7.
Yumashev, D. et al., 2019: Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nature communications*, **10**(1), 1-11.
Zarnetske, P. L. et al., 2021: Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth, e1921854118 pp.
Zhan, P. et al., 2019: Impacts of Sulfate Geoengineering on Rice Yield in China: Results From a Multimodel Ensemble. *Earth's Future*, **7**(4), 395-410, doi:10.1029/2018EF001094.
Zhang, B., Z. Fu, J. Wang and L. Zhang, 2019: Farmers' adoption of water-saving irrigation technology alleviates water scarcity in metropolis suburbs: A case study of Beijing, China. *Agricultural Water Management*, **212**, 349-357, doi:10.1016/j.agwat.2018.09.021.
Zhang, J., K. Zhang, J. Liu and G. Ban-Weiss, 2016: Revisiting the climate impacts of cool roofs around the globe using an Earth system model. *Environmental Research Letters*, **11**(8), 084014.
Zhao, H. et al., 2019: Virtual water scarcity risk to global trade under climate change. *Journal of Cleaner Production*, **230**, 1013-1026, doi:10.1016/j.jclepro.2019.05.114.
Zhao, L. et al., 2018: Interactions between urban heat islands and heat waves. *Environmental research letters*, **13**(3), 034003.
Zhao, Q. et al., 2021: Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study, e415-e425 pp.
Zhu, C. et al., 2018: Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. *Science Advances*, **4**(5), eaaq1012, doi:10.1126/sciadv.aaq1012.
Zinia, N. J. and P. McShane, 2018: Ecosystem services management: An evaluation of green adaptations for urban development in Dhaka, Bangladesh. *LANDSCAPE AND URBAN PLANNING*, **173**, 23-32, doi:10.1016/j.landurbplan.2018.01.008.
Zommers, Z. et al., 2020: Burning embers: towards more transparent and robust climate-change risk assessments. *Nature Reviews Earth & Environment*, **1**(10), 516-529, doi:10.1038/s43017-020-0088-0.
Zwiers, F. W., X. Zhang and Y. Feng, 2011: Anthropogenic influence on long return period daily temperature extremes at regional scales. *Journal of Climate*, **24**(3), 881-892.

Chapter 17: Decision Making Options for Managing Risk

Coordinating Lead Authors: Mark New (South Africa), Diana Reckien (Netherlands), David Viner (United Kingdom)

Lead Authors: Carolina Adler (Switzerland/Chile/Australia), So-Min Cheong (Republic of Korea), Cecilia Conde (Mexico), Andrew Constable (Australia), Erin Coughlan de Perez (USA), Annamaria Lammel (France), Reinhard Mechler (Austria), Ben Orlove (USA), William Solecki (USA)

Contributing Authors: Rachel Bezner Kerr (Canada), Sukaina Bharwani (United Kingdom), Robbert Biesbroek (Netherlands), Laurens Bouwer (The Netherlands), Lily Burge (United Kingdom), Massimo Cattino (Italy), Isabelle Cojocaru-Durand (Canada), Mauricio Domínguez Aguilar (Mexico), Hannah Farkas (USA), Simon French (United Kingdom), Adugna Gemeda (Ethiopia), Michael Gerrard (USA), Elisabeth Anne Gilmore (USA), Nicoletta Giulivi (Italy/Guatemala), Maron Greenleaf (USA), Marjolijn Haasnoot (The Netherlands), Ralph Hamman (Germany), Kirstin Holsman (USA), Christian Huggel (Switzerland), Margot Hurlbert (Canada), Kripa Jagannathan (India/USA), Catalina Jaime (UK/Colombia), Sirkku Juhola (Finland), Zoe Klobus (USA), Carola Kloeck (Germany/France), Bettina Koelle (South Africa/Germany), Robert Kopp (USA), Carolien Kraan (The Netherlands), Judy Lawrence (New Zealand), Timo Leiter (Germany/United Kingdom), Robert Lempert (USA), Debora Ley (Mexico), Megan Lukas-Sithole (South Africa), Katharine Mach (USA), Alexandre Magnan (France), Kathleen Miller (USA), Lionel Mok (Canada), Veruska Muccione (Italy), Rupa Mukerji (India), Baysa Naran (Mongolia), (Camille Parmesan (USA), Lei Pei (China), Lavinia Perumal (South Africa), Madeleine Rawlins (United Kingdom), Neha Rai (United Kingdom), Britta Rennkamp (South Africa/Germany), Alexandra Rinaldi (USA), Olivia Rumble (South Africa), Liane Schalatek (USA), Emma Lisa Freia Schipper (Sweden/USA), Pasang Yangjee Sherpa (USA/Nepal), Sabrina Shih (USA), Roopam Shukla (India/Germany), Rachael Shwom (USA), Chandni Singh (India), M. Cristina Tirado-von der Pahlen (USA/Spain), Cathy Vaughn (USA), Maria Alejandra Velez (Colombia), Ivo Wallimar-Helmer (Switzerland), Charlene Watson (United Kingdom), Romain Weikmans (Belgium), Andrew Jordan Wilson (USA), Katy Wilson (United Kingdom), Mark Workman (United Kingdom)

Review Editors: Richard Klein (Germany/The Netherlands), Zinta Zommers (Latvia/Sierra Leone)

Chapter Scientists: Megan Lukas-Sithole (South Africa), Massimo Cattino (Italy), Lauren Arendse (South Africa), Vita Karoblyte (United Kingdom), Leah Jones (USA)

Date of Final Draft: 1 October 2021

Note: TSU Compiled Version

Table of Contents

Executive Summary

Introduction and Framing

Chapter 17 assesses the options, processes and enabling conditions for climate risk management, a key component of climate resilient development. While Chapter 16 assesses the risks that society and ecosystems face, and residual risks after adaptation, this chapter focuses on the "how" of climate risk management and adaptation. It covers: the adaptation and risk management options that are available; the governance and applicability of options in different contexts; residual risk and Loss & Damage; the methods and tools that can be drawn on to support climate risk management planning and implementation; enabling conditions and drivers for adaptation; the role of monitoring and evaluation for integrated risk management and tracking progress, success and the risk of maladaptation; and finally, integration of risk management across sectors, jurisdictions and time horizons, under dynamic conditions of environmental and societal change.

Adaptation options for managing a wide range of climate risks have been proposed, planned, or implemented across all sectors and regions, with prospects for wide-ranging benefits to nearly all people and ecosystems (*high confidence*[1]) {17.2.1}. Many options are widely applicable and could be scaled up to reduce vulnerability or exposure for the majority of the world's population and the ecosystems they depend on (*high confidence*). These include nature restoration (*high confidence*), changing diets and reducing food waste (*high confidence*), infrastructure retrofitting (*high confidence*), building codes (*medium confidence*), disaster early warning (*high confidence*), and cooperative governance (*medium confidence*). The portfolio of adaptation options that could be successfully implemented varies across locations, with resource-limited and conflict-affected contexts bearing large amounts of residual risk (*high confidence*) {17.2, 17.5.1}.

The majority of climate risk management and adaptation currently being planned and implemented is incremental (*high confidence*). Transformational adaptation will become increasingly necessary at higher global warming levels *(medium confidence*) but can be associated with significant and inequitable trade-offs (*medium confidence*). Adaptations with some of the highest transformative potential include migration (*high confidence*), spatial planning (*medium confidence*), governance cooperation (*medium confidence*), universal access to healthcare (*medium confidence*) and changing food systems (*medium confidence*). Options that tend to modify existing systems incrementally include early warning systems (*high confidence)*, insurance (*medium confidence*), and improved water use efficiency (*high confidence*) {17.2, 17.5.1}.

Governance, especially when inclusive and context-sensitive, is an important enabling condition for climate risk management and adaptation (*very high confidence*). The use of formal and informal governance approaches, often in polycentric arrangements of public, private and community actors, is being increasingly recognised as important across many decision-making settings (*high confidence*) {17.3.2; 17.4.2}. Public governance leadership has the largest role for social safety nets, spatial planning, and building codes (*high confidence*) {17.2.1}. Private sector governance is important for insurance and for minimizing the stressors that can negatively impact ecosystems and their functions especially in the absence of public regulations or enforcement (*medium confidence*) {17.2.1}. Communities and individuals play the largest role in governance of adaptations to farming and fishery practices and ecosystem-based adaptations (*medium confidence*) {17.2.1}. Informal or individual-led decision-making is more common in food security and livelihood related adaptations, such as changes to diets, livelihood diversification and seasonal migration (*high confidence*) {17.2.1}. People who have experienced climate shocks are more likely to take on informal adaptation measures, and in places where people are more exposed to extreme events, autonomous adaptation is more common (*high confidence*) {17.2.1}.

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

National and international legal and policy frameworks and instruments support the planning and implementation of adaptation and climate risk management across scales, especially when combined with guidelines for action (*medium confidence*) {17.4.2}. Nationally Determined Contributions (NDCs) have been drivers of national adaptation planning, with cascading effects on sectors and sub-national action, especially in developing countries (*high confidence*) {17.4.2}. Nearly all developing countries (particularly SIDS) that included an adaptation component in their NDCs consider adaptation the most urgent aspect of their national climate change response (*high confidence*) {17.4.2}. A steady increase in national and sub-national laws, policies, along with regulations that mandate reporting and risk disclosure have promoted adaptation response across public agencies, private firms and community organizations *(high confidence*) {17.4.2}. Greater adaptation is present where national climate laws and policies require adaptation action from lower levels of government and include guidelines on how to do so (*medium confidence*) {17.4.2}.

Recognition of the critical role of financing for adaptation and resilience as an important enabler for climate risk management has strengthened (*high confidence*). Yet, since AR5, the gap between the estimated costs of adaptation and the documented (tracked) finance allocated to adaptation has widened (*high confidence*). Estimated global and regional costs of adaptation vary widely due to differences in assumptions, methods, and data; the majority of more recent estimates are higher than the figures presented in AR5 (*high confidence*). Although the estimated cost of adaptation is higher for developed countries (*medium confidence*), for developing countries they are much higher as a proportion of national income, making the self-financing of adaptation more difficult (*high confidence*). A high proportion of developing country NDC adaptation contributions are conditional on external financial support, underscoring the crucial role of international finance to achieve adaptation efforts commensurate with climate risks (*high confidence*) {17.4.2; Cross-Chapter Box FINANCE in this Chapter}. Developed country climate finance leveraged for developing countries for mitigation and adaptation has fallen short of the 100 USD billion per year Copenhagen commitment for 2020 (*very high confidence*) {Cross-Chapter Box FINANCE in this Chapter}. Substantial opportunities exist for improving access to climate finance, as well as its impact and effectiveness {17.4.2; Cross-Chapter Box FINANCE in this Chapter}.

Private sector financing for adaptation has been increasingly promoted as a response to realized adaptation finance needs (*high confidence*). However, private sector financing of adaptation has been limited, especially in developing countries (*high confidence*). Tracked private sector finance for climate change action has grown substantially since 2015, but the proportion directed towards adaptation has remained small (*high confidence*) {Cross-Chapter Box FINANCE in this Chapter}; in 2018 these contributions were 0.05% of total climate finance and 1% of adaptation finance. A key challenge for private sector financing of adaptation is demonstrating financial return on investment, as many benefits of adaptation arise as avoided damages or public goods, rather than direct revenue streams (*medium confidence*). Leveraging private finance in developing countries is often more difficult because of risk (perceived and real) to investors, reducing the pool of potential investors and/or raising the cost (interest) of investment (*medium confidence*) {17.4.3.; Cross-Chapter Box Finance in this Chapter}.

Information and knowledge on climate risk and adaptation options, derived from different knowledge systems, can support risk management and adaptation decisions (*high confidence*) {17.4.4}. Processes, such as co-production, that link scientific, Indigenous, local, practitioner and other forms of knowledge can make climate risk management processes and outcomes more effective and sustainable (*high confidence*) {17.3.2; 17.4.4}.

Climate services that provide reliable, relevant, and usable climate information for the short or long term are increasingly being produced and used in climate risk management (*high confidence*) {17.4.4}. In many regions and sectors, the utility of climate services is strengthened by sustained engagement between stakeholders and experts and by co-production (*medium confidence*) {17.4.4; Cross-Chapter Box Climate Services WGI Chapter 12}. Significant gaps remain in the evaluation of climate services, and some studies indicate that climate services often do not reach the most vulnerable and more isolated people, maintaining or exacerbating inequality.

Catalyzing conditions and windows of opportunity can drive shifts in motivation and adaptation effort, stimulating more rapid uptake of existing and new adaptation options (*medium confidence*) {17.4.5}. Decision-makers can take advantage of windows of opportunity to promote rapid and

effective responses in reactive and proactive cases {17.4.5}. Disaster events or shocks such as wildfires, tropical cyclones, heatwaves or coral bleaching have catalyzing characteristics (*high confidence*) {17.4.5.2}. Additional types of catalyzing conditions include climate litigation and the presence of individuals and organizations that act as policy and decision innovators, including government and business innovators in cities (*medium confidence*) {17.4.5.3}, stimulating action within and beyond their immediate contexts (*medium confidence*). Litigation on failure of government and business to adapt is becoming more frequent and is expected to increase as climate impact attribution science matures further (*high confidence*) {Cross-Chapter Box LOSS in this Chapter; 17.4.5.3}.

Urgency can stimulate prompt climate risk management *(high confidence*). A moderate level of urgency contributes to enhanced climate action, while both high and low levels of urgency can impede response (*high confidence*) {17.4.5.1}. Well-designed communication strategies can move decision makers from low to moderate levels of urgency, stimulating action. As conditions approach a crisis state, however, urgency can weaken decision-making rather than support it (*medium confidence*) {17.4.5.1}.

Decision support tools and decision-analytic methods are available and are being applied for managing climate risks in varied contexts, including where deep uncertainty is present (*high confidence*). These tools and methods have been shown to support deliberative processes where stakeholders jointly consider factors such as the rate and magnitude of change and their uncertainties, associated impacts and timescales of adaptation needed along multiple pathways and scenarios of future risks (*high confidence*) {17.3.2; Cross-Chapter Box DEEP in this Chapter}. However, comparative evidence on the relative utility of different analytical methods in their use by decision makers for managing climate risks is an important gap (*medium confidence*). Nevertheless, robust decision-making, using pathway analyses to determine 'no regrets' options amongst trade-offs, has been shown to be a useful starting point under deep uncertainty (*medium confidence*). Methods for analysing options differ across geo-political scales, with modeling studies being a particularly prominent method across scales from community and urban to regional and national (*high confidence*) {17.3.1; 17.6, Cross-Chapter Box DEEP in this Chapter}.

Successful adaptation and maladaptation form the opposite poles of a continuum (*medium confidence*). The evaluation of an adaptation option and its location on this continuum are context-specific and vary across time, place and evaluation perspectives (*high confidence*) {17.5.2}. Despite knowledge gaps, adaptation options can be assessed according to several criteria, such as benefits to humans, benefits to ecosystem services, benefits to equity (marginalized ethnic groups, gender, low-income populations), transformational potential, and contribution to greenhouse gas emission reduction (*medium confidence*) {17.5.1}. These factors can aid evaluation of co-benefits and trade-offs within and between adaptation responses (*high confidence*) facilitating successful adaptation and reducing the likelihood of maladaptation (*medium confidence*) {17.5.1}.

Adaptation options across a range of climate risk settings (Representative Key Risks) have potential for some degree of maladaptation alongside varied potential for success (*very high confidence*) {17.5.2}. Maladaptation can result from unaccounted trade-offs with low-income groups and the transformational potential of adaptation (*medium confidence*) {17.5.2}. Success is greatest when adaptation enhances gender equity (*medium confidence*) {17.5.2} and supports ecosystem function and services (*medium confidence*) {17.5.2}. Among adaptation options, coastal infrastructure is an example that has particularly high risk for maladaptation through trade-offs for natural system functioning and human vulnerability over time. Examples of options with high potential for successful adaptation are nature restoration (*medium confidence*) {17.5.2}, social safety nets (*medium confidence*) {17.5.2} and adaptations relating to changes of diets and reducing food waste (*medium confidence*) {17.5.2}.

Monitoring and evaluation (M&E) are key for iterative climate risk management, in particular tracking adaptation progress and learning about adaptation success and maladaptation (*high confidence*). M&E application has increased since AR5 at the local, project and national level, but is still at an early stage in most countries (*high confidence*) and underutilized as a way to assess adaptation outcomes at longer timeframes (*high confidence*) {17.5.2}. About one-third of countries have undertaken steps to develop national adaptation M&E systems, but fewer than half of these are reporting on implementation (*medium confidence*) {17.5.2}. M&E, as well as tracking global progress on adaptation, are confronted with a number of challenges (*high confidence*), such as a comparability in what counts as adaptation and limited availability of data across scales {17.5.2; Cross-Chapter Box PROGRESS in this Chapter}. The relative strength and weaknesses of different approaches and their applicability have not been systematically assessed, but the diversity of approaches being used could provide a more comprehensive assessment of global adaptation progress (Cross-Chapter Box PROGRESS in this Chapter).

Understanding of residual impacts and risks in vulnerable regions and implications for Loss & Damage (L&D) has become increasingly relevant as the limits to adaptation are projected to be reached in natural and human systems (*high confidence*) {17.2.2.5; Cross-Chapter Box LOSS in this Chapter}. The international L&D policy debate has seen heightened attention, with some coalescence around key issues, including risk management, limits to adaptation, existential risk, finance and support, including liability, compensation and litigation. Advisory groups have been set up with participation of policy and experts from research, civil society and practice to inform debate. Yet, the policy space and concrete remit for L&D has remained vague, which renders policy formulation complex (*high confidence*) {17.2; Cross-Chapter Box LOSS in this Chapter}.

Effective management of climate risks is dependent on systematically integrating adaptations across interacting climate risks, ensuring that measures of success include factors important to climate resilient development, and accounting for the dynamic nature of climate risks over time *(very high confidence)* {17.6}. Across the Working Group II report are examples of how managing adaptations to reduce climate risks can negatively or positively affect sustainable development, thereby impacting the potential for climate resilient development. Climate risks can emerge at different rates and time horizons, and the interactions between risks vary from region to region (*very high confidence*) {17.6}. The need to manage these risks in an integrated manner is demonstrated by the diverse and interacting impacts of climate risks on ecosystems, cities, health, and poverty and livelihoods, such as in the Water-Energy-Food nexus (*high confidence*) {17.6}. Expertise and resources for integrated risk management varies between the developed and developing countries (*high confidence*) {17.6}. Integrated pathways for managing climate risks will be most suitable when 'low regrets' anticipatory options are established jointly across sectors in a timely manner, path dependencies are avoided in order to not limit future options for climate resilient development, and maladaptations across sectors are avoided (*high confidence*) {17.6}. National Adaptation Plans have potential to integrate participatory, iterative processes to monitor, review, and update adaptations as knowledge, experience and resources become available {Cross-Chapter Box DEEP in this Chapter; 17.6}.

17.1 Objectives and Framing of the Chapter

17.1.1 Introduction

Addressing the impacts and risks associated with observed and projected climate change (see Chapter 16) is fundamentally and intricately tied to the decision-making options available to manage those risks. Climate risk decision-making focuses on the processes needed to identify and characterise those risks, generate plans, policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks (derived from the definition of risk and risk management in Chapter 1). This chapter presents an assessment of the evidence on climate risk decision-making as a set of processes that involve a range of actors in different contexts resulting in diverse outcomes. The climate risk decision-makers and their actions are the central focus of the assessment. The chapter is an assessment of the evidence of the decision-making options that are available in practice, and functions as a central pivot point between the identification of key climate risks (Chapter 16) and the means to integrate and leverage action on climate risk decision-making into the broader requirements of climate resilient development pathways (Chapter 18). This section introduces the main entry points on decision-making that have framed this assessment (Sections 17.1.1.1 to 17.1.1.5), as well as the key terms used to frame this assessment and its organisation in this chapter (Section 17.1.2).

A central framing point is the connection between climate risk decision-making and adaptation. Adaptation for human systems in this report is introduced in Chapter 1 and defined in the Glossary as 'the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities'. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects (see AR6 Glossary). In this chapter, we consider adaptations that may be implemented by people, whether they be to support human, managed, or natural systems, and the processes and factors that underpin adaptation in these diverse settings. Different types of adaptation have been distinguished in Chapter 1, including anticipatory versus reactive, autonomous versus planned, and incremental versus transformational (IPCC WGII glossaries; Chapters 16-18). These dichotomies and interactions are assessed here. Implementation of adaptation through iterative risk management decision-making emphasizes that anticipating and responding to climate change does not consist of a single set of judgments at a single point in time, but rather an on-going cycle of assessment, action, reassessment, learn, and response' (Chapter 1).

17.1.1.1 Decision-Making for Managing Climate Risks in AR6

The UN 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), as well the UNFCCC Paris Climate Agreement, the UN Sendai Framework Disaster Risk Reduction, and the UN Habitat New Urban Agenda helped push climate risk management and adaptation forward from the global to the national level, from the planning stage into implementation and provides benchmarks for adaptation progress. To assess adaptation progress (17.5), the interplay between top-down (institutional) and bottom-up (individual/social/community) processes, multi-scale interaction (local, regional, national, and international), iterative risk management, differing forms of knowledge, and equity are especially crucial (particularly Sections 17.2, 17.4). Parallel to these advances is an understanding and assessment of appropriate decision support tools, methods, and evaluation metrics (Section 17.3).

Since AR5, significant advances have been made in regard to the understanding of the drivers of decision-making and contexts in which climate risk decision-making takes place. Climate risk decision-making generally, and adaptation specifically, has been a focus within the IPCC special reports in the sixth assessment cycle. An overall goal of climate risk management is to eliminate or reduce the risk to levels that are to a level that is socio-politically and economically acceptable. Risk management to an acceptable level may not be feasible because of limits or barriers to adaptation. Future potential risks are a more complex matter given the need to define time scales and spatial extent, and uncertainties. In the Special Report on the impacts of global warming of 1.5C [SR1.5] (IPCC, 2018a), the risks associated with climate-related impacts were found to be higher under emission scenarios above 1.5°C, raising awareness for the need to limit the impacts of warming through the acceleration of climate mitigation and both incremental and transformational adaptation (IPCC, 2018a).

The AR6 SRCCL (IPCC, 2019b) added the dimensions of pace, intensity, and scale of climate impacts and adaptation or mitigation responses and adverse consequences. Relevant land-based adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social, and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

While a generic understanding of the decision-making process has emerged from the literature, the chapter assesses how these components and their dimensions interact across a range of temporal (short, long-term as defined in SROCC), scalar (household to global), institutional/governance (formal, informal, bottom up, top down), and magnitude (micro adaptation - small scale and macro adaptation - large scale) (Section 17.2). The IPCC SRCCL placed emphasis on acknowledging co-benefits and trade-offs to avoid barriers to implementation, with particular attention to land use decisions. It states that this coordination can be supported by building networks of decision-makers across scales and sectors, including local stakeholders from vulnerable groups, and by adopting and implementing policies in a flexible and iterative manner (IPCC, 2019b).

17.1.1.2 Approaches to Assess and Synthesise Options for Managing Risk

This chapter utilizes several points of departure to assess climate risk management that emerge from AR5 and AR6, specifically. SR Climate Change and Land, especially Chapter 7 and throughout SROCC. These works provide foundational assessment of evidence on decision-making systems that connect different spatial and temporal scales and diverse cultural contexts in which climate risk management takes place, the varying interactions of decision-makers and their stakeholder groups, and the barriers and enablers to decision making, including governance, finance, and knowledge (Section 17.4).

Another significant advance is that instead of cataloguing decision-making strategies, the literature has now evolved to the point where adaptation progress, effectiveness and efficiency can be more meaningfully assessed through increased monitoring and evaluation capacity. Although the ability to measure success and effectiveness is not fully developed and hampered by lack of data, agreed methods and terms, and time to fully evaluate adaptation actions (see Sections 17.3.3 and 17.5, Cross-Chapter Box PROGRESS in this Chapter).). The ambition to describe effectiveness and success illustrates further maturation of the literature on climate risk decision-making as a system process. Overall, the process of climate risk decision-making remains dynamic, and the chapter attempts to assess a variety of proactive management approaches being developed and tested to address adverse, diverse and complex risks in a wide range of developing and developed country contexts (see Figure 17.1). The chapter provides a synthesis of how these new approaches are reflected in the sectoral and regional chapters and cross-chapter papers of this report (Chapters 2-15; CCPs 1-7). Specifically, the goal is to provide a line of sight between the sectoral and regional chapters and cross-chapter papers' decision-making assessment to sections in this chapter. This synthesis also helps to present the varying and context-driven character of adaptation strategies now in practice and being considered.

17.1.1.3 Key Risks Considered in the Assessment of Climate Risk Decision-making

In AR6 (Chapter 16 and Cross-Chapter Papers), over 100 key risks have been identified across regions and sectors, which have the potential to manifest into severe impacts that are relevant to the interpretation of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, specifically on the objective to avoid dangerous anthropogenic interference with the climate system. These risks are *likely*[2] to become more severe under higher warming scenarios and social-ecological conditions that yield high exposure and vulnerability to the associated climate-related hazards. In this report, these key risks have been grouped into categories represented by eight overarching risks (called Representative Key Risks, RKRs) relating to: 1) coastal socio-ecological systems; 2) terrestrial and ocean ecosystems; 3) critical physical infrastructure, networks, and services; 4) living standards; 5) human health; 6) food security; 7) water

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

security; and 8) peace and human mobility (see Chapter 16). Decision-making options for managing these risks, such as selecting the relevant adaptation options to implement, require an assessment of the local context in which these impacts are likely to be experienced, as well as the local to global collective implications of those actions (see Sections 17.2 and 17.5).

17.1.2 Objectives and Key Terms

17.1.2.1 Drivers

AR5 provides a broad overview of drivers as the determinants of climate decision-making by individuals and organizations, including social, institutional, and regulatory contexts, cultural values and norms, economic resources and constraints, and the availability of information and of tools to process it. This chapter expands the discussion of the contexts for decision-making in a number of ways (see Section 17.4), including an examination of informal as well as formal decisions, an attention to emerging actors, particularly social movements, and consideration of several dimensions of governance. It expands the treatment of decision processes, with particular attention to framing and to the integration of multiple time frames (Sections 17.3 and 17.6).

Since AR5, there has been an increasing ambition for adaptation, signalled by growing attention to the adaptation gaps and deficits, which call for extensive and intensive levels of action (Chen et al., 2016; UNEP, 2017; Tompkins et al., 2018; Valente and Veloso-Gomes, 2020; UNEP, 2021a), as well as increased attention to co-benefits between climate risk reduction and other benefits, such as equity and biodiversity conservation (Colloff et al., 2017, Section 17.5.1; Smith et al., 2020). Climate risk decision-making as an object of study has emerged in a more central location within the literature as adaptation moves from planning into the realm of practice. The broad sense of urgency (summarized in Wilson and Orlove, 2019; Wilson and Orlove, 2021), show growth of the term "urgency" in both scholarly publications and the popular press since 2014, building on earlier increases starting around 2005, and a dramatic spike of the terms "climate crisis" and "climate emergency." Paralleling this call for more extensive and rapid action is the emergence of the term "transformational" adaptation and decision-making. Transformational adaptation (defined and deeply examined in Chapter 1, Chapter 16, and Section 17.2) highlights efforts that involve large-scale, systemic change (Wilson et al., 2020) and involves "adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices including approaches that enable new ways of decision-making on adaptation" (IPCC, 2018a). The complex relationship between incremental adaptation and transformational adaptation is presented and reviewed in 17.2. Furthermore, the literature since the AR5 report has moved beyond the question of limits and barriers to adaptation as relevant aspects for decision-making to additionally assessing drivers of change, with increasing focus devoted to more nuanced and differentiated contexts for action.

17.1.2.2 Enabling Conditions

AR5 extensively assessed the conditions of adaptation with a focus on the role of governance, finance, knowledge, and capacity. AR6 extends this examination of adaptation and the decision-making process around it by focusing on enablers. Adaptation enablers are defined as those conditions or properties that specifically promote or advance the adaptation process (see Chapter 1). Enablers are positively associated with likelihood that adaptation planning occurs, and strategies will be put into practice. Three broad enabling conditions are presented in the chapter (Section 17.4): governance (legislation, regulation, institutions, litigation), finance (needs, sources, intermediaries, instruments flows, and equity) and knowledge (capacities, climate services, big data, indigenous/local knowledge, co-production, boundary organizations). As an extension of enabling conditions, the chapter also examines catalysing conditions for adaptation (Section 17.4.5). Catalysing conditions motivate and accelerate the process of decision-making leading to more frequent and potentially substantial adaptations. The chapter recognises that the relative influence of enabling conditions and catalysing conditions are set within the human dimensions of climate change including vulnerability, inequality, poverty, and the achievement/non-achievement of SDGs (see Figure 8.1).

17.1.2.3 Mechanisms for Decision-making

The mechanisms and conditions for decision-making provide the basis for the chapter. AR5 provided a detailed chapter on the support of climate decision-making. Chapter 2 of AR5 concluded, with high confidence, that risk management provides a useful framework for most climate change decision making, and that iterative risk management is most suitable in situations characterised by large uncertainties, long time frames, the potential for learning over time, and the influence of both climate as well as other socioeconomic and biophysical changes. Furthermore, decision support is situated at the intersection of data provision, expert knowledge, and human decision-making at a range of scales from the individual to the organization and institution.

The climate risk management decision-making process follows a set of general considerations. The detail of each decision is often highly context specific. Climate risk decision-making is bound to the question of how and under what circumstance it is appropriate to alter, reduce or transfer and retain risk. Different types of risk (e.g., gradual compared with catastrophic) and conditions of risk (e.g., known versus uncertain) are associated with different types of responses (e.g., incremental versus transformational). As the risk decision process precedes, individuals and organizations will formally or informally utilize any number of mechanisms to guide, aid, or facilitate the decision-making process. Decision-making can then take place in a linear set of steps or through a complex iterative process involving reflexive and recursive steps.

17.1.2.4 Costs and Non-Monetised Loss, Benefits, Synergies, and Trade-Off

AR5 provided an extensive discussion of the costs to human and natural systems associated with climate risks. It recognized the challenges which long time frames, uncertainty and the differing values held by stakeholders create for the monetisation of losses. The AR6 SROCC built on the discussion of cultural values—typically also difficult to monetise—through a consideration of cultural ecosystem services and cultural forms of valuation, with cases from high mountain areas and polar regions (Hock et al., 2019; Meredith et al., 2019; IPCC, 2019c). AR6 expands this discussion of multiple forms of valuation in several ways. It considers regulation and litigation as mechanisms for promoting the consideration of both monetisable and non-monetisable losses in decision-making (Cross-Chapter Box LOSS in this Chapter). AR5 treated the issues of equity and justice primarily with regard to mitigation, especially in WGIII AR5 Chapter 3; these issues in the adaptation sphere are considered extensively in this chapter in areas such as finance, governance, success of adaptation, maladaptation, and monitoring and evaluation. The discussions of maladaptation and success of adaptation (Section 17.5) consider questions of synergies and trade-offs across values and goals, while the consideration of decision processes and tools shows opportunities to use co-benefits to promote effective decision-making, including approaches to decision-making under conditions of deep uncertainty (Section 17.3; Cross-Chapter Box DEEP in this Chapter). Successful adaptation across the report (as specified in Ch1) is associated with conditions when co-benefits are high and (negative) trade-offs are low.

17.1.2.5 Monitoring and Evaluation

This chapter assesses the evidence of monitoring and evaluation (M&E) (see AR6 Glossary) and their approaches as part of the adaptation process at the national, local, and project level as well as in global assessments (17.5.2; Cross-Chapter Box PROGRESS in this Chapter). M&E can serve multiple functions, e.g., to: 1) facilitate an understanding on whether and how interventions work in achieving intended objectives; 2) inform ongoing and future implementation, and 3) provide information that helps to substantiate upward and downward accountability (Preston et al., 2009; UNFCCC, 2010b; Pringle, 2011; Spearman and McGray, 2011) (see BOX 17.1 for more discussion). This chapter also addresses the relevance of iterative learning as part of the design of M&E processes, as a means by which actors and institutions engaged in M&E acquire new insights on how these processes work (or not) to achieve set objectives.

[START BOX 17.1 HERE]

Box 17.1: How is Success in Adaptation Characterised in Chapter 17?

Whether an adaptation is considered successful is context specific. It depends on who evaluates adaptation and at what time as well as on the ability to compare the outcome of adaptation with a hypothetical situation without adaptation and without other parallel changes, such as development interventions (Singh et al., 2021; Dilling et al., 2019a). The ability to compare the risk situation post and prior adaptation is complicated through the long time-horizons at which adaptation outcomes often become apparent (see Cross-Chapter Box ADAPT in Chapter 1; Section 17.5.1; Dilling et al., 2019a).

However, a wealth of information has recently become available on how success and effectiveness of adaptation could be assessed, defined, or investigated in certain settings (Patt and Schröter, 2008; Morecroft Michael et al., 2019; Tubi and Williams, 2021) or across a larger set of adaptations (Hegger et al., 2012; Eriksen et al., 2015; Gajjar et al., 2019a; Owen, 2020; Singh et al., 2021). Accordingly, successful adaptation is understood as effective adaptation, in that it reduces climate impacts, vulnerabilities and risk, and additionally balances synergies and trade-offs across diverse objectives, perspectives, expectations, and values (Eriksen et al., 2015; Juhola et al., 2016; Gajjar et al., 2019a; Owen, 2020; Singh et al., 2021). Across this report, four factors are identified as enabling conditions of successful adaptation, which include a focus on recognitional, procedural, and distributional justice as well as flexible and strong institutions that seek policy integration and account for long-term goals.

To operationalizable 'success' in this chapter, it is characterised by the degree to which an adaptation response benefits (1) human systems (number of people); (2) ecosystems or ecosystem services; (3) marginalized ethnic groups, (4) women and girls, (5) and low-income populations, and can be characterised as (6) transformational adaptation, and (7) contributing to greenhouse gases emission reductions (Section 17.5.1). Overarching to these factors are uncertainty and potential path-dependency of decisions that may result in lock-in and maladaptation in the long-term, and recognition that what is successful in the near-term is not necessarily successful in the long-term.

Success in adaptation is antithetical to maladaptation. Maladaptation refers to current or potential future negative consequences, including failed or partially successful adaptation (or risk reduction), but also trade-offs or side-effects of adaptation (see Glossary). Thus, success of adaptation and maladaptation form the ends of a continuum that represents the balancing of synergies and trade-offs across regions, populations, or sectors (Singh et al., 2016; Magnan et al., 2020; Schipper, 2020). Every adaptation action may be placed along such a continuum reflecting the empirical evidence of adaptation practices and their assessment (Section 17.5).

[END BOX 17.1 HERE]

17.1.3 Outline of the Chapter

The chapter is organised around the broad narrative of climate risk decision-making and management (Figure 17.1), building from the assessment of risks within RKRs (Chapter 16) and options available to address these risks and within a broader context of climate resilient development pathways (Chapter 18). Decision-making is considered to be a reflexive and recursive process where different evidentiary threads and information inputs become relevant to the understanding and assessment of factors underlying specific decisions. Additionally, this is also a discursive process, whereby actors and institutions' interpretations of climate risks are also key to these deliberations.

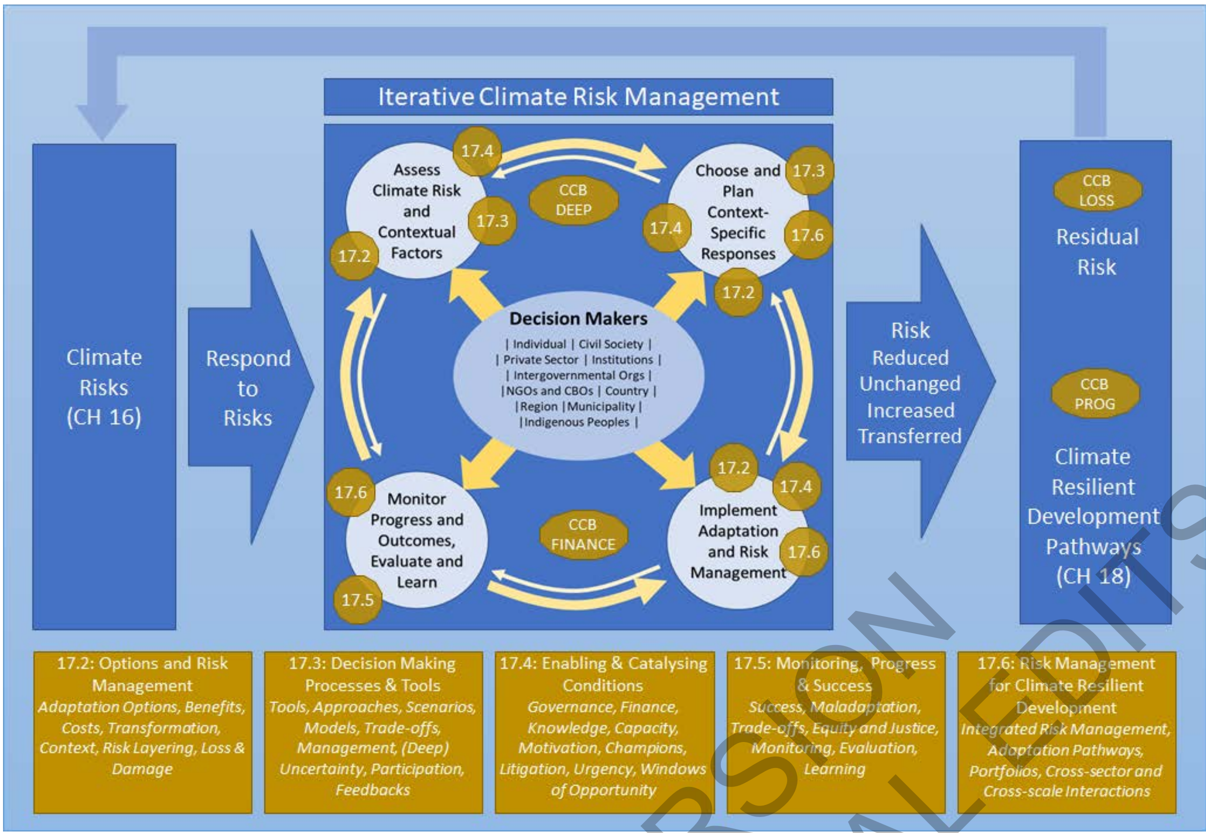


Figure 17.1: Schematic representation of the climate risk management decision-making process as introduced in Chapter 1 (Figure 1.6) and the key elements of this Chapter that address additional aspects of this process. In Chapter 17, climate risk management (middle box) is framed as the iterative response (i.e., what society could do and how it could be done) to the climate risks described in Chapter 16, with outcomes (ideally reduced risk) that can support (or perhaps hinder) climate resilient development, Chapter 18. Decision makers from diverse contexts sit at the centre of the climate risk decision making process, and interact with and drive these processes as they play out. The main sections of Chapter 17 (bottom panel of boxes) address a wide range of issues (keywords in bottom panel) that manifest at one or more stages of climate risk management processes, illustrated by icons for section numbers and Cross-Chapter Boxes in the interactive risk management process.

Decision-making processes of risk management and adaptation are varied and numerous. Section 17.2 assesses the risk management and adaptation options already in practice. Section 17.3 assesses decision-support methods and tools available for application and the effectiveness of these in supporting climate decision-making across degrees of uncertainties and levels of governance and expected reach (scale) across populations from households to international cooperation. Closely interlinked across the decision-making process, are the enabling and catalysing conditions for decisions on adaptation and risk management (section 17.4). Section 17.5 synthesizes evidence on maladaptation and adaptation successes, and assesses the current knowledge on M&E of adaptation, including financial accounting, to support learning on those, respectively. Here, M&E is considered distinct from the tracking of financial flows related to adaptation, given that financial accounting does not necessarily provide information on the implementation of adaptation measures and their results (see also Section 17.2.1.2). Finally, in Section 17.6, decision-making, climate risk responses, and their relevance for climate resilient development are presented, where evidence on their respective contributions to facilitate actions in the adaptation solution space within a broader context for development is shown (Chapter 18). Throughout the decision-making process, crucial feedback loops are present that define the results of specific actions and recursive nature of climate risk management and adaptation.

17.2 Risk Management and Adaptation Options

There has been substantial progress in risk management and adaptation responses around the world, as demonstrated in the sectoral and regional chapters of this report and illustrated in Chapter 16. This section presents an overview of different options available to manage risk, explaining how they are currently governed and the extent to which they can be applied around the world. This section contains an assessment of the ways in which different options are being combined to create adaptation portfolios, and describes how incremental and transformational change is starting to be considered. Based on the human dimension of climate change, as described in Chapter 8, vulnerability, inequality, and poverty influence these portfolios of adaptation and transformational change. Particularly for change where residual risks remain that may lead to exceeding the limits of adaptation, increasingly transformational adaptation and policy innovation will be important.17.2.1 assesses options for climate risk management from around the world that reduce, manage, or retain climate-related risks and assesses their contribution to reducing vulnerability and exposure, how they are governed, and the benefits to humans and ecosystems. 17.2.2 presents portfolios of risk management including the design principles and observed variations across the globe, before it discusses the need and potential for transformational adaptation to complement incremental adaptation, for which we present evidence across the report for selected adaptation options and some key risks. The Cross-Chapter Box LOSS in this Chapter synthesises recent literature and assesses key strands of the international dialogue policy on Loss & Damage, concerned with options that help to deal with residual impacts and risks in vulnerable countries.

17.2.1 Adaptation Options for Climate Risk Management

This section assesses options for climate risk management (CRM) across common risk settings that have been grouped into Representative Key Risks (RKRs). These risk management and adaptation actions target the components of risk: hazards, vulnerabilities, and exposure associated with sudden or slow-onset events (see Chapter 1 for more details on the definition of risk).

For each of the RKRs, three commonly discussed adaptation options are identified across the regional, sectoral, and cross-chapters papers of this report. These 24 options have been selected to cover a representative variety of strategies to adapt to climate change, while a particular adaptation option can be relevant to many of the RKRs. For example, the adaptations listed under the RKR of "Food security" are also related to the RKR on "Human health" (Ebi and Prats, 2015). See SM17.1 for more details. The list is not comprehensive of all possible adaptations listed in the regional and sectoral chapters. For example, this does not include adaptations by institutions who might become unable to cope with increasing pace and magnitude of extreme events (see Chapter 11).

17.2.1.1 Adaptation Options and Their Contribution to Reduce Vulnerability and Exposure

Table 17.1 provides examples of each of these 24 adaptation options from across AR6 WGII. Detailed information about sectors and regions where these adaptations are being discussed can be found in the indicated chapters. Note that this list is curated to ensure a diversity of options, therefore most of the options will apply to more than one RKR.

Table 17.1: Selected adaptation options per RKR, with examples of how each option can reduce vulnerability or exposure, or support risk financing. Many of the adaptation options are relevant to multiple RKRs, and have been selected to be representative of the wide variety of adaptation options implemented or suggested around the world.

RKR	Adaptation option	Examples from regional and sectoral chapters and cross-chapter papers
Risk to coastal socio-ecological systems	Coastal accommodation	Raising of dwellings, raising of coastal roads (15.5.2), amphibious building designs (CCP2), improved drainage (11.3.5.3)
	Coastal infrastructure	Seawalls, beach and shore nourishment (3.6, 15.5.1), breakwater structures (15.5.1), dikes, revetments, groynes, or tidal barriers. (6.3.4.8)., land reclamation (15.5.2)
	Strategic coastal retreat	Retreating from coastal areas (3.6, Cross-Chapter Box SLR in Chapter 3, 6.3.5.1, CCP2), relocation/resettlement (CCP2)
Risk to terrestrial and ocean ecosystems	Restore/create natural areas	Marine protected areas (FAQ 3.5), active restoration of coral reefs (3.6.2.3.2), ridge-to-reef management (CCP1), restoring dunes (CCP4), planting salinity-tolerant trees (4.5.2.1) Increasing forest cover (CCP7), detect and manage forest pests (11.3.4.3)
	Reduce ecosystem stress	Reduce pollution and eutrophication (3.3.3), reduce anthropogenic pressures on the Great Barrier Reef (Box 11.2), sustainable fisheries harvest (3.6.2), increasing connectivity between natural areas (2.6.2)
	Ecosystem-based adaptation	Marine habitats to protect against storm surge (3.6), agroecology (5.14.1.1), coastal and marine vegetation and reefs (6.3.3.4), vegetation corridors, greenspace, wetlands (FAQ 6.3), mangrove habitat restoration (8.5.2.2, 9.8.5.1), restoring coasts, rivers, wetlands to reduce flood risk (2.6.3, CCP1), wrban green space to reduce temperatures (2.6.3)
Risks associated with critical physical infrastructure, networks, and services	Infrastructure retrofitting	Air conditioning (6.3.4), using thermosiphons for permafrost degradation (10.4.6.4.1), increasing rooftop albedo (for reflectivity) (11.3.5.3), shading (13.A.4)
	Building codes	Drainage systems (4.5.2.1), architectural and urban design regulations (6.3.4.2), infrastructure standards initiatives (CCP6), Chile's Sustainable Housing Construction Code (12.5.5.3)
	Spatially redirect development	Zoning/land use planning (6.3.2.1), spatial development planning to regulate coastal development (CCP2)
Risk to living standards and equity	Insurance	Agricultural insurance and micro-credit (4.5.2.1, 10.4.5.5), index-based insurance, market and price insurance (5.14.1.3), flood insurance (10.5.3.2), collective insurance schemes (12.5.7.5)
	Diversification of livelihoods	Combining income-generating activities within fisheries sector (3.6.2.2) Community level adaptation by Pangnirtung Inuit through diversification to stabilize income and food resources (CCP6)
	Social safety nets	Food for work programmes (4.5.2.1), school feeding programmes (7.4.2.1.3), social protection programmes, such as unemployment compensation (10.5.6)
Risk to human health	Availability of health infrastructure	Safe drinking water infrastructure (4.5.2.1), temperature-controlled low-income housing (11.3.6.3), Health care clinics (6.4 case study), place-specific mental health infrastructure and “nature therapy” (14.4.6.8)
	Access to health care	Access to healthcare services (11.3.6.3), Access to Health, Nutrition Services and Healthy Environments (water and sanitation) (7.6), enhanced access to culturally-appropriate mental health resources; “Telemedicine” (information technologies and telecommunications for health and public health service delivery) (12.6.1.5)
	Disaster early warning	Early warning of marine heatwaves (3.6.2.3.3) early warning for pests (5.12.5), Heat Action Plans (HAP) (7.4.2.1.2), raising public awareness through campaigns (FAQ13.3)

Risk to food security	Farm/fishery improvements	Changing fishing gear or vessel power (3.6.2.2.3), change crop variety or timing (4.5.2.1, CCP5, 8.5), close productivity gaps (5.12.5), biotechnology (5.12.5), irrigation schemes (9.12.5.3), integrated crop/livestock systems (5.10.1), relocating livestock linked to improved pasture management (13.5.2)
	Food storage/distribution improvements	Improve transportation infrastructure and trade networks, shortened supply chains (5.12.5, 9.12.5.3), improved food storage (5.12.5, 7.4.2), local food production/chains (Cross-Chapter Box COVID in Chapter 7)
	Behaviour change in diets and food waste	Reduce food loss and waste (5.12.5), shifts to more plant-based diets (7.4.5.2), creating demand for organically sourced food (10.5.3.2)
Risk to water security	Water capture/storage	Farm ponds and revival of water bodies (4.5.2.1), rain gardens, bioswales or retention ponds (6.3.3.6), water storage tanks (10.5.3.2), multi-purpose water reservoirs and dams (CCP5)
	Efficient water use/demand	Precision/drip irrigation (4.5.2.1), Managed Aquifer Recharge (MAR) (9.4), cooperative policies across multiple sectors (CCP4), changing water consumption patterns (CCP4)
	Efficient water supply/distribution	Constructing irrigation infrastructure (4.5.2.1), inter-basin transfers (6.3.3.6), water reuse (13.A.3), slum/water upgrading (6.4.3)
Risk to peace and migration	Seasonal/temporary mobility	Fishing fleet mobility to follow species distribution (3.6.2.2.2), mobility for seasonal employment and remittances (4.5.2.1, Cross-Chapter Box MIGRATE in Chapter 7), legal/illegal labour migration (CCP3), pastoralist seasonal migrations (Cross-Chapter Box MIGRATE in Chapter 7)
	Cooperative governance	Transboundary fishing agreements (3.6.4.1), ocean governance (3.6.2.2), collective water management (4.5.2.1), indigenous water-sharing systems (4.5.2.1), enforcing the land rights of indigenous populations (CCP7), adaptive co-management in Arctic fisheries (CCP6), international compact on migration (Cross-Chapter Box MIGRATE in Chapter 7), policies for adaptive governance (8.5)
	Permanent migration	Resettlement of flood-prone communities (4.5.2.1), rural-urban migration (6.1 case study), internal migration (Box 10.2), international migration and remittances (8.6.3, 14.4.7.3)

Of this list of adaptation options, many focus on reducing vulnerability to climate change (*high confidence*), as vulnerability is one of the components of risk (see Chapter 1 and Chapter 8). Vulnerability is the propensity or predisposition to be adversely affected, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (see Chapter 1 for more details). In the world's threatened ecosystems, reducing vulnerability often means reducing other non-climate negative pressures on ecosystems, such as pesticide use or fishery overexploitation (see Chapter 3.3).

Vulnerability reduction is also a major focus in human systems, and this includes development of investments that help people adapt to climate change. Examples include irrigation or diversifying crops. Building infrastructure resilient to climate-related risks is another example; many of the structural and physical adaptation options can reduce sensitivity to disasters, such as elevating houses or doing beach nourishment in coastal areas (see Section 15.5 in Chapter 15). Extreme events often catalyse investment in adaptation to reduce vulnerability for the future (Kreibich et al., 2017; Slavíková et al., 2021).

Next to vulnerability reduction, a large number of adaptation options focus on reducing exposure to climate change (*high confidence*). Selecting low-risk locations is the most basic example of reducing exposure; for example, private companies are relocating factories to reduce flood-related disruptions to their supply chain (Neise and Revilla Diez, 2019) and species are autonomously adjusting their ranges to a changing climate (see Section 2.4). Land use planning or investing in resilient infrastructure can avoid exposure in rapidly urbanizing areas, however, the design and enforcement of these regulations can negatively impact marginalized people (Anguelovski et al., 2016).

Managed retreat is an example of exposure reduction that, while often controversial, is increasingly being considered and implemented (CCP 2.2.2, Section 15.3.4; Cross-Chapter Box LOSS in this Chapter; Siders et al., 2019). Examples include the US Hazard Mitigation Grant Programme, which, among other activities, has helped people resettle outside of flood zones, and a "no-build zone" established in the Philippines after Typhoon Haiyan (Hino et al., 2017). However, relocation is not always an option; immobility is sometimes involuntary, e.g., in the case of "trapped" populations in Zambia (Nawrotzki and DeWaard, 2018; Section 8.2.1.3).

However, adaptation efforts can have negative impacts on ecosystems and vulnerable groups (*high confidence*); see Table 17.2 and Section 17.5 for further information on maladaptation. While "hard" structural investments have been popular to reduce exposure to climate extremes, barrier-type measures provide protection only up to a certain limit, and are designed to fail in more extreme events. Given the risk of catastrophe from a climate extreme overcoming a physical barrier, policy advancements in recent years encourage any investment in structural measures to be complemented by "softer" vulnerability reduction measures, such as accommodating building construction (Wesselink, 2016).

When it comes to "softer" vulnerability reduction initiatives, these were traditionally seen as "no regrets" options for adaptation. However, subsequent studies have cautioned that notion as vulnerability is a dynamic quality, and can be co-created while development or adaptation efforts are being implemented (Schipper and Pelling, 2006; Tempels and Hartmann, 2014; Dilling et al., 2015). Some scholars have suggested the application of a "do no harm" principle to climate change adaptation efforts (Mayer, 2016).

17.2.1.2 Governance of Adaptation Options

For each adaptation option identified for the RKRs (Table 17.1), this section presents an assessment of how decisions are made and how the adaptations are being governed. The following section then covers benefits to humans and ecosystems, and potential for maladaptation is covered in section 17.5. See SM17.1 for more information on the assessment methods and underlying citations.

The following analysis of adaptation options provides a synthesized overview of adaptation globally, but does not prescribe how important each adaptation should be in specific locations. Chapter 16 finds that the "scope" and "speed" of adaptation is limited in many areas.

When it comes to decision-making, most of these 24 adaptations rely strongly on formal decision-making (*high confidence*), which follows the procedures of a group of people rather than ad-hoc individual action.

Formal decisions play a particularly strong role in the adaptations identified for infrastructure, early warning systems, and water systems (Kolen and Helsloot, 2014; Calvello et al., 2015; Zhao et al., 2017; Belčáková et al., 2019; Teo et al., 2019).

In contrast, informal or individual-led decision-making is more common in several food security-related and livelihood related adaptations, such as changes to diets, livelihood diversification and seasonal migration (*high confidence*) (Li et al., 2017; Radel et al., 2018; Robinson et al., 2020). People who have experienced climate shocks are more likely to take individual decisions to implement adaptation measures, and in countries where people are more exposed to extreme events, autonomous adaptation is more common (Koerth et al., 2017; Aerts et al., 2018b; van Valkengoed and Steg, 2019).

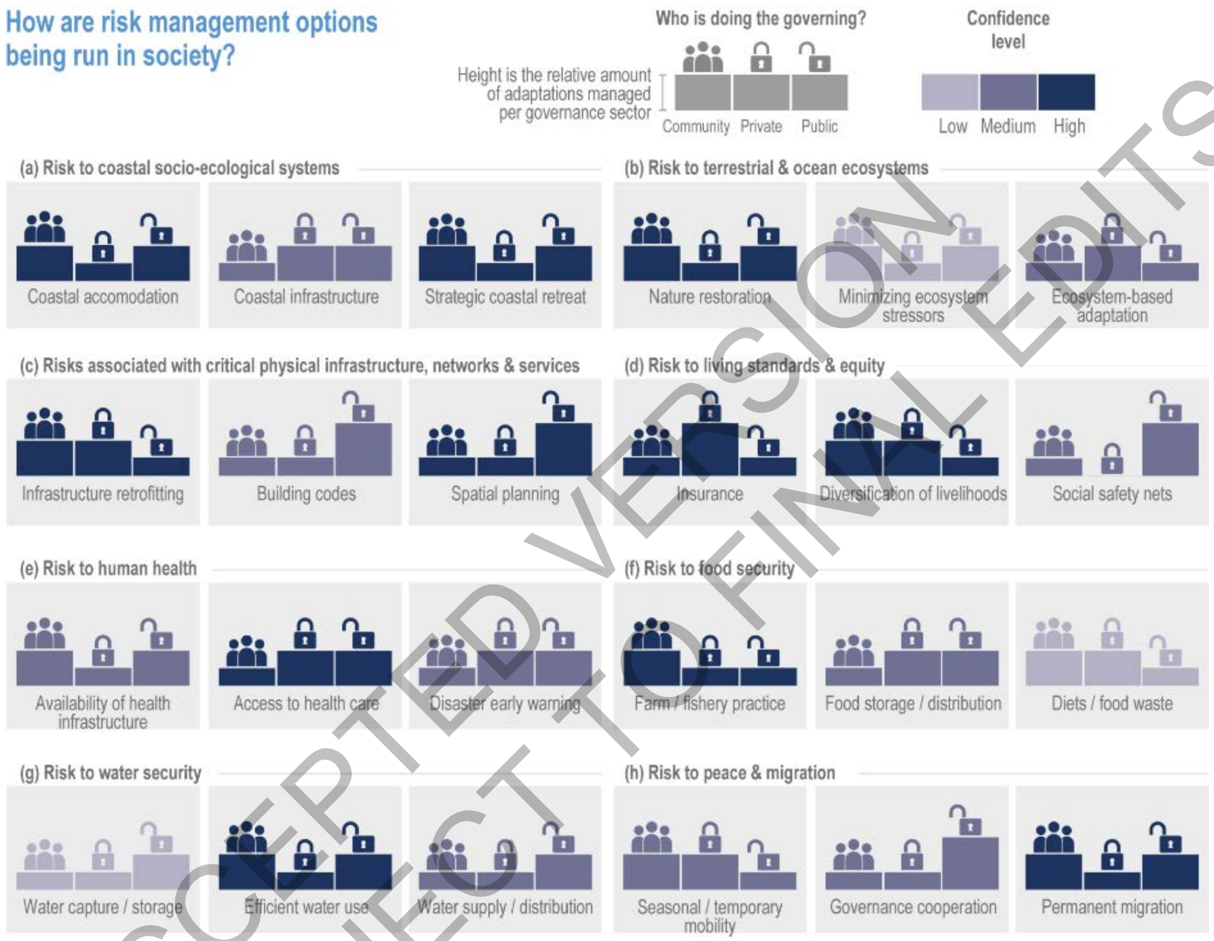


Figure 17.2: Governance of 24 major risk management options, grouped by relevance to the representative key risks. Each option depicts the relative governance roles, between communities/individuals, private sector, and public sector. The intensity of the colour refers to the level of confidence in the assessment.

All adaptation options can occur under a range of governance arrangements (*high confidence*), with cases of either private, public, or community governance typically playing the dominant role, as depicted in Figure 17.2. Public governance is the most frequent governance type for most adaptations considered. This is particularly true for social safety nets and spatial planning, where governments are often required to lead adaptation efforts *(high confidence)* (Mesquita and Bursztyn, 2016; Hssaisoune et al., 2020; Wang et al., 2021). While government actors do the day-to-day management of these systems, civil society and international organizations also play a role in shaping agendas and priorities of government actors (Nagle Alverio et al., 2021).

The private sector plays a large role in governance of insurance, minimizing ecosystem stressors, and livelihood diversification *(medium confidence)* (Allen et al., 2018; Mimet et al., 2020; Alam et al., 2020a). While having a key role in shaping and implementing many other adaptations, the private sector is not often the governing entity.

There are a number of adaptation options that tend to be governed by communities and individuals, including adaptations to farming and fishery practices and ecosystem-based adaptations *(high confidence)* (Reid, 2016; Basupi et al., 2019; Giffin et al., 2020; Karlsson and Mclean, 2020). In rapidly urbanizing areas of Asia and Africa, individual or community-led adaptation is the norm in informal settlements that have poor governance structures. Residents of Mathare slum in Nairobi have established methods to pool risks, such as pooling labour to police looting during flood events and developing community health centres in churches (Thorn et al., 2015). This is in addition to risk reduction measures such as building structures to withstand rising water levels (Thorn et al., 2015). Residents in Bangkok have built walls around settlements, dug informal drainage channels to vacant lots, and filled areas of land (Limthongsakul et al., 2017). In these cases, individual-lead adaptation can have negative side-effects, such as the building of flood defences in affluent communities increasing the flood impacts in less affluent regions of a city (Limthongsakul et al., 2017).

17.2.1.3 Benefit to Humans and Ecosystems

While some of the 24 adaptation options are specific to certain risk contexts (e.g. coastal areas, agricultural production), others are more widely applicable (e.g. early warning systems, health care systems, creation/restoration of natural areas). Figure 17.3 depicts which of these are most context-specific, e.g. benefitting less than 1 billion people. This is contrasted with the extent to which each adaptation option is beneficial to ecosystem services. Many of the more generalizable adaptations have also been shown to have benefits to ecosystem services, such as nature restoration and changes to diets/food waste (*medium confidence*). While health care systems and the establishment of health-related infrastructure can be widely used as adaptation options, their design and application to-date have not generally benefited ecosystems or ecosystem services (*medium evidence, low agreement*).

Table 17.2: Breadth of applicability of each adaptation option benefiting humans, i.e number of people (x axis), estimated by the degree to which each adaptation can be applied across multiple contexts. The benefit of each adaptation option for ecosystems and ecosystem services (y axis). See Annex A for literature underpinning each assessment. This figure uses the 24 representative adaptation options from Table 17.1 and Figure 17.2. Reduce water demand**

Benefit to humans & ecosystems
from representative adaptation options

Confidence level: • Low, •• Medium, ••• High

Breadth of applicability of each adaptation option in its benefit to humans

Benefits of each adaptation option for ecosystems & ecosystem services	Can reduce the exposure or vulnerability **of specific groups of people** i.e. <1 billion people	Can reduce the exposure or vulnerability **of many people** i.e. between 1–5 billion people	Can reduce the exposure or vulnerability **for most people in the world** i.e. >5 billion people
Highly beneficial	- Ecosystem-based adaptation (•••)	- Minimizing ecosystem stressors (••)	- Nature restoration (•••) - Diets/food waste (•••)
Moderately beneficial	- Strategic coastal retreat (•••) - Efficient water use/demand (••) - Seasonal/temporary mobility (••) - Permanent migration (••)	- Diversification of livelihoods (••) - Farm/fishery practice (•••)	- Infrastructure retrofitting (•••) - Building codes (••) - Disaster early warning (•••) - Governance cooperation (••)
No clear & different benefits / harms	- Coastal accommodation (••) - Food storage/distribution (••) - Water supply/distribution (•)	- Social safety nets (•) - Water capture/storage (•)	- Spatial planning (•) - Availability of health infrastructure (••) - Access to health care (••)
Worsens the situation	- Coastal infrastructure (•••)	- Insurance (••)	

As a general method related to adaptive management, "early warnings" are the most frequently discussed adaptation option to deal with a changing climate across all key risks, sectors, and regions. Early warning systems are an adaptation that can benefit more than 5 billion people (*high confidence*). Examples range from short-term disaster early warning systems to revision of sea level rise plans based on monitoring. For example, the humanitarian community is investing in forecast-based financing systems to prepare for extreme events (Coughlan de Perez et al., 2015; MacLeod et al., 2021). Forecasts are also used to manage hydropower dams (Ahmad and Hossain, 2020), to trigger interventions before public health emergencies (Chapter 7.4.2) and to alert fishermen of algal blooms in the world's oceans (Chapter 3.6.2.3.3). Table 17.3 provides examples of adaptations using early warning systems that have been used to address each of the key risks.

In addition to immediate investments that reduce vulnerability and exposure, monitoring and early warning systems allow people to take additional actions when there is an imminent event on the horizon (e.g. temporary evacuation during extreme events rather than permanent migration). This allows for ongoing adaptive decision making (Alessa et al., 2016; Ebi et al., 2016; Barnard et al., 2017; Haasnoot et al., 2018). However, these systems are only cost-effective for forecastable and actionable hazards, and require effective institutional governance (Wilkinson et al., 2018; IPCC, 2019c).

Table 17.3: Examples of adaptation investments and early warning system options for adaptive management for each of the key risks in Chapter 16.

Key risk	Adaptive Early Warning Systems-based measures
Risk to coastal socio-ecological systems	Storm surge early warnings (15.5.7) Early warnings of water-borne disease (Ch 3.6.2.3.3)
Risk to terrestrial and ocean ecosystems	Fishery marine heatwave warnings and mobile fishing equipment (Ch 3.6.2.3, 13) Forecast of shifts and regime changes in ecosystems (Pace et al., 2015; Bauch et al., 2016; Burthe et al., 2016).
Risks associated with critical physical infrastructure, networks, and services	Early warning for infrastructure and services (Ch 13.2.2.1, 10.4.6.4.1)
Risk to living standards and equity	Adaptive social protection systems (Schwan and Yu, 2018; Ulrichs et al., 2019; Daron et al., 2021).
Risk to human health	Heat health early warning systems (Ch 7.4.2.1.2) Health and disease monitoring and outbreak prediction (Ch 7.4.2.1.1, Ch 12.5.6)
Risk to food security	Forecasting rainfall and droughts for seed selection (Ch 10.5.2.2.3), Food price early warnings (Ch 7.4.2.1.3)
Risk to water security	Early warnings for flood and drought (Ch 4.4.1, 10.5.2.2.3, 15.5.7)
Risk to peace and migration	Transboundary flood early warnings (Tuncok, 2015).

17.2.2 Combining Adaptation Options: Portfolios of Risk Management and Risk Governance

While the above assessments underlying Figures 17.2 and 17.3 isolate specific risk management options for specific risks, several adaptation measures are present in any given location, affecting the overall risk of a particular place. Policymakers are charged to evaluate risk comprehensively, deciding on a variety of measures that are effective, feasible, and aligned with other policy goals for a specific place, or implementing a new activity because of how it complements the existing package of risk management activities (Girard et al., 2015).

17.2.2.1 From Risk Prevention to Risk Financing and Risk Retention

Portfolios of adaptation options generally include actions to reduce vulnerability and exposure, complemented by risk financing mechanisms that help people avoid the impacts of loss events, particularly very rare ones. There is also explicit or implicit risk retention, where further risk management is not desirable, cost-effective or feasible (Mechler and Deubelli, 2021). Risk financing can include a variety of instruments, with insurance as the most widely known. Formal insurance uptake is less in developing and emerging economies than in wealthier countries (Ali et al., 2020). To overcome some of the barriers to insurance uptake, index insurance has been offered for agriculture and livestock in many developing economies, with varying levels of success (Chantarat et al., 2013; Isakson, 2015; Dewi et al., 2018). In recent years, regional disaster insurance pools for sovereign states have been established, such as the Caribbean Catastrophe Risk Insurance Facility (CCRIF) (Iyahen and Syroka, 2018). Insurance can encourage the quantitative evaluation of climate-related risks and adaptation limits, and it can incentivize risk reduction by charging lower premiums for less risky situations (Schäfer et al., 2019).

While insurance is increasingly accepted as an adaptation option (Linnerooth-Bayer and Hochrainer-Stigler, 2015), positive outcomes are not guaranteed *(high confidence)*. First, there are concerns as to whether this will shift responsibility to the most vulnerable people to pay premiums (Surminski et al., 2016). There is also high risk for insurance to cause maladaptation (Müller et al., 2017); for example, Annan and Schlenker (2015) showed that insured crops were less well adapted to heat stress. To avoid this, people simultaneously invest in insurance and adaptations that reduce vulnerability/exposure *(medium confidence)* (Surminski et al., 2016; Highfield and Brody, 2017; Schäfer et al., 2019; Reguero et al., 2020).

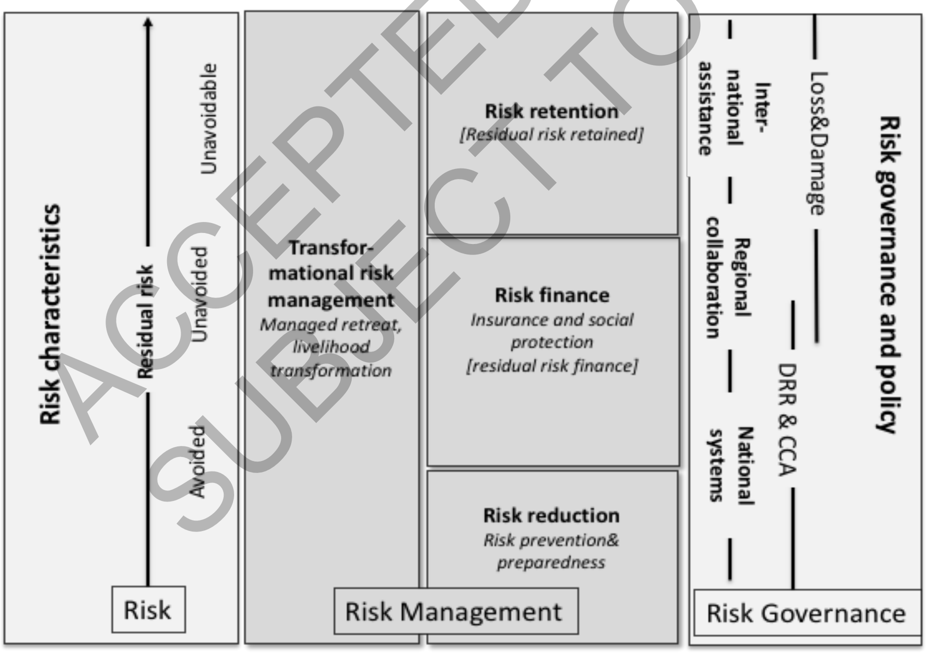


Figure 17.3: A graphical representation of layered risk management. Risks can be reduced or managed by risk finance (insurance and other means), but some residual risk remains, particularly for high impact unavoided and unavoidable risk, which is retained implicitly or explicitly. Where incremental and in situ adaptation is not effective in managing risks, transformational adaptation supports systemic change. Risk management occurs in national systems and regional insurance systems have stimulated regional collaboration. Particularly for high impact risks and impacts in specific events, international assistance is required. Policy domains on Disaster Risk Reduction (DRR) and CCA (Climate adaptation) as well as Loss&Damage overlap in their governance of risk management. Figure building on Mechler et al. (2014); Cummins and Mahul (2009); Lal et al. (2012); Mechler and Deubelli (2021).

The combination of interventions that reduce risk and risk finance for residual risk (often through insurance for sudden-onset events, or social protection for risks including linked to slow-onset processes) will reduce collective risk to a certain level. For very extreme and potentially catastrophic events, it is often impossible (or financially infeasible) to fully reduce vulnerability and exposure, and people, communities and countries therefore retain requiring the ex-post management of unavoided and unavoidable residual impacts in case of events.

Ex-post risk management relies on national assistance, social safety nets (Ch. 7.4.2.1.3; Béné et al., 2012; Elmi and Minja, 2019), and support from social networks as well as lending from international institutions (*high confidence*) (Hochrainer-Stigler et al., 2014). Even in places where normalized losses have stabilized in recent years with investments in adaptation, effective planning to manage losses remains necessary (Jongman, 2018). Resilient recovery can support adaptation goals in periods of loss and damage (Slavíková et al., 2021).

To coordinate between a suite of applicable risk management interventions, the concept of risk layering has been discussed and used in (financial) risk governance for disaster risk management (Mechler et al., 2006; Cummins and Mahul, 2009; Clarke and Mahul, 2011) and climate risk management (Lal et al., 2012; Mechler et al., 2014; Herron et al., 2015; Schäfer et al., 2016; Mechler and Deubelli, 2021). Incremental risk prevention and preparedness as well as risk financing occur within national systems. Over the years, regional cooperation, such as through the regional sovereign insurance pools in the Caribbean, Pacific, Africa, but also transboundary risk management elsewhere have become more important (*medium confidence*) (see Martinez-Diaz et al., 2019). Also, with risks increasingly experienced as severe and existential (Boyd et al., 2017), global governance and solidarity have been invoked (see, Linnerooth-Bayer et al., 2019; Pill, 2021), largely as part of the policy discourse on Loss & Damage (Mechler et al., 2019) with further momentum provided by discussions on the global goal of adaptation and recognition of climate risk as transboundary (Benzie and Persson, 2019; Cross-Chapter Box INTERREG in Chapter 16). Transformational risk management has emerged where incremental and in situ adaptation is not effective in managing risks, such as for managed or strategic retreat for communities facing severe coastal and riverine flooding (Siders et al., 2019). Transformation has not been well documented including as to its governance (see 17.2.2.5).

17.2.2.2 Global Variation in Portfolios of Risk Management

While many studies assess adaptation trends by geographical region or by sector, the amount of residual risk varies across countries with different income and governance structures. Vulnerability, poverty, and inequality, which constitute the human dimensions of climate change, affect how these portfolios of adaptation options are structured around the world (see Chapter 8). Figure 17.4 depicts several illustrative "typologies" of how risk is addressed. While no country or location fits any one typology, this illustrates a range of risk portfolios found in different contexts.

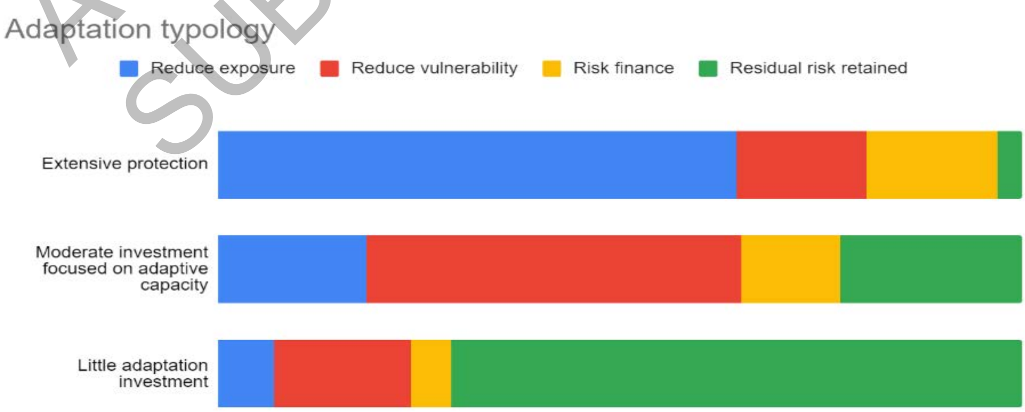


Figure 17.4: Several illustrative typologies for how risk has been managed. The first is "extensive protection", in which the bulk of investments are made in reducing exposure, through protection up to limits (e.g. flood levees) and including

retreat. The second category is "Moderate investment focused on adaptive capacity", in which the bulk of investment is made in reducing vulnerability (e.g. improved housing). The third category is "Little adaptation investment", in which there is little investment in either reducing vulnerability or exposure, and the bulk of risk is residual, borne by the population.

Extensive protection category

The first category in this typology, that of "extensive protection", requires substantial financial investment (Figure 17.4). In higher-income contexts, this is often more feasible than in contexts with limited resources, and adaptation investments are more likely to include structural measures to reduce exposure, complemented by vulnerability-reducing measures and insurance protections (*medium confidence*). While this typology is not universally representative of high-income areas (within or between countries), expensive exposure-reduction measures tend to be easier to implement in high-income countries. For example, flood protection is largest in countries with larger amounts of public spending and least amounts of corruption (Scussolini et al., 2016). It is seen as more economically efficient to invest in expensive protection measures in wealthy regions, under different scenarios of sea level rise and river flooding, although these calculations have equity and justice implications (Peduzzi, 2017; Lincke and Hinkel, 2018). After flood events happen in regions with high levels of protection, damages are comparatively limited, and people tend to continue living in close proximity to the protected river (Mard et al., 2018). In contrast, flood displacement is higher in low-income countries (Kakinuma et al., 2020).

Risk financing, especially insurance, is also common in higher-income countries with well-developed insurance markets and higher levels of insurance penetration than in lower income countries, illustrated by the green bar in Figure 17.4 (*high confidence*) (Linnerooth-Bayer et al., 2019). Of climate-related disasters, floods and storms cause the largest amount of reported economic losses, however, at least 40% of these losses are uninsured, even in the regions with high insurance penetration (Baur et al., 2018). Government involvement in insurance schemes is associated with higher penetration rates of the general population (Paleari, 2019). While some, predominantly high income countries can make use of disaster contingency funds or dedicated budget items, these do not exist or are not well endowed to adequately support relief, recovery and reconstruction (Linnerooth-Bayer and Hochrainer-Stigler, 2015). To help stabilize public finance in regions with little market-based insurance coverage and fiscal response mechanisms, regional public insurance pools have been set up with donor assistance, e.g., in the Caribbean, Africa and the Pacific for flood and droughts (Schäfer et al., 2016; Surminski et al., 2016; Linnerooth-Bayer et al., 2019).

Moderate investment focused on adaptive capacity

In contrast to the "extensive protection" scenario, many regions of the world bear greater resemblance to the second typology in Figure 17.4 "moderate investment focused on adaptive capacity" (*medium confidence*). These contexts see greater adaptation funding invested in capacity building activities to reduce vulnerability, rather than structural or ecosystem-based protection measures to reduce exposure (Biagini et al., 2014). Because of limited international and domestic finance for large structural investments to reduce exposure, the most prevalent adaptation choices in low-income contexts are household-level vulnerability-reducing measures (Koerth et al., 2017).

Lack of access to finance can be one of the reasons countries engage more readily in adaptive capacity-building activities. Countries that rank highly on the Corruption Perceptions Index engage less in technological solutions for risk management (Berrang-Ford et al., 2014). In addition, countries with higher levels of corruption receive less adaptation aid (Betzold and Mohamed, 2017; Weiler et al., 2018). Countries are more likely to receive adaptation aid if they import goods from a donor country, or are a former colony of that donor (Betzold and Mohamed, 2017; Weiler et al., 2018). In countries with poor governance and limited aid flows, remittances make up a substantial portion of finance available to the local population for risk management (Samuwai and Hills, 2018).

Risk financing does play a large role in the "moderate investment" category; there are a variety of instruments in use globally. Many countries in the Global South have created national policies and a number of regional catastrophe risk insurance pools, subsidized by international assistance, which make pay-outs to the national government of affected nations when an extreme event happens and have helped to build risk awareness (Clarke et al., 2015; Thirawat et al., 2017). Beyond this, residual risk is often borne directly by affected people (Andrianarimanana, 2015).

Little adaptation investment typology

In the third typology, there are limited resources for adaptation, and populations bear large amounts of residual risk (depicted by the orange bar in the third typology in Figure 17.4, "little adaptation investment"). Small Island Developing States can often find themselves in this situation, because small populations, small economies, lack of economies of scale, subsistence livelihoods, and other challenges mean risk reduction and risk financing are both costly (see Chapter 15).

Another example of this third typology are people living in conflict-affected areas. These populations are highly vulnerable to the impacts of climate change (Basher, 2006; OCHA, 2011; IPCC, 2012; Zommers and Singh, 2014; Marktanner et al., 2015; Walch, 2018; Eckstein et al., 2019; Peters et al., 2019). In conflict-affected areas similar to the third category of "little adaptation investment", a combination of high vulnerability and relatively few supports for adaptation means that there is a large amount of "residual risk", in which residents cope with the impacts of extreme events on a regular basis (*high confidence*). For example, deaths from "natural" disasters are 40% higher in areas that are undergoing armed conflict (Marktanner et al., 2015) (see Box 17.2).

[START BOX 17.2 HERE]

Box 17.2: Climate Risk Management in Conflict-affected Areas

Consequences of conflict that exacerbate vulnerability to climate change include: displacement, loss of access to employment leading to illegal livelihoods, gender-based violence, lack of land tenure, low literacy, poor access to social and health services, destruction, looting and theft of key assets, such as houses, food stocks and livestock, among others (Jaspars and Maxwell, 2009; Chandra et al., 2017; Anguita Olmedo and González Gómez del Miño, 2019). Such impacts perpetuate cycles of poverty (World Bank, 2013), making conflict-affected populations more susceptible to suffer from climate related events (Basher, 2006; Coughlan de Perez et al., 2019). For example, in Mindanao, Philippines, poverty is closely linked to long-standing armed conflicts; both climate change and conflict have significantly increased smallholder vulnerability, resulting in loss of livelihoods, financial assets, agricultural yield and the worsening of debt problems (Chandra et al., 2017). In Colombia, displacement induced by conflict has pushed the population to live in high-risk areas such as steep slopes susceptible to landslides and river banks exposed to flooding (Albuja and Adarve, 2011). This conflict-induced vulnerability, with little adaptation activity, has in turn resulted in climate-related disasters (Kuipers, 2019; Siddiqi et al., 2019).

Conflict can also limit the effectiveness of adaptation measures that do exist; a study across Africa, the Caribbean, and Asia concluded that poor governance can limit the effectiveness of early warning systems in these regions (Lumbroso et al., 2016). Poor state services have health consequences and can limit social support networks (Peters, 2018). States are unable (even if they are willing) to assist or protect citizens in disasters. Non-governmental stakeholders play a large role in these contexts, but questions of long-term implications and accountability remain unaddressed (Peters, 2018).

Climate risk management and adaptation in conflict-affected contexts is challenging, first, given the complex and dynamic nature of vulnerability (Hilhorst, 2003; Frerks et al., 2004) and second given factors such as weak or nonexistence disaster risk governance, restricted access, human rights violations, power dynamics between parties in conflict, and environmental degradation, among others (Kloos et al., 2013; Marktanner et al., 2015; ICRC, 2016; Quinn et al., 2017; Field and Kelman, 2018; Siddiqi, 2018). Climate can also be a contributing factor to conflict (Mach et al., 2019). There is little peer-reviewed documentation available on adaptation in climate-affected contexts, and what exists is narrowly focused on agriculture at the expense of other sectors, such as cities, infrastructure, and humanitarian operations (Sitati et al., Accepted).

To address risks to livelihoods, conflict-sensitive livelihood programming has used vouchers to meet immediate needs, legal support to resolve land disputes, and disaster preparedness planning to identify safe places for displacement (Jaspars and Maxwell, 2009). For example, cooperation in the Philippines between

Moro Islamic Liberation Front and United Nations agencies included training of farmers in disaster risk reduction, drought management, and production of improved crop varieties to support a transition away from subsistence farming (Walch, 2018). In Mali, negotiations on fertilizer access and safe transport to agricultural lands were brokered by the International Committee of the Red Cross, and in Afghanistan, conflict-sensitive approaches have promoted ecosystem-based adaptation to support reforestation (Walch, 2018; Mena and Hilhorst, 2020). Despite several examples of conflict-sensitive adaptation practices, little is known about the effectiveness of such efforts in reducing climate risks in these complex contexts (see Section 17.5 for further discussion of "effectiveness").

[END BOX 17.2 HERE]

17.2.2.3 Adaptation Beyond Risk: Exploiting Opportunities

Several studies and many government planning documents reference how people can benefit from a changed climate, beyond reducing risks. For example, several regions are expecting an increase in visitors to eco-tourism sites or national parks with a changing climate (Fisichelli NA, 2015; Lwasa, 2015). In Europe, several national adaptation plans include planning for potential benefits of a changing climate, including reduced winter mortality and improved conditions for hydropower (Biesbroek et al., 2010). Recognizing the need for economic diversification, people working in certain industries, such as coastal management, perceive climate change as a factor increasing the need for their services (Fatorić et al., 2017). Northern countries are taking advantage of ice-free waters for shipping routes in the Arctic (Eguiluz et al., 2016; Melia et al., 2016; IPCC, 2019e-a). In Africa, opportunistic adaptation has been observed by smallholder farmers, who plant crops that are better suited for a changing climate (Lalou et al., 2019). Similar agricultural adaptation in Pakistan has been associated with improved food security and reduced poverty (Ali and Erenstein, 2017; Rahman et al., 2020). In each of these cases documenting benefits, there are also potential negative impacts on other populations or ecosystems, such as ecosystem impacts from increased Arctic shipping (Ng et al., 2018).

While adaptation is rarely focused on taking advantage of opportunities presented by a changed climate, there are numerous co-benefits of adaptation opportunities, from health to reduced emissions to ecosystem services (*high confidence*) (Watts et al., 2015; Geneletti and Zardo, 2016; Spencer et al., 2016). There is also literature proposing that the actual process of adaptation planning can enable people to take advantage of opportunities, including, e.g., opportunities for larger policy and governance reform (Coleman and Sandhu, 1965; Ernst and Preston, 2017; Brown et al., 2017a).

17.2.2.4 The Spectrum from Incremental to Transformational Adaptation [Or Maybe Measures] in Risk Management Portfolios

Chapter 1.4.5 noted that transformational adaptation is increasingly being considered necessary to allow a system to extend beyond its (soft) limits as incremental adaptation cannot guarantee to avoid intolerable risks. Chapter 16.4 presents evidence on RKRs where a need for transformational adaptation and climate risk management has been identified in order to further reduce climate risks and avoid breaching adaptation limits. The following section identifies how the 24 adaptation options representative of the RKRs may support incremental and transformational risk management/adaptation that can lead to small, medium, and large systemic change, often as part of portfolios of options. This subsection further discusses the role of transformational adaptation vis a vis incremental adaptation by reviewing evidence across chapters (see also Box 17.3). The Cross Chapter Box on Loss and Damage further expands on the international debate regarding the role of decision-making on incremental and transformational adaptation for dealing with residual risks to address soft as well as hard adaptation limits (see Cross-Chapter Box LOSS in this Chapter).

As the literature distinguishes active transformation to shape future risks from passive and unintended transformation (Lonsdale et al., 2015; Chapter 1), the section queries how to inspire actors to consider how to develop or implement transformational adaptation to complement incremental adaptation/risk management when and where appropriate.

In contrast to a broadening literature on conceptualization and policy proposal, there has been little evidence reported in the literature of transformational adaptation and risk management at scale of implementation (*high confidence*) (Klein et al., 2017; Ajibade and Egge, 2019; Tàbara et al., 2019; Mechler and Deubelli, 2021). Deubelli and Venkateswaran (2021) review evidence on largely NGO -implemented community-level adaptation for floods, heat and drought across the globe. They suggest that transformational adaptation success, while multi-facetted and challenging, depends on the availability of appropriate enabling environments including experiential and niche learning, alignment of transformational change objectives with strategic (government or other actor's) priorities, strong bottom-up governance grounded in local contexts, phased long-term program support and appropriate financing.

In order to distinguish incremental from transformational adaptation, Lonsdale et al. (2015), building on Mustelin and Handmer (2013), identify criteria related to framing, learning and decision-making, space and time, power, and type of change management. Tàbara et al. (2019), additionally, discuss transformation in light of informing climate pathways, strategies and solutions. Broadly considering these criteria, they identify twelve dimensions with additional discussion of change with regard to systems and dynamics, options and solutions, agency, and the consideration of equity (see also Chapters 1, 6, 18 for more discussion). In particular, the following key aspects for understanding the spectrum from incremental to transformational adaptation are of relevance: change - within or across the system; agency-single or heterogenous, a role for visioning and normative futures, the type of learning required (from first order, business-as-usual, to second order), as well as how equity and distributional issues are explicit.

Applying these key aspects to the list of 24 adaptation options from Table 17.1, certain options are assessed to be more transformational, often requiring large system changes that go beyond addressing individual risks. Adaptations that are more transformative offer potential to lead to systemic change. Less transformative adaptations allow people to address specific climate-related risks while maintaining existing systems (See SM17.1 for more details; see also Box 17.3).

For example, several adaptations related to the RKR on risks to peace and migration, namely permanent migration, and cooperative governance, require moderate to high levels of transformation (*high confidence*). Some behavioural adaptations, such as changing diets and reducing food waste, can also require large transformations in land use and food culture (*medium confidence*). Spatial planning, including urban zoning, also tends to be more transformative (*medium confidence*).

On the other end of the spectrum, disaster early warning systems tend to be incremental rather than transformational (*high confidence*), because they enable people to maintain/protect existing systems. Several other adaptations allow people to maintain livelihoods and systems in the face of changing risks. For example, improvements in agricultural and fishing practices can be done with moderate transformation to systems (*medium confidence*). Similarly, insurance tends to require less transformation, as it can allow people to maintain existing systems while being more resilient to climate-related shocks (*medium confidence*).

None of the 24 adaptation options are consistently beneficial for vulnerable and marginalized groups (*high confidence*). For each adaptation, there are examples of how it has been implemented in a way that benefits poor, low-income, ethnic groups and/ or females, and other examples of implementation in different contexts that have worsened the risks for those groups specifically. For example, while the goal of cooperative governance can be to support the marginalized, these same marginalised groups are usually excluded from participating in the design of the solutions, and many articles criticise governance results as protecting only the interests of the wealthier and more powerful parties in the negotiations, especially in governance of migration (Groutsis et al., 2015; Pijnenburg et al., 2018). This reinforces the need for context-specific planning to ensure marginalized groups will benefit from an adaptation plan. See Table 17.4 for examples of how each adaptation option can have or not have equity benefits.

Table 17.4: The 24 adaptation options from Table 17.1 grouped and coloured by their potential for transformation. (See Appendix A for assessment methodology.) Adaptations in red tend to require small amounts of transformation, adaptations in orange tend to require middling levels of transformation, and adaptations in yellow tend to require large levels of transformation, or systemic change. Each option is paired with examples of how that adaptation can be done in a way that does not benefit, or worsens the situation for marginalized groups, as well as an example in which that

adaptation has benefitted those groups. Examples of equity focus on benefits to poor, low-income, ethnic groups, or females.
** low confidence, ** medium confidence, *** high confidence*

Adaptation	Example of the adaptation excluding or worsening the situation for marginalized groups	Example of the adaptation benefitting marginalized groups
Less transformation (small systemic change)		
Insurance**	Index-based insurance policies in Mongolia were accessible primarily to wealthy herders (Taylor, 2016b).	The availability of capital after disaster events can avoid a poverty trap from disasters (Alam et al., 2020a).
Coastal accommodation***	Accommodation strategies in Jakarta have led to a false sense of security in an impoverished and vulnerable neighbourhood (Esteban et al., 2017).	The mosaic restoration project provided training for women to support local accommodation of climate changes on Yap (Krishnapillai, 2018).
Early warning systems***	People of higher socio-economic status tend to receive warnings, while marginalized groups can be left out (Baudoin et al., 2016).	Famine and drought early warning systems have helped avoid starvation among the world's most vulnerable people (Funk et al., 2019).
Water use/demand***	Small farmers were unable to access supports to implement drip irrigation in Morocco, and uptake was greater among wealthy farmers (Jobbins et al., 2015).	Retrofits for water use efficiency were made available free of charge to low-income communities in the US (Lee and Tansel, 2013).
Coastal hard protection**	Construction of hard barriers increased flood risk for several low-income communities in Bangladesh (Adnan et al., 2020).	Successful coastal embankments can help people avoid poverty traps in Bangladesh by reducing exposure to flood events (Borgomeo et al., 2017).
Moderate transformation (medium systemic change)		
Infrastructure retrofitting**	Low-income people often do not own their homes, and there are few incentives for landlords to upgrade (Tardy and Lee, 2019).	Energy policy could promote solar infrastructure in Nigeria, which can offer electrification in underserved regions (Ohunakin et al., 2014).
Building codes***	Building codes in Nepal and Bangladesh often fail to increase resilience because many buildings are built informally (Ahmed et al., 2019).	Slum upgrading projects in Latin America reduced the vulnerability of informal settlements by improving built infrastructure (Núñez Collado and Wang, 2020).
Farm/fishery practice**	Many agriculture improvement strategies create higher workloads for women and do not directly enfranchise them, as seen in Uganda, Ghana, and Bangladesh (Jost et al., 2015).	Improved crop varieties have supported the income of low-income farmers in Zambia (Khonje et al., 2015).
Diversification of livelihoods*	Diversifying livelihoods can increase women's workloads, in a review of semi-arid	A study on diversity of income sources in Ghana indicated that diversification can

	regions across Africa and Asia (Rao et al., 2020).	make people less vulnerable to extreme events (Baffoe and Matsuda, 2017).
Social safety nets**	Social protection systems in Bangladesh focus on specific groups in rural areas, and they often fail to reach urban poor and other very disadvantaged people (Coirolo et al., 2013).	Adaptive social protection can help poor people avoid the impact of extreme events by scaling up support at critical moments (Bowen et al., 2020).
Infrastructure for health***	The development of sanitary water infrastructure in Germany had less benefit in areas with higher income inequality (Gallardo-Albarrán, 2020).	Improvements to water and sanitation infrastructure that avoid people fetching water is associated with improvements to women's health (Geere and Hunter, 2020).
Food storage/distribution**	Increasing/improving livestock markets can favour high-income livestock producers (Gautier et al., 2016).	Investments in large produce storage houses has supported indigenous livelihoods in the face of climate change (Mugambiwa, 2018).
Restoration/creation of natural areas**	Urban greening programmes in the US avoided minority neighbourhoods or caused displacement of people of colour (Anguelovski et al., 2016; Watkins et al., 2016).	Afforestation reduced landslide risk for informal settlements in Brazil (Sandholz et al., 2018).
Minimizing ecosystem stressors*	Fish quota reduction had negative economic impacts when done quickly (Barbeaux et al., 2020).	South Africa's Working for Water programme employed poor people to control invasive species (van Wilgen and Wannenburgh, 2016).
Ecosystem-based adaptation**	Payments to indigenous groups in return for protecting conservation land can be less than their original livelihoods and disadvantage those not receiving the payments, such as women (Bedelian and Ogutu, 2017).	Integrated water resource management is proposed in the Caribbean as a way to maintain ecosystem services while improving economic welfare (Mycoo, 2017).
Water supply/distribution**	Water tariffs during the Cape Town drought negatively impacted poor households (Millington and Scheba, 2021).	City Water Forums in Nepal have focused on equitable water allocation as an adaptation (Pandey and Bajracharya, 2017).
Seasonal/temporary mobility**	Women tend to have greater restrictions on mobility than men (Lama, 2018).	Indigenous communities in Guatemala use temporary migration to manage rainfall variability (Ruano and Milan, 2014).
Most transformation (largest systemic changes needed)		
Spatial planning**	Spatial planning in American cities has often resulted in less green space in ethnic minority neighbourhoods (Connolly and Anguelovski, 2021)	While difficult, strategic approaches to urban planning can promote inclusive development (Chu et al., 2017).
Diets/food waste*	Low-income groups have less opportunity to diversify diets if certain foods become more expensive or difficult to obtain (Reynolds et al., 2019).	Changing dietary intake during heatwaves (e.g. eating cooler foods) is seen as a low-cost adaptation accessible to low-income people in the UK (Porter et al., 2014).
Health care systems**	Facilities in poor communities are often poorly sited and can lack capacity to support	Universal health coverage can be highly beneficial to poor people (Atun et al., 2015),

	people during climate-related extreme events (Codjoe et al., 2020).	when needed for climate-related health outcomes.
Water capture/storage**	Many indignous populations have been negatively affected by loss of their land when displaced for dam construction (Siciliano and Urban, 2017).	Improving water harvesting supports marginalized populations in dryland areas (Bobadoye et al., 2016).
Cooperative governance**	International cooperation among national governments regarding migration can encourage human rights abuses and increase migration (Crawley and Skleparis, 2018).	International cooperation has the potential to remove barriers to adaptation in informal settlements in developing countries by sharing knowledge and expectations (Oberlack and Eisenack, 2014).
Permanent migration***	Permanent migration from small island nations can entail a loss of identity for indigenous groups (Bordner et al., 2020).	Migration supported by social protection systems can be sustainable for poor populations (Schwan and Yu, 2018).
Strategic coastal retreat***	Muslim people faced tensions with host communities when relocated in India, and faced difficulties in terms of fishing access and land size (Mortreux et al., 2018).	In several cases of post-disaster relocation, community members initiated the retreat and there were broader benefits to society (Hino et al., 2017).

17.2.2.5 Incremental and Transformational Adaptation for Managing Risk in the Context of Adaptation Limits

With evidence on soft and hard limits being experienced in natural and human systems including in terrestrial, aquatic and marine ecosystems, coastal and island systems, agriculture, health systems, urban spaces and tourism (Table 16.5, 16.4.2, *medium confidence*) transformation is also being considered to expand the adaptation space beyond soft limits and before hard limits are being reached. As a key area of advancement since AR5, this section assesses the relationship of residual risks, limits and incremental as well transformational adaptation integrating the assessment of limits in 16.4 with ch.17 adaptation and risk management assessment along a spectrum of adaptation change. 17.2.2.5 thus contributes to understanding in which systems and regions transformational adaptation is increasingly required and considered once incremental adjustments are exhausted in the context of soft and hard limits.

Assessing risk and limits requires in-depth analysis of the adaptability of human and natural systems under different warming and risk levels, also considering socio-economic exposure and vulnerability drivers, informed by perspectives on what breaching limits means, especially if significant change and losses and damages may occur (see 16.4, 8.4). Assessments differ between natural systems (where adaptation potential is often very limited; Klein et al., 2014) and human systems where incremental and transformational adaptation can help to extend soft limits so that hard limits are not met or to buy time until hard limits are reached with higher levels of warming.

The assessment synthesises global and regional evidence across regional and thematic report chapters along a continuum from observed to projected impacts and risks, the spectrum of incremental and transformational adaptation, and finally any evidence on soft and hard limits. We present regional evidence for two types of salient natural and human systems and Representative Key Risks: RKR-B (risk to terrestrial and ocean ecosystems), where we assess risks from marine heatwaves to coral reefs; and RKR- E (risk of heat on human health as a human system). Both RKRs and systems are facing substantial (residual) risk, characterised by adaptation limits and share heatwaves as the hazard, for which climate change has been considered the major driver of increasing intensity and frequency (*high confidence*)(IPCC, 2021). The assessment synthesises evidence on transformation as reported in the chapters as well as categorizes identified adaptation options along an adaptation spectrum according to the criteria discussed in 17.2.2.4, specifically whether adaptation leads to systems' change or only change within a system, is driven by multi-scale agency and considers equity impacts specifically.

Figure 17.5 organises global and regional findings for observed and projected health risks from heat (RKR-E) from chapters across the report and organizes options according to findings on the potential for transformational change as presented in17.2 and table 17.4. The discussion shows that heat has become a significant health risk globally, incurring severe mortality and morbidity in all world regions with annual heat related deaths estimated around ~300 000 with millions affected (*high confidence*) (9.3.1). Evidence shows that adaptation and risk management, can be effective in reducing (relative) risks in developed countries, with inconclusive evidence in low-middle incomes states (9.2.4.1, 13.7.3, 13.6). In absolute terms, risk in terms of heat-related mortality and morbidity is projected to increase under medium and high heating scenarios in many regions, even with implemented adaptation. By 2050 (compared to 1961-1991 and for a mid-range emissions scenario), an excess of 94,000 deaths per year is projected globally as attributable to climate change (9.3.1).

Planned and implemented adaptation interventions in all regions have remained largely incremental, while uptake is being intensified in some regions; options have included air conditioning (as autonomously deployed), public cooling spaces, heat action plans that incorporate early warning and response and heat-adapted building design (9.9.5, 11.3.6, 12.5.6.1.1,13.11.3, 13.11.3, 15.6.2).

Given increasing risks projected and already reported soft and hard limits, transformation is being considered as a complement potentially leading to systemic and transformational change. Adaptation, if upgraded to also consider transformational interventions, will thus help to reduce heat risks (medium-high confidence, limited evidence) albeit with reduced effectiveness at higher levels of warming, particularly in regions (Africa, Asia) where lethal heat waves are projected to occur almost annually towards later in the 21st (*medium confidence*) (9.1, 10.4.7).

This may involve urban redesign using nature-based solutions (such as green roofs and infrastructure) as well as rescheduling of outdoor labour or cross-sectorial coordination. Integrated approaches across interdependent systems (e.g. ecosystem- based approaches and climate-sensitive urban design) are being proposed. Also, it may mean bolstering social safety nets and health systems that better attend to heat impacts by providing universal coverage. Societal and political transformations to reduce climate change risks for vulnerable groups are considered particularly relevant in some regions (9.4.2.1.2, 9.9.5, 10.4.6.4.3, 12.5.3.2, 13.6.2.1, 14.6). Yet, across all regions there is limited evidence on proposed transformational adaptation and very little evidence regarding implementation (*high confidence*).

As a consequence, studies project soft limits to be further reached as increased mortality and morbidity will add stress to health systems, and labour productivity will be severely hampered impacting economic systems (*medium to high confidence*) at medium to higher levels of global warming (7.2.4.1, 9.10, 10.4.4.4, 11.9.1, 13.6.2.3, 13.7.2, 13.7.4, 13.10.2.1, 13.8, 15.3.4.9).

Hard limits may be breached in some regions where critical heat tolerance thresholds are projected to be surpassed at medium to higher levels of global warming, such as physiological survivability thresholds, which, e.g., may render urban outdoor labour in Asia, Africa and North America infeasible (10.4.6.3.2, 14.8, Box 9.1).

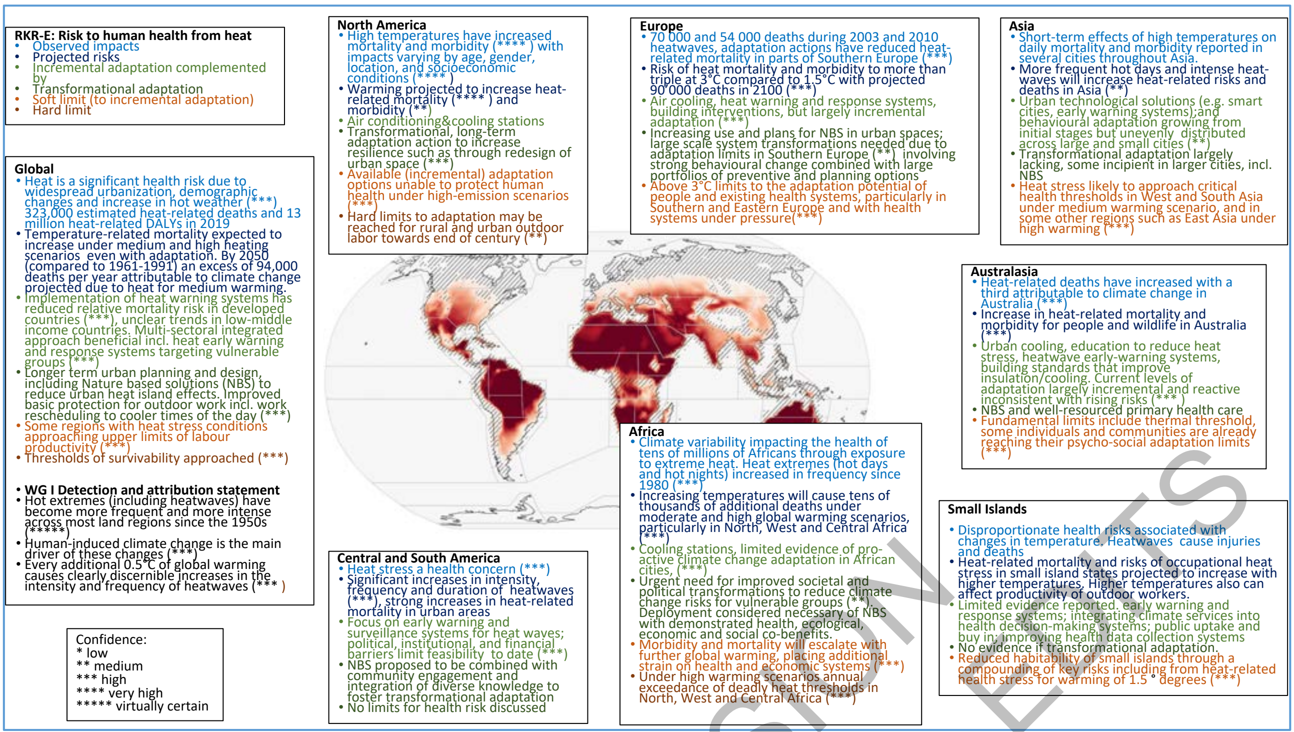


Figure 17.5: Understanding the spectrum of incremental to transformational planned adaptation for managing climate related heat risk to health including associated soft and hard adaptation limits (RKR-E). Evidence from regional and thematic chapters. The figure from the WG I Atlas shows the change in extreme hot days (above 35ºC) across regions for a medium-term scenario and medium global warming relative to 1850-1900. See table SI 17.2.2.5 RKR E.

Marine heatwaves have affected tropical coral reefs, which are analysed as part of RKR-B (see SM17.4). Coral reefs across the tropic have recently seen massive bleaching events (such as for the Great Barrier reefs) (*very high confidence*) Risks are projected to be further exacerbated by increases in intensity, frequency and duration of marine heatwaves (*high confidence*) as well as impacts from extreme events such as tropical cyclones (*low to medium confidence*) (3.4.2).

Although there is some evidence of autonomous natural thermal adaptation, as indicated by the presence of stress tolerant symbionts adapted to higher thermal thresholds observed in the Persian/Arabian Gulf. Yet, there is low confidence (with limited evidence, low agreement) that enhanced thermal tolerance can be maintained over time (Ch.3 Box 5) as the adaptability in natural system is considered very limited and risk are driven by water temperature. Evidence suggests that already at further warming of 1.5C coral reefs are put at large risk (*very high confidence*) (3.4.2.1).

Planned adaptation can help to buy some limited time including through recovery and restoration efforts that target resistant coral populations and interventions to culture heat-tolerant algal symbionts as well as by setting up marine protected areas. Under higher warming levels, transformation has been proposed as possibly complementing available management approaches with high-risk interventions, including enhanced corals and reef shading, which may help to sustain some coral reef systems beyond 1.5°C of global warming. Modelling has shown, however, that the effectiveness of such high-risk interventions declines beyond 2°C of global warming (Figure 3.23, 3.4.2.1) (*medium confidence*).

Already for limited warming beyond 1.5°C for mid-century with increasing intensity and frequency of marine heatwaves hard limits are projected to become manifest in terms of widespread decline and loss of structural integrity (*very high confidence*) (3.4.2.1), including for the two largest such systems, the Great Barrier Reef and the Mesoamerican coral reef (11.3.2, Box 11.2, Table 11.14, 12.4).

In terms of planned adaptation options that would provide benefits to populations, evidence suggest these are very limited, uncertain and bring along substantial risks to people, culture and ecosystems (3.5.2. Cross-Chapter Box SLR). Concurrent with the loss of coral reefs important ecosystem services, including to fishery, tourism and coastal protection would be lost. Transformational adaptation, while requiring to make difficult choices, is being discussed to help overcome soft limits through livelihood diversification for alternative income sources, assisted migration and planned relocation of communities dependent on the services provided by the reef ecosystem (*medium confidence*) (3.5.2).

[START CROSS-CHAPTER BOX LOSS HERE]

Cross-Chapter Box LOSS: Loss and Damage

Authors: Reinhard Mechler (17), Adelle Thomas (16), Christian Huggel [MR1] (12), Emily Boyd (8), Veruska Muccione (13), Ivo Wallimann-Helmer (CA), Laurens Bouwer (CA), Sirkku Juhola (CA), Chandni Singh (10), Carolina Adler (17), Kris Ebi (7), Patricia Pinho (8), Rawshan Ara Begum (1), Adugna Woyessa (9), Johanna Nalau (15), Katja Frieler (16), Richard Jones (WG I), Riyanti Djalante (8), Rosa Perez (18), Tabea Lissner (4), Anita Wreford (11), Mark Pelling (6), Francois Gemenne (8), Nick Simpson (9), Doreen Stabinsky (WG III)

An intensifying dialogue

This Cross-Chapter Box offers an assessment of the growing literature on Loss & Damage. Capitalised letter ‘Loss and Damage’ (L&D) has been used to refer to political negotiation under the UNFCCC. Research has used lowercase ‘losses and damages’ for residual effects from (observed) impacts and (projected) risks (see Glossary).

Dialogue around L&D issues started with a proposal for insurance and compensation by the Alliance of Small Island States (AOSIS) (INC, 1991) and has intensified over recent years with suggestions made to consider complements to adaptation in order to manage residual impacts and risks ‘beyond adaptation’ in vulnerable developing countries (1.4.5). L&D was formally recognized in 2013 at COP19 through the *Warsaw International Mechanism on Loss and Damage* (UNFCCC, 2013), governed by an Executive Committee (ExCom), to advance knowledge, foster dialogue as well as enhance action and support. Article 8 of the Paris Agreement provided a permanent legal basis for the WIM (UN, 2015).

IPCC’s first assessment of L&D in 2018 found residual risks to rise with further global warming leading to soft and hard adaptation limits in some natural and human systems (e.g., coral reefs, human health, coastal livelihoods (Roy et al., 2018). Sections 8.4.5.6, 16.4 and 17.2 corroborate these findings concluding that, depending on mitigation and adaptation pathways residual risks in key systems in many regions will create potential for negative impacts beyond adaptation limits (*medium confidence*). The assessment in 2018 also noted that there is “not one definition of L&D.” This ambiguity has persisted and a policy space for L&D has not clearly been delimited (*high confidence*). There is, however, coalescence in dialogue among academia, civil society and policy around a distinct set of themes as identified by stakeholder surveys as well as literature, methods and evidence reviews (Vanhala and Hestbaek, 2016; Boyd et al., 2017; Mechler et al., 2018; Calliari, 2019; McNamara and Jackson, 2019): risk management, limits to adaptation, existential risk, finance and support including liability, compensation and litigation (8.3, 16.4; *medium confidence;* Figure Cross-Chapter Box LOSS.1). Various advisory groups have been set up with participation of policy and experts from research, civil society and practice to help inform the implementation of WIM workplans (UN, 2015; UN, 2019).

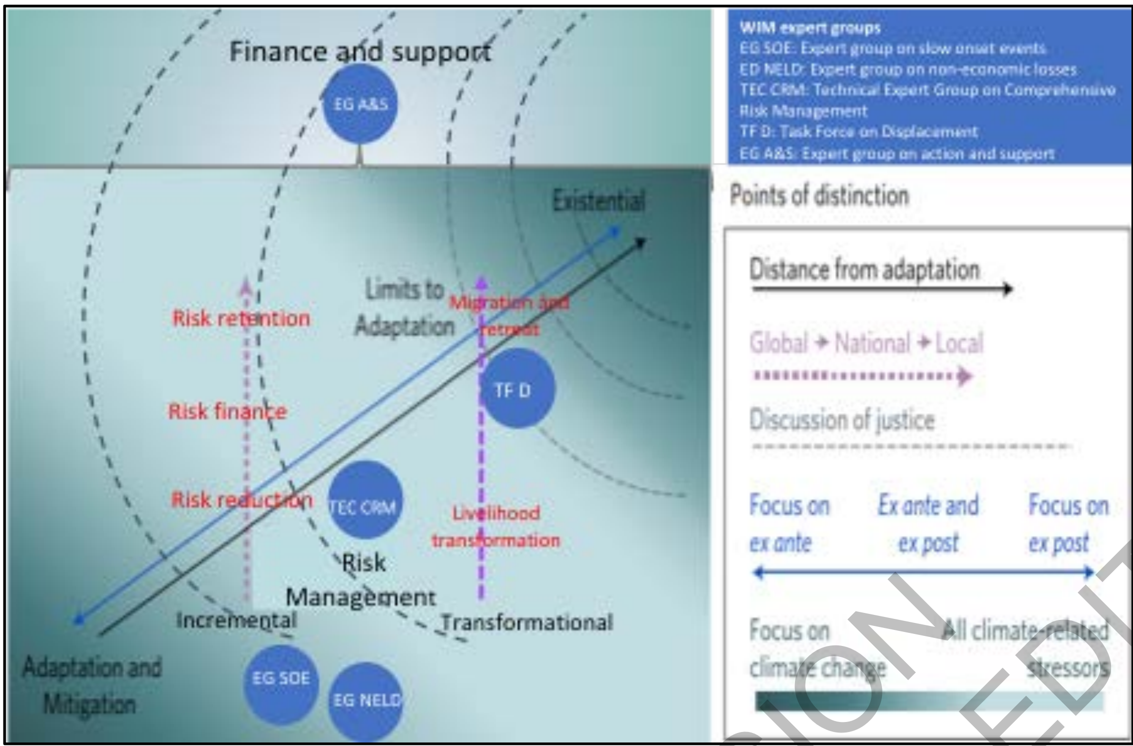


Figure Box Cross-Chapter Box LOSS.1: Charting out the L&D discursive and policy space. The figure shows key discursive strands relevant for L&D including their interrelationships with and distinction from adaptation. The figure also identifies expert groups set up under the WIM and showcases the scale of responses discussed, a focus on ex ante risk management and ex post attention to losses and damages as well as contributions by climate change and other stresses for the themes. Adapted from Boyd et al. (2017) and building on Vanhala and Hestbaek (2016), Mechler et al. (2018), McNamara and Jackson (2019), and Calliari (2019).

Risk management

An increasing body of research has focussed on the role of climate risk management (8.3; 16.4 and 17.2; *high confidence*) (Birkmann and Welle, 2015; Gall, 2015; van der Geest and Warner, 2015; Mechler and Schinko, 2016; Boyd et al., 2017; IPCC, 2018b; IPCC, 2019b; Boda et al., 2020; Broberg and Romera, 2020). A technical advisory group on comprehensive risk management (TEG CRM) advises the WIM ExCom while other expert groups focus on slow-onset events and non-economic L&D (UNFCCC, 2019a).

There is evidence that, without strong risk management and adaptation, losses and damages will continue to affect the poorest vulnerable populations potentially creating poverty traps (*high confidence*) (8.3; 8.4.5.6 and Table 8.7; 17.2; Serdeczny, 2019; Tschakert et al., 2019; Thomas et al., 2020). Research has started to develop global inventories on losses and damages including on intangible effects (Tschakert et al., 2019; Otto et al., 2020) and engaged with the practice community for data collection. Practice has provided guidance to report on losses and damages in countries' (I)NDCs (WWF & Practical Action, 2020). Yet, systematic risk assessments of climate-related losses and damages including adaptation limits (see, e.g. Leal Filho and Nalau, 2018; Robinson, 2018) have remained scarce (16.4; *high confidence*). Thus many vulnerable countries lack comprehensive data at scale of risk management including on economic (e.g. loss of livelihood assets and infrastructure), and non-economic losses and damages (e.g. culture, health, biodiversity) thus hampering effective risk management (Thomas and Benjamin, 2018; Martyr-Koller et al., 2021; Singh et al. 2021). van den Homberg and McQuistan (2019) propose a losses and damages inventory also to be used to monitor how technologies may shape risks as well as adaptation limits. While early warning and other risk reduction options as well as risk retention considerations are being discussed, L&D dialogue has strongly focussed on risk finance for residual risks, particularly through the donor-supported provision of public insurance systems (Linnerooth-Bayer et al., 2019; Schäfer et al., 2019; Broberg and Romera, 2020; Nordlander et al., 2020).

Transformation

The role of transformation in risk management for overcoming any soft limits to adaptation is seeing emerging attention (*medium confidence*, *limited evidence*), and the TEG CRM has also been tasked to consider transformation. Relocation and retreat of assets and communities, where *in situ* adaptation is considered impossible, is increasingly being debated in research and practice, including in terms of finance and L&D implications (8.4.4; Boston et al., 2021; Desai et al., 2021; Mach and Siders, 2021; van der Geest and van den Berg, 2021; Zickgraf, 2021). Livelihood transformation occurs where current livelihoods become unfeasible in the face of multiple climatic and non-climatic stressors (8.3.4.1) requiring change within sectors (such as switching from cropping to livestock rearing (Escarcha et al., 2020) or across sectors, when farming households relocate to offer labour elsewhere (9.1; Rasel et al., 2013). Biermann and Boas (2017) suggest revamping global governance systems to effectively address the protection and voluntary resettlement of those displaced by climate variability and change. A WIM taskforce on displacement is tasked to further advise on human mobility, including migration, displacement and planned relocation (UNFCCC, 2019a).

The *existential dimension*

There has been less and often implicit discussion on the existential dimension of climate-related risk as pertaining to L&D (*medium confidence*).McNamara and Jackson (2019) infer an existential dimension from notions of inevitability and irreversibility associated with migration and relocation of communities (Eckersley, 2015; Mayer, 2017; McNamara et al., 2018), socio-cultural impacts linked to glacial retreat (Jurt et al., 2015), as well as adverse psychological and intersubjective effects (Herington, 2017; Adams et al., 2021). Many SIDS in their NDCs refer to sea level rise in particular posing existential threats, and call for enhanced international support for L&D (Thomas and Benjamin, 2017).

Finance and support

International support and finance, including compensation for losses and damages, have been in the spotlight from the beginning of the dialogue (*high confidence*), starting with AOSIS' proposal (INC, 1991). Recent work has focussed on *finance sources*, such as solidarity-based donor and other support for experienced losses and damages and climate-induced displacement as well as questions of compensation and litigation (Roberts et al., 2017; Gewirtzman et al., 2018; Mechler and Deubelli, 2021; Robinson et al., 2021). A selection of finance *options* has also been explored such as donor-supported insurance systems with built-in risk reduction provisions (Gewirtzman et al., 2018) as well as roles for social protection (Aleksandrova and Costella, 2021). International policy and donors have provided technical assistance for insurance-related options such as (Insuresilience Global Partnership, 2018).

As national and donor-related funding for impacts and risk management remains limited (Schäfer and Künzel, 2019; 17.2; Serdeczny, 2019) even at current global warming, many highly exposed developing countries remain financially constrained in their capacity to attend to residual impacts and risk management needs (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Roberts et al., 2017; UNEP, 2021a) (*high confidence*). Discussion on options for the risk retention layer 'beyond adaptation" are likely to see further attention as the dialogue proceeds.

Although there is no explicit mandate regarding L&D, about a quarter of the Green Climate Fund's approved projects explicitly refer to L&D while 16% of projects have thematic links to L&D across their main project activities (Kempa et al., 2021). Any estimate of L&D finance needs and spending, however, remains highly speculative, as long as its exact remit including in relation to adaptation has not been clarified politically (*medium evidence, high agreement*) (Markandya and González-Eguino, 2019).

Liability and compensation, implying legally defined reimbursement of losses and damages attributable to climate change, remain contentious in L&D dialogue (*high confidence*). In half of the academic and grey literature surveyed by McNamara and Jackson (2019), compensation is mentioned. Studies have laid out responsibility principles, such as historical responsibility based on the polluter pays principle, beneficiary pays, as well as ability to pay. Discussions on compensation are closely linked to justice and equity scholarship which has studied compensatory, distributive and procedural equity considerations for burden sharing (Roser et al., 2015; Wallimann-Helmer, 2015; Huggel et al., 2016; Boran, 2017; Page and Heyward, 2017; Roberts et al., 2017; Shockley and Hourdequin, 2017; Wallimann-Helmer et al., 2019; Garcia-Portela, 2020).

Litigation and liability are linked and a growing research body has examined the role of litigation and international law for the L&D context finding that litigation risks for governments and business may increase as the science, particularly on attribution matures further (Mayer, 2016; Banda and Fulton, 2017; WGI CWGB Attribution, 8.2.1.2); Marjanac and Patton, 2018; James et al., 2019; Simlinger and Mayer, 2019; Wewerinke-Singh and Salili, 2019; Toussaint and Martinez Blanco, 2020) (*high agreement, medium evidence*).

Outlook

The WIM has been reviewed twice as to its delivery on its key functions. As an outcome of the second review in 2019, an expert group on Action and Support has been set up to further discuss issues pertaining to finance, technology and capacity-building and a Santiago Network for Technical Assistance will be established to consider providing technical support directly to developing countries (UNFCCC, 2019b). Overall, the L&D dialogue under the WIM supported by an increasing body of research has made important advances with regard to the two functions of knowledge generation and coordination; however, less so on action and support (*medium confidence*) (Calliari et al., 2020). Resolution on the last item will need additional attention as, despite the coalescence of themes, the L&D dialogue continues to proceed across interlinked yet contested discussion strands.

[END CROSS-CHAPTER BOX LOSS HERE]

17.3 Decision-making Processes of Risk Management and Adaptation

AR5 (Chambwera et al., 2014; Jones et al., 2014; Klein et al., 2014; Kunreuther et al., 2014; Mimura et al., 2014) represented a significant step forward in focusing attention on how decision-making may facilitate effective and robust responses to climate risks remaining after mitigation measures have been taken, following recognition of these needs in AR4, including the diverse contexts that face decision-makers (Klein et al., 2007).

AR5 (Jones et al., 2014; Kunreuther et al., 2014) recognised that the decision-making procedures are as important to consider in managing risks as are the options for responding to climate change, mostly because the procedures can themselves constrain the choices of actions, which could, in turn, lead to constrained pathways which are undesirable. It emphasised the importance of iterative risk management because risk and adaptation are dynamic. It also identified that (i) risk assessments, decision-support tools, early warning systems, accounting for uncertainty and delivering no-regret options by examining trade-offs are important, (ii) integration across different governance portfolios is needed due to potential conflict of different actions between portfolios, and (iii) planning, implementation and decision-making, including the use of methods, are dependent on local context.

Since AR5, the IPCC special reports have provided assessed the value of integrated assessment processes for assessing trade-offs and synergies (IPCC, 2018a), adaptive management and governance, the roles of formal and informal decision making (IPCC, 2019b), and the importance of developing policy and governance options for risk management, including managing disasters, enhancing resilience, addressing decision-relevant uncertainties, and being prepared for abrupt change and extreme events (IPCC, 2019c)

Chapter 16 has shown that climate risks vary greatly from small to large, local to regional, uncertain to deeply uncertain. The plethora of risks means there are many types of decisions, and many forms of analyses and processes that may be drawn on. Decisions can differ according to whether they are strategic, tactical or operational; whether there are one or many decision makers, from a domestic setting to national governments; the level of uncertainty present; the time available to take the decision; and many more factors (Chapter 1; Section 17.1).

The pathway to a decision may not be linear, depending on when and in what detail the decision-making or consultative group may need to be understanding the climate risk and its real world context (*sense-making, modelling*), has sufficient background to analyse and explore options for ameliorating the risk (*analysis, exploration*), or is ready for interpreting the analyses and deciding on the requirements and strategies for implementing a chosen strategy (*interpretation-implementation*) (*high confidence*) (Figure 17.6; French et al., 2020). The development of decision-support tools for climate risk management (Palutikof et al., 2019a; Palutikof et al., 2019b) and more generally (Papathanasiou et al., 2016) along with archives of experiences from practitioners (Watkiss and Hunt, 2013; Section 17.5; Bowyer et al., 2014; French, 2020a) means that some aspects of the decision-making process can be circumvented or at least streamlined as that experience is re-used (*high confidence*).

No single approach to decision making best suits an individual climate risk across any adaptation context (Richards et al., 2013), although there is now a greater awareness of the methods and approaches that are available and their requirements for best practice (Hurlbert et al., 2019) (*high confidence*). This section aims, firstly, to assess the factors that people responsible for organising and facilitating decision-making may wish to consider in choosing the methods and approach for them to make decisions in their context. It also assesses existing experience in analysing the utility of methods for climate risk decision-making. The second part then assesses progress in integrating decision-making across a portfolio of risks.

Processes and methods to facilitate decision-making, from problem recognition to implementing a solution, have evolved in many contexts, disciplines and applications over the last century (*high confidence*). As a result, decision-making terminology has a vast number of synonyms that are not compiled here. For clarity, the term 'decision-analytic methods' refers to procedures or tools that may be used by decision-makers to help develop, analyse and contrast alternative actions/adaptations; 'approaches' refers to processes that may be undertaken by decision-makers to facilitate the development of proposed actions/adaptations; 'decision-support tools' refers to software or procedures that facilitate the use of knowledge and data (Papathanasiou et al., 2016).

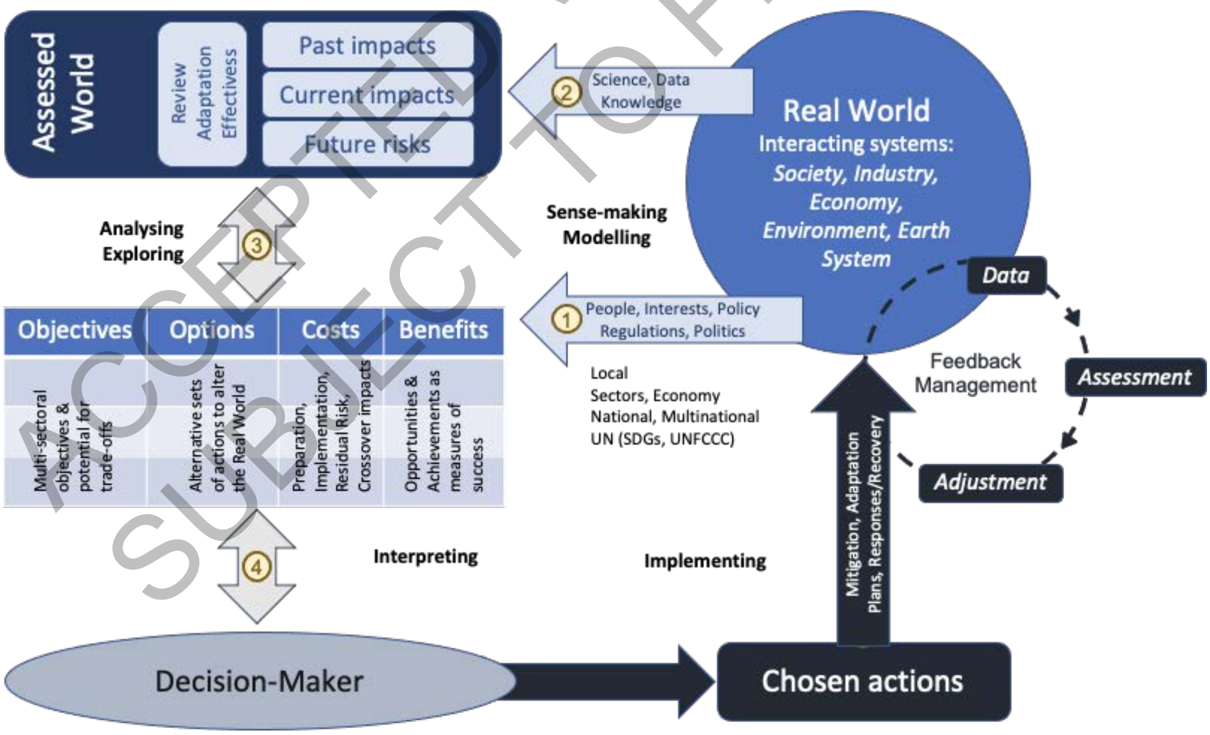


Figure 17.6: Relationships between different processes of decision-making to manage climate-related risks in the real world, noting that, when appropriate, some aspects may only require experience to be re-used. **1.** Formulation of risks of concern and accompanying policies and objectives for managing those risks, forming prescriptive models for the decision maker. **2.** Knowledge, understanding and observations of the real world are used to assess past and current impacts and future risks using descriptive models, based on the perspectives and prescriptive models arising from (1). If not well formulated from other experience, processes in (1) and (2) interact to make sense of the world and what

needs to be done. In iterative management, (1) and (2) also form the basis for monitoring, reviewing, and evaluating effectiveness of adaptations. **3.** Use of decision-support and decision-analytic tools to appraise costs and benefits of different options for ameliorating future risks. The double-headed arrow indicates where two-way interactions occur between different activities (likely to be iterative, feedback and non-linear processes) – modelling and assessments are repeated and revised in tandem with the planning and evaluation of options, based on interactions with the policy-makers and stakeholders. **4.** The decision-maker, which may be a group of people, interacts with the evaluation of options (two-way interaction) and interprets the efficacy of the options and the implications for the real world, ultimately choosing one or more actions to satisfy the policy objectives to manage the risks. **5.** Implementation of the actions in the real world, which may be once-only actions or instigation of a feedback management system that enables ongoing adjustments to meet objectives.

17.3.1 Decision-analytic Methods and Approaches

Different classes of decision-analytic methods have been variously presented in IPCC reports since AR4 but without a summary assessment of their capacity to deal with different contexts of the decision maker. 'Communities-of-practice' are developing tool-boxes to support analysing and making of decisions generally (French, 2020a). These communities of decision analysts can act like broad-based statisticians to advise on matching methods to the climate risk and its context, before individual decision specialists are consulted. Some scientific literature is presenting guides for choosing different methods, tools and approaches (Shi et al., 2019). This sub-subsection provides a summary guide for policy analysts and decision-makers to help identify the classes of decision-analytic methods that may be suitable for their context for managing climate risks. It focuses on decision-analytic methods, noting that decision-support tools will underpin many of these methods by organising information (Bourne et al., 2016; Papathanasiou et al., 2016; Ceccato et al., 2018; Haße and Kind, 2018) or support modelling (Papathanasiou et al., 2016; Kwakkel, 2017; Gardiner et al., 2018), sometimes with a particular decision-analytic process in mind (Hadka et al., 2015; Torresan et al., 2016; Tonmoy et al., 2018).

17.3.1.1 Factors to Consider in Selecting Methods to Facilitate Decision-Making

The choice of methods and approaches to decision-making for climate risks (next section) will depend on (i) the cognitive needs of the deliberations, otherwise considered to be the phase in developing a decision, (ii) the types of models and modelling available to facilitate the deliberations, (iii) the degree of uncertainty surrounding the choices, and the (iv) context of a choice (*high confidence*) (Richards et al., 2013; Jones et al., 2014; Shi et al., 2019; French, 2021).

17.3.1.1.1 Cognitive phases of decision making

The decision process often involves overlapping and iterative development of the components leading toward a decision, resulting in the blurring of stages but involving different phases of cognitive activity (Figure 17.6; Holtzman, 1989; French, 2015; French, 2020a). Framing the problem (Orlove et al., 2020), by modelling its relationships with the human and natural systems and eliciting objectives, values and scope of the problem from stakeholders, is a precursor to analyses of options but may be returned to whenever a phase of '*sense-making and modelling*' is required (*high confidence*) (Ackermann, 2012; Keeney, 2012; Slotte and Hämäläinen, 2014; Abbas and Howard, 2015; Marttunen et al., 2017; Korhonen and Wallenius, 2020; French, 2021).

The cognitive phase of *'analysing and exploring'* uses models and existing data and/or knowledge services as available to explore the relevance/efficacy of adaptations to ameliorate risk or to meet other adaptation objectives, as well as possible flow-on effects of those actions (Section 17.3.1.4). Sensitivity and robustness analyses can be useful if conditions are favourable to supplement the decision analysis, setting bounds on some of the residual uncertainty (*high confidence*) (Borgonovo and Plischke, 2016; Ferretti et al., 2016). Validation of models and verification of data (Tittensor et al., 2018) are becoming highlighted as important steps in this phase or in the sense-making phase, particularly in their capacity to understand and test decision-makers and stakeholders' perceptions (*medium confidence*). Randomisation methods, Bayesian methods, interval methods, MCDA, DMDU and economic and financial approaches (e.g., Real Options Analysis) are tools of choice in this phase (*high confidence*) (Table 17.5) (Abbas and Howard, 2015; Bendoly and Clark, 2016; Borgonovo and Plischke, 2016; Iooss and Saltelli, 2017; Korhonen and Wallenius, 2020; Saltelli et al., 2020). Decision-support tools in the provision of data and/or modelling methods are regularly used in this and the sense-making phase (*high confidence*) (17.3.1.2).

The phase of interpreting the analyses to make decisions on climate adaptation followed by implementation are the least described in the literature (Figure 17.7). Decision process management tools and methods for communicating choices, outcomes and implementation are expected to be used to provide support in this phase, particularly for understanding whether the advice is fit-for-purpose, and the efficacy of choices are clear (*low confidence*) (Spetzler et al., 2016).

17.3.1.1.2 Types and capacity of models to support decision making

'Descriptive models' of socio-biophysical systems and their responses to different drivers (Argyris and French, 2017; French and Argyris, 2018; Saltelli et al., 2020) and 'prescriptive models', which capture the beliefs, values and objectives of decision-makers and stakeholders (Parnell et al., 2013; Keisler et al., 2014; French and Argyris, 2018), provide the foundations of sense making (*high confidence*) and thereby influencing the options and choices available in the phase of analysis and exploration (*medium confidence*) (Gorddard et al., 2016).

Socio-biophysical models may be qualitative network models, statistical models or dynamic mathematical models (Melbourne-Thomas et al., 2017). Qualitative network modelling can help assess the nature and consequences of the interactions, as well as facilitating understanding of possible structures to be used in dynamic models for assessing long term adaptation options (Reckien et al., 2013; Reckien, 2014; Reckien and Luedeke, 2014; Symstad et al., 2017). These approaches help articulate the direct and indirect effects of fixed, long-term engineering or structural adaptations. Dynamic stochastic modelling (Fulton and Link, 2014; Ianelli et al., 2016) has been used to assess short to medium term interactions of more dynamic and variable sectors, such as those with annual adjustments and management of water, agriculture, land and marine uses (Holsman et al., 2019; Hollowed et al., 2020; Bahri et al., 2021). On a longer timeframe, scenarios are used to test long term interactions but often with less variability and chance (Giupponi et al., 2013; Adam et al., 2014; Rosenzweig et al., 2017).

Many sensitivity analyses based on scenarios, including procedures to randomise across model uncertainty, relate to descriptive dynamic mathematical models with the user of the models characterised as an objective observer (Borgonovo and Plischke, 2016; Ferretti et al., 2016; Symstad et al., 2017; French, 2020a). Bayesian approaches enable these descriptive analyses to take account of the subjective choices in model construction and implementation (Abbas and Howard, 2015; Sperotto et al., 2017; Jäger et al., 2018; Sperotto et al., 2019; French, 2020a). Organising descriptive analyses and deciding on a suitable option across a diversity of opinions amongst stakeholders use prescriptive processes, which can be supported with prescriptive modelling tools (Williamson and Goldstein, 2012; Gelman et al., 2013; Abbas and Howard, 2015; Dias et al., 2018; Phan et al., 2019; Hanea et al., 2021). These approaches are subjective, in that they are constrained or directed by the particular views and emphases of the decision-making group (Gorddard et al., 2016). Not all tools are appropriate for all these activities.

Decision-makers will be better able to choose decision-analytic methods when they have an understanding of the types, scale and breadth of uncertainties around the climate risk (*high confidence*) (Symstad et al., 2017). The *Cynefin* framework (Snowden, 2002; French, 2013) is a policy-driven framework that broadly categorises the decision context of uncertainty within which decision makers and policy analysts may find themselves (*medium confidence*) (Hurlbert et al., 2019; Helmrich and Chester, 2020). As *Cynefin* has helped frame previous IPCC presentations on contexts of uncertainty (Hurlbert et al., 2019) and has a community of practice to consult on its use (French, 2020a), it is used here, also because it considers the uncertainty in knowledge around cause and effect in general terms, rather than specifically focussing on uncertainty in formal models. Helmrich and Chester (2020) show how *Cynefin* can be used to frame climate adaptation decision making in the infrastructure sector.

The *Cynefin* contexts relate to how well the system is understood for knowing precisely the outcomes of actions that may be taken - range from known, knowable, complex to chaotic. If a context is known or knowable, then it will be possible to build sophisticated models and make sound predictions. If the context is complex and chaotic the outcomes of actions will be less predictable, no matter how complex the models may be, although more complex dynamic models may be useful to test 'what if' scenarios in these cases

(Marchau et al., 2019). Under complex and chaotic circumstances an ensemble of models and approaches may be needed to help categorise a satisfactory 'solution space' across the broad knowledge of relationships and dependencies, but will need to have iterative processes to update and refine adaptations as knowledge improves (Marchau et al., 2019).

17.3.1.1.3 Uncertainty and attitudes to risk

Uncertainty does not just relate to what might happen given climate drivers or adaptations, but also about how much one values potential consequences (Butler et al., 2016; Beven et al., 2018a; Cross-Chapter Boc DEEP; Beven et al., 2018b; French, 2020a) *(high confidence);* the balance between how particular decision analyses address uncertainties relating to the external world (descriptive models) and those relating to the values driving the decision making (prescriptive models) is important (Butler et al., 2016). Some analyses partially ignore uncertainties relating to the former in order to focus on conflicts in the values held by different stakeholders and help structure debate (Korhonen and Wallenius, 2020; French, 2020a), while others build very sophisticated models of the external world to predict potential consequences, but in doing so lose transparency and risk becoming untrustworthy black boxes to many stakeholders (*low confidence*) (Peterson and Thompson, 2020).

Much of the readily-available literature on how uncertainties affect decision-making relates to the uncertainty in the biophysical models, with a recognition that the choice of tools will be influenced by the types of uncertainty to be addressed (Le Cozannet et al., 2017; Symstad et al., 2017; Beven et al., 2018a; Beven et al., 2018b; Durbach and Stewart, 2020b; French, 2020a). While terminology varies amongst disciplines, three types of uncertainty are important in understanding assessments of the future from descriptive models – epistemic (uncertainty in model construction relating to the lack of knowledge about the system being represented), analytic (the degree to which a model fits observations, and its accuracy), and stochastic (the natural variability or randomness in the system). The probability of an event arising in the future is determined from all three uncertainties, noting that stochastic uncertainty is a property of the system rather than a limitation of research (Le Cozannet et al., 2017; Beven et al., 2018a; Beven et al., 2018b).

Uncertainty in what constitutes a risk of concern is increasingly identified as important to consider when managing risk (Chapter 16; Butler et al., 2016; Prober et al., 2017; French et al., 2020; Reis and Shortridge, 2020). The uncertainty here arises from what is an acceptable risk. Acceptability relates to the value or importance of the consequence, which may include moral and ethical uncertainties (Prober et al., 2017), as well as how ambiguous the understanding of the consequence may be between different groups (Beven et al., 2018a; Beven et al., 2018b). The development of strategies to ameliorate risk will benefit from considering these two uncertainties in specifying the risk to be managed (Prober et al., 2017; French et al., 2020) because they can help set boundaries on a required likelihood of success, rather than simply casting stakeholders or decision-makers as risk averse or risk tolerant, and can help identify and accept pathways of success (Gregory et al., 2012). This can be important when decisions need to be made well in advance of the actions needing to take effect, such as for many climate risks (Chapter 1; Chapter 16; Section 17.2.3; Cross-Chapter Box DEEP in this Chapter).

Elicitation methods help reduce these uncertainties (*high confidence*) (Butler et al., 2016; Prober et al., 2017; Symstad et al., 2017; Beven et al., 2018b). In addition, informal decision processes can assist in developing consensus in approaches and outcomes (Orlove et al., 2020).

17.3.1.2 Decision Analytic Methods Used in Decision-Making and Climate Risk Management

Entities making decisions (countries, regions, organisations and individuals) select methods that best suit them in their context (Fünfgeld et al., 2018; Shi et al., 2019; French, 2020a) *(high confidence)*.
Classes of tools (Watkiss and Hunt, 2013; French, 2020a) include Bayesian methods, Interval methods, decision making under deep uncertainty (DMDU; see Cross-Chapter Box DEEP in this Chapter), cost-benefit analyses, multicriteria decision analysis, elicitation and general decision support tools (Table 17.5). A summary guide for policy analysts and decision-makers is presented in Table 17.5 to help identify the classes of decision-analytic methods that may be suitable for their context for managing climate risks. The table summarises how well the methods address the *Cynefin* context, phase of decision making, the types of uncertainties that exist through the decision-making process and the resources required. As terminology may vary between disciplines and research groups, suitable references to better explain the methods within the

class are provided. Also, there may be overlap between the classes as individual methods are often paired with other methods to address specific requirements and approaches (Buurman and Babovic, 2016; Haasnoot et al., 2019). In that respect, these methods are referred to in the next section discussing advances in the different approaches to managing climate risks.

Case studies in Table 17.5 describe the utility of classes of decision-analytic tools to facilitate decisions about climate adaptations (SM 17.2). These case studies are presented in Figure 17.7 according to the type of decision-making body and mapped according to their contribution to a decision outcome relative to the geopolitical scale of the actions being assessed. The effectiveness of these methods and tools in Table 17.5 in the context of climate change adaptation (Box 17.1) has yet to be evaluated.

Table 17.5: Characteristics of the main approaches to decision analysis with respect to their *Cynefin* context, the manner in which they can be used to address different uncertainties, where they may be used in different cognitive phases of the decision-making process, the resources required, and some case studies for further exploring how they might be used. Numbers in square brackets after references in Case Studies refer to the references plotted in Figure 17.7.

<table>
<tr><td colspan="5">Bayesian Methods (Keeney and Raiffa, 1993; Smith, 2010; Gelman et al., 2013; Reilly and Clemen, 2013; Abbas and Howard, 2015; Sperotto et al., 2017; Marchau et al., 2019)
A structured approach to assembling information around the consequences of choices, either by modelling, analysis of multiple scenarios or by structuring deliberation; Underpinned by a theoretical base, coherent assumptions and powerful computational methods; Can use both observational data and expert knowledge, weighting them appropriately; Same approaches as in Artificial Intelligence algorithms. Biases (information, stakeholders, decision-makers) can be made explicit. Traditionally, Bayesian methods computationally identify an ‘optimal’ decision, based on maximising the expected utility across a number of specified requirements, represented as functions.</td></tr>
<tr><td colspan="5">Examples include the general application of decision network models (Richards et al., 2013; Sperotto et al., 2017), the use of decision network analyses based on elicitation to choose adaptations to coastal management in a lagoonal area in Italy (Catenacci and Giupponi, 2013) and coastal community in UK (Jäger et al., 2018); combination of economic models and decision models to assess research and development priorities (Baker and Solak, 2011); combining outputs from models, observations and opinions in a decision framework for assessing climate impacts on water nutrient loads in Italy (Sperotto et al., 2019) and a general review for water resource management (Phan et al., 2019); combining results from different dynamic models to assess human mortality from ozone in the USA (Alexeeff et al., 2016), assessing adaptive capacity of surf lifesaving in Australia (Richards et al., 2016), and assessing urban flood risks in Denmark (Åström et al., 2014).</td></tr>
<tr><td colspan="3">Cognitive Phase</td><td rowspan="2">Resources required</td><td rowspan="2">Case Studies</td></tr>
<tr><td>Sense-making and Modelling</td><td>Analysing and Exploring</td><td>Interpreting and Implementing</td></tr>
<tr><td>Construction of hierarchical models, belief nets (Sperotto et al., 2017; Phan et al., 2019), decision trees (Keeney and Raiffa, 1993) and influence diagrams (Keeney and Raiffa, 1993; Reilly and Clemen, 2013), supplemented by many soft elicitation techniques help build models for quantitative analysis (Gelman, 2003; Bendoly and Clark, 2016)</td><td>Bayesian updating and expected utility analysis, supplemented by robustness and sensitivity analyses (Rios Insua, 1999; Rios Insua and Ruggeri, 2000; French et al., 2009; Smith, 2010; Reilly and Clemen, 2013; Abbas and Howard, 2015).</td><td>Use of graphical models (decision trees, belief nets and influence diagrams) and sensitivity plots can help make transparent and explain reasoning for strategy to stakeholders and implementers (Bendoly and Clark, 2016) and provide for auditable building of consensus.</td><td>Bayesian decision analytic models can be applied with increasing complexity and sophistication to any given problem. Coherence between different levels of sophistication can be maintained. Thus, the resources can be tailored to the time and support available for the analysis. The most sophisticated analyses are computationally demanding.</td><td>(Alexeeff et al., 2016) [1], (Åström et al., 2014) [2], (Baker and Solak, 2011) [3], (Catenacci and Giupponi, 2013) [4], (Jäger et al., 2018) [5], (Phan et al., 2019) [6], (Richards et al., 2013)[7], (Richards et al., 2016) [8], (Sperotto et al., 2017) [9], (Sperotto et al., 2019) [10]</td></tr>
</table>

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical (Descriptive Modelling)	*Ambiguity Value (Prescriptive Modelling)*	*Known*	*Knowable*	*Complex*	*Chaotic*
All can be modelled probabilistically, perhaps supplemented by sensitivity analysis (Rios Insua, 1999; Rios Insua and Ruggeri, 2000; Iooss and Saltelli, 2017). Deep uncertainties can be investigated via scenarios (French, 2020a).	Uncertainties resolved or reduced by discussion, then values modelled by multi-attribute values and utilities (Keeney, 1992; Keeney and Raiffa, 1993; Gregory et al., 2012). Residual uncertainties explored via sensitivity analysis.	Any stochastic uncertainties modelled probabilistically; otherwise, deterministic modelling with sensitivity analysis. Value functions tend to be used more than utility functions (Keeney and Raiffa, 1993; Goodwin and Wright, 2014).	Epistemic uncertainties updated via Bayesian statistics/machine learning, then remaining stochastic uncertainties modelled probabilistically. Full Bayesian decision modelling possible (French et al., 2009; Smith, 2010; Abbas and Howard, 2015).	More exploratory analysis (Gelman, 2003) to understand behaviours with less complex Bayesian modelling support by sensitivity and robustness studies (Rios Insua, 1999; French, 2003). Scenario focused decision analysis to cope with deep uncertainties (French, 2020a). Careful deliberations to construct values and utilities. (Keeney and Raiffa, 1993; Gregory et al., 2012).	Formal modelling impossible. Much exploratory work to identify potential causes and effects. Little if any complex analysis.

Decision-making under deep uncertainty (DMDU) (Hallegatte et al., 2012; Weaver et al., 2013; Marchau et al., 2019; Workman et al., 2021)

Deep uncertainty relates to circumstances in which data are too sparse, experts in too much disagreement or time is too short to model the uncertainty. As such, DMDU methods are focused on working in the *Cynefin* Complex Space context. Approaches emphasise robustness ("no regrets" options) and the use of scenarios, and often link well with scenario-focused robust Bayesian studies (Cross-Chapter Box DEEP in this Chapter). DMDU studies draw in many other approaches to decision analysis, using them to identify robust rather than optimal strategies, as in Robust Decision Making (RDM). DMDU analyses can help decision makers to think contingently and build a more wide-ranging recognition of the risks. They often integrate with other classes of tools.

Examples include RDM for hydro-power design using down-scaled climate data in sub-Saharan Africa (Taner et al., 2017), RDM for water management in California, USA (Lempert and Groves, 2010), the Colorado River, USA, and for international climate investment strategies (Groves et al., 2019), use of decision-scaling (Brown et al., 2019), comparison of RDM and Info-gap methods (Hall et al., 2012) and review of using climate modelling in RDM (Weaver et al., 2013).

Cognitive Phase			***Resources required***	***Case Studies***
Sense-making and Modelling	*Analysing and Exploring*	*Interpreting and Implementing*		
Some of the simpler DMDU tools complement soft	Many Bayesian or MCDA tools can be used here but with	DMDU with its emphasis on robustness encourages	Some of the simpler models do not require substantial resources,	(Brown et al., 2019) [11], (Groves et al., 2019) [12],

elicitation tools and can help to identify relevant scenarios and help formulate problems.	DMDU's additional emphasis on robustness and the exploration of several/many scenarios.	contingency planning in implementation with careful monitoring to identify emerging risks.	but the application of parallel sophisticated analyses in several scenarios can be computationally demanding. Also, the emphasis on discussion of robustness can be demanding on the time of problem-owners, experts and stakeholders.	(Hall et al., 2012) [13], (Lempert and Groves, 2010), [14], (Taner et al., 2017) [15], (Weaver et al., 2013) [16]

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical (Descriptive Modelling)	*Ambiguity Value (Prescriptive Modelling)*	*Known*	*Knowable*	*Complex*	*Chaotic*
Methods are designed for deep epistemic uncertainties. Some can deal with stochastic uncertainties. Analytical uncertainties seldom accounted for.	Some DMDU methods draw on MCDA methods and thus consider ambiguity and value uncertainties. In any case, DMDU methods support wide deliberation with stakeholders.	Deep uncertainty is absent but the principles and processes of decision making may be used.	Deep uncertainty is absent but the principles of decision making may be used.	The complex and chaotic spaces are home to deep uncertainties. DMDU tools and more particularly processes are relevant here. The emphasis on robustness is very relevant. The tools themselves are relatively simply structured but are effective at stimulating discussion.	Deep uncertainties are rife in the chaotic contexts. DMDU emphases on robustness and possible scenarios can stimulate creative discussions of ill understood issues.

Decision Process Management (Raz and Micheal, 2001; Dalkir, 2005; Burstein and W. Holsapple, 2008; Jashapara, 2011; Bonczek et al., 2014; Sauter, 2014; Holsapple et al., 2019)
A range of tools and techniques to help manage the decision-making process and support risk management and the implementation of the chosen strategy. Some tools organise data and analyses, often being built on a geographic information system, known as decision support tools. Others manage processes, organising workflows. Some have inevitably expanded in function to support decision-making itself, even though their primary focus might be on, say, implementation and monitoring risks. Such tools are closely related to knowledge management systems; knowledge management processes and decision process management differ more in terminology than in substance.

Examples include tools for agriculture (Biehl et al., 2017), evaluating and comparing CMIP climate models (Parding et al., 2020), development of action cycles (Park et al., 2012), and decision support systems across a range of sectors and decision-group applications (Papathanasiou et al., 2016).

Cognitive Phase			***Resources required***	***Case Studies***
Sense-making and Modelling	*Analysing and Exploring*	*Interpreting and Implementing*		
Process, project, knowledge elicitation and risk management	Tools help structure decision-making processes and ensure	Project management tools plan implementation and	Decision process management tools can reduce resources	(Biehl et al., 2017)[17], (Papathanasiou et

tools help identify how to structure decision-making processes. Decision process tools can capture details for implementation and document process for audit trail.	timely involvement of problem owners, stakeholders, and experts. Knowledge management tools can capture details for implementation and document process for audit trail.	risk management tools identify what to monitor during implementation. Knowledge management tools maintain audit trail and track reasoning for choices made during implementation	needed in the decision-making process. However, this assumes that the tools are already installed on local information systems and that the analysis team is experienced in using them. Otherwise, resource is needed to understand and train in the use of the tools.	al., 2016), [18], (Parding et al., 2020) [19], (Park et al., 2012) [20]

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical (Descriptive Modelling)	*Ambiguity Value (Prescriptive Modelling)*	*Known*	*Knowable*	*Complex*	*Chaotic*
Not designed to address uncertainties involved in the decision itself, but may handle project risks in the decision process, especially implementation.	Not usually addressed, since ambiguities and value uncertainties will be addressed in the decision making itself, but may use those values in risk management of implementation.	Simple project management tools may be sufficient here.	Project management and risk management tools apply easily here.	Project management and risk management tools may be used but attention needs to be paid to risks that are complex in nature with little knowledge of precise relationships between cause and effects.	Project management and risk management tools may be used but attention needs to be paid to risks that are complex in nature with little knowledge of precise relationships between cause and effects.

Economic and Financial Methods (Howell et al., 2001; Pearce et al., 2006; Boardman et al., 2017; Atkinson et al., 2018a; Hurlbert et al., 2019)
Stem from economic theory and accounting practices: e.g. cost-benefit analysis, which seeks to price out all aspects of the consequence of a strategy, portfolio analysis, or real options theory, which seeks to value financial investments allowing for their risks and the contingent buying and selling. Such methods are perceived as objective when dealing with tangibles, but are more controversial in their valuing of intangibles. Since these methods model uncertainties with probabilities and then work with expectations, they share much in common with Bayesian methods. However, many applications of cost-benefit analysis omit any detailed treatment of uncertainty.

Examples examine the economic costs and benefits of adaptation pathways for storm water infrastructure in Singapore (Manocha and Babovic, 2017), and a coastal mega city, Los Angeles in the USA (de Ruig et al., 2019)

Cognitive Phase			***Resources required***	***Case Studies***
Sense-making and Modelling	*Analysing and Exploring*	*Interpreting and Implementing*		

In themselves, these methods do not support sense-making and modelling, though discussions of how to value impacts, both tangible and intangible can be catalytic in understanding the issues.	These tools focus mainly on analysis and evaluating the costs and benefits of various options. They are not designed to be used interactively so are more often deployed and communicated via reports than interactive workshops.	Since CBA methods do not emphasise the analysis of uncertainties and risks, they are less suited for use in developing and communicating an implementation plan. Real options with their emphasis on contingency are much more suited (Fischhoff, 2015).	Cost benefit analysis for complex projects is a major undertaking with much data collection needed to value outcomes. Real options also require data on risks and uncertainties. Both may have high computational needs.	(de Ruig et al., 2019) [21], (Manocha and Babovic, 2017) [22]

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical (Descriptive Modelling)	*Ambiguity Value (Prescriptive Modelling)*	*Known*	*Knowable*	*Complex*	*Chaotic*
Cost-benefit methods usually deal with uncertainty via expectations with little attention to probability distributions; real options methods tend to treat uncertainty in much more sophisticated ways. Both methods, when applied fully have many points of contact with Bayesian methods (Neely and de Neufville, 2001; Bedford et al., 2005)	These methods reduce all value and preference information to financial equivalents. The key issue is to find a market in which all outcomes may be valued financially. Modern CBA methods use much more subtle techniques for this than those applied in the last century (Bedford et al., 2005; Saarikoski et al., 2016).	Although CBA and many financial methods work in theory, the complexity makes it seldom worth the effort.	The methods may be applied to evaluate complex projects but CBA tends to 'average out' rather than analyse uncertainty.	The recognition of the need to treat deep uncertainties using real options has been investigated (Hallegatte et al., 2012; Buurman and Babovic, 2016).	Formal modelling impossible. Much exploratory work to identify potential causes and effects. Little if any complex analysis.

Interval Methods (Shafer, 1976; Pedrycz et al., 2011)
Because of concerns that the statistical accuracy of some data is unknown, and that decision-makers and experts cannot make numerical judgements accurately, analyses have been suggested which work with ranges of values in categories (intervals) as their inputs. While avoiding accuracy issues, weakening the arithmetic may result in other foundational assumptions not being met, including some basic principles of rationality. Different types of uncertainty can often be confused, and the analyses can contradict basic probability theory. Interval models of semantics and imprecision can be useful in exploring ambiguity and value uncertainty, though modelling rather than resolving such uncertainties does not necessary help in decision-making. Some interval methods can be thought of more as sensitivity techniques applied to other decision analytic approaches. Typical approaches here relate to the fuzzy or possibility theory, and evidential reasoning.

Examples include using fuzzy methods to. assessing climate adaptations in ports in China (Yang et al., 2018), water supply vulnerability in South Korea (Kim and Chung, 2013) and resilience of the Nile River delta (Batisha, 2015); and evidential reasoning in an environmental impact assessment for flood mitigation in Manila Philippines (Gilbuena et al., 2013).

Cognitive Phase			***Resources required***	***Case Studies***
Sense-making and Modelling	*Analysing and Exploring*	*Interpreting and Implementing*		
The emphasis on modelling ambiguity may help structure a model initially, but the lack of structures to model and explore complex interdependencies may inhibit the ability to build a valid representation of the issues.	If there is substantial data available, then even the simplest of these methods can produce useful results. But with small quantities of data, their data analysis may be too inefficient. Evidential reasoning MCDA can be insightful on the preference side.	The emphasis on linguistic uncertainty may in some cases it may mask some of the issues (French, 1995).	Many methods are rather simple in application and require only moderate resources, but they may face issues in scaling up to major complex problems.	(Batisha, 2015) [23], (Gilbuena et al., 2013) [24], (Kim and Chung, 2013) [25], (Yang et al., 2018) [26]

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical (Descriptive Modelling)	*Ambiguity Value (Prescriptive Modelling)*	*Known*	*Knowable*	*Complex*	*Chaotic*
There are issues of operational definition of quantities in some methodologies. Some simpler interval methods have no concept of conditionality so cannot model learning effectively, but there are some very sophisticated theories of evidence that can. Interval methods can also provide sensitivity analyses for Bayesian and MCDA methods (Shafer, 1976; Rios Insua, 1990).	Some methods can be simplistic with quantities not being operationally defined. The evidential reasoning approach to MCDA allows exploration of the relative weights on different criteria or between levels in criteria (Xu, 2012; Zhang et al., 2017).	Methods can be applied here without major issue, possibly because the simple, repetitive nature of the problem allows access to much data and the possibility of tuning the methods to the application.	Since the methods often capture rather than explore and resolve ambiguity and value uncertainties, they can hide issues. Also, the lack, in some cases, of operational definitions may mean that some quantification is dubious. Evidential reasoning methods can help analyse conflicting objectives (French, 1995; Xu, 2012).	The recognition of the need to treat deep uncertainties using real options has been investigated (Hallegatte et al., 2012; Buurman and Babovic, 2016).	The ability to deal with ambiguity may be helpful in poorly understood situations, but the emphasis on capturing ambiguity may ultimately slow the building of understanding.

Multi-Criteria Decision Analysis (MCDA): Full ranking and optimal seeking (Bell et al., 2001; Belton and Stewart, 2002; Bouyssou et al., 2006; Zopounidis and Pardalos, 2010; Tzeng and Huang, 2011; Velasquez and Hester, 2013; Kumar et al., 2017)

Covers many approaches: indeed, Bayesian, DMDU and interval methods are sometimes considered MCDA. Some MCDA seek an optimal or best strategy; others form partial rankings, eliminating weak strategies but not discriminating fully between the better ones. Many MCDA methods eschew dealing with uncertainties and focus on modelling and exploring conflicting objectives and balancing these. MCDA techniques are especially useful in working with senior decision-makers in setting policy and broad objectives, and in processes of stakeholder engagement.

Examples include ranking adaptation and mitigation priorities at a national level in the Netherlands (de Bruin et al., 2009), Lithuania (Streimikiene and Balezentis, 2013) and Bangladesh (Haque, 2016), in the forestry sector in Nicaragua (Guillén Bolaños et al., 2018); and in emissions trading in the European Union (Konidari and Mavrakis, 2007).

Cognitive Phase			***Resources required***	***Case Studies***
Sense-making and Modelling	*Analysing and Exploring*	*Interpreting and Implementing*		
There is growing experience in combining soft elicitation with tools to formulate problems (Marttunen et al., 2017). Many MCDA tools naturally encourage discussion and deliberation on developing appropriate value structures. However, exploration and formulation of stochastic and epistemological uncertainties is less developed (Durbach and Stewart, 2020a).	Emphasis is usually on analysing and exploring, resolving conflicting objectives. MCDA Methods come into their own at this stage of the process. Sensitivity tools and intuitive graphical displays exist for many of the methods (Gunawan and Azarm, 2005; Boardman et al., 2017).	Use of graphical models and sensitivity plots can help explain reasoning for strategy to stakeholders and implementers (Bendoly and Clark, 2016).	The more exploratory methods can be quite light in terms of computational resource, but require interactions with decision makers and stakeholders in workshops. Methods with use complex stochastic mathematical programming can be computationally demanding and require substantial data.	(de Bruin et al., 2009) [27], (Guillén Bolaños et al., 2018) [28], (Haque, 2016) [29], (Konidari and Mavrakis, 2007) [30], (Streimikiene and Balezentis, 2013) [31]

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical (Descriptive Modelling)	*Ambiguity Value (Prescriptive Modelling)*	*Known*	*Knowable*	*Complex*	*Chaotic*
These methods tend to focus on balancing and resolving conflicting objectives and include little or no analysis of stochastic and epistemic uncertainties. Interactive	Many methods here use multi-attribute value functions and focus on using weights to explore different emphases on conflicting objectives. One very popular method is AHP	Usually in the known context, the objective function is well understood; but in cases where it is not, interactive multi-objective programming can offer a way forward (Klamroth et al., 2018).	If the objective function is not well understood, then these methods can be useful and can be extended to stochastic programming, but epistemic uncertainties are not really addressed	Methods can explore conflicting objectives, but seldom are able to address deep epistemic uncertainties, unless combined with scenarios (Stewart et al., 2013; Marchau et	Formal modelling impossible. Much exploratory work to identify potential causes and effects. Little if any complex analysis.

methods that use complex objective functions do need to consider convergence criteria for analytic uncertainties.	(Saaty, 1980) though this has issues in scaling up to evaluate more than a handful of policies.		(Gutjahr and Pichler, 2016).	al., 2019; Durbach and Stewart, 2020a).	

Multi-Criteria Decision Analysis (MCDA): Partial ranking (Roy, 1996; Bell et al., 2001; Belton and Stewart, 2002; Bouyssou et al., 2006; Behzadian et al., 2010; Zopounidis and Pardalos, 2010; Tzeng and Huang, 2011; Bouyssou and others, 2012; De Smet and Lidouh, 2012; Velasquez and Hester, 2013; Figueira et al., 2016; Govindan and Jepsen, 2016)
Examples include developing criteria for assessing climate protection strategies and applying these to retrofitting a school to manage climate risks in Germany (Markl-Hummel and Geldermann, 2014); evaluating outranking approaches for managing heat stress in a large city in Australia (El-Zein and Tonmoy, 2015); using MCDA to manage the interactions of climate change with tourism in Greece (Michailidou et al., 2016); and identifying priorities to manage droughts and floods in agriculture in Bangladesh (Xenarios and Polatidis, 2015).

Cognitive Phase			***Resources required***	***Case Studies***
Sense-making and Modelling	*Analysing and Exploring*	*Interpreting and Implementing*		
Graphical representations of partial orders are useful in model formulation, and the emphasis on exploring what can be said objectively about dominance relations can build a kernel of consensus between decision-makers and stakeholders.	ELECTRE and PROMETHEE implementations of outranking approaches have many tools for exploring partial relations and analysing agreements and the reasoning behind these.	The analysis of dominance can provide a sound footing for building risk registers to aid implementation. Understanding the kernel of consensus can also aid communication.	If an outranking algorithm is essentially combinatorial in its approach, then for complex problems there may be computational problems. Some of the methods may require less interaction with decision-makers and stakeholders if they can deduce many partial relations from objective data.	(El-Zein and Tonmoy, 2015) [32], (Markl-Hummel and Geldermann, 2014) [33], (Michailidou et al., 2016) [34], (Xenarios and Polatidis, 2015) [35]

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical (Descriptive Modelling)	*Ambiguity Value (Prescriptive Modelling)*	*Known*	*Knowable*	*Complex*	*Chaotic*
Modelling of all forms of uncertainty including epistemic uncertainty is not the primary objective of these methods. Stochastic uncertainty may be included as probability distributions but there is no formalism for	Partial ranking or outranking methods seek, first of all, to identify dominance between options and preference relations that can be agreed somewhat	Usually in the known context, the objective function is well understood; but when it is not, outranking methods can identify a partial ranking without need too many	Since epistemic uncertainties are not fully addressed, these methods can only help in relation to conflicting objectives, but robustness to uncertainties will need addressing	Outranking methods may be combined with scenarios to explore and analyse decisions under deep uncertainty (Hyde et al., 2003; Durbach, 2014).	Formal modelling impossible. Much exploratory work to identify potential causes and effects. Little if any

learning to address epistemic uncertainties (Hyde et al., 2003; Behzadian et al., 2010; Gervásio and Simões da Silva, 2012).	objectively. Thus, first they eliminate suboptimal alternatives before seeking a fuller ranking. Ambiguity and value uncertainty may also be quantified (Behzadian et al., 2010; Figueira et al., 2016; Govindan and Jepsen, 2016).	interactions with problem-owners.	(Hyde et al., 2003).		complex analysis.

Soft Elicitation (Rosenhead and Mingers, 2001; Shaw et al., 2006; Shaw et al., 2007; Ackermann, 2012; Bendoly and Clark, 2016)

Also known as problem structuring, it is the process of asking problem owners, experts and stakeholders for the knowledge, perceptions, beliefs, uncertainties and values that a model needs to embody before being populated with numbers. Methods here help in problem formulation, structuring understanding: e.g. cognitive maps, soft operational research diagrams, soft systems, prompts such as PESTLE and other qualitative tools (Prober et al., 2017; Symstad et al., 2017). The output of soft elicitation can lead to the building of sophisticated quantitative models (Symstad et al., 2017); and can also structure communications and deliberations with stakeholders. Exploratory data analysis and visual analytics are also relevant. Soft elicitation has enormous advantages in setting the frame for communication between all parties (Prober et al., 2017); there are many cases in which the clarity brought by framing the issues well has obviated the need for formal quantitative analysis.

Examples include Adaptation Pathway planning and elicitation on managing a national park in the USA (Symstad et al., 2017), poverty alleviation in a province in Indonesia (Butler et al., 2016), woodland landscapes in Australia (Prober et al., 2017), as well as general considerations for contested adaptations (Bosomworth et al., 2017).

Cognitive Phase			***Resources required***	***Case Studies***
Sense-making and Modelling	*Analysing and Exploring*	*Interpreting and Implementing*		
Soft elicitation tools provide much support to sense-making, formulating problems and identifying relevant issues to be addressed (Shaw et al., 2006; Shaw et al., 2007; Ackermann, 2012).	Soft elicitation is not relevant to quantitative analysis and evaluation per se, but can support the exploration of residuals to understand the quality of the models and detect further factors to be addressed.	The results of soft elicitation provide the dimensions for communication by identifying the issues that are important to stakeholders and building understanding in those implementing the policies.	Physical resources requirements are relatively slight: sometimes post-its and a white board can be sufficient, though modern visual analytics can require substantial computing resource. However, the demands on the time of problem-owners, stakeholders and experts can be significant	(Bosomworth et al., 2017) [36], (Butler et al., 2016) [37], (Prober et al., 2017) [38], (Symstad et al., 2017) [39]

Uncertainties		***Cynefin context***			
Stochastic, Epistemic, Analytical	*Ambiguity Value*	*Known*	*Knowable*	*Complex*	*Chaotic*

(Descriptive Modelling)	*(Prescriptive Modelling)*				
Soft elicitation tools are available to elicit problem-owners' and experts' perceptions of these uncertainties and, more particularly, dependences and independences between them. Exploratory data analysis is also relevant (Steed et al., 2013; Bendoly and Clark, 2016).	There are tools to catalyse deliberations and help problem-owners and stakeholders clarify their meanings and contextualise their values to the specific issues being considered (Keeney, 1992).	Usually problems falling into known contexts are well-understood and there is little need to elicit or structure models to perform analyses.	Problems falling into knowable space are usually well structured and problem owners' values are also well understood. However, there may be a need to explore error structures in preparation to estimate parameters in the models (Gelman, 2003; Steed et al., 2013; Fekete and Primet, 2016).	Many soft elicitation tools were developed for complex contexts: 'wicked' problems with deep uncertainties: e.g., soft systems, cognitive maps and similar tools to elicit perceptions of relationships between entities and problem-owners' and stakeholder's values (Keeney, 1992; Rosenhead and Mingers, 2001)	Soft elicitation tools and processes can be used to catalyse creative thinking about poorly understood contexts.

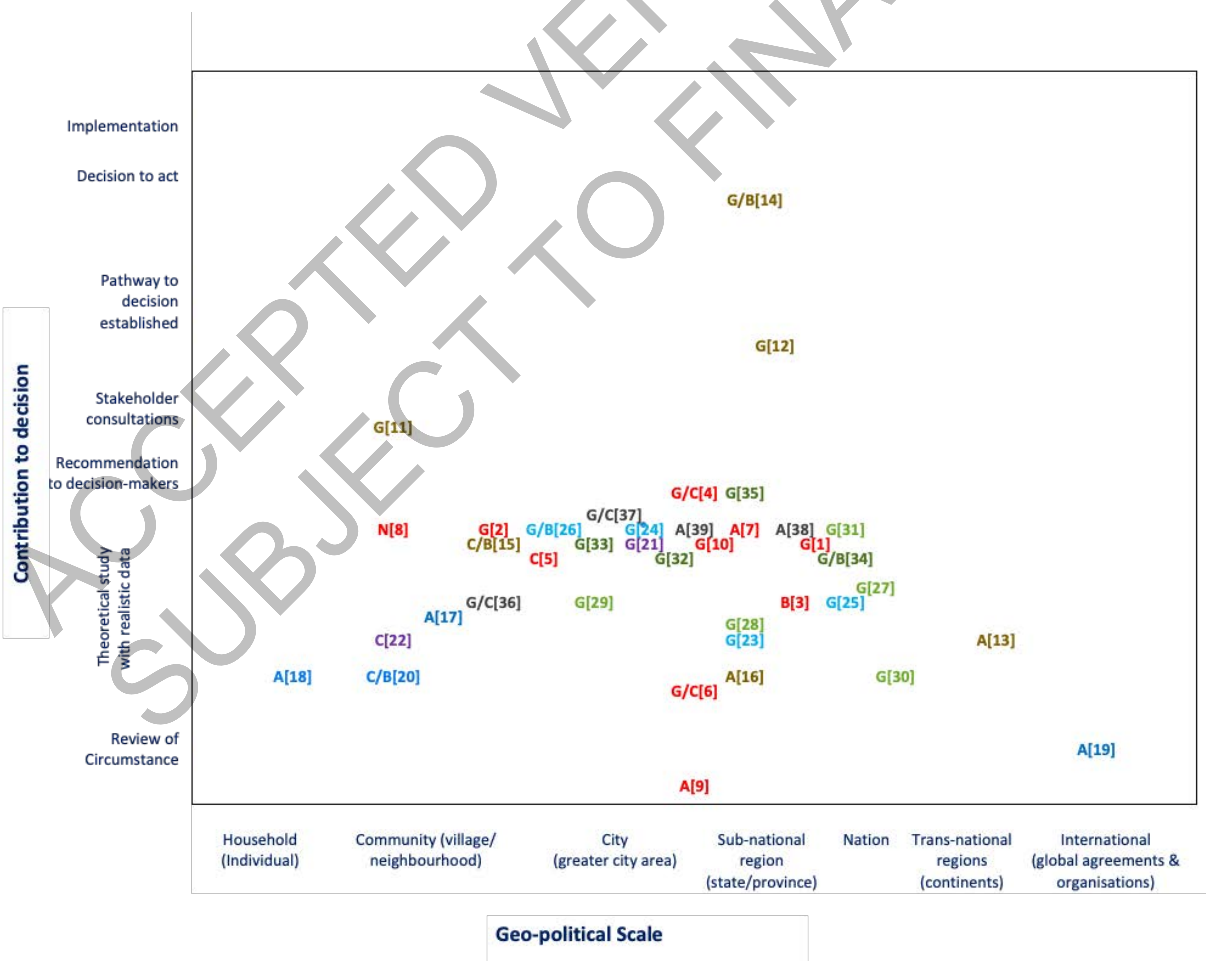


Figure 17.7: Decision-analytic tools used across different geo-political scales and how they contributed to decision outcomes. Points comprise the type of decision-making body (C = Community; G = Government; B = Business/Industry; F = Finance; N = NGO; A = All categories) coupled with the reference number in square brackets, which correspond to numbered references in the case studies of Table 17.5. Colours of the points correspond to the

class of decision-analytic tool as presented in Table 17.3: Bayesian (red), DMDU (Decision Making under Deep Uncertainty) (brown), Decision Process Management (dark blue), Economic and Financial Methods (purple), Interval Methods (light blue), MCDA – full ranking (light green) or partial ranking (dark green), Soft Elicitation (Black).

Many published studies on the utility of decision-analytic methods in managing climate risks are theoretical and therefore it is difficult to find studies on p the value of analytic methods for underpinning final decisions on climate risk adaptation. Bayesian, Deep Uncertainty and elicitation methods and tools to support decision making were the most easily located classes of methods to be used in different contexts (Figure 17.6) while the other classes were more oriented towards government processes. This result highlights a key gap at present in the need to have real world experiences published and mapped for their utility for different tasks, thereby creating a resource for policy-makers to identify suitable tools, such as in emerging communities-of-practice of decision practitioners (Watkiss and Hunt, 2013; Street et al., 2019; French, 2020a).

17.3.1.3 Approaches to Support Decision-making

The common approaches presented here are not undertaken in isolation and are often combined throughout, or applied at different stages of, a decision process, as illustrated in Figure 17.6.

17.3.1.3.1 Role of informal processes

Informal decision-making pervades decision-making in all contexts (*high confidence*) (Orlove et al., 2020); decisions relating to climate change are affected not only by rational processes but also by many informal, often behavioural responses to the situation, some of which may not require formal processes. Informal processes were officially studied in only a few of the publications contributing to Figure 17.7, but all of the studies have hints to informal decision-making that pervades all levels of governance. Although there are not many concrete studies, citing roles of study participants can lead to a perception of a disconnect between the process and the outcome that resulted (see Section 17.5.1 for enablers of success).

Generally, while governance requirements may define the processes of formal deliberations and decision-making, informal deliberations will carry on in parallel, supported by social media, and these informal deliberations may be used to affect the outcome of the formal processes. Stakeholders may feel excluded from the formal deliberations either by governance structures or because they do not agree with their representatives. Conflicting value systems may cause some stakeholders to feel side-lined, particularly if some of the key decision-makers are perceived holding different personal views and interests or to have engaged in political horse-trading, which connect independent decisions. There may be emotional responses, driven by poor comprehension of risk and probabilistic information, and potential for group biases or insularity of participants (Engler et al., 2019). Well-designed decision processes recognise the informal and seek to gain information from it without introducing bias (*medium confidence*) (French and Argyris, 2018).

17.3.1.3.2 Stakeholder engagement

Stakeholder engagement has become increasingly part of climate-relevant decision processes (Orlove et al., 2020). The degree of stakeholder engagement ranges from instructive, consultative to cooperative that are equivalent to information exchange, influence, and partners in decision-making (Sen, 2000; Cattino and Reckien, in press). Since the AR5, climate change adaptation and resilience literature has seen an increase in participatory approaches that deepen engagement and overcome challenges, as well as making some assessments of their effectiveness (Newton Mann et al., 2017; Wamsler, 2017; Esteve et al., 2018), including structured interactions among different types of stakeholders, the use of place-based boundary organizations to strengthen the interactions and heighten the awareness of the institutional context. A higher degree of public participation can lead to more transformational adaptation as well as to higher ambition for local mitigation (*medium confidence*) (17.4.4.2; Cattino and Reckien, in press). Challenges to stakeholder participation are access to state-of-the-art science, capacity to recognize and respond to non-reliable or false climate science information, and the removal of cognitive and other biases (*high confidence*) (Gorddard et al., 2016; Engler et al., 2019; Fulton, 2021).

Participatory and elicitation approaches, where the concerns and involvement of a broader range of interest groups and stakeholders are taken into account, can improve the effectiveness of decision-making (*medium confidence*) (Gregory et al., 2012; Cvitanovic et al., 2019). Participatory planning includes a variety of cogenerative strategies and approaches (e.g., qualitative scenario or adaptation pathway development) through which goals and objectives, knowledge, and strategy implementation and evaluation can be decided collaboratively between practitioners, policymaking, local interests and groups, and scientists (Butler et al., 2016; Prober et al., 2017; Symstad et al., 2017). Specifically, for climate change adaptation, these decision-making strategies can incorporate expert, indigenous and local knowledge (*high confidence*) (Cross-Chapter Box INDIG; Gustafson et al., 2016). The challenge will be to bring together these different actors, as stakeholders tend to act within rather than among systems and procedures, and it is important that platforms are developed to integrate data effectively (Rizzo et al., 2020). Furthermore, reflexive and iterative risk management may further ensure acceptance by participating groups.

Bayesian Methods are increasingly used in advancing approaches for decision-making and support in climate adaptation (Sperotto et al., 2017), by being able to include stakeholder and decision-maker perceptions and biases (Dias et al., 2018; Engler et al., 2019; Phan et al., 2019; Fulton, 2021) in a transparent modelling environment, thereby facilitating consensus and impartiality (*medium confidence*) (Catenacci and Giupponi, 2013; Gelman and Hennig, 2017). Increasing computational efficiency means that these methods can enable different approaches to be addressed and different descriptive and prescriptive models to be included within a single probabilistic environment, which also can be updated in iterative processes (*high confidence*) (Table 17.5; Sperotto et al., 2017; Phan et al., 2019).

17.3.1.3.3 Scenario analyses

Scenarios are described in SR1.5 (IPCC, 2018a) and SRCCL (IPCC, 2019b) as a description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g. rate of technological change, prices) and relationships. Scenarios are neither predictions nor forecasts but are used to provide narratives and trajectories equipped with alternate outcomes. SR1.5 and the SRCCL describe a range of scenarios methods and how scenarios are used to guide risk management decision making. Scenario analysis includes a range of potential future conditions from low end, mid-range, to high-end projections. Scenarios can also include a temporal component from short term, medium term and long term, as defined in the SROCC (IPCC, 2019c).

Scenarios and pathways, combined with elicitation methods, are becoming widely used to assess adaptation and resilience strategies (*high confidence*) (Butler et al., 2016; Prober et al., 2017; Symstad et al., 2017; Lawrence et al., 2019; Phan et al., 2019; Sperotto et al., 2019; Haasnoot et al., 2020a). They can support the consideration of a wide range of alternative possible futures (Catenacci and Giupponi, 2013; Jäger et al., 2018), enabling identification of potential path dependencies caused by adaptation options (*high confidence*) (Pretorius, 2017; Haasnoot et al., 2020a). They can also increase the willingness of stakeholders to consider costly actions, by placing them within broader sequences of action (*limited evidence*) (Barnett et al., 2014). The development, consideration and understanding of scenarios can be enhanced by using visualisation tools to better display storylines, enabling the discussion of alternative futures by participants in decision-making processes (*limited evidence*) (Winters et al., 2016).

17.3.1.3.4 Evaluating trade-offs, robust decision making, and deep uncertainty

Trade-offs are pervasive in decision-making for climate change adaptation, including between adaptation and mitigation, economic/social and environmental cost including distributional/equity considerations, affordability and risk reduction, short and long-term consequences, and spatial variations (Borgomeo et al., 2016; Hudson et al., 2016; Gil et al., 2018; Landauer et al., 2019).

Trade-offs are often directly compared in cost-benefit analyses which require rigorous estimation of the monetized costs and benefits, where monetization is feasible and values uncontested (such as for infrastructure) (*high confidence*) (de Ruig et al., 2019; Table 17.5). Other tools can be employed, such as cost-effectiveness analysis and multi-criteria analysis in order to draw stakeholders into the process (Posner, 2004; Matheny, 2007; Mechler and Schinko, 2016). Stakeholder participation in measuring costs and benefits and in the modelling can aid the process (Doukas and Nikas, 2020).

Logic trees include a range of decision protocols and multi-criteria rules, either based on quantitative or qualitative categories (Roncoli et al., 2016), often termed multi-criteria analyses. The concept of the logic tree has been increasingly applied in climate risk decision-making contexts (Nikas et al., 2018).

Since the AR5, robust decision-making methods are increasingly used to account for deep uncertainty in many climate related risks (*high confidence*) (Marchau et al., 2019; Table 17.5), particularly when decisions need to be made well in advance of when the adaptations need to be implemented (Cross-Chapter Box.5 in SROCC Chapter 1; Cross-Chapter Box DEEP in this Chapter). Reducing risk and building resilience under the context of these types of wicked problems require asking "what if" questions about the future, remain flexible in the face of uncertainty, and seek out policies that provide good outcomes no matter what the future climate might bring (*high confidence*) (17.6; e.g. Larson et al., 2015; Bhave et al., 2016; Bhave et al., 2018). In these cases, trade-offs can be assessed and options can be prioritized through iterative decision-making processes, such as multi-criteria decision-making, robust decision-making, and dynamic adaptation pathway planning (*high confidence*) (Table 17.5; Kwakkel et al., 2014; Kwakkel et al., 2016; Shortridge et al., 2016; Lawrence and Haasnoot, 2017; Haasnoot et al., 2019; Lempert, 2019; Roelich and Giesekam, 2019; Haasnoot et al., 2020a). They can address limitations of data-intensive robust decision-making in developing countries (Daron, 2015), can use proxy data to enable the use of robust decisions in data scarce contexts (Shortridge and Guikema, 2016; Ahmad et al., 2019), incorporate multiple-objectives into robust decision making (Singh et al., 2015), and pathway development supplemented by real options analysis (Buurman and Babovic, 2016; Smet, 2017; Haasnoot et al., 2019; Lawrence et al., 2019). Often, there are close synergies between the application of these methods and using scenario analyses (Workman et al., 2021).

[START CROSS CHAPTER BOX DEEP HERE]

Cross Chapter Box DEEP: Effective adaptation and decision-making under deep uncertainties

Authors: Carolina Adler, Robert Lempert, Andrew Constable, Marjolijn Haasnoot, Judy Lawrence, Katharine J. Mach, Simon French, Robert Kopp, Camille Parmesan, Mauricio Domínguez Aguilar, Elisabeth A. Gilmore, Rachel Bezner Kerr, Adugna Gemeda, Cristina Tirado-von der Pahlen, Debora Ley, Rupa Mukerji.

Decision relevant uncertainties for managing climate risk

Adaptation decision-making can benefit from assessments that support planning for both 'what is most likely' as well as for stress-testing adaptation options over a range of scenarios (Sections 11.7 and 17.3; Cross-Chapter Box.5 in SROCC Chapter 1). This Cross-Chapter Box summarises how deep uncertainties (Section 1.2; IPCC, 2019a) can be assessed in decision-making and addressed practically for adaptation. The concept of deep uncertainty has evolved in IPCC assessments, expanding beyond a focus on reducing uncertainty, to also considering a range of tools and approaches that guide robust and timely decisions to address climate risks. Deep uncertainty is defined as circumstances where experts or stakeholders do not know or cannot agree on one or more of the following: (1) appropriate conceptual models that describe relationships among drivers in a system; (2) the probability distributions used to represent uncertainty about variables and parameters; and/or (3) how to weigh and value desirable alternative outcomes (Cross-Chapter Box.5 in Chapter 1; Lempert et al., 2003; IPCC, 2019a; IPCC, 2019c).

Decisions by individuals, households, the private sector, governments, and public-private partnerships are generally made with partial or uncertain information. This is also the case for adaptation and development decisions where there is often deep uncertainty about the impacts and the societal conditions, preferences and priorities, and responses over time. Under such conditions, decision-makers employ decision processes and scientific information differently from situations where most decision-relevant information is available, uncontested, and confidently characterized with single joint probability distribution. Assuming scientific information is certain, when it is not, is a barrier to effective communication of risks and to successful decisions under uncertainty, increasing the potential for failure and regret of investments, lost opportunities, and transfers of costs to future generations (Sarewitz and Byerly, 2000; Marchau et al., 2019; Sections 11.7 and 17.6).

Addressing deep uncertainty is contextual as it depends on the decision options available, outcomes at stake, and the available scientific information (Box 1.1. in Marchau et al., 2019). The IPCC uncertainty guidance note (Mastrandrea et al., 2010) addresses only the latter (see also Mastrandrea and Mach, 2011; Section

1.3.4). Deep uncertainty is generally more salient when policy-relevant statements have *low confidence* or lack relevant data or information, or in cases where significant uncertainty contributes to disagreements and disputes (Sriver et al., 2018). Recent work has also included moral uncertainty (MacAskill et al., 2020) by evaluating the outcomes of alternative strategies with analyses organized around different perspectives on the appropriate principles of justice (Ciullo et al., 2020; Section 17.3; Jafino et al., 2021; Lempert and Turner, 2021).

To better communicate deep uncertainty, WGI AR6 complements projections of likely global mean sea-level change, driven by processes in which there is at least *medium confidence*, with projections that incorporate ice-sheet processes in which there is *low confidence* (Section 9.6.3 in Fox-Kemper et al., 2021). The latter are accompanied by storylines to highlight the physical processes that would generate extreme outcomes (Box 9.4 in Fox-Kemper et al., 2021). These low-confidence projections and storylines are useful because the likelihood of high-end (> 1.5 m) global mean sea level (GMSL) rise in the 21st century is difficult to determine but important to consider in coastal settings (e.g., CCP2; Cross-Chapter Box SLR in Chapter 3). High-end GMSL rise by 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of Marine Ice Sheet Instability and Marine Ice Cliff Instability around Antarctica, or faster-than-projected changes in the surface mass balance and dynamical ice loss from Greenland (Box TS.4 in Arias et al., 2021; Box 9.4 in Fox-Kemper et al., 2021). In a low-likelihood, high-impact storyline and a high CO_2 emissions scenario, such processes could in combination contribute more than one additional meter of sea level rise by 2100 (Box TS.4 in Arias et al., 2021; Section 9.6.3 and Box 9.4 in Fox-Kemper et al., 2021). Other hazards assessed in WGI AR6 that address similar aspects that are relevant for decision-making under deep uncertainty, include drought (Section 8.4.1.6 in Douville et al., 2021; Section 11.6.5 in Seneviratne et al., 2021), flood (Section 8.4.1.5 in Douville et al., 2021); (Section 11.5.5 in Seneviratne et al., 2021), wildfire weather (days) (Section 11.8.3 and Box 11.2 in Seneviratne et al., 2021), among others.

Approaches and information requirements for managing deep uncertainty

Many approaches are available for evaluating robust decisions under conditions of deep uncertainty (Sections 17.3 and 11.7; Box 11.5 in Chapter 11). The majority use multiple scenarios to stress-test adaptation options and explore how alternative adaptation pathways might evolve under a range of different conditions (Swanson). Approaches differ in terms of their focus, types of strategies best addressed, and data and other resources required (Marchau et al., 2019).

"Low regret" options are one simple and common approach to deep uncertainty (Sections 17.3 and 17.6) expected to perform well over a wide range of scenarios and represent one example of robust strategies. However, such options will generally be insufficient for adaptive responses to adapt over long timeframes and to avoid lock-in of investments (Section 11.7; Box 11.5 in Chapter 11).

"Adaptation pathways" provide another approach for addressing deep uncertainty and staging decisions over time (Haasnoot et al., 2013), by linking the choice of near-term adaptation actions with predetermined future thresholds. Observation of such thresholds trigger subsequent actions in the planning or implementation stages of adaptation strategies. Adaptation pathways can begin with low-regret, near-term actions that aim to create and preserve future options to adjust if and when necessary. Alternative pathways can be explored and evaluated to design an adaptive plan with short-term actions and long-term options.

Climate resilient development (CRD), and the pathways to it, can also involve decision making under deep uncertainty. Literature assessed in sectoral and regional chapters of this report present several examples of potential risks to achieving development goals under climate change, at global as well as national and local levels (*high confidence*) (Chapter 18). Achieving CRD depends on negotiation, contestation, and reconciliation of trade-offs among diverse actors, who in turn value preferred outcomes differently with respect to associated climate risks and uncertainties, hence the prospect for deep uncertainty to manifest (Section 18.5). Deep uncertainty also characterizes the development process itself, given that fundamental changes and disruptions are part of the transformational changes required to shift towards CRDPs.
The "keeping options open" approach, plans by using a series of sequential decisions and actions in the near-term to avoid closing off potentially promising future options (Rosenhead, 2001; Section 2.6), or by using real options, take near-term actions that create currently unavailable options in the future (Kwakkel, 2020).

Deep uncertainty approaches use a wide range of storylines as scenarios to test low regret options and to provide information relevant for potential thresholds for use in adaptation pathways (Haasnoot et al., 2013; Box 11.4; Box 11.6; Sections 11.7; 17.3).

Deep uncertainty approaches enhance the value of monitoring to detect signals of change in a timely manner (*medium confidence*). Actionable warning can come from climate signals, and socio-economic indicators/signposts, including drivers of change, vulnerability, and impacts, best suited for timely, reliable and convincing signals for decision making that anticipate future changes and the need for adaptation or the potential to seize opportunities (Hermans et al., 2017; Haasnoot et al., 2018; Stephens et al., 2018; Oppenheimer et al., 2019). For early warning signals to be decision-relevant, they need to have institutional connectivity to enable action (Haasnoot et al., 2018; Sections 1.4; 11.4; 11.7; Table 11.18) (*medium confidence*).

Examples and case studies from across the WGII report

There are diverse examples of the practical application of deep uncertainty methods across different climate change hazards in many regions of the world. For instance, low-regret options have been used to address the impacts and risks of landslides and debris flows in mountains (Section CCP5.2.6). Their frequency and magnitude are already widely experienced (Section CCP5.2.6) and projected to increase (Section CCP5.3.2.1). However, managing these associated risks also requires joint consideration of projected vulnerabilities and exposure of people and infrastructure, including the multiple and dynamic non-climate related factors that are relevant for how the impacts manifest in context, such as population growth and land use planning (CCP5.2.6). Here, context-specific deliberative processes are used that include scenarios to guide and specify preventive measures with higher effectiveness than protective (infrastructure) measures could achieve alone. Low-regret adaptation involves raising awareness and accounting for long planning horizons to address the uncertainties associated with such risks, for instance in mountain regions, including education (Sections CCP5.4.1; CCP5.2.6), with co-benefits such as addressing changes in water availability for supply and demand (CCP5.4.1).

Adaptation pathways have been used to address SLR and changes in extreme rainfall through flood risk and management (Cross-Chapter Box SLR in Chapter 3; CCP2; Sections 13.2, 11.3 and 11.7): for example, adaptive plans in the Netherlands (Van Alphen, 2016; Bloemen et al., 2019), climate resilient development in Bangladesh (Hossain et al., 2018; Zevenbergen et al., 2018), adaptive spatial pathways for infrastructure retreat and for flood risk management in New Zealand (Lawrence et al., 2019a; Kool et al., 2020) and adaptive strategies such as in the cities of London (Ranger et al., 2013; Hall et al., 2019), New York (Rosenzweig and Solecki, 2014), and Los Angeles (Aerts et al., 2018a). This approach is mainstreamed into guidance documents such as the Climate Risk Informed Decision Analysis (CRIDA) (Mendoza et al., 2018), national guidance and policy briefs to address coastal hazards and sea-level rise planning in New Zealand (Lawrence et al., 2018; Lawrence et al., 2019b), planning for sea-level rise in California (OCP, 2018), and synthesis documents by the government of Canada on marine coasts (Lemmen et al., 2016). Furthermore, examples from the United Kingdom, New Zealand and The Netherlands point to the development of monitoring plans to detect signals for climate adaptation (Stephens et al., 2017; Haasnoot et al., 2018; Bloemen et al., 2019).

Climate smart planning, with a focus on keeping options open, can play a role in reducing species extinction rates (Sections 2.5; 2.6). When and where and for whom particular irreversible impacts will occur is deeply uncertain, for example the extinction of a species. Even at the lowest emissions scenarios, some local species will become extinct, but estimates of extinction risk are highly uncertain, typically varying by factors of 2-3 even for one species (Section 2.5) (*medium confidence*). Risks of species' extinctions are lowered by reducing emissions but keeping options open for as long as possible and avoiding irreversible actions are key to developing a climate-resilient adaptive pathway so that real-time climate-driven changes can inform actions. Nature-based solutions (NBS) are emerging as key players for mitigation. With smart planning, NBS offer approaches that not only provide substantial mitigation, but also considerable adaptation benefit to biodiversity, and human health and well-being. Done poorly, such projects can result in large negative impacts on humans and nature. An NBS climate-sensitive decision framework leading to "win-win" solutions for mitigation and adaptation is shown in Figure 1 Cross-Chapter Box NATURAL in Chapter 2 (see also Sections 2.4.2.5, 2.5, 2.6, 5.4.4.4, and 5.14.1; Cross-Chapter Box ILLNES in Chapter 2; Cross-Chapter Box COVID in Chapter 7).

In view of these multiple and diverse examples, it is evident that the application of deep uncertainty methods is enabling decisions to be made in a timely manner that avoid foreseeable and undesirable outcomes and take opportunities as they arise (*high confidence*).

Prospects for adaptation decision-making

Deep uncertainty is increasingly salient for decision-making as recognition of climate-related risks and related uncertainties has increased (*high confidence*). These risks can compound and cascade to become new risks, increasing the breadth, frequency and severity of climate change impacts and the consequently increasing scale and scope of adaptation (*high confidence*) (Cross-Chapter Box Extremes in Chapter 2; Sections 1.3.1.2, 2.3, 2.5, 2.6, 11.5, 11.7, and CCP5.3.1). Waiting until uncertainties are resolved (if they ever can) may leave little or no time to adapt. The lead-time for planning and implementation of adaptation can take decades (Haasnoot et al., 2020b; Cross-Chapter Box SLR in Chapter 3) and socio-economic developments can lock-in undesirable pathways where underlying vulnerabilities and exposure, such as poverty, conflict, and their associated displacement of people, remain unaddressed (Sections 5.13.4; 16.5.2.3.8; Cross-Chapter Box Migrate in Chapter 7).

Overall, there is growing evidence that effective implementation of strategies developed for deeply uncertain problems require adequate mandates and funding frameworks, preparedness and disaster response plans, and monitoring and evaluation of the strategy outcomes, against how the future unfolds (*medium confidence*). Collaborative and adaptive governance arrangements, and education and awareness raising, promote learning environments for community engagement, and are essential for the effective implementation of robust adaptation plans (*medium confidence*) (Sections 5.14.1; 17.3 and 11.7).

[END CROSS CHAPTER BOX DEEP HERE]

17.3.1.3.5 Adaptive feedback management

Iterative decision making requires that the implementation of adaptations are reviewed to determine whether the adaptation effectively achieved the objectives, and whether adjustments or additional actions were required (17.5). Adaptive feedback management is an approach to managing dynamic climate risks by designing a field monitoring program to provide data to an assessment procedure which in turn advises on what adjustments need to be made to a 'control action', all of which are part of the adaptation to be implemented (Hurlbert et al., 2019; Figure 17.6). Adaptive feedback management is more able to account for the dynamic nature of risk and the future emergence of unforeseen risks because of the active design of how to adjust the management approach (Dickey-Collas, 2014).

Adaptive feedback management is important for managing climate risks that fall within the *Cynefin* context of chaos, relying on observations and indicators to learn about the system and to trigger actions (*medium confidence*) (Helmrich and Chester, 2020). It has been a valued approach for managing wildfish fisheries in many oceans (*high confidence*) (Fulton et al., 2019; Hollowed et al., 2020; Bahri et al., 2021), and is important for responding to the challenges of climate change (*high confidence*) (Holsman et al., 2019; Hollowed et al., 2020; Bahri et al., 2021).

While the benefits of investment in data and assessments can outweigh the costs of implementation (*low confidence*) (Fulton et al., 2019), the implementation may take time when resources are limited, particularly in developing nations, where low-cost approaches will be needed for deciding on pathways for adaptation (Bhave et al., 2016; Shortridge et al., 2016).

Iterative decision making and adaptive feedback management meet when the feedback management procedure is reviewed in total for its effectiveness in one of the review and adjustment iterations. At present, a common approach for assessing different adaptation options and their interaction is by using, e.g., scenarios in dynamic models (Adam et al., 2014; Girard et al., 2015). An emerging field in adapting fisheries to climate change is to embed the decision-making system in the scenario models in order to assess the capability of feedback management (decision-making, monitoring and capacity for adjustment of the options over time) to achieve satisfactory trade-offs amongst the objectives of the different stakeholders (*medium confidence*) (Melbourne-Thomas et al., 2017; Holsman et al., 2019; Hollowed et al., 2020). This method can enable prospective evaluation of future whole-of-management scenarios described in this chapter.

17.3.2 Integration Across Portfolios of Adaptation Responses

In recent years, methods for simultaneously considering multiple societal and sectoral objectives, climate risks and adaptation options have been emerging, often termed 'integrated' approaches (Hadka et al., 2015; Garner et al., 2016; Rosenzweig et al., 2017; Giupponi and Gain, 2017a; Stelzenmuller et al., 2018; Marchau et al., 2019). Different decision-making approaches can be complementary (Kwakkel et al., 2016) and multiple approaches will be needed to manage risks across sectors, in space and over short to long time scales (see Section 17.6).

Higher level integration was first presented in SREX (Burton et al., 2012; Lal et al., 2012; O'Brien et al., 2012) and includes concepts of planning, coordination and mainstreaming (Lal et al., 2012), consideration of cross-scale dynamics and nested vulnerabilities (Klein et al., 2014), as well as decision-making across governments and sectors (Denton et al., 2014; Mimura et al., 2014).

Since AR5, recognition of the importance of using integrated adaptation to improve climate risk management across the nexus between many sectors and across regions has increased *(high confidence)* (Harrison et al., 2016; Challinor et al., 2018). This was highlighted in the Special Report on Climate Change and Land (Hurlbert et al., 2019); advanced planning and integration of adaptation responses are needed over many levels *(medium confidence)* (Göpfert et al., 2019; Section 17.6; Woodruff and Regan, 2019). The complexity of managing this nexus may be compounded by the potential for antagonistic or synergistic effects among and between climate impacts, and changes arising from local sectoral activities and independent adaptation responses to those risks *(high confidence)* (Crain et al., 2008; Piggott et al., 2015; Adger et al., 2018; Brown et al., 2018; Stelzenmuller et al., 2018; Simpson et al., 2021), such as the cross-sectoral demands for freshwater (Xue et al., 2015; Azhoni et al., 2018). Integrated adaptation will also help facilitate management of new and emerging risks, help identify when response plans may need to be changed in light of the dynamics of risk over time, and help identify solutions that are less likely to constrain future options for adapting to future needs (Wise et al., 2016).

Implicit to managing cross-sectoral interactions, including the nexus concept, is that the interlinkages between multiple sectors are systemic, and therefore solutions to challenges arising from any one sector can only be satisfactorily addressed by considering the connections to other sectors at the same time (Wichelns, 2017). Challenges for integrated adaptation include: (1) to sufficiently capture the complexities between the nexus dimensions (Weitz et al., 2017); (2) to adequately consider the time, costs and challenges of coordination and cooperation (Wichelns, 2017); (3) to consider the political economy in which progress toward more integrated solutions could take place, not only account for technological requirements(Leck and Roberts, 2015); (4) to obtain sufficient temporal or spatial data to capture the interactions between natural and social processes (Shannak et al., 2018); (5) to connect these considerations to decision-making and policy processes in order to gain insights into the conditions for collaboration and coordination across sectors, including external dynamics and political and cognitive factors determining change (Weitz et al., 2017); and (6) to develop a coherent framework against which to assess results and observations (Crain et al., 2008; Wichelns, 2017).

17.4 Enabling and Catalysing Conditions for Adaptation and Risk Management

17.4.1 Introduction

The WGII AR5 identified - with high confidence - a range of factors that could enable or limit planning and implementation of adaptation options and potentially their effectiveness (Klein et al., 2014; Mimura et al., 2014; Noble et al., 2014). These included governance, finance, knowledge and capacity as enabling factors, as well as cultural, social, political and economic differences that influence individual and collective willingness and capability to act. The AR6 SRs (specifically, de Coninck et al., 2018; Roy et al., 2018;

Collins et al., 2019; Hurlbert et al., 2019) reinforced the AR5 findings, further noting that the transitions needed for climate resilient development would need to be supported by radical shifts in governance, knowledge development, technology application, finance and economics, and social norms.

This section builds on the AR5 and AR6 SRs by reviewing new evidence on three key enablers identified in the AR5: governance, finance and knowledge. The focus is on assessing new evidence on (i) understanding of these enabling conditions, (ii) how they have changed on the ground, and (iii) whether these conditions have enabled progress on adaptation and risk management. The section also addresses an emerging related topic, the role of catalysing conditions and actors in accelerating action on climate change adaptation, such as litigation on failure to adapt, understandings of urgency, and the aftermath of extreme weather events. While enabling conditions are necessary for action, they are not by their presence enough; catalyzing conditions emerge when game-changing circumstances become present, such as when a high-profile extreme weather event occurs or when a champion drives change in an organisation.

17.4.2 Enabling Condition 1: Governance

Governance is an inclusive concept of the range of means for deciding, managing, implementing, and monitoring climate change responses. It can involve the contributions of various levels of government (global, international, regional, sub-national and local) along with those from the private sector, of nongovernmental organisations, and of civil society. The importance of supportive governance arrangements is reiterated widely across regional and sectoral chapters in this report, in multiple different contexts (very high confidence).

17.4.2.1 Legal, Policy and Regulatory Instruments

17.4.2.1.1 Climate legislation

Legal systems play an important governance role in facilitating responses to climate change across all levels of society (*high confidence*) (Ruhl, 2010; McDonald and Styles, 2014; Mehling, 2015). Laws can facilitate climate action in multiple ways, including through: (i) mandating and guiding the behaviour of governance structures and actors, (ii) fostering coordination between different levels of government, (iii) enforcing climate responses, (iv) its symbolic value as well as (iv) aligning scientific evidence and societal norms (Mehling, 2015; Scotford et al., 2017). Laws also can embed climate change planning within the administrative structure of a state rendering policy less vulnerable to revocation (Scotford et al., 2017). Extensive revision to laws has occurred in the last decade: a survey of 164 countries showed that over 1200 climate-related national laws and policies have been published with approximately 44% being acts of parliament (Nachmany et al., 2017).

National climate change laws are important for transposing ratified international commitments into domestic regimes, such as the Paris Agreement and the Convention on Biodiversity, as well as voluntary agreements such as the Sendai Framework for Disaster Risk Reduction. In turn, the enactment of domestic laws can yield useful experiences and foster engagements that positively influence and support the development of international commitments (Townshend and Matthews, 2013; Mehling, 2015). Strong and consistent regulatory frameworks also support the flow of climate finance to developing countries that have such frameworks (Nachmany et al., 2017). The successful implementation of national and sub-national climate change and related policies and strategies are often contingent upon the underlying legislative framework empowering, mandating or guiding their review, implementation and enforcement (Averchenkova and Matikainen, 2017; Scotford et al., 2017) (*medium confidence*).

Existing legal systems also pose potential barriers to adaptation, as described in Chapter 9 (Africa) and Chapter 8 (Poverty, Livelihoods and Sustainable Development). Laws may reinforce governance arrangements and regulations state that do not support responses to climate change, and exacerbate existing vulnerabilities and inequalities (Craig, 2010; Arnold and Gunderson, 2013; Wenta et al., 2019). In such cases laws may require review and revision or replacement, and at the same be written in ways that foster adaptive management (Craig, 2010; Ruhl, 2010; Cosens et al., 2017).

Even though there is no agreed definition of or typology for climate change laws (Mehling, 2015), studies have tended to classify climate change laws as being ‘framework’ or ‘sectoral’ (see Table 17.6 for examples). Framework laws offer a comprehensive, unifying basis for climate change policy, addressing multiple aspects or areas of climate change mitigation or adaptation (or both) in a holistic and overarching manner (Townshend et al., 2011; Fankhauser et al., 2014; Nachmany et al., 2015; Clare et al., 2017b); they are powerful levers for setting national and sub-national agendas, creating climate change institutional structures, enabling policy implementation, and driving the passage of additional sectoral legislation and regulations (Clare et al., 2017b). Prior to 2010, national framework laws tended to have a mitigation focus while more recent laws or amendments thereto have an increased adaptation focus (Rumble, 2019b). No evidence indicates whether general or specific framework laws yield better outcomes; however, reviews of more recent examples of framework laws in Africa suggest a trend towards more specificity in the required content of adaptation strategies and duties (Rumble, 2019b).

A sectoral approach to climate change legislation grafts climate-related provisions into existing laws, such as environmental impact assessment, flood insurance and infrastructure planning, collectively creating an aggregated legal landscape (Townshend et al., 2011; Gerrard and Fischer, 2012; Nachmany et al., 2015; Scotford et al., 2017; Rumble, 2019a). This approach is particularly relevant to adaptation challenges which intersect with numerous bodies of law that are dedicated to other societal concerns (Gerrard and Fischer, 2012). However, integrating such considerations can be challenging in certain areas of law, particularly those relating to property rights, water rights and endangered species protection (Gerrard and Fischer, 2012). The incorporation of adaptive management principles (including monitoring, periodic evaluation, and response modification) within existing laws can enhance their enabling role and foster greater resilience (Godden, 2012; Arnold and Gunderson, 2013; McDonald and Styles, 2014).

The legal regime for adaptation is too embryonic for assessment of good practice design and content, although similarities can be seen in the framework laws and draft bills across several countries. Some studies highlight the importance of domestic ‘whole of legal system’ analysis prior to developing of modifying law. This can identify the range of existing legislative instruments that can directly intersect with climate change, along with related contextual factors such as national circumstances, governance frameworks, and political and economic realities as well as national administrative culture (Scotford et al., 2017). This helps any new climate change laws to be absorbed into, and harmonise with, the established legal system of each country (Scotford et al., 2017). Efforts are underway to assist countries in such assessments and the identification of areas for legislative reform, for example through the Commonwealth and UN Environment’s Law and Climate Change Toolkit. Similarly, databases such as the Grantham Research Institute on Climate Change and the Environment and the Sabin Center on Climate Change Law are expanding the knowledge base of national climate legislation developments.

Table 17.6: Selected examples of framework and sectoral law approaches adopted by different nations that represent a variety of regional contexts.

Example	Legal Approach	Description	References
United Kingdom Climate Change Act 2008	Framework	Provides for development of climate change impact reports and programmes for adaptation. Dedicated institutional structure with advisory body, adaptation planning provision, reporting/information obligations, climate change mainstreaming, climate change trusts, or financial arrangements.	(Averchenkova et al., 2021)
Kenya Climate Change Act 2016	Framework	Modelled on the United Kingdom Climate Change Act. Provides for development of climate change impact reports and programmes for adaptation. Dedicated institutional structure with advisory body, adaptation planning provision, reporting/information obligations, climate change mainstreaming, climate change trusts, or financial arrangements.	(Rumble, 2019b)

Mexican General Law on Climate Change 2012	Framework	Imposes positive duties upon government to implement "adaptation actions" - conservation, sustainable use and rehabilitation of beaches and coasts; water programmes for watersheds; the establishment of protected areas and biological corridors; the development of risk atlases; human settlement and urban development programmes; and prevention programs targeting diseases exacerbated by climate change. Includes development of economic instruments including fiscal incentives, credits, bonds, civil liability insurance, market-based instruments.	(Averchenkova and Guzman Luna, 2018)
New Zealand Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act 2012	Sectoral	Incorporates adaptive management principles by regulating the issuance of marine consents with conditions allowing change based on ecological change and indicators.	(Godden, 2012)
Seychelles Conservation and Climate Adaptation Trust of Seychelles Act 18 of 2015	Sectoral	Provides for the establishment of a dedicated trust fund for conservation measures and climate change adaptation measures.	(Etongo et al., 2021)
Commonwealth of Dominica Climate Resilience Act 16 of 2018	Sectoral	Promotes disaster recovery and resilience building. Establishes the Dominica Climate Resilience Policy Board and sets out its functions and duties. Requires the development of a Climate Resilience and Recovery Plan.	(Government of the Commonwealth of Dominica, 2018)
Swedish National Strategy for Climate Change Adaptation (Government Proposition 2017/18:163)	Sectoral	Amends Sweden's Planning and Building Act (2010: 900) by requiring Municipalities to assess the risk of damage to the built environment from climate risks well as how such risks may change in the future; requires detailed plans for measures to address land permeability when issuing a land permit; adopts the Swedish National Climate Strategy into law.	(Government of Sweden, 2017)
Argentinian Glaciers Preservation Law N 32.016 (2010)	Sectoral	Provides for minimum budgets to protect the national glacial water sources that supply the Mendoza oasis. Establishes that all of Argentina's glaciers and its periglacial environment are to be protected, irrespective of size.	(Warner et al., 2019)
Netherlands Delta Act on Water Safety and Fresh Water Supply	Sectoral	Protects the Netherlands from risks such as sea level rise and extreme rainfall. Establishes a Delta Programme to secure fresh water supply and address climate risks/sea level rise; a Delta Fund to operate the Programme and a Commissioner.	(Van Alphen, 2016)

17.4.2.1.2 Climate change policies, strategies and plans

Climate change policies and plans are important in the translation of national commitments and legal requirements into specific on the ground strategies and guidelines, which enable actions across multiple spheres and scales of government and non-government institutions and actors.

Substantial developments in adaptation policy have occurred since AR5 (*high confidence*). Perhaps the most significant is the Nationally Determined Contributions (NDCs) required under the Paris Agreement, where 184 out of 197 parties to the UNFCCC have already submitted their first plans (UNDP and UNFCCC, 2019). The NDCs have allowed countries to articulate their priorities and ambition with respect to climate action and it has been suggested that these can in turn lead to cascading policies (and laws) that drive and enable adaptation and climate risk management. Analysis of the first NDCs submitted in the lead up to and after the

Paris Agreement showed that adaptation priorities were more often articulated by developing countries and least developed countries, while developed countries and emerging economies focused mostly on mitigation (Pauw et al., 2019). As of 2019, over 90 developing nations are at various stages of preparing National Adaptation Plans and 112 nations have indicated their intention to revise their NDCs for the 2020 update (UNDP and UNFCCC, 2019).

Several other international agreements including the Sendai Framework for Disaster Risk Reduction and the UN Agenda 2030 Sustainable Development Goals have had significant impacts on the adaptation and risk-management decision-making processes. For example, the Sendai Framework articulates the need for improved understanding of disaster risk in all its dimensions of exposure, vulnerability and hazard characteristics; accountability for disaster risk management; preparedness to "Build Back Better"; recognition of stakeholders and their roles; mobilization of risk-sensitive investment to avoid the creation of new risk resilience of health infrastructure, cultural heritage and workplaces; strengthening of international cooperation and partnership, and risk-informed donor policies and programs, including financial support and loans from international financial institutions.

Specific adaptation policies have been formulated at national, regional/state and local levels across 68 countries and 136 coastal cities (Olazabal et al., 2019a). At the national level, the quantity and complexity of adaptation policies have increased since AR5, with most policies coming into force since 2009 (Nachmany and Setzer, 2018). Adaptation is addressed in the executive climate policies of at least 170 countries (Nachmany et al., 2019a). Documented sub-national adaptation policies are more prevalent in developed countries and emerging economies, as compared with low- and middle-income ones (Olazabal et al., 2019b). For example, by 2017 26% of large and medium-sized European cities had an adaptation plan or a joint adaptation-mitigation plan in place (Reckien et al., 2018a).

Adaptation policies often comprise multiple goals and instruments, which develop over time, especially where jurisdiction over policy issues is shared among agencies or levels of government (Río and Howlett, 2013). The increase in the number and complexity of policy instruments across geared towards adaptation raises questions of coherence and alignment between the selected policy mixes and their effectiveness (England et al., 2018; Ranabhat et al., 2018; Lesnikowski et al., 2019).

Evaluation of national adaptation plans (NAPs) has only recently been undertaken. Woodruff and Regan (2019) compared national adaptation plans from 38 countries and concluded that most were strong in identifying vulnerabilities and identifying potential adaptation options but were weaker in articulating implementation pathways and monitoring of progress; plans written by multi-agency teams were nearly always of higher quality. Garschagen et al. (2021) showed that while most NAPs consider future changes in climate hazard, many do not consider how vulnerability and exposure might change, concluding that this limits the potential effectiveness of the plans. Morgan et al. (2019) showed that NAPs that are consistent with the Paris Agreement can enable development pathways that promote synergies between environmental, social, and economic goals.

17.4.2.1.3 Impact of legal and policy instruments

Commitment to act, and guidance on how to do so, from international and national governance levels can drive national and sub-national adaptation (Reckien et al., 2013; Heidrich et al., 2016; Reckien et al., 2018a). For example, more local plans have been developed in European countries where it is obligatory for local municipalities to develop climate change plans (Reckien et al., 2018a). Local government have also drawn on non-binding national climate frameworks, as well as international frameworks (such as European law) or international networks (such as Global Covenant of Mayors for Climate and Energy) to guide their actions (Reckien et al., 2013; De Gregorio Hurtado et al., 2015; Reckien et al., 2015; Heidrich et al., 2016; Reckien et al., 2018a).

However, a national framework is not always sufficient to trigger climate change action on the lower level, in particular when the national guiding document fails to clearly formulate how it should be used and “translated down” to lower governance levels (De Gregorio Hurtado et al., 2015). Guidance on how to apply a national framework at lower governance levels can assist in their uptake.

In the case of climate change legislation, research on the impact of adaptation laws is limited, save for a few studies (Averchenkova and Matikainen, 2017), because many framework laws, particularly those with more of an adaptation focus, have only been published recently (Rumble, 2019b). Reviews of the implementation of the risk assessment and adaptation components of the UK's Climate Change Act 2008 suggest that they had a weaker implementation record compared to mitigation provisions (Fankhauser et al., 2018), potentially because implementation of adaptation is more complex as compared to mitigation as shown for the local level (Reckien et al., 2019). However, the UK Act is considered to have made action on climate change more predictable, more structured and more evidence-based (Averchenkova et al., 2021).

There are numerous examples of regulatory and project-based innovations by local governments. Their impact, however, is uneven, with much depending on the implementation capacity of local governments and other socio-institutional barriers, including those relating to mandate and joint project implementation, cross-departmental working, planning cycles, concerns relating to legal liability and compensation, political appetite and cost (Godden, 2012; Taylor, 2016a). Notwithstanding implementation challenges, evidence is emerging that overarching framework laws play a foundational and distinctive role in supporting effective climate governance, including adaptation governance (Fankhauser et al., 2018) and are drivers of subsequent activity (Townshend et al., 2011; Fankhauser et al., 2014; Clare et al., 2017b), especially when formulated with clear guidance for all related actors, including lower level of governance (De Gregorio Hurtado et al., 2015). This may explain the rapid increase in both local and national climate change laws, now with an increased emphasis on regulatory provisions to increase resilience and reduce vulnerability.

17.4.2.1.4 Regulations and standards

The presence and articulation of regulations and standards that address climate risk, such as building codes and land use zoning are key enabling factors for effective decision-making (Kim et al., 2020). Regulations and standards provide a framework for common understanding of when and under what conditions action should be taken specifically in relation to the construction and maintenance of the built environment, infrastructure and environmental and social practice (Grynning et al., 2020). Regulations and standards for climate action emerge primarily from two settings. First, as an addition or augmentation to existing regulations and standards that emerged initially to address existing potential climate extremes and stresses (e.g. size of culverts in response to maximum rainfall and runoff conditions). And second, new regulations and standards that were developed in direct response to new or emergent climate risks (e.g. regulations in response to new presence of mean monthly high tide flooding) (Qiao et al., 2018). Commonly agreed upon social norms and conventions also can be described as regulatory and providing a set of standards.

The regional and sectoral chapters of this report provide significant evidence of how regulations and standards enhance or hinder opportunities for climate risk management and adaptation. Relevant regulations and standards are especially evident in the oceans and coastal domains (Chapter 3 and CCP2, in cities and infrastructure (Chapter 6), and the water (Chapter 4) and food sectors (Chapter 5). Europe and North and South America (Chapters 12, 13 and 14) have the most frequent documented occurrences of examples of regulations and standards. Regulations and standards focused on building codes to protect against extreme event and loss, water regulations and agreements to protect water supply and lessen drought impacts, and health codes to limit heat exposure are the most frequent examples of such practices. Deficiencies of regulations and standards have been noted with respect to their capacity to manage species migrating from climate change, and to provide opportunities for transformative adaptation. The evidence from the sectors and chapters illustrate that more comprehensive regulations and standards lead to positive adaptation outcomes.

17.4.2.1.5 Environmental and social governance

Environmental and social governance refers to voluntary or non-legally required actions taken by participating parties to achieve a commonly defined goal (Bodin, 2017; DeCaro et al., 2017; Partzsch, 2020). While not explicitly described in the sectoral and regional chapters of this report, the maintenance and exercise of environmental and social governance decision-making strategies do enable adaptation practice and have become especially important when formal legal and policy regimes are not yet present. As formal regulation promotes clear and common understanding of climate risks and mechanisms to develop context specific appropriate solutions, voluntary code-making and self-regulation can forestall the need for legal action or can function as precursors to the formulation and implementation of legislation, laws, and regulations.

Social and environmental governance long has been presented within climate risk decision-making, although more typically in the domain of climate mitigation (Wright and Nyberg, 2016; Vandenbergh and Gilligan, 2017). Corporate climate decision-making emphasizes the importance of profit motives in shaping decisions however reputational factors as appropriate environmental stewards also can be important when linked to sensitivity of other stakeholders such as investors, lenders, customers, and employees (Vandenbergh and Gilligan, 2017). Pulver (2011) notes that climate issues influence corporate decision-making more strongly in organizations that are networked with other organizations that also consider these issues and through direct experience with climate-related events and associated organizational learning.

Since AR5, more case studies of social and environmental governance within the domain of climate adaptation have become evident, especially within the context of adaptive management experimentation (Vella et al., 2016; Beunen and Patterson, 2019; Blühdorn and Deflorian, 2019). Environmental and social governance strategies for climate adaptation are diverse and reflect context specific conditions of the decision-making process including the role of the state, the individual and private interests, formality/informality, social responsibility, sources of financing, and transparency. Environmental and social governance enables the testing and definition of implementation solutions, enhancing the opportunities for defining successful adaptation (Surminski, 2013). Several models and approaches to adaptive governance to promote adaptation and resilience in response to extreme weather events have been observed. These include polycentric and multi-layered institutions, participation and collaboration, self-organization and networks, and learning and innovation (Djalante et al., 2011).

The effectiveness of social and environmental governance varies by sector. For example, in the private business sector, Aragòn-Correa et al. (2019) assess the effects of mandatory and voluntary regulatory pressure on firms' environmental strategies. In summary, they find that analyses of the effects of voluntary pressure demonstrate that by themselves they are unlikely to bring about significant improvement in environmental outcomes. Professional organisations, however, have made progress in addressing sectoral standards relative to the adaptation process. This includes the development of new industry guidelines, codes, standards, specifications, in addition to the implementation of infrastructure inventories that incorporate evaluation of vulnerabilities and identification of priority at-risk areas (Chapter 14). Voluntary pressures by themselves are not likely to result in positive outcomes and instead should be coupled with mandatory regulatory pressure to achieve the environmental response desired (Bianco, 2020).

Since AR5, another key development in environmental and social governance has been the establishment of the Task Force on Climate-related Financial Disclosures (TCFD), which aimed to develop guidelines for companies to voluntarily report the financial implications of two broad categories of climate risk: the transition risks of shifting to a lower-carbon economy and the physical risks of climate change itself (TCFD, 2017). As of 2019, ~1,340 companies with a market capitalization of USD12.6 trillion and financial institutions responsible for assets of USD 150 trillion have expressed support for the TCFD (TCFD, 2020). An analysis of reports to the TCFD in 2016 showed that 83% of companies report on physical risks of climate change, and of these 82% reported on strategies to adapt to some of the identified risks (Goldstein et al., 2019). The same analysis also noted that: (i) the total of estimates of assets at risk were two orders of magnitude lower than generally accepted estimates of total financial risk; (ii) a minority of companies consider risks outside of their own operations or in their value chains; (iii) most underestimate or do not estimate the costs of adaptation; and (iv) many assume linear impacts and responses, neglecting the potential for tipping points or acceleration in risk and potentially transformative adaptation requirements. At this stage, TCFD has influenced many companies' thinking and comprehension of physical climate risk, but it appears too early to assess whether this has driven substantive responses to manage these risks.

17.4.3 Enabling Condition 2: Finance

Finance has long been recognised as an important enabling and catalysing factor for adaptation, climate resilient development and climate risk management. In Chapter 17, financing for adaptation and climate risk management is covered in the extended cross chapter box, Financing for Adaptation and Resilience (FAR), below. The Cross-Chapter Box aims to highlight key emerging evidence on financing of adaptation, covering both public and private sources and instruments. Climate finance is also covered in a dedicated chapter in the WGIII Report (WGIII AR6 Chapter 15), and readers should refer to this Chapter for a more comprehensive assessment of this subject from both a mitigation and adaptation perspective.

[START CROSS-CHAPTER BOX FINANCE HERE]

Cross-Chapter Box FINANCE: Finance for Adaptation and Resilience

Authors: Mark New, Madeleine Rawlins, David Viner, Charlene Watson, Lily Burge, Lionel Mok, Lauren Arendse, Vita Karoblyte, Liane Schalatek and Neha Rai and Baysa Naran, So-Min Cheong, Nicoletta Giulivi.

Introduction

This Cross-Chapter Box reports on: (i) new evidence on the finance needed for adaptation and resilience, and uncertainties in these estimates; (ii) the emerging public and private climate finance architecture; (iii) the status of financing for AR, including sources, total flows, regional and sectoral distributions, (iv) equity considerations; (iv) opportunities and challenges for financing adaptation and resilience during and after the COVID-19 pandemic. This Cross-Chapter Box does not focus on finance for mitigation, which is covered in WGIII Chapter 15, nor the economic damages of climate change or financial aspects of Loss and Damage, which are covered in Cross-Working Group Box ECONOMIC (Chapter 16) and Cross-Chapter Box LOSS (this chapter), respectively.

Successive reports of the IPCC (Vellinga et al., 2001; Mimura et al., 2008; Yohe et al., 2008; Klein et al., 2014) and the AR6 Special Reports have noted the importance of finance as an enabler for adaptation, across both developed and developing nations. While various definitions for climate finance have been suggested, and the UNFCCC has yet to have an agreed definition, the IPCC (see Glossary) defines climate financing as "*the financial resources devoted to addressing climate change by all public and private actors from global to local scales, including international financial flows to developing countries to assist them in addressing climate change. [It] aims to reduce net greenhouse gas emissions and/or to enhance adaptation and increase resilience to the impacts of current and projected climate change. Finance can come from private and public sources, channelled by various intermediaries, and is delivered by a range of instruments, including grants, concessional and non-concessional debt, and internal budget reallocations".* Adaptation and resilience are often used interchangeably in climate finance discussions, although adaptation is a process while resilience (to climate risk) is the ability to progress towards desired outcomes in face of impacts from a changing climate (see Section 1.2.1).

[START BOX CROSS-CHAPTER BOX FINANCE.1 HERE]

Box Cross-Chapter Box FINANCE.1: The 100 Billion Climate Finance Commitment to Developing Countries

At COP16 in Copenhagen in 2009, developed country Parties to the UNFCCC committed to a goal of jointly mobilizing USD 100 billion per year by 2020 to address the climate change needs of developing countries (UNFCCC, 2009). This was in response to a threat by developing countries to walk out of the negotiations, as they perceived developed country support to be lagging and lacking in ambition (Roberts et al., 2021). The commitment was formalized in the Cancun Agreements (Decision 1/CP.16) in 2010 and was reaffirmed as a key element of the Paris Agreement in 2015 (Article 9, paragraph 4). At COP26 in 2021, formal deliberations will begin on a new climate finance goal to be adopted in 2025; the current USD 100 billion target will serve as the annual minimum until 2025 (Chhetri et al., 2020).

The "100 Billion" does not represent the total need to respond to climate change in developing countries, nor the global cost across all countries, as is sometimes interpreted in the literature and media. As shown below in this Cross-Chapter Box, the estimated cost of adaptation for developing countries ranges 15-411 billion USD per year for climate change impacts out to 2030, with the majority of estimates being well above 100 billion.

Proposed sources for the developed country commitment included "*a wide variety of sources, public and private, bilateral and multilateral, including alternative sources of finance"* and several instruments including grants and loans. Nonetheless, there remain differences of opinion on the types of finance that should count towards this goal, with several issues identified (*high confidence)* (Bodnar et al., 2015; Bhattacharya et al., 2020; Roberts et al., 2021), including: (i) counting non-grant finance, such as market and concessional loans (public and private), where developing countries ultimately have to repay the investment; (ii) what is counted as "climate" by different funders, especially when climate is not the prime objective; (iii) the extent to which some funds are "new and additional" rather than a repurposing of development finance.

Progress towards the 100 Billion target has shown an upward trend over the last several years *(high confidence)*, but will fall short in 2020, even when the most generous criteria are included *(high confidence)*. In 2017/18, the most recent year for which data have been comprehensively analysed, estimates using different (but overlapping) data sources and methods were in the range 48-75 billion USD per year, compared to 45-75 in 2015/16 and 41-52 in 2013/14 (Carty et al., 2020; SM17.3; CPI, 2020; OECD, 2020; UNFCCC, 2020). The distribution between adaptation and mitigation has remained strongly weighted towards mitigation, although the proportion allocated to adaptation has increased from 17-25% in 2013/14 to 19-30% in 2017/18 *(high confidence)*. One analysis that excludes debt repayments indicates that the debt-adjusted flows are about half the total flows reported above, of which circa 31-33 % was for adaptation between 2015/16 and 2017/18 (Carty et al., 2020).

[END BOX CROSS-CHAPTER BOX FINANCE.1 HERE]

Adaptation Finance Needs

Estimates of global, regional, or national finance needs for adaptation and resilience vary depending on both analysis approach, the level of climate change, and the geographic and sectoral scope of analysis *(high confidence)* (UNEP, 2016; Chapagain et al., 2020; UNEP, 2020). Recent estimates have adopted one of main approaches: (i) aggregation of individual case studies, along with scaling to generate global or regional costs; (ii) analysis of NDC adaptation cost estimates (Weischer et al., 2016; Hallegatte et al., 2018); (iii) integrated assessment model simulation of impacts and adaptation costs (Markandya and González-Eguino, 2019; Chapagain et al., 2020).

All approaches suffer from limitations that can cause both over and underestimates, including incomplete coverage of sectors and risks, inability to account for autonomous/unreported adaptation; incorrect cost estimations; soft and hard limits to adaptation; balance between adaptation, mitigation, and residual cost; benefits and co-benefits on cost; and learning and innovation as climate change progresses (UNEP, 2020). Global or developing region estimates based on scaling NDC data is particularly uncertain, as most NDCs did not specify how the costs were calculated. Also, scaling from a relatively small set of NDCs with costs to the global scale is not particularly robust, indicating a need for more transparency and better guidance for calculating adaptation costs (Watkiss et al., 2015b; Zhang and Pan, 2016; Hallegatte et al., 2018; AfDB, 2019).

Most estimated of adaptation cost in the literature are for developing countries. Chapagain et al. (2020) assessed various estimates of adaptation for developing countries, under different emissions scenarios for 2030 and 2050. The median estimates (and range) from these studies are 127 (15-411) and 295 (47-1088) billion USD per year for climate change impacts out to 2030 and 2050, respectively (see SM17.3). All but one study report adaptation costs higher than the 70-100 billion estimated in 2010 by the World Bank (World Bank, 2010).

The cost of adaptation for developed countries is rarely reported; most literature either reports a global cost or developing country costs, or costs for a specific country or sector. Baarsch et al. (2015), using an IAM, report adaptation annual costs (2012 prices) in 2030 (and 2050) as 272 (660) billion globally and 205 (521) in developing countries only under the RCP2.6 scenario, indicating that developed country costs are around 25 (21) % of total cost.

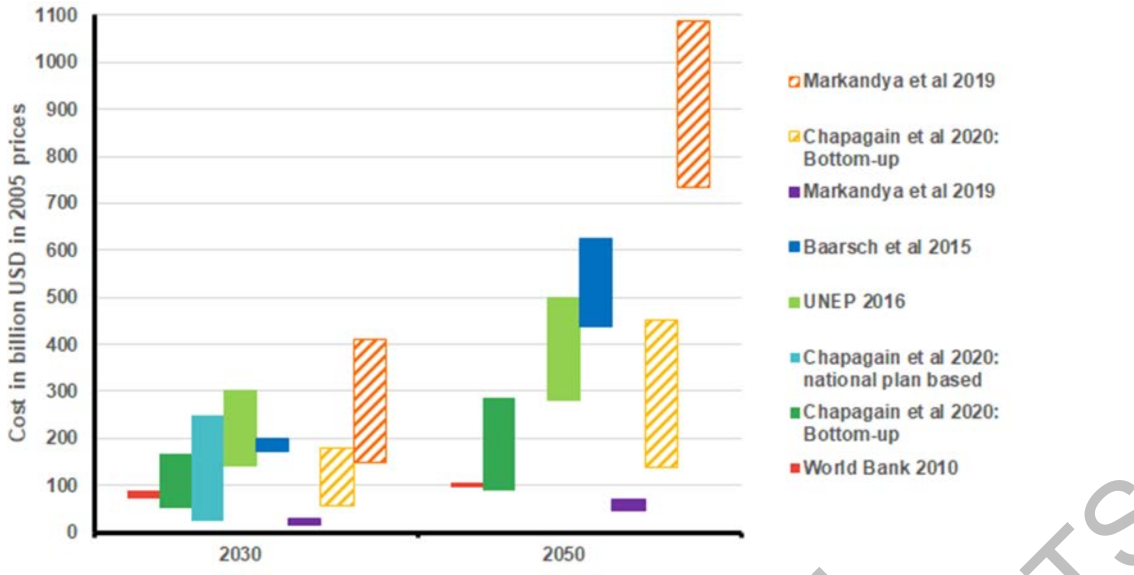


Figure Cross-Chapter Box FINANCE.1: Comparison of recent studies that estimated developing country adaptation costs in billion USD (in 2005 prices) per year, for 2030 and 2050. Figure based on Chapagain et al. (2020). Major studies are World Bank (2010), Chapagain et al. (2020), UNEP (2016), Baarsch et al. (2015) and Markandya and González-Eguino (2019). The solid-coloured bars are based on RCP2.6 and pattern-bars are based on RCP 8.5; the width of the bars indicates the range of estimates (maximum and minimum) produced in each study.

In addition to global estimated adaptation costs, there are many studies that have focused on specific regions, countries, or sectors, such as estimated adaptation cost for coastal environments, water related infrastructure, urban infrastructure, agriculture, energy (UNEP, 2014; Watkiss et al., 2015b; UNEP, 2016). Examples of such estimates are reported in various chapters in this report and summarised in SM17.3.

Estimating the benefit of adaptation, in terms of damage avoided, remains challenging. For example, Ricke et al. (2018) show that the social cost of carbon (monetary damage per tCO_2 emitted) varies by up to two orders of magnitude depending on country, socio-economic scenario, damage function, total GHG forcing, and local climate change. In addition, non-monetary benefits such as cultural identity, sacred places, human health and lives are often ignored (Tschakert et al., 2017; Serdeczny, 2019; see also Cross-Working Group Box ECONOMIC in Chapter 16; Cross-Chapter Box LOSS, this chapter). Recent case studies and global level analyses continue to support the conclusion in IPCC AR5 WGII Chapter 17 (Chambwera et al., 2014) that the benefits of adaptation generally remain larger than the costs *(medium confidence)*, but the cost-benefit ratio varies widely by context and assumptions (OECD, 2015; Global Commission on Adaptation, 2019; WRI, 2019)

The Climate Finance Landscape

The adaptation and resilience finance landscape spans multiple sources, intermediaries, instruments, and recipients, operating across global to sub-national scales (Buchner et al., 2019; Carter, 2020; Watson and Schalatek, 2021). Public finance is provided by national and subnational governments and distributed directly by government or intermediaries such as development finance institutions and climate funds, either nationally or internationally. Private finance comes from five main sources: commercial financial institutions (banks), institutional investors (including asset managers, insurance companies, and pension funds), other private equity (venture capital and infrastructure funds), non-financial corporations such as renewable energy or water companies, individual households and communities. Across these different sources, the main instruments used are grants, concessional debt, market debt, internal budget allocation, including personal savings in households, and insurance. Public and private sources of funding can be blended into a single instrument, for example for insurance where public funds provide capital for both sovereign catastrophe instruments and microinsurance (Jarzabkowski et al., 2019) or for concessional loans. Similarly, public finance is often ultimately be derived from commercial debt instruments such as bonds.

International public climate finance

International public climate finance flows are realised through bilateral and multilateral channels (Watson and Schalatek, 2021) where contributions to these channels are received from Annex II and non-Annex I countries (UNFCCC SCF, 2018; Buchner et al., 2019). Annex II countries contribute as part of their commitments in the Paris Agreement, while non-Annex I countries commit climate finance through these channels on a voluntary basis (Pickering et al., 2015; Roberts and Weikmans, 2017; Egli and Stünzi, 2019). Bilateral intermediaries include development cooperation agencies and national development banks. These institutions often have long standing development-cooperation experience, and offer climate change projects, facilities and financial instruments based on their differing mandates, structures and priorities (Atteridge et al., 2009; Buchner et al., 2019).

Multilateral channels include the UNFCCC financial mechanisms, such as the Green Climate Fund, and the multilateral development banks (MDBs), such as the World Bank. Both pool contributor resources before committing such resources for climate change projects and programmes. Funding through multilateral channels promotes recipient country engagement in the governance and prioritisation of funding decisions, with concurrent processes in the multilaterals often existing to support country ownership of funded climate action (Ciplet et al., 2013; Ha et al., 2016).

There are five multilateral climate change funds of the UNFCCC and Paris Agreement financial mechanisms. There are further multilateral climate change funds that are not governed by the UNFCCC or Paris Agreement, the largest of which is the World Bank governed Climate Investment Funds (Watson and Schalatek, 2021). Some of the major multilateral climate change funds have been established with a specific focus on adaptation, while some bilateral donors have thematic or sectoral priorities. Multilateral climate change funds operate through accredited implementing entities. These have historically been multilateral in nature, such as the development banks, but recent years have seen a rise in the accreditation of national and regional institutions (UNFCCC SCF, 2018). In addition to programming funds from external sources, such as through the multilateral climate change funds, the MDBs also raise and programme their own climate finance (UNFCCC SCF, 2018; MDBs, 2019).

Several major multilateral climate change funds work through grant-only programmes, whereas others include concessional loan, equity and guarantee instruments. The broader suite of instruments used by the MDBs includes grant, investment loan, equity, guarantee, line of credit, policy-based financing and results-based financing (MDBs, 2019).

Public funding of a concessional nature that flows from Annex II to non-Annex I countries supports research and capacity building and can also facilitate private finance flows into climate action, with the intention to avoid creating a high debt burden in developing countries, in response to climate impacts for which they have little historic responsibility (Watson, 2016; Carter, 2020; Schalatek, 2020). Less concessional public finance flows include other official flows that are not developmental in nature and can be trade related, including for example export credits.

Critiques of the public climate finance architecture are aimed at the overlapping mandates of the institutions programming climate finance, particularly the multilateral climate funds, and the challenges in accessing funding (Nakhooda et al., 2014; Amerasinghe et al., 2017; Pickering et al., 2017). However, Pickering et al. (2017) further note that institutional fragmentation of climate finance could result in more flexibility, resilience and innovation. There have also been important governance changes leveraged by some of these funds and instruments, such as integration of gender considerations into projects (Schalatek, 2020).

Private financing of adaptation and resilience

There is an increasing focus on the role of the private sector to support large-scale financing of adaptation and resilience (UNEP, 2016; UNEP, 2018). To date it has been difficult to track adaptation and resilience finance within the private sector (UNEP, 2016)as it is either not disclosed or not easily identifiable, since it is often built into capital and operating expenditure and is not a standalone investment. Several private mechanisms are emerging as important sources of climate finance (Gupta et al., 2014; Eccles and Krzus, 2018; Miller et al., 2019).

Green, social impact and resilience bonds are similar to traditional bonds - fixed-income financial instruments raised on commercial markets by companies, governments or financial institutions - but the proceeds are used to fund activities that have positive environmental, social or climate benefit (Tuhkanen, 2020). Green bonds align to voluntary principles, such as the Green Bond Principles set out by the International Capital Market Association, the Climate Bonds Initiative's Climate Resilience Principles (Sartzetakis, 2020)Given the voluntary nature and lack of standardization of green bond principles, there are concerns around their additionality and there is also a lack of data on how green bonds contribute to a scaling up of green projects (Dupre et al., 2018).

Green bond annual issuance reached 260 billion in 2019 (CBI, 2020) but, as of 2018, only 3-5% (USD 12 billion) of green bond total proceeds can be explicitly traced to climate resilience related efforts (CBI, 2019). Examples of AR focused bonds include those issued by Fiji in 2017, dedicating 91% of spending to adaptation and resilience (Shukla and Peyraud, 2017; Ministry of Economy, 2019), and by the European Bank for Reconstruction and Development's 2019 Climate Resilience Bond for USD 700 million to finance climate resilient infrastructure, commercial operations, agriculture or ecological systems (EBRD, 2019).

Dedicated investment vehicles are equity funds that are created to invest in products and services that enhance resilience and reduce risks. An example is the Climate Resilience and Adaptation Finance and Technology Transfer Facility that is proposed as a USD 500 million private equity fund to invest in companies providing climate resilience solutions for developing countries. Initial funding has been provided by donors (Miller et al., 2019).

Balance sheet finance occurs when an entity directly invests in resilience and adaptation rather than as a separate project. This source of funding may be from exiting reserves, reallocation from other budget lines, or via external commercial finance, but the investment is financed by the firm rather than as a separate project (Gupta et al., 2014; Buchner et al., 2019).

Insurance can play an important role in managing residual climate risks at any given level of adaptation, but insurers can also be important r risk assessment and risk reduction as part of any insurance package (Jarzabkowski et al., 2019; Chapter 11.3.8.3). While traditional indemnity insurance is important for repair and rebuilding of damaged property and infrastructure, parametric insurance has become increasingly popular for supporting rapid post-disaster responses such as drought, hurricane damage and flooding. Examples include sovereign insurance facilities such as African Risk Capacity and the Caribbean Catastrophe Risk Insurance Facility (Broberg, 2019) as well as weather-index insurance targeted at individuals, especially in agriculture (Greatrex et al., 2015; Isakson, 2015; Surminski et al., 2016; Jensen and Barrett, 2017; Fischer, 2019). The role of insurance as a climate risk management option, as well as limitations, is covered in more depth in Section 17.2 and Cross-Chapter Box LOSS (this Chapter).

Mainstreaming physical climate risks and resilience in the private sector

The data on tracked climate finance and green bond issuance for adaptation and resilience both show a substantial gap between the adaptation needs and the finance deployed. Scaling up these instruments is unlikely to close this gap given the challenges with financing adaptation projects, particularly from the private sector. There is therefore a need for more systematic action to manage climate risks and mainstream climate change considerations (Miller et al., 2019).

The financial case for mitigation investment can often be demonstrated through revenues from, for example, the sale of renewable electricity. On contrast, the benefits from investment in adaptation and resilience are typically considered in terms of avoided losses and cost benefit ratios. For example, the Global Commission on Adaptation (2019) estimates that the overall rate of return on investments in improved resilience is very high, with benefit-cost ratios ranging from 2:1 to 10:1, and in some cases even higher.

The private sector is becoming increasingly aware of the need to assess physical climate risks to avoid the long-term risks to assets and enhance climate resilience. The task force on climate-related financial disclosures (TCFD) is likely to create additional pressure from investors for companies to identify, manage and reduce risks from climate change (Eccles and Krzus, 2018; ERM and CBEY, 2018; Tuhkanen, 2020).

A key factor for the impact of the TCFD on mainstreaming of physical climate risks and demonstrating the case for investment in adaptation and resilience will be how investors systematically incorporate physical climate risks, adaptation, and resilience into their investment decisions. The Coalition for Climate Resilient Investment (DFID et al., 2019) was established to look at this from the private sector viewpoint and is working to systematically incorporate resilience into cash flow modelling and asset valuation practices, so that investors may quantify the investment in resilience for an asset and the benefits associated with reduced costs and more reliable revenue streams.

Recent trends in climate finance flows

Considerable progress has been made in tracking climate finance since AR5, but substantial gaps remain, especially regarding domestic public finance and private sector balance sheet investment in adaptation (Section 17.5.1.5; CPI, 2020; Richmond et al., 2020). The best documented information comes from international climate funds, which provide detail at the project level. Most bilateral and multilateral investment institutions report on whether debt, grants and other instruments are for climate projects, but with less detail. Private finance is harder to track, as reporting is voluntary; even for green bonds, where certification identifies the range of sectors a bond aims to cover, reporting of how the bond is spent is infrequent.

The Climate Policy Initiative (CPI) has been tracking climate finance since 2009, allowing for trends to be assessed; however, trends reported are a function of both real changes in finance and changes in methods and information sources (Richmond et al., 2020). Total climate finance tracked by CPI has increased from USD 364 billion per year in 2010/11 to 579 billion in 2017/18 (SM17.3). Tracked finance remained relatively constant from 2010/11 to 2013/14 but has increased steeply in more recent years. The proportion of finance allocated to adaptation has remained small throughout, between 4 and 8% *(high confidence)*; a further 1-2% of global finance has been classified as “multiple-objectives”. The large majority of tracked adaptation finance is from public sources *(high confidence)*, with only 2% coming from private sources in 2017/18 (CPI, 2020). This is at least partly because of the difficulty in demonstrating financial (as opposed to public good and avoided damages) return on investment for adaptation.

The majority of the most recently (2017/18) tracked adaptation and multiple-objective finance was supplied through public donors, largely through grants, concessional and non-concessional instruments (Figure FAR.1). Most finance (44,1%) was spent transregionally (allocated in specific projects to recipients in more than a single region). For regionally specific funding, Sub-Saharan Africa, South Asia, along with the Latin America & Caribbean region, received the largest gross amounts, although Oceania has received the greatest per-capita funding. The largest proportion of AR funding has been allocated to increasing the resilience of infrastructure, energy, and the built environment, followed by agriculture, forestry, and natural management, and then water and wastewater.

Across financial instruments, sub-Saharan Africa received the highest relative proportion through grants (38%), followed by the Latin America & Caribbean region (23%), with other non-OECD regions receiving between 16 and 10% (SM17.3). Concessional debt as a proportion of the regional total varies from 84% in South Asia to as low as 29% in Latin America & Caribbean, which has the highest proportion of non-concessional debt (48%).

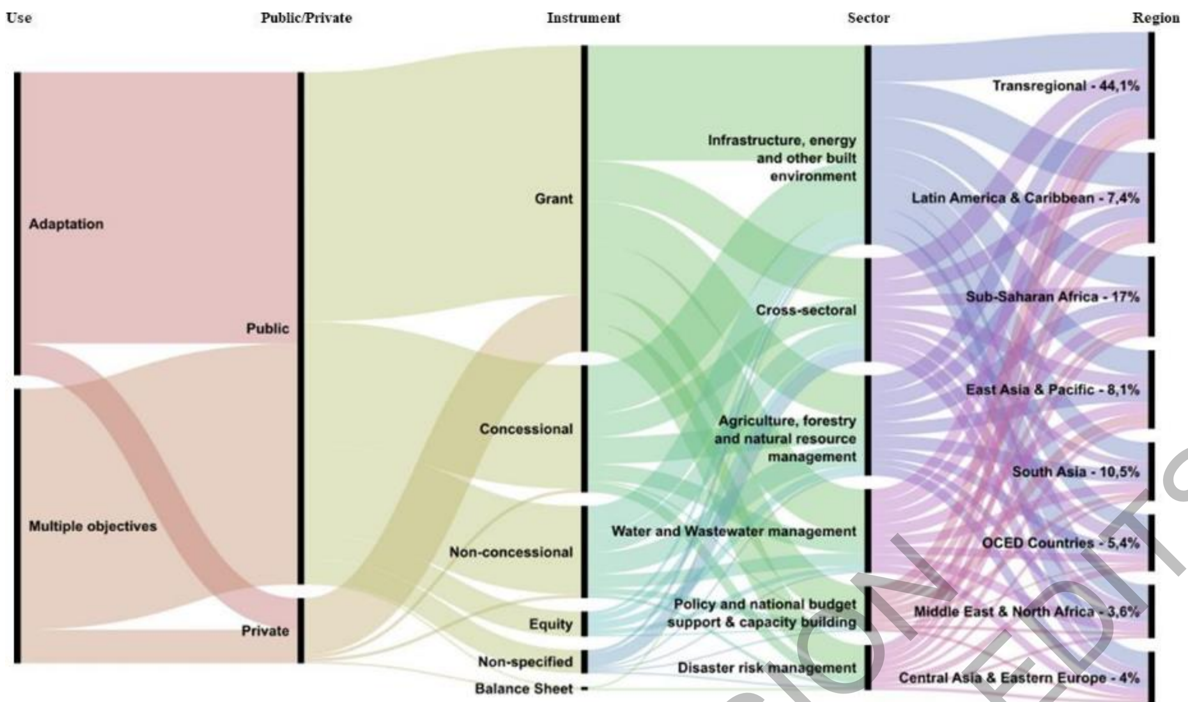


Figure Cross-Chapter Box FINANCE.2: The flow and distribution of globally tracked adaptation and resilience finance in 2018 from different sources, through different instruments into different sectors and regions. Each strand shows the relative proportion of finance flowing from one category to another (for example from private or public sources to different instruments). Categories from left to right are: (a) whether the finance is solely for adaptation or for adaptation and other objectives, including mitigation (multiple objectives); (b) whether the finance comes from public or private sources; (c) the financing instrument; (d) the broad sectoral allocation; (e) the geographical distribution of funding (proportion of total in % and per-capita allocation). Based on data collated by CPI (2020).

The importance of public and private finance for adaptation and resilience

Adaptation finance provided by international public mechanisms remains the core source of tracked flows in support of adaptation and resilience to developing countries (Micale et al., 2018; UNEP, 2018), although these public funds alone are insufficient to meet rapidly growing needs and constitute only a minority share of all public climate finance flows (UNEP, 2016; Global Commission on Adaptation, 2019).

Public mechanisms can play a role in leveraging private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers through blended finance approaches, public-private partnerships or innovative financial instruments and structuring in support of private sector requirements for risk management and guaranteed investment returns (Pillay et al., 2017; Miller et al., 2019).

There is growing agreement on the sectors (such as infrastructure, agriculture or water management) and approaches (contingency finance or insurance) where private sector adaptation investments alone, or leveraged by public mechanisms, might be best targeted, such as by reducing the risk of providing financial services for adaptation investments to domestic micro-, small-, and medium enterprises or agricultural smallholders, many of them women (Biagini and Miller, 2013; Chambwera et al., 2014; Pauw et al., 2016; Global Commission on Adaptation, 2019; Miller et al., 2019; Resurrección et al., 2019; Richmond et al., 2020). A remaining open question is how to allocate limited public adaptation funds in a way that is equitable, effective and efficient between mobilizing private investments and safeguarding adequate financial support for necessary adaptation efforts, such as the provision of public goods, which the private sector will not invest in (Fankhauser and Burton, 2011; Abadie et al., 2013; Baatz, 2018; Omari-Motsumi et al., 2019).

Many adaptation interventions in the most vulnerable countries, communities and people provide no adequate financial return on investments and can therefore can only be funded with highly concessional public finance. Grant support is most appropriate for measures such as capacity building, planning, public policy and regulatory reforms, disaster risk management and response, community engagement or support for social safety nets, and for addressing social vulnerabilities, including poverty or gender inequality, which constrain adaptation (Grasso, 2010a; Pillay et al., 2017; Agrawal et al., 2019; Buchner et al., 2019). Access to adequate adaptation grant finance is further constrained because several public mechanisms provide grants only for the additional costs of adaptation measures compared to a development baseline in the absence of climate impacts. Calculating the incremental costs of adaptation measures imposes additional time and resource burden on the most vulnerable recipients, who are often faced with data gaps or technical capacity constraints (Chambwera et al., 2014; GCF, 2018; UNEP, 2018; Omari-Motsumi et al., 2019). An exact delineation of respective costs for adaptation and development components is difficult and might be unsuitable as many adaptation measures are intrinsically linked to development. It may also prevent realizing necessary synergies between both (McGray et al., 2007; Smith et al., 2011; Denton et al., 2014; Resch et al., 2017; Micale et al., 2018).

Equality and fairness in climate finance

Climate finance literature recognises that poor and least developed households, communities, and countries are most affected and marginalized by climate change, and least responsible for its causes, but receive relatively little financial support for adaptation (Chapter 15; Chapter 8; Olsson et al., 2014; Rozenberg and Hallegatte, 2015; Hallegatte et al., 2016; Rai and Fisher, 2017; Shakya and Byrnes, 2017).

Several factors affecting fair and just financing in developing countries have been identified in recent literature (Klein et al., 2014; Colenbrander et al., 2018; Mfitumukiza et al., 2019; Khan et al., 2019a; Doshi and Garschagen, 2020). First, financing is skewed in favour of mitigation, and therefore towards fast-growing upper- and middle-income countries offering the biggest gains in emission reductions, especially in Southeast Asia, but also in Sub-Saharan Africa (Rai et al., 2016). Further, as much of current finance uses debt-based instruments, mitigation projects are further preferred as returns are more assured (Lee and Hong, 2018; Carty et al., 2020).

Second, the requirement of many funders for readiness and fiduciary capacity means that LDCs have been less able to access finance, despite many support mechanisms being offered. Additionally, geopolitical preferences of some countries mean that some developing countries are preferred to others for bilateral funding (Doshi and Garschagen, 2020). This is exacerbated for private sector investment, where lower credit ratings make finance more expensive, and increasing understanding of exposure to physical climate risks could lead to ‘capital flight’ from most vulnerable countries (Global Commission on Adaptation, 2019; Miller et al., 2019; Cooper, 2020).

Third, within climate-vulnerable countries, very little is channelled to local communities who need it most; the few analyses available suggest that less than 10% of total climate finance supports decentralized actions (Rai et al., 2016; Soanes et al., 2017). Reasons include: (i) lack of consideration of procedural equity in programme design (Grasso, 2010b; Wang and Gao, 2018; Venn, 2019; Khan et al., 2019a); (ii) finance being managed by multilateral implementers, rather than agencies that are closer to local communities; (iii) the higher transaction costs of decentralized projects in low-income communities reduce their attractiveness to funders as well as the ability of local organisations to meet the fiduciary standards (Fonta et al., 2018; Omari-Motsumi et al., 2019).

It has been proposed that, as middle-income countries can leverage mitigation finance from the private sector, targeting scarce public finance towards LDCs and SIDS may be necessary to ensure sufficient funds reach these countries (Steele, 2015). Matching domestic climate spending with international support is one way to ensure LDCs get the funds they need (Grasso, 2010b; Bird, 2014). Targeting specific marginalized communities and women within countries can also help make climate finance more effective and fairer, such as the Asian Development Bank’s efforts to make lending portfolios more inclusive and pro-poor (ADB, 2018).

Post-COVID recovery packages, debt relief and finance for adaptation and resilience

Recent literature has highlighted the opportunity that COVID recovery packages offer for environmentally sustainable, low carbon and climate resilient economic growth (Forster et al., 2020; Hepburn et al., 2020; Hanna et al., 2021). Assessment of whether this is indeed happening is limited, although the few available studies suggest that that this opportunity is not being realised in many nations (O'Callaghan and Murdock, 2021; VIVID Economics, 2021). One study of the G20 and 10 other nations suggested that stimulus packages would have net negative environmental impact in two thirds of these countries (VIVID Economics, 2021), while another showed that around half of G20 recovery investment targeted at energy has had gone towards fossil fuels, rather than to cleaner energy sources (Dibley et al., 2021).

Concerns have also been raised about the interactions between debt service, COVID economic recession and post COVID recovery in developing countries (Simmons et al., 2021; Volz et al., 2021). Debt service grows as a proportion of national budget during recession, reducing scope for investment in recovery, is a self-reinforcing cycle. It has been suggested that linking debt-relief to Paris-aligned objectives can act as an additional source of climate finance (Fenton et al., 2014). The G20 has begun addressing this debt crisis through its Debt Service Suspension Initiative and the Common Framework for Debt Treatments (IMF, 2020). It has been suggested that these initiatives could be expanded to prioritize climate-focused debt-relief instruments and to include more countries (Steele and Patel, 2020; Volz et al., 2021). If debt-relief is used to invest in national instrument for green and inclusive recovery, national ownership of the use of the finance can occur, avoiding some of the negative connotations of historical debt restructuring (Volz et al., 2021).

[END CROSS-CHAPTER BOX FINANCE HERE]

17.4.4 Enabling Condition 3: Knowledge and Capacity

17.4.4.1 Overview of Knowledge Systems

AR5 emphasized the importance of knowledge systems as an enabling condition for decision making, as did earlier ARs, all of which include a focus on the policy-relevance of knowledge (Section 1.1.4) First introduced in IPCC reports in AR4, the term "knowledge system" is used extensively in AR5 and the SRs. The discussion below follows a widely-cited definition of knowledge systems as sets of interacting "agents, practices and institutions that organize the production, transfer and use of knowledge" (Cornell et al., 2013: 61). This definition emphasizes the social nature of knowledge and the importance of the link between knowledge and action, rather than presenting knowledge simply as information about past, present and future states of the world which can be of use to decision-makers.

This definition of knowledge systems indicates the importance of capacity--the ability and the motivation to use knowledge for action--since capacity is an important feature which allows knowledge systems to function. Capacity is a necessary enabling condition for knowledge to be put to use in adaptation activities (*high confidence*), as shown across sectors such as water (Section 4.5.2), food security (Sections 5.12.3, 5.14.3), cities and settlements (Sections 6.4.2, 6.4.4) and health and well-being (Sections 7.1.3, 7.2.6), and across regions, including Africa (Sections 9.13.1, 9.14.5), Asia (Sections 10.3.6, 10.4.4) and North America (Section 14.4.5).

Some research on knowledge systems retains the earlier attention to information as a resource for decision-makers. A major focus, discussed elsewhere in this chapter, has been increasing the precision about the certainty, likelihood, and the confidence with which certain statements are made in relation to underlying evidence (See Cross-Chapter Box DEEP in this Chapter). This topic, which was first introduced in AR4, advanced significantly in AR5 (Mach et al., 2017).

In addition to these characteristics of information, the social and organizational aspects of knowledge systems have also been the subject of recent research. One strand of this discussion emphasizes the distinctiveness of different knowledge systems, often focusing on three types of knowledge: scientific, Indigenous, and local, and the latter two sometimes grouped as "traditional" knowledge (See Cross-Chapter Box INDIG in Chapter 18). This strand emphasizes the specific forms of knowledge production and circulation in each type. Another strand of discussion emphasizes the networks of interactions between different groups. This strand follows the influential "Knowledge systems for sustainable development" (Cash et al., 2003), which was cited in Chapter 2, 7 and 8 in WGII AR5; Cash et al. (2003) emphasizes the usability and acceptability of scientific knowledge, and underscores the relations between knowledge producers and users. The discussion in 17.4.4 on knowledge as an enabling factor integrates these two strands of discussion of knowledge systems.

It was well established in AR5 and SRs that a component of knowledge systems for good climate decision-making is the production of "information on climate, its impacts, potential risks, and vulnerability" which can "be integrated into an existing or proposed decision-making context" (Jones et al., 2014: 200). Also important are two other components of knowledge: of response options and knowledge of other enabling conditions, particularly governance and finance, which were mentioned less frequently and more indirectly in AR5 and SR1.5, SROCC and SRLAND. Decision-makers assess the feasibility of different alternatives (see Cross-Chapter Box FEASIB) and develop strategies for the implementation and modification of the alternative, requiring a level of knowledge of the governance, policy and finance landscapes at national (Tanner et al., 2019; Lopes et al., 2020; Roberts et al., 2020) and international scales (Woodruff, 2018).

Examples of the importance of these other two components--knowledge of response options and knowledge of enabling conditions--are provided by networks of cities, including internal institutional networks (Aylett, 2015), intermunicipal networks (e.g., those supported by ICLEI- Local Governments for Sustainability and the international United Cities and Local Governments (UCLG) network), transnational municipal networks (e.g. 100 Resilient Cities, Asian Cities Climate Change Resilience Network (ACCCRN), and city to city regional transdisciplinary learning networks (Ndebele-Murisa et al., 2020). These networks generate and exchange knowledge which can be critical to decision-makers for understanding and evaluating the feasibility of different response options, identifying synergies across sectors, and mainstreaming adaptation to climate change (Haupt et al., 2020). However, the question of how to finance such network activities remains under-studied (Bracking, 2021; See Box 17.3).

In addition to these general considerations of knowledge systems, research since AR5 has contributed to the understanding of specific types of knowledge. Scientific knowledge is thoroughly discussed in Chapter 1, especially in Section 1.3 Understanding and Evaluating Climate Risk, which shows recent advances in the well-established IPCC categories of observation of past conditions and model-based projections of future conditions. We add here a consideration of a new area within scientific knowledge, artificial intelligence, which offers new methods for producing information that can be incorporated into knowledge systems.

Applying Artificial Intelligence (AI) to climate change is predominantly in the area of climate modelling and forecasting, inclusive of weather extremes (Monteleoni et al., 2013; Jones, 2017; Huntingford et al., 2019). Recent efforts conceptualize the potential uses of AI for mitigation and adaptation (Rolnick et al., 2019; Cheong et al., 2020b) in addition to forecasting (Rolnick et al., 2019; Chattopadhyay et al., 2020; Cheong et al., 2020b; Prabhat et al., 2021). There are very few cases to assess AI applications in these domains given that AI is a new field for climate change impact and adaptation. To this date, sectoral applications of AI relevant to climate change adaptation and risk reduction mainly have advanced in the areas of crop yields, early warning system, and water management.

These sectoral advances using AI employ various learning techniques inclusive of supervised and unsupervised learning, multimodal learning and transfer learning techniques to generate more accurate predictions than afforded by traditional climate projection methods (Cheong et al., 2020b; Camps-Valls et al., 2021). AI applications use finer resolution data such as sub-daily weather-related data, remote and wearable sensor data, text data, and real-time survey data. They are fed into neural networks and semi/unsupervised learning to configure detailed and more precise predictions of climate change impact on crop yields (Crane-Droesch, 2018), early warning (Moon et al., 2019), impact of extreme heat on older adults (Cheong et al., 2020a), poverty in Africa (Oshri et al., 2018), and multi-scale water management combining blockchain technology with remote water sensors (Lin et al., 2018).

Indigenous knowledge and local knowledge are thoroughly covered in SROCC (Abram et al., 2019; IPCC, 2019c; IPCC, 2019e-b) and in Section 1.3.3. We here add relevant points to decision making, and an additional form of knowledge, practitioner knowledge.

Indigenous knowledge and local knowledge are gaining recognition at multiple scales (Kleiche-Dray and Waast, 2016; David-Chavez and Gavin, 2018; Nakashima et al., 2018). Of note is their association with ecosystem-based adaptations, showcasing the long-term place-based knowledge of Indigenous peoples

(Johnson et al., 2015; Walshe and Argumedo, 2016; Carter, 2019; Mazzocchi, 2020). These knowledges and practices can be an important enabling condition in decision making processes, complementing scientific information by identifying impacts (Fernández-Llamazares et al., 2017; Katz et al., 2020), emphasizing values to consider (Huambachano, 2018), offering solutions (Chanza and de Wit, 2016; Cuaton and Su, 2020; Orlove et al., 2020), guiding land use and resource management (Brondízio et al., 2021) and filling gaps in scientific knowledge (Hiwasaki et al., 2014; Audefroy and Sánchez, 2017; Makondo and Thomas, 2018; Son et al., 2019; Latulippe and Klenk, 2020; Wheeler et al., 2020a).

Practitioner knowledge—the pragmatic, practice-based knowledge that comes from the regular exercise of craft or professional work—was also acknowledged briefly in AR5 (Jones et al., 2014) and treated significantly in SROCC (Abram et al., 2019). Practitioner knowledge resembles local knowledge in that it is acquired through participation in activities, and yet it differs from local knowledge, which is often place-based and tied directly to specific landscapes and communities. Local knowledge typically covers a variety of environmental domains. Practitioner knowledge may be shared with people in different locations and is often more focused on a narrower set of work activities. Recent calls have recommended bringing practitioners more fully into the IPCC assessment process, to promote more effective decision-making (Howarth et al., 2018).

Practitioner knowledge makes significant contributions to decision-making by broadening the range of alternatives which are considered and by bringing in understandings of systems to the selection and implementation of alternatives. Such knowledge is applicable to a large number domains, including biodiversity management (Tengö et al., 2014; Rathwell et al., 2015), and natural hazard risk management in urban settings, as reported in Denmark (Madsen et al., 2019), the US (Matsler, 2019), Canada (Yumagulova and Vertinsky, 2019), Mexico (Aguilar-Barajas et al., 2019), and the Caribbean (Ramsey et al., 2019). Other contexts, all at regional scales, include watershed management in Peru (Ostovar, 2019), livestock management in Finland (Rasmus et al., 2020), agricultural adaptation in a context of water scarcity in Iran (Zarei et al., 2020), and the water-energy nexus in the US (Gim et al., 2019).

Literature indicates the importance of effective governance for promoting integration of local and practitioner knowledge with scientific knowledge (*high confidence*). This integration is most extensive, and promotes a wider consideration of alternatives, where governance arrangements promote ongoing exchanges of information and discussion of solutions, whether through formal mechanisms such as regional committees (Gim et al., 2019; Ostovar, 2019; Rasmus et al., 2020; Zarei et al., 2020) or informal mechanisms such as personal networks and local discussion groups (Madsen et al., 2019; Yumagulova and Vertinsky, 2019). Where such arrangements are absent, practitioner knowledge is side-lined from the formulation and implementation of decisions (Aguilar-Barajas et al., 2019; Matsler, 2019; Ramsey et al., 2019).

17.4.4.2 Co-production and Other Composite Knowledge Systems

There is strong evidence that composite knowledge systems – characterized by interactions between the producers and potential users of climate change information -- can help facilitate climate-related decision making (Prokopy and Power, 2015; Richards, 2018; Ramsey et al., 2019). Several institutional forms and structures have been created to link scientific knowledge, Indigenous knowledge, and local and practitioner knowledge, to climate change decision making.

17.4.4.2.1 Co-production

The co-production of knowledge by different actors provides important avenues for exchanging and integrating climate-related knowledge in decisions made across society (*high confidence*). Though many definitions of co-production have been offered in recent years (Bremer and Meisch, 2017; Vincent et al., 2018; Bremer et al., 2019; Harvey et al., 2019a), most describe a set of individuals or organizations who work together to generate a set of products that entail new knowledge products and that guide action (Miller and Wyborn, 2020). Some major forms of co-production include action research (Baztan et al., 2017; Laursen et al., 2018; Zanocco et al., 2018a), trans-disciplinarity (Howarth and Monasterolo, 2016; Wamsler, 2017; Lanier et al., 2018; Scott et al., 2018; Knapp et al., 2019; Young et al., 2019a); rapid assessment processes (Atkinson et al., 2018b); and participatory integrated assessments (Howarth et al., 2018; Krkoška Lorencová et al., 2018; Bitsura-Meszaros et al., 2019; Carter et al., 2019a; Cremades et al., 2019; Leitch et al., 2019; Martínez-Tagüeña et al., 2020; Section 17.3.1.3.1).

Co-production promotes iterative dialogue, experimentation, the tailoring of knowledge to context, needs and priorities, and learning, often promoting integration of Indigenous knowledge, local knowledge and practitioner knowledge with scientific knowledge (*high confidence*). It generally entails long-lasting ties and fully inclusive partnerships between different parties (Kench et al., 2018). Governance measures and adequate financing can act as enablers of such co-production. This integration is most extensive, and promotes a wider consideration of alternatives where governance arrangements promote ongoing exchanges of information and discussion of solutions, whether through formal mechanisms such as regional committees (Gim et al., 2019; Ostovar, 2019; Rasmus et al., 2020; Zarei et al., 2020) or informal mechanisms such as personal networks and local discussion groups (Madsen et al., 2019; Yumagulova and Vertinsky, 2019). Where such arrangements are absent, practitioner knowledge is side-lined from the formulation and implementation of decisions (Orleans Reed et al., 2013; Aguilar-Barajas et al., 2019; Matsler, 2019; Ramsey et al., 2019).

An important mechanism of co-production is the boundary organization, a knowledge-producing organization comprised of individuals who reflect different disciplines or knowledge systems and who represent different activities, sectors or forms of governance (Blades et al., 2016; Graham and Mitchell, 2016; Guido et al., 2016; Jeuring et al., 2019; Serrao-Neumann et al., 2020; Zarei et al., 2020). Boundary organizations themselves can be linked into boundary chains (Lemos et al., 2014; Meyer et al., 2015; Kirchhoff et al., 2015a; Pretorius et al., 2019; Daniels et al., 2020). When individuals and organizations from different disciplinary backgrounds and missions coordinate their activities informally, the resulting ties have been termed ‘knowledge networks’ (Ziaja and Fullerton, 2015; Brugger et al., 2016; Guido et al., 2016; Davies et al., 2018; Klenk, 2018; Muccione et al., 2019; Ziaja, 2019). When such networks interact with each other, the resulting associations have been called “communities of practice,” which can work to collectively shape information to shared contextual circumstances (Orsato et al., 2018; Wang et al., 2019b).

There is extensive evidence that co-production can generate useful climate knowledge (Djenontin and Meadow, 2018; Bisbal, 2019; Ryan and Bustos, 2019; Hewitt et al., 2020; Jack et al., 2020; Lavorel et al., 2020; Ruiz-Mallén, 2020) and that it can increase the likelihood that knowledge will be used in decision-making (Vogel et al., 2016; Prokopy et al., 2017; Skelton et al., 2017; Sylvester and Brooks, 2020). Co-production is not without its costs, since it requires more time, money, facilitation expertise and personal commitment from participants than more conventional modes of knowledge production (Lemos et al., 2018; Sletto et al., 2019; Wamsler et al., 2019; Blair et al., 2020). Some research has shown ways to decrease the costs of co-production for participants, such as funding and time to enable and sustain interactions and to build trust and legitimacy, or to create boundary organizations (Young et al., 2016; Klenk et al., 2017).

Co-production is supported by project cycles that provide for the involvement of stakeholders from the outset (Daly and Dilling, 2019; Brady and Leichenko, 2020); flexible research agendas that do not assume a climate related question (Daniels et al., 2020); support for interactivity and reflexivity (Araujo et al., 2020), and, institutionalizing incentives which address the different values, norms, perceptions and work patterns of scientists, policy-makers and civil society representatives (Cvitanovic et al., 2015; Vincent et al., 2015; Bruno Soares and Dessai, 2016; Singh et al., 2017; Djenontin and Meadow, 2018; Norström et al., 2020; Turnhout et al., 2020). Certain roles, such as policy entrepreneurs (Tanner et al., 2019), embedded researchers (Pretorius et al., 2019) and knowledge brokers (Cvitanovic et al., 2015), can facilitate co-production.

17.4.4.2.2 Climate services

Climate services (refer to CWG Box on Climate Services) can be important enablers of climate risk management, provided they are credible, relevant and usable (*high confidence*), and will become increasingly important as human influence on weather and climate extremes grows across all regions (Chapter 11; Fischer et al., 2021; IPCC, 2021). Climate services are more effective and more widely used when they are tailored to specific decisions and decision-makers (*high confidence*). Sustained iterative engagement between climate information users, producers and translators can improve the quality of the information and the decision-making and avoid maladaptation (*medium confidence*).

Historically, climate services have been organized by climate information providers, based in meteorological, hydrological, and agricultural faculties and services, serving to improve through climate risk management, including the use of historical information, monitoring, seasonal forecasts, and long-term climate projections (Hewitt et al., 2012; Blome, 2017; Bessembinder et al., 2019; Vaughan et al., 2019b).

Recent research on climate services shows that transdisciplinary knowledge co-production is a key enabler, starting to shift emphasis from the creation of climate services *products* to climate services *processes* (Vincent et al., 2018; Carter et al., 2019b; Daniels et al., 2020), potentially increasing uptake and sustainability (Norström et al., 2020). This shift is a result of the recognition of benefits which a co-production approach can offer, in addition to the provision of information; information; these additional benefits include building confidence, capacities, learning, knowledge, social capital, institutional capacity, stakeholder relationships, social networks, beneficial management practices, and strengthened institutions (Bruno Soares and Dessai, 2016; Djenontin and Meadow, 2018; Bremer et al., 2019).

Cross-Chapter Box 12.2 in WGI AR6, Climate information for climate services, shows that users are widely distributed across civil society. Relevant users of climate services include humanitarian organizations (Coughlan de Perez and Mason, 2014; Harvey et al., 2019b), government offices (Mahon et al., 2019), international agencies (Perkins and Nachmany, 2019), and the private sector (Beckett, 2016; Hudson et al., 2019). Climate services currently exist at local, national, regional, and international scales, at time scales which range from sub-seasonal to decadal and longer (White et al., 2017; Hewitt et al., 2020) and in a range of different sectors (Bruno Soares and Buontempo, 2019). Agriculture is the sector with the largest number of examples (Zebiak et al., 2015; Burke and Emerick, 2016; Cliffe et al., 2016; Haigh et al., 2018; Buontempo et al., 2020); others include health (Ghebreyesus et al., 2010; Ballester et al., 2016), forestry (Caurla and Lobianco, 2020), fisheries (Busch et al., 2016), disaster risk reduction (Street et al., 2019), and water resources management (van Vliet et al., 2015; Golding et al., 2019). Evaluations of the extent to which climate services are accessed, used, and deliver benefits to decision makers remain in an initial stage (Perrels, 2020), though studies suggest that these contributions vary widely depending on context. A review of evaluation of weather and climate agricultural services in Africa, for instance, found that most farmers use climate services when they are available , but that on-farm outcomes varied, with some farmers experiencing yield losses and others gains upward of 60% (Vaughan et al., 2019a). Other studies express concern that large climate service projects have run for decades at significant expense, without adequate evaluation at all (Gerlak et al., 2020).

Recent reviews (Carr and Onzere, 2018; Hewitt et al., 2020) provide evidence that the use of climate services is affected by (a) the quality, reliability and skill of the climate information (Zebiak, 2019); (b) the fit, tailoring and contextualization of that information with respect to the specific decision-making needs of particular users (Clarkson et al., 2019); (c) the mode and method by which the service is communicated (Golding et al., 2017); and (d) the characteristics of the users themselves – including the users' access to resources that would allow them to alter their decisions based on the information provided (Clarkson et al., 2019).

A related literature characterizes the extent to which the development, reach and effectiveness of climate services is affected by factors that can be termed 'climate service governance' (Stegmaier et al., 2020). Elements of this governance include the arrangements by which those parties engage with each other (Vaughan et al., 2016; Daniels et al., 2020) and the financial arrangements, and associated responsibilities, which support the service (Lourenço et al., 2015; Bruno Soares and Buontempo, 2019). Though governance varies by context, evidence suggests that engaging a range of experts and potential users in the co-design and co-production of climate services increases the use and utility of services (Lemos et al., 2014; Pope et al., 2017; Masuda et al., 2018; Harvey et al., 2019b). However, some studies warn that even with broad and inclusive participation, power differentials can create barriers to co-production reducing the usefulness information products (Alexander et al., 2020) and the neglect of non-meteorological sources of information which may also possess useful predictive power (Coughlan de Perez et al., 2019).

A small but growing number of papers consider the business models that support climate services, including, for instance, the role of open data (Iturbide et al., 2019; Chimani et al., 2020), the standards or institutional mandates by which users come to understand the credibility and legitimacy of certain services (Bruno Soares and Buontempo, 2019), and the role of public-private partnerships (Cortekar et al., 2020). While the commercialization of climate services holds significant promise that more and more specifically targeted services will be provided, there is not yet agreement on which business models best support this in different contexts. There is also concern that commercialization of climate services may disadvantage under-resourced actors at the expense of wealthier or more powerful ones (Webber, 2017; Webber and Donner, 2017; Cortekar et al., 2020). It has been noted that some climate services, such as weather forecasts and early warnings, are an example of a public good, best provided by public agencies (*high confidence*) (Sutter, 2013; Kitchell, 2016; Hansen et al., 2018).

17.4.4.2.3 Capacity and motivation within knowledge systems

Knowledge of climate change influences decision-making not only by providing information but also by increasing the motivation to act and by promoting behaviour change. Evidence from many sectors (including water (4.5.2), ocean and coastal ecosystems (3.6.2), and agriculture (5.4.2) and regions (including Africa (9.8.4), Asia (10.4.6), and North America (10.4.5) show that building capacity (e.g. adaptive capacity, institutional capacity, education/training in human capacity) can support adaptation and limited governance capacity can constrain it (*high confidence*). An emerging area of research examines the contribution of building capacity within public and technical organizations and agencies to draw on Indigenous knowledge and local knowledge (Adger et al., 2017; Hochman et al., 2017; Bacud, 2018). A number of factors influence the effect of knowledge on motivation and behaviour change, including values and education.

Decision-makers who shape options for managing climate risk can evaluate stakeholders' capacities and motivations to participate in the implementation process of these options. Stakeholder engagement in climate change risk management supports successful adaptation (Gray et al., 2014; Elsawah et al., 2015; Siders, 2017; Giordano et al., 2020). Research in psychology and related fields shows that the cognitive mechanisms by which individuals and organizations process climate information influence this capacity, motivation and engagement (Grothmann and Patt, 2005; Grothmann et al., 2013; Masud et al., 2016; Nelson et al., 2016; Takahashi et al., 2016; Hügel and Davies, 2020; Grothmann and Michel, 2021).

The perception of climate change as a major threat that requires action has increased since AR5, reflecting both the growth of information about climate change and the processing of that information (Lee et al., 2015; Fagan and Huang, 2019). Global social movements play an important role in raising public awareness of climate urgency (Thackeray et al., 2020). Climate change concern plays an important role in decision-making outcomes which entail public participation (Lammel, 2015; Chiang, 2018; van Valkengoed and Steg, 2019; Arıkan and Günay, 2020). Nonetheless, public risk perception varies sharply on spatial and temporal scales, reflecting environmental changes, social influences (Kousser and Tranter, 2018; Rousseau and Deschacht, 2020), economic capacities (Arıkan and Günay, 2020) and culture (Noll et al., 2020), as well as individual characteristics (van Valkengoed and Steg, 2019). The importance of values and norms is demonstrated by recent research which highlights how intrinsic motivation (altruistic, self-transcendental and ecocentric values) (Corner et al., 2014; Braito et al., 2017; Xiang et al., 2019; Bouman et al., 2020) and extrinsic social motivation (e.g., economic gains and social desirability) (van Valkengoed and Steg, 2019) can drive action.

Recent research shows the importance of education as a predictor of risk perception, motivation and action. Education level is the strongest predictor of public awareness of climate change risk in a study across 119 countries of public awareness of climate change risk (Lee, 2015), though this relationship varies in different nations, and is influenced by mediating variables (Muttarak and Chankrajang, 2015; Blennow et al., 2016) (Ballew et al., 2020). Knowledge and awareness of climate change are correlated with the motivation to undertake action on climate change (Hornsey and Fielding, 2017). The integration of climate science in educational curricula has been shown to be effective (Hess and Maki, 2019; Molthan-Hill et al., 2019), including approaches such as integration of the complex system approach (Jacobson et al., 2017), experiential climate change education (Siegner, 2018), including climate games (O'Garra et al., 2021; Pfirman et al., 2021), massive open online courses , and informal science learning centres (Geiger et al., 2017).

Attention to behavioural change of individuals has grown since AR5, including cases which address both adaptation and mitigation (e.g. dietary changes, modification of buildings, transport alternatives) (Azadi et al., 2019; Fischer, 2019; Willett et al., 2019; Sharifi, 2020; Sharifi, 2021). The interventions to promote behavioural change can be bottom-up, initiated by individuals, communities, non-governmental organizations or the private sector, or top-down, coming from governments at various levels (Robertson and Barling, 2015; Stern et al., 2016). They are supported by a number of mechanisms, including education, information strategies, and campaigns, financial incentives, regulatory processes and legislation (Rosenow et al., 2017; Creutzig et al., 2018; Carlsson et al., 2019). These behavioural changes contribute significantly to effective risk management.

17.4.5 Enabling Condition 4: Catalysing Conditions

A clear difference between enabling conditions and catalysing conditions is emerging in the climate mitigation literature (Hermwille et al., 2019; Michaelowa et al., 2021), with some examples in the adaptation literature as well (Madsen et al., 2019; Booysen et al., 2019a; Bolorinos et al., 2020). Though enabling conditions are necessary preconditions that allow response options to be formulated and implemented, their presence alone does not guarantee that these response options will occur in a timely fashion or at a scale commensurate with the risk, or even that they will occur at all. Catalysing conditions address this deficit in advancing action. They serve to overcome the inertia that often operates as a barrier to action and motivate individuals and organizations to initiate or accelerate action. Different forms of catalyzing conditions, described below, lead individuals and organizations to weigh more seriously the costs of delaying action or keeping action at low levels. Catalysing conditions focus the attention of individuals and organizations on particular risks, leading actors to augment their decision-making processes and to allocate financial and social resources to respond to those risks. This attention and deliberation can lead to more frequent and potentially substantial adaptations, whether through more extensive action on existing forms of adaptation or through the adoption of entirely new adaptations (Bolorinos et al., 2020).

The first two catalysing conditions described below address the costs of delaying action. Urgency increases the awareness of individuals and organizations of such costs, while windows of opportunity, including extreme events, are time-bound periods during which certain actions are possible, but after which they are more difficult or impossible. The other two conditions stimulate new forms or levels of action by promoting or directing step changes from one policy or management regime to another (Solecki et al., 2017). Litigation over adaptation issues, for example, can open new lines of action or close off old ones, while catalysing agents advance action through a variety of means (e.g., communicating the urgency of climate action, revising agendas for action, expanding coalitions which undertake action). As detailed below, these four catalysing conditions can operate together as well as separately to promote more prompt and extensive adaptations.

17.4.5.1 Urgency

Urgency can catalyse action for individuals and organizations. A moderate level of urgency serves as an important driver of climate action, but both high and low levels of urgency impede response (*high confidence*). Wilson and Orlove (2021) review five experimental and twenty observational papers that examine the relationship between urgency and levels of response in climate decision-making, across a range of settings: from individuals and households, to communities, managed ecosystems, sub-national regions and international river basin. Urgency in the papers is defined primarily through objective and subjective time pressure, including the recognition of the costs of delaying action and the importance of using windows of opportunity during which new forms and higher levels of response are possible. All the experimental papers and all but three of the observational papers provide support for an inverted U-shaped relationship between urgency and response intensity (including motivation and action), with higher levels of response at intermediate levels of urgency and lower levels of response at low or high levels of urgency (Figure 17.8). The general shape of this relationship also is supported for other decision domains by a well-established line of research within psychology (Heitz, 2014; Zakay, 2014; Prem et al., 2017).

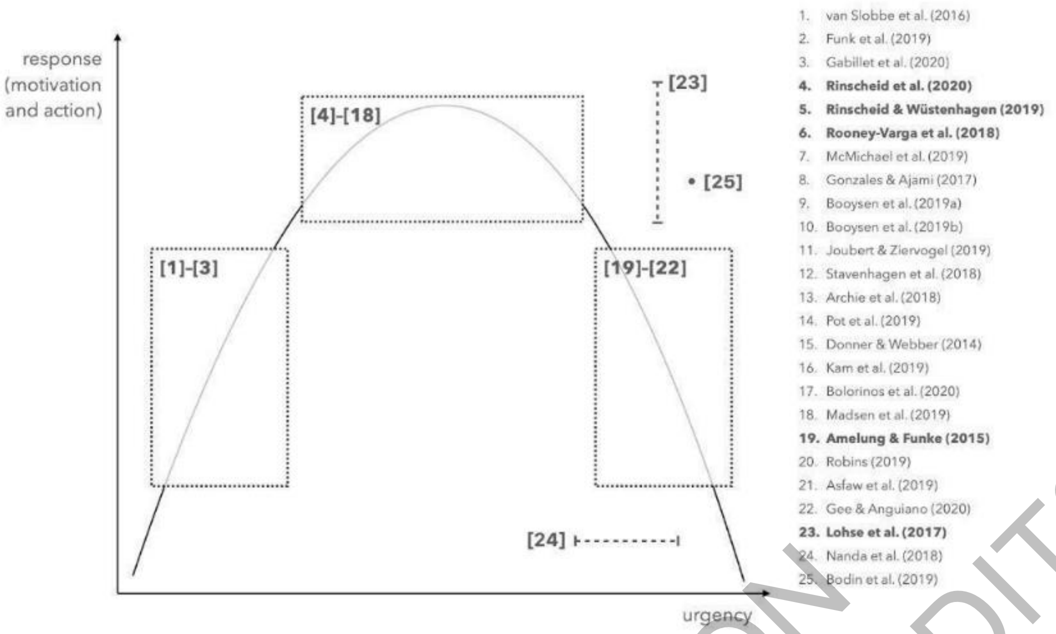


Figure 17.8: A moderate level of urgency serves as an important driver of climate action, but both high and low levels of urgency impede response [derived from Wilson and Orlove (2021)].

The synthesis of the studies on urgency offers two central lessons for policy makers, community groups, and others involved in addressing climate change. First, that greater levels of response to climate change-induced challenges can be motivated by communication strategies that move decision makers from low to moderate levels of urgency (*high confidence*). In the case of drought, a number of studies show that urgent messages promote water conservation, especially when these messages are repeated, perceived as trustworthy, and linked to concrete suggestions for action (Gonzales and Ajami, 2017; Joubert and Ziervogel, 2019; Kam et al., 2019; Booysen et al., 2019a; Booysen et al., 2019b; Bolorinos et al., 2020). These effects are also demonstrated in experimental studies of adaptation planning in contexts including European flood preparations (Madsen et al., 2019; Pot et al., 2019), and Pacific Island coastal planning (Donner and Webber, 2014).

Second, very high levels of urgency are a barrier to effective action (*medium confidence*), because last-minute actions to reduce risk during crises can create haste and panic, often leading to insufficient deliberation. In these cases, decision-makers fail to consider a full range of alternative actions, make rash choices and poorly mobilize available resources (Asfaw et al., 2019; Robins, 2019; Gee, 2020). Given that climate decision makers in many regions and sectors are experiencing greater pressure to act; this finding suggests the existence of windows for planning and action during which climate risks have led to moderate levels of urgency, but before these risks have resulted in urgency exceeding some upper threshold (see 17.4.5.2).

In addition, these studies point to potential weaknesses as well as strengths in strategic communication to modulate urgency. Such messages may instead lead to lower levels of response if they induce very high levels of urgency (Asfaw et al., 2019), though this effect may be somewhat mitigated by messages that simultaneously increase recipients' sense of self-efficacy or they are experienced in the specific risk domain discussed in the messages (Bodin et al., 2019). Future research on the relationships between urgency and effective risk management could help refine the measurement of urgency, how the relationship varies in different contexts, the role of different forms of messaging about urgency and action (Fesenfeld and Rinscheid, 2021), as well as the effects of urgency on decision-making by high-level decision-makers within polities and by climate social movements.

17.4.5.2 Windows of Opportunity

Windows of opportunity are time-bounded periods during which conditions are present for advancing and often accelerating climate adaptation strategies. They can act as significant catalysing conditions for climate action and are connected to a range of possible outcomes from small incremental shifts to larger scale more profound transformation adaptations (Novalia and Malekpour, 2020).

Windows can open because of extreme weather events (Birkmann and Fernando, 2008), political shifts, such as new institutions, new laws and regulations, and presence of a new policy entrepreneur or new policies (Haasnoot et al., 2013; Bell and Morrison, 2015), relevant and achievable policy goals, and emergence of new knowledge (Abunnasr et al., 2013), and close after the initial causes recede and become less efficacious. They also serve as focusing events whereby a coalition of groups address specific policy questions or response options (Rudel, 2019). Recognizing that windows of opportunity often catalyze action does not mean that action outside such windows is insignificant or impossible.

Extreme events such as disasters often act as proximate drivers of windows of opportunity (Birkmann and Fernando, 2008; McSweeney and Coomes, 2011). Climate disasters in a specific location become significant windows for new debate, policymaking and financing (McSweeney and Coomes, 2011). Extreme events also can facilitate change at locations distant from the most impacted site when remote actors gain perspective on their own risks (Friedman et al., 2019; Solecki et al., 2019). Factors that facilitate extreme events driving proactive as opposed to reactive responses include access to relevant risk and vulnerability data, pre-existing experience with similar events, and appropriate governance (Brown et al., 2017a). Page and Dilling (2020) find that worldview or ideology plays a central role in sense-making and in shaping what organizational decision-makers 'see' in terms of acceptable actions in response to an extreme event.

Significant variation is present across the mix and intensity of conditions that promotes action through a window of opportunity. Capacity to respond to is a function of the presence of enabling conditions as well as tools and methods to aid decision-making (Shi et al., 2015). Political activism provides windows of opportunity for climate adaptation (Lauer and Eguavoen, 2016; see also 17.4.5.3.1).

Sudden shifts in institutions and legal framework can also catalyse climate action. For example, the year 2015 included a series of international frameworks such as the Sendai Framework for Disaster Risk Reduction 2015-2030 (van Niekerk et al., 2020; Hofmann, 2021), the 2030 Agenda for Sustainable Development, which established the Sustainable Development Goals (Sanchez Rodriguez et al., 2018), and the Paris Climate Agreement, which dramatically enhanced the promotion and implementation of altered the conditions under which climate adaptation occurred.

17.4.5.3 Climate Litigation on Adaptation

Litigation for loss and damage from climate change was first noted as a potential motivator for emissions reduction in AR4 and AR5 noted that litigation was pending but not tested and that while legal systems were beginning to define the boundaries of responsibility for climate change, it was 'unclear liability exists'. The SR1.5 (IPCC, 2018a) reported, with high confidence, that litigation risks of government and business had increased and the SRCCL (IPCC, 2019b) noted that recent developments in climate attribution improve the ability to detect human influence on climate and broaden liability.

Since AR5 there has been growing recognition of the potential of litigation for failure to take measures to adapt to climate change to drive climate risk management (Banda and Fulton, 2017; Peel et al., 2017; Bouwer, 2018). Litigation cases on adaptation and loss and damage comprise about one third of those covered in the literature (Setzer and Vanhala, 2019a). Reasons for this growth are: (i) the growing gap between projected climate change impacts and current adaptation efforts (Stezer and Byrnes, 2019) and (ii) expanded legal duty of government, business, and others to manage foreseeable harms (Marjanac and Patton, 2018). Climate change litigation is expanding geographically into the Americas, Asia (and the Pacific region), and Europe with several cases brought in low- and middle-income countries (Stezer and Byrnes, 2019) (See Table 17.7).

Lawsuits against private entities contribute to articulating climate change as a legal and financial risk (*medium confidence*) (Peel and Osofsky, 2015; Ganguly et al., 2018; McCormick et al., 2018; Peel and

Osofsky, 2018). Even if unsuccessful, Estrin (2016) concludes they are important in underlining the high level of public concern.

Climate-related, legal, financial disclosure requirements are improving investment decision making of corporations as well as augmenting ex post liability for failure to consider climate change risk in decision making. Organizations are required to disclose governance around climate related risks (impact of climate change on businesses, products, services, supply or value chain, adaptation and mitigation activities, investment in research and development and operations). This functions as a vehicle for identifying climate-related risk and the organization's resilience strategy taking into consideration different climate-related scenarios including a 2˚C or lower scenario (Sarra, 2018). Institutions such as the G20 (Carney, 2019), the American Bar Association (Brammer and Chakrabarti, 2019), the European Commission (Zadek, 2018) have adopted or endorsed these standards.

Table 17.7: Examples of types of climate-related litigation

Litigation Type	Detail and Examples	Supporting Literature
Challenge government decisions for not considering climate change risks	Challenging government or administrative planning decisions for failure to consider, or adequately address, climate change in relation to developing and protecting coastal zones, water stressed regions, flood prone areas, or decisions affecting endangered species whose habitat is at risk. For example, the Victorian Civil and Administrative Tribunal in Australia rejected a planned housing project in a coastal area, citing the risks from climate change (Gippsland Coastal Bd. v. South Gippsland Sc & Ors (No2), 2008).	(Banda and Fulton, 2017; Peel et al., 2017; Bouwer, 2018; Clarke and Hussain, 2018)
Petitions to act	Constitutional petitions to force governments to take adaptation measures. As an example, in Leghari v. Pakistan a farmer initiated public interest litigation against federal and provincial governments for failure to develop climate change resilience through adaptation to floods, droughts and other impacts because it violated his rights to life and dignity. The High Court of Lahore found for Mr. Leghari and created a commission to develop and implement a wide range of adaptation actions.	(Banda and Fulton, 2017; Ashgar Leghari v. Federation of Pakistan, April 2015; Ashgar Leghari v. Federation of Pakistan, September 2015)
Regulatory proceedings	Environmental groups and city and state officials intervened in the application of the electric utility serving New York City, Consolidated Edison Company, to the New York State Public Service Commission for a rate increase. The intervenors argued that the company was not adequately preparing for flooding, heat waves and other climate-related impacts. As a result, the Commission directed the company to undertake a study of its vulnerability to climate change, and write and implement a plan to address these risks.	(Consolidated Edison Co., 2019)
Failure to act by public authorities	Liability of public authorities for failure to undertake necessary adaptation actions to avoid damage to life or property especially where statutory framework is proven ineffective or out of step with international commitments; in some areas these are class action suits. An example is private lawsuits for failure of a built environment to consider adaptation needs in a built environment (energy efficiency works, overheating because of increased temperatures).	(Banda and Fulton, 2017; Peel et al., 2017; Bouwer, 2018)
Failure by private sector to consider climate change	Examples include: (i) A citizen suit against ExxonMobil for failure to adapt Everett Terminal to the impacts of	(Benjamin, 2017; Stezer and Byrnes,

adaptation in their business practice	climate change including increased precipitation, sea level rise and storm surges occurring with increasing frequency; (ii) A citizen suit against. Shell Oil Products US alleging Shell failed to incorporate climate risks in its investment in a bulk storage and fuel terminal in Rhode Island, USA; (iii) Shareholder action against ExxonMobil for failure to report climate risks or complying with recommendations to do so and for issuing misleading corporate disclosure relied on by investors; (iv) A suit brought an NGO, the Conservation Law Foundation, against Exxon Mobil alleging that the company had taken insufficient precautions to protect a major oil tank farm near Boston, USA, from coastal storms that are worsened by climate change, creating a danger of an oil spill into Boston Harbour. The U.S. Court of Appeals for the First Circuit ruled in 2021 that the lawsuit could proceed, and that the NGO could attempt to make out its case that Exxon Mobil should take greater precautions.; (v) Government and citizen claims for public nuisance against fossil fuel companies for the costs of adaptation such as infrastructure to protect against sea level rise.	2019; Street and Jude, 2019; Wasim, 2019; Conservation Law Foundation v. Exxon Mobil Corporation, 2021)
Youth public trust claims	Government inter-generational liability for inadequate climate change mitigation and adaptation efforts. Our Children's Trust (a non-profit organization) and others brought an action against the United States and several executive branch individuals in 2015 claiming damages for their loss of the environment and the defendant's failure to preserve a habitable climate system. Similarly, a public trust claim could be brought in a coastal town for failure to adapt to climate change.	(Schneider et al., 2017; Bouwer, 2018)
Human rights claims	Human rights may be a powerful tool for organizing and unifying adaptation decision making, especially for the most vulnerable, through enforcement mechanisms of progressive realization as well as ex post liability (see Chapter 8). For example, a persons' right to food implores state parties to take necessary actions to alleviate hunger caused by climate change; during natural and other disasters rights to water, and life are impacted; sea-level rise and storm surges impact many coastal settlements and the right to adequate housing and an adequate standard of living. This is in part due to increasing acceptance of the impact of climate change on health, livelihoods, shelter and fundamental rights.	(Hall and Weiss, 2012; Peel and Osofsky, 2018; Setzer and Vanhala, 2019b; Stezer and Byrnes, 2019)

17.4.5.4 Catalysing Agents

Individuals and organizations often serve as catalysing agents of climate risk decision-making. They promote greater levels of new forms of climate action by communicating the urgency of climate action and by developing coalitions which undertake action. Agents include individuals, organisations or collectives, or multiple organizations linked together.

17.4.5.4.1 Social movements and other mobilizations

Recent studies of climate-related social movements show that they can act as catalysing agents which promote action to manage climate-related risks (*medium confidence*). However, these studies use varying definitions of climate movements within the broader context of environmental movements. A prominent topic of research is the rapidity and the large scale of the proliferation of these movements around the world, primarily in urban settings but also in rural and Indigenous contexts (Claeys and Delgado Pugley, 2017).

These movements usually focus on climate mitigation but sometimes include adaptation. Their social bases include groups which had not previously been active in climate politics, notably children and youth, as well as sectors with long traditions of environmental activism, such as women and Indigenous peoples (see Cross-Chapter Boxes GENDER and INDIG in Chapter 18). Much of the literature on youth movements traces the emergence of the movements themselves (Sanson et al., 2019; Treichel, 2020), their framings of climate change as a social justice issue (Holmberg and Alvinius, 2019) and their presence in demonstrations and on social media (Boulianne et al., 2020). Climate action catalysed by youth and other climate movements include visible international events such as the signing of Declaration on Children, Youth, and Climate Action at COP25 in Madrid 2019 (Han and Ahn, 2020), as well as national efforts, including lawsuits, and local events such as in tree-planting and waste reduction initiatives (Bandura and Cherry, 2019).

A recent review examines 2743 cases around the world of mobilizations for environmental justice causes (Scheidel et al., 2020); roughly half the cases occurred between 1970 and 2007, and half between 2008 and 2019. Of these environmental mobilizations, 17% are directly related to climate and energy, and others are related to climate-sensitive issues (15% for biomass and land use, 14% for water management). This study reports the proportion of positive outcomes for different strategies, defined as meeting the goals of the movements, which generally align with climate adaptation and sustainable resource management. These rates vary from 10% for negotiated solutions to 34% for court decisions. It notes the corresponding higher rates of failure, as well as the costs borne by the movements, which include criminalization (20% of cases), violence (18%) and assassination (13%). These costs are significantly higher for Indigenous communities that engage in these mobilizations.

At a global scale, climate movements succeeded in pressing for the greater recognition of the importance of Indigenous knowledge within international agreements (Tormos-Aponte and García-López, 2018) but did not achieve the major reforms of climate finance which they sought (Khan et al., 2019a); these differing outcomes reflect the sensitivity of the issues and the formation of coalitions which supported or opposed the movements. At national and local scales, one review of US cases reports limited effectiveness of climate movements because of the ability of governmental agencies to coopt them (Pulido et al., 2016), while another review in Pakistan shows a number of successes, because the movements were able to build alliances with other public sector and community groups (Shawoo and McDermott, 2020).

17.4.5.4.2 Policy leaders and entrepreneurs

Policy leaders, often described as policy entrepreneurs within the scholarly literature, are individuals in positions of leadership who set agendas and build coalitions to drive decision-making processes, and hence can function as catalysers of climate adaptation (Petridou and Mintrom, 2020). Political leaders who have taken on climate change as a key policy issue function as policy entrepreneurs at international, national and sub-national levels. City officials including mayors and other executives often play the role of climate policy entrepreneurs, while the absence of effective leadership negatively affects adaptation success (Becker and Kretsch, 2019). Such entrepreneurs can be important forces for change in both reactive contexts following an extreme or focusing event and in proactive context. They can be effective especially in contexts where they navigate and link together formal and informal networks of complex climate governance systems (Tanner et al., 2019). Their capacity to act has been increased when they and their institutions are embedded within partnership networks (Bellinson and Chu, 2019). It is in these contexts that the leadership and position of a policy entrepreneur becomes even more catalytic when operating at the interface of formal and informal networks (Mintrom, 2019; Stone, 2019).

Sub-national actors and city officials including mayors and other executives are among the individuals most often described and assessed as climate policy entrepreneurs (Kalafatis and Lemos, 2017). City level climate policy entrepreneurs often operate using their own experience, connections, and persistence to address issues of importance to their constituency. Climate risk concerns are often inherently local and in turn local decision-makers perceive it being appropriate to engage. Conversely, the absence of effective leadership negatively affects adaptation success (Kalafatis and Lemos, 2017; Becker and Kretsch, 2019). Urban climate policy entrepreneurs operate in four key spheres of policy development and implementation: attention and support seeking strategies; linking strategies (e.g., coalition building); relational management strategies (e.g., networking and trusting building); and arena strategies including timing (Brouwer and Huitema, 2018). The presence and operation of urban climate policy entrepreneurs is positively associated in settings with multiple jurisdictions and across differing spatial scales (Kalafatis and Lemos, 2017; Renner and Meijerink, 2018). It is these contexts that their capacity to operate simultaneously at the interface of multiple networks is particularly valuable for promoting climate action. Urban climate policy entrepreneurs can directly engage with a range of constituent groups and offer and promote climate adaptation strategies that can have direct impact on the daily lives of these residents and their interests.

[START BOX 17.3 HERE]

Box 17.3: Climate Risk Decision-Making in Settlements: From Incrementalism to Transformational Adaptation

Cities are important sites of experimentation where the integration and management of adaptation decision-making complexity often takes place. These actions provide early evidence of what aspects of complex climate risk management decision-making functions well, but also what does not work (Revi et al., 2020). Cities are seen as locales where case examples of transformative adaptation can be examined (Rosenzweig and Solecki, 2018; Vermeulen et al., 2018). Cities act as testbeds of how to integrate climate response into issues of equity, health, resource allocation, and sustainability in ways that utilize innovative use of new and emerging decision-support tools, methods and protocols.

Risk management has been an integral part of the community development and settlement building process. Three key sets of drivers influence risk management decision-making in cities (Solecki et al., 2017). These include 1) root – i.e., cultural norms and social traditions; 2) context – i.e., policy and governance conditions and 3) proximate – i.e., extreme events. Settlements have developed informal and formal strategies including climate protection levels to respond to local conditions of climate risk and hazards. In formal contexts, these strategies are contextualized in local climate change action plans (Araos et al., 2016a; Stults and Woodruff, 2017; Reckien et al., 2018a; Singh et al., 2021) and defined around a set of evaluation tools and methods and building codes, standards, and regulations (see discussion in 17.4.4).

Climate change has begun to alter the environmental baseline of cities changing their risk and hazard profiles. In recent years, national and local risk management can benefit from assessments of current decision-making strategies and from evaluations of opportunities for change in risk management policy. These changes can be adjustments of existing policies or transitions to a new policy for current (i.e., conditions already experienced by getting worse) or emerging risks (i.e., conditions not previously or widely experienced but now increasingly present).

With increasing impacts of climate change, settlements of all sizes are considering how to make their communities more resilient to climate risk (see Cross-Working Group Box URBAN in Chapter 6; Araos et al., 2016a; Araos et al., 2017; Reckien et al., 2018a). In many settlements demands for heightened resiliency are being coupled with opportunities to enhance the social and economic equity and quality of life of residents. Transformational adaptation (transformational, as being outcome-oriented; Vermeulen et al., 2018) and associated adjustments to the urban risk management decision-making requires an integration of climate resiliency pathways and conditions of sustainable development (Mendizabal et al., 2018). At the same time, growing conflict is present between requirements for greater resiliency and continued economic development, in particular in low-income environments (Ahenkan et al., 2020). Cities and their residents have the capacity to transform their own governance and decision-making systems (Birkmann et al., 2014; Chu, 2018; Romero-Lankao et al., 2018). Furthermore, cities have recognized the opportunity and demand to transform in order to be more ambitious (Mendizabal et al., 2018) and more successful, more equitable (Reckien et al., 2018b) and better able to connect the climate action to the sustainable development process (Singh et al., 2021).

In some cases, transformational adaptation is associated with large-scale, top-down, formal decision processes leading to significant policy shifts. For coastal cities this might include actions to build massive flood protection systems (as opposed to simple increase of existing structures) (Albers et al., 2015; Hinkel et al., 2018; Ajibade, 2019; see also Section 2.3.5, Cross-Chapter Paper 2) or policies to encourage managed retreat from increasing at risk locations (Hino et al., 2017; Rulleau and Rey-Valette, 2017). In more extreme instances, the relocation of cities is presented as a possibility, such as planned for the city of Jakarta

(Garschagen et al., 2018b). However, acceptability of top-down approaches to relocation are usually low and bottom-up drivers of relocation are important, especially to avoid inequitable outcomes (Mach and Siders, 2021). Intensity of extreme events and changing risk perceptions and expectations of property prices have been identified as important behavioural drivers of voluntary relocation (de Koning et al., 2019; de Koning and Filatova, 2020). Yet, when not supported by equitable public adaptation policies, the transformational adaptation left to the influence of autonomous adaptation and market institutions alone leads to climate gentrification low-income households are priced out from the hazard-free zones (de Koning and Filatova, 2020).

These circumstances also have revealed potential advances in decision-making by encouraging greater participation, more effective generation and use of information and data, and more prominent inclusion of questions of social and economic equity (Ziervogel et al., 2017; Reckien et al., 2018b; Solecki et al., In Press). Adaptation planning and decision-making, in general, within cities has increasingly focused on actively engaging residents in participatory and neighbourhood scale co-production processes (Broto et al., 2015; Sarzynski, 2015; Wamsler, 2017; Foster et al., 2019). However, engaging residents in risk management and adaptation has not always led to transformative decision-making and resiliency, but can at times also reinforce existing maladaptive systems (D'Alisa and Kallis, 2016).

Now increasing amounts of data are being collected via surveys or in participatory settings next to advanced methods, such as using citizen science, big data and AI, to integrate these social dimensions of climate adaptation decisions in cities in formal models (Abebe et al., 2019; Taberna et al., 2020). Linking to social data on individual decisions, risk perceptions, social norms, and governmental policy, advanced social models trace and quantify how adaptation in cities evolve and would cumulatively induce transformational change. Although wider application of these models is outstanding there is opportunity to simulate and learn from the integration of social and behavioural data with political and cultural norms (de Koning and Filatova, 2020).

Although non-urban areas could in many instances act in the same way as urban areas, the density of people, assets, infrastructure, and economical values drives cities to act as testbeds, implement adaptation, and strive for resiliency. Cities are showcases for the larger environmental systems of governments that also support mitigation ambition of national actors and are therefore demanding to be recognized as valuable actors in the international negotiations, highlighting their contribution in emissions reductions (Chan et al., 2015; Hale, 2016), e.g., in the preparation for the first Global Stocktake of the Paris Agreement in 2023 (see Cross-Chapter Box PROGRESS in this Chapter).

[END BOX 17.3 HERE]

17.5 Adaptation Success and Maladaptation, Monitoring, Evaluation and Learning

17.5.1 Adaptation Success and Maladaptation

17.5.1.1 The Adaptation-Maladaptation Continuum

As evidence on adaptation implementation grows (Berrang-Ford et al., 2021; Eriksen et al., 2021), there is a need to examine the outcomes of adaptation (Ford et al., 2011) for effectiveness, adequacy, justice/ equity in both outcomes and process, as well as synergies and trade-offs with mitigation, ecosystem functioning, and other societal goals. There is also a growing recognition of the observed and potential negative consequences of some adaptation interventions, often referred to as maladaptation (Juhola et al., 2016; Magnan et al., 2016; Schipper, 2020; Eriksen et al., 2021). This section advances a new framing to allow for an improved assessment of the potential positive or negative outcomes of adaptation options, therefore allowing navigation of the adaptation-maladaptation continuum.

17.5.1.1.1 Defining and assessing success in adaptation vis a vis maladaptation

The highly contextual nature of adaptation, a multitude of applied definitions of adaptation (e.g cost effectiveness versus outcomes), its overlaps with development interventions, and the long time horizons over which outcomes accrue, deter a universal definition of adaptation success (Dilling et al., 2019a; section

17.5.1.2; Owen, 2020; Singh et al., 2021). Moser and Boykoff (2013), Olazabal et al. (2019b), and Sherman and Ford (2013) suggest criteria against which successful adaptation could potentially be tracked. The literature is converging to suggest that successful adaptation broadly refers to actions and policies that effectively and substantially reduce climate vulnerability, and exposure to and/or impacts of climate risk (Noble et al., 2014; Juhola et al., 2016), while creating synergies to other climate-related goals, increasing co-benefits to non-climate-related goals (such as current and future economic, societal, and other environmental goals) and minimize trade-offs (Grafakos et al., 2019) across diverse objectives, perspectives, expectations, and values (Eriksen et al., 2015; Gajjar et al., 2019a; Owen, 2020) (*high confidence*).

Maladaptation refers to current or potential negative consequences of adaptation-related responses that lead to an increase in the climate vulnerability of a system, sector, or group (Barnett and O'Neill, 2010) by exacerbating or shifting vulnerability or exposure now or in the future (Antwi-Agyei et al., 2014; Noble et al., 2014; Juhola et al., 2016; Magnan et al., 2020) and eroding sustainable development (Juhola et al., 2016). Conceptually, maladaptation differs from 'failed' or 'unsuccessful' adaptation (Schipper, 2020), which "describes a failed adaptation initiative not producing any significant detrimental effect" (Magnan et al., 2016: 648). Several frameworks have been proposed to explain and better assess maladaptation (Hallegatte, 2009; Barnett and O'Neill, 2010; Magnan, 2014; Magnan et al., 2016; Gajjar et al., 2019b). In order to limit the risk of maladaptation, a common focus of these frameworks is on intentionally avoiding negative consequences of adaptation interventions, anticipating detrimental lock-ins and path dependence, and minimizing spatio-temporal trade-offs.

The adaptation literature challenges the simplistic dichotomy of interventions being either successful or maladaptive (e.g. Moser and Boykoff, 2013; Singh et al., 2016; Magnan et al., 2020; Schipper, 2020). There is no clear cut boundary between these two categories; rather, successful adaptation and maladaptation need to be considered the two ends of a continuum of risk management strategies (Figure 17.9) emphasising that:

- no options are "bad" or "good" *a priori* with respect to reducing climate risk/vulnerability.
- positive and negative outcomes of adaptation depend on local context specificities (including the presence/ absence of enabling conditions [1]), how adaptation is planned and implemented, who is judging the outcomes (i.e. adaptation decision-maker, planner, implementer or recipient) and when adaptation outcomes are assessed.
- *ex ante* assessment of where options fall on the continuum can help anticipate maladaptive outcomes.

Along the adaptation-maladaptation continuum, adaptation options can score high or low on different outcome criteria identified in this section as: benefits to the number of people, benefits to ecosystem services, equity outcomes (for marginalized ethnic groups, gender, low-income populations), transformational potential and contribution to GHG emission reduction (see SM 17.1 for full descriptions). Importantly, the outcome of the assessment, and consequently location of a given adaptation option along this continuum, is dynamic, depending on multiple components including changes in the characteristics of climate hazards and the effects of iterative risk management. Unfortunately, this temporal dimension is understudied in the literature (including studying thresholds or speed), preventing advances on this specific point.

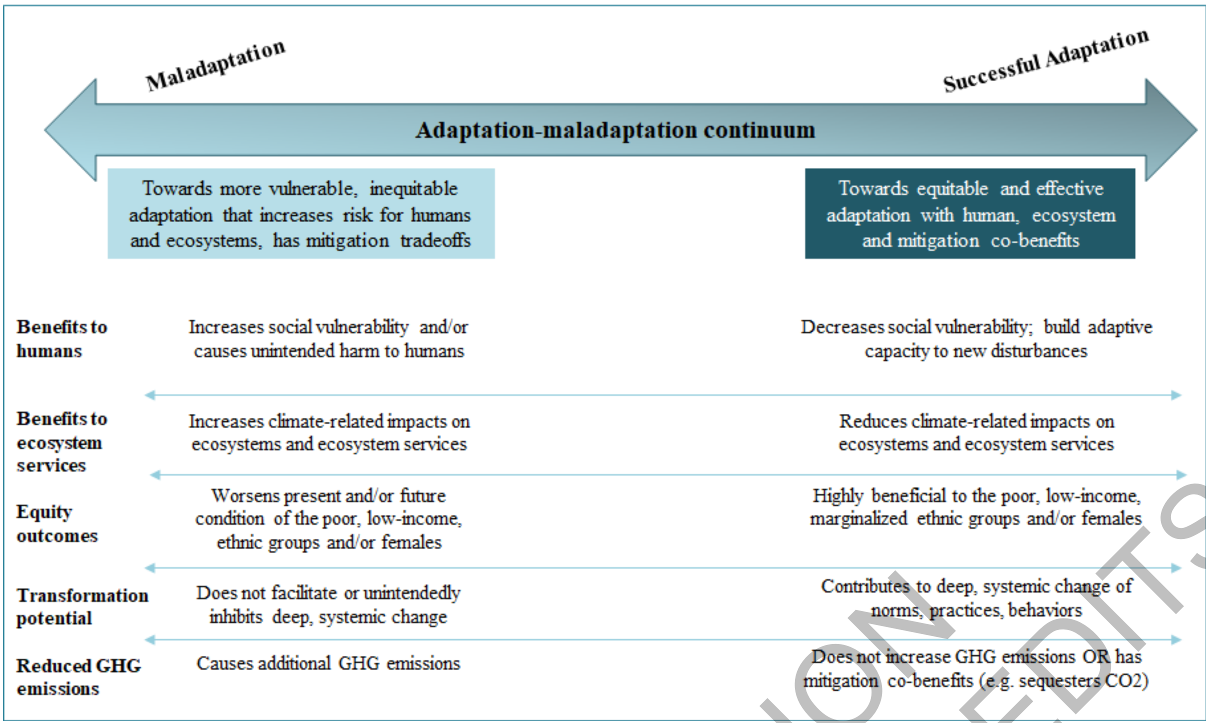


Figure 17.9: Successful adaptation and maladaptation are conceptualised as the two end points of a continuum, with adaptation options being located along the continuum based on outcome criteria (how they benefit humans and ecosystems; how they contribute to or hinder equity goals; whether they enable transformative change to climatic risks, and synergies and trade-offs with climate mitigation). As indicated in SM 17.1 and figure 17.9, adaptation options might rate largely positive and slightly negative across outcome criteria (tending towards successful adaptation), while other adaptation options might have small positive aspects and larger negative ones across different outcome criteria (tending towards maladaptation). The figure draws on Singh et al. (2016); Magnan et al. (2020), and Schipper (2020).

17.5.1.1.2 Empirical evidence on success of adaptation vis a vis maladaptation

Although the empirical evidence on current and potential successful adaptation and maladaptation remains small and fragmented (Magnan et al., 2020; Berrang-Ford et al., 2021; see Section 17.3.2 in this Chapter), the above framing allows for moving a step further in assessing the potential contribution of a wide range of adaptation-related options to success or maladaptation.

According to an assessment (Figure 17.10; see SM 17.1 for full descriptions) of maladaptation-relevant outcome dimensions, here called criteria, i.e. benefits to people, benefits to ecosystem services, benefits to equity (marginalized ethnic groups, gender, low-income populations), transformational potential, and contribution to GHG emission reduction, no option is located at one or the other end of the adaptation-maladaptation continuum (Figure 17.10, right panel), showing that all options have some maladaptation potential, i.e. trade-offs (*very high confidence*). This is also shown by the wide confidence bars of most options (right panel) signifying that most adaptation can be done in a way that involves a higher or a lower risk of maladaptation (*medium confidence*; see also Table 17.2). The option of ‘coastal infrastructure’ signifies the highest risk for maladaptation. While it can be an efficient adaptation option in highly densely populated areas (Oppenheimer et al., 2019; CCP2.3), it has potential tradeoffs for natural system functioning and human vulnerability over time. The option most widely associated with successful adaptation is ‘nature restoration’, closely followed by ‘social safety nets' and options relating to ‘farm/ fishery practices’, and ‘diets/ food waste’ (*high confidence*).

Some options show the dominant influence of certain criteria (Figure 17.10, central panel rows). For example, ‘availability of health infrastructure’ and ‘access to health care’ are dominated by the criterion ‘greenhouse gas emissions’. Similarly, ‘spatial planning’ carries a high risk of disadvantages to marginalized ethnic and low-income groups. This means that these adaptations could be transformed into successful adaptations more easily than others, if attention is paid to the dominant criterion. For example, if healthcare could be provided with low GHG emissions it would move closer towards successful adaptation (*high confidence*). For other options, the criteria’s influence is more evenly distributed, as illustrated for the 'diversification of livelihoods' and the three options to address climate risks to peace and mobility, denoting multiple entry points to reduce the risk of maladaptive outcomes for these options.

Some criteria score highly across a number of options (Figure 17.10, central panel columns), showing that many adaptations do not pay attention to different trade-offs. For example, particular attention should be paid to prioritising benefits to low-income groups and leveraging the transformational potential of adaptation (having the largest number of large circles), i.e. many evaluated options become maladaptive by exacerbating the vulnerability of low-income groups and by fortifying the status-quo (*medium confidence*). On the contrary, most evaluated adaptation options are widely applicable across populations (benefits to humans), and deliver ecosystem services, while some also respect gender equity (largest number of small bubbles across options), through these criteria a number of adaptation options contribute to a higher potential for successful adaptation (*high confidence*).

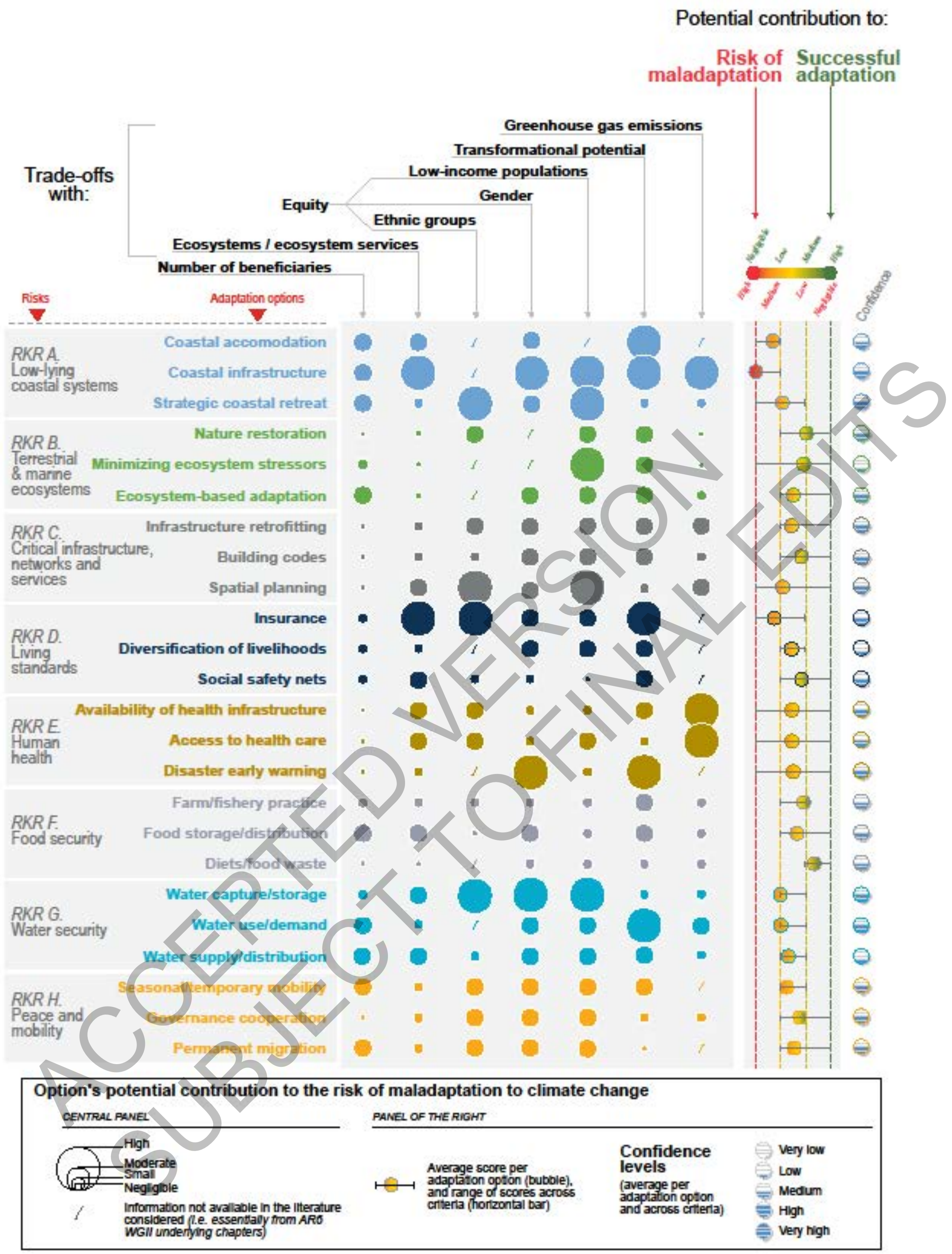


Figure 17.10: The potential contribution of 24 adaptation-related options to maladaptation and successful adaptation. The figure builds on evidence provided in the underlying sectoral and regional chapters and the Cross-Chapter Papers (SM17.1) to map 24 adaptation options identified as relevant to the eight Representative Key Risks (see Ch16.5) onto the adaptation-maladaptation continuum. It assesses the potential contribution of each of these adaptation options to successful adaptation and the risk of maladaptation. The figure permits a review of options in multiple ways: a) Looking at adaptation options (first column) one can see which adaptation options score highest across the criteria (the central rows). Results by options show which ones carry the highest risk of maladaptation (=largest circles per row). b): Looking at criteria (top centre) one can see which criteria seem to be most influential to contribute to

maladaptation outcomes (=largest circles per central column). c) The panel on the right: Merging the scores of each adaptation option across criteria helps highlighting whether the options are likely to end up as successful adaptation or maladaptation.

The results displayed in Figure 17.10 are not rigorous predictions but illustrate the maladaptive potential of options based on a synthesis of literature from underlying WGII chapters and cross-chapter papers. This leads to findings for general situations, potentially obscuring critical contextual specificities which can mediate successful adaptation or maladaptation outcomes. In a certain context, Figure 17.10 will appear different. Moreover, the analysis is based on a static interpretation of adaptation outcomes, while risk and risk reduction are dynamic. The current, underlying literature does not help understanding the temporal dimension of the options, their flexibility or risk of lock-in, and related potential contribution to long-term maladaptation or successful adaptation. The added value of the analysis lies in the approach to assess the potential contribution to maladaptation or successful adaptation (via the seven criteria at the top of the figure), rather than in the final results themselves. This overview illustrates how in a particular context and for particular groups of people, adaptation options and their location on the adaptation-maladaptation continuum can be assessed for a set of outcome dimensions, focuses on assessing potential contributions per and across criteria, as well as per and across options (critical information to support the identification of adaptation pathways; Cross-Chapter Box DEEP in this Chapter).

17.5.1.1.3 Enabling successful adaptation and pre-empting maladaptation

Considering evidence on enabling successful adaptation in the sectoral (Chapters 2-8) and regional chapters (9-15), four conditions stand out as particularly key to enabling adaptation success: recognitional equity and justice, including the integration of Indigenous and local communities and knowledge; procedural equity and justice; distributive equity and justice; and flexible and strong institutions that seek integration of climate risk management with other policies and address long-term risk reduction goals (Table 17.8). For a wider discussion of enablers for adaptation and climate risk management, see Section 17.4.

Recognitional equity and justice: Recognitional justice focuses on inclusion and agency, i.e. examining who is recognised as a legitimate actor and how their rights, needs and interests are acknowledged and incorporated into action (Singh et al., 2021).

A global assessment of 1682 papers on adaptation responses yields that low-income groups (*high agreement*, 37% of 1682 articles), women (*medium agreement*, 20% articles), Indigenous peoples (10%), the elderly (8%), youths (5%), racial and ethnic minorities (4%), and migrants (4%) were the most frequently considered groups in adaptation responses. Individuals with disabilities are the least considered, with only 1% of articles including this group. There is a category of "other" capturing characteristics of social disadvantage that are distinct from the categories above. This includes, for example, spatially marginalized populations (e.g., groups relegated to flood-prone or cyclone-prone areas) and groups marginalized due to marital status or assets (education, farm size, and land tenure) (Araos, in press).

Procedural equity and justice: Participation is employed to enable procedures that aim to redress power imbalances, which are assumed to be the root causes of vulnerability (i.e. the reasons that lead certain people and places to be differentially vulnerable to climate risks) (Tschakert and Machado, 2012; Shackleton et al., 2015; Schlosberg et al., 2017; Ziervogel et al., 2017). However, participation is often constrained by gender (Cross-Chapter Box GENDER, Ch 18), social status, unequal citizenship (as concerns education, access to information, finance and media) (Wallimann-Helmer et al., 2019), entrenched political interests (Shackleton et al., 2015; Chu et al., 2017), power dynamics (Rusca et al., 2015; Taylor and Bhasme, 2018; Kita, 2019; Omukuti, 2020; Taylor and Bhasme, 2020), or institutional shortcomings (Nightingale, 2017, in Nepal), which allow the most powerful access to funding and reinforce marginalisation of the powerless (Schipper et al., 2014; Khatri, 2018; McNamara et al., 2020). Vulnerability is also sometimes used as a pretext to exclude groups from participation, often because vulnerable groups do not own land, lack legal status, time, or the ability to commit labour or material inputs for adaptation, all drivers of vulnerability in the first place (Nyantakyi-Frimpong and Bezner Kerr, 2015; Camargo and Ojeda, 2017; Nagoda and Nightingale, 2017; Nightingale, 2017; Thomas and Warner, 2019; Mikulewicz, 2020).

Reporting from the global assessment of equity considerations in adaptation, procedural equity and justice, was slightly more often mentioned (~52%) than not (~48) (*medium agreement*). However, the robustness of the evidence on inclusion of vulnerable and marginalized groups in the planning of adaptation responses is low (63%) (*high agreement*). Only for ~6% of the articles that provide evidence for inclusion of vulnerable groups the robustness of evidence is high (*low agreement*). Globally, the category of low-income (~25%) and women (~13%) are most often included, although the robustness remains low. Most of the robust evidence comes from Africa and Asia, where adaptation responses mostly focus on low-income and women groups in the food (28%) and poverty (32%) sectors (*medium agreement*). With regards to other vulnerability categories, such as disabled populations, almost negligible evidence was found for the inclusion of this group, globally. There is also little reporting of procedural equity in community-based or ecosystem-based responses (Araos, in press).

Distributive equity and justice: Attention to distributional equity and justice aims to ensure that adaptation interventions do not exacerbate inequities (Atteridge and Remling, 2018) and that the benefits and burdens of interventions are distributed fairly (Tschakert et al., 2013; Reckien et al., 2017; Reckien et al., 2018b; Pelling and Garschagen, 2019).

A global assessment of 1682 papers on adaptation (Araos, in press) finds that about 60% of articles mentioned at least one vulnerable group being involved in the implementation of adaptation or targeted by it (*medium confidence*). Low-income groups (*high agreement*, 37% of 1682 articles) and women (*medium agreement*, 20% articles) are the most frequently mentioned. Particularly in sectors and regions that incorporated coping measures in their adaptation response (Poverty, Food, Africa, Asia, Central & South America), these groups are prevalent. In sectors where responses were more strategic or planned, such as in cities, terrestrial and water, a larger proportion of articles (51%, 47% and 47% of articles respectively) vulnerable groups were not frequently included in the response (medium agreement). There was also a stark difference in inclusion of marginalized and vulnerable groups between high-income and low-income countries regions, with the majority of the responses from Australia, Europe and North America, not including marginalized groups (*high agreement* with 70%, 69% & 55% of articles respectively), showing the need for increasing attention in particular on a cross-sectoral and cross-regional relation (Araos, in press).

Flexible and strong institutions: There is *medium confidence* that flexible institutions can enable adoption of new adaptation measures or course-correct established ones based on ongoing monitoring and evaluation, which is key to avoiding potential maladaptation (e.g. Granberg and Glover, 2014, in Australia; Magnan et al., 2016; Torabi et al., 2018; Gajjar et al., 2019a, in India). Cross-sectoral, cross-jurisdictional and cross-spatial institutional frameworks enable successful adaptation by improving the ability of societies to respond to changes in their environment in a timely manner. The latter points to the vital role of monitoring and evaluation, as the tool to detect change in risk and vulnerability, together with environmental or societal conditions determining risk and the effectiveness, efficiency, adequacy, or success of adaptation responses.

Table 17.8: Key factors that enable successful adaptation. The evidence and examples draw on the underlying sectoral and regional chapters as well as a synthesis of adaptation literature.

Enablers	What this enables	Key characteristics	Examples and traceability
Recognitional justice	Pluralising the ambit of who is 'counted' as vulnerable, drawing on multiple knowledge systems	- Focuses on inclusion and agency, i.e., who is recognised as a legitimate actor and how their rights, needs and interests are acknowledged and incorporated into adaptation (Chu and Michael, 2018; Singh et al., 2021). - Acknowledges how differential vulnerability to climate change stems from historical and structural inequalities, which can unevenly distribute adaptation benefits, especially for the poorest and the most marginalized (Tschakert and Machado, 2012; Shackleton et al., 2015; Schlosberg et al., 2017; Ziervogel et al., 2017; Eriksen et al., 2021). - Informs more equitable adaptation priorities (Ziervogel et al., 2017), legitimizes adaptation	- Co-production of knowledge and inclusion of Indigenous and local knowledge (Loboguerrero et al., 2018; Dannenberg et al., 2019, Cross-Chapter Box ILK; Ziervogel et al., 2019). - Co-production of knowledge and inclusion of marginalized groups across sectors, see e.g., in the health sector (Ch 7), food systems (Ch 5) and fire management (Ch 12).

		actions (Myers et al., 2018; Ellis and Tschakert, 2019), supports inclusion of marginalized groups (Chu and Michael, 2018) (*medium confidence)*.	
Procedural justice	Differential participation and power for more inclusive adaptation planning and implementation	- Ensures that processes of representation and participation in adaptation planning, prioritisation and implementation are inclusive (Holland, 2017; Reckien et al., 2017; Reckien et al., 2018b) (*medium confidence*). - Enable adaptations to advance more quickly and generate higher levels of wellbeing (e.g. Dannenberg et al., 2019 comparing cases of strategic retreat), while also benefiting poorer households (Chu and Michael, 2018). - Higher participation can enable more legitimate outcomes, greater awareness about societal problems addressed, larger willingness for community cooperation, and increased individual behavioural change (Burton and Mustelin, 2013). - Participation in design and implementation of adaptation projects can be a critical element for avoiding maladaptive outcomes (Taylor, 2015; Nightingale, 2017; Forsyth, 2018; Mikulewicz, 2019).	- Participation of multiple stakeholders enables co-production of adaptation strategies and devolution of decision-making (Ziervogel, 2019) and often, even if not always (D'Alisa and Kallis, 2016), a higher level of transformational adaptation (and more ambitious local mitigation goals) (Cattino and Reckien, in press). - Participatory processes can have more equitable outcomes as evidenced in informal settlements (Ziervogel, 2019, South Africa), small farmers (Loboguerrero et al., 2018, Colombia); migrants (Gajjar et al., 2019b, India), and deliberative dialogues (Ojha and et al., 2019). - But participation does not always address unequal power relations (e.g. Buggy and McNamara, 2016; Karlsson et al., 2017).
Distributive justice	Delivering adaptation for vulnerable groups and correcting structural vulnerabilities	- Ensures that adaptation interventions do not exacerbate inequities (Atteridge and Remling, 2018) and that the benefits and burdens of interventions are distributed fairly (Tschakert et al., 2013; Reckien et al., 2017; Reckien et al., 2018b; Pelling and Garschagen, 2019). - However, low levels of commitment to distributive justice, e.g. when justice is one of many goals of adaptation instead of the prime one, are insufficient to promote equitable distribution of benefits and harms (*medium evidence, high agreement*) (Anguelovski et al., 2016; Pulido et al., 2016; Weinstein et al., 2019; Shawoo and McDermott, 2020).	- Women and men have very different access to mobile phones, entailing lower responsiveness with climate services among women (Partey et al., 2020, across Africa). - Slow progress on prioritizing distributional and procedural justice limits the expansion of adaptation funding to poorest and most vulnerable social groups and nations (Khan et al., 2019a). - Focussing only on distributive justice alone is less effective than a holistic integration of recognitional and procedural justice (*limited evidence, medium agreement*); e.g., only including poor households as recipients provides benefits to wealthier households, in sectors such as insurance for herders in Mongolia (Taylor, 2016b), urban water supply in Malawi (Rusca et al., 2017), informal urban settlements in Kenya (Pelling and Garschagen, 2019), and

			forest management in Cambodia (Work et al., 2019).
Flexible and strong institutions	Seeks policy integration, dynamic risk management, and account for long-term goals	- Institutional flexibility allows a society to respond quickly to the demands of a changing environment by developing new institutions or adjusting existing ones quickly (Davis, 2010); possibly avoiding lock-ins and addressing future climate risks (*very high evidence, high agreement*) (Levi-Faur, 2012; Sherman and Ford, 2013; Boyd and Juhola, 2015; Magnan et al., 2016). - Stability (and familiarity) is often desired in governance arrangements and balancing the need for stability with goals of flexibility, without causing rigidity is key (Craig et al., 2017, in USA; Ch 11). This is possible through deliberate, consultative changes that build awareness, develop shared norms, rules, and goals, and develop inclusive decision-making processes (Ch 3).	- Capacity building of adaptation funders, planners, and implementers and reorienting existing institutions to make decisions under uncertainty, institute long-term climate risk management that goes beyond typical political/ planning cycles, and develop learning mechanisms between sectors, actors, and projects needed (Moser and Boykoff, 2013; Granberg and Glover, 2014 in Australia; Boyd and Juhola, 2015 in cities; Ziervogel, 2019 in Africa and; Olazabal et al., 2019b in India; Ch 3 Oceans; Ch 10; Ch 11; Ch 12). - Flexible institutions enable adoption of new adaptation measures or course-correct based on ongoing M&E (e.g. Granberg and Glover, 2014 in Australia; Magnan et al., 2016; Torabi et al., 2018; Gajjar et al., 2019a in India) (*medium evidence, high agreement)*. - Sectoral or spatial policy integration (Chu et al., 2017; section 17.6; Hino et al., 2017; Robinson and Wren, 2020); integration of jurisdictional frameworks of different agencies (Poesch et al., 2016; Ch 5; Ch 9); and adaptive and flexible legal systems, which disaggregate socio-ecological systems into smaller components (Arnold and Gunderson, 2013; Wenta et al., 2019) are key enablers.

17.5.2 Adaptation Monitoring, Evaluation & Learning

17.5.2.1 Purpose of Monitoring and Evaluation

Adaptation responses have been observed in every region and across a wide variety of sectors (Ch16.3), but little evidence exists of their outcomes in terms of climate risk reduction (*high confidence*) (Ch 1.4.3; Ford and Berrang-Ford, 2016; Tompkins et al., 2018; Berrang-Ford et al., 2021; Eriksen et al., 2021; UNEP, 2021a). To advance on that, the Paris Agreement is encouraging countries to engage in "Monitoring and evaluating and learning from adaptation plans, policies, programmes and actions" (UN, 2015, Article 7.9d). Monitoring and Evaluation (M&E) is the systematic process of collecting, analyzing and using information to assess the progress of adaptation and evaluate its effects--e.g., risk reduction outcomes, co-benefits and trade-offs--mostly during and after implementation (AR6 Glossary). Distinctions between monitoring and evaluation typically view monitoring as a continuous process of tracking implementation and informing management to allow for corrective action including in situations of deep uncertainty (see Cross-Chapter

Box DEEP in this Chapter) while evaluation is described as a more comprehensive assessment of achievements, unintended effects and lessons learned carried out at certain point in time (OECD, 2002). Monitoring and evaluation is an important part of the adaptation process (Figure 1.9). It can help to generate information on adaptation success or maladaptive outcomes.

M&E of adaptation is undertaken for different purposes, including: (1) understanding whether responses have achieved their intended objectives and contributed to a reduction in climate risks and vulnerability or to an increase of adaptive capacity and resilience, (2) informing ongoing implementation and future responses, and (3) providing upward and downward accountability (Preston et al., 2009; UNFCCC, 2010a; Pringle, 2011; Spearman and McGray, 2011). M&E is also commonly linked to learning (section 17.5.2.7). By continuously monitoring implementation, e.g., to assess whether adaptation is on track or needs to be accelerated— M&E can aid decision-making under uncertainty. Adaptation M&E is distinct from tracking financial flows related to adaptation since financial accounting does not provide information on implementation and outcomes (17.5.2.5; Adaptation Partnership, 2012; World Bank Independent Evaluation Group, 2012).

17.5.2.2 Adaptation M&E Approaches

Adaptation M&E can be conducted for various purposes and in a wide variety of different contexts ranging from the local to the global level (McKenzie Hedger et al., 2008; UNFCCC, 2010a; Spearman and McGray, 2011). The context and specific purpose of M&E determine what information needs to be generated, and together with the available resources also determine the suitability of particular approaches and methods (Leiter, 2016; Leiter, 2017). Several frameworks and approaches have been proposed for M&E of adaptation and climate resilience (Bours et al., 2014d; Schipper and Langston, 2015; Adaptation Committee, 2016; ODI, 2016; Cai et al., 2018; Gregorowski et al., 2018) including sector-specific ones for agriculture (FAO, 2017; FAO, 2019a; FAO, 2019b), health (Ebi et al., 2018), ecosystem-based adaptation (Donatti et al., 2018; Donatti et al., 2020; GIZ, 2020a) and cities (section 6.4.6).

Adaptation M&E generally seeks to answer whether implementation is taking place and what effects it has (figure 17.11). Accordingly, M&E can focus on the processes, activities and outputs or on their outcomes and ultimate impacts (Harley et al., 2008; Pringle, 2011; Ford et al., 2013). Most of the available guidance for the development of adaptation M&E systems is aimed at the household, local or project level (Pringle, 2011; Villanueva, 2012; Olivier et al., 2013; CARE, 2014; BRACED, 2015; Leiter, 2016; Jones, 2019b) with only limited guidance for national or cross-sectoral M&E systems (Price-Kelly et al., 2015) or frameworks that are applicable at different scales (Brooks et al., 2014). The available guidebooks take users through a series of steps which are synthesized in Figure 17.11.

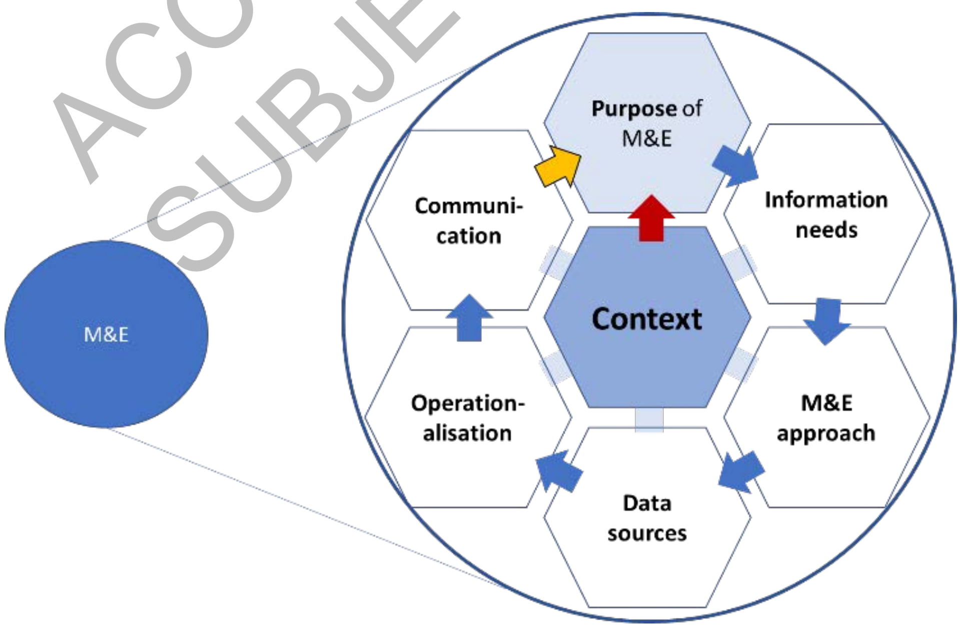


Figure 17.11: Adaptation M&E and learning as part of the adaptation process (based on Hammill et al., 2014a; Price-Kelly et al., 2015; Leiter, 2016). This figure shows the main steps involved in developing an adaptation M&E system where the context informs the purpose of M&E which in turn determines the information needs. To achieve the M&E purposes, the chosen approach and data sources need to be able to generate the needed information which needs to be communicated in a suitable way to the target audiences.

The majority of adaptation M&E efforts have so far focused on processes and outputs rather than on achieved outcomes, e.g. climate risks, vulnerability, well-being or development (Droesch et al., 2008; GIZ and Adelphi, 2014; UNDP Cambodia, 2014; Fawcett et al., 2017) (*high confidenc*e) or use a combination thereof (Brooks et al., 2011; Brooks et al., 2014). Newly emerging approaches include perception-based measurements and the use of data collected via mobile phones (Jones et al., 2018; Jones, 2019a), which can be collected frequently (Clare et al., 2017a; Knippenberg et al., 2019; Jones and Ballon, 2020). Such advances call into question the common reliance on "objective" indicators defined from an external perspective. Instead, they suggest that multiple complementary approaches combined with higher frequency data collection produce a more elaborate picture of the effects of adaptation and resilience responses (Jones and d'Errico, 2019; Knippenberg et al., 2019; Singh et al., 2019; Jones, 2019a; see Cross-Chapter Box PROGRESS in this Chapter) (*medium confidence*).

Central to designing, monitoring and evaluating adaptation responses is outlining how activities are expected to lead to intended objectives, e.g., via a theory of change (Bours et al., 2014c; Oberlack and al., 2019). Theories of change or similar change models provide a basis to decide what to measure but more attention needs to be paid to how theories of change are constructed and who is involved (Mason and Barnes, 2007; Forsyth, 2018). Participatory approaches can support understanding how climate risks affect the respective population, how these risks interact with social and cultural processes, and how responses could most effectively address climate risks (Conway et al., 2019). Inclusive M&E systems can facilitate ownership and enhance the meaningfulness and usability of the generated information (CARE, 2014; Faulkner et al., 2015). Meaningfulness is not associated with a particular approach or method but depends on whether the chosen M&E design fits the M&E purpose and the information needs of the intended audience (Fisher et al., 2015; Leiter, 2017). Effective communication of M&E findings and feedback into decision making processes is essential to achieve the respective M&E purpose and facilitate learning (section 17.5.2.7).

17.5.2.3 Adaptation Indicators and Indices

A set of all-purpose and globally applicable standard indicators that could comprehensively measure adaptation does not exist (*high confidence*) (IPCC, 2014a; Leiter and Pringle, 2018). A wide variety of indicators have been used to assess adaptation and its results (CARE, 2010; Harvey et al., 2011; Lamhauge et al., 2013; Brooks et al., 2014; Hammill et al., 2014b; Mäkinen et al., 2018; HM Government, 2019). Literature has also noted unrealistic expectations of what indicators can accomplish. For instance, decisions involving competing political interests would not be adequately informed through simple indicators; and learning requires knowledge of how and why change has happened, something that indicators often do not capture (Hinkel, 2011; Bours et al., 2014d). Indicators can also become misguided incentives and might steer attention away from what matters (Leiter and Pringle, 2018; Hallegatte and Engle, 2019; Klonschinski, 2021). Surveys, scorecards, interviews and focus groups are alternative methods of gaining insights on adaptation progress (Brooks et al., 2014; Porter et al., 2015; Das, 2019; McNamara et al., 2020).

The difficulties of assessing adaptation and an emphasis on short-term results have contributed to the common practice of relying on easily quantifiable indicators rather than assessing actual changes, i.e. outcomes and impacts (World Bank Independent Evaluation Group, 2012; Fisher et al., 2015). In fact, indicators used by international climate funds largely measure outputs which provide little evidence of the actual effectiveness of adaptation, i.e. its outcomes and impacts (GCF Independent Evaluation Unit, 2018; Leiter et al., 2019; Pauw et al., 2020).

Indices, the combination of multiple indicators into a single score, are common products of risk and vulnerability assessments to compare countries or other entities, often in the form of rankings or maps (Preston et al., 2011; Reckien, 2018; de Sherbinin and et al., 2019). They can indicate changes in vulnerability over time within their respective conceptualisation of vulnerability or risk. The construction of indices including indicator selection, their weighting, normalisation and data sources have a profound impact on their scores (Reckien, 2018). Research has consistently found large discrepancies between country vulnerability rankings (Brooks et al., 2005; Eriksen and Kelly, 2007; Leiter et al., 2017b; Visser et al., 2020). Reviews of vulnerability and resilience indices identified "substantial conceptual, methodological and empirical weaknesses" (Füssel, 2010: 8) and a widespread lack of validation (Cai et al., 2018). Using countries as a unit of analysis also masks significant subnational variation (Otto et al., 2015; Mohammadpour et al., 2019). Individual indices therefore "fail to convene a robust guidance for policy makers" (Muccione et al., 2017: 4) and should not present the sole basis for policy decisions (Brooks et al., 2005; Leiter and Pringle, 2018). Due to their limitations (Singh et al., 2017), the OECD suggests that indices are primarily used for "initiating discussion and stimulating public interest" (OECD, 2008: 13).

17.5.2.4 Empirical Evidence of National Adaptation M&E Systems

Tracking the implementation of national adaptation plans is essential for understanding their effectiveness, i.e. the progress made in addressing climate risks, and can support assessing the success of adaptation and the risk of maladaptation. Over 60 countries have developed or started developing national adaptation M&E systems, although less than half are yet reporting on implementation (Leiter, 2021b; Table 17.9). Country-specific adaptation M&E systems vary considerably regarding their legal mandate, purpose, content, involved actors and types of reporting (Hammill et al., 2014a; EEA, 2015; Leiter, 2015; Leiter et al., 2017a; EEA, 2020). In most cases, they focus primarily on monitoring implementation rather than assessing outcomes, although some are linked to national climate risk or vulnerability assessments (e.g. in Germany and the United Kingdom) (EEA, 2018). At least 15 countries have published evaluations of national adaptation plans which help inform the development of successive adaptation plans or strategies (Table 17.9). Nevertheless, there is only limited empirical evidence of the ability of M&E systems to facilitate action or increase the level of ambition of revised policies. More research is needed to determine the quality of national adaptation M&E systems and how well they support the policy cycle.

Under the Paris Agreement countries are encouraged to provide information on adaptation including its adequacy and effectiveness (Möhner et al., 2017; Adaptation Committee, 2021). National adaptation M&E systems can inform both national as well as international reporting and contribute to the global stocktake (see Cross-Chapter Box PROGRESS in this Chapter; Craft and Fisher, 2015; Leiter et al., 2017a). Guidance for and examples of national adaptation progress assessments are provided by Price-Kelly et al. (2015); Brooks et al. (2014); Brooks et al. (2019); EEA (2015); GIZ (2017); Karani (2018); and van Rüth and Schönthaler (2018). Global assessments of adaptation progress have so far often focused on adaptation planning and, to a lesser extent, implementation whilst evidence of the collective effect of adaptation globally remains limited (*high confidence*) (UNEP, 2021a; Cross-Chapter Box PROGRESS in this Chapter).

Table 17.9: Countries in different stages of developing or operating a national adaptation M&E system as of 1 August 2021 (Source: Leiter (2021b). Countries can appear twice if they have published both a progress report and an evaluation.

	National adaptation M&E system		
	Stage	Definition	Country
Under develop-ment	Early stage	Tangible steps have been undertaken to develop a national adaptation M&E system, for example a stocktake of relevant existing data sources and engagement with stakeholders on the objectives of the M&E system	Benin, Cook Islands, Jordan, Paraguay, Sri Lanka, Uganda
	Advanced stage	Details of the adaptation M&E system have been developed, including, for instance, institutional arrangements, indicators and data sources, but it has not yet been applied	Albania, Bulgaria, Cameroon, Canada, Colombia, Ethiopia, Fiji, Grenada, Indonesia, Moldova, Morocco, Mozambique, Nauru, Peru, Rwanda, Senegal, St.Lucia, St. Vincent and the Grenadines, Suriname, Thailand, Togo, Tonga, Turkey, Vietnam

In operation	Adaptation progress report published	A progress report on the implementation of the national adaptation plan or strategy has been published	Austria, Belgium (Flanders), Brazil, Burkina Faso, Cambodia, Chile, Cyprus, France, Germany, Japan, Kenya, Kiribati, Lithuania, Mexico, Netherlands (Delta Programme), Norway, Portugal, Slovakia, Spain, South Africa, South Korea, Switzerland, United Kingdom
	Evaluation published	An evaluation of the implementation of the national adaptation plan or strategy has been undertaken and published.	Belgium, Cambodia, Chile, Czech Republic, Finland, France, Germany, Ireland, Mexico, Netherlands, Philippines, South Korea, Spain, Switzerland, United Kingdom

17.5.2.5 Challenges of Assessing Adaptation

To date, literature has largely focused on aspects prior to implementation such as assessments of climate vulnerability and risks or appraisals of adaptation options (Sietsma et al., 2021; Cross-Chapter Box Adaptation). To understand adaptation progress, the assessment of implemented adaptation actions and their outcomes requires more attention (*very high confidence*) (Cross-Chapter Box PROGRESS in this Chapter).

Outcomes on risk reduction are typically expressed in ways that are specific to the respective sector or context (e.g., as agricultural yields, health benefits or reduced water stress) highlighting that "adaptation has no common reference metrics in the same way that tonnes of GHGs or radiative forcing values are for mitigation" (IPCC, 2014a: 856). Assessments of adaptation progress therefore need to specify what they are measuring and how they are measuring it. The way adaptation is conceptualised, e.g. as a continuum between successful adaptation and maladaptation (Section 17.1.1) and the way adaptation is framed, e.g. as a technical challenge or a political process (Juhola et al., 2011; Bassett and Fogelman, 2013; Eriksen et al., 2015), shape the understanding of progress and its subsequent measurement (Singh et al., 2021).

Furthermore, people can be differently affected even in the same location due to, amongst others, differential vulnerability amongst the population (Reckien and Petkova, 2019; Thomas et al., 2019). Different views and values can also affect what it means to adapt (Few et al., 2021). Assessments of adaptation progress therefore need to be transparent and reflective about how they define and measure adaptation and account for culturally and geographic contingent concepts of what it means to adapt in light of the global diversity of livelihoods and concepts.

The lack of knowledge on adaptation progress is associated with further measurement challenges including that avoided impacts are difficult to measure and that risk levels change over time, meaning what is effective today may not be effective in the future (Brooks et al., 2011; Pringle, 2011; Spearman and McGray, 2011; Villanueva, 2012; Bours et al., 2014a). Moreover, adaptation is embedded in complex political and social realities where power and politics shape outcomes and where simplistic views of how adaptation would take place may be ill-conceived (Nightingale, 2017; Mikulewicz, 2018; Mikulewicz, 2020). In practice this means that theories of change of adaptation projects may miss important causes of risks and could subsequently lead to inaccurate assessments (Forsyth, 2018). Measuring adaptation is therefore a matter of understanding drivers of vulnerability and risk and of designing responses and M&E systems accordingly (UNFCCC, 2019a, section V).

The importance of context and the dependence on viewpoints make comparative assessments of adaptation across nations, regions or responses challenging. Comparison requires a consistent conceptualisation of adaptation, comparable units of analysis and access to relevant datasets (Ford et al., 2015; Ford and Berrang-Ford, 2016). Comparative adaptation policy assessments to date often lack clarity in concepts and explanatory variables (Dupuis and Biesbroek, 2013; Biesbroek R, 2018a). The trade-off between standardisation and context-specificity also complicates attempts to aggregate adaptation progress across scales to the national or global level (Leiter and Pringle, 2018; Cross-Chapter Box PROGRESS in this Chapter).

[START CROSS-CHAPTER BOX PROGRESS HERE]

Cross-Chapter Box PROGRESS: Approaches and Challenges to Assess Adaptation Progress at the Global Level

Authors: Matthias Garschagen, Timo Leiter, Robbert Biesbroek, Alexandre K. Magnan, Diana Reckien, Mark New, Lea Berrang-Ford, So Min Cheong, Lisa Schipper, Robert Lempert

This Cross-Chapter Box responds to a growing demand for assessing global climate change adaptation progress, which currently faces the challenge of lacking consensus on how adaptation progress at this level can be tracked (*high confidence*). The box therefore assesses the rationale and methodological approaches for understanding adaptation progress globally across sectors and regions. It discusses strengths and weaknesses of existing approaches and sources of information, with a view towards informing the first Global Stocktake of the Paris Agreement in 2023.

Rationale for assessing adaptation progress at the global level

Global assessments of adaptation are expected to help answer key questions of climate policy (Ford et al., 2015; UNEP, 2017; Adaptation Committee, 2021) (*low evidence, high agreement,*), including: Do the observed, collective investments in adaptation lead humanity to being better able to avoid or reduce the negative consequences from climate change? Where is progress being made and what gaps remain in the global adaptation response to climate risks?

Whilst more than 170 countries have policies that address adaptation (Nachmany et al., 2019b; 17.4.2), very few have operational frameworks to track and evaluate implementation and results (Leiter, 2021a; 17.5.2.4). In Europe, for example, most countries have adopted a national adaptation plan or strategy, but only few are tracking whether ambitions are realised (EEA, 2020; 13.11.2). Moreover, climate risks are interconnected across scales, regions and sectors (Eakin et al., 2009; Challinor et al., 2017; Cross-Chapter Box INTERREG in Chapter 16; Hedlund et al., 2018) (*high confidence*), complicating causal attribution. National assessments of progress usually do not assess private sector and non-governmental adaptation and barely account for climate risks that transcend across borders, for example through supply chains or shared ecosystems (EEA, 2018; Benzie and Persson, 2019). In addition, adaptation action in one place or time can potentially lead to negative effects elsewhere (externalities) (Magnan and Ribera, 2016; Atteridge and Remling, 2018; 17.5.1). Hence, determining the collective adequacy and effectiveness (see Figure 1.7 in Chapter 1) of adaptation responses is different from simple aggregates of national and sub-national information (UNEP, 2017).

Assessing global progress on adaptation is therefore of high relevance to the scientific community, to policy makers and other actors. Global assessments serve different information needs than local assessments and their meaningfulness depends on the chosen approaches and their limitations. Aggregated global assessments of adaptation progress are therefore not meant to substitute place-specific ones but to complement them to enhance the knowledge base on adaptation beyond actions by or within individual countries. The Paris Agreement stipulates a Global Stocktake to be undertaken every five years to assess the collective progress towards its long-term goals including on adaptation (UNFCCC, 2015, Article 14). Yet very few scientific studies have addressed the adaptation-specific aspects of the Global Stocktake (Craft and Fisher, 2018; Tompkins et al., 2018) and there are different views and options on how assessing global progress could take place (*high confidence*).

Considerations in designing global adaptation assessments

A number of key considerations for the design of global adaptation assessment approaches are discussed in the literature (Ford and Berrang-Ford, 2016; Berrang-Ford et al., 2017). Some of these involve trade-offs, e.g. global applicability vs. context-specificity, for which there is no simple solution. Design considerations directly depend on the objectives of global adaptation assessments, which can differ between actors and can include e.g. providing transparency, enabling accountability, understanding effectiveness, or guiding policy development (Section 17.5.2.1). The underlying objectives determine the suitability of approaches and the data requirements.

Comparability

Global assessments may have the objective to compare adaptation over time and across sectors and regions (Ford et al., 2015). Such comparison requires a consistent definition of concepts (Hall, 2017; Berrang-Ford et al., 2019) and the identification of variables that are both generic enough to be applicable from one context to another and specific enough to illustrate national circumstances. To date, finding such balance has proven to be challenging (Dupuis and Biesbroek, 2013). The context-dependence of adaptation outcomes poses limits for meaningful comparisons. Even people exposed to the same climate hazard may be differentially affected due to varying levels of vulnerability and resilience (Jones et al., 2018; Thomas et al., 2019), meaning that perceptions on adaptation outcomes can also differ (Jones and d'Errico, 2019).

Aggregation

The aggregation of data from local or regional to global scales can take different forms ranging from qualitative synthesis to quantitative aggregation which may involve condensing a diverse set of variables into a single score (Leiter, 2015; 17.5.2.3). In contrast to climate change mitigation, adaptation does not have a global reference metric against which adaptation levels could be assessed to identify progress or gaps. Experience from the Global Environment Facility, for example, has shown that mechanical aggregation based on standardized indicators fails to capture what makes the greatest difference on the ground (Chen and Uitto, 2014).

Results: Input, process, output or outcome

Adaptation progress at any spatial scale can in principle be assessed in terms of input (e.g. resources spent), process (i.e. the way adaptation is organized), output (i.e. adaptation capacities and actions) and outcomes (i.e. actual changes induced) (Section 17.5.2.2). Due to the challenges inherent in measuring adaptation outcomes (Sections 16.3, 17.5.1 and 17.5.2.5), most global assessments to date have focused on outputs, e.g. whether countries have adopted adaptation plans (Berrang-Ford et al., 2021; UNEP, 2021a) (*high confidence*). Understanding the effectiveness of adaptation responses globally requires a way to conceptualize and capture outcomes, for example in terms of effective climate risk reduction, whilst avoiding simplifications that mask maladaptation at the global level, e.g. where climate risks are shifted to other countries, sectors or population groups (Cross-Chapter Box INTERREG in Chapter 16, Section 17.5.1).

Data

Global assessments typically require global availability of consistent data, be it quantitative or qualitative, which has proven to be a constraining factor for attempts to assess global adaptation (*high confidence*). For example, many countries face difficulties in reporting adequately on progress in implementing the Sendai Framework and risk-related SDGs (UNDRR, 2019: vi). The availability of data also influences which variables can be eventually selected in an assessment. This limitation can affect the ability to meet the initial objectives and lead to biases in the framing and interpretation of assessment outcomes. For some variables, an alternative to relying on nationally provided data can be to develop new global datasets (Magnan and Chalastani, 2019), or utilising data from Earth Observation (Andries et al., 2018). Adaptation is hence faced with a dilemma between globally available yet generic data and regionally or locally more detailed yet patchy data (*high confidence*).

Assessment of existing approaches to assess adaptation progress at the global level

Only few global assessments of adaptation progress across sectors have been undertaken to date (*high confidence*). They focus, for example, on whether countries have progressed their adaptation policies and actions over time (Lesnikowski et al., 2015; Nachmany et al., 2019b), the extent of implemented adaptation globally (Leiter, 2021a; Leiter, 2021b), and the type and actors of responses (Berrang-Ford et al., 2021), evidence for reduced vulnerability to climate-related hazards (Formetta and Feyen, 2019; UNDRR, 2019) or adaptation planning in cities across the globe (Araos et al., 2016a; Reckien et al., 2018a; Olazabal et al., 2019a). Each of these assessments draw on different approaches and data, and all have particular potential but also limitations (Table Cross-Chapter Box PROGRESS.1) (*high confidence*). The application of differing approaches shows that there is no single 'best' approach or data source to assess global progress on adaptation (*high confidence*). Existing global assessments have provided valuable insights into the extent and types of responses and their level of planning and implementation (16.3.2.4). They do, however, not provide comprehensive and robust answers so far on whether climate risk and vulnerability have been reduced

(Berrang-Ford et al., 2021) (*high confidence*). As a result, combining different approaches and integrating data on climate risk levels, policy measures, implemented actions and their effects on climate risk reduction is currently regarded the most robust approach (Berrang-Ford et al., 2019) (*medium evidence, high agreement*).

Table Cross-Chapter Box PROGRESS.1: Key approaches and data sources used for global adaptation assessments.

Approach / Data source	Potential added-value	Limitations
Systematic assessment of adaptation responses reported in academic literature (e.g. systematic reviews, evidence synthesis, meta-analysis, large-n comparative studies) Examples: Berrang-Ford, 2011 #188}, Global Adaptation Mapping Initiative (Berrang-Ford et al., 2021)	Provides an indication of the status, trends and gaps in adaptation responses	Not a representative sample; biased towards responses published in scientific literature; excludes grey literature; some topics and regions not well covered; challenges in terms of comparability and aggregation; inconsistency in definitions and use of concepts; English language bias
Self-reported progress documents by countries (e.g. National Communications, Biennial Transparency Reports or domestic progress and evaluation) Examples: (Gagnon-Lebrun and Agrawala, 2007; Lesnikowski et al., 2015; Lesnikowski et al., 2016; Leiter, 2021a)	Context-specific information; official government documents enable assessments of national progress	May only be available every few years; content is sensitive to political and policy changes; possible bias towards positive examples; challenges in terms of comparability and aggregation; inconsistency in definitions and use of concepts
Self-reported information from the private sector (e.g. information on actions taken in response to climate risks within the context of climate-related financial disclosure or in company reports). Examples: (Committee on Climate Change, 2017; Street and Jude, 2019; UNFCCC, 2021), responses reported under Climate-related Financial Disclosure	Provides an indication of the status, trends and gaps in adaptation responses by the private sector; complements information published in the scientific literature; could enable better understanding of supply chain risks	Sample biased towards larger companies; challenges in terms of comparability and aggregation; potential inconsistencies in definitions and use of concepts
Project documents and evaluations (e.g. from climate funds or implementing organisations) Examples: (Leiter, 2021b); (Eriksen et al., 2021)	Detailed information on context, intended or achieved results and activities	Actual implementation can differ from what was proposed; fragmented picture of local/regional actions; results may be challenging to aggregate; challenges in terms of comparability and aggregation; inconsistency in definitions and use of concepts
Existing global data sets of mostly quantitative indicators Examples: United Nations (UN, 2016a; UN, 2016b; UN, 2019; UNDRR, 2019)	Comparable information based on globally defined indicators	Global data availability constrains indicator choice; reporting burden for new indicators; trade-off between global applicability and national circumstances; usefulness and meaningfulness of global indicators is contested (Leiter and Pringle, 2018; Lyytimäki et al., 2020; Pauw et al., 2020).
Tracking financial flows Examples: (CPI, 2019), (OECD, 2018a), (MDBs, 2019)	Comparable data on financial flows directed at adaptation; standardised methodologies (e.g. OECD RIO markers; climate	No information about implementation of measures and their adaptation effect (Eriksen et al, 2021), i.e. it tracks inputs, not

	finance tracking method of multilateral development banks; chapter 17.5.2.6; Cross-Chapter Box FINANCE in this Chapter)	outputs or outcomes; inconsistency in what gets counted as adaptation finance (Donner et al., 2016; Doshi and Garschagen, 2020); evidence of over-reporting (Michaelowa and Michaelowa, 2011; Weikmans et al., 2017)

Conclusion -- Combining approaches for assessing adaptation progress at the global level

Understanding to what extent the world is on track to adapt to climate change impacts and risks globally is a pressing question in scientific and policy communities, especially in light of the Global Stocktake under the Paris Agreement. Important considerations for a robust assessment framework (e.g. consistency), as well as the associated scientific challenges (e.g. aggregation, externalities, breath vs. depth of data) and the role of underlying objectives (e.g. on the contested issue of comparability) are increasingly understood (*high confidence*). There is also a growing and diverse body of information on adaptation progress, although most assessments of global progress undertaken to date focus on processes and outputs (e.g. policies and plans) rather than outcomes (i.e. risk reduction). A variety of approaches and data sources are employed, such as systematic reviews of observed adaptation, formal communications by Parties to the UNFCCC, and project documents to international funding agencies. Novel approaches, including big data tools (Ford et al., 2016; Biesbroek et al., 2020), are also being explored but still have to prove their practical value. Each approach and source of information can contribute additional knowledge, but also demonstrates limitations, so that there is no single 'best' approach (*high confidence*). Yet to date, the international community has not sufficiently explored the relative strengths and weaknesses of different approaches and their applicability, and therefore their potential synergies in complementing each other. Triangulated assessments have only rarely been applied (*high confidence*) due to multiple conceptual and methodological challenges, despite their potential for increasing the robustness of knowledge. One overarching conclusion of this Cross-Chapter Box therefore is that the combination of different approaches will provide a more comprehensive picture of global adaptation progress than is currently available from individual approaches (*low evidence, high agreement*).

[END CROSS-CHAPTER BOX PROGRESS HERE]

17.5.2.6 Tracking Adaptation Finance

Adaptation finance tracking is capturing the financial flows associated with adaptation. It can indicate how much is being spent on adaptation, where funds are going to, and whether spending matches allocated budgets. Thus, adaptation finance tracking can provide useful information for decision making, but it does not provide information on the achievements resulting from the invested funds. Accordingly, it can complement, but not substitute, M&E of actions and outcomes. Adaptation finance tracking can be applied domestically (Guzmán et al., 2017; Guzmán et al., 2018) as well as internationally, for instance by developed countries to report on the goal to mobilize US$100 billion a year by 2020 in climate finance (UNFCCC SCF, 2018). Data on adaptation finance can be used alongside information on planning and implementation to assess adaptation progress (UNEP, 2021a).

Tracking adaptation finance requires defining what counts as adaptation. Different definitions can lead to large variations in the estimated amount of adaptation finance (Donner et al., 2016; Hall, 2017). A further challenge is how to account for adaptation that is mainstreamed, i.e. where adaptation-specific investments form only part of a larger programme or budget line, or where actions contribute to adaptation without being labelled as adaptation. These challenges limit the direct comparability between adaptation and mitigation finance (UNFCCC, 2019a). In fact, tracking adaptation finance differs from tracking mitigation finance since activities cannot be a-priori assumed to constitute adaptation but instead have to be assessed for their linkage to climate risks in a particular context (MDBs & IDFC, 2018). Methods for adaptation finance tracking continue to be further developed aiming at better comparability and completeness (Richmond and Hallmeyer, 2019; Richmond et al., 2021).

Various methods are used to track adaptation finance, which makes comparisons between adaptation finance figures challenging (UNFCCC SCF, 2018; Weikmans and Roberts, 2019). For example, multilateral development banks use a different methodology than countries do under the OECD Development Assistance Committee (DAC) (see Box 17.4; MDBs, 2019). One of the differences concerns the treatment of partially adaptation-relevant projects, namely whether only parts or the full amount of a given project volume are counted as adaptation finance (see e.g. MDBs, 2019). Under the OECD DAC methodology, countries often use a fixed percentage (e.g., 50% of the total project value) whereas the MDB methodology attempts for a project-specific estimation of the adaptation-relevant proportion (MDBs & IDFC, 2018). Another aspect is whether tracking distinguishes between financial instruments, e.g., grants or loans. Different accounting rules can lead to large differences in reported amounts of adaptation finance and to a lack of comparability between providers (Weikmans and Roberts, 2019). Studies identified an over-reporting (i.e., counting non-adaptation related finance) by a factor of two to three, which suggests the need for a more consistent and transparent accounting system (Weikmans et al., 2017; CARE, 2021).

Good coverage of adaptation finance data exists around international public finance flows, predominantly official development assistance flows from OECD DAC members and from multilateral development banks. Less data exists around domestic public finance and private finance flows to adaptation activities, but data sources continue to be further expanded e.g. through climate change expenditure tagging and city-level data (Weikmans et al., 2017; UNFCCC SCF, 2018; Richmond et al., 2021). Recent estimates of adaptation finance are provided in UNFCCC SCF (2018); Macquarie et al. (2020); and in Cross-Chapter Box FAR.

[START BOX 17.4 HERE]

BOX 17.4: The Rio Markers Methodology to Track Climate Finance

The OECD Development Assistance Committee (DAC) introduced a methodology to track the amount of bilateral official development assistance (ODA) that is targeting climate change mitigation and/or adaptation. It distinguishes whether activities have adaptation as a "principal" objective (score "2"), as a "significant" objective (score "1"), or as not targeting it (score "0") (OECD, 2016). The associated project value is counted in full, in part, or not counted as adaptation finance, respectively. Countries count the volume of partial adaptation projects (score "1") to a different extent which limits comparability and can lead to over-reporting (OECD, 2019a). The first data on this "adaptation marker" became available in 2012 for the financial flows of 2010. It forms the basis for developed countries' reporting to the UNFCCC Secretariat on their financial commitments towards developing countries (Weikmans and Roberts, 2019).

While a guidebook with requirements for adaptation as a principle or significant objective has been developed (OECD, 2016), several studies have shown that OECD DAC donors tend to overestimate the number of activities in their portfolio that genuinely have adaptation objectives (Michaelowa and Michaelowa, 2011; Weikmans et al., 2017; CARE, 2021). Hence, the amount of adaptation finance from public sources may be lower than reported. The use of just three categories leads to a broad range of the extent of adaptation being concentrated in the middle category ("significant objective"). Accordingly, the category "principle objective adaptation" provides a more robust predictor of the relevance of an activity to adaptation (Donner et al., 2016).

[END BOX 17.4 HERE]

17.5.2.7 Evaluation and Learning

Most adaptation M&E frameworks and tools proposed to date refer to monitoring rather than evaluation (*high confidence*) (Adaptation Committee, 2016). Evaluations are envisioned to go beyond monitoring by examining how and why results have been achieved and what could be improved (Brousselle and Buregeya, 2018; Vähämäki and Verger, 2019). Evaluations of adaptation outcomes are still rare, particularly quantitative impact evaluations (Weldegebriel and Prowse, 2013; Das, 2019; Béné et al., 2020). Impact evaluations of adaptation need to address several methodological as well as practical challenges (Dinshaw et al., 2014; Fisher et al., 2015; Béné et al., 2017; Puri et al., 2020). Different types of evaluations are appropriate for different evaluation questions (Silvestrini et al., 2015). Evaluations of the available evidence of effective adaptation in particular topics or sectors have emerged more recently, for instance on mainstreaming (Runhaar et al., 2018) and agricultural climate services (Vaughan et al., 2019a). Impact evaluations of capacity building measures are important because capacity building is assumed to lead to adaptation, but its actual effects are seldom examined (Mortreux and Barnett, 2017; Alpizar F and Meiselman, 2019). If well designed and utilised for learning, evaluations can play an important role in improving adaptation responses (Hildén, 2011).

Learning requires information about how and why change occurred and what experiences have been made (Feinstein, 2012). M&E is frequently associated with learning, but it is rarely made explicit how learning is supposed to take place (Armitage et al., 2008; Baird et al., 2015; Borras and Hølund, 2015). The design of adaptation M&E systems can support learning by gathering relevant information and disseminating it in a way that is accessible and effectively linked to decision making processes (Spearman and McGray, 2011; Villanueva, 2012; Fisher et al., 2015). Options include institutionalised feedback mechanisms, peer learning and knowledge sharing events, a learning culture and ways to gather in-depth insights beyond indicators (ibid; Oswald and Taylor, 2010). Since AR5, adaptation programmes and funds such as the BRACED programme, the Adaptation Fund, the Climate Investment Funds and the Green Climate Fund have created knowledge-sharing units and provide resources to support learning activities(BRACED, 2015; Roehrer and Kouadio, 2015; Adaptation Fund, 2016; Leavy et al., 2018; CIF, 2020; Puri et al., 2020), but there is little information about their longer-term effectiveness.

17.6 Managing and Adapting to Climate Risks for Climate Resilient Development

Actions to ameliorate a climate risk have consequences beyond the immediate effects on exposure or vulnerability to a hazard. They may aim to combat many risks, could adversely interact with other risks and actions, or may be nested within a suite of actions across many risks. Some actions may have negative consequences for climate resilient development. In this broader context, the effectiveness of adaptations for supporting climate resilient development is now better articulated (Box 17.1). Importantly, adaptations need to be designed to not only combat current and future climate risks, but also ensuring that they do not lock in undesirable pathways in the future as risks develop and change (*very high confidence*) (17.2, 17.3.1, 17.5). Effective management of climate risks will therefore be dependent on satisfactorily managing current climate risks (Box 17.1, 17.2, 17.5), coupled with assessing prognoses for future climate risks, and developing responses in advance for reducing those risks to tolerable residual levels (*very high confidence*) (1.4, 1.6, 16.6, 17.2, Box 16.1; e.g. water risks - 4.7.1). The dynamic nature of risk (Viner et al., 2019; Simpson et al., 2021; 16.3, 16.6) also means that the contribution of current adaptations to ameliorating future risks needs to be regularly reviewed (*high confidence*) (17.5.2). Across the Working Group II report are examples of how managing adaptations to ameliorate climate risks can negatively or positively affect sustainable development, thereby impacting the potential for climate resilient development discussed in Chapter 18. Drawing on the assessment of sectoral and regional chapters in this report, this section examines three broad components for orienting decision-making for climate adaptation towards climate resilient development.

17.6.1 Need for Integrated Risk Management

The complex, interacting and compounding nature of climate risks means that single risks cannot be managed in isolation (*very high confidence*) (16.5, Figure 16.11; 17.3.2; Nhamo et al., 2018), including accounting for potential risks arising from adaptations (Simpson et al., 2021). Regional examples of needs for cross-sectoral integrated management include the water-energy-food nexus in Africa (10.5.1), Asia (10.6.3), Australasia (11.6), Europe (13.2.2) and North America (Table 14.8), and ecosystem-oriented adaptations and/or nature-based solutions, in Africa (9.6.5), Asia (10.4.2), Australasia (Box 11.4, 11.3.5), Central and South America (12.5.1), Europe (13.3.2), North America (14.6.1, Box14.3) and Small Islands (15.5.4). The cross-sectoral interactions within humans systems, including impacts on cities, settlements and infrastructure, are reflected in those subjects as well as for health in Africa (9.10.2), Asia (10.4.5), Australasia (11.3.6), Central & South America (12.5.6), Europe (13.7.2), North America (14.6.1), and Small

Islands (15.6.2), and poverty and livelihoods in Africa (9.11.3), Asia (10.4.5, 10.5), Australasia (11.4), Central & South America (12.5.7), Europe (13.8.2), North America (14.6.1), and Small Islands (15.3.4). These examples demonstrate that the emergence of climate risks can be at different rates, different time horizons, and the interactions between risks vary from region to region (*very high confidence*). The need to manage these risks in an integrated manner is readily identified in the Water-Energy-Food nexus (Box 9.5). However, in terms of climate resilient development, the need for integration is demonstrated by the diverse and interacting impacts of climate risks on ecosystems (2.7, 3.6), cities (6.2.3, 6.2.4, Box 6.2, 6.3), health (7.4), and poverty and livelihoods (8.6).

17.6.2 Strategies for Managing a Portfolio of Climate Risks

Since WG2 AR5, new methods for simultaneously considering multiple societal and sectoral objectives, climate risks and adaptation options have emerged (17.3.2; Adam et al., 2014; Hadka et al., 2015; Garner et al., 2016; Rosenzweig et al., 2017; Giupponi and Gain, 2017a; Stelzenmuller et al., 2018; Marchau et al., 2019), including methods for accounting for different sources of uncertainty and types of risk (17.3.1; Giupponi and Gain, 2017a). Different decision-making approaches can be complementary (*high confidence*) (17.3.1; Kwakkel et al., 2016) and multiple approaches will likely be necessary in managing the risks across sectors, over different spatial scales, and over short to long time scales (*medium confidence*) (Cross-Chapter Box PROGRESS in this Chapter; Girard et al., 2015; Rouillard and Spray, 2016).

Deciding on which adaptations to adopt when managing climate risks inevitably needs examination of trade-offs in outcomes *(very high confidence*) (17.3.1, 17.5.1; Cross-Chapter Box FEASIB in Chapter 18). A current difficulty with integrated assessments is to develop a set of metrics that are appropriately scaled for the different sectors or outcomes to be compared (e.g., 12.5.2.6; 17.3.1; 17.5.2; Cross-Chapter Box PROGRESS in this Chapter). For climate resilient development, dimensions of poverty, equity, justice, and health need to be factored into analyses (Box 17.1, 17.5), many of which are difficult to quantify (*high confidence*) (18.2.4). Moreover, uncertainties on the interactions within and between sectors can make trade-off analyses uneven in their precision across sectors and uncertain as to the outcome of an implemented adaptation (*medium confidence*) (4.7.2, 17.4, 17.5).

Expertise and resources for using tools and approaches for integrated risk management varies between the developed and developing countries (*high confidence*) (e.g. 4.7.2). Exploration of adaptation scenarios can be derived from Earth System Models (high confidence) (e.g. 4.7.1.2, 11.7.3.1). However, the feasibility of possible adaptations and the degree to which they are likely to be effective (Box 17.1) will require further exploration as success will depend on appropriate enabling conditions including institutional support and capacity, available financial resources and knowledge, and suitable conditions for stakeholder participation (*high confidence*) (17.4). The current levels of uncertainty surrounding the effectiveness of many adaptation options (17.5.2; Cross-Chapter Box PROGRESS in this Chapter) means that decision-making approaches applicable to deep uncertainty (Cross-Chapter Box DEEP in this Chapter; 17.3.1) will apply in many if not most cases (*medium confidence*). An early step in identifying suitable integrated pathways for managing climate risks, establish 'no regrets' anticipatory options in a timely manner, and avoiding path dependencies, is to jointly map the steps for adapting to sectoral risks, and determine suitable ways to avoid maladaptations arising (*high confidence*) (17.3.1, Cross-Working Group Box URBAN in Chapter 6 and Cross-Chapter Boxes DEEP in this Chapter). The application of Dynamic Adaptive Pathway planning has been successfully used in this way in Australasia (11.7.3) and Europe (13.6.2.2, 13.10.2) (Lawrence et al., 2019a; Haasnoot et al., 2020a). Current experience suggests that synergies between sectors can save resources and effort (*limited evidence*) (13.11.2). Iterative processes can then enhance adaptation programs by including more detailed modelling and updated knowledge as the experience is acquired (17.3.1).

17.6.3 Mainstreaming Climate Risk Management in Support of Climate Resilient Development

This chapter has assessed and detailed a number of decision-making tools (17.3) and enabling mechanisms and catalysing conditions (17.4) that could be used in mainstreaming the management of climate risk and adaptation in the sustainable development of communities, different sectors and nations. Since AR5, the challenges facing the management of climate risks have been articulated (Adger et al., 2018; Balasubramanian, 2018) and greater clarity on the steps that could be taken to better mainstream adaptation has been developed (*high confidence*) (Cuevas, 2016; Giupponi and Gain, 2017a; Gomez-Echeverri, 2018;

Sanchez Rodriguez et al., 2018). Nevertheless, the choice of decision processes is recognized as being dependent on a variety of local factors influencing development (Ayers et al., 2014; Szabo et al., 2016).

Adaptation strategies or plans, some of which incorporate elements of climate resilient development, have been developed in many jurisdictions from local (Cuevas, 2016; Araos et al., 2016a; Reckien et al., 2018a; Göpfert et al., 2019) to provincial/state (Warnken and Mosadeghi, 2018) to national governments (Markolf et al., 2015; CSIRO, 2018; Warnken and Mosadeghi, 2018; Brown et al., 2018a; Table 17.9). National Adaptation Plans have been a requirement under the UNFCCC and establish the general approach taken by nations for adapting to climate change (Woodruff and Regan, 2019). Integrated risk assessments and adaptation processes are being developed but with much less experience evident in their implementation (*high confidence*) (Wise et al., 2014; Woodruff and Stults, 2016; Brown et al., 2018a).

National Adaptation Plans (NAPs) submitted to the UNFCCC have been reviewed for quality by Woodruff and Regan (2019). In their review, Woodruff & Regan used a number of indicators grouped within established "quality principles". They found that the plans were more oriented at the strategic level or at the level of specific projects rather than identifying methods for resolving cross-sectoral or cross-jurisdictional interactions or issues (*medium confidence*). A key recommendation from their review and supported by other studies (e.g. Abutaleb et al., 2018) is that plans would be improved greatly by having inputs from multiple government agencies and multiple sectors (*medium confidence*), which could provide the basis for planning and review of integrated adaptation. Also, the plans need greater attention to implementation (9.4.1, 11.8, 13.11.2), and the identification of metrics by which success (17.5.1) and performance can be measured (Cross-Chapter Box PROGRESS in this Chapter), a common issue for adaptation planning generally (e.g. 12.5.2.6, 17.5).

Hence, satisfactorily managing intersecting climate risks in different settings, of which RKRs provide examples, is central to achieving sustainable development (*high confidence*) (16.6.4), requiring integrated risk management within and across regions, jurisdictions, sectors and ecosystems (*high confidence*) (more cross references please CCP5.4.2; CCP5.4.3). Iterative processes will enable measuring progress and updating adaptation at a satisfactory rate, in order to account for the different needs within regions and across sectors at different times (*high confidence*). The degree to which equity and justice will be achieved will be determined by the participatory processes in deciding on suitable adaptation options, the investment in the adaptation processes and the coordination and collaboration built amongst institutions and people across regions (*high confidence*).

[START FAQ17.1 HERE]

FAQ17.1: Which guidelines, instruments and resources are available for decision-makers to recognize climate risks and decide on the best course of action?

Guidelines, instruments, and resources to identify options for managing risks, and support decisions on the most suitable course of actions to take, can be collectively referred to as decision-support frameworks. These can include data services, decision-support tools, processes for making decisions and methods for monitoring and evaluating progress and success. Data services enable the identification, location and timing of risks that could manifest with negative impacts, as well as potential opportunities. Often, these are termed 'climate services' and assist with mapping hazards and how they are changing. Decision-support tools range from qualitative approaches to determine overlap of areas of concern with those hazards in the future, to more quantitative and dynamic simulation approaches that enable dynamic stress-testing of adaptation options and strategies to determine if proposed plans for adapting to the future could be successful. An important consideration is whether options for risk management or capitalisation on opportunities will limit options and flexibility for responding to unforeseen events in the future. If these options have a negative effect on other areas of concern, then they could be identified in these planning scenarios as maladaptations, and therefore avoided.

A great challenge for decision-makers is how to choose effective options when the future is uncertain. Uncertainty can arise not just in the statistical error of the magnitude of risk but also in the nature and consequence of risk from uncertainty about mechanisms that link areas of concern to hazards, uncertainty in the decision processes itself and so on. Methods are available to help develop no-regret options, commonly referred to as "decision making under conditions of deep uncertainty". Decision-support frameworks are most successful when they are iterative, integrative, and consultative. Rather than a single decision be made, and an action taken, there are processes for making the best decision possible then monitoring progress toward delivering a successful outcome. Given a set of suitable indicators with regular monitoring, decisions can be revised, updated, or changed as the future unfolds and foundations for the original decision tested. This is important because climate responses need to be initiated well in advance of them being needed due to the time required to implement suitable responses. These forward-looking approaches allow errors to occur and corrections made before problems arise. They also enable action to be taken without having to wait for the circumstances to arise, which if this were to occur could result in only limited reactions being available and the outcomes then dependent upon recovery from events rather than proactive planning and avoidance of events. Integrated approaches to risk management are available to help manage portfolios of interacting risks, including the potential for compounding and cascading risks when climate-related events arise.

Managing uncertainty with forward-looking processes needs to be more deliberative and oriented towards building trust in a collaborative process. Building relationships through informal, bottom-up processes enables this to occur. Top-down planning processes are important for ensuring the management of risks and opportunities do not end up with maladaptations and that the approaches are equitable and proportional to that which is needed to manage the risks.

[END FAQ17.1 HERE]

[START FAQ17.2 HERE]

FAQ17.2: What financing options are available to support adaptation and climate resilience?

What do we mean by "climate finance"?
The UNFCCC has no formally agreed definition of climate finance. The current IPCC definition is: "*the financial resources devoted to addressing climate change by all public and private actors from global to local scales, ~~i~~including international financial flows to developing countries to assist them in addressing climate change"* (see Annex I: Glossary).

What needs to be financed?
Financial resources might be needed for a range of adaptation and resilience building activities. These include research, education and capacity building; development of laws, regulations, and standards; provision of climate services and other information; reducing the vulnerability of existing assets, activities, and services; and ensuring future development - such as new infrastructure, settlements, health services and business activities - is climate resilient. Finance is also needed to recover and rebuild from the damage of climate hazards that cannot be completely avoided through adaptation. Adaptation actions can be undertaken by many different actors, alone or in partnership, including national and sub-national governments, public and private utilities, businesses of varying size, communities, households, and individuals.

Table FAQ17.2.1 Examples of adaptation and resilience activities that might need to be financed

Training of agricultural extension officers so that their advice to small-holder farmers can support implementation of climate adapted agriculture. Additional financial support is needed for the costs of farmers transitioning to climate resilient agricultural practices.	A new urban development requires higher standards (and up-front costs) for buildings, roads, stormwater systems, water re-use and to be resilient to expected changes in heavy rainfall, runoff, temperature, and water supply reliability.
A water utility requires capital expenditure to increase supply through a desalination plant and to reduce leakage from its reticulation system in response to a scenario of	A catastrophe risk insurance facility is established to provide post-disaster (drought, hurricane, flooding, pest outbreaks) recovery finance to national governments.

reduced surface water availability and an increase in customers.	The facility requires capital to be able to underwrite the insurance products it offers.

How much finance is needed?

The amount of adaptation finance depends on global, regional, and local factors, including: the amount and timing of global warming, how this translates into impacts and adaptation needs across the world; the levels of adaptation already in place; the type of risk being adapted to; and the adaptation options being chosen, including whether the adaptation required is incremental or transformational.

The most mentioned figure for finance need is the developed countries commitment to provide USD 100 billion per year by 2020 to support developing countries efforts in mitigation and adaptation. Negotiations will start in 2021 on updating this amount for 2025. While sometimes thought to represent the actual cost of responding to climate change in developing countries, this is not the case. More recent estimates of the global cost of adaptation by 2030 across developed and developing countries range between about USD 80-300 billion per year.

What types of finance are available?

Four main types (or instruments) of finance are currently being used to support adaptation. These different types are not mutually exclusive; grants can be combined with loans to provide blended finance.

Table FAQ17.2.2 The main instruments through which adaptation is being financed

Grants provide finance without any repayment requirements. Most grants for adaptation have been provided by multilateral funds such as the Green Climate Fund or a fund managed by a single OECD country such as Germany's International Climate Initiative. Some countries have national climate or environment funds that provide grants for their own climate adaptation actions. Grants are also provided by philanthropic foundations and sometimes by companies as part of their environmental and social responsiveness mandate.	**Concessional loans** require partial repayment of the finance provided. These involve either capital repayment coupled to below market interest rates or capital repayment only. Concessional finance is almost entirely provided through multilateral development banks such as the World Bank. This finance is particularly important for developing countries where market interests are high due to poor credit ratings or other risk factors, or where the return on investment is too low make a commercial loan viable.
Non-concessional loans (or debts) are commercial instruments, where capital repayment and market interest rates apply. These may be provided through development banks or private banks. Green bonds are a relatively new form of market loan, designed to meet climate and other environmental sustainability criteria in terms of how the proceeds are used. In recent years green bonds have offered better interest than ordinary bonds due to oversubscription by investors who are looking to move towards environmentally sustainable investment portfolios.	**Budget reallocation** does not require raising of new finance; rather it involves moving funds already secured away from other purposes towards adaptation. In government, this might involve reallocation towards flood defence. In the private sector a company might move budget from marketing, research and development, or perhaps dividends, towards increasing the climate resilience of operation, infrastructure or their value chain.

Where are different types of finance most useful?

Grants are useful for a range of adaptation actions where it is hard to generate a financial return. These include capacity building activities, piloting new adaptation innovations, high risk investment settings, or projects where there are considerable non-financial benefits. In contrast loans and other debt instruments can often support larger investments, for example for scaling out of successful pilot projects or for building adaptation and resilience into general development investment. To date, a large proportion of international climate finance for adaptation in developing countries, especially in sub-Saharan Africa and Oceania has been grant led, sourced from OECD public funds, indicating that in many instances financing via loans is either considered too risky by the commercial investment sector or it has been hard to demonstrate sufficient return on investment.

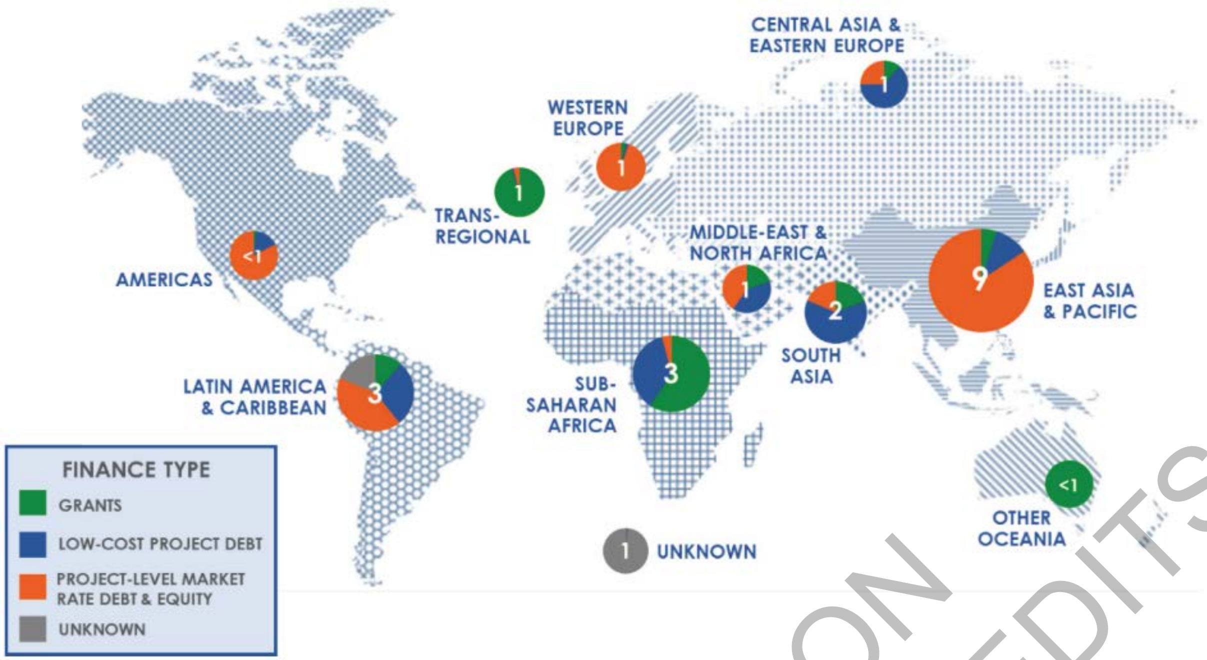


Figure FAQ17.2.1. The distribution of adaptation finance across different regions and different types of finance in 2015-2016, as tracked the Climate Policy Initiative. The size of each circle represents the amount of finance, with amount in billions USD superimposed. Based on data tracked by the Climate Policy Initiative.

[END FAQ17.2 HERE]

[START FAQ17.3 HERE]

FAQ17.3: Why is adaptation planning along a spectrum from incremental to transformational adaptation important in a warming world?

In a warming world, incremental adaptation, i.e. proven standard measures of adaptation, will not always suffice to adjust to the negative impacts from climate change leading to substantial residual risks and, in some cases, the breaching of adaptation limits; transformational adaptation, involving larger system-wide change (as compared to in system change), will increasingly be necessary as a complement for helping individuals and communities to cope with climate change. As an example of incremental adaptation, a farmer may decide to use drought-tolerant crops to deal with increasing occurrences of heatwaves. With further warming and increases in heat waves and drought, however, the impacts of climate change may necessitate the consideration of system-wide change, such as moving to an entirely new agricultural system in areas where the climate is no longer suitable for current practices; or switching to livestock rearing. Where on-site adaptation becomes infeasible and pull factors exist, the farming households may decide to seek employment in other sectors, which may also lead to migration for work. As another example, physical protection through sea walls to stop coastal flooding is a proven adaptation measure. With further projected flooding due to increasing sea level rise attributable to climate change transformational city planning, that would systemically change how flood water is managed throughout the whole city requiring deeper institutional, structural, and financial support, may become necessary. Also, the deliberate relocation of settlements (managed retreat) is seeing attention in the face of increasingly severe coastal or riverine flooding in some regions. While transformational adaptation is increasingly being considered in theory and planning, implementation is only beginning to see attention.

[END FAQ17.3 HERE]

[START FAQ17.4 HERE]

FAQ17.4: Given the existing state of adaptation, and the remaining risks that are not being managed, who bears the burden of these residual risks around the world?

A warming climate brings along increasing risks, part of which can be reduced or insured. What remains is called residual risks and needs to be retained by households, the private and public sectors. People living in conflict-affected areas benefit only marginally from adaptation investments by governments, private sector, or other institutions. These people bear most of the changing climate risks themselves. Higher-income countries generally have invested heavily in structural adaptation to make sure people are not exposed to extreme events (e.g. dykes) and have developed a variety of private or public insurance systems to finance the risk of the most rare or extreme events. In other, middle or lower-income countries, these very extreme events are less likely to be insured, and the impacts are borne by the most vulnerable people. Absent risk reduction or insurance, coping with residual risks generally means reducing consumption (e.g. food) or drawing down assets (selling machinery, houses etc), which all can bring along longer-term adverse developmental implications. Adaptation investments in low-income countries tend to focus more heavily on increasing capacity and reducing vulnerability; people remain exposed to the changing climate risks, and bear the burden of reacting and responding.

[END FAQ17.4 HERE]

[START FAQ17.5 HERE]

FAQ17.5: How do we know whether adaptation is successful?

Adaptation aims to reduce exposure and vulnerability to climate change by responding to dynamic and multi-scalar combinations of climatic risks. What might be seen as successful at one scale or at one point in time might not be at another, particularly if climate risks continue to rise. Moreover, the benefits of adaptation interventions may not reach all intended beneficiaries or everyone affected by climate impact and risk, causing different people to have different views on how successful adaptation has been.

There is, therefore, no universal way to measure adaptation success, but there is high agreement that success is associated with a reduction of climate risks and vulnerabilities (for humans and ecosystems) and an equitable balancing of synergies and trade-offs across diverse objectives, perspectives, expectations, and values. Adaptation that is successful is also commonly expected to be inclusive of different socio-economic groups, especially the most vulnerable, and to be based on flexible and integrative planning processes that take into account different climate scenarios.

Conceptually, the opposite of successful adaptation is maladaptation, i.e. when adaptation responses produce unintended negative side effects such as exacerbating or shifting vulnerability, increasing risk for certain people or ecosystems, or increasing greenhouse gas emissions. Among the adaptation options assessed in this report (Figure FAQ 17.5.1), physical infrastructure along coasts (e.g., sea walls) has the highest risk for maladaptation over time through negative side-effects on ecosystem functioning and coastal livelihood opportunities. However, such adaptations may appear valuable in the short and even longer term for already densely populated urban coasts, demonstrating that an adaptation can be differently judged based on the context it is implemented in (Figure FAQ 17.5.1). Many other adaptation options have a larger potential to contribute to successful adaptation (Figure FAQ17.5.1), such as nature restoration, providing social safety nets, and changing diets/ minimizing food waste.

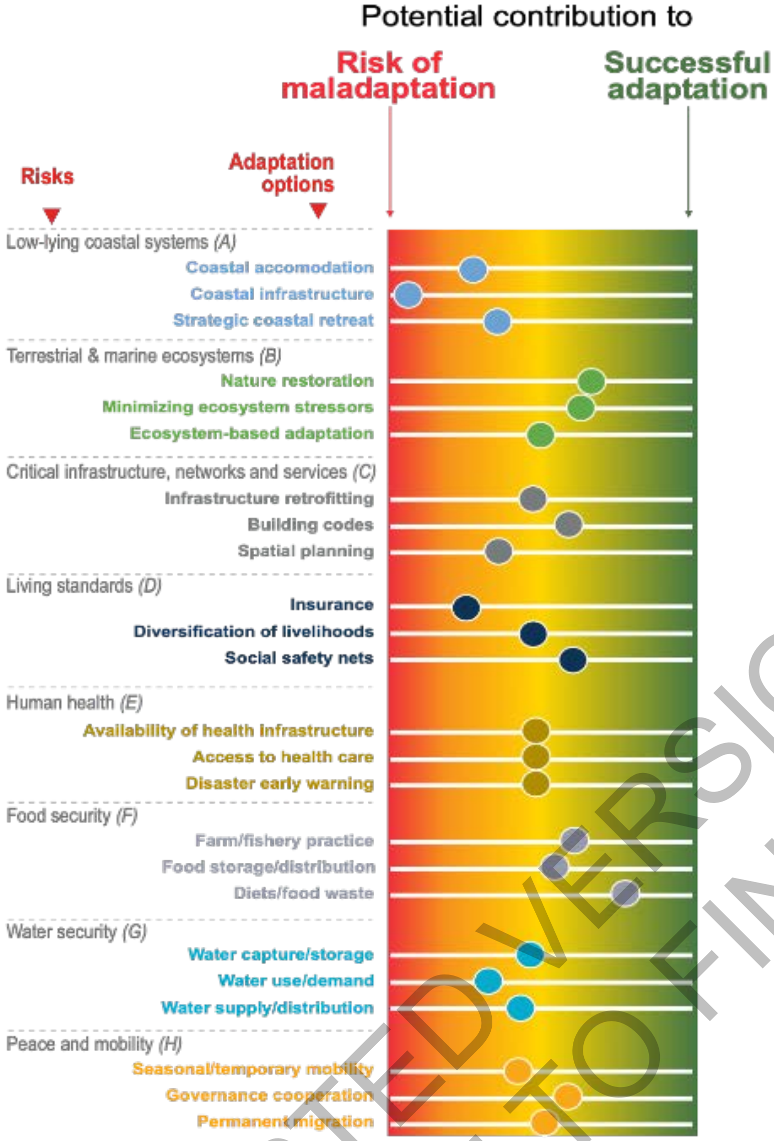


Figure FAQ17.5.1: Contribution of adaptation options to potentially successful adaptation and to the risk of maladaptation. Note: A similar figure is part of Ch17.5.2.

Assessments of adaptation need to be transparent about how they are measuring success. Monitoring and Evaluation (M&E) can be used to track progress and evaluate success and to identify if course corrections during adaptation implementation are needed to achieve the envisaged objectives. Given the diversity of adaptation actions and contexts, no one-size-fits-all approach to M&E and no common reference metrics for adaptation exist. To date, assessments of progress of adaptation have often focused on processes and outputs (i.e. actions taken, such as adaptation plans adopted) that are easier to measure than the effects of these actions in terms of long-term reduction of risks and vulnerabilities. However, knowledge about the outcomes in terms of reducing climate risk, impact and vulnerability is critically required to know if adaptation has been successful.

Tracking progress, in particular outcomes and impacts of adaptation, involves a number of challenges. First, in order to determine progress over time, risk and vulnerability assessments need to be repeated at least once after starting an adaptation process. This is rarely done, as it demands resources that are usually not factored into the adaptation response. Second, attributing changes in climate risks and vulnerabilities to the adaptation response is often difficult due to other influencing factors, such as socio-economic development over time. Expected causal relationships between responses and their outcomes should already be outlined during the adaptation planning phase, for example by mapping the way from activities to outcomes, and they should be monitored during implementation. Third, as adaptation can occur in multiple forms and target multiple temporal and spatial scales, the engagement of a diversity of stakeholders is vital to understand how responses enable adaptation and adaptation success across vulnerable groups. Though, stakeholder engagement can be time intensive and costly, in particular when reaching out to populations that are usually not part of policy and planning processes it can support evaluating co-benefits and trade-offs of adaptation responses. Consideration and analysis of co-benefits and trade-offs along with a focus on short, medium, and long time horizons of adaptation goals, which is usually possible through flexible and strong institutions, facilitate successful adaptation and reduce the likelihood of maladaptation.

[END FAQ 17.5 HERE]

References

Abadie, L. M., I. Galarraga and D. Rübbelke, 2013: An analysis of the causes of the mitigation bias in international climate finance. *Mitigation and Adaptation Strategies for Global Change*, **18**(7), 943-955, doi:10.1007/s11027-012-9401-7.

Abbas, A. and R. Howard, 2015: Foundations of Decision Analysis.

Abebe, Y. A. et al., 2019: Flood risk management in Sint Maarten – A coupled agent-based and flood modelling method. *Journal of Environmental Management*, **248**, doi:10.1016/j.jenvman.2019.109317.

Abram, N. et al., 2019: Framing and Context of the Report. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.

Abunnasr, Y., E. M. Hamin and E. Brabec, 2013: Windows of opportunity: addressing climate uncertainty through adaptation plan implementation. *Journal of Environmental Planning and Management*, **58**(1), 135-155, doi:10.1080/09640568.2013.849233.

Abutaleb, K. A. A., A. H. E.-S. Mohammed and M. H. M. Ahmed, 2018: Climate Change Impacts, Vulnerabilities and Adaption Measures for Egypt's Nile Delta. *Earth Systems and Environment*, **2**(2), 183-192, doi:10.1007/s41748-018-0047-9.

Ackermann, F., 2012: Problem structuring methods 'in the Dock': Arguing the case for Soft OR. *European Journal of Operational Research*, **219**(3), 652-658, doi:10.1016/j.ejor.2011.11.014.

Adam, J. C. et al., 2014: BioEarth: Envisioning and developing a new regional earth system model to inform natural and agricultural resource management. *Climatic Change*, **129**(3-4), 555-571, doi:10.1007/s10584-014-1115-2.

Adams, H., S. Blackburn and N. Mantovani, 2021: Psychological resilience for climate change transformation: relational, differentiated and situated perspectives. *Current Opinion in Environmental Sustainability*, **50**, 303-309.

Adaptation Committee, 2016: *Inventory of ongoing monitoring and evaluation work of adaptation prepared under the Nairobi work programme on impacts, vulnerability and adaptation to climate change*. Note by the secretariat, **16**. Available at: https://unfccc.int/files/adaptation/groups_committees/adaptation_committee/application/pdf/ac10_5b_m_and_e_.pdf.

Adaptation Committee, 2021: *Approaches to reviewing the overall progress made in achieving the global goal on adaptation. Technical Paper*. UNFCCC Secretariat.

Adaptation Fund, 2016: *Knowledge Management Strategy & Action Plan*. Available at: https://www.adaptation-fund.org/document/knowledge-management-strategy-action-plan/.

Adaptation Partnership, 2012: *Tracking successful adaptation – smart monitoring for good results*. Results report, Federal Ministry for Economic Cooperation and Development (BMZ). Available at: https://www.adaptationcommunity.net/publications/tracking-successful-adaptation-workshop-report-2012/

ADB, 2018: *Strategy 2030: Achieving a Prosperous, Inclusive, Resilient, and Sustainable Asia and the Pacific*. Asian Development Bank. ISBN 9789292612856.

Adger, W. N., I. Brown and S. Surminski, 2018: Advances in risk assessment for climate change adaptation policy. *Philos Trans A Math Phys Eng Sci*, **376**(2121), 20180106, doi:10.1098/rsta.2018.0106.

Adger, W. N., C. Butler and K. Walker-Springett, 2017: Moral reasoning in adaptation to climate change. *Environmental Politics*, **26**(3), 371-390, doi:10.1080/09644016.2017.1287624.

Adnan, M. S. G., A. Y. M. Abdullah, A. Dewan and J. W. Hall, 2020: The effects of changing land use and flood hazard on poverty in coastal Bangladesh. *Land Use Policy*, **99**, 104868, doi:10.1016/j.landusepol.2020.104868.

Aerts, J. C. J. H. et al., 2018a: Pathways to resilience: adapting to sea level rise in Los Angeles. *Annals of the New York Academy of Sciences*, **1427**(1), 1-90, doi:10.1111/nyas.13917.

Aerts, J. C. J. H. et al., 2018b: Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change*, **8**(3), 193-199, doi:10.1038/s41558-018-0085-1.

AfDB, 2019: *Analysis of Adaptation Components in African Nationally Determined Contributions (NDCs)*. African Ndc Hub Secretariat, A. D. B. Available at: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/Analysis_of_Adaptation_Components_in_African_NDCs_2019.pdf.

Agrawal, A. et al., 2019: *Climate Resilence through Social Protection*. Background Paper for Global Commission on Adaptation, IIED.

Aguilar-Barajas, I., N. P. Sisto, A. I. Ramirez and V. Magaña-Rueda, 2019: Building urban resilience and knowledge co-production in the face of weather hazards: flash floods in the Monterrey Metropolitan Area (Mexico). *Environmental Science and Policy*, **99**, 37-47, doi:10.1016/j.envsci.2019.05.021.

Ahenkan, A., D. N. Chutab and E. K. Boon, 2020: Mainstreaming climate change adaptation into pro-poor development initiatives: evidence from local economic development programmes in Ghana. *Climate and Development*, 1-13.

Ahmad, B., S. Ali Bukhari and S. Babar Cheema, 2019: Generation of Cressman Interpolated High-resolution Gauge-based Gridded Observations (CIHGGO) for climatic variables using in-situ data over Pakistan. *European Journal of Scientific Exploration*, **2**(4), 7 pp.

Ahmad, S. K. and F. Hossain, 2020: Maximizing energy production from hydropower dams using short-term weather forecasts. *Renewable Energy*, **146**, 1560-1577, doi:https://doi.org/10.1016/j.renene.2019.07.126.

Ahmed, I. et al., 2019: Opportunities and challenges of compliance to safe building codes: Bangladesh and Nepal. *APN Science Bulletin*.
Ajibade, I., 2019: Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. *Climatic Change*, **157**(2), 299-317.
Ajibade, I. and M. Egge, 2019: SDGs and climate change adaptation in Asian megacities: synergies and opportunities for transformation. In: *Achieving the Sustainable Development Goals*. Routledge, pp. 100-116. ISBN 0429029624.
Alam, A. S. A. F. et al., 2020a: Agriculture insurance for disaster risk reduction: A case study of Malaysia. *International Journal of Disaster Risk Reduction*, **47**, 101626, doi:https://doi.org/10.1016/j.ijdrr.2020.101626.
Albers, R. et al., 2015: Overview of challenges and achievements in the climate adaptation of cities and in the Climate Proof Cities program. Elsevier.
Albuja, S. and I. C. Adarve, 2011: Protecting people displaced by disasters in the context of climate change: Challenges from a mixed conflict/disaster context. *Tulane Environmental Law Journal*, **24**(2), 239-252.
Aleksandrova, M. and C. Costella, 2021: Reaching the poorest and most vulnerable: addressing loss and damage through social protection. *Current Opinion in Environmental Sustainability*, **50**, 121-128.
Alessa, L. et al., 2016: The role of Indigenous science and local knowledge in integrated observing systems: moving toward adaptive capacity indices and early warning systems. *Sustainability Science*, **11**(1), 91-102.
Alexander, S. et al., 2020: Development of an interdisciplinary, multi-method approach to seasonal climate forecast communication at the local scale. *Climatic Change*, **162**(4), 2021-2042, doi:10.1007/s10584-020-02845-9.
Alexeeff, S. E., G. G. Pfister and D. Nychka, 2016: A Bayesian model for quantifying the change in mortality associated with future ozone exposures under climate change. *Biometrics*, **72**(1), 281-288, doi:10.1111/biom.12383.
Ali, A. and O. Erenstein, 2017: Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management*, **16**, 183-194, doi:10.1016/j.crm.2016.12.001.
Ali, S., S. Zhang and T. Yue, 2020: Environmental and economic assessment of rainwater harvesting systems under five climatic conditions of Pakistan. *Journal of Cleaner Production*, **259**, 120829-120829.
Allen, T., P. Heinrigs and I. Heo, 2018: Agriculture, food and jobs in West Africa. *West African Papers (OECD) eng no. 14*.
Alpizar F, d. C. M. B. F. P. J. and B. S. Meiselman, 2019: The impacts of a capacity-building workshop in a randomized adaptation project. *Nature Climate Change*, **9**, 587-591.
Amerasinghe, N., J. Thwaites, G. Larsen and A. Ballesteros, 2017: *Future of the Funds: Exploring the Architecture of Multilateral Climate Finance*. World Resources Institute, 100 pp. ISBN 9781569739150.
Andrianarimanana, D., 2015: The role of inter-household transfers in coping with post-disaster losses in Madagascar. In: *Disaster Risk Financing and Insurance: Issues and results* [Clarke, D., A. d. Janvry, E. Sadoulet and E. Skoufias (eds.)].
Andries, A. et al., 2018: Translation of Earth observation data into sustainable development indicators: An analytical framework. *Sustainable Development*, **27**(3), 366-376.
Anguelovski, I. et al., 2016: Equity Impacts of Urban Land Use Planning for Climate Adaptation. *Journal of Planning Education and Research*, **36**(3), 333-348, doi:10.1177/0739456x16645166.
Anguita Olmedo, C. and P. González Gómez del Miño, 2019: El Sahel: dimensión transfronteriza y dinámicas geopolíticas. *Geopolítica (s). Revista de estudios sobre espacio y poder*, **10**(2), 281-303.
Annan, F. and W. Schlenker, 2015: Federal Crop Insurance and the Disincentive to Adapt to Extreme Heat. *The American Economic Review*, **105**(5), 262-266.
Antwi-Agyei, P., A. J. Dougill and L. C. Stringer, 2014: Barriers to climate change adaptation: evidence from northeast Ghana in the context of a systematic literature review. *Climate and Development*, **7**(4), 297-309, doi:10.1080/17565529.2014.951013.
Aragòn-Correa, J. A., A. A. Marcus and D. Vogel, 2019: The Effects of Mandatory and Voluntary Regulatory Pressures on Firms' Environmental Strategies: A Review and Recommendations for Future Research. *Academy of Management Annals*, **14**(1), 339-365, doi:10.5465/annals.2018.0014.
Araos, J. e. a., in press: Equity in human adaptation-related responses: a systematic global review. *OneEarth*.
Araos, M. et al., 2016a: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science & Policy*, **66**, 375-382.
Araos, M. et al., 2017: Climate change adaptation planning for Global South megacities: the case of Dhaka. *Journal of Environmental Policy and Planning*, **19**(6), 682-696, doi:10.1080/1523908X.2016.1264873.
Araujo, J., B. Harvey and Y. Huang, 2020: *A critical reflection on learning from the FCFA programme*. Future Climate for Africa. Available at: https://media.africaportal.org/documents/a_critical_reflection_on_learning_from_the_fcfa_programme_CuvAQxO.pdf.
Argyris, N. and S. French, 2017: Behavioural Issues and Impacts in Nuclear Emergency Decision Support, 180-193 pp.
Arias, P. et al., 2021: *Technical Summary*. Climate Change, Cambridge University Press.
Arıkan, G. and D. Günay, 2020: Public attitudes towards climate change: A cross-country analysis. *The British Journal of Politics and International Relations*, 136914812095101, doi:10.1177/1369148120951013.

Armitage, D., M. Marschkeb and R. Plummer, 2008: Adaptive Co-Management and the Paradox of Learning. *Global Environmental Change*, **18**, 86-98.

Arnold, C. A. and L. Gunderson, 2013: Adaptive Law and Resiliencer. *Environmental Law Reporter, University of Louisville School of Law Legal Studies Research Paper Series*, **43**(4), 10426-10443.

Asfaw, H. W., N. Sandy Lake First, T. K. McGee and A. C. Christianson, 2019: Evacuation preparedness and the challenges of emergency evacuation in Indigenous communities in Canada: The case of Sandy Lake First Nation, Northern Ontario. *International Journal of Disaster Risk Reduction*, **34**, 55-63, doi:10.1016/j.ijdrr.2018.11.005.

Ashgar Leghari v. Federation of Pakistan, L. H. C., April 2015. Available at: http://climatecasechart.com/climate-change-litigation/wp-content/uploads/sites/16/non-us-case-documents/2015/20150404_2015-W.P.-No.-25501201_decision.pdf.

Ashgar Leghari v. Federation of Pakistan, L. H. C., September 2015. Available at: http://climatecasechart.com/climate-change-litigation/wp-content/uploads/sites/16/non-us-case-documents/2015/20150414_2015-W.P.-No.-25501201_decision.pdf.

Åström, H. L. A. et al. (eds.), Describing concurrent flood hazards in a risk assessment decision framework using a bayesian network methodology. 13th International Conference on Urban Drainage, IWA Publishing, 90 pp.

Atkinson, G., N. A. Braathen, B. Groom and S. Mourato, 2018a: *Cost-benefit analysis and the environment: further developments and policy use, Organisation for Economic Co-operation and Development*. OECD, Paris, France. Available at: https://www.oecd.org/governance/cost-benefit-analysis-and-the-environment-9789264085169-en.htm.

Atkinson, R., T. Dörfler and E. Rothfuß, 2018b: Self-Organisation and the Co-Production of Governance: The Challenge of Local Responses to Climate Change. *Politics and Governance*, **6**(1), 169-179, doi:10.17645/pag.v6i1.1210.

Atteridge, A. and E. Remling, 2018: Is adaptation reducing vulnerability or redistributing it? *Wiley Interdisciplinary Reviews Climate Change*, **9**(1), 1-16.

Atteridge, A. et al., 2009: *Bilateral Finance Institutions and Climate Change: A Mapping of Climate Portfolios*. Stockholm Environment Institute, Stockholm. ISBN 9789186125202.

Atun, R. et al., 2015: Health-system reform and universal health coverage in Latin America. *The Lancet*, **385**(9974), 1230-1247.

Audefroy, J. F. and B. N. C. Sánchez, 2017: Integrating local knowledge for climate change adaptation in Yucatán, Mexico. *International Journal of Sustainable Built Environment*, **6**(1), 228-237, doi:10.1016/j.ijsbe.2017.03.007.

Averchenkova, A., 2019: Legislating for a low carbon and climate resilient transition: learning from international experiences. vol. Elcano Policy Paper, Real Instituto Elcano, Madrid. Available at: http://www.realinstitutoelcano.org/wps/portal/rielcano_en/contenido?WCM_GLOBAL_CONTEXT=/elcano/elcano_in/zonas_in/policy-paper-2019-legislating-low-carbon-climate-resilient-transition.

Averchenkova, A., S. Fankhauser and J. J. Finnegan, 2021: The impact of strategic climate legislation: evidence from expert interviews on the UK Climate Change Act. *Climate Policy*, **21**(2), 251-263, doi:10.1080/14693062.2020.1819190.

Averchenkova, A. and S. Guzman Luna, 2018: *Mexico's General Law on Climate Change: Key achievements and challenges ahead* [Environment, G. R. I. o. C. C. a. t. (ed.)]. London School of Economics and Political Science.

Averchenkova, A. and S. Matikainen, 2017: Climate legislation and international commitments. In: *Trends in Climate Change Legislation*. Edward Elgar Publishing, pp. 193-208. ISBN 9781786435781.

Ayers, J. et al., 2014: Mainstreaming climate change adaptation into development in Bangladesh. *Climate and Development*, **6**(4), 293-305, doi:10.1080/17565529.2014.977761.

Aylett, A., 2015: Institutionalizing the urban governance of climate change adaptation: Results of an international survey. *Urban Climate*, **14**, 4-16, doi:10.1016/j.uclim.2015.06.005.

Azadi, Y., M. Yazdanpanah and H. Mahmoudi, 2019: Understanding smallholder farmers' adaptation behaviors through climate change beliefs, risk perception, trust, and psychological distance: Evidence from wheat growers in Iran. *Journal of environmental management*, **250**, 109456, doi:10.1016/j.jenvman.2019.109456.

Azhoni, A., S. Jude and I. Holman, 2018: Adapting to climate change by water management organisations: Enablers and barriers. *Journal of Hydrology*, **559**, 736-748, doi:https://doi.org/10.1016/j.jhydrol.2018.02.047.

Baarsch, F. et al., 2015: *Impacts of Low Aggregate INDCs Ambition*.

Baatz, C., 2018: Climate Adaptation Finance and Justice. A Criteria-Based Assessment of Policy Instruments. *Analyse & Kritik*, **40**(1), 73-106, doi:10.1515/auk-2018-0004.

Bacud, S. T. (ed.), Integration of Indigenous and Scientific Knowledge in Disaster Risk Reduction: Resilience Building of a Marginalized Sampaguita Growing Community in the Philippines. Procedia Engineering, 2018, 511-518 pp.

Baffoe, G. and H. Matsuda, 2017: An Empirical Assessment of Households Livelihood Vulnerability: The Case of Rural Ghana. *Social Indicators Research*, **140**(3), 1225-1257, doi:10.1007/s11205-017-1796-9.

Bahri, T. et al., 2021: *Adaptive management of fisheries in response to climate change*. FAO Fisheries and Aquaculture Technical Paper, **No. 667**, FAO, Rome, 301 pp.

Baird, J., R. Plummer, C. Haug and D. Huitema, 2015: Learning effects of interactive decision-making processes for climate change adaptation. *Global Environmental Change*, **27**, 51-63.

Baker, E. and S. Solak, 2011: Climate change and optimal energy technology R&D policy. *European journal of operational research*, **213**(2), 442-454, doi:10.1016/j.ejor.2011.03.046.

Balasubramanian, M., 2018: Climate change, famine, and low-income communities challenge Sustainable Development Goals. *The Lancet Planetary Health*, **2**(10), e421-e422, doi:10.1016/s2542-5196(18)30212-2.
Ballester, J., R. Lowe, P. J. Diggle and X. Rodó, 2016: *Seasonal forecasting and health impact models: Challenges and opportunities*. Annals of the New York Academy of Sciences, vol. 1382, 8 pp.
Ballew, M. T. et al., 2020: Does socioeconomic status moderate the political divide on climate change? The roles of education, income, and individualism. *Global Environmental Change*, **60**, doi:10.1016/j.gloenvcha.2019.102024.
Banda, M. L. and C. S. Fulton, 2017: Litigating Climate Change in National Courts: Recent Trends and Developments in Global Climate Law. *Environmental Law Reporter, University of Louisville School of Law Legal Studies Research Paper Series*, **47**(2).
Bandura, A. and L. Cherry, 2019: Enlisting the power of youth for climate change. *American Psychologist*, doi:10.1037/amp0000512.
Barbeaux, S. J., K. Holsman and S. Zador, 2020: Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific Cod Fishery. *Frontiers in Marine Science*, **7**, 703.
Barnard, P., R. Altwegg, I. Ebrahim and L. G. Underhill, 2017: Early warning systems for biodiversity in southern Africa–How much can citizen science mitigate imperfect data? *Biological conservation*, **208**, 183-188.
Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4**(12), 1103-1108, doi:10.1038/nclimate2383.
Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **2**(20), 211-213.
Basher, R., 2006: Global early warning systems for natural hazards: systematic and people-centred. *Philos Trans A Math Phys Eng Sci*, **364**(1845), 2167-2182, doi:10.1098/rsta.2006.1819.
Bassett, T. J. and C. Fogelman, 2013: Déjà vu or something new? The adaptation concept in the climate change literature. *Geoforum*, **48**, 42-53.
Basupi, L. V., C. H. Quinn and A. J. Dougill, 2019: Adaptation strategies to environmental and policy change in semi-arid pastoral landscapes: Evidence from Ngamiland, Botswana. *Journal of Arid Environments*, **166**, 17-27, doi:https://doi.org/10.1016/j.jaridenv.2019.01.011.
Batisha, A. F., 2015: Implementing fuzzy decision making technique in analyzing the Nile Delta resilience to climate change. *Alexandria engineering journal*, **54**(4), 1043-1056, doi:10.1016/j.aej.2015.05.019.
Bauch, C. T., R. Sigdel, J. Pharaon and M. Anand, 2016: Early warning signals of regime shifts in coupled human-environment systems. *Proc Natl Acad Sci U S A*, **113**(51), 14560-14567, doi:10.1073/pnas.1604978113.
Baudoin, M.-A. et al., 2016: From Top-Down to "Community-Centric" Approaches to Early Warning Systems: Exploring Pathways to Improve Disaster Risk Reduction Through Community Participation. *International Journal of Disaster Risk Science*, **7**(2), 163-174, doi:10.1007/s13753-016-0085-6.
Baur, E., R. Schnarwiler, A. Prystav and L. Sundermann, 2018: *Disaster risk financing: Smart solutions for the public sector*. Closing the Protection Gap, SwissRe, Zurich.
Baztan, J. et al., 2017: Life on thin ice: Insights from Uummannaq, Greenland for connecting climate science with Arctic communities. *Polar science*, **13**, 100-108, doi:10.1016/j.polar.2017.05.002.
Becker, A. and E. Kretsch, 2019: The Leadership Void for Climate Adaptation Planning: Case Study of the Port of Providence (Rhode Island, United States). *Frontiers in Earth Science*, **7**, 29.
Beckett, V., 2016: Insuring the geopolitics of climate change. *ReActions (London)*.
Bedelian, C. and J. O. Ogutu, 2017: Trade-offs for climate-resilient pastoral livelihoods in wildlife conservancies in the Mara ecosystem, Kenya. *Pastoralism*, **7**(1), 10, doi:10.1186/s13570-017-0085-1.
Bedford, T., S. French and E. Atherton, 2005: Supporting ALARP decision making by cost benefit analysis and multiattribute utility theory. *Journal of Risk Research*, **8**(3), 207-223, doi:10.1080/1366987042000192408.
Behzadian, M., R. B. Kazemzadeh, A. Albadvi and M. Aghdasi, 2010: PROMETHEE: A comprehensive literature review on methodologies and applications. *European journal of operational research*, **200**(1), 198-215, doi:10.1016/j.ejor.2009.01.021.
Belčáková, I., M. Świąder and M. Bartyna-Zielińska, 2019: The green infrastructure in cities as A tool for climate change adaptation and mitigation: slovakian and polish experiences. *Atmosphere*, **10**(9), 552.
Bell, J. and T. Morrison, 2015: A Comparative Analysis of the Transformation of Governance Systems: Land-Use Planning for Flood Risk. *Journal of Environmental Policy & Planning*, **17**(4), 516-534, doi:10.1080/1523908x.2014.986567.
Bell, M. L. et al., 2001: An evaluation of multi-criteria methods in integrated assessment of climate policy. *Journal of multi-criteria decision analysis*, **10**(5), 229-256, doi:10.1002/mcda.305.
Bellinson, R. and E. Chu, 2019: Learning pathways and the governance of innovations in urban climate change resilience and adaptation. *Journal of Environmental Policy & Planning*, **21**(1), 76-89, doi:10.1080/1523908x.2018.1493916.
Belton, V. and T. Stewart, 2002: *Multiple Criteria Decision Analysis: An Integrated Approach*. Kluwer Academic Publishers, Boston.
Bendoly, E. and S. Clark, 2016: *Visual Analytics for Management: Translational Science and Applications in Practice*. Taylor & Francis, New York. ISBN 9781315640891.
Béné, C. et al., 2017: Squaring the Circle: Reconciling the Need for Rigor with the Reality on the Ground in Resilience Impact Assessment. *World Development*, **97**, 212-231.

Béné, C., S. Devereux and R. Sabates-Wheeler, 2012: Shocks and social protection in the Horn of Africa: analysis from the Productive Safety Net programme in Ethiopia. *IDS Working Papers*, **2012**(395), 1-120, doi:https://doi.org/10.1111/j.2040-0209.2012.00395.x.
Béné, C., A. Riba and D. Wilson, 2020: Impacts of resilience interventions – Evidence from a quasi-experimental assessment in Niger. *International Journal of Disaster Risk Reduction*, **43**, 101390, doi:https://doi.org/10.1016/j.ijdrr.2019.101390.
Benjamin, L., 2017: The Duty of Due Consideration in the Anthropocene: Climate Risk and English Directorial Duties. *Carbon & Climate Law Review*, **11**(2), 90-99.
Benzie, M. and A. Persson, 2019: Governing borderless climate risks: moving beyond the territorial framing of adaptation. *International Environmental Agreements*, **19**, 369-393.
Berrang-Ford, L. et al., 2019: Tracking global climate change adaptation among governments. *Nature Climate Change*, **9**, 440-449.
Berrang-Ford, L. et al., 2014: What drives national adaptation? A global assessment. *Climatic Change*, **124**(1-2), 441-450, doi:10.1007/s10584-014-1078-3.
Berrang-Ford, L. et al., 2021: Mapping evidence of human adaptation to climate change. *Nature Climate Change*.
Berrang-Ford, L. et al., 2017: Towards the assessment of global adaptation progress. United Nations Environment Programme (UNEP), Nairobi, Kenya, pp. 35-47.
Bessembinder, J. et al., 2019: Need for a common typology of climate services. *Climate services*, **16**, 100135, doi:10.1016/j.cliser.2019.100135.
Betzold, C. and I. Mohamed, 2017: Seawalls as a response to coastal erosion and flooding: a case study from Grande Comore, Comoros (West Indian Ocean). *Regional Environmental Change*, **17**(4), 1077-1087.
Beunen, R. and J. J. Patterson, 2019: Analysing institutional change in environmental governance: Exploring the concept of 'institutional work'. *Journal of Environmental Planning and Management*, **62**(1), 12-29.
Beven, K. J. et al., 2018a: Epistemic uncertainties and natural hazard risk assessment – Part 1: A review of different natural hazard areas. *Natural Hazards and Earth System Sciences*, **18**(10), 2741-2768, doi:10.5194/nhess-18-2741-2018.
Beven, K. J. et al., 2018b: Epistemic uncertainties and natural hazard risk assessment – Part 2: What should constitute good practice? *Natural Hazards and Earth System Sciences*, **18**(10), 2769-2783, doi:10.5194/nhess-18-2769-2018.
Bhattacharya, A. et al., 2020: *Delivering on the $100 billion climate finance commitment and transforming climate finance*. Independent Expert Group on Climate Finance, Finance, I. E. G. o. C. Available at: https://www.un.org/sites/un2.un.org/files/100_billion_climate_finance_report.pdf (accessed 2021/08/14).
Bhave, A. G., D. Conway, S. Dessai and D. A. Stainforth, 2016: Barriers and opportunities for robust decision making approaches to support climate change adaptation in the developing world. *Climate Risk Management*, **14**, 1-10, doi:https://doi.org/10.1016/j.crm.2016.09.004.
Bhave, A. G., D. Conway, S. Dessai and D. A. Stainforth, 2018: Water Resource Planning Under Future Climate and Socioeconomic Uncertainty in the Cauvery River Basin in Karnataka, India. *Water Resources Research*, **54**(2), 708-728, doi:10.1002/2017wr020970.
Biagini, B. et al., 2014: A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. *Global Environmental Change*, **25**(1), 97-108, doi:10.1016/j.gloenvcha.2014.01.003.
Biagini, B. and A. Miller, 2013: Engaging the private sector in adaptation to climate change in developing countries: importance, status, and challenges. *Climate and Development*, **5**(3), 242-252, doi:10.1080/17565529.2013.821053.
Bianco, G. B., 2020: Climate change adaptation, coffee, and corporate social responsibility: challenges and opportunities. *International Journal of Corporate Social Responsibility*, **5**(1), 3, doi:10.1186/s40991-020-00048-0.
Biehl, L. L., L. Zhao, C. X. Song and C. G. Panza, 2017: Cyberinfrastructure for the collaborative development of U2U decision support tools. *Climate Risk Management*, **15**(C), 90-108, doi:10.1016/j.crm.2016.10.003.
Biermann, F. and I. Boas, 2017: Towards a global governance system to protect climate migrants: taking stock. In: *Research Handbook on Climate Change, Migration and the Law*. Edward Elgar Publishing.
Biesbroek, G. R. et al., 2010: Europe adapts to climate change: Comparing National Adaptation Strategies. *Global Environmental Change*, **20**(3), 440-450, doi:10.1016/j.gloenvcha.2010.03.005.
Biesbroek R, B.-F. L. F. J. T. A. A. S. E. L. A., 2018a: Data, concepts and methods for large-n comparative climate change adaptation policy research: A systematic literature review. *Wiley Interdisciplinary Reviews Climate Change*, **9**(6 e548).
Bird, N., 2014: *Fair share: climate finance to vulnerable countries*. Briefing Papers, Overseas Development Institute. Available at: https://www.odi.org/publications/8517-fair-share-climate-finance-vulnerable-countries.
Birkmann, J. and N. Fernando, 2008: Measuring revealed and emergent vulnerabilities of coastal communities to tsunami in Sri Lanka. *Disasters*, **32**(1), 82-105, doi:10.1111/j.1467-7717.2007.01028.x.
Birkmann, J., M. Garschagen and N. Setiadi, 2014: New challenges for adaptive urban governance in highly dynamic environments: Revisiting planning systems and tools for adaptive and strategic planning. *Urban Climate*, **7**, 115-133.
Birkmann, J. and T. Welle, 2015: Assessing the risk of loss and damage: exposure, vulnerability and risk to climate-related hazards for different country classifications. *International Journal of Global Warming*, **8**(2), 191-212.

Bisbal, G. A., 2019: Practical tips to establish an actionable science portfolio for climate adaptation. *Science and Public Policy*, **46**(1), 148-153, doi:10.1093/scipol/scy070.
Bitsura-Meszaros, K., E. Seekamp, M. Davenport and J. W. Smith, 2019: A PGIS-Based Climate Change Risk Assessment Process for Outdoor Recreation and Tourism Dependent Communities. *Sustainability*, **11**(12), 3300, doi:10.3390/su11123300.
Blades, J. J. et al., 2016: Forest managers' response to climate change science: Evaluating the constructs of boundary objects and organizations. *Forest Ecology and Management*, **360**, 376-387, doi:10.1016/j.foreco.2015.07.020.
Blair, B., O. A. Lee and M. Lamers, 2020: Four Paradoxes of the User–Provider Interface: A Responsible Innovation Framework for Sea Ice Services. *Sustainability*, **12**(2), 448, doi:10.3390/su12020448.
Blennow, K., J. Persson, E. Persson and M. Hanewinkel, 2016: Forest owners' response to climate change: University education trumps value profile. *PLoS ONE*, **11**(5), doi:10.1371/journal.pone.0155137.
Bloemen, P. J. T. M. et al., 2019: DMDU into Practice: Adaptive Delta Management in The Netherlands. In: *Decision Making under Deep Uncertainty: From Theory to Practice* [Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen and S. W. Popper (eds.)]. Springer International Publishing, Cham, pp. 321-351. ISBN 978-3-030-05252-2.
Blome, T. H. A. M.-C. M. J. D., 2017: *IInnovation in Climate Services and Capacity Building - Conference report: Fifth International Conference on Climate Services (ICCS5), February 28 - March 2 2017*. Cape Town, South Africa.
Blühdorn, I. and M. Deflorian, 2019: The collaborative management of sustained unsustainability: On the performance of participatory forms of environmental governance. *Sustainability*, **11**(4), 1189.
Boardman, A. E., D. H. Greenberg, A. R. Vining and D. L. Weimer, 2017: Cost-benefit analysis: concepts and practice. Cambridge University Press.
Bobadoye, A., W. Ogara, G. Ouma and J. Onono, 2016: Assessing Climate Change Adaptation Strategies among Rural Maasai pastoralist in Kenya. *American Journal of Rural Development*, **4**(6), 120-128.
Boda, C. et al., 2020: Framing Loss and Damage from Climate Change as the Failure of Sustainable Development.
Bodin, Ö., 2017: Collaborative environmental governance: Achieving collective action in social-ecological systems. *Science*, **357**(6352), eaan1114, doi:10.1126/science.aan1114.
Bodin, Ö. et al., 2019: Working at the "speed of trust": pre-existing and emerging social ties in wildfire responder networks in Sweden and Canada. *Regional Environmental Change*, **19**(8), 2353-2364, doi:10.1007/s10113-019-01546-z.
Bodnar, P., J. Brown and S. Nakhooda, 2015: *What Counts: Tools to Help Define and Understand Progress Towards the $100 Billion Climate Finance Commitment*. Climate Policy Initiative, World Resources Institute and Overseas Development Institute. Available at: https://www.odi.org/publications/9504-what-counts-tools-help-define-and-understand-progress-towards-100-billion-climate-finance-commitment.
Bolorinos, J., N. K. Ajami and R. Rajagopal, 2020: Consumption Change Detection for Urban Planning: Monitoring and Segmenting Water Customers During Drought. *Water Resources Research*, **56**(3), e2019WR025812, doi:10.1029/2019wr025812.
Bonczek, R. H., C. W. Holsapple and A. B. Whinston 2014: *Foundations of Decision Support Systems*. Academic Press, 412 pp. ISBN 9781483236391.
Booysen, M. J., M. Visser and R. Burger, 2019a: Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data. *Water Research*, **149**, 414-420, doi:https://doi.org/10.1016/j.watres.2018.11.035.
Booysen, M. J., B. Wijesiri, C. Ripunda and A. Goonetilleke, 2019b: Fees and governance: Towards sustainability in water resources management at schools in post-apartheid South Africa. *Sustainable Cities and Society*, **51**, 101694, doi:10.1016/j.scs.2019.101694.
Boran, I., 2017: Two concepts of wrongful harm: A conceptual map for the warsaw international mechanism for loss and damage. *Ethics, Policy & Environment*, **20**(2), 195-207.
Bordner, A. S., C. E. Ferguson and L. Ortolano, 2020: Colonial dynamics limit climate adaptation in Oceania: Perspectives from the Marshall Islands. *Global Environmental Change*, **61**, 102054.
Borgomeo, E., J. W. Hall and M. Salehin, 2017: Avoiding the water-poverty trap: insights from a conceptual human-water dynamical model for coastal Bangladesh. *International Journal of Water Resources Development*, **34**(6), 900-922, doi:10.1080/07900627.2017.1331842.
Borgomeo, E. et al., 2016: Trading-off tolerable risk with climate change adaptation costs in water supply systems. *Water Resources Research*, **52**(2), 622-643, doi:10.1002/2015wr018164.
Borgonovo, E. and E. Plischke, 2016: Sensitivity analysis: a review of recent advances. *European Journal of Operational Research*, **248**(3), 869-887.
Borras, S. and S. Hølund, 2015: Evaluation and policy learning: The learners' perspective. *European Journal of Political Research*, **54**, 99-120.
Bosomworth, K., P. Leith, A. Harwood and P. J. Wallis, 2017: What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. *Environmental Science & Policy*, **76**, 23-28, doi:10.1016/j.envsci.2017.06.007.

Boston, J., A. Panda and S. Surminski, 2021: Designing a funding framework for the impacts of slow-onset climate change—insights from recent experiences with planned relocation. *Current Opinion in Environmental Sustainability*, **50**, 159-168.
Boulianne, S., M. Lalancette and D. Ilkiw, 2020: "School Strike 4 Climate": Social Media and the International Youth Protest on Climate Change. *Media and Communication*, **8**(2), 208-218.
Bouman, T. et al., 2020: When worry about climate change leads to climate action: How values, worry and personal responsibility relate to various climate actions. *Global Environmental Change*, **62**, 102061, doi:10.1016/j.gloenvcha.2020.102061.
Bourne, A. et al., 2016: A Socio-Ecological Approach for Identifying and Contextualising Spatial Ecosystem-Based Adaptation Priorities at the Sub-National Level. *PLoS One*, **11**(5), e0155235, doi:10.1371/journal.pone.0155235.
Bours, D., C. McGinn and P. Pringle, 2014a: *Guidance note 1: twelve reasons why climate change adaptation M&E is challenging*. Available at: https://www.ukcip.org.uk/wp-content/PDFs/MandE-Guidance-Note1.pdf.
Bours, D., C. McGinn and P. Pringle, 2014c: Guidance note 3: Theory of Change approach to climate change adaptation programming. *SEA Change CoP and UKCIP*.
Bours, D., C. McGinn and P. Pringle, 2014d: *Guidance note 2: Selecting indicators for climate change adaptation programming*. Available at: https://ukcip.ouce.ox.ac.uk/wp-content/PDFs/MandE-Guidance-Note2.pdf.
Bouwer, K., 2018: The Unsexy Future of Climate Change Litigation. *Journal of Environmental Law*, **30**(3), 483-506, doi:10.1093/jel/eqy017.
Bouyssou, D. et al., 2006: *Evaluation and Decision Models with Multiple Criteria: Stepping stones for the analyst*. International Series in Operations Research & Management Science, Springer-Verlag, 445 pp.
Bouyssou, D. and others, 2012: Aiding decisions with multiple criteria: essays in honor of Bernard Roy. Springer Science & Business Media.
Bowen, T. et al., 2020: *Adaptive Social Protection: Building Resilience to Shocks*. International Development in Focus, The World Bank, 152 pp. ISBN 978-1-4648-1575-1.
Bowyer, P., S. Bender, D. Rechid and M. Schaller, 2014: Adapting to Climate Change: Methods and Tools for Climate Risk Management. 124.
Boyd, E. et al., 2017: A typology of loss and damage perspectives. *Nature Climate Change*, **7**(10), 723.
Boyd, E. and S. Juhola, 2015: Adaptive climate change governance for urban resilience. *Urban studies*, **52**(7), 1234-1264.
BRACED, 2015: *BRACED Programme Monitoring & Evaluation (M&E) Guidance Notes*. Available at: http://www.braced.org/contentAsset/raw-data/761757df-7b3f-4cc0-9598-a684c40df788/attachmentFile.
Bracking, S. L. N., 2021: Climate finance governance: Fit for purpose? *WIREs Climate Change*, doi:10.1002/WCC.709.
Brady, M. B. and R. Leichenko, 2020: The impacts of coastal erosion on Alaska's North Slope communities: a co-production assessment of land use damages and risks. *Polar Geography*, 1-21, doi:10.1080/1088937x.2020.1755907.
Braito, M. T. et al., 2017: Human-Nature Relationships and Linkages to Environmental Behaviour. *Environmental Values*, **26**(3), 365-389, doi:10.3197/096327117x14913285800706.
Brammer, R. F. and P. Chakrabarti, 2019: Scitech and the Task Force on Climate-Related Financial Disclosures. *Scitech Lawyer, Chicago*, **15**(4), 14-17.
Bremer, S. and S. Meisch, 2017: Co-production in climate change research: reviewing different perspectives. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(6), e482, doi:10.1002/wcc.482.
Bremer, S. et al., 2019: Toward a multi-faceted conception of co-production of climate services. *Climate Services*, **13**, 42-50, doi:10.1016/j.cliser.2019.01.003.
Broberg, M., 2019: Parametric loss and damage insurance schemes as a means to enhance climate change resilience in developing countries. *Climate Policy*, **20**(6), 693-703, doi:10.1080/14693062.2019.1641461.
Broberg, M. and B. M. Romera, 2020: Loss and damage after Paris: more bark than bite? *Climate Policy*, **20**(6), 661-668, doi:10.1080/14693062.2020.1778885.
Brondízio, E. S. et al., 2021: Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature. *Annual Review of Environment and Resources*, doi:10.1146/annurev-environ-012220-012127.
Brooks, N., W. N. Adger and P. M. Kelly, 2005: The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*, **15**, 151-163.
Brooks, N. et al., 2019: *Framing and tracking 21st century climate adaptation: monitoring, evaluation and learning for Paris, the SDGs and beyond. IIED Working Paper*.
Brooks, N. et al., 2011: *Tracking adaptation and measuring development*. IIED Working Paper No. 1, International Institute for Environment and Development (IIED), London, UK.
Brooks, N. et al., 2014: *Tracking Adaptation and Measuring Development: a step-by-step guide*. International Institute for Environment and Development (IIED), London.
Broto, V. C., E. Boyd and J. Ensor, 2015: Participatory urban planning for climate change adaptation in coastal cities: lessons from a pilot experience in Maputo, Mozambique. *Current Opinion in Environmental Sustainability*, **13**, 11-18.
Brousselle, A. and J. M. Buregeya, 2018: Theory-based evaluations: Framing the existence of a new theory in evaluation and the rise of the 5th generation. *Evaluation*, **24**(2), 153-168.

Brouwer, S. and D. Huitema, 2018: Policy entrepreneurs and strategies for change. *Regional Environmental Change*, **18**(5), 1259-1272, doi:10.1007/s10113-017-1139-z.
Brown, C. et al., 2019: Decision Scaling (DS): Decision Support for Climate Change. In: *Decision Making under Deep Uncertainty From Theory to Practice* [Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen and S. W. Popper (eds.)]. Springer International Publishing, Cham, pp. 255-287. ISBN 978-3-030-05251-5 978-3-030-05252-2.
Brown, K. et al., 2018: Turning risk assessment and adaptation policy priorities into meaningful interventions and governance processes. *Philos Trans A Math Phys Eng Sci*, **376**(2121), doi:10.1098/rsta.2017.0303.
Brown, K. et al., 2018a: Turning risk assessment and adaptation policy priorities into meaningful interventions and governance processes. *Philos Trans A Math Phys Eng Sci*, **376**(2121), 20170303, doi:10.1098/rsta.2017.0303.
Brown, K., L. Naylor and T. Quinn, 2017a: Making Space for Proactive Adaptation of Rapidly Changing Coasts: A Windows of Opportunity Approach. *Sustainability*, **9**(8), doi:10.3390/su9081408.
Brugger, J., A. Meadow and A. Horangic, 2016: Lessons from First-Generation Climate Science Integrators. *Bulletin of the American Meteorological Society*, **97**(3), 355-366, doi:10.1175/bams-d-14-00289.1.
Bruno Soares, M. and C. Buontempo, 2019: Challenges to the sustainability of climate services in Europe.
Bruno Soares, M. and S. Dessai, 2016: Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe. *Climatic Change*, **137**(1), 89-103, doi:10.1007/s10584-016-1671-8.
Buchner, B. et al., 2019: *Global Landscape of Climate Finance 2019*. Climate Policy Initiative, London. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2019/11/2019-Global-Landscape-of-Climate-Finance.pdf.
Buggy, L. and K. E. McNamara, 2016: The need to reinterpret "community" for climate change adaptation: a case study of Pele Island, Vanuatu. *Climate and Development*, **8**(3), 270-280.
Buontempo, C. et al., 2020: Fostering the development of climate services through Copernicus Climate Change Service (C3S) for agriculture applications. *Weather and Climate Extremes*, **27**, 100226, doi:10.1016/j.wace.2019.100226.
Burke, M. and K. Emerick, 2016: Adaptation to Climate Change: Evidence from US Agriculture. *American Economic Journal: Economic Policy*, **8**(3), 106-140, doi:10.1257/pol.20130025.
Burstein, F. and C. W. Holsapple, 2008: *Handbook on Decision Support Systems 1: Basic Themes*. International Handbooks on Information Systems, Springer-Verlag, Berlin Heidelberg. ISBN 978-3-540-48712-8 978-3-540-48713-5.
Burthe, S. J. et al., 2016: Do early warning indicators consistently predict nonlinear change in long-term ecological data? *Journal of Applied Ecology*, **53**(3), 666-676, doi:10.1111/1365-2664.12519.
Burton, I. et al., 2012: Managing the risks: international level and integration across scales. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C. B., v. Barros, t. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. pp. 393-435.
Burton, P. and J. Mustelin, 2013: Planning for Climate Change: Is Greater Public Participation the Key to Success? *Urban Policy and Research*, **31**(4), 399-415, doi:10.1080/08111146.2013.778196.
Busch, D. S. et al., 2016: Climate science strategy of the US National Marine Fisheries Service. *Marine Policy*, **74**, 58-67, doi:10.1016/j.marpol.2016.09.001.
Butler, J. R. A. et al., 2016: Priming adaptation pathways through adaptive co-management: Design and evaluation for developing countries. *Climate Risk Management*, **12**(C), 1-16, doi:10.1016/j.crm.2016.01.001.
Buurman, J. and V. Babovic, 2016: Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society*, **35**(2), 137-150.
Cai, H. et al., 2018: A synthesis of disaster resilience measurement methods and indices. *International Journal of Disaster Risk Reduction*, **31**, 844-855.
Calliari, E., O. Serdeczny and L. Vanhala, 2020: Making sense of the politics in the climate change loss & damage debate. *Global Environmental Change*, **64**, 102133.
Calliari, E., Surminski, S. and J. Mysiak 2019: The Politics of (and behind) the UNFCCC's Loss and Damage Mechanism. In: *Loss and Damage from Climate Change. Concepts, Methods and Policy Options* [Mechler, R., Bouwer, L., Schinko, T., Surminski, S., Linnerooth-Bayer, J. (ed.)]. Springer, Cham, pp. 155-178.
Calvello, M. et al., 2015: The Rio de Janeiro early warning system for rainfall-induced landslides: analysis of performance for the years 2010–2013. *International journal of disaster risk reduction*, **12**, 3-15.
Camargo, A. and D. Ojeda, 2017: Ambivalent desires: State formation and dispossession in the face of climate crisis. *Political Geography*, **60**, 57-65.
Camps-Valls, G., D. Tuia, X. X. Zhu and M. Reichstein, 2021: *Deep learning for the Earth Sciences: A comprehensive approach to remote sensing, climate science and geosciences*. John Wiley & Sons. ISBN 1119646146.
CARE, 2010: *Framework of Milestones and Indicators for Community-Based Adaptation*. Available at: https://careclimatechange.org/wp-content/uploads/2015/04/CBA_Framework.pdf.
CARE, 2014: *Participatory Monitoring, Evaluation, Reflection and Learning for Community-based Adaptation: A revised manual for local practitioners*. Available at: http://www.careclimatechange.org/files/2014_PMERL.pdf.
CARE, 2021: *Climate Adaptation Finance – Fact or Fiction?* [Centre, C. C. a. R. I. (ed.)]. Available at: https://careclimatechange.org/climate-adaptation-finance-fact-or-fiction/.

Carlsson, F., C. Gravert, O. Johansson-Stenman and V. Kurz, 2019: *Nudging as an Environmental Policy Instrument*. University of Gothenburg, Department of Economics. Available at: https://EconPapers.repec.org/RePEc:hhs:gunwpe:0756.
Carney, M., 2019: Fifty Shade of Green: The world needs a new, sustainable financial system to stop runaway climate change. Internation Monetary Fund, 12-15 pp.
Carr, E. R. and S. N. Onzere, 2018: Really effective (for 15% of the men): Lessons in understanding and addressing user needs in climate services from Mali. *Climate Risk Management*, **22**, 82-95, doi:10.1016/j.crm.2017.03.002.
Carter, L., 2019: Traditional Ecological Knowledge in Climate Change. In: *Indigenous Pacific Approaches to Climate Change*, pp. 25-38. ISBN 978-3-319-96438-6 978-3-319-96439-3.
Carter, L., 2020: *The Ecosystem of Private Investment in Climate Action*. Invest4Climate Knowledge Series, United Nations Development Programme, New York, USA.
Carter, N. A. et al., 2019a: Lessons Learned through Research Partnership and Capacity Enhancement in Inuit Nunangat. *Arctic*, **72**(4), 381-403, doi:10.14430/arctic69507.
Carter, S. et al., 2019b: *Co-production of African weather and climate services*. Africa, W., A. Climate Information Services for and f. Future Climate. Available at: https://futureclimateafrica.org/coproduction-manual.
Carty, T., J. Kowalzig and B. Zagema, 2020: *Climate Finance Shadow Report 2020: Assessing progress towards the $100 billion commitment*. Oxfam International, Oxford. ISBN 9781787486621.
Cash, D. W. et al., 2003: Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences - PNAS*, **100**(14), 8086-8091, doi:10.1073/pnas.1231332100.
Catenacci, M. and C. Giupponi, 2013: Integrated assessment of sea-level rise adaptation strategies using a Bayesian decision network approach. *Environmental Modelling & Software*, **44**, 87-100, doi:10.1016/j.envsoft.2012.10.010.
Cattino, M. and D. Reckien, in press: Does public participation lead to more ambitious and transformative local climate change planning? *Current Opinion in Environmental Sustainability*.
Caurla, S. and A. Lobianco, 2020: Estimating climate service value in forestry: The case of climate information on drought for maritime pine in Southwestern France. *Climate Services*, **17**, 100106, doi:10.1016/j.cliser.2019.100106.
CBI, 2019: *Climate Resilience Principles: A framework for assessing climate resilience investments*. Initiative, C. B. Available at: https://www.climatebonds.net/files/page/files/climate-resilience-principles-climate-bonds-initiative-20190917-.pdf.
CBI, 2020: *Green Bonds Global State of the Market 2019*. Initiative, C. B. Available at: https://www.climatebonds.net/files/reports/cbi_sotm_2019_vol1_04d.pdf.
Ceccato, P. et al., 2018: Data and tools to integrate climate and environmental information into public health. *Infect Dis Poverty*, **7**(1), 126, doi:10.1186/s40249-018-0501-9.
Challinor, A. J., W. N. Adger and T. G. Benton, 2017: Climate risks across borders and scales. *Nature Climate Change*, **7**(9), 621-623.
Challinor, A. J. et al., 2018: Transmission of climate risks across sectors and borders. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2121), 20170301, doi:10.1098/rsta.2017.0301.
Chambwera, M. et al., 2014: Economics of Adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977. ISBN 9781107058071.
Chan, S. et al., 2015: Reinvigorating international climate policy: A comprehensive framework for effective nonstate action. *Global Policy*, **6**(4), 466-473.
Chandra, A. et al., 2017: Gendered vulnerabilities of smallholder farmers to climate change in conflict-prone areas: A case study from Mindanao, Philippines. *Journal of Rural Studies*, **50**, 45-59.
Chantarat, S., A. G. Mude, C. B. Barrett and M. R. Carter, 2013: Designing Index-Based Livestock Insurance for Managing Asset Risk in Northern Kenya. *Journal of Risk and Insurance*, **80**(1), 205-237, doi:https://doi.org/10.1111/j.1539-6975.2012.01463.x.
Chanza, N. and A. de Wit, 2016: Enhancing climate governance through indigenous knowledge: Case in sustainability science. *South African journal of science*, **112**(Number 3/4), 35-37, doi:10.17159/sajs.2016/20140286.
Chapagain, D., F. Baarsch, M. Schaeffer and S. D'Haen, 2020: Climate change adaptation costs in developing countries: insights from existing estimates. *Climate and Development*, 1-9, doi:10.1080/17565529.2020.1711698.
Chattopadhyay, A., E. Nabizadeh and P. Hassanzadeh, 2020: Analog Forecasting of Extreme-Causing Weather Patterns Using Deep Learning. *Journal of Advances in Modeling Earth Systems*, **12**(2), doi:10.1029/2019MS001958.
Chen, C. et al., 2016: Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. *Environmental Science & Policy*, **66**, 403-419.
Chen, S. and J. I. Uitto, 2014: Small grants, big impacts: aggregation challenges. [Uitto, J. I. (ed.)]. Routledge, pp. 105-122.
Cheong, S.-M., C. Bautista and L. Ortiz, 2020a: Sensing Physiological Change and Mental Stress in Older Adults From Hot Weather. *IEEE Access*, **8**, 70171-70181, doi:10.1109/access.2020.2982153.

Cheong, S.-M. et al. (eds.), AI for Climate Change Adaptation. 2020 Annual Meeting, Washington State Convention Center, American Association for the Advancement of Science.
Chhetri, R. P. et al., 2020: *CFAS Policy Brief: Options for the post-2025 climate finance goal*. Climate Finance Advisory, S., 20 pp. Available at: https://cfas.info/en/publication/options-post-2025-climate-finance-goal (accessed 2021/08/23).
Chiang, Y.-C., 2018: Exploring community risk perceptions of climate change-A case study of a flood-prone urban area of Taiwan. *Cities*, **74**, 42-51.
Chimani, B. et al., 2020: Compilation of a guideline providing comprehensive information on freely available climate change data and facilitating their efficient retrieval. *Climate Services*, **19**, 100179, doi:10.1016/j.cliser.2020.100179.
Chu, E., I. Anguelovski and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**(A), 378-387, doi:10.1016/j.cities.2016.10.016.
Chu, E. and K. Michael, 2018: Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. *Environment and Urbanization*, **31**(1), 139-156, doi:10.1177/0956247818814449.
Chu, E. K., 2018: Urban climate adaptation and the reshaping of state–society relations: The politics of community knowledge and mobilisation in Indore, India. *Urban Studies*, **55**(8), 1766-1782.
CIF, 2020: *Evaluation and Learning Special Initiative: FY20 Annual Report and FY21 Work Plan. Document Joint CTF-SCF/TFC.22/5*.
Ciplet, D., J. T. Roberts and M. Khan, 2013: The Politics of International Climate Adaptation Funding: Justice and Divisions in the Greenhouse. *Global Environmental Politics*, **13**(1), 49-68, doi:10.1162/GLEP_a_00153.
Ciullo, A. et al., 2020: Efficient or fair? Operationalizing ethical principles in flood risk management: A case study on the Dutch-German Rhine. *Risk analysis*, **40**(9), 1844-1862.
Claeys, P. and D. Delgado Pugley, 2017: Peasant and indigenous transnational social movements engaging with climate justice. *Canadian Journal of Development Studies*, **38**(3), 325-340, doi:10.1080/02255189.2016.1235018.
Clare, A., S. Fankhauser and C. Gennaioli, 2017b: The national and international drivers of climate change legislation. In: *Trends in Climate Change Legislation* [Averchenkova, A., S. Fankhauser and M. Nachmany (eds.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 19-36. ISBN 9781786435781.
Clare, A., R. Graber, L. Jones and D. Conway, 2017a: Subjective measures of climate resilience: What is the added value for policy and programming? *Global Environmental Change*, **46**(9), 17-22.
Clarke, D., A. de Janvry, E. Sadoulet and E. Skoufias (eds.), Disaster Risk Financing and Insurance: Issues and results. Report on a workshop held at the Ferdi on June.
Clarke, D. and O. Mahul, 2011: Disaster risk financing and contingent credit: a dynamic analysis. *World Bank Policy Research Working Paper*,(5693).
Clarke, M. and T. Hussain, 2018: Climate change litigation: A new class of action. White & Case, 8 pp.
Clarkson, G. et al., 2019: An investigation of the effects of PICSA on smallholder farmers' decision-making and livelihoods when implemented at large scale – The case of Northern Ghana. *Climate Services*, **14**, 1-14, doi:10.1016/j.cliser.2019.02.002.
Cliffe, N. et al., 2016: Developing the capacity of farmers to understand and apply seasonal climate forecasts through collaborative learning processes. *Journal of Agricultural Education and Extension*, **22**(4), 311-325, doi:10.1080/1389224X.2016.1154473.
Codjoe, S. N. et al., 2020: Impact of extreme weather conditions on healthcare provision in urban Ghana. *Social Science & Medicine*, **258**, 113072.
Coirolo, C., S. Commins, I. Haque and G. Pierce, 2013: Climate Change and Social Protection in Bangladesh: Are Existing Programmes Able to Address the Impacts of Climate Change? *Development Policy Review*, **31**(s2), o74-o90, doi:10.1111/dpr.12040.
Coleman, J. C. and M. Sandhu, 1965: Intelligence level and background factors in learning disorders. *Psychol Rep*, **17**(1), 69-70, doi:10.2466/pr0.1965.17.1.69.
Colenbrander, S., D. Dodman and D. Mitlin, 2018: Using climate finance to advance climate justice: the politics and practice of channelling resources to the local level. *Climate Policy*, **18**(7), 902-915, doi:10.1080/14693062.2017.1388212.
Collins, M. et al., 2019: Extremes, Abrupt Changes and Managing Risks. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Colloff, M. J. et al., 2017: An integrative research framework for enabling transformative adaptation. *Environmental Science & Policy*, **68**(C), 87-96, doi:10.1016/j.envsci.2016.11.007.
Committee on Climate Change, 2017: *Adaptation Reporting Power: second round review*. Available at: https://d423d1558e1d71897434.b-cdn.net/wp-content/uploads/2017/03/Adaptation-Reporting-Power-Second-round-review-Committee-on-Climate-Change-March-2017.pdf.
Connolly, J. J. T. and I. Anguelovski, 2021: Three Histories of Greening and Whiteness in American Cities. *Frontiers in Ecology and Evolution*, **9**(101), doi:10.3389/fevo.2021.621783.

Conservation Law Foundation v. Exxon Mobil Corporation, 2021. Available at: http://climatecasechart.com/climate-change-litigation/wp-content/uploads/sites/16/case-documents/2021/20210701_docket-20-1456_opinion.pdf.
Consolidated Edison Co., C. C. V. S., 2019. Available at: https://www.coned.com/-/media/files/coned/documents/our-energy-future/our-energy-projects/climate-change-resiliency-plan/climate-change-vulnerability-study.pdf.
Conway, D. et al., 2019: The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions. *Nature Climate Change*, **9**(7), 503-511.
Cooper, R., 2020: *Risk of capital flight due to a better understanding of climate change risks*. K4D Helpdesk, **Report 727**, Institute of Development Studies, Brighton, UK. Available at: https://gsdrc.org/publications/risk-of-capital-flight-due-to-a-better-uunderstanding-of-climate-change/.
Cornell, S. et al., 2013: Opening up knowledge systems for better responses to global environmental change. *Environmental Science and Policy*, **28**, 60-70, doi:10.1016/j.envsci.2012.11.008.
Corner, A., E. Markowitz and N. Pidgeon, 2014: Public engagement with climate change: the role of human values. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(3), 411-422, doi:10.1002/wcc.269.
Cortekar, J., M. Themessl and K. Lamich, 2020: Systematic analysis of EU-based climate service providers. *Climate Services*, **17**, 100125, doi:10.1016/j.cliser.2019.100125.
Cosens, B. A. et al., 2017: The role of law in adaptive governance. *Ecology and society: a journal of integrative science for resilience and sustainability*, **22**(1), 1.
Coughlan de Perez, E. and S. J. Mason, 2014: Climate information for humanitarian agencies: some basic principles. *Earth Perspectives*, **1**(1), 1-6, doi:10.1186/2194-6434-1-11.
Coughlan de Perez, E. et al., 2019: From rain to famine: assessing the utility of rainfall observations and seasonal forecasts to anticipate food insecurity in East Africa. *Food Security*, **11**(1), 57-68, doi:10.1007/s12571-018-00885-9.
Coughlan de Perez, E. et al., 2015: Forecast-based financing: an approach for catalyzing humanitarian action based on extreme weather and climate forecasts. *Natural Hazards and Earth System Sciences*, **15**(4), 895-904, doi:10.5194/nhess-15-895-2015.
CPI, 2019: *Global Landscape of Climate Finance 2019*. Initiative, C. P. Available at: https://climatepolicyinitiative.org/wp-content/uploads/2019/11/2019-Global-Landscape-of-Climate-Finance.pdf.
CPI, 2020: *Updated View of the Global Landscape of Climate Finance 2019*. Rob Macquarie, Baysa Naran, Paul Rosane, Matthew Solomon, Cooper Wetherbee, Climate Policy, I., London. Available at: https://www.climatepolicyinitiative.org/publication/updated-view-on-the-global-landscape-of-climate-finance-2019 (accessed 2021/06/26).
Craft, B. and S. Fisher, 2015: *National experiences can inform a global goal for climate change adaptation*. IIED Briefing, International Institute for Environment and Development (IIED), London.
Craft, B. and S. Fisher, 2018: Measuring the adaptation goal in the global stocktake of the Paris Agreement. *Climate Policy*, **18**(9), 1203-1209, doi:10.1080/14693062.2018.1485546.
Craig, R. K. (ed.), 'Stationarity is Dead' - Long Live Transformation: Five Principles for Climate Change Adaptation Law.
Craig, R. K. et al., 2017: Balancing stability and flexibility in adaptive governance: an analysis of tools available in US environmental law. *Ecology and society: a journal of integrative science for resilience and sustainability*, **22**(2), 1.
Crain, C. M., K. Kroeker and B. S. Halpern, 2008: Interactive and cumulative effects of multiple human stressors in marine systems. *Ecol Lett*, **11**(12), 1304-1315, doi:10.1111/j.1461-0248.2008.01253.x.
Crane-Droesch, A., 2018: Machine learning methods for crop yield prediction and climate change impact assessment in agriculture. *Environmental Research Letters*, **13**(11), 114003, doi:10.1088/1748-9326/aae159.
Crawley, H. and D. Skleparis, 2018: Refugees, migrants, neither, both: categorical fetishism and the politics of bounding in Europe's 'migration crisis'. *Journal of Ethnic and Migration Studies*, **44**(1), 48-64.
Cremades, R. et al., 2019: Ten principles to integrate the water-energy-land nexus with climate services for co-producing local and regional integrated assessments. *Sci Total Environ*, **693**, 133662, doi:10.1016/j.scitotenv.2019.133662.
Creutzig, F. et al., 2018: Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, **8**(4), 260-263, doi:10.1038/s41558-018-0121-1.
CSIRO, 2018: *Climate Compass: A climate risk management framework for Commonwealth agencies*. CSIRO, Australia.
Cuaton, G. P. and Y. Su, 2020: Local-indigenous knowledge on disaster risk reduction: Insights from the Mamanwa indigenous peoples in Basey, Samar after Typhoon Haiyan in the Philippines. *International Journal of Disaster Risk Reduction*, **48**, 101596, doi:10.1016/j.ijdrr.2020.101596.
Cuevas, S. C., 2016: The interconnected nature of the challenges in mainstreaming climate change adaptation: evidence from local land use planning. *Climatic Change*, **136**(3-4), 661-676, doi:10.1007/s10584-016-1625-1.
Cummins, J. D. and O. Mahul, 2009: *Catastrophe risk financing in developing countries: principles for public intervention*. World Bank Publications. ISBN 0821377361.
Cvitanovic, C. et al., 2015: Improving knowledge exchange among scientists and decision-makers to facilitate the adaptive governance of marine resources: A review of knowledge and research needs. *Ocean & Coastal Management*, **112**, 25-35, doi:10.1016/j.ocecoaman.2015.05.002.

Cvitanovic, C. et al., 2019: Maximising the benefits of participatory climate adaptation research by understanding and managing the associated challenges and risks. *Environmental Science & Policy*, **94**, 20-31, doi:10.1016/j.envsci.2018.12.028.
D'Alisa, G. and G. A. Kallis, 2016: Political ecology of maladaptation: Insights from a Gramscian theory of the State. *Global Environmental Change*, **38**, 230-242.
Dalkir, K., 2005: *Knowledge Management in Theory and Practice*. Elsevier Butterworth–Heinemann, Oxford. ISBN 075067864X.
Daly, M. and L. Dilling, 2019: The politics of "usable" knowledge: examining the development of climate services in Tanzania. *Climatic Change*, **157**(1), 61-80, doi:10.1007/s10584-019-02510-w.
Daniels, E. et al., 2020: Refocusing the climate services lens: Introducing a framework for co-designing "transdisciplinary knowledge integration processes" to build climate resilience. *Climate services*, **19**, 100181, doi:10.1016/j.cliser.2020.100181.
Dannenberg, A. L., H. Frumkin, J. J. Hess and K. L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: Public health implications. *Climatic Change*, **153**(1), 1-14.
Daron, J., 2015: Challenges in using a Robust Decision Making approach to guide climate change adaptation in South Africa. *Climatic Change*, **132**(3), 459-473.
Daron, J. et al., 2021: Integrating seasonal climate forecasts into adaptive social protection in the Sahel. *Climate and development*, **13**(6), 543-550.
Das, S., 2019: Evaluating climate change adaptation through evacuation decisions: a case study of cyclone management in India. *Climatic Change*, **152**, 291-305.
David-Chavez, D. M. and M. C. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environmental research letters*, **13**(12), 123005, doi:10.1088/1748-9326/aaf300.
Davies, K. et al., 2018: Navigating collaborative networks and cumulative effects for Sustainable Seas. *Environmental science & policy*, **83**, 22-32, doi:10.1016/j.envsci.2018.01.013.
Davis, L. S., 2010: Institutional flexibility and economic growth. *Journal of Comparative Economics*, **38**(3), 306-320.
de Bruin, K. et al., 2009: Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic change*, **95**(1-2), 23-45, doi:10.1007/s10584-009-9576-4.
de Coninck, H. et al., 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
De Gregorio Hurtado, S. et al., 2015: Understanding How and Why Cities Engage with Climate Policy: An Analysis of Local Climate Action in Spain and Italy. *TeMA - Journal of Land Use, Mobility and Environment*, 23-46, doi:10.6092/1970-9870/3649.
de Koning, K. and T. Filatova, 2020: Repetitive floods intensify outmigration and climate gentrification in coastal cities. *Environmental Research Letters*, **15**(3), 034008, doi:10.1088/1748-9326/ab6668.
de Koning, K., T. Filatova, A. Need and O. Bin, 2019: Avoiding or mitigating flooding: Bottom-up drivers of urban resilience to climate change in the USA. *Global Environmental Change*, **59**, 101981, doi:https://doi.org/10.1016/j.gloenvcha.2019.101981.
de Ruig, L. T. et al., 2019: An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles. *The Science of the total environment*, **678**, 647-659, doi:10.1016/j.scitotenv.2019.04.308.
de Sherbinin, A. and et al., 2019: Climate vulnerability mapping: A systematic review and future prospects. *Wiley Interdisciplinary Reviews Climate Change*, **10**(5), e600-e600.
De Smet, Y. and K. Lidouh (eds.), An introduction to multicriteria decision aid: The PROMETHEE and GAIA methods.
DeCaro, D. A. et al., 2017: Legal and institutional foundations of adaptive environmental governance. *Ecology and Society*, **22**(1), 32, doi:https://doi.org/10.5751/ES-09036-220132.
Denton, F. et al., 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.
Desai, B. et al., 2021: Addressing the human cost in a changing climate. *Science*, **372**(6548), 1284-1287.
Deubelli, T. and K. Venkateswaran, 2021: Transforming resilience-building today for sustainable futures tomorrow: Insights from the forthcoming book "Transformation and Disaster Resilience". *IIASA Working Paper*.
Dewi, N., K. Kusnandar and E. Rahayu, 2018: Risk mitigation of climate change impacts on rice farming through crop insurance: an analysis of farmer's willingness to participate (a case study in Karawang Regency, Indonesia). *IOP Conference Series: Earth and Environmental Science*, **200**, 012059, doi:10.1088/1755-1315/200/1/012059.

DFID, WEF, WTW and GCA (eds.), Coalition for Climate Resilient Investment (CCRI). UN Climate Action Summit Call to Action: Resilence & Adptation Initiatives, Global Resilience Partnership.
Dias, L., A. Morton and J. Quigley, 2018: Elicitation of Preferences and Uncertainty: Processes and Procedures. Springer.
Dibley, A., T. Wetzer and C. Hepburn, 2021: National COVID debts: climate change imperils countries' ability to repay. *Nature*, **592**, 184-187.
Dickey-Collas, M., 2014: Why the complex nature of integrated ecosystem assessments requires a flexible and adaptive approach. *ICES Journal of Marine Science*, **71**(5), 1174-1182, doi:10.1093/icesjms/fsu027.
Dilling, L. et al., 2015: The dynamics of vulnerability: why adapting to climate variability will not always prepare us for climate change. *Wiley Interdisciplinary Reviews Climate Change*, **6**(4), 413-425.
Dilling, L. et al., 2019a: Is adaptation success a flawed concept? *Nature Climate Change*, **9**, 572-574.
Dinshaw, A. et al., 2014: *Monitoring and Evaluation of Climate Change Adaptation: Methodological Approaches*. OECD Environment Working Papers, OECD Publishing. ISBN 1997-0900.
Djalante, R., C. Holley and F. Thomalla, 2011: Adaptive governance and managing resilience to natural hazards. *International Journal of Disaster Risk Science*, **2**(4), 1-14, doi:10.1007/s13753-011-0015-6.
Djenontin, I. N. S. and A. M. Meadow, 2018: The art of co-production of knowledge in environmental sciences and management: lessons from international practice. *Environmental management (New York)*, **61**(6), 885-903, doi:10.1007/s00267-018-1028-3.
Donatti, C. et al., 2020: Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. *Climatic Change*, **158**, 413-433.
Donatti, C. et al., 2018: *Guidelines for designing, implementing and monitoring ecosystem-based adaptation interventions*. Conservation International.
Donner, S. D., M. Kandlikar and S. Webber, 2016: Measuring and tracking the flow of climate change adaptation aid to the developing world. *Environmental Research Letters*, **11**(5), 054006.
Donner, S. D. and S. Webber, 2014: Obstacles to climate change adaptation decisions: a case study of sea-level rise and coastal protection measures in Kiribati. *Sustainability Science*, **9**(3), 331-345, doi:10.1007/s11625-014-0242-z.
Doshi, D. and M. Garschagen, 2020: Understanding Adaptation Finance Allocation: Which Factors Enable or Constrain Vulnerable Countries to Access Funding? *Sustainability*, **12**(10), doi:https://doi.org/10.3390/su12104308.
Doukas, H. and A. Nikas, 2020: Decision support models in climate policy. *European Journal of Operational Research*, **280**(1), 1-24, doi:10.1016/j.ejor.2019.01.017.
Douville, H. et al., 2021: *Water Cycle Changes*. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
Droesch, A. C. et al., 2008: *A Guide to the Vulnerability Reduction Assessment*. UNDP Working Paper, United Nations Development Programme, Community-Based Adaptation Programme.
Dupre, S., T. Posey, T. Wang and T. Jamison, 2018: *Shooting for the moon in a hot air balloon? Measuring how green bonds contribute to scaling up investments in green projects* [Initiative, D. I. (ed.)].
Dupuis, J. and R. Biesbroek, 2013: Comparing apples and oranges: The dependent variable problem in comparing and evaluating climate change adaptation policies. *Global Environmental Change*, **23**(6), 1476-1487, doi:10.1016/j.gloenvcha.2013.07.022.
Durbach, I. and T. J. Stewart, 2020a: Probability and Beyond: Including Uncertainties in Decision Analysis. In: *Behavioral Operational Research*. Springer International Publishing, pp. 75-91. ISBN 978-3-030-25404-9.
Durbach, I. N., 2014: Outranking under uncertainty using scenarios. *European journal of operational research*, **232**(1), 98-108, doi:10.1016/j.ejor.2013.06.041.
Durbach, I. N. and T. J. Stewart, 2020b: Probability and Beyond: Including Uncertainties in Decision Analysis. Springer, 75-91 pp.
Eakin, H., A. Winkels and J. Sendzimir, 2009: Nested vulnerability: exploring cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. *Environmental Science & Policy*, **12**, 398-412.
Ebi, K. L. et al., 2018: Monitoring and evaluation indicators for climate change-related health impacts, risks, adaptation, and resilience. *International Journal of Environmental Research and Public Health*, **15**(9), doi:10.3390/ijerph15091943.
Ebi, K. L., J. J. Hess and T. B. Isaksen, 2016: Using uncertain climate and development information in health adaptation planning. *Current environmental health reports*, **3**(1), 99-105.
Ebi, K. L. and E. V. Prats, 2015: Health in National Climate Change Adaptation Planning. *Ann Glob Health*, **81**(3), 418-426, doi:10.1016/j.aogh.2015.07.001.
EBRD, 2019: *Framework for Environmental Sustainability Bonds*. Development, E. B. f. R. a.
Eccles, R. G. and M. P. Krzus, 2018: Why companies should report financial risks from climate change. *MIT Sloan Management Review*, **59**(3).
Eckersley, R., 2015: The common but differentiated responsibilities of states to assist and receive 'climate refugees'. *European Journal of Political Theory*, **14**(4), 481-500.
Eckstein, D., M. Winges, V. Künzel and L. Schäfer, 2019: *Global Climate Risk Index 2020: Who Suffers Most from Extreme Weather Events? Wether-Related Loss Events in 2018 and 1999 to 2018*. Germanwatch Nord-Süd Initiative eV. ISBN 3943704777.

EEA, National monitoring, reporting and evaluation of climate change adaptation in Europe. Available at: https://www.eea.europa.eu/publications/national-monitoring-reporting-and-evaluation.
EEA, 2018: *National climate change vulnerability and risk assessments in Europe*. Available at: https://www.eea.europa.eu/publications/national-climate-change-vulnerability-2018.
EEA, 2020: *Monitoring and evaluation of national adaptation policies throughout the policy cycle*. Available at: https://www.eea.europa.eu/publications/national-adaptation-policies.
Egli, F. and A. Stünzi, 2019: A dynamic climate finance allocation mechanism reflecting the Paris Agreement. *Environmental Research Letters*, **14**(11), 114024, doi:10.1088/1748-9326/ab443b.
Eguiluz, V. M., J. Fernandez-Gracia, X. Irigoien and C. M. Duarte, 2016: A quantitative assessment of Arctic shipping in 2010-2014. *Sci Rep*, **6**, 30682, doi:10.1038/srep30682.
El-Zein, A. and F. N. Tonmoy, 2015: Assessment of vulnerability to climate change using a multi-criteria outranking approach with application to heat stress in Sydney, 207-217 pp.
Ellis, N. R. and P. Tschakert, 2019: Triple-wins as pathways to transformation? A critical review. *Geoforum*, **103**, 167-170, doi:10.1016/j.geoforum.2018.12.006.
Elmi, O. H. and D. Minja, 2019: Effects of hunger safety net program on livelihood improvement in Wajir County, Kenya. *International Academic Journal of Law and Society*, **1**(2), 435-449.
Elsawah, S. et al., 2015: A methodology for eliciting, representing, and analysing stakeholder knowledge for decision making on complex socio-ecological systems: from cognitive maps to agent-based models. *Journal of environmental management*, **151**, 500-516.
England, M. I. et al., 2018: Climate change adaptation and cross-sectoral policy coherence in southern Africa. *Regional Environmental Change*, **18**(7), 2059-2071, doi:10.1007/s10113-018-1283-0.
Engler, J. O., D. J. Abson and H. von Wehrden, 2019: Navigating cognition biases in the search of sustainability. *Ambio*, **48**(6), 605-618, doi:10.1007/s13280-018-1100-5.
Eriksen, S. et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383.
Eriksen, S. H. and P. M. Kelly, 2007: Developing credible vulnerability indicators for climate adaptation policy assessment. *Mitigation and Adaptation Strategies for Global Change*, **12**, 495-524.
Eriksen, S. H., A. J. Nightingale and H. Eakin, 2015: Reframing adaptation: The political nature of climate change adaptation. *Global Environmental Change*, **35**, 523-533.
ERM and CBEY, 2018: *Investors Push the Pace of Climate Risk Financial Disclosures* [Cort, T. and J. Stacey (eds.)]. Environmental Resources Management and Yale Center for Business and the Environment.
Ernst, K. M. and B. L. Preston, 2017: Adaptation opportunities and constraints in coupled systems: Evidence from the U.S. energy-water nexus. *Environmental Science & Policy*, **70**, 38-45, doi:10.1016/j.envsci.2017.01.001.
Escarcha, J. F., J. A. Lassa, E. P. Palacpac and K. K. Zander, 2020: Livelihoods transformation and climate change adaptation: The case of smallholder water buffalo farmers in the Philippines. *Environmental Development*, **33**, 100468.
Esteban, M. et al., 2017: Awareness of coastal floods in impoverished subsiding coastal communities in Jakarta: Tsunamis, typhoon storm surges and dyke-induced tsunamis. *International Journal of Disaster Risk Reduction*, **23**, 70-79, doi:https://doi.org/10.1016/j.ijdrr.2017.04.007.
Esteve, P., C. Varela-Ortega and T. E. Downing, 2018: A stakeholder-based assessment of barriers to climate change adaptation in a water-scarce basin in Spain. *Regional environmental change*, **18**(8), 2505-2517.
Estrin, D., 2016: *Limiting Dangerous Climate Change: The Critical Role of Citizen Suits and Domestic Courts—Despite the Paris Agreement*. CIGI Papers Series, **No. 101**, Centre for International Governance Innovation, Ontario, Canda. Available at: https://www.cigionline.org/publications/limiting-dangerous-climate-change-critical-role-citizen-suits-and-domestic-courts.
Etongo, D., V. Amelie, A. Pouponneau and W. L. Filho, 2021: Identifying and Overcoming Barriers to Climate Change Adaptation in the Seychelles. In: *African Handbook of Climate Change Adaptation* [Oguge, N., D. Ayal, L. Adeleke and I. da Silva (eds.)]. Springer International Publishing, Cham, pp. 2675-2692. ISBN 978-3-030-45106-6.
Fagan, M. and C. Huang, 2019: A look at how people around the world view climate change. Pew Research Center.
Fankhauser, S., A. Averchenkova and J. Finnegan, 2018: *10 years of the UK Climate Change Act*. Grantham Research Institute on Climate Change and the Environment. Available at: http://www.lse.ac.uk/GranthamInstitute/publication/10-years-climate-change-act.
Fankhauser, S. and I. Burton, 2011: Spending adaptation money wisely. *Climate Policy*, **11**(3), 1037-1049.
Fankhauser, S., C. Gennaioli and M. Collins, 2014: Domestic dynamics and international influence: What explains the passage of climate change legislation? *Centre for Climate Change Economics and Policy Working Paper*,(156).
FAO, 2017: *Tracking adaptation in agricultural sectors. Climate change adaptation indicators*. Food and Agriculture Organization of the United Nations, Rome.
FAO, 2019a: *Operational guidelines for the design, implementation and harmonization of monitoring and evaluation systems for climate-smart agriculture*. Food and Agriculture Organization of the United Nations, Rome.
FAO, 2019b: *Strengthening monitoring and evaluation for adaptation planning in the agriculture sectors* [Nations, F. a. A. O. o. t. U. (ed.)]. Rome.

Fatorić, S., R. Morén-Alegret, R. J. Niven and G. Tan, 2017: Living with climate change risks: stakeholders' employment and coastal relocation in mediterranean climate regions of Australia and Spain. *Environment Systems Decisions*, **37**(3), 276-288.
Faulkner, L., J. Ayers and S. Huq, 2015: Meaningful measurement for community-based adaptation. *New Directions for Evaluation*, **147**, 89-104.
Fawcett, D., T. Pearce, J. D. Ford and L. Archer, 2017: Operationalizing longitudinal approaches to climate change vulnerability assessment. *Global Environmental Change*, **45**, 79-88.
Feinstein, O., 2012: Evaluation as a learning tool. *New Directions for Evaluation*, **134**, 103-112.
Fekete, J.-D. and R. Primet, 2016: Progressive Analytics: A Computation Paradigm for Exploratory Data Analysis.
Fenton, A. et al., 2014: Debt relief and financing climate change action. *Nature Climate Change*, **4**(8), 650-653.
Fernández-Llamazares, Á. et al., 2017: An empirically tested overlap between indigenous and scientific knowledge of a changing climate in Bolivian Amazonia. *Regional environmental change*, **17**(6), 1673-1685, doi:10.1007/s10113-017-1125-5.
Ferretti, F., A. Saltelli and S. Tarantola, 2016: Trends in sensitivity analysis practice in the last decade. *Science of the total environment*, **568**, 666-670.
Fesenfeld, L. P. and A. Rinscheid, 2021: Emphasizing urgency of climate change is insufficient to increase policy support. *One Earth*, **4**(3), 411-424, doi:10.1016/j.oneear.2021.02.010.
Few, R. et al., 2021: Culture as a mediator of climate change adaptation: Neither static nor unidirectional. *Wiley Interdisciplinary Reviews: Climate Change*, **12**(1), e687.
Field, J. and I. Kelman, 2018: The impact on disaster governance of the intersection of environmental hazards, border conflict and disaster responses in Ladakh, India. *International journal of disaster risk reduction*, **31**, 650-658.
Figueira, J. R., V. Mousseau and B. Roy, 2016: Electre Methods. In: *Multiple Criteria Decision Analysis*. Springer, New York, pp. 155-185. ISBN 9781493930937.
Fischer, A. P., 2019: Characterizing behavioral adaptation to climate change in temperate forests. *Landscape and urban planning*, **188**, 72-79, doi:10.1016/j.landurbplan.2018.09.024.
Fischer, E. M., S. Sippel and R. Knutti, 2021: Increasing probability of record-shattering climate extremes. *Nature Climate Change*, **11**(8), 689-695, doi:10.1038/s41558-021-01092-9.
Fischhoff, B., 2015: The realities of risk-cost-benefit analysis, aaa6516 pp.
Fisher, S. et al., 2015: Evaluating climate change adaptation: Learning from methods in international development. *New Directions for Evaluation*, **147**, 13-35.
Fisichelli NA, S. G., Monahan WB, Ziesler PS, 2015: Protected Area Tourism in a Changing Climate: Will Visitation at US National Parks Warm Up or Overheat? *PLoS ONE*, **10**(6), e0128226.
Fonta, W. M., E. T. Ayuk and T. van Huysen, 2018: Africa and the Green Climate Fund: current challenges and future opportunities. *Climate Policy*, **18**(9), 1210-1225, doi:10.1080/14693062.2018.1459447.
Ford, J. and L. Berrang-Ford, 2016: The 4Cs of adaptation tracking: consistency, comparability, comprehensiveness, coherency. *Mitigation and Adaptation Strategies for Global Change*, **21**, 839-859.
Ford, J. D. et al., 2015: Adaptation tracking for a post-2015 climate agreement. *Nature Climate Change*, **5**(11), 967-969, doi:10.1038/nclimate2744.
Ford, J. D. et al., 2013: How to Track Adaptation to Climate Change: A Typology of Approaches for National-Level Application. *Ecology and Society*, **18**(3), doi:10.5751/es-05732-180340.
Ford, J. D., L. Berrang-Ford and J. Paterson, 2011: A systematic review of observed climate change adaptation in developed nations. *Climatic Change*, **106**(2), 327-336, doi:10.1007/s10584-011-0045-5.
Formetta, G. and L. Feyen, 2019: Empirical evidence of declining global vulnerability to climate-related hazards. *Glob Environ Change*, **57**, 101920, doi:10.1016/j.gloenvcha.2019.05.004.
Forster, P. M. et al., 2020: Current and future global climate impacts resulting from COVID-19. *Nature Climate Change*, **10**(10), 913-919, doi:10.1038/s41558-020-0883-0.
Forsyth, T., 2018: Is resilience to climate change socially inclusive? Investigating theories of change processes in Myanmar. *World Development*, **111**, 13-26, doi:10.1016/j.worlddev.2018.06.023.
Foster, S. et al., 2019: New York City Panel on Climate Change 2019 Report Chapter 6: Community-Based Assessments of Adaptation and Equity. *Ann N Y Acad Sci*, **1439**(1), 126-173, doi:10.1111/nyas.14009.
Fox-Kemper, B. et al., 2021: *Ocean, Cryosphere and Sea Level Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
French, S., 1995: Uncertainty and Imprecision: Modelling and Analysis. *Journal of the Operational Research Society*, **46**(1), 70-79, doi:10.1057/jors.1995.8.
French, S., 2003: Modelling, making inferences and making decisions: The roles of sensitivity analysis. *Top*, **11**(2), 229-251, doi:10.1007/bf02579043.
French, S., 2013: Cynefin, statistics and decision analysis. *Journal of the Operational Research Society*, **64**(4), 547-561, doi:10.1057/jors.2012.23.
French, S. (ed.), 2015: *Cynefin: uncertainty, small worlds and scenarios*, Journal of the Operational Research Society, vol. 66, 1635-1645 pp. ISBN 0160-5682 1476-9360.

French, S., 2020a: Decision support tools for complex decisions under uncertainty, 2nd Edition. 34.
French, S., 2021: *From soft to hard elicitation*. Journal of the Operational Research Society, 1-17 pp. ISBN 0160-5682.
French, S. and N. Argyris, 2018: Decision Analysis and Political Processes, 208-222 pp.
French, S., S. Haywood, D. Oughton and C. Turcanu, 2020: Different types of uncertainty in nuclear emergency management. *Radioprotection*, **55**, S175-S180.
French, S., A. J. Maule and K. N. Papamichail, 2009: Decision Behaviour, Analysis and Support. Cambridge University Press, Cambridge.
Frerks, G., D. Hilhorst and G. Bankoff, 2004: *Mapping vulnerability: disasters, development and people*. London, GB: Earthscan.
Friedman, E., R. Breitzer and W. Solecki, 2019: Communicating extreme event policy windows: Discourses on Hurricane Sandy and policy change in Boston and New York City. *Environmental Science & Policy*, **100**, 55-65, doi:https://doi.org/10.1016/j.envsci.2019.06.006.
Fulton, E. and J. Link, 2014: Modeling Approaches for Marine Ecosystem-Based Management. In: *The Sea, Volume 16: Marine Ecosystem-Based Management* [Fogarty, M. J. and J. J. McCarthy (eds.)]. Harvard University Press, Cambridge, USA, pp.??-??
Fulton, E. A., 2021: Opportunities to improve ecosystem-based fisheries management by recognizing and overcoming path dependency and cognitive bias. *Fish and Fisheries*, **22**(2), 428-448, doi:10.1111/faf.12537.
Fulton, E. A. et al., 2019: Ecosystems say good management pays off. *Fish and Fisheries*, **20**(1), 66-96, doi:10.1111/faf.12324.
Fünfgeld, H., K. Lonsdale and K. Bosomworth, 2018: Beyond the tools: supporting adaptation when organisational resources and capacities are in short supply. *Climatic Change*, **153**(4), 625-641, doi:10.1007/s10584-018-2238-7.
Funk, C. et al., 2019: Recognizing the Famine Early Warning Systems Network: Over 30 Years of Drought Early Warning Science Advances and Partnerships Promoting Global Food Security. *Bulletin of the American Meteorological Society*, **100**(6), 1011-1027, doi:10.1175/bams-d-17-0233.1.
Füssel, H. M., 2010: *Review and Quantitative Analysis of Indices of Climate Change Exposure, Adaptive Capacity, Sensitivity, and Impacts. Background note of the 2010 World Development Report 'Development and Climate Change'*.
Gagnon-Lebrun, F. and S. Agrawala, 2007: Implementing adaptation in developed countries: an analysis of progress and trends. *Climate Policy*, **7**(5), 392-408.
Gajjar, S. P., G. Jain, K. Michael and C. Singh, 2019b: Entrenched Vulnerabilities: Evaluating Climate Justice Across Development and Adaptation Responses in South India. In: *Climate Futures: Reimagining Global Climate Justice*. Zed Books.
Gajjar, S. P., C. Singh and T. Deshpande, 2019a: Tracing back to move ahead: a review of development pathways that constrain adaptation futures. *Climate and Development*, **11**(3), 223-237.
Gall, M., 2015: The suitability of disaster loss databases to measure loss and damage from climate change. *International Journal of Global Warming*, **8**(2), 170-190.
Gallardo-Albarrán, D., 2020: Sanitary infrastructures and the decline of mortality in Germany, 1877–1913†. *The Economic History Review*, **73**(3), 730-757, doi:10.1111/ehr.12942.
Ganguly, G., J. Setzer and V. Heyvaert, 2018: If at First You Don't Succeed: Suing Corporations for Climate Change. *Oxford Journal of Legal Studies*, **38**(4), 841-868, doi:10.1093/ojls/gqy029.
Garcia-Portela, L., 2020: Moral Responsibility for Climate Change Loss and Damage: A Response to the Excusable Ignorance Objection. *Teorema: International Journal of Philosophy*, **1**(39).
Gardiner, E. P., D. D. Herring and J. F. Fox, 2018: The U.S. Climate Resilience Toolkit: evidence of progress. *Climatic Change*, **153**(4), 477-490, doi:10.1007/s10584-018-2216-0.
Garner, G., P. Reed and K. Keller, 2016: Climate risk management requires explicit representation of societal trade-offs. *Climatic Change*, **134**(4), 713-723, doi:10.1007/s10584-016-1607-3.
Garschagen, M. et al., 2021: The consideration of future risk trends in national adaptation planning: conceptual gaps and empirical lessons. *Climate Risk Management*, 100357.
Garschagen, M., G. A. K. Surtiari and M. Harb, 2018b: Is Jakarta's new flood risk reduction strategy transformational? *Sustainability*, **10**(8), 2934.
Gautier, D., B. Locatelli, C. Corniaux and V. Alary, 2016: Global changes, livestock and vulnerability: the social construction of markets as an adaptive strategy. *The Geographical Journal*, **182**(2), 153-164.
GCF (ed.), Approach and scope for providing support to adaptation activities – Addendum I: The GCF's approach to adaptation: analysis and implications for the Fund. Meeting of the Board, Manama, Bahrain, Green Climate Fund.
GCF Independent Evaluation Unit, 2018: *The IEU's independent review of the GCF's results management framework*. Available at: https://ieu.greenclimate.fund/documents/977793/1472147/RMF_GEvalBrief_02_EN.pdf/752e00ad-0817-d74b-0f33-86fa5823625b.
Gee, A., 2020: *Fire in Paradise : an American tragedy*, First edition. ed. [Anguiano, D. (ed.)]. New York. ISBN 978-1-324-00514-8 1-324-00514-9.
Geere, J.-A. L. and P. R. Hunter, 2020: The association of water carriage, water supply and sanitation usage with maternal and child health. A combined analysis of 49 Multiple Indicator Cluster Surveys from 41 countries. *International journal of hygiene and environmental health*, **223**(1), 238-247.

Geiger, N., J. K. Swim, J. Fraser and K. Flinner, 2017: Catalyzing Public Engagement With Climate Change Through Informal Science Learning Centers. *Science Communication*, **39**(2), 221-249, doi:10.1177/1075547017697980.
Gelman, A., 2003: A Bayesian Formulation of Exploratory Data Analysis and Goodness-of-Fit Testing. *International statistical review*, **71**(2), 369-382, doi:10.1111/j.1751-5823.2003.tb00203.x.
Gelman, A. et al., 2013: Bayesian Data Analysis. Chapman and Hall, London.
Gelman, A. and C. Hennig, 2017: Beyond subjective and objective in statistics. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, **180**(4), 967-1033, doi:10.1111/rssa.12276.
Geneletti, D. and L. Zardo, 2016: Ecosystem-based adaptation in cities: An analysis of European urban climate adaptation plans. *Land Use Policy*, **50**, 38-47, doi:https://doi.org/10.1016/j.landusepol.2015.09.003.
Gerlak, A. K. et al., 2020: The Gnat and the Bull Do Climate Outlook Forums Make a Difference? *Bulletin of the American Meteorological Society*, **101**(6), E771-E784, doi:10.1175/bams-d-19-0008.1.
Gerrard, M. B. and K. Fischer, 2012: *The law adaptation to climate change: United States and International aspects*. American Bar Association Natural Resources Law Section. ISBN 161438696X.
Gervásio, H. and L. Simões da Silva, 2012: A probabilistic decision-making approach for the sustainable assessment of infrastructures. *Expert systems with applications*, **39**(8), 7121-7131, doi:10.1016/j.eswa.2012.01.032.
Gewirtzman, J. et al., 2018: Financing loss and damage: reviewing options under the Warsaw International Mechanism. *Climate Policy*, **18**(8), 1076-1086.
Ghebreyesus, T. A. et al., 2010: Using climate information in the health sector. *Field Actions Science Reports*.
Giffin, A. L. et al., 2020: Marine and coastal ecosystem-based adaptation in Asia and Oceania: review of approaches and integration with marine spatial planning. *Pacific Conservation Biology*, **27**(2), 104-117, doi:https://doi.org/10.1071/PC20025.
Gil, J. D. et al., 2018: Tradeoffs in the quest for climate smart agricultural intensification in Mato Grosso, Brazil. *Environmental Research Letters*, **13**(6), 064025.
Gilbuena, R. et al., 2013: Environmental impact assessment using a utility-based recursive evidential reasoning approach for structural flood mitigation measures in Metro Manila, Philippines. *Journal of environmental management*, **131**, 92-102, doi:10.1016/j.jenvman.2013.09.020.
Gim, C., C. A. Miller and P. W. Hirt, 2019: The resilience work of institutions. *Environmental Science and Policy*, **97**, 36-43, doi:10.1016/j.envsci.2019.03.004.
Giordano, R. et al., 2020: Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. *Science of the Total Environment*, **713**, 136552.
Gippsland Coastal Bd. v. South Gippsland Sc & Ors (No2), 2008, **VCAT 1545**.
Girard, C. et al., 2015: Integrating top–down and bottom–up approaches to design global change adaptation at the river basin scale. *Global Environmental Change*, **34**, 132-146, doi:10.1016/j.gloenvcha.2015.07.002.
Giupponi, C., M. E. Borsuk, B. J. M. de Vries and K. Hasselmann, 2013: Innovative approaches to integrated global change modelling. *Environmental Modelling & Software*, **44**, 1-9, doi:https://doi.org/10.1016/j.envsoft.2013.01.013.
Giupponi, C. and A. K. Gain, 2017a: Integrated spatial assessment of the water, energy and food dimensions of the Sustainable Development Goals. *Regional Environmental Change*, **17**(7), 1881-1893, doi:10.1007/s10113-016-0998-z.
GIZ, 2017: *Factsheets of national adaptation monitoring and evaluation systems*. Available at: https://www.adaptationcommunity.net/monitoring-evaluation/national-level-adaptation/examples-of-national-me-systems/.
GIZ, 2020a: *Tool for Assessing Adaptation in the NDCs (TAAN)*. Available at: https://www.adaptationcommunity.net/nap-ndc/tool-assessing-adaptation-ndcs-taan/taan/#.
GIZ and Adelphi, 2014: *The vulnerability sourcebook: concept and guidelines for standardised vulnerability assessments*. Available at: https://www.adaptationcommunity.net/vulnerability-assessment/vulnerability-sourcebook/.
Global Commission on Adaptation, 2019: *Adapt Now : A Global Call for Leadership on Climate Resilience* [Institute, W. R. (ed.)]. Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/32362
Godden, L., 2012: Legal frameworks for local adaptation in Australia: The role of local government in water governance in a climate change era. pp. 325-388.
Golding, N., C. Hewitt and P. Zhang, 2017: Effective engagement for climate services: Methods in practice in China. *Climate Services*, **8**, 72-76, doi:10.1016/j.cliser.2017.11.002.
Golding, N. et al., 2019: Co-development of a seasonal rainfall forecast service: Supporting flood risk management for the Yangtze River basin. *Climate Risk Management*, **23**, 43-49, doi:10.1016/j.crm.2019.01.002.
Goldstein, A., W. R. Turner, J. Gladstone and D. G. Hole, 2019: The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, **9**(1), 18-25, doi:10.1038/s41558-018-0340-5.
Gomez-Echeverri, L., 2018: Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs). *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, **376**(2119), 20160444, doi:10.1098/rsta.2016.0444.
Gonzales, P. and N. Ajami, 2017: Social and Structural Patterns of Drought-Related Water Conservation and Rebound. *Water Resources Research*, **53**(12), 10619-10634, doi:10.1002/2017wr021852.

Goodwin, P. and G. Wright, 2014: *Decision Analysis for Management Judgment 5th ed*. John Wiley & Sons Inc., New York. ISBN 9781118740736.
Göpfert, C., C. Wamsler and W. Lang, 2019: A framework for the joint institutionalization of climate change mitigation and adaptation in city administrations. *Mitigation and Adaptation Strategies for Global Change*, **24**(1), doi:10.1007/s11027-018-9789-9.
Gorddard, R. et al., 2016: Values, rules and knowledge: Adaptation as change in the decision context. In: *Environmental Science & Policy*, pp. 60-69. ISBN 14629011.
Government of Sweden, 2017: Swedish National Strategy for Climate Change Adaptation. Government Proposition 2017/18:163. Available at: https://www.regeringen.se/494483/contentassets/8c1f4fe980ec4fcb8448251acde6bd08/171816300_webb.pdf.
Government of the Commonwealth of Dominica, 2018: Commonwealth of Dominica Climate Resilience Act 16 of 2018. Available at: http://www.dominica.gov.dm/laws/2018/Climate%20Resilience%20Act%202018.pdf.
Govindan, K. and M. B. Jepsen, 2016: ELECTRE: A comprehensive literature review on methodologies and applications. *European journal of operational research*, **250**(1), 1-29, doi:10.1016/j.ejor.2015.07.019.
Grafakos, S. et al., 2019: Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities. *Climatic change*, **154**(1), 87-106.
Graham, A. and C. L. Mitchell, 2016: The role of boundary organizations in climate change adaptation from the perspective of municipal practitioners. *Climatic Change*, **139**(3), 381-395, doi:10.1007/s10584-016-1799-6.
Granberg, M. and L. Glover, 2014: Adaptation and maladaptation in Australian national climate change policy. *Journal of Environmental Policy & Planning*, **16**(2), 147-159.
Grasso, M., 2010a: An ethical approach to climate adaptation finance. *Global Environmental Change*, **20**(1), 74-81, doi:https://doi.org/10.1016/j.gloenvcha.2009.10.006.
Grasso, M., 2010b: Justice in Funding Adaptation under the International Climate Change Regime. *Marco Grasso*, doi:10.1007/978-90-481-3439-7_1.
Gray, S. et al., 2014: Are coastal managers detecting the problem? Assessing stakeholder perception of climate vulnerability using Fuzzy Cognitive Mapping. *Ocean & Coastal Management*, **94**, 74-89.
Greatrex, H. et al., 2015: Scaling up index insurance for smallholder farmers: Recent evidence and insights.
Gregorowski, R., A. Dorgan and C. Hutchings, 2018: *Resilience Measurement-MEL approaches in practice*. Resilience Measurement Evidence & Learning Community of Practice.
Gregory, R. et al., 2012: *Structured Decision Making: A Practical Guide to Environmental Management Choices*. Wiley-Backwell. ISBN 9781444333411.
Grothmann, T., K. Grecksch, M. Winges and B. Siebenhüner, 2013: Assessing institutional capacities to adapt to climate change: integrating psychological dimensions in the Adaptive Capacity Wheel. *Natural Hazards and Earth System Sciences*, **13**(12), 3369-3384.
Grothmann, T. and T. A. Michel, 2021: Participation for building urban climate resilience? Results from four cities in Germany. In: *Building Resilience to Natural Hazards in the Context of Climate Change*. Springer, pp. 173-208.
Grothmann, T. and A. Patt, 2005: Adaptive capacity and human cognition: the process of individual adaptation to climate change. *Global environmental change*, **15**(3), 199-213.
Groutsis, D., D. van den Broek and W. S. Harvey, 2015: Transformations in network governance: The case of migration intermediaries. *Journal of Ethnic and Migration Studies*, **41**(10), 1558-1576.
Groves, D. G., E. Molina-Perez, E. Bloom and J. R. Fischbach, 2019: Robust Decision Making (RDM): Application to Water Planning and Climate Policy. In: *Decision Making under Deep Uncertainty: From Theory to Practice* [Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen and S. W. Popper (eds.)]. Springer International Publishing, Cham, pp. 135-163. ISBN 978-3-030-05252-2.
Grynning, S. et al., 2020: Climate Adaptation in Maintenance Operation and Management of Buildings. *Buildings*, **10**(6), 107.
Guido, Z. et al., 2016: Connecting Climate Information Producers and Users: Boundary Organization, Knowledge Networks, and Information Brokers at Caribbean Climate Outlook Forums. *Weather, climate, and society*, **8**(3), 285-298, doi:10.1175/wcas-d-15-0076.1.
Guillén Bolaños, T., M. Máñez Costa and U. Nehren, 2018: Development of a prioritization tool for climate change adaptation measures in the forestry sector. *Economic tools and methods for the analysis of global change impacts on agriculture and food security*, 165-177.
Gunawan, S. and S. Azarm, 2005: Multi-objective robust optimization using a sensitivity region concept, 50-60 pp.
Gupta, S. et al., 2014: Cross-cutting Investment and Finance Issues. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1207-1246. ISBN 9781107058217.
Gustafson, S., A. J. Cadena and P. Hartman, 2016: Adaptation planning in the Lower Mekong Basin: merging scientific data with local perspective to improve community resilience to climate change. *Climate and Development*, **10**(2), 152-166, doi:10.1080/17565529.2016.1223593.

Gutjahr, W. J. and A. Pichler, 2016: Stochastic multi-objective optimization: a survey on non-scalarizing methods, 475-499 pp.
Guzmán, S., T. Guillén and J. Manda, 2018: *A Review of Domestic Data Sources for Climate Finance Flows in Recipient Countries* [GFLAC, U.-. (ed.)]. Available at: https://www.adaptation-undp.org/resources/reports-and-publications-relevance-country-teams/review-domestic-data-sources-climate.
Guzmán, S. et al., 2017: *Toward Climate Finance Reporting Systems in Latin America* [Adams, K. and D. Falzon (eds.)]. Toward Implementation: The 2017 AdaptationWatch Report. Available at: http://ow.ly/S3Be30gWJ9S.
Ha, S., T. Hale and P. Ogden, 2016: Climate Finance in and between Developing Countries: An Emerging Opportunity to Build On. *Global Policy*, **7**(1), 102-108, doi:10.1111/1758-5899.12293.
Haasnoot, M. et al., 2020a: Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, **20**(2), doi:10.1007/s10113-020-01623-8.
Haasnoot, M. et al., 2020b: Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environmental Research Letters*, **15**(3), 034007, doi:10.1088/1748-9326/ab666c.
Haasnoot, M., J. H. Kwakkel, W. E. Walker and J. ter Maat, 2013: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, **23**(2), 485-498, doi:https://doi.org/10.1016/j.gloenvcha.2012.12.006.
Haasnoot, M., S. van 't Klooster and J. van Alphen, 2018: Designing a monitoring system to detect signals to adapt to uncertain climate change. *Global Environmental Change*, **52**, 273-285, doi:10.1016/j.gloenvcha.2018.08.003.
Haasnoot, M. et al., 2019: Investments under non-stationarity: economic evaluation of adaptation pathways. *Climatic Change*, **161**(3), 451-463, doi:10.1007/s10584-019-02409-6.
Hadka, D., J. Herman, P. Reed and K. Keller, 2015: An open source framework for many-objective robust decision making. *Environmental Modelling & Software*, **74**, 114-129, doi:https://doi.org/10.1016/j.envsoft.2015.07.014.
Haigh, T. et al., 2018: Provision of Climate Services for Agriculture: Public and Private Pathways to Farm Decision-Making. *Bulletin of the American Meteorological Society*, **99**(9), 1781-1790, doi:10.1175/bams-d-17-0253.1.
Hale, T., 2016: "All hands on deck": The Paris agreement and nonstate climate action. *Global Environmental Politics*, **16**(3), 12-22.
Hall, J. W., H. Harvey and L. J. Manning, 2019: Adaptation thresholds and pathways for tidal flood risk management in London. *Climate Risk Management*.
Hall, J. W. et al., 2012: Robust Climate Policies Under Uncertainty: A Comparison of Robust Decision Making and Info-Gap Methods. *Risk Analysis*, **32**(10), 1657-1672, doi:10.1111/j.1539-6924.2012.01802.x.
Hall, M. J. and D. C. Weiss, 2012: Avoiding adaptation apartheid: climate change adaptation and human rights law. *The Yale journal of international law*, **37**(2), 309.
Hall, N., 2017: What is adaptation to climate change? Epistemic ambiguity in the climate finance system. *International Environmental Agreements: Politics, Law and Economics*, **17**(1), 37-53, doi:10.1007/s10784-016-9345-6.
Hallegatte, S., 2009: Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19**(2), 240-247.
Hallegatte, S. et al., 2016: *Shock Waves: Managing the Impacts of Climate Change on Poverty*. Climate Change and Development, The World Bank, 224 pp. ISBN 978-1-4648-0673-5.
Hallegatte, S. et al. (eds.), The Economics (and Obstacles to) aligning Development and Climate Change Adaptation. Global Commission on Adaptation.
Hallegatte, S. and N. L. Engle, 2019: The search for the perfect indicator: Reflections on monitoring and evaluation of resilience for improved climate risk management. *Climate Risk Management*, **23**, 1-6, doi:10.1016/j.crm.2018.12.001.
Hallegatte, S. et al., 2012: Investment Decision Making Under Deep Uncertainty : Application to Climate Change. World Bank, Washington, DC.
Hammill, A. et al., 2014b: *Repository of Adaptation Indicators: real case examples from national Monitoring and Evaluation Systems*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.
Hammill, A. et al., 2014a: *Monitoring and evaluating adaptation at aggregated levels: a comparative analysis of ten systems*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.
Han, H. and S. W. Ahn, 2020: Youth Mobilization to Stop Global Climate Change: Narratives and Impact. *Sustainability*, **12**(10), doi:https://doi.org/10.3390/su12104127.
Hanea, A., G. F. Nane, T. Bedford and others, 2021: Expert Judgement in Risk and Decision Analysis. Springer, Switzerland.
Hanna, R., Y. Xu and D. G. Victor, 2021: After COVID-19, green investment must deliver jobs to get political traction. *Nature*, **582**, 178-180.
Hansen, J. et al., 2018: Strengthening Climate Services for the Food Security Sector. *WMO Bulletin*, **67**(2), 20-26.
Haque, A. N., 2016: Application of Multi-Criteria Analysis on Climate Adaptation Assessment in the Context of Least Developed Countries. *Journal of Multi-Criteria Decision Analysis*, **23**(5-6), 210-224, doi:10.1002/mcda.1571.
Harley, M., L. Horrocks, N. Hodgson and J. Van Minnen, 2008: *Climate change vulnerability and adaptation indicators*.
Harrison, P. A., R. W. Dunford, I. P. Holman and M. D. A. Rounsevell, 2016: Climate change impact modelling needs to include cross-sectoral interactions. *Nature Climate Change*, **6**(9), 885-890, doi:10.1038/nclimate3039.
Harvey, A. et al., 2011: *Provision of research to identify indicators for the Adaptation Sub-Committee*.

Harvey, B., L. Cochrane and M. Van Epp, 2019a: Charting knowledge co-production pathways in climate and development. *Environmental policy and governance*, **29**(2), 107-117, doi:10.1002/eet.1834.
Harvey, B., L. Jones, L. Cochrane and R. Singh, 2019b: The evolving landscape of climate services in sub-Saharan Africa: What roles have NGOs played? *Climatic change*, **157**(1), 81-98, doi:10.1007/s10584-019-02410-z.
Haße, C. and C. Kind, 2018: Updating an existing online adaptation support tool: insights from an evaluation. *Climatic Change*, **153**(4), 559-567, doi:10.1007/s10584-018-2166-6.
Haupt, W., L. Chelleri, S. van Herk and C. Zevenbergen, 2020: City-to-city learning within climate city networks: definition, significance, and challenges from a global perspective. *International Journal of Urban Sustainable Development*, **12**(2), 143-159, doi:10.1080/19463138.2019.1691007.
Hedlund, J., S. Fick, H. Carlsen and M. Benzie, 2018: Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk. *Global Environmental Change*, **52**, 75-85.
Heidrich, O. et al., 2016: National climate policies across Europe and their impacts on cities strategies. *Journal of Environmental Management*, **168**, 36-45, doi:10.1016/j.jenvman.2015.11.043.
Heitz, R. P., 2014: The speed-accuracy tradeoff: History, physiology, methodology, and behavior. *Frontiers in Neuroscience*,(8 JUN), doi:10.3389/fnins.2014.00150.
Helmrich, A. M. and M. V. Chester, 2020: *Reconciling complexity and deep uncertainty in infrastructure design for climate adaptation*. Sustainable and Resilient Infrastructure, 1-17 pp. ISBN 2378-9689 2378-9697.
Hepburn, C. et al., 2020: Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Review of Economic Policy*, **36**(Supplement_1), S359-S381.
Herington, J., 2017: Climate-related insecurity, loss and damage. *Ethics, Policy & Environment*, **20**(2), 184-194.
Hermans, L. M., M. Haasnoot, J. ter Maat and J. H. Kwakkel, 2017: Designing monitoring arrangements for collaborative learning about adaptation pathways. *Environmental Science & Policy*, **69**, 29-38, doi:https://doi.org/10.1016/j.envsci.2016.12.005.
Hermwille, L., A. Siemons, H. Förster and L. Jeffery, 2019: Catalyzing mitigation ambition under the Paris Agreement: elements for an effective Global Stocktake. *Climate Policy*, **19**(8), 988-1001.
Herron, H. et al., 2015: Addressing Climate Change within Disaster Risk Management. *A Practical Guide for IDB Project Preparation Environmental Safeguards Unit TECHNICAL NOTE Nº IDB-TN-806. Washington, DC: Banco Interamericano de Desarrollo*.
Hess, D. J. and A. Maki, 2019: Climate change belief, sustainability education, and political values: Assessing the need for higher-education curriculum reform. *Journal of Cleaner Production*, **228**, 1157-1166, doi:10.1016/j.jclepro.2019.04.291.
Hewitt, C., S. Mason and D. Walland, 2012: The Global Framework for Climate Services. *Nature climate change*, **2**(12), 831-832, doi:10.1038/nclimate1745.
Hewitt, C. D. et al., 2020: The Process and Benefits of Developing Prototype Climate Services—Examples in China. *Journal of Meteorological Research*, **34**(5), 893-903, doi:10.1007/s1335102000426.
Highfield, W. E. and S. D. Brody, 2017: Determining the effects of the FEMA Community Rating System program on flood losses in the United States. *International Journal of Disaster Risk Reduction*, **21**, 396-404, doi:10.1016/j.ijdrr.2017.01.013.
Hildén, M., 2011: The evolution of climate policies: The role of learning and evaluations. *Journal of Cleaner Production*, **19**(16), 1798-1811.
Hilhorst, D., 2003: Responding to disasters. Diversity of bureaucrats, technocrats and local people. *International Journal of Mass Emergencies and Disasters*, **21**(1), 37-56.
Hinkel, J., 2011: 'Indicators of vulnerability and adaptive capacity': towards a clarification of the science–policy interface. *Global Environmental Change*, **21**, 198-208.
Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8**(7), 570-578.
Hino, M., C. B. Field and K. J. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, **7**, 364, doi:10.1038/nclimate3252 https://www.nature.com/articles/nclimate3252#supplementary-information.
Hiwasaki, L., E. Luna, Syamsidik and R. Shaw, 2014: Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. *International Journal of Disaster Risk Reduction*, **10**, 15-27, doi:https://doi.org/10.1016/j.ijdrr.2014.07.007.
HM Government, 2019: *Number of people whose resilience has been improved as a result of ICF* [Compass, C. C. (ed.)]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835527/KPI-4-number-people-resilience-improved1.pdf.
Hochman, Z. et al., 2017: Smallholder farmers managing climate risk in India: 1. Adapting to a variable climate. *Agricultural Systems*, **150**, 54-66, doi:10.1016/j.agsy.2016.10.001.
Hochrainer-Stigler, S., R. Mechler, G. Pflug and K. Williges, 2014: Funding public adaptation to climate-related disasters. Estimates for a global fund. *Global Environmental Change*, **25**, 87-96.
Hock, R. et al., 2019: High Mountain Areas: In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Hofmann, S. Z., 2021: 100 Resilient Cities program and the role of the Sendai framework and disaster risk reduction for resilient cities. *Progress in Disaster Science*, **11**, 100189.
Holland, B., 2017: Procedural justice in local climate adaptation: political capabilities and transformational change. *Environmental Politics*, **26**(3), 391-412.
Hollowed, A. B. et al., 2020: Integrated modeling to evaluate climate change impacts on coupled social-ecological systems in Alaska.
Holmberg, A. and A. Alvinius, 2019: Children's protest in relation to the climate emergency: A qualitative study on a new form of resistance promoting political and social change. *Childhood*, **27**(1), 78-92, doi:10.1177/0907568219879970.
Holsapple, C., M. Sena and W. Wagner, 2019: The perceived success of ERP systems for decision support. *Information technology and management*, **20**(1), 1-7, doi:10.1007/s10799-017-0285-9.
Holsman, K. K. et al., 2019: Towards climate resiliency in fisheries management, 1368-1378 pp.
Holtzman, S., 1989: Intelligent Decision Systems. Addison-Wesley., Reading, MA.
Hornsey, M. J. and K. S. Fielding, 2017: Attitude roots and Jiu Jitsu persuasion: Understanding and overcoming the motivated rejection of science. *The American psychologist*, **72**(5), 459-473, doi:10.1037/a0040437.
Hossain, P., F. Ludwig and R. Leemans, 2018: Adaptation pathways to cope with salinization in south-west coastal region of Bangladesh. *Ecology and Society*, **23**, doi:10.5751/es-10215-230327.
Howarth, C. and I. Monasterolo, 2016: Understanding barriers to decision making in the UK energy-food-water nexus: The added value of interdisciplinary approaches. *Environmental science & policy*, **61**, 53-60, doi:10.1016/j.envsci.2016.03.014.
Howarth, C., S. Morse-Jones, K. Brooks and A. P. Kythreotis, 2018: Co-producing UK climate change adaptation policy: An analysis of the 2012 and 2017 UK Climate Change Risk Assessments. *Environmental science & policy*, **89**, 412-420, doi:10.1016/j.envsci.2018.09.010.
Howell, S. et al., 2001: *Real Options - Evaluating Corporate Investment Opportunities in a Dynamic World*. Financial Times: Prentice Hall.
Hssaisoune, M. et al., 2020: Moroccan Groundwater Resources and Evolution with Global Climate Changes. *Geosciences*, **10**(2), doi:10.3390/geosciences10020081.
Huambachano, M., 2018: Enacting food sovereignty in Aotearoa New Zealand and Peru: revitalizing Indigenous knowledge, food practices and ecological philosophies. *Agroecology and Sustainable Food Systems*, **42**(9), 1003-1028, doi:10.1080/21683565.2018.1468380.
Hudson, P., W. J. W. Botzen and J. C. J. H. Aerts, 2019: Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change. *Global environmental change*, **58**, 101966, doi:10.1016/j.gloenvcha.2019.101966.
Hudson, P., W. W. Botzen, L. Feyen and J. C. Aerts, 2016: Incentivising flood risk adaptation through risk based insurance premiums: trade-offs between affordability and risk reduction. *Ecological Economics*, **125**, 1-13.
Hügel, S. and A. R. Davies, 2020: Public participation, engagement, and climate change adaptation: A review of the research literature. *Wiley Interdisciplinary Reviews: Climate Change*, **11**(4), e645.
Huggel, C., I. Wallimann-Helmer, D. Stone and W. Cramer, 2016: Reconciling justice and attribution research to advance climate policy. *Nature Climate Change*, **6**(10), 901.
Huntingford, C. et al., 2019: Machine learning and artificial intelligence to aid climate change research and preparedness. *Environmental Research Letters*, **14**(12), doi:10.1088/1748-9326/ab4e55.
Hurlbert, M. et al., 2019: Risk management and decision-making in relation to sustainable development. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.
Hyde, K., H. R. Maier and C. Colby, 2003: Incorporating uncertainty in the PROMETHEE MCDA method. *Journal of multi-criteria decision analysis*, **12**(4-5), 245-259, doi:10.1002/mcda.361.
Ianelli, J., K. K. Holsman, A. E. Punt and K. Aydin, 2016: Multi-model inference for incorporating trophic and climate uncertainty into stock assessments. *Deep Sea Research Part II: Topical Studies in Oceanography*, **134**, 379-389, doi:10.1016/j.dsr2.2015.04.002.
ICRC, 2016: *Protracted conflict and humanitarian action: some recent ICRC experiences* [Cross, I. C. o. t. R. (ed.)]. Geneva.
IMF, 2020: *World Economic Outlook October 2020: Executive Summary* [Bank, W. (ed.)]. COVID 19: Debt Service Suspension Initiative, **26**.
INC, 1991: *Vanuatu: Draft annex relating to Article 23 (Insurance) for inclusion in the revised single text on elements relating to mechanisms (A/AC.237/WG.II/Misc.13)* [II, C.-C. o. W. G. (ed.)]. Intergovernmental Negotiating Committee for a Framework Convention on Climate Change, Working Group II.
Insuresilience Global Partnership, 2018: The Insuresilience Global Partnership. InsuResilience Secretariat, Bonn.
Iooss, B. and A. Saltelli, 2017: Introduction to Sensitivity Analysis. In: *Handbook of Uncertainty Quantification* [Ghanem, R., D. Higdon and H. Owhadi (eds.)]. Springer International Publishing.

IPCC, 2012: *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C. B. B. V. S. T. F. Q. D. D. D. E. K. L. M. M. D. M. K. J. P. G. K. and P. M. Midgley (eds.)]. Cambridge.

IPCC, 2014a: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* [Field, C. B. V. R. B. D. J. D. K. J. M. M. D. M. T. E. B. M. C. K. L. E. Y. and L. L. White (eds.)]. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U., Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC, 2018a: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Zhai, P., H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. Masson-Delmotte, V., In press pp. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf.

IPCC, 2018b: *Summary for Policymakers: Global warming of 1.5°C* [V. Masson-Delmotte, P. Z. H. O. P. r. D. R. J. S. P. R. S. A. P. W. M.-O. C. P. a. R. (ed.)]. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, Organization, W. M., Geneva, 32 pp.

IPCC, 2019a: *Annex I: Glossary* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Available at: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf.

IPCC, 2019b: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R. (ed.)]. In press pp.

IPCC, 2019c: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O. (ed.)]. In press pp.

IPCC, 2019e-a: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O. (ed.)]. In press pp.

IPCC, 2019e-b: *Summary for Policymakers: Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D. C. R. V. M.-D. P. Z. M. T. E. P. K. M. M. N. A. O. J. P. B. R. (ed.)]. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, press, I.

IPCC, 2021: *Summary for Policymakers* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Z. (eds.) (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U.

Isakson, S. R., 2015: Derivatives for Development? Small-Farmer Vulnerability and the Financialization of Climate Risk Management. *Journal of Agrarian Change*, **15**(4), 569-580, doi:10.1111/joac.12124.

Iturbide, M. et al., 2019: The R-based climate4R open framework for reproducible climate data access and post-processing. *Environmental modelling & software : with environment data news*, **111**, 42-54, doi:10.1016/j.envsoft.2018.09.009.

Iyahen, E. and J. Syroka, 2018: Managing Risks from Climate Change on the African Continent: The African Risk Capacity (ARC) as an Innovative Risk Financing Mechanism. In: *Resilience*. Elsevier, pp. 243-252.

Jack, C. D., R. Jones, L. Burgin and J. Daron, 2020: Climate risk narratives: An iterative reflective process for co-producing and integrating climate knowledge. *Climate risk management*, **29**, 100239, doi:10.1016/j.crm.2020.100239.

Jacobson, M. J. et al., 2017: Designs for learning about climate change as a complex system. *Learning and Instruction*, **52**, 1-14, doi:10.1016/j.learninstruc.2017.03.007.

Jafino, B. A., J. H. Kwakkel and B. Taebi, 2021: Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. *Wiley Interdisciplinary Reviews: Climate Change*, e721.

Jäger, W. S. et al., 2018: A Bayesian network approach for coastal risk analysis and decision making. *Coastal engineering (Amsterdam)*, **134**, 48-61, doi:10.1016/j.coastaleng.2017.05.004.

James, R. A. et al., 2019: Attribution: How Is It Relevant for Loss and Damage Policy and Practice? In: *Loss and Damage from Climate Change*. Springer, pp. 113-154.

Jarzabkowski, P. et al., 2019: *Insurance for Climate Adaptation (Background Paper for the Global Commission on Adaptation)*. Global Commission on, A., Rotterdam and Washington, DC. Available at: www.gca.org (accessed 2020/09/01).

Jashapara, A., 2011: *Knowledge management : an integrated approach*. Pearson/Financial Times/Prentice Hall, Harlow, Essex; New York. ISBN 9780273728191 0273728199.

Jaspars, S. and D. Maxwell, 2009: Food security and livelihoods programming in conflict: a review. *HPN Network Paper-Humanitarian Practice Network, Overseas Development Institute*,(65).
Jensen, N. and C. Barrett, 2017: Agricultural index insurance for development. *Applied Economic Perspectives and Policy*, **39**(2), 199-219.
Jeuring, J., M. Knol-Kauffman and A. Sivle, 2019: Toward valuable weather and sea-ice services for the marine Arctic: exploring user–producer interfaces of the Norwegian Meteorological Institute.
Jobbins, G. et al., 2015: To what end? Drip irrigation and the water–energy–food nexus in Morocco. *International Journal of Water Resources Development*, **31**(3), 393-406, doi:10.1080/07900627.2015.1020146.
Johnson, J. T. et al., 2015: Weaving Indigenous and sustainability sciences to diversify our methods. *Sustainability science*, **11**(1), 1-11, doi:10.1007/s11625-015-0349-x.
Jones, L., 2019a: Resilience isn't the same for all: Comparing subjective and objective approaches to resilience measurement. *Wiley Interdisciplinary Reviews Climate Change*, **10**(1), 1-19.
Jones, L., 2019b: *A how-to guide for subjective evaluations of resilience*. Available at: http://www.braced.org/resources/i/A-how-to.
Jones, L. and P. Ballon, 2020: Tracking changes in resilience and recovery after natural hazards: Insights from a high-frequency mobile-phone panel survey. *Global Environmental Change*, **62**, 102-153.
Jones, L. and M. d'Errico, 2019: Whose resilience matters? Like-for-like comparison of objective and subjective evaluations of resilience. *World Development*, **124**.
Jones, L., E. Samman and P. Vinck, 2018: Subjective measures of household resilience to climate variability and change: insights from a nationally representative survey of Tanzania. *Ecology and Society*, **23**, 1-1.
Jones, N., 2017: How machine learning could help to improve climate forecasts. *Nature (London)*, **548**(7668), 379-379, doi:10.1038/548379a.
Jones, R. N. et al., 2014: *Foundations for decision making* [Field, C. B. V. R. B. D. J. D. K. J. M. M. D. M. T. E. B. M. C. K. L. E. Y. and L. L. White (eds.)]. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U., Cambridge, United Kingdom and New York, NY, USA, 195-228 pp.
Jongman, B., 2018: Effective adaptation to rising flood risk. *Nat Commun*, **9**(1), 1986, doi:10.1038/s41467-018-04396-1.
Jost, C. et al., 2015: Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, **8**(2), 133-144, doi:10.1080/17565529.2015.1050978.
Joubert, L. and G. Ziervogel, 2019: *Day Zero: One City's Response to a Record-Breaking Drought*. Cape Town. ISBN 9780620839488.
Juhola, S., E. Glaas, B.-O. Linnér and T.-S. Neset, 2016: Redefining maladaptation. *Environmental Science & Policy*, **55**, 135-140, doi:10.1016/j.envsci.2015.09.014.
Juhola, S., E. C. H. Keskitalo and L. Westerhoff, 2011: Understanding the framings of climate change adaptation across multiple scales of governance in Europe. *Environmental Politics*, **20**(4), 445-463.
Jurt, C. et al., 2015: Cultural values of glaciers. In: *The high-mountain cryosphere: Environmental changes and human risks*. Cambridge University Press, pp. 90-106.
Kakinuma, K. et al., 2020: Flood-induced population displacements in the world. *Environmental Research Letters*, **15**(12), 124029, doi:10.1088/1748-9326/abc586.
Kalafatis, S. E. and M. C. Lemos, 2017: The emergence of climate change policy entrepreneurs in urban regions. *Regional environmental change*, **17**(6), 1791-1799, doi:10.1007/s10113-017-1154-0.
Kam, J., K. Stowers and S. Kim, 2019: Monitoring of Drought Awareness from Google Trends: A Case Study of the 2011–17 California Drought. *Weather, Climate, and Society*, **11**(2), 419-429, doi:10.1175/wcas-d-18-0085.1.
Karani, I., 2018: *Development of national and sub-national adaptation metrics: Lessons from Kenya*. vol. Adaptation, Copenhagen: UNEP DTU Partnership.
Karlsson, L., A. J. Nightingale, L. O. Naess and J. Thompson, 2017: *Triple wins or `triple faults'? Analysing policy discourses on climate-smart agriculture (CSA)*. Available at: https://hdl.handle.net/10568/80746.
Karlsson, M. and E. L. Mclean, 2020: Caribbean Small-Scale Fishers' Strategies for Extreme Weather Events: Lessons for Adaptive Capacity from the Dominican Republic and Belize. *Coastal Management*, **48**(5), 456-480.
Katz, E., A. Lammel and M.-P. Bonnet, 2020: Climate Change in a Floodplain of the Brazilian Amazon: Scientific Observation and Local Knowledge. In: *Changing Climate, Changing Worlds: Local Knowledge and the Challenges of Social and Ecological Change* [Welch-Devine, M., A. Sourdril and B. J. Burke (eds.)]. Springer International Publishing, Cham, pp. 123-144. ISBN 978-3-030-37312-2.
Keeney, R. L., 1992: *Value-Focused Thinking: A Path to Creative Decisionmaking*. Harvard University Press.
Keeney, R. L., 2012: Value-focused brainstorming, 303-313 pp.
Keeney, R. L. and H. Raiffa, 1993: *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. Cambridge University Press.
Keisler, J., D. A. Turcotte, R. Drew and others, 2014: Value-focused thinking for community-based organizations: objectives and acceptance in local development, 221-256 pp.
Kempa, L., L. Zamarioli, W. P. Pauw and C. Çevik, 2021: *Financing measures to avert, minimise and address loss and damage: options for the Green Climate Fund* [paper, F. S.-U. C. r. (ed.)].

Kench, P. S. et al., 2018: Co-creating Resilience Solutions to Coastal Hazards Through an Interdisciplinary Research Project in New Zealand. *Journal of Coastal Research*, **85**, 1496-1500, doi:10.2112/SI85-300.1.
Khan, M. et al., 2019a: Twenty-five years of adaptation finance through a climate justice lens. *Climatic change*, **161**(2), 251-269, doi:10.1007/s10584-019-02563-x.
Khatri, D., 2018: Climate and development at the third pole: Dynamics of power and knowledge reshaping community forest governance in Nepal. Swedish University of Agricultural Sciences, Sweden.
Khonje, M., J. Manda, A. D. Alene and M. Kassie, 2015: Analysis of Adoption and Impacts of Improved Maize Varieties in Eastern Zambia. *World Development*, **66**, 695-706, doi:10.1016/j.worlddev.2014.09.008.
Kim, H., D. W. Marcouiller and K. M. Woosnam, 2020: Coordinated planning effort as multilevel climate governance: Insights from coastal resilience and climate adaptation. *Geoforum*, **114**, 77-88, doi:https://doi.org/10.1016/j.geoforum.2020.05.023.
Kim, Y. and E.-S. Chung, 2013: Fuzzy VIKOR approach for assessing the vulnerability of the water supply to climate change and variability in South Korea. *Applied mathematical modelling*, **37**(22), 9419-9430, doi:10.1016/j.apm.2013.04.040.
Kirchhoff, C. J., M. C. Lemos and S. Kalafatis, 2015a: Creating synergy with boundary chains: Can they improve usability of climate information? *Climate risk management*, **9**(C), 77-85, doi:10.1016/j.crm.2015.05.002.
Kita, S. M., 2019: Barriers or enablers? Chiefs, elite capture, disasters, and resettlement in rural Malawi. *Disasters*, **43**(1), 135-156, doi:10.1111/disa.12295.
Kitchell, E., 2016: Information sharing and climate risk management among Senegalese agropastoralists. *Climate and Development*, **8**(2), 158-168, doi:10.1080/17565529.2015.1034225.
Klamroth, K., J. D. Knowles, G. Rudolph and M. M. Wiecek (eds.), Personalized Multiobjective Optimization: An Analytics Perspective (Dagstuhl Seminar 18031). Dagstuhl Reports, Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 33-99 pp.
Kleiche-Dray, M. and R. Waast, 2016: Indigenous Knowledge in Mexico: Between Environmentalism and Rural Development. pp. 86–110.
Klein, R. J. et al., 2017: *Advancing climate adaptation practices and solutions: emerging research priorities*. JSTOR.
Klein, R. J. et al., 2014: *Adaptation Opportunities, Constraints, and Limits* [IPCC (ed.)]. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
4pp.
Klein, R. J. T. et al., 2007: Inter-relationships between adaptation and mitigation. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 745-777. ISBN 9780521880107.
Klenk, N., 2018: From network to meshwork: Becoming attuned to difference in transdisciplinary environmental research encounters. *Environmental science & policy*, **89**, 315-321, doi:10.1016/j.envsci.2018.08.007.
Klenk, N., A. Fiume, K. Meehan and C. Gibbes, 2017: Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co-production. *WIREs Climate Change*, **8**(5), e475, doi:10.1002/wcc.475.
Klonschinski, A., 2021: Universal Metrics for Climate Change Adaptation Finance? A Cautionary Tale. *Sustainability*, **13**(16), 9428.
Kloos, J., N. Gebert, T. Rosenfeld and F. Renaud, 2013: Climate change, water conflicts and human security. *Regional assessment and policy guidelines for the Mediterranean, Middle East and Sahel. CLICO final report. UNited Nations University–Institute for Environment and Human Security (Report, 10), updated on*, **8**(27), 2013.
Knapp, C. N. et al., 2019: Placing Transdisciplinarity in Context: A Review of Approaches to Connect Scholars, Society and Action. *Sustainability (Basel, Switzerland)*, **11**(18), 4899, doi:10.3390/su11184899.
Knippenberg, E., N. Jensen and M. Constas, 2019: Quantifying household resilience with high frequency data: Temporal dynamics and methodological options. *World Development*, **121**, 1-15.
Koerth, J., A. T. Vafeidis and J. Hinkel, 2017: Household-Level Coastal Adaptation and Its Drivers: A Systematic Case Study Review. *Risk Anal*, **37**(4), 629-646, doi:10.1111/risa.12663.
Kolen, B. and I. Helsloot, 2014: Decision-making and evacuation planning for flood risk management in the Netherlands. *Disasters*, **38**(3), 610-635.
Konidari, P. and D. Mavrakis, 2007: A multi-criteria evaluation method for climate change mitigation policy instruments. *Energy policy*, **35**(12), 6235-6257, doi:10.1016/j.enpol.2007.07.007.
Kool, R., J. Lawrence, M. Drews and R. Bell, 2020: Preparing for sea-level rise through adaptive managed retreat of a New Zealand stormwater and wastewater network. *Infrastructures*, **5**(11), 92.
Korhonen, P. J. and J. Wallenius, 2020: Making Operations More Efficient. Springer, Cham, 131-139 pp.
Kousser, T. and B. Tranter, 2018: The influence of political leaders on climate change attitudes. *Global Environmental Change*, **50**, 100.
Kreibich, H. et al., 2017: Adaptation to flood risk: Results of international paired flood event studies. *Earth's Future*, **5**(10), 953-965, doi:10.1002/2017ef000606.

Krishnapillai, M., 2018: Enhancing Adaptive Capacity and Climate Change Resilience of Coastal Communities in Yap. In: *Climate Change Impacts and Adaptation Strategies for Coastal Communities* [Leal Filho, W. (ed.)]. Springer International Publishing, Cham, pp. 87-118. ISBN 978-3-319-70703-7.
Krkoška Lorencová, E. et al., 2018: Participatory climate change impact assessment in three Czech cities: the case of heatwaves. *Sustainability*, **10**(6), 1906.
Kuipers, E., 2019: Using disaster response to the 2017 Mocoa mudslide to build legitimacy in the post-Acuerdo de Paz context, Rotterdam.
Kumar, A. et al., 2017: A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable & sustainable energy reviews*, **69**, 596-609, doi:10.1016/j.rser.2016.11.191.
Kunreuther, H. et al., 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 56.
Kwakkel, J., 2020: Is real options analysis fit for purpose in supporting climate adaptation planning and decision-making? *WIREs Climate Change*, **11**, doi:10.1002/wcc.638.
Kwakkel, J. H., 2017: The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software*, **96**, 239-250, doi:10.1016/j.envsoft.2017.06.054.
Kwakkel, J. H., M. Haasnoot and W. E. Walker, 2014: Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change*, **132**(3), 373-386, doi:10.1007/s10584-014-1210-4.
Kwakkel, J. H., M. Haasnoot and W. E. Walker, 2016: Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. *Environmental Modelling & Software*, **86**, 168-183, doi:10.1016/j.envsoft.2016.09.017.
Lal, P. et al., 2012: National systems for managing the risks from climate extremes and disasters. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C. B., v. Barros, t. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. pp. 339-392.
Lalou, R., B. Sultan, B. Muller and A. Ndonky, 2019: Does climate opportunity facilitate smallholder farmers' adaptive capacity in the Sahel? *Palgrave Communications*, **5**(1), 81, doi:10.1057/s41599-019-0288-8.
Lama, P. D., 2018: Gendered consequences of mobility for adaptation in small island developing states: case studies from Maafushi and Kudafari in the Maldives. *Island Studies Journal*, **13**(2), 111-128.
Lamhauge, N., E. Lanzi and S. Agrawala, 2013: The use of indicators for monitoring and evaluation of adaptation: lessons from development cooperation agencies. *Climate and Development*, **5**(3), 229-241, doi:10.1080/17565529.2013.801824.
Lammel, A., 2015: Climate change. From perception to action. *Les Notes de la Fondation d'Ecologie Politique*.
Landauer, M., S. Juhola and J. Klein, 2019: The role of scale in integrating climate change adaptation and mitigation in cities. *Journal of Environmental Planning and Management*, **62**(5), 741-765, doi:10.1080/09640568.2018.1430022.
Lanier, A. L. et al., 2018: Facilitating Integration in Interdisciplinary Research: Lessons from a South Florida Water, Sustainability, and Climate Project. *Environmental Management*, **62**(6), 1025-1037, doi:10.1007/s00267-018-1099-1.
Larson, K., D. White, P. Gober and A. Wutich, 2015: Decision-making under uncertainty for water sustainability and urban climate change adaptation. *Sustainability*, **7**(11), 14761-14784.
Latulippe, N. and N. Klenk, 2020: Making room and moving over: knowledge co-production, Indigenous knowledge sovereignty and the politics of global environmental change decision-making. *Current opinion in environmental sustainability*, **42**, 7-14, doi:10.1016/j.cosust.2019.10.010.
Lauer, H. and I. Eguavoen, 2016: Mainstreaming Climate Change Adaptation into Development in the Gambia: A Window of Opportunity for Transformative Processes? In: *Innovation in Climate Change Adaptation* [Leal Filho, W. (ed.)]. Springer International Publishing, Cham, pp. 87-98. ISBN 978-3-319-25814-0.
Laursen, S. et al., 2018: Collaboration Across Worldviews: Managers and Scientists on Hawai'i Island Utilize Knowledge Coproduction to Facilitate Climate Change Adaptation. *Environmental management (New York)*, **62**(4), 619-630, doi:10.1007/s00267-018-1069-7.
Lavorel, S., B. Locatelli, M. J. Colloff and E. Bruley, 2020: Co-producing ecosystem services for adapting to climate change. *Philosophical transactions. Biological sciences*, **375**(1794), 20190119, doi:10.1098/rstb.2019.0119.
Lawrence, J. et al., 2019b: A Practice Brief: Adaptation transition at the coast.
Lawrence, J. et al., 2018: National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. *Environmental science & policy*, **82**, 100-107.
Lawrence, J. and M. Haasnoot, 2017: What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environmental Science & Policy*, **68**, 47-57, doi:10.1016/j.envsci.2016.12.003.
Lawrence, J. et al., 2019: Dynamic Adaptive Policy Pathways (DAPP): From Theory to Practice. In: *Decision Making under Deep Uncertainty: from theory to practice* [Marchau, V., W. E. Walker, P. Bloemen and S. W. Popper (eds.)]. Springer, pp. 187-199. ISBN 3030052516.

Lawrence, J. et al., 2019a: From theory to practice: a timeline of interventions by a change agent with the developers and users of Dynamic Adaptive Policy Pathways (DAPP). In: *Decision making under deep uncertainty: From theory to practice* [Marchau, V., W. Walker and P. Bloeman (eds.)]. Springer International Publishing.
Le Cozannet, G., J.-C. Manceau and J. Rohmer, 2017: *Bounding probabilistic sea-level projections within the framework of the possibility theory*. Environmental Research Letters, **12**, 014012 pp. Available at: http://dx.doi.org/10.1088/1748-9326/aa5528.
Leal Filho, W. and J. Nalau, 2018: *Limits to climate change adaptation*. Springer. ISBN 3319645994.
Leavy, J., E. Boydell, S. McDowell and B. Sladkova, 2018: *Resilience Results. Braced Final Evaluation. Synthesis Paper*. Available at: https://itad.com/wp-content/uploads/2018/09/BRCJ6513-Final-Evaluation-report-1709-WEB.pdf.
Leck, H. and D. Roberts, 2015: What lies beneath: understanding the invisible aspects of municipal climate change governance. *Current Opinion in Environmental Sustainability*, **13**, 61-67, doi:https://doi.org/10.1016/j.cosust.2015.02.004.
Lee, K. W. and M. Hong, 2018: Relative Effectiveness of Various Development Finance Flows: A Comparative Study. *kdijournalofeconomicpolicy*, **40**(3), 91-115, doi:10.23895/kdijep.2018.40.3.91.
Lee, M. and B. Tansel, 2013: Water conservation quantities vs customer opinion and satisfaction with water efficient appliances in Miami, Florida. *J Environ Manage*, **128**, 683-689, doi:10.1016/j.jenvman.2013.05.044.
Lee, S. Y., 2015: Motivations for local resistance in international peacebuilding. Taylor \& Francis, 1437-1452 pp.
Lee, T. M. et al., 2015: Predictors of public climate change awareness and risk perception around the world. *Nature Climate Change*, **5**(11), 1014-1020, doi:10.1038/nclimate2728.
Leitch, A. M. et al., 2019: Co-development of a climate change decision support framework through engagement with stakeholders. *Climatic change*, **153**(4), 587-605, doi:10.1007/s10584-019-02401-0.
Leiter, T., 2015: Linking Monitoring and Evaluation of Adaptation to Climate Change Across Scales: Avenues and Practical Approaches. *New Directions for Evaluation*, **2015**(147), 117-127, doi:10.1002/ev.20135.
Leiter, T., 2016: Key considerations for monitoring and evaluation of community-based adaptation to climate change: lessons from experience. [Atela, J. and others (eds.)]. African Centre for Technology Studies Press.
Leiter, T., 2017: The Adaptation M&E Navigator. A decision support tool for the selection of suitable approaches to monitor and evaluate adaptation to climate change. [Uitto, J., J. Puri and R. D. van den Berg (eds.)]. Springer, pp. 327-341.
Leiter, T., 2021a: *Progress in implementing adaptation: insights from project proposals and scientific literature* [UNEP (ed.)]. Adaptation Gap Report 2020, United Nations Environment Programme (UNEP), Nairobi, Kenya, 33-40 pp.
Leiter, T., 2021b: Do governments track the implementation of national climate change adaptation plans? An evidence-based global stocktake of monitoring and evaluation systems. *Environmental Science and Policy*.
Leiter, T. et al., 2017a: Country-specific assessments of adaptation progress. United Nations Environment Programme (UNEP), Nairobi, Kenya, pp. 23-33.
Leiter, T. et al., 2019: *Adaptation metrics: Current landscape and evolving practices. Background paper for the Global Commission on Adaptation*. Available at: https://cdn.gca.org/assets/2019-09/AdaptationMetrics.pdf.
Leiter, T. et al., 2017b: *Can climate vulnerability and risk be measured through global indices? Policy Brief*. Available at: http://www.adaptationcommunity.net/wp-content/uploads/2017/09/Measuring-vulnerability-through-global-indices-Policy-Brief-GIZ-2017.pdf.
Leiter, T. and P. Pringle, 2018: Pitfalls and potential of measuring adaptation through adaptation metrics. [L. Christiansen, G. M. and P. Naswa (eds.)]. Copenhagen: UNEP DTU Partnership, pp. (pp. 29-48).
Lemmen, D. S., F. J. Warren, T. S. James and C. S. L. Mercer Clarke, 2016: *Canada's Marine Coasts in a Changing Climate*. Government of Canada, Ottawa, 274 pp. Available at: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/files/pdf/NRCAN_fullBook%20%20accessible.pdf.
Lemos, M. C. et al., 2018: To co-produce or not to co-produce. *Nature Sustainability*, **1**(12), 722-724, doi:10.1038/s41893-018-0191-0.
Lemos, M. C. et al., 2014: Moving Climate Information off the Shelf: Boundary Chains and the Role of RISAs as Adaptive Organizations. *Weather, climate, and society*, **6**(2), 273-285, doi:10.1175/wcas-d-13-00044.1.
Lempert, R., 2019: Robust decision making (RDM). In: *Decision Making under Deep Uncertainty: from theory to practice* [Marchau, V., W. E. Walker, P. Bloemen and S. W. Popper (eds.)]. Springer, pp. 23-51. ISBN 3030052516.
Lempert, R., S. Popper, S. Bankes and Rand, 2003: *Shaping the Next One Hundred Years: New Methods for Quantitative Long-Term Policy Analysis*. ISBN 0-8330-3275-5.
Lempert, R. J. and D. G. Groves, 2010: Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technological forecasting & social change*, **77**(6), 960-974, doi:10.1016/j.techfore.2010.04.007.
Lempert, R. J. and S. Turner, 2021: Engaging multiple worldviews with quantitative decision support: A robust decision-making demonstration using the lake model. *Risk Analysis*, **41**(6), 845-865.
Lesnikowski, A. et al., 2015: National-level progress on adaptation. *Nature Climate Change*, **6**(3), 261-264, doi:10.1038/nclimate2863.

Lesnikowski, A. et al., 2016: What does the Paris Agreement mean for adaptation? *Climate Policy*, **17**(7), 825-831, doi:10.1080/14693062.2016.1248889.
Lesnikowski, A., J. D. Ford, R. Biesbroek and L. Berrang-Ford, 2019: A policy mixes approach to conceptualizing and measuring climate change adaptation policy. *Climatic Change*, **156**(4), 447-469, doi:10.1007/s10584-019-02533-3.
Levi-Faur, D., 2012: From "Big Government" to "Big Governance"? [Levi-Faur, D. (ed.)]. Oxford University Press., New York, United States.
Li, X. et al., 2017: Patterns of herders' adaptation to changes in social–ecological systems across northern China's grasslands over the past three decades. *The Rangeland Journal*, **39**(4), 317-328.
Limthongsakul, S., V. Nitivattananon and S. D. Arifwidodo, 2017: Localized flooding and autonomous adaptation in peri-urban Bangkok. *Environment and Urbanization*, **29**(1), 51-68, doi:10.1177/0956247816683854.
Lin, Y.-P., J. Petway, W.-Y. Lien and J. Settele, 2018: Blockchain with Artificial Intelligence to Efficiently Manage Water Use under Climate Change. *Environments (Basel, Switzerland)*, **5**(3), 34, doi:10.3390/environments5030034.
Lincke, D. and J. Hinkel, 2018: Economically robust protection against 21st century sea-level rise. *Global Environmental Change*, **51**, 67-73, doi:10.1016/j.gloenvcha.2018.05.003.
Linnerooth-Bayer, J. and S. Hochrainer-Stigler, 2015: Financial instruments for disaster risk management and climate change adaptation. *Climatic Change*, **133**(1), 85-100.
Linnerooth-Bayer, J. et al., 2019: Insurance as a Response to Loss and Damage? In: *Loss and Damage from Climate Change*. Springer, pp. 483-512.
Loboguerrero, A. M. et al., 2018: Bridging the gap between climate science and farmers in Colombia. *Climate Risk Management*, **22**, 67-81.
Lonsdale, K., P. Pringle and B. Turner, 2015: *Transformative adaptation: What it is, why it matters and what is needed*. UK Climate Impacts Programme, Oxford, U. o., Oxford, UK.
Lopes, J. et al., 2020: Determinants of Foreign Investment and International Aid for Meeting the Sustainable Development Goals in Africa: A Visual Cognitive Review of the Literature. In: *Sustainability Challenges in Sub-Saharan Africa I*. Springer, Spingapore, pp. 161-187. ISBN 978-981-15-4457-6.
Lourenço, T. C., R. Swart, H. Goosen and R. Street, 2015: The rise of demand-driven climate services. *Nature climate change*, **6**(1), 13-14, doi:10.1038/nclimate2836.
Lumbroso, D., E. Brown and N. Ranger, 2016: Stakeholders' perceptions of the overall effectiveness of early warning systems and risk assessments for weather-related hazards in Africa, the Caribbean and South Asia. *Natural Hazards*, **84**(3), 2121-2144, doi:10.1007/s11069-016-2537-0.
Lwasa, S., 2015: A systematic review of research on climate change adaptation policy and practice in Africa and South Asia deltas. *Regional Environmental Change*, **15**(5), 815-824.
Lyytimäki, J. et al., 2020: Risks of producing and using indicators of sustainable development goals. *Sustainable Development*.
MacAskill, M., K. Bykvist and T. Ord, 2020: *Moral uncertainty*. Oxford University Press. ISBN 0198722273.
Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-197, doi:10.1038/s41586-019-1300-6.
Mach, K. J., M. D. Mastrandrea, P. T. Freeman and C. B. Field, 2017: Unleashing expert judgment in assessment. *Global Environmental Change-Human and Policy Dimensions*, **44**, 1-14, doi:10.1016/j.gloenvcha.2017.02.005.
Mach, K. J. and A. Siders, 2021: Reframing strategic, managed retreat for transformative climate adaptation. *Science*, **372**(6548), 1294-1299.
MacLeod, D. et al., 2021: Are Kenya Meteorological Department heavy rainfall advisories useful for forecast-based early action and early preparedness for flooding? *Nat. Hazards Earth Syst. Sci.*, **21**(1), 261-277, doi:10.5194/nhess-21-261-2021.
Macquarie, R. et al., 2020: *Updated view on the Global Landscape of Climate Finance* [Initiative, C. P. (ed.)]. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2020/12/Updated-View-on-the-2019-Global-Landscape-of-Climate-Finance-1.pdf.
Madsen, H. M., P. S. Mikkelsen and A. Blok, 2019: Framing professional climate risk knowledge: Extreme weather events as drivers of adaptation innovation in Copenhagen, Denmark. *Environmental Science & Policy*, **98**, 30-38, doi:https://doi.org/10.1016/j.envsci.2019.04.004.
Magnan, A., 2014: Avoiding maladaptation to climate change: towards guiding principles. *SAPI EN. S. Surveys and Perspectives Integrating Environment and Society*,(7.1).
Magnan, A. K. and S. Chalastani, 2019: *Towards a Global Adaptation Progress Tracker: first thoughts* [Iddri (ed.)].
Magnan, A. K. and T. Ribera, 2016: Global adaptation after Paris. *Science*, **352**(6291), 1280-1282, doi:10.1126/science.aaf5002.
Magnan, A. K. et al., 2016: Addressing the risk of maladaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **7**(5), 646-665, doi:10.1002/wcc.409.
Magnan, A. K., E. L. F. Schipper and V. K. Duvat, 2020: Frontiers in climate change adaptation science: advancing guidelines to design adaptation pathways. *Current Climate Change Reports*, 1-12.
Mahon, R. et al., 2019: Fit for purpose? Transforming National Meteorological and Hydrological Services into National Climate Service Centers. *Climate services*, **13**, 14-23, doi:10.1016/j.cliser.2019.01.002.

Mäkinen, K. et al., 2018: *Indicators for adaptation to climate change at national level - Lessons from emerging practice in Europe*.
Makondo, C. C. and D. S. Thomas, 2018: Climate change adaptation: Linking indigenous knowledge with western science for effective adaptation. *Environmental Science & Policy*, **88**, 83-91.
Manocha, N. and V. Babovic, 2017: Development and valuation of adaptation pathways for storm water management infrastructure. *Environmental science & policy*, **77**, 86-97, doi:10.1016/j.envsci.2017.08.001.
Marchau, V. A., W. E. Walker, P. J. Bloemen and S. W. Popper, 2019: *Decision making under deep uncertainty: from theory to practice*. Springer Nature.
Mard, J., G. Di Baldassarre and M. Mazzoleni, 2018: Nighttime light data reveal how flood protection shapes human proximity to rivers. *Sci Adv*, **4**(8), eaar5779, doi:10.1126/sciadv.aar5779.
Marjanac, S. and L. Patton, 2018: Extreme weather event attribution science and climate change litigation: an essential step in the causal chain? *Journal of Energy & Natural Resources Law*, **36**(3), 265-298, doi:10.1080/02646811.2018.1451020.
Markandya, A. and M. González-Eguino, 2019: Integrated Assessment for Identifying Climate Finance Needs for Loss and Damage: A Critical Review. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, pp. 343-362. ISBN 978-3-319-72026-5.
Markl-Hummel, L. and J. Geldermann, 2014: A local-level, multiple criteria decision aid for climate protection. *EURO Journal on Decision Processes*, **2**(1), 121-152, doi:10.1007/s40070-013-0011-8.
Markolf, S. A., K. Klima and T. L. Wong, 2015: Adaptation frameworks used by US decision-makers: a literature review. *Environment Systems and Decisions*, **35**(4), 427-436, doi:10.1007/s10669-015-9572-3.
Marktanner, M., E. Mienie and L. Noiset, 2015: From armed conflict to disaster vulnerability. *Disaster Prevention and Management: An International Journal*, **24**(1), 53-69, doi:10.1108/dpm-04-2013-0077.
Martinez-Diaz, L., L. Sidner and J. McClamrock, 2019: The future of disaster risk pooling for developing countries: Where do we go from here?, Washington DC.
Martínez-Tagüeña, N. et al., 2020: *Conservation and Development in the Biosphere Reserve of Mapimí: A Transdisciplinary and Participatory Project to Understand Climate Change Adaptation*. Springer Climate, 163 pp.
Marttunen, M., J. Lienert and V. Belton, 2017: Structuring problems for Multi-Criteria Decision Analysis in practice: A literature review of method combinations. *European journal of operational research*, **263**(1), 1-17, doi:10.1016/j.ejor.2017.04.041.
Mason, P. and M. Barnes, 2007: Constructing Theories of Change. Methods and Sources. *Evaluation*, **13**(2), 151-170.
Mastrandrea, M. C. et al., 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. 4 pp. Available at: https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf (accessed 22/09/2020).
Mastrandrea, M. D. and K. J. Mach, 2011: Treatment of uncertainties in IPCC Assessment Reports: past approaches and considerations for the Fifth Assessment Report. *Climatic Change*, **108**(4), 659-673.
Masud, M. M. et al., 2016: Climate change issue and theory of planned behaviour: relationship by empirical evidence. *Journal of Cleaner Production*, **113**, 613-623, doi:10.1016/j.jclepro.2015.11.080.
Masuda, Y. J. et al., 2018: Innovation diffusion within large environmental NGOs through informal network agents. *Nature Sustainability*, **1**(4), 190-197, doi:10.1038/s41893-018-0045-9.
Matheny, J. G., 2007: Reducing the risk of human extinction. *Risk Analysis: An International Journal*, **27**(5), 1335-1344.
Matsler, A. M., 2019: Making 'green' fit in a 'grey' accounting system: The institutional knowledge system challenges of valuing urban nature as infrastructural assets. *Environmental Science & Policy*, **99**, 160-168, doi:https://doi.org/10.1016/j.envsci.2019.05.023.
Mayer, B., 2016: The relevance of the no-harm principle to climate change law and politics. *Asia Pacific Journal of Environmental Law*, **19**, 79–104.
Mayer, B., 2017: Migration in the UNFCCC workstream on loss and damage: An assessment of alternative framings and conceivable responses. *Transnational Environmental Law*, **6**(1), 107-129.
Mazzocchi, F., 2020: A deeper meaning of sustainability: Insights from indigenous knowledge. *The anthropocene review*, **7**(1), 77-93, doi:10.1177/2053019619898888.
McCormick, S. et al., 2018: Strategies in and outcomes of climate change litigation in the United States. *Nature Climate Change*, **8**(9), 829-833, doi:10.1038/s41558-018-0240-8.
McDonald, J. and M. C. Styles, 2014: Legal strategies for adaptive management under climate change. *Journal of environmental law*, **26**(1), 25-53.
McGray, H. et al., 2007: *Weathering the Storm: Options for Framing Adaptation and Development*. WRI Report, World Resources Institute.
McKenzie Hedger, M. M. M. T. et al., 2008: *Evaluation of adaptation to climate change from a development perspective, desk review*.
McNamara, K. E., R. Bronen, N. Fernando and S. Klepp, 2018: The complex decision-making of climate-induced relocation: Adaptation and loss and damage. *Climate Policy*, **18**(1), 111-117.

McNamara, K. E. et al., 2020: An assessment of community-based adaptation initiatives in the Pacific Islands. *Nature Climate Change*, **10**(7), 628-639.
McNamara, K. E. and G. Jackson, 2019: Loss and damage: A review of the literature and directions for future research. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(2), 1-16.
McSweeney, K. and O. T. Coomes, 2011: Climate-related disaster opens a window of opportunity for rural poor in northeastern Honduras. *Proceedings of the National Academy of Sciences*, **108**(13), 5203, doi:10.1073/pnas.1014123108.
MDBs, 2019: *Joint report on Multilateral Development Banks' Climate Finance 2019*. Available at: https://publications.iadb.org/publications/english/document/2019-Joint-Report-on-Multilateral-Development-Banks-Climate-Finance.pdf.
MDBs & IDFC, 2018: *Lessons Learned from Three Years of Implementing the MDB-IDFC COMMON PRINCIPLES FOR CLIMATE CHANGE ADAPTATION FINANCE TRACKING*. Available at: https://www.ebrd.com/documents/climate-finance/lessons-learned-from-three-years-of-implementing-the-mdbidfc-common-principles-for-climate-change-adaptation-finance-tracking.pdf?blobnocache=true.
Mechler, R. et al., 2014: Managing unnatural disaster risk from climate extremes. *Nature Climate Change*, **4**(4), 235-237, doi:10.1038/nclimate2137.
Mechler, R. et al., 2018: *Loss and damage from climate change: Concepts, methods and policy options*. Springer Nature.
Mechler, R. et al., 2019: Science for loss and damage. Findings and propositions. In: *Loss and Damage from Climate Change*. Springer, pp. 3-37.
Mechler, R. and T. M. Deubelli, 2021: Finance for Loss and Damage: a comprehensive risk analytical approach. *Current Opinion in Environmental Sustainability*, **50**, 185-196.
Mechler, R., S. Hochrainer-Stigler and J. Linnerooth-Bayer, 2006: Public sector financial vulnerability to disasters.
Mechler, R. and T. Schinko, 2016: Identifying the policy space for climate loss and damage. *Science (New York, N.Y.)*, **354**(6310), 290, doi:10.1126/science.aag2514.
Mehling, M., 2015: The comparative law of climate change: a research agenda. *Review of European, Comparative & International Environmental Law*, **24**(3), 341-352.
Melbourne-Thomas, J. et al., 2017: Integrated modelling to support decision-making for marine social–ecological systems in Australia. *ICES Journal of Marine Science*, **74**(9), 2298-2308, doi:10.1093/icesjms/fsx078.
Melia, N., K. Haines and E. Hawkins, 2016: Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters*, **43**(18), 9720-9728, doi:10.1002/2016gl069315.
Mena, R. and D. Hilhorst, 2020: The (im)possibilities of disaster risk reduction in the context of high-intensity conflict: the case of Afghanistan. *Environmental Hazards*, 1-21, doi:10.1080/17477891.2020.1771250.
Mendizabal, M. et al., 2018: Stimulating urban transition and transformation to achieve sustainable and resilient cities. *Renewable and Sustainable Energy Reviews*, **94**, 410-418.
Mendoza, G. et al., 2018: *Climate Risk Informed Decision Analysis (CRIDA): collaborative water resources planning for an uncertain future*. UNESCO Publishing. Available at: https://agwaguide.org/docs/CRIDA_Nov_2018.pdf.
Meredith, M. P. et al., 2019: Polar Regions. In: *The Ocean and Cryosphere in a Changing Climate: Summary for Policymakers*. Intergovernmental Panel on Climate Change, pp. 3-1-3-173.
Mesquita, P. S. and M. Bursztyn, 2016: Integration of social protection and climate change adaptation in Brazil. *British Food Journal*.
Meyer, R., S. McAfee and E. Whiteman, 2015: How California is mobilizing boundary chains to integrate science, policy and management for changing ocean chemistry. *Climate Risk Management*, **9**, 50-61, doi:https://doi.org/10.1016/j.crm.2015.04.002.
Mfitumukiza, D. et al., 2019: *Scaling local and community-based adaptation*. Background Paper for Global Commission on Adaptation.
Micale, V., B. Tonkonogy and F. Mazza, 2018: *Understanding and Increasing Finance for Climate Adaptation in Developing Countries*. Initiative, C. P. Available at: https://climatepolicyinitiative.org/our-work/publications (accessed 28 September 2019).
Michaelowa, A. and K. Michaelowa, 2011: Coding Error or Statistical Embellishment? The Political Economy of Reporting Climate Aid. *World Development*, **39**(11), 2010-2020.
Michaelowa, A., K. Michaelowa, I. Shishlov and D. Brescia, 2021: Catalysing private and public action for climate change mitigation: the World Bank's role in international carbon markets. *Climate Policy*, **21**(1), 120-132.
Michailidou, A. V., C. Vlachokostas and N. Moussiopoulos, 2016: Interactions between climate change and the tourism sector: Multiple-criteria decision analysis to assess mitigation and adaptation options in tourism areas. *Tourism management (1982)*, **55**, 1-12, doi:10.1016/j.tourman.2016.01.010.
Mikulewicz, M., 2018: Politicizing vulnerability and adaptation: on the need to democratize local responses to climate impacts in developing countries. *Climate & Development*, **10**(1), 18-34.
Mikulewicz, M., 2019: Thwarting adaptation's potential? A critique of resilience and climate-resilient development. *Geoforum*, **104**, 267-282.
Mikulewicz, M., 2020: Disintegrating labour relations and depoliticised adaptation to climate change in rural São Tomé and Príncipe. *Area*, **00**, 1-9, doi:10.1111/area.12630.

Miller, A., S. Swann, S. Cheng and A. Eil, 2019: *Driving Finance Today for the Climate Resilient Society of Tomorrow: for Global Comission on Adaptation*. Climate Finance Advisors, Unepfi.
Miller, C. A. and C. Wyborn, 2020: Co-Production in Global Sustainability: Histories and Theories. *Environmental Science and Policy*, **113**, 88-95, doi:10.1016/j.envsci.2018.01.016.
Millington, N. and S. Scheba, 2021: Day zero and the infrastructures of climate change: Water governance, inequality, and infrastructural politics in Cape Town's water crisis. *International Journal of Urban and Regional Research*, **45**(1), 116-132.
Mimet, A. et al., 2020: Contribution of private gardens to habitat availability, connectivity and conservation of the common pipistrelle in Paris. *Landscape and Urban Planning*, **193**, 103671, doi:https://doi.org/10.1016/j.landurbplan.2019.103671.
Mimura, N. et al., 2008: Small islands. Cambridge University Press, Cambridge, UK, 681-716 pp.
Mimura, N. et al., 2014: Adaptation planning and implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869-898.
Ministry of Economy, 2019: *The Fiji Sovereign Green Bond 2019 Update*. Ministry of Economy, Suva, Fiji. Available at: https://www.rbf.gov.fj/wp-content/uploads/2020/03/Fiji-Sovereign-Green-Bond-Impact-Report-2019.pdf.
Mintrom, M., 2019: Policy Entrepreneurs and Dynamic Change. Elements in Public Policy, Cambridge University Press, Cambridge. Available at: https://www.cambridge.org/core/elements/policy-entrepreneurs-and-dynamic-change/AA75C2D1EA0ADD4C43C1C5987E84280F.
Mohammadpour, P., T. Mahjabin, J. Fernandez and C. Grady, 2019: From national indices to regional action—An Analysis of food, energy, water security in Ecuador, Bolivia, and Peru. *Environmental Science & Policy*, **101**, 291-301.
Möhner, A., T. Leiter and T. Kato, 2017: Adaptation in the Paris Agreement and provisions for review and reporting. United Nations Environment Programme (UNEP), Nairobi, Kenya.
Molthan-Hill, P., N. Worsfold, G. J. Nagy and W. Leal Filho, 2019: Climate change education for universities: A conceptual framework from an international study (Book review).
Monteleoni, C., G. A. Schmidt and S. McQuade, 2013: Climate Informatics: Accelerating Discovering in Climate Science with Machine Learning. *Computing in Science & Engineering*, **15**(5), 32-40, doi:10.1109/mcse.2013.50.
Moon, S.-H., Y.-H. Kim, Y. H. Lee and B.-R. Moon, 2019: Application of machine learning to an early warning system for very short-term heavy rainfall. *Journal of hydrology (Amsterdam)*, **568**, 1042-1054, doi:10.1016/j.jhydrol.2018.11.060.
Morgan, E. A., J. Nalau and B. Mackey, 2019: Assessing the alignment of national-level adaptation plans to the Paris Agreement. *Environmental Science and Policy*, **93**, 208-220, doi:10.1016/j.envsci.2018.10.012.
Mortreux, C. and J. Barnett, 2017: Adaptive capacity: Exploring the research frontier. *Wiley Interdisciplinary Reviews Climate Change*, **8**(e467).
Mortreux, C. et al., 2018: Political economy of planned relocation: A model of action and inaction in government responses. *Global Environmental Change*, **50**, 123-132, doi:10.1016/j.gloenvcha.2018.03.008.
Moser, S. C. and M. T. Boykoff, 2013: Climate change and adaptation success: the scope of the challenge. In: *Successful adaptation to climate change*. Routledge, pp. 25-58.
Muccione, V., S. K. Allen, C. Huggel and J. Birkmann, 2017: *Differentiating regions for adaptation financing: the role of global vulnerability and risk distributions*.
Muccione, V. et al., 2019: Joint knowledge production in climate change adaptation networks. doi:10.1016/j.cosust.2019.09.011.
Mugambiwa, S. S., 2018: Adaptation measures to sustain indigenous practices and the use of indigenous knowledge systems to adapt to climate change in Mutoko rural district of Zimbabwe. *Jamba*, **10**(1), 388, doi:10.4102/jamba.v10i1.388.
Müller, B., L. Johnson and D. Kreuer, 2017: Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change*, **46**, 23-33, doi:10.1016/j.gloenvcha.2017.06.010.
Mustelin, J. and J. Handmer, 2013: Triggering transformation: Managing resilience or invoking real change. *Proceedings of transformation in a changing climate*, 19-21.
Muttarak, R. and T. Chankrajang, 2015: Who is concerned about and takes action on climate change? Gender and education divides among Thais. *Vienna Yearbook of Population Research*, 193-220.
Mycoo, M. A., 2017: Beyond 1.5 °C: vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional Environmental Change*, **18**(8), 2341-2353, doi:10.1007/s10113-017-1248-8.
Myers, R. et al., 2018: Messiness of forest governance: How technical approaches suppress politics in REDD+ and conservation projects. *Global Environmental Change*, **50**, 314-324, doi:10.1016/j.gloenvcha.2018.02.015.
Nachmany, M., A. Abeysinghe and S. Barakat, 2017: Climate change legislation in the least developing countries. *Trends in Climate Change Legislation*, 59.
Nachmany, M., R. Byrnes and S. Surminski, 2019a: *National laws and policies on climate change adaptation: a global review*. Policy Publication, Grantham Research Institute on Climate Change and the Environment and Centre for

Climate Change Economics and Policy, London. Available at: https://www.lse.ac.uk/granthaminstitute/publication/national-laws-and-policies-on-climate-change-adaptation-a-global-review/.
Nachmany, M., R. Byrnes and S. Surminski, 2019b: *Policy brief: National laws and policies on climate change adaptation: a global review*. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.
Nachmany, M. et al., 2015: The 2015 global climate legislation study: a review of climate change legislation in 99 countries: summary for policy-makers.
Nachmany, M. and J. Setzer, 2018: *Global trends in climate change legislation and litigation: 2018 snapshot*. Policy Publication, Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London. Available at: https://www.lse.ac.uk/granthaminstitute/publication/global-trends-in-climate-change-legislation-and-litigation-2018-snapshot/.
Nagle Alverio, G., S. H. Hoagland, E. Coughlan de Perez and K. J. Mach, 2021: The role of international organizations in equitable and just planned relocation. *J Environ Stud Sci*, 1-12, doi:10.1007/s13412-021-00698-x.
Nagoda, S. and A. J. Nightingale, 2017: Participation and power in climate change adaptation policies: Vulnerability in food security programs in Nepal. *World Dev*, **100**, 85-93.
Nakashima, D., I. Krupnik and J. T. Rubis, 2018: *Indigenous Knowledge for Climate Change Assessment and Adaptation*. Cambridge University Press, Cambridge. ISBN 9781107137882.
Nakhooda, S. et al., 2014: *Climate Finance: is it making a difference? A review of the effectiveness of Multilateral Climate Funds*. Overseas Development Institute, London, UK. ISBN 20527209.
Nawrotzki, R. J. and J. DeWaard, 2018: Putting trapped populations into place: Climate change and inter-district migration flows in Zambia. *Regional environmental change*, **18**(2), 533-546.
Ndebele-Murisa, M. R. et al., 2020: City to city learning and knowledge exchange for climate resilience in southern Africa. *PLoS ONE*, **15**(1), doi:10.1371/journal.pone.0227915.
Neely, J. E. and R. de Neufville, 2001: Hybrid real options valuation of risky product development projects. *Int. J. of Technology*, **1**, 29-46, doi:10.1504/ijtpm.2001.001743.
Neise, T. and J. Revilla Diez, 2019: Adapt, move or surrender? Manufacturing firms' routines and dynamic capabilities on flood risk reduction in coastal cities of Indonesia. *International Journal of Disaster Risk Reduction*, **33**, 332-342, doi:10.1016/j.ijdrr.2018.10.018.
Nelson, H. W., T. B. Williamson, C. Macaulay and C. Mahony, 2016: Assessing the potential for forest management practitioner participation in climate change adaptation. *Forest Ecology and Management*, **360**, 388-399.
Newton Mann, A., P. Grifman and J. Finzi Hart, 2017: The Stakes are Rising: Lessons on Engaging Coastal Communities on Climate Adaptation in Southern California. *Cities and the Environment (CATE)*, **10**(2), 6.
Ng, A. K. Y. et al., 2018: Implications of climate change for shipping: Opening the Arctic seas. *WIREs Climate Change*, **9**(2), e507, doi:https://doi.org/10.1002/wcc.507.
Nhamo, L. et al., 2018: The Water-Energy-Food Nexus: Climate Risks and Opportunities in Southern Africa. *Water*, **10**(5), 567-567, doi:10.3390/w10050567.
Nightingale, A. J., 2017: Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, **84**, 11-20.
Nikas, A., H. Doukas and L. Martínez López, 2018: A group decision making tool for assessing climate policy risks against multiple criteria. *Heliyon*, **4**(3), e00588, doi:https://doi.org/10.1016/j.heliyon.2018.e00588.
Noble, I. R. et al., 2014: Adaptation Needs and Options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 833-868. ISBN 9781107058071.
Noll, B., T. Filatova and A. Need, 2020: How does private adaptation motivation to climate change vary across cultures? Evidence from a meta-analysis. *International journal of disaster risk reduction*, **46**, 101615, doi:10.1016/j.ijdrr.2020.101615.
Nordlander, L., M. Pill and B. M. Romera, 2020: Insurance schemes for loss and damage: fools' gold? *Climate Policy*, **20**(6), 704-714.
Norström, A. V. et al., 2020: Principles for knowledge co-production in sustainability research. *Nature Sustainability*, **3**(3), 182-190, doi:10.1038/s41893-019-0448-2.
Novalia, W. and S. Malekpour, 2020: Theorising the role of crisis for transformative adaptation. *Environmental Science & Policy*, **112**, 361-370, doi:https://doi.org/10.1016/j.envsci.2020.07.009.
Núñez Collado, J. R. and H.-H. Wang, 2020: Slum upgrading and climate change adaptation and mitigation: Lessons from Latin America. *Cities*, **104**, 102791, doi:10.1016/j.cities.2020.102791.
Nyantakyi-Frimpong, H. and R. Bezner Kerr, 2015: A political ecology of high-input agriculture in northern Ghana. *African Geographical Review*, **34**(1), 13-35.
O'Garra, T. et al., 2021: Impact of gameplay vs. Reading on mental models of social-ecological systems: A fuzzy cognitive mapping approach. *Ecology and Society*, **26**(2), doi:10.5751/ES-12425-260225.

O'Brien, K. et al., 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C. B., v. Barros, t. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. pp. 437-486.
O'Callaghan, B. J. and E. Murdock, 2021: *Are We Building Back Better? Evidence from 2020 and Pathways for Inclusive Green Recovery Spending*. Programme, U. N. E., Oxford & Nairobi. Available at: https://www.unep.org/resources/publication/are-we-building-back-better-evidence-2020-and-pathways-inclusive-green (accessed 2021/08/21).
Oberlack, C. and e. al., 2019: Theories of change in sustainability science. Understanding how change happens. *Gaia*, **28**(2), 106-111.
Oberlack, C. and K. Eisenack, 2014: Alleviating barriers to urban climate change adaptation through international cooperation. *Global Environmental Change*, **24**, 349-362, doi:10.1016/j.gloenvcha.2013.08.016.
OCHA, 2011: *Humanitarian Action Plan for the Conflict-Affected Provinces of Mindanao*. United Nations, New York.
ODI, 2016: *Analysis of resilience measurement frameworks and approaches*.
OECD, 2002: *Glossary of Key Terms in Evaluation and Results Based Management*. Publications, O., Paris.
OECD, 2008: *Handbook on Constructing Composite Indicators. Methodology and User Guide*. Published by the OECD in cooperation with the Joint Research Centre of the European Commission.
OECD, 2015: Overview of costs and benefits of adaptation at national and regional scale. In: *Climate Change Risks and Adaptation: LInking Policy and Economics*. OCED Publishing, Paris, pp. 37-75.
OECD, 2016: *Converged Statistical Reporting Directives for the Creditor Reporting System (CRS) and the Annual DAC Questionnaire*. Available at: https://www.oecd.org/dac/environment-development/Annex.
OECD, 2018a: *Climate-related Development Finance Data*. Available at: https://www.oecd.org/dac/financing-sustainable-development/development-finance-topics/climate-change.htm.
OECD, 2019a: *Results of the first survey on coefficients that Members apply to the Rio marker data when reporting to the UN Conventions on Climate Change and Biodiversity*. Available at: http://www.oecd.org/dac/financing-sustainable-development/Results.
OECD, 2020: *Climate Finance Provided and Mobilised by Developed Countries in 2013-18*. Publishing, O., Paris. Available at: https://doi.org/10.1787/f0773d55-en (accessed 2021/08/15).
Ohunakin, O. S., M. S. Adaramola, O. M. Oyewola and R. O. Fagbenle, 2014: Solar energy applications and development in Nigeria: drivers and barriers. *Renewable and Sustainable Energy Reviews*, **32**, 294-301.
Ojha and et al., 2019: Improving science-policy interface: Lessons from the policy lab methodology in Nepal's community forest governance. *Forest Policy and Economics*, 101997-101997.
Olazabal, M. et al., 2019a: A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, **14**(12), 124056-124056.
Olazabal, M. et al., 2019b: Are local climate adaptation policies credible? A conceptual and operational assessment framework. *International Journal of Urban Sustainable Development*, **11**(3), 277-296, doi:10.1080/19463138.2019.1583234.
Olivier, J., T. Leiter and J. Linke, 2013: *Adaptation made to measure: a guidebook to the design and results-based monitoring of climate change adaptation projects*, Second Edi ed., Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.
Olsson, L. et al., 2014: Livelihoods and Poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793-832. ISBN 9781107058071.
Omari-Motsumi, K., M. Barnett and L. Schalatek, 2019: *Broken Connections and Systemic Barriers: Overcoming the Challenge of the 'Missing Middle' in Adaptation Finance*. Background Paper for Global Comission on Adaptation. Available at: https://us.boell.org/en/2020/01/10/broken-connections-and-systemic-barriers-overcoming-challenge-missing-middle-adaptation.
Omukuti, J., 2020: Challenging the obsession with local level institutions in country ownership of climate change adaptation. *Land Use Policy*, **94**, 104525-104525.
Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Orleans Reed, S. et al., 2013: "Shared learning" for building urban climate resilience-experiences from Asian cities. *Environment and Urbanization*, **25**(2), 393-412, doi:10.1177/0956247813501136.
Orlove, B., R. Shwom, E. Markowitz and S.-M. Cheong, 2020: Climate Decision-Making. *Annual Review of Environment and Resources*, **45**(1), 271-303, doi:10.1146/annurev-environ-012320-085130.

Orsato, R. J., J. G. Ferraz de Campos and S. R. Barakat, 2018: Social Learning for Anticipatory Adaptation to Climate Change: Evidence From a Community of Practice. *Organization and Environment*, doi:10.1177/1086026618775325.
Oshri, B. et al., 2018: Infrastructure Quality Assessment in Africa using Satellite Imagery and Deep Learning. ACM, 616-625 pp.
Ostovar, A. L., 2019: Investing upstream: Watershed protection in Piura, Peru. *Environmental Science and Policy*, **96**, 9-17, doi:10.1016/j.envsci.2019.02.005.
Oswald, K. and P. Taylor, 2010: A Learning Approach to Monitoring and Evaluation. *IDS Bulletin*, **41**(6), 115-120.
Otto, F. E. et al., 2020: Towards an inventory of the impacts of human-induced climate change. *Bulletin of the American Meteorological Society*, 1-17.
Otto, I. M. et al., 2015: Socio-economic data for global environmental change research. *Nature Climate Change*, **5**(6), 503-506.
Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**(102071).
Pace, M. L., S. R. Carpenter and J. J. Cole, 2015: With and without warning: managing ecosystems in a changing world. *Frontiers in Ecology and the Environment*, **13**(9), 460-467, doi:10.1890/150003.
Page, E. A. and C. Heyward, 2017: Compensating for climate change loss and damage. *Political Studies*, **65**(2), 356-372.
Page, R. and L. Dilling, 2020: How experiences of climate extremes motivate adaptation among water managers. *Climatic Change*, **161**(3), 499-516, doi:10.1007/s10584-020-02712-7.
Paleari, S., 2019: Disaster risk insurance: A comparison of national schemes in the EU-28. *International Journal of Disaster Risk Reduction*, **35**, 101059, doi:10.1016/j.ijdrr.2018.12.021.
Palutikof, J. P., R. B. Street and E. P. Gardiner, 2019a: Decision support platforms for climate change adaptation: an overview and introduction. *Climatic Change*, **153**(4), 459-476, doi:10.1007/s10584-019-02445-2.
Palutikof, J. P., R. B. Street and E. P. Gardiner, 2019b: Looking to the future: guidelines for decision support as adaptation practice matures. In: *Climatic Change*, pp. 643-655. ISBN 0165-0009 1573-1480.
Pandey, C. L. and R. M. Bajracharya, 2017: Climate Adaptive Water Management Practices in Small and Midsized Cities of Nepal: Case Studies of Dharan and Dhulikhel. *Sustainability: The Journal of Record*, **10**(5), 300-307, doi:10.1089/sus.2017.0008.
Papathanasiou, J., N. Ploskas and I. Linden, 2016: *Real-World Decision Support Systems: Case Studies*, 1 ed. Integrated Series in Information Systems, Springer International Publishing, Switzerland, 327 pp.
Parding, K. M. et al., 2020: GCMeval – An interactive tool for evaluation and selection of climate model ensembles. *Climate services*, **18**, 100167, doi:10.1016/j.cliser.2020.100167.
Park, S. E. et al., 2012: Informing adaptation responses to climate change through theories of transformation. *Global environmental change*, **22**(1), 115-126, doi:10.1016/j.gloenvcha.2011.10.003.
Parnell, G. S., D. W. Hughes, R. C. Burk and others, 2013: Invited review—Survey of value-focused thinking: Applications, research developments and areas for future research, 49-60 pp.
Partey, S. T. et al., 2020: Gender and climate risk management: evidence of climate information use in Ghana. *Climatic Change*, **158**(1), 61-75.
Partzsch, L., 2020: *Alternatives to Multilateralism: New Forms of Social and Environmental Governance*. Earth System Governance, MIT Press. ISBN 9780262539227.
Pauw, P. W., C. Grüning and C. Menzel, 2020: *Number of beneficiaries as an indicator for adaptation: do the numbers add up?* GCF Monitor, FS-UNEP Collaboration Centre of the Frankfurt School of Finance and Management.
Pauw, W. P., R. J. T. Klein, P. Vellinga and F. Biermann, 2016: Private finance for adaptation: do private realities meet public ambitions? *Climatic Change*, **134**(4), 489-503, doi:10.1007/s10584-015-1539-3.
Pearce, D., G. Atkinson and S. Mourato, 2006: Cost-benefit analysis and the environment: Recent developments. *Benefits Transfer*, doi:10.1787/9789264010055-en.
Pedrycz, W., P. Ekel and R. Parreiras, 2011: *Fuzzy multicriteria decision-making : models, methods and applications*. Wiley, Chichester, West Sussex, U.K, 360 pp. ISBN 9780470682258.
Peduzzi, P., 2017: Flooding: prioritizing protection? *Nature Climate Change*, **7**(9), 625.
Peel, J., H. Osofsky and A. Foerster, 2017: Shaping the 'next generation' of climate change litigation in Australia. *Melbourne University Law Review*, **41**, 793-844.
Peel, J. and H. M. Osofsky, 2015: *Climate Change Litigation: Regulatory Pathways to Cleaner Energy*. Cambridge Studies in International and Comparative Law, Cambridge University Press, Cambridge. ISBN 9781107036062.
Peel, J. and H. M. Osofsky, 2018: A Rights Turn in Climate Change Litigation? *Transnational Environmental Law*, **7**(1), 37-67, doi:10.1017/s2047102517000292.
Pelling, M. and M. Garschagen, 2019: Put equity first in climate adaptation. *Nature*, **569**(7756), 327-329, doi:10.1038/d41586-019-01497-9.
Perkins, R. and M. Nachmany, 2019: 'A very human business'—Transnational networking initiatives and domestic climate action. *Global Environmental Change*, **54**, 250-259, doi:10.1016/j.gloenvcha.2018.11.008.
Perrels, A., 2020: Quantifying the uptake of climate services at micro and macro level. *Climate services*, **17**, 100152, doi:10.1016/j.cliser.2020.100152.
Peters, B. G., 2018: *Policy problems and policy design*. Edward Elgar Publishing. ISBN 1786431351.

Peters, K. et al., 2019: Double vulnerability: The humanitarian implications of intersecting climate and conflict risk. *London: ODI, March*.
Peterson, T. R. and J. L. Thompson, 2020: Environmental risk communication: responding to challenges of complexity and uncertainty. Routledge, 591-606 pp.
Petridou, E. and M. Mintrom, 2020: A Research Agenda for the Study of Policy Entrepreneurs. *Policy Studies Journal*, doi:10.1111/psj.12405.
Pfirman, S. et al., 2021: "Stickier" learning through gameplay: An effective approach to climate change education. *Journal of Geoscience Education*, **69**(2), 192-206, doi:10.1080/10899995.2020.1858266.
Phan, T. D. et al., 2019: Applications of Bayesian Networks as Decision Support Tools for Water Resource Management under Climate Change and Socio-Economic Stressors: A Critical Appraisal, 26-42 pp.
Pickering, J., C. Betzold and J. Skovgaard, 2017: Special issue: managing fragmentation and complexity in the emerging system of international climate finance. *International Environmental Agreements: Politics, Law and Economics*, **17**(1), 1-16, doi:10.1007/s10784-016-9349-2.
Pickering, J., F. Jotzo and P. J. Wood, 2015: Sharing the Global Climate Finance Effort Fairly with Limited Coordination. *Global Environmental Politics*, **15**(4), 39-62, doi:10.1162/GLEP_a_00325.
Piggott, J. J., C. R. Townsend and C. D. Matthaei, 2015: Reconceptualizing synergism and antagonism among multiple stressors. *Ecol Evol*, **5**(7), 1538-1547, doi:10.1002/ece3.1465.
Pijnenburg, A., T. Gammeltoft-Hansen and C. Rijken, 2018: Controlling migration through international cooperation. *European Journal of Migration and Law*, **20**(4), 365-371.
Pill, M., 2021: Linking solidarity funds and philanthropic giving to finance loss and damage from climate change related slow-onset events. *Current opinion in environmental sustainability*, **v. 50**, pp. 169-174-2021 v.2050, doi:10.1016/j.cosust.2021.04.003.
Pillay, K., S. Aakre and A. Torvanger, 2017: *Mobilizing Adaptation Finance in Developing Countries*. **2**, Center for International Climate Research (CICERO), Olso, Norway.
Poesch, M. S. et al., 2016: Climate change impacts on freshwater fishes: a Canadian perspective. *Fisheries*, **41**(7), 385-391.
Pope, E. C. D., C. Buontempo and T. Economou, 2017: Quantifying how user-interaction can modify the perception of the value of climate information: A Bayesian approach. *Climate services*, **6**(C), 41-47, doi:10.1016/j.cliser.2017.06.006.
Porter, J. J., D. Demeritt and S. Dessai, 2015: The right stuff? informing adaptation to climate change in British Local Government. *Global Environmental Change*, **35**, 411-422, doi:10.1016/j.gloenvcha.2015.10.004.
Porter, J. J., S. Dessai and E. L. Tompkins, 2014: What do we know about UK household adaptation to climate change? A systematic review. *Clim Change*, **127**(2), 371-379, doi:10.1007/s10584-014-1252-7.
Posner, R. A., 2004: *Catastrophe: risk and response*. Oxford University Press. ISBN 0195178130.
Pot, W. D., A. Dewulf, G. R. Biesbroek and S. Verweij, 2019: What makes decisions about urban water infrastructure forward looking? A fuzzy-set qualitative comparative analysis of investment decisions in 40 Dutch municipalities. *Land Use Policy*, **82**, 781-795, doi:10.1016/j.landusepol.2018.12.012.
Prabhat et al., 2021: ClimateNet: An expert-labeled open dataset and deep learning architecture for enabling high-precision analyses of extreme weather. *Geoscientific Model Development*, **14**(1), 107-124, doi:10.5194/gmd-14-107-2021.
Prem, R., S. Ohly, B. Kubicek and C. Korunka, 2017: Thriving on challenge stressors? Exploring time pressure and learning demands as antecedents of thriving at work. *Journal of Organizational Behavior*, **38**(1), 108-123, doi:10.1002/job.2115.
Preston, B., E. J. Yuen and R. M. Westaway, 2011: Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks. *Sustainability Science*, **6**, 177-202.
Preston, B. L., R. Westaway, S. Dessai and T. F. Smith (eds.), Are we adapting to climate change? Research and methods for evaluating progress. 89th American Meteorological Society Annual Meeting: Fourth Symposium on Policy and Socio-Economic Research, Phoenix, AZ, 1-15 pp.
Pretorius, C., 2017: Exploring procedural decision support systems for wicked problem resolution. *South African Computer Journal*, **29**(1), 191-219, doi:10.18489/sacj.v29i1.448.
Pretorius, L. et al., 2019: *An Embedded Researcher Approach to Integrate Climate Information into Decision Making in Southern African Cities: Lessons from FRACTAL*. FRACTAL Working Paper, **8**, Future Climate for Africa.
Price-Kelly, H., T. Leiter, J. Olivier and D. Hammill, 2015: *Developing national adaptation monitoring and evaluation systems: a guidebook*. Available at: https://www.adaptationcommunity.net/monitoring-evaluation/national-level-adaptation/.
Pringle, P., 2011: *AdaptME Toolkit: Adaptation Monitoring and Evaluation*. United Kingdom Climate Impacts Programme (UKCIP).
Prober, S. M. et al., 2017: Informing climate adaptation pathways in multi-use woodland landscapes using the values-rules-knowledge framework. *Agriculture, ecosystems & environment*, **241**, 39-53, doi:10.1016/j.agee.2017.02.021.
Prokopy, L. S. et al., 2017: Useful to Usable: Developing usable climate science for agriculture. *Climate risk management*, **15**(C), 1-7, doi:10.1016/j.crm.2016.10.004.
Prokopy, L. S. and R. Power, 2015: Envisioning New Roles for Land-Grant University Extension: Lessons Learned from Climate Change Outreach in the Midwest. *Journal of Extension*, **53**(6).

Pulido, L., E. Kohl and N. M. Cotton, 2016: State Regulation and Environmental Justice: The Need for Strategy Reassessment. *Capitalism, Nature, Socialism*, **27**(2), 12-31, doi:10.1080/10455752.2016.1146782.
Pulver, S., 2011: Corporate Responses. In: *The Oxford Handbook of Climate Change and Society* [Dryzek, J. S., R. B. Norgaard and D. Schlosberg (eds.)]. Oxford University Press, New York.
Puri, J., A. Rastogi, M. Prowse and S. Asfaw, 2020: Good will hunting: Challenges of theory-based impact evaluations for climate investments in a multilateral setting. *World Development*, **127**, 104784, doi:https://doi.org/10.1016/j.worlddev.2019.104784.
Qiao, X.-J., A. Kristoffersson and T. B. Randrup, 2018: Challenges to implementing urban sustainable stormwater management from a governance perspective: A literature review. *Journal of Cleaner Production*, **196**, 943-952, doi:https://doi.org/10.1016/j.jclepro.2018.06.049.
Quinn, J. et al., 2017: Public health crisis: the need for primary prevention in failed and fragile states. *Central European journal of public health*, **25**(3), 171-176.
Radel, C., B. Schmook, L. Carte and S. Mardero, 2018: Toward a political ecology of migration: Land, labor migration, and climate change in northwestern Nicaragua. *World Development*, **108**, 263-273.
Rahman, M. H. u. et al., 2020: Climate Resilient Cotton Production System: A Case Study in Pakistan. In: *Cotton Production and Uses: Agronomy, Crop Protection, and Postharvest Technologies* [Ahmad, S. and M. Hasanuzzaman (eds.)]. Springer Singapore, Singapore, pp. 447-484. ISBN 978-981-15-1472-2.
Rai, N., S. Best and M. Soanes, 2016: *Unlocking climate finance for decentralised energy access*. Working Paper, IIED. ISBN 9781784313593.
Rai, N. and S. Fisher, 2017: *The Political Economy of Low Carbon Resilient Development: planning and implementation*. Routledge. ISBN 9781138393431.
Ramsey, M. M. et al., 2019: Overcoming barriers to knowledge integration for urban resilience: A knowledge systems analysis of two-flood prone communities in San Juan, Puerto Rico. *Environmental science & policy*, **99**, 48-57, doi:10.1016/j.envsci.2019.04.013.
Ranabhat, S. et al., 2018: Policy Coherence and Interplay between Climate Change Adaptation Policies and the Forestry Sector in Nepal. *Environmental Management*, **61**, doi:10.1007/s00267-018-1027-4.
Ranger, N., T. Reeder and J. Lowe, 2013: Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO Journal on Decision Processes*, **1**(3), 233-262, doi:10.1007/s40070-013-0014-5.
Rao, N. et al., 2020: Managing risk, changing aspirations and household dynamics: Implications for wellbeing and adaptation in semi-arid Africa and India. *World Development*, **125**, 104667.
Rasel, H., M. Hasan, B. Ahmed and M. Miah, 2013: Investigation of soil and water salinity, its effect on crop production and adaptation strategy. *International journal of water resources and Environmental Engineering*, **5**(8), 475-481.
Rasmus, S. et al., 2020: Climate change and reindeer management in Finland: Co-analysis of practitioner knowledge and meteorological data for better adaptation. *Science of the Total Environment*, **710**, doi:10.1016/j.scitotenv.2019.136229.
Rathwell, K. J., D. Armitage and F. Berkes, 2015: Bridging knowledge systems to enhance governance of the environmental commons: A typology of settings. *International Journal of the Commons*, **9**(2), 851-880, doi:10.18352/ijc.584.
Raz, T. and E. Micheal, 2001: Use and benefit of tools for project risk management. *International Journal of Project Management*, **19**(1), 9-17.
Reckien, D., 2014: Weather extremes and street life in India—Implications of Fuzzy Cognitive Mapping as a new tool for semi-quantitative impact assessment and ranking of adaptation measures. *Global Environmental Change*, **26**, 1-13.
Reckien, D., 2018: What is in an index? Construction method, data metric, and weighting scheme determine the outcome of composite social vulnerability indices in New York City. *Regional Environmental Change*, **18**(5), 1439-1451.
Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environment and Urbanization*, **29**(1), 159-182.
Reckien, D., J. Flacke, M. Olazabal and O. Heidrich, 2015: The Influence of Drivers and Barriers on Urban Adaptation and Mitigation Plans-An Empirical Analysis of European Cities. *PLoS One*, **10**(8), e0135597, doi:10.1371/journal.pone.0135597.
Reckien, D. and M. K. B. Luedeke, 2014: The Social Dynamics of Suburbanization: Insights from a Qualitative Model. *Environment and Planning A: Economy and Space*, **46**(4), 980-1000, doi:10.1068/a4639.
Reckien, D. et al., 2018b: Equity, environmental justice, and urban climate change. *Climate change and cities: Second assessment report of the urban climate change research network*, 173-224.
Reckien, D. and E. P. Petkova, 2019: Who is responsible for climate change adaptation? *Environmental Research Letters*, **14**(014010).
Reckien, D. et al., 2018a: How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *Journal of Cleaner Production*, **191**, 207-219, doi:10.1016/j.jclepro.2018.03.220.
Reckien, D. et al., 2019: Dedicated versus mainstreaming approaches in local climate plans in Europe. *Renewable and Sustainable Energy Reviews*, **112,** 948-959, doi: https://doi.org/10.1016/j.rser.2019.05.014

Reckien, D., M. Wildenberg and M. Bachhofer, 2013: Subjective realities of climate change: how mental maps of impacts deliver socially sensible adaptation options. *Sustainability Science*, **8**(2), 159-172, doi:10.1007/s11625-012-0179-z.
Reguero, B. G. et al., 2020: Financing coastal resilience by combining nature-based risk reduction with insurance. *Ecological Economics*, **169**, 106487, doi:https://doi.org/10.1016/j.ecolecon.2019.106487.
Reid, H., 2016: Ecosystem-and community-based adaptation: learning from community-based natural resource management. *Climate and development*, **8**(1), 4-9.
Reilly, T. and R. T. Clemen, 2013: *Making Hard Decisions with Decision Tools*. South-Western Cengage Learning. ISBN 9781285708348.
Reis, J. and J. Shortridge, 2020: Impact of Uncertainty Parameter Distribution on Robust Decision Making Outcomes for Climate Change Adaptation under Deep Uncertainty. *Risk Anal*, **40**(3), 494-511, doi:10.1111/risa.13405.
Renner, T. and S. Meijerink, 2018: Policy entrepreneurs in international river basins—getting climate adaptation on the cross-border water policy agenda. *Regional Environmental Change*, **18**(5), 1287-1298, doi:10.1007/s10113-017-1178-5.
Resch, E., S. Allan, L. G. Álvarez and H. Bisht, 2017: *Mainstreaming, accessing and institutionalising finance for climate change adaptation*. Learning Paper, Action on Climate Today.
Resurrección, B. P. et al., 2019: *Gender-Transformative Climate Change Adaptation: Advancing Social Equity*. ackground paper to the 2019 report of the Global Commission on Adaptation, Stockholm Environment Institute. Available at: https://www.sei.org/publications/gender-transformative-climate-change-adaptation-advancing-social-equity/.
Revi, A. et al., 2020: Transformative adaptation in cities. *One Earth*, **3**(4), 384-387.
Reynolds, C. J., G. W. Horgan, S. Whybrow and J. I. Macdiarmid, 2019: Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK. *Public Health Nutr*, **22**(8), 1503-1517, doi:10.1017/s1368980018003774.
Richards, G. W., 2018: The Science–Policy Relationship Hierarchy (SPRHi) model of co-production: how climate science organizations have influenced the policy process in Canadian case studies. *Policy sciences*, **52**(1), 67-95, doi:10.1007/s11077-018-9328-2.
Richards, R. et al., 2013: Bayesian belief modeling of climate change impacts for informing regional adaptation options. *Environmental modelling & software : with environment data news*, **44**, 113-121, doi:10.1016/j.envsoft.2012.07.008.
Richards, R. G., M. Sanò and O. Sahin, 2016: Exploring climate change adaptive capacity of surf life saving in Australia using Bayesian belief networks. *Ocean & coastal management*, **120**, 148-159, doi:10.1016/j.ocecoaman.2015.11.007.
Richmond, M. and K. Hallmeyer, 2019: *Tracking Adaptation Finance: Advancing Methods to Capture Finance Flows in the Landscape* [Initiative, C. P. (ed.)]. A CPI Climate Finance Tracking Brief. Available at: https://climatepolicyinitiative.org/wp-content/uploads/2019/12/Tracking-Adaptation-Finance-Brief.pdf.
Richmond, M. et al., 2020: *A Snapshot of Global Adaptation Investment and Tracking Methods*. Climate Policy Initiative. Available at: https://www.climatepolicyinitiative.org/publication/a-snapshot-of-global-adaptation-investment-and-tracking-methods/.
Richmond, M., N. Upadhyaya and A. O. Pastor, 2021: *An Analysis of Urban Climate Adaptation Finance* [Alliance, C. C. F. L. (ed.)]. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2021/02/An-Analysis-of-Urban-Climate-Adaptation-Finance.pdf.
Ricke, K., L. Drouet, K. Caldeira and M. Tavoni, 2018: Country-level social cost of carbon. *Nature Climate Change*, **8**(10), 895-900, doi:10.1038/s41558-018-0282-y.
Río, P. d. and M. P. Howlett, 2013: Beyond the 'Tinbergen Rule' in Policy Design: Matching Tools and Goals in Policy Portfolios. *Lee Kuan Yew School of Public Policy Research Paper Series*.
Rios Insua, D., 1990: *Sensitivity Analysis in Multi-objective Decision Making*, 1 ed. Lecture Notes in Economics and Mathematical Systems, Springer-Verlag, Berlin Heidelberg, 193 pp.
Rios Insua, D., 1999: Sensitivity Analysis in MCDA. *Journal of Multi-Criteria Decision Analysis*, **8**(3), 117-187, doi:10.1002/(SICI)1099-1360(199905)8:3<117::AID-MCDA251>3.0.CO;2-5.
Rios Insua, D. and F. Ruggeri, 2000: Robust Bayesian Analysis. Lecture Notes in Statistics, Springer-Verlag, New York, 422 pp. Available at: https://www.springer.com/gp/book/9780387988665#aboutBook.
Rizzo, A. et al., 2020: The Agadir platform: a transatlantic cooperation to achieve sustainable drylands. In: *Stewardship of Future Drylands and Climate Change in the Global South*. Springer, pp. 227-251.
Roberts, D., J. Douwes, C. Sutherland and V. Sim, 2020: Durban's 100 Resilient Cities journey: governing resilience from within. *Environment and urbanization*, **32**(2), 547-568, doi:10.1177/0956247820946555.
Roberts, J. T. et al., 2017: How will we pay for loss and damage? *Ethics, Policy & Environment*, **20**(2), 208-226.
Roberts, J. T. and R. Weikmans, 2017: Postface: fragmentation, failing trust and enduring tensions over what counts as climate finance. *International Environmental Agreements: Politics, Law and Economics*, **17**(1), 129-137, doi:10.1007/s10784-016-9347-4.
Roberts, J. T. et al., 2021: Rebooting a failed promise of climate finance. *Nature Climate Change*, **11**(3), 180-182, doi:10.1038/s41558-021-00990-2.
Robertson, J. and J. Barling, 2015: *The Psychology of Green Organizations*. ISBN -13: 9780199997480.

Robins, S., 2019: 'Day Zero', Hydraulic Citizenship and the Defence of the Commons in Cape Town: A Case Study of the Politics of Water and its Infrastructures (2017–2018). *Journal of Southern African Studies*, doi:10.1080/03057070.2019.1552424.
Robinson, J. P. et al., 2020: Diversification insulates fisher catch and revenue in heavily exploited tropical fisheries. *Science advances*, **6**(8), eaaz0587.
Robinson, S.-a., 2018: Adapting to climate change at the national level in Caribbean small island developing states. *Island Studies Journal*, **13**(1).
Robinson, S.-a. et al., 2021: Financing loss and damage from slow onset events in developing countries. *Current Opinion in Environmental Sustainability*, **50**, 138-148.
Robinson, S. and C. Wren, 2020: Geographies of vulnerability: A research note on human system adaptations to climate change in the Caribbean. *Geografisk Tidsskrift-Danish Journal of Geography*, 1-8.
Roehrer, C. and K. E. Kouadio, 2015: Monitoring, Reporting, and Evidence-Based Learning in the Climate Investment Funds' Pilot Program for Climate Resilience. *New Directions for Evaluation*, **147**, 129-145.
Roelich, K. and J. Giesekam, 2019: Decision making under uncertainty in climate change mitigation: introducing multiple actor motivations, agency and influence. *Climate Policy*, **19**(2), 175-188, doi:10.1080/14693062.2018.1479238.
Rolnick, D. et al., 2019: Tackling Climate Change with Machine Learning.
Romero-Lankao, P. et al., 2018: Urban transformative potential in a changing climate. *Nature Climate Change*, **8**(9), 754-756.
Roncoli, C., T. Crane and B. Orlove, 2016: Fielding climate change in cultural anthropology. In: *Anthropology and climate change*. Routledge, pp. 87-115. ISBN 1315434776.
Rosenhead, J., 2001: Robust Analysis: Keeping Your Options Open. In: *Rational Analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty, and Conflict* [Rosenhead, J. and J. Mingers (eds.)]. John Wiley & Sons, Chichester, United Kingdom, pp. 181-207.
Rosenhead, J. and J. Mingers, 2001: *Rational Analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty and Conflict, 2nd Edition*. John Wiley and Sons, 386 pp. ISBN 9780471495239.
Rosenow, J., F. Kern and K. Rogge, 2017: The need for comprehensive and well targeted instrument mixes to stimulate energy transitions: The case of energy efficiency policy. *Energy research & social science*, **33**, 95-104, doi:10.1016/j.erss.2017.09.013.
Rosenzweig, C. et al., 2017: Assessing inter-sectoral climate change risks: The role of ISIMIP. *Environmental Research Letters*, **12**(1), doi:10.1088/1748-9326/12/1/010301.
Rosenzweig, C. and W. Solecki, 2014: Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change*, **28**, 395-408.
Rosenzweig, C. and W. Solecki, 2018: Action pathways for transforming cities. *Nature Climate Change*, **8**(9), 756-759.
Roser, D., C. Huggel, M. Ohndorf and I. Wallimann-Helmer, 2015: Advancing the interdisciplinary dialogue on climate justice. *Climatic Change*, **133**(3), 349-359.
Rouillard, J. J. and C. J. Spray, 2016: Working across scales in integrated catchment management: lessons learned for adaptive water governance from regional experiences. *Regional Environmental Change*, **17**(7), 1869-1880, doi:10.1007/s10113-016-0988-1.
Rousseau, S. and N. Deschacht, 2020: Public Awareness of Nature and the Environment During the COVID-19 Crisis. *Environmental & resource economics*, **76**(4), 1149-1159, doi:10.1007/s10640-020-00445-w.
Roy, B., 1996: *Multicriteria Methodology for Decision Aiding*. Kluwer Academic Publishers (Springer-Verlag), Dordrecht, Netherlands.
Roy, J. et al., 2018: Sustainable development, poverty eradication and reducing inequalities. In: *Global Warming of 1.5° c*. IPCC: Intergovernmental Panel on Climate Change.
Rozenberg, J. and S. Hallegatte, 2015: *The Impacts of Climate Change on Poverty in 2030 and the Potential from Rapid, Inclusive, and Climate-Informed Development*. World Bank Policy Research Working Paper, **7483**, 52 pp.
Ruano, S. and A. Milan, 2014: *Climate change, rainfall patterns, livelihoods and migration in Cabricán, Guatemala*. United Nations University, I. f. E. a. H. S. U.-E., Bonn.
Rudel, T. K., 2019: Shocks, states, and societal corporatism: a shorter path to sustainability? *Journal of Environmental Studies and Sciences*, **9**(4), 429-436, doi:10.1007/s13412-019-00560-1.
Ruhl, J., 2010: Climate change adaptation and the structural transformation of environmental law. *Envtl. L.*, **40**, 363.
Ruiz-Mallén, I., 2020: Co-production and Resilient Cities to Climate Change. In: *Participatory Research and Planning in Practice* [Nared, J. and D. Bole (eds.)]. Springer International Publishing, Cham, pp. 1-11. ISBN 978-3-030-28014-7.
Rulleau, B. and H. Rey-Valette, 2017: Forward planning to maintain the attractiveness of coastal areas: Choosing between seawalls and managed retreat. *Environmental Science & Policy*, **72**, 12-19.
Rumble, O. (ed.), Climate change legislative development on the African continent. Law| Environment| Africa, Nomos Verlagsgesellschaft mbH & Co. KG, 31-60 pp. ISBN 3848752875.
Rumble, O., 2019b: Facilitating African Climate Change Adaptation Through Framework Laws. *Carbon & Climate Law Review*, **13**, doi:10.21552/cclr/2019/4/4.

Runhaar, H. et al., 2018: Mainstreaming climate adaptation: taking stock about "what works" from empirical research worldwide. *Regional Environmental Change*, **18**(4), 1201-1210, doi:10.1007/s10113-017-1259-5.
Rusca, M. et al., 2017: An interdisciplinary political ecology of drinking water quality. Exploring socio-ecological inequalities in Lilongwe's water supply network. *Geoforum*, **84**, 138-146, doi:10.1016/j.geoforum.2017.06.013.
Rusca, M., K. Schwartza, L. Hadzovica and R. Ahlers, 2015: Adapting Generic Models through Bricolage: Elite Capture of Water Users Associations in Peri-urban Lilongwe. *European Journal of Development Research*, **27**(5), 777-792.
Ryan, D. and E. Bustos, 2019: Knowledge gaps and climate adaptation policy: a comparative analysis of six Latin American countries. *Climate policy*, **19**(10), 1-13, doi:10.1080/14693062.2019.1661819.
Saarikoski, H. et al., 2016: Multi-Criteria Decision Analysis and Cost-Benefit Analysis: Comparing alternative frameworks for integrated valuation of ecosystem services. *Ecosystem services*, **22**, 238-249, doi:10.1016/j.ecoser.2016.10.014.
Saaty, T. L., 1980: *The Analytical Hierarchy Process*. McGraw-Hill., New York.
Saltelli, A., G. Bammer, I. Bruno and others, 2020: Five ways to ensure that models serve society: a manifesto. Nature Publishing Group.
Samuwai, J. and J. Hills, 2018: Assessing Climate Finance Readiness in the Asia-Pacific Region. *Sustainability*, **10**(4), 1192, doi:10.3390/su10041192.
Sanchez Rodriguez, R., D. Ürge-Vorsatz and A. S. Barau, 2018: Sustainable Development Goals and climate change adaptation in cities. *Nature Climate Change*, **8**(3), 181-183, doi:10.1038/s41558-018-0098-9.
Sandholz, S., W. Lange and U. Nehren, 2018: Governing green change: ecosystem-based measures for reducing landslide risk in Rio de Janeiro. *International journal of disaster risk reduction*, **32**, 75-86.
Sanson, A. V., J. Van Hoorn and S. E. L. Burke, 2019: Responding to the Impacts of the Climate Crisis on Children and Youth. *Child Development Perspectives*, **13**(4), 201-207, doi:10.1111/cdep.12342.
Sarewitz, D. R. and R. J. Byerly, 2000: *Prediction: science, decision making, and the future of nature*. Island Press.
Sarra, J., 2018: The Anthropocene in the Time of Trump, Financial Markets, Climate Change Risk, and Vulnerability. *UBS Law Review*, **51**(2), 489-547.
Sartzetakis, E. S., 2020: Green bonds as an instrument to finance low carbon transition. *Economic change and restructuring*, doi:10.1007/s10644-020-09266-9.
Sarzynski, A., 2015: Public participation, civic capacity, and climate change adaptation in cities. *Urban Climate*, **14**, 52-67, doi:10.1016/j.uclim.2015.08.002.
Sauter, V. L., 2014: Decision Support Systems for Business Intelligence, 2nd Edition. John Wiley & Sons.
Schäfer, L. and V. Künzel, 2019: *Steps towards closing the Loss & Damage finance gap*. German Watch. Available at: http://www.germanwatch.org/en/17301.
Schäfer, L., K. Warner and S. Kreft, 2019: Exploring and managing adaptation frontiers with climate risk insurance. In: *Loss and Damage from Climate Change*. Springer, pp. 317-341.
Schäfer, L. et al., 2016: *Making climate risk insurance work for the most vulnerable: Seven guiding principles* [(UNU-EHS), I. f. E. a. H. S. (ed.)]. United Nations University Policy Report 2016 No. 1 United Nations University (UNU).
Schalatek, L., 2020: *Gender and Climate Finance*. Climate Finance Fundamentals, **10**, Heinrich Böll Stiftung, Washington, DC. Available at: https://us.boell.org/en/2019/11/30/climate-finance-fundamentals-10-gender-and-climate-finance.
Scheidel, A. et al., 2020: Environmental conflicts and defenders: A global overview. *Global Environmental Change*, **63**, doi:10.1016/j.gloenvcha.2020.102104.
Schipper, E. L. F., 2020: Maladaptation: when adaptation to climate change goes very wrong. *One Earth*, **3**(4), 409-414.
Schipper, E. L. F., J. Ayers, H. Reid and S. Huq, 2014: *Community-based adaptation to climate change. Scaling it up*. Routledge, London, UK.
Schipper, L. and L. Langston, 2015: *A comparative overview of resilience measurement frameworks. Analysing indicators and approaches*.
Schipper, L. and M. Pelling, 2006: Disaster risk, climate change and international development: scope for, and challenges to, integration. *Disasters*, **30**(1), 19-38, doi:10.1111/j.1467-9523.2006.00304.x.
Schlosberg, D., L. B. Collins and S. Niemeyer, 2017: Adaptation policy and community discourse: risk, vulnerability, and just transformation. *Environmental Politics*, **26**(3), 413-437, doi:10.1080/09644016.2017.1287628.
Schneider, T., G. Michelon and M. Maier, 2017: Environmental liabilities and diversity in practice under international financial reporting standards. *Accounting, Auditing & Accountability Journal*, **30**(2), 378-403, doi:10.1108/AAAJ-01-2014-1585.
Schwan, S. and X. Yu, 2018: Social protection as a strategy to address climate-induced migration. *Management*, **10**(1), 43-64.
Scotford, E., S. Minas and A. Macintosh, 2017: Climate change and national laws across Commonwealth countries. *Commonwealth Law Bulletin*, **43**(3-4), 318-361.
Scott, D. et al., 2018: The Story of Water in Windhoek: A Narrative Approach to Interpreting a Transdisciplinary Process. *Water (Basel)*, **10**(10), 1366, doi:10.3390/w10101366.

Scussolini, P. et al., 2016: FLOPROS: an evolving global database of flood protection standards. *Natural Hazards and Earth System Sciences*, **16**(5), 1049-1061.
Sen, S. (ed.), Involving stakeholders in aquaculture policy-making, planning and management. Aquaculture in the Third Millennium». Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20-25 pp.
Seneviratne, S. I. et al., 2021: *Weather and Climate Extreme Events in a Changing Climate* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change
Serdeczny, O., 2019: Non-economic Loss and Damage and the Warsaw International Mechanism. In: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* [Mechler, R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, pp. 205-220. ISBN 978-3-319-72026-5.
Serrao-Neumann, S., G. Di Giulio and D. Low Choy, 2020: When salient science is not enough to advance climate change adaptation: Lessons from Brazil and Australia. *Environmental science & policy*, **109**, 73-82, doi:10.1016/j.envsci.2020.04.004.
Setzer, J. and L. C. Vanhala, 2019a: Climate change litigation: A review of research on courts and litigants in climate governance. *WIREs Climate Change*, **10**(3), e580, doi:10.1002/wcc.580.
Setzer, J. and L. C. Vanhala, 2019b: Climate change litigation: A review of research on courts and litigants in climate governance. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(3), e580.
Shackleton, S. et al., 2015: Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(3), 321-344, doi:10.1002/wcc.335.
Shafer, G., 1976: *A Mathematical Theory of Evidence*. Princeton University Press, Princeton, USA.
Shakya, C. and R. Byrnes, 2017: *Turning up the volume: Financial aggregation for off-grid energy*. Issue Paper, IIED, London. ISBN 9781784315429.
Shannak, S. d., D. Mabrey and M. Vittorio, 2018: Moving from theory to practice in the water–energy–food nexus: An evaluation of existing models and frameworks. *Water-Energy Nexus*, **1**(1), 17-25, doi:10.1016/j.wen.2018.04.001.
Sharifi, A., 2020: Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. *Journal of Cleaner Production*, **276**, doi:10.1016/j.jclepro.2020.122813.
Sharifi, A., 2021: Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. *The Science of the total environment*, **750**, 141642, doi:10.1016/j.scitotenv.2020.141642.
Shaw, D., A. Franco and M. Westcombe, 2006: Special Issue: Problem Structuring Methods I, 757-878 pp.
Shaw, D., A. Franco and M. Westcombe, 2007: Special Issue: Problem Structuring Methods II, 545-682 pp.
Shawoo, Z. and C. L. McDermott, 2020: Justice through polycentricity? A critical examination of climate justice framings in Pakistani climate policymaking. *Climate Policy*, **20**(2), 199-216, doi:10.1080/14693062.2019.1707640.
Sherman, M. H. and J. Ford, 2013: Stakeholder engagement in adaptation interventions: an evaluation of projects in developing nations. *Climate Policy*, **14**(3), 417-441, doi:10.1080/14693062.2014.859501.
Shi, R., B. F. Hobbs and H. Jiang, 2019: When can decision analysis improve climate adaptation planning? Two procedures to match analysis approaches with adaptation problems. *Climatic Change*, **157**(3-4), 611-630, doi:10.1007/s10584-019-02579-3.
Shockley, K. and M. Hourdequin, 2017: Addressing the Harms of Climate Change: Making Sense of Loss and Damage. *Ethics, Policy & Environment*, **20**(2), 125-128, doi:10.1080/21550085.2017.1342965.
Shortridge, J., S. Guikema and B. Zaitchik, 2016: Robust decision making in data scarce contexts: addressing data and model limitations for infrastructure planning under transient climate change. *Climatic Change*, **140**(2), 323-337, doi:10.1007/s10584-016-1845-4.
Shortridge, J. E. and S. D. Guikema, 2016: Scenario Discovery with Multiple Criteria: An Evaluation of the Robust Decision-Making Framework for Climate Change Adaptation. *Risk Anal*, **36**(12), 2298-2312, doi:10.1111/risa.12582.
Shukla, A. and C. Peyraud, 2017: *Klabin Green Bond: Framework Overview and Second Part Opinion by Sustainalytics*. Sustainalytics. Available at: https://www.sustainalytics.com/wp-content/uploads/2017/09/Klabin-Green-Bond-Framework-and-Opinion-08302017_FINAL.pdf.
Siciliano, G. and F. Urban, 2017: Equity-based natural resource allocation for infrastructure development: evidence from large hydropower dams in Africa and Asia. *Ecological Economics*, **134**, 130-139.
Siddiqi, A., 2018: Disasters in conflict areas: finding the politics. *Disasters*, **42 Suppl 2**, S161-S172, doi:10.1111/disa.12302.
Siddiqi, A., K. Peters and J. Zulver, 2019: 'Doble afectación': living with disasters and conflict in Colombia.
Siders, A., M. Hino and K. J. Mach, 2019: The case for strategic and managed climate retreat. *Science*, **365**(6455), 761-763.
Siders, A. R., 2017: A role for strategies in urban climate change adaptation planning: Lessons from London. *Regional Environmental Change*, **17**(6), 1801-1810.

Siegner, A. B., 2018: Experiential climate change education: Challenges of conducting mixed-methods, interdisciplinary research in San Juan Islands, WA and Oakland, CA. *Energy Research & Social Science*, **45**, 374-384, doi:10.1016/j.erss.2018.06.023.
Sietsma, A. J., J. D. Ford, M. W. Callaghan and J. C. Minx, 2021: Progress in climate change adaptation research. *Environmental Research Letters*, **16**(5), 054038.
Silvestrini, S., I. Bellino and S. Väth, 2015: *Impact Evaluation Guidebook for Climate Change Adaptation Projects*. Available at: https://www.adaptationcommunity.net/?wpfb_dl=260.
Simlinger, F. and B. Mayer, 2019: Legal responses to climate change induced loss and damage. In: *Loss and Damage from Climate Change*. Springer, pp. 179-203.
Simmons, B. A., R. Ray, H. Yang and K. P. Gallagher, 2021: China can help solve the debt and environmental crises. *Science*, **371**(6528), 468-470, doi:10.1126/science.abf4049.
Simpson, N. P. et al., 2021: *A framework for complex climate change risk assessment*. One Earth, vol. 4, 489-501 pp. ISBN 25903322.
Singh, C. et al., 2017: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and development*, **10**(5), 389-405, doi:10.1080/17565529.2017.1318744.
Singh, C., P. Dorward and H. Osbahr, 2016: Developing a holistic approach to the analysis of farmer decision-making: Implications for adaptation policy and practice in developing countries. *Land Use Policy*, **59**, 329-343, doi:10.1016/j.landusepol.2016.06.041.
Singh, C. et al., 2021: Interrogating 'effectiveness' in climate change adaptation: 11 guiding principles for adaptation research and practice. *Climate and Development*, 1-15, doi:10.1080/17565529.2021.1964937.
Singh, C. et al., 2019: Opening up the methodological toolkit on climate change vulnerability and adaptation research: reflections from using life history approaches. *Reg. Environ. Change*.
Singh, R., P. M. Reed and K. Keller, 2015: Many-objective robust decision making for managing an ecosystem with a deeply uncertain threshold response. *Ecology and Society*, **20**(3).
Sitati, A. et al., Accepted: Climate change adaptation in conflict-affected countries: A systematic assessment of evidence. *Climate and Development*.
Skelton, M. et al., 2017: The social and scientific values that shape national climate scenarios: a comparison of the Netherlands, Switzerland and the UK. *Regional environmental change*, **17**(8), 2325-2338, doi:10.1007/s10113-017-1155-z.
Slavíková, L., T. Hartmann and T. Thaler, 2021: Paradoxes of financial schemes for resilient flood recovery of households. *Wiley Interdisciplinary Reviews: Water*, **8**(2), e1497.
Sletto, B., S. Tabory and K. Strickler, 2019: Sustainable urban water management and integrated development in informal settlements: The contested politics of co-production in Santo Domingo, Dominican Republic. *Global environmental change*, **54**, 195-202, doi:10.1016/j.gloenvcha.2018.12.004.
Slotte, S. and R. P. Hämäläinen, 2014: Decision Structuring Dialogue, 141-159 pp.
Smet, K. S. M., 2017: Engineering options: A proactive planning approach for aging water resource infrastructure under uncertainty. Harvard University.
Smith, J. B. et al., 2011: Development and climate change adaptation funding: coordination and integration. *Climate Policy*, **11**(3), 987-1000, doi:10.1080/14693062.2011.582385.
Smith, J. Q., 2010: Bayesian decision analysis : principles and practice.
Smith, P. et al., 2020: Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Global change biology*, **26**(3), 1532-1575.
Snowden, D., 2002: Complex acts of knowing: paradox and descriptive self awareness. *Journal of Knowledge Management*, **62**(2), 100-111.
Soanes, M. et al., 2017: *Delivering real change: getting international climate finance to the local level*. Working Paper, IIED.
Solecki, W. et al., In Press: Accelerating Climate Research and Action in Cities through Advanced Science-Policy-Practice Partnerships. *Nature Urban Sustainabilty*.
Solecki, W. et al., 2019: Extreme events and climate adaptation-mitigation linkages: Understanding low-carbon transitions in the era of global urbanization. *WIREs Climate Change*, **10**(6), e616, doi:10.1002/wcc.616.
Solecki, W., M. Pelling and M. Garschagen, 2017: Transitions between risk management regimes in cities. *Ecology and Society*, **22**(2), doi:10.5751/ES-09102-220238.
Son, H. N., D. T. L. Chi and A. Kingsbury, 2019: Indigenous knowledge and climate change adaptation of ethnic minorities in the mountainous regions of Vietnam: A case study of the Yao people in Bac Kan Province. *Agricultural systems*, **176**, 102683, doi:10.1016/j.agsy.2019.102683.
Spearman, M. and H. McGray, 2011: *Making adaptation count: concepts and options for monitoring and evaluation of climate change adaptation*. Available at: http://star-www.giz.de/dokumente/bib-2011/giz2011-0219en-monitoring-evaluation-climate-change.pdf.
Spencer, B. et al., 2016: Case studies in co-benefits approaches to climate change mitigation and adaptation. *Journal of Environmental Planning and Management*, **60**(4), 647-667, doi:10.1080/09640568.2016.1168287.

Sperotto, A. et al., 2017: Reviewing Bayesian Networks potentials for climate change impacts assessment and management: A multi-risk perspective. *Journal of environmental management*, **202**(Pt 1), 320-331, doi:10.1016/j.jenvman.2017.07.044.

Sperotto, A. et al., 2019: A Bayesian Networks approach for the assessment of climate change impacts on nutrients loading. *Environmental science & policy*, **100**, 21-36, doi:10.1016/j.envsci.2019.06.004.

Spetzler, C. S., H. Winter and J. Meyer, 2016: Decision Quality: Value Creation from Better Business Decisions. John Wiley & Sons, Hoboken.

Sriver, R. L., R. J. Lempert, P. Wikman-Svahn and K. Keller, 2018: Characterizing uncertain sea-level rise projections to support investment decisions. *PLOS ONE*, **13**(2), e0190641, doi:10.1371/journal.pone.0190641.

Steed, C. A. et al., 2013: Big data visual analytics for exploratory earth system simulation analysis. *Computers & geosciences*, **61**, 71-82, doi:10.1016/j.cageo.2013.07.025.

Steele, P., 2015: *Development finance and climate finance: achieving zero poverty and zero emissions*. vol. 16587IIED, IIED, London, 32 pp. ISBN 9781784311698.

Steele, P. and S. Patel, 2020: *Tackling the triple crisis: Using debt swaps to address debt, climate and nature loss post-COVID-19*. Issue Paper, International Institute for, E. and Development, London. Available at: https://pubs.iied.org/16674iied?a=S%20Patel (accessed 2021/86/26).

Stegmaier, P., R. Hamaker-Taylor and E. Jiménez Alonso, 2020: Reflexive climate service infrastructure relations. *Climate services*, **17**, 100151, doi:10.1016/j.cliser.2020.100151.

Stelzenmuller, V. et al., 2018: A risk-based approach to cumulative effect assessments for marine management. *Sci Total Environ*, **612**, 1132-1140, doi:10.1016/j.scitotenv.2017.08.289.

Stephens, S. A., R. G. Bell and J. Lawrence, 2017: Applying principles of uncertainty within coastal hazard assessments to better support coastal adaptation. *Journal of Marine Science and Engineering*, **5**(3), 40.

Stephens, S. A., R. G. Bell and J. Lawrence, 2018: Developing signals to trigger adaptation to sea-level rise. *Environmental Research Letters*, **13**(10), 104004, doi:10.1088/1748-9326/aadf96.

Stern, P. C. et al., 2016: Opportunities and insights for reducing fossil fuel consumption by households and organizations. *Nature Energy*, **1**(5), 16043, doi:10.1038/nenergy.2016.43.

Stewart, T. J., S. French and J. Rios, 2013: Integrating multicriteria decision analysis and scenario planning—Review and extension. *Omega*, **41**(4), 679-688, doi:https://doi.org/10.1016/j.omega.2012.09.003.

Stezer, J. and R. Byrnes, 2019: *Global trends in climate change litigation: 2019 snapshot*. Policy Publication, Grantham Research Institute on Climate Change and the Environment and Centre for Climate change Economics and Policy, London. Available at: https://www.lse.ac.uk/granthaminstitute/publication/global-trends-in-climate-change-litigation-2019-snapshot/.

Stone, D., 2019: Transnational policy entrepreneurs and the cultivation of influence: individuals, organizations and their networks. *Globalizations*, **16**(7), 1128-1144, doi:10.1080/14747731.2019.1567976.

Street, R. B. et al., 2019: How could climate services support disaster risk reduction in the 21st century. *International Journal of Disaster Risk Reduction*, **34**, 28-33, doi:10.1016/j.ijdrr.2018.12.001.

Street, R. B. and S. Jude, 2019: Enhancing the value of adaptation reporting as a driver for action: lessons from the UK. *Climate Policy*, **19**(10), 1340-1350, doi:10.1080/14693062.2019.1652141.

Streimikiene, D. and T. Balezentis, 2013: Multi-objective ranking of climate change mitigation policies and measures in Lithuania. *Renewable & sustainable energy reviews*, **18**, 144-153, doi:10.1016/j.rser.2012.09.040.

Stults, M. and S. C. Woodruff, 2017: Looking under the hood of local adaptation plans: shedding light on the actions prioritized to build local resilience to climate change. *Mitigation and Adaptation Strategies for Global Change*, **22**(8), 1249-1279.

Surminski, S., 2013: Private-sector adaptation to climate risk. *Nature Climate Change*, **3**(11), 943-945, doi:10.1038/nclimate2040.

Surminski, S., L. M. Bouwer and J. Linnerooth-Bayer, 2016: How insurance can support climate resilience. *Nature climate change*, **6**(4), 333-334, doi:10.1038/nclimate2979.

Sutter, D., 2013: Broadcast meteorology and the supply of weather forecasts: An exploration. *Journal of Economics and Finance*, **37**(3), 463-477, doi:10.1007/s12197-011-9186-7.

Swanson, D., Suruchi Bhadwal, eds. 2009. *Creating Adaptive Policies: A Guide for Policy-Making in an Uncertain World*.

Sylvester, Z. T. and C. M. Brooks, 2020: Protecting Antarctica through Co-production of actionable science: Lessons from the CCAMLR marine protected area process. *Marine policy*, **111**, 103720, doi:10.1016/j.marpol.2019.103720.

Symstad, A. J. et al., 2017: Multiple methods for multiple futures: Integrating qualitative scenario planning and quantitative simulation modeling for natural resource decision making. *Climate risk management*, **17**(C), 78-91, doi:10.1016/j.crm.2017.07.002.

Szabo, S. et al., 2016: Making SDGs Work for Climate Change Hotspots. *Environment: Science and Policy for Sustainable Development*, **58**(6), 24-33, doi:10.1080/00139157.2016.1209016.

Tàbara, J. D., J. Jäger, D. Mangalagiu and M. Grasso, 2019: Defining transformative climate science to address high-end climate change. *Regional Environmental Change*, **19**(3), 807-818.

Taberna, A., T. Filatova, D. Roy and B. Noll, 2020: Tracing resilience, social dynamics and behavioral change: a review of agent-based flood risk models. *Socio-Environmental Systems Modelling*, **2**, 17938-17938.

Takahashi, B. et al., 2016: Climate change perceptions of NY state farmers: the role of risk perceptions and adaptive capacity. *Environmental management*, **58**(6), 946-957.
Taner, M. Ü., P. Ray and C. Brown, 2017: Robustness-based evaluation of hydropower infrastructure design under climate change. *Climate risk management*, **18**(C), 34-50, doi:10.1016/j.crm.2017.08.002.
Tanner, T. et al., 2019: Influencing resilience: the role of policy entrepreneurs in mainstreaming climate adaptation. *Disasters*, **43**(S3), S388-S411, doi:10.1111/disa.12338.
Tardy, F. and B. Lee, 2019: Building related energy poverty in developed countries – Past, present, and future from a Canadian perspective. *Energy and Buildings*, **194**, 46-61, doi:10.1016/j.enbuild.2019.04.013.
Taylor, A., 2016a: Urban Adaptation. In: *Climate change law and governance in South Africa* [Gilder, A., T. L. Humby, L. Kotzé and O. Rumble (eds.)]. Juta, South Africa. ISBN 9781485118824.
Taylor, M., 2015: *The Political Ecology of Climate Change Adaptation: Livelihoods, Agrarian Change and the Conflicts of Development*. Routledge, London, UK.
Taylor, M., 2016b: Risky Ventures: Financial Inclusion, Risk Management and the Uncertain Rise of Index-Based Insurance. In: *Risking Capitalism*. Emerald Group Publishing Limited, pp. 237-266. ISBN 978-1-78635-236-1 978-1-78635-235-4.
Taylor, M. and S. Bhasme, 2018: Model Farmers, Extension Networks and the Politics of Agricultural Knowledge Transfer. *Journal of Rural Studies*, **64**, 1-10.
Taylor, M. and S. Bhasme, 2020: Between deficit rains and surplus populations: The political ecology of a climate-resilient village in South India. *Geoforum*.
TCFD, 2017: *Implementing the Recommendations of the Task Force on Climate-related Financial Disclosures*. Task Force on Climate-related Financial Disclosures.
TCFD, 2020: *Task Force on Climate-related Financial Disclosures: Status Report*. Disclosures, T. F. o. C.-r. F.
Tempels, B. and T. Hartmann, 2014: A co-evolving frontier between land and water: dilemmas of flexibility versus robustness in flood risk management. *Water International*, **39**(6), 872-883, doi:10.1080/02508060.2014.958797.
Tengö, M. et al., 2014: Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. *Ambio*, **43**(5), 579-591, doi:10.1007/s13280-014-0501-3.
Teo, H. C. et al., 2019: Environmental impacts of infrastructure development under the belt and road initiative. *Environments*, **6**(6), 72.
Thackeray, S. J. et al., 2020: Civil disobedience movements such as School Strike for the Climate are raising public awareness of the climate change emergency. *Global change biology*, **26**(3), 1042-1044, doi:10.1111/gcb.14978.
Thirawat, N., S. Udompol and P. Ponjan, 2017: Disaster risk reduction and international catastrophe risk insurance facility. *Mitigation Adaptation Strategies for Global Change*, **22**(7), 1021-1039.
Thomas, A. et al., 2020: Climate change and small island developing states. *Annual Review of Environment and Resources*, **45**, 1-27.
Thomas, A. and L. Benjamin, 2017: Management of loss and damage in small island developing states: implications for a 1.5 °C or warmer world. *Regional Environmental Change*, **18**(8), 2369-2378, doi:10.1007/s10113-017-1184-7.
Thomas, K. et al., 2019: Explaining differential vulnerability to climate change: A social science review. *Wiley Interdiscip Rev Clim Change*, **10**(2), e565, doi:10.1002/wcc.565.
Thomas, K. A. and B. P. Warner, 2019: Weaponizing vulnerability to climate change. *Global Environmental Change*, **57**, 101928-101928, doi:10.1016/j.gloenvcha.2019.101928.
Thorn, J., T. F. Thornton and A. Helfgott, 2015: Autonomous adaptation to global environmental change in peri-urban settlements: Evidence of a growing culture of innovation and revitalisation in Mathare Valley Slums, Nairobi. *Global Environmental Change*, **31**, 121.
Tittensor, D. P. et al., 2018: A protocol for the intercomparison of marine fishery and ecosystem models: Fish-MIP v1.0. *Geosci. Model Dev.*, **11**(4), 1421-1442, doi:10.5194/gmd-11-1421-2018.
Tompkins, E. L., K. Vincent, R. J. Nicholls and N. Suckall, 2018: Documenting the state of adaptation for the global stocktake of the Paris Agreement. *Wiley Interdisciplinary Reviews: Climate Change*, **9**(5), doi:10.1002/wcc.545.
Tonmoy, F. N., D. Wainwright, D. C. Verdon-Kidd and D. Rissik, 2018: An investigation of coastal climate change risk assessment practice in Australia. *Environmental Science & Policy*, **80**, 9-20, doi:10.1016/j.envsci.2017.11.003.
Torabi, E., A. Dedekorkut-Howes and M. Howes, 2018: Adapting or maladapting: Building resilience to climate-related disasters in coastal cities. *Cities*, **72**, 295-309.
Tormos-Aponte, F. and G. A. García-López, 2018: Polycentric struggles: The experience of the global climate justice movement. *Environmental Policy and Governance*, **28**(4), 284-294, doi:10.1002/eet.1815.
Torresan, S. et al., 2016: DESYCO: A decision support system for the regional risk assessment of climate change impacts in coastal zones. *Ocean and Coastal Management*, **120**, 49-63, doi:10.1016/j.ocecoaman.2015.11.003.
Toussaint, P. and A. Martinez Blanco, 2020: A human rights-based approach to loss and damage under the climate change regime. *Climate policy*, **20**(6), 743-757.
Townshend, T. et al., 2011: Legislating climate change on a national level. *Environment: Science and Policy for Sustainable Development*, **53**(5), 5-17.
Townshend, T. and A. Matthews, 2013: *National climate change legislation: the key to more ambitious international agreements*. CDKN/Globe International, London. Available at: https://cdkn.org/resource/national-climate-change-legislation-the-key-to-more-ambitious-international-agreements (accessed 30 September 2019).

Treichel, P., 2020: Why Focus on Children: A literature review of child-centred climate change adaptation approaches. *Australian Journal of Emergency Management*, **35**(2), 26-33.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(5), e476.
Tschakert, P. et al., 2019: One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change*, **55**, 58-72.
Tschakert, P. and M. Machado, 2012: Gender Justice and Rights in Climate Change Adaptation: Opportunities and Pitfalls. *Ethics and Social Welfare*, **6**(3), 275-289, doi:10.1080/17496535.2012.704929.
Tschakert, P., B. van Oort, A. L. St. Clair and A. LaMadrid, 2013: Inequality and transformation analyses: a complementary lens for addressing vulnerability to climate change. *Climate and Development*, **5**(4), 340-350, doi:10.1080/17565529.2013.828583.
Tubi, A. and J. Williams, 2021: Beyond binary outcomes in climate adaptation: The illustrative case of desalination. *Wiley Interdisciplinary Reviews: Climate Change*, **12**(2), e695.
Tuhkanen, H., 2020: *Green bonds: a mechanism for bridging the adaptation gap?* SEI Working Paper, **February 2020**, Stockholm Environment Institute, Stockholm. Available at: https://www.sei.org/publications/green-bonds-a-mechanism-for-bridging-the-adaptation-gap/.
Tuncok, I. K., 2015: Transboundary river basin flood forecasting and early warning system experience in Maritza River basin between Bulgaria and Turkey. *Natural Hazards*, **75**(1), 191-214.
Turnhout, E. et al., 2020: The politics of co-production: participation, power, and transformation. *Current opinion in environmental sustainability*, **42**, 15-21, doi:10.1016/j.cosust.2019.11.009.
Tzeng, G.-H. and J.-J. Huang, 2011: *Multiple Attribute Decision Making: Methods and Applications*. CRC Press, Taylor & Francis Group, United States of America. ISBN 9780429110702.
Ulrichs, M., R. Slater and C. Costella, 2019: Building resilience to climate risks through social protection: from individualised models to systemic transformation. *Disasters*, **43 Suppl 3**(S3), S368-S387, doi:10.1111/disa.12339.
UN, 2015: *Adoption of the Paris Agreement* [Change, U. N. F. C. o. C. (ed.)]. 21st Conference of the Parties, Paris.
UN, 2016a: *Final list of proposed Sustainable Development Goal indicators*. Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators.
UN, 2016b: *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. Note by the Secretary-General.
UN, 2019: *Special edition: progress towards the Sustainable Development Goals*. Report of the Secretary-General. Available at: https://unstats.un.org/sdgs/files/report/2019/secretary-general-sdg-report-2019--EN.pdf.
UNDP Cambodia, 2014: *Practitioner's Handbook: Implementing the Vulnerability Reduction Assessment*, Second ed., Phnom Penh, Cambodia.
UNDRR, 2019: *Global assessment report on disaster risk reduction*. Available at: https://www.undrr.org/publication/global-assessment-report-disaster-risk-reduction-2019.
UNEP, 2014: *The Adaptation Gap Report*. UNEP. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/9331/-Adaptation_gap_report_a_prel.pdf?sequence=2&isAllowed=y.
UNEP, 2016: *The Adaptation Finance Gap Report 2016*. United Nations Environment Programme, Programme, U. N. E., Nairobi, Kenya. Available at: https://climateanalytics.org/media/agr2016.pdf.
UNEP, 2017: *The Adaptation Gap Report 2017* [Programme, U. N. E. (ed.)]. Nairobi.
UNEP, 2018: *The Adaptation Gap Report 2018*. UNEP, Nairobi.
UNEP, 2020: *Annex 1. Challenges in estimating adaptation costs* [Unep (ed.)]. Adaptation Gap Report 2020. Available at: https://www.unep.org/resources/adaptation-gap-report-2020 (accessed 2021/08/23).
UNEP, 2021a: *The Adaptation Gap Report 2020*. Nairobi, Kenya.
UNDP and UNFCCC, 2019: *The Heat is on: Taking Stock of Global Climate Ambition*. United Nations Development Programme and UNFCCC Secretariat. Available at: https://unfccc.int/news/the-heat-is-on-taking-stock-of-global-climate-ambition#:~:text=This%20is%20according%20to%20a,date%20of%20intentions%20for%202020.
UNFCCC, 2009: Decision 2/CP. 15 Copenhagen Accord. FCCC/CP/2009/11/Add. 1, United Nations Framework Convention on Climate Change.
UNFCCC, 2010a: *Report of the Conference of the Parties on its fifteenth session*. Copenhagen. Available at: http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf.
UNFCCC, 2010b: *Synthesis report on efforts undertaken to monitor and evaluate the implementation of adaptation projects, policies and programmes and the costs and effectiveness of completed projects, policies and programmes, and views on lessons learned, good practices, gaps and needs*.
UNFCCC, 2013: *Decision 2/CP.19: Warsaw international mechanism for loss and damage associated with climate change impacts*.
UNFCCC, 2015: The Paris Agreement, United Nations Framework Convention on Climate Change.
UNFCCC, 2019a: *Opportunities and options for adaptation finance, including in relation to the private sector*. Available at: https://unfccc.int/sites/default/files/resource/tp2019_03E.pdf.
UNFCCC, 2019b: *CMA.2 Warsaw International Mechanism for Loss and Damage associated with Climate Change Impacts and its 2019 review* [UNFCCC (ed.)]. Bonn.

UNFCCC, 2020: *Compilation and synthesis of fourth biennial reports of Parties included in Annex I to the Convention*. United Nations Framework Convention on Climate, C., Berlin, 101 pp. Available at: https://unfccc.int/sites/default/files/resource/sbi2020_inf10a01.pdf (accessed 2021/08/15).
UNFCCC, 2021: *Private Sector Initiative (PSI) database*. Available at: https://unfccc.int/topics/resilience/resources/psi-database
UNFCCC SCF, 2018: *2018 Biennial Assessment and Overview of Climate Finance Flows*. Available at: https://unfccc.int/sites/default/files/resource/2018.
Vähämäki, J. and C. Verger, 2019: *Learning from results-based management evaluations and reviews*.
Valente, S. and F. Veloso-Gomes, 2020: Coastal climate adaptation in port-cities: adaptation deficits, barriers, and challenges ahead. *Journal of Environmental Planning and Management*, **63**(3), 389-414.
Van Alphen, J., 2016: The Delta Programme and updated flood risk management policies in the Netherlands. *Journal of Flood Risk Management*, **9**(4), 310-319, doi:10.1111/jfr3.12183.
van den Homberg, M. and C. McQuistan, 2019: Technology for Climate Justice: A Reporting Framework for Loss and Damage as Part of Key Global Agreements. In: *Loss and Damage from Climate Change*. Springer, pp. 513-545.
van der Geest, K. and R. van den Berg, 2021: Slow-onset events: a review of the evidence from the IPCC Special Reports on Land, Oceans and Cryosphere. *Current Opinion in Environmental Sustainability*, **50**, 109-120.
van der Geest, K. and K. Warner, 2015: Loss and damage from climate change: emerging perspectives. *International Journal of Global Warming*, **8**(2), 133-140.
van Niekerk, D., C. Coetzee and L. Nemakonde, 2020: Implementing the Sendai Framework in Africa: Progress Against the Targets (2015–2018). *International Journal of Disaster Risk Science*, **11**(2), 179-189.
van Rüth, P. and K. Schönthaler, 2018: Setting up a national monitoring system for climate change impacts and adaptation. [L. Christiansen, G. M. and P. Naswa (eds.)]. Copenhagen: UNEP DTU Partnership, pp. (pp. 97-111).
van Valkengoed, A. M. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, **9**(2), 158-163, doi:10.1038/s41558-018-0371-y.
van Vliet, M. T. H. et al., 2015: European scale climate information services for water use sectors. *Journal of hydrology (Amsterdam)*, **528**, 503-513, doi:10.1016/j.jhydrol.2015.06.060.
van Wilgen, B. W. and A. Wannenburgh, 2016: Co-facilitating invasive species control, water conservation and poverty relief: achievements and challenges in South Africa's Working for Water programme. *Current opinion in environmental sustainability*, **19**, 7-17.
Vandenbergh, M. P. and J. M. Gilligan, 2017: *Beyond Politics: The Private Governance Response to Climate Change*. Business and Public Policy, Cambridge University Press, Cambridge. ISBN 9781107181229.
Vanhala, L. and C. Hestbaek, 2016: Framing climate change loss and damage in UNFCCC negotiations. *Global Environmental Politics*, **16**(4), 111-129.
Vaughan, C., L. Buja, A. Kruczkiewicz and L. Goddard, 2016: Identifying research priorities to advance climate services. *Climate Services*, **4**, 65-74, doi:10.1016/j.cliser.2016.11.004.
Vaughan, C. et al., 2019a: Evaluating agricultural weather and climate services in Africa: Evidence, methods, and a learning agenda. *Wiley Interdisciplinary Reviews Climate Change*, **10**(4), e586-e586.
Vaughan, C., M. F. Muth and D. P. Brown, 2019b: Evaluation of regional climate services: Learning from seasonal-scale examples across the Americas. *Climate services*, **15**, 100104, doi:10.1016/j.cliser.2019.100104.
Velasquez, M. and P. T. Hester, 2013: An analysis of multi-criteria decision making methods. *International Journal of Operations Research*, **10**, 56-66.
Vella, K. et al., 2016: Voluntary Collaboration for Adaptive Governance: The Southeast Florida Regional Climate Change Compact. *Journal of Planning Education and Research*, **36**(3), 363-376, doi:10.1177/0739456x16659700.
Vellinga, P. et al., 2001: Insurance and other financial services. Cambridge University Press, Cambridge, 417-450 pp.
Venn, A., 2019: Social justice and climate change☆. In: *Managing Global Warming* [Letcher, T. M. (ed.)]. Academic Press, pp. 711-728. ISBN 978-0-12-814104-5.
Vermeulen, S. J. et al., 2018: Transformation in practice: a review of empirical cases of transformational adaptation in agriculture under climate change. *Frontiers in Sustainable Food Systems*, **2**, 65.
Villanueva, P. S., 2012: *Learning to ADAPT: Monitoring and Evaluation Approaches in Climate Change Adaptation and Disaster Risk Reduction—Challenges, Gaps and Ways Forward*. Available at: https://www.ids.ac.uk/files/dmfile/SilvaVillanueva_2012_Learning-to-ADAPTDP92.pdf.
Vincent, K., M. Daly, C. Scannell and B. Leathes, 2018: What can climate services learn from theory and practice of co-production? *Climate services*, **12**, 48-58, doi:10.1016/j.cliser.2018.11.001.
Vincent, K. et al., 2015: Identifying climate services needs for national planning: insights from Malawi. *Climate policy*, **17**(2), 189-202, doi:10.1080/14693062.2015.1075374.
Visser, H., S. de Bruin, J. Knoop and W. Ligtvoet, 2020: What users of global risk indicators should know. *Global Environmental Change*, **62**(102068).
VIVID Economics, 2021: *Greenness of Stimulus Index* [Initiative, V. E. F. f. B. (ed.)]. 6th ed., London. Available at: https://www.vivideconomics.com/casestudy/greenness-for-stimulus-index
Vogel, J., E. McNie and D. Behar, 2016: Co-producing actionable science for water utilities. *Climate services*, **2-3**(C), 30-40, doi:10.1016/j.cliser.2016.06.003.
Volz, U. et al., 2021: *Debt Relief for a Green and Inclusive Recovery: Securing Private-Sector Participation and Creating Policy Space for Sustainable Development*. Heinrich Böll, S., U. o. L. Soas and U. Boston, Berlin,

London and Boston, 44 pp. Available at: https://www.boell.de/sites/default/files/2021-06/DRGR%20Report%202021%20Endf.pdf (accessed 2021/04/09).
Walch, C., 2018: Disaster risk reduction amidst armed conflict: informal institutions, rebel groups, and wartime political orders. *Disasters*, **42 Suppl 2**, S239-S264, doi:10.1111/disa.12309.
Wallimann-Helmer, I., 2015: Justice for climate loss and damage. *Climate Change*, **133**(3), 469-480.
Wallimann-Helmer, I. et al., 2019: The ethical challenges in the context of climate loss and damage. In: *Loss and Damage from Climate Change*. Springer, pp. 39-62.
Walshe, R. and A. Argumedo, 2016: Ayni, Ayllu, Yanantin and Chanincha: The Cultural Values Enabling Adaptation to Climate Change in Communities of the Potato Park, in the Peruvian Andes. *Gaia (Heidelberg, Germany)*, **25**(3), 166-173, doi:10.14512/gaia.25.3.7.
Wamsler, C., 2017: Stakeholder involvement in strategic adaptation planning: Transdisciplinarity and co-production at stake? *Environmental Science & Policy*, **75**, 148-157.
Wamsler, C. et al., 2019: Beyond participation: when citizen engagement leads to undesirable outcomes for nature-based solutions and climate change adaptation. *Climatic change*, **158**(2), 235-254, doi:10.1007/s10584-019-02557-9.
Wang, L., A. Yang and K. Thorson, 2019b: Serial participants of social media climate discussion as a community of practice: a longitudinal network analysis. *Information, communication & society*, 1-19, doi:10.1080/1369118x.2019.1668457.
Wang, T. and X. Gao, 2018: Reflection and operationalization of the common but differentiated responsibilities and respective capabilities principle in the transparency framework under the international climate change regime. *Advances in Climate Change Research*, **9**(4), 253-263, doi:https://doi.org/10.1016/j.accre.2018.12.004.
Wang, Y., M. van Roon and S. Knight-Lenihan, 2021: Opportunities and challenges in water sensitive industrial development: an Auckland case study, New Zealand. *International Journal of Sustainable Development & World Ecology*, **28**(2), 143-156.
Warner, K. et al., 2019: Characteristics of Transformational Adaptation in Climate-Land-Society Interactions. *Sustainability*, **11**(2), doi:10.3390/su11020356.
Warnken, J. and R. Mosadeghi, 2018: Challenges of implementing integrated coastal zone management into local planning policies, a case study of Queensland, Australia. *Marine Policy*, **91**, 75-84, doi:10.1016/j.marpol.2018.01.031.
Wasim, R., 2019: Corporate (non)Disclosure of Climate Change Information. *Columbia Law Review*, **119**(5), 1311-1356.
Watkins, S. L., S. K. Mincey, J. Vogt and S. P. Sweeney, 2016: Is Planting Equitable? An Examination of the Spatial Distribution of Nonprofit Urban Tree-Planting Programs by Canopy Cover, Income, Race, and Ethnicity. *Environment and Behavior*, **49**(4), 452-482, doi:10.1177/0013916516636423.
Watkiss, P. and A. Hunt, 2013: Method Overview: Decision Support Methods for Adaptation, Briefing Note 1. Summary of Methods and Case Study Examples from the MEDIATION Project. Funded by the EC's 7FWP. 18.
Watkiss, P. et al., 2015b: *The costs and benefits of adaptation: results from the ECONADAPT project. Policy report.*
Watson, C., 2016: *Financing our shared future: navigating the humanitarian, development and climate finance agendas*. Overseas Development Institute (ODI), London, UK.
Watson, C. and L. Schalatek, 2021: *The Global Climate Finance Architecture*. Climate Finance Fundamentals, Overseas Development Institute and Heinrich Böll Stiftung North America. Available at: https://climatefundsupdate.org/about-climate-finance/global-climate-finance-architecture (accessed 2021/08/13).
Watts, N. et al., 2015: Health and climate change: policy responses to protect public health. *Lancet*, **386**(10006), 1861-1914, doi:10.1016/s0140-6736(15)60854-6.
Weaver, C. P. et al., 2013: Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *WIREs Climate Change*, **4**(1), 39-60, doi:10.1002/wcc.202.
Webber, S., 2017: Circulating climate services: Commercializing science for climate change adaptation in Pacific Islands. *Geoforum*, **85**, 82-91, doi:10.1016/j.geoforum.2017.07.009.
Webber, S. and S. D. Donner, 2017: Climate service warnings: cautions about commercializing climate science for adaptation in the developing world. *WIREs Climate Change*, **8**(1), e424, doi:10.1002/wcc.424.
Weikmans, R. and J. T. Roberts, 2019: The International Climate Finance Accounting Muddle: Is There Hope on the Horizon? *Climate and Development*, **11**(2), 97-111, doi:10.1080/17565529.2017.1410087.
Weikmans, R. et al., 2017: Assessing the credibility of how climate adaptation aid projects are categorised. *Development in Practice*, **27**(4), 458-471.
Weiler, F., C. Klöck and M. Dornan, 2018: Vulnerability, good governance, or donor interests? The allocation of aid for climate change adaptation. *World Development*, **104**, 65.
Weinstein, L., A. Rumbach and S. Sinha, 2019: Resilient Growth: Fantasy Plans and Unplanned Developments in India's Flood-Prone Coastal Cities. *International Journal of Urban and Regional Research*, **43**(2), 273-291.
Weischer, L. et al., 2016: Investing in ambition: Analysis of the financial aspects in (Intended) nationally determined contributions. *THINK TANK & RESEARCH*.
Weitz, N., C. Strambo, E. Kemp-Benedict and M. Nilsson, 2017: Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Global Environmental Change*, **45**, 165-173, doi:10.1016/j.gloenvcha.2017.06.006.

Weldegebriel, Z. B. and M. Prowse, 2013: Climate-Change Adaptation in Ethiopia: To What Extent Does Social Protection Influence Livelihood Diversification? *Development Policy Review*, **31**(2), 35-56.

Wenta, J., J. McDonald and J. S. McGee, 2019: Enhancing Resilience and Justice in Climate Adaptation Laws. *Transnational Environmental Law*, **8**(1), 89-118, doi:10.1017/s2047102518000286.

Wesselink, A., 2016: Trends in flood risk management in deltas around the world: Are we going 'soft'? *International Journal of Water Governance*, **4**(4), 25-46, doi:10.7564/15-ijwg90.

Wewerinke-Singh, M. and D. H. Salili, 2019: Between negotiations and litigation: Vanuatu's perspective on loss and damage from climate change. *Climate Policy*, **20**(6), 681-692, doi:10.1080/14693062.2019.1623166.

Wheeler, H. C. et al., 2020a: The need for transformative changes in the use of Indigenous knowledge along with science for environmental decision-making in the Arctic. *People and nature (Hoboken, N.J.)*, **2**(3), 544-556, doi:10.1002/pan3.10131.

White, C. J. et al., 2017: Potential applications of subseasonal-to-seasonal (S2S) predictions. *Meteorological Applications*, **24**(3), 315-325, doi:10.1002/met.1654.

Wichelns, D., 2017: The water-energy-food nexus: Is the increasing attention warranted, from either a research or policy perspective? *Environmental Science & Policy*, **69**, 113-123, doi:10.1016/j.envsci.2016.12.018.

Wilkinson, E. et al., 2018: *Forecasting hazards, averting disasters: Implementing forecast-based early action at scale*. Overseas Development Institute (ODI).

Willett, W. et al., 2019: Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, **393**(10170), 447-492, doi:10.1016/s0140-6736(18)31788-4.

Williamson, D. and M. Goldstein, 2012: Bayesian policy support for adaptive strategies using computer models for complex physical systems, 1021-1033 pp.

Wilson, A. J. and B. Orlove, 2019: What do we mean when we say climate change is urgent? *Columbia Academic Commons: Columbia University*, **Center for Research on Environmental Decisions Working Paper 1**.

Wilson, A. J. and B. Orlove, 2021: Climate urgency: evidence of its effects on decision making in the laboratory and the field. *Current Opinion in Environmental Sustainability*, **51**, 65-76.

Wilson, R. S., A. Herziger, M. Hamilton and J. S. Brooks, 2020: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, 1-9.

Winters, K. M., J. B. Cushing and D. Lach, 2016: Designing visualization software for super-wicked problems. *Information Polity*, **21**(4), 399-409, doi:10.3233/ip-160400.

Wise, R. M. et al., 2016: How climate compatible are livelihood adaptation strategies and development programs in rural Indonesia? *Climate Risk Management*, **12**, 100-114, doi:10.1016/j.crm.2015.11.001.

Wise, R. M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325-336, doi:10.1016/j.gloenvcha.2013.12.002.

Woodruff, S. C., 2018: City membership in climate change adaptation networks. *Environmental science & policy*, **84**, 60-68, doi:10.1016/j.envsci.2018.03.002.

Woodruff, S. C. and P. Regan, 2019: Quality of national adaptation plans and opportunities for improvement. *Mitigation and Adaptation Strategies for Global Change*, **24**(1), 53-71, doi:10.1007/s11027-018-9794-z.

Woodruff, S. C. and M. Stults, 2016: Numerous strategies but limited implementation guidance in US local adaptation plans. *Nature Climate Change*, **6**(8), 796-802, doi:10.1038/nclimate3012.

Work, C., V. Rong, D. Song and A. Scheidel, 2019: Maladaptation and development as usual? Investigating climate change mitigation and adaptation projects in Cambodia. *Climate Policy*, **19(sup1)**, S47-S62.

Workman, M., G. Darch, K. Dooley and others, 2021: Climate policy decision making in contexts of deep uncertainty - from optimisation to robustness, 127-137 pp.

World Bank, 2010: *Economics of Adaptation to Climate Change: Synthesis report*. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/12750/702670ESW0P10800EACCSynthesisReport.pdf?sequence=1&isAllowed=y.

World Bank, 2013: *World Development Report 2014*. World Development Report, The World Bank, 360 pp. ISBN 978-0-8213-9903-3 978-0-8213-9982-8.

World Bank Independent Evaluation Group, 2012: *Adapting to Climate Change: Assessing the World Bank Group Experience*. Available at: http://ieg.worldbankgroup.org/evaluations/adapting-climate-change-assessing-world-bank-group-experience.

WRI, 2019: *Estimating the Economic Benefits of Climate Adaptation Investments*. Background Paper for Global Comission on Adaptation, Worlds Resources Institute.

Wright, C. and D. Nyberg, 2016: An Inconvenient Truth: How Organizations Translate Climate Change into Business as Usual. *Academy of Management Journal*, **60**(5), 1633-1661, doi:10.5465/amj.2015.0718.

WWF & Practical Action, 2020: *Anchoring Loss & Damage in Enhanced NDCs* [Nature, W. W. F. F. (ed.)]. Available at: wwfeu.awsassets.panda.org/downloads/wwf_pa_anchoring_loss_and_damage_in_ndcs_report.pdf.

Xenarios, S. and H. Polatidis, 2015: Alleviating climate change impacts in rural Bangladesh: a PROMETHEE outranking-based approach for prioritizing agricultural interventions. *Environment, Development and Sustainability*, **17**(5), 963-985, doi:10.1007/s10668-014-9583-0.

Xiang, P. et al., 2019: Individualist-Collectivist Differences in Climate Change Inaction: The Role of Perceived Intractability. *Front Psychol*, **10**, 187, doi:10.3389/fpsyg.2019.00187.

Xu, D. L., 2012: An introduction and survey of the evidential reasoning approach for multiple criteria decision analysis, 163-187 pp.
Xue, X. et al., 2015: *Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches*, 2015/04/13 ed. Water Res, vol. 77, 155-169 pp. ISBN 1879-2448 (Electronic) 0043-1354 (Linking).
Yang, Z. et al., 2018: Risk and cost evaluation of port adaptation measures to climate change impacts. *Transportation research. Part D, Transport and environment*, **61**, 444-458, doi:10.1016/j.trd.2017.03.004.
Yohe, G. W. et al., 2008: Perspectives on climate change and sustainability, Cambridge, UK, 811-841 pp.
Young, N. et al., 2016: Knowledge users' perspectives and advice on how to improve knowledge exchange and mobilization in the case of a co-managed fishery. *Environmental science & policy*, **66**, 170-178, doi:10.1016/j.envsci.2016.09.002.
Young, S. L., N. W. Goldowsky-Dill, J. Muhammad and M. M. Epstein, 2019a: Connecting experts in the agricultural and meteorological sciences to advance knowledge of pest management in a changing climate. *The Science of the total environment*, **673**, 694-698, doi:10.1016/j.scitotenv.2019.04.126.
Yumagulova, L. and I. Vertinsky, 2019: Moving beyond engineering supremacy: Knowledge systems for urban resilience in Canada's Metro Vancouver region. *Environmental Science and Policy*, **100**, 66-73, doi:10.1016/j.envsci.2019.05.022.
Zadek, S., 2018: Financing a Just Transition. *Organization & Environment*, **32**(1), 18-25, doi:10.1177/1086026618794176.
Zakay, D., 2014: Psychological time as information: The case of boredom. *Frontiers in Psychology*, **5**(AUG), doi:10.3389/fpsyg.2014.00917.
Zanocco, C. et al., 2018a: Great Basin land managers provide detailed feedback about usefulness of two climate information web applications. *Climate risk management*, **20**, 78-94, doi:10.1016/j.crm.2018.04.001.
Zarei, Z., E. Karami and M. Keshavarz, 2020: Co-production of knowledge and adaptation to water scarcity in developing countries. *Journal of environmental management*, **262**, 110283, doi:10.1016/j.jenvman.2020.110283.
Zebiak, S. E., 2019: International Conference on Climate Services - 5 – An introduction. *Climate services*, **15**, 100121, doi:10.1016/j.cliser.2019.100121.
Zebiak, S. E. et al., 2015: Investigating El Niño-Southern Oscillation and society relationships. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(1), 17-34, doi:10.1002/wcc.294.
Zevenbergen, C. et al., 2018: Adaptive delta management: a comparison between the Netherlands and Bangladesh Delta Program. *International Journal of River Basin Management*, **16**(3), 299-305, doi:10.1080/15715124.2018.1433185.
Zhang, M.-J., Y.-M. Wang, L.-H. Li and S.-Q. Chen, 2017: A general evidential reasoning algorithm for multi-attribute decision analysis under interval uncertainty, 1005-1015 pp.
Zhang, W. and X. Pan, 2016: Study on the demand of climate finance for developing countries based on submitted INDC. *Advances in climate change research*, **7**(1-2), 99-104, doi:10.1016/j.accre.2016.05.002.
Zhao, Z.-Y., J. Zuo and G. Zillante, 2017: Transformation of water resource management: a case study of the South-to-North Water Diversion project. *Journal of cleaner production*, **163**, 136-145.
Ziaja, S., 2019: Role of Knowledge Networks and Boundary Organizations in Coproduction: A Short History of a Decision-Support Tool and Model for Adapting Multiuse Reservoir and Water-Energy Governance to Climate Change in California. *Weather, Climate, and Society*, **11**(4), 823-849, doi:10.1175/wcas-d-19-0007.1.
Ziaja, S. and C. Fullerton, 2015: Judging Science: The Rewards and Perils of Courts as Boundary Organizations. *Hastings Environmental Law Journal*, **21**(2), 217-246.
Zickgraf, C., 2021: Climate change, slow onset events and human mobility: reviewing the evidence. *Current Opinion in Environmental Sustainability*, **50**, 21-30.
Ziervogel, G., 2019: Building transformative capacity for adaptation planning and implementation that works for the urban poor: Insights from South Africa. *Ambio*, **48**(5), 494-506.
Ziervogel, G. et al., 2017: Inserting rights and justice into urban resilience: a focus on everyday risk. *Environment and Urbanization*, **29**(1), 123-138.
Ziervogel, G. et al., 2019: Vertical integration for climate change adaptation in the water sector: lessons from decentralisation in Africa and India. *Reg Environ Change*, **19**, 2729-2743.
Zommers, Z. and A. Singh, 2014: *Reducing disaster: early warning systems for climate change*. Springer. ISBN 9401785988.
Zopounidis, C. and P. M. Pardalos, 2010: *Handbook of Multicriteria Analysis. Applied Optimization*. Springer-Verlag, Berlin Heidelberg. ISBN 9783540928270.

Chapter 18: Climate Resilient Development Pathways

Coordinating Lead Authors: E. Lisa F. Schipper (Sweden/United Kingdom), Aromar Revi (India), Benjamin L. Preston (Australia/USA)

Lead Authors: Edward. R. Carr (USA), Siri H. Eriksen (Norway), Luis R. Fernández-Carril (Mexico), Bruce Glavovic (South Africa/New Zealand), Nathalie J.M. Hilmi (France/Monaco), Debora Ley (Mexico/Guatemala), Rupa Mukerji (India/Switzerland), M. Silvia Muylaert de Araujo (Brazil), Rosa Perez (Philippines), Steven K. Rose (USA), Pramod K. Singh (India)

Contributing Authors: Paulina Aldunce (Chile), Aditya Bahadur (India), Natália Barbosa de Carvalho (Brazil), Ritwika Basu (India), Donald A. Brown (USA), Anna Carthy (Ireland), Vanesa Castán Broto (Spain/United Kingdom), Ralph Chami (USA), John Cook (USA), Daniel de Berrêdo Viana (Brazil), Frode Degvold (Norway), Shekoofeh Farahmend (Iran), Roger Few (United Kingdom), Gianfranco Gianfrate (France), H. Carina Keskitalo (Sweden), Florian Krampe (Germany/Sweden), Rinchen Lama (South Africa), Julia Leventon (Czech Republic/United Kingdom), Rebecca McNaught (New Zealand), Yu Mo (China/United Kingdom), Marianne Mosberg (Norway), Michelle Mycoo (Trinidad and Tobago), Johanna Nalau (Australia/Finland), Karen O'Brien (Norway), Meg Parsons (New Zealand), Alain Safa (France), Zoha Shawoo (Pakistan/United Kingdom), Marcus Taylor (Canada/United Kingdom), Mark G.L. Tebboth (United Kingdom), Bejoy K. Thomas (India), Kirsten Ulsrud (Norway), Saskia Werners (The Netherlands/Germany), Keren Zhu (China), Monika Zurek (Germany/United Kingdom)

Review Editors: Diana Liverman (USA), Nobuo Mimura (Japan)

Chapter Scientists: Ritwika Basu (India/United Kingdom), Zoha Shawoo (Pakistan/United Kingdom), Yu Mo (China/United Kingdom)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Climate resilient development (CRD) is a process of implementing greenhouse gas mitigation and adaptation options to support sustainable development for all (18.1). Climate action and sustainable development are interdependent processes and climate resilient development is possible when this interdependence is leveraged. Pursuing these goals in an integrated manner increases their effectiveness in enhancing human and ecological well-being. Climate resilient development can help build capacity for climate action, including contributing to reductions in greenhouse gas emissions while enabling the implementation of adaptation options that enhance social, economic and ecological resilience to climate change as the prospect of crossing the 1.5°C global warming level in the early 2030s approaches (WG1 Table SPM1). For example, incorporating clean energy generation, healthy diets from sustainable food systems, appropriate urban planning and transport, universal health coverage and social protection, can generate substantial health and wellbeing co-benefits (*very high confidence*[1]) (7.4.4, Cross-Chapter Box HEALTH in Chapter 7). Similarly, universal water and energy access can help to reduce poverty and improve well-being while making populations less vulnerable and more resilient to adverse climate impacts (*very high confidence*) (18.1, Box 4.7).

Current development pathways combined with the observed impacts of climate change, are leading away from, rather than toward, sustainable development, as reported in recent literature (*moderate agreement, robust evidence*). While demonstrable progress has been made on some of the SDGs, significant gains across a range of targets are still necessary, as is enhancing synergies and balancing and managing trade-offs. Severe risks to natural and human systems are already observed in some places (high confidence), and could occur in many more systems, worldwide before mid-century (*medium confidence*), by end-century at all scales, from the local to the global, and at all latitudes and altitudes (*high confidence*). The COVID-19 pandemic revealed the vulnerability of development progress to shocks and stresses, potentially delaying the implementation of the 2030 Agenda for all (8.1, Cross-Chapter Box COVID in Chapter 7). Various global trends including rising income inequality, continued growth in greenhouse gas emissions, land use change, food and water insecurity, human displacement, and reversals of long-term increasing life expectancy trends in some nations run counter to the SDGs (*very high confidence*) as well as efforts to mitigate greenhouse gas emissions and adapt to a changing climate (18.2). These development trends contribute to worsening poverty, injustice and inequity, and environmental degradation. Climate change can exacerbate these conditions by undermining human and ecological well-being (18.2).

Social and economic inequities linked to gender, poverty, race/ethnicity, religion, age, or geographic location compound vulnerability to climate change and have created and could further exacerbate injustices, and constrain the implementation of CRD for all (*very high confidence*). Climate change intensifies existing vulnerability and inequality, with adverse impacts of climate change on the most vulnerable groups, including women and children in low-income households, Indigenous or other minority groups, small-scale producers and fishing communities, and low-income countries (*high confidence*). Most vulnerable regions and population groups, such as in East, Central and West Africa, South Asia, Micronesia and Melanesia and in Central America, present the most urgent need for adaptation (*high confidence*) (Ch 10, 12, 15). Climate justice initiatives explicitly address these multi-dimensional distributional issues as part of climate change adaptation. However, adaptation strategies can worsen social inequities, including gender, unless explicit efforts are made to change those unequal power dynamics, including spaces to foster inclusive decision-making. Drawing upon Indigenous knowledge and local knowledge can contribute to overcoming the combined challenges of climate change, food security, biodiversity conservation, and combating desertification and land degradation. (18.2; Cross-Chapter Box GENDER; Cross-Chapter Box INDIG}

Opportunities for climate resilient development vary by location (*very high confidence*). Over 3.3 billion people live in regions that are very high and highly vulnerable to climate change, while 2 billion people live in regions with low and very low vulnerability. Response to global greenhouse gas emissions

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

trajectories, regional and local development pathways, climate risk exposure, socio-economic and ecological vulnerability, and the local capacity to implement effective adaptation and greenhouse gas mitigation options, differ depending on local contexts and conditions (Table 18.3). As an example, underlying social and economic vulnerabilities in Australasia, exacerbate disadvantage among particular social groups and there is deep underinvestment in adaptation, given current and projected risks (Ch 11). There is also significant regional heterogeneity in climate change, exposure, and vulnerability, indicating different starting points for CRD, as well as mitigation, adaptation, and sustainable development opportunities, synergies, and trade-offs (18.5).

There are multiple possible pathways by which communities, nations and the world can pursue climate resilient development. Moving toward different pathways involves confronting complex synergies and trade-offs between development pathways, and the options, contested values, and interests that underpin climate mitigation and adaptation choices (*very high confidence*). Climate resilient development pathways are trajectories for the pursuit of climate resilient development and navigating its complexities. Different actors, the private sector, and civil society, influenced by science, local and Indigenous knowledges, and the media are both active and passive in designing and navigating CRD pathways (18.1, 18.4). Increasing levels of warming may narrow the options and choices available for local survival and sustainable development for human societies and ecosystems. Limiting warming to Paris Agreement goals will reduce the magnitude of climate risks to which people, places, the economy and ecosystems will have to adapt. Reconciling the costs, benefits, and trade-offs associated with adaptation, mitigation, and sustainable development interventions and how they are distributed among different populations and geographies is essential and challenging, but also creates the potential to pursue synergies that benefit human and ecological well-being. For example, in parts of Asia sustainable development pathways that connect climate change adaptation and disaster risk reduction can reduce climate vulnerability and increase resilience (Table 18.3. 10.6.2). Different actors and stakeholders have different priorities regarding these opportunities, which can exacerbate or diminish existing social, economic and ecological vulnerabilities and inequities. For example, in parts of Africa, intensive irrigation contributes to the development of agriculture but has come at a cost to ecosystem integrity and human well-being (Table 18.3., 9.15.2). Careful and explicit consideration for the ethical and equity dimensions of policies and practices associated with a climate resilient development pathway can help limit these negative externalities.

Prevailing development pathways are not advancing climate resilient development *(very high confidence)*. Societal choices in the near-term will determine future pathways. Some low-emissions pathways and climate outcomes are *unlikely*[2] to be realized (*very high confidence*). Rapid climate change is affecting every region across the globe and affecting natural and human systems relevant to the pursuit of the SDGs (18.1, 18.2, Fig. 18.1). Even the most ambitious greenhouse gas mitigation scenarios indicate climate change will continue for decades to centuries (WGI, 18.2). Increasing mitigation effort across multiple sectors exhibits opportunities for synergies with sustainable development, but also trade-offs that increase with mitigation effort that need to be balanced and managed (*high confidence*). The uncertainty associated with achieving specific pathways and climate outcomes is a risk factor to consider in planning, with plausibility and transformational challenges, as well as trade-offs and synergies, affected by technology, policy design, and societal choices (18.2). For instance, restrictions on utilization of individual mitigation options to manage trade-offs (e.g., bioenergy with CCS, afforestation, nuclear power) can also affect the mitigation cost to households (e.g., energy security, commodity prices) and the likelihood of a desired climate outcome being realized. Developing and transitional economies are estimated as low-cost mitigation opportunities, but are often at high risk from climate change due to their regional and development context (*high confidence*) (18.2,18.5). For example in Africa, competing uses for water such as hydropower generation, irrigation, and ecosystem requirements can create trade-offs among different management and development objectives (9.7.3). In Asia, intensive irrigation and other forms of water consumption can have a negative effect on water quality and aquatic ecosystems (Ch 10.6.3). Developed countries also,

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

face trade-offs, including in Australasia where adapting to fire risk in peri-urban zones introduces potential trade-offs among ecological values and fuel reduction in treed landscapes (Ch 11.3.5) and in North America where new coastal and alpine developments generate economic activity but enhance local social inequalities (15.4.10).

Systems transitions can enable climate resilient development, when accompanied by appropriate enabling conditions and inclusive arenas of engagement (*very high confidence*). Five systems transitions are considered: energy, industry, urban and infrastructure, land and ecosystems, and societal. Advancing climate resilient development in specific contexts may necessitate simultaneous progress on all five transitions. Collectively, these system transitions can widen the solution space and accelerate and deepen the implementation of sustainable development, adaptation, and mitigation actions by equipping actors and decision-makers with more effective options. For example, urban ecological infrastructure linked to an appropriate land use mix, street connectivity, open and green spaces, and job-housing proximity provides adaptation and mitigation benefits that can aid urban transformation. (Table 18.4, Cross-Working Group Box URBAN in Chapter 6) These system transitions are necessary precursors for more fundamental climate and sustainable-development transformations; but can simultaneously be outcomes of transformative actions. However, the way they are pursued may not necessarily be perceived as ethical or desirable to all actors. Hence, enhancing equity and agency are cross-cutting considerations for all five transitions. Such transitions can generate benefits across different sectors and regions, provided they are facilitated by appropriate enabling conditions including effective governance, policy implementation, innovation, and climate and development finance, which are currently insufficient (18.3, 18.4).

There is a rapidly narrowing window of opportunity to implement system transitions needed to enable CRD. Past choices have already eliminated some development pathways, but other pathways for climate-resilient development remain (*very high confidence*). In spite of a growth in national net-zero commitments, the current prospects of surpassing 1.5°C global mean temperatures by the 2030s are high (WG1 Table SPM1). There is strong evidence of the worsening of multiple climate impact drivers in all regions, that will place additional pressures on ecosystem services that support food and water systems, increasing the risks of malnutrition, ill-health and poverty in many regions (WG1 Fig SPM9, Table 18.4). This implies that significant additional adaptation will be needed. Over the near-term, implementing such transformational change could be disruptive to various economic and social systems. Over the long-term, however, they could generate benefits to human well-being and planetary health. Strengthening coordinated adaptation and mitigation actions can enhance the potential of local and regional development pathways to support CRD. Planning for CRD can support both adaptation and decarbonization via effective land-use, promoting resilient and low-carbon infrastructure; protecting biodiversity and integrating ecosystem services (Table 18.4), assuming advancing just and equitable development processes.

Prospects for transformation towards climate resilient development increase when key governance actors work together in inclusive and constructive ways to create a set of appropriate enabling conditions (18.4.2) (*high confidence*). These enabling conditions include effective governance and information flow, policy frameworks that incentivize sustainability solutions; adequate financing for adaptation, mitigation, and sustainable development; institutional capacity; science, technology and innovation; monitoring and evaluation of climate resilient development policies, programs, and practices; and international cooperation. Investment in social and technological innovation, could generate the knowledge and entrepreneurship needed to catalyze system transitions, and their transfer. The implementation of policies that incentivize the deployment of low-carbon technologies and practices within specific sectors such as energy, buildings, and agriculture could accelerate greenhouse gas mitigation and deployment of climate resilient infrastructure, in urban and rural areas. Civic engagement is an important element of building societal consensus and reducing barriers to action on adaptation, mitigation, and sustainable development. (18.4)

CRD pathways are determined through engagement in different arenas degree to which the emergent pathways foster just, and climate resilient development depends on how contending societal interests, values and worldviews are reconciled through inclusive and participatory interactions between governance actors in these arenas of engagement (18.4.3) (*high confidence*). These interactions occur in many different arenas (e.g., governmental, economic and financial, political, knowledge, science & technology, and community) that represent the settings, places, and spaces in which societal actors interact to influence the nature and course of development. For instance, the Agenda 2030 highlights the importance of multi-level adaptation governance, including non-state actors from civil society and the private sector. This implies the need for wider arenas and modes of engagement around adaptation that facilitate coordination, convergence, and productive contestation among these diverse actors to collectively solve problems and to unlock the synergies between adaptation and mitigation and sustainable development.

Regional and national differences mean different capacities for pursuing climate resilient development pathways. Economic sectors and global regions are exposed to different opportunities and challenges in facilitating climate resilient development, suggesting adaptation and mitigation options should be aligned to local and regional context and development pathways (*very high confidence*). Given their current state of development, some regions may prioritize poverty and inequality reduction, and economic development over the near-term as a means of building capacity for climate action and low-carbon development over the long-term. For example, Africa, South Asia, and Central and South America are highly exposed, vulnerable and impacted by climate change, which is amplified by poverty, population growth, land use change and high dependence on natural resources for commodity production. In contrast, developed economies with mature economies and high levels of resilience may prioritize climate action to transition their energy systems and reduce greenhouse gas emissions. Some interventions may be robust in that they are relevant to a broad range of potential development trajectories and could be deployed in a flexible manner. For example, conservation of land and water could be achieved through a variety of means and offer benefits to populations in the global North and South alike. However, other types of interventions, such as those that are dependent upon emerging technologies, may require a specific set of enhanced enabling conditions or factors including infrastructure, supply chains, international cooperation, and education and training that currently limit their implementation to certain settings (18.5). Notwithstanding national and regional differences, development practices that are aligned to people, prosperity, partnerships, peace and the planet as defined in Agenda 2030, could enable more climate resilient development (see Figure 18.1).

People, acting through enabling social, economic and political institutions, are the agents of system transitions and societal transformations that facilitate climate resilient development founded on the principles of inclusion, equity, climate justice, ecosystem health, and human well-being (*very high confidence*). While much literature on climate action has focused on the role of technology and policy as the factors that drive change, recent literature has focused on the role of specific actors – citizens, civil society, knowledge institutions (including local and Indigenous Peoples and science), governments, investors and businesses. Greater attention to, and transparency of, which actors' benefit, fail to benefit, or are impacted by mitigation and adaptation choices actions could better support climate-resilient and sustainable development. For example, grounding adaptation actions in local realities could help to ensure that adaptive actions do not worsen existing gender and other inequities within society (e.g., leading to maladaptation practices) *(high confidence)*. Differences in the ability of different actors to effect change ultimately influence which interventions for sustainable development or climate action are implemented and thus what development outcomes are achieved. Recent literature has focused on the social, political, and economic arenas of engagement, in which these different actors interact. More focused attention on these arenas of engagement could prove beneficial to reconciling divergent views on climate action, integrating Indigenous knowledge and local knowledges, elevating diverse voices that have historically been marginalized from the policy discourse, thereby reducing vulnerability, deepening adaptive capacity and the ability to implement CRD (18.4; Cross-Chapter Box GENDER; Cross-Chapter Box INDIG)

Pursuing climate resilient development involves considering a broader range of sustainable development priorities, policies and practices, as well as enabling societal choices to accelerate and deepen their implementation *(very high confidence)*. Scientific assessments of climate change have traditionally framed solutions around the implementation of specific adaptation and mitigation options as mechanisms for reducing climate-related risks. They have given less attention to a fuller set of societal priorities and the role of non-climate policies, social norms, lifestyles, power relationships and worldviews in enabling climate action and sustainable development. Because climate resilient development involves different actors pursuing plural development trajectories in diverse contexts, the pursuit of solutions that are equitable for all requires opening the space for engagement and action to a diversity of people, institutions, forms of knowledge, and worldviews. Through inclusive modes of engagement that enhance knowledge sharing and realize the productive potential of diverse perspectives and worldviews, societies could alter institutional structures and arrangements, development processes, choices and actions that have precipitated dangerous climate change, constrained the achievement of SDGs, and thus limited pathways to achieving CRD (Box 18.1, 18.4). There are only a few decades remaining to chart CRD pathways that catalyze the transformation of prevailing development practices and offer the greatest promise and potential for human well-being and planetary health.

18.1 Ways Forward for Climate Resilient Development

The links between climate change and development have been long recognized by various research communities (Nagoda, 2015; Winkler et al., 2015; Webber, 2016; Carr, 2019) and have been assessed by Working Group II in every IPCC Assessment Report since AR3 (Smit et al., 2001; Yohe et al., 2007; Denton et al., 2014). For the AR1-3 reports, these links were largely framed in the context of sustainable development, a concept that has been well described in the literature for decades (Brundtland, 1987). The AR5 introduced the framing of climate resilient pathways, which narrowed the discussion around sustainable development to specifically address the contributions of mitigation and adaptation actions to the reduction of risk to development and the various institutions, strategies, and choices involved in risk management (Denton et al., 2014). That assessment concluded that identifying and implementing appropriate technical and governance options for mitigation and adaptation as well as development strategies and choices that contribute to climate resilience are central to the successful implementation of such strategies. The AR5 also recognized that transformation of current development pathways in terms of wider political, economic and social systems may be necessary (Denton et al., 2014).

The literature presenting research findings on climate resilient development (CRD) and pathways and processes for successfully achieving CRD has expanded significantly in the several years since the AR5 (*very high confidence*). This includes both qualitative studies of development as well as illustrative, quantitative analyses of development trajectories linked to specific scenarios, such as the Shared Socioeconomic Pathways (SSPs) (18.2.2). Furthermore, the literature describing the role of system transitions and societal transformation in enabling climate action (Box 18.1, 18.3), compliance with the Paris Agreement (18.1.3, 18.2.1), and achievement of the Sustainable Development Goals (18.1.3; Box 18.4) has expanded significantly (*very high confidence*). This expansion is comprised of studies spanning a broad range of disciplinary perspectives, some of which have been underrepresented in prior IPCC assessments (*high agreement, limited evidence)* (Minx et al., 2017; Pearce et al., 2018b)).

This chapter therefore focuses on assessing this more recent literature and the diverse scientific understandings of CRD and the pathways for pursuing it. Notably, this chapter takes off where Chapters 16 and 17 end: recognizing the decision-making context to address the representative key risks and their intersections with development, among others. This chapter therefore highlights not only how climate risk undermines CRD, but also how current patterns of development contribute to climate risk, both generally and in different sectoral and regional contexts. In particular, the chapter focuses on achieving CRD through systems transitions, discussing these in relation to societal transformation, and how different actors engage one another in order to pursue policy and practice consistent with CRD.

18.1.1 Understanding Climate Resilient Development

Past IPCC Assessment Reports have consistently examined an extensive literature on the links between climate change, adaptation, and sustainable development (Smit et al., 2001; Klein et al., 2007; Yohe et al., 2007). However, studies that explicitly refer to CRD as a concept or a guide for policy and practice remain modest (*very high confidence*). The concept of CRD appeared in scholarly literature as well as development program documents over a decade ago (Kamal Uddin et al., 2006; Garg and Halsnæs, 2007) and has been used in more recent IPCC assessment reports and special reports (e.g., Denton et al., 2014; Roy et al., 2018). Similarly, the use of the term climate resilient development pathways dates to 2009 (Ayers and Huq, 2009), but its use accelerated after appearing in UNFCCC publications around the launch of the Green Climate Fund (UNFCCC, 2011). While this chapter prioritizes the CRD literature, it also recognizes a broad range of literature, disciplinary expertise, and development practice is relevant to the concept of CRD.

Much of this literature is assessed in recent IPCC Special Reports (Rogelj et al., 2018; Roy et al., 2018; Bindoff et al., 2019; Hurlbert et al., 2019; Oppenheimer et al., 2019), but new studies have continued to emerge. More specific uses of CRD found in the literature describe development that seeks to achieve poverty reduction and adaptation to climate change simultaneously without explicit mention of mitigation (USAID, 2014)), as well as mitigation and poverty reduction, described as 'low-carbon development,' without explicit mention of adaptation (Alam et al., 2011; Fankhauser and McDermott, 2016). Other similar terms include 'climate safe', 'climate compatible' and 'climate smart' development (Huxham et al., 2015; Kim et al., 2017b; Ficklin et al., 2018; Mcleod et al., 2018), each with varying nuances. Climate-compatible development coined by Mitchell and Maxwell (2010) specifically describes a 'triple win' of adaptation, mitigation and development (Antwi-Agyei et al., 2017; Favretto et al., 2018) (see also 8.6). In this spirit, AR5 specifically referred to climate-resilient development as "*development trajectories that combine adaptation and mitigation to realize the goal of sustainable development*" (Denton et al., 2014). This chapter builds on the AR5 and, for the purposes of assessment, formally defines CRD as *a process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all.* This extension of the earlier definition reflects the emphasis in recent literature on equity as a core element of sustainable development as well as the objective of the SDGs to "*create conditions for sustainable, inclusive and sustained economic growth, shared prosperity and decent work for all, taking into account different levels of national development and capacities*" (United Nations, 2015: 3/35).

Past, present, and future concentrations of greenhouse gases in the atmosphere are the direct result of both natural and anthropogenic greenhouse gas emissions which are, in turn, a function of past and current patterns of human and economic development (*very high confidence*, WGI SPM). This includes development processes that drive land use change, extractive industries, manufacturing and trade, energy production, food production, infrastructure development, and transportation. These patterns of development are therefore drivers of current and future climate risk to specific sectors, regions, and populations (Byers et al., 2018), as well as the demand for both mitigation and adaptation as a means of preventing climate change from undermining development goals. The Sustainable Development Goals (SDGs) represent targets for supporting human and ecological well-being in a sustainable manner. Yet, while progress is being made toward a number of the Sustainable Development Goals (SDGs), success in achieving all of the SDGs by 2030 across all global regions remains uncertain (*high agreement, medium evidence*) (United Nations, 2021). Moreover, current commitments to reduce greenhouse gas emissions are not yet consistent with limiting changes in global mean temperature elevation to less than 2°C or 1.5°C (*very high confidence*) (IPCC, 2018a) (see also 18.2).

Atmospheric concentrations of greenhouse gases are just one of a number of planetary boundaries which define safe operating spaces for humanity and therefore opportunities for achieving sustainable and climate-resilient development. Exceeding these boundaries poses increased risk of large-scale abrupt or irreversible environmental changes that would threaten human and ecological well-being (*very high confidence*) (Rockström et al., 2009a; Rockström et al., 2009b; Butler, 2017; Schleussner et al., 2021). Other planetary boundaries reported in the literature such as biodiversity loss, changes in land systems, and freshwater use are also directly influenced by patterns of development as well as climate change (18.2; 18.5). Current rates of species extinction, conversion of land for crop production, and exploitation of water resources exceed planetary boundaries, thereby undermining CRD. Moreover, studies indicate that achievement of the sustainable development goals, while consistent with maintaining some planetary boundaries, could undermine others (O'Neill et al., 2018; Hickel, 2019; Randers et al., 2019) (18.2), suggesting significant shifts in current patterns of development are necessary to maintain development within planetary boundaries.

Exceedance of planetary boundaries contributes to human and ecological vulnerability to climate change and other shocks and stressors. People and regions that already face high rates of natural resource use, ecosystem degradation, and poverty are more vulnerable to climate change impacts, compounding existing development challenges in regions that are already strained (IPCC, 2014a; Hallegatte et al., 2019). The International Monetary Fund, for example, found that for a medium and low-income developing country with an annual average temperature of 25°C, the effect of a 1°C increase in temperature is a reduction in economic growth by 1.2% (Acevedo et al., 2018). Countries whose economies are projected to be hard hit by an increase in temperature account for only about 20% of global Gross Domestic Product (GDP) in 2016, but are home to nearly 60% of the global population. This is expected to rise to more than 75% by the end of the century. These economic impacts are a function of the underlying vulnerability of low- and middle-income developing economies to the impacts of climate change (see 18.5). Such vulnerability was also evidenced and enhanced by the COVID-19 pandemic which slowed progress on the SDGs in multiple nations (Naidoo and Fisher, 2020; Srivastava et al., 2020; Bherwani et al., 2021).

18.1.2 Pathways for Climate Resilient Development

One approach for operationalizing the concept of climate-resilient development in a decision-making context is to link the concept of CRD to that of pathways (Figure 18.1). A pathway can be defined as *"a trajectory in* *time, reflecting a particular sequence of actions and consequences against a background of autonomous developments, leading to a specific future situation"* (Haasnoot et al., 2013; Bourgeois, 2015). As such, a pathway represents changes over time in response to policies and practices as well spontaneous and exogenous events. For example, the SR1.5 report suggested that CRD pathways are "*a conceptual and aspirational idea for steering societies towards low-carbon, prosperous and ecologically safe futures*" (Roy et al., 2018: 468), and a way to highlight the complexity of decision-making processes at different levels. Here, consistent with the aforementioned definition of CRD, we define CRD pathways as *development trajectories that successfully integrate mitigation, adaptation, and sustainable development to achieve development goals*.

As illustrated in Figure 18.1, the ultimate aim of CRD pathways is to support sustainable development for ensuring planetary health and human well-being. CRD is both an outcome at a point in space and time, as observed through SDG achievement indicators, but also a process consisting of actions and social choices made by multiple actors—government, industry, media, civil society, and science (18.4). These actions and social choices are performed within different dimensions of governance—politics, institutions (norms, rules), and practice, and bounded by ethics, values and worldviews. The development outcomes and processes pertain to political, economic, ecological, socio-cultural, knowledge-technology, and community arenas (Figure 18.2). A CRDP will, for example, aspire to achieve ecological outcomes in terms of planetary health and achievement of Paris Agreement goals as well as human well-being, solidarity and social justice, in addition to political, economic, and science-technology outcomes. These outcomes are enabled by achieving progress in core system transitions that catalyze broader societal transformations (Figure 18.3).

While there are many possible successful pathways to future development in the context of climate change, history has shown that pathways that are positive for the vast majority, often induce notable impacts and costs, especially on marginal and vulnerable people (Hickel, 2017; Ramalho, 2019), placing them in direct contradiction with the commitment to 'leave no one behind' (United Nations, 2015). Similarly, contemporary scenario analyses find that there are plausible development trajectories that lead toward sustainability (Figure 18.1, 18.2.2). Yet, a number of plausible trajectories that perpetuate or exacerbate unstainable forms of development also appear in the literature (Figure 18.1, 18.2.2). A significant challenge lies in identifying pathways that address current climate variability and change, while allowing for improvements in human well-being. Furthermore, while a given pathway might lead to a set of desired outcomes for one region or set of actors, the process of getting there may come at high environmental, socio- and economic cost to others *(very high confidence*) (Raworth, 2017; Faist, 2018). Frequently, considerations of social difference and equity are not prioritized in the evaluation of different development choices. The assumption that a growing economy lifts opportunity for all, could for example, further marginalize those who are the most vulnerable to climate change (Matin et al., 2018; Diffenbaugh and Burke, 2019; Hickel et al., 2021).

Placing pathways and climate actions within development processes implies a broadening of enablers to include the ethical-political quality of socio-environmental processes that are required to shift such processes in directions that support CRD and the pursuit of sustainability outcomes. This chapter therefore departs from the AR5s alignment of CRD with adaptation pathways and the emphasis on decision points that enable one to manage (or fail to manage) climate risk towards a framing that integrates a range of possible futures each offering different opportunities, risks, and trade-offs to different actors and stakeholders (see WGII AR5, IPCC, 2014b, Figure SPM.9). Instead, CRD emerges from everyday formal and informal decisions, actions, and adaptation or mitigation policy interventions. This is inclusive of system transitions, increased resilience, environmental integrity, social justice, equity, and reduced poverty and vulnerability, all facets of human well-being and planetary health. Rather than encompassing a formula or blueprint for particular actions, sustainable development is a process that provides a compass for the direction that these multiple actions should take (Anders, 2016). This creates opportunities for actors to apply a diverse toolkit of adaptation, mitigation, and sustainable development interventions, thereby opening up the solution space.

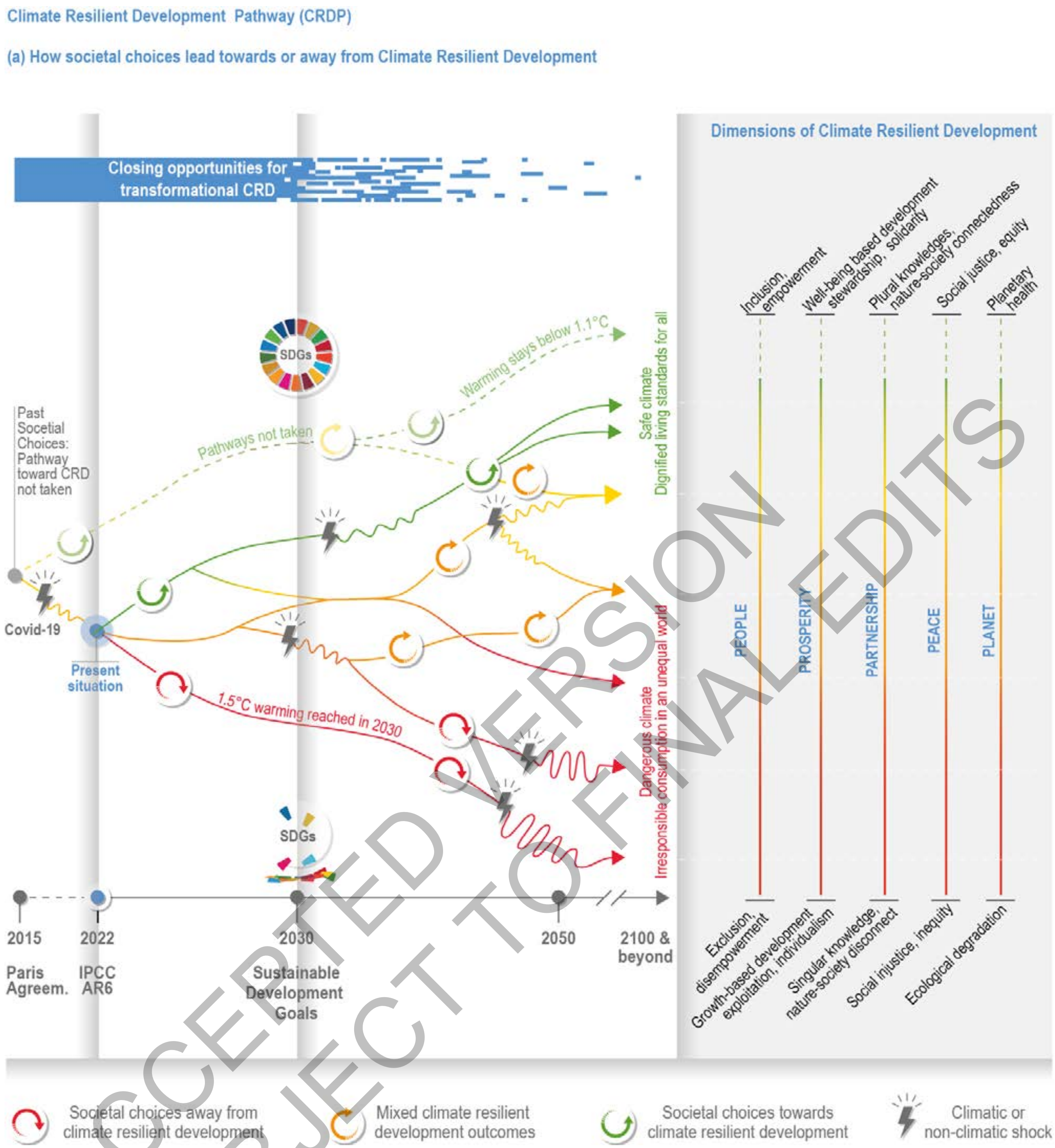


Figure 18.1: Climate Resilient Development Pathways. Climate resilient development is a process that takes place through societal choices towards (green pathways) or away from (red pathways) five development dimensions (people, prosperity, partnership, peace, planet) on which the SDGs build. Some societal choices have mixed outcomes for CRD (orange pathways). This figure builds on figure SPM.9 in AR5 WGII depicting climate resilient pathways) by describing how CRDPs emerge from societal choices within multiple arenas – rather than solely from discrete decision points. Societal choices, often contested, are made in these arenas through interactions between key actors in civil society, the private sector and government (see Figure 18.2). The quality of interactions between these actors in these arenas determine whether societal choices shift development towards or away from CRD. For example, inclusion vs exclusion and influence over choices shapes the quality of these interactions, and the outcomes of emergent societal choices. These qualities thus also characterize alternative futures resulting from different pathways, along five development dimensions (people, prosperity, partnership, peace, planet) on which the SDGs build. five CRD dimensions underline the close interconnectedness between the biosphere and humans, the two necessarily intertwined in interactions, actions, transitions, and futures (Figure 18.3). There is a narrow and closing window of opportunity to make transformational changes to move towards and not away from development futures that are more climate-resilient and sustainable. Pathways not taken (dotted line) show that the pathways towards the highest CRD futures are no longer available due to past societal choices and increasing temperatures. Present societal choices determine whether we shift towards CRD in future or whether pathways will be limited to less CRD.

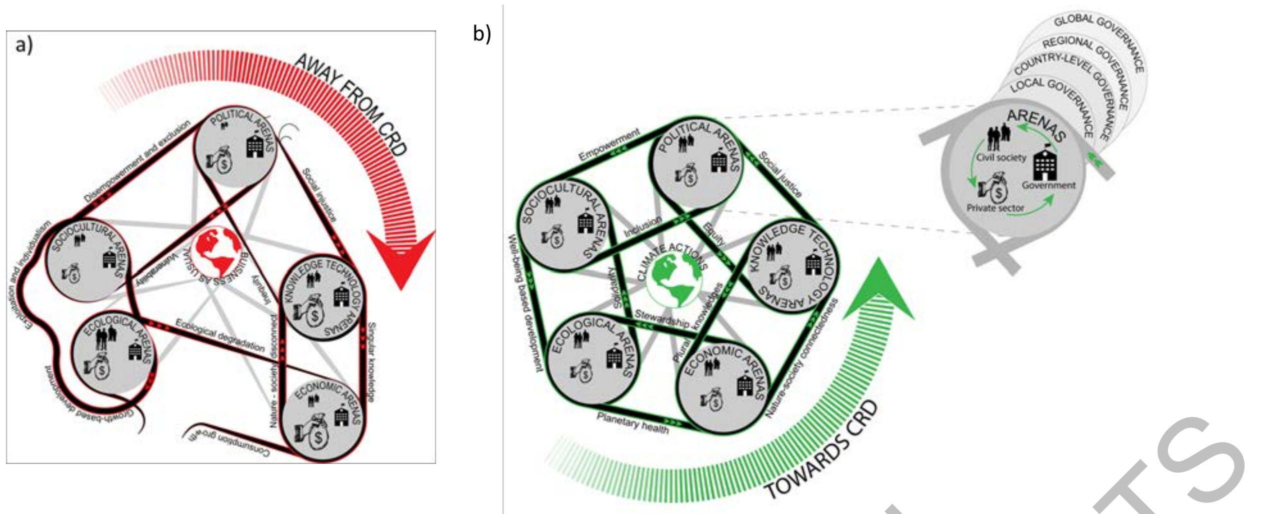


Figure 18.2: Societal choices in arenas of engagement shaping actions and systems. The settings, places and spaces in which key actors from government, civil society and the private sector interact to influence the nature and course of development can be called arenas of engagement, including political, economic, socio-cultural, ecological, knowledge-technology and community arenas. For instance, political arenas include formal political settings such as voting procedures to elect local representatives as well as less formal and transparent political arenas. Streets, town squares and post-disaster landscapes can become sites of interaction and political struggle as citizens strive to have their voices heard. Arenas exist across scales from the local to national level, and beyond. Arenas of engagement can take the form of "struggle arenas" – in which power and influence are used to include/exclude, set agendas, and make and implement decisions – with inevitable winners and losers. The quality of interactions in these arenas leads to development outcomes that can be characterized as CRD dimensions that underpin the SDGs – people, prosperity, partnership, peace, planet (see Figure 18.1). a) Interactions characterized by inequitable relations and domination of some actors over others may lead to societal choices away from CRD, including exacerbating disempowerment and vulnerability among marginalized groups. b) Prospects for moving towards CRD increase when governance actors work together constructively in these different arenas. Interactions and actions that are inclusive and synchronous, as opposed to fragmented or contradictory, enable system transitions and transformational change towards CRD (Figure 18.3b, Box 18.3). b) Well-intentioned efforts often fail to be transformative, but instead entrench inequities. Instead, marginalized groups and future trends in vulnerability need to be placed at the center of efforts to chart CRDPs. Unlocking the productive potential of conflict that often characterizes interactions in these arenas of engagement is central to advancing human well-being and planetary health. Moreover, the window for doing so is closing rapidly to avert dangerous climate change and unsustainable development.

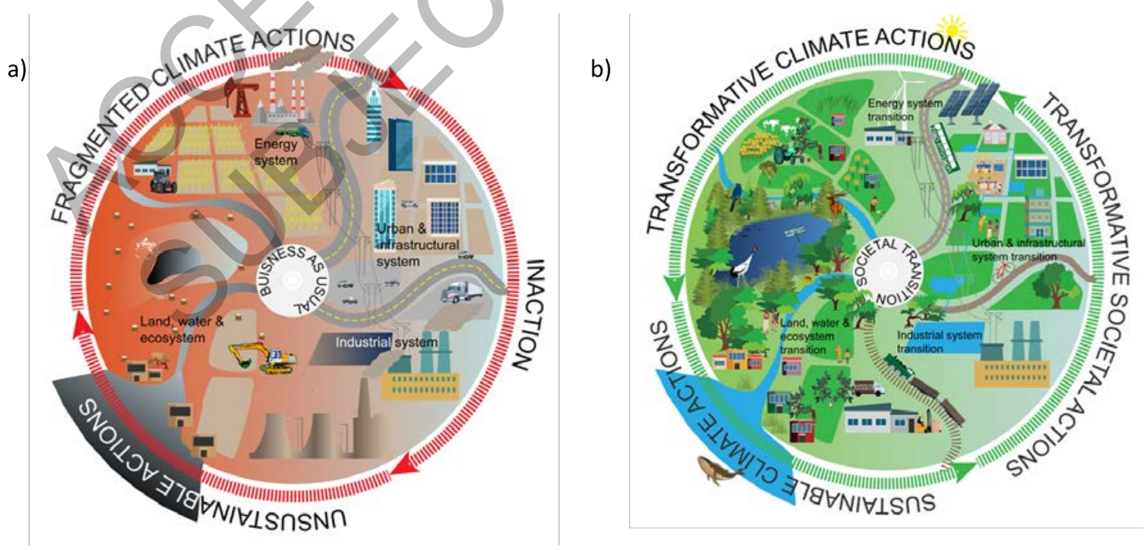


Figure 18.3: Transformative actions and system transitions a) Societal choices that generate fragmented climate action or inaction and unsustainable development perpetuate business as usual development. b) Societal choices that support CRD involve transformative actions that drive five systems transitions (energy, land and other ecosystems, urban and infrastructure, industrial and societal). There is close interdependence between these systems. The system transition

framework allows for a comprehensive assessment of the synergies and trade-offs between mitigation, adaptation and sustainable development. For example, land and water use in one system impacts the other systems and their surrounding ecosystems, thus reflecting how agricultural practices can have an impact on energy usage in urban centers. Finally, societal system transitions within each of the other systems enable the transitions to occur

This understanding of CRD implies that different actors – governments, businesses, and civic organizations – will have to design and navigate their own CRD pathways toward climate resilient and sustainable development. This includes determining the appropriate balance of adaptation, mitigation, and sustainable development actions and investments that are consistent with individual actors' development circumstances and goals while also ensuring that the collective actions remain consistent with global agreements and goals (such as the SDGs, Sendai Framework, and the Paris Agreement; 18.1.3), planetary boundaries, and other principles of CRD including social justice and equity (Roy et al., 2018). Empowering individual actors to pursue CRD in context-specific manner while coordinating action among actors and a diversity of scales, local to global, is a key challenge associated with achieving CRD (*high agreement, limited evidence*).

18.1.3 Policy Context for Climate Resilient Development

As reflected in Chapter 1 of the AR6 WGII report, CRD is emerging as one of the guiding principles for climate policy, both at the international level (Denton et al., 2014; Segger, 2016), as reflected in the Paris Agreement (Article 2, UNFCCC, 2015), and within specific countries (Simonet and Jobbins, 2016; Kim et al., 2017b; Vincent and Colenbrander, 2018; Yalew, 2020). This framing of development recognizes the risks posed by climate change to development objectives (18.2; see also Chapter 16); the opportunities, constraints and limits associated with reducing risk through adaptation; synergies and trade-offs between mitigation, adaptation, and sustainable development (18.2.5, 18.5, Box 18.4); and the role of system transitions in enabling large-scale transformations that limit future global warming to less than 1.5°C while boosting resilience (IPCC, 2018a) (18.3, Box 18.1).

Since the AR5, the volume of research at the nexus of climate action and sustainable development has changed markedly (*very high confidence*). A rapidly growing, multi-disciplinary literature has emerged on climate resilient development (Mitchell et al., 2015; Clapp and Sillmann, 2019; Hardoy et al., 2019; Yalew, 2020) and associated pathways (Naess et al., 2015; Winkler and Dubash, 2016; Brechin and Espinoza, 2017; Solecki et al., 2017; Ellis and Tschakert, 2019) (18.2.2). Nevertheless, the concept of resilience generally, and climate resilient development specifically, has come under increasing criticism in recent years (*very high confidence*) (Joakim et al., 2015; Schlosberg et al., 2017; Mikulewicz, 2018; Mikulewicz, 2019), suggesting the need to enhance understanding of how resilience is being operationalized at the program and project level and the net implications for human and ecological well-being.

This expansion of research has been accompanied by a shift in the policy context for climate action including an increasingly strong link between climate actions and sustainable development. In particular, the SDGs represent a near-term framework linking sustainability and human development in a manner that not only addresses planetary health and human wellbeing, but also help better plan and implement mitigation and adaptation actions to achieve these linked goals (Conway et al., 2015; Griscom et al., 2017; Allen et al., 2018b; Roy et al., 2018; P.R. Shukla E. Calvo Buendia, 2019). The SDGs explicitly identify climate action (SDG 13) among the goals needed to achieve sustainable development. Meanwhile, the text of the Paris Agreement makes explicit mention of the importance of considering climate "in the context of sustainable development" (Articles 2, 4, 6) or as "contributing to sustainable development" (Article 7) (Article 7, UNFCCC, 2015). Similarly, sustainable development appears prominently within the text of the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015), and the Global Assessment Reports on Disaster Risk Reduction (Undrr, 2019). At the micro-level, a growing literature recognizes that climate impacts tend to exacerbate existing inequalities within societies, even at the level of gender inequalities within households (Sultana, 2010; Arora-Jonsson, 2011; Carr, 2013). Thus, climate change impacts threaten even short-term gains in sustainable development, which could be rolled back over longer adaptation and mitigation horizons. For example, the COVID-19 pandemic is estimated to have reversed gains over the past several years in terms of global poverty reduction (*very high confidence*) (Phillips et al., 2020; Sultana, 2021; Wilhelmi et al., 2021) (Cross-Chapter Box COVID in Chapter 7), reflecting the risks posed by global, systemic threats to development.

The WGII AR5 Report noted that adapting to the risks associated with climate change becomes more challenging at higher levels of global warming (IPCC, 2014a). This was evidenced by contrasting impacts and adaptive capacity for 2° and 4°C of warming. This relationship between levels of warming, climate risk, and reasons for concern (see Chapter 16) is also relevant to the concept of CRD. For example, recent literature on CRD emphasizes the urgency of climate action that achieve significant reduction in greenhouse gas emissions as well as the implementation of adaptation options that result in significant gains in human and natural system resilience (*very high confidence*) (Haines et al., 2017; Shindell et al., 2017; Xu and Ramanathan, 2017; Fuso Nerini et al., 2018). This was explored extensively in the IPCC's SR1.5 report in its comparison of impacts associated with 1.5°C versus 2°C climate objectives and synergies and trade-offs with the SDGs (IPCC, 2018a). However, the SR1.5 report and other literature also identified potential trade-offs between aggressive mitigation and the SDGs (see also Frank et al., 2017; Hasegawa et al., 2018). This indicates that while future magnitudes of warming are a fundamental consideration in climate-resilient development, such development involves more than just achieving temperature targets. Rather, CRD considers the possible transitions that enable those targets to be achieved including the evaluation of different adaptation and mitigation options and how the implementation of these strategies interacts with broader sustainable development efforts and goals. This interdependence between patterns of development, climate risk, and the demand for mitigation and adaptation action is fundamental to the concept of CRD (Fankhauser and McDermott, 2016). Therefore, climate change and sustainable development cannot be assessed or planned in isolation of one another.

18.1.4 Assessing Climate Resilient Development

In operationalizing the aforementioned definitions of CRD and CRD pathways this chapter builds its assessment around five core elements that provide insights relevant to policymakers actively pursuing the integration of climate resilience into development. First, as noted above, climate change poses a potential risk to the achievement of development goals, including global goals such as the SDGs, as well as nationally- or locally-specific goals. Accordingly, Chapter 16's discussion of key risks, their implications for the SDGs, and the options for risk management are fundamental to the pursuit of CRD. This includes the opportunities for implementing adaptation, mitigation, or other risk management options. Yet, the management of climate risk must be accompanied by interventions that address social and ecological vulnerabilities that enhance climate risk.

Second, CRD is dependent on achieving transitions in key systems including energy, land and ecosystem, urban and infrastructure, and industrial systems (*very high confidence*) (Box 18.1, Figure 18.3). In this context, CRD links to the discussion of system transitions in the SR1.5 report (IPCC, 2018b; IPCC, 2018a). However, in building on the SR1.5, here the assessment of CRD also recognizes the importance of transitions in societal systems that drive innovation, preferences for alternative patterns of consumption and development, and the power relationships among different actors that engage in CRD. In particular, the rate at which actors can achieve system transitions has important implications for the pursuit of CRD. Transitions that are slow to evolve or that are more incremental in nature may not be sufficient to enable CRD in comparison with faster transitions that contribute to more fundamental system transformations.

Third, equity and social justice are consistently identified in the literature as being central to climate resilient development (*very high confidence*; 18.1.1, 18.3.1.5, 18.4, 18.5). This includes designing and implementing adaptation, resilience, and climate risk management options in a manner that promotes equity in the allocation of the costs and benefits of those options. Similarly, the literature on CRD emphasizes equity should be pursued in the implementation of options for greenhouse gas mitigation, transitions in energy systems, and low-carbon development. This emphasis on equity is consistent with the SDGs which place an emphasis on reducing inequality and achieving sustainable development for all.

Fourth, success in CRD and alignment of development interventions to CRD pathways (CRDPs) is contingent on the presence of multiple enabling conditions (*very high confidence*, 18.4.2), that operate at different scales ranging from those that provide capacity to implement specific adaptation options to those that enable large-scale transformational change (Box 18.1). The qualities that describe sustainable development processes (e.g., social justice, alternative development models, equity and solidarity as described above and in Figure 18.1) lead to short-term outcomes and conditions, such as those represented by SDGs, that in an iterative fashion enable or constraint subsequent efforts toward CRD. For example, success or failure in achieving the SDGs or the Paris Agreement would shape future efforts in pursuit of CRD and the options available to different actors.

Fifth, CRD involves processes involving diverse actors, at different scales operating within an environmental, developmental, socio-economic, cultural, and political context, as typified in the SDG and the Paris Agreement negotiations *(very high confidence*) (Kamau et al., 2018) (18.4). The dependence of CRD on processes of negotiation and reconciliation among diverse actors and interests leads to the dismissal of the notion that there is a single, optimal pathway that captures the objectives, values, and development contexts of all actors, even for a particular sector, country or region. Rather, preferences for different pathways and specific actions in pursuit of those pathways will be subjected to intense scrutiny and debate among diverse actors within various arenas of engagement (18.4), meaning the settings, places and spaces in which key actors from government, civil society and the private sector interact to influence the nature and course of development.

18.1.5 Chapter Roadmap

This chapter engages with understanding CRD and the pathways to achieving it by building on the concepts introduced in Chapter 1 of this Working Group II report as well as the regional and sectoral context presented in other chapters (18.5). Notably, this chapter takes off where Chapters 16 and 17 end: recognizing the significance of the representative key risks for CRD as well as the decision-making context of different actors who are implementing policies and practices to pursue different CRD pathways and manage climate risk. Therefore, the chapter assesses options for pursuing CRD as well as the broader system transitions and enabling conditions in support of CRD.

This chapter hosts three Cross-Chapter Boxes, which have their natural home here. The Cross-Chapter Box on Gender, Justice and Transformative Pathways (Cross-Chapter Box GENDER) assesses literature specifically on gender and climate change to uncover the importance of a justice focus to facilitate transformative pathways, both toward CRD, as well as a means to achieving gender equity and social justice. The Cross-Chapter Box on The Role of Indigenous Knowledge in Understanding and Adapting to Climate Change (Cross-Chapter Box INDIG) highlights that achieving CRD requires confronting the uncertainty of a climate change future. There are many perspectives about what future is desired and how to reach it. Integrating multiple forms of knowledge is a strategy to build resilience and develop institutional arrangements that provide temporary solutions able to satisfy competing interests (Grove, 2018). Indigenous knowledge is proven to enhance resilience in multiple contexts (e.g., Chowdhooree, 2019; Inaotombi and Mahanta, 2019). Meanwhile, Cross-Chapter Box FEASIB acts as an appendix to the WGII report, synthesizing information on the feasibility associated with different adaptation options for reducing risk.

In assessing the opportunities and constraints associated with the pursuit of sustainable development, this chapter proceeds in Section 18.2 to assess the links between sustainable development and climate action, including examination of current patterns of development and consideration for synergies and trade-offs among different strategies and options. Then, in Section 18.3, the chapter assesses five systems transitions to identify the shifts in development that would enable CRD. Section 18.4 assesses the role of different actors in the pursuit of CRD as well as the public and private arenas in which they engage. Section 18.5 synthesizes CRD assessments from different WGII sectoral and regional chapters to identify commonalities and differences. The chapter concludes in Section 18.6 with a summary of key opportunities for enhancing the knowledge needed to enable different actors to pursue CRD.

[START BOX 18.1 HERE]

Box 18.1: Transformations in Support of Climate Resilient Development Pathways

Transformational changes in the pursuit of CRDPs involve interactions between individual, collective, and systems change (see Figures 18.1–18.3). There are complex interconnections between transformation and transition (Feola, 2015; Hölscher et al., 2018), and they are sometimes used as synonyms in the literature (Hölscher et al., 2018). Much of the transitions literature focuses on how societal change occurs within existing political and economic systems. Transformations are often considered to involve deeper and more fundamental changes than transitions, including changes to underlying values, worldviews, ideologies, structures, and power relationships (Göpel, 2016; O'Brien, 2016; Kuenkel, 2019; Waddock, 2019). Systems transitions alone are insufficient to achieve the rapid, fundamental and comprehensive changes required for humanity and planetary health in the face of climate change (*high confidence)*. Transformative action is increasingly urgent across all sectors, systems and scales to avert dangerous climate change and meet the SDGs (Pelling et al., 2015; IPCC, 2018a; IPCC, 2021b; Shi and Moser, 2021; Vogel and O'Brien, 2021) (*high confidence*). The SR1.5 identified transformative change as necessary to achieve transitions within land, water and ecosystems systems; urban and infrastructural systems; energy systems; and industrial systems. This box summarises key points in the transformations literature relevant to climate resilient development.

Transformative actions aimed at 'deliberately and fundamentally changing systems to achieve more just and equitable outcomes', (Shi and Moser, 2021: 2) shift pathways towards CRD (*high confidence)*. Transformative action in the context of CRD specifically concerns leveraging change in the five dimensions of development (people, prosperity, partnership, peace, planet) that drive societal choices and climate actions towards sustainability (18.2.2; Figure 18.1). Climate actions that support CRD are embedded in these dimensions of development; for example, social cohesion and equity, individual and collective agency, and democratising knowledge processes have been identified as steps to transform practices and governance systems for increased resilience (Ziervogel et al., 2016b; Nightingale et al., 2020; Colloff et al., 2021; Vogel and O'Brien, 2021) (*high confidence)*. Transformative actions toward sustainability and increased well-being, which are dominant components of climate resilient development, include those that explicitly redress social drivers of vulnerability, shift dominant worldviews, decolonialise knowledge systems, activate human agency, contest political arrangements, and insert a plurality of knowledges and ways of knowing (Görg et al., 2017; Fazey et al., 2018a; Brand et al., 2020; Gram-Hanssen et al., 2021; Shi and Moser, 2021). They alter the governance and political economic arrangements through which unsustainable and unjust development logics and knowledges are implemented (Patterson et al., 2017; Shi and Moser, 2021) by shifting the goals of a system or altering the mindset or paradigm from which a system arises, e.g from individualism and nature-society disconnect to solidarity and nature-society connectedness along the CRD dimensions in figure 18.1, and connecting inner and external dimensions of sustainability, (Göpel, 2016; Abson et al., 2017; Wamsler and Brink, 2018; Fischer and Riechers, 2019; Horcea-Milcu et al., 2019; Wamsler, 2019).

There is no blueprint for how transformation is generated. An expanding literature suggests that transformation takes place through diverse modalities and context-dependent actions (O'Brien, 2021). Transformation may require actions that disrupt moral or social boundaries and structures that are perpetuating unsustainable systems and pathways (Vogel and O'Brien, 2021) (*high confidence*). Extreme events and long-term climatic changes can trigger a realigning of practices, politics and knowledges (Carr, 2019; Schipper et al., 2020b) (*high confidence*). While some see opportunities for generating social and political conditions needed for CRD in such actions and events (Beck, 2015; Han, 2015; Shim, 2015; Mythen and Walklate, 2016; Domingo, 2018), this is not guaranteed. Climate shocks, when managed within socio-political systems in ways that safeguard rather than alter practices and structures, can also reinforce rather than shift the status quo (Mosberg et al., 2017; Carr, 2019; Marmot and Allen, 2020; Arifeen and Nyborg, 2021) (*high confidence*). Further, in the absence of equitable and inclusive decision-making and planning, realignments resulting from disruptive actions and events can limit inclusiveness and lead to poor or coercive decision-making processes that undermine the equity and justice foundations of sustainable development (Orlove et al., 2020; Shi and Moser, 2021) and lead to adverse socio-environmental outcomes that generate transformations away from CRD (Vogel and O'Brien, 2021) *(high confidence*, see also CCP2).

Evidence for transformative actions largely exists at the community or city level. While identifying how to rapidly and equitably generate transformations at a global scale has remained elusive, there is *high agreement* but *limited evidence* from studies of ecosystem services that suggest facilitating a wide range of locally-appropriate management decisions and actions can bring about positive global-scale outcomes (Millennium Ecosystem, 2005). Diverse local efforts to transform towards sustainability in the face of climate change have been observed, such as community mobilization for equitable and just adaptation actions and alternative visions of societal well-being (Shi, 2020b) and farmer-led shifts in agricultural production systems (Rosenberg, 2021). There has been an increase in transformative actions taking place through city-level resilience building aimed at shifting inequitable relations and opening up space for a plurality of actors (Rosenzweig and Solecki, 2018; Ziervogel et al., 2021) (*high confidence)*.

Prospects for transformation towards climate resilient development increase when key governance actors work together in inclusive and constructive ways through engagement in political, knowledge-technology, ecological, economic, and socio-cultural arenas (*high confidence*,18.4.3). Yet, the interactions between key governance actors involve struggles and negotiations in addition to collaborations (Kakenmaster, 2019; Muok et al., 2021). Transformative actions meet resistance by precisely the political, social, knowledge and technical systems and structures they are attempting to transform (Blythe et al., 2018; Shi and Moser, 2021) (*high confidence*). There is expanding evidence that many adaptation efforts have failed to be transformative, but instead entrenched inequities, exacerbated power imbalances and reinforced vulnerability among marginalized groups, and that, instead, marginalized groups and future trends in vulnerability need to be placed at the center of adaptation planning (Atteridge and Remling, 2018; Mikulewicz, 2019; Owen, 2020; Eriksen et al., 2021a; Eriksen et al., 2021b; Garschagen et al., 2021) (*high confidence*). Beyond the enablers, drivers, or modalities, another question tackled in the literature is how to evaluate transformation by establishing criteria for transformation assessments (Ofir, 2021; Patton, 2021; Williams et al., 2021), experience-based lessons on managing transformative adaptation processes (Vermeulen et al., 2018), climate policy integration (Plank et al., 2021), investment criteria (Kasdan et al., 2021), political economy analysis frameworks for climate governance (Price, 2021).

[END BOX 18.1 HERE]

[START BOX 18.2 HERE]

Box 18.2: Visions of Climate Resilient Development in Kenya

The Government of Kenya's (GoK) ambition is to transform Kenya into a 'newly industrializing, middle-income country providing a high-quality life to all its citizens by 2030 in a clean and secure environment' (Government of Kenya, 2008). Dryland regions in Kenya occupy 80-90 per cent of the land mass, are home to 36% of the population (Government of Kenya, 2012) and contribute about 10 per cent of Kenya's Gross Domestic Product (GDP) (Government of Kenya, 2012) which includes half of its agricultural GDP (Kabubo-Mariara, 2009). In dryland regions, pastoralism has long been the predominant form of livelihood and subsistence (Catley et al., 2013; Nyariki and Amwata, 2019). The GoK seeks to improve connectivity and communication infrastructure within the drylands to better exploit and develop livestock, agriculture, tourism, energy, and extractive sectors (Government of Kenya, 2018). It argues that the transformation of dryland regions is crucial to enhance the development outcomes for the more than 15 million people who inhabit these areas (Government of Kenya, 2016: 17) and to help the country to realize its wider national ambitions including a 10 percent year on year growth in GDP (Government of Kenya, 2012). A key element within this vision is the promotion and implementation of the Lamu Port South Sudan Ethiopia (LAPSSET) project, a 2,000km long, 100 km wide economic and development corridor extending from Mombasa to Sudan and Ethiopia (Enns, 2018). Supporters of the LAPSSET project argue that it will help achieve priorities laid out in the Vision 2030 by opening up poorly connected regions, enabling the development of pertinent economic sectors such as agriculture, livestock and energy, and supporting the attainment of a range of social goals made possible as the economy grows (Stein and Kalina, 2019).

However, the development narrative surrounding LAPSSET remains controversial in its assumptions, not least because it is being promoted in the context of a highly complex and dynamic social, economic and biophysical setting (Cervigni and Morris, 2016; Atsiaya et al., 2019; Chome, 2020; Lesutis, 2020). Some of the key trends driving contemporary and likely future change in dryland regions are changing household organization, evolving customary rules and institutions at local and community levels, and shifting cultures and aspirations (Catley et al., 2013; Washington-Ottombre and Pijanowski, 2013; Tari and Pattison, 2014; Cormack, 2016; Rao, 2019). Dryland regions are also witnessing demographic growth and change in land-use patterns linked to shifts in the composition of livestock (for example from grazers to browsers), a decrease in nomadic and increase in semi-nomadic pastoralism, and transition to more urban and sedentary livelihoods (Mganga et al., 2015; Cervigni et al., 2016; Greiner, 2016; Watson et al., 2016). At a landscape level, land is becoming more fragmented and enclosed, often associated with increases in subsistence and commercial agriculture, and the establishment of conservancies and other group or private land holdings (Reid et al., 2014; Carabine et al., 2015; Nyberg et al., 2015; Greiner, 2016; Mosley and Watson, 2016). In addition, there are political dynamics associated with Kenya Vision 2030 and decentralization, the influence of international capital, foreign investors and incorporation into global markets (Cormack, 2016; Kochore, 2016; Mosley and Watson, 2016; Enns and Bersaglio, 2020), as well as increasing militarization and conflict in the drylands (Lind, 2018). Allied to these social and political dynamics are ongoing processes of habitat modification and degradation and biophysical changes linked in part to climate variability (Galvin, 2009; Mganga et al., 2015). The interconnected nature of these drivers will intersect with LAPSSET in myriad ways. For example, the implementation of LAPSSET may accentuate some trends, such as increases in land enclosure and a shift towards more urban and sedentary livelihoods (Lesutis, 2020). Conversely, the perceived threat LAPSSET could pose to pastoral lifestyles may lead to greater visibility, solidarity and strength of pastoralist institutions (Cormack, 2016).

There is a recognized need to adapt and chose development pathways that are resilient to climate change whilst addressing key developmental challenges within dryland regions, notably, poverty, water and food insecurity, and a highly dispersed population with poor access to services (Government of Kenya, 2012; Bizikova et al., 2015; Herrero et al., 2016). The current vision for development of dryland regions comes with both opportunities and threats to achieve a more climate resilient future. For example, the growth in and exploitation of renewable energy resources, made possible through increased connectivity, brings climate mitigation gains but also risks. These risks include the uneven distribution of costs in terms of where the industry is sited compared with where benefits primarily accrue, and may exacerbate issues around water and food insecurity as strategic areas of land become harder to access (Opiyo et al., 2016; Cormack and Kurewa, 2018; Enns, 2018; Lind, 2018). Whilst LAPSSET will bring greater freedom of movement for commodities, benefitting investors, improving access to markets and urban centers, supporting trade, or ease of movement for tourists supporting economic goals, it can also result in the relocation of people and impede access to certain locations for the resident populations. Mobility is a key adaptation behavior employed in the short and long term to address issues linked with climatic variability (Opiyo et al., 2014; Muricho et al., 2019). With modelled changes in the climate suggesting decreases in income associated with agricultural staples and livestock-dependent livelihoods, development that constrains mobility of local populations could retard resilience gains (Ochieng et al., 2017; ASSAR, 2018; Enns, 2018; Nkemelang et al., 2018). The likely increase in urban populations and the growth in tourism and agriculture may lead to increases in water demand at a time when water availability could become more constrained owing to the reliance on surface water sources and the modelled increases in evapotranspiration due to rising mean temperature, more heatwave days and greater percentage of precipitation falling as storms (ASSAR, 2018; Nkemelang et al., 2018; USAID, 2018). These pressures could make it harder to meet basic health and sanitation goals for rural and poorer urban populations, issues compounded further by likely increases in child malnutrition and diarrheal deaths linked to climate change (WHO, 2016; ASSAR, 2018; Hirpa et al., 2018; Nkemelang et al., 2018; Lesutis, 2020). Development must pay adequate attention to these interconnections to ensure that costs and benefits of achieving climate mitigation and adaptation goals are distributed fairly within a population.

[END BOX 18.2. HERE]

18.2 Linking Development and Climate Action

The AR5 examined the relationship between climate and sustainable development in Chapter 13 (Olsson et al., 2014) and Chapter 20 (Denton et al., 2014) in Working Group II and Chapter 4 (Fleurbaey et al., 2014) in Working Group III. It concluded that dangerous levels of climate change would limit efforts to reduce poverty (Denton et al., 2014; Fleurbaey et al., 2014). Since the AR5, the adoption of the Paris Agreement and Agenda 2030 have demonstrated increased international consensus regarding the need to pursue climate change as a component of sustainable development. For example, climate change impacts *"undermine the ability of all countries to achieve sustainable development"* (United Nations, 2015) and can reverse or erase improvements in living conditions and decades of development (Hallegatte and Rozenberg, 2017). However, recent analysis shows that actions to meet the goals of the Paris Agreement can undermine progress toward some SDGs (*high agreement, medium evidence*) (Pearce et al., 2018b; Liu et al., 2019; Hegre et al., 2020) (18.2.5.3). Meanwhile efforts to achieve the SDGs can contribute to worsening climate change (*high agreement, medium evidence*) (Fuso Nerini et al., 2018). These findings in the literature highlight the importance of identifying clear goals and priorities for both climate action and sustainable development as well as mechanisms for capitalizing on potential synergies between them and for managing trade-offs. In assessing literature relevant to the intersection between climate action and development, we first explore the implications of different patterns of development and development trajectories followed by more focused assessment of the links between development and climate risk.

18.2.1 Implications of Current Development Trends

Understanding the interactions between climate change, climate action, and sustainable development necessitates consideration for the current development context in which different communities, nations, and regions find themselves. For example, wealthy economies of the global North will encounter different opportunities and challenges vis-à-vis climate change and sustainable development than developing economies of the global South. Moreover, all economies are already following an existing development trajectory that has implications for the type and scale of interventions associated with pursuing CRD and managing climate risk. Some nations may experience particular challenges with reducing greenhouse gas emissions due to the carbon-intensive nature of their energy systems *(very high confidence)* (18.3.1.1). Others may experience acute challenges with adaptation due to existing vulnerability associated with poverty and social inequality *(very high confidence*) (18.2.5.1). Overcoming such challenges is fundamental to the pursuit of CRD.

While demonstrable progress has been made toward the SDGs and improving human well-being, globally and in specific nations, some observed patterns of development are inconsistent with sustainable development and the principles of CRD *(very high confidence*) (van Dooren et al., 2018; Eisenmenger et al., 2020; Leal Filho et al., 2020). A significant literature, for example, links development to the loss of biodiversity and the extinction crisis (Ceballos et al., 2017; Gonçalves-Souza et al., 2020; Oke et al., 2021). Meanwhile, in human systems, indicators such as the limited convergence in income, life expectancy, and other measures of well-being between poor and wealthy countries (with notable outliers such as China) (Bangura, 2019), and the increase in income inequality and the decline in life expectancy and well-being in rich countries (Rougoor and van Marrewijk, 2015; Alvaredo et al., 2017; Goda et al., 2017; Harper et al., 2017; Goldman et al., 2018), suggest limitations of the current development paradigm to successfully deliver universal human and ecological well-being, by the 2030s or even mid-century (TWI, 2019).

18.2.2 Understanding Development in Climate Resilient Development

Development in this report is defined as efforts, both formal and informal, to improve standards of human well-being, particularly in places historically disadvantaged by colonialism and other features of early global integration. Development is not limited to the SDGs, however these represent an internationally agreed sub-set of goals. Prior IPCC reports employed development as a typological framing of the current state of a given country or population (IPCC, 2014a) (Section 1.1.4). Such framings frequently rest upon measures of economic activity, using them as proxies for the wider well-being of the population whose activity is measured. For example, the level of gross domestic product (GDP) is often equated with levels of social welfare, even though as a measure of market output it can be an inadequate metric for gauging well-being over time particularly in its environmental and social dimensions (Van den Bergh, 2007; Stiglitz et al., 2009).

The result of this broad framing linking economic growth to human well-being has been decades of policies, programs, and projects aimed at growing economies at scales from the household to regional and global. However, linking development to past and current modes of economic growth creates significant challenges for CRD, as it implies that the very processes that have contributed to current climate challenges, including economic growth and the resource use and energy regimes it relies upon, are also the pathways to improvements in human well-being. This places climate resilience and development in opposition to one another.

While there are many possible successful pathways to future development in the context of climate change, history shows that pathways positive for the vast majority of people, typically induce significant impacts and costs, especially on marginal and vulnerable people (Hickel, 2017). Frequently, considerations for social difference and equity are side-lined in these processes, for example through the assumption that a growing economy lifts opportunity for all, further marginalizing those who are the most vulnerable to climate change (Matin et al., 2018; Diffenbaugh and Burke, 2019).

The Agenda 2030 and its 17 SDGs and 169 targets seeks to 'leave no one behind' through five pillars (5Ps): People, Planet, Prosperity, Peace and Partnership (United Nations, 2015). The five pillars align with the dimensions of development that influence motion toward or away from CRD. The focus on **people** refers to inclusion rather than exclusion, and the extent to which people are empowered or disempowered to make decisions about their well-being, determine their futures and be in a position to assert their rights. This means being able to make decisions that determine whether people are on a pathway toward or away from CRD (Figures 18.1–18.3. The focus on **planet** refers to protecting the planet, ensuring a balance of ecosystems, biodiversity and human activities, and giving equal space and respect for its integrity. The focus on **prosperity** refers to equity in well-being grounded in unanimity over shared goals and resources, rather than individualism, and economic, social and technological progress grounded in stewardship and care, rather than exploitation. The focus on **partnership** refers to mutual respect embedded in solidarity that recognizes multiple worldviews and their respective knowledges, rather than singular or hierarchy of knowledge, and acknowledges inherent nature-society connections, rather than posing nature as opposites or competitors. The focus on **peace** emphasizes the need for just and equitable societies. These five pillars are interrelated but local and national contexts situate current status differently around the world. Successful achievement of Agenda 2030 is aligned with a safe climate with adequate mitigation and adaptation, and effective and inclusive systems transitions. With these conditions, a high CRD world can be attained, noting that when approached individually, the transformative potential of the SDGs is limited (Veland et al., 2021).

The need for transformational changes across sectors and scales to address the urgency and scope of action needed to enable a climate resilient future in which goals like the SDGs might be realized requires attention to the specific ways in which development action is defined and enacted (Box 18.1).

18.2.2.1 Development Perspectives

Development is about 'improvement'. However there have been different and oftentimes conflicting viewpoints on the improvement of 'what' and 'how' to improve. The diversity of positions has resulted in a multitude of metrics to track development, some more influential than others on policy. Alternative measures of development, while numerous, generally seek to nuance the connection between economic growth and human well-being. Because they maintain core notions of progress and, in some cases, economic growth seen in more mainstream models of development, they are less vehicles for transformation than continuations of thinking and action fundamentally at odds with the needs of climate resilient development. These include the Measure of Economic Welfare (Nordhaus and Tobin, 1973), the Index of Sustainable Economic Welfare (Cobb and Daly, 1989), the Genuine Progress Indicator (Escobar, 1995), the Adjusted Net Saving Index or the Genuine Savings Index (GSI), The Human Development Index (HDI), the Inequality-adjusted Human Development Index (UNDP, 2016a), the Gender Development Index, the Gender Inequality Index, and the Multidimensional Poverty Index, the Index of Sustainable Economic Welfare (ISEW) (Daly and Cobb, 1989), the Genuine Progress Indicator (GPI) (Kubiszewski et al., 2013), Gross National Happiness (GNH) (Ura and Galay, 2004), Measures of Australia's Progress (MAP) (Trewin and Hall, 2004), the OECD Better Life Index (OECD, 2019a), and the Happy Planet Index (NEF, 2016).

In terms of their historical trajectory, different perspectives on development can be broadly divided into five categories.

a) *Development as economic growth (1950s onwards)*: Equating development with economic growth was a natural outcome of the dominance of economics as the major discipline to study problems of newly independent countries in the 1950s (Escobar, 1995), measured through GDP. Environment was not a policy concern in the immediate period after decolonization. The GDP measure has withstood the test of time, in spite of being an inexact measure of human well-being, and is the widely used metric globally to track development. Recent improvements to GDP have tried to account for environmental factors (Gundimeda et al., 2007; United Nations, 2021).

b) *Development as distributional improvements (1970s onwards)*: That economic growth does not automatically result in decline in poverty and improved distribution of income became apparent in the 1970s. Welfare measures were thus promoted that involved 'redistribution with growth' (Chenery, 1974). These distributional concerns have re-emerged in the last two decades with the widening gap between the richer and poorer groups of the population (Chancel and Piketty, 2019) and also the increased attention to 'ecological distribution conflicts' (Martinez-Alier, 2021). The political economy perspective, highlighting continued dependencies of countries in the Global South on the Global North, now evolved into political ecology highlighting environmental concerns between and within countries. Environment was not yet a policy priority, despite that the links between development and environment were becoming clearer.

c) *Development as participation (1980s onwards)*: Bottom-up responses emphasizing sustainable livelihoods and local-level development emerged in the 1980s. The movement which involved independent and uncoordinated efforts by grassroots activists, social movements and NGOs became 'mainstreamed' into development in the 1990s (Chambers, 2012). The multidimensional nature of poverty was acknowledged at the global policy level (World Bank, 2000) and there was wider acceptance of the role of non-economics social sciences as well as critical approaches in research on development and poverty (Thomas, 2008). Participatory development involved decentralization and local planning, emphasizing protection of local natural resources in addition to improving living standards.

d) *Development as expansion of human capabilities (1980s onwards)*: The human development and capabilities approach was the first formidable response to the GDP-centric view of development (Sen, 2000; Deneulin and Shahani, 2009). Studies showed that improvements in income did not necessarily improve human well-being in other dimensions such as health and education, or more broadly put, 'freedoms' (Ruggeri Laderchi et al., 2003). The capabilities idea was influential in global policy making through Human Development Reports and metrics such as Human Development Index (HDI) and Multidimensional Poverty Index (MPI). However, environmental sustainability was not a major component in this approach until much later (Alkire and Jahan, 2018). Recent improvements to HDI such as the Planetary pressures-adjusted HDI (United Nations, 2020) is a step in this direction.

e) *Development as post-growth (2010 onwards)*: The late 1980s saw a big push towards taking the environment to the center of the global policy agenda (World Commission on Environment and Development, 1987). However, progress in addressing environmental questions has been slow. As compared to Millennium Development Goals (MDGs), SDGs aim to tackle environmental concerns by explicitly tracking progress on multiple indicators. Nevertheless, the approach in these policy propositions sits largely within the economic growth framework itself. The climate change challenge and the financial crisis of 2008 led many scholars, ecological economists and environmental social scientists in particular, to argue for a post-growth world. Post-growth (Jackson, 2021), degrowth (Kallis, 2018; Hickel et al., 2021) and other environmentalist scholarship takes inspiration from critiques of development such as post-development (Escobar, 1995). The argument here is not for better metrics but for imagining and working towards systemic change in the wake of the climate crisis. The challenge however is how to account for historical differences in economic growth and living standards between Global North and Global South and to protect the interests of Global South in the spirit of 'common but differentiated responsibilities' to climate change adaptation and mitigation. As empirical studies in Global South have demonstrated (Lele et al., 2018), developing countries face multiple stressors, climate change being just one among them, and there are multiple normative concerns in developing country contexts, such as equity and justice, and not merely resilience (*very high confidence)*.

To achieve climate resilient development requires framings of development that move away from linear paradigms of development as material progress by focusing on diversity and heterogeneity, wellbeing and equality, not only in contemporary practices, but also pathways of change over time (Gibson-Graham, 2005; Gibson-Graham, 2006). Such approaches, which are fundamentally aligned with ecological and ecosystem-based environmental assessments which identified heterogeneity of approaches and actions as the most effective path to a sustainable world (Millennium Ecosystem Assessment, 2005), emphasize the importance of cultural, linguistic and religious diversity, not merely as alternative sources of information about the world, but as different paradigms of well-being (Kallis, 2018). These include indigenous and local knowledges that provide alternatives to these framings of the world (Cross-Chapter Box INDIG). This broad reframing of development includes a focus on visions such as 'buen vivir' (Cubillo-Guevara et al., 2014; Walsh, 2018; Acosta et al., 2019), ecological Swaraj (Kothari et al., 2014; Demaria and Kothari, 2017; Shiva, 2017), and Ubuntu (Dreyer, 2015; Ewuoso and Hall, 2019), among others. All are linked by relationships with nature radically different from the Western mechanistic vision, presenting not only framings of development and the environment that yield locally-appropriate climate resilient development pathways, but serve as examples of alternative ways of living in balance with nature that might inform similar thinking in other places.

18.2.2.2. Complexity of Development and Climate Action

Differing perspectives on development are in part determined by the multiple diverse priorities held by different actors and nations. Another reason is that development is not a linear process with a single goal, and active development planning requires simultaneously taking multiple processes and factors into account. This is well illustrated by growing attention to climate security. The AR5 delivered conflicting messages regarding climate change and security (Gleditsch and Nordås, 2014), yet the understanding of climate-related security risks has made substantial progress in recent years (von Uexkull and Buhaug, 2021). Although there remains a considerable research gaps in certain regions (Adams et al., 2018), a large body of qualitative and quantitative studies from different disciplines provides new insight into the relationship of climate change and security (Buhaug, 2015; De Juan, 2015; Brzoska and Fröhlich, 2016; Abrahams and Carr, 2017; Sakaguchi et al., 2017; Moran et al, 2018; Scheffran, 2020). Though not the only cause (Sakaguchi et al., 2017; Mach et al., 2019), climate change undermines human livelihoods and security, because it increases the populations vulnerabilities, grievances, and political tensions through an array of indirect – at times non-linear – pathways, thereby increasing human insecurity and the risk of violent conflict (van Baalen and Mobjörk, 2018; Koubi, 2019; von Uexkull and Buhaug, 2021). Indeed, context, as well as timing and spatial distribution matter and need to be accounted for (Abrahams, 2020).

In line with this better understanding, climate change and security have been reframed in the political space, to focus more on human security. The solutions to climate-related security risks cannot be military, but are linked to development and people's vulnerabilities in complex social and politically fragile settings (Abrahams, 2020). This has resulted in integration of climate-related security risk into institutional and national frameworks (Dellmuth et al., 2018; Scott and Ku, 2018; Aminga and Krampe, 2020), including several NDCs (Jernnäs and Linnér, 2019; Remling, 2021). One example is the UN Climate Security Mechanism – set up in 2018 between UNDP, UNEP and UN DPPA to help the UN more systematically address climate-related security risks and devise prevention and management strategies. Yet, work remains in bridging these concerns with practical responses on the ground (Busby, 2021). Especially since emerging research building on the maladaptation literature, shows that this practice cannot just mean adding adaptation and mitigation to the mix of development strategies in a given location, as this may have unintended and unanticipated effects and might even backfire completely (Dabelko et al., 2013; Magnan et al., 2020; Mirumachi et al., 2020; Schipper, 2020; Swatuk et al., 2021). In extremely underdeveloped, fragile contexts such as Afghanistan, the local-level side effects of climate adaptation and mitigation projects might result in different development outcomes and question the potential for sustainable peace (Krampe et al., 2021). Given the clearer understanding of the intertwined nature of climate change, security, and development – especially in fragile and conflict affected regions – a rethinking of how to transfer this knowledge into policy solutions is necessary for the formulation of climate resilient development.

18.2.3 Scenarios as a Method for Representing Future Development Trajectories

Sustainable development represents specific development processes and priorities that can affect climate risk. As a result, sustainable development both shapes the context in which different actors experience climate change and represents a potential opportunity, particularly by reducing climate risk by addressing vulnerability, inequity, and shifting development toward more sustainable trajectories (IPCC, 2012; Denton et al., 2014; IPCC, 2014b; IPCC, 2014a; IPCC, 2018a; IPCC, 2019b). As assessed in past IPCC special reports and assessment reports, this same literature has also illustrated how different socioeconomic conditions affect mitigation options and costs. For example, variations in future economic growth, population size and composition, technology availability and cost, energy efficiency, resource availability, demand for goods and services, and non-climate-related policies (e.g., air quality, trade) individually and collectively have all been shown to result in different climates and contexts for mitigation and adaptation.

One common approach for exploring the implications of different development trajectories is the use of scenarios of future socioeconomic conditions, such as the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017). The SSPs represent sets of future global societal assumptions based on different societal, technological, and economic assumptions that result in different development trajectories. Such scenarios often correspond to a small set of scenario archetypes (Harrison et al., 2019; Sitas et al., 2019; Fergnani and Song, 2020) in that they reflect core themes regarding the future of development such as sustainability versus rapid growth. Scenarios with assumptions more closely aligned with sustainability agendas (e.g., SSP1-Sustainability) commonly imply lower greenhouse gas emissions and projected climate change (see WGIII

AR6 Chapter 3), lower mitigation costs for ambitious climate goals (see WGIII AR6 Chapter 3), lower climate exposure due in large part to the size of society (see Chapter 16), and greater adaptive capacity (Roy et al., 2018) (see also Chapter 16). In contrast, scenarios with rapid global economic and fossil energy growth (e.g., SSP5-Fossil-Fueld Development) imply higher emissions and project climate change, higher mitigation costs, as well as greater social and economic capacity to adapt to climate change impacts (Hunt et al., 2012) (Table 18.1).

The SSPs incorporate various assumptions regarding population, GDP, and greenhouse gas emissions, for example, that are relevant to development and climate resilience. In addition, the SSPs have been used to explore a broad range of development outcomes for human and ecological systems (Table 18.1), including multiple studies explore futures for food systems, water resources, human health, and income inequality. Limited, top-down modelling studies have used the SSPs to explore issues such as societal resilience (Schleussner et al., 2021) or gender equity (Andrijevic et al., 2020a). Such studies indicate that different development trajectories have different implications for future development outcomes, but results vary significantly among different climate (e.g., representative concentration pathways [RCPs]) and development contexts, resulting in *limited agreement* among different SSPs (Table 18.1). Nevertheless, for some outcomes, SSPs are associated with generally similar outcomes. Over the near-term (e.g., 2030), those outcomes are strongly influenced by development inertia and path dependence, reducing differences among SSPs. Outcomes diverge later in the century, but fewer studies explore futures beyond 2050. Collectively, the scenarios reflect trade-offs associated with different development trajectories (Roy et al., 2018), with some SSPs foreshadowing outcomes that are positive in some contexts, but negative in others (Table 18.1). For example, pathways that lead to poverty reduction can have synergies with food security, water, gender, terrestrial and ocean ecosystems that support climate risk management, but also poverty alleviation projects with unintended negative consequences that increase vulnerability (e.g., Ley, 2017; Ley et al., 2020).

Table 18.1: Implications of different socioeconomic development pathways for CRD indicators. Studies presented in the above table include qualitative storylines and quantitative scenarios for two or more SSPs. Arrows and color coding reflect the positive or negative impacts on sustainability based on aggregation of results for the 2030-2050 time horizon across the identified studies. Confidence language reflects the number of studies upon which results are based (evidence) and the agreement among studies regarding the direction of change (agreement).

Development Indicator	Relevant SDG	Shared Socioeconomic Pathway					Confidence Evidence/ Agreement	References
		Sustainability (SSP1)	Middle of the Road (SSP2)	Regional Rialry (SSP3)	Inequality (SSP4)	Fossil-fueled Development (SSP5)		
Agriculture, Food, & Forestry • *Agriculture production* • *Forestry production* • *Food security* • *Hunger*	SDG 2	↗	↔	↘	↘	↘	*Low Agreement/ Robust Evidence*	(Hasegawa et al., 2015; Palazzo et al., 2017; Riahi et al., 2017; Duku et al., 2018; Chen et al., 2019; Daigneault et al., 2019; Mitter et al., 2020; Mora et al., 2020)
Health & Well-Being • *Excess mortality* • *Air quality*	SDG 3	↔	↔	↔	↘	↘	*Medium Agreement/ Robust Evidence*	(Chen et al., 2017; Mora et al., 2017; Aleluia Reis et al., 2018; Asefi-Najafabady

• *Vector-borne disease* • *Life Satisfaction*								et al., 2018; Chen et al., 2018; Harrington and Otto, 2018; Marsha et al., 2018; Sellers and Ebi, 2018; Ikeda and Managi, 2019; Rohat et al., 2019; Wang et al., 2019; Chae et al., 2020)
Water & Sanitation • *Water use* • *Sanitation access* • *Sewage discharge*	SDG 6	↗	↘	↘	↔	↔	*High Agreement/ Medium Evidence*	(Wada et al., 2016) (van Puijenbroek et al., 2014; Yao et al., 2017) (Mouratiadou et al., 2016; Graham et al., 2018)
Inequality • *Gini coefficient*	SDG 10	↗	↗	↗	↔	↗	*Medium Agreement/ Limited Evidence*	(Rao et al., 2019b; Emmerling and Tavoni, 2021; Gazzotti et al., 2021)
Ecosystems and Ecosystem Services • *Aquatic resources* • *Urban expansion* • *Habitat provision* • *Carbon sequestration* • *Biodiversity*	SDG 14 SDG 15	↘	↘	↘	↘	↘	*High Agreement/ Medium Evidence*	(Li et al., 2017; Chen et al., 2019; Li et al., 2019b; Chen et al., 2020b; Song et al., 2020b; McManamay et al., 2021; Pinnegar et al., 2021)

Legend
↓ Balance of studies suggest large increasing threat to sustainable development
↘ Balance of studies suggest moderate increasing threat to sustainable development
↔Studies suggest both threats and benefits to sustainable development
↗ Balance of studies suggest moderate increasing benefit to sustainable development
↑ Balance of studies suggest large increasing benefit to sustainable development

Table Notes:
Studies presented in the above table include qualitative storylines and quantitative scenarios for two or more SSPs. Arrows and color coding reflect the positive or negative impacts on sustainability based on aggregation of results for

the 2030-2050 time horizon across the identified studies. Confidence language reflects the number of studies upon which results are based (evidence) and the agreement among studies regarding the direction of change (agreement).

While the scenarios literature is useful for characterizing the potential climate risk implications of different global societal futures, important limitations impact their use in climate risk management planning *(very high confidence*). The first is the often highly geographically aggregated nature of the SSPs and other scenarios, which, in the absence of application of nesting or downscaling methods, often lack regional, national, or sub-national context, particularly regarding social and cultural determinants of vulnerability (van Ruijven et al., 2014). Furthermore, there is limited understanding of the cost and what is required to transform from today into each socioeconomic future, or the opportunity to shift from one pathway to another (18.3). Furthermore, the characteristics of the pathways suggest that they are not equally likely, there are relationships implied in assumptions that are uncertainties to consider (e.g., land productivity improvements are land saving), it is difficult to identify the role of different development characteristics, and policy implementation is stylized. In general, global assessments are not designed to inform local planning given that there are many local circumstances consistent with a global future and unique local development context and uncertainties to manage—demographic, economic, technological, cultural, policy.

Overall, pursuing sustainable development in the future is shown to have synergies and trade-offs in its relationships with every element of climate risk: the emissions and mitigation determining hazard, the size, location, and composition of development determining exposure; and the adaptive capacity determining vulnerability. Importantly, the scenarios literature overall has found trade-offs such that none of the global societal projections achieve all the sustainable development goals *(very high confidence*) (Roy et al., 2018) (18.2.5.3). Historical evidence supports this as well, for example, finding low-cost energy and food access historically associated with higher emissions but greater adaptive capacity, and energy efficiency innovation contributing to lower emissions and greater adaptive capacity (e.g., Blanford et al., 2012; Blanco et al., 2014; Mbow et al., 2019; USEPA, 2019). The literature suggests that trade-offs in the pursuit of sustainable development are inevitable. Managing those trade-offs, as well as capitalizing on the synergies, will be important for CRD, particularly given trade-offs have distributional implications that could contribute to inequities (18.2.5.3).

18.2.4 Climate Change Risks to Development

Over the next decade, additional climate change is expected regardless of the scale of greenhouse gas mitigation efforts (IPCC, 2021a). Across the global scenarios analyzed in the AR6, global average temperature changes relative to the reference period 1850-1900 range from 1.2˚C to 1.9˚C for the period 2021–2040 and 1.2˚C to 3.0˚C for the period 2041-2060 (WGI AR6 SPM *very likely* range). However, the feasibility of emissions pathways (particularly, RCP8.5) affect the plausibility of the associated climate projections, potentially lowering the upper end of these ranges (see WGIII AR6 Chapter 3). There is significant overlap between climate scenario ensemble ranges from different emissions scenarios through 2050, more so than through 2100 (Lee et al., 2021). There is also overlap between emissions scenario ensembles consistent with different temperature outcomes (see WGIII AR6 Chapter 3). Emissions pathway ranges represent uncertainties for policy-makers and organizations to consider and manage (Rose and Scott, 2018, 2020) regarding, among other things, economic growth and structure, available technologies, markets, behavioral dynamics, policies, and non-CO_2 climate forcings (see WGIII AR6 Chapter 3), while climate pathway ranges represent bio-physical climate system and carbon cycle uncertainties (Lee et al., 2021). For all climate projections and variables, there is significant regional heterogeneity and uncertainty in projected climate change *(very high confidence*) (IPCC, 2021a). Figure 18.4 (left panel) presents examples for average and extreme temperature precipitation change (see also 18.5 and Tables 18.4−18.5 for more regional detail). Similarly, for all emissions projections, there is significant regional, sectoral, and local heterogeneity and uncertainty regarding potential pathways for climate action (see WGIII AR6 Chapter 3 and Chapter 4). Not all uncertainties are represented in projected emissions pathway ensembles, such as policy timing and design (e.g., Rose and Scott, 2018) or climate projection ensembles.

The projected ranges for near-term and mid-term global average warming levels are estimated to result in increasing key risks and reasons for concern (Chapter 16). Chapter 16 developed aggregate "Representative Key Risks" (RKRs) as indicators for subsets of approximately one hundred sectoral and regional key risks indicators. The RKRs include risks to coastal socio-ecological systems, terrestrial and ocean ecosystems, critical physical infrastructure, networks and services, living standards and equity, human health, food security, water security, and peace and migration. The majority of these risks are directly linked to sustainable development priorities and the SDGs (Chapter 16, WGII AR6 sectoral and regional chapters; (Roy et al., 2018; IPCC, 2019d; IPCC, 2019b). Therefore, climate risks represent a potential additional challenge to pursuing sustainable development priorities, but also potential opportunities due to geographic variation in climate impacts. In addition, positive synergies have been found between sustainable development and adaptation, but trade-offs are also possible (e.g., Roy et al., 2018).

For all RKRs, additional global average warming is expected to increase risk. However, the increases vary significantly by RKR, and across the underlying key risks represented within each RKR. Geographic variation in key risk implications is only partially assessed in Chapter 16, but evidence can be drawn from the WGII individual regional chapters. Regionally, key risks are found to be potentially greatest in developing and transition economies (Chapter 16 and sectoral chapters), which is also where the least-cost emissions reductions are shown to be (see WGIII AR6 Chapter 3). See Figure 18.4 for an example of key risk geographic heterogeneity (see also 18.5 for regional detail). Chapter 16 also maps the RKRs to an updated aggregate "Reasons for Concern" (RFC) framing. Thus, increasing RKR risk implies increasing RFC associated with unique and threatened systems, extreme weather events, distribution of impacts, global aggregate impacts, and large-scale singular events.

Climate risks are found to vary with future warming levels, the development context and trajectory, as well as by the level of investment in adaptation. Together, these three dimensions define risk – with projected climate changes defining the hazard, development defining the exposure, and development and adaptation defining vulnerability. However, how these different dimensions interact and the level of scientific understanding vary significantly among different types of risk. For human systems, in general, the poor and marginalized are found to have greater vulnerability for a given hazard and exposure level. With some level of global average warming expected regardless of mitigation efforts, human and natural systems will be exposed to new conditions, but some level of adaptation should also be expected.

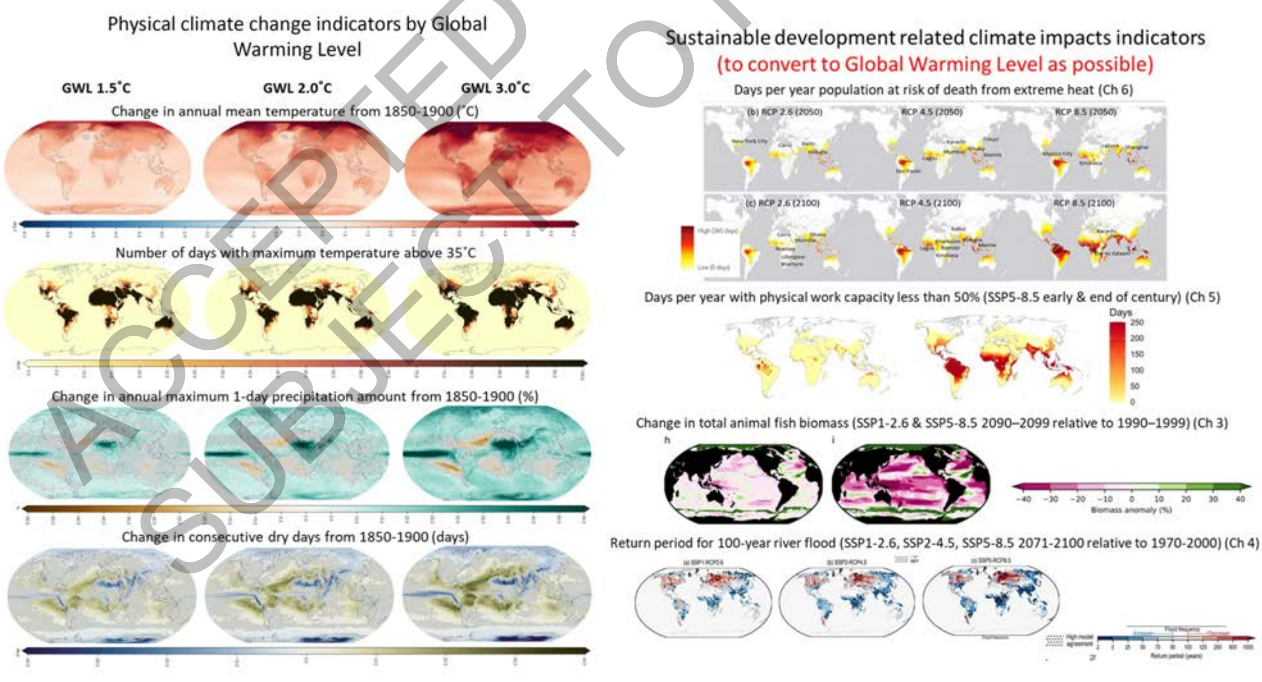


Figure 18.4: Regional projected select climate change and sustainable-development-related climate impact variables by global warming level. Sources: WGI and WGII AR6 reports.

18.2.5 Options for Managing Future Risks to Climate Resilient Development

The pursuit of CRD requires not only the implementation of individual adaptation, mitigation, and sustainable development initiatives, but also their careful coordination and integration. This section assesses the literature on CRD in the context of key climate change risks (Chapter 16); gaps in adaptation that contribute to risk; potential synergies and trade-offs among mitigation, adaptation and sustainable development; and the mechanisms for managing those trade-offs.

18.2.5.1 Adaptation

18.2.5.1.1 Adaptation and climate-resilient development

Given adaptation is recognized as a key element of addressing climate risk and CRD, the capacity for adaptation implementation is an important consideration for CRD. The AR5 noted a significant overlap between indicators of sustainable development and the determinants of adaptive capacity, and suggested that adaptation presents an opportunity to reduce stresses on development processes and the socio-ecological foundations upon which they depend (Denton et al., 2014). At the same time, it also noted that building adaptive capacity for sustainable development might require transformational changes that shift impacted systems to new patterns, dynamics, or places (Denton et al., 2014). Thus, adaptation interventions and pathways can further the achievement of development goals such as food security (Campbell et al., 2016; Douxchamps et al., 2016; Richardson et al., 2018; Bezner Kerr et al., 2019) and improvements in human health (Watts et al., 2019) including in systems where animals and humans live in close proximity *(very high confidence*) (Zinsstag et al., 2018). However, to do so requires not only the avoidance of incremental adaptation actions that extend current unsustainable practices, but also the ability to manage and overcome the barriers which arise when the limits of incremental adaptation are reached (*high agreement; medium evidence)* (Few et al., 2017; Vermeulen et al., 2018; Fedele et al., 2019).

Since AR5, the scientific community has deepened its understanding of the relationship between adaptation and sustainable development *(very high confidence*), particularly with regard to the place of resilience at the intersection of these two arenas. The literature has moved forward in its identification of specific overlaps in sustainable development indicators and determinants of adaptive capacity, how adaptation might reduce stress on development processes and their socio-ecological foundation, and how building adaptive capacity might facilitate needed transformative changes. Broadly speaking, work on these topics comes from one of two perspectives. One perspective speaks to adaptation practices that might further sustainable development outcomes, while another perspective draws on deeper understandings of the socio-ecological dynamics of the systems in which we live, and which we may have to transform in the face of climate change impacts. These two literatures are not yet well-integrated, leaving gaps in our knowledge of how best to implement adaptation in a manner that achieves sustainable development.

The literature considering adaptation and development in practice since AR5 suggests that efforts to connect adaptation to sustainable development should address proximate and systemic drivers of vulnerability (Wise et al., 2016) while remaining flexible and reversable to avoid the lock-in of undesirable or mal-adaptive trajectories (Cannon and Müller-Mahn, 2010; Wise et al., 2016). Such goals require critical reflection on processes for decision-making and learning. In the AR5, more inclusive, participatory adaptation processes were presumed to benefit development planning by including a wider set of actors in discussions of future goals (Denton et al., 2014). The post-AR5 literature expands on these critical perspectives to provide context regarding when participation is most effective. For example, (Eriksen et al., 2015) emphasize the need to build participatory adaptation processes to avoid subsuming adaptation goals to development-as-usual while (Kim et al., 2017b) argues that this practice is most effective when it is focused on development efforts and considers how climate change will challenge the goals of those efforts. Adaptation, while presenting an opportunity to foster transformations needed to address the impacts of climate change on human well-being, is also a contested process that is inherently political (*medium agreement, medium evidence*) (Eriksen et al., 2015; Mikulewicz, 2019; Nightingale Böhler, 2019; Eriksen et al., 2021b). How adaptation can challenge development and create a situation where CRD effectively becomes transformative adaptation, adaptation that generates transformation of broader aspects of development, remains unclear (*medium agreement, limited evidence*) (Few et al., 2017; Schipper et al., 2020c).

The critical literature on socio-ecological resilience, which has grown substantially since the last AR *(very high confidence*), speaks to some of these questions. Since AR5, the IPCC and the wider literature on socio-ecological resilience have shifted their use of the term to reflect not only the capacity to cope with a hazardous event or trend or disturbance, but also the ability to adapt, learn, and transform in ways that maintains a socio-ecology's essential function, identity and structure (WGII Chapter 1, Glossary). This change in usage is significant in that it shifts resilience from an emergent property of complex socio-ecological systems to a deeply human product of efforts to manage ecology, economy, and society to specific ends. This definition of resilience recognizes the need to define what is an essential identity, function, and structure for a given system, questions rooted not in ecological dynamics, but in politics, agency, difference, and power that emerge around the management of ecological dynamics (Cote and Nightingale, 2011; Brown, 2013; Cretney, 2014; Forsyth, 2018; Matin et al., 2018; Carr, 2019).

By connecting this framing of socio-ecological dynamics to the literature on the principles for adaptation efforts that meet development goals, new work has begun to identify 1) how adaptation can reduce stress on development processes, 2) how it might facilitate transformative change, and 3) where adaptation interventions might either drive system rigidity and precarity, or otherwise challenge development goals (Castells-Quintana et al., 2018; Carr, 2020). For example, Jordan (2019) draws upon these contemporary framings of resilience to highlight the ways in which coping strategies perpetuate the gendered norms and practices at the heart of women's vulnerability in Bangladesh. Forsyth (2018) draws upon this work to highlight the ways in which the theory of change processes used by development organizations tend to exclude local experiences and sources of risk, and thus foreclose the need for transformative pathways to achieve development goals. Carr (Carr, 2019; 2020) draws upon evidence from sub-Saharan Africa to develop more nuanced understandings of the ways in which different stressors and interventions either facilitate or foreclose transformative pathways, while pointing to the existence of yet poorly-understood thresholds for transformation in systems that can be identified and targeted by interventions.

18.2.5.1.2 Adaptation Gaps

Adaptation gaps are defined as "the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities" (UNEP, 2014; UNEP, 2018a). Adaptation deficit is a similar concept, described as an inadequate or insufficient adaptation to current conditions (see Ch 1). Adaptation gaps or deficits arise from a lack of adequate technological, financial, social, and institutional capacities to adapt effectively to climate change and extreme weather events, which are in turn linked to development *(very high confidence)* (Fankhauser and McDermott, 2014; Milman and Arsano, 2014; Chen et al., 2016; Asfaw et al., 2018) (18.2.2).

Currently, there is no consensus around approaches to assess the effectiveness of adaptation actions across contexts and therefore measure adaptation gaps at a global scale (Singh et al., 2021a). UNEP (2021) suggests that comprehensiveness, inclusiveness, implementability, integration and monitoring and evaluation can be used to assess them (see also Cross-Chapter Box FEASIB). However, limited information is available about future trends in national-level adaptation, and the development of monitoring and evaluation mechanisms. Despite the challenges of measurement associated with adaptation gaps, available evidence from smaller scales across several regions, communities, and businesses suggest that significant adaptation gaps have existed in historical contexts of climate change, while expectations of extreme heat, increasing storm intensity, and rising sea levels will create the context for the emergence of new gaps *(very high confidence*) (Hallegatte et al., 2018; UNEP, 2018a; Dellink et al., 2019; UNEP, 2021). These adaptation gaps create risks to well-being, economic growth, equity, the health of natural systems, and other societal goals. The negative impacts of these gaps can be compounded by adaptation efforts that are considered maladaptive or by development actions that are labelled as adaptation (see Chapter 16).

A higher level of adaptation finance is critical to enhance adaptation planning and implementation and reduce adaptation gaps, particularly in developing countries *(very high confidence*) (UNEP, 2021) (Cross-Chapter Box FINANCE in Chapter 17, 18.4.2.2). However, adaptation finance is not keeping pace with the rising adaptation costs in the context of increasing and accelerating climate change, as "annual adaptation costs in developing countries alone are currently estimated to be in the range of US$70 billion, with the expectation of reaching US$140–300 billion in 2030 and US$280–500 billion in 2050" (UNEP, 2021). Investment in attaining SDGs helps bridge adaptation gaps (Birkmann et al., 2021), but care needs to be taken to avoid maladaptation through mislabeling. Integration of the indigenous and local knowledge systems is anticipated to reduce existing adaptation gaps and secure livelihood transitions.

Analysis of investments by four major climate and development funds (the Global Environment Facility, the Green Climate Fund, the Adaptation Fund and the International Climate Initiative) by UNEP (2021) suggests that support for green and hybrid adaptation solutions has been increasing over the past two decades. These could be effective at reducing climate risks and bridging adaptation gaps while simultaneously bringing important additional benefits for the economy, environment, livelihoods (UNEP, 2021) (see also Cross-Chapter Box NATURAL in Chapter 2).

Lately, the evidence of adaptation activity in the health sector has been increasing (Watts et al., 2019), yet substantial adaptation gaps persist (UNEP, 2018a; UNEP, 2021), including gaps in humanitarian response to climate-related disasters (Watts et al., 2019). It is the under-investment in climate and health research in general and health adaptation in particular that has led to adaptation gaps in the health sector (Ebi et al., 2017).

Costs of implementing efficient adaptation measures and water-related infrastructure in water-deficient regions have received attention at the global and regional level to bridge the 'adaptation gap' (Hallegatte et al., 2018; UNEP, 2018a; Dellink et al., 2019; UNEP, 2021). Livelihood sustainability the drylands, which cover more than 40% of land surface area, are home to roughly 2.5 billion people, and support approximately 50% of the livestock and 45% of the food production, is threatened by a complex and interrelated range of social, economic, and environmental changes that present significant challenges to rural communities, especially women (Abu-Rabia-Queder and Morris, 2018; Gaur and Squires, 2018). Adaptation deficits in arid and semi-arid regions are of high order (see CCP 3). In order to reduce adaptation deficit in arid and semi-arid regions comprehensive and efficient adaptation interventions integrating better water management, use of non-traditional water sources, changes in reservoir operations, soil ecosystem rejuvenation, and enhanced institutional effectiveness are needed (18.5) (Makuvaro et al., 2017; Mohammed and Scholz, 2017; Morote et al., 2019). Communities facing the lack of adequate technological, financial, human, and institutional capacities to adapt effectively to current and future climate change often encounter adaptation deficits. In order to address current adaptation barriers and adaptation deficits, there is a need to promote efficient adaptation measures, coupled with inclusive and adaptive governance involving marginalized groups such as indigenous communities and women.

Although unevenly distributed urban adaptation gaps exist in all world regions (see Chapter 6). Such gaps are higher in the urban centers of the poorer nations. Chapter 6 identified the critical capacity gaps at city and community levels that are responsible for adaptation gaps are: "ability to identify social vulnerability and community strengths, and to plan in integrated ways to protect communities, alongside the ability to access innovative funding arrangements and manage finance and commercial insurance; and locally accountable decision-making with sufficient access to science, technology and local knowledge to support the application of adaptation solutions at scale".

Insufficient financial resources are the main reasons for the coastal adaptation gap particularly in the Global South (see CCP2). Engaging the private sector with a range of financial tools is crucial to address such gaps (see CCP2). An urgent and transformative action to institutionalize locally-relevant integrative adaptation pathways is crucial for closing coastal adaptation gaps. Additional efforts are in place for assessing global adaptation progress (see Cross-Chapter Box PROGRESS in Chapter 17].

18.2.5.1.3 Adaptation implementation

As discussed in Chapter 16, adaptation is a key mechanism for managing climate risks (Chapter 16), and therefore for pursuing CRD. The lower estimates in Table 18.2 are associated with higher levels of adaptation and more conducive development conditions. Furthermore, additional adaptation demand is associated with greater levels of climate change. Adaptation is a broad term referring to many different levels of response and options for natural and human systems, from individuals, specific locations, and specific technologies, to nations, markets, global dynamics, and strategies at the system level. Adaptation also includes endogenous reflexive and exogenous policy responses. Perspectives on limits to adaptation, synergies, trade-offs, and feasibility therefore depend on where the boundaries are drawn and the objective. Overall, there are a broad range of adaptation options relevant to reducing risks posed by climate change to development. However, current understanding of how such options are implemented in practice, their effectiveness across a range of possible climate futures, and their potential limits, is modest.

Past assessments have evaluated individual adaptation options in terms of economic, technological, institutional, socio-cultural, environmental/ecological, and geophysical feasibility (de Coninck et al., 2018). This analysis has been updated for AR6 (Cross-Chapter Box FEASIB). These assessments identify types of barriers that could affect an option's feasibility. Among other things, this work finds that every adaptation option evaluated had at least one feasibility dimension that represented a barrier or obstacle. The barriers also imply that there are trade-offs in these feasibility dimensions to consider. Overall, insights from this work are high-level and difficult to apply to a specific adaptation context. The feasibility and ranking of adaptation opportunities, as well as the list of opportunities themselves, for a given location will vary from location-to-location, with different criteria and weighting of criteria that reflect the relevant social priorities and differences in markets, technology options, and policies for managing risks and trade-offs. Integrated evaluation of criteria and options is needed, that accounts for the relevant geographic context and interactions between options and systems (18.5).

Sustainable development is regarded as generally consistent with climate change adaptation, helping build adaptive capacity by addressing poverty and inequalities and improving inclusion and institutions (Roy et al., 2018). Some sustainable development strategies could facilitate adaptation effectiveness by addressing wider socio-economic barriers, addressing social inequalities, and promoting livelihood security (Roy et al., 2018). With a common goal of reducing risks, sustainable development and adaptation are relatively synergistic. However, trade-offs have been found and important to consider and potentially manage. Synergies have been found between adaptation and poverty reduction, hunger reduction, clean water access, and health; while, trade-offs have also been found, particularly when adaptation strategies prioritize one development objective (e.g., food security or heat-stress risk reduction) or promote high-cost solutions with budget allocation and equity implications (Roy et al., 2018) (18.2.5.3, 18.5). There are also opportunities for managing the trade-offs, in particular distributional effects—by recognizing that there are trade-offs and considering alternatives and complementary strategies to offset the trade-offs (Section 18.2.5.3).

[START BOX 18.3 HERE]

Box 18.3: Climate Resilient Development in Small Islands

Small Islands are particularly vulnerable to climate change and many are already pursuing climate resilient development pathways that enable integrated responses (Allen et al., 2018a; Mycoo, 2018; Hay et al., 2019; Robinson et al., 2021). Countries, such as Belize, have opted for a systems-approach and are working across the SDGs to increase integration (Allen et al., 2018a). This includes rethinking disaster reconstruction mechanisms in the Caribbean and introducing more diversified and sustainable tourism economies that can better withstand external shocks such as disruptions and loss of markets from COVID-19 (Sheller, 2021). In the Seychelles, various government and tourism industry initiatives are focused on the promotion of sustainable tourism ventures that lower emissions, protect and promote biodiversity conservation (e.g. new marine protected areas with mitigation and adaptation benefits), and are climate resilient (Robinson et al., 2021). In 2016 the Seychelles signed the world's first nature-for-debt swap wherein an NGO (The Nature Conservancy) agreed to pay off Seychelles' public debt to the Paris Club (foreign creditors) in return for the Seychelles government establishing marine conservation areas (Silver and Campbell, 2018).

One key area where enhanced climate risk integration is critical is infrastructure-related decisions especially on coastal areas (World Bank, 2017). However, despite increasing awareness of climate risks and experienced impacts, decisions on for example infrastructure locations still reflect cultural preferences. For example, Hay et al. (2019) report that despite recommendations to relocate the redevelopment site of the Parliamentary Complex in Samoa away from the coast, multiple cultural and historical factors influenced the decisions to redevelop at the original site. In the Solomon Islands, however, emerging evidence suggests that adaptation efforts to enhance the resilience of infrastructure are also serving to help urban areas address problems associated with rapid urbanization and provide new opportunities for sustainable development (Robinson et al., 2021).

Energy system transitions in small islands can produce synergies with SDG implementation, and can lead to transformational outcomes. The Pacific island territory of Tokelau has demonstrated a nationwide energy transition, sourcing 100% of their energy needs from solar power (Michalena and Hills, 2018), and many other countries such as Fiji, Niue, Tuvalu, Vanuatu, Solomon Islands and Cook Islands also have 100% renewable energy targets. Benefits of small island distributed energy systems (such as solar photovoltaic (PV) systems) include less need for large, centralized infrastructure; reduced reliance on volatile fossil fuel markets; enhanced international climate negotiations power and enhanced local job markets/skills (Dornan, 2015; Cole and Banks, 2017; Weir, 2018). Additionally, renewable systems can enhance resilience to hydro-meteorological disasters (Weir and Kumar, 2020). For example, well secured ground based PV systems withstood cyclones in the Pacific island of Tonga during cyclone Gita and across the Caribbean during Hurricane Maria with power restored in days rather than weeks associated with more centralized systems (Weir and Kumar, 2020). Yet, a multitude of challenges remain. In the Pacific islands region, these include: the high up front capital investment of renewables; lack of private sector investment; limited renewable energy data for policy making; land tenure/rent costs; ongoing infrastructure maintenance skills and requirements; political turnover; failed experimentation; difficulty in obtaining and transporting replacement parts and a highly corrosive environment for equipment (Dornan, 2015; Cole and Banks, 2017; Lucas et al., 2017; Weir, 2018; Weir and Kumar, 2020). The example of Pacific energy transitions demonstrates that a nuanced and context specific analysis of synergies and trade-offs for energy transitions is required in order to lessen the impact on fragile economies and maximize benefits for remote populations.

Labor migration is increasingly recognized as a significant factor that can contribute to climate resilient development pathways for small islands. In the Pacific Islands region, labor mobility schemes are already allowing for climate change adaptation and economic development to occur in labor migrants' countries of origin (Smith and McNamara, 2015; Klepp and Herbeck, 2016; Dun et al., 2020). Dun et al. (2020) demonstrates that temporary or circular migrants from the Solomon Islands, working in Australia under its Seasonal Worker Program (similar programs operate in other developed countries), are using the money they earn to invest in adaptation and development activities back home. Similarly, labor migrants from Vanuatu, Kiribati, and Samoa contribute to development and in-situ climate change adaptation (at a household, village, and regional level) that enable discussions about more resilient futures for their countries (Barnett and McMichael, 2018; Parsons et al., 2018).

[END BOX 18.3 HERE]

[START BOX 18.4 HERE]

Box 18.4: Adaptation and the Sustainable Development Goals

The achievement of the SDGs represents near-term positive sustainability as well as indicating the quality of development processes and actions (inclusion and social justice, degrowth and alternative development models, planetary health, well-being, equity, solidary, plural knowledges and human-nature connectivity) that enable CRD in the long term (18.2.2.2, 18.2.5.3). A key question is the extent to which adaptation actions (or non-action) may contribute to (or undermine) SDG achievement, and in particular to shift the quality of development processes and engagement within the political, economic, ecological, socio-ethical and knowledge-technology arenas and hence contribute to CRDPs. Here, the relationship between adaptation and SDGs is illustrated through an examination of SDG3 good health and well-being and SDG16 peace, justice and strong institutions. These two are foundational to social equity and justice that underpin sustainability outcomes as well as enablers of CRD.

Table Box 18.4.1 (below) provides a set of examples of how adaptation actions can either contribute to or undermine SDG achievement, for SDGs 2, 3, 6, 11 and 16. In general, evidence suggests positive effects of formal interventions as well as household and community-based adaptation strategies on discrete social variables among target populations, particularly if they are shaped by the local context and needs, with real participation and leadership by target populations (Remling and Veitayaki, 2016; Buckwell et al., 2020; McNamara et al., 2020; Owen, 2020). For example, integrated adaptation approaches to the Water-Energy-Food (WEF) Nexus aiming to build resilience in those sectors can lead to increased resource use efficiency and coherent strategies for managing the complex interactions and tradeoffs among the water, energy and food SDGs (Mpandeli et al., 2018; Nhamo et al., 2020). One such approach could involve cultivating indigenous crops suited to harsh growing conditions, which would allow for agricultural expansion for food and energy without increased water withdrawals (Mpandeli et al., 2018). Overall, adaptation commitments aiming to build resilience of vulnerable populations have typically shown to contribute to SDGs focused on ending extreme poverty (SDG 1), improving food security (SDG 2), improving access to water (SDG 6), ensuring clean energy (SDG 7), tackling climate change (SDG 13) and halting land degradation and deforestation (SDG 15) (Antwi-Agyei et al., 2018).

However, evidence also suggests limitations of adaptation actions, with the objectives and actions often being too narrow to address social justice and enable CRD. As such, adaptation actions can sometimes undermine SDG achievement through exacerbating social vulnerability, inequity and uneven power relations (Antwi-Agyei et al., 2018; Atteridge and Remling, 2018; Paprocki, 2018; Mikulewicz, 2019; Satyal et al., 2020; Scoville-Simonds et al., 2020). This is due to adaptation practices often not accounting for the differentiated ways in which minority groups are especially vulnerable. For example, designs of emergency shelters should consider the fear of social stigma or abuse faced by women and girls (Pelling and Garschagen, 2019).

Such maladaptive adaptation practices can undermine SDG achievement through increasing vulnerability of marginalized groups by failing to address the underlying root causes of vulnerability and poverty that are related to political economy, power dynamics and vested interests more broadly, instead treating the symptoms as the cause (Magnan et al., 2016; Ajibade and Egge, 2019; Schipper, 2020). For example, evidence exists of flood defense measures through large scale infrastructure development leading to the violent displacement of poor communities, forcibly resettling people in areas far from their employment or pushing up land and housing costs without providing compensation (Fuso Nerini et al., 2018; Reckien et al., 2018). Moreover, sectoral approaches to adaptation that fail to acknowledge the linkages between SDGs can counter development efforts and generate further tradeoffs (Terry, 2009; Rasul and Sharma, 2016; von Stechow et al., 2016; Klinsky et al., 2017; Hallegatte et al., 2019).

The literature recommends a set of strategies for ensuring that adaptation actions are aligned with SDG achievement and do not further perpetuate poverty and inequality. These include ensuring that marginalized voices are central to adaptation decision-making, with participatory approaches that empower and compensate affected communities (Moser and Ekstrom, 2011; Broto et al., 2015; Pelling and Garschagen, 2019; Palermo and Hernandez, 2020). Gender mainstreaming and gender transformative approaches within climate policies can also help ensure gender-sensitive design of adaptation projects, with appropriate equity analyses of policy (Klinsky et al., 2017) decisions to identify the actual implications of trade-offs for vulnerable groups (Beuchelt and Badstue, 2013; Alston, 2014; Bowen et al., 2017; Fuso Nerini et al., 2018).

In addition, a substantial literature also argues for policy coherence measures that adopt whole-of-government approaches and mainstream and nationalize SDG targets within national climate policies (Nilsson et al., 2012; Le Blanc, 2015; Ari, 2017; Collste et al., 2017; Dzebo et al., 2017; Nilsson and Weitz, 2019). Institutional coordination mechanisms that aim to break down silos between different agencies and actors at the national level are suggested as beneficial for avoiding tradeoffs between adaptation actions and SDGs (Mirzabaev et al., 2015; Howlett and Saguin, 2018; Scherer et al., 2018). However, these need to be paired with an investigation of the deep-seated ideologies and vested interests that are creating goal conflicts and negatively impacting marginalized groups to begin with (Purdon, 2014; Bocquillon, 2018). Ultimately, adaptation measures need to acknowledge and address the underlying drivers that make certain groups particularly vulnerable, such as social disenfranchisement, unequal power dynamics and historical legacies of colonialism and exploitation (Magnan et al., 2016; Schipper, 2020)

Table Box 18.4.1: Examples of linkages between adaptation and the SDGs. For several key SDGs aligned with the concept of CRD, the table below identifies evidence from the literature where adaptation policies and practices contribute to achievement of the SDG as well as where they undermine achievement of the SDG.

SDG	***Evidence of adaptation contributing to SDG***	***Evidence of adaptation undermining SDG***
SDG 2: Zero Hunger	Adaptation measures implemented by smallholder farmers (e.g. adjustments in farm operations timing, on-farm diversification, soil-water management)	Some adaptation policies can increase land and food prices, negatively impacting smallholder farmers (Fuso Nerini et al., 2018; Zavaleta et al., 2018; Albizua et al., 2019)

	exhibit higher levels of productivity and technical efficiency in food production (Bai et al., 2019; Sloat et al., 2020; Khanal et al., 2021) Some climate smart agriculture measures (e.g. intercropping) can significantly increase yields and contribute to zero hunger (Lipper et al., 2014; Arslan et al., 2015; Saj et al., 2017)	Potential tradeoffs for food production through adaptation actions within the water or energy sector, if integrated approaches not taken (Howells et al., 2013; FAO, 2014; Biswas and Tortajada, 2016)
SDG 3: Good Health and Wellbeing	Increased resilience of societies and reduced vulnerability through investments in public health care and access (Marmot, 2020; Mullins and White, 2020) Adaptation measures that leverage solidarity, equity and nature connectedness contribute to physical and psychological health and wellbeing (Gambrel and Cafaro, 2009; Capaldi et al., 2015; Soga and Gaston, 2016; Woiwode, 2020)	Societal measures beyond adaptation required to address underlying causes of inequities that drive poor health and well-being, including cuts in public spending and neoliberalization and commodification of healthcare (Hall, 2020; Walsh and Dillard-Wright, 2020)
SDG 6: Clean Water and Sanitation	Integrated water resources management as an adaptation strategy (Tan and Foo, 2018; Sadoff et al., 2020)	Potential tradeoffs for water security through adaptation actions within the food or energy sector, if integrated approaches not taken (Howells et al., 2013; Rasul and Sharma, 2016; Mpandeli et al., 2018) Local, regional, or national "grabs" for water from shared resources to with poorly defined property rights (Olmstead, 2014)
SDG 11: Sustainable Cities and Communities	Vulnerability reducing adaptation measures that aim to upgrade informal settlements, create affordable housing and protect populations living in disaster prone areas (Major et al., 2018; Sanchez Rodriguez et al., 2018; Ajibade and Egge, 2019)	Need to ensure that adaptation measures understand how power dynamics and cultural norms shape urban form and communities' vulnerability and adaptive capacity (Sanchez Rodriguez et al., 2018) Risk of built infrastructure aiming to increase resilience ignoring local population needs and creating low-skilled jobs that concentrate land, capital and resources in the hands of the elite (Ajibade and Egge, 2019)
SDG 16: Peace, Justice and Strong Institutions	Potential for adaptation projects to support livelihoods incomes and resource management, and thereby reduce tensions and the risk of conflicts (Matthew, 2014; Dresse et al., 2018; Barnett, 2019)	Studies from Bangladesh, Cambodia and Nepal found that climate change adaptation-related policies and projects were an underlying cause of natural resource-based conflicts, as well as land dispossession and exclusion, entrenchment of dependency relations, elite capture, and inequity (Sovacool, 2018; Sultana et al., 2019) Adaptation projects can reinforce top-down knowledge and decision-making processes, asymmetric power relations and elite capture of adaptation resources (Nightingale, 2017; Eriksen et al., 2021b) Need for conflict-sensitive adaptation approaches that aim to 'do no harm' (Babcicky, 2013; Ide, 2020)

[END BOX 18.4 HERE]

18.2.5.2 Mitigation

Mitigation entails greenhouse gas emissions reductions, avoidance, and removal and sequestration, as well as management of other climate forcing factors (WGIII AR6). There are numerous individual and system mitigation options throughout the economy and within human and natural systems (very high confidence) (Chapter 16; 18.5). Limiting global average warming has been found to reduce climate risks (IPCC, 2018a; IPCC, 2019b), and limiting global average warming to any temperature level has also been found to be associated with broad ranges of emissions pathways representing socioeconomic, technological, market, physical uncertainties (very high confidence) (Rose and Scott, 2018; Rose and Scott, 2020). Pathways consistent with limiting warming to 2˚C and below have been found to require significant deployment of mitigation options spanning energy, land use, and societal transformation (WGIII AR6 Chapter 3 and Chapter 4; 18.3). and substantial economic, energy, land use, policy, and societal transformation (WGIII AR6 Chapter 3 and Chapter 4). Such emissions pathways would represent deviations from current trends that raise issues about their feasibility and therefore plausibility (Rose and Scott, 2018; Rose and Scott, 2020).

The technical and economic challenge of limiting warming has been found to increase non-linearly with greater ambition, fewer mitigation options, less than global cooperative policy designs, and delayed mitigation action (WGIII AR6 Chapter 3; Table 18.2). Table 18.2 provides a high-level summary of pathway characteristic ranges based on the WGIII AR6 assessment. Global pathways find large regional differences in mitigation potential, as well as the degree of regional non-linearity with greater mitigation ambition. These represent opportunities for mitigation, but how this effort and cost would be facilitated and distributed respectively is a policy question.

Table 18.2 illustrates that greater climate ambition implies more aggressive emissions reductions in each region, and earlier regional peaking of emissions (if they have not peaked to date). Near-term regional emissions increases are possible, even for 1.5°C compatible pathways, but significantly lower emissions than today are shown in all regions by 2050. Increases in total regional energy consumption, as well as fossil energy, are observed for many pathways, even in the most ambitious where energy consumption growth is potentially slower compared to less ambitious pathways. By 2050, regional fossil energy declines, but is not eliminated in any region. Regional growth in electricity use is substantial in all pathways, even the most ambitious, with the growth continuing and accelerating with time and regional dependence on electricity (share of total energy consumption) also growing significantly. The broad ranges are an indication of uncertainty and risk for regional transitions, noting that full uncertainty is likely broader than what is captured by emissions scenario databases (Rose and Scott, 2018; Rose and Scott, 2020). Among other things, pathways commonly assume idealized climate policies with immediate implementation; and model infeasibilities (i.e., models unable to solve) increase with climate ambition and pessimism about mitigation technologies (e.g., Clarke et al., 2014; Bauer et al., 2018; Rogelj et al., 2018; Muratori et al., 2020), highlighting the increasing challenge and potential for actual infeasibility with lower global warming targets. Together, Table 18.2 provides insights into the increasingly demanding system and development transitions associated with lower global warming levels, as well as some of the low-carbon transition uncertainties and risks (see also Figure 18.5).

Past assessment has evaluated representative mitigation strategies in terms of economic, technological, institutional, socio-cultural, environmental/ecological, and geophysical viability, as well as relationships to sustainable development goals (de Coninck et al., 2018). The strategies assessment analysis has been updated for AR6 (Cross-Chapter Box FEASIB). These assessments identify types of barriers that could affect an option's feasibility. Among other things, this work finds that, other than public transport and non-motorized transport, every other mitigation option evaluated had at least one feasibility dimension that represented a barrier or obstacle. The barriers also imply that there are trade-offs in these feasibility dimensions to consider. The assessment of mitigation option-sustainable development relationships identifies related literature and derives aggregate characterizations. Concerns about the potential sustainable development implications of some mitigation technologies may be motivation for precluding the use of some mitigation options. For instance, the potential food security and environmental quality implications of bioenergy have received significant attention in the literature (e.g., Smith et al., 2013). However, constraining or precluding the use of bioenergy without or with CCS could have significant implications for the cost of pursuing ambitious climate goals, and potentially the attainability of those goals (e.g., Clarke et al., 2014; Bauer et al., 2018; Rogelj et al., 2018; Muratori et al., 2020). Bioenergy is not unique in this regard. Social and sustainability concerns have also been raised about the large-scale deployment of many low-carbon technologies, e.g., REDD+, wind, solar, nuclear, fossil with CCS, and batteries. See WGIII Chapter 3 for examples of the potential implications of limiting or precluding different low-carbon technologies.

Overall, like with adaptation options, insights from this aggregate feasibility and sustainable development mapping work are high-level and difficult to apply to a specific mitigation context. The feasibility, ranking, and sustainable development implications of mitigation options, as well as the list of options themselves, for a given location will vary from location-to-location, with different criteria and weighting of criteria that reflect the relevant social priorities and differences in markets, technology options, and policies for managing risks and trade-offs. Integrated evaluation of criteria and options is needed here as well, that accounts for the relevant geographic context and interactions between options, systems, and implications.

Analyses of the potential implications of mitigation on sustainable development has various strands of literature—studies exploring general greenhouse gas mitigation feedbacks to society, assessments of mitigation implications on specific societal objectives other than climate, and literature evaluating mitigation implications specifically for sustainable development objectives (WGIII AR6 Chapter 3, Chapter 4, Chapter 17). In general, mitigation alters development opportunities by constraining the emissions future society can produce, which affects markets, resource allocation, economic structure, income distribution, consumers, and the environment (besides climate) (very high confidence). Examples of general development feedbacks from mitigation, include estimated price changes, macroeconomic costs, and low carbon energy and land system transformations (e.g., WGIII AR6 Chapter 3 and Chapter 4) (Fisher et al., 2007; Clarke et al., 2014; Popp et al., 2014; Rose et al., 2014; Weyant and Kriegler, 2014; Bauer et al., 2018; Rogelj et al., 2018). Examples of mitigation implications for specific other variables of societal interest include evaluating potential effects on air pollutant emissions, crop prices, water, and land use change (e.g., McCollum et al., 2018b; Roy et al., 2018), while the literature evaluating mitigation implications specifically for sustainable development objectives includes evaluations on energy access, food security, and income equality (e.g., Roy et al., 2018; Arneth et al., 2019; Mbow et al., 2019). Proxy indicators are frequently used to represent whether there might be implications for a sustainable development objective. For example, changes in energy prices are used as a proxy for effects on energy security (e.g., Roy et al., 2018). This is common with aggregate modelling studies, like those associated with global or regional emissions scenarios and energy systems.

Figure 18.5, derived from WGIII scenarios data, illustrates estimated relationships between mitigation and various sustainable development proxy variables for different global regions. Figure 18.5 illustrates synergies and trade-offs with mitigation, as well as regional heterogeneity, that can intensify with the level of climate ambition—synergies in air pollutants, such as black carbon, NOx, and SO2; and trade-offs in overall economic development, household consumption, food crop prices, and energy prices for electricity and natural gas. For comparison, recent IPCC assessments also observed similar synergies and trade-offs but did not directly make comparisons regarding overall development nor evaluate potential climates above 2˚C (Rogelj et al., 2018; Roy et al., 2018; Mbow et al., 2019). Regional non-linearity in the economic costs of mitigation with greater climate ambition (i.e., costs rising at an increasing rate with lower warming goals) can be significant within individual models (Rose and Scott, 2018; Rose and Scott, 2020). Figure 18.5 also illustrates transition risks in the potential for significant synergistic and trade-off implications with, for instance, potentially large regional commodity price implications and household consumption losses, as well as more significant air pollution benefits. Note that the 1.5˚C results in Figure 18.5 (and Table 18.2) are biased by model infeasibilities. Many models are unable to solve, especially with less optimistic assumptions, resulting in small sample sizes and a different representation of models compared to the 2˚C and higher results.

Results like those in Figure 18.5 illustrate that mitigation-development trade-offs and balancing of societal priorities are inevitable and need to be considered. For instance, Roy (2018) found that none of the 1.5˚C and 2˚C pathways assessed achieved all of the UN's Sustainable Develop Goals (SDGs). A newer literature is developing evaluating the potential for managing SDG trade-offs. For instance, Roy et al. (2018) discuss the potential for policies that address distributional implications, such as payments, food support, revenue recycling, as well as education, retraining, and technology outreach, subsidies, or prioritization. Recent studies have begun to estimate potential payments to offset trade-offs, such as related to food, water, and energy access (e.g., McCollum et al., 2018a). These analyses estimate investments to address specific trade-offs; however, with mitigation redirecting resources away from other productive activities, there is a need to also evaluate the aggregate economy-wide, distributional, and welfare effects, including the redistribution effects of managing sustainable development trade-offs.

There are a wide range of mitigation options and systems to consider, with assessment suggesting that a diverse portfolio is practical for pursing climate policy ambitions. However, local context will impact mitigation choices, with unique sustainable development priorities, available mitigation options, sustainable development synergies and trade-offs, and policy design and implementation possibilities.

Table 18.2: Emissions pathway regional characteristics from WGIII scenarios database for pathways associated with different global warming levels (1.5˚C, 2˚C, 3˚C, and 4˚C). Sample sizes: n = 13-15, 151-160, 66, and 34 emissions pathways for 1.5˚C, 2˚C, 3˚C, and 4˚C global warming levels respectively. Sample size ranges for the same warming level indicate that the sample size varies by variable due to differences in model reporting. Sample size varies by warming level due to model infeasibilities and differences in model reporting.

Variable	**Peak global warming to 2100**	**Asia**	**Latin America**	**Middle East / Africa**	**OECD**	**Reforming Economies**
Peak CO2 emissions year	1.5˚C	2020	2010 to 2030	2010 to 2030	2010 to 2020	2015 to 2030
	2˚C	2015 to 2030	2010 to 2035	2010 to 2030	2010 to 2020	2015 to 2030
	3˚C	2020 to 2080	2010 to 2100	2030 to 2100	2010 to 2002	2015 to 2100
	4˚C	2030 to 2100	2010 to 2100	2070 to 2100	2010 to 2100	2040 to 2100

Variable	**Peak global warming to 2100**	**Asia**		**Latin America**		**Middle East / Africa**		**OECD**		**Reforming Economies**	
		2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Net CO2 emissions (% from 2010)	1.5˚C	-36 to 10%	-89 to -55%	-61 to 19%	-98 to 68%	-26 to 40%	-73 to -41%	-56 to -24%	-96 to -78%	-42 to 14%	-95 to -48%
	2˚C	-31 to 50%	-89 to -29%	-62 to 31%	-98 to -3%	-30 to 67%	-66 to 8%	-50 to -11%	-96 to -48%	-52 to 33%	-105 to -27%
	3˚C	10 to 50%	-5 to 69%	-58 to 16%	-132 to 50%	7 to 84%	37 to 158%	-44 to 2%	-69 to -12%	-18 to 34%	-35 to 41%
	4˚C	26 to 80%	18 to 205%	-49 to 26%	-41 to 36%	19 to 121%	78 to 225%	-30 to 8%	-55 to 5%	-13 to 36%	0 to 77%
Energy consumption growth (% from 2010)	1.5˚C	9 to 57%	1 to 87%	18 to 68%	17 to 146%	31 to 57%	51 to 91%	-16 to 8%	-43 to 3%	-21 to 10%	-41 to 21%
	2˚C	17 to 91%	16 to 130%	3 to 72%	8 to 162%	18 to 82%	42 to 145%	-16 to 10%	-36 to 25%	-15 to 37%	-33 to 29%
	3˚C	43 to 80%	70 to 129%	-9 to 74%	17 to 170%	21 to 82%	81 to 174%	-16 to 13%	-28 to 21%	-3 to 37%	-6 to 86%
	4˚C	47 to 109%	88 to 245%	20 to 65%	36 to 163%	47 to 95%	94 to 254%	-9 to 7%	-15 to 31%	-8 to 37%	-4 to 66%
Fossil energy use growth (% from 2010	1.5˚C	-23 to 39%	-51 to 7%	-12 to 47%	-66 to 30%	-4 to 40%	-38 to -2%	-47 to -9%	-86 to -40%	-38 to 5%	-85 to -17%
	2˚C	-33 to 66%	-73 to 18%	-20 to 65%	-78 to 63%	-6 to 71%	-78 to 61%	-47 to -8%	-78 to -28%	-51 to 31%	-84 to 18%
	3˚C	15 to 70%	29 to 103%	-20 to 65%	-10 to 124%	7 to 79%	31 to 158%	-37 to 3%	-61 to 3%	-24 to 32%	-26 to 43%
	4˚C	38 to 112%	39 to 264%	12 to 63%	24 to 176%	41 to 115%	103 to 301%	-26 to -5%	-45 to 10%	-14 to 29%	-5 to 66%
Electricity consumption growth (% from 2010)	1.5˚C	58 to 178%	141 to 463%	86 to 156%	275 to 430%	95 to 155%	296 to 791%	3 to 26%	32 to 103%	2 to 45%	45 to 173%
	2˚C	41 to 232%	109 to 580%	11 to 156%	68 to 489%	27 to 172%	88 to 749%	-2 to 35%	16 to 143%	-8 to 112%	18 to 187%
	3˚C	57 to 198%	126 to 472%	34 to 129%	140 to 364%	75 to 175%	260 to 600%	-3 to 39%	15 to 128%	3 to 112%	38 to 221%
	4˚C	107 to 243%	203 to 568%	49 to 127%	157 to 416%	87 to 200%	332 to 752%	10 to 33%	20 to 88%	36 to 83%	78 to 190%
Electricity share of energy consumption growth (% from 2010)	1.5˚C	-6 to 67%	12 to 166%	26 to 47%	61 to 181%	24 to 70%	100 to 258%	-2 to 21%	23 to 126%	-14 to 39%	9 to 145%
	2˚C	-10 to 69%	2 to 156%	-13 to 79%	-1 to 161%	-9 to 72%	10 to 227%	-11 to 22%	11 to 121%	-18 to 57%	-11 to 143%
	3˚C	-7 to 69%	5 to 134%	-9 to 79%	20 to 146%	-4 to 80%	42 to 149%	-12 to 33%	7 to 87%	-12 to 57%	6 to 100%
	4˚C	28 to 66%	40 to 120%	18 to 44%	46 to 95%	30 to 55%	87 to 142%	4 to 25%	13 to 69%	27 to 59%	43 to 98%

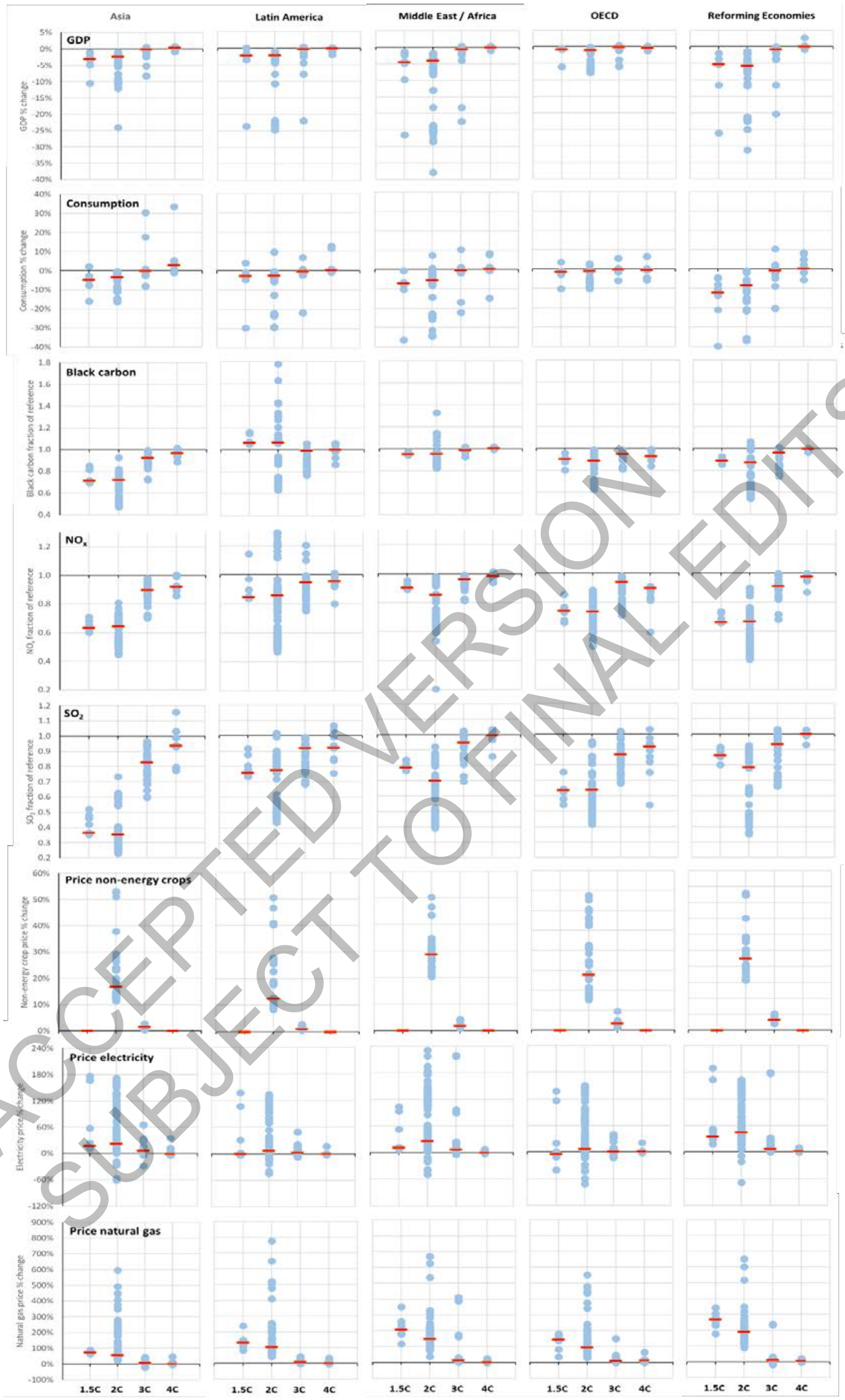


Figure 18.5: Implications of mitigation for different global mean temperature outcomes on various development and sustainable development proxy variables. Example of 2050 global implications of mitigation for different global mean temperature outcomes on various development and sustainable development proxy variables. Developed from the

scenarios associated with (Bauer et al., 2018). Data sample sizes (not shown, but to be added) vary across temperature levels and variables due to model infeasibilities and model differences in reporting.

18.2.5.3 Combining adaptation, mitigation, and sustainable development options

In practice, adaptation, mitigation, and sustainable development interventions are likely to be implemented in portfolio packages rather than as individual discrete options in isolation (*high agreement, limited evidence*). However, there is a dearth of literature estimating optimal portfolios of global adaptation and mitigation strategies. This is not surprising given the geographic-specific nature of climate impacts and adaptation and the information and computational complexity of representing that detail, as well as mitigation options and interactions. There are, however, different literatures relevant to considering potential combinations of adaptation, mitigation, and sustainable development.

At the most aggregate level, there is a long-standing literature exploring economically optimal global trade-offs between climate risks and mitigation (e.g., Manne and Richels, 1992; Nordhaus, 2017; Rose, 2017), as well as global stochastic analysis exploring global risk hedging for a small number of uncertainties (e.g., (Lemoine and Traeger, 2014). Recent work has found optimal global emissions and climate pathways to be highly sensitive to uncertainties and plausible alternative assumptions, with uncertainties throughout the causal chain from society to emissions to climate to climate damages shown to imply a wide range of different possible economically optimal pathways (Rose, 2017). Among other things, this work identifies assumptions consistent with limiting warming to different temperature levels. For example, the combination of potential annual climate damages of 15% of global GDP at 4˚C of warming and a less sensitive climate system were consistent with an economically efficient global pathway limiting warming to 2˚C. In addition, this work highlights the importance of characterizing and managing uncertainties. These types of global aggregate analyses inform discussions regarding long-run global pathways and goals but are of limited value to local near-term planning.

As discussed in Section 18.2.5.3.1, there are synergies and trade-offs mitigation, adaptation, and sustainable development. For instance, the literature on the global cost-effectiveness of mitigation pathways provides insights regarding aggregate synergies and trade-offs between mitigation and sustainable development (e.g., Figure 18.5). Furthermore, linkages between mitigation and adaptation options have been shown, such as expected changes in energy demand due to climate change interacting with energy system development and mitigation options, changes in future agricultural production practices to manage the risks of potential changes in weather patterns affecting land based emissions and mitigation strategies, or mitigation strategies placing additional demands on resources and markets which increases pressure on and costs for adaptation, or ecosystem restoration that provides carbon sequestration and natural and managed ecosystem resiliency benefits, but also could constrain mitigation and impact consumer welfare (WGIII AR6).

Non-linearities are an important consideration in evaluating risk management combinations. Non-linearities have been estimated in global and regional mitigation costs and potential economic damages from climate change (WGIII AR6 Chapter 3; (Clarke et al., 2014; Burke et al., 2015; Rose, 2017). Non-linear mitigation costs mean increasingly higher costs for each additional incremental reduction in emissions (or incremental reduction in global average temperature). Non-linear estimated economic climate damage means increasingly higher damages for each additional incremental increase in climate change (e.g., global average temperature) *(very high confidence*). Non-linearities are also suggested in estimated changes in key risks and adaptation costs (Chapter 16, WGII sector and regional chapters). However, to date, they have not been as explicitly characterized. These non-linearities imply non-linearities in climate risk management synergies and trade-offs with sustainable development. Not only do trade-offs vary by climate level, as do synergies, but they increase at an increasing rate and their relative importance can shift across climate levels *(very high confidence*). Some of this is evident in results like those shown in Figure 18.5 for mitigation (keeping in mind differences in sample sizes across temperature levels). Uncertainty about the degree of non-linearity in mitigation, climate damages, key risks, and adaptation costs creates uncertainties in the strength of the trade-offs and synergies, but also represents opportunities. For instance, additional mitigation options and more economically efficient policy designs have been shown to reduce mitigation costs and the non-linearities in mitigation costs *(very high confidence*) (WGIII AR6 Chapter 3). The same is true for adaptation options and adaptation costs.

Infeasibilities of mitigation and adaptation options (Section 18.4.2.2.1 and 18.4.2.2.2), as well as global pathways (WGIII AR6 Chapter 3), are also relevant to consideration of combinations of risk management options. Infeasibility of options implies higher costs and greater cost non-linearity due to fewer and/or more expensive options, while infeasibility of pathways bounds some of the uncertainty about the pathways relevant to decision-making and planning.

18.2.5.3.1 Trade-offs in adaptation, mitigation, and climate-resilient development

Since AR5, a growing body of literature has emerged that frames adaptation processes as endogenous socioeconomic dynamics, exogenous driving forces, and explicit decisions (Barnett et al., 2014; Maru et al., 2014; Butler et al., 2016; Kingsborough et al., 2016; Werners et al., 2018). Central to this framing is a shift away from viewing adaptation as discrete sets of options that are selected and implemented to manage risk, to thinking about adaptation as a social process that evolves over time, includes multiple decision-points, and requires dynamic adjustments in response to new information about climate risk, socioeconomic conditions, and the value of potential adaptation responses *(very high confidence)* (Haasnoot et al., 2013; Wise et al., 2016). This aligns adaptation with aspects of development thinking, including questions around the capacity and agency of different actors to effect change, the governance of adaptation, and the contingent nature of adaptation needs and effectiveness on the future evolution of society and climate change risk.

While ensuring development and adaptation produce synergies that allow for the achievement of sustainable development is challenging, modelling exercises suggest that there are pathways where synergies among the SDGs are realized *(very high confidence)* (Roy et al., 2018; Van Vuuren et al., 2019) (18.5), particularly if longer time-horizons are used. These pathways require progress on multiple social, economic, technological, institutional, and governance aspects of development including building human capacity, managing consumption behavior, decarbonization of the global economy, improving food and water security, modernizing cities and infrastructure, and innovations in science and technology (Van Vuuren et al., 2019) (18.3). In addition, Olsson et al, (Olsson et al., 2014) and Roy et al. (2018) emphasize the importance of integrating considerations for social justice and equity in the pursuit of sustainable development (Gupta and Pouw, 2017).

The significant overlaps and linkages between development and adaptation practice and a lack of conceptual clarity about adaptation pose a conundrum for scholars (e.g., Bassett and Fogelman, 2013; Webber, 2016), who raise concerns that this potentially leads to trade-offs or mislabeling (Few et al., 2017). This framing of adaptation and development can result in competition between attainment of sustainable development and policies to reduce the impacts of climate change (Ribot, 2011). Such trade-offs are illustrated by (Moyer and Bohl, 2019) who use a baseline development trajectory based on current trends to project progress on SDGs by 2030. This work concluded that only marginal gains are likely to be achieved under that pathway over the next decade (Barnes et al., 2019).

Emerging evidence also suggests that many adaptation-labelled strategies may exacerbate existing poverty and vulnerability or introduce new inequalities, for example by affecting certain disadvantaged groups more than others, even to the point of protecting the wealthy elite at the expense of the most vulnerable (Eriksen et al., 2019). Pelling et al. (2016) find that adaptation has been conceived and implemented in such a manner that most projects preserve rather than challenge the status quo. Specifically, the potential for knowledge and the goals of adaptation to be contested by different actors and stakeholders and the need to sustain progress over extended periods of time can constrain the ability to effectively implement actions that lead to sustainable development outcomes that are protected from the impacts of climate change while also delivering climate mitigation outcomes, that is, for climate resilient development (Bosomworth et al., 2017; Bloemen et al., 2019). This creates the possibility for specific adaptation actions to result in outcomes that undermine greenhouse gas mitigation and/or broader development goals (Fazey et al., 2016; Wise et al., 2016; Magnan et al., 2020). For example, a study in Bangladesh revealed how local elites and donors used adaptation projects as a lever to push vulnerable populations away from their agrarian livelihoods and into uncertain urban wage labour (Paprocki, 2018). These types of outcomes are categorised as maladaptation, interventions that increase rather than decrease vulnerability, and/or undermine or eradicate future opportunities for adaptation and development (Barnett and O'Neill, 2010; Juhola et al., 2015; Magnan et al., 2016; Antwi-Agyei et al., 2017; Schipper, 2020). This inadvertent impact on equity appears to fundamentally contradict a benevolent understanding of transformative adaptation that also champions social justice (Patterson et al., 2018), thus posing long-term maladaptation in opposition to transformative adaptation (Magnan et al., 2020).

Similarly, mitigation efforts, while reducing emissions, can also increase climate impacts vulnerability and undermine adaptation efforts. The same can be said for some poverty alleviation and sustainable development efforts that increase vulnerability for specific segments of the population. For example, in Central America, an evaluation of twelve rural renewable energy projects (either for CDM, early warning systems or rural electrification goals) found that some mitigation and poverty alleviation projects increased vulnerability to families—by excluding them, not adhering to local safety and quality codes and standards, or significantly altering community power dynamics and contributing to conflict (Ley, 2017; Ley et al., 2020).

Synergies between adaptation, mitigation and sustainable development might be promoted by prioritizing those CRD strategies most likely to generate synergies *(very high confidence)* (Roy et al., 2018; Karlsson et al., 2020). This could include focusing on poverty alleviation that improves adaptive capacity (e.g., Kaya and Chinsamy, 2016; Kuper et al., 2017; Ley, 2017; Sánchez and Izzo, 2017; Stańczuk-Gałwiaczek et al., 2018; Ley et al., 2020); renewable energy systems that improve water management and preservation of river ecological integrity (e.g., Berga, 2016; Rasul and Sharma, 2016); or internalizing positive externalities, such as subsidies for mitigation options thought to also improve water use efficiency (e.g., Roy et al., 2018). Similarly, trade-offs might be managed by prioritizing strategies such as disqualifying mitigation options thought to have negative social implications (Section 18.2.5.3.1), internalizing externalities, such as placing a fee or constraint on a negative externality or related activity (e.g., WGIII AR6 Chapter 13) (Bistline and Rose, 2018), or using complementary policies, such as transfer payments to offset negative mitigation, adaptation, or sustainable development strategy implications *(very high confidence)* (e.g., McCollum et al., 2018b). Roy et al. (2018) discusses the latter, noting, for instance, the possibility of complementary sustainable development payments to avoid global energy access, food security, and clean water trade-offs.

SR1.5 and AR6 assessments of system transitions also find opportunities for synergies and managing trade-offs (18.3; Cross-Chapter Box FEASIB). Within each system, mitigation and adaptation options are assessed for their specific benefits and the impacts they can have on one another, as well as with sustainable development. For example, within energy system transitions, the three adaptation options (power infrastructure resilience, reliability of power systems, efficient water use management) have strong synergies with mitigation. While not all mitigation options have strong synergies, the trade-offs can be managed when adaptation and sustainable development goals are also considered. Under land and other ecosystems system transitions, the main trade-off is the competition for land-use between potential alternative uses, e.g., sustainable agriculture, afforestation/reforestation, purpose-grown biomass for energy. On the other hand, assessment of urban and infrastructure system transitions finds mainly synergies between mitigation and adaptation options with trade-offs that are considered manageable, and there is growing evidence of rural landscape infrastructure benefits to adaptation.

Overall, this literature is relatively new and still developing. It highlights the importance of sets of societal priorities and policy design. However, it is not well developed in terms of joint optimization of multiple priorities, evaluating alternative mechanisms and shifts in trade-offs, and evaluating redistribution implications with transfers.

18.2.5.3.2 Risk management combinations with lower to higher climate change

The different strands of literature discussed above can be integrated to help inform thinking about combinations of approaches to risk management. Globally, low climate change projections, versus higher climate change projections, imply greater mitigation, lower climate risks, and less adaptation. This implies greater mitigation trade-offs in terms of overall economic development, food crop prices, energy prices, and overall household consumption, but lower climate risk, with sustainable development synergies like human health and lower adaptation trade-offs, and an uneven distribution of effects *(very high confidence)* (Roy et al., 2018).

Sustainable development considerations could be used to prioritize mitigation options, but as noted earlier there are trade-offs, with a potentially significant impact on the economic cost of mitigation, as well as a potential trade-off in terms of the climate outcomes that are still viable (WGIII AR6 Chapter 3). For instance, all of the 1.5˚C scenarios used in IPCC (2018a) deploy carbon dioxide removal technologies

(Rogelj et al., 2018). Without these technologies, most models cannot generate pathways that limit warming to 1.5˚C, and those that do adopt strong assumptions about global policy development and socioeconomic changes. Sustainable development might also affect the design of policies by prioritizing specific sustainable development objectives. However, there are trade-offs here as well, with costs and the distribution of costs varying with alternative policy designs. For instance, prioritizing air quality has climate co-benefits but does not ensure the lowest cost climate strategy (Arneth et al., 2009; Kandlikar et al., 2009). Similarly, prioritizing land protection has a variety of co-benefits but could increase food prices significantly, as well as the overall cost of climate mitigation (IPCC, 2019b). In this context with lower climate risk and adaptation levels and larger mitigation effort, managing mitigation trade-offs could be a sustainable development priority. Furthermore, sustainable development could also be tailored to facilitate adaptation as well as manage mitigation costs.

Globally, high climate change projections imply lower mitigation effort, higher climate risks, and greater adaptation. This implies lower mitigation trade-offs, but greater climate risk with greater demand of adaptation and potential for trade-offs in terms of competing sustainable development priorities. Sustainable development considerations could affect adaptation options. For instance, constraining options such as relocation or facilitating adaptation capacity and community resilience. Sustainable development might also be tailored to affect the climate outcome by shaping the development of emissions. In this context with greater climate risk and adaptation levels and less mitigation effort, facilitating adaptation and managing adaptation costs and trade-offs could be a sustainable development priority.

Locally, there are many qualitative similarities to the global perspective in thinking about risk management combinations across lower versus higher climates. However, there is one very important difference. Local decision makers are confronted with uncertainty about what others will do beyond their local jurisdiction. With future climate a function of the sum of global decisions, sustainable development planning needs to consider the possibility of more and less emissions reduction action globally and the potential associated climates. This implies the need for sustainable development to manage for the possibility of higher climates by further facilitating adaptation and managing adaptation trade-offs. Prioritizing sustainable development locally is also supported by the insight that the impacts on poverty depend at least as much or more on development than on the level of climate change (*very high confidence*) (Wiebe et al., 2015; Hallegatte and Rozenberg, 2017).

There is nothing in the current literature to suggest that CRD is necessarily associated with a specific climate outcome, like limiting global average warming 1.5˚C or 2˚C, or a specific pathway. Instead, there are many possible pathways for climate-resilient development (*medium agreement, limited evidence*) (e.g., David Tàbara et al., 2018; O'Brien, 2018). The current literature suggests that different mixes of adaptation and mitigation strategies, and sustainable development and trade-off management priorities, measures, and reallocations (Section 18.5.3.1), will be appropriate for different expected climates and locations (18.1.2); while trade-offs between climates will be dictated by relative non-linearities, feasibilities, shifts in priorities, and trade-off and reallocation options across future climates.

Finally, it is important to note that there is currently limited information available regarding the following: (1) local implications of 1.5˚C versus warmer futures with respect to avoided impacts and sustainable development implications and interactions and applying global conclusions to local, national, and regional settings can be misleading, (2) local context-specific synergies and trade-offs with respect to adaptation, mitigation, and sustainable development for 1.5˚C futures, and (3) standard indicators for monitoring factors related to CRD (Roy et al., 2018).

18.3 Transitions to Climate Resilient Development

A key finding emerging from the IPCC SR1.5 is the critical role that system transitions play in enabling mitigation pathways consistent with a 1.5°C or less world (IPCC, 2018a; IPCC, 2019b).Such transitions are similarly critical for the broader pursuit of climate-resilient development, and the various AR6 special reports as well as subsequent literature provide new evidence of why such transitions are needed for CRD, as well as both the opportunities for accelerating system transitions and their limitations for delivering on the goals of CRD.

18.3.1 System Transitions as a Foundation for Climate Resilient Development

In the AR6, system transitions are defined as "*the process of changing (the system in focus) from one state or condition to another in a given period of time*" (IPCC, 2018a; IPCC, 2019b). In the climate change solution space, system transitions represent an important mechanism for linking and enabling mitigation, adaptation, and sustainable development options and actions (*very high confidence*). SR1.5C identified the need for rapid and far-reaching transitions in four systems – energy, land and terrestrial ecosystems, urban and infrastructure, and industrial systems (IPCC, 2018b; IPCC, 2018a) (1.5.1 and 18.1). The SRCCL expanded on this with a focus on terrestrial systems, while SROCC added additional evidence from ocean and cryosphere systems. This section assesses the four system transitions discussed in the SR1.5C assessment in the context of CRD, while also extending the assessment to consider societal transitions as a cross-cutting, fifth transition important for climate-resilient development. Literature to support this assessment is also drawn from AR6 regional and sectoral chapters, which is synthesized later in this chapter (18.5).

As discussed in Box 18.3 (Hölscher et al., 2018), system transitions are linked to system transformation, which is defined as "*a change in the fundamental attributes of a system including altered goals or values*" (Figure 18.1) (IPCC, 2018a). In a systems context, transitions focus on 'complex adaptive systems; social, institutional and technological change in societal sub-systems', while transformations are "*large scale societal change processes … involving social-ecological interactions"* (IPCC, 2018a) (Box 18.1). Although system transitions are often identified in the literature as being necessary processes for large-scale transformations (Roggema et al., 2012; Hölscher et al., 2018), thereby making them a core enabler of CRD. Yet, they are not necessarily transformative in themselves.

18.3.1.1 Energy Systems

Recent observed changes in global energy systems include continued growth in energy demand, led by increased demand for electricity by industry and buildings *(very high confidence*) (AR6 WGIII Chapter 2). Growth in energy demand has also been driven by increased demand for industrial products, materials, building energy services, floor space, and all modes of transportation. This growth in demand, however, has been moderated by improvements in energy efficiency in industry, buildings, and transportation sectors (*very high confidence*) (AR6 WGIII Chapter 2). There is also a trend of moving away from coal towards cleaner fuels, due to lower natural gas prices and lower cost renewable technologies, and structural changes away from more energy-intensive industry.

Features of sustainable development such as enhanced energy access, energy security, reductions in air pollution, and economic growth continue to be the dominant influence on the evolution of energy systems and decision-making regarding energy investments and portfolios (*very high confidence*) (WGIII AR6 Chapter 6). To date, climate policy has been comparatively less influential in driving energy transitions globally. Yet, there are examples at the local, regional, and national level of policy incentivizing rapid changes in energy systems (*very high confidence*) (WGIII AR6 Chapter 6). Many sustainable development priorities have co-benefits in terms of climate mitigation, such as air pollution and conservation policies reducing short-lived climate forcers and sequestering carbon respectively, as well adaptation benefits, such as improved energy access and environmental quality enhancing adaptive capacity (*very high confidence*) (WGIII AR6 Chapter 6) (de Coninck et al., 2018). Alternatively, sustainable development projects can have negative climate implications with, for instance, hydroelectric projects shut down by droughts or floods resulting in greater use of bunker and fuel oil, as well as natural gas.

In addition to sustainable development priorities driving change in energy systems, observed energy system trends have implications for sustainable development (e.g., IEA et al., 2019). Observed changes in energy system size, rate of growth, composition and operations impact energy access, equity, environmental quality and wellbeing, with both synergies and trade-offs, including recent improvements in global access to affordable, reliable, and modern energy services. For instance, in some countries, such as the United States, there has been a significant shift away from coal as a fuel source for electricity generation in favor of natural gas. More recently, however, renewables have emerged as the dominant form of new electricity generation (Gielen et al., 2019). Similarly, for energy access in developing countries, renewable energy or hybrid distributed generation systems are increasingly being prioritized due to challenges associated with access, costs and environmental impacts from traditional fossil fuel-based energy technologies (Mulugetta et al., 2019).

Energy systems have been a historical driver of climate change, but are also adversely affected by climate change impacts, including short-term shocks and stressors from extreme weather as well as long-term shifts in climatic conditions (*very high confidence*). The potential for such factors is often incorporated into local system designs, operations, and response strategies. There have been changes in observed weather and extreme event hazards for the energy system, but to date many are not attributable solely to anthropogenic climate change (USGCRP, 2017; IPCC, 2021a). Nevertheless, with observed extremes shifting outside of what has been observed historically, existing design criteria and operations may not be optimal for future climate conditions and contingencies (Chapter 16; sectoral and regional chapters). Overall, there is limited historical evidence on the efficacy of adaptation responses in reducing vulnerability of energy systems (*high agreement, limited evidence*). However, sustainable development trends, such as improving incomes, reducing poverty, and improving health and education have reduced vulnerability (Chapter 16), and improvements in system resiliency to extreme weather events and more efficient water management have occurred that have synergies with adaptation and sustainable development in general.

Available literature indicates that greenhouse gas emissions reductions have been achieved in response to climate actions including financial incentives to promote renewable energy, carbon taxes and emissions trading, removal of fossil fuel subsidies, and promotion of energy efficiency standards *(very high confidence)* (WGIII AR6 Chapter 6). Such policies tend to lead to a lower carbon intensity of GDP, due to structural changes in the use of energy and the adoption of new energy technologies. However, other drivers of change are also present and thus ongoing energy transitions and their future evolution are a response to both climatic and non-climatic considerations, with broader sustainable development priorities being a significant driver of change (see WGIII AR6 Chapter 6).

18.3.1.2 Urban and infrastructure systems

Urban areas their associated infrastructure are critical targets for CRD processes. This is a function of urban areas being the dominant settlement pattern with over 55% of the global population living in cities (World Bank, 2021). As a consequence, urban areas are also the focal point for energy use, land use change, and consumption of natural resources, thereby making them responsible for an estimated 70% of global CO2 emissions (Johansson et al., 2012; Ribeiro et al., 2019). The trend toward increasing urbanization is anticipated to create both challenges and opportunities for sustainable development, as well as climate action (Güneralp et al., 2017; Li et al., 2019a).

The built environment is increasingly exposed to climate stresses and more frequent co-occurrences of climate shocks than in the past. This has the potential to increase rates of building and infrastructure degradation, increase damage from extreme weather events. The existing adaptation gaps and everyday risks within many cities, particularly those of the global South, combined with escalating risk from climate change, makes rapid progress in enhancing urban resilience a high priority for CRD (Pelling et al., 2018; Davidson et al., 2019; Lenzholzer et al., 2020). Strategic investments in disaster risk reduction, including climate-resilient green infrastructure, updated building codes, and land use planning can provide significant long-term cost savings and social benefits. Moreover, evaluating the relative merits of "fail safe" versus "safe to fail" approaches to infrastructure planning can help to identify more design principles that are more robust to the uncertainties of climate change and urbanization (Kim et al., 2017a; Kim et al., 2019).

Much of the literature on urban resilience and sustainability focuses on addressing discrete challenges for urban infrastructure sub-systems. Climate change has the potential to enhance stress on lifeline infrastructure services such as the provision of electricity, water and wastewater, communications, and transportation – sub-systems which often underdeveloped in many regions of the world (Arku and Marais, 2021; Sitas et al., 2021). For example, a warming and more variable climate can increase stress on electricity grids by reducing transmission efficiency, increasing cooling demand requirements, and by increasing exposure to climate shocks such as heat waves, floods, and storms (Bartos and Chester, 2015; Auffhammer et al., 2017; Perera et al., 2020). Accordingly a significant focus on the energy transition is on achieving the dual goals of reducing the carbon footprint of energy while also increasing resilience of energy supply to current and future threats.

For example, renewable energy generation and storage technologies that modular and distributed and provide enhanced resilience to shocks and stresses from climate change (Venema and Temmer, 2017a).

Similarly, building and maintaining urban water systems that are resilient to climate shocks requires significant changes in water demand, infrastructure, and management. Enhancing redundancy in water supply and the flexibility to shift between surface and groundwater options aids adaptation. Decentralized water supply and sanitation options are now feasible and can provide greater resilience than most centralized systems (Parry, 2017), provided they have adequate supply (Leigh and Lee, 2019; Rabaey et al., 2020). Water conservation and green infrastructure options for stormwater management are proven approaches for reducing climate risks (Venema and Temmer, 2017b), with adaptation and mitigation co-benefits. Water demand management and rainwater harvesting contribute to climate change mitigation and increase adaptive capacity by increasing resilience to climate change impacts such as drought and flooding (Paton et al., 2014; Berry et al., 2015). In addition, they can contribute to restoring urban ecosystems that offer multiple ecosystem services to citizens (Berry et al., 2015) (see WGIII AR6 Chapter 8). The context-appropriate development of green spaces, protecting ecosystem services and developing nature-based solutions, can increase the set of available urban adaptation options (IPCC, 2018b), while creating opportunities for more complex and dynamic approaches to urban water management (Franco-Torres et al., 2020). For example, the Netherlands' 'Room for the River' policy focuses on ont only achieving higher flood resilience, but also improving the quality of riverine areas for human and ecological wellbeing (Busscher et al., 2019).

An overarching focus of urban sustainability is the reversal of long-standing trends of ecosystem fragmentation and degradation that have resulted in growing separation between human and natural systems within urban environments (IPBES, 2019) (see WGIII AR6 Chapter 8). Urban ecosystems and the integration of nature-based solutions and green infrastructure into urban areas can yield benefits that facilitate achievement of the SDGs. There has been growing recognition of urban ecosystems as social, cultural, and economic assets that can support economic development while also enhancing resilience to extreme weather events and improving air and water quality (Shaneyfelt et al., 2017; Matos et al., 2019). Investing in urban ecosystems and green infrastructure can provide lower-cost solutions to multiple urban development challenges when compared to traditional infrastructure systems (Terton, 2017). Relatedly, agriculture, while largely a rural system, is increasingly expanding within urban areas. Urban agriculture enables citizens to fulfil some of their food needs, improving urban resilience to food shortages, enhancing biodiversity, and increasing coping capacity during disasters (Demuzere et al., 2014; Clucas et al., 2018) (see WGIII AR6 Chapter 8). Strengthening urban agroecosystems therefore increases resilience to supply shocks from climate change impacts and can contribute to community cohesion (Temmer, 2017a).

Overall, the discourse in the literature regarding the future of cities emphasizes the importance of viewing cities as more than just their physical infrastructure that can be made more resilient through engineering solutions (Davidson et al., 2019). Rather, urban areas are increasingly conceptualized as complex socioecological or sociotechnical systems (*very high confidence*) (Patorniti et al., 2017; Patorniti et al., 2018; Visvizi et al., 2018; Savaget et al., 2019). Such frameworks integrate physical, cyber, social, and ecological elements of cities in pursuit of resilience and sustainability transitions, and they recognize the role of governance and engagement processes as being central to system change (Temmer, 2017b). Nevertheless, some authors have cautioned that urban transitions will be associated with synergies as well as trade-offs with respect to sustainable development (*very high confidence*) (Maes et al., 2019; Sharifi, 2020).

[START BOX 18.5 HERE]

Box 18.5: The Implications of the Belt and Road Initiative (BRI) for Climate Resilient Development

In 2013, Chinese President Xi Jinping announced plans for a grand transcontinental infrastructure initiative. China would work with partner countries under two programs termed the Silk Road Economic Belt and the 21st Century Maritime Silk Road. Together, these have come to be known as the Belt and Road Initiative (BRI). Set to encompass 4.4 billion people and a cumulative GDP of around $21 trillion, the BRI has been implemented in over 120 countries with wide infrastructure funding gaps, as exemplified by the China-Myanmar Gas Pipeline, Gwadar Port in Pakistan, Trans-Mongolian Railway, China Belarus Industrial Park, and urban rehabilitation in Ethiopia. Its stated objectives even extend beyond infrastructure connectivity to include trade promotion, financial integration, policy coordination and cultural dialogue. Having been written into the Communist Party's constitution in 2017, the BRI will be China's flagship international development strategy for years to come.

The 126 countries participating in the BRI account for 23% of global GDP, but also 28% of global carbon emissions (PBCSF, 2019). By 2050, even based on an optimistic scenario, the total carbon emission by these countries will be 17% higher than what would be allowed under a 2°C carbon budget (Duan et al., 2018). The BRI covers regions with high reserve of carbon-based fuels and could have significant impact on global energy consumption and carbon emission patterns. For example, according to the EIA statistics, the proven reserves of oil, natural gas, and coal in nations under the BRI make up 58.8%, 79.9%, and 54.0% of the world's total (China Meteorological Administration, 2019).

Meanwhile, countries along the BRI are highly vulnerable to the impact of climate change, spanning highly diverse climate zones with fragile ecological conditions. Currently, many of the regions have a low level of infrastructure development and high population densities (The People's Republic of China, 2017). Changes in temperature, precipitation, vegetation and hydrological conditions could in turn pose threats to the development and operation of infrastructure projects in these regions. Given the scope and scale of the BRI, a key question is whether it will incentivize continued exploitation of available fossil fuel resources or provide the innovation and economic development needed to transition participating nations to more resilient and less carbon-intensive economies.

BRI and its commitment to climate resilient development (CRD)

Recognizing these feedbacks between the BRI and climate change, the Chinese government, included climate change in developing the key guiding documents on BRI development in 2015. These include "*taking into consideration the impact of climate change, strengthening exchange and cooperation with countries along the Belt and Road, leveraging the support and guarantee function of Chinese meteorological departments in promoting the BRI*" (NDRC, 2015). The second BRI Forum held in 2019 reiterated the importance of green development "*as the foundation of the BRI*" and promoted green infrastructure development and green investment, in addition to plans for increasing capacity in response to climate change, promoting low-carbon infrastructure, energy source, climate-related disaster alarm system, climate finance integration, as well as low-carbon technology development.

The Chinese Meteorological Administration, the governmental agency responsible for climate change related issues, responded to BRI official guidelines by establishing BRI integrated meteorological service system and proposed meteorological development plan 2017-2025 (China Meteorological Administration, 2019), which includes policy coordination on climate change, promoting intergovernmental cooperation, completing BRI disaster prevention and relief mechanisms, strengthening climate change support capacity, enhancing prediction and evaluation capacity related with climate change (China Meteorological Administration, 2019). China has established South-South cooperation in support of other countries to mitigate climate change. Efforts have been made to promote joint research with countries along the BRI on regional climate change, climate change prediction, and develop products in response to climate conditions in different regions.

The China Clean Development Mechanism Fund (CCDMF) is a national climate fund that supports low carbon growth and climate resilience in China (UNFCCC, 2017). More than USD 81 million in grants committed to support over 200 projects. A combination of funding enterprises, mobilizing market capital and achieving verified emission reduction effects contributes to a direct reduction of over seven million tons of CO2 equivalent. Government representatives from Brazil, Vietnam, and Cambodia have already visited CCDMF to learn more about this type of climate financing.

Trade-offs between BRI and CRD

Despite the implementation of such financing mechanisms for low-carbon development, their net effect is not necessarily sufficient to offset the carbon footprint generated by overseas fossil fuel projects funded or financed by China. As such, BRI stakeholders must navigate a number of trade-offs among different objectives of the initiative.

For the Chinese government and state-owned enterprises, an immediate trade-off is that between the short-term profits gained through carbon-intensive infrastructure investments overseas and long-term sustainable development with the introduction of low-carbon technology in infrastructure development. On one hand, the energy solutions that China proposes tend to involve carbon-intensive infrastructures such as coal factories, which increases carbon emissions of these countries. But at the same time, China also provides climate finance for these countries in support of renewable energy projects such as hydropower projects and solar panel production facilities.

For the governments and people hosting BRI projects, the tradeoff is between short-term economic prosperity and long-term sustainable development. Infrastructure development driven by carbon-intensive technologies are cheaper and more consistent for developing countries (for example, electricity generated through coal-based power plants is more consistent than that generated through hydropower stations), which is conducive to more rapid industrialization of these countries, generating immediate urbanization and economic prosperity. Yet the industrialization process would exacerbate carbon emission and accelerate the climate change process, with long-term impact on food security, livelihood, migration, water demand, disease control, posing potential hazards to sustainable development in these regions.

Winners and losers in incorporating CRD into BRI development

An emphasis on CRD within the BRI could create a number of opportunities for sustainable development. For example, adherence to CRD principles of low-carbon development would incentive growth of renewable energy, clean technologies, thereby growing the global market for such goods and services. This could have significant benefits for developing nations of the BRI in terms of enabling sustainability transitions that might otherwise not be feasible. However, a CRD orientation of the BRI would also have consequences for fossil fuel and carbon-intensive industries. This could affect both private and state-owned enterprises in BRI nations resulting in stranded assets, loss of some forms of employment.

[END BOX 18.5 HERE]

18.3.1.3 Land, Oceans, and Ecosystems

Land, oceans, and terrestrial ecosystems are in transition globally, with anthropogenic factors including climate change being a major driving force *(very high confidence)* (IPBES, 2019) (Box 6). Seventy-five per cent of the land surface has been significantly altered, 66 percent of the ocean area is experiencing increasing cumulative impacts, and over 85 percent of wetland areas have been lost (IPBES, 2019). Since 1970, only four out of eighteen recognized ecosystem services assessed have improved in their functioning: agricultural production, fish harvest, bioenergy production and material harvests. The other 14 ecosystem services have declined (IPBES, 2019), raising concerns about the capacity of ecosystems and their services to support sustainable and climate-resilient development.

Given the pressures on land, oceans, and ecosystems, enhancing resilience to climate change and other pressures of human development is a core priority of transition in these systems. Yet, there are a few recorded initiatives that provide evidence of successful improvement in ecosystem resilience (*high agreement, limited evidence*). Similarly, although there is significant evidence that a broad range of adaptation initiatives have been pursued across global regions and sectors, including a rapid expansion of nature- or ecosystem-based solutions (Mainali et al., 2020), there is limited evidence of how these planned climate adaptation efforts have contributed to enhanced ecosystem resilience. Additional research is necessary to evaluate these efforts in terms of their performance and also to identify mechanisms for scaling them up in different contexts. As an example, Paik (Paik et al., 2020) record the increased diffusion of salt tolerant rice varieties in the Mekong River Delta, which is at risk of sea-level rise and an associated saline intrusion. This is a low-cost adaption to saline ingress, that increases food productivity and reduces the risk of outmigration for this vulnerable agricultural region.

Evidence of the interactions between ecosystems and resilience come from a range of sources including both regional and sectoral examples (Box 18.2; Tables 18.7‑18.8. For example, regional examples suggest that the use of land to produce biofuels could increase the resilience of production systems and address mitigation needs (Box 2.2). Nevertheless, the potential of BECCS to induce maladaptation needs deeper analysis (Hoegh-Guldberg et al., 2019). Climate Smart Forestry (CSF) in Europe provides an example of the use of sustainable forest management to unlock the EU's forest sector potential (Nabuurs et al., 2017). This is in response to diverse climate impacts ranging from pressure on spruce stocks in Norway and the Baltics, on regional biodiversity in the Mediterranean region, and the opportunity to use afforestation and reforestation to store carbon in forests (Nabuurs et al., 2019). CSF considers the full value chain from forest to wood products and energy and uses a wide range of measures to provide positive incentives to firmly integrate climate objectives into the forestry sector. CSF has three main objectives; (i) reducing and/or removing greenhouse gas emissions; (ii) adapting and building forest resilience to climate change; and (iii) sustainably increasing forest productivity and incomes (Verkerk et al., 2020).

Other solutions focus on specific subsectors. Mutually supportive climate and land policies have the potential to save resources, amplify social resilience, support ecological restoration, and foster engagement and collaboration between multiple stakeholders. (IPCC, 2019f, C.1). Land-based solutions can combat desertification in specific contexts: water harvesting and micro-irrigation, restoring degraded lands using drought-resilient ecologically appropriate plants, agroforestry, and other agroecological and ecosystem-based adaptation practices (IPCC, 2019f, B.4.1). Reducing dust and sand storms and sand dune movement can lessen the negative effects of wind erosion and improve air quality and health. Depending on water availability and soil conditions, afforestation, tree planting and ecosystem restoration programs, using native and other climate resilient tree species with low water needs, can reduce sand storms, avert wind erosion, and contribute to carbon sinks, while improving micro-climates, soil nutrients and water retention (IPCC, 2019f, B.4.2).

Coastal blue carbon ecosystems, such as mangroves, salt marshes and seagrasses, can help reduce the risks and impacts of climate change, with multiple co-benefits. Over 150 countries contain at least one of these coastal blue carbon ecosystems and over 70 contain all three. Successful implementation of measures of carbon storage in coastal ecosystems could assist several countries in achieving a balance between emissions and removal of greenhouse gases. Carbon storage in marine habitats can be up to 1,000 tC ha–1, higher than most terrestrial ecosystems. Conservation of these habitats would also sustain a wide range of ecosystem services, assist with climate adaptation by improving critical habitats for biodiversity, enhancing local fishery production, and protect coastal communities from SLR and storm events (IPCC, 2019b). Ecosystem-based adaptation is a cost-effective coastal protection tool that can have many co-benefits, including supporting livelihoods, contributing to carbon sequestration and the provision of a range of other valuable ecosystem services (IPCC, 2019b).

Diversification of food systems is another component of land, ocean, and ecosystem transitions that are consistent with CRD. Balanced diets, featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission manner, are major opportunities for adaptation and mitigation and improving human health. By 2050, dietary changes could free several million sq. km of land and provide a mitigation potential of 0.7 to 8.0 GtCO2eq yr-1, relative to business-as-usual projections.

For coastal systems, many frameworks for climate resilience and adaptation have been developed since the AR5 (Hoegh-Guldberg et al., 2014; Settele et al., 2014) with substantial variations in approach between and within countries, and across development status. Few studies have assessed the success of implementing these frameworks due to the time-lag between implementation, monitoring, evaluation and reporting (IPCC, 2019g). As an example, the Nature-Based Climate Solutions for Oceans initiative has the potential to: restore, protect and manage coastal and marine ecosystems, adapt to climate change, improve coastal resilience, and enhance their ability to sequester and store carbon (Hoegh-Guldberg et al., 2019).

Polar regions will be profoundly different in the future. The degree and nature of that difference will depend strongly on the rate and magnitude of global climate change, which will influence adaptation responses regionally and worldwide. Future climate-induced changes in the polar oceans, sea ice, snow and permafrost will drive habitat and biome shifts, with associated changes in the ranges and abundance of ecologically important species (IPCC, 2019g). Innovative tools and practices in polar resource management and planning show strong potential in improving society's capacity to respond to climate change. Networks of protected areas, participatory scenario analysis, decision support systems, community-based ecological monitoring that draws on local and indigenous knowledge and self-assessments of community resilience contribute to strategic plans for sustaining biodiversity and limit risk to human livelihoods and wellbeing. Experimenting, assessing, and continually refining practices while strengthening links with decision making has the potential to ready society for the expected and unexpected impacts of climate change (IPCC, 2019g).

[START BOX 18.6 HERE]

Box 18.6: The Role of Ecosystems in Climate-Resilient Development

Ecosystems and their services closely relate to CRD. Climate change has impacted ecosystems across a range of scales, and those impacts have been exacerbated by other ecological impacts associated with human activities. Ecosystem based adaptation strategies have been developed and is crucial to CRD. However, knowledge and evidence still missing, and cultural services—in contrast to provision and regulation services as main benefits and supporting services as co-benefits—are less well addressed in the literature.

Ecosystems play a key role in CRD

A key element of CRD is ensuring that actions taken to mitigate climate change do not compromise adaptation, biodiversity, and human needs. Maintaining ecosystem health, linked to planetary health, is an integral part of the goals of CRD. The 2005 Millennium Ecosystem Assessment defined ecosystem services as "*the benefits people obtain from ecosystems*", and categorized the services in to provisioning, regulating, supporting, and cultural services (Millennium Ecosystem Assessment, 2005; IPBES, 2019). The 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) broadened the definition to "*the contributions, both positive and negative, of living nature to the quality of life for people*", and developed a classification of 18 categories (IPBES, 2019).

Table Box 18.6.1 demonstrates how ecosystem services connect to sustainable development goals (SDGs) and CRD. MEA's provisioning service generally connects to the IPBES' material services, mostly contributing to the SDG cluster associated with nature's contribution to people (NCP) (Millennium Ecosystem Assessment, 2005; IPBES, 2019) and to "**D**evelopment" in CRD. MEA's regulating and supporting services connect to IPBES' non-material services, contributing to SDG clusters of Nature and Driver of change in nature and NCP and to "**R**esilience" in CRD. MEA's cultural services connect to IPBES' non-material services, contributing to SDG clusters of good quality of lift (GQL) and to **E**nabling conditions for CRD.

Table Box 18.6.1: Ecosystem services (based on the Millennium Ecosystem Assessment, MEA, and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES, classifications) and their connections to sustainable development goals (SGCs) and climate resilient development (CRD) (Millennium Ecosystem Assessment, 2005; IPBES, 2019).

Ecosystem services		SDGs	CRD
MEA	**IPBES**		
Provisioning services	11 Energy 12 Food and feed 13 Materials and assistance 14 Medicinal, biochemical, and genetic resources	1 No poverty 2 Zero hunger 3 Good health and well-being 11 Sustainable cities communities 7 Affordable clean energy 8 Decent work and economic growth 9 Industry, innovation, and infrastructure 12 Responsible consumption and production	**D**evelopment
Regulating services	3 Regulation of air quality 4 Regulation of climate 5 Regulation of ocean acidification 6 Regulation of freshwater quantity, location, and timing 7 Regulation of freshwater and coastal water quality	6 Clean water and sanitation 13 Climate action	**C**limate adaptation and mitigation

	9 Regulation of hazards and extreme events 10 Regulation of organisms detrimental to humans		
Supporting services	1 Habitat creation and maintenance 2 Pollination and dispersal of seeds 8 Formation, protection, and decontamination of soils and sediments 18 Maintenance of options	14 Life below water 15 Life on land	
Cultural services	15 Learning and inspiration 16 Physical and psychological experiences 17 Supporting identities	4 Quality education 5 Gender equality 10 Reduce inequality 16 Peace, justice, and strong institutions 17 Partnerships for the goals	**E**nabling Conditions

Climate change impacts on ecosystems and their services

Climate change connects to ecosystem services through two links: climate change and its influence on ecosystems as well as its influence on services (Chapter 2.2). The key climatic drivers are changes in temperature, precipitation, and extreme events, which are unprecedented over millennia and highly variable by regions (Chapter 2.3, 3.2; Cross-Chapter Box EXTREMES in Chapter 2). These climatic drivers influence physical and chemical conditions of the environment, and worsen the impacts of non-climate anthropogenic drivers including eutrophication, hypoxia, sedimentation (Chapter 3.4). Such changes have led to changes in terrestrial, freshwater, oceanic and coastal ecosystems at all different levels, from species shifts and extinctions, to biome migration, and to ecosystem structure and processes changes (Chapter 2.4, 2.5, 3.4, Cross-Chapter Box MOVING PLATE in Chapter 5). Changes in ecosystems leads to changes in ecosystem services including food and limber prevision, air and water quality regulation, biodiversity and habitat conservation, and cultural and mental support (Chapter 2.4, 3.5). Table Box 18.6.2 presents examples of climate change's impact on ecosystems and their services from other chapters in the WGII report. The degradation of ecosystem services is felt disproportionately by people who are already vulnerable due to historical and systemic injustices, including women and children in low-income households, Indigenous or other minority groups, small-scale producers and fishing communities, and low-income countries (Chapter 3.5, 4.3, 5.13).

Table Box 18.6.2: Examples of key risks to ecosystems from climate change and their connections to ecosystem services (ES) in the WGII report and cross-chapter papers (CCPs). (See Table 1 for the description of the categories of ES)

Climate factors	Key risk	ES			
		P	R	S	C
***Terrestrial and freshwater ecosystems* (Chapter 2, 4, 5; CCP 1; CCP 7; CCP 3; CCP 5)**					
- Increase in average and extreme temperatures - Changes in precipitation amount and timing - Increase in aridity - Increase in frequency and severity of drought - Increased atmospheric CO_2	Species extinction and range shifts	X		X	X
	Ecosystem structure and process change	X	X		
	Ecosystem carbon loss	X	X		
	Wildfire		X	X	
	Water cycle & scarcity	X	X		
***Ocean and coastal* (Chapter 3; CCP 1; CCP 6)**					
- Ocean warming - Marine heatwaves - Ocean acidification - Loss of oxygen - Sea level rise - Increased atmospheric CO_2 - Extreme events	Species extinction and range shifts	X		X	X
	Ecosystem structure and process change	X	X		
	Habitat loss	X		X	
	Ocean carbon sink less effective		X		
	Erosion and land loss	X	X		
***Food, Fiber, and other Ecosystem Products* (Chapter 5)**					
- Global warming	Species distribution	X			

- Water stress - Extreme events - Ocean acidification - Salt intrusion	Timing of key biological events change	X			
	Corp productivity and quality decrease	X			
	Diseases and insect	X			

Adaptation practices and enabling conditions for CRD

Ecosystem protection and restoration, ecosystem-based adaptation (EbA), and nature-based solution (NbS) can lower climate risk to people and achieve multiple benefits including food and material provision, climate mitigation, and social benefits (Chapter 2.6, 3.6, 4.6, 5.13,6.3, 8.6). Table Box 18.6.3 presents some examples of ecosystem adaptation practices reported in WGII sectoral and regional chapters and CCPs, as well as their co-benefits, potential for maladaptation, and enabling conditions. Many of the strategies focus on integrated systems (managing for multiple objectives and trade-offs) as well as the fair use of resources. However, there is limited evidence of the extent to which adaptation is taking place and virtually no evaluation of the effectiveness of adaptation in the scientific literature (Chapter 2.6, 3.5). Enabling conditions for the successful implementation ecosystem-based practice include regional and community-based based approaches, multistakeholder and multi-level governance approaches, Integration of Local Knowledge and Indigenous Knowledge, finance, and social equity (Chapter 2.6, 3.6).

Table Box 18.6.3: Examples of adaptation practices and their connections to ecosystem services (ES) and climate resilient development pathways (CRDP) in the WGII sectoral and regional chapters and cross-chapter papers (CCPs). (See Table 1 for the description of the categories of ES and CRDP)

Adaptation practices (and - *examples*)	**Main benefit (and & co-benefit; - trade off; + enabling conditions; X barrier and potential maladaptation)**	**ES**			
		P	**R**	**S**	**C**
Agroforestry (Table 2.7; Table 5.ES; Chapter 5.10.4; Chapter 5.12.5.2; Box 5.10; Table 16.2) - *Climate Adaptation and Maladaptation in Cocoa and Coffee Production* (Box 5.7)	Food provision **&** Fuel (wood) provision, carbon sequestration, biodiversity and ecosystem conservation, diversification and improved economic incomes, water and soil conservation, and aesthetics **+** Secure tenure arrangements, supporting Indigenous knowledge, inclusive networks and socio-cultural values, access to information and management skill **X** Higher water demand; disruption of hydrology; loss of native biodiversity; reduced resilience of certain plants; degraded soil and water quality; improper and increased use of agrochemicals, pesticides, and fertilizers	***	**		**
Forest maintenance and restoration (Box 2.2; Table 16.2; Table Cross-Chapter Box NATURAL.1 in Chapter 2) - *Protected area planning in Thailand* (Chapter 2.6.5.3) - *Conserving Joshua trees in* the *Joshua National Park* (Chapter 2.6.5.6) - *Addressing Vulnerability of Peat Swamp Forests in South East Asia* (Chapter 2.6.5.10) - *Reduce emissions from deforestation and forest degradation (REDD+)* (Chapter 5.6.3.3; Table 16.2)	Ecosystem conservation **&** Food provision, fuel provision, job creation, carbon sequestration, biodiversity conservation, air quality regulation, water and soil conservation, vector-borne disease control, improved mental health, cultural benefits, natural resources relative conflict prevention **+** Cooperation of indigenous peoples and other local communities **X** Planting large scale non-native monocultures leads to loss of biodiversity and poor climate change resilience, increased vulnerability to landslide, increased sensitivity of new tree species, reduced resilience of certain plants, high water demand, trees planted damaged buildings during heavy storms, lack of carbon rights in national legislations	**	**	***	**
Traditional practices/indigenous knowledge and local knowledge (IKLK) (Table 2.7; Chapter 5.6.3; Chapter 5.14.2.2; Table 16.2) - *Crop and livestock farmers on observed changes in climate in the* Sahel (Box 5.6)	Food and material provision **&** Carbon sequestration **+** Partnerships between key stakeholders such as researchers, forest managers, and local actors, indigenous and local knowledge	***	**		

- *Karuk Tribe in northern California* (Chapter 5.6.3.2)					
Restoring natural fire regimes (Table 2.7) - *Protecting Gondwanan wildfire refugia in Tasmania, Australia* (Chapter 2.6.5.8)	Fire regulation **&** Biodiversity conservation		***		
Natural flood risk management (Table 2.7) - *Natural Flood Management (NFM) in England, United Kingdom* (Chapter 2.6.5.2)	Water security, flood regulation, sediment retention **&** Biodiversity and ecosystem conservation		***	**	
Coastal ecosystem conservation (Table Cross-Chapter Box NATURAL.1 in Chapter 2) (Table 16.2)(Table 2.7) - *African penguin on-site adaptation* (Chapter 2.6.5.5)	Coastal protection against sea level rise and storm surges **&** Fisheries, carbon sequestration, biodiversity and ecosystem conservation, flood regulation, water purification, recreation, and cultural benefits **X** NH_4 emissions, digging channels and sand walls around homes, loss of recreational value of beaches, shifted the flood impacts to poor informal urban settlers, erosion and degraded coastal lands		**	***	**
Eco-tourism within protected areas (Table 2.7)	Tourism **&** Habitat protection	***		**	
Aquaculture (Chapter 5.9.4; Table 16.2; Table Cross-Chapter Box NATURAL.1 in Chapter 2)	Food provision **&** Biodiversity conservation + Farmer incentives, participatory adaptation to context **X** Lack of financial, technical or institutional capacity; short value chains; productivity varies by system; over-fertilizing; deforestation of mangroves; salt intrusion; increased flood vulnerability	***		*	
Water-energy-food (WEF) nexus (Box 4.7) - *Food Water Energy Nexus in Asia* (Chapter 10.6.3) - *New Zealand's Land, Water and People Nexus under a changing climate* (Box 11.7)	Water, energy, and food provision **X** Insufficient data, information, and knowledge in understanding the WEF inter-linkages; lack of systematic tools to address trade-offs involved in the nexus	***			
Urban greening (Table 2.7; table 16.2; Table Cross-Chapter Box NATURAL.1 in Chapter 2) - *Ecosystem based adaptation in Durban, South Africa* (Chapter 2.6.5.7)	Urban flood management, water savings, urban heat island mitigation **&** Reduced carbon emissions, air and noise regulation, improved mental health, energy savings, recreation, and aesthetics + Meaningful partnerships, long-term financial commitments, and significant political and administrative **X** Storage of large quantities of water in the home; water contamination; increased breeding sites for mosquitoes and flies; vectors and diseases; intensified cultivation of marginal lands; clearing of virgin forests for farmland; frequent weeding; increased competition for water and nutrients; reduced soil fertility, invasive species		***		**

[END BOX 18.6 HERE]

18.3.1.4 Industrial systems

Industrial emissions have been growing faster since 2000 compared to emissions in any other sector, driven by increased extraction and production of basic materials (Crippa et al., 2019; IEA, 2019) (*very high confidence*). About one-third of the total emissions are contributed by the industry sector, if indirect emissions from energy use are considered (Crippa et al., 2019). The COVID-19 pandemic has caused a significant decrease in demand for fuels, oil, coal, gas, and nuclear energy (IEA, 2020). However, there is concern that the rebound in the crisis will reverse this trend (IEA, 2020). Accordingly, the literature suggests a combined set of measures is beneficial for facilitation a transition of industrial systems in support of CRD. This includes (i) dematerialization and decarbonization of industrial systems, (ii) establishment of supportive governance, policies, and regulations, and (iii) implementation of enabling corporate strategies.

Decarbonization and dematerialization strategies have been proposed as key drivers for the transition of industrial systems (Fischedick et al., 2014; Worrell et al., 2016). The former involves limiting carbon emissions from industrial processes (IEA, 2017; Hildingsson et al., 2019), while the latter involves improving material efficiency, developing circular economies, raw material demand management, environmentally friendly product and process innovations, and environmentally friendly supply chain management (Worrell et al., 2016; Petrides et al., 2018).

Recent modelling suggests that stocks of manufactured capital, including buildings, infrastructure, machinery, and equipment, stabilize as countries develop and decouple from GDP (*high agreement, medium evidence)*. For instance, Bleischwitz et al. (2018) confirmed the occurrence of a saturation effect for materials in four energy-intensive sectors (steel, cement, aluminum and copper) in five industrialized countries (Germany, Japan, the United Kingdom, the United States and China). High growth in the supply of materials may still drive global demand for new products in the coming years for developing countries that are still far from saturation levels. Therefore, accelerating industrial transitions to drive the decoupling of industrial emissions from economic growth and facilitate broader transformation in industrial systems can be one component of CRD.

Continued transitions in the industrial sector will be contingent on technological innovation. Although technologies exist to drive emissions in industrial sectors to very low or zero emissions, but they require 5 to 15 years of innovation, commercialization, and intensive policies to ensure uptake (Åhman et al., 2017) (*high agreement, medium evidence*). For instance, several options exist to reduce GHG emission related to steel production process including increasing the share of the secondary route (Pauliuk et al., 2013), hydrogen-based direct reduced iron (Vogl et al., 2018), aqueous electrolysis rout (Cavaliere, 2019), and plasma process (Quader et al., 2016).

Industrial transitions are also contingent upon consumer behavior in terms of preferences for, and rates of, consumption of industrial products. Sustainable consumption can play an important role in sustainable production (Allwood et al., 2013; Allwood et al., 2019). This suggests feedbacks between industrial production and consumption in driving industrial transitions. For example, sustainable consumption can be triggered and/or enabled through sustainable production processes that provide more sustainable options to consumers as well as public or private promotional campaigns that promote those options. Meanwhile, demand from consumers for more sustainable options helps to drive the expansion of markets and innovation among industrial producers to meet that demand.

18.3.1.5 Societal systems

This chapter contributes a fifth system transition in addition to the four which have already been introduced by SR1.5: the societal systems transition. While society and people also feature in the other systems transitions, the purpose of defining a fifth transition is to explicitly highlight the challenges associated with changes in behavior, attitudes, values and consciousness required to achieve CRD. One caveat of considering transitions in societal systems is the limit to which the nature of change is known: transitions accomplish reconfigurations towards a relatively known destination. Historical and current differences between and within nations translate to a multitude of equally valid but diverse priorities for development, for example the understanding of development toward progress as linear has been challenged as being a Western concept by scholars of colonialization (Sultana et al., 2019). Thus societal transitions are understood as being intrinsically diverse for the purpose of achieving climate resilient development.

The four systems transitions identified in SR1.5 already include a component of societal change – for example, attitude change is part of public acceptance that facilitates shifts in energy including changing electricity to renewables (Ch 4 SR1.5 4.3.1.1) and developing nuclear power (4.3.1.3), and behavioral change is a part of shifting irrigation practices to drive required land and ecosystems transitions (4.3.2.1).

Extracting societal transitions also allows for a detailed examination of other societal dimensions that facilitate systems transitions, for example justice issues relating to water and energy access and distribution, and land use. Societal transition, sometimes known as 'societal transformation', is an established concept in different literatures, as described below. Transformation and transition are terms often used as synonyms (Hölscher et al., 2018) although different schools of thought understand them as sub-components of each other, eg. transition driving transformation, or transformation driving transition. For a more detailed discussion on the differences between transition and transformation represented in the literature, see Box 18.1.

Societal transitions for the purpose of this report are understood as the collection of shifts in attitudes, values, consciousness and behavior required to move toward CRD. This builds on the SR1.5 (IPCC, 2018a: 599) definition of societal (social) transformation: "A profound and often deliberate shift initiated by communities toward sustainability, facilitated by changes in individual and collective values and behaviors, and a fairer balance of political, cultural, and institutional power in society." This includes accepting IK/LK as an equally valid form of knowledge as compared with Western, scientific knowledge (see Cross-Chapter Box INDIG) and recognition of the role of shifting gender norms to achieve climate resilience (see Cross-Chapter Box GENDER). Changes associated with societal transitions are not specific to defined systems (e.g. energy, industry, land/ecosystems or urban/infrastructure). Rather, these sectoral systems are embedded within broader societal systems, including e.g. political systems, economic systems, knowledge systems, cultural systems (Davelaar, 2021; Turnhout et al., 2021; Visseren-Hamakers et al., 2021). Changes that happen in these broader social systems can therefore prompt changes in all systems embedded within them, meaning that societal transition is key to transforming across a range of sectors and topics (Leventon et al., 2021). Furthermore, societal transition requires changes in individual behaviors, but also in the broader conditions that shape these behaviors. These broader conditions are largely related to questions of power, in enforcing dominant political economies and social-technological mindsets (Stoddard et al., 2021). This section also briefly describes the various trains of research on societal transitions and transformation.

Because of the multiple sectors, interests and scales that are involved in societal transitions, understanding and creating evidence on transitions requires shifting across system boundaries and finding ways to transcend disciplinary silos. Relevant research includes work within the topic of transformation and transitions (Hölscher et al., 2018). Transformations literature can be split into multiple sub-concepts and requires engagement with multiple schools of thought (Feola, 2015; Feola et al., 2021). Much focus within transformations research is currently related to biodiversity conservation (Massarella et al., 2021), and transitions work tends towards a focus in urban areas (Loorbach et al., 2017). Though there is also work in both that is more broadly labelled as sustainability transformations or transitions (Luederitz et al., 2017). Furthermore, there is likely to be much relevant literature that does not explicitly label itself as transformations or transitions (Feola et al., 2021). For example, we could look to political science theories on policy change (Leventon et al., 2021) and historical perspectives on social change. Bridging these divides will require a deeper rethinking in the research community to undo power structures that marginalize diverse knowledges (Caniglia et al., 2021; Lahsen and Turnhout, 2021).

There are a number of concepts proposed as pathways to creating societal transitions; usually centered around the idea of working with individuals and communities to change their mindsets as a way to change the way they manage their local environments or behave. Transformations work explores how values are pathways towards sustainability, for example by changing values, through making values explicit, through negotiation, and by eliciting values (Horcea-Milcu et al., 2019). Human nature connections is a further concept that is identified as a way to shift values and behaviors across a range of disciplines (Ives et al., 2017). The role of learning and indigenous knowledge is also explored (Lam et al., 2020). These three concepts have had particular salience in discussions around transformations for biodiversity conservation and restoration, related to the IPBES assessment on Values (Pascual et al., 2017; Peterson et al., 2018). They largely focus on the need to engage with people's values, connections and knowledge to better manage the social-ecological system they are in.

Focusing on bottom-up and community-led transformations, there is emphasis on the role of grassroots organizations in transformations. Community actions around specific locations or topics have parallels to the idea of transformative spaces. They are sites of innovative activity (Seyfang and Smith, 2007). Grassroots organizations can bridge the local and the political scales by politicizing actors and creating new interactions between individuals and political processes (Novák, 2021). They are a collective approach to pushing for both individual and societal change (Sage et al., 2021).

Despite a current lack of empirical evidence, there are numerous frameworks emerging for exploring societal transitions across levels. There is focus on pathways for sustainability transitions, which tends to look at projected, normative scenarios for the future, and explore or back-cast the institutional and societal changes that are required to get there (Westley et al., 2011; Sharpe et al., 2016). There is also work that looks at scaling up of smaller sustainability initiatives, through processes of scaling up, scaling out and scaling deep (Moore et al., 2015; Lam et al., 2020). In particular, systems thinking provides an organizing framework for bringing together multiple disciplines and perspectives, to understand problem framings, and normative and design aspects of social systems and behaviors (Foster-Fishman et al., 2007). Within this, Meadows (1999) framework of leverage points for systems transformation has been operationalized within the sustainability transformations debate (Abson et al., 2017). Here, system properties relating to system paradigms and design are leverage points where interventions can create greatest system change; shallower leverage points relate to materials and processes. This framework is increasingly being used across a range of sustainability problems as boundary objects for cross-disciplinary, critical research (Fischer and Riechers, 2019; Leventon et al., 2021; Riechers et al., 2021).

Analyses of societal transitions have had limited engagement with adaptation questions. The focus of the sub-field of sustainability transitions on a few industrialized nations, mostly in North America and Europe, limited the field's development to assumptions born from the experiences in those areas. More recent studies have sought to understand sustainability transitions in other countries, especially emerging economies (Wieczorek, 2018; Köhler et al., 2019). In particular, China has received attention from scholars on sustainability transitions (Huang et al., 2018; Lo and Castán Broto, 2019; Castán Broto et al., 2020; Huang and Sun, 2020). As a result, some pressing issues related to societal transitions for adaptation have received limited attention compared with that paid to other system transitions. However, more recently, scholarship has begun examining transitions that have turned to nature and nature-based solutions. Adaptive transitions are an intermediary step towards sustainability transitions whereby multiple actions at material and institutional levels are combined towards improving adaptation outcomes (Pant et al., 2015; Scarano, 2017).

Table 18.3: Specific options for facilitating the five system transitions that can support CRD

Transition	Examples	Reference
Energy Systems	• Fuel switching from coal to natural gas • Expansion of renewable energy technologies • Financial incentives to promote renewable energy • Reduced energy intensity of industry • Improvements in power system resilience and reliability • Increased water use efficiency in electricity generation • Energy demand management strategies	(Gielen et al., 2019) (Mulugetta et al., 2019) (IEA et al., 2019) AR6 WGIII Chapter 2
Urban and infrastructure systems	• Increased investment in physical and social infrastructure • Enhance urban and regional planning • Enhanced governance and institutional capacity supports post-disaster recovery and reconstruction (Kull, 2016)	(IPCC, 2018b): D3.1)
Land, Oceans, and Ecosystems	• Expanding access to agricultural and climate services • Strengthening land tenure security and access to land • Empowering women farmers • Improved access to markets • Facilitating payments for ecosystem services	(IPCC, 2019f): C2.1) (IPCC, 2019f): C4.5) (IPCC, 2019f): C4)

	• Promotion of healthy and sustainable diets • Enhancing multi-level governance by supporting local management of natural resources • Strengthening cooperation between institutions and actors • Building on local, indigenous and scientific knowledge funding, and institutional support • Monitoring and forecasting • Education and climate literacy and social learning and participation	
Industrial systems	• Promote material efficiency and high-quality circularity • Materials demand management (IEA 2019, 2020) • Application of new processes and technologies for GHG emission reduction • Carbon pricing or regulations with provisions on competitiveness to drive innovation and systemic carbon efficiency • Low-cost, long-term financing mechanisms to enable investment and reduce risk • Better planning of transport infrastructure • Labour market training and transition support • Electricity market reform • Regulations – standards and labelling, material efficiency • Mandating technologies and targets • Green taxes and carbon pricing, preferential loans and subsidies • voluntary action agreements, expanded producer responsibilities • information programs: monitoring, evaluation, partnerships, and research and development • government provisioning of services—government procurements, technology push and market-pull	(Åhman et al., 2017; Bataille et al., 2018; Material, 2019) (Tanaka, 2011; Schwarz et al., 2020) (Ciwmb, 2003) (Romero Mosquera, 2019) (Tanaka, 2011) (Ryan et al., 2011; Boyce, 2018) (Taylor, 2008) (UNEP, 2018b) (Kaza et al., 2018) (Söderholm and Tilton, 2012) (Bataille et al., 2018) (Ghisetti et al., 2017) (Taylor, 2008; Fischedick et al., 2014; Hansen and Lema, 2019) (Crippa et al., 2019; IEA, 2019) (Cavaliere, 2019; IEA, 2020)(Vogl et al., 2018)(Pauliuk et al., 2013; Quader et al., 2016)
Societal Systems	• Inclusive governance • Empowerment of excluded stakeholders, especially women and youth • transforming economies • finance and technology aligned with local needs • overcoming uneven consumption and production patterns • allowing people to live a life in dignity and enhancing their capabilities • involving local governments, enterprises and civil society organisations across different scales	(Fazey et al., 2018b; O'Brien, 2018; Patterson et al., 2018) (MRFCJ, 2015; Dumont et al., 2019) (Popescu et al., 2017; David Tàbara et al., 2018) (de Coninck and Sagar, 2015; IEA, 2015; Parikh et al., 2018) (Dearing et al., 2014; Häyhä et al., 2016; Raworth, 2017) (Klinsky and Winkler, 2018), (Hajer et al., 2015; Labriet et al., 2015; Hale, 2016; Pelling et al., 2016; Kalafatis, 2017; Lyon, 2018) (Holden et al., 2017) (Cundill et al., 2014; Butler et al., 2016; Ensor, 2016; Fazey et al., 2016;

	• reconceptualising development around well-being rather than economic growth (Gupta and Pouw, 2017), • rethinking, prevailing values, ethics and behaviour • improving decision-making processes that incorporate diverse values and world views • creating space for negotiating diverse interests and preferences	Gorddard et al., 2016; Aipira et al., 2017; Chung Tiam Fook, 2017; Maor et al., 2017) (O'Brien and Selboe, 2015; Gillard et al., 2016; DeCaro et al., 2017; Harris et al., 2018; Lahn, 2018; Roy et al., 2018) Sections 5.6.1 and 5.5.3.1

[START CROSS-CHAPTER BOX GENDER HERE]

Cross-Chapter Box GENDER: Gender, Climate Justice and Transformative Pathways

Authors: Anjal Prakash (India), Cecilia Conde (Mexico), Ayansina Ayanlade (Nigeria), Rachel Bezner Kerr (Canada/USA), Emily Boyd (Sweden), Martina A Caretta (Sweden), Susan Clayton (USA), Marta G. Rivera Ferre (Spain), Laura Ramajo Gallardo (Chile), Sharina Abdul Halim (Malaysia), Nina Lansbury (Australia), Oksana Lipka (Russia), Ruth Morgan (Australia), Joyashree Roy (India), Diana Reckien (Netherlands/Germany), E. Lisa F. Schipper (Sweden/UK), Chandni Singh (India), Maria Cristina Tirado von der Pahlen (Spain/USA), Edmond Totin (Benin), Kripa Vasant (India), Morgan Wairiu (Solomon Islands), Zelina Zaiton Ibrahim (Malaysia).

Contributing Authors: Seema Arora-Jonsson (Sweden/India), Emily Baker (USA), Graeme Dean (Ireland), Emily Hillenbrand (USA), Alison Irvine (Canada), Farjana Islam (Bangladesh/ United Kingdom), Katriona McGlade (United Kingdom/Germany), Hanson Nyantakyi-Frimpong (Ghana), Nitya Rao (United Kingdom /India), Federica Ravera (Italy), Emilia Reyes (Mexico), Diana Hinge Salili (Fiji), Corinne Schuster-Wallace (Canada), Alcade C. Segnon (Benin), Divya Solomon (India), Shreya Some (India), Indrakshi Tandon (India), Sumit Vij (India), Katharine Vincent (United Kingdom/South Africa), Margreet Zwarteveen (The Netherlands)

Key Messages

- Gender and other social inequities (e.g., racial, ethnic, age, income, geographic location) compound vulnerability to climate change impacts (*high confidence*). Climate justice initiatives explicitly address these multi-dimensional inequalities as part of a climate change adaptation strategy. [Box 9.2: Vulnerability Synthesis: Differential Vulnerability by Gender and Age in Ch 9]

- Addressing inequities in access to resources, assets, and services as well as participation in decision-making and leadership is essential to achieving gender and climate justice (*high confidence*).

- Intentional long-term policy and program measures and investments to support shifts in social rules, norms, and behaviours are essential to address structural inequalities and support an enabling environment for marginalised groups to effectively adapt to climate change (*very high confidence*). [Equity and Justice box in Ch 17]

- Climate adaptation actions are grounded in local realities so understanding links with SDG 5 is important to ensure that adaptive actions do not worsen existing gender and other inequities within society (e.g., leading to maladaptation practices) *(high confidence).* [17.5.1]

- Adaptation actions do not automatically have positive outcomes for gender equality. Understanding the positive and negative links of adaptation actions with gender equality goals, (i.e., SDG 5), is important to ensure that adaptive actions do not exacerbate existing gender-based and other social inequalities [16.1.4.4]. Efforts are needed to change unequal power dynamics and ´to foster inclusive decision-making for climate adaptation to have a positive impact for gender equality *(high confidence).*

- There are very few examples of successful integration of gender and other social inequities in climate policies to address climate change vulnerabilities and questions of social justice, (*Very high confidence*).

Gender, climate justice, and climate change

This Cross-Chapter Box highlights the intersecting issues of gender, climate change adaptation, climate justice, and transformative pathways. A gender perspective does not centre only on women or men but examines structures, processes, and relationships of power between and among groups of men and women and how gender, particularly in its non-binary form, intersects with other social categories such as race, class, socio-economic status, nationality, or education to create multidimensional inequalities (Hopkins, 2019). A gender transformative approach aims to change structural inequalities. Attention to gender in climate change adaptation is thus central to questions of climate justice that aim for a radically different future (Bhavnani et al., 2019). As a normative concept highlighting the unequal distribution of climate change impacts and opportunities for adaptation and mitigation, climate justice (Wood, 2017; Jafry et al., 2018; Chu and Michael, 2019; Shi, 2020a) calls for transformative pathways for human and ecological wellbeing. These address the concentration of wealth, unsustainable extraction, and distribution of resources (Schipper et al., 2020a; Vander Stichele, 2020) as well as the importance of equitable participation in environmental decision-making for climate justice (Arora-Jonsson, 2019).

Research on gender and climate change demonstrates that an understanding of gendered relations is central to addressing the issue of climate change. This is because gender relations mediate experiences with climate change, whether in relation to water (Köhler et al., 2019) (see also Sections 4.7, 4.3.3; 4.6.4, 5.3), forests (Arora-Jonsson, 2019), agriculture (Carr and Thompson, 2014; Balehey et al., 2018; Garcia et al., 2020) (see also Chapter 4, Section 5.4), marine systems (Mcleod et al., 2018; Garcia et al., 2020) (see also Section 5.9) or urban environments (Reckien et al., 2018; Susan Solomon et al., 2021) (see also Chapter 6). Climate change has direct negative impacts on women's livelihoods due to their unequal control over and access to resources (e.g., land, credit) and because they are often the ones with the least formal protection (Eastin, 2018) (see also Box 9.2 in Ch 9). Women represent 43% of the agricultural labour force globally, but only 15% of agricultural landholders (OECD, 2019b). Gendered and other social inequities also exist with non-land assets and financial services (OECD, 2019b) often due to social norms, local institutions, and inadequate social protection (Collins et al., 2019b). Men may experience different adverse impacts due to gender roles and expectations (Bryant and Garnham, 2015; Gonda, 2017). These impacts can lead to irreversible losses and damages from climate change across vulnerability hotspots (Section 8.3).

Participation in environmental decision-making tends to favour certain social groups of men, whether in local environmental committees, international climate negotiations (Gay-Antaki and Liverman, 2018) or the IPCC (Nhamo and Nhamo, 2018). Addressing climate justice reinforces the importance of considering the legacy of colonialism on developing regional and local adaptation strategies. Scholars have criticized climate programs for setting aside forestland that poor people rely on and appropriating the labor of women in the global South without compensatory social policy or rights; where women are expected to work with Non Timber Forest Products to compensate for the lack of logging and for global climate goals but where their work of social reproduction and care is paid little attention (Westholm and Arora-Jonsson, 2015; Arora-Jonsson et al., 2016). A global ecologically unequal exchange, biopiracy, damage from toxic exports, or the disproportionate use of carbon sinks and reservoirs by high-income countries enhance the negative impacts of climate change, women in LDC's and SIDS also endure the harshest impacts of the debt crisis due to imposed debt measures in their countries (Appiah and Gbeddy, 2018; Fresnillo Sallan, 2020). The austerity measures derived as conditionalities for fiscal consolidation in public services increases gender-based violence (Castañeda Carney et al., 2020) and brings additional burdens for women in the form of increasing unpaid care and domestic work (Bohoslavsky, 2019).

Gendered vulnerability

Land, ecosystem, and urban transitions to climate-resilient development need to address gender and other social inequities to meet sustainability and equity goals, otherwise, marginalised groups may continue to be excluded from climate change adaptation. In the water sector, increasing floods and droughts and diminishing groundwater and runoff have gendered effects on both production systems and domestic use (Sections 4.3.1, 4.3.3, 4.5.3). Climate change is reducing the quantity and quality of safe water available in many regions of the world and increasing domestic water management responsibilities (*high confidence*). In regions with poor drinking water infrastructure, it is forcing, primarily women and girls, to walk long distances to access water, and limiting time available for other activities, including education and income generation (Eakin et al., 2014; Kookana et al., 2016; Yadav and Lal, 2018). Water insecurity and the lack of water, sanitation, and hygiene (WASH) infrastructure have resulted in psychosocial distress, gender-based violence, as well as poor maternal and child health and nutrition (Collins et al., 2019a; Wilson et al., 2019; Geere and Hunter, 2020; Islam et al., 2020; Mainali et al., 2020) (Sections 4.3.3 and 4.6.4.4) (*high confidence*). Climate-related extreme events also affect women's health – by increasing the risk of maternal and infant mortality, disrupting access to family planning and prevention of mother to child transmission regimens for HIV positive pregnant women (Undrr, 2019) (see also Section 7.2). Women and the elderly are also disproportionately affected by heat events (Section 7.1.7.2.1, 7.1.7.2.3, 13.7.1).

Extreme events impact food prices and reduce food availability and quality, especially affecting vulnerable groups, including low-income urban consumers, wage labourers, and low-income rural households who are net food buyers (Green et al., 2013; Fao, 2016) (Section 5.12). Low-income women, ethnic minorities, and Indigenous communities are often more vulnerable to food insecurity and malnutrition from climate change impacts, as poverty, discrimination, and marginalisation intersect in their cases (Vinyeta et al., 2016; Clay et al., 2018) (Section 5.12). Increased domestic responsibilities of women and youth, due to migration of men, can increase their vulnerability due to their reduced capacity for investment in off-farm activities and reduced access to information (Sugden et al., 2014; O'Neil et al., 2017) (Section 4.3; 4.6) (*high confidence*).

In the forest sector, the increased frequency and severity of drought, fires, pests and diseases, and changes to growing seasons, has led to reduced harvest revenues, fluctuations in timber supply and availability of wood (Lamsal et al., 2017; Fadrique et al., 2018; Esquivel-Muelbert et al., 2019). Climate programs in the global South such as REDD+ have led to greater social insecurity and the conservation of the forests have led to more pressure on women to contribute to household incomes but without enough supporting market access mechanisms or social policy (Westholm and Arora-Jonsson, 2015; Arora-Jonsson et al., 2016). In countries in the global North, reduced harvestable wood and revenues have led to employment restructuring that has important gendered effects and negatively affects community transition opportunities (Reed et al., 2014).

Integrating gender in climate policy and practice

Climate change policies and programs across regions reveal wide variation in the degree and approach to addressing gender inequities (see Table SMCCB GENDER.2). In most regions where there are climate change policies that consider gender, they inadequately address structural inequalities t resulting from climate change impacts, or how gender and other social inequalities can compound risk (*high confidence*). Experiences show that it is more frequent to address specific gender inequality gaps in access to resources. Regionally, Central and South American countries (section 12.5.8) have a range of gender-sensitive or gender-specific policies such as the intersectoral coordination initiative Gender and Climate Change Action Plans (PAGcc), adopted in Perú, Cuba, Costa Rica, and Panamá (Casas Varez, 2017), or the Gender Environmental policy in Guatemala that has a focus on climate change (Bárcena-Martín et al., 2021). However, countries often have limited commitment and capacity to evaluate the impact of such policies (Tramutola, 2019). In North and South America, policies have failed to address how climate change vulnerability is compounded by the intersection of race, ethnicity, and gender (Radcliffe, 2014; Vinyeta et al., 2016) (see also section 14.6.3). gender is rarely discussed in African national policies or programmes beyond the initial consultation stage (Holvoet and Inberg, 2014; Mersha and van Laerhoven, 2019), although there are gender and climate change action strategies in countries such as Liberia, Mozambique, Tanzania, and Zambia (Mozambique and IUCN, 2014; Zambia and IUCN, 2017). European climate change adaptation strategies and policies are weak on gender and other social equity issues (Allwood, 2014; Boeckmann and Zeeb, 2014; Allwood, 2020), while in Australasia, there is a lack of gender-responsive climate change policies. In Asia, there are several countries that recognize gendered vulnerability to climate change (Jafry, 2016; Singh et al., 2021b), but policies tend to be gender-specific, with a focus on targeting women, for example in the national action plan on climate change as in India (Roy et al., 2018) or in national climate change plan as in Malaysia (Susskind et al., 2020).

Potential for Change and Solutions

The sexual division of labour, systemic racism and other social structural inequities lead to increased vulnerabilities and climate change impacts for social groups such as women, youth, Indigenous peoples, ethnic minorities. Their marginal positions not only affect their lives negatively but their work in maintaining healthy environments is ignored and invisible in policy affecting their ability to work towards sustainable adaptation and aspirations in the SDGs (Arora-Jonsson, 2019). However, attention to the following has the potential to bring about change:

Creation of new, deliberative policy-making spaces that support inclusive decision-making processes and opportunities to (re)negotiate pervasive gender and other social inequalities in the context of climate change for transformation (Tschakert et al., 2016; Harris et al., 2018; Ziervogel, 2019; Garcia et al., 2020). (*high confidence*)

Increased access to reproductive health and family planning services, which contributes to climate change resilience and socio-economic development through improved health and well-being of women and their children, including increased access to education, gender equity, and economic status (Onarheim et al., 2016; Starbird et al., 2016; Lopez-Carr, 2017; Hardee et al., 2018) (Sections 7.4) (*high confidence*).

Engagement with women's collectives is important for sustainable environments and better climate decision-making whether at the global, national, or local levels (Westholm and Arora-Jonsson, 2018; Agarwal, 2020). The work of such collectives in maintaining their societies and environments and in resisting gendered and community violence is unacknowledged (Jenkins, 2017; Arora-Jonsson, 2019) but is indispensable especially when combined with good leadership, community acceptance, and long-term economic sustainability (Chu, 2018; Singh, 2019) (Section 4.6.4). Networking by gender experts in environmental organizations and bureaucracies has also been important for ensuring questions of social justice (Arora-Jonsson and Sijapati, 2018).

Investment in appropriate reliable water supplies, storage techniques, and climate-proofed WASH infrastructure as key adaptation strategies that reduce both burdens and impacts on women and girls (Alam et al., 2011; Woroniecki, 2019) (Sections 4.3.3 and 4.6.44).

Improved gender-sensitive early warning system design and vulnerability assessments to reduce vulnerabilities, prioritising effective adaptation pathways to women and marginalized groups (Mustafa et al., 2019; Tanner et al., 2019; Werners et al., 2021).

Established effective social protection, including both cash and food transfers, such as the universal public distribution system (PDS) for cereals in India, or pensions and social grants in Namibia, that have been demonstrated to contribute towards relieving immediate pressures on survival and support processes at the community level, including climate effects (Kattumuri et al., 2017; Lindoso et al., 2018; Rao et al., 2019a; Carr, 2020).

Strengthened adaptive capacity and resilience through integrated approaches to adaptation that include social protection measures, disaster risk management, and ecosystem-based climate change adaptation (*high confidence*), particularly when undertaken within a gender-transformative framework (Gumucio et al., 2018; Bezner Kerr et al., 2019; Deaconu et al., 2019) (Cross-Chapter Box NATURAL in Chapter 2, Section 5.12, Section 5.14).

For example, gender-transformative and nutrition-sensitive agroecological approaches strengthen adaptive capacities and enable more resilient food systems by increasing leadership for women and their participation in decision-making and a gender-equitable domestic work (*high confidence)* (Gumucio et al., 2018; Bezner Kerr et al., 2019; Deaconu et al., 2019) (Cross-Chapter Box NATURAL in Chapter 2, Section 5.12, Section 5.14)

New initiatives such as the Sahel Adaptive Social Protection Program represent an integrated approach to resilience that promotes coordination among social protection, disaster risk management, and climate change adaptation. Accompanying measures including, health, education, nutrition, family planning, among others (Daron et al., 2021).

Climate change adaptation and SDG 5

Adaptation actions may reinforce social inequities, including gender unless explicit efforts are made to change (Nagoda and Nightingale, 2017; Garcia et al., 2020) (*high evidence and high agreement*). Participation in climate action increases if is inclusive and fair (Huntjens and Zhang, 2016). Roy et al. (2018) assessed links among various SDGs and mitigation options. Adaptation actions are grounded in local realities especially in terms of their impacts so understanding links with the goals of SDG 5 becomes more important to make sure that adaptive actions do not worsen prevalent gender and other social inequities within society (*high evidence, high agreement)*. In the IPCC 1.5°C Special Report, Roy et al. (2018) assessed links between various SDGs and mitigation options, adaptation options were not considered. The current SDG 13 climate action targets do not specifically mention gender as a component for action, which makes it even more imperative to link SDG 5 targets and other gender-related targets to adaptive actions under SDG 13 to ensure that adaptation projects are synergistic rather than maladaptive (16.3.2.6, Table 16.6) (Susan Solomon et al., 2021).

This assessment is based on a systematic rapid review of scientific publications (McCartney et al., 2017; Liem et al., 2020) published on adaptation actions in 9 sectors from 2014 to 2020 (see Table SMCCB GENDER.1) and how they integrated gender perspectives impacting gender equity. The assessment is based on over 17,000 titles and abstracts that were initially found through keyword search and were reviewed. Finally, 319 relevant papers on case studies, regional assessments, and meta-reviews were assessed. Gender impact was classified by various targets under SDG 5. Following the approach taken in Roy et al. (2018) and (Hoegh-Guldberg et al., 2019), the linkages were classified into synergies (positive impacts or co-benefits) and trade-offs (negative impacts) based on the evidence obtained from the literature review which is finally used to develop net impact (positive or negative) scores (See Table Cross-Chapter Box GENDER.1 and Supplementary Material)

Table Cross-Chapter Box GENDER.1: Interrelations between SDG5 (gender equality) and adaptation initiatives in 9 major sectors

Sector	**Adaptation categories**			
	Ecosystem-based	***Technological /infrastructure /information***	***Institutional***	***Behavioural / cultural***
Terrestrial & freshwater ecosystem	□□		□□	
Ocean & coastal ecosystem	□□	□	□□□	
Mountain ecosystem	□	□□	□	□□
Food, fibre & others	□□		□□	□□
Urban water & sanitation	□	□□		□□
Poverty, livelihood & Sustainable Development			□	□□
Cities, settlement & key infrastructure	□□	□□	□□	□□□
Health, well-being, and changing communities' structure	□□□□	□□	□□□	□□
Industrial system transition			□□	□□□

Colour code	**Description**
	All net positive links
	All net negative links

Confidence levels	**Symbol**
Very High	□□□□□
High	□□□□

	Number of net positive links > number of net negative links
	Number of net negative links > number of net positive links
	no literature/options

Medium	□□□
Low	□□
Very low	□

Table Notes:
Potential net synergies and trade-offs between a sectoral portfolio of adaptation actions and SDG 5 are shown. Colour codes showing the relative strength of net positive and net negative impacts and confidence levels. The strength of net positive and net negative connections across all adaptation actions within a sector are aggregated to show sector-specific links. The links are only one-sided on how adaptation action is linked to gender equality (SDG5) targets and not vice versa. Adaptation options assessed in Ecosystem-based actions are: 22 in number, options in Technological /infrastructure /information are 10, in Institutional are 17 and in Behavioural/ cultural are 13. The assessment presented here is based on literature presenting impacts on gender equality and equity of various adaptation actions implemented in various local contexts and in regional climate change policies (Table SMCCB GENDER.2).

Adaptation actions being implemented in each sector in different local contexts can have positive (synergies) or negative (trade-offs) effects with SDG5. This can potentially lead to net positive or net negative connections at an aggregate level. How they are finally realized depends on how they are implemented, managed, and combined with various other interventions in particular, place-based circumstances. Ecosystem-based adaptation actions and terrestrial & freshwater ecosystems have higher potential for net positive connections (Roy et al., 2018) (Table Cross-Chapter Box GENDER.1 and Supplementary Material). Adaptation in terrestrial and freshwater ecosystems has the strongest net positive links with all SDG-5 targets (*medium evidence, low agreement*). For example, community-based natural resource management increases the participation of women, especially when they are organised into women's groups (Pineda-López et al., 2015; de la Torre-Castro et al., 2017) (Supplementary Material). For poverty, livelihood and sustainable development sector adaptation actions have generated more net negative scores (*low evidence, low agreement*) (Table Cross-Chapter Box GENDER.1). For example, patriarchal institutions and structural discriminations curtail access to services or economic resources as compared to men, including less control over income, fewer productive assets, lack of property rights, as well as less access to credit, irrigation, climate information, and seeds which devaluate women's farm-related adaptation options (Adzawla et al., 2019; Friedman et al., 2019; Ullah et al., 2019) (Supplementary Material).

Among the adaptation actions, ecosystem-based actions have the strongest net positive links with SDG-5 targets (Table Cross-Chapter Box GENDER.1, Table SMCCB GENDER.1). In the health, well-being and changing communities' sector, this is with *high evidence and medium agreement*, while in all other sectors there is *medium evidence and low agreement*. Net negative links are most prominent in institutional adaptation actions (Table Cross-Chapter Box GENDER.1). For example, in mountain ecosystems, changes in gender roles in response to climatic and socioeconomic stressors is not supported by institutional practices, mechanisms, and policies that remain patriarchal (Goodrich et al., 2019). Additionally, women often have less access to credit for climate change adaptation practices, including post-disaster relief, for example, to deal with salinization of water or flooding impacts (Hossain and Zaman 2018). Lack of coordination among different city authorities can also limit women's contribution in informal settlements towards adaptation. Women are typically underrepresented in decision-making on home construction and planning and home-design decisions in informal settlements, but examples from Bangladesh show they play a significant role in adopting climate-resilient measures (e.g., the use of corrugated metal roofs and partitions which is important in protection from heat) (Jabeen, 2014; Jabeen and Guy, 2015; Araos et al., 2017; Susan Solomon et al., 2021).

Towards climate-resilient, gender-responsive transformative pathways

The climate change adaptation and gender literature call for research and adaptation interventions that are 'gender-sensitive' (Jost et al., 2016; Thompson-Hall et al., 2016; Kristjanson et al., 2017; Pearce et al., 2018a) and "gender-responsive", as established in Article 7 of the Paris Agreement (UNFCCC, 2015). In addition, attention is drawn to the importance of 'mainstreaming' gender in climate/development policy (Alston, 2014; Rochette, 2016; Mcleod et al., 2018; Westholm and Arora-Jonsson, 2018). Many calls have been made to consider gender in policy and practice (Ford et al., 2015; Jost et al., 2016; Rochette, 2016; Thompson-Hall et al., 2016; Kristjanson et al., 2017; Mcleod et al., 2018; Lau et al., 2021; Singh et al., 2021b). Rather than merely emphasising the inclusion of women in patriarchal systems, transforming systems that perpetuate inequality can help to address broader structural inequalities not only in relation to gender but also other dimensions such as race and ethnicity (Djoudi et al., 2016; Pearse, 2017; Gay-Antaki, 2020). Adaptation researchers and practitioners play a critical role here and can enable gender-transformative processes by creating new, deliberative spaces that foster inclusive decision-making and opportunities for renegotiating inequitable power relations (Tschakert et al., 2016; Ziervogel, 2019; Garcia et al., 2020).

To date, empirical evidence on such transformational change is sparse, although there is some evidence of incremental change (e.g., increasing women's participation in specific adaptation projects, mainstreaming gender in national climate policies). Even when national policies attempt to be more gendered, there is criticism that they use gender-neutral language or include gender analysis without proposing how to alter differential vulnerability (Mersha and van Laerhoven, 2019; Singh et al., 2021b). More importantly, the mere inclusion of women and men in planning does not necessarily translate to substantial gender-transformative action, for example in National Adaptation Programmes of Action across sub-Saharan Africa (Holvoet and Inberg, 2014; Nyasimi et al., 2018) and national and sub-national climate action plans in India (Singh et al., 2021b). Importantly, there is often an overemphasis on the gender binary (and household headship as an entry point), which masks complex ways in which marginalisation and oppression can be augmented due to the interaction of gender with other social factors and intra-household dynamics (Djoudi et al., 2016; Thompson-Hall et al., 2016; Rao et al., 2019a; Lau et al., 2021; Singh et al., 2021b).

Climate justice and gender transformative adaptation can provide multiple beneficial impacts that align with sustainable development. Addressing poverty (SDG 1), energy poverty (SDG 7), WaSH (SDG 6), health (SDG 3), education (SDG 4) and hunger (SDG 2) —along with inequalities (SDG 5 and SDG 10) - improves resilience to climate impacts for those groups that are disproportionately affected (women, low-income and marginalised groups). Inclusive and fair decision-making can enhance resilience (SDG 16; Section 13.4.4), although adaptation measures may also lead to resource conflicts (SDG 16; Section 13.7). Nature-based solutions attentive to gender equity also support ecosystem health (SDGs 14 and 15) (Dzebo et al., 2019). Gender and climate justice will be achieved when the root causes of global and structural issues are addressed, challenging unethical and unacceptable use of power for the benefit of the powerful and elites (MacGregor, 2014; Wijsman and Feagan, 2019; Vander Stichele, 2020). Justice and equality need to be at the centre of climate adaptation decision-making processes. A transformative pathway needs to include the voice of the disenfranchised (MacGregor, 2020; Schipper et al., 2020a).

[END CROSS-CHAPTER BOX GENDER HERE]

18.3.2 Accelerating Transitions

Successfully implementing climate actions and managing trade-offs between mitigation, adaptation and sustainable development (18.2.4) has important time considerations that imply significant urgency, making substantive progress in system transitions critical for CRD. Both the SDGs and the Sendai Framework, for example, have target dates of 2030. Meanwhile, the Paris Agreement sets specific time horizons for NDCs and the SR1.5 indicated that limiting warming to 1.5°C would similarly require substantial climate action by 2030 (IPCC, 2018a). While the literature is unambiguous regarding the need for significant system transitions to achieve CRD (Section 18.1.3), the current pace of global emissions reductions, poverty alleviation, and development of equitable systems of governance is incommensurate with these policy time tables (Rogelj et al., 2010; Burke et al., 2016; Oleribe and Taylor-Robinson, 2016; Kriegler et al., 2018; Frank et al., 2019; Sadoff et al., 2020). As noted previously in the AR5, "*delaying action in the present may reduce options for climate-resilient pathways in the future*" (Denton et al., 2014: 1123). Accordingly, significant acceleration in the pace of system transitions is necessary to enable the implementation of mitigation, adaptation, and sustainable development initiatives consistent with CRD *(very high confidence*).

Studies since the AR5 directly address the issue of how to accelerate transitions within the broader system transitions, sustainability transitions, and socio-technical transitions literature (Frantzeskaki et al., 2017; Gliedt et al., 2018; Gorissen et al., 2018; Johnstone and Newell, 2018; Kuokkanen et al., 2019; Markard et al., 2020). Such literature explores several core themes to facilitate acceleration, which are aligned with the discussion later in this chapter on arenas of engagement for CRD (Section 18.4.3). One dominant theme is accelerating the implementation of sustainability or low-carbon policies that target specific sectors or industries (Bhamidipati et al., 2019). For example, Altenburg and Rodrik (Altenburg and Rodrik, 2017) discuss green industrial polices including taxes, mandated technology phase outs, and the removal of subsidies as means of constraining polluting industries. Kivimaa et al. (Kivimaa and Martiskainen, 2018; Kivimaa et al., 2019a; Kivimaa et al., 2019b; Kivimaa et al., 2020) and Vihemäki et al. (2020) discuss low-carbon transitions in buildings, noting the important role that intermediaries play in facilitating policy reform. Nikulina et al. (2019) identify mechanisms for facilitating policy change in personal mobility including political leadership, combining carrots and sticks to incentivize behavioral change, and challenging current policy frameworks. These various examples reflect a fragmented approach to system transitions, suggesting a large portfolio of such transition initiatives would be required to accelerate change or more fundamental and cross-cutting policy drivers are needed (*high agreement, limited evidence*). Policies that seek to promote social justice and equity, for example, could ultimately catalyze a broader range of sustainability and climate actions than policies designed to address a specific sector or class of technology (Delina and Sovacool, 2018; White, 2020).

In contrast with formal government policies, a second theme in accelerating transitions is that of civic engagement (see also 18.4.3), which is reported to be an important opportunity for driving transitions forward (*high agreement, medium evidence*). Ehnert et al. (2018) describe local organizations and civic engagement in policy processes as an important engine for sustainability activities in European states. Similarly, Ruggiero et al. (2021) note the potential to use civic organizations to appeal to local identities in order to mobilize citizens to pursue energy transition initiatives among communities in the Baltic Sea region. Gernert et al. (2018) attribute such influence to the ability of grassroots movements to bypass traditional social and political norms and thereby experiment with new behaviors and processes. Moreover, civic engagement is also the foundation for collective action including protest and civil disobedience (Welch and Yates, 2018, Section 18.5.3.7). However, Haukkala (2018) observes that while green-transition coalitions in Finland could be an agent of change driving energy transitions, the diversity of views among the various grassroots actors could make consensus building difficult, thereby slowing transition initiatives.

A third theme is that of innovation, generally, and sustainability-oriented innovation, specifically (de Vries et al., 2016; Geradts and Bocken, 2019; Loorbach et al., 2020), which creates opportunities for overcoming existing transition barriers *(very high confidence*). For example, Valta (2020) describes the role of innovation ecosystems – partnerships among companies, investors, governments, and academics – in accelerating innovation (see also World Economic Forum, 2019). Burch et al. (Burch et al., 2016) describe the role of small and medium-sized business entrepreneurship in promoting rapid innovation. Innovation extends beyond pure technology considerations to consider innovation in practices and social organization (Li et al., 2018; Psaltoglou and Calle, 2018; Repo and Matschoss, 2020). Zivkovic (2018), for example, discusses "innovation labs" as accelerators for addressing so-called wicked problems like climate change through multi-stakeholder groups. Meanwhile, Chaminade and Randelli (2020) describe a case study where structural preconditions and place-based agency were important drivers of transitions to organic viticulture in Tuscany, Italy.

The fourth theme is that of transition management (Goddard and Farrelly, 2018), particularly vis a vis, disruptive technologies (Iñigo and Albareda, 2016; Kuokkanen et al., 2019) or broader societal disruptions (Brundiers, 2020; Davidsson, 2020; Hepburn et al., 2020; Schipper et al., 2020b). Recent literature has given attention to how actors can use disruptive events, such as disasters, as a window-of-opportunity for accelerating changes in policies, practices, and behaviors (*high agreement, medium evidence*) (Brundiers, 2018; Brundiers and Eakin, 2018). This is consistent with concepts in resilience thinking around 'building back better' after disasters (Fernandez and Ahmed, 2019). For example, Hepburn et al. discuss fiscal recovery packages for COVID-19 as a means of accelerating climate action, with a particular influence on clean physical infrastructure, building efficiency retrofits, investment in education and training, natural capital investment, and clean research and development (Andrijevic et al., 2020b).

18.4 Agency and Empowerment for Climate Resilient Development

As reflected in the discussion of societal transitions (18.3), people and their values and choices play an instrumental role in CRD. The agency of people to act on CRD is grounded in their worldviews, beliefs, values, and consciousness (Woiwode, 2020) and is shaped through social and political processes including how policies and decision-making recognize the voices, knowledges and rights of particular actors over others *(very high confidence)* (Harris and Clarke, 2017; Nightingale, 2017; Bond and Barth, 2020; Muok et al., 2021). Since the AR5, evidence on diverse forms of engagement by and among social, political and economic actors to support climate resilient development and sustainability outcomes, has increased. New forms of decision-making and engagement are emerging within the formal policy making and planning sphere, including co-production of knowledge, interventions grounded in the arts and humanities, civil participation and partnerships with business (Ziervogel et al., 2016a; Roberts et al., 2020). In addition, the set of actors that drive climate and development actions are recognized to extend beyond government and formal policy actors to include civil society, education, industry, media, science and art (Ojwang et al., 2017; Solecki et al., 2018; Heinrichs, 2020; Omukuti, 2020). This makes the power dynamics among actors and institutions critical for understanding the role of actors in CRD (Buggy and McNamara, 2016; Camargo and Ojeda, 2017; Silva Rodríguez de San Miguel, 2018).

The formal space for national, sub-national and international adaptation governance emerged at COP 16 (UNFCCC, 2010) when adaptation was recognized as a similar level of priority as greenhouse gas mitigation. The Paris Agreement (UNFCCC, 2015) built on this and the 2030 Sustainable Development Agenda (United Nations, 2015) to link adaptation to development and climate justice. It also highlighted the importance of multi-level adaptation governance, including new non-state voices and climate actors that widen the scope of adaptation governance beyond formal government institutions. For example, individuals can act as agents of changes in their own behavior, such as via change in their consumption patterns, but also generate change within organizations, fields of practice, and the political landscape of governance. Accordingly, these interactions among actors across different scales implies the need for wider modes of, and arena for, engagement around adaptation in order to accommodate a diversity of perspectives (*high agreement, medium evidence*) (Chung Tiam Fook, 2017; Lesnikowski et al., 2017; IPCC, 2018a).

In most regions, such new institutional and informal arrangements are at an early stage of development (*high agreement, limited evidence*). Further clarification and strengthening are needed to enable the fair sharing of resources, responsibilities, and authorities to enable climate action to enable climate-resilient development (Wood et al., 2017; IPCC, 2018a; Reckien et al., 2018). These are strongly linked to contested and complementary worldviews of climate change and the actors that use these worldviews to justify, direct, accelerate and deepen transformational adaptation and climate action.

18.4.1 Political Economy of Climate Resilient Development

Political economy studies (i.e., the origins, nature and distribution of wealth, and the ideologies, interests, and institutions that shape it) explicitly addressing CRD are quite limited. Yet, there is an extensive post-AR5 literature on political economy associated with various elements relevant to CRD including climate change and development (Naess et al., 2015); vulnerability, adaptation, and climate risk (Sovacool et al., 2015; Sovacool et al., 2017; Barnett, 2020); energy, decarbonization, and negative emissions technologies (Kuzemko et al., 2019; Newell, 2019); degrowth and low-carbon economies (Perkins, 2019; Newell and Lane, 2020); solar radiation management (Ott, 2018); planetary health and sustainability transitions and transformation (Kohler et al., 2019) (Gill and Benatar, 2020).

Four key insights regarding the nexus of political economy and CRD emerge from this literature. First, political economy drives coupled development-climate change trajectories and determines vulnerability, thereby potentially subjecting those least responsible for climate change to the greatest risk (Sovacool et al., 2015; Barnett, 2020). The prevailing political economy is itself now at risk as its legitimacy, viability and sustainability are called into question (Barnett, 2020). Yet, as underpinning ideologies, interests and institutions change, the drivers of vulnerability are often appropriated, the adaptation agenda is depoliticized, and market-based solutions advocated (Barnett, 2020).

Second, assessment of this literature suggests four attributes of the political economy of adaptation influence development trajectories in diverse settings, from Australia to Honduras and the Maldives (Sovacool et al., 2015), as delivered through the Global Environment Facility's Least Developed Countries Fund (Sovacool et al., 2017). These include enclosure (public resources or authority captured by private interests); exclusion (stakeholders are marginalized from decision-making); encroachment (natural systems and ecosystem services compromised); and entrenchment (inequality exacerbated). These attributes hamper adaptation efforts, and reveal the political nature of adaptation (Dolšak and Prakash, 2018) and by extension CRD. Paradoxically, development initiatives labelled as 'risk' reduction or resilience building or 'equitable and environmentally sustainable', such as coastal restoration efforts in Louisiana, USA, can compound inequity and climate risk, and perpetuate unsustainable development (Gotham, 2016; Eriksen et al., 2021b).

Third, a long-held view is that the effects of mitigation are global while those of adaptation are local. A political economy perspective, however, underscores cross-scale linkages, and shows that local adaptation efforts, vulnerability and climate resilience are manifest in development trajectories that are shaped by both local and trans-local drivers, and defined by unequal power relations that cross scales and levels (Sovacool et al., 2015; Barnett, 2020; Newell, 2020), including in key sectors like energy (Baker et al., 2014) and agriculture (Houser et al., 2019), as well as emergent blocs like BRICS (Power et al., 2016; Schmitz, 2017); and sub-national constellations, like cities (Fragkias and Boone, 2016; Béné et al., 2018).

Fourth, transitions towards CRD may be technically and economically feasible but are 'saturated' with power and politics (Tanner and Allouche, 2011) (18.3), necessitating focused attention to political barriers and enablers of CRD (Newell, 2019). With a narrow window of time to contain dangerous levels of global warming, political economy research calls for CRD trajectories that counter the globalized neoliberal hegemony (Newell and Lane, 2020), especially given the pandemic, and the intersection of economic power and public health, environmental quality, climate change, and human and indigenous rights (Bernauer and Slowey, 2020; Schipper et al., 2020b).

Given these insights, CRD can be understood as the sum of complex multi-dimensional processes consisting of large numbers of actions and social choices made by multiple actors from government, the private sector, and civil society, with important influences by science and the media *(very high confidence*). These actions and social choices are determined by the available solution space and options, along with a range of enabling conditions (Section 18.4.2) that are largely bounded by individual and collective worldviews, and related ethics and values. This view is consistent with sustainable development being a *process constituted by multiple actions that are contested and have path dependencies and context-sensitive synergies and trade-offs with natural and embedded human systems* as well as bounded by multiple and contested knowledges and worldviews (Goldman et al., 2018; Heinrichs, 2020; Nightingale et al., 2020; Schipper et al., 2020b).

18.4.2 Enabling Conditions for Near-Term System Transitions

Given actors, institutions, and their engagement is fundamental to supporting system transitions needed for CRD (18.3) this section assesses recent literature with respect to how the values, choices and behaviors of those actors enable or constrain specific enabling conditions. Such enabling conditions represent opportunities for policymakers to pursue actions that contribute to CRD beyond direct risk management options such as climate adaptation and greenhouse gas mitigation (18.2.5.1, 18.2.5.2).

18.4.2.1 Governance and Policy

An overarching enabling conditions for achieving system transitions and transformations is the presence of enabling governance systems *(very high confidence).* Recent literature on the translation of governance into system transitions in practice suggests four key actions are important. The first is the critical reflection on so-called 'development solutions,' alternatively framed by some as 'empty promises,' that worsen climate risk, inequity, injustice and ultimately lead to unsustainable development (Mikulewicz, 2018; Mikulewicz and Taylor, 2020). Examples include development aid (Scoville-Simonds et al., 2020), large-scale development projects such as biofuel production in Ethiopia (Tufa et al., 2018), and urban growth management in Vietnam (DiGregorio, 2015). The second is the recognition that while the power of different actors and institutions is often tied to access to resources and the ability to constrain the actions of others, other dimensions of power such as its ability to produce knowledge as well as its contingency on circumstances and relationships are also important in enabling energy transitions: (Avelino et al., 2016; Avelino and Wittmayer, 2016; Lockwood et al., 2016; Ahlborg, 2017; Avelino and Grin, 2017; Partzsch, 2017; Smith and Stirling, 2018). Third, governance systems can help to develop productive interactions between formal government institutions, the private sector, and civil society including the provision 'safe arenas' for social actors to deliberate and pursue transitional and transformational change (Haukkala, 2018; Törnberg, 2018;

Strazds; Ferragina et al., 2020; Koch, 2020) (18.3.1, Box 18.1). Fourth, governance can address challenges such as climate change from a systems perspective and pursue interventions that address the interactions among development, climate change, equity and justice, and planetary health (Harvey et al., 2019; Hölscher et al., 2019). This is evidenced by recent experience with the COVID-19 pandemic response as well as ongoing escalation of disaster risk associated with extreme weather events (Walch, 2019; Cohen, 2020; Schipper et al., 2020b; Wells et al., 2020).

One output from systems of governance is formal policy frameworks and policies that influence processes and outcomes of system transitions that support CRD (18.1.3). The Paris Agreement, for example, provides a framework for CRD by defining a mitigation-centric goal of 'limiting warming to well below 2°C and enabling a transition to 1.5°C' (UNFCCC, 2015). It also provides for a broadly defined global adaptation goal (UNFCCC, 2015: Art. 7.1). The Nationally Determined Contributions (NDCs) are the core mechanism for achieving and enhancing climate ambitions under the Paris Agreement. However, the pursuit of a given NDC within a specific country will likely necessitate a range of other policy interventions that have more immediate impact on technologies and behavior, implicating transitions in energy, industry, land, and infrastructure *(very high confidence* (18.3.1). SDG-relevant activities are increasingly incorporated into climate commitments in the NDCs (at last count 94 NDCs also addressed SDGs), contributing to several (154 out of the 169) SDG targets (Brandi and Dzebo; Pauw et al., 2018). This reflects the potential of the NDCs as near-term policy instruments and sign-posts for progress toward CRD (*medium agreement, limited evidence*) (McCollum et al., 2018b).

As reflected by the SDGs (and SDG 13 specifically), the mainstreaming of climate change concerns into development policies is one mechanism for pursuing sustainable development and CRD *(very high confidence*). However, such mainstreaming has also been critiqued for perpetuating 'development as usual', reinforcing established development logics, structures and worldviews that are themselves contributing to climate change and vulnerability (O'Brien et al., 2015) and for obscuring and depoliticizing adaptation choices into technocratic choices (Murtinho, 2016; Webber and Donner, 2017; Benjaminsen and Kaarhus, 2018; Khatri, 2018; Scoville-Simonds et al., 2020). The coordinated implementation of sustainable development policy and climate action is nonetheless crucial for ensuring that the attainment of one does not come at the expense of others (Stafford-Smith et al., 2017). For example, aggressive pursuit of climate policies that facilitate transitions in energy systems can undermine efforts to secure sustainability transitions in other systems (18.3.1.1, 18.2.5.3, Table 18.7).

Several non-climate international policy agreements provide context for CRD such as the 1948 UN Universal Declaration of Human Rights, the UN Declaration on the Rights of Indigenous Peoples (Hjerpe et al., 2015); the Convention on Biological Diversity (CBD; UNFCCC, 1992) as well as the more recent Sendai Framework for Disaster Risk Reduction (UNDRR, 2015) and the 'new humanitarianisms' which seeks to reduce the gap between emergency assistance and longer term development (Marin and Naess, 2017). Collectively they provide a global policy framework that protects people's rights that are potentially threatened by climate change (Olsson et al., 2014). These policies are relevant to transitions across multiple systems, particular in societal systems toward more equitable and just development.

18.4.2.2 Economics and Sustainable Finance

18.4.2.2.1 Economics

System transitions toward CRD is contingent on reducing the costs of current climate variability on society while making investments that prepare for the future effects of climate change. Climate change and responses to climate change will affect many different economic sectors both directly and indirectly (Stern, 2007; IPCC, 2014a; Hilmi et al., 2017). As a consequence, the characteristics of economic systems will play an important role in determining their resilience *(very high confidence*). These effects will occur within the context of other developments, such as a growing world population, which increases environmental pressures and pollution (González-Hidalgo and Zografos, 2019; González-Hidalgo and Zografos, 2020). This impact is higher for developing countries than for high-income countries (Liobikienė and Butkus, 2018). While looking for sustainable climate-resilient policies, many complex and interconnected systems, including economic development, must be considered in the face of global-scale changes (Hilmi and Safa, 2010).

Miller (2017) discusses some of the planning for, and application of, adaptation measures that improve sustainability noting the importance of considering a range of factors including complexities of interconnected systems, the inherent uncertainties associated with projections of climate change impacts, and the effects of global-scale changes such as technological and economic development for decision makers. For example, addressing climate impacts in isolation is unlikely to achieve equitable, efficient, or effective adaptation outcomes *(very high confidence*). Instead, integrating climate resilience into growth and development planning allows decision makers to identify what sustainable development policies can support climate resilient growth and poverty reduction and understand better how patterns and trends of economic development affect vulnerability and exposure to climate impacts across sectors and populations, including distributional effects (Doczi, 2015). Markkanen and Anger-Kraavi (2019) highlighted that climate change mitigation policy can influence inequality both positively and negatively. Although higher levels of poverty, corruption and economic and social inequalities can increase the risk of negative outcomes, these potential negative effects would be mitigated if inequality impacts were taken into consideration in all stages of policy making *(very high confidence*).

The primary objective of economic and financial incentives around carbon emissions is to redirect investment from high to low carbon technologies (Komendantova et al., 2016). Recent years have seen policy interventions to incentivize transitions in energy, land, and industrial systems to address climate change and sustainability focus on price-based, as opposed to quantity-based, interventions. Price-based interventions aim at leveraging market mechanisms to achieve greater efficiency in the allocation of resources and costs of mitigating climate change. For example, carbon pricing initiatives around the world today cover approximately 8 gigatons of carbon dioxide emissions, equivalent to about 20% of global fossil energy fuel emissions and 15% of total carbon dioxide greenhouse gas emissions (Boyce, 2018). Meanwhile, environmental taxes and green public procurement push producers to eliminate the negative environmental effects of production (Danilina and Trionfetti, 2019). There are several advantages for environmental taxation including environmental effectiveness, economic efficiency, the ability to raise public revenue, and transparency *(very high confidence*). These gains can provide more resource-efficient production technologies and positively affect economic competitiveness (Costantini et al., 2018).

Policies encouraging eco-innovation, defined as "*new ideas, behavior, products, and processes that contribute to a decreased environmental burden*" (Yurdakul and Kazan, 2020), can positively affect economic competitiveness. By implementing policies to encourage eco-innovation, countries enhance their energy efficiency. These gains can provide more resource-efficient production technologies and positively affect economic competitiveness *(very high confidence*) (Liobikienė and Butkus, 2018) (Costantini et al., 2018). Other than eco-innovation, it is important to also consider exnovation, meaning the phasing out of old technologies, as otherwise the expansion of supply could lead to a rebound due to cheaper prices for carbon-based products (Arne Heyen et al., 2017; David, 2017). Hence, decarbonization strategies that set limits to carbon-based trajectories can be beneficial. Quantity-based interventions—or so-called 'command-and-control' policies—involve constraints on the quantity of energy consumption or greenhouse gas emissions through laws, regulations, standards and enforcement, with a focus on effectiveness rather than efficiency.

For a transition from dirty (more advanced) technologies to clean (less advanced) ones, market-based instruments such as carbon taxes should be considered alongside subsidies and other incentives that stimulate innovation (Acemoglu et al., 2016). Research and development in energy technologies, for example, can help reduce costs of deployment and therefore the costs of operating in a carbon-constrained world. Hémous (2016) indicates that a unilateral environmental policy which includes both clean research subsidies and trade tax can ensure sustainable growth, but unilateral carbon taxes alone might increase innovation in polluting sectors and would not generally lead to sustainable growth.

18.4.2.2.2 Climate finance

Achieving progress on system transitions will be contingent on the ability of actors and institutions to access the financing they need to invest in innovation, adaptation and mitigation, and broader system change *(very high confidence*). By greening their investment portfolios, investors can support reduction in vulnerability to the consequences of climate change and the reduction of greenhouse gas emissions. Finance can contribute to the reduction of GHG emissions, for example, by efficiently pricing the social cost of carbon, by reflecting the transition risks in the valuation of financial assets, and by channeling investments in low-carbon technologies (OECD, 2017). At the same time, there is a growing need to spur greater public and private capital into climate adaptation and resilience including climate-resilient infrastructure and nature-based solutions to climate change. For instance, the Green Climate Fund, established within the framework of the UNFCCC, is assisting developing countries in adaptation and mitigation initiatives to counter climate change.

Recent evidence sheds light on the magnitude and pervasiveness of climate risk exposure for global banks and financial institutions. According to Dietz et al. (2016), up to about 17% of global financial assets are directly exposed to climate risks, particularly the impacts of extreme weather events on assets and their outputs. However, when indirect exposures via financial counterparts are considered, the share of assets subject to climate risks is much larger (40-54%) (Battiston et al., 2017). Hence, the magnitude of climate-change-related risks is substantial, and similar to the ones that started the 2008 financial crisis (*high agreement, limited evidence*).

Financial actors increasingly recognize that the generation of long-term, sustainable financial returns is dependent on a stable, well-functioning and well-governed social, environmental and economic systems *(very high confidence*) (Shiller, 2012; Schoenmaker and Schramade, 2020). Institutional approaches to a variety of environmental domains (Krueger et al., 2019), which seek to integrate the pursuit of green strategies with financial returns include targeted investments in green assets (e.g., green bonds, clean energy public equity) and specialized funds/vehicles for as renewable energy infrastructure (Tolliver et al., 2019; Gibon et al., 2020); cleantech venture capital and alternative finance (Gianfrate and Peri, 2019); investment screening to steer capital to green industries (Nielsen and Skov, 2019; Ambrosio et al., 2020); and active ownership to influence organizational behavior (Silvola and Landau, 2021).

Despite the expansion of green mandates across the investment chain, definitions of some of the asset classes associated with green investing are ambiguous and poorly defined. The EU taxonomy for sustainable activities is a promising step in the right direction. For example, a "green" label for bonds is often stretched to encompass financing facilities of issuers that misrepresent the actual environmental footprint of their operations (the so-called risk of "greenwashing"). Even in cases where the bonds' proceeds are actually used to finance green projects, investors often remain exposed to both the green and "brown" assets of the issuers (Gianfrate and Peri, 2019; Flammer, 2020). The heterogeneity of metrics and rating methodologies (along with inherent conflict of interests between issuers, investors and score/rating providers) results in inconsistent and unreliable quantification of the actual environmental footprint of corporate and sovereign issuers (Battiston et al., 2017; Busch et al.).

In order to promote financial climate-related disclosures for companies and financial intermediaries, the financial system could play a key role in pricing carbon and in allocating capital toward low-carbon emission companies (Aldy and Gianfrate, 2019; Bento and Gianfrate, 2020; Aldy et al., 2021). Stable and predictable carbon-pricing regimes would significantly contribute to fostering financial innovation that can help further accelerate the decarbonization of the global economy even in jurisdictions which are more lenient in implementing climate mitigation actions *(very high confidence*) (Baranzini et al., 2017). A growing number of financial regulators are intensifying efforts to enhance climate-related disclosure of financial actors. In particular, the Financial Stability Board created the Task Force on Climate-related Financial Disclosures (TCFD) to improve and increase reporting of climate-related financial information. Several countries are considering implementing mandatory climate risk disclosure in line with TCFD's recommendations. Central Banks are also considering mandatory disclosure and climate stress-testing for banks. For instance, in November 2020 the European Central Bank (ECB) published a guide on climate-related and environmental risks explaining how the ECB expects banks to prudently manage and transparently disclose such risks under current prudential rules. The ECB also announced that banks in the Euro-zone will be stress tested on their ability to withstand climate change related risks. In addition to disclosure requirements and stress-testing, some Central Banks are considering the possibility of steering or tilting the allocation of their assets to favor the less polluting issuers (Schoenmaker, 2019). This, in turn, would translate into lower cost of capital for cleaner sectors, significantly accelerating the greening of the real economy.

[START BOX 18.7 HERE]

Box 18.7: 'Green' Strategies of Institutional Investors

Negative and positive screening. Investors assess the carbon footprint of issuers and identify the best and worst performers (Boermans and Galema, 2019). The issuers with excessive carbon footprint are divested and fall into the "exclusion lists" (negative screening). Alternatively, the investors commit to pick only the best in class (positive screening). As a bare minimum, screening approaches force more transparent environmental reporting from issuers. In the most optimistic scenario, in order to avoid exclusion lists issuers may progressively divest their non-green operations. In the long term, the combination of positive and negative screening will reward sustainable issuers relative to non-green sectors, thus reducing the cost of capital for less polluting entities.

Active ownership. Equity investors can exercise the voting rights at shareholders' meetings in relation to governance and business strategy, including the environmental performance. In addition, institutional investors engage with the management and the boards of directors of investee companies. Active ownership is therefore defined as the full exercise of the rights that accrue to the "owners" of the securities issued by companies (Dimson et al., 2015; Dimson et al., 2020). Active owners are entitled to question and challenge the robustness of financial analyses and the risk assessment behind strategic decisions including the environmental footprint ones. For instance, since fossil fuel businesses face the prospect of dramatic business decline (Ansar et al., 2013) and must revisit their business model to survive, active ownership by institutional investors may foster the transition to cleaner production and supply chain. Companies more exposed to carbon risks particularly need the active support of long-term shareholders. In turn, investors adopting an active ownership approach can manage their holdings' exposure to climate change risks, thus protecting the value of their investments on a long-term horizon (Krueger et al., 2019).

Specialized financial instruments and investors. New asset classes have been created to address the climate change challenge. Also specialized investment funds and vehicles came to life with the primary objective of addressing climate issues. While these financial instruments and funds prioritize the achievement of climate objectives, they do not sacrifice financial returns and are able to attract private capital. To mention a few examples:

- *Green bonds* are typically issued by companies, banks, municipalities, and governments with the commitment to use the proceeds exclusively to finance or refinance green projects, assets or business activities. These bonds are equivalent to any other bond issued by the same entity except for the label of "greenness" that ideally is verified ex-ante at the launch and ex-post when the proceeds are actually used by the issuer. Early evidence show that green bonds do not penalize financially issuers (Gianfrate and Peri, 2019; Flammer, 2020).
- *Carbon funds* are designed to help countries achieve long-term sustainability typically financing forest conservation. They are intended to reduce climate change impacts from forest loss and degradation.
- *Project finance.* New renewable energy initiatives are likely to recur more and more to project finance. Project finance relies on the creation of a special purpose vehicle (SPV), which is legally and commercially self-contained and serves only to run the renewable energy project. The SPV is financed without (or very limited) guarantees from the sponsors (typically energy companies: investors are therefore paid back on the basis only of SPV's future cash flows only and cannot recourse on the sponsors' assets (Steffen, 2018).
- *Cleantech venture capital*. These funds invest exclusively in early-stage companies working on innovative but not yet fully tested clean technologies. The risk profile of such investments is usually very high. The extent to which this segment of the financial industry can successfully support "deep" energy innovations is still debated (Gaddy et al., 2017). When cleantech start-ups develop hardware requiring a high upfront investment, support from the public sector seems necessary in order to attract further investments from large corporations and patient institutional investors.
- *Crowdfunding and alternative finance* are emerging as a channel to both finance small-scale clean energy projects as well as fund early stage innovative clean technologies (Cumming et al., 2017; Bento et al., 2019).

[END BOX 18.7 HERE]

18.4.2.3 Institutional capacity

Institutional capacity for system transitions refers to the capacity of structures and processes, rules, norms, and cultures to shape development expectations and actions aimed at durable improvements in human well-being. The AR5 highlighted the need for strong institutions to create enabling environments for adaptation and greenhouse gas mitigation action (Denton et al., 2014). Institutions stand within the social and political practices and broader systems of governance that ultimately drive adaptation and development processes and outcomes. They are thus produced by them and can become tools by which some actors constrain the actions of others (Gebreyes, 2018). As a consequence, they and can become a significant barrier to change, whether incremental or more transformational *(very high confidence*). The post-AR5 focus on transformational adaptation and resilience present in the literature suggests that institutions that enable system transitions toward CRD are secure enough to facilitate a wide range of voices, and legitimate enough to change goals or processes over time, without reducing confidence in their efficacy.

The limited literature on institutions and pathways relevant to system transitions and CRD suggests that institutions are most effective when taking a development-first approach to adaptation. This is consistent with the principles of CRD which emphasizes not simply reducing climate risk, but rather making development processes resilient to the changing climate. There is agreement in this literature that such an approach allows for the effective integration of climate challenges into existing policy and planning processes *(very high confidence*) (Pervin et al., 2013; Kim et al., 2017b; Mogelgaard et al., 2018). However, this approach generally rests on an incremental framing of institutional change (Mahoney and Thelen, 2009) based on two critical assumptions. The first is that existing processes and institutions are capable of bringing about system transitions that generate desired development outcomes and thus can be considered appropriate vehicles for the achievement of CRD. A large critical literature questions the efficacy of formal state and multilateral institutions. The evidence for the ability of local, informal institutions to achieve development goals remains uneven, with robust evidence of positive impacts on public service delivery, but more ambiguous evidence on behavior changes associated with strengthened institutions (Berkhout et al., 2018). The second is that the mainstreaming of adaptation will bring about changes to currently unsustainable development practices and pathways, instead of merely strengthening development-as-usual by subsuming adaptation to existing development pathways and allowing them to endure in the face of growing stresses (Eriksen et al., 2015; Godfrey-Wood and Otto Naess, 2016; Scoville-Simonds et al., 2020). There is evidence that countries with poor governance have limited adaptation planning or action at the national level, even when other determinants of adaptive capacity are present (Berrang-Ford et al., 2014). This suggests that, in these contexts, adaptation efforts are likely to be subsumed to existing government goals and actions, rather than having transformational impact.

18.4.2.4 Science, Technology & Innovation

Ongoing innovations in technology, finance, and policy have enabled more ambitious climate action over the past decade, including significant growth in renewable energy, electrical vehicles, and energy efficiency. However, access to, and the benefits of, that innovation have not been evenly distributed among global regions and communities and continued innovation is needed to facilitate climate action and sustainable development *(very high confidence*). Policymakers need useful science and information (Kirchhoff et al., 2013; Calkins, 2015; IPCC, 2019f) to make informed decisions about possible risks, and the benefits, costs, and trade-offs of available adaptation, mitigation, and sustainable development solutions (i.e., Article 4.1 of the Paris Agreement; UNFCCC, 2015). Moreover, recent literature has emphasized the need for deep technological, as well social, changes to avert the risks of conventional development trajectories (Gerst et al., 2013; IPCC, 2014a).

An effective and innovative technological regime is one that is integrated with local social entities across different modes of life, local governance processes (Pereira, 2018; Nightingale et al., 2020); and local knowledge(s), which increasingly support adaptation to socio-environmental drivers of vulnerability (Schipper et al., 2014; Nalau et al., 2018; IPCC, 2019f). These actors and their knowledge are often ignored in favor of knowledge held by experts and policymakers, exacerbating uneven power relations (Naess, 2013; Nightingale et al., 2020). For example, achieving sustainability and shifting towards a low carbon energy system (e.g., hydropower dams, wind farms) remains a contested space with divergent interests, values and prospects of future (Bradley and Hedrén, 2014; Avila, 2018; Mikulewicz, 2019), and potential impacts on human rights as embodied by the Paris Agreement (UNFCCC, 2015). A number of studies have emphasized the limits of relying upon technology innovation and deployment (e.g., expansion of renewable energy systems and/or carbon capture) as a solution to challenges of climate change and sustainable development (18.3.1.2). This is because such solutions may fail to consider the local historical contexts and barriers to participation of vulnerable communities, restricting their access to land, food, energy, and resources for their livelihoods.

18.4.2.5 Monitoring and Evaluation Frameworks

Enabling system transitions toward CRD is dependent in part on the ability to monitor and evaluate system transitions and broader development pathways to identify effective interventions and barriers to their implementation *(very high confidence*). However, the monitoring and evaluation of individual system transitions, much less CRD, remains highly challenging for multiple reasons (Persson, 2019). The highly contextual nature of resilience, adaptation and sustainable development means that, unlike climate mitigation, it is difficult to define universal metrics or targets for adaptation and resilience (Pringle and Leiter, 2018), (Brooks et al., 2014). This is demonstrated by the Paris Agreement's global goal for adaptation, The mismatch between timescales associated with resilience and adaptation interventions and those over which the results of such interventions are expected to become apparent tends to result in a focus on the measurement of spending, outputs, and short-term outcomes, rather than longer-term impacts (Brooks et al., 2014; Pringle and Leiter, 2018). The need to assess resilience and adaptation against a background of evolving climate hazards, and to link resilience and adaptation with development outcomes, present further methodological challenges *(very high confidence*) (Brooks et al., 2014).

Currently, the ability to monitor different components of CRD are in various stages of maturity *(very high confidence*). Monitoring of the sustainable development goals, for example, is a routine established practice at global and regional levels, and UNDP publishes annual updates on progress toward the SDGs (United Nations, 2021). For resilience, Brooks et al. (2014) identify three broad approaches to its measurement, each of which could offer potential mechanisms for monitoring progress toward CRD. One is a 'hazards' approach, in which resilience is described in terms of the magnitude of a particular hazard that can be accommodated by a system, useful in contexts where thresholds in climate and related parameters can be identified and linked with adverse impacts on human populations, infrastructure and other systems (Naylor et al., 2020). An 'impacts' approach is one in which resilience is measured in terms of actual or avoided impacts and is suited for tracking adaptation success in delivering CRD over longer timescales, for example at the national level (Brooks et al., 2014). Finally, a 'systems' approach is one where resilience is described in terms of the characteristics of a system using quantitative or qualitative indicators which are often associated with different 'dimensions' of resilience (Serfilippi and Ramnath, 2018; Saja et al., 2019). This allows measurement of key indicators that are proxies for resilience at regular intervals, even in the absence of significant climate hazards and associated disruptions (*very high confidence*) (Brooks et al., 2014) (see also Cross-Chapter Box ADAPT in Chapter 1). Similar criteria could be applied to evaluating adaptation options and their implementation as well as various interventions in pursuit of SDGs.

18.4.3 Arenas of Engagement

Much of the enabling conditions for system transitions discussed in 18.4.2 are inherently linked to actors and their agency in pursuing system change. Yet, a significant literature has developed since the AR5 exploring note only the role of different actors in pursuing adaptation, mitigation, and sustainable development options, but also how those actors interact with one another to drive outcomes. CRD pathways are determined by the interactions between societal actors and networks, including government, civil society and the private sector, as well as science and the media. The resultant social choices and cumulative private and public actions (and inactions) are institutionalized through both formal and informal institutions that evolve over time and seek to provide societal stability in the face of change. The degree to which the emergent pathways foster just and climate resilient development depends on how contending societal interests, values and worldviews are reconciled through these interactions. These interactions occur in many different arenas of engagement, i.e., the settings, places and spaces in which societal actors interact to influence the nature and course of development, including political, economic, socio-cultural, ecological, knowledge-technology and community arenas (Figures 18.1, 18.2).

For example, political arenas range from formalized election and voting procedures to more informal and less transparent practices, like special interest lobbying. Town squares and streets can become sites of political struggle and dissent, including protests against climate inaction. As a more specific case-in-point, the formal space for national, sub-national and international adaptation governance emerged at COP 16 (UNFCCC, 2010) when adaptation was recognized as having a similar level of priority as mitigation. The Paris Agreement (UNFCCC, 2015) built on this and the 2030 Sustainable Development Agenda (United Nations, 2015) to link adaptation to development and climate justice, widening the scope of adaptation governance beyond formal government institutions. It also highlighted the importance of multi-level adaptation governance, including non-state voices from civil society and the private sector. This implied the need for wider arenas and modes of engagement around adaptation (Chung Tiam Fook, 2017; Lesnikowski et al., 2017; IPCC, 2018a) that facilitate coordination and convergence among these diverse actors including individual citizens to collectively solve problems and unlock the synergies between adaptation and mitigation and sustainable development (IPCC, 2018a; Romero-Lankao et al., 2018).

There are many other visible and less visible arenas of engagement in the other interconnected spheres of societal interaction spanning scales from the local to international level. The metaphor of arenas derives from diverse social and political theory, with applications in studies of, among other things, governance transformation and transitions (Healey, 2006; Jørgensen, 2012; Jørgensen et al., 2017). It underscores that these arenas can be enduring or temporary in nature, are historically situated and often spatially bounded, and signifies the many different mechanisms by which societal actors interact in dynamic and emergent ways. Power and politics impact access and influence in these arenas of engagement – with varying levels of inclusion and exclusion shaping the nature and trajectory of development. In practice, some arenas of engagement are 'struggle arenas' as different societal actors strive to influence the trajectory of development, with inevitable winners and losers.

Institutional arrangements to foster CRD are at an early stage of development in most regions (*medium agreement, limited evidence*). They need to be further clarified and strengthened to enable a sharing of resources and responsibilities that facilitate climate actions embracing climate resilience, equity, justice, poverty alleviation and sustainable development (Wood et al., 2017; IPCC, 2018a; Reckien et al., 2018). These endeavours are strongly influenced by how contested and complementary worldviews about climate change and development are mobilised by societal actors to justify, direct, accelerate and deepen transformational climate action or entrench maladaptive business as usual practices (18.4.3.1).

18.4.3.1 Worldviews

Worldviews are overarching systems of meaning and meaning-making that inform how people interpret, enact, and co-create reality (De Witt et al., 2016). Worldviews shape the vision, beliefs, attitudes, values, emotions, actions, and even political and institutional arrangements. As such, they can promote holistic, egalitarian approaches to enable, accelerate and deepen climate action and environmental care (Ramkissoon and Smith, 2014; De Witt et al., 2016; Lacroix and Gifford, 2017; Sanganyado et al., 2018; Brink and Wamsler, 2019). Alternatively, they can also serve as significant barriers to system transitions and transformation, based on anthropocentric, mechanistic and materialistic, worldviews and the utilitarian, individualist or skeptical values and attitudes they often promote *(very high confidence*) (Beddoe et al., 2009; van Egmond and de Vries, 2011; Stevenson et al., 2014; Zummo et al., 2020).

Traditional, modern and postmodern worldviews have different, and in many ways, complementary potentials for integrative diverse approaches to climate action and sustainable development. They can also destabilize climate-sensitive societal values (van Egmond and de Vries, 2011; Van Opstal and Hugé, 2013; De Witt et al., 2016; Shaw, 2016) which are predictors of concern (Shi et al., 2015). Among the challenges of strongly different climate-related worldviews, is that they rarely co-exist. Some worldviews become incompatible or hostile to other worldviews, openly seeking to dominate, eliminate or segregate competing perspectives (*medium agreement, medium evidence*) (de Witt, 2015; Jackson, 2016; Nightingale, 2016; Xue et al., 2016; Goldman et al., 2018).

To address these difficult contests, climate- and global environmental change-related worldviews are often scientized. This can exclude other worldviews which ultimately narrows understanding of climate change and the solution space. Hence, the post-AR5 literature on worldviews focuses on the numerous meanings, associations, narratives and frames of climate change and how these shape perceptions, attitudes and values (Morton, 2013; Boulton, 2016; Hulme, 2018; Nightingale Böhler, 2019). The recognition of the diversity of interpretations and meanings has led to multidisciplinary and transdisciplinary research that incorporates the humanities and the arts (Murphy, 2011; Elliott and Cullis, 2017; Steelman et al., 2019; Tauginienė et al., 2020), feminist studies (MacGregor, 2003; Demeritt et al., 2011; Bell, 2013; Brink and Wamsler, 2019; Plesa, 2019) and religious studies (Sachdeva, 2016; McPhetres and Zuckerman, 2018) to examine diverse understandings of reality and knowledge possibilities around climate change. In addition, literature on cultural cognition, epistemological plurality and relational ontologies draws on non-Western worldviews and forms of knowledge (Goldman et al., 2018) (Jackson, 2016; Nightingale, 2016; Xue et al., 2016).

On the other hand, the tendence for certain worldviews to dominate the policy discourse has the potential to exacerbate social, economic and political inequities *(very high confidence*). ontological, epistemic and procedural injustices. Research aimed at exploring the existing political ontology and knowledge politics of exclusion that marginalize certain communities and actors originated in academic, or scientific perspectives. This includes institutions such as the IPCC and is subsequently replicated in social representations, including the media, public policy and the development agenda, narrowing possibilities for social transformation (Jackson, 2014; Luton, 2015; Escobar, 2016; Burman, 2017; Newman et al., 2018; Sanganyado et al., 2018; Wilson and Inkster, 2018).

[START CROSS-CHAPTER BOX INDIG HERE]

Cross-Chapter Box INDIG: The Role of Indigenous Knowledge and Local Knowledge in Understanding and Adapting to Climate Change

Authors: Tero Mustonen (Finland), Sherilee Harper (Canada), Gretta Pecl (Australia), Vanesa Castán Broto (Spain), Nina Lansbury (Australia), Andrew Okem (Nigeria/South Africa), Ayansina Ayanlade (Nigeria), Jackie Dawson (Canada), Pauline Harris (Aotearoa-New Zealand), Pauliina Feodoroff (Finland), Deborah McGregor (Canada)

Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (UNESCO, 2018; IPCC, 2019a). Local knowledge refers to the understandings and skills developed by individuals and populations, specific to the places where they live (UNESCO, 2018; IPCC, 2019a). Indigenous knowledge and local knowledge are inherently valuable but have only recently begun to be appreciated and in western scientific assessment processes in their own right (Ford et al., 2016). In the past these often endangered ways of knowing have been suppressed or attacked (Mustonen, 2014). Yet these knowledge systems represent a range of cultural practices, wisdom, traditions, and ways of knowing the world that provide accurate and useful climate change information, observations, and solutions (*very high confidence*) (Table Cross-Chapter Box INDIG.1). Rooted in their own contextual and relative embedded locations, some of these knowledges represent unbroken engagement with the earth, nature and weather for many tens of thousands of years, with an understanding of the ecosystem and climatic changes over longer-term timescales that is held both as knowledge by Indigenous Peoples and Local Peoples as well as in the archaeological record (Barnhardt and Angayuqaq, 2005; UNESCO, 2018).

Indigenous Peoples around the world often hold unique worldviews that link today's generations with past generations. In particular, many Indigenous Peoples consider concepts of responsibility through intergenerational equity, thereby honouring both past and future generations (Matsui, 2015; McGregor et al., 2020). This can often be in sharp contrast to environmental valuing and decision-making that occurs in Western societies (Barnhardt and Angayuqaq, 2005). Therefore, consideration of Indigenous knowledge and local knowledge needs to be a priority in the assessment of adaptation futures (Nakashima et al., 2012)(Ford et al., 2016) (Chapter 1), although adequate Indigenous cultural and intellectual property rights require legal and non-legal measures for recognition and protection (Janke, 2018).

Indigenous knowledge and local knowledge are crucial to address environmental impacts, such as climate change, where the uncertainty of outcome is high and a range of responses are required (Mackey and Claudie, 2015). However, working with this knowledge in an appropriate and ethically acceptable way can be challenging. For instance, questions of data 'validity' and the requirement to communicate such knowledge in the dominant language can lead to inaccurate portrayals of Indigenous knowledge as inferior to science. This may overlook the uniqueness of Indigenous knowledge and then lead to the overall devaluation of Indigenous political economies, cultural ecologies, languages, educational systems, and spiritual practices (Smith, 2013; Sillitoe, 2016; Naude, 2019; Barker and Pickerill, 2020). Furthermore, Indigenous knowledge is too often only sought superficially – focusing only on the 'what', rather than the 'how' of climate change adaptation and/or seen through the lenses of 'romantic glorification' leaving little room for the knowledge to be expressed as authored by the communities and knowledge holders themselves (Yunkaporta, 2019).

Multiple knowledge systems and frameworks

Indigenous knowledge systems include not only the specific narratives and practices to make sense of the world, but also profound sources of ethics and wisdom. They are networks of actors and institutions that organise the production, transfer and use of knowledge (Löfmarck and Lidskog, 2017). There is a pluralism of forms of knowledge that emerge from oral traditions, local engagement with multiple spaces, and Indigenous cultures (Peterson et al., 2018). Recognising such multiplicity of forms of knowledge has long been an important concern within sustainability science (Folke et al., 2016). Less dominant forms of knowledge should not be put aside because they are not comparable or complementary with scientific knowledge (Brattland and Mustonen, 2018; Mustonen, 2018; Ford et al., 2020; Ogar et al., 2020). Instead, Indigenous knowledge and local knowledge can shape how climate change risk is understood and experienced, the possibility of developing climate change solutions grounded in place-based experiences, and the development of governance systems that match the expectations of different Indigenous knowledge and local knowledge holders (*very high confidence*).

Different frameworks that enable the inclusion of Indigenous knowledge have emerged from efforts to utilise more than one knowledge system (*high evidence, high agreement*). For example, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has developed a 'nature's contribution to peoples' framework that provides a common conceptual vocabulary and structural analysis (Díaz et al., 2015; Tengö et al., 2017; Díaz et al., 2018; Peterson et al., 2018). The IPBES approach complements other efforts to study areas of intersection between scientific and Indigenous worldviews (Barnhardt and Angayuqaq, 2005; Huaman and Sriraman, 2015) or 'boundaries' that illustrate 'blind spots' in scientific knowledge (Cash et al., 2003; Clark et al., 2016; Brattland and Mustonen, 2018). These frameworks highlight areas of collaboration but provide less guidance in areas where sources of evidence conflict across different knowledge systems (Löfmarck and Lidskog, 2017). These experiences suggest that the inclusion of Indigenous knowledge and local knowledge in international assessments may transform the process of assessment of scientific, technical, and socio-economic evidence (*medium evidence, high agreement*). These knowledge systems also point to novel discoveries that may be still unknown to the scientific world but have been known by communities for millennia (Mustonen and Feodoroff, 2020).

The importance of free and prior-informed consent

Obtaining free and prior-informed consent is a necessary but not sufficient condition to engage in knowledge production with Indigenous Peoples (Sillitoe, 2016). Self-determination in climate change assessment, response, and governance is critical (Chakraborty and Sherpa, 2021), and Indigenous Peoples are actively contributing to respond to climate change (Etchart, 2017). Climate change assessment and adaptation should be self-determined and led by Indigenous Peoples, acknowledge the importance of developing genuine partnerships, respect Indigenous knowledge and ways of knowing, and acknowledge Indigenous Peoples as stewards of their environment (Country et al., 2016; Country et al., 2018; ITK, 2019; Barker and Pickerill, 2020; Chakraborty and Sherpa, 2021). Supporting Indigenous Peoples' leadership and rights in climate adaptation options at the local, regional, national and international levels is an effective way to ensure that such options are adapted to their living conditions and do not pose additional detrimental impacts to their lives (*very high confidence*). Chapter 18 shows that the transformations required to deliver climate resilient futures will create societal disruptions, with impacts that are most often unevenly experienced by groups with high exposure and sensitivity to climate change, including Indigenous Peoples and local communities (Schipper et al., 2020a). Climate-resilient futures depend on finding strategies to address the causes and drivers of deep inequities (Chapter 18). For example, climate resilient futures will depend on recognising the socio-economic, political and health inequities that often affect Indigenous Peoples (Mapfumo et al., 2016; Ludwig and Poliseli, 2018) (*very high confidence*).

International conventions to support and utilize Indigenous knowledge and local knowledge

Several tools within international conventions may support instruments to develop equitable processes that facilitate the inclusion Indigenous knowledge and leadership in climate change adaptation initiatives. The International Labour Convention 69 recognised Indigenous People's right to self-determination in 1989 (ILO, 1989). The United Nations' Declaration on the Rights of Indigenous Peoples (United Nations, 2007) includes articles on the right to development (Article 23), the right to maintain and strengthen their distinctive spiritual relationship and to uphold responsibilities to future generations (Article 25), and the right to the conservation and protection of the environment and the productive capacity of their territories (Article 29). Article 26 upholds the right to the lands, territories and resources, the right to own, use, develop and control the lands, and legal recognition and protection of these lands, territories, and resources. Indigenous Peoples are also recognized within the Sustainable Development Goals as a priority group (Carino and Tamayo, 2019). International events such as the 'Resilience in a time of uncertainty: Indigenous Peoples and Climate Change' Conference brought together Indigenous Peoples' representatives and government leaders from around the world to discuss the role of Indigenous Peoples in climate adaptation (UNESCO, 2015).

The value of Indigenous knowledge and local knowledge in climate adaptation planning

There have been increasing efforts to enable Indigenous knowledge holders to participate directly in IPCC assessment reports (Ford et al., 2012; Nakashima et al., 2012; Ford et al., 2016). Adaptation efforts have benefited from the inclusion of Indigenous knowledge and local knowledge (IPCC, 2019e) (*very high confidence*). Moreover, it has been recognized that including Indigenous knowledge and local knowledge in IPCC reports can contribute to overcoming the combined challenges of climate change, food security, biodiversity conservation, and combating desertification and land degradation (IPCC, 2019c) (*high confidence*). Limiting warming to 1.5°C necessitates building the capability of formal assessment processes to respect, include and utilize Indigenous knowledge and local knowledge (IPCC, 2018a) (*medium evidence, high agreement*).

However, these efforts have been accompanied by a recognition that 'integration' of Indigenous knowledge and local knowledge cannot mean that those knowledge systems are subsumed or required to be validated through typical scientific means (Gratani et al., 2011; Matsui, 2015). Such a critique of 'validity' can be inappropriate, unnecessary, can disrespect Indigenous Peoples' own identities and histories, limits the advancement and sharing of these perspectives in the formal literature, and overlooks the structural drivers of oppression and endangerment that are associated with Western civilization (Ford et al., 2016). Moreover, by underutilizing Indigenous knowledge and local knowledge systems, opportunities that could otherwise facilitate effective and feasible adaptation action can be overlooked. We should also reserve space for the understanding that each cultural knowledge system, building on linguistic-cultural endemicity, is unique and inherently valuable.

Indigenous Peoples have often constructed their ways of knowing using oral histories as one of the vehicles of mind and memory, observance, governance, and maintenance of customary law (Table Cross-Chapter Box INDIG.2). These ways of knowing can also incorporate the relationships between multiple factors simultaneously which adds particular value towards understanding complex systems that is in contrast to the dominant reductionist, Western approach- noting that non-reductionist approaches also exist (Ludwig et al., 2014; Hoagland, 2017).

For climate research, the role of oral histories as a part of Indigenous knowledge and local knowledge is extremely relevant. For example, ocean adaptation initiatives can be guided by oral historians and keepers of knowledge who can convey new knowledge and baselines of ecosystem change over long-time frames (Nunn and Reid, 2016). Oral histories can also convey cultural indicators and linguistic devices of species identification as a part of a local dialect matrix and changes in ecosystems and species using interlinkages not available to science (Mustonen, 2013; Frainer et al., 2020). Oral histories attached to maritime place names, especially underwater areas (Brattland and Nilsen, 2011), can position observations relevant for understanding climate change over long ecological timeframes (Nunn and Reid, 2016). Species abundances, well-being and locations are some of the examples present in the ever-evolving oral histories as living ways of knowing. Indigenous knowledge and oral histories may also have the potential to convey governance, moral, and ethical frameworks of sustainable livelihoods and cultures (Mustonen and Shadrin, 2020) rooted in the particular Indigenous or local contexts that are not otherwise available in written or published forms.

Climate change research involving Indigenous Peoples and local communities has shown that the generation, innovation, transmission, and preservation of Indigenous knowledge is threatened by climate change (Kermoal and Altamirano-Jiménez, 2016; Simonee et al., 2021). This is because Indigenous knowledge is taught, local knowledge is gained through experience, and relationships with the land are sustained through social engagement within and among families, communities, and other societies (Tobias J.K, 2014; Kermoal and Altamirano-Jiménez, 2016). The knowledge that has traditionally been passed on in support of identity, language and purpose has been disrupted at an intergenerational level (Lemke and Delormier, 2017). Many of these dynamics have affected local knowledge transfers equally (Mustonen, 2013). This scenario represents a tension for Indigenous Peoples, where Indigenous knowledge in the form of land-based life ways, languages, food security, intergenerational transmission and application are threatened by climate change, yet in parallel, these same practices can enable adaptation and resilience (McGregor et al., 2020).

Table Cross-Chapter Box INDIG.1: Examples of Indigenous knowledge and local knowledge about climate change used in this Assessment Report

Issue	Examples of Indigenous Peoples' and local communities' action	Context, peoples, and location	Source
Climate forecasting/early warning	Phenological cues to forecast and respond to climate change	Smallholder farmers, Delta State, Nigeria	Ch9
	Forecasting of weather and climate variation through observation of the natural environment (e.g. changes in insects, and wildlife).	Afar pastoralists, north-eastern Ethiopia	
	Observation of wind patterns to plan response to coastal erosion/flooding	Inupiat, Alaska, US	Ch14
	Sky and moon observation to determine the onset of rainy season	Maya, Guatemala	Ch12
Fire hazards	Prescribed burning	Indigenous nations in Venezuela, Brazil, Guyana, Canada, and US	Ch12 Ch14
Crop yield / food security	Water management, native seeds conservation and exchange, crop rotation, polyculture, and agroforestry	Mapuche, Chile	Ch12
	Crop association (milpa) agroforestry, land preparation and tillage practices, native seed selection and exchange, adjusting planting calendars,	Maya, Guatemala	Ch12
	Harvesting rain-water and the use of maize landraces by Indigenous farmers to adapt to climate impacts and promote food security in Mexico	Yucatán Peninsula, Mexico	Ch14
Livelihood and well-being	Cultural values ingrained in knowledge system: reciprocity, collectiveness, equilibrium, and solidarity	Quechua, Cusco, Peru	Ch12
Ecosystem degradation	Ecosystem restoration including rewilding	Sámi, Nenets, and Komi, Scandinavia and Siberia	Ch13
	Collaboration with researchers, foresters, and landowners to manage native black ash deciduous trees against emerald ash borer	Indigenous Nations in Canada and US	Ch14
	Selection and planting of native plants that reduce erosion Whole-of-island approaches that embed IK and LK in environmental governance	Small islands states (as defined by Chapter 15)	Ch15
Fisheries	Traditional climate-resilient fishing approaches	Indigenous nations across North America and the Arctic	Ch14 CCP6

Management of urban resources	Restoration of traditional network of water tanks	Traditional communities and activists in South Indian cities such as Bengaluru	Ch6

Table Cross-Chapter Box INDIG.2: Case Study Summary

Region	Summary
Africa	Many rural smallholder farmers in Africa use their ingrained Indigenous knowledge systems to navigate climatic changes as many do not have access to Western systems of weather forecasting. Instead, these farmers have been reported to use observations of clouds and thunderstorms, and migration of local birds to determine the start of the wet season, as well as create temporary walls by rivers to store water during droughts. Indigenous knowledge systems should be incorporated into strategic plans for climate change adaptation policies to help smallholder farmers cope with climate change (Mapfumo et al., 2016).
Arctic	For local Inuit hunters and others who travel across Arctic land, ice and sea, there is evidence that the most accurate approach to reduce risk and enable informed decision-making for safe travel, is to combine Indigenous knowledge and local observations of weather with official online weather and marine services information that is available nationally (Simonee et al., 2021). Combining Inuit and local knowledge of weather, water, ice, and climate information with official forecasts has provided local hunters with more accurate, locally relevant information, and has on several occasions helped to avoid major weather-related accidents.
Latin America	In Venezuela, Brazil, and Guyana, Indigenous knowledge systems have led to a lower incidence of wildfires, reducing the risk of rising temperatures and droughts (Mistry et al., 2016). The Mapuche Indigenous Peoples in Chile use various traditional and sustainable agricultural practices, including: native seed conservation and exchange (*trafkintu*), crop rotation, polyculture, and tree-crop association. They also give thanks to Mother Earth through rituals to nurture socioecological sustainability (Parraguez-Vergara et al., 2018). In rural Cusco Region of Peru, “cultures values known in Quechua as *ayni* (reciprocity), *ayllu* (collectiveness), *yanantin* (equilibrium) and *chanincha* (solidarity)” have led to successful adaptation to climate change (Walshe and Argumedo, 2016).
Māori (Aotearoa New Zealand)	The traditional calendar system (*maramataka*) used by the Māori in Aotearoa-New Zealand incorporates ecological, environmental and celestial Indigenous knowledge. Māori practitioners are collaborating with scientists through the Effect of Climate Change on Traditional Māori Calendars project (Harris et al., 2017) to examine if climatic changes are impacting the use of the *maramataka*, which can be used as a framework to identify and explain environmental changes. Observations are being documented across Aotearoa, New Zealand to improve understandings of environmental changes and explore the use of Indigenous Māori knowledge in climate change assessment and adaptation.
Skolt Sámi (Finland)	In 2011, the Skolt Sámi in Finland began the first co-governance initiative where collaborative management and Indigenous knowledge were utilized to effectively manage a river and Atlantic Salmon (*Salmo salar*). This species is culturally and spiritually significant to the Skolt Sámi and has been adversely impacted by rising water temperatures and habitat loss (Brattland and Mustonen, 2018; Feodoroff, 2020; Ogar et al., 2020) (see also CCP Polar). Using Indigenous knowledge, they mapped changes in catchment areas and used cultural indicators to determine the severity of changes. Through collaborative management efforts that utilized both Indigenous knowledge and science, spawning and juvenile habitat areas for trout and grayling were restored, demonstrating the autonomous community capacity (Huntington et al., 2017) of the Indigenous Skolt Sámi and the capacity of Indigenous knowledge to address climate change impacts and detection of very first microplastics pollution together with science (Pecl et al., 2017; Brattland and Mustonen, 2018; Mustonen and Feodoroff, 2020).

[END CROSS-CHAPTER BOX INDIG HERE]

18.4.3.2 Political and government arenas

Climate resilient development is embedded in social systems, in the political economy and its underlying ideologies, interests and institutions (see 18.4.1). The pursuit of CRD, and shifting development pathways away from prevailing trends, unfolds in an array of political arenas, from the offices of bureaucrats to parliament buildings, sidewalks and streets, to discursive arenas in which governance actors interact – from the village level to global forums (Jørgensen et al., 2017; Montoute et al., 2019; Sørensen and Torfing, 2019; Pasquini, 2020). Paradoxically, the post-AR5 literature suggests that political arenas are often used to shut down efforts to explore the solution space for climate change and sustainable development (*medium agreement, robust evidence*) (e.g., Kenis and Mathijs, 2012; Kenis and Mathijs, 2014; Beveridge and Koch, 2016; Kenis and Lievens, 2016; Driver et al., 2018; Meriluoto, 2018; Swyngedouw, 2018; Mocca and Osborne, 2019). Power relationships among different actors create opportunities for people to be included or excluded in collective action (Siméant-Germanos, 2019) (18.3.1.6, 18.4.3.5). Therefore, as evidenced by examples from the UK (MacGregor, 2019) and China (Huang and Sun, 2020) small-scale collective environmental action has transformative potential in part due to its ability to increase levels of cooperation among different actors (*medium agreement, limited evidence*) (Green et al., 2020; Blühdorn and Deflorian, 2021).

In addition to the 'arm's length' acts of voting, social mobilisation, protest, and dissent can be critical catalysts for transformative change (Porta, 2020). These are competitions for recognition, power, and authority (Nightingale, 2017) that take place in settings. This is evidenced by experiences from the energy sector in Bangladesh which became a contested national policy domain and where social movements eventually transformed the nation's energy politics (Faruque, 2017). Similarly, in Germany, the nation's energy transition led to marked changes in agency, legal frameworks, and energy markets drove the proliferation of so-called municipalizations of energy systems – a reversal of years of system privatization (Becker et al., 2016). Meanwhile, experience in Bolivia demonstrate that the transformative potential of political conflict depends on transcending narrow issues to form broad coalitions with a collective identity that challenge prevailing development objectives and trajectories (Andreucci, 2019). Such examples illustrate the power of the communities as a vanguard against environmentally destructive practices (Villamayor-Tomas and García-López, 2018). Social movements have been successful at countering fossil fuel extraction (Piggot, 2018) and open up political opportunities in the face of increasing efforts to capture natural resources (Tramel, 2018) and are bolstered by resistance from within some corporations and/or their shareholders (Fougère and Bond, 2016; Swaffield, 2017).

Coincident with these social movements targeting climate change and sustainability has been a rise of political conservatism and populism as well as growth in misinformation (*high agreement, medium evidence*) (Mahony and Hulme, 2016; Swyngedouw, 2019). This reflects efforts to maintain the status quo by actors in positions of power in the face of rising social inertia for climate action (Brulle and Norgaard, 2019). Political arenas of the future may even require a new body politic that includes non-humans and a new geo-spatial politics (Latour et al., 2018).

As introduced in the discussion of governance as an enabling condition (18.4.2.1), a wide range of actors are involved in successful adaptation, mitigation, and sustainability policy and practice including national, regional and local governments, communities, and international agencies (Lwasa, 2015). As of 2018, 197 countries had between them over 1,500 laws and policies addressing climate change as compared to 60 countries with such legislation in 1997 when the Kyoto Protocol was agreed upon (Nachmany et al., 2017; Nachmany and Setzer, 2018). In judicial branches, climate change litigation is increasingly becoming an important influence on policy and corporate behavior among investors, activists, and local and state governments (Setzer and Byrnes, 2019). There is enhanced action on climate change at both national and subnational levels, even in cases where national policies are inimical as in USA (Carmin et al., 2012; Hansen et al., 2013).

The strong role of governments in climate action has implications for the nature of democracy, the relationship between the local and the national state, and between citizens and the state (Dodman and Mitlin, 2015). More integration of government policy and interventions across scales, accompanied by capacity building to accelerate adaptation is needed *(very high confidence*). Key needs include enhanced funding, clear roles and responsibilities, increased institutional capability, strategic approaches, community engagement, judicial integrity (Lawrence et al., 2015). More resources, and more active involvement of the private sector and civil society can help maintain adaptation on the policy agenda. Multilevel adaptation approaches are also relevant in low-income countries where local governments have limited financial resources and human capabilities often leading to dependency on national governments and donor organizations (Donner et al., 2016; Adenle et al., 2017).

Unlike mitigation, adaptation has traditionally been viewed as a local process, involving local authorities, communities, and stakeholders (Preston et al., 2015). The literature on the governance of adaptation continues to emphasize that local governments have demonstrated leadership in implementation by collaborating with the private sector and academia. Local governments can also play a key role (Melica et al., 2018; Romero-Lankao et al., 2018) in converging mitigation and adaptation strategies, coordinating and develop effective local responses, enabling community engagement and more effective policies around exposure and vulnerability reduction (Fudge et al., 2016). Local authorities are well-positioned to involve the wider community in designing and implementing climate policies and adaptation implementation (Slee, 2015; Fudge et al., 2016). Local governments also help deliver basic services, and protect their integrity from climate impacts (Austin et al., 2015; Cloutier et al., 2015; Nalau et al., 2015; Araos et al., 2017). However, the resource limitations of local governments as well as their small geographic sphere of influence suggests the need for more funding for this from higher levels of government, particularly national governments, to address adaptation gaps *(very high confidence*) (Dekker, 2020). Local adaptation implementation gaps can be linked to limited political commitment at higher levels of government and weak cooperation between key stakeholders (Runhaar, 2018). Incongruities and conflicts can exist between adaptation agendas pursued by national governments and the spontaneous adaptation practices of communities. There may be grounds for re-evaluating current consultative processes integral to policy development, if narrow technical approaches emerge as the norm for adaptation (Smucker et al., 2015).

Therefore, the traditional view of adaptation as a local process has now widened to recognize it as a multi-actor process that transcends scales from the local and sub-national to national and even international *(very high confidence* (Mimura et al., 2014). Many of the impacts of climate change are both local and transboundary, so that local, bilateral and multilateral cooperation are needed (Nalau et al., 2015; Donner et al., 2016; Magnan and Ribera, 2016; Tilleard and Ford, 2016; Lesnikowski et al., 2017). National policies and transnational governance should be seen as complementary, especially where they favor transnational engagement with sub- and non-state actors (Andonova et al., 2017). National governments typically act as a pivot for adaptation coordination, planning, determining policy priorities, and distributing financial, institutional and sometimes knowledge resources. National governments are also accountable to the international community through international agreements. National governments have helped enhance adaptive capacity through building awareness of climate impacts, encouraging economic growth, providing incentives, establishing legislative frameworks conducive to adaptation, and communicating climate change information (Berrang-Ford et al., 2014; Massey et al., 2014; Austin et al., 2015; Huitema et al., 2016).

18.4.3.3 Economic and financial arenas

The performance of local, national, and the global economies is a priority consideration shaping perceptions of climate risk and the costs and benefits of different policy responses to climate change. The most commonly used indicator of performance is gross domestic product (GDP) (Hoekstra et al., 2017). Traditionally, national development efforts have sought to maximize the growth of GDP under the assumption that GDP growth equates not only to economic prosperity (including poverty reduction) but also to increased efficiency and reduced environmental externalities (Ota, 2017). Such assumptions often employ models such as the environmental Kuznets curve (EKC) that postulates that economic development initially increases environmental impacts, but these trends eventually reverse with continued economic growth. Wealthy nations of the global North, including for example the United States, Great Britain, Iceland, Japan, have had success over the past decade in reducing their greenhouse gas emissions while growing their economies *(very high confidence*). However, attempts to empirically test EKC in different national contexts has yielded mixed results. Case studies in Myanmar, China, and Singapore, for example, suggest that the impacts of GDP on environmental quality are contingent on the development context and the environmental impact under consideration (Aung et al., 2017; Lee and Thiel, 2017; Xu, 2018; Chen and Taylor, 2020). In addition, an extensive literature now argues that current patterns of development, and the economic systems underpinning that development, are unsustainable (Washington and Twomey, 2016), and thus economic growth may not necessarily continue indefinitely in the absence of more concerted effort to pursue sustainable development, including reducing the impacts of climate change.

Given such criticisms of the link between development and economic growth, a growing number of researchers argue for the need for alternatives to GDP to guide development and evaluate the costs and benefits of different policy interventions (Hilmi et al., 2015). For example, while GDP growth can drive growth in income, it can also drive growth in inequality which can undermine poverty reduction efforts *(very high confidence*) (Fosu, 2017). Hence, recent years have seen significant interest in the concept of well-being as a more robust measure for linking policy and the economy with sustainable development for a healthy Anthropocene era (Fioramonti et al., 2019).

Another mechanism for evaluating environmental performance is to include environmental data in the System of National Accounts (SNA) through the System of Environmental-Economic Accounting (SEEA) introduced by the UN. As the international statistical standard for environmental-economic accounting (Pirmana et al., 2019), SEEA includes natural capital resources in national accounting. A number of recent studies conclude that failure to account for natural capital in macroeconomic impact assessments results in overly optimistic outcomes (Pirmana et al., 2019; Jendrzejewski, 2020; Naspolini et al., 2020), (Banerjee et al., 2019; Kabir and Salim, 2019; Keith et al., 2019). For example, Jendrzejewski (2020) inserted natural capital into a computable general equilibrium model of the 2017 European windstorm on state-owned forests in Poland. This resulted in more negative assessment of impacts, suggesting excluding natural capital could lead to erroneous investments, strategies. or policies. Similarly, other studies rely on Quality of life (QOL) measurements as alternatives for GDP. Estoque et al. (2018) suggested a “QOL-Climate” assessment framework, designed to capture the social-ecological impacts of climate change and variability.

Another alternative to GDP is Green GDP which seeks to incorporate the environmental consequences of economic growth (Boyd, 2007; Stjepanović et al., 2017; Stjepanović et al., 2019). Green GDP is difficult to measure, because it is difficult to evaluate the environmental depletion and ecological damages of growth (Stjepanović et al., 2019). Although there is no consensus in measuring Green GDP, attempts have been made for select countries including the United States (Garcia and You, 2017), Europe (Stjepanović et al., 2019), China (Chi and Rauch, 2010; Yu et al., 2019; Wang et al., 2020), Ukraine and Thailand (Harnphatananusorn et al., 2019), and Malaysia (Vaghefi et al., 2015). Le (2016) illustrated the potential negative impacts of climate change vulnerability on green growth. Some studies have suggested that focusing on green growth as the only strategy to address climate change would be risky. Hickel and Kallis (2020) argue that green growth is likely to be a misguided goal due to the difficulties of separating economic growth from resource use and, therefore, carbon emissions (see also (Antal and van den Bergh, 2014). Therefore, alternative strategies are required (Hickel and Kallis, 2020). In addition, green growth should also be able to justly respond to social movements involving contestation, internal debates and tensions (Mathai et al., 2018).

The emphasis on Green GDP is mirrored by another concept, Blue Growth, that focuses on the pursuing sustainable development through the ecosystem services derived from ocean conservation (Mustafa et al., 2019). Synthesis studies suggest that more intensive use of ocean resources, such as scaling up seaweed aquaculture, can be used to enhance CO2eq sequestration, thereby contributing to greenhouse gas mitigation, while also achieving other economic goals (Lillebø et al., 2017; Froehlich et al., 2019). Similarly, Sarker et al. (2018) present a framework for linking Blue Growth and climate resilient development in Bangladesh, with Blue Growth representing an opportunity for adapting to climate change. Bethel et al. (2021) also links Blue Growth to resilience, noting that a Blue economy can help facilitate recovery from the COVID-19 pandemic. Nevertheless, consistent with earlier assessment of enabling conditions for system transitions (18.4.2.1), implementation of Blue Growth initiatives is contingent upon the successful achievement of social innovation as well as creating an inclusive and cooperative governance structure *(very high confidence*) (Larik et al., 2017; Soma et al., 2018).

A potential critique of the various alternative metrics and models for economic development is that they are all framed in the context of growth. Over the past decade, ecological economists and political scientists have proposed Degrowth (e.g., Kallis, 2011; Demaria et al., 2013) and managing without growth (e.g., Jackson, 2009) as a solution for achieving environmental sustainability and socio-economic progress. Such concepts are a deliberate response to concerns about ecological limits to growth and the compatibility between growth-oriented development and sustainability (Kallis et al., 2009). Sustainable degrowth is not the same as negative GDP growth which is typically referred to as a recession (Kallis, 2011). Degrowth goes beyond criticizing economic growth; it explores the intersection among environmental sustainability, social justice, and well-being (Demaria et al., 2013). Under current economic and fiscal policies (see Box 18.8), degrowth has been argued as an unstable development paradigm because declining consumer demand leads to rising unemployment, declining competitiveness, and a spiral of recession (Jackson, 2009: 46). More comprehensive modelling of socio-economic performance understands the segments of sufficient social transformation to guarantee maintenance and rise in wellbeing coupled with reduced 'footprints' (Raworth, 2017; Hickel, 2019; D'Alessandro et al., 2020).

START BOX 18.8 HERE

Box 18.8: Macroeconomic policies in support of Climate-Resilient Development

Climate change risk may differ from other economic and financial risks in a number of ways: climate change is global; involves long-term impact; and involves a great deal of uncertainty; and with the possibility of irreversible change (Hansen, 2021). The macroeconomic implications will differ across countries with less developed countries are likely to suffer more relative to more advanced ones (Batten, 2018). Hence, policymakers need to understand the impact of climate change on macroeconomic issues such as potential output growth, capital formation, productivity, and long run level of interest rates, in order to better design policy interventions, be it monetary or fiscal (Economides and Xepapadeas, 2018; Bank of England, 2019; Rudebusch, 2019). As discussed, below a range of fiscal tools can be leveraged to mitigate the effects of climate change (Krogstrup and Oman, 2019).

Monetary Policy

Changes in climate and subsequent policy responses could increase volatility of food and energy prices, resulting in higher headline inflation rates. Thus, Central Banks (CBs) have to pay careful attention to underlying inflationary factors in order to maintain their inflationary targets. In response, CBs can take a number of actions. For example, they could require that collateral comprises assets that support the move to low-carbon economy, or their refinancing operations and crisis facilities could incentivize borrowers' move to low-carbon activities, particularly in countries where CBs' mandate has been expanded to account for climate impact (Papoutsi et al., 2021). Other actions that CBs could take include adoption of sustainable and responsible investment principles (Rudebusch, 2019), require financial firms to disclose their climate related risks (ECB, 2020; Lee, 2020). Despite these opportunities, there is ongoing debate regarding whether CBs should actively use monetary policy to address climate change and its risks (Honohan, 2019).

Fiscal policy

The application of green fiscal policies to address climate change could lead to environmental benefits including environmental revenues that may be used for broader fiscal reforms (OECD, 2021). As the US aims at becoming carbon neutral by 2050, fiscal policies at the national, sectoral, and international level can help to achieve this goal, along with investment, regulatory, and technology policies (Parry, 2021). The effectiveness of green fiscal policies are through their fiscal potential, opportunities for efficiency gains, distributional and macroeconomic impacts, and their political economy implications (Metcalf, 2016). The International Monetary Fund argues public support for green policies may rise in response to the COVID-19 crisis (IMF, 2017). For example, Leibenluft (2020) argues that investments to combat climate change should be an important component of the efforts to rebuild the economy in the wake of COVID-19. Such action is justified not only on ecological and social welfare grounds, but from a long-term fiscal perspective. For example, climate change impacts and/or efforts to adapt to those impacts drive increased spending in areas such as public health and disaster mitigation or response. Preventive and corrective actions would strengthen resilience to shocks and alleviate the financial constraints they create, particularly for small countries (Catalano et al., 2020). For example, Mallucci (2020) found that natural disasters exacerbate fiscal vulnerabilities and trigger sovereign defaults in seven Caribbean countries. Ryota (2019) illustrates how to include natural disaster and climate change in a fiscal policy framework to developing countries.

Carbon pricing

Pricing of greenhouse gases, including carbon, is a crucial tool in any cost-effective climate change mitigation strategy, as it provides a mechanism for linking climate action to economic development (IMF/OECD, 2021). By 2019, 57 nations around the world had implemented or scheduled implementation of carbon pricing. These initiatives cover 11 gigatons of carbon dioxide or about 20% of greenhouse gases emissions. Carbon prices in existing initiatives range between $1 and $127 per ton of carbon dioxide, while 51% of the emissions that are covered are priced more than $10 per ton of carbon dioxide. Moreover, in 2018, Governments raised about $44 billion in carbon pricing revenues (World Bank, 2019). However, the carbon prices are lower than the levels required for attaining the ambitious goal of climate change mitigation, and therefore, prices would need to increase if pricing alone is going to be used to drive compliance with the Paris Agreement. Higher carbon prices would also be warranted if prices are based on the social cost of carbon, which represents the present value of the marginal damage to economic output caused by carbon emissions (Cai and Lontzek, 2018). This cost needs to be considered with the social benefits of reducing carbon emissions through cost-benefit analyses in order to make the intended regulation acceptable.

Taxes

Carbon taxes represent another financial mechanism for addressing climate (Metcalf, 2019), 2019b). For example, the implementation of a carbon tax and a value-added tax on transport fuel in Sweden resulted in a reduction of CO2 emissions from transport of about 11% in which the carbon tax had the largest share (Andersson, 2019). In the United States, for example, a carbon tax could increase fiscal flexibility by collecting new revenues that can be redeployed to finance reforms and help stimulate economic growth. However, U.S. tax-inclusive energy prices would have to be 273% higher than laissez faire levels in 2055 in order to meet international agreements (Casey, 2019). Similarly, limiting global warming to 2 degrees or less would likely require a carbon tax rate in the Asia/Pacific region to be significantly higher than $25 per ton (IMF, 2021). Therefore, using tax revenues to issue payments back to taxpayers that are disproportionately impacted or to redistribute capital among regions may be one of the most important features of carbon tax policies. Although the average effect of carbon tax on welfare would be positive, some regions (56%) will gain and some regions (44%) lose (Scobie, 2013). Therefore, large transfer payments are needed to compensate those losing from carbon tax (Krusell and Smith, 2018). IMF (2019) argues that, of the various mitigation strategies to reduce fossil fuel CO2 emissions, carbon taxes are the most powerful and efficient, because they allow firms and households to find the lowest-cost ways of reducing energy use and shifting toward cleaner alternatives.

Subsidies

The World Bank has been encouraging both developed and developing states, especially those with petroleum reserves, to use the removal of subsidies as a mechanism for promoting energy transitions away from fossil fuels. The transition has led to social unrest in some cases, especially where there is a culture of entitlement to low-cost energy because it is an indigenous resource. Such reforms have been more effective when governments have been able to clearly show how savings are applied to social and health programs that benefit human well-being. Nevertheless, policy makers should not underestimate the complexity of issues involved in the removal of subsidies that will increase the cost of carbon and hasten the transition to cleaner fuels (Scobie, 2017; Scobie et al., 2018; Chen et al., 2020a). A crucial issue to take into account is the harmful effects some subsidies have on biodiversity. Although governments agreed in 2010 to make progress on reducing subsidies in 2010, by 2020 few governments had identified specific incentives to remove or taken action toward their removal. Further investigation of the positive and negative effects of subsidy redirection or elimination on people and the environment (Dempsey et al., 2020).

END BOX 18.8 HERE

18.4.3.4 Knowledge-technology and ecological arenas

Knowledge-technology arenas comprise the interaction in knowledge spaces connected to technology transitions. The institutional and political architecture through which knowledge and technology interact is described in sustainability transitions literature (Fazey et al., 2018b; Sengers et al., 2019l Kanger, 2020 #3709). A common theme explored in that literature is the ability of actors to access and apply various forms of knowledge as a means of effecting change. Different forms of innovation are recognized as a core enabling condition for achieving system transitions for CRD (18.3.3; Cross-Chapter Box INDIG). However, while scientific and technology knowledge may be useful, in some cases, they remain subordinate to political agendas, or are controlled by actors in positions of power and thus not equitably distributed *(very high confidence*) (Mormina, 2019). Participatory decision-making, for example, assumes that multiple actors, with differing motivations, agency and influence, engage with climate decision making and co-produce actions. Yet, some actors may not participate in the process if the proposed actions do not align with their motivations or if they do not have adequate agency (Roelich and Giesekam, 2019). Hence, effectively using knowledge to inform policy is challenging for both scientists, policymakers, and civil society alike.

Science, technology, and innovation (STI) policies are expected to shape expectations of the potential for a better world based on clean technologies, higher labor productivity, economic growth and a healthier environment (Schot and Steinmueller, 2018; Mormina, 2019). STI policies are considered as 'social goods for development'. Hence, STI policies are often proposed or implemented as means of addressing environmental challenges such as climate change along with sustainable development goals such as the reduction of inequality, poverty, and environmental pollution (Mormina, 2019). Realizing the benefits of STI, however, may be contingent on building broader STI capacity and bolstering nations' systems of innovation (*very high confidence)* (Mormina, 2019). This could include building global research partnerships to address priority STI needs as well as long-standing gaps between the global North and South. Such an approach shifts the framing of STI as one focused on individual investigators to one comprised of building knowledge networks. It also creates opportunities for integration of disparate forms of knowledge and innovation, including local and indigenous knowledge, into global knowledge systems (Cross-Chapter Box INDIG).

Furthermore, an extensive literature increasingly incorporates natural and ecological systems as knowledge domains relevant to understanding opportunities for sustainability and CRD. For example, the literature on socioecological systems (SES) (Sterk et al., 2017; Holzer et al., 2018; Avriel-Avni and Dick, 2019; Martínez-Fernández et al., 2021) as well as social, ecological, and technological systems (SETS) (McPhearson and Wijsman, 2017; Webb et al., 2018; Ahlborg et al., 2019), explicitly integrate ecological knowledge into sustainability including concepts such as planetary boundaries (18.1.1), adaptation and nature-based solutions, natural resources management, rights and access to nature, and understanding of how humans govern society-nature interactions in the face of climate change (Benjaminsen and Kaarhus, 2018; Mikulewicz, 2019; Nightingale et al., 2020). Some of these interactions are explained in Cross-Chapter Box INDIG including conflict over which knowledges are recognized as valuable in understanding and responding to climate change and therefore shape the nature of climate actions. Actor engagement in stewardship, solidarity, inclusion of multiple knowledges and nature-society connectedness can highlight the intertwined nature of ecological change and knowledge relations thereby support shifts to sustainability (Pelling, 2010; Hulme, 2018; Ives et al., 2019; Nightingale et al., 2020) (see also Box 18.6).

The expanding definition of what constitutes credible, relevant, and legitimate knowledge is leading to the democratization of knowledge and efforts to address historical inequities in access to knowledge (Ott and Kiteme, 2016; Rowell and Feldman, 2019). This is reflected in the communication of science, which is increasingly focused on reducing the distance between internal scientific and public communication and more engagement in public science governance and knowledge production (Waldherr, 2012; Peters, 2013). One innovative approach in co-production of knowledge is mobilizing communities through citizen science (Heigl et al., 2019). This also presents additional opportunities to incorporate local knowledge with scientific research, and better match scientific capability to societal needs.

18.4.3.5 Community arenas

Societal choices and development trajectories emerge from decisions made in different arenas which intersect and interact across levels and scales, in diverse institutional settings - some formal with their associated instruments and interventions, while others are informal. Since AR5, both formal and informal setting are increasingly arenas of debate and contestation regarding development choices and pathways *(very high confidence*) (see 18.4.4, Chapters 1, 6, 8, 10 and 17). Community arenas exist from the local to the global scale and constitute the many interactions between governance actors, often transcending any one scale to reflect the emergent outcomes of interactions in political, economic, socio-cultural, knowledge-technology and ecological arenas of engagement. Actions within and between these five arenas hence come together in the community arena of engagement. While community engagement is often described at the level of villages and cities (Ziervogel et al., 2021) (Chapter 8), communities in terms of people interacting with each other sharing worldviews, values and behaviors, also exist at the regional and global levels. For example, civil society engagement in climate action reached a peak in 2019, notably through the global youth movement which led to large global mobilisation and street demonstrations on all continents and in many large cities (Bandura and Cherry, 2020; Han and Ahn, 2020; Martiskainen et al., 2020). Calling for enhanced climate action by governments and other societal actors, the youth movement was supported by many other societal groups and networks, including arenas of community interaction.

While the SR1.5 (de Coninck et al., 2018) for the first time comprehensively assessed behavioral dimensions of climate change adaptation, most literature still has a greater focus on what triggers mitigation behavior (Lorenzoni and Whitmarsh, 2014; Clayton et al., 2015). Meanwhile, with CRD still a relatively young concept, there is little literature focused on what motivates action in pursuit of CRD rather than its subcomponents of climate action and sustainable development. Nevertheless, a common motivation that is emerging in the literature is clinically significant levels of climate distress among individuals (Bodnar, 2008), which is experienced as a continuing distress over a changed landscape which no longer offers solace, also known as solastalgia (*high agreement, medium evidence*) (Albrecht et al., 2007). This is accompanied by a shift from blaming natural forces for disasters to attributing it to human negligence which is known to lead to more acute perceptions of risk as well as more prolonged PTSD than trauma arising from non-human causes. Improving social connections, acknowledging anxiety, reconnecting to nature, and finding creative ways to re-engage are identified as ways of managing this growing anxiety (Lertzman, 2010; Clayton et al., 2017). Climate action in communities at various scales could fulfil many of these needs.

18.4.4 Frontiers of Climate Action

After decades of limited government action and social inertia to reduce the risk of climate change, there is also increasing social dissent toward the current political, economic and environmental policies to address climate (Brulle and Norgaard, 2019; Carpenter et al., 2019). Social movements are demanding radical action as the only option to achieve the mobilization necessary for deep societal transformation *(very high confidence*) (Hallam, 2019; Berglund and Schmidt, 2020).

Prompted by SR1.5, new youth movements seek to use science-based policy to break with incremental reforms and demand radical climate action beyond emissions reductions (Hallam, 2019; Klein, 2020; Thackeray et al., 2020; Thew et al., 2020). Recent social movements and climate protests embrace new modalities of action related to political responsibility for climate injustice through disruptive collective political action (Young, 2003; Langlois, 2014). This is complemented by a regenerative culture and ethics of care (Westwell and Bunting, 2020). These new social movements are based on nonviolent methods of resistance, including actions classified as dutiful, disruptive and dangerous dissent (O'Brien, 2018).

The new climate movement mixes messages of fear and hope to propel urgency and the need to respond to a climate emergency (Gills and Morgan, 2020). While some consider the mix between fear and hope as beneficial to success depending on psychological factors (Salamon, 2019) or political geography (Kleres and Wettergren, 2017) others warn of the risks of a rhetoric of emergency and its political outcomes (Hulme and Apollo-University Of Cambridge Repository, 2019; Slaven and Heydon, 2020).

Research shows that new climate movements have increased public awareness, and also stimulated unprecedented public engagement with climate change *(very high confidence*) (Lee et al., 2020; Thackeray et al., 2020) and has helped rethink the role of science with society (Isgren et al., 2019). Such movements may represent new approaches to accelerate social transformation and have resulted in notable political successes, such as declarations of climate emergency at the national and local level, as well as in universities. Their methods have also proven effective to end fossil fuel sponsorship (Piggot, 2018). Social demands for radical action are likely to continue to grow, as there is growing discontent with political inertia and a rejection of reformist positions.

[START BOX 18.9 HERE]

Box 18.9: The Role of the Private Sector in Climate Resilient Development via Climate Finance, Investments and Innovation.

Climate finance broadly refers to resources that catalyze low-carbon and climate-resilient development. It covers the costs and risks of climate action, supports an enabling environment and capacity for adaptation and mitigation, and encourages R&D and deployment of new technologies. Climate finance can be mobilized through a range of instruments from a variety of sources, international and domestic, public and private (see Sections 18.4.2.2).

The private sector has particular competencies which can make significant contributions to adaptation, through innovative technology, design of resilient infrastructure, development and implementation of improved information systems and the management of major projects. The private sector can be seen as a "supplier of innovative goods and services" to meet the adaptation priorities of developing countries with expertise in technology and service delivery (Biagini and Miller, 2013).

Future investment opportunities in CRD are in water resources, agriculture and environmental services. Provision of clean water is another opportunity, requiring investment in water purification and treatment technologies such as desalination, and wastewater treatment. Weather and climate services are a possible area for private investment. (Hov et al., 2017; Hewitt et al., 2020).

[END BOX 18.9 HERE]

18.5 Sectoral and Regional Synthesis of Climate Resilient Development

Prior sections of this chapter assessed the literature relevant to CRD inclusive of climate risk management, systems transitions and transformation, and actors and the arenas in which they engage one another to enable or constrain CRD. Here, this knowledge is explored in different climatological and development contexts through a synthesis of CRD-relevant assessments within the WGII sectoral and regional chapters.

18.5.1 Regional Synthesis of Climate-Resilient Development

In synthesizing regional knowledge relevant to the pursuit of CRD, this section first considers geographic heterogeneity in regional responses of common climate variables to increases in globally averaged temperatures. Such heterogeneity is a key driver of climate risk in different global regions, as well as human and natural systems within those regions. This is followed by synthesis of various national development indicators, aggregated to the regional level, as well as various challenges, opportunities, and options supporting CRD reported within WGII regional chapters.

18.5.1.1 Climate Change Risk for Different Global Regions

Two important elements of understanding the opportunities and challenges associated with the pursuit of CRD in different regional contexts are a) the geographic variability in climate conditions that shape livelihoods, behaviors, and responses of human and natural systems; and b) how those conditions could shift in the future in response to climate change, which determines the additional burden that climate change could create for adaptation and sustainable development.

The climate analyses of WGI provide information on regional differences in temperature, rainfall, and sea-surface temperatures for different global regions and how they are projected to change in response to different levels of aggregate global warming (Table 18.4). Such data reveal that even when aggregated to broad geographic regions, significant variations exist for all of these parameters, which is a function of the baseline climatology of each region. For example, temperatures in Africa and Australia are, on average, warmer than in Europe or North America. Significant variations are also observed for rainfall variables. Such regional variation in climate conditions is part of the regional context that shapes current patterns of development of the past present and future. They influence biodiversity and natural resource availability as well as exposure to climatic extremes (tropical storms, heat waves, and drought) that contribute to disasters.

The WGI data also indicate that increases in globally averaged temperatures will have different consequences for regional climate change (Table 18.4), including variation in the magnitude and, for precipitation, even the direction of change (*very high confidence*). For example, although average temperatures, daily minimum temperature, and the number of days over a given thresholds are projected to increase in all regions except Antarctica, the magnitude of the change varies. Moreover, little change is projected for daily maximum temperatures across different regions. Nevertheless, the number of days over different temperature thresholds such as 35°C increases markedly in most regions, reflecting the disproportionate impact that global warming has on the tails of temperature distributions. Given outcomes in many systems including public health, agriculture, ecosystems and biodiversity, and infrastructure are often associated with biophysical thresholds (e.g., physiological or design thresholds), those regions where such thresholds are increasingly exceeded due to climate change may experience disproportionately higher impacts (*very high confidence*). Given such temperatures occur more frequently in regions such as Africa and Central and South America, this disproportionate exposure is exacerbated by disproportionate vulnerability, adaptation gaps, and development needs (*very high confidence*; 18.2.4; Table 18.4).

The regional response of precipitation to globally averaged temperatures increases is less clear than temperature, in part due to high intra-region variability. Average daily precipitation remains fairly stable in all global regions in response to higher magnitudes of global warming (Table 18.4). However, 5-day precipitation totals provide a clearer signal of increasing hydrologic activity in response to higher globally averaged temperatures (Table 18.4). Such data no not necessarily reflect changes in rainfall extremes that could occur with downstream consequences for hazards such as drought or flooding. Similarly, while SSTs are more uniform across global ocean basins, all basins are anticipated to warm in response to higher globally averaged temperatures (Table 18.5). Unlike temperature, however, SST increases are anticipated to be only a fraction of the globally averaged increase in temperature, due in large part to the heat capacity of the oceans. Nevertheless, such higher SSTs have implications not only for ocean ecosystems and the distribution of marine species, but also for weather patterns, such as formation and intensity of tropical cyclones (*very high confidence*).

The other aspect of the regional climate responses to global temperature increases that is important for CRD is the marked differences observed between changes in response to 1.5°C versus 4°C of warming. Higher levels of global warming are associated with higher regional changes, including changes in extremes of temperature. This in turn increases climate risk to exposed and vulnerable human and natural systems, thereby increasing demand for adaptation. If that demand is not met, then the adaptation gap will be larger with greater risk of loss and damage (*very high confidence)* (Schaeffer et al., 2015; Chen et al., 2016; United Nations Environment Programme, 2021). This is true not only for regions, but also at the sectoral level (18.5.2). Therefore, CRD pathways must balance the demands for emissions reductions to reduce exposure, adaptation to manage residual climate change risks, and sustainable development to address vulnerability and enhance capacity for sustainable development.

Table 18.4: Projected continental level result ranges for select temperature and precipitation climate change variables by global warming level. Ranges are 5th and 95th percentiles from SSP5-8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 projections. Source: WGI AR6 Interactive Atlas (https://interactive-atlas.ipcc.ch/).

Climate variable	Global warming level	All Regions	North America	Europe	Asia	Centra-South America	Africa	Australia	Antarctica
Mean temperature (degrees C)	4˚C	12 to 15	8 to 11	5 to 9	12 to 14	24 to 27	26 to 29	24 to 27	-33 to -27
	3˚C	11 to 14	6 to 11	4 to 7	10 to 14	23 to 26	25 to 28	23 to 26	-35 to -26
	2˚C	10 to 13	5 to 9	3 to 6	8 to 12	22 to 25	24 to 27	22 to 25	-36 to -27
	1.5˚C	9 to 12	4 to 8	2 to 5	8 to 12	22 to 24	24 to 26	22 to 24	-36 to -27
Minimum of daily minimum temperatures (degrees C)	4˚C	-12 to -5	-25 to -15	-22 to -14	-18 to -9	11 to 15	10 to 14	5 to 10	-64 to -48
	3˚C	-13 to -6	-27 to -15	-24 to -15	-20 to -11	10 to 15	8 to 14	4 to 10	-64 to -50
	2˚C	-15 to -8	-30 to -18	-27 to -17	-22 to -13	9 to 14	7 to 13	3 to 9	-65 to -51
	1.5˚C	-16 to -9	-32 to -20	-28 to -19	-23 to -14	8 to 14	6 to 12	3 to 9	-66 to -51
Maximum of daily maximum temperatures (degrees C)	4˚C	32 to 37	32 to 38	28 to 33	35 to 40	36 to 43	40 to 47	41 to 49	-12 to -5
	3˚C	31 to 39	31 to 38	28 to 34	35 to 41	35 to 44	39 to 51	41 to 54	-12 to -3
	2˚C	30 to 37	30 to 36	26 to 33	33 to 39	34 to 43	38 to 50	39 to 53	-13 to -4
	1.5˚C	29 to 36	29 to 35	25 to 31	32 to 39	33 to 42	38 to 49	39 to 52	-14 to -5
Number of days with maximum temperature above 35˚C – bias adjusted	4˚C	81 to 106	36 to 50	11 to 22	57 to 77	138 to 194	153 to 210	140 to 168	0 to 0
	3˚C	66 to 87	27 to 40	6 to 15	44 to 59	100 to 153	131 to 183	124 to 147	0 to 0
	2˚C	52 to 68	19 to 29	4 to 8	33 to 45	61 to 106	116 to 151	102 to 124	0 to 0
	1.5˚C	45 to 58	16 to 24	2 to 5	30 to 39	43 to 85	107 to 133	94 to 115	0 to 0
Near-surface total precipitation (mm/day)	4˚C	2 to 3	2 to 3	2 to 2	2 to 3	4 to 5	2 to 3	1 to 2	1 to 1
	3˚C	2 to 3	2 to 3	2 to 2	2 to 3	3 to 5	2 to 3	1 to 2	1 to 1
	2˚C	2 to 3	2 to 3	2 to 2	2 to 3	3 to 5	2 to 3	1 to 2	1 to 1
	1.5˚C	2 to 3	2 to 3	2 to 2	2 to 3	3 to 5	2 to 3	1 to 2	1 to 1
Maximum 5-day precipitation amount (mm)	4˚C	79 to 99	75 to 93	53 to 71	81 to 105	118 to 168	68 to 113	81 to 124	20 to 29
	3˚C	66 to 99	68 to 87	48 to 68	70 to 101	97 to 165	60 to 118	76 to 129	19 to 27
	2˚C	64 to 93	65 to 84	47 to 65	66 to 95	93 to 162	55 to 107	73 to 122	18 to 26
	1.5˚C	63 to 91	63 to 83	46 to 64	64 to 93	92 to 160	52 to 105	74 to 119	18 to 25

Table 18.5: Projected sea surface temperature change ranges by global warming level and ocean biome (degrees Celsius). Ranges are 5th and 95th percentiles from SSP5-8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 projections. Source: WGI AR6 Interactive Atlas (https://interactive-atlas.ipcc.ch/).

Global warming level	All ocean biomes	Northern Hemisphere - High Latitudes	Northern Hemisphere - Subtropics	Equatorial	Southern Hemisphere - Subtropics	Southern Hemisphere - High Latitudes	Gulf of Mexico	Eastern Boundaries	Amazon River	Arabian Sea	Indonesian Flowthrough
4˚C	1.9 to 2.4	2.0 to 3.3	2.2 to 2.8	2.1 to 3.0	1.8 to 2.4	1.3 to 2.0	2.1 to 2.8	2.1 to 2.7	1.7 to 2.5	2.3 to 2.9	1.9 to 2.7
3˚C	1.3 to 1.7	1.2 to 2.2	1.4 to 2.4	1.4 to 2.2	1.2 to 1.7	0.7 to 1.4	1.5 to 2.3	1.4 to 2.1	1.2 to 2.0	1.6 to 2.2	1.3 to 1.9
2˚C	0.6 to 1.0	0.5 to 1.4	0.7 to 1.4	0.7 to 1.3	0.5 to 1	0.3 to 0.8	0.6 to 1.4	0.6 to 1.3	0.6 to 1.3	0.6 to 1.3	0.5 to 1.2
1.5˚C	0.2 to 0.7	0.1 to 0.9	0.2 to 1.0	0.2 to 0.8	0.2 to 0.6	0.1 to 0.5	0.2 to 1.0	0.2 to 0.9	0.2 to 0.9	0.2 to 0.9	0.1 to 0.8

18.5.1.2 Regional Perspectives on Climate-Resilient Development

The various regional chapters within the AR6 WGII report each provide insights into progress toward CRD as well as the opportunities and challenges associated with future pursuit of different CRD pathways. Common indicators of development reflect the significant diversity that exists across different global regions with respect to their development context (*very high confidence)*. For example, the Human Development Index, recently adjusted to reflect the effect of planetary pressures (PPAHDI), illustrates the overall higher levels of development of North America and European countries of the global North as well as Australasia compared with Asia, Africa, Central and South America and small islands of the global South. Generally, this reflects the higher levels of vulnerability and greater need for both sustainable development to reduce poverty and support sustainable economies as well as climate action to address climate risk (Table 18.6).

However, even within a given region, there is significant variation in PPAHDI among nations. Such differences reflect fundamental differences in historical patterns of development, as well as current development needs and challenges, and they imply differences in what future development pathways would be consistent with CRD. In addition, nations and regions with lower PPAHDI values suggests greater capacity challenges for both greenhouse gas mitigation and climate adaptation. However, nations and regions with high PPAHDI values also tend to have higher per capita CO_2e emissions production, indicating that economic development based on fossil fuel use undermines both efforts on climate action as well as the SDGs (*very high confidence*) (Figure 18.6). Such challenges are also reflected by differential Gini coefficients and metrics of state fragility among regions, which reflect inequities in income distribution and broader vulnerability of nations and regions to shocks and stressors (Figure 18.6). In addition, high variation is observed in CO2 emissions production, even among comparatively wealthy nations, suggesting CO2e emissions of some nations are tightly coupled to development, while others have pursued more carbon neutral development trajectories. Even within regions such as Africa, Asia, Central and South America, and Europe, large within-region variations are observed in inequality and state fragility, suggesting high variability among nations. Given the emphasis in the sustainable development and CRD literature on equity and vulnerability, addressing such determinants of vulnerability is a core design principle for CRD pathways.

In addition to development indicators, the literature assessed in the WGII regional chapters indicates that different regions experience a range of development challenges and opportunities that affect the pursuit of CRD (*very high confidence*). These represent dimensions of governance, institutions, economic development, capacity, and social and cultural factors that shape decision-making, investment, and development trajectories. For example, significant challenges exist within regions with respect to managing debt and the ability to fund or finance climate action and sustainable development interventions (*very high confidence*). On the other hand, a broad range of opportunities exist to pursue CRD including challenges with debt and financing of adaptation competing policy objectives, social protection programs, economic diversification, investing in education and human capital development, and expanding disaster risk reduction efforts (*very high confidence*).

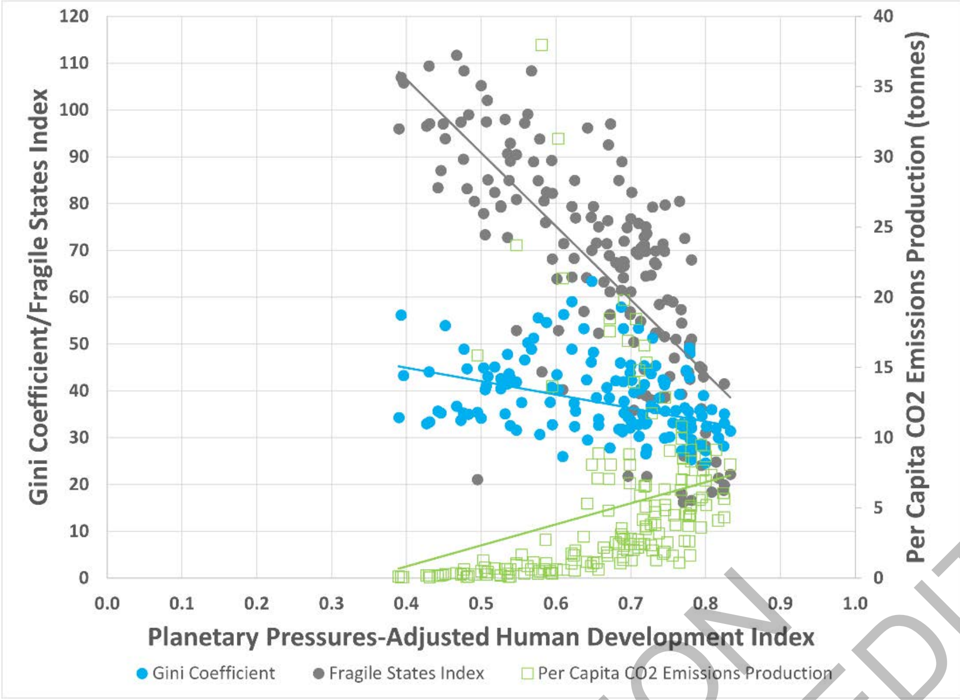


Figure 18.6: Relationship among development indicators relevant to climate-resilient development. National Gini coefficients (most recent year available; n=141; (World Bank, 2021)), the Fragile States Index (2021; n=163; (Fund for Peace, 2021)), and per capita CO2 emissions (2018; n=169; (Human Development Report Office, 2020)) are plotted against the Planetary Pressures-Adjusted Human Development Index (2020, n=163; (Human Development Report Office, 2020)

There are a wide variety of more focused options for climate action and sustainable development (*very high confidence*). Such options have potential for synergies and trade-offs including implications for greenhouse gas mitigation, land use change and conservation, food and water, or social equity. Despite variation in development context, regional assessments suggest CRD efforts will be associated with some common features. For example, in all regions, existing vulnerability and inequality exacerbate climate risk and therefore pose challenges to CRD (*very high confidence*). Furthermore, low prioritization of sustainability and climate action in government decision making, low perceptions of climate risk, and path dependence in governance systems and decision-making processes all pose barriers to system transitions, transformation, and CRD (*very high confidence*).

18.5.2 Sectoral Synthesis of Climate-Resilient Development

The sectoral chapters of the WGII report provide insights regarding how development processes interact with sectors to shape the potential for climate-resilient development. Similar to global regions, each sector is associated with various challenges, opportunities, and options that enable or constrain CRD (Table 18.7). A number of challenges are common across sectors and mirror those associated with different regions. For example, issues associated with natural resource dependency, access to information for decision-making, access to human and financial capital, and path dependence of institutions represent barriers that must be overcome if sectors are to support transitions that enable CRD. These challenges are more acute within vulnerable communities or nations where capacity to innovate and invest are constrained and social inequities reinforce the status quo (*very high confidence*). At the same time, a number of sector-specific opportunities for mitigation, adaptation, and sustainable development can be used to integrate sectors into CRD pathways. This could include policies and planning initiatives to enhance sector sustainability and resilience as well as capacity building and greater inclusion of different actors and groups in decision making including capitalizing on local and indigenous knowledge as a mechanism for more representative and equitable action.

In addition, the sectoral assessments identify a broad range of specific adaptation, mitigation, and sustainable development options that could play a role in facilitating CRD. Many of these options appear initially to be specific to a given sector. For example, options for the water sector (Chapter 4) are assessed independently from those for health and well-being (Chapter 7). In practice, however, evidence suggests the importance of thinking about sectoral options as cross-cutting, mutually supportive, and synergistic packages rather than singular options. First, each of the sectoral chapters has links to multiple SDGs (Table 18.7), implying each sector is important for achieving a range of sustainability goals that extend beyond sectoral boundaries. Moreover, progress across multiple sectors simultaneously creates opportunities for synergies for achieving the SDGs, but also enhances the risk of potential trade-offs (*very high confidence*). Second, a number of options are common to multiple sectors. For example, options associated with ecosystem-based adaptation and nature-based approaches to environmental management appear in multiple sectors (Table 18.7). Similarly, climate-smart agriculture and agroecological approaches to food systems create opportunities for food security, but those same options also benefit land-based ecosystems, water, poverty and livelihoods, and human well-being. Joint implementation

18.5.3 Feasibility and Efficacy of Options for Climate-Resilient Development

While both the sectoral and regional assessments indicate a rich toolkit of management options is available to decision-makers to facilitate CRD, two key uncertainties undermine efforts to implement those options. The first is the feasibility of implementation. Options that seem promising could nevertheless encounter implementation barriers due to cost, absence of necessary capacity, lack of public acceptance, or competition with alternative options. Progress in the literature since the AR5 and SR1.5 reports enables improved consideration for options feasibility for both mitigation (SR1.5 ref) and adaptation (Cross-Chapter Box FEASIB). This assessment allows the range of available options to be considered in a more critical light, particular when on is considering opportunities for implementation over the near-term. Meanwhile, the other challenge is that of option efficacy. Significant uncertainties remain regarding how well a given option will perform in a specific context and whether it is capable of adequately addressing risk (18.6.1). Such uncertainties can undermine the pursuit of CRD or at least efforts to accelerate system transitions that support CRD (*medium evidence, medium agreement)* (18.3). Accordingly, closer examination of option implementation in the real world, including within different sectoral and regional contexts, would enhance the knowledge available to decision-makers regarding which options will best fit the needs of a given CRD pathway.

Table 18.6: Regional synthesis of dimensions of climate-resilient development. For each region, quantitative information is provided on common development indicators including the planetary pressures-adjusted human development index (PPHDI, 2020, n=169; (Human Development Report Office, 2020)), Gini coefficients (GINI, most recent year available; n=156; (World Bank, 2021)), Fragile States Index (FRAGILITY; 2021; n=173; (Fund for Peace, 2021)), and per capita CO2 emissions production (CO2/PC, 2018; n=169; (Human Development Report Office, 2020)). Each indicator is associated with a mean value among nations within a specific region as well as the range (minimum to maximum) value. In addition, the table contains evidence of sustainable development challenges and opportunities as well as adaptation/sustainable development options and potential synergies and trade-offs associated with their implementation. Synergies and trade-offs are categorized as follows: (T) Trade-off among policies and practices; (S+) Synergy among policies and practices that enhances sustainability; (S-) Synergy among policies and practices that undermines sustainability.

Region	***Development Indicators mean (range)***		***Challenges***	***Opportunities***	***Options***	***Synergies and Trade-Offs***
Africa	PPAHDI	0.53 (0.39-0.72)	• institutional and financial challenges in programming and implementing activities to support concrete adaptation measures (9.14.5) • high debt levels exacerbate fiscal challenges and undermine economic resilience (9.14) • insufficient development and adaptation finance and accessibility of finance (9.14.5) • complexity of estimating the costs and benefits for adaptation measures in specific contexts (9.14.2) • exclusions of migrants and other vulnerable populations from social programs (9.9.4) • mismatch between the supply of, and demand for, climate services (9.5)	• climate change literacy can enable the mainstreaming of climate change into national and sub-national developmental agendas (9.4.2) • Adaptive responses can be used as an opportunity for comprehensive, transformative change (9.6.2) • Investments in human capital, can facilitate socioeconomic development and poverty reduction (9.9.1) • Strengthening the participation of women in decision-making as well as advance traditional and local knowledge can support climate action and sustainable livelihoods (9.9.3)	• strengthening climate services (9.4.2) • ecosystem based adaptation (9.11.4.2) • economic diversification (9.12.3) • intensive irrigation9.15.2 • agricultural and livelihood diversification (9.12.3) • drought resistant crop varieties (9.15.2) • soil and water conservation (9.15.2	• (T) competing uses for water such as hydropower generation, irrigation, and ecosystem requirements create trade-offs among different management objectives (9.7.3) • (T) migration in response to unfavorable environmental conditions provides opportunities for farmers but puts pressure on the provision of social services and reduces farm labor (9.15.2) • (T) intensive Irrigation contributes to the development of agriculture but has come at a cost to ecosystem integrity and human well-being (9.15.2)
	GINI	42.8 (27.6-63.4)				
	FRAGILITY	87.3 (57.0-110.9)				
	CO2/PC	1.1 (0.0-8.1)				
Asia	HPAHDI	0.65 (0.47-0.78)	• migration and displacement (Box 10.6) • uneven economic development (10.4.6) • rapid land use change (10.4.6)	• Investing in climate-resilient and sustainable infrastructure can be a source of green jobs as well as a means of reducing climate vulnerability (10.6.2)	• risk insurance 10.5.5 • climate-smart agriculture 10.4.5.5, (Table 10.6) • wetland protection and restoration (Table 10.6)	• (S+) nature-based adaptation solutions, wetland protection, and climate-smart agriculture enhance carbon sequestration (Table 10.6)
	GINI	34.9 (26.6-43.9)				
	FRAGILITY	73.6				

		(32.3-111.7)	• increasing inequality (10.4.6) • large, socially differentiated vulnerable populations (10.4.6)	• sustainable development pathways that connect climate change adaptation and disaster risk reduction efforts can reduce climate vulnerability and increase resilience (10.6.2) • social protection programs can develop risk management strategies to address loss and damage from climate change (10.5.6)	• aquifer storage and recovery (Table 10.6) • integrated smart water grids (Table 10.6) • disaster risk management (Table 10.6) • early warning systems (Table 10.6) • resettlement and migration (Table 10.6) • nature-based solutions in urban areas • coastal green infrastructure (Table 10.6)	• (S+) disaster risk reduction and capacity building has synergistic interactions with climate adaptation when the two are effectively integrated (10.6.2) • (S+) environmental sustainability has benefits for relieving poverty and promoting social equity (10.6.4) • (T) intensive irrigation and other forms of water consumption can have a negative effect on water quality and aquatic ecosystems (10.6.3)
	CO2/PC	6.3 (0.3-38.0)				
Australasia	PPAHDI	0.75 (0.70-0.81)	• Underinvestment in adaptation, particularly in public health systems, given current and projected risks (11.3.6.3) • Underlying social and economic vulnerabilities exacerbate disadvantage among particular social groups (11.8.2) • Competing policy and planning objectives within governments (11.7.2) • Limits to adaptation across the region and among neighbors (11.7.2) • Fear of litigation and demands for compensation create disincentives for climate adaptation (11.7.2) • different climate change risk perceptions among different groups (11.7.2)	• implementation of national policies and guidance on climate adaptation and resilience (Box 11.5) • cooperation among individual farmers for adaptation and regional innovation (11.7.1) • enhancing understanding of Indigenous knowledge and practices (Table 11.11)	• climate adaptation services, planning and tools from government and private sector providers (11.7.1) • enhancing governance frameworks (Table 11.17) • building capacity for adaptation (Table 11.17) • community partnership and collaborative engagement(Table 11.17) • flexible decision-making (Table 11.17) • reducing systemic vulnerabilities (Table 11.17) • providing adaptation funding and compensation mechanisms (Table 11.17) • addressing social attitudes and engagement in adaptation and climate action (Table 11.17)	• (T) adapting to fire risk in peri-urban zones introduces potential trade-offs among ecological values and fuel reduction in treed landscapes (11.3.5)
	GINI	34.4 (34.4-34.4)				
	FRAGILITY	20.1 (18.4-21.8)				
	CO2/PC	12.1 (7.3-16.9)				
	PPAHDI	0.71				

Central and South America		(0.62-0.78)	• vulnerability of informal settlements with chronic exposure to everyday, non-climate risks • limited political influence of poor and most vulnerable groups • poor market access of rural households • little consideration of the implications of NDCs for poverty and livelihoods • corruption, particularly in the construction and infrastructure sector • gender inequities in labor markets • limits to adaptation	• Address existing development deficits, particularly the needs of informal settlements and economies • Adopt collaborative approaches to decision-making that integrate civic groups and communities as well as the private sector • Enhance adoption of sustainable tourism and livelihood diversification	• upgrading of informal and vulnerable settlements • capacity building in national and city level government institutions • enhancing social protection programs • integrated land use planning and risk-sensitive zoning • infrastructure greening • disaster risk mitigation and management • emergency medical and public health preparedness • improving insurance mechanisms and climate financing • ecosystem conservation, protection, and restoration • appropriate use of climate information and development of climate services	• (S+) conservation and restoration of natural ecosystems have synergies with mitigation, adaptation and sustainable development (12.7.1)
	GINI	47.2 (38.6-57.9)				
	FRAGILITY	65.9 (35.9-92.6)				
	CO2/PC	2.2 (0.9-4.8)				
Europe	PPAHDI	0.76 (0.52-0.83)	• mitigation and adaptation remain siloed around sectoral approaches (Box 13.3) • institutional, policy, and behavioral lock-ins constrain the rate of system transitions (13.11.4) • legislative and decision-making process constraints on climate action (13.11.4) • high adaptation costs and concerns about effectiveness and feasibility (13.3.2, Table 13.A.5) • competition for land use among adaptation and other uses (13.3.2)	• engagement in climate change knowledge, policy, and practice networks (Box 13.3) • national policies can lead to more ambitious and integrated climate planning and action with associated co-benefits (Box 13.3) • system transformations towards more adaptive and climate resilient systems (13.11.4, Box 13.3)	• ecological restoration of habitats agroforestry and reforestation (13.8.2) • “smart farming” and knowledge training (13.5.2.1) • soil management practices (13.5.2.1) • changing sowing dates and changes in cultivars (13.5.2.1) • stricter enforcement of existing health regulations (13.7.2) • integrated coastal zone management and marine spatial planning (13.4.2) • nature-based solutions (13.4.2) • climate services 13.6.2.3	• (T) wind farms support greenhouse gas mitigation but have ecosystem implications and impacts (13.4.2) • (T) adapting and mitigating climate change through afforestation and forest management may be hampered by biophysical and land use trade-offs (13.3.2)
	GINI	31.9 (24.6-41.3)				
	FRAGILITY	41.1 (16.2-72.9)				
	CO2/PC	6.8 (1.3-21.3)				

			• perceptions of climate change as irrelevant or not urgent (13.3.2) • public budget and human capital limitations (13.3.2)		• tailored insurance products for specific physical climate risks13.6.2.5 • protection of world heritage sites (13.8.2)	
North America	PPAHDI	0.72 (0.72-0.73)	• lack of representation of all groups and communities in politics and decision-making (14.6.3) • economic and financial constraints on adaptation within communities 14.6.2 • persistent social vulnerability and inequities 14.6.3, 14.4.7.3 • adaptation actions that are maladaptive and exacerbate existing inequities (14.6.2.1) • constraints on capacity for data collection (Table 14.8) • limited organizational willingness implement new and untested solutions (Table 14.8)	• increased focus on building adaptive capacity in small towns and rural areas (14.6.3) • greater use of SDGs as a framework for equitable adaptation measures (14.6.3) • broader and deeper recognition of the role of Indigenous knowledge and local knowledge systems in adaptation (14.6.3) • greater emphasis on participatory governance and co-production of knowledge in adaptation decision-making (14.6.2.2) • enhanced use of risk-based decision analysis frameworks and flexible adaptation pathways (14.6.2.2) • coordination of policies to support transformational adaptation (14.6.2.2)	• indigenous knowledge-based land and resource management (Section 14.4.4) • adaptive co-management of agriculture and freshwater resources (Section 14.4.3) • ecosystem based management and nature based solutions (Box 14.3) Section 14.4.2, 14.4.3, 14.4.4) (Table 14.9). • increase efficiency and equity of water management and allocation (14.4.3.3) • energy conservation measures (14.6.1.3) • guidelines, codes, standards, and specifications for infrastructure (14.6.1.6) • modifying zoning and buying properties in floodplains (14.6.1.3) • web-based tools for visualizing and exploring climate information scenario planning and risk analyses (s14.6.1.6)	• (S+) Post-fire ecosystem recovery measures, restoration of habitat connectivity, and managing for carbon storage enhance adaptation potential and offers co-benefits with carbon mitigation (Box 14.1) • (T) REDD+ represents a trade-off between carbon mitigation and the ability of communities to improve their food security (14.4.7) • (T) New coastal and alpine developments generate economic activity but enhance local social inequalities (15.4.10)
	GINI	40.0 (33.3-45.4)				
	FRAGILITY	45.4 (21.7-69.9)				
	CO2/PC	11.9 (3.8-16.6)				
Small Islands	PPAHDI	0.68 (0.51-0.76)	• high dependence of economic activity on tourism (15.3.4.5) • Lack of coordination among government departments (15.6.1) • limited regional cooperation (15.6.1)	• increasing women's access to climate change funding and support from organizations (15.6.5)promoting agroecology, food sovereignty, and regenerative economies (15.7)	• raising dwellings and other infrastructure (15.5.2) • land reclamation (15.5.2) • migration and planned resettlement (15.5.2) • ecosystem-based adaptation including Indigenous and local knowledge (15.5.2)	• (S+) development decisions and outcomes are strengthened by consideration of climate and disaster risk (15.7) • (S-) impacts of invasive alien species on islands are projected to increase with
	GINI	40.2 (28.7-56.3)				
	FRAGILITY	64.6 (38.1-97.5)				

	CO2/PC	3.7 (0.3-31.3)	• absence of planning frameworks (15.6.1) • corruption and corrupt people in political and public life (15.6.1) • insufficient human capital (15.6.1) • competing development priorities (15.5.5) • lack of education and awareness around climate change (15.6.4) • failure of externally driven adaptation (15.6.5) • constraints on economic, legislative, and technical capacity of local governments (15.7)	• expanding sustainable tourism economies (15.7) • integrating climate change and disaster management with broader development planning and implementation (15.7) • using climate risk insurance as a way to support development and adaptation processes (15.7) • improving cross sectoral and cross agency coordination (15.7) • enhanced integration between development assistance, public financial management, and climate finance (15.5.7)	• protected areas (15.5.2) • ecosystem restoration and improved agroforestry practices (15.5.2 15.5.4) • community-based adaptation (15.5.5) • livelihood diversification and use of improved technologies and equipment (15.5.6) • diversifying cropping patterns, expanding or prioritizing other cash crops (15.5.6) • small-scale livestock husbandry (15.5.6) • irrigation technologies (15.5.6) • diversification away from coastal tourism • disaster risk management (DRM) (15.5.7) • early warning systems and climate services (15.5.7)	time due to synergies between climate change and other drivers (15.3.3) • (S-) synergies between changing climate and other natural and anthropogenic stressors could lead to disproportionate impacts on biodiversity (15.3.3)

Table 18.7: Sectoral synthesis of dimensions of climate-resilient development. For each sectoral chapter of the WGII report, this table identifies those SDGs that are discussed in the relevant chapter as being particularly relevant to the sector. In addition, the table contains evidence of sustainable development challenges and opportunities as well as adaptation/sustainable development options and potential synergies and trade-offs associated with their implementation. Synergies and trade-offs are categorized as follows: (T) Trade-off among policies and practices; (S+) Synergy among policies and practices that enhances sustainability; (S-) Synergy among policies and practices that undermines sustainability.

Sector	*Relevant SDGs*	*Challenges*	*Opportunities*	*Options*	*Trade-offs*
Terrestrial and freshwater ecosystems and their services	SDG 1, SDG 2, SDG 3, SDG 6, SDG 7, SDG 9, SDG 10, SDG 11,	• low capacity for dispersal limits range shifts to match climate (2.6.1) • constraints on the evolution of greater stress tolerance among species (2.4.2, 2.6.1) • altered peatland drainage and repeated disturbances pose	• nature based solutions offer the opportunity to address climate change and biodiversity problems in an integrated way (2.6) • adaptation can be integrated with the protection of biodiversity and land-based	• habitat restoration, connectivity, and creation of protected areas (Table 2.5) • integrated landscape management (Table Cross-Chapter Box NATURAL.1 in Chapter 2)	• (S+) ecosystem-based adaptation measures, such as restoration of forests and wetlands for flood and erosion control help maintain freshwater supply and quality (2.2.2) • (S-) over-grazing/stocking of pastures and grasslands can result

	SDG 12, SDG 13, SDG 15, SDG 17	barriers to restoration of tropical peatlands (2.4.3) • demonstrating the efficacy of natural flood management efforts poses challenges to its deployment (2.6.5) • uncertainties in climate and socioeconomic projections constrain adaptation planning and implementation (2.7)	climate change mitigation initiatives (2.6.2)	• community-based natural resource management (2.6.5.7) • maintain or restore natural species and structural diversity (Table Cross-Chapter Box NATURAL.1 in Chapter 2) • restoration of hydrological flows and catchment vegetation (Table Cross-Chapter Box NATURAL.1 in Chapter 2) • control of feral herbivores with (Table Cross-Chapter Box NATURAL.1 in Chapter 2) • reduce non-climatic stressors to land-based ecosystems (Table 2.6)	in soil erosion and the loss of biodiversity (Table Cross-Chapter BoxNATURAL1 in Chapter 2) • (T) planting non-native monocultures for mitigation can reduce biodiversity and resilience • (T) inappropriate hydrological restoration can result in increased methane emissions (Table Cross-Chapter Box NATURAL1 in Chapter 2) • (T) afforestation/reforestation and bioenergy initiatives can conflict with other land uses such as food and timber production (Table Cross-Chapter Box BECCS, 2.2.2, Box 2.2)
Ocean and coastal ecosystems and their services	SDG1, SDG2, SDG3, SDG5, SDG7, SDG8, SDG9, SDG10, SDG11, SDG12, SDG13, SDG14	• shifts in the distribution of fish species across exclusive economic zones present governance, ecological, and conservation challenges (3.4.3) • resource constraints impede the implementation of ecosystem-based and community-based adaptation for low- to middle-income nations (3.6.2) • governance in marine social-ecological systems is highly complex with poorly-defined legal frameworks (3.6.2) • "Coastal squeeze" challenges adaptation, creating tensions between coastal development and coastal habitat management (3.6.3)	• development assistance can help address resource constraints associated with marine ecosystem management (3.6.3) • improving coordination among actors and projects will contribute to achieving SDGs (3.6.3) • private finance can support restoration of blue-carbon systems (3.6.3) • joint implementation of coastal and marine management initiatives can address governance challenges across scales and sectors (3.6.3) • ocean-based renewable energy options can reduce reliance on imported fuel (3.6.3)	• maritime spatial planning and integrated coastal management (3.6.2; Figure 3.2.6) • adaptive and sustainable fisheries management (3.6.2) • habitat restoration (3.6.2) • fishery mobility (Figure 3.6.2) • assisted evolution (Figure 3.2.6) • increase participation in management and governance (Figure 3.2.6) • nature-based solutions (3.6.2) • hard and soft infrastructure (Figure 3.2.6) • livelihood diversification (Figure 3.6.2)	• (S+) adaptation in ocean and coastal systems can be designed in ways that substantially contribute to the SDGs and not only support but allow the attainment of social, environmental and economic targets (3.6.4) • (S+) blue/green economies can reduce emissions and finance adaptation pathways (3.6.3) • (T) built infrastructure conflicts with mitigation goals and can create potential ecological, social and cultural impacts that undermines ecosystem health (3.6.2)

				• disaster mitigation and response (Figure 3.2.6) • finance and market mechanisms (Figure 3.2.6)	
Water	SDG 1, SDG 2, SDG 3, SDG 6, SDG 7, SDG 10, SDG 11, SDG 13	• uncertainty in future water availability (Box 4.1, Box 4.4) • lack of sufficient data, information and knowledge in understanding the water energy food nexus (Box 4.6) • increasing urbanization is creating new and difficult demands for urban water management. (4.3.4) • barriers to adapting water-dependent livelihoods in rural communities (4.3.1) • mainstreaming water management across sectors and enhancing finance for adaptation (4.3.5) • path-dependency of institutions, and the speed at which these allow for changes in the decision-making process (4.5.3)	• a resilient circular economy delivers access to water, sanitation, wastewater, and ecological flows (Box 4.7) • adaptive sanitation systems and sustainable urban drainage contribute to a 'one health approach' which can prevent water and sanitation contamination risks during floods and droughts. (Box 4.7) • climate-proof infrastructure would reduce infection risks in flood-prone areas (Box 4.7) • governance can derive legitimacy from inclusion of multiple stakeholders, including women, indigenous communities and young people (4.6.6) • Indigenous and local knowledge can help ensure solutions align with the interests of communities (FAQ 4.5)	• changes in crop cultivars and agronomic practices (4.5) • changes in irrigation and water management practices (4.5) • water and soil conservation (4.5) • migration and off-farm livelihood diversification (4.5) • collective action, policies and institutions (4.5) • economic and financial incentives (4.5) • training and capacity building (4.5) • flood risk reduction measures (4.5) • urban water management (4.5) • water, sanitation, and hygiene adaptations (4.5) • agro-forestry and forestry responses (4.5) • livestock and fishery responses (4.5) • indigenous and local knowledge (4.5) • energy related adaptations (4.5)	• (S+) increasing the proportion of sewerage, treated wastewater, recycling and safe reuse would help reach climate and water targets (Box 4.7) • (S+) solar irrigation pumps provide for income diversification for small and marginal farmers while also generating renewable energy (Box 4.7) • (T) desalination of seawater or brackish inland water is energy-intensive, high salinity brine, and other contaminants (4.5.5) • (T) negative-emission technologies, such as direct air capture can result in a net increase in water consumption (4.5.5)
Food, fiber, and other ecosystem products	SDG1, SDG2, SDG3, SDG4, SDG5, SDG6,	• increased cost and management challenges of providing safe food (5.2.2) • warming-induced shifts of species create resource allocation	• integrated approaches to food, water, health, biodiversity and energy that involve vulnerable groups can help to address current and future food security challenges, reduce vulnerability	• livelihood diversification (5.4.4) • social protection policies and programs (5.4.4) • changes in crop management including irrigation,	• (S+) agricultural production systems that integrate crops, livestock, forestry, fisheries and aquaculture can increase food production per unit of land, reduce

	SDG7, SDG9, SDG9, SDG10, SDG11, SDG12, SDG13, SDG14, SDG15, SDG16	challenges among different fishing fleets (5.2.1) • challenges related to REDD+ implementation and forest use (5.6.3) • differences in perceptions about the validity of different forms of knowledge (5.8.4) • inequality in access to climate services (5.14.1) • lack of support, policies, and incentives for the adoption of agroecological approaches (BIOECO.1) • financial barriers limit implementation of adaptation options in agriculture, fisheries, aquaculture and forestry (5.14.3)	of Indigenous people, small-scale landholders and pastoralists, and promote resilient ecosystems. (5.12.3, 5.13.2; 5.14) • agroforestry delivers benefits for climate change mitigation, adaptation, desertification, land degradation, and food security and is considered to have broad adaptation and moderate mitigation potential (5.10.4) • partnerships between key stakeholders such as researchers, forest managers, and local actors can lead to a shared understanding of climate-related challenges and more effective decisions. (5.6.3)	fertilizers, planting schedules, and crop varieties (5.4.4.1) • adjusting water management for forage production (5.5.4) • rotational grazing of livestock (5.5.4) • fire management to control woody thickening of grass (5.5.4) • using more suitable livestock breeds or species (5.5.4) • migratory pastoralist activities (5.5.4) • monitor and manage the spread of pests, weeds, and diseases (5.5.4) • nature- or ecosystem-based strategies (5.12.5.2)	climatic risk, and reduce emissions (Chapter 5 ES) • (S+) integrated approaches to food, water, health, biodiversity and energy can help address current and future food security challenges, reduce vulnerability of Indigenous people, small-scale landholders and pastoralists, and promote resilient ecosystems. (5.12.3, 5.13.2; 5.14) • (T) growing biomass demand for producing sustainable bioproducts competes with food production with potential effects on food prices and knock-on effects related to civil unrest (BIOECO.1)
Cities, settlements and key infrastructure	SDG11, SDG13, SDG17	• poor municipal funding, data collection, and collaboration hinders sustainable development initiatives, capacity building, and climate action (6.1.5, 6.4.5, 6.4.9) • high urbanization rates pose challenges to areas that already have high levels of poverty, unemployment, informality, and housing and service backlogs (6.2.1) • Limited capacity for early-warning systems in low-income countries (6.3.2) • lack of administrative capacities, coordination across sectors and efforts, transparency and accountability slows sustainability transitions and disaster risk reduction (Case Study 6.4)	• urban ecological infrastructure including green, blue, turquoise and others can be a source of nature-based solutions that can improve both adaptation and mitigation in urban areas (6.1.2) • transition architecture movements can drive urban adaptation (6.4.1) • transformative capacities support adaptation efforts and systemic change processes (6.4.4) • incorporating Indigenous and local knowledge help generate more people-oriented and place-specific adaptation policies (6.4.7) • climate finance offers the opportunity to overcome structural impediments to climate action (Box 6.5)	• green infrastructure, sustainable land use and planning, and sustainable water management (6.1.2) • nature-based solutions (6.3.3) • insurance (6.3.2) • switching to air cooling for thermal power plants (6.3.4) • increasing the efficiency of hydro and thermoelectric power plants (6.3.4) • changing reservoir operation rules (6.3.4) • upgrading infrastructure and strengthening, or relocating (critical) assets (6.3.4) • including green, blue, turquoise and nature-based solutions (Cross-Chapter Box URBAN in Chapter 6)	• (S+) sustainable urban energy planning that includes opportunities to avoid and reduce the UHI effect can provide synergies for both climate mitigation and adaptation in urban areas (Cross-Chapter Box URBAN in Chapter 6) • (S+) natural ventilation and passive energy strategies can capture synergies between climate mitigation and adaptation (Cross-Chapter Box URBAN in Chapter 6) • (S+) community-based adaptation has potential to be better integrated to enhance well-being and create synergies with the Sustainable Development Goals • (T) urban mitigation efforts can create trade-offs with adaptation such as intensifying the Urban

			• urban ecological infrastructure can be a source of nature-based solutions that can improve both adaptation and mitigation in urban areas (Cross-Chapter Box URBAN in Chapter 6) • high density environments coupled with other design measures can provide mitigation and adaptation benefits (Cross-Chapter Box URBAN in Chapter 6)	• cooling networks (Cross-Chapter Box URBAN in Chapter 6) • early warning systems (Table 6.4) • resource demand and supply side management strategies (Table 6.4) • enhanced monitoring of air quality in rapidly developing cities (Table 6.4) • investment in air pollution controls (Table 6.4) • core and shell preservation, elevation and relocation for heritage buildings (6.3.2)	Heat Island (UHI) effect (Cross-Chapter Box URBAN in Chapter 6) • (T) efforts aimed at increasing adaptation may undermine mitigation objectives by increasing investment in hard infrastructure that increases emissions (Cross-Chapter Box URBAN in Chapter 6) • (T) lack of open and green spaces may induce long-distance leisure trips thereby increasing emissions and (Cross-Chapter Box URBAN in Chapter 6)
Health, wellbeing and the changing structure of communities	SDG3, SDG5, SDG8, SDG10, SDG13	• a lack of capacity for adaptation has resulted in only moderate or low levels of adaptation implementation across different countries (7.4.2) • transitioning to renewable energy sources presents opportunities for realizing health co-benefits (7.4.4) • shifting to healthier plant-rich diets can reduce GHG emissions and reduce land-use (Cross-Chapter Box HEALTH in Chapter 7) • future flows of migration within and between countries are likely to respond strongly to particular combinations of climatic hazards and may present challenges for future adaptation policies and programs • climate change disruptions to natural environments can be expected to disrupt livelihood practices, stimulate higher rates	• COVID-19 recovery investments offer an opportunity to contribute to climate resilient development through a green, resilient, healthy and inclusive recovery (Cross-Chapter Box COVID in Chapter 7) • investing in basic infrastructure for all can transform development opportunities, increase adaptive capacity and reduce climate risk (Cross-Chapter Box HEALTH in Chapter 7) • Integrated agroecological systems offer opportunities to increase dietary diversity while building local resilience to climate-related food insecurity (7.4.2) • Incorporating climate change and health considerations into disaster reduction and management strategies could	• improved building and urban design including use of passive cooling systems (Table 7.2) • better access to public health systems for the most vulnerable (Table 7.2) • deployment of renewable energy sources (Table 7.2) • improved water, sanitation and hygiene conditions (Table 7.2) • early-warning system of vector-borne diseases, insecticide treated bed nets, and indoor spraying of insecticide (Table 7.2) • targeted efforts to develop vaccines for infectious diseases exacerbated by climate change (Table 7.2) • improved personal drinking and eating habits (Table 7.2)	• (T) energy strategies for energy efficiency and GHG emissions reductions can generate health co-benefits through improved air quality but may slow poverty reduction efforts (7.4.2, 7.4.5) • (S+) investing in adaptation for health and community wellbeing has the potential to generate considerable co-benefits in terms of reducing impacts of non-climate health challenges • (S+) investments in mitigating greenhouse gas emissions will not only reduce risks associated with dangerous climate change, but will increase population health and wellbeing through a number of pathways. (7.4)

		of outmigration to urban centers, and in some instances necessitate planned or organized relocations of exposed settlements (Cross-Chapter Box MIGRATE in Chapter 7)	potentially improve funding opportunities (7.4.2) • adaptive urban design that provides access to healthy natural spaces can promote social cohesion and mitigate mental health challenges (7.4.2)	• improved food storage, food processing, and food preservation (Table 7.2) • emergency shelters for people to escape heat (Table 7.2) • improved funding and access to mental health care (Table 7.2) • improved education for girls and women (Table 7.2) • improved maternal and child health services (Table 7.2)	
Poverty, livelihoods and sustainable development	SDG1, SDG2, SDG3, SDG5, SDG10, SDG14	• use of political frameworks for decision-making that are unfavorable towards adaptation and system transitions (Table 8.4) • attitudes toward risk and other cultural values limit responses (Table 8.4) • psychological distress causes insecurity and behaviors that increase vulnerability (Table 8.4) • limited financial resources to support adaptation projects (8.2.2, Table 8.4) • small-holder farmers have poor access to markets and land tenure (8.6.1) • unsuitable infrastructure may increase exposure (Table 8.4) • lack of access to technologies that can support adaptation (Table 8.4) • gender-based inequalities constrain women's access to resources for adaptation (Table 8.7) • poverty constrains livelihood diversification, resilience or adaptive capacity (Table 8.7)	• polycentric governance, adaptive governance, multi-level governance, collaborative governance, or network governance are increasingly used to understand transitions towards climate-compatible development (8.6.2) • well-coordinated and integrated nexus approaches to adaptation offer opportunities to build resilient systems while harmonizing interventions, mitigating trade-offs and improving sustainability (8.6.2) • income from new livelihood activities can support recovery following disasters linked to climate variability and change (8.4.5) • improving industrial processes can contribute to the optimized use of energy, reuse of waste, reducing GHG emissions, use of biomass and more efficient equipment (Table 8.3) • industrialization and technological innovation in rural areas may assist vulnerable	• expanded private sector activity and public-private partnerships (8.6.1) • credit and insurance (8.6.1) • use of climate-smart agricultural practices and technologies (8.6.1) • crop insurance (8.6.1) • conservation agriculture (8.6.1) • changing farmers' perception and enhancing farmers' adaptive capacity (8.6.1) • REDD+ (8.6.1) • improving industrial processes (Table 8.3) • renewable energy and energy efficiency (Table 8.3) • smart electricity grids (8.6.1) • green buildings (8.6.1) • efficient fuels (8.6.1) • pollution control investments (8.6.1) • public transit and non-motorized transport with increased use of biofuels (8.6.1)	• (S+) agriculture technologies facilitate mitigation to climate change and adaptation such as saving water while maintaining grain yield (8.6.1) • (S+) sustainable pastoralism increases carbon sequestration but can also contribute to adaptation by changing grazing management, livestock breeds, pest management, and production structures (8.6.1) • (S+) REDD+ may provide adaptation benefits by enhancing households' economic resilience through positive livelihood impacts (8.6.1) • (S+) solar energy contributes to reducing GHG emissions and improving air quality (8.6.1) • (S+) hydropower contributes to mitigation and adaptation through water resource availability for irrigation and drinking water (8.6.1) • (S+) green roofed buildings contribute to cooler temperatures, thereby reducing energy use for air-conditioning (8.6.1)

		• indigenous peoples and other populations with strong attachments to place face barriers to adaptation (Table 8.7) • local institutions face ongoing challenges in gaining support from higher governance levels, particularly in developing countries. (8.5.2)	communities through provision of resources, enhanced forecast information, or reuse of biowaste (Table 8.3) • responses to climate change can create significant development opportunities including job creation and livelihood diversification (8.4.3)	• integrated natural resource management (Table 8.2) • disaster risk management (Table 8.2) • relocation of vulnerable communities (Table 8.2) • Education and communication (Table 8.2) • land use planning (Table 8.3)	• (T) mitigation measures such as bioenergy may result in trade-offs with efforts to achieve sustainable development, eradicate poverty and reduce inequalities (8.6.1) • (T) migration to urban centers can be a form of adaptation, but can increase the vulnerability of communities of origin or at destinations (8.2.2)

18.6 Conclusions and Research Needs

18.6.1 Knowledge Gaps

Research to improve the understanding of CRD currently exists in a nascent state, because, as noted in the AR5, "*integrating climate change mitigation, climate change adaptation, and sustainable development is a relatively new challenge*" (Denton et al., 2014). While a large volume of literature has emerged since the AR5 that spans the nexus of sustainable development, CRD, and climate action, the identified research gaps in AR5 (Denton et al., 2014) continue to be priorities for informing CRD. These include enhancing understanding of mainstreaming of climate change into institutional decision-making, managing risk under conditions of uncertainty, catalyzing system transitions and transformation, and processes for enhancing participation, equity, and accountability in sustainable development (*very high confidence*).

The more recent literature adds significant context to the concept of CRD, but also introduces broader perspectives regarding its significance in the arena of climate action. Hence, concepts that are both complementary to, and competitive with, CRD, such as climate safe', 'climate compatible' and 'climate smart' development (Huxham et al., 2015; Kim et al., 2017b; Ficklin et al., 2018; Mcleod et al., 2019) (18.1.1). These different framings of the intersection between sustainable development and climate action are used in different communities of research and practice, which complicates efforts to provide clear guidance to decision-makers regarding the goals of CRD and how best to achieve it. This is attributable in part to persistent conceptual confusion and disciplinary divides over more fundamental concepts such as resilience and sustainability (Rogers et al., 2020; Zaman, 2021), not to mention contested perspectives regarding development (Lo et al., 2020; Song et al., 2020a; Morton, 2021) (*medium agreement; medium evidence*).

Reconciling different perspectives on CRD is not simply a matter of academic debate. Climate action, resilience, and sustainable development are all active areas of policy and practice with significant economic, social, environmental, and political implications (18.1.3). Hence, enhancing the role of CRD as a practical framework for development and a guide for action may necessitate improving the science-policy discourse regarding CRD (Winterfeldt, 2013; Jones et al., 2014; Ryan and Bustos, 2019). This includes consideration for risk and science communication; decision analysis and decision support systems; and mechanisms for knowledge co-production between scientists and public policy actors (*very high confidence)*.

In addition, the AR6 WGII report highlights a number of elements of CRD that are associated with significant knowledge gaps and uncertainties. As a result, enhancing the value of CRD as a unifying concept in development would benefit from further conceptualization and socialization of the concept as well as efforts to address the following knowledge gaps:

- The challenges posed by different levels of global warming to achieving CRD and the magnitude and nature of the adaptation gap (and associated finance needs) that must be addressed to enable climate resilience.
- The efficacy of different adaptation, mitigation, and sustainable development interventions in reducing climate risk and/or enhancing opportunities for CRD in the short, medium and long term.
- How different CRD pathways can be designed such that they illustrate opportunities for the practical pursuit of CRD in a manner consistent with principles of inclusion, equity, and justice.
- How deliberative, participatory learning can be integrated into approaches to CRD in order to enhance the representation of diverse actors, forms of knowledge, governance regimes, economic systems, and models for decision-making in CRD.
- The synergies and trade-offs associated with the implementation of different policy packages and the design principles and development contexts that enhance the ability to successfully manage potential trade-offs.
- The limits of incremental system transitions to achieving CRD on a timeline that reflects the urgency associated with the Paris Agreement and the Sustainable Development Goals.
- The capacity of governments, social institutions, and individuals to drive large-scale social transformations that open up the solutions space for CRD.

- Best practices for avoiding maladaptation and ensuring that adaptation interventions are designed so they do not exacerbate vulnerability to climate change to support CRD.

18.6.2 Conclusions

The concept of CRD presents an ambitious agenda for actors at multiple scales – global to local, particularly in the manner in which it reframes climate action to integrate a broader set of objectives than simply reducing greenhouse gas emissions or adapting to the impacts of climate change. Specifically, recent literature extends policy goals for climate action beyond avoiding dangerous interference with the climate system to adopt normative goals of meeting basic human needs, eliminating poverty and enabling sustainable development in ways that are just and equitable. This creates a policy landscape for climate action that is not only richer, but also more complex in that it situates responses to climate change squarely within the development arena. Current policy goals associated with the Paris Agreement, Sendai Framework, and the SDGs imply aggressive timetables. Yet, as noted in the AR5 and supported by more recent literature (Section 18.2.1), the world is neither on track to achieve all of the SDGs nor fulfil the Paris Agreement's objective of limiting warming to well-below 2°C (Denton et al., 2014; IPCC, 2018a). This places aspirations for CRD in a precarious position. Transitions will be necessary across multiple systems (Section 18.1.3). While some may be already underway, the pace of those transitions must accelerate, and societal transformations may be necessary, to enable CRD (18.3, 18.4, Box 18.1)

Given the pace of climate change and the inherent challenge of sustainable development, particularly in the face of inevitable disruptions and setbacks such as the COVID-19 pandemic (Cross-Chapter Box COVID in Chapter 7), the feasibility of achieving CRD is an open question. Rapid changes will be required to shift public and private investments, strengthen institutions and orient them toward more sustainable policies and practices, expand the inclusiveness of governance and the equity of decision-making, and shift societal and consumer preferences to more climate-resilient lifestyles. Nevertheless, the collective body of recent literature on CRD, system transitions, and societal transformation, combined with the assessments within recent IPCC Special Reports (IPCC, 2018a; IPCC, 2019b; IPCC, 2019d) indicate that there are a broad range of opportunities for designing and implementing adaptation and mitigation options that enable the climate goals in the Paris Agreement to be achieved while enhancing resilience and meeting sustainable development objectives. However, options should be considered alongside the mechanisms by which societies can engage in order to create the conditions that can support the implementation of those options (Section 18.4). This includes formal policy mechanisms pursued by governments, the catalyzation of innovation by private firms and entrepreneurship, as well as informal, grassroots interventions by civil society. While there is no "one-size-fits-all" solution for CRD that will work for all actors at all scales, exploring different pathways by which actors can achieve their development and climate goals can make valuable contributions to developing effective strategies for CRD.

A fundamental challenge for achieving CRD globally is reconciling different perspectives on CRD. As noted in the AR5, "*as policy makers explore what pathways to pursue, they will increasingly face questions about managing discourses about what societal objectives to pursue*" (Denton et al., 2014: 1124). Since the AR5, such discourses have become prominent in policy debates over climate action and sustainable development due to different nations, communities, and subpopulations having different understandings of what constitutes CRD. Aggressive efforts to rapidly reduce greenhouse gas emissions or enhance resilience to climate change, for example, could have negative externalities for the development objectives of some actors. This potential for trade-offs complicates efforts to build consensus regarding what constitutes appropriate climate and development policies and practices and by whom. The CRD pathways preferred by one actor are likely to be contested by others. This means operationalizing concepts such as CRD in practice is likely to necessitate ongoing negotiation.

Ultimately, one of the critical developments within the literature is the emergence of procedural and distributive justice as key criteria for evaluating climate action and CRD more specifically. This trend not only recognizes the need to prevent vulnerable human and ecological systems from experiencing disproportionate harm from the changing climate, but also the need to prevent those same systems from being harmed by mitigation, adaptation, and sustainable development policies and practices. Failure to adequately engage with equity and justice when designing sustainability transitions could lead to maladaptation, aggravated poverty, reinforcement of existing inequalities, and entrenched gender bias and exclusion of Indigenous and marginalized communities (Jenkins et al., 2018; Fisher et al., 2019; Schipper et al., 2020b). These consequences could ultimately slow, rather than accelerate, CRD. Hence, developing programs and practices for prioritizing equity in effective transition risk management is an important dimension of enabling CRD.

As indicated by the literature assessed within this chapter, keeping windows of opportunity open for CRD will necessitate urgent action, even under diverse assumptions regarding how future mitigation and adaptation interventions evolve. If nations are to collectively limit warming to well-below 2°C, for example, unprecedented emissions reductions will be necessary over the next decade (IPCC, 2018a). These reductions would necessitate rapid progression of system transitions (18.3). If, despite the Paris Agreement, future emissions trajectories take the world beyond 2°C, a greater demand will be placed on adaptation as a means of enhancing the resilience of development. Given the long-lived nature of human systems, and the built environment in particular, significant adaptation investments would be needed over the near-term to meet this demand. Yet, it is important to note that even in the absence of consideration for climate change, substantial development needs exist for communities around the world at present. Hence, a robust strategy for the pursuit of CRDPs is a near-term focus on portfolios of policies and practices that promote of human and ecological well-being.

[START FAQ18.1 HERE]

FAQ18.1: What is a climate resilient development pathway?

Climate resilient development pathways (CRDPs) are continuous processes that strengthen sustainable development, efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar capacities for adaptation to global warming and reduction of greenhouse gases in the atmosphere.

A pathway is defined in IPCC reports as a temporal evolution of natural and/or human systems towards a future state. These can range from sets of scenarios, narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals.

When used in the context of climate resilient development (CRD), pathways refer to continuous processes that strengthen sustainable development, efforts to eradicate poverty, and reduce inequalities while promoting fair and cross-scalar adaptation and mitigation. As they imply deep societal changes and/or transformation, CRDPs raise questions of ethics, equity, and feasibility of options to drastically reduce emission of greenhouse gasses (mitigation) that limit global warming (e.g., to well below 2°C) and achieve desirable and livable futures and wellbeing for all.

There in no one true, correct pathway to pursue but multiple ways, modalities, depending on numerous factors, such as political, cultural and economic contexts. Pathways are not one single decision or action, nor is there an absolute, universal, fixed, final goal to be pursued, yet there are undesirable and non-CRDPs. Hence, a CRDP is a continuum of coherent, consistent decisions, actions and interventions within each country, and as a global community. While dependent on past development and its socio-ethical, political, economic, ecological and knowledge-technology outcomes at any point in time, transformation, ecological tipping points and shocks can create sudden shifts and unexpected non-linear development pathways. Actions taken today also foreclose some future potential pathways. The differentiated impacts of hurricanes and COVID-19 illustrate how the character of societal development such as equity and inclusion have enabled some societies to be more resilient than others.

[END FAQ18.1 HERE]

[START FAQ18.2 HERE]

FAQ18.2: What is climate resilient development and how can climate change adaptation (measures) contribute to achieving this?

The key purpose of CRD is to pursue sustainable development, engaging climate actions in ways that support human and planetary health and well-being, equity and justice. Climate resilient development combines adaptation and mitigation with underlying development choices and everyday actions, carried out by multiple actors within political, economic, ecological, socio-ethical and knowledge-technology arenas. The character of processes within these development arenas are intrinsic to how social choices are made, directing actions in a CRD or non-CRD direction. For example, inclusion, agency and social justice are qualities within the political arena that underpin actions that enable CRD.

CRD addresses the relationship between greenhouse gas emissions, levels of warming and related climate risks. However, CRD involves more than just achieving temperature targets. It considers the possible transitions that enable those targets to be achieved as well as the evaluation of different adaptation strategies and how the implementation of these strategies interact with broader sustainable development efforts and objectives. This interdependence between patterns of development, climate risk, and the demand for mitigation and adaptation action is fundamental to the concept of CRD. Therefore, climate change and sustainable development cannot be assessed or planned in isolation of one another.

Hence, CRD is defined as the development that deliberately adopts mitigation and adaptation measures to secure a safe climate on earth, meet basic needs for each human being, eliminate poverty and enable equitable, just and sustainable development. It halts practices causing dangerous levels of global warming. CRD may involve deep societal transformation to ensure well-being for all. CRD is now emerging as one of the guiding principles for climate policy, both at the international level, reflected in the Paris Agreement (UNFCCC, 2015) and within specific countries.

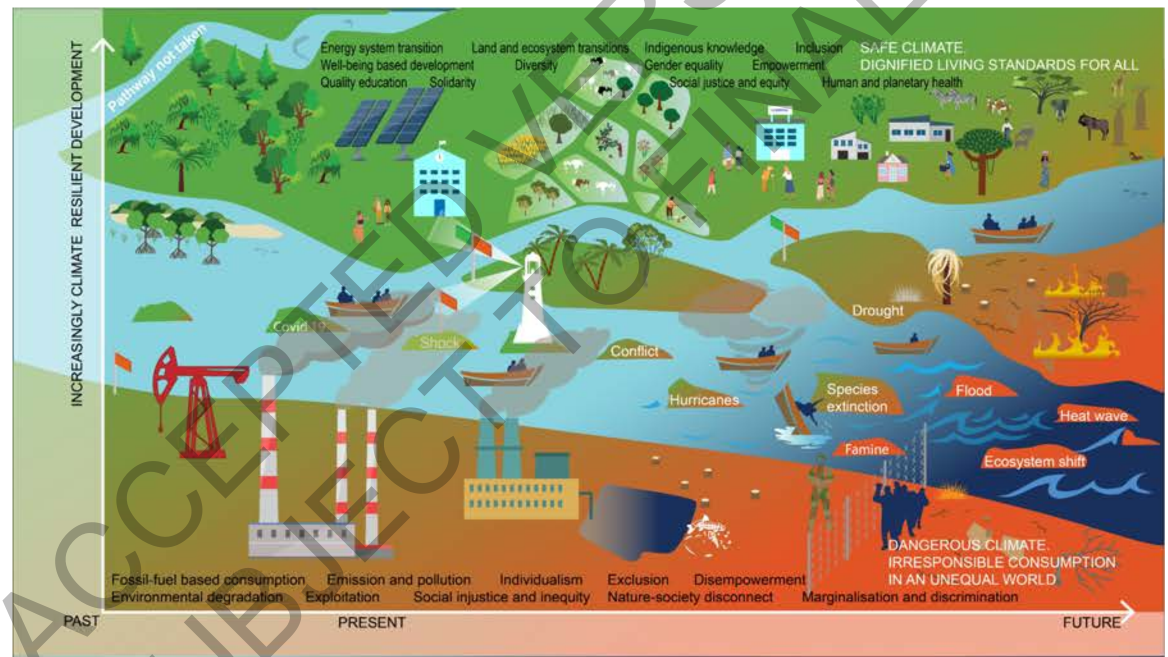


Figure FAQ18.2.1: Multiple intertwined climate resilient development pathways. Climate change adaptation is one of several climatic and non-climatic measures carried out through decision-making by multiple actors that may drive a pathway in a CRD or non-CRD direction. Adaptation, mitigation and sustainable development actions can push a society in a CRD direction, but only if these measures are just and equitable. There are multiple simultaneous pathways in the past, present and future. Societies (illustrated as boats) move on different pathways, towards CRD and non-CRD, with some pathways more dominant than others. The direction of pathways is emergent, taking place through contestations and social choices, through social transformation as well as through surprises and shocks (illustrated as rocks). Path dependency means it is possible but often turbulent to shift from a non-CRD to a CRD pathway. Such a shift becomes more difficult in as risks/shocks increase (more rocks) and non-CRD processes and outcomes progress, limiting future options. Low CRD processes and outcomes at the bottom are characterized by inequity, exclusion, polarization, environmental and social exploitation, entrenchment of business as usual, with increasing risks/shocks. High CRD processes and outcomes (at the top of the figure) are characterized by equity, solidarity, justice, human well-being, planetary health, stewardship/care and system transitions.

Climate change adaptation is one of several climatic and non-climatic measures carried out through decision-making by multiple actors that may drive a pathway in a CRD or non-CRD direction. Adaptation, mitigation and sustainable development actions can push a society in a CRD direction, but only if these measures are just and equitable. There are multiple simultaneous pathways in the past, present and future. Societies (illustrated as boats) move on different pathways, towards CRD and non-CRD, with some pathways more dominant than others. The direction of pathways is emergent, taking place through contestations and social choices, through social transformation as well as through surprises and shocks (illustrated as rocks). Path dependency means it is possible but often turbulent to shift from a non-CRD to a CRD pathway. Such a shift becomes more difficult in as risks/shocks increase (more rocks) and non-CRD processes and outcomes progress, limiting future options. Low CRD processes and outcomes at the bottom are characterized by inequity, exclusion, polarization, environmental and social exploitation, entrenchment of business as usual, with increasing risks/shocks. High CRD processes and outcomes (at the top of the figure) are characterized by equity, solidarity, justice, human well-being, planetary health, stewardship/care and system transitions.

[END FAQ18.2 HERE]

[START FAQ18.3 HERE]

FAQ18.3: How can different actors across society and levels of government be empowered to pursue climate resilient development?

CRD entails trade-offs between different policy objectives. Governments, political and economic elites may play a key role in defining the direction of development at a national and sub-national scale; but in practice, these pathways can be influenced and even resisted by local people, NGOs and civil society.

Contestation and debate are inherent in its construct and implementation. An active civil society and citizenship create the enabling conditions for deliberation, protest, dissent and pressure which are fundamental for an inclusive participatory process. These enable a multiplicity of actors to engage across multiple arenas, from decision-making and everyday actions Hence, decisions and actions may be influenced by uneven interactions between actors, including socio-political relations of domination, marginalization, contestation, compliance and resistance with diverse and often unpredictable outcomes.

In this way, recent social movements and climate protests show new modalities of action related to political responsibility for inaction based on contestation. The new climate movement led mostly by youngsters, markedly seek science-based policy and more importantly, demand to break with a reformist stance and social inertia through radical climate action. This is mostly done through collective disruptive action, and non-violent resistance to promote awareness, a regenerative culture and ethics of care. These movements have resulted in notable political successes, such as declarations of climate emergency at the national and local level, as well as in universities. Also, their methods have proven effective to end fossil fuel sponsorship.

The success and importance of recent climate movements also provide elements to rethink the role of science in society. In one hand, the new climate movements demanding political action were prompted by the findings of scientific reports, mainly the IPCC (2018a) and IPBES (2019) reports. On the other hand, these movements have increased public awareness, and also stimulated public engagement with climate change at unprecedented levels.

[END FAQ18.3 HERE]

[START FAQ18.4 HERE]

FAQ18.4: What role do transitions and transformations in energy, urban and infrastructure, industrial, land and ocean ecosystems, and in society, play in climate resilient development?

The IPCC 1.5 report identified transitions and transformations in key systems, such as energy, land, and ocean ecosystems, and urban and infrastructure, that are needed for a climate resilient development. A system transitions focus helps visualize the interdependence between each system as well as how sustainable development, mitigation, and adaptation interact. A societal transformation, in terms of values and worldviews that shape aspirations, lifestyles and consumption patterns, is a constraining/enabling condition for such transformations. This report however identifies societal transformation as one of the five major transformations currently underway. It delves into the implications of this on how we assess options, value different outcomes from the perspectives of ethics, equity, justice and inclusion.

[END FAQ18.4 HERE]

[START FAQ18.5 HERE]

FAQ18.5: What are success criteria in climate resilient development and how can actors satisfy those criteria?

Climate resilient development is not a predefined goal to be achieved at a certain point or stage in the future. It is a constant process of evaluating, valuing, acting and adjusting various options for mitigation, adaptation and sustainable development, shaped by societal values as well as contestations of these. Any achievement or success is always a work in progress, with continuous, directed, intentional actions. These actions will vary according to the priorities and needs of each population or system; therefore, specific indicators will vary according to each specific context, ensuring we prioritize people, planet, prosperity, peace, and partnership, per the broad goals of the Agenda 2030 on sustainable development.

If Climate Resilient Development is defined as the development that deliberately adopts mitigation and adaptation measures to secure a safe climate, meet basic needs, eliminate poverty and enable equitable, just and sustainable development, then, the 17 United Nations' Sustainable Development Goals (SDGs) provide a good (although limited) measure of progress. They aim at ending poverty and hunger globally and protect life on land and under water until the year 2030. Although there are proven synergies between the SDGs and mitigation, there remains to explore clear synergies between the SDGs and adaptation in terms of how adaptation relates to the fulfilment of the SDGs.

References

Abrahams, D., 2020: Conflict in abundance and peacebuilding in scarcity: Challenges and opportunities in addressing climate change and conflict. *World Development*, **132**, 104998, doi:10.1016/j.worlddev.2020.104998.

Abrahams, D. and E. Carr, 2017: Understanding the Connections Between Climate Change and Conflict: Contributions From Geography and Political Ecology. *Current Climate Change Reports*, **3**, doi:10.1007/s40641-017-0080-z.

Abson, D. J. et al., 2017: Leverage points for sustainability transformation. *Ambio*, **46**(1), 30-39, doi:10.1007/s13280-016-0800-y.

Abu-Rabia-Queder, S. and A. Morris, 2018: Women in Drylands: Barriers and Benefits for Sustainable Livelihood. *Journal of Arid Environments*, **149**, 1-3, doi:10.1016/j.jaridenv.2017.11.009.

Acemoglu, D., U. Akcigit, D. Hanley and W. Kerr, 2016: Transition to Clean Technology. *Journal of Political Economy*, **124**(1), 52-104, doi:10.1086/684511.

Acevedo, S. et al., 2018: *The Effects of Weather Shocks on Economic Activity: What are the Channels of Impact?*, **18 (144): 1**, IMF Working Papers. Available at: https://www.imf.org/en/Publications/WP/Issues/2018/06/22/The-Effects-of-Weather-Shocks-on-Economic-Activity-What-are-the-Channels-of-Impact-45970#: :text=IMF Working Papers&text=In these countries%2C a rise,slower investment%2C and poorer health.

Acosta, M. et al., 2019: Discursive translations of gender mainstreaming norms: The case of agricultural and climate change policies in Uganda. *Women's Studies International Forum*, **74**, 9-19, doi:10.1016/j.wsif.2019.02.010.

Adams, C., T. Ide, J. Barnett and A. Detges, 2018: Sampling bias in climate–conflict research. *Nature Climate Change*, **8**(3), 200-203, doi:10.1038/s41558-018-0068-2.

Adenle, A. A. et al., 2017: Managing Climate Change Risks in Africa - A Global Perspective. *Ecological Economics*, **141**, 190-201.

Adzawla, W., S. B. Azumah, P. Y. Anani and S. A. Donkoh, 2019: Gender perspectives of climate change adaptation in two selected districts of Ghana. *Heliyon*, **5**(11), e02854, doi:10.1016/j.heliyon.2019.e02854.

Agarwal, B., 2020: Does group farming empower rural women? Lessons from India's experiments. *The Journal of Peasant Studies*, **47**(4), 841-872, doi:10.1080/03066150.2019.1628020.

Ahlborg, H., 2017: Towards a conceptualization of power in energy transitions. *Environmental Innovation and Societal Transitions*, **25**, 122-141, doi:10.1016/j.eist.2017.01.004.

Ahlborg, H., I. Ruiz-Mercado, S. Molander and O. Masera, 2019: Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach. *Sustainability*, **11**(7), 2009, doi:10.3390/su11072009.

Åhman, M., L. J. Nilsson and B. Johansson, 2017: Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy*, **17**(5), 634-649, doi:10.1080/14693062.2016.1167009.

Aipira, C., A. Kidd and K. Morioka, 2017: Climate Change Adaptation in Pacific Countries: Fostering Resilience Through Gender Equality. In: *Climate Change Adaptation in Pacific Countries* [Leal Filho, W. (ed.)]. Springer International Publishing, Cham, pp. 225-239. ISBN 978-3-319-50093-5 978-3-319-50094-2.

Ajibade, I. and M. Egge, 2019: SDGs and climate change adaptation in Asian megacities: Synergies and opportunities for transformation. In: *Achieving the Sustainable Development Goals*. Routledge. ISBN 978-0-429-02962-2.

Alam, K. et al., 2011: The Political Economy of Climate Resilient Development Planning in Bangladesh. *IDS Bulletin*, **42**(3), 52-61, doi:10.1111/j.1759-5436.2011.00222.x.

Albizua, A., E. Corbera and U. Pascual, 2019: Farmers' vulnerability to global change in Navarre, Spain: large-scale irrigation as maladaptation. *Regional Environmental Change*, **19**(4), 1147-1158, doi:10.1007/s10113-019-01462-2.

Albrecht, G. et al., 2007: Solastalgia: The Distress Caused by Environmental Change. *Australasian Psychiatry*, doi:10.1080/10398560701701288.

Aldy, J. E., N. Bento and G. Gianfrate, 2021: National Climate Policies and Corporate Internal Carbon Pricing. *The Energy Journal*, **42**(5), 87-98.

Aldy, J. E. and G. Gianfrate, 2019: Future-Proof Your Climate Strategy.

Aleluia Reis, L., L. Drouet, R. Van Dingenen and J. Emmerling, 2018: Future Global Air Quality Indices under Different Socioeconomic and Climate Assumptions. *Sustainability*, **10**(10), doi:10.3390/su10103645.

Alkire, S. and S. Jahan, 2018: *The New Global MPI 2018: Aligning with the Sustainable Development Goals*.

Allen, C., G. Metternicht and T. Wiedmann, 2018a: Initial progress in implementing the Sustainable Development Goals (SDGs): a review of evidence from countries. *Sustainability Science*, **13**(5), 1453-1467, doi:10.1007/s11625-018-0572-3.

Allen, M. R. et al., 2018b: *Framing and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the*. 29–91 pp.

Allwood, G., 2014: Gender mainstreaming and EU climate change policy. *European Integration online Papers (EIoP)*, **18**.

Allwood, G., 2020: Gender Equality in European Union Development Policy in Times of Crisis. *Political Studies Review*, **18**(3), 329-345, doi:10.1177/1478929919863224.

Allwood, J. et al., 2019: *Absolute Zero*. Available at: https://www.repository.cam.ac.uk/handle/1810/299414 (accessed 2020/11/04/15:23:44).

Allwood, J. M., M. F. Ashby, T. G. Gutowski and E. Worrell, 2013: Material efficiency: providing material services with less material production. *Philos Trans A Math Phys Eng Sci*, **371**(1986), doi:10.1098/rsta.2012.0496.

Alston, M., 2014: Gender mainstreaming and climate change. *Women's Studies International Forum*, **47**, 287-294, doi:10.1016/j.wsif.2013.01.016.

Altenburg, T. and D. Rodrik, 2017: Green industrial policy: Accelerating structural change towards wealthy green economies. *Green Industrial Policy*.

Alvaredo, F. et al., 2017: Global Inequality Dynamics: New Findings from WID.world. *American Economic Review*, **107**(5), 404-409.

Ambrosio, N., Y. H. Kim, S. Swann and Z. Wang, 2020: Chapter 7 - Addressing Climate Risk in Financial Decision Making. In: *Optimizing Community Infrastructure* [Colker, R. (ed.)]. Butterworth-Heinemann, pp. 123-142. ISBN 978-0-12-816240-8.

Aminga, V. M. and F. Krampe, 2020: *Climate-related Security Risks and the African Union*. SIPRI (accessed 2021-08-30 19:39:22).

Anders, J. C., 2016: *Theories of Sustainable Development*.

Andersson, J. J., 2019: Carbon Taxes and CO₂ Emissions: Sweden as a Case Study. *American Economic Journal: Economic Policy*, **11**(4), 1-30, doi:10.1257/pol.20170144.

Andonova, L. B., T. N. Hale and C. B. Roger, 2017: National Policy and Transnational Governance of Climate Change: Substitutes or Complements? *International Studies Quarterly*, **61**(2), 253-268.

Andreucci, D., 2019: Populism, Emancipation, and Environmental Governance: Insights from Bolivia. *Annals of the American Association of Geographers*, **109**(2), 624-633, doi:10.1080/24694452.2018.1506696.

Andrijevic, M. et al., 2020a: Overcoming gender inequality for climate resilient development. *Nature Communications*, **11**(1), 6261, doi:10.1038/s41467-020-19856-w.

Andrijevic, M. et al., 2020b: COVID-19 recovery funds dwarf clean energy investment needs. *Science*, **370**(6514), 298-300, doi:10.1126/science.abc9697.

Ansar, A., B. Caldecott and J. Tilbury, 2013: Stranded assets and the fossil fuel divestment campaign: What does divestment mean for the valuation of fossil fuel assets? *Business*.

Antal, M. and J. van den Bergh, 2014: Green growth and climate change: Conceptual and empirical considerations. *Climate Policy*, **16**, 1-13, doi:10.1080/14693062.2014.992003.

Antwi-Agyei, P., A. J. Dougill, T. P. Agyekum and L. C. Stringer, 2018: Alignment between nationally determined contributions and the sustainable development goals for West Africa. *Climate Policy*, **18**(10), 1296-1312, doi:10.1080/14693062.2018.1431199.

Antwi-Agyei, P., A. J. Dougill and L. C. Stringer, 2017: Assessing Coherence between Sector Policies and Climate Compatible Development: Opportunities for Triple Wins. *Sustainability*, **9**(11), 2130, doi:10.3390/su9112130.

Appiah, D. O. and S. E. A. Gbeddy, 2018: A synthesis of the implementation ambivalence of REDD+ in Sub-Saharan Africa and Southeast Asia. *Forest and Society*, 92-111, doi:10.24259/fs.v2i1.2918.

Araos, M., J. Ford, L. Berrang-ford and R. Biesbroek, 2017: Climate change adaptation planning for Global South megacities : the case of Dhaka. *Journal of Environmental Policy & Planning*, **19**(6), 1–15.

Ari, İ., 2017: THE INTERCONNECTION BETWEEN SUSTAINABLE DEVELOPMENT GOALS AND THE CLIMATE CHANGE NEGOTIATIONS: THE PARIS AGREEMENT CASE. *Alternatif Politika*, **9**(Special), 27-45.

Arifeen, A. and I. Nyborg, 2021: How humanitarian assistance practices exacerbate vulnerability: Knowledges, authority and legitimacy in disaster interventions in Baltistan, Pakistan. *International Journal of Disaster Risk Reduction*, **54**, 102027, doi:10.1016/j.ijdrr.2020.102027.

Arku, G. and L. Marais (eds.), Global South Urbanisms and Urban Sustainability—Challenges and the Way Forward. 2021.

Arne Heyen, D., L. Hermwille and T. Wehnert, 2017: Out of the Comfort Zone! Governing the Exnovation of Unsustainable Technologies and Practices. *GAIA - Ecological Perspectives for Science and Society*, **26**(4), 326-331, doi:10.14512/gaia.26.4.9.

Arneth, A. et al., 2019: Framing and context. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.

Arneth, A., N. Unger, M. Kulmala and M. O. Andreae, 2009: Clean the Air, Heat the Planet? *Science*, **326**(5953), 672-673, doi:10.1126/science.1181568.

Arora-Jonsson, S., 2011: Virtue and vulnerability: Discourses on women, gender and climate change. *Global Environmental Change*, **21**(2), 744-751, doi:10.1016/j.gloenvcha.2011.01.005.

Arora-Jonsson, S., 2019: Indigeneity and Climate Justice in Northern Sweden. ISBN Paperback: 9781786997821 eBook ePub: 9781786997852 eBook Kindle: 9781786997845 Library Edition: 9781786997814.

Arora-Jonsson, S. and B. B. Sijapati, 2018: Disciplining Gender in Environmental Organizations: The Texts and Practices of Gender Mainstreaming. *Gender, Work & Organization*, **25**(3), 309-325, doi:10.1111/gwao.12195.

Arora-Jonsson, S., L. Westholm, B. J. Temu and A. Petitt, 2016: Carbon and Cash in Climate Assemblages: The Making of a New Global Citizenship. *Antipode*, **48**(1), 74-96, doi:10.1111/anti.12170.

Arslan, A. et al., 2015: Climate Smart Agriculture? Assessing the Adaptation Implications in Zambia. *Journal of Agricultural Economics*, **66**(3), 753-780, doi:10.1111/1477-9552.12107.
Asefi-Najafabady, S. et al., 2018: Climate change, population, and poverty: vulnerability and exposure to heat stress in countries bordering the Great Lakes of Africa. *Climatic Change*, **148**(4), 561-573, doi:10.1007/s10584-018-2211-5.
Asfaw, S., G. Pallante and A. Palma, 2018: Diversification Strategies and Adaptation Deficit: Evidence from Rural Communities in Niger. *World Development*, **101**, 219-234, doi:10.1016/j.worlddev.2017.09.004.
ASSAR, 2018: *What global warming of 1.5°C and higher means for Kenya*. University of Cape Town, (ASSAR), A. a. S. i. S. A. R. Available at: https://www.weadapt.org/sites/weadapt.org/files/kenya_1.5_infographic_and_climate-by-zones_table.pdf.
Atsiaya, G. O., O. I. Ayuya, L. W. Nakhone and J. K. Lagat, 2019: Drivers and responses to climate variability by agro-pastoralists in Kenya: the case of Laikipia County. *SN Applied Sciences*, **1**(8), 827.
Atteridge, A. and E. Remling, 2018: Is adaptation reducing vulnerability or redistributing it? *WIREs Climate Change*, **9**(1), e500, doi:10.1002/wcc.500.
Auffhammer, M., P. Baylis and C. H. Hausman, 2017: Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proceedings of the National Academy of Sciences*, **114**(8), 1886-1891, doi:10.1073/pnas.1613193114.
Aung, T. S., B. Saboori and E. Rasoulinezhad, 2017: Economic growth and environmental pollution in Myanmar: an analysis of environmental Kuznets curve. *Environmental Science and Pollution Research*, **24**(25), 20487-20501, doi:10.1007/s11356-017-9567-3.
Austin, S. et al., 2015: Public Health Adaptation to Climate Change in Canadian Jurisdictions. *International Journal of Environmental Research and Public Health*, **12**(1), 623-651.
Avelino, F. and J. Grin, 2017: Beyond deconstruction. a reconstructive perspective on sustainability transition governance. *Environmental Innovation and Societal Transitions*, **22**, 15-25, doi:10.1016/j.eist.2016.07.003.
Avelino, F., J. Grin, B. Pel and S. Jhagroe, 2016: The politics of sustainability transitions. *Journal of Environmental Policy & Planning*, **18**(5), 557-567, doi:10.1080/1523908X.2016.1216782.
Avelino, F. and J. M. Wittmayer, 2016: Shifting Power Relations in Sustainability Transitions: A Multi-actor Perspective. *Journal of Environmental Policy & Planning*, **18**(5), 628-649, doi:10.1080/1523908X.2015.1112259.
Avila, S., 2018: Environmental justice and the expanding geography of wind power conflicts. *Sustain Sci*, **13**(3), 599-616, doi:10.1007/s11625-018-0547-4.
Avriel-Avni, N. and J. Dick, 2019: Chapter Five - Differing perceptions of socio-ecological systems: Insights for future transdisciplinary research. In: *Advances in Ecological Research* [Bohan, D. A. and A. J. Dumbrell (eds.)]. Academic Press, pp. 153-190.
Ayers, J. M. and S. Huq, 2009: Supporting Adaptation to Climate Change: What Role for Official Development Assistance? *Development Policy Review*, **27**(6), 675-692, doi:10.1111/j.1467-7679.2009.00465.x.
Babcicky, P., 2013: A Conflict-Sensitive Approach to Climate Change Adaptation. *Peace Review*, **25**(4), 480-488, doi:10.1080/10402659.2013.846131.
Bai, Y. et al., 2019: Does climate adaptation of vulnerable households to extreme events benefit livestock production? *Journal of Cleaner Production*, **210**, 358-365, doi:10.1016/j.jclepro.2018.10.250.
Baker, L., P. Newell and J. Phillips, 2014: The Political Economy of Energy Transitions: The Case of South Africa. *New Political Economy*, **19**(6), 791-818, doi:10.1080/13563467.2013.849674.
Balehey, S., G. Tesfay and M. Balehegn, 2018: Traditional gender inequalities limit pastoral women's opportunities for adaptation to climate change: Evidence from the Afar pastoralists of Ethiopia. *Pastoralism*, **8**(1), 23, doi:10.1186/s13570-018-0129-1.
Bandura, A. and L. Cherry, 2020: Enlisting the power of youth for climate change. *The American Psychologist*, **75**(7), 945-951, doi:10.1037/amp0000512.
Banerjee, O., M. Cicowiez, R. Vargas and M. Horridge, 2019: The SEEA-Based Integrated Economic-Environmental Modelling Framework: An Illustration with Guatemala's Forest and Fuelwood Sector. *Environmental and Resource Economics*, **72**(2), 539-558.
Bangura, Y., 2019: Convergence Is Not Equality. *Development and Change*, **50**(2), 394-409, doi:https://doi.org/10.1111/dech.12489.
Bank of England, 2019: *The 2021 biennial exploratory scenario on the financial risks from climate change*.
Baranzini, A. et al., 2017: Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. *WIREs Climate Change*, **8**(4), e462, doi:10.1002/wcc.462.
Bárcena-Martín, E., S. Medina-Claros and S. Pérez-Moreno, 2021: Economic regulation, opportunity-driven entrepreneurship and gender gap: emerging versus high-income economies. *International Journal of Entrepreneurial Behavior & Research*, **27**(5), 1311-1328, doi:10.1108/IJEBR-05-2020-0321.
Barker, A. J. and J. Pickerill, 2020: Doings with the land and sea: Decolonising geographies, Indigeneity, and enacting place-agency. *Progress in Human Geography*, **44**(4), 640-662, doi:doi:10.1177/0309132519839863.
Barnes, P. W. et al., 2019: Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future. *Nature Sustainability*, **2**(7), 569-579, doi:10.1038/s41893-019-0314-2.
Barnett, J., 2019: Global environmental change I: Climate resilient peace? *Progress in Human Geography*, **43**(5), 927–936.

Barnett, J., 2020: Global environmental change II: Political economies of vulnerability to climate change. *Progress in Human Geography*, doi:10.1177/0309132519898254.
Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4**(12), 1103-1108, doi:10.1038/nclimate2383.
Barnett, J. and C. McMichael, 2018: The effects of climate change on the geography and timing of human mobility. *Population and Environment*, **39**(4), 339-356, doi:10.1007/s11111-018-0295-5.
Barnett, J. and S. O'Neill, 2010: Maladaptation. *Global Environmental Change*, **20**, 211-213, doi:10.1016/j.gloenvcha.2009.11.004.
Barnhardt, R. and O. K. Angayuqaq, 2005: Indigenous Knowledge Systems and Alaska Native Ways of Knowing. *Anthropol. Educ. Q.*, **36**(1), 8-23, doi:10.1525/aeq.2005.36.1.008.
Bartos, M. D. and M. V. Chester, 2015: Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change*, **5**(8), 748-752, doi:10.1038/nclimate2648.
Bassett, T. J. and C. Fogelman, 2013: Déjà vu or something new? The adaptation concept in the climate change literature. *Geoforum*, **48**, 42-53, doi:10.1016/j.geoforum.2013.04.010.
Bataille, C. et al., 2018: A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production*, **187**, 960-973, doi:10.1016/j.jclepro.2018.03.107.
Batten, S., 2018: Climate change and the macro-economy: a critical review. *Bank of England*, **Staff Working Paper No.706**.
Battiston, S. et al., 2017: A climate stress-test of the financial system. *Nature Climate Change*, **7**(4), 283-288, doi:10.1038/nclimate3255.
Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, doi:10.1007/s10584-018-2226-y.
Beck, U., 2015: Emancipatory catastrophism: What does it mean to climate change and risk society? *Current Sociology*, **63**(1), 75-88, doi:10.1177/0011392114559951.
Becker, S., T. Blanchet and C. Kunze, 2016: Social movements and urban energy policy: Assessing contexts, agency and outcomes of remunicipalisation processes in Hamburg and Berlin. *Utilities Policy*, **41**, 228-236, doi:10.1016/j.jup.2016.02.001.
Beddoe, R. et al., 2009: Overcoming Systemic Roadblocks to Sustainability: The Evolutionary Redesign of Worldviews, Institutions, and Technologies. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(8), 2483-2489.
Bell, K., 2013: Post-conventional Approaches to Gender, Climate Change and Social Justice. In: *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change* [Alston, M. and K. Whittenbury (eds.)]. Springer Netherlands, Dordrecht, pp. 53-61. ISBN 978-94-007-5518-5.
Béné, C. et al., 2018: Resilience as a policy narrative: potentials and limits in the context of urban planning. *Climate and Development*, **10**(2), 116-133, doi:10.1080/17565529.2017.1301868.
Benjaminsen, G. and R. Kaarhus, 2018: Commodification of forest carbon: REDD+ and socially embedded forest practices in Zanzibar. *Geoforum*, **93**, doi:10.1016/j.geoforum.2018.04.021.
Bento, N. and G. Gianfrate, 2020: Determinants of internal carbon pricing. *Energy Policy*, **143**, 111499, doi:10.1016/j.enpol.2020.111499.
Bento, N., G. Gianfrate and M. H. Thoni, 2019: Crowdfunding for sustainability ventures. *Journal of Cleaner Production*, **237**, 117751, doi:10.1016/j.jclepro.2019.117751.
Berga, L., 2016: The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. *Engineering*, **2**(3), 313-318, doi:10.1016/J.ENG.2016.03.004.
Berglund, O. and D. Schmidt, 2020: A Theory of Change: The Civil Resistance Model. In: *Extinction Rebellion and Climate Change Activism*. Springer International Publishing, Cham, pp. 79-95. ISBN 978-3-030-48358-6 978-3-030-48359-3.
Berkhout, E., J. Bouma, N. Terzidis and M. Voors, 2018: Supporting local institutions for inclusive green growth: Developing an Evidence Gap Map. *NJAS - Wageningen Journal of Life Sciences*, **84**, 51-71, doi:10.1016/j.njas.2017.10.001.
Bernauer, W. and G. Slowey, 2020: COVID-19, extractive industries, and indigenous communities in Canada: Notes towards a political economy research agenda. *The Extractive Industries and Society*, **7**(3), 844-846, doi:10.1016/j.exis.2020.05.012.
Berrang-Ford, L. et al., 2014: What drives national adaptation? A global assessment. *Climatic Change*, **124**(1), 441-450, doi:10.1007/s10584-014-1078-3.
Berry, P. M. et al., 2015: Cross-sectoral interactions of adaptation and mitigation measures. *Climatic Change*, **128**(3), 381-393, doi:10.1007/s10584-014-1214-0.
Bethel, B. J., Y. Buravleva and D. Tang, 2021: Blue Economy and Blue Activities: Opportunities, Challenges, and Recommendations for The Bahamas. *Water*, **13**(10), 1399, doi:10.3390/w13101399.
Beuchelt, T. D. and L. Badstue, 2013: Gender, nutrition- and climate-smart food production: Opportunities and trade-offs. *Food Security*, **5**(5), 709-721, doi:10.1007/s12571-013-0290-8.
Beveridge, R. and P. Koch, 2016: The post-political trap? Reflections on politics, agency and the city. *Urban Studies*, doi:10.1177/0042098016671477.

Bezner Kerr, R. et al., 2019: Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agriculture, Ecosystems & Environment*, **279**, 109-121, doi:10.1016/j.agee.2019.04.004.
Bhamidipati, P. L., J. Haselip and U. Elmer Hansen, 2019: How do energy policies accelerate sustainable transitions? Unpacking the policy transfer process in the case of GETFiT Uganda. *Energy Policy*, **132**, 1320-1332, doi:https://doi.org/10.1016/j.enpol.2019.05.053.
Bhavnani, K.-K., J. Foran, P. A. Kurian and D. Munshi, 2019: *Climate futures: Re-imagining global climate justice*. Zed Books Ltd. ISBN 1786997851.
Bherwani, H., S. Gautam and A. Gupta, 2021: Qualitative and quantitative analyses of impact of COVID-19 on sustainable development goals (SDGs) in Indian subcontinent with a focus on air quality. *International Journal of Environmental Science and Technology*, **18**, doi:10.1007/s13762-020-03122-z.
Biagini, B. and A. Miller, 2013: Engaging the private sector in adaptation to climate change in developing countries: importance, status, and challenges. *Climate and Development*, **5**(3), 242-252.
Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Birkmann, J. et al., 2021: New methods for local vulnerability scenarios to heat stress to inform urban planning—case study City of Ludwigsburg/Germany. *Climatic Change*, **165**(1), 37, doi:10.1007/s10584-021-03005-3.
Bistline, J. E. and S. K. Rose, 2018: Social cost of carbon pricing of power sector CO 2 : accounting for leakage and other social implications from subnational policies. *Environmental Research Letters*, **13**(1), 014027, doi:10.1088/1748-9326/aa9c89.
Biswas, A. K. and C. Tortajada, 2016: Water Security, Climate Change and Sustainable Development: An Introduction. In: *Water Security, Climate Change and Sustainable Development* [Biswas, A. K. and C. Tortajada (eds.)]. Springer Singapore, Singapore, pp. 1-5. ISBN 978-981-287-974-5 978-981-287-976-9.
Bizikova, L., J.-E. Parry, J. Karami and D. Echeverria, 2015: Review of key initiatives and approaches to adaptation planning at the national level in semi-arid areas. *Regional Environmental Change*, **15**(5), 837-850.
Blanco, G. et al., 2014: Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 351-411. ISBN 9781107058217.
Blanford, G. J., S. K. Rose and M. Tavoni, 2012: Baseline projections of energy and emissions in Asia. *Energy Economics*, **34**, S284-S292, doi:10.1016/j.eneco.2012.08.006.
Bleischwitz, R. et al., 2018: Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling. *Global Environmental Change*, **48**, 86-96, doi:10.1016/j.gloenvcha.2017.11.008.
Bloemen, P., M. V. D. Steen and Z. V. D. Wal, 2019: Designing a century ahead: climate change adaptation in the Dutch Delta. *Policy and Society*, **38**(1), 58-76, doi:10.1080/14494035.2018.1513731.
Blühdorn, I. and M. Deflorian, 2021: Politicisation beyond post-politics: new social activism and the reconfiguration of political discourse. *Social Movement Studies*, **20**(3), 259-275, doi:10.1080/14742837.2021.1872375.
Blythe, J. et al., 2018: The Dark Side of Transformation: Latent Risks in Contemporary Sustainability Discourse. *Antipode*, **50**(5), 1206-1223, doi:https://doi.org/10.1111/anti.12405.
Bocquillon, P., 2018: (De-)Constructing coherence? Strategic entrepreneurs, policy frames and the integration of climate and energy policies in the European Union. *Environmental Policy and Governance*, **28**(5), 339-349, doi:10.1002/eet.1820.
Bodnar, S., 2008: Wasted and Bombed: Clinical Enactments of a Changing Relationship to the Earth. *Psychoanalytic Dialogues*, **18**(4), 484-512.
Boeckmann, M. and H. Zeeb, 2014: Using a social justice and health framework to assess European climate change adaptation strategies. *International Journal of Environmental Research and Public Health*, **11**(12), 12389-12411, doi:10.3390/ijerph111212389.
Boermans, M. A. and R. Galema, 2019: Are pension funds actively decarbonizing their portfolios? *Ecological Economics*, **161**, 50-60, doi:10.1016/j.ecolecon.2019.03.008.
Bohoslavsky, J. P., 2019: *The impact of economic reforms and austerity measures on women's human rights*. Center for Women's Global Leadership – OHCHR.
Bond, S. and J. Barth, 2020: Care-full and just: Making a difference through climate change adaptation. *Cities*, **102**, 102734, doi:10.1016/j.cities.2020.102734.
Bosomworth, K., P. Leith, A. Harwood and P. J. Wallis, 2017: What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. *Environmental Science & Policy*, **76**, 23-28, doi:10.1016/j.envsci.2017.06.007.
Boulton, E., 2016: Climate change as a 'hyperobject': a critical review of Timothy Morton's reframing narrative. *WIREs Climate Change*, **7**(5), 772-785, doi:10.1002/wcc.410.
Bourgeois, R., 2015: *A Glossary of Terms commonly used in Futures Studies*.

Bowen, K. J. et al., 2017: Implementing the "Sustainable Development Goals": towards addressing three key governance challenges—collective action, trade-offs, and accountability. *Current Opinion in Environmental Sustainability*, **26-27**, 90-96, doi:10.1016/j.cosust.2017.05.002.
Boyce, J. K., 2018: Carbon Pricing: Effectiveness and Equity. *Ecological Economics*, **150**, 52-61, doi:10.1016/j.ecolecon.2018.03.030.
Boyd, J., 2007: Nonmarket benefits of nature: What should be counted in green GDP? *Ecological Economics*, **61**(4), 716-723.
Bradley, K. and J. Hedrén, 2014: Utopian Thought in the Making of Green Futures. In: *Green Utopianism: Perspectives, Politics and Micro-Practices*, pp. 1-20. ISBN 978-0-415-81444-7.
Brand, U., C. Görg and M. Wissen, 2020: Overcoming neoliberal globalization: social-ecological transformation from a Polanyian perspective and beyond. *Globalizations*, **17**(1), 161-176, doi:10.1080/14747731.2019.1644708.
Brandi, C. and A. Dzebo, 2017: The case for connecting the implementation of the Paris Climate Agreement and the 2030 Agenda for Sustainable Development.
Brattland, C. and T. Mustonen, 2018: How Traditional Knowledge Comes to Matter in Atlantic Salmon Governance in Norway and Finland. *Arctic Institute of North America*, **71**(4), 375-392, doi:https://doi.org/10.14430/arctic4751.
Brattland, C. and S. Nilsen, 2011: Reclaiming indigenous seascapes. Sami place names in Norwegian sea charts. *Polar Geography*, **34**, 275-297, doi:10.1080/1088937x.2011.644871.
Brechin, S. and M. Espinoza, 2017: A case for further refinement of the Green Climate Fund's 50:50 ratio climate change mitigation and adaptation allocation framework: toward a more targeted approach. *Climatic Change*, **142**, doi:10.1007/s10584-017-1938-8.
Brink, E. and C. Wamsler, 2019: Citizen engagement in climate adaptation surveyed: The role of values, worldviews, gender and place. *Journal of Cleaner Production*, **209**, 1342-1353, doi:10.1016/j.jclepro.2018.10.164.
Brooks, N. et al., 2014: Tracking Adaptation and Measuring Development: a step-by-step guide. *International Institute for Environment and Development*.
Broto, V. C., E. Boyd and J. Ensor, 2015: Participatory urban planning for climate change adaptation in coastal cities: lessons from a pilot experience in Maputo, Mozambique. *Current Opinion in Environmental Sustainability*, **13**, 11-18, doi:10.1016/j.cosust.2014.12.005.
Brown, K., 2013: Global environmental change I: A social turn for resilience? *Progress in Human Geography*, doi:10.1177/0309132513498837.
Brulle, R. J. and K. M. Norgaard, 2019: Avoiding cultural trauma: climate change and social inertia. *Environmental Politics*, **28**(5), 886-908.
Brundiers, K., 2018: Disasters as opportunities for sustainability: the case of Christchurch, Aotearoa New Zealand. *Sustainability Science*, **13**(4), 1075-1091, doi:10.1007/s11625-017-0523-4.
Brundiers, K., 2020: Leveraging Disasters for Sustainable Development. *Environment: Science and Policy for Sustainable Development*, **62**(1), 15-27, doi:10.1080/00139157.2020.1687226.
Brundiers, K. and H. C. Eakin, 2018: Leveraging post-disaster windows of opportunities for change towards sustainability: A framework. *Sustainability*, **10**(5), 1390.
Brundtland, C., 1987: *Our Common Future*. Oxford University Press.
Bryant, L. and B. Garnham, 2015: The fallen hero: masculinity, shame and farmer suicide in Australia. *Gender, Place & Culture*, **22**(1), 67-82, doi:10.1080/0966369X.2013.855628.
Brzoska, M. and C. Fröhlich, 2016: Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migration and Development*, **5**(2), 190-210, doi:10.1080/21632324.2015.1022973.
Buckwell, A. et al., 2020: Social benefit cost analysis of ecosystem-based climate change adaptations: a community-level case study in Tanna Island, Vanuatu. *Climate and Development*, **12**(6), 495-510, doi:10.1080/17565529.2019.1642179.
Buggy, L. and K. E. McNamara, 2016: The need to reinterpret "community" for climate change adaptation: a case study of Pele Island, Vanuatu. *Climate and Development*, **8**(3), 270-280, doi:10.1080/17565529.2015.1041445.
Buhaug, H., 2015: Climate–conflict research: some reflections on the way forward. *WIREs Climate Change*, **6**(3), 269-275, doi:10.1002/wcc.336.
Burch, S. et al., 2016: Governing and accelerating transformative entrepreneurship: exploring the potential for small business innovation on urban sustainability transitions. *Current Opinion in Environmental Sustainability*, **22**, 26-32, doi:10.1016/j.cosust.2017.04.002.
Burke, M., S. Heft-Neal and E. Bendavid, 2016: Sources of variation in under-5 mortality across sub-Saharan Africa: a spatial analysis. *The Lancet Global Health*, **4**(12), e936-e945, doi:https://doi.org/10.1016/S2214-109X(16)30212-1.
Burke, M., S. M. Hsiang and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**(7577), 235-239, doi:10.1038/nature15725.
Burman, A., 2017: The political ontology of climate change: moral meteorology, climate justice, and the coloniality of reality in the Bolivian Andes. *Journal of Political Ecology*, **24**(1), 921-930, doi:10.2458/v24i1.20974.
Busby, J. W., 2021: Beyond internal conflict: The emergent practice of climate security. *Journal of Peace Research*, **58**(1), 186-194, doi:10.1177/0022343320971019.
Busch, T., M. Johnson and T. Pioch, 2020: Corporate carbon performance data: Quo vadis? *Journal of Industrial Ecology*, **n/a**(n/a), doi:10.1111/jiec.13008.

Busscher, T., M. v. d. Brink and S. Verweij, 2019: Strategies for integrating water management and spatial planning: Organising for spatial quality in the Dutch "Room for the River" program. *Journal of Flood Risk Management*, **12**(1), e12448, doi:10.1111/jfr3.12448.
Butler, C. D., 2017: Limits to growth, planetary boundaries, and planetary health. *Current Opinion in Environmental Sustainability*, **25**, 59-65, doi:10.1016/j.cosust.2017.08.002.
Butler, J. R. A. et al., 2016: Priming adaptation pathways through adaptive co-management: Design and evaluation for developing countries. *Climate Risk Management*, **12**, 1–16.
Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, **13**(5), 055012, doi:10.1088/1748-9326/aabf45.
Cai, Y. and T. S. Lontzek, 2018: The Social Cost of Carbon with Economic and Climate Risks. *Journal of Political Economy*, **127**(6), 2684-2734, doi:10.1086/701890.
Calkins, J., 2015: Moving Forward after Sendai: How Countries Want to Use Science, Evidence and Technology for Disaster Risk Reduction. *PLoS Curr*, **7**, doi:10.1371/currents.dis.22247d6293d4109d09794890bcda1878.
Camargo, A. and D. Ojeda, 2017: Ambivalent desires: State formation and dispossession in the face of climate crisis. *Political Geography*, **60**, 57-65, doi:10.1016/j.polgeo.2017.04.003.
Campbell, B. M. et al., 2016: Reducing risks to food security from climate change. *Global Food Security*, **11**, 34-43, doi:10.1016/j.gfs.2016.06.002.
Caniglia, G. et al., 2021: A pluralistic and integrated approach to action-oriented knowledge for sustainability. *Nature Sustainability*, **4**(2), 93-100, doi:10.1038/s41893-020-00616-z.
Cannon, T. and D. Müller-Mahn, 2010: Vulnerability, resilience and development discourses in context of climate change. *Natural Hazards*, **55**(3), 621-635, doi:10.1007/s11069-010-9499-4.
Capaldi, C. A. et al., 2015: Flourishing in nature: A review of the benefits of connecting with nature and its application as a wellbeing intervention. *Intnl. J. Wellbeing*, **5**(4), doi:10.5502/ijw.v5i4.449.
Carabine, E., M. Jouanjean and J. Tsui, 2015: Kenya ending drought emergencies policy review: Scenarios for building resilience in the ASALs. *International Livestock Research Institute (ILRI), Nairobi, Kenya*, 35.
Carino, J. and L. Tamayo, 2019: *Global Report on the Situation of Lands, Territories and Resources of Indigenous Peoples*. Indigenous Peoples Major Group for Sustainable Development. Available at: www.indigenouspeoples-sdg.org.
Carmin, J., N. Nadkarni and C. Rhie, 2012: Progress and Challenges in Urban Climate Adaptation Planning: Results of a Global. In: *Progress and Challenges in Urban Climate Adaptation Planning: Results of a Global*. Massachusetts Institute of Technology (MIT).
Carpenter, S. R., C. Folke, M. Scheffer and F. R. Westley, 2019: Dancing on the volcano: social exploration in times of discontent. *Ecology and Society*, **24**(1), art23.
Carr, C., 2013: Discourse Yes, Implementation Maybe: An Immobility and Paralysis of Sustainable Development Policy. *European Planning Studies*, **22**(9), 1824–1840.
Carr, E., 2019: Properties and projects: Reconciling resilience and transformation for adaptation and development. *World Development*, **122**, 70-84, doi:10.1016/j.worlddev.2019.05.011.
Carr, E. R., 2020: Resilient livelihoods in an era of global transformation. *Global Environmental Change*, **64**, 102155, doi:10.1016/j.gloenvcha.2020.102155.
Carr, E. R. and M. C. Thompson, 2014: Gender and Climate Change Adaptation in Agrarian Settings: Current Thinking, New Directions, and Research Frontiers: Gender and Climate Change Adaptation in Agrarian Settings. *Geography Compass*, **8**(3), 182-197.
Casas Varez, M., 2017: La transversalización del enfoque de género en las políticas públicas frente al cambio climático en América Latina.
Casey, G., 2019: *Energy Efficiency and Directed Technical Change: Implications for Climate Change Mitigation*. Department of Economics Working Papers, Department of Economics, Williams College. Available at: https://ideas.repec.org/p/wil/wileco/2019-17.html (accessed 2020/11/10/16:48:20).
Cash, D. W. et al., 2003: Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci. U. S. A.*, **100**(14), 8086-8091, doi:10.1073/pnas.1231332100.
Castán Broto, V. et al., 2020: Spatiotemporal perspectives on urban energy transitions: a comparative study of three cities in China. *Urban Transformations*, **2**(1), 11, doi:10.1186/s42854-020-00015-9.
Castañeda Carney, I. et al., 2020: *Gender-based violence and environment linkages*. IUCN. ISBN 978-2-8317-2034-0.
Castells-Quintana, D., M. d. P. Lopez-Uribe and T. K. J. McDermott, 2018: Adaptation to climate change: A review through a development economics lens. *World Development*, **104**(C), 183-196.
Catalano, M., L. Forni and E. Pezzolla, 2020: Climate-change adaptation: The role of fiscal policy. *Resource and Energy Economics*, **59**, 101111, doi:10.1016/j.reseneeco.2019.07.005.
Catley, A., J. Lind and I. Scoones, 2013: *Pastoralism and development in Africa: dynamic change at the margins*. Routledge. ISBN 1136255850.
Cavaliere, P., 2019: Electrolysis of Iron Ores: Most Efficient Technologies for Greenhouse Emissions Abatement. In: *Clean Ironmaking and Steelmaking Processes: Efficient Technologies for Greenhouse Emissions Abatement* [Cavaliere, P. (ed.)]. Springer International Publishing, Cham, pp. 555-576. ISBN 978-3-030-21209-4.

Ceballos, G., P. R. Ehrlich and R. Dirzo, 2017: Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proceedings of the National Academy of Sciences*, **114**(30), E6089-E6096, doi:10.1073/pnas.1704949114.
Cervigni, R. and M. Morris, 2016: *Confronting Drought in Africa's Drylands: Opportunities for Enhancing Resilience*. Washington, DC: World Bank; and Agence Française de Développement. ISBN 978-1-4648-0817-3.
Cervigni, R. et al., 2016: Vulnerability in Drylands Tomorrow: Business as Usual Raising Ominous Prospects.
Chae, Y., S. H. Choi and Y. J. Kim, 2020: Climate Change Policy Implications of Sustainable Development Pathways in Korea at Sub-National Scale. *Sustainability*, **12**(10), doi:10.3390/su12104310.
Chakraborty, R. and P. Y. Sherpa, 2021: From climate adaptation to climate justice: Critical reflections on the IPCC and Himalayan climate knowledges. *Climatic Change*, **167**, 49, doi:10.1007/s10584-021-03158-1.
Chambers, R., 2012: *Revolutions in Development Inquiry*, 1st edition ed., Routledge, 258 pp.
Chaminade, C. and F. Randelli, 2020: The Role of Territorially Embedded Innovation Ecosystems Accelerating Sustainability Transformations: A Case Study of the Transformation to Organic Wine Production in Tuscany (Italy). *Sustainability*, **12**(11), 4621.
Chancel, L. and T. Piketty, 2019: Indian Income Inequality, 1922-2015: From British Raj to Billionaire Raj? *Review of Income and Wealth*, **65**(S1), S33-S62, doi:10.1111/roiw.12439.
Chen, A. A. et al., 2020a: Pathways to climate change mitigation and stable energy by 100% renewable for a small island: Jamaica as an example. *Renewable and Sustainable Energy Reviews*, **121**, 109671, doi:10.1016/j.rser.2019.109671.
Chen, C. et al., 2016: Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. *Environmental Science & Policy*, **66**, 403-419, doi:https://doi.org/10.1016/j.envsci.2016.05.007.
Chen, G. et al., 2020b: Global projections of future urban land expansion under shared socioeconomic pathways. *Nature Communications*, **11**(1), 537, doi:10.1038/s41467-020-14386-x.
Chen, K. et al., 2018: Future ozone-related acute excess mortality under climate and population change scenarios in China: A modeling study. *PLOS Medicine*, **15**(7), e1002598, doi:10.1371/journal.pmed.1002598.
Chen, K. et al., 2017: Impact of climate change on heat-related mortality in Jiangsu Province, China. *Environmental Pollution*, **224**, 317-325, doi:https://doi.org/10.1016/j.envpol.2017.02.011.
Chen, Q. and D. Taylor, 2020: Economic development and pollution emissions in Singapore: Evidence in support of the Environmental Kuznets Curve hypothesis and its implications for regional sustainability. *Journal of Cleaner Production*, **243**, 118637, doi:10.1016/j.jclepro.2019.118637.
Chen, Y. et al., 2019: Tele-connecting China's future urban growth to impacts on ecosystem services under the shared socioeconomic pathways. *Science of The Total Environment*, **652**, 765-779, doi:10.1016/j.scitotenv.2018.10.283.
Chenery, H., 1974: *Redistribution with growth: Policies to improve income distribution in developing countries in the context of economic growth : a joint study ... of Development Studies, University of Sussex*. London, 304 pp. ISBN 978-0-19-920069-6.
Chi, Y. F. and J. N. Rauch, 2010: The Plight of Green GDP in China.
China Meteorological Administration, 2019.
Chome, N., 2020: Land, livelihoods and belonging: negotiating change and anticipating LAPSSET in Kenya's Lamu county. *Journal of Eastern African Studies*, **14**(2), 310-331.
Chowdhooree, I., 2019: Indigenous knowledge for enhancing community resilience: An experience from the south-western coastal region of Bangladesh. *International Journal of Disaster Risk Reduction*, **40**, 101259, doi:10.1016/j.ijdrr.2019.101259.
Chu, E. and K. Michael, 2019: Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. *Environment and Urbanization*, **31**(1), 139-156, doi:10.1177/0956247818814449.
Chu, E. K., 2018: Urban climate adaptation and the reshaping of state–society relations: The politics of community knowledge and mobilisation in Indore, India. *Urban Studies*, **55**(8), 1766-1782.
Chung Tiam Fook, T., 2017: Transformational processes for community-focused adaptation and social change: a synthesis. *Climate and Development*, **9**(1), 5-21.
Ciwmb, 2003: *Plastics White Paper—optimizing plastics use, recycling, and disposal in California*. California Integrated Waste Management Board. Available at: https://www2.calrecycle.ca.gov/Publications/Details/1010.
Clapp, C. and J. Sillmann, 2019: Facilitating Climate-Smart Investments. *One Earth*, **1**(1), 57-61, doi:10.1016/j.oneear.2019.08.009.
Clark, W. C. et al., 2016: Boundary work for sustainable development: Natural resource management at the Consultative Group on International Agricultural Research (CGIAR). *Proc. Natl. Acad. Sci. U. S. A.*, **113**(17), 4615-4622, doi:10.1073/pnas.0900231108.
Clarke, L. et al., 2014: Assessing Transformation Pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510. ISBN 9781107058217.

Clay, L., M. Papas, K. Gill and D. Abramson, 2018: Factors Associated with Continued Food Insecurity among Households Recovering from Hurricane Katrina. *International Journal of Environmental Research and Public Health*, **15**(8), 1647.
Clayton, S. et al., 2015: Psychological research and global climate change. *Nature Climate Change*, **5**(7), 640-646.
Clayton, S., C. Manning, K. Krygsman and M. Speiser, 2017: Mental Health and Our Changing Climate: Impacts. *Implications, and Guidance*.
Cloutier, G. et al., 2015: Planning adaptation based on local actors' knowledge and participation: a climate governance experiment. *Climate Policy*, **15**(4), 458-474.
Clucas, B., I. D. Parker and A. M. Feldpausch-Parker, 2018: A systematic review of the relationship between urban agriculture and biodiversity. *Urban Ecosystems*, **21**(4), 635-643, doi:10.1007/s11252-018-0748-8.
Cobb, C. W. and H. Daly, 1989: The index for sustainable economic welfare. *Daly, HE, Cobb, JB (Eds)*.
Cohen, M. J., 2020: Does the COVID-19 outbreak mark the onset of a sustainable consumption transition? *Sustainability: Science, Practice and Policy*, **16**(1), 1-3, doi:10.1080/15487733.2020.1740472.
Cole, P. and G. Banks, 2017: Renewable energy programmes in the South Pacific – Are these a solution to dependency? *Energy Policy*, **110**, 500-508, doi:10.1016/j.enpol.2017.08.048.
Collins, A. M., J. A. Grant and P. Ackah-Baidoo, 2019a: The glocal dynamics of land reform in natural resource sectors: Insights from Tanzania. *Land Use Policy*, **81**, 889-896.
Collins, S. M. et al., 2019b: 'I know how stressful it is to lack water!' Exploring the lived experiences of household water insecurity among pregnant and postpartum women in western Kenya. *Global Public Health*, **14**(5), 649-662.
Colloff, M. J. et al., 2021: Adapting transformation and transforming adaptation to climate change using a pathways approach. *Environmental Science & Policy*, **124**, 163-174, doi:10.1016/j.envsci.2021.06.014.
Collste, D., M. Pedercini and S. E. Cornell, 2017: Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. *Sustainability Science*, **12**(6), 921-931, doi:10.1007/s11625-017-0457-x.
Conway, D. et al., 2015: Climate and southern Africa's water–energy–food nexus. *Nature Climate Change*, **5**(9), 837-846, doi:10.1038/nclimate2735.
Cormack, Z., 2016: The promotion of pastoralist heritage and alternative 'visions' for the future of Northern Kenya. *Journal of Eastern African Studies*, **10**(3), 548–567.
Cormack, Z. and A. Kurewa, 2018: The changing value of land in Northern Kenya: the case of Lake Turkana Wind Power. *Critical African Studies*, **10**(1), 89-107.
Costantini, V., A. Markandya, E. Paglialunga and G. Sforna, 2018: Impact and distribution of climatic damages: a methodological proposal with a dynamic CGE model applied to global climate negotiations. *Econ Polit*, **35**(3), 809-843, doi:10.1007/s40888-018-0129-z.
Cote, M. and A. J. Nightingale, 2011: Resilience thinking meets social theory: Situating social change in socio-ecological systems (SES) research. *Progress in Human Geography*, doi:10.1177/0309132511425708.
Country, B. et al., 2018: Intercultural Communication Handbook. doi:http://bawakacollective.com/handbook/.
Country, B. et al., 2016: Co-becoming Bawaka:Towards a relational understanding of place/space. *Progress in Human Geography*, **40**(4), 455-475, doi:10.1177/0309132515589437.
Cretney, R., 2014: Resilience for Whom? Emerging Critical Geographies of Socio-ecological Resilience. *Geography Compass*, **8**(9), 627-640, doi:10.1111/gec3.12154.
Crippa, M. et al., 2019: *Fossil CO2 and GHG emissions of all world countries*. Publications Office of the European Union. Available at: https://publications.jrc.ec.europa.eu/repository/handle/111111111/57649 (accessed 2020/11/04/15:25:48).
Cubillo-Guevara, A. P., A. L. Hidalgo-Capitán and J. A. Domínguez-Gómez, 2014: El pensamiento sobre el Buen Vivir. Entre el indigenismo, el socialismo y el posdesarrollismo. *Revista del CLAD Reforma y Democracia*,(60), 27-58.
Cumming, D. J., G. Leboeuf and A. Schwienbacher, 2017: Crowdfunding cleantech. *Energy Economics*, **65**, 292-303, doi:10.1016/j.eneco.2017.04.030.
Cundill, G. et al., 2014: Social learning for adaptation: a descriptive handbook for practitioners and action researchers.
D'Alessandro, S., A. Cieplinski, T. Distefano and K. Dittmer, 2020: Feasible alternatives to green growth. *Nature Sustainability*, **3**(4), 329-335, doi:10.1038/s41893-020-0484-y.
Dabelko, G., L. Risi and S. Null, 2013: *Backdraft: The Conflict Potential of Climate Change Adaptation and Mitigation*. Woodrow Wilson International Center for Scholars.
Daigneault, A. et al., 2019: Developing Detailed Shared Socioeconomic Pathway (SSP) Narratives for the Global Forest Sector. *Journal of Forest Economics*, **34**(1-2), 7-45, doi:10.1561/112.00000441.
Daly, H. and J. Cobb, 1989: For the Common Good. Redirecting the Economy Toward Community, the Environment and a Sustainable Future. Beacon Press, Boston, Massachusetts.
Danilina, V. and Trionfetti, 2019: *Green Public Procurement vs Environmental Taxation: implications for the EU-MENA environmental policy*.
Daron, J. et al., 2021: Integrating seasonal climate forecasts into adaptive social protection in the Sahel. *Climate and Development*, **13**(6), 543-550, doi:10.1080/17565529.2020.1825920.
Davelaar, D., 2021: Transformation for sustainability: a deep leverage points approach. *Sustainability Science*, **16**(3), 727-747, doi:10.1007/s11625-020-00872-0.

David, M., 2017: Moving beyond the heuristic of creative destruction: Targeting exnovation with policy mixes for energy transitions. *Energy Research & Social Science*, **33**, 138-146, doi:10.1016/j.erss.2017.09.023.
David Tàbara, J. et al., 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, **31**, 120-129, doi:10.1016/j.cosust.2018.01.012.
Davidson, K., T. M. P. Nguyen, R. Beilin and J. Briggs, 2019: The emerging addition of resilience as a component of sustainability in urban policy. *Cities*, **92**, 1-9, doi:10.1016/j.cities.2019.03.012.
Davidsson, Å., 2020: Disasters as an opportunity for improved environmental conditions. *International Journal of Disaster Risk Reduction*, **48**, 101590, doi:https://doi.org/10.1016/j.ijdrr.2020.101590.
de Coninck, H. et al., 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
de Coninck, H. and A. Sagar, 2015: Making sense of policy for climate technology development and transfer. *Climate Policy*, **15**(1), 1–11.
De Juan, A., 2015: Long-term environmental change and geographical patterns of violence in Darfur, 2003–2005. *Political Geography*, **45**, 22-33, doi:10.1016/j.polgeo.2014.09.001.
de la Torre-Castro, M. et al., 2017: Gender analysis for better coastal management – Increasing our understanding of social-ecological seascapes. *Marine Policy*, **83**, 62-74, doi:10.1016/j.marpol.2017.05.015.
de Vries, G. W., W. P. C. Boon and A. Peine, 2016: User-led innovation in civic energy communities. *Environmental Innovation and Societal Transitions*, **19**, 51-65, doi:https://doi.org/10.1016/j.eist.2015.09.001.
de Witt, A., 2015: Climate Change and the Clash of Worldviews: An Exploration of How to Move Forward in a Polarized Debate. *Zygon®*, **50**(4), 906-921, doi:10.1111/zygo.12226.
De Witt, A., J. de Boer, N. Hedlund and P. Osseweijer, 2016: A new tool to map the major worldviews in the Netherlands and USA, and explore how they relate to climate change. *Environmental Science & Policy*, **63**, 101-112, doi:10.1016/j.envsci.2016.05.012.
Deaconu, A., G. Mercille and M. Batal, 2019: The Agroecological Farmer's Pathways from Agriculture to Nutrition: A Practice-Based Case from Ecuador's Highlands. *Ecology of Food and Nutrition*, **58**(2), 142-165.
Dearing, J. A. et al., 2014: Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, **28**, 227-238.
DeCaro, D. A., C. A. Arnold, E. Frimpong Boamah and A. S. Garmestani, 2017: Understanding and applying principles of social cognition and decision making in adaptive environmental governance. *Ecology and Society*, **22**(1), art33.
Dekker, S., 2020: Responding to Climate Change : The Role of Local Government in Ireland. *Ireland and the Climate Crisis*, 109–127.
Delina, L. L. and B. K. Sovacool, 2018: Of temporality and plurality: an epistemic and governance agenda for accelerating just transitions for energy access and sustainable development. *Current Opinion in Environmental Sustainability*, **34**, 1-6, doi:https://doi.org/10.1016/j.cosust.2018.05.016.
Dellink, R., E. Lanzi and J. Chateau, 2019: The Sectoral and Regional Economic Consequences of Climate Change to 2060. *Environmental and Resource Economics*, **72**(2), 309-363, doi:10.1007/s10640-017-0197-5.
Dellmuth, L. M., M.-T. Gustafsson, N. Bremberg and M. Mobjörk, 2018: Intergovernmental organizations and climate security: advancing the research agenda. *WIREs Climate Change*, **9**(1), e496, doi:10.1002/wcc.496.
Demaria, F. and A. Kothari, 2017: The Post-Development Dictionary agenda: paths to the pluriverse. *Third World Quarterly*, **38**(12), 2588-2599, doi:10.1080/01436597.2017.1350821.
Demaria, F., F. Schneider, F. Sekulova and J. Martinez-Alier, 2013: What is Degrowth? From an Activist Slogan to a Social Movement. *Environmental Values*, **22**(2), 191-215, doi:10.3197/096327113X13581561725194.
Demeritt, D. et al., 2011: Pathways to Sustainability: Perspectives and Provocations. *Environ Plan A*, **43**(5), 1226-1237, doi:10.1068/a227sym.
Dempsey, J., T. G. Martin and U. R. Sumaila, 2020: Subsidizing extinction? *Conservation Letters*, **13**(1), e12705, doi:10.1111/conl.12705.
Demuzere, M. et al., 2014: Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, **146**, 107-115, doi:10.1016/j.jenvman.2014.07.025.
Deneulin, S. and L. Shahani, 2009: *An Introduction to the Human Development and Capability Approach: Freedom and Agency*, 1st edition ed. [Deneulin, S. and L. Shahani (eds.)]. Routledge, London ; Sterling, VA : Ottawa, ON, 376 pp. ISBN 978-1-84407-806-6.
Denton, F. et al., 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White

(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131. ISBN 9781107058071.
Díaz, S. et al., 2015: The IPBES Conceptual Framework—connecting nature and people. *Current Opinion in Environmental Sustainability*, **14**, 1-16.
Díaz, S. et al., 2018: Assessing nature's contributions to people. *Science*, **359**(6373), 270-272, doi:10.1126/science.aap8826.
Dietz, S., A. Bowen, C. Dixon and P. Gradwell, 2016: 'Climate value at risk' of global financial assets. *Nature Climate Change*, **6**(7), 676-679, doi:10.1038/nclimate2972.
Diffenbaugh, N. and M. Burke, 2019: Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences*, **116**, 201816020, doi:10.1073/pnas.1816020116.
DiGregorio, M., 2015: Bargaining with Disaster: Flooding, Climate Change, and Urban Growth Ambitions in Quy Nhon, Vietnam. *Pacific Affairs*, **88**(3), 577-597, doi:10.5509/2015883577.
Dimson, E., O. Karakaş and X. Li, 2015: Active Ownership. *The Review of Financial Studies*, **28**(12), 3225-3268, doi:10.1093/rfs/hhv044.
Dimson, E., O. Karakaş and X. Li, 2020: *Coordinated Engagements*. Social Science Research Network, Rochester, NY (accessed 2021-08-26 22:38:57).
Djoudi, H. et al., 2016: Beyond dichotomies: Gender and intersecting inequalities in climate change studies. *Ambio*, **45**(S3), 248-262.
Doczi, J., 2015: *Understanding patterns of climate resilient economic development*. Available at: https://www.odi.org/publications/10101-understanding-patterns-climate-resilient-economic-development.
Dodman, D. and D. Mitlin, 2015: The national and local politics of climate change adaptation in Zimbabwe. *Climate and Development*, **7**(3), 223–234.
Dolšak, N. and A. Prakash, 2018: The Politics of Climate Change Adaptation. *Annual Review of Environment and Resources*, **43**(1), 317-341, doi:10.1146/annurev-environ-102017-025739.
Domingo, A., 2018: Analyzing Zombie Dystopia as Neoliberal Scenario: An Exercise in Emancipatory Catastrophism. *Frontiers in Sociology*, **3**, 20, doi:10.3389/fsoc.2018.00020.
Donner, S. D., M. Kandlikar and S. Webber, 2016: Measuring and tracking the flow of climate change adaptation aid to the developing world. *Environmental Research Letters*, **11**(5), 054006.
Dornan, M., 2015: Renewable Energy Development in Small Island Developing States of the Pacific. *Resources*, **4**(3), 490-506, doi:10.3390/resources4030490.
Douxchamps, S. et al., 2016: Linking agricultural adaptation strategies, food security and vulnerability: evidence from West Africa. *Regional Environmental Change*, **16**(5), 1305-1317, doi:10.1007/s10113-015-0838-6.
Dresse, A., I. Fischhendler, J. Ø. Nielsen and D. Zikos, 2018: Environmental peacebuilding: Towards a theoretical framework. *Cooperation and Conflict*, doi:10.1177/0010836718808331.
Dreyer, J. S., 2015: Ubuntu. *International Journal of Practical Theology*, **19**(1), 189-209, doi:10.1515/ijpt-2015-0022.
Driver, E., M. Parsons and K. Fisher, 2018: Technically political: The post-politics(?) of the New Zealand Emissions Trading Scheme. *Geoforum*, **97**, 253-267, doi:10.1016/j.geoforum.2018.09.023.
Duan, F., Q. Ji, B.-Y. Liu and Y. Fan, 2018: Energy investment risk assessment for nations along China's Belt & Road Initiative. *Journal of Cleaner Production*, **170**, 535-547, doi:10.1016/j.jclepro.2017.09.152.
Duku, C., S. J. Zwart and L. Hein, 2018: Impacts of climate change on cropping patterns in a tropical, sub-humid watershed. *PLoS One*, **13**(3), e0192642, doi:10.1371/journal.pone.0192642.
Dumont, E. S., S. Bonhomme, T. F. Pagella and F. L. Sinclair, 2019: STRUCTURED STAKEHOLDER ENGAGEMENT LEADS TO DEVELOPMENT OF MORE DIVERSE AND INCLUSIVE AGROFORESTRY OPTIONS. *Experimental Agriculture*, **55**(S1), 252-274.
Dun, O., C. McMichael, K. McNamara and C. Farbotko, 2020: Investing in home: development outcomes and climate change adaptation for seasonal workers living between Solomon Islands and Australia. *Migration and Development*, **0**(0), 1-24, doi:10.1080/21632324.2020.1837535.
Dzebo, A. et al., 2017: *Exploring connections between the Paris Agreement and the 2030 Agenda for Sustainable Development*. Stockholm Environment Institute.
Dzebo, A., H. Janetschek, C. Brandi and G. Iacobuta, 2019: Connections between the Paris Agreement and the 2030 Agenda: the case for policy coherence.
Eakin, H. C., M. C. Lemos and D. R. Nelson, 2014: Differentiating capacities as a means to sustainable climate change adaptation. *Global Environmental Change*, **27**(1), 1–8.
Eastin, J., 2018: Climate change and gender equality in developing states. *World Development*, **107**, 289-305.
Ebi, K. L., N. H. Ogden, J. C. Semenza and A. Woodward, 2017: Detecting and Attributing Health Burdens to Climate Change. *Environ Health Perspect*, **125**(8), 085004, doi:10.1289/EHP1509.
ECB, 2020: *Guide on Climate-Related and Environmental Risks*.
Economides, G. and A. Xepapadeas, 2018: Monetary Policy under Climate Change. *CESifo Working Paper No.7021*.
Ehnert, F. et al., 2018: Urban sustainability transitions in a context of multi-level governance: A comparison of four European states. *Environmental Innovation and Societal Transitions*, **26**, 101-116, doi:https://doi.org/10.1016/j.eist.2017.05.002.

Eisenmenger, N. et al., 2020: The Sustainable Development Goals prioritize economic growth over sustainable resource use: a critical reflection on the SDGs from a socio-ecological perspective. *Sustainability Science*, **15**(4), 1101-1110, doi:10.1007/s11625-020-00813-x.
Elliott, A. and J. Cullis, 2017: The Importance of the Humanities to the Climate Change Debate. In: *Climate Change and the Humanities: Historical, Philosophical and Interdisciplinary Approaches to the Contemporary Environmental Crisis* [Elliott, A., J. Cullis and V. Damodaran (eds.)]. Palgrave Macmillan UK, London, pp. 15-42. ISBN 978-1-137-55124-5.
Ellis, N. R. and P. Tschakert, 2019: Triple-wins as pathways to transformation? A critical review. *Geoforum*, **103**, 167-170, doi:10.1016/j.geoforum.2018.12.006.
Emmerling, J. and M. Tavoni, 2021: Representing inequalities in integrated assessment modeling of climate change. *One Earth*, **4**(2), 177-180, doi:https://doi.org/10.1016/j.oneear.2021.01.013.
Enns, C., 2018: Mobilizing research on Africa's development corridors. *Geoforum*, **88**, 105-108.
Enns, C. and B. Bersaglio, 2020: On the Coloniality of "New" Mega-Infrastructure Projects in East Africa. *Antipode*, **52**(1), 101-123.
Ensor, J., 2016: Adaptation and resilience in Vanuatu: Interpreting community perceptions of vulnerability, knowledge and power for community-based adaptation programming. *Report by SEI for Oxfam Australia, Carlton*.
Eriksen, S., R. Grøndahl and A.-M. Sæbønes, 2021a: On CRDP and CRPD: Why the rights of persons with disabilities are critical for understanding climate resilient development pathways. *The Lancet Planetary Health*, In Press.
Eriksen, S. et al., 2021b: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383, doi:10.1016/j.worlddev.2020.105383.
Eriksen, S. H., L. K. Cramer, I. Vetrhus and P. Thornton, 2019: Can Climate Interventions Open Up Space for Transformation? Examining the Case of Climate-Smart Agriculture (CSA) in Uganda. *Frontiers in Sustainable Food Systems*, **3**.
Eriksen, S. H., A. J. Nightingale and H. Eakin, 2015: Reframing adaptation: The political nature of climate change adaptation. *Global Environmental Change*, **35**, 523-533, doi:10.1016/j.gloenvcha.2015.09.014.
Escobar, A., 1995: Imagining a post-development era. *Power of development*, 211-227.
Escobar, A., 2016: Thinking-feeling with the Earth; Territorial Struggles and the Ontological Dimension of the Epistemologies of the South. *AIBR Revista de Antropologia Iberoamericana*, **11**(1), 11-32.
Esquivel-Muelbert, A. et al., 2019: Compositional response of Amazon forests to climate change. *Global Change Biology*, **25**(1), 39-56, doi:10.1111/gcb.14413.
Estoque, R. et al., 2018: A review of quality of life (QOL) assessments and indicators: Towards a "QOL-Climate" assessment framework. *Ambio*, **48**, doi:10.1007/s13280-018-1090-3.
Etchart, L., 2017: The role of indigenous peoples in combating climate change. *Palgrave Communications*, **3**(1), 1-4, doi:10.1057/palcomms.2017.85.
Ewuoso, C. and S. Hall, 2019: Core aspects of ubuntu: A systematic review. *South African Journal of Bioethics and Law*, **12**(2), 93-103, doi:10.7196/SAJBL.2019.v12i2.679.
Fadrique, B. et al., 2018: Widespread but heterogeneous responses of Andean forests to climate change. *Nature*, **564**(7735), 207-212, doi:10.1038/s41586-018-0715-9.
Faist, T., 2018: The Socio-Natural Question: How Climate Change Adds to Social Inequalities. *Journal of Intercultural Studies*, **39**(2), 195-206, doi:10.1080/07256868.2018.1446670.
Fankhauser, S. and T. McDermott, 2016: *The Economics of Climate-Resilient Development*. Edward Elgar Publishing. ISBN 978-1-78536-031-2.
Fankhauser, S. and T. K. J. McDermott, 2014: Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change*, **27**, 9-18, doi:10.1016/j.gloenvcha.2014.04.014.
FAO, 2014: *Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative*. Food and Agriculture Organization of the United Nations.
Fao, 2016: *Base de datos Género y derecho a la tierra, FAO*. Available at: http://www.fao.org/gender-landrights-database.
Faruque, M. O., 2017: Neoliberal resource governance and counter-hegemonic social movement in Bangladesh. *Social Movement Studies*, **16**(2), 254-259, doi:10.1080/14742837.2016.1268957.
Favretto, N. et al., 2018: Links between Climate Change Mitigation, Adaptation and Development in Land Policy and Ecosystem Restoration Projects: Lessons from South Africa. *Sustainability*, **10**(3), 779, doi:10.3390/su10030779.
Fazey, I. et al., 2018a: Transformation in a changing climate: a research agenda. *Climate and Development*, **10**(3), 197-217.
Fazey, I. et al., 2018b: Ten essentials for action-oriented and second order energy transitions, transformations and climate change research. *Energy Research & Social Science*, **40**, 54–70.
Fazey, I. et al., 2016: Past and future adaptation pathways. *Climate and Development*, **8**(1), 26–44.
Fedele, G. et al., 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116-125, doi:10.1016/j.envsci.2019.07.001.
Feodoroff, P., 2020: *Indigenous Female Bodies as Indicators of Change*. Global Report of Indigenous Knowledge and Local Knowledge on Climate Change 2020.

Feola, G., 2015: Societal transformation in response to global environmental change: A review of emerging concepts. *Ambio*, **44**(5), 376-390, doi:10.1007/s13280-014-0582-z.
Feola, G., O. Koretskaya and D. Moore, 2021: (Un)making in sustainability transformation beyond capitalism. *Global Environmental Change*, **69**, 102290, doi:10.1016/j.gloenvcha.2021.102290.
Fergnani, A. and Z. Song, 2020: The six scenario archetypes framework: A systematic investigation of science fiction films set in the future. *Futures*, **124**, 102645, doi:https://doi.org/10.1016/j.futures.2020.102645.
Fernandez, G. and I. Ahmed, 2019: "Build back better" approach to disaster recovery: Research trends since 2006. *Progress in Disaster Science*, **1**, 100003, doi:https://doi.org/10.1016/j.pdisas.2019.100003.
Ferragina, E., A. Arrigoni and T. F. Spreckelsen, 2020: The rising invisible majority. *Review of International Political Economy*, **0**(0), 1-38, doi:10.1080/09692290.2020.1797853.
Few, R. et al., 2017: Transformation, adaptation and development: relating concepts to practice. *Palgrave Communications*, **3**(1), 1-9, doi:10.1057/palcomms.2017.92.
Ficklin, L., L. C. Stringer, A. J. Dougill and S. M. Sallu, 2018: Climate compatible development reconsidered: calling for a critical perspective. *Climate and Development*, **10**(3), 193-196, doi:10.1080/17565529.2017.1372260.
Fioramonti, L., L. Coscieme and L. F. Mortensen, 2019: From gross domestic product to wellbeing: How alternative indicators can help connect the new economy with the Sustainable Development Goals. *The Anthropocene Review*, doi:10.1177/2053019619869947.
Fischedick, M. et al., 2014: Industry. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 739-810. ISBN 9781107058217.
Fischer, J. and M. Riechers, 2019: A leverage points perspective on sustainability. *People and Nature*, **1**(1), 115-120, doi:10.1002/pan3.13.
Fisher, B. S. et al., 2007: Issues related to mitigation in the long term context. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169-250. ISBN 9780521880114.
Fisher, E., J. Hellin, H. Greatrex and N. Jensen, 2019: Index insurance and climate risk management: Addressing social equity. *Development Policy Review*, **37**(5), 581-602, doi:10.1111/dpr.12387.
Flammer, C., 2020: *Green Bonds: Effectiveness and Implications for Public Policy*. National Bureau of Economic Research. Available at: https://www.nber.org/papers/w25950 (accessed 2020/11/10/16:31:26).
Fleurbaey, M. et al., 2014: Sustainable Development and Equity. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Folke, C. et al., 2016: Social-ecological resilience and biosphere-based sustainability science.
Ford, J. et al., 2016: Including indigenous knowledge and experience in IPCC assessment reports. *Nature Climate Change*, **64**(4), 349.
Ford , J., W. Vanderbilt and L. Berrang-Ford, 2012: Authorship in IPCC AR5 and its implications for content: climate change and Indigenous populations in WGII. *Climatic Change*, **113**(2), 201-213, doi:10.1007/s10584-011-0350-z.
Ford, J. D. et al., 2015: The status of climate change adaptation in Africa and Asia. *Regional Environmental Change*, **15**(5), 801–814.
Ford, J. D. et al., 2020: The resilience of Indigenous Peoples to environmental change. *One Earth*, **2**, 532-543.
Forsyth, T., 2018: Is resilience to climate change socially inclusive? Investigating theories of change processes in Myanmar. *World Development*, **111**, 13-26, doi:10.1016/j.worlddev.2018.06.023.
Foster-Fishman, P. G., B. Nowell and H. Yang, 2007: Putting the system back into systems change: a framework for understanding and changing organizational and community systems. *American Journal of Community Psychology*, **39**(3-4), 197-215, doi:10.1007/s10464-007-9109-0.
Fougère, L. and S. Bond, 2016: Legitimising activism in democracy: A place for antagonism in environmental governance. *Planning Theory*, doi:10.1177/1473095216682795.
Fragkias, M. and C. G. Boone, 2016: Modern political economy, global environmental change and urban sustainability transitions. *Current Opinion in Environmental Sustainability*, **22**, 63-68, doi:10.1016/j.cosust.2017.04.007.
Frainer, A. et al., 2020: Cultural and linguistic diversities are underappreciated pillars of biodiversity. *Proceedings of the National Academy of Sciences*, **117**(43), 26539-26543, doi:https://doi.org/10.1073/pnas.2019469117.
Franco-Torres, M., B. C. Rogers and R. Harder, 2020: Articulating the new urban water paradigm. *Critical Reviews in Environmental Science and Technology*, **0**(0), 1-47, doi:10.1080/10643389.2020.1803686.
Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12**(10), 105004, doi:10.1088/1748-9326/aa8c83.

Frank, T. D. et al., 2019: Global, regional, and national incidence, prevalence, and mortality of HIV, 1980-2017, and forecasts to 2030, for 195 countries and territories: a systematic analysis for the Global Burden of Diseases, Injuries, and Risk Factors Study 2017. *The Lancet HIV*, **6**(12), e831-e859, doi:10.1016/s2352-3018(19)30196-1.
Frantzeskaki, N. et al., 2017: Nature-based solutions accelerating urban sustainability transitions in cities: lessons from Dresden, Genk and Stockholm cities. In: *Nature-Based Solutions to Climate Change Adaptation in Urban Areas*. Springer, Cham, pp. 65-88.
Fresnillo Sallan, I., 2020: Debt and climate: entangled emergencies derailing women's rights and gender justice. *Gender & Development*, **28**(3), 499-513, doi:10.1080/13552074.2020.1838168.
Friedman, S., S. Schmer-Galunder, A. Chen and J. Rye (eds.), Relating Word Embedding Gender Biases to Gender Gaps: A Cross-Cultural Analysis. 2019-08, Association for Computational Linguistics, Florence, Italy, 18–24 pp.
Froehlich, H. E., J. C. Afflerbach, M. Frazier and B. S. Halpern, 2019: Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. *Current Biology*, **29**(18), 3087-3093.e3083, doi:10.1016/j.cub.2019.07.041.
Fudge, S., M. Peters and B. Woodman, 2016: Local authorities as niche actors: the case of energy governance in the UK. *Environmental Innovation and Societal Transitions*, **18**, 1-17.
Fund for Peace, 2021: *Fragile States Index Annual Report 2021*. Fund for Peace, Peace, F. f., Washington, DC, 51 pp.
Fuso Nerini, F. et al., 2018: Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy*, **3**(1), 10-15, doi:10.1038/s41560-017-0036-5.
Gaddy, B. E., V. Sivaram, T. B. Jones and L. Wayman, 2017: Venture Capital and Cleantech: The wrong model for energy innovation. *Energy Policy*, **102**, 385-395, doi:10.1016/j.enpol.2016.12.035.
Galvin, K. A., 2009: Transitions: Pastoralists Living with Change. *Annual Review of Anthropology*, **38**(1), 185-198.
Gambrel, J. C. and P. Cafaro, 2009: The Virtue of Simplicity. *J Agric Environ Ethics*, **23**(1), 85, doi:10.1007/s10806-009-9187-0.
Garcia, A., P. Tschakert and N. A. Karikari, 2020: 'Less able': how gendered subjectivities warp climate change adaptation in Ghana's Central Region. *Gender, Place & Culture*, **27**(11), 1602-1627, doi:10.1080/0966369X.2020.1786017.
Garcia, D. J. and F. You, 2017: Introducing Green GDP as an Objective to Account for Changes in Global Ecosystem Services Due to Biofuel Production. In: *Computer Aided Chemical Engineering* [Espuña, A., M. Graells and L. Puigjaner (eds.)]. Elsevier, pp. 505-510.
Garg, A. and K. Halsnæs, 2007: Sustainable development to enhance resilience to climate change vulnerability. *From vulnerability to resilience: The challenge of adaptation to climate change*, 17-25.
Garschagen, M. et al., 2021: The consideration of future risk trends in national adaptation planning: conceptual gaps and empirical lessons. *Climate Risk Management*, In press.
Gaur, M. and V. R. Squires, 2018: *Climate Variability Impacts on Land Use and Livelihoods in Drylands* [GAUR, M. and V. R. Squires (eds.)]. Springer International Publishing. ISBN 978-3-319-56680-1.
Gay-Antaki, M., 2020: Feminist geographies of climate change: Negotiating gender at climate talks. *Geoforum*, **115**, 1-10.
Gay-Antaki, M. and D. Liverman, 2018: Climate for women in climate science: Women scientists and the Intergovernmental Panel on Climate Change. *Proceedings of the National Academy of Sciences*, **115**(9), 2060-2065.
Gazzotti, P. et al., 2021: Persistent inequality in economically optimal climate policies. *Nature Communications*, **12**(1), 3421, doi:10.1038/s41467-021-23613-y.
Gebreyes, M., 2018: 'Producing' institutions of climate change adaptation and food security in north eastern Ethiopia. *NJAS - Wageningen Journal of Life Sciences*, **84**, 123-132, doi:10.1016/j.njas.2017.10.007.
Geere, J.-A. L. and P. R. Hunter, 2020: The association of water carriage, water supply and sanitation usage with maternal and child health. A combined analysis of 49 Multiple Indicator Cluster Surveys from 41 countries. *International Journal of Hygiene and Environmental Health*, **223**(1), 238-247.
Geradts, T. H. and N. M. Bocken, 2019: Driving sustainability-oriented innovation. *Mit Sloan Management Review*, **60**(2), 1.
Gernert, M., H. El Bilali and C. Strassner, 2018: Grassroots Initiatives as Sustainability Transition Pioneers: Implications and Lessons for Urban Food Systems. *Urban Science*, **2**(1), 23.
Gerst, M., P. Raskin and J. Rockström, 2013: Contours of a Resilient Global Future. *Sustainability*, **6**, 123-135, doi:10.3390/su6010123.
Ghisetti, C., S. Mancinelli, M. Mazzanti and M. Zoli, 2017: Financial barriers and environmental innovations: evidence from EU manufacturing firms. *Climate Policy*, **17**(sup1), S131-S147, doi:10.1080/14693062.2016.1242057.
Gianfrate, G. and M. Peri, 2019: The green advantage: Exploring the convenience of issuing green bonds. *Journal of Cleaner Production*, **219**, 127-135, doi:10.1016/j.jclepro.2019.02.022.
Gibon, T. et al., 2020: Shades of green: life cycle assessment of renewable energy projects financed through green bonds. *Environmental Research Letters*, **15**, 104045, doi:10.1088/1748-9326/abaa0c.
Gibson-Graham, J. K., 2006: *A Postcapitalist Politics*, First edition ed., University of Minnesota Press, Minneapolis, 316 pp. ISBN 978-0-8166-4804-7.
Gibson-Graham, J. K., 2005: Surplus possibilities: postdevelopment and community economies. *Singapore Journal of Tropical Geography*, **26**(1), 4-26.

Gielen, D. et al., 2019: The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, **24**, 38-50, doi:10.1016/j.esr.2019.01.006.
Gill, S. R. and S. R. Benatar, 2020: Reflections on the political economy of planetary health. *Review of International Political Economy*, **27**(1), 167-190, doi:10.1080/09692290.2019.1607769.
Gillard, R. et al., 2016: Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **7**, 251–265.
Gills, B. and J. Morgan, 2020: Global Climate Emergency: after COP24, climate science, urgency, and the threat to humanity. *Globalizations*, **17**(6), 885-902, doi:10.1080/14747731.2019.1669915.
Gleditsch, N. P. and R. Nordås, 2014: Conflicting messages? The IPCC on conflict and human security. *Political Geography*, **43**, 82-90, doi:10.1016/j.polgeo.2014.08.007.
Gliedt, T., C. E. Hoicka and N. Jackson, 2018: Innovation intermediaries accelerating environmental sustainability transitions. *Journal of Cleaner Production*, **174**, 1247-1261.
Goda, T., Ö. Onaran and E. Stockhammer, 2017: Income Inequality and Wealth Concentration in the Recent Crisis. *Development and Change*, **48**(1), 3-27, doi:https://doi.org/10.1111/dech.12280.
Goddard, G. and M. A. Farrelly, 2018: Just transition management: Balancing just outcomes with just processes in Australian renewable energy transitions. *Applied Energy*, **225**, 110-123, doi:https://doi.org/10.1016/j.apenergy.2018.05.025.
Godfrey-Wood, R. and L. Otto Naess, 2016: *Adapting to climate change: Transforming development?* Available at: https://bulletin.ids.ac.uk/index.php/idsbo/article/view/2717.
Goldman, M. J., M. D. Turner and M. Daly, 2018: A critical political ecology of human dimensions of climate change: Epistemology, ontology, and ethics. *WIREs Climate Change*, **9**(4), e526, doi:10.1002/wcc.526.
Gonçalves-Souza, D., P. H. Verburg and R. Dobrovolski, 2020: Habitat loss, extinction predictability and conservation efforts in the terrestrial ecoregions. *Biological Conservation*, **246**, 108579, doi:10.1016/j.biocon.2020.108579.
Gonda, N., 2017: Revealing the patriarchal sides of climate change adaptation through intersectionality: a case study from Nicaragua. pp. 173-189. ISBN 978-1-315-66160-5.
González-Hidalgo, M. and C. Zografos, 2019: Emotions, power, and environmental conflict: Expanding the 'emotional turn' in political ecology. *Progress in Human Geography*, doi:10.1177/0309132518824644.
González-Hidalgo, M. and C. Zografos, 2020: Emotions, power, and environmental conflict: Expanding the 'emotional turn' in political ecology. *Progress in Human Geography*, **44**(2), 235–255.
Goodrich, C. G., A. Prakash and P. B. Udas, 2019: Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. *Environmental Development*, **31**, 1-8, doi:10.1016/j.envdev.2019.01.001.
Göpel, M., 2016: *The Great Mindshift: How a New Economic Paradigm and Sustainability Transformations Go Hand in Hand*.
Gorddard, R. et al., 2016: Values, rules and knowledge: Adaptation as change in the decision context. *Environmental Science and Policy*, **57**, 60–69.
Görg, C. et al., 2017: Challenges for Social-Ecological Transformations: Contributions from Social and Political Ecology. *Sustainability*, **9**, 1045, doi:10.3390/su9071045.
Gorissen, L. et al., 2018: Moving towards systemic change? Investigating acceleration dynamics of urban sustainability transitions in the Belgian City of Genk. *Journal of cleaner production*, **173**, 171-185.
Gotham, K. F., 2016: Antinomies of risk reduction: climate change and the contradictions of coastal restoration. *Environmental Sociology*, **2**(2), 208-219, doi:10.1080/23251042.2016.1177363.
Government of Kenya, 2008: About Vision 2030. Retrieved from. *ABOUT VISION 2030*.
Government of Kenya, 2012: Vision 2030 Development Strategy for Northern Kenya and other Arid Lands. Kenya: Government of Kenya.
Government of Kenya, 2016: Brief on LAPSSET corridor project. Retrieved from.
Government of Kenya, 2018: *Ministry Of Devolution And ASALs, State Department For Development Of The Arid And Semi Arid Lands Strategic Plan (2018 – 2022)*.
Graham, N. T. et al., 2018: Water Sector Assumptions for the Shared Socioeconomic Pathways in an Integrated Modeling Framework. *Water Resources Research*, **54**(9), 6423-6440, doi:https://doi.org/10.1029/2018WR023452.
Gram-Hanssen, I., N. Schafenacker and J. Bentz, 2021: Decolonizing transformations through 'right relations'. *Sustainability Science*, doi:10.1007/s11625-021-00960-9.
Gratani, M. et al., 2011: Is Validation of Indigenous Ecological Knowledge a Disrespectful Process? A Case Study of Traditional Fishing Poisons and Invasive Fish Management from the Wet Tropics, Australia. *Ecology and Society*, **16**(3), doi:10.5751/es-04249-160325.
Green, A. S. et al., 2020: An interdisciplinary framework for using archaeology, history and collective action to enhance India's agricultural resilience and sustainability. *Environmental Research Letters*, **15**(10), 105021, doi:10.1088/1748-9326/aba780.
Green, R. et al., 2013: The effect of rising food prices on food consumption: systematic review with meta-regression. *BMJ*, **346**(jun17 1), f3703-f3703.
Greiner, C., 2016: Land-use change, territorial restructuring, and economies of anticipation in dryland Kenya. *Journal of Eastern African Studies*, **10**(3), 530-547.
Griscom, B. W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114**(44), 11645–11650.

Grove, K., 2018: *Resilience*. Routledge.
Gumucio, T., M. d. A. Alves, N. Orentlicher and M. C. Hernández Ceballos, 2018: Analysis of gender research on forest, tree and agroforestry value chains in Latin America. *Forests, Trees and Livelihoods*, **27**(2), 69-85.
Gundimeda, H., P. Sukhdev, R. K. Sinha and S. Sanyal, 2007: Natural resource accounting for Indian states - Illustrating the case of forest resources. *Ecological Economics*, **61**(4), 635-649, doi:10.1016/j.ecolecon.2006.07.035.
Güneralp, B. et al., 2017: Urbanization in Africa: challenges and opportunities for conservation. *Environmental Research Letters*, **13**(1), 015002, doi:10.1088/1748-9326/aa94fe.
Gupta, J. and N. Pouw, 2017: Towards a trans-disciplinary conceptualization of inclusive development. *Current Opinion in Environmental Sustainability*, **24**, 96-103.
Haasnoot, M., J. H. Kwakkel, W. E. Walker and J. ter Maat, 2013: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, **23**(2), 485-498, doi:10.1016/j.gloenvcha.2012.12.006.
Haines, A. et al., 2017: Short-lived climate pollutant mitigation and the Sustainable Development Goals. *Nature Climate Change*, **7**(12), 863-869, doi:10.1038/s41558-017-0012-x.
Hajer, M. et al., 2015: Beyond Cockpit-ism: Four Insights to Enhance the Transformative Potential of the Sustainable Development Goals. *Sustainability*, **7**(2), 1651–1660.
Hale, T., 2016: "All Hands on Deck": The Paris Agreement and Nonstate Climate Action. *Global Environmental Politics*, **16**(3), 12-22, doi:10.1162/GLEP_a_00362.
Hall, S. M., 2020: The personal is political: Feminist geographies of/in austerity. *Geoforum*, **110**, 242-251, doi:10.1016/j.geoforum.2018.04.010.
Hallam, R., 2019: *Common sense for the 21st century: only nonviolent rebellion can now stop climate breakdown and social collapse*. ISBN 978-1-5272-4674-4.
Hallegatte, S., C. Brandon and e. al, 2018: *The economics of (and obstacles to) aligning development and climate change adaptation: A World Bank Group Contribution to the Global Commission on Adaptation*. (accessed 2021-08-10 19:26:35).
Hallegatte, S., J. Rentschler and J. Rozenberg, 2019: *Lifelines: The Resilient Infrastructure Opportunity*. Washington, DC: World Bank. ISBN 978-1-4648-1430-3.
Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**(4), 250-256, doi:10.1038/nclimate3253.
Han, H. and S. W. Ahn, 2020: Youth Mobilization to Stop Global Climate Change: Narratives and Impact. *Sustainability*, **12**(10), 4127, doi:10.3390/su12104127.
Han, S.-J., 2015: Emancipatory catastrophism from an East Asian perspective: Feedback from the dialogue organizer. *Current Sociology*, **63**(1), 115-120, doi:10.1177/0011392114559851.
Hansen, L., 2021: Central Banking Challenges Posed by Uncertain Climate Change and Natural Disasters.
Hansen, L. et al., 2013: The state of adaptation in the United States: an overview. *A report for the John D. and Catherine T. MacArthur Foundation. Ecoadapt, Bainbridge Island, WA, USA*.
Hansen, U. E. and R. Lema, 2019: The co-evolution of learning mechanisms and technological capabilities: Lessons from energy technologies in emerging economies. *Technological Forecasting and Social Change*, **140**, 241-257, doi:10.1016/j.techfore.2018.12.007.
Hardee, K. et al., 2018: Family planning and resilience: associations found in a Population, Health, and Environment (PHE) project in Western Tanzania. *Population and Environment*, **40**(2), 204-238, doi:10.1007/s11111-018-0310-x.
Hardoy, J., E. Gencer and M. Winograd, 2019: Participatory planning for climate resilient and inclusive urban development in Dosquebradas, Santa Ana and Santa Tomé. *Environment and Urbanization*, **31**(1), 33-52, doi:10.1177/0956247819825539.
Harnphatananusorn, S., S. Santipolvut and C. Sonthi, 2019: Concepts and empirical calculation of the green GDP for Thailand. *International Journal of Green Economics*, **13**, 68, doi:10.1504/IJGE.2019.10023001.
Harper, S., J. S. Kaufman and R. S. Cooper, 2017: Declining US Life Expectancy. *Epidemiology*, **28**(6), e54–e56.
Harrington, L. J. and F. E. L. Otto, 2018: Changing population dynamics and uneven temperature emergence combine to exacerbate regional exposure to heat extremes under 1.5 °C and 2 °C of warming. *Environmental Research Letters*, **13**(3), 034011, doi:10.1088/1748-9326/aaaa99.
Harris, L. M., E. K. Chu and G. Ziervogel, 2018: Negotiated resilience. *Resilience*, **6**(3), 196-214, doi:10.1080/21693293.2017.1353196.
Harris, P. and L. Clarke, 2017: Maramataka. In: *He Whare Hangarau M?ori-Language, Culture and Technology* [Whaanga, H., T. T. Keegan and M. Apperley (eds.)].
Harris, P., L. Clarke and 2017: Maramataka. In: *He Whare Hangarau M?ori-Language, Culture and Technology* [Whaanga, H., T. T. Keegan and M. Apperley (eds.)].
Harrison, P. et al., 2019: Synthesizing plausible futures for biodiversity and ecosystem services in Europe and Central Asia using scenario archetypes. *Ecology and Society*, **24**(2), doi:10.5751/ES-10818-240227.
Harvey, B., L. Cochrane and M. V. Epp, 2019: Charting knowledge co-production pathways in climate and development. *Environmental Policy and Governance*, **29**(2), 107-117, doi:10.1002/eet.1834.

Hasegawa, T. et al., 2018: Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, **8**(8), 699-703, doi:10.1038/s41558-018-0230-x.
Hasegawa, T., S. Fujimori, K. Takahashi and T. Masui, 2015: Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. *Environmental Research Letters*, **10**(1), 014010, doi:10.1088/1748-9326/10/1/014010.
Haukkala, T., 2018: A struggle for change—The formation of a green-transition advocacy coalition in Finland. *Environmental Innovation and Societal Transitions*, **27**, 146-156, doi:https://doi.org/10.1016/j.eist.2017.12.001.
Hay, J. E., P. Hartley and J. Roop, 2019: Climate risk assessments and management options for redevelopment of the Parliamentary Complex in Samoa, South Pacific. *Weather and Climate Extremes*, **25**, 100214, doi:10.1016/j.wace.2019.100214.
Häyhä, T. et al., 2016: From Planetary Boundaries to national fair shares of the global safe operating space — How can the scales be bridged? *Global Environmental Change*, **40**, 60-72.
Healey, P., 2006: Transforming governance: Challenges of institutional adaptation and a new politics of space. *European Planning Studies*, **14**(3), 299-320, doi:10.1080/09654310500420792.
Hegre, H., K. Petrova and N. von Uexkull, 2020: Synergies and Trade-Offs in Reaching the Sustainable Development Goals. *Sustainability*, **12**(20), doi:10.3390/su12208729.
Heigl, F. et al., 2019: Opinion: Toward an international definition of citizen science. *Proceedings of the National Academy of Sciences*, **116**(17), 8089-8092.
Heinrichs, H., 2020: Artful sustainability governance—Foundational considerations on sensory-informed policymaking for sustainable development. *Sustainable Development*, **28**(4), 791-799, doi:10.1002/sd.2029.
Hémous, D., 2016: The dynamic impact of unilateral environmental policies. *Journal of International Economics*, **103**, 80-95, doi:10.1016/j.jinteco.2016.09.001.
Hepburn, C. et al., 2020: Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Review of Economic Policy*, **36**.
Herrero, M. et al., 2016: Climate change and pastoralism: impacts, consequences and adaptation: -EN- -FR- Le changement climatique et le pastoralisme : effets, conséquences et adaptation -ES- Cambio climático y pastoreo: efectos directos, repercusiones y adaptación. *Revue Scientifique et Technique de l'OIE*, **35**(2), 417-433.
Hewitt, C. D. et al., 2020: Making Society Climate Resilient: International Progress under the Global Framework for Climate Services. *Bulletin of the American Meteorological Society*, **101**(2), E237-E252.
Hickel, J., 2017: Is global inequality getting better or worse? A critique of the World Bank's convergence narrative. *Third World Quarterly*, **38**(10), 2208-2222, doi:10.1080/01436597.2017.1333414.
Hickel, J., 2019: Is it possible to achieve a good life for all within planetary boundaries? *Third World Quarterly*, **40**(1), 18-35, doi:10.1080/01436597.2018.1535895.
Hickel, J. et al., 2021: Urgent need for post-growth climate mitigation scenarios. *Nature Energy*, **6**(8), 766-768, doi:10.1038/s41560-021-00884-9.
Hickel, J. and G. Kallis, 2020: Is Green Growth Possible? *New Political Economy*, **25**(4), 469-486, doi:10.1080/13563467.2019.1598964.
Hildingsson, R., A. Kronsell and J. Khan, 2019: The green state and industrial decarbonisation. *Environmental Politics*, **28**(5), 909-928, doi:10.1080/09644016.2018.1488484.
Hilmi, N. et al., 2017: The effects of energetic transition on economic growth in Iran. *Marmara İktisat Dergisi*, **1**(1), 77-93.
Hilmi, N. and A. Safa, 2010: The Economic and Financial Policies to Fight against Climate Change: The case of Maghreb. *MEEA online journal*, **12**.
Hilmi, N., A. Safa, N. Peridy and M. Zemouri, 2015: Taking into account sustainable development for MENA countries: The calculation of a modified HDI index. *Topics in Middle Eastern and North African Economies*, **17**.
Hirpa, F. A. et al., 2018: Finding sustainable water futures in data-sparse regions under climate change: Insights from the Turkwel River basin, Kenya. *Journal of Hydrology: Regional Studies*, **19**, 124-135.
Hjerpe, M., S. Storbjörk and J. Alberth, 2015: "There is nothing political in it": triggers of local political leaders' engagement in climate adaptation. *Local Environment*, **20**(8), 855-873, doi:10.1080/13549839.2013.872092.
Hoagland, S. J., 2017: Integrating traditional ecological knowledge with western science for optimal natural resource management. *IK: Other Ways of Knowing. 3(1): 1-15.*, **3**(1), 1-15, doi:10.18113/P8ik359744.
Hoegh-Guldberg, O. et al., 2014: The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731. ISBN 9781107058163.
Hoegh-Guldberg, O. et al., 2019: *The Ocean as a Solution to Climate Change: Five Opportunities for Action*.
Hoekstra, A., M. Steinbuch and G. Verbong, 2017: Creating Agent-Based Energy Transition Management Models That Can Uncover Profitable Pathways to Climate Change Mitigation. *Complexity*.
Holden, E. et al., 2017: *The Imperatives of Sustainable Development*. Routledge. ISBN 978-0-203-02217-7.

Hölscher, K., N. Frantzeskaki and D. Loorbach, 2019: Steering transformations under climate change: capacities for transformative climate governance and the case of Rotterdam, the Netherlands. *Regional Environmental Change*, **19**(3), 791-805, doi:10.1007/s10113-018-1329-3.
Hölscher, K., J. M. Wittmayer and D. Loorbach, 2018: Transition versus transformation: What's the difference? *Environmental Innovation and Societal Transitions*, **27**, 1-3, doi:https://doi.org/10.1016/j.eist.2017.10.007.
Holvoet, N. and L. Inberg, 2014: Gender sensitivity of Sub-Saharan Africa National Adaptation Programmes of Action: findings from a desk review of 31 countries. *Climate and Development*, **6**(3), 266-276.
Holzer, J. M., N. Carmon and D. E. Orenstein, 2018: A methodology for evaluating transdisciplinary research on coupled socio-ecological systems. *Ecological Indicators*, **85**, 808-819, doi:10.1016/j.ecolind.2017.10.074.
Honohan, P., 2019: *Should Monetary Policy Take Inequality and Climate Change into Account?* Working Paper Series, Peterson Institute for International Economics (accessed 2021-08-26 22:06:19).
Hopkins, P., 2019: Social geography I: Intersectionality. *Progress in Human Geography*, **43**(5), 937-947, doi:10.1177/0309132517743677.
Horcea-Milcu, A.-I. et al., 2019: Values in transformational sustainability science: four perspectives for change. *Sustainability Science*, **14**(5), 1425-1437, doi:10.1007/s11625-019-00656-1.
Houser, M., R. Gunderson and D. Stuart, 2019: Farmers' Perceptions of Climate Change in Context: Toward a Political Economy of Relevance. *Sociologia Ruralis*, **59**(4), 789-809, doi:https://doi.org/10.1111/soru.12268.
Hov, Ø. et al., 2017: Five priorities for weather and climate research. *Nature*, **552**(7684), 168-170.
Howells, M. et al., 2013: Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, **3**(7), 621-626, doi:10.1038/nclimate1789.
Howlett, M. P. and K. Saguin, 2018: *Policy Capacity for Policy Integration: Implications for the Sustainable Development Goals*. (accessed 2019-11-14 08:26:43).
Huaman, E. S. and B. Sriraman, 2015: *Indigenous Innovation: Universalities and Peculiarities*. Springer, 214 pp. ISBN 9789463002264.
Huang, P., V. Castán Broto, Y. Liu and H. Ma, 2018: The governance of urban energy transitions: A comparative study of solar water heating systems in two Chinese cities. *Journal of Cleaner Production*, **180**, 222-231, doi:10.1016/j.jclepro.2018.01.053.
Huang, R. and X. Sun, 2020: Dual mediation and success of environmental protests in China: a qualitative comparative analysis of 10 cases. *Social Movement Studies*, **19**(4), 408-425, doi:10.1080/14742837.2019.1682539.
Huitema, D. et al., 2016: The governance of adaptation: choices, reasons, and effects. Introduction to the Special Feature. *Ecology and Society*, **21**(3), doi:10.5751/ES-08797-210337.
Hulme, M., 2018: "Gaps" in Climate Change Knowledge. *Environmental Humanities*, **10**, 330-337, doi:10.1215/22011919-4385599.
Hulme, M. and Apollo-University Of Cambridge Repository, 2019: Climate Emergency Politics Is Dangerous.
Human Development Report Office, 2020: *Human Development Report 2020: The Next Frontier Human development and the Anthropocene*. United Nations Development Programme, Programme, U. N. D., New York, New York, 412 pp. Available at: http://hdr.undp.org/sites/default/files/hdr2020.pdf.
Hunt, D. et al., 2012: Scenario Archetypes: Converging Rather than Diverging Themes. *Sustainability*, **4**, 740-772, doi:10.3390/su4040740.
Huntington, H. P. et al., 2017: How small communities respond to environmental change: patterns from tropical to polar ecosystems. *Ecology and Society*, **22**(3).
Huntjens, P. and T. Zhang, 2016: Climate justice: Equitable and inclusive governance of climate action. *The Hague Institute*, **Working Paper**(16).
Hurlbert, M. et al., 2019: Risk management and decision-making in relation to sustainable development. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.
Huxham, M. et al., 2015: Applying Climate Compatible Development and economic valuation to coastal management: A case study of Kenya's mangrove forests. *Journal of Environmental Management*, **157**, 168-181, doi:10.1016/j.jenvman.2015.04.018.
Ide, T., 2020: The dark side of environmental peacebuilding. *World Development*, **127**, 104777, doi:10.1016/j.worlddev.2019.104777.
IEA, 2015: *Energy and climate change, world energy outlook special report*.
IEA, 2017: *Energy Technology Perspectives 2017*. International Energy Agency (IEA). Available at: https://www.iea.org/reports/energy-technology-perspectives-2017.
IEA, 2019: *Material efficiency in clean energy transitions*. International Energy Agency (IEA).
IEA, 2020: *Global Energy Review 2020: The impacts of the Covid-19 crisis on global energy demand and CO2 emissions*. International Energy Agency (IEA).
IEA et al., 2019: *Tracking SDG 7: The Energy Progress Report 2019*. Available at: https://trackingsdg7.esmap.org/.

Ikeda, S. and S. Managi, 2019: Future inclusive wealth and human well-being in regional Japan: projections of sustainability indices based on shared socioeconomic pathways. *Sustainability Science*, **14**(1), 147-158, doi:10.1007/s11625-018-0589-7.

ILO, 1989: *Indigenous and Tribal Peoples Convention, C169*. **C169**, International Labour Organisation.

IMF, 2017: *World Economic Outlook Chapter 3*.

IMF, 2019: *Fiscal Monitor: How to Mitigate Climate Change*.

IMF, 2021: *Fiscal Policies to Address Climate Change in Asia and the Pacific*.

IMF/OECD, 2021: *Tax Policy and Climate Change: IMF/OECD Report for the G20 Finance Ministers and Central Bank Governors*.

Inaotombi, S. and P. C. Mahanta, 2019: Pathways of socio-ecological resilience to climate change for fisheries through indigenous knowledge. *Human and Ecological Risk Assessment: An International Journal*, **25**(8), 2032-2044, doi:10.1080/10807039.2018.1482197.

Iñigo, E. A. and L. Albareda, 2016: Understanding sustainable innovation as a complex adaptive system: a systemic approach to the firm. *Journal of Cleaner Production*, **126**, 1-20, doi:https://doi.org/10.1016/j.jclepro.2016.03.036.

IPBES, 2019: *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany, 56 pp. ISBN 9783947851133.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C. B., V. Barros, T. F. Stocker, Q. Dahe, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 582 pp. ISBN 9781107025066.

IPCC, 2014a: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp. ISBN 9781107058163.

IPCC, 2014b: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32. ISBN 9781107058071.

IPCC, 2018a: *Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson, D., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and Waterfield (eds.)]. Organization, W. M., Geneva, Switzerland, 32 pp.

IPCC, 2018b: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.

IPCC, 2019a: Annex I: Glossary [Weyer, N.M. (ed.)]. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.

IPCC, 2019b: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)]. In press pp.

IPCC, 2019c: *Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)]. Available at: https://www.ipcc.ch/srccl-report-download-page/ (accessed 2019/10/2).

IPCC, 2019d: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. In press pp.
IPCC, 2019e: *Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. Available at: https://www.ipcc.ch/srocc/home/ (accessed 2019/10/2).
IPCC, 2019f: Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.
IPCC, 2019g: Technical Summary. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
IPCC, 2021a: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
IPCC, 2021b: *WG1 Summary for Policymakers*.
Isgren, E., C. S. Boda, D. Harnesk and D. O'Byrne, 2019: Science has much to offer social movements in the face of planetary emergencies. *Nature Ecology & Evolution*, **3**(11), 1498-1498.
Islam, S., C. Chu and J. C. R. Smart, 2020: Challenges in integrating disaster risk reduction and climate change adaptation: Exploring the Bangladesh case. *International Journal of Disaster Risk Reduction*, **47**, 101540, doi:10.1016/j.ijdrr.2020.101540.
ITK, 2019: *National Inuit Climate Change Strategy, Inuit Tapiriit Kanatami (ITK), Ottawa.* (accessed 2021-09-02).
Ives, C., R. Freeth and J. Fischer, 2019: Inside-out sustainability: The neglect of inner worlds. *Ambio*, **49**, doi:10.1007/s13280-019-01187-w.
Ives, C. D. et al., 2017: Human–nature connection: a multidisciplinary review. *Current Opinion in Environmental Sustainability*, **26-27**, 106-113, doi:10.1016/j.cosust.2017.05.005.
Jabeen, H., 2014: Adapting the built environment: the role of gender in shaping vulnerability and resilience to climate extremes in Dhaka. *Environment and Urbanization*, **26**(1), 147-165, doi:10.1177/0956247813517851.
Jabeen, H. and S. Guy, 2015: Fluid engagements: Responding to the co-evolution of poverty and climate change in Dhaka, Bangladesh. *Habitat International*, **47**, 307-314, doi:10.1016/j.habitatint.2015.02.005.
Jackson, E. A., 2016: *Ontological and Epistemological Discourse(s) on Sustainable Development: Perspective on Sierra Leone in the Aftermath of a Decade of Civil Unrest*. Social Science Research Network, Rochester, NY. Available at: https://papers.ssrn.com/abstract=2811522 (accessed 2020/11/04/19:08:27).
Jackson, M., 2014: Composing postcolonial geographies: Postconstructivism, ecology and overcoming ontologies of critique. *Singapore Journal of Tropical Geography*, **35**(1), 72-87, doi:10.1111/sjtg.12052.
Jackson, T., 2009: *Prosperity Without Growth: Economics for a Finite Planet*.
Jackson, T., 2021: *Post Growth: Life after Capitalism*, 1st edition ed., Polity, Cambridge, UK Medford, MA, USA, 256 pp. ISBN 978-1-5095-4252-9.
Jafry, T., 2016: Making the case for gender sensitive climate policy – lessons from South Asia/IGP. *International Journal of Climate Change Strategies and Management*, **8**(4), 559-577, doi:10.1108/IJCCSM-04-2015-0049.
Jafry, T., M. Mikulewicz and K. Helwig, 2018: Introduction: justice in the era of climate change. *Routledge Handbook of Climate Justice*, 1-9.
Janke, T., 2018: Protecting indigenous cultural expressions in Australia and New Zealand: Two decades after the 'Mataatua Declaration and our culture, our future'. *Intellectual Property Forum: Journal of the Intellectual and Industrial Property Society of Australia and New Zealand*,(114), 21-30, doi:10.3316/informit.204204436835200.
Jendrzejewski, B., 2020: Bioeconomic modelling – An application of environmentally adjusted economic accounts and the computable general equilibrium model. *Land Use Policy*, **92**, 104431.
Jenkins, K., 2017: Women anti-mining activists' narratives of everyday resistance in the Andes: staying put and carrying on in Peru and Ecuador. *Gender, Place & Culture*, **24**(10), 1441-1459, doi:10.1080/0966369X.2017.1387102.
Jenkins, K., B. K. Sovacool and D. McCauley, 2018: Humanizing sociotechnical transitions through energy justice: An ethical framework for global transformative change. *Energy Policy*, **117**, 66-74, doi:10.1016/j.enpol.2018.02.036.
Jernnäs, M. and B.-O. Linnér, 2019: A discursive cartography of nationally determined contributions to the Paris climate agreement. *Global Environmental Change*, **55**, 73-83, doi:10.1016/j.gloenvcha.2019.01.006.
Joakim, E. P., L. Mortsch and G. Oulahen, 2015: Using vulnerability and resilience concepts to advance climate change adaptation. *Environmental Hazards*, **14**(2), 137-155, doi:10.1080/17477891.2014.1003777.
Johansson, T., A. Patwardhan, N. Nakicenovic and L. Gomez-Echeverri, 2012: *Global Energy Assessment: Toward a Sustainable Future*. ISBN 978-0-521-18293-5.
Johnstone, P. and P. Newell, 2018: Sustainability transitions and the state. *Environmental innovation and societal transitions*, **27**, 72-82.
Jones, L. et al., 2014: *Exploring the role of climate science in supporting long-term adaptation and decision-making in sub-Saharan Africa*.

Jordan, J. C., 2019: Deconstructing resilience: why gender and power matter in responding to climate stress in Bangladesh. *Climate and Development*, **11**(2), 167-179, doi:10.1080/17565529.2018.1442790.
Jørgensen, M. S., U. Jørgensen and J. S. Jensen, 2017: Navigations and governance in the Danish energy transition reflecting changing Arenas of Development, controversies and policy mixes. *Energy Research & Social Science*, **33**, 173-185, doi:10.1016/j.erss.2017.09.034.
Jørgensen, U., 2012: Mapping and navigating transitions—The multi-level perspective compared with arenas of development. *Research Policy*, **41**(6), 996-1010, doi:10.1016/j.respol.2012.03.001.
Jost, C. et al., 2016: Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, **8**(2), 133-144.
Juhola, S., E. Glaas, B.-O. Linnér and T.-S. Neset, 2015: Redefining maladaptation. *Environmental Science & Policy*, **2016**, 135-140, doi:10.1016/j.envsci.2015.09.014.
Kabir, M. and R. Salim, 2019: Valuation of subsoil minerals in Bangladesh: An application of the system of environmental-economic accounting. *Resources Policy*, **62**, 193-204.
Kabubo-Mariara, M. J., 2009: Adaptation to Climate Change and Livestock Biodiversity: Evidence from Kenya. In: *Conserving and Valuing Ecosystem Services and Biodiversity: Economic, Social and Institutional Challenges in the New Millennium* [Ninan, K. N. (ed.)]. Earthscan, pp. 345–369.
Kakenmaster, W., 2019: Articulating Resistance: Agonism, Radical Democracy and Climate Change Activism. *Millennium*, **47**(3), 373-397, doi:10.1177/0305829819839862.
Kalafatis, S., 2017: Identifying the Potential for Climate Compatible Development Efforts and the Missing Links. *Sustainability*, **9**(9), 1642.
Kallis, G., 2011: In defence of degrowth. *Ecological Economics*, **70**(5), 873-880.
Kallis, G., 2018: *Degrowth*. Agenda Publishing, Newcastle upon Tyne, UK, 176 pp. ISBN 978-1-911116-80-6.
Kallis, G., J. Martinez-Alier and R. B. Norgaard, 2009: Paper assets, real debts: An ecological-economic exploration of the global economic crisis. *Critical perspectives on international business*, **5**(1/2), 14-25.
Kamal Uddin, A. M. et al., 2006: *Climate resilient development: country framework to mainstream climate risk management and adaptation : working paper*. Climate Change Cell, Dept. of Environment, Dhaka. ISBN 978-984-32-3704-0.
Kamau, M., P. Chasek and D. O'Connor, 2018: *Transforming Multilateral Diplomacy: The Inside Story of the Sustainable Development Goals*, 1st edition ed., Routledge, London New York, 366 pp. ISBN 978-0-8133-5086-8.
Kandlikar, M., C. Reynolds and A. Grieshop, 2009: A Perspective Paper on Black Carbon Mitigation as a Response to Climate Change.
Karlsson, M., E. Alfredsson and N. Westling, 2020: Climate policy co-benefits: a review. *Climate Policy*, **20**(3), 292-316, doi:10.1080/14693062.2020.1724070.
Kasdan, M., L. Kuhl and P. Kurukulasuriya, 2021: The evolution of transformational change in multilateral funds dedicated to financing adaptation to climate change. *Climate and Development*, **13**(5), 427-442, doi:10.1080/17565529.2020.1790333.
Kattumuri, R., D. Ravindranath and T. Esteves, 2017: Local adaptation strategies in semi-arid regions: study of two villages in Karnataka, India. *Climate and Development*, **9**(1), 36-49.
Kaya, H. O. and M. Chinsamy, 2016: Community-based Environmental Resource Management Systems for Sustainable Livelihood and Climate Change Adaptation: A Review of Best Practices in Africa. *Journal of Social Sciences*, **46**(2), 123-129, doi:10.1080/09718923.2016.11893519.
Kaza, S., L. Yao, P. Bhada-Tata and F. V. Woerden, 2018: *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. World Bank Publications, 230 pp. ISBN 978-1-4648-1347-4.
Keith, H., M. Vardon, J. A. Stein and D. Lindenmayer, 2019: Contribution of native forests to climate change mitigation – A common approach to carbon accounting that aligns results from environmental-economic accounting with rules for emissions reduction. *Environmental Science & Policy*, **93**, 189-199.
Kenis, A. and M. Lievens, 2016: Imagining the carbon neutral city: The (post)politics of time and space. *Environ Plan A*, doi:10.1177/0308518X16680617.
Kenis, A. and E. Mathijs, 2012: Beyond individual behaviour change: the role of power, knowledge and strategy in tackling climate change. *Environmental Education Research*, **18**(1), 45-65, doi:10.1080/13504622.2011.576315.
Kenis, A. and E. Mathijs, 2014: Climate change and post-politics: Repoliticizing the present by imagining the future? *Geoforum*, **52**, 148-156, doi:10.1016/j.geoforum.2014.01.009.
Kermoal , N. and I. Altamirano-Jiménez, 2016: *Kermoal and Altamirano-Jiménez, 2016*. Athabasca University Press, Athabasca.
Khanal, U. et al., 2021: Smallholder farmers' adaptation to climate change and its potential contribution to UN's sustainable development goals of zero hunger and no poverty. *Journal of Cleaner Production*, **281**, 124999, doi:10.1016/j.jclepro.2020.124999.
Khatri, D. B., 2018: *Climate and development at the third pole*. Available at: https://pub.epsilon.slu.se/15564/.
Kim, Y., M. V. Chester, D. A. Eisenberg and C. L. Redman, 2019: The Infrastructure Trolley Problem: Positioning Safe-to-fail Infrastructure for Climate Change Adaptation. *Earth's Future*, **7**(7), 704-717, doi:10.1029/2019EF001208.

Kim, Y. et al., 2017a: Fail-safe and safe-to-fail adaptation: decision-making for urban flooding under climate change. *Climatic Change*, doi:10.1007/s10584-017-2090-1.
Kim, Y. et al., 2017b: A perspective on climate-resilient development and national adaptation planning based on USAID's experience. *Climate and Development*, **9**(2), 141-151.
Kingsborough, A., E. Borgomeo and J. W. Hall, 2016: Adaptation pathways in practice: Mapping options and trade-offs for London's water resources. *Sustainable Cities and Society*, **27**, 386-397, doi:10.1016/j.scs.2016.08.013.
Kirchhoff, C. J., M. Carmen Lemos and S. Dessai, 2013: Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science. *Annual Review of Environment and Resources*, **38**(1), 393-414, doi:10.1146/annurev-environ-022112-112828.
Kivimaa, P., W. Boon, S. Hyysalo and L. Klerkx, 2019a: Towards a typology of intermediaries in sustainability transitions: A systematic review and a research agenda. *Research Policy*, **48**(4), 1062-1075, doi:https://doi.org/10.1016/j.respol.2018.10.006.
Kivimaa, P. et al., 2019b: Passing the baton: How intermediaries advance sustainability transitions in different phases. *Environmental Innovation and Societal Transitions*, **31**, 110-125, doi:https://doi.org/10.1016/j.eist.2019.01.001.
Kivimaa, P. and M. Martiskainen, 2018: Dynamics of policy change and intermediation: The arduous transition towards low-energy homes in the United Kingdom. *Energy Research & Social Science*, **44**, 83-99, doi:https://doi.org/10.1016/j.erss.2018.04.032.
Kivimaa, P., E. Primmer and J. Lukkarinen, 2020: Intermediating policy for transitions towards net-zero energy buildings. *Environmental Innovation and Societal Transitions*.
Klein, N., 2020: *On fire: the (burning) case for a green new deal*. Simon & Schuster. ISBN 1982129921.
Klein, R. J. T. et al., 2007: Inter-relationships between adaptation and mitigation. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 745-777. ISBN 9780521880107.
Klepp, S. and J. Herbeck, 2016: The politics of environmental migration and climate justice in the Pacific region. *Journal of Human Rights and the Environment*, **7**, 54-73, doi:10.4337/jhre.2016.01.03.
Kleres, J. and Å. Wettergren, 2017: Fear, hope, anger, and guilt in climate activism. *Social Movement Studies*, 1-13, doi:10.1080/14742837.2017.1344546.
Klinsky, S. et al., 2017: Why equity is fundamental in climate change policy research. *Global Environmental Change*, **44**, 170–173.
Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160461.
Koch, M., 2020: Structure, action and change: a Bourdieusian perspective on the preconditions for a degrowth transition. *Sustainability: Science, Practice and Policy*, **16**(1), 4-14, doi:10.1080/15487733.2020.1754693.
Kochore, H. H., 2016: The road to Kenya?: Visions, expectations and anxieties around new infrastructure development in Northern Kenya. *Journal of Eastern African Studies*, **10**(3), 494-510.
Köhler, J. et al., 2019: An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, **31**, 1-32, doi:10.1016/j.eist.2019.01.004.
Kohler, P., S. Renggli and C. Lüthi, 2019: WASH and gender in health care facilities: The uncharted territory. *Health Care for Women International*, **40**(1), 3-12.
Komendantova, N. et al., 2016: Multi-risk approach and urban resilience. *International Journal of Disaster Resilience in the Built Environment*, **7**, 114-132, doi:10.1108/IJDRBE-03-2015-0013.
Kookana, R. S. et al., 2016: Groundwater scarcity impact on inclusiveness and women empowerment: Insights from school absenteeism of female students in two watersheds in India. *International Journal of Inclusive Education*, **20**(11), 1155-1171.
Kothari, A., F. Demaria and A. Acosta, 2014: Buen Vivir, Degrowth and Ecological Swaraj: Alternatives to sustainable development and the Green Economy. *Development*, **57**(3), 362-375, doi:10.1057/dev.2015.24.
Koubi, V., 2019: Climate Change and Conflict. *Annual Review of Political Science*, **22**(1), 343-360, doi:10.1146/annurev-polisci-050317-070830.
Krampe, F., E. S. Smith and M. D. Hamidi, 2021: Security implications of climate development in conflict-affected states implications of local-level effects of rural hydropower development on farmers in Herat. *Political Geography*, **90**, 102454, doi:10.1016/j.polgeo.2021.102454.
Kriegler, E. et al., 2018: Pathways limiting warming to 1.5°C: a tale of turning around in no time? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160457, doi:10.1098/rsta.2016.0457.
Kristjanson, P. et al., 2017: Addressing gender in agricultural research for development in the face of a changing climate: where are we and where should we be going? *International Journal of Agricultural Sustainability*, **15**(5), 482-500.
Krogstrup, S. and W. Oman, 2019: Macroeconomic and Financial Policies for Climate Change Mitigation: A Review of the Literature. *IMF Working Papers*, **19**, doi:10.5089/9781513511955.001.

Krueger, P., Z. Sautner and L. T. Starks, 2019: *The Importance of Climate Risks for Institutional Investors*. Social Science Research Network, Rochester, NY. Available at: https://papers.ssrn.com/abstract=3235190 https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3235190 (accessed 2019/10/02/10:07:25).
Krusell, P. and A. Smith, 2018: *Climate Change Around the World*. Slides from ifo Institute Workshop on "Heterogeneous Agents and the Macroeconomics of Climate Change".
Kubiszewski, I. et al., 2013: Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics*, **93**, 57-68.
Kuenkel, P., 2019: *Stewarding Sustainability Transformations: An Emerging Theory and Practice of SDG Implementation*. Springer International Publishing. ISBN 978-3-030-03690-4.
Kull, M., 2016: Multi-Level Governance and Structural Constructivism–Understanding Multilevel Politics in the European Union. In: *European Integration and Rural Development*. Routledge.
Kuokkanen, A., V. Uusitalo and K. Koistinen, 2019: A framework of disruptive sustainable innovation: an example of the Finnish food system. *Technology Analysis & Strategic Management*, **31**(7), 749-764, doi:10.1080/09537325.2018.1550254.
Kuper, M., H. Amichi and P.-L. Mayaux, 2017: Groundwater use in North Africa as a cautionary tale for climate change adaptation. *Water International*, **42**(6), 725-740, doi:10.1080/02508060.2017.1351058.
Kuzemko, C., A. Lawrence and M. Watson, 2019: New directions in the international political economy of energy. *Review of International Political Economy*, **26**(1), 1-24, doi:10.1080/09692290.2018.1553796.
Labriet, M. et al., 2015: Worldwide impacts of climate change on energy for heating and cooling. *Mitigation and Adaptation Strategies for Global Change*, **20**(7), 1111–1136.
Lacroix, K. and R. Gifford, 2017: Psychological Barriers to Energy Conservation Behavior: The Role of Worldviews and Climate Change Risk Perception. *Environment and Behavior*, doi:10.1177/0013916517715296.
Lahn, B. a., 2018: In the light of equity and science: scientific expertise and climate justice after Paris. *International Environmental Agreements: Politics, Law and Economics*, **18**(1), 29–43.
Lahsen, M. and E. Turnhout, 2021: How norms, needs, and power in science obstruct transformations towards sustainability. *Environmental Research Letters*, **16**(2), 025008, doi:10.1088/1748-9326/abdcf0.
Lam, D. P. M. et al., 2020: Indigenous and local knowledge in sustainability transformations research: a literature review. *Ecology and Society*, **25**(1), doi:10.5751/ES-11305-250103.
Lamsal, P., L. Kumar, K. Atreya and K. P. Pant, 2017: Vulnerability and impacts of climate change on forest and freshwater wetland ecosystems in Nepal: A review. *Ambio*, **46**(8), 915-930, doi:10.1007/s13280-017-0923-9.
Langlois, A. J., 2014: Social Connection & Political Responsibility: An Engagement with Iris Marion Young. *St Antony's International Review*, **10**(1), 43-63.
Larik, J. E. et al., 2017: Blue Growth and Sustainable Development in Indian Ocean Governance. *The Hague Institute for Global Justice Policy Brief*.
Latour, B., D. Milstein, I. Marrero-Guillamón and I. Rodríguez-Giralt, 2018: Down to earth social movements: an interview with Bruno Latour. *Social Movement Studies*, **17**(3), 353-361, doi:10.1080/14742837.2018.1459298.
Lau, J. D., D. Kleiber, S. Lawless and P. J. Cohen, 2021: Gender equality in climate policy and practice hindered by assumptions. *Nature Climate Change*, **11**(3), 186-192, doi:10.1038/s41558-021-00999-7.
Lawrence, J. et al., 2015: Adapting to changing climate risk by local government in New Zealand : institutional practice barriers and enablers. *Local environment*, **20**(3), 298–320.
Le Blanc, D., 2015: Towards Integration at Last? The Sustainable Development Goals as a Network of Targets: The sustainable development goals as a network of targets. *Sustainable Development*, **23**(3), 176-187, doi:10.1002/sd.1582.
Le, T.-H., Y. Chang and D. Park, 2016: Trade openness and environmental quality: International evidence. *Energy Policy*, **92**(C), 45-55.
Leal Filho, W. et al., 2020: COVID-19 and the UN Sustainable Development Goals: Threat to Solidarity or an Opportunity? *Sustainability*, **12**(13), 5343, doi:10.3390/su12135343.
Lee, J. Y. et al., 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
Lee, K., N. Gjersoe, S. O'Neill and J. Barnett, 2020: Youth perceptions of climate change: A narrative synthesis. *WIREs Climate Change*, **11**(3).
Lee, S.-H. and M. Thiel, 2017: Relations between GDP growth and environmental performance using latent growth curve model applied for environmental Kuznets curve. *International Journal of Sustainable Economy*, **9**(2), 87-104, doi:10.1504/IJSE.2017.083362.
Lee, S. A., 2020: *Playing the Long Game: The intersection of Climate Change Risk and Financial Regulation*.
Leibenluft, J., 2020: *Rethinking the Intersection of Climate Policy and the Federal Budget*. Center for American Progress.
Leigh, N. G. and H. Lee, 2019: Sustainable and Resilient Urban Water Systems: The Role of Decentralization and Planning. *Sustainability*, **11**(3), 918, doi:10.3390/su11030918.
Lele, S., V. Srinivasan, B. K. Thomas and P. Jamwal, 2018: Adapting to climate change in rapidly urbanizing river basins: insights from a multiple-concerns, multiple-stressors, and multi-level approach. *Water International*, **43**(2), 281-304, doi:10.1080/02508060.2017.1416442.

Lemke, S. and T. Delormier, 2017: Indigenous Peoples' food systems, nutrition, and gender: Conceptual and methodological considerations. *Maternal & Child Nutrition*, **Suppl 3**, doi:10.1111/mcn.12499.
Lemoine, D. and C. Traeger, 2014: Watch Your Step: Optimal Policy in a Tipping Climate. *American Economic Journal: Economic Policy*, **6**, doi:10.1257/pol.6.1.137.
Lenzholzer, S. et al., 2020: Urban climate awareness and urgency to adapt: An international overview. *Urban Climate*, **33**, 100667, doi:10.1016/j.uclim.2020.100667.
Lertzman, R. A., 2010: *Myth of apathy: psychoanalytic explorations of environmental degradation*. Cardiff University (United Kingdom). ISBN 1073291227.
Lesnikowski, A. et al., 2017: What does the Paris Agreement mean for adaptation? *Climate Policy*, **17**(7), 825-831.
Lesutis, G., 2020: How to understand a development corridor? The case of Lamu Port–South Sudan–Ethiopia-Transport corridor in Kenya. *Area*, **52**(3), 600-608.
Leventon, J., D. J. Abson and D. J. Lang, 2021: Leverage points for sustainability transformations: nine guiding questions for sustainability science and practice. *Sustainability Science*, **16**(3), 721-726, doi:10.1007/s11625-021-00961-8.
Ley, D., 2017: Sustainable Development, Climate Change, and Renewable Energy in Rural Central America. In: *Evaluating Climate Change Action for Sustainable Development* [Uitto, J. I., J. Puri and R. D. van den Berg (eds.)]. Springer International Publishing, Cham, pp. 187-212. ISBN 978-3-319-43702-6.
Ley, D., H. J. Corsair, S. Fuss and C. Singh, 2020: Evaluating the Use of Renewable Energy and Communal Governance Systems for Climate Change Adaptation. *The Central European Review of Economics and Management*, **4**(1), 53-70, doi:10.29015/cerem.850.
Li, D. et al., 2019a: Challenges and opportunities for the development of MEGACITIES. *International Journal of Digital Earth*, **12**(12), 1382-1395, doi:10.1080/17538947.2018.1512662.
Li, L. et al., 2018: Service Learning, Service Climate, and Service-Based Social Innovation for Sustainability. *Sustainability*, **10**(7), 2566.
Li, S. et al., 2017: Integrated modelling of urban spatial development under uncertain climate futures: A case study in Hungary. *Environmental Modelling & Software*, **96**, 251-264, doi:https://doi.org/10.1016/j.envsoft.2017.07.005.
Li, X. et al., 2019b: Projecting Global Urban Area Growth Through 2100 Based on Historical Time Series Data and Future Shared Socioeconomic Pathways. *Earth's Future*, **7**(4), 351-362, doi:10.1029/2019EF001152.
Liem, A., R. B. Natari, Jimmy and B. J. Hall, 2020: Digital Health Applications in Mental Health Care for Immigrants and Refugees: A Rapid Review. *Telemedicine and e-Health*, tmj.2020.0012.
Lillebø, A. I. et al., 2017: How can marine ecosystem services support the Blue Growth agenda? *Marine Policy*, **81**, 132-142, doi:10.1016/j.marpol.2017.03.008.
Lind, J., 2018: Devolution, shifting centre-periphery relationships and conflict in northern Kenya. *Political Geography*, **63**, 135-147.
Lindoso, D. et al., 2018: Harvesting Water for Living with Drought: Insights from the Brazilian Human Coexistence with Semi-Aridity Approach towards Achieving the Sustainable Development Goals. *Sustainability*, **10**(3), 622.
Liobikienė, G. and M. Butkus, 2018: The challenges and opportunities of climate change policy under different stages of economic development. *Sci Total Environ*, **642**, 999-1007, doi:10.1016/j.scitotenv.2018.06.140.
Lipper, L. et al., 2014: Climate-smart agriculture for food security. *Nature Climate Change*, **4**(12), 1068-1072, doi:10.1038/nclimate2437.
Liu, J.-Y. et al., 2019: Identifying trade-offs and co-benefits of climate policies in China to align policies with SDGs and achieve the 2 °C goal. *Environmental Research Letters*, **14**(12), 124070, doi:10.1088/1748-9326/ab59c4.
Lo, A. Y., S. Liu, L. T. O. Cheung and F. K. S. Chan, 2020: Contested Transformations: Sustainable Economic Development and Capacity for Adapting to Climate Change. *Annals of the American Association of Geographers*, **110**(1), 223-241, doi:10.1080/24694452.2019.1625748.
Lo, K. and V. Castán Broto, 2019: Co-benefits, contradictions, and multi-level governance of low-carbon experimentation: Leveraging solar energy for sustainable development in China. *Global Environmental Change*, **59**, 101993, doi:10.1016/j.gloenvcha.2019.101993.
Lockwood, M., C. Kuzemko, C. Mitchell and R. Hoggett, 2016: Historical institutionalism and the politics of sustainable energy transitions: A research agenda. *Environment and Planning C: Politics and Space*, doi:10.1177/0263774X16660561.
Löfmarck, E. and R. Lidskog, 2017: Bumping against the boundary: IPBES and the knowledge divide. *Environ. Sci. Policy*, **69**, 22-28, doi:10.1016/j.envsci.2016.12.008.
Loorbach, D., N. Frantzeskaki and F. Avelino, 2017: Sustainability Transitions Research: Transforming Science and Practice for Societal Change. *Annual Review of Environment and Resources*, **42**(1), 599-626, doi:10.1146/annurev-environ-102014-021340.
Loorbach, D. et al., 2020: Transformative innovation and translocal diffusion. *Environmental Innovation and Societal Transitions*, **35**, 251-260, doi:https://doi.org/10.1016/j.eist.2020.01.009.
Lopez-Carr, D., POPULATION-HEALTH-ENVIRONMENT (PHE) SYNERGIES ? EVIDENCE FROM USAID-SPONSORED PROGRAMS IN AFRICAN AND ASIAN CORE CONSERVATION AREAS (accessed 2021-08-20 19:36:24).

Lorenzoni, I. and L. Whitmarsh, 2014: Climate change and perceptions, behaviors, and communication research after the IPCC 5th Assessment Report - a WIREs Editorial: Climate change and perceptions, behaviors, and communication research. *Wiley Interdisciplinary Reviews: Climate Change*, **5**(6), 703-708.
Lucas, H. et al., 2017: Critical challenges and capacity building needs for renewable energy deployment in Pacific Small Island Developing States (Pacific SIDS). *Renewable Energy*, **107**, 42-52, doi:10.1016/j.renene.2017.01.029.
Ludwig, D. and L. Poliseli, 2018: Relating traditional and academic ecological knowledge: mechanistic and holistic epistemologies across cultures. *Biology & Philosophy*, **33**(5), 43, doi:10.1007/s10539-018-9655-x.
Ludwig, F., E. van Slobbe and W. Cofino, 2014: Climate change adaptation and Integrated Water Resource Management in the water sector. *Journal of Hydrology*, **518**, 235-242, doi:10.1016/j.jhydrol.2013.08.010.
Luederitz, C., D. J. Abson, R. Audet and D. J. Lang, 2017: Many pathways toward sustainability: not conflict but co-learning between transition narratives. *Sustainability Science*, **12**(3), 393-407, doi:10.1007/s11625-016-0414-0.
Luton, L. S., 2015: Climate Scientists and the Intergovernmental Panel on Climate Change: Evolving Dynamics of a Belief in Political Neutrality. *Administrative Theory & Praxis*, **37**(3), 144-161, doi:10.1080/10841806.2015.1053360.
Lwasa, S., 2015: A systematic review of research on climate change adaptation policy and practice in Africa and South Asia deltas. *Regional Environmental Change*, **15**(5), 815–824.
Lyon, C., 2018: Complexity ethics and UNFCCC practices for 1.5 °C climate change. *Current Opinion in Environmental Sustainability*, **31**, 48-55.
MacGregor, S., 2003: Feminist perspectives on sustainability. *UNESCO Encyclopedia of Life Support Systems: Introduction to Sustainable Development*, 467-492.
MacGregor, S., 2014: Only Resist: Feminist Ecological Citizenship and the Post-politics of Climate Change. *Hypatia*, **29**(3), 617-633.
MacGregor, S., 2019: Finding transformative potential in the cracks? The ambiguities of urban environmental activism in a neoliberal city. *Social Movement Studies*, **0**(0), 1-17, doi:10.1080/14742837.2019.1677224.
MacGregor, S., 2020: Gender matters in environmental justice. In: *Environmental Justice*, 1 ed. [Coolsaet, B. (ed.)]. Routledge, Abingdon, Oxon ; New York, NY : Routledge, 2020. | Series: Key issues in environment and sustainability, pp. 234-248. ISBN 978-0-429-02958-5.
Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-197, doi:10.1038/s41586-019-1300-6.
Mackey, B. and D. Claudie, 2015: Points of Contact: Integrating Traditional and Scientific Knowledge for Biocultural Conservation. *Environmental Ethics*, **Fall**, 341-357.
Maes, M. J. A., K. E. Jones, M. B. Toledano and B. Milligan, 2019: Mapping synergies and trade-offs between urban ecosystems and the sustainable development goals. *Environmental Science & Policy*, **93**, 181-188, doi:10.1016/j.envsci.2018.12.010.
Magnan, A. K. and T. Ribera, 2016: Global adaptation after Paris. *Science*, **352**(6291), 1280-1282.
Magnan, A. K. et al., 2016: Addressing the risk of maladaptation to climate change. *WIREs Climate Change*, **7**(5), 646-665, doi:10.1002/wcc.409.
Magnan, A. K., E. L. F. Schipper and V. K. E. Duvat, 2020: Frontiers in Climate Change Adaptation Science: Advancing Guidelines to Design Adaptation Pathways. *Current Climate Change Reports*, **6**(4), 166-177, doi:10.1007/s40641-020-00166-8.
Mahoney, J. L. and K. Thelen, 2009: A theory of gradual institutional change. *Explaining Institutional Change: Ambiguity, Agency, and Power*, 1-37, doi:10.1017/CBO9780511806414.003.
Mahony, M. and M. Hulme, 2016: Modelling and the Nation: Institutionalising Climate Prediction in the UK, 1988–92. *Minerva*, **54**(4), 445-470, doi:10.1007/s11024-016-9302-0.
Mainali, K. et al., 2020: Contrasting responses to climate change at Himalayan treelines revealed by population demographics of two dominant species. *Ecology and Evolution*, **10**(3), 1209-1222, doi:https://doi.org/10.1002/ece3.5968.
Major, D. C., M. Lehmann and J. Fitton, 2018: Linking the management of climate change adaptation in small coastal towns and cities to the Sustainable Development Goals. *Ocean & Coastal Management*, **163**, 205-208, doi:10.1016/j.ocecoaman.2018.06.010.
Makuvaro, V. et al., 2017: Constraints to crop production and adaptation strategies of smallholder farmers in semi-arid Central and Western Zimbabwe. *African Crop Science Journal*, **25**(2), 221-235, doi:10.4314/acsj.v25i2.7.
Mallucci, E., 2020: Natural Disasters, Climate Change, and Sovereign Risk.
Manne, A. S. and R. G. Richels, 1992: *Buying Greenhouse Insurance: The Economic Costs of CO2 Emission Limits*, New ed. edition ed., The MIT Press, Cambridge, Mass, 194 pp. ISBN 978-0-262-13280-0.
Maor, M., J. Tosun and A. Jordan, 2017: Proportionate and disproportionate policy responses to climate change: core concepts and empirical applications. *Journal of Environmental Policy & Planning*, **0**(0), 1–13.
Mapfumo, P., M. F. and R. Chikowo, 2016: Building on indigenous knowledge to strengthen the capacity of smallholder farming communities to adapt to climate change and variability in southern Africa. *Climate and Development*, **8**, 72-81, doi:https://doi.org/10.1080/17565529.2014.998604.
Marin, A. and L. O. Naess, 2017: Climate Change Adaptation Through Humanitarian Aid? Promises, Perils and Potentials of the 'New Humanitarianism. *IDS Bulletin*.

Markard, J., F. W. Geels and R. Raven, 2020: Challenges in the acceleration of sustainability transitions. *Environmental Research Letters*.
Markkanen, S. and A. Anger-Kraavi, 2019: Social impacts of climate change mitigation policies and their implications for inequality. *Climate Policy*, **19**(7), 827-844, doi:10.1080/14693062.2019.1596873.
Marmot, M., 2020: The Art of Medicine - Society and the slow burn of inequality. *Institute of Health Equity*, **395**, 1413–1414.
Marmot, M. and J. Allen, 2020: COVID-19: exposing and amplifying inequalities. *Journal of Epidemiology and Community Health*, jech–2020–214720.
Marsha, A. et al., 2018: Influences of climatic and population changes on heat-related mortality in Houston, Texas, USA. *Climatic Change*, **146**(3), 471-485, doi:10.1007/s10584-016-1775-1.
Martinez-Alier, J., 2021: Mapping ecological distribution conflicts: The EJAtlas. *The Extractive Industries and Society*, doi:10.1016/j.exis.2021.02.003.
Martínez-Fernández, J., I. Banos-González and M. Á. Esteve-Selma, 2021: An integral approach to address socio-ecological systems sustainability and their uncertainties. *Science of The Total Environment*, **762**, 144457, doi:10.1016/j.scitotenv.2020.144457.
Martiskainen, M. et al., 2020: Contextualizing climate justice activism: Knowledge, emotions, motivations, and actions among climate strikers in six cities. *Global Environmental Change*, **65**, 102180, doi:10.1016/j.gloenvcha.2020.102180.
Maru, Y. T. et al., 2014: A linked vulnerability and resilience framework for adaptation pathways in remote disadvantaged communities. *Global Environmental Change*, **28**, 337-350, doi:10.1016/j.gloenvcha.2013.12.007.
Massarella, K. et al., 2021: Transformation beyond conservation: how critical social science can contribute to a radical new agenda in biodiversity conservation. *Current Opinion in Environmental Sustainability*, **49**, 79-87, doi:10.1016/j.cosust.2021.03.005.
Massey, E., R. Biesbroek, D. Huitema and A. Jordan, 2014: Climate policy innovation: The adoption and diffusion of adaptation policies across Europe. *Global Environmental Change*, **29**, 434-443.
Material, E., 2019: *Industrial Transformation 2050: Pathways to net-zero emissions from EU Heavy Industry*. Available at: https://materialeconomics.com/publications/industrial-transformation-2050.
Mathai, M. V., J. A. P. d. Oliveira and G. Dale, 2018: The rise and flaws of green growth. *APN Science Bulletin*, doi:10.30852/sb.2018.359.
Matin, N., J. Forrester and J. Ensor, 2018: What is equitable resilience? *World development*, **109**, 197-205.
Matos, P. et al., 2019: Modeling the provision of air-quality regulation ecosystem service provided by urban green spaces using lichens as ecological indicators. *Science of The Total Environment*, **665**, 521-530, doi:10.1016/j.scitotenv.2019.02.023.
Matsui, K., 2015: Problems of Defining and Validating Traditional Knowledge: A Historical Approach. *The International Indigenous Policy Journal*, **6**(2), 2, doi:10.18584/iipj.2015.6.2.2.
Matthew, R., 2014: Integrating climate change into peacebuilding. *Climatic Change*, **123**(1), 83-93, doi:10.1007/s10584-013-0894-1.
Mbow, C. et al., 2019: Food security. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)], pp. In press.
McCartney, G. et al., 2017: Regeneration and health: a structured, rapid literature review. *Public Health*, **148**, 69-87.
McCollum, D. L. et al., 2018a: Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters*, **13**(3), 033006, doi:10.1088/1748-9326/aaafe3.
McCollum, D. L. et al., 2018b: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, **3**(7), 589-599, doi:10.1038/s41560-018-0179-z.
McGregor, D., S. Whitaker and M. Sritharan, 2020: Indigenous environmental justice and sustainability. *Current Opinion in Environmental Sustainability*, **43**, 35-40, doi:https://doi.org/10.1016/j.cosust.2020.01.007.
Mcleod, E. et al., 2018: Raising the voices of Pacific Island women to inform climate adaptation policies. *Marine Policy*, **93**, 178-185.
Mcleod, E. et al., 2019: Lessons From the Pacific Islands – Adapting to Climate Change by Supporting Social and Ecological Resilience. *Frontiers in Marine Science*, **6**(289), doi:10.3389/fmars.2019.00289.
McManamay, R. A., C. R. Vernon and H. I. Jager, 2021: Global Biodiversity Implications of Alternative Electrification Strategies Under the Shared Socioeconomic Pathways. *Biological Conservation*, **260**, 109234, doi:https://doi.org/10.1016/j.biocon.2021.109234.
McNamara, K. E. et al., 2020: An assessment of community-based adaptation initiatives in the Pacific Islands. *Nature Climate Change*, **10**(7), 628-639, doi:10.1038/s41558-020-0813-1.
McPhearson, T. and K. Wijsman, 2017: Transitioning complex urban systems: The Importance of Urban Ecology for Sustainability in New York City. In: *Urban Sustainability Transitions*. Routledge. ISBN 978-1-315-22838-9.
McPhetres, J. and M. Zuckerman, 2018: Religiosity predicts negative attitudes towards science and lower levels of science literacy. *PLoS One*, **13**(11), doi:10.1371/journal.pone.0207125.
Meadows, D., 1999: *Leverage Points: Places to Intervene in a System*. The Sustainability Institute.

Melica, G. et al., 2018: Multilevel governance of sustainable energy policies: The role of regions and provinces to support the participation of small local authorities in the Covenant of Mayors. *Sustainable Cities and Society*, **39**, 729-739.
Meriluoto, T., 2018: 'The will to not be empowered (according to your rules)': Resistance in Finnish participatory social policy. *Critical Social Policy*, doi:10.1177/0261018318764322.
Mersha, A. A. and F. van Laerhoven, 2019: Gender and climate policy: a discursive institutional analysis of Ethiopia's climate resilient strategy. *Regional Environmental Change*, **19**(2), 429-440.
Metcalf, G. E., 2016: A Conceptual Framework for Measuring the Effectiveness of Green Fiscal Reforms. *International Journal of Green Growth and Development*, **2**(2), 87-126.
Metcalf, G. E., 2019: *On the Economics of a Carbon Tax for the United States*. Brookings Papers on Economic Activity.
Mganga, K. Z., N. K. R. Musimba and D. M. Nyariki, 2015: Combining Sustainable Land Management Technologies to Combat Land Degradation and Improve Rural Livelihoods in Semi-arid Lands in Kenya. *Environmental Management*, **56**(6), 1538-1548.
Michalena, E. and J. M. Hills, 2018: Paths of renewable energy development in small island developing states of the South Pacific. *Renewable and Sustainable Energy Reviews*, **82**, 343-352, doi:10.1016/j.rser.2017.09.017.
Mikulewicz, M., 2018: Politicizing vulnerability and adaptation: on the need to democratize local responses to climate impacts in developing countries. *Climate and Development*, **10**(1), 18-34, doi:10.1080/17565529.2017.1304887.
Mikulewicz, M., 2019: Thwarting adaptation's potential? A critique of resilience and climate-resilient development. *Geoforum*, **104**, 267-282, doi:10.1016/j.geoforum.2019.05.010.
Mikulewicz, M. and M. Taylor, 2020: Getting the Resilience Right: Climate Change and Development Policy in the 'African Age'. *New Political Economy*, **25**(4), 626-641, doi:10.1080/13563467.2019.1625317.
Millennium Ecosystem, A., 2005: *Millennium Ecosystem Assessment*. Available at: https://www.millenniumassessment.org/en/index.html.
Millennium Ecosystem Assessment, 2005: *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington, D.C.
Miller, C. A., 2017: Incorporating Sustainability into Climate Change Adaptation. In: *Encyclopedia of Sustainable Technologies* [Abraham, M. A. (ed.)]. Elsevier, Oxford, pp. 175-182. ISBN 978-0-12-804792-7.
Milman, A. and Y. Arsano, 2014: Climate adaptation and development: Contradictions for human security in Gambella, Ethiopia. *Global Environmental Change*, **29**, 349-359, doi:10.1016/j.gloenvcha.2013.11.017.
Mimura, N. et al., 2014: Adaptation Planning and Implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869-898. ISBN 9781107058071.
Minx, J. C. et al., 2017: Learning about climate change solutions in the IPCC and beyond. *Environmental Science & Policy*, **77**, 252-259, doi:https://doi.org/10.1016/j.envsci.2017.05.014.
Mirumachi, N., A. Sawas and M. Workman, 2020: Unveiling the security concerns of low carbon development: climate security analysis of the undesirable and unintended effects of mitigation and adaptation. *Climate and Development*, **12**(2), 97-109, doi:10.1080/17565529.2019.1604310.
Mirzabaev, A. et al., 2015: Bioenergy, food security and poverty reduction: trade-offs and synergies along the water–energy–food security nexus. *Water International*, **40**(5-6), 772-790, doi:10.1080/02508060.2015.1048924.
Mistry, J., B. A. Bilbao and A. Berardi, 2016: Community owned solutions for fire management in tropical ecosystems: casestudies from Indigenous communities of South. *Philosophyical Transactions*, **371**, 1-10.
Mitchell, D., S. Enemark and P. van der Molen, 2015: Climate resilient urban development: Why responsible land governance is important. *Land Use Policy*, **48**, 190-198, doi:10.1016/j.landusepol.2015.05.026.
Mitchell, T. and S. Maxwell, 2010: *Defining climate compatible development*. CDKR.
Mitter, H. et al., 2020: Shared Socio-economic Pathways for European agriculture and food systems: The Eur-Agri-SSPs. *Global Environmental Change*, **65**, 102159, doi:https://doi.org/10.1016/j.gloenvcha.2020.102159.
Mocca, E. and S. Osborne, 2019: "Solidarity is our weapon": Social Mobilisation in Scotland in the Contest of the Post-Political Condition. *Antipode*, **51**(2), 620-641, doi:10.1111/anti.12466.
Mogelgaard, K. et al., 2018: From Planning to Action: Mainstreaming Climate Change Adaptation Into Development.
Mohammed, R. and M. Scholz, 2017: Adaptation Strategy to Mitigate the Impact of Climate Change on Water Resources in Arid and Semi-Arid Regions: a Case Study. *Water Resources Management*, **31**(11), 3557-3573, doi:10.1007/s11269-017-1685-7.
Montoute, A., D. Mohammed and J. Francis, 2019: Prospects and Challenges for Civil Society and Climate Change Engagement in the Caribbean: The Case of Trinidad and Tobago. *Caribbean Studies*, **47**(2), 81-109, doi:10.1353/crb.2019.0015.
Moore, M.-L., D. Riddell and D. Vocisano, 2015: Scaling Out, Scaling Up, Scaling Deep: Strategies of Non-profits in Advancing Systemic Social Innovation. *The Journal of Corporate Citizenship*,(58), 67-84.
Mora, C. et al., 2017: Global risk of deadly heat. *Nature Climate Change*, **7**(7), 501-506, doi:10.1038/nclimate3322.

Mora, O. et al., 2020: Exploring the future of land use and food security: A new set of global scenarios. *PLoS One*, **15**(7), e0235597.
Moran et al, 2018: *The Intersection of Global Fragility and Climate Risks*. United States Agency for International Development, Washington, D.C.
Mormina, M., 2019: Science, Technology and Innovation as Social Goods for Development: Rethinking Research Capacity Building from Sen's Capabilities Approach. *Science and Engineering Ethics*, **25**(3), 671-692.
Morote, Á.-F., J. Olcina and M. Hernández, 2019: The Use of Non-Conventional Water Resources as a Means of Adaptation to Drought and Climate Change in Semi-Arid Regions: South-Eastern Spain. *Water*, **11**(1), 93, doi:10.3390/w11010093.
Morton, T., 2013: *Hyperobjects: Philosophy and Ecology after the End of the World*, 1st edition ed., Univ Of Minnesota Press, Minneapolis, 240 pp. ISBN 978-0-8166-8923-1.
Morton, T., 2021: Contesting Coal, Contesting Climate: Materializing the Social Drama of Climate Change in Australia and Germany. *Environmental Communication*, **15**(4), 465-481, doi:10.1080/17524032.2020.1865428.
Mosberg, M., E. Nyukuri and L. O. Naess, 2017: The Power of 'Know-Who': Adaptation to Climate Change in a Changing Humanitarian Landscape in Isiolo, Kenya. *IDS Bulletin*, **48**(4), doi:10.19088/1968-2017.154.
Moser, S. C. and J. A. Ekstrom, 2011: Taking ownership of climate change: participatory adaptation planning in two local case studies from California. *Journal of Environmental Studies and Sciences*, **1**(1), 63-74, doi:10.1007/s13412-011-0012-5.
Mosley, J. and E. E. Watson, 2016: Frontier transformations: development visions, spaces and processes in Northern Kenya and Southern Ethiopia. *Journal of Eastern African Studies*, **10**(3), 452-475.
Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48-58, doi:https://doi.org/10.1016/j.envsci.2016.06.007.
Moyer, J. D. and D. K. Bohl, 2019: Alternative pathways to human development: Assessing trade-offs and synergies in achieving the Sustainable Development Goals. *Futures*, **105**, 199-210, doi:10.1016/j.futures.2018.10.007.
Mozambique, R. o. and IUCN, 2014: *Climate Change and Gender Action Plan for the Republic of Mozambique*. The Global Gender Office of the International Union for Conservation of Nature (IUCN GGO) (accessed 2019-09-24).
Mpandeli, S. et al., 2018: Climate Change Adaptation through the Water-Energy-Food Nexus in Southern Africa. *International Journal of Environmental Research and Public Health*, **15**(10), 2306, doi:10.3390/ijerph15102306.
MRFCJ, 2015: *Rights for Action: Putting People at the Centre of Action on Climate Change*. Dublin, Ireland, 28 pp. Available at: https://www.mrfcj.org/wp-content/uploads/2015/11/MRFCJ-Rights-for-Action-edition-2.pdf.
Mullins, J. T. and C. White, 2020: Can access to health care mitigate the effects of temperature on mortality? *Journal of Public Economics*, **191**, 104259, doi:10.1016/j.jpubeco.2020.104259.
Mulugetta, Y., E. B. Hagan and D. Kammen, 2019: Energy access for sustainable development. *Environmental Research Letters*, **14**(2), 020201, doi:10.1088/1748-9326/aaf449.
Muok, B., M. Mosberg, S. Eriksen and D. Ochieng, 2021: The politics of forest governance in a changing climate: Political reforms, conflict and socio-environmental changes in Laikipia, Kenya. *Forest Policy and Economics*, In press.
Muratori, M. et al., 2020: EMF-33 insights on bioenergy with carbon capture and storage (BECCS). *Climatic Change*, doi:10.1007/s10584-020-02784-5.
Muricho, D. N., D. J. Otieno, W. Oluoch-Kosura and M. Jirström, 2019: Building pastoralists' resilience to shocks for sustainable disaster risk mitigation: Lessons from West Pokot County, Kenya. *International Journal of Disaster Risk Reduction*, **34**, 429–435.
Murphy, B. L., 2011: From interdisciplinary to inter-epistemological approaches: Confronting the challenges of integrated climate change research. *The Canadian Geographer / Le Géographe canadien*, **55**(4), 490-509, doi:10.1111/j.1541-0064.2011.00388.x.
Murtinho, F., 2016: What facilitates adaptation? An analysis of community-based adaptation to environmental change in the Andes. *International Journal of the Commons*, **10**(1), 119-141, doi:10.18352/ijc.585.
Mustafa, S., A. Estim and R. Shapawi, 2019: Future-Proofing Oceans for Food Security and Poverty Alleviation. pp. 1-11. ISBN 978-3-319-69627-0.
Mustonen, T., 2013: Oral histories as a baseline of landscape restoration – Co-management and watershed knowledge in Jukajoki River. *Fennia - International Journal of Geography*, **191(%P 76-91**.
Mustonen, T., 2014: Endemic time-spaces of Finland: Aquatic regimes. *Fennia - International Journal of Geography*, **192**(2), 120-139.
Mustonen, T., 2018: Meaningful engagement and oral histories of the indigenous peoples of the north. *Nordia Geographical Publications*, **47**(2), 1–38.
Mustonen, T. and P. Feodoroff, 2020: What is a River? A Cross-Disciplinary and Indigenous Assessment. In: *Indigenous Wellbeing and Enterprise Self-Determination and Sustainable Economic Development* [Colborne, R. (ed.)]. Routledge.
Mustonen, T. and V. Shadrin, 2020: The River Alazeya: Shifting socio-ecological systems connected to a Northeastern Siberian Rive. *Arctic Institute of North America*.
Mycoo, M. A., 2018: Beyond 1.5 °C: vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional environmental change*.

Mythen, G. and S. Walklate, 2016: Not knowing, emancipatory catastrophism and metamorphosis: Embracing the spirit of Ulrich Beck. *Security Dialogue*, **47**(5), 403-419, doi:10.1177/0967010616651027.
Nabuurs, G.-J. et al., 2017: By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. *Forests*, **8**, 484, doi:10.3390/f8120484.
Nabuurs, G.-J. et al., 2019: Next-generation information to support a sustainable course for European forests. *Nature Sustainability*, **2**(9), 815-818, doi:10.1038/s41893-019-0374-3.
Nachmany, M., S. Fankhauser, J. Setzer and A. Averchenkova, 2017: Global trends in climate change legislation and litigation: 2017 update.
Nachmany, M. and J. Setzer, 2018: Policy brief Global trends in climate change legislation and litigation: 2018 snapshot. *London: Grantham Research Center on Climate Change and the Environment and Center for Climate Change Economics and Policy*.
Naess, L. O., 2013: The role of local knowledge in adaptation to climate change. *WIREs Climate Change*, **4**(2), 99-106, doi:10.1002/wcc.204.
Naess, L. O. et al., 2015: Climate policy meets national development contexts: Insights from Kenya and Mozambique. *Global Environmental Change*, **35**, 534-544, doi:10.1016/j.gloenvcha.2015.08.015.
Nagoda, S., 2015: New discourses but same old development approaches? Climate change adaptation policies, chronic food insecurity and development interventions in northwestern Nepal. *Global Environmental Change*, **35**, 570-579, doi:10.1016/j.gloenvcha.2015.08.014.
Nagoda, S. and A. J. Nightingale, 2017: Participation and Power in Climate Change Adaptation Policies: Vulnerability in Food Security Programs in Nepal. *World Development*, **100**, 85-93, doi:10.1016/j.worlddev.2017.07.022.
Naidoo, R. and B. Fisher, 2020: Reset Sustainable Development Goals for a pandemic world. *Nature*, **583**(7815), 198-201, doi:10.1038/d41586-020-01999-x.
Nakashima, D. J. et al., 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. UNESCO, and Darwin, UNU, Paris.
Nalau, J. et al., 2018: The Role of Indigenous and Traditional Knowledge in Ecosystem-Based Adaptation: A Review of the Literature and Case Studies from the Pacific Islands. *Wea. Climate Soc.*, **10**(4), 851-865, doi:10.1175/WCAS-D-18-0032.1.
Nalau, J., B. L. Preston and M. C. Maloney, 2015: Is adaptation a local responsibility? *Environmental Science & Policy*, **48**, 89-98.
Naspolini, G. F., B. S. Ciasca, E. L. La Rovere and A. O. Pereira Jr, 2020: Brazilian Environmental-Economic Accounting for Water: A structural decomposition analysis. *Journal of Environmental Management*, **265**, 110508.
Naude, P., 2019: Decolonising Knowledge: Can Ubuntu Ethics Save Us from Coloniality? *J Bus Ethics*, **159**(1), 23-37, doi:http://dx.doi.org/10.1007/s10551-017-3763-4.
Naylor, A., J. Ford, T. Pearce and J. Van Alstine, 2020: Conceptualizing Climate Vulnerability in Complex Adaptive Systems. *One Earth*, **2**(5), 444-454.
NDRC, 2015: *China Belt and Road Initiative*.
NEF, 2016: Happy Planet Index.
Newell, P., 2019: Trasformismo or transformation? The global political economy of energy transitions. *Review of International Political Economy*, **26**(1), 25-48, doi:10.1080/09692290.2018.1511448.
Newell, P., 2020: Towards a global political economy of transitions: a comment on the transitions research agenda. *Environmental Innovation and Societal Transitions*, **34**, 344-345, doi:10.1016/j.eist.2019.10.007.
Newell, P. and R. Lane, 2020: A climate for change? The impacts of climate change on energy politics. *Cambridge Review of International Affairs*, **33**(3), 347-364, doi:10.1080/09557571.2018.1508203.
Newman, T. P., E. C. Nisbet and M. C. Nisbet, 2018: Climate change, cultural cognition, and media effects: Worldviews drive news selectivity, biased processing, and polarized attitudes. *Public Understanding of Science*, doi:10.1177/0963662518801170.
Nhamo, G. and S. Nhamo, 2018: Gender and Geographical Balance: With a Focus on the UN Secretariat and the Intergovernmental Panel on Climate Change. *Gender Questions*, **5**(1).
Nhamo, L., B. Ndlela, S. Mpandeli and T. Mabhaudhi, 2020: The Water-Energy-Food Nexus as an Adaptation Strategy for Achieving Sustainable Livelihoods at a Local Level. *Sustainability*, **12**(20), 8582, doi:10.3390/su12208582.
Nielsen, S. and I. R. Skov, 2019: Investment screening model for spatial deployment of power-to-gas plants on a national scale – A Danish case. *International Journal of Hydrogen Energy*, **44**(19), 9544-9557, doi:10.1016/j.ijhydene.2018.09.129.
Nightingale, A. J., 2016: Adaptive scholarship and situated knowledges? Hybrid methodologies and plural epistemologies in climate change adaptation research. *Area*, **48**(1), 41-47, doi:10.1111/area.12195.
Nightingale, A. J., 2017: Power and politics in climate change adaptation e ff orts : Struggles over authority and recognition in the context of political instability. *Geoforum*, **84**, 11–20.
Nightingale, A. J. et al., 2020: Beyond Technical Fixes: climate solutions and the great derangement. *Climate and Development*, **12**(4), 343-352.
Nightingale Böhler, T., Campbell, B., Karlsson, L., A.j., 2019: Background and History of Sustainability. In: *Environment and Sustainability in a Globalizing World*. Routledge, pp. 13–34. ISBN 978-0-7656-4644-6.
Nikulina, V., D. Simon, H. Ny and H. Baumann, 2019: Context-adapted urban planning for rapid transitioning of personal mobility towards sustainability: A systematic literature review. *Sustainability*, **11**(4), 1007.

Nilsson, M. and N. Weitz, 2019: Governing Trade-Offs and Building Coherence in Policy-Making for the 2030 Agenda. *Politics and Governance*, **7**(4), 254-263, doi:10.17645/pag.v7i4.2229.
Nilsson, M. et al., 2012: Understanding Policy Coherence: Analytical Framework and Examples of Sector–Environment Policy Interactions in the EU. *Environmental Policy and Governance*, **22**(6), 395-423, doi:10.1002/eet.1589.
Nkemelang, T., M. New and M. Zaroug, 2018: Temperature and precipitation extremes under current, 1.5 °C and 2.0 °C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability. *Environmental Research Letters*, **13**(6), 065016.
Nordhaus, W. D., 2017: Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, **114**(7), 1518-1523, doi:10.1073/pnas.1609244114.
Nordhaus, W. D. and J. Tobin, 1973: Is growth obsolete? In: *The measurement of economic and social performance*. Nber, pp. 509-564.
Novák, A., 2021: Every city needs a Klinika: The struggle for autonomy in the post-political city. *Social Movement Studies*, **20**(3), 276-291, doi:10.1080/14742837.2020.1770070.
Nunn, P. and N. Reid, 2016: Aboriginal Memories of Inundation of the Australian Coast Dating from More than 7000 Years Ago. *Australian Geographer*, **47**(1), 11-47, doi:10.1080/00049182.2015.1077539.
Nyariki, D. M. and D. A. Amwata, 2019: The value of pastoralism in Kenya: Application of total economic value approach. *Pastoralism*, **9**(1), 9.
Nyasimi, M. et al., 2018: Inclusion of Gender in Africa's Climate Change Policies and Strategies. pp. 171-185. ISBN 978-3-319-69837-3.
Nyberg, G. et al., 2015: Enclosures in West Pokot, Kenya: Transforming land, livestock and livelihoods in drylands. *Pastoralism*, **5**(1), 25.
O'Brien, K., S. Eriksen, T. H. a. Inderberg and L. Sygna, 2015: *Climate change adaptation and development: transforming through paradigms and practices*. Routledge, New York.
O'Brien, K. and E. Selboe, 2015: Social Transformation: The Real Adaptive Challenge. pp. 311-324. ISBN 978-1-139-14938-9.
O'Brien, K. L., 2016: Climate change and social transformations: is it time for a quantum leap? *WIREs Climate Change*, **7**(5), 618-626, doi:10.1002/wcc.413.
O'Brien, K., 2018: Is the 1.5°C target possible? Exploring the three spheres of transformation. *Current Opinion in Environmental Sustainability*, **31**, 153-160, doi:10.1016/j.cosust.2018.04.010.
O'Brien, K., 2021: Reflecting on the Anthropocene: The Call for Deeper Transformations. *Ambio*, **50**(10), 1793-1797, doi:10.1007/s13280-020-01468-9.
O'Neil, T., A. Fleury and M. Foresti, 2017: Gender equality, migration and the 2030 Agenda for Sustainable Development. *Louise Arbour, UN Special Representative for International Migration*, 45.
O'Neill, B. C. et al., 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169-180, doi:10.1016/j.gloenvcha.2015.01.004.
O'Neill, D. W., A. L. Fanning, W. F. Lamb and J. K. Steinberger, 2018: A good life for all within planetary boundaries. *Nature Sustainability*, **1**(2), 88-95, doi:10.1038/s41893-018-0021-4.
Ochieng, J., L. Kirimi and J. Makau, 2017: Adapting to climate variability and change in rural Kenya: farmer perceptions, strategies and climate trends. *Natural Resources Forum*, **41**(4), 195–208.
OECD, 2017: *Mobilising investment in clean energy infrastructure*. Available at: http://www.oecd.org/daf/inv/investment-policy/clean-energy-infrastructure.htm.
OECD, 2019a: Better Life Index.
OECD, 2019b: *Society at a Glance 2019*.
OECD, 2021: *CLIMATE CHANGE AND LONG TERM FISCAL SUSTAINABILITY*.
Ofir, Z., 2021: The DAC Criteria Guidance 2021 - EVALUATION FOR TRANSFORMATION.
Ogar, E., G. Pecl and T. Mustonen, 2020: Science Must Embrace Traditional and Indigenous Knowledge to Solve Our Biodiversity Crisis. *One Earth*, 162-164, doi:https://doi.org/10.1016/j.oneear.2020.07.006.
Ojwang, L. et al., 2017: Assessment of Coastal Governance for Climate Change Adaptation in Kenya. *Earth's Future*, **5**(11), 1119-1132, doi:10.1002/2017EF000595.
Oke, C. et al., 2021: Cities should respond to the biodiversity extinction crisis. *npj Urban Sustainability*, **1**(1), 1-4, doi:10.1038/s42949-020-00010-w.
Oleribe, O. O. and S. D. Taylor-Robinson, 2016: Before Sustainable Development Goals (SDG): why Nigeria failed to achieve the Millennium Development Goals (MDGs). *Pan Afr Med J*, **24**, 156-156, doi:10.11604/pamj.2016.24.156.8447.
Olmstead, S. M., 2014: Climate change adaptation and water resource management: A review of the literature. *Energy Economics*, **46**, 500-509, doi:10.1016/j.eneco.2013.09.005.
Olsson, L. et al., 2014: Livelihoods and Poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793-832. ISBN 9781107058071.

Omukuti, J., 2020: Country ownership of adaptation: Stakeholder influence or government control? *Geoforum*, **113**, 26-38, doi:10.1016/j.geoforum.2020.04.019.
Onarheim, K. H., J. H. Iversen and D. E. Bloom, 2016: Economic Benefits of Investing in Women's Health: A Systematic Review. *PLoS One*, **11**(3), e0150120, doi:10.1371/journal.pone.0150120.
Opiyo, F. et al., 2016: Determinants of perceptions of climate change and adaptation among Turkana pastoralists in northwestern Kenya. *Climate and Development*, **8**(2), 179-189.
Opiyo, F. E., O. V. Wasonga and M. M. Nyangito, 2014: Measuring household vulnerability to climate-induced stresses in pastoral rangelands of Kenya: Implications for resilience programming. *Pastoralism*, **4**(1), 10.
Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Orlove, B., R. Shwom, E. Markowitz and S.-M. Cheong, 2020: Climate Decision-Making. *Annual Review of Environment and Resources*, **45**(1), 271-303, doi:10.1146/annurev-environ-012320-085130.
Ota, T., 2017: Economic growth, income inequality and environment: assessing the applicability of the Kuznets hypotheses to Asia. *Palgrave Communications*, **3**(1), 1-23, doi:10.1057/palcomms.2017.69.
Ott, C. and B. Kiteme, 2016: Concepts and practices for the democratisation of knowledge generation in research partnerships for sustainable development. *Evidence & Policy: A Journal of Research, Debate and Practice*, **12**(3), 405-430, doi:10.1332/174426416X14700793045951.
Ott, K. K., 2018: On the Political Economy of Solar Radiation Management. *Front. Environ. Sci.*, **6**, doi:10.3389/fenvs.2018.00043.
Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071, doi:10.1016/j.gloenvcha.2020.102071.
P.R. Shukla E. Calvo Buendia, V. M.-D., H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, , ., J Skea, 2019: Technical Summary, 2019. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.
Paik, S., D. T. P. Le, L. T. Nhu and B. F. Mills, 2020: Salt-tolerant rice variety adoption in the Mekong River Delta: Farmer adaptation to sea-level rise. *PLoS One*, **15**(3), e0229464, doi:10.1371/journal.pone.0229464.
Palazzo, A. et al., 2017: Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. *Global Environmental Change*, **45**, 227-242, doi:https://doi.org/10.1016/j.gloenvcha.2016.12.002.
Palermo, V. and Y. Hernandez, 2020: Group discussions on how to implement a participatory process in climate adaptation planning: a case study in Malaysia. *Ecological Economics*, **177**, 106791, doi:10.1016/j.ecolecon.2020.106791.
Pant, L. P., B. Adhikari and K. K. Bhattarai, 2015: Adaptive transition for transformations to sustainability in developing countries. *Current Opinion in Environmental Sustainability*, **14**, 206-212, doi:10.1016/j.cosust.2015.07.006.
Papoutsi, M., M. Piaszzesi and M. Schneider, 2021: *How Unconventional is Green Monetary Policy?*
Paprocki, K., 2018: Threatening Dystopias: Development and Adaptation Regimes in Bangladesh. *Annals of the American Association of Geographers*, **108**(4), 955-973, doi:10.1080/24694452.2017.1406330.
Parikh, K. S., J. K. Parikh and P. P. Ghosh, 2018: Can India grow and live within a 1.5 degree CO2 emissions budget? *Energy Policy*, **120**, 24-37.
Parraguez-Vergara, E. et al., 2018: Does indigenous and campesino traditional agriculture have anything to contribute to food sovereignty in Latin America? Evidence from Chile, Peru, Ecuador, Colombia, Guatemala and Mexico. *International Journal of Agricultural Sustainability*, 326-341, doi:10.1080/14735903.2018.1489361.
Parry, I., 2021: *Implementing the United States' Domestic and International Climate Mitigation Goals: A Supportive Fiscal Policy Approach*. IMF Working Paper Fiscal Affairs Department.
Parry, J.-E., 2017: *Building a Climate-Resilient City: Transformational adaptation*. IISD. Available at: http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-climate-resilient-city-transformational-adaptation.pdf.
Parsons, M., C. Brown, J. Nalau and K. Fisher, 2018: Assessing adaptive capacity and adaptation: insights from Samoan tourism operators. *Climate and Development*, **10**(7), 644-663, doi:10.1080/17565529.2017.1410082.
Partzsch, L., 2017: 'Power with' and 'power to' in environmental politics and the transition to sustainability. *Environmental Politics*, **26**(2), 193-211, doi:10.1080/09644016.2016.1256961.
Pascual, U. et al., 2017: Valuing nature's contributions to people: the IPBES approach. *Current Opinion in Environmental Sustainability*, **26-27**, 7-16, doi:10.1016/j.cosust.2016.12.006.
Pasquini, L., 2020: The urban governance of climate change adaptation in least-developed African countries and in small cities: the engagement of local decision-makers in Dar es Salaam, Tanzania, and Karonga, Malawi. *Climate and Development*, **12**(5), 408-419, doi:10.1080/17565529.2019.1632166.

Paton, F. L., H. R. Maier and G. C. Dandy, 2014: Including adaptation and mitigation responses to climate change in a multiobjective evolutionary algorithm framework for urban water supply systems incorporating GHG emissions. *Water Resources Research*, **50**(8), 6285-6304, doi:10.1002/2013WR015195.
Patorniti, N. P., N. J. Stevens and P. M. Salmon, 2017: A systems approach to city design: Exploring the compatibility of sociotechnical systems. *Habitat International*, **66**, 42-48, doi:10.1016/j.habitatint.2017.05.008.
Patorniti, N. P., N. J. Stevens and P. M. Salmon, 2018: A sociotechnical systems approach to understand complex urban systems: A global transdisciplinary perspective. *Human Factors and Ergonomics in Manufacturing & Service Industries*, **28**(6), 281-296, doi:10.1002/hfm.20742.
Patterson, J. et al., 2017: Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions*, **24**, 1-16, doi:10.1016/j.eist.2016.09.001.
Patterson, J. J. et al., 2018: Political feasibility of 1.5° C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1-9.
Patton, M. Q., 2021: Evaluation Criteria for Evaluating Transformation: Implications for the Coronavirus Pandemic and the Global Climate Emergency. *American Journal of Evaluation*, **42**(1), 53-89, doi:10.1177/1098214020933689.
Pauliuk, S., T. Wang and D. B. Müller, 2013: Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resources, Conservation and Recycling*, **71**, 22-30, doi:10.1016/j.resconrec.2012.11.008.
Pauw, W. P. et al., 2018: Beyond headline mitigation numbers: we need more transparent and comparable NDCs to achieve the Paris Agreement on climate change. *Climatic Change*, **147**(1), 23-29, doi:10.1007/s10584-017-2122-x.
PBCSF, 2019: *Support for BRI low carbon development: a green finance roadmap*.
Pearce, T. D., E. H. Rodríguez, D. Fawcett and J. D. Ford, 2018a: How Is Australia Adapting to Climate Change Based on a Systematic Review? *Sustainability*, **10**(9), 3280, doi:10.3390/su10093280.
Pearce, W., M. Mahony and S. Raman, 2018b: Science advice for global challenges: Learning from trade-offs in the IPCC. *Environmental Science & Policy*, **80**, 125-131, doi:https://doi.org/10.1016/j.envsci.2017.11.017.
Pearse, R., 2017: Gender and climate change. *WIREs Climate Change*, **8**(2), e451, doi:10.1002/wcc.451.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355**(6332), doi:10.1126/science.aai9214.
Pelling, M., 2010: *Adaptation to Climate Change: From Resilience to Transformation*, 1 ed., Routledge. ISBN 978-0-203-88904-6.
Pelling, M., T. Abeling and M. Garschagen, 2016: Emergence and Transition in London's Climate Change Adaptation Pathways. *Journal of Extreme Events*, **03**(03), 1650012.
Pelling, M. and M. Garschagen, 2019: Put equity first in climate adaptation. *Nature*, **569**(7756), 327-329, doi:10.1038/d41586-019-01497-9.
Pelling, M. et al., 2018: Africa's urban adaptation transition under a 1.5° climate. *Current Opinion in Environmental Sustainability*, **31**, 10-15, doi:10.1016/j.cosust.2017.11.005.
Pelling, M., K. O'Brien and D. Matyas, 2015: Adaptation and transformation. *Climatic Change*, **133**(1), 113-127, doi:10.1007/s10584-014-1303-0.
Pereira, J. J., 2018: 3 - Science and technology to enhance disaster resilience in a changing climate. In: *Science and Technology in Disaster Risk Reduction in Asia* [Shaw, R., K. Shiwaku and T. Izumi (eds.)]. Academic Press, pp. 31-38. ISBN 978-0-12-812711-7.
Perera, A. T. D. et al., 2020: Quantifying the impacts of climate change and extreme climate events on energy systems. *Nature Energy*, **5**(2), 150-159, doi:10.1038/s41560-020-0558-0.
Perkins, P. E., 2019: Climate justice, commons, and degrowth. *Ecological Economics*, **160**, 183-190, doi:10.1016/j.ecolecon.2019.02.005.
Persson, Å., 2019: Global adaptation governance: An emerging but contested domain. *WIREs Climate Change*, **10**(6), e618, doi:10.1002/wcc.618.
Pervin, M. et al., 2013: *A framework for mainstreaming climate resilience into development planning*. Available at: https://pubs.iied.org/pdfs/10050IIED.pdf.
Peters, H. P., 2013: Gap between science and media revisited: Scientists as public communicators. *Proceedings of the National Academy of Sciences*, **110**(Supplement_3), 14102-14109.
Peterson, G. D. et al., 2018: Welcoming different perspectives in IPBES: "Nature's contributions to people" and "Ecosystem services". *Ecology and Society*, **23**(1), doi:10.5751/es-10134-230139.
Petrides, D., A. Papacharalampopoulos, P. Stavropoulos and G. Chryssolouris, 2018: Dematerialisation of products and manufacturing-generated knowledge content: relationship through paradigms. *International Journal of Production Research*, **56**(1-2), 86-96, doi:10.1080/00207543.2017.1401246.
Phillips, C. A. et al., 2020: Compound climate risks in the COVID-19 pandemic. *Nature Climate Change*, **10**(7), 586-588, doi:10.1038/s41558-020-0804-2.
Piggot, G., 2018: The influence of social movements on policies that constrain fossil fuel supply. *Climate Policy*, **18**(7), 942-954, doi:10.1080/14693062.2017.1394255.
Pineda-López, M. d. R. et al., 2015: The Role of Women in the Forest Conservation in a Mexican National Park: Pruning Firs for the Manufacture of Christmas Wreaths. *Human Ecology*, **43**(3), 493-501, doi:10.1007/s10745-015-9756-y.

Pinnegar, J. K. et al., 2021: Future Socio-Political Scenarios for Aquatic Resources in Europe: A Common Framework Based on Shared-Socioeconomic-Pathways (SSPs). *Front. Mar. Sci.*, **7**(1096), doi:10.3389/fmars.2020.568219.
Pirmana, V., A. S. Alisjahbana, R. Hoekstra and A. Tukker, 2019: Implementation Barriers for a System of Environmental-Economic Accounting in Developing Countries and Its Implications for Monitoring Sustainable Development Goals. *Sustainability*, **11**(22), 6417, doi:10.3390/su11226417.
Plank, C. et al., 2021: Climate policy integration viewed through the stakeholders' eyes: A co-production of knowledge in social-ecological transformation research. *Environmental Policy and Governance*, **31**(4), 387-399, doi:10.1002/eet.1938.
Plesa, P., 2019: A theoretical foundation for ecopsychology: Looking at ecofeminist epistemology. *New Ideas in Psychology*, **52**, 18-25, doi:10.1016/j.newideapsych.2018.10.002.
Popescu, G. H. et al., 2017: Stabilizing Valences of an Optimum Monetary Zone in a Resilient Economy—Approaches and Limitations. *Sustainability*, **9**(6), 1051, doi:10.3390/su9061051.
Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123**(3), 495-509, doi:10.1007/s10584-013-0926-x.
Porta, D. d., 2020: Protests as critical junctures: some reflections towards a momentous approach to social movements. *Social Movement Studies*, **19**(5-6), 556-575, doi:10.1080/14742837.2018.1555458.
Power, M. et al., 2016: The political economy of energy transitions in Mozambique and South Africa: The role of the Rising Powers. *Energy Research & Social Science*, **17**, 10-19, doi:10.1016/j.erss.2016.03.007.
Preston, B. L., L. Rickards, H. Fünfgeld and R. J. Keenan, 2015: Toward reflexive climate adaptation research. *Current Opinion in Environmental Sustainability*, **14**, 127-135.
Price, 2021: *Overview of political economy analysis frameworks in the area of climate governance and key issues to consider*. Institute of Development Studies.
Pringle, P. and T. Leiter, 2018: Pitfalls and potential of measuring climate change adaptation through adaptation metrics. ISBN 978-87-93458-27-7.
Psaltoglou, A. and E. Calle, 2018: Enhanced connectivity index - A new measure for identifying critical points in urban public transportation networks. *Int. J. Crit. Infrastruct. Prot.*, **21**, 22-32, doi:10.1016/j.ijcip.2018.02.003.
Purdon, M., 2014: *The Comparative Turn in Climate Change Adaptation and Food Security Governance Research*. CGIAR.
Quader, M. A., S. Ahmed and R. A. R. Ghazillaa, 2016: Recent Progress and Future Trends of CO2 Breakthrough Iron and Steelmaking Technologies for CO2 Mitigation. In: *Ironmaking and Steelmaking Processes: Greenhouse Emissions, Control, and Reduction* [Cavaliere, P. (ed.)]. Springer International Publishing, Cham, pp. 373-388. ISBN 978-3-319-39529-6.
Rabaey, K., T. Vandekerckhove, A. V. de Walle and D. L. Sedlak, 2020: The third route: Using extreme decentralization to create resilient urban water systems. *Water Research*, **185**, 116276, doi:10.1016/j.watres.2020.116276.
Radcliffe, S. A., 2014: Gendered frontiers of land control: indigenous territory, women and contests over land in Ecuador. *Gender, Place & Culture*, **21**(7), 854-871, doi:10.1080/0966369X.2013.802675.
Ramalho, J., 2019: Worlding aspirations and resilient futures: Framings of risk and contemporary city-making in Metro Cebu, the Philippines. *Asia Pacific Viewpoint*, **60**(1), 24-36, doi:10.1111/apv.12208.
Ramkissoon, H. and L. Smith, 2014: The Relationship between Environmental Worldviews, Emotions and Personal Efficacy in Climate Change.
Randers, J. et al., 2019: Achieving the 17 Sustainable Development Goals within 9 planetary boundaries. *Global Sustainability*, **2**, e24.
Rao, N., 2019: From abandonment to autonomy: Gendered strategies for coping with climate change, Isiolo County, Kenya. *Geoforum*, **102**, 27-37.
Rao, N. et al., 2019a: A qualitative comparative analysis of women's agency and adaptive capacity in climate change hotspots in Asia and Africa. *Nature Climate Change*, **9**(12), 964-971, doi:10.1038/s41558-019-0638-y.
Rao, N. D., P. Sauer, M. Gidden and K. Riahi, 2019b: Income inequality projections for the Shared Socioeconomic Pathways (SSPs). *Futures*, **105**, 27-39, doi:https://doi.org/10.1016/j.futures.2018.07.001.
Rasul, G. and B. Sharma, 2016: The nexus approach to water–energy–food security: an option for adaptation to climate change. *Climate Policy*, **16**(6), 682-702, doi:10.1080/14693062.2015.1029865.
Raworth, K., 2017: *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Chelsea Green Publishing, White River Junction, Vermont, 320 pp. ISBN 978-1-60358-674-0.
Reckien, D. et al., 2018: Equity, Environmental Justice, and Urban Climate Change. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., P. Romero-Lankao, S. Mehrotra, S. Dhakal, S. Ali Ibrahim and W. D. Solecki (eds.)]. Cambridge University Press, Cambridge, pp. 173-224. ISBN 978-1-316-60333-8.
Reed, M. G., A. Scott, D. Natcher and M. Johnston, 2014: Linking gender, climate change, adaptive capacity, and forest-based communities in Canada. *Canadian Journal of Forest Research*, **44**(9), 995-1004, doi:10.1139/cjfr-2014-0174.
Reid, R. S., M. E. Fernández-Giménez and K. A. Galvin, 2014: Dynamics and Resilience of Rangelands and Pastoral Peoples Around the Globe. *Annual Review of Environment and Resources*, **39**(1), 217-242.

Remling, E., 2021: *Climate-related Security Risks in the 2020 Updated Nationally Determined Contributions*. SIPRI (accessed 2021-08-30 19:39:38).

Remling, E. and J. Veitayaki, 2016: Community-based action in Fiji's Gau Island: a model for the Pacific? *International Journal of Climate Change Strategies and Management*, **8**(3), 375-398, doi:10.1108/IJCCSM-07-2015-0101.

Repo, P. and K. Matschoss, 2020: Social Innovation for Sustainability Challenges. *Sustainability*, **12**(1), 319.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153-168, doi:https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Ribeiro, H. V., D. Rybski and J. P. Kropp, 2019: Effects of changing population or density on urban carbon dioxide emissions. *Nature Communications*, **10**(1), 3204, doi:10.1038/s41467-019-11184-y.

Ribot, J., 2011: Vulnerability Before Adaptation: Toward Transformative Climate Action. *Global Environmental Change*, **21**, 1160-1162, doi:10.1016/j.gloenvcha.2011.07.008.

Richardson, K. J. et al., 2018: Food security outcomes under a changing climate: impacts of mitigation and adaptation on vulnerability to food insecurity. *Climatic Change*, **147**(1), 327-341, doi:10.1007/s10584-018-2137-y.

Riechers, M., Á. Balázsi, M. García-Llorente and J. Loos, 2021: Human-nature connectedness as leverage point. *Ecosystems and People*, **17**(1), 215-221, doi:10.1080/26395916.2021.1912830.

Roberts, D., J. Douwes, C. Sutherland and V. Sim, 2020: Durban's 100 Resilient Cities journey: governing resilience from within. *Environment and Urbanization*, **32**(2), 547-568, doi:10.1177/0956247820946555.

Robinson, S.-a. et al., 2021: Climate compatible development in practice. *Development in Practice*, **0**(0), 1-11, doi:10.1080/09614524.2021.1907534.

Rochette, A., 2016: Climate change is a social justice issue: The need for a gender-based analysis of mitigation and adaptation policies in Canada and Quebec. *Journal of Environmental Law and Practice*, **29**, 383-410.

Rockström, J. et al., 2009a: A safe operating space for humanity. *Nature*, **461**(7263), 472-475, doi:10.1038/461472a.

Rockström, J. et al., 2009b: Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, **14**(2), doi:10.5751/ES-03180-140232.

Roelich, K. and J. Giesekam, 2019: Decision making under uncertainty in climate change mitigation: introducing multiple actor motivations, agency and influence. *Climate Policy*, **19**(2), 175-188.

Rogelj, J. et al., 2010: Copenhagen Accord pledges are paltry. *Nature*, **464**(7292), 1126-1128, doi:10.1038/4641126a.

Rogelj, J. et al., 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.

Rogers, P., J. J. Bohland and J. Lawrence, 2020: Resilience and values: Global perspectives on the values and worldviews underpinning the resilience concept. *Political Geography*, **83**, 102280, doi:https://doi.org/10.1016/j.polgeo.2020.102280.

Roggema, R., T. Vermeend and A. V. Dobbelsteen, 2012: Incremental Change, Transition or Transformation? Optimising Change Pathways for Climate Adaptation in Spatial Planning. *Sustainability*, **4**(10), doi:10.3390/su4102525.

Rohat, G. et al., 2019: Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe. *Global and Planetary Change*, **172**, 45-59, doi:https://doi.org/10.1016/j.gloplacha.2018.09.013.

Romero-Lankao, P. et al., 2018: Urban transformative potential in a changing climate. *Nature Climate Change*, **8**(9), 754-756, doi:10.1038/s41558-018-0264-0.

Romero Mosquera, M., 2019: Banning Plastic Straws: The Beginning of the War Against Plastics. *Environmental and Earth Law Journal (EELJ)*, **9**(1).

Rose, S. K., 2017: *Managing Climate Damages: Exploring Trade-offs*. EPRI. Available at: http://web.stanford.edu/group/emf-research/docs/sm/2019/wk2/Rose.pdf.

Rose, S. K. et al., 2014: Bioenergy in energy transformation and climate management. *Climatic Change*, **123**(3), 477-493, doi:10.1007/s10584-013-0965-3.

Rose, S. K. and M. Scott, 2018: *Grounding Decisions: A Scientific Foundation for Companies Considering Global Climate Scenarios and Greenhouse Gases*. EPRI. Available at: https://www.epri.com/research/products/000000003002014510.

Rose, S. K. and M. Scott, 2020: *Review of 1.5˚C and Other Newer Global Emissions Scenarios: Insights for Company and Financial Climate Low-Carbon Transition Risk Assessment and Greenhouse Gas Goal Setting*. EPRI. Available at: https://www.epri.com/research/products/000000003002018053/.

Rosenberg, M. N., 2021: What matters? The role of values in transformations toward sustainability: a case study of coffee production in Burundi. *Sustainability Science*, doi:10.1007/s11625-021-00974-3.

Rosenzweig, C. and W. Solecki, 2018: Action pathways for transforming cities. *Nature Climate Change*, **8**(9), 756-759, doi:10.1038/s41558-018-0267-x.

Rougoor, W. and C. van Marrewijk, 2015: Demography, Growth, and Global Income Inequality. *World Development*, **74**(C), 220-232.
Rowell, L. and A. Feldman, 2019: Knowledge democracy and action research. *Educational Action Research*, **27**(1), 1-6, doi:10.1080/09650792.2019.1557456.
Roy, J. et al., 2018: Sustainable Development, Poverty Eradication and Reducing Inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
Rudebusch, G., 2019: *Climate change and the Federal Reserve*. FRBS Economic Letter.
Ruggeri Laderchi, C., R. Saith and F. Stewart, 2003: Does it Matter That We Do Not Agree on the Definition of Poverty? A Comparison of Four Approaches. *Oxford Development Studies*, **31**, 243-274, doi:10.1080/1360081032000111698.
Ruggiero, S., H. Busch, T. Hansen and A. Isakovic, 2021: Context and agency in urban community energy initiatives: An analysis of six case studies from the Baltic Sea Region. *Energy Policy*, **148**, 111956, doi:https://doi.org/10.1016/j.enpol.2020.111956.
Runhaar, H., 2018: Mainstreaming climate adaptation : taking stock about B what works ^ from empirical research worldwide. *Regional Environmental Change*, **18**, 1201–1210.
Ryan, D. and E. Bustos, 2019: Knowledge gaps and climate adaptation policy: a comparative analysis of six Latin American countries. *Climate Policy*, **19**(10), 1297-1309, doi:10.1080/14693062.2019.1661819.
Ryan, L., S. Moarif, E. Levina and R. Baron, 2011: *Energy efficiency policy and carbon pricing*. IEA Information Paper.
Ryota, N., 2019: *A Possible Approach to Fiscal Rules in Small Islands — Incorporating Natural Disasters and Climate ChangeRyot*. IMF Working paper, WP/19/186.
Sachdeva, S., 2016: Religious Identity, Beliefs, and Views about Climate Change.
Sadoff, C. W., E. Borgomeo and S. Uhlenbrook, 2020: Rethinking water for SDG 6. *Nature Sustainability*, **3**(5), 346-347, doi:10.1038/s41893-020-0530-9.
Sage, C., C. Kropp and I. Antoni-Komar, 2021: Grassroots initiatives in food system transformation: the role of food movements in the second 'Great Transformation'. pp. 1-19. ISBN 978-1-00-313130-4.
Saj, S. et al., 2017: The way forward: An agroecological perspective for Climate-Smart Agriculture. *Agriculture, Ecosystems & Environment*, **250**, 20-24, doi:10.1016/j.agee.2017.09.003.
Saja, A. M. A., A. Goonetilleke, M. Teo and A. M. Ziyath, 2019: A critical review of social resilience assessment frameworks in disaster management. *International Journal of Disaster Risk Reduction*, **35**, 101096.
Sakaguchi, K., A. Varughese and G. Auld, 2017: Climate Wars? A Systematic Review of Empirical Analyses on the Links between Climate Change and Violent Conflict. *International Studies Review*, **19**(4), 622-645, doi:10.1093/isr/vix022.
Salamon, M. K., 2019: Leading the Public into Emergency Mode. *The Climate Mobilization*.
Sánchez, A. and M. Izzo, 2017: Micro hydropower: an alternative for climate change mitigation, adaptation, and development of marginalized local communities in Hispaniola Island. *Climatic Change*, **140**(1), 79-87, doi:10.1007/s10584-016-1865-0.
Sanchez Rodriguez, R., D. Ürge-Vorsatz and A. S. Barau, 2018: Sustainable Development Goals and climate change adaptation in cities. *Nature Climate Change*, **8**(3), 181-183, doi:10.1038/s41558-018-0098-9.
Sanganyado, E., C. Teta and B. Masiri, 2018: Impact of African traditional worldviews on climate change adaptation. *Integrated Environmental Assessment and Management*, **14**(2), 189-193, doi:10.1002/ieam.2010.
Sarker, S. et al., 2018: From science to action: Exploring the potentials of Blue Economy for enhancing economic sustainability in Bangladesh. *Ocean & Coastal Management*, **157**, 180-192, doi:10.1016/j.ocecoaman.2018.03.001.
Satyal, P., M. F. Byskov and K. Hyams, 2020: Addressing multi-dimensional injustice in indigenous adaptation: the case of Uganda's Batwa community. *Climate and Development*, **0**(0), 1-14, doi:10.1080/17565529.2020.1824888.
Savaget, P., M. Geissdoerfer, A. Kharrazi and S. Evans, 2019: The theoretical foundations of sociotechnical systems change for sustainability: A systematic literature review. *Journal of Cleaner Production*, **206**, 878-892, doi:10.1016/j.jclepro.2018.09.208.
Scarano, F. R., 2017: Ecosystem-based adaptation to climate change: concept, scalability and a role for conservation science. *Perspectives in Ecology and Conservation*, **15**(2), 65-73, doi:10.1016/j.pecon.2017.05.003.
Schaeffer, M. et al., 2015: Mid- and long-term climate projections for fragmented and delayed-action scenarios. *Technological Forecasting and Social Change*, **90**, 257-268, doi:https://doi.org/10.1016/j.techfore.2013.09.013.
Scheffran, J., 2020: Chapter 16 - Climate extremes and conflict dynamics. In: *Climate Extremes and Their Implications for Impact and Risk Assessment* [Sillmann, J., S. Sippel and S. Russo (eds.)]. Elsevier, pp. 293-315. ISBN 978-0-12-814895-2.
Scherer, L. et al., 2018: Trade-offs between social and environmental Sustainable Development Goals. *Environmental Science & Policy*, **90**, 65-72, doi:10.1016/j.envsci.2018.10.002.

Schipper, E. L. F., 2020: Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, **3**(4), 409-414, doi:https://doi.org/10.1016/j.oneear.2020.09.014.
Schipper, E. L. F. et al., 2014: *Community-Based Adaptation to Climate Change : Scaling it up*. Routledge. ISBN 978-0-203-10506-1.
Schipper, E. L. F. et al., 2020a: Turbulent transformation: abrupt societal disruption and climate resilient development. *Climate and Development*, **0**(0), 1-8, doi:10.1080/17565529.2020.1799738.
Schipper, E. L. F. et al., 2020b: Turbulent transformation: abrupt societal disruption and climate resilient development. *Climate and Development*.
Schipper, E. L. F. et al., 2020c: The debate: Is global development adapting to climate change? *World Development Perspectives*, **18**, 100205, doi:10.1016/j.wdp.2020.100205.
Schleussner, C.-F. et al., 2021: Pathways of climate resilience over the 21st century. *Environmental Research Letters*, **16**(5), 054058, doi:10.1088/1748-9326/abed79.
Schlosberg, D., L. B. Collins and S. Niemeyer, 2017: Adaptation policy and community discourse: risk, vulnerability, and just transformation. *Environmental Politics*, **26**(3), 413-437, doi:10.1080/09644016.2017.1287628.
Schmitz, H., 2017: Who drives climate-relevant policies in the rising powers? *New Political Economy*, **22**(5), 521-540, doi:10.1080/13563467.2017.1257597.
Schoenmaker, D., 2019: *Greening monetary policy*. Available at: https://www.bruegel.org/2019/02/greening-monetary-policy/.
Schoenmaker, D. and W. Schramade, 2020: *Asset Pricing and Sustainability: A Teaching Note*. Social Science Research Network, Rochester, NY. Available at: https://papers.ssrn.com/abstract=3539080
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3539080 (accessed 2020/11/10/16:30:11).
Schot, J. and W. E. Steinmueller, 2018: Three frames for innovation policy: R&D, systems of innovation and transformative change. *Research Policy*, **47**(9), 1554-1567.
Schwarz, M., C. Nakhle and C. Knoeri, 2020: Innovative designs of building energy codes for building decarbonization and their implementation challenges. *Journal of Cleaner Production*, **248**, 119260, doi:10.1016/j.jclepro.2019.119260.
Scobie, M., 2013: Climate Regulation: Implications for Trade Competitiveness in Caribbean States. In: *Climate-Smart Technologies Integrating Renewable Energy and Energy Efficiency in Mitigation and Adaptation Responses*. Springer Berlin Heidelberg, pp. 33-49.
Scobie, M., 2017: Fossil fuel reform in developing states: The case of Trinidad and Tobago, a petroleum producing small Island developing State. *Energy Policy*, **104**, 265-273, doi:10.1016/j.enpol.2017.02.008.
Scobie, M., J. Skovgaard and H. Asselt, 2018: Actors, Frames and Contexts in Fossil Fuel Subsidy Reform: The Case of Trinidad and Tobago. pp. 283-302. ISBN 978-1-108-41679-5.
Scott, S. and C. Ku, 2018: The UN Security Council and global action on climate change. *Faculty Scholarship*, 1-24, doi:10.4337/9781785364648.00008.
Scoville-Simonds, M., H. Jamali and M. Hufty, 2020: The Hazards of Mainstreaming: Climate change adaptation politics in three dimensions. *World Development*, **125**, 104683, doi:10.1016/j.worlddev.2019.104683.
Segger, M.-C., 2016: Advancing the Paris Agreement on Climate Change for Sustainable Development. *Cambridge International Law Journal*, **5**, 202-237, doi:10.4337/cilj.2016.02.03.
Sellers, S. and K. L. Ebi, 2018: Climate Change and Health under the Shared Socioeconomic Pathway Framework. *International Journal of Environmental Research and Public Health*, **15**(1), doi:10.3390/ijerph15010003.
Sen, A., 2000: *Development as Freedom*, Reprint edition ed., Anchor, New York, 384 pp. ISBN 978-0-385-72027-4.
Sengers, F., A. J. Wieczorek and R. Raven, 2019: Experimenting for sustainability transitions: A systematic literature review. *Technological Forecasting and Social Change*, **145**, 153-164, doi:10.1016/j.techfore.2016.08.031.
Serfilippi, E. and G. Ramnath, 2018: Resilience measurement and conceptual frameworks: a review of the literature. *Annals of Public and Cooperative Economics*, **89**(4), 645-664.
Settele, J. et al., 2014: Terrestrial and Inland Water Systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359. ISBN 9781107058071.
Setzer, J. and R. Byrnes, 2019: Global trends in climate change litigation: 2019 snapshot. *Policy report. URL: www. lse. ac. uk/GranthamInstitute*.
Seyfang, G. and A. Smith, 2007: Grassroots innovations for sustainable development: Towards a new research and policy agenda. *Environmental Politics*, **16**(4), 584-603, doi:10.1080/09644010701419121.
Shaneyfelt, K. M., A. R. Anderson, P. Kumar and W. F. Hunt, 2017: Air quality considerations for stormwater green street design. *Environmental Pollution*, **231**, 768-778, doi:10.1016/j.envpol.2017.08.081.
Sharifi, A., 2020: Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. *Journal of Cleaner Production*, **276**, 122813, doi:10.1016/j.jclepro.2020.122813.
Sharpe, B. et al., 2016: Three horizons: a pathways practice for transformation. *Ecology and Society*, **21**(2), doi:10.5751/ES-08388-210247.

Shaw, J., 2016: Archaeology, climate change and environmental ethics: diachronic perspectives on human:non-human:environment worldviews, activism and care. *World Archaeology*, **48**(4), 449-465, doi:10.1080/00438243.2016.1326754.
Sheller, M., 2021: Reconstructing tourism in the Caribbean: connecting pandemic recovery, climate resilience and sustainable tourism through mobility justice. *Journal of Sustainable Tourism*, **29**(9), 1436-1449, doi:10.1080/09669582.2020.1791141.
Shi, J., V. H. M. Visschers and M. Siegrist, 2015: Public Perception of Climate Change: The Importance of Knowledge and Cultural Worldviews. *Risk Analysis*, **35**(12), 2183-2201, doi:10.1111/risa.12406.
Shi, L., 2020a: Beyond flood risk reduction: How can green infrastructure advance both social justice and regional impact? *Socio-Ecological Practice Research*, **2**(4), 311-320, doi:10.1007/s42532-020-00065-0.
Shi, L., 2020b: From Progressive Cities to Resilient Cities: Lessons from History for New Debates in Equitable Adaptation to Climate Change. *Urban Affairs Review*, 1078087419910827, doi:10.1177/1078087419910827.
Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372**(6549), doi:10.1126/science.abc8054.
Shiller, R., 2012: *Finance and the Good Society*. Princeton University Press.
Shim, Y.-H., 2015: A research methodological debate on emancipatory catastrophism: The case of transnational marriage. *Current Sociology*, **63**(1), 105-109, doi:10.1177/0011392114559850.
Shindell, D. et al., 2017: A climate policy pathway for near- and long-term benefits. *Science*, **356**(6337), 493-494, doi:10.1126/science.aak9521.
Shiva, V., 2017: Swaraj. In: *The Wiley Blackwell Companion to Religion and Ecology*. John Wiley & Sons, Ltd, pp. 12-19. ISBN 978-1-118-46552-3.
Sillitoe, P., 2016: *Indigenous studies and engaged anthropology: The collaborative moment*. Routledge.
Silva Rodríguez de San Miguel, J. A., 2018: Gender and water management in Mexico. *Management of Environmental Quality: An International Journal*, **29**(5), 842-858, doi:10.1108/MEQ-10-2017-0112.
Silver, J. J. and L. M. Campbell, 2018: Conservation, development and the blue frontier: the Republic of Seychelles' Debt Restructuring for Marine Conservation and Climate Adaptation Program. *International Social Science Journal*, **68**(229-230), 241-256, doi:10.1111/issj.12156.
Silvola, H. and T. Landau, 2021: *Sustainable Investing: Beating the Market with ESG*, 1st ed. 2021 edition ed., Palgrave Macmillan, Cham, Switzerland, 266 pp. ISBN 978-3-030-71488-8.
Siméant-Germanos, J., 2019: Conceptualizing contexts or contextualizing concepts? On some issues of the modeling of relational spaces in the study of collective action. *Social Movement Studies*, **0**(0), 1-16, doi:10.1080/14742837.2019.1629899.
Simonee, N. et al., 2021: Sila qanuippa? (how's the weather?): Integrating Inuit Qaujimajatuqangit and environmental forecasting products to support travel safety around Pond Inlet, Nunavut in a changing climate. Weather, Climate, and Society,DOI: https://doi.org/10.1175/WCAS-D-20-0174.1Simonet, C. and G. Jobbins, 2016: *Understanding patterns of climate resilient development – the case of Senegal*. Overseas Development Institute, London. Available at: http://prise.odi.org/wp-content/uploads/2016/04/Understanding-patterns-of-climate-resilient-development-%E2%80%93-the-case-of-Senegal_Low-Res.pdf.
Singh, C., 2019: Migration as a driver of changing household structures: implications for local livelihoods and adaptation. *Migration and Development*, **8**(3), 301-319, doi:10.1080/21632324.2019.1589073.
Singh, C. et al., 2021a: Interrogating 'effectiveness' in climate change adaptation: 11 guiding principles for adaptation research and practice. *Climate and Development*, 1-15, doi:10.1080/17565529.2021.1964937.
Singh, C., D. Solomon and N. Rao, 2021b: How does climate change adaptation policy in India consider gender? An analysis of 28 state action plans. *Climate Policy*, **21**(7), 958-975, doi:10.1080/14693062.2021.1953434.
Sitas, N. et al., 2019: Exploring the usefulness of scenario archetypes in science-policy processes: experience across IPBES assessments. *Ecology and Society*, **24**(3), doi:10.5751/ES-11039-240335.
Sitas, N., O. Selomane, M. Hamann and S. P. S. Gajjar, 2021: Towards Equitable Urban Resilience in the Global South Within a Context of Planning and Management. In: *Urban Ecology in the Global South* [Shackleton, C. M., S. S. Cilliers, E. Davoren and M. J. du Toit (eds.)]. Springer International Publishing, Cham, pp. 325-345. ISBN 978-3-030-67650-6.
Slaven, M. and J. Heydon, 2020: Crisis, deliberation, and Extinction Rebellion. *Critical Studies on Security*, **8**(1), 59-62.
Slee, B., 2015: Is there a case for community-based equity participation in Scottish on-shore wind energy production? Gaps in evidence and research needs. *Renewable and Sustainable Energy Reviews*, **41**, 540-549.
Sloat, L. L. et al., 2020: Climate adaptation by crop migration. *Nature Communications*, **11**(1), 1243, doi:10.1038/s41467-020-15076-4.
Smit, B. et al., 2001: Adaptation to Climate Change in the Context of Sustainable Development and Equity. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 877-912. ISBN 0521807689.
Smith, A. and A. Stirling, 2018: INNOVATION, SUSTAINABILITY AND DEMOCRACY: AN ANALYSIS OF GRASSROOTS CONTRIBUTIONS. *J. Self-Gov. Manag. Econ.*, **6**(1), 64, doi:10.22381/JSME6120183.

Smith, L. T., 2013: *Decolonizing methodologies: Research and indigenous peoples*. Zed Books Ltd.
Smith, P. et al., 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, **19**(8), 2285-2302, doi:10.1111/gcb.12160.
Smith, R. and K. McNamara, 2015: Future migrations from Tuvalu and Kiribati: exploring government, civil society and donor perceptions. *Climate and Development*, **7**, doi:10.1080/17565529.2014.900603.
Smucker, T. A. et al., 2015: Differentiated livelihoods, local institutions, and the adaptation imperative: Assessing climate change adaptation policy in Tanzania. *Geoforum*, **59**, 39–50.
Söderholm, P. and J. E. Tilton, 2012: Material efficiency: An economic perspective. *Resources, Conservation and Recycling*, **61**, 75-82, doi:10.1016/j.resconrec.2012.01.003.
Soga, M. and K. J. Gaston, 2016: Extinction of experience: the loss of human–nature interactions. *Frontiers in Ecology and the Environment*, **14**(2), 94-101, doi:10.1002/fee.1225.
Solecki, W., M. Pelling and M. Garschagen, 2017: Transitions between risk management regimes in cities. *Ecology and Society*, **22**, 38, doi:10.5751/ES-09102-220238.
Solecki, W. et al., 2018: City transformations in a 1.5 °C warmer world. *Nature Climate Change*, **8**(3), 177-181, doi:10.1038/s41558-018-0101-5.
Soma, K. et al., 2018: Social innovation – A future pathway for Blue growth? *Marine Policy*, **87**, 363-370, doi:10.1016/j.marpol.2017.10.008.
Song, L. et al., 2020a: Contested energy futures, conflicted rewards? Examining low-carbon transition risks and governance dynamics in China's built environment. *Energy Research & Social Science*, **59**, 101306, doi:https://doi.org/10.1016/j.erss.2019.101306.
Song, S., Z. Liu, C. He and W. Lu, 2020b: Evaluating the effects of urban expansion on natural habitat quality by coupling localized shared socioeconomic pathways and the land use scenario dynamics-urban model. *Ecological Indicators*, **112**, 106071, doi:https://doi.org/10.1016/j.ecolind.2020.106071.
Sørensen, E. and J. Torfing, 2019: Designing institutional platforms and arenas for interactive political leadership. *Public Management Review*, **21**(10), 1443-1463, doi:10.1080/14719037.2018.1559342.
Sovacool, B. K., 2018: Bamboo Beating Bandits: Conflict, Inequality, and Vulnerability in the Political Ecology of Climate Change Adaptation in Bangladesh. *World Development*, **102**, 183-194, doi:10.1016/j.worlddev.2017.10.014.
Sovacool, B. K. et al., 2015: The political economy of climate adaptation. *Nature Climate Change*, **5**(7), 616–618.
Sovacool, B. K., M. Tan-Mullins, D. Ockwell and P. Newell, 2017: Political economy, poverty, and polycentrism in the Global Environment Facility's Least Developed Countries Fund (LDCF) for Climate Change Adaptation. *Third World Quarterly*, **38**(6), 1249-1271, doi:10.1080/01436597.2017.1282816.
Srivastava, A., R. Sharma and A. Suresh, 2020: Impact of Covid-19 on Sustainable Development Goals. **29**, 4968-4972.
Stafford-Smith, M. et al., 2017: Integration: the key to implementing the Sustainable Development Goals. *Sustainability Science*, **12**(6), 911-919, doi:10.1007/s11625-016-0383-3.
Stańczuk-Gałwiaczek, M., K. Sobolewska-Mikulska, H. Ritzema and J. M. van Loon-Steensma, 2018: Integration of water management and land consolidation in rural areas to adapt to climate change: Experiences from Poland and the Netherlands. *Land Use Policy*, **77**, 498-511, doi:10.1016/j.landusepol.2018.06.005.
Starbird, E., M. Norton and R. Marcus, 2016: Investing in Family Planning: Key to Achieving the Sustainable Development Goals. *Global Health: Science and Practice*, **4**(2), 191-210, doi:10.9745/GHSP-D-15-00374.
Steelman, T. A. et al., 2019: Identifying transformational space for transdisciplinarity: using art to access the hidden third. *Sustainability Science*, **14**(3), 771-790, doi:10.1007/s11625-018-0644-4.
Steffen, B., 2018: The importance of project finance for renewable energy projects. *Energy Economics*, **69**, 280-294, doi:10.1016/j.eneco.2017.11.006.
Stein, S. and M. Kalina, 2019: Becoming an Agricultural Growth Corridor. *Environment and Society*, **10**(1), 83-100.
Sterk, M., I. A. van de Leemput and E. T. Peeters, 2017: How to conceptualize and operationalize resilience in socio-ecological systems? *Current Opinion in Environmental Sustainability*, **28**, 108-113, doi:10.1016/j.cosust.2017.09.003.
Stern, N., 2007: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge. ISBN 978-0-511-81743-4.
Stevenson, K. T. et al., 2014: Overcoming skepticism with education: interacting influences of worldview and climate change knowledge on perceived climate change risk among adolescents. *Climatic Change*, **126**(3), 293-304, doi:10.1007/s10584-014-1228-7.
Stiglitz, J. E., A. Sen and J.-P. Fitoussi, 2009: Report by the commission on the measurement of economic performance and social progress. Citeseer.
Stjepanović, S., D. Tomic and M. Skare, 2017: A new approach to measuring green GDP: a cross-country analysis. *ENTREPRENEURSHIP AND SUSTAINABILITY ISSUES*, **4**, 574-590, doi:10.9770/jesi.2017.4.4(13).
Stjepanović, S., D. Tomic and M. Skare, 2019: Green GDP: an analysis for developing and developed countries. *E+M Ekonomie a Management*, **22**, 4-17, doi:10.15240/tul/001/2019-4-001.
Stoddard, I. et al., 2021: Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? *Annual Review of Environment and Resources*, doi:10.1146/annurev-environ-012220-011104.
Strazds, L., 2019: Radical hope: Transforming sustainability « Journal of Sustainability Education. *Journal of Sustainability Education*.

Sugden, F. et al., 2014: Agrarian stress and climate change in the Eastern Gangetic Plains: Gendered vulnerability in a stratified social formation. *Global Environmental Change*, **29**, 258-269, doi:10.1016/j.gloenvcha.2014.10.008.
Sultana, F., 2010: Living in hazardous waterscapes: Gendered vulnerabilities and experiences of floods and disasters. *Environmental Hazards*, **9**(1), 43-53, doi:10.3763/ehaz.2010.SI02.
Sultana, F., 2021: Climate change, COVID-19, and the co-production of injustices: a feminist reading of overlapping crises. *Social & Cultural Geography*, **22**(4), 447-460, doi:10.1080/14649365.2021.1910994.
Sultana, P. et al., 2019: Transforming local natural resource conflicts to cooperation in a changing climate: Bangladesh and Nepal lessons. *Climate Policy*, **19**(sup1), S94-S106, doi:10.1080/14693062.2018.1527678.
Susan Solomon, D., C. Singh and F. Islam, 2021: Examining the outcomes of urban adaptation interventions on gender equality using SDG 5. *Climate and Development*, **0**(0), 1-12, doi:10.1080/17565529.2021.1939643.
Susskind, L. et al., 2020: Breaking Out of Carbon Lock-In: Malaysia's Path to Decarbonization. *Frontiers in Built Environment*, **6**, 21, doi:10.3389/fbuil.2020.00021.
Swaffield, J., 2017: Freebies, freedom and fundamental change: resistance to neoliberal environmentalism in large "green" corporations. *Local Environment*, **22**(5), 553-567, doi:10.1080/13549839.2016.1233952.
Swatuk, L. A. et al., 2021: The 'boomerang effect': insights for improved climate action. *Climate and Development*, **13**(1), 61-67, doi:10.1080/17565529.2020.1723470.
Swyngedouw, E., 2018: *Promises of the Political: Insurgent Cities in a Post-Political Environment*. The MIT Press, Cambridge, Massachusetts, 232 pp. ISBN 978-0-262-53565-6.
Swyngedouw, E., 2019: The Perverse Lure of Autocratic Postdemocracy. *South Atlantic Quarterly*, **118**(2), 267-286, doi:10.1215/00382876-7381134.
Tan, R. R. and D. C. Y. Foo, 2018: Integrated multi-scale water management as a climate change adaptation strategy. *Clean Technologies and Environmental Policy*, **20**(6), 1123-1125, doi:10.1007/s10098-018-1551-1.
Tanaka, K., 2011: Review of policies and measures for energy efficiency in industry sector. *Energy Policy*, **39**(10), 6532-6550, doi:10.1016/j.enpol.2011.07.058.
Tanner, T. and J. Allouche, 2011: Towards a New Political Economy of Climate Change and Development. *IDS Bulletin*, **42**(3), 1-14, doi:https://doi.org/10.1111/j.1759-5436.2011.00217.x.
Tanner, T. et al., 2019: Influencing resilience: the role of policy entrepreneurs in mainstreaming climate adaptation. *Disasters*, **43**(S3), S388-S411, doi:10.1111/disa.12338.
Tari, D. and J. Pattison, 2014: *Evolving Customary Institutions in the Drylands An opportunity for devolved natural resource governance in Kenya ?* ISBN 978-1-78431-042-4.
Tauginienė, L. et al., 2020: Citizen science in the social sciences and humanities: the power of interdisciplinarity. *Palgrave Communications*, **6**(1), 1-11, doi:10.1057/s41599-020-0471-y.
Taylor, M., 2008: Beyond technology-push and demand-pull: Lessons from California's solar policy. *Energy Economics*, **30**(6), 2829-2854, doi:10.1016/j.eneco.2008.06.004.
Temmer, J., 2017a: *Building a Climate-Resilient City: Agriculture and food security*. IISD. Available at: http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-climate-resilient-city-agriculture-food.pdf.
Temmer, J., 2017b: *Building a Climate-Resilient City: Disaster preparedness and emergency management*. IISD. Available at: http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-disaster-mangement-emergency-preparedness.pdf.
Tengö, M. et al., 2017: Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. *Current Opinion in Environmental Sustainability*, **26-27**, 17-25, doi:10.1016/j.cosust.2016.12.005.
Terry, G., 2009: No climate justice without gender justice: an overview of the issues. *Gender & Development*, **17**(1), 5-18, doi:10.1080/13552070802696839.
Terton, A., 2017: *Building a Climate-Resilient City: Urban ecosystems*. IISD. Available at: http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-climate-resilient-city-urban-ecosystems.pdf.
Thackeray, S. J. et al., 2020: Civil disobedience movements such as School Strike for the Climate are raising public awareness of the climate change emergency. *Global Change Biology*, **26**(3), 1042-1044.
The People's Republic of China, 2017: *Vision for Maritime Cooperation under the Belt and Road Initiative*.
Thew, H., L. Middlemiss and J. Paavola, 2020: "Youth is not a political position": Exploring justice claims-making in the UN Climate Change Negotiations. *Global Environmental Change*, **61**, 102036.
Thomas, B. K., 2008: Methodological debate in poverty studies: towards 'participatory qual–quant'? *Development in Practice*, **18**(2), 280-288, doi:10.1080/09614520801899218.
Thompson-Hall, M., E. R. Carr and U. Pascual, 2016: Enhancing and expanding intersectional research for climate change adaptation in agrarian settings. *Ambio*, **45**(3), 373-382, doi:10.1007/s13280-016-0827-0.
Tilleard, S. and J. Ford, 2016: Adaptation readiness and adaptive capacity of transboundary river basins. *Climatic Change*, **137**(3-4), 575-591.
Tobias J.K, R. C. A., 2014: "That land means everything to us as Anishinaabe….": Environmental dispossession and resilience on the North Shore of Lake Superior. *Health Place*, **29**, 26-33, doi:10.1016/j.healthplace.2014.05.008.
Tolliver, C., A. R. Keeley and S. Managi, 2019: Green bonds for the Paris agreement and sustainable development goals. *Environmental Research Letters*, **14**(6), 064009, doi:10.1088/1748-9326/ab1118.
Törnberg, A., 2018: Combining transition studies and social movement theory: towards a new research agenda. *Theor Soc*, **47**(3), 381-408, doi:10.1007/s11186-018-9318-6.

Tramel, S., 2018: Convergence as political strategy: social justice movements, natural resources and climate change. *Third World Quarterly*, **39**(7), 1290-1307, doi:10.1080/01436597.2018.1460196.
Tramutola, M. J., 2019: *Adpatación al Cambio Climático ¿Con Perspectiva de Género?*, LatinoAdapta. Available at: http://www.cambioclimaticoydecisiones.org/wp-content/uploads/2019/08/PolicyBrief-Genero_5_09_2019.pdf.
Trewin, D. and J. Hall, 2004: Measures of Australia's progress: key economic, social and environment indicators. *OECD Observer*,(246-247), 35-37.
Tschakert, P. et al., 2016: TCHANGE: the role of values and visioning in transformation science. *Current Opinion in Environmental Sustainability*, **20**, 21-25, doi:10.1016/j.cosust.2016.04.003.
Tufa, F., A. Amsalu and E. B. Zoomers, 2018: Failed promises: governance regimes and conflict transformation related to Jatropha cultivation in Ethiopia. *Ecology and Society*, **23**(4), doi:10.5751/ES-10486-230426.
Turnhout, E. et al., 2021: Enabling transformative economic change in the post-2020 biodiversity agenda. *Conservation Letters*, **14**(4), e12805, doi:10.1111/conl.12805.
TWI, 2019: *TWI2050 Report: The Digital Revolution and Sustainable Development: Opportunities and Challenges*. Available at: https://iiasa.ac.at/web/home/research/twi/Report2019.html.
Ullah, I., H. Fang and K. Jebran, 2019: Do gender diversity and CEO gender enhance firm's value? Evidence from an emerging economy. *Corporate Governance: The International Journal of Business in Society*, **20**(1), 44-66, doi:10.1108/CG-03-2019-0085.
UNDRR, 2015: *Sendai Framework for Disaster Risk Reduction 2015–2030*. United Nations International Strategy for Disaster Reduction, Geneva, Switzerland.
Undrr, 2019: *Global Assessment Report on Disaster Risk Reduction*. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland.
UNEP, 2014: *Adaptation Gap Report 2014*.
UNEP, 2018a: *Adaptation Gap Report 2018*.
UNEP, 2018b: *Single-Use Plastics: A Roadmap for Sustainability*. Available at: https://www.unenvironment.org/resources/report/single-use-plastics-roadmap-sustainability.
UNEP, 2021: *Adaptation Gap Report 2020*.
UNESCO, 2019: Resilience in a Time of Uncertainty: Indigenous peoples and climate change. Available at: https://en.unesco.org/events/resilience-time-uncertainty-indigenous-peoples-and-climate-change.
UNESCO, 2018: What is Local and Indigenous Knowledge | United Nations Educational, Scientific and Cultural Organization.
UNFCCC, 1992: *United Nations Framework Convention on Climate Change*. Available at: https://unfccc.int/resource/docs/convkp/conveng.pdf.
UNFCCC, 2010: *Cancún Climate Change Conference*.
UNFCCC, 2011: *Launching the Green Climate Fund*. Available at: https://unfccc.int/resource/docs/2011/cop17/eng/09a01.pdf#page=55.
UNFCCC, 2015: Paris Agreement. United Nations Framework Convention on Climate Change, United Nations.
UNFCCC, 2017: *The China Clean Development Mechanism Fund (CCDMF)*.
United Nations, 2007: *United Nations Declaration on the Rights of Indigenous Peoples*. United Nations, New York. Available at: https://www.un.org/development/desa/indigenouspeoples/wp-content/uploads/sites/19/2018/11/UNDRIP_E_web.pdf.
United Nations, 2015: *Transforming our world: the 2030 Agenda for Sustainable Development*. United Nations. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld.
United Nations, 2020: *Human Development Report 2020. The Next Frontier: Human Development and the Anthropocene*. United Nations Development Programme.
United Nations, 2021: *The Sustainable Development Goals Report*. Department of Economic and Social Affairs, United Nations, New York, N.Y.
United Nations Environment Programme, 2021: *Adaptation Gap Report 2020*. United Nations Environment Programme, Programme, U. N. E., Nairobi, Kenya, 99 pp. Available at: https://www.unep.org/adaptation-gap-report-2020.
Ura, K. and K. Galay, 2004: *Gross National Happiness and Development*.
USAID, 2014: *Climate-resilient development a framework for understanding and addressing climate change*. Available at: https://pdf.usaid.gov/pdf_docs/PBAAA245.pdf.
USAID, 2018: Climate Risk Profile: Kenya.
USEPA, 2019: Global Greenhouse Gas Emissions Data.
USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart and T. K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp.
Vaghefi, N., C. Siwar and S. Aziz, 2015: Green GDP and Sustainable Development in Malaysia. *Current World Environment*, **10**(1), 01-08.
Valta, J., 2020: Innovation Ecosystem Perspective Accelerating Sustainable Business Models. In: *Affordable and Clean Energy* [Leal Filho, W., A. M. Azul, L. Brandli, P. G. Özuyar and T. Wall (eds.)]. Springer International Publishing, Cham, pp. 1-11. ISBN 978-3-319-71057-0.

van Baalen, S. and M. Mobjörk, 2018: Climate Change and Violent Conflict in East Africa: Integrating Qualitative and Quantitative Research to Probe the Mechanisms. *International Studies Review*, **20**(4), 547-575, doi:10.1093/isr/vix043.
Van den Bergh, J. C., 2007: Abolishing GDP.
van Dooren, C. et al., 2018: Unsustainable dietary habits of specific subgroups require dedicated transition strategies: Evidence from the Netherlands. *Food Policy*, **79**, 44-57, doi:10.1016/j.foodpol.2018.05.002.
van Egmond, N. D. and H. J. M. de Vries, 2011: Sustainability: The search for the integral worldview. *Futures*, **43**(8), 853-867, doi:10.1016/j.futures.2011.05.027.
Van Opstal, M. and J. Hugé, 2013: Knowledge for sustainable development: a worldviews perspective. *Environ Dev Sustain*, **15**(3), 687-709, doi:10.1007/s10668-012-9401-5.
van Puijenbroek, P. J. T. M., A. F. Bouwman, A. H. W. Beusen and P. L. Lucas, 2014: Global implementation of two shared socioeconomic pathways for future sanitation and wastewater flows. *Water Science and Technology*, **71**(2), 227-233, doi:10.2166/wst.2014.498.
van Ruijven, B. J. et al., 2014: Enhancing the relevance of Shared Socioeconomic Pathways for climate change impacts, adaptation and vulnerability research. *Climatic Change*, **122**(3), 481-494, doi:10.1007/s10584-013-0931-0.
Van Vuuren, D. P. et al., 2019: Integrated scenarios to support analysis of the food–energy–water nexus. *Nature Sustainability*, **2**(12), 1132-1141, doi:10.1038/s41893-019-0418-8.
Vander Stichele, M., 2020: The Financialised Firm.
Veland, S., I. Gram-Hanssen, D. Maggs and A. H. Lynch, 2021: Can the sustainable development goals harness the means and the manner of transformation? *Sustainability Science*, doi:10.1007/s11625-021-01032-8.
Venema, H. and J. Temmer, 2017a: *Building a Climate-Resilient City: Electricity and information and communication technology infrastructure*. IISD. Available at: http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-climate-resilient-city-electricity-ict.pdf.
Venema, H. and J. Temmer, 2017b: *Building a Climate-Resilient City: Water supply and sanitation systems*. IISD. Available at: http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-climate-resilient-city-water-supply-sanitation.pdf.
Verkerk, P. J. et al., 2020: Climate-Smart Forestry: the missing link. *Forest Policy and Economics*, **115**, 102164, doi:10.1016/j.forpol.2020.102164.
Vermeulen, S. J. et al., 2018: Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change. *Frontiers in Sustainable Food Systems*, **2**, doi:10.3389/fsufs.2018.00065.
Vihemäki, H., A. Toppinen and R. Toivonen, 2020: Intermediaries to accelerate the diffusion of wooden multi-storey construction in Finland. *Environmental Innovation and Societal Transitions*, **36**, 433-448, doi:https://doi.org/10.1016/j.eist.2020.04.002.
Villamayor-Tomas, S. and G. García-López, 2018: Social movements as key actors in governing the commons: Evidence from community-based resource management cases across the world. *Global Environmental Change*, **53**, 114-126, doi:10.1016/j.gloenvcha.2018.09.005.
Vincent, K. and W. Colenbrander, 2018: Developing and applying a five step process for mainstreaming climate change into local development plans: A case study from Zambia. *Climate Risk Management*, **21**, 26-38, doi:10.1016/j.crm.2018.04.005.
Vinyeta, K., K. Whyte and K. Lynn, 2016: *Climate Change Through an Intersectional Lens: Gendered Vulnerability and Resilience in Indigenous Communities in the United States*. Social Science Research Network, Rochester, NY. Available at: https://papers.ssrn.com/abstract=2770089
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2770089 (accessed 2020/11/07/22:45:13).
Visseren-Hamakers, I. J. et al., 2021: Transformative governance of biodiversity: insights for sustainable development. *Current Opinion in Environmental Sustainability*, **53**, 20-28, doi:10.1016/j.cosust.2021.06.002.
Visvizi, A., M. D. Lytras, E. Damiani and H. Mathkour, 2018: Policy making for smart cities: innovation and social inclusive economic growth for sustainability. *Journal of Science and Technology Policy Management*, **9**(2), 126-133, doi:10.1108/JSTPM-07-2018-079.
Vogel, C. and K. O'Brien, 2021: Getting to the heart of transformation. *Sustainability Science*, doi:10.1007/s11625-021-01016-8.
Vogl, V., M. Åhman and L. J. Nilsson, 2018: Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, **203**, 736-745, doi:10.1016/j.jclepro.2018.08.279.
von Stechow, C. et al., 2016: 2°C and SDGs: united they stand, divided they fall? *Environmental Research Letters*, **11**(3), e034022.
von Uexkull, N. and H. Buhaug, 2021: Security implications of climate change: A decade of scientific progress. *Journal of Peace Research*, **58**(1), 3-17, doi:10.1177/0022343320984210.
Wada, Y. et al., 2016: Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. *Geosci. Model Dev.*, **9**(1), 175-222, doi:10.5194/gmd-9-175-2016.
Waddock, S., 2019: Shaping the Shift: Shamanic Leadership, Memes, and Transformation. *J Bus Ethics*, **155**(4), 931-939, doi:10.1007/s10551-018-3900-8.
Walch, C., 2019: Adaptive governance in the developing world: disaster risk reduction in the State of Odisha, India. *Climate and Development*, **11**(3), 238-252, doi:10.1080/17565529.2018.1442794.

Waldherr, A., 2012: The Mass Media as Actors in Innovation Systems. In: *Innovation Policy and Governance in High-Tech Industries* [Bauer, J., A. Lang and V. Schneider (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 77-100. ISBN 978-3-642-12562-1 978-3-642-12563-8.
Walsh, C., 2018: 9. Development as Buen Vivir: Institutional Arrangements and (De)Colonial Entanglements. In: *Constructing the Pluriverse: The Geopolitics of Knowledge*. Duke University Press, pp. 184-194. ISBN 978-1-4780-0201-7.
Walsh, J. H. and J. Dillard-Wright, 2020: The case for "structural missingness:" A critical discourse of missed care. *Nursing Philosophy*, **21**(1), e12279, doi:10.1111/nup.12279.
Walshe, R. and A. G. Argumedo, 25 , 166-173, doi:10.14512/gaia.25.3.7., 2016: Ayni, Ayllu, Yanantin and Chanincha: The Cultural Values Enabling Adaptation to Climate Change in Communities of the Potato Park, in the Peruvian Andes. *GAIA - Ecological Perspectives for Science and Society*, **25**(3), 166-173, doi:https://doi.org/10.14512/gaia.25.3.7.
Wamsler, C., 2019: Contemplative Sustainable Futures: The Role of Individual Inner Dimensions and Transformation in Sustainability Research and Education. In: *Sustainability and the Humanities* [Leal Filho, W. and A. Consorte McCrea (eds.)]. Springer International Publishing, Cham, pp. 359-373. ISBN 978-3-319-95336-6.
Wamsler, C. and E. Brink, 2018: Mindsets for Sustainability: Exploring the Link Between Mindfulness and Sustainable Climate Adaptation. *Ecological Economics*, **151**, 55-61, doi:10.1016/j.ecolecon.2018.04.029.
Wang, F., R. Wang and J. Wang, 2020: Measurement of China's green GDP and its dynamic variation based on industrial perspective. *Environmental Science and Pollution Research*.
Wang, Y. et al., 2019: Tens of thousands additional deaths annually in cities of China between 1.5 °C and 2.0 °C warming. *Nature Communications*, **10**(1), 3376, doi:10.1038/s41467-019-11283-w.
Washington-Ottombre, C. and B. C. Pijanowski, 2013: Rural organizations and adaptation to climate change and variability in rural Kenya. *Regional Environmental Change*, **13**(3), 537-550.
Washington, H. and P. Twomey (eds.), 2016: *A Future Beyond Growth: Towards a steady state economy*, 1st edition ed., Routledge, 282 pp.
Watson, E. E., H. H. Kochore and B. H. Dabasso, 2016: Camels and Climate Resilience: Adaptation in Northern Kenya. *Human Ecology*, **44**(6), 701-713.
Watts, N. et al., 2019: The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *The Lancet*, **394**, doi:10.1016/S0140-6736(19)32596-6.
Webb, R. et al., 2018: Sustainable urban systems: Co-design and framing for transformation. *Ambio*, **47**(1), 57-77, doi:10.1007/s13280-017-0934-6.
Webber, S., 2016: Climate Change Adaptation as a Growing Development Priority: Towards Critical Adaptation Scholarship. *Geography Compass*, **10**(10), 401-413, doi:10.1111/gec3.12278.
Webber, S. and S. D. Donner, 2017: Climate service warnings: cautions about commercializing climate science for adaptation in the developing world. *WIREs Climate Change*, **8**(1), e424, doi:10.1002/wcc.424.
Weir, T., 2018: Renewable energy in the Pacific Islands: Its role and status. *Renewable and Sustainable Energy Reviews*, **94**, 762-771, doi:10.1016/j.rser.2018.05.069.
Weir, T. and M. Kumar, 2020: Renewable energy can enhance resilience of small islands. *Natural Hazards*, **104**(3), 2719-2725, doi:10.1007/s11069-020-04266-4.
Welch, D. and L. Yates, 2018: The practices of collective action: Practice theory, sustainability transitions and social change. *Journal for the Theory of Social Behaviour*, **48**(3), 288-305, doi:10.1111/jtsb.12168.
Wells, P., W. Abouarghoub, S. Pettit and A. Beresford, 2020: A socio-technical transitions perspective for assessing future sustainability following the COVID-19 pandemic. *Sustainability: Science, Practice and Policy*, **16**(1), 29-36, doi:10.1080/15487733.2020.1763002.
Werners, S. E. et al., 2018: *Towards climate-resilient development pathways for the people in the Hindu Kush Himalayan region*. HI-AWARE, Kathmandu.
Werners, S. E. et al., 2021: Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, **116**, 266-275, doi:10.1016/j.envsci.2020.11.003.
Westholm, L. and S. Arora-Jonsson, 2015: Defining Solutions, Finding Problems: Deforestation, Gender, and REDD+ in Burkina Faso. *Conservation and Society*, **13**(2), 189-199.
Westholm, L. and S. Arora-Jonsson, 2018: What room for politics and change in global climate governance? Addressing gender in co-benefits and safeguards. *Environmental Politics*, **27**(5), 917-938, doi:10.1080/09644016.2018.1479115.
Westley, F. et al., 2011: Tipping Toward Sustainability: Emerging Pathways of Transformation. *AMBIO*, **40**(7), 762, doi:10.1007/s13280-011-0186-9.
Westwell, E. and J. Bunting, 2020: The regenerative culture of Extinction Rebellion: self-care, people care, planet care. *Environmental Politics*, **29**(3), 546-551.
Weyant, J. and E. Kriegler, 2014: Preface and introduction to EMF 27. *Climatic Change*, **123**(3), 345-352, doi:10.1007/s10584-014-1102-7.
White, D., 2020: Just Transitions/Design for Transitions: Preliminary Notes on a Design Politics for a Green New Deal. *Capitalism Nature Socialism*, **31**(2), 20-39, doi:10.1080/10455752.2019.1583762.
WHO, 2016: *Climate And Health Country Profile – 2015: Kenya*. World Health Organisation.

Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10**(8), 085010, doi:10.1088/1748-9326/10/8/085010.
Wieczorek, A. J., 2018: Sustainability transitions in developing countries: Major insights and their implications for research and policy. *Environmental Science & Policy*, **84**, 204-216, doi:10.1016/j.envsci.2017.08.008.
Wijsman, K. and M. Feagan, 2019: Rethinking knowledge systems for urban resilience: Feminist and decolonial contributions to just transformations. *Environmental Science & Policy*, **98**, 70-76, doi:10.1016/j.envsci.2019.04.017.
Wilhelmi, O. V., P. D. Howe, M. H. Hayden and C. R. O'Lenick, 2021: Compounding hazards and intersecting vulnerabilities: experiences and responses to extreme heat during COVID-19. *Environmental Research Letters*, **16**(8), 084060, doi:10.1088/1748-9326/ac1760.
Williams, A., J. Dickman and R. Smurthwaite, 2021: Advancing Evaluation and Learning on Transformational Change: Lessons From the Climate Investment Funds' Transformational Change Learning Partnership. *American Journal of Evaluation*, **42**(1), 90-109, doi:10.1177/1098214020970283.
Wilson, N. J. et al., 2019: Water is Medicine: Reimagining Water Security through Tr'ondëk Hwëch'in Relationships to Treated and Traditional Water Sources in Yukon, Canada. *Water*, **11**(3), 624, doi:10.3390/w11030624.
Wilson, N. J. and J. Inkster, 2018: Respecting water: Indigenous water governance, ontologies, and the politics of kinship on the ground. *Environment and Planning E: Nature and Space*, doi:10.1177/2514848618789378.
Winkler, H., A. Boyd, M. Torres Gunfaus and S. Raubenheimer, 2015: Reconsidering development by reflecting on climate change. *International Environmental Agreements: Politics, Law and Economics*, **15**(4), 369-385, doi:10.1007/s10784-015-9304-7.
Winkler, H. and N. K. Dubash, 2016: Who determines transformational change in development and climate finance? *Climate Policy*, **16**(6), 783-791, doi:10.1080/14693062.2015.1033674.
Winterfeldt, D. v., 2013: Bridging the gap between science and decision making. *Proceedings of the National Academy of Sciences*, **110**(Supplement 3), 14055-14061, doi:10.1073/pnas.1213532110.
Wise, R. M. et al., 2016: How climate compatible are livelihood adaptation strategies and development programs in rural Indonesia? *Climate Risk Management*, **12**, 100-114, doi:10.1016/j.crm.2015.11.001.
Woiwode, C., 2020: Inner Transformation for 21st-Century Futures: The Missing Dimension in Higher Education. *Environment: Science and Policy for Sustainable Development*, **62**(4), 30-38, doi:10.1080/00139157.2020.1764299.
Wood, B. T., 2017: Socially just triple-wins? An evaluation of projects that pursue climate compatible development goals in Malawi. University of Leeds.
Wood, B. T., C. H. Quinn, L. C. Stringer and A. J. Dougill, 2017: Investigating Climate Compatible Development Outcomes and their Implications for Distributive Justice: Evidence from Malawi. *Environmental Management*, **60**(3), 436–453.
World Bank, 2000: *World Development Report 2000/2001: Attacking Poverty*. World Bank Group. Available at: https://openknowledge.worldbank.org/handle/10986/11856.
World Bank, 2017: *Climate Vulnerability Assessment: Making Fiji Climate Resistent*. Washington, DC, USA.
World Bank, 2021: GINI Index. *The World Development Indicators (WDI)* [Bank, W. (ed.)], Washington, DC.
World Bank, G., 2019: *Using Carbon Revenues*. Available at: https://openknowledge.worldbank.org/handle/10986/32247.
World Commission on Environment and Development, 1987: *Our Common Future*. Oxford University Press.
World Economic Forum, 2019: *Innovate Europe: Competing for Global Innovation Leadership*.
Woroniecki, S., 2019: Enabling Environments? Examining Social Co-Benefits of Ecosystem-Based Adaptation to Climate Change in Sri Lanka. *Sustainability*, **11**(3), 772, doi:10.3390/su11030772.
Worrell, E., J. Allwood and T. Gutowski, 2016: The Role of Material Efficiency in Environmental Stewardship. *Annual Review of Environment and Resources*, **41**(1), 575-598, doi:10.1146/annurev-environ-110615-085737.
Xu, T., 2018: Investigating Environmental Kuznets Curve in China–Aggregation bias and policy implications. *Energy Policy*, **114**, 315-322, doi:10.1016/j.enpol.2017.12.027.
Xu, Y. and V. Ramanathan, 2017: Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proceedings of the National Academy of Sciences*, **114**(39), 10315-10323, doi:10.1073/pnas.1618481114.
Xue, W. et al., 2016: Cultural worldviews and climate change: A view from China. *Asian Journal of Social Psychology*, **19**(2), 134-144, doi:10.1111/ajsp.12116.
Yadav, S. S. and R. Lal, 2018: Vulnerability of women to climate change in arid and semi-arid regions: The case of India and South Asia. *Journal of Arid Environments*, **149**, 4-17, doi:10.1016/j.jaridenv.2017.08.001.
Yalew, A. W., 2020: Climate-Resilient Development. In: *Economic Development under Climate Change : Economy-Wide and Regional Analysis for Ethiopia* [Yalew, A. W. (ed.)]. Springer Fachmedien, Wiesbaden, pp. 99-108. ISBN 978-3-658-29413-7.
Yao, M. et al., 2017: Building regional water-use scenarios consistent with global shared socioeconomic pathways. *Environmental Processes*, **4**(1), 15-31.
Yohe, G. W. et al., 2007: Perspectives on climate change and sustainability. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden

and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 811-841. ISBN 9780521880107.
Young, I. M., 2003: *Political Responsibility and Structural Injustice*. University of Kansas, Department of Philosophy.
Yu, Y. et al., 2019: National Green GDP Assessment and Prediction for China Based on a CA-Markov Land Use Simulation Model. *Sustainability*, **11**(3), 576.
Yunkaporta, T., 2019: *Sand Talk: How Indigenous thinking can save the world*. Text Publishing, Melbourne.
Yurdakul, M. and H. Kazan, 2020: Effects of Eco-Innovation on Economic and Environmental Performance: Evidence from Turkey's Manufacturing Companies. *Sustainability*, **12**(8), 3167, doi:10.3390/su12083167.
Zaman, F., 2021: The role of popular discourse about climate change in disaster preparedness: A critical discourse analysis. *International Journal of Disaster Risk Reduction*, **60**, 102270, doi:https://doi.org/10.1016/j.ijdrr.2021.102270.
Zambia, R. o. and IUCN, 2017: *Climate Change Gender Action Plan of The Republic of Zambia*. International Union for Conservation of Nature Global Gender Office (IUCN GGO) (accessed 2019-09-24).
Zavaleta, C. et al., 2018: Multiple non-climatic drivers of food insecurity reinforce climate change maladaptation trajectories among Peruvian Indigenous Shawi in the Amazon. *PLoS One*, **13**(10), e0205714, doi:10.1371/journal.pone.0205714.
Ziervogel, G., 2019: Building transformative capacity for adaptation planning and implementation that works for the urban poor: Insights from South Africa. *Ambio*, **48**(5), 494-506, doi:10.1007/s13280-018-1141-9.
Ziervogel, G., E. Archer van Garderen and P. Price, 2016a: Strengthening the knowledge–policy interface through co-production of a climate adaptation plan: leveraging opportunities in Bergrivier Municipality, South Africa. *Environment and Urbanization*, **28**(2), 455-474.
Ziervogel, G., A. Cowen and J. Ziniades, 2016b: Moving from Adaptive to Transformative Capacity: Building Foundations for Inclusive, Thriving, and Regenerative Urban Settlements. *Sustainability*, **8**(9), 955, doi:10.3390/su8090955.
Ziervogel, G., J. Enqvist, L. Metelerkamp and J. van Breda, 2021: Supporting transformative climate adaptation: community-level capacity building and knowledge co-creation in South Africa. *Climate Policy*, **0**(0), 1-16, doi:10.1080/14693062.2020.1863180.
Zinsstag, J. et al., 2018: Climate change and One Health. *FEMS Microbiol Lett*, **365**(11), doi:10.1093/femsle/fny085.
Zivkovic, S., 2018: Systemic Innovation Labs: A lab for wicked problems. *Social Enterprise Journal*.
Zummo, L., B. Donovan and K. C. Busch, 2020: Complex influences of mechanistic knowledge, worldview, and quantitative reasoning on climate change discourse: Evidence for ideologically motivated reasoning among youth. *Journal of Research in Science Teaching*, doi:10.1002/tea.21648.

[START CROSS-CHAPTER BOX FEASIB HERE]

Cross-Chapter Box FEASIB: Feasibility Assessment of Adaptation Options: An Update of the SR1.5

Authors: Debora Ley (Guatemala/Mexico), Helen Adams (United Kingdom), Malcolm Araos (Canada/USA), Ritwika Basu (India/United Kingdom), Amir Bazaz (India), Luigi Conte (Italy), Katy Davis (United Kingdom), Constantino Dockendorff (Chile/Germany), James Ford (United Kingdom/Canada), Sabine Fuss (Germany), Elisabeth A Gilmore (USA/Canada), Tania Guillén Bolaños (Nicaragua/Germany), Ove Hoegh-Guldberg (Australia), Mark Howden (Australia), Bavisha Kalyan (South Africa/USA), Laura Moro (Italy), Anuszka Mosurska (United Kingdom/Poland), Reinhard Mechler (Germany), Joana Portugal-Pereira (Brazil), Aromar Revi (India), Swarnika Sharma (India), Anne J. Sietsma (The Netherlands/United Kingdom), Chandni Singh (India), Alessandro Triacca (Italy), Bianca van Bavel (Canada/Ireland/United Kingdom), Ivan Villaverde Canosa (Spain/United Kingdom), Mustafa Babiker (Sudan/Saudi Arabia), Paolo Bertoldi (Italy), Brett Cohen (South Africa), Annette Cowie (Australia), Kiane de Kleijne (The Netherlands), Jeremy Emmet-Booth (Ireland), Amit Garg (India), Gert-Jan Nabuurs (The Netherlands), André Frossard Pereira de Lucena (Brazil), Adrian Leip (Italy/Germany), Lars J. Nilsson (Sweden), Pete Smith (United Kingdom), Linda Steg (The Netherlands), Masahiro Sugiyama (Japan)

Key Messages

The feasibility assessment presents a systematic work towards providing a suite of adaptation and mitigation options organised by system transitions. This Cross-Chapter Box assessed the feasibility over six
dimensions: geophysical, environmental-ecological, technological, economic, socio-cultural and institutional to identify factors within each dimension that present barriers to the achievement of the option. The results are presented

For energy systems transitions the options of infrastructure resilience, efficient water use and water management, and reliable power systems enable systems to work during disasters with reduced costs demonstrating the synergistic relationships of mitigation and adaptation (*high confidence*). There is high confidence in the high feasibility of infrastructure resilience and reliable power systems as they enable power systems to provide emergency services during disasters as well as for the continuance of these services during recovery periods. New evidence has focused on both options for peri-urban and rural areas through distributed generation and isolated renewable energy systems, which also provide multiple social co-benefits (medium confidence). For efficient water use and management, there is also high confidence on the synergistic potential with mitigation as it can make processes more efficient and cost effective. With regards to adaptation feasibility, efficient water use is especially useful in drought-stricken areas and provides a better water management for multiple uses (high confidence).

There are multiple options for land and other ecosystems. Forest- and biodiversity-based adaptation solutions are generally promoted on the basis of their positive impacts on adaptive and ecological capacities, increased provision of ecosystem services and goods, with a particularly strong contribution to carbon sequestration (high confidence). However, large afforestation projects and the introduction of non-native and fast-growing vegetation have been found to reduce water availability, impoverish habitats for wildlife, and reduce overall ecological resilience, threatening the achievement of some SDGs, and potentially leading to maladaptation (high confidence). In addition, over-reliance on forest-based solutions may increase the susceptibility to wildfires, with detrimental consequences both for mitigation and adaptation (medium confidence). Over the last decade, forest- and biodiversity-based solutions have gained considerable political traction and social acceptability (high confidence), but in countries with economies highly dependent on the export of agricultural commodities, opportunity costs continue to hinder the expansion of these alternatives, particularly against more profitable land uses (high confidence). In such cases, government support and innovative financial schemes, including payments for ecosystem services, are fundamental for broader adherence to forest- and biodiversity-based options.

Agroforestry solutions have strong ecological and adaptive co-benefits (high confidence), including improved provision of ecosystem services, synergies with the water-energy-land-food nexus, and positive outcomes in agricultural intensification, job diversification and household income. While broad inclusion of agroforestry schemes in countries' Nationally Determined Contributions reflect growing international interest in these strategies, insufficient financial support to small farmers continues to limit the expansion of agroforestry initiatives in developing and tropical countries.

Implementing environmentally and biodiversity-sensitive coastal defense options - often as part of Integrated Coastal Zone Management - is limited by economic, environmental, institutional and social barriers. Successful implementation requires a strong socio-economic framework and can offer diverse social, ecological and economic benefits, as well as sequestering carbon (high confidence). There is extensive experience with hard engineering coastal defense structures, which can be cost-effective in economic terms, depending on the location (*medium confidence*); however they are considered non-adaptive and unsustainable in some contexts (*medium confidence*) due to their lack of flexibility or robustness in response to a changing climate, as well as their carbon-intensiveness and potential ecological impacts (*medium confidence*).

There is *medium confidence* on the feasibility of sustainable aquaculture as adaptation measure. There are financial barriers to implementing sustainable aquaculture, even though it can improve employment opportunities, which would benefit local communities (*medium confidence*). Technical resource availability is still lacking and could represent a barrier to implementing sustainable aquaculture (*medium confidence*). Robust institutional and legal frameworks are needed to guarantee successful sustainable adaptation (*high confidence*). Social aspects, such as social acceptability, inclusiveness, and gender equity are relevant for the feasibility of sustainable aquaculture (*medium confidence*). Sustainable aquaculture is highly dependent on healthy and resilient ecosystems (*high confidence*). It can provide diverse ecosystem services and support efforts for coastal ecosystems restoration (*medium confidence*).

There are a range of strategies to improve livestock system efficiency including improved livestock diets, enhanced animal health, breeding and manure management, and grassland management. This suite of strategies has strong feasibility to build resilience while improving incomes (medium confidence) and providing mitigation co-benefits (high confidence). While technological and ecological feasibility is high, institutional, market-linked, and socio-political acceptability remain significant barriers (medium confidence).

Improving water use efficiency and water resource management under land and ecosystem transitions has high technological feasibility (high confidence) with positive resilience building and socio-economic co-benefits. However, economic and institutional barriers based on type, scale, and location of interventions
(medium confidence). Notably, inadequate institutional capacities to prepare for changing water availability, especially in the long term, unsustainable and unequal water use and sharing practices, and fragmented water resource management approaches remain critical barriers to feasibility (high confidence).

Improved cropland management includes agricultural adaptation strategies such as integrated soil management, no/reduced tillage, conservation agriculture, planting of stress-resistant or early maturing crop varieties, and mulching. These strategies have high economic and environmental feasibility (high confidence) and also have substantial mitigation co-benefits (medium confidence). However, costs, inadequate information and technical know-how, delays between actions and tangible benefits, lack of comprehensive policies, fragmentation across different sectors, inadequate access to credit, and unequal access to resources constrain technological, institutional and socio-cultural feasibility (medium confidence).

For urban and infrastructure system transitions, urban planning can support both adaptation and decarbonization by mainstreaming climate concerns, including effective land-use into urban policies, by promoting resilient and low-carbon infrastructure; and by protecting and integrating carbon-reducing biodiversity and ecosystem services into city planning (medium confidence). Urban green infrastructure and ecosystem services have high feasibility to support climate adaptation and mitigation efforts in cities, for example to reduce flood exposure and attenuate the urban heat island (high confidence). While green infrastructure options are cost-effective and provide co-benefits in terms of ecosystem services such as improved air quality or other health benefits (high confidence), there remains a need for systematically assessing co-benefits, particularly for flood risk management and sustainable material flow analysis. Governments across scales can support urban sustainable water management by undertaking projects to recycle wastewater and runoff through green infrastructure; greater coherence between urban water and riverine basin management; decentralization of water systems; supporting networks for sharing best practices in water supply and storm runoff treatment to scale sustainable management; and foregrounding equity and justice concerns, especially participation involving informal settlement residents (medium confidence).

Strong and equitable health systems can protect the health of populations in the face of known and unexpected stressors (medium confidence). Public health system adaptation is feasible where capacity is well-developed, and where options align with national priorities and engage local and international communities (medium confidence). Socio-cultural acceptability of public health adaptation is high and there is significant potential for risk-mitigation and social co-benefits where adaptation addresses the needs of vulnerable regions and populations (medium confidence). Microeconomic feasibility, and socio-economic vulnerability reduction potential are also high (high confidence), though macroeconomic feasibility may pose a significant challenge in low-income settings (medium confidence). However, inadequate institutional capacity and resource availability represent major barriers, particularly for health systems struggling to manage current health risks (high confidence).

There is strong evidence that disaster risk management (DRM) is highly feasible when supported by strong institutions, good governance, local engagement, and trust across actors (medium confidence). DRM are constrained by lack of capacity, inadequate institutions, limited coordination across levels of government (high confidence), lack of transparency and accountability and poor communication (medium confidence). There is a preference for top-down DRM processes, which can undermine local institutions and perpetuate uneven power relationships (medium confidence). However, local integration of worldviews, belief systems and Local and Indigenous Knowledge into DRM activities can facilitate successful, disability-inclusive and gender-focused DRM (medium confidence). Moves towards community-based and ecosystem-based DRM are promising but uneven and may increase vulnerability if they fail to address underlying and structural determinants of vulnerability (high confidence).

There is *high confidence* that climate services that are demand-driven and context-specific (e.g., to a particular crop or agricultural system) build adaptation capacity and enable short- and longer-term risk management decisions. Metrics to assess the economic outcomes of climate services remain insufficient to capture longer-term benefits of interventions (medium confidence). While technological capacity and political acceptance is high (medium confidence), institutional barriers, poor fit with user requirements, and inadequate regional coverage constrain the option's overall feasibility.

Risk insurance can be a feasible tool to adapt to climate risks and support sustainable development (*high confidence*). They can reduce both vulnerability and exposure, support post-disaster recovery, and reduce financial burden on governments, households, and business. Insurance mechanisms enjoy wide legal and regulatory acceptability among policy makers and are institutionally feasible (*high confidence*). However, socio-cultural and financial barriers have made insurance spatially and temporally challenging to implement (*high confidence*), even though it can improve the health and well-being of populations (*medium confidence*). The risk of generating maladaptive outcomes can further limit the uptake of insurance, as it can provide disincentives for reducing risk over the long term (*medium confidence*). Expanding the knowledge base on insurance is fundamental to successfully implement insurance among all relevant stakeholders, and ensuring an equitable access to and benefits from innovative financial products (e.g. loans) is also needed to guarantee successful uptake of insurance across all the population (*high confidence*).

Migration has been used by millions around the world to maintain and improve their wellbeing in the face of changed circumstances, often as part of labour or livelihood diversification (*very high confidence*). Properly supported and where levels of agency and assets are high, migration as an adaptation to climate change can reduce exposure and socioeconomic vulnerability (*medium confidence*). Households and communities in climate-exposed regions experience a range of intersecting stressors. These households can undertake distress migration, which results in negative adaptive and resilience outcomes (*high confidence*). Outcomes can be improved through a systematic examination of the political economy of local and regional sectors that employ precarious communities and by addressing vulnerabilities that pose barriers to *in situ* adaptation and livelihood strategies (*medium confidence*). Migrants and their sending and receiving communities can be supported through temporary labour migration schemes; improving discourses on migration; and meeting existing migration agreements and development objectives (*medium confidence*).

Planned relocation and resettlement have low feasibility as an adaptation option (*medium confidence*). Previous disaster- and development-related relocation has been expensive, contentious, posed multiple challenges for governments and amplified existing, and generated new, vulnerabilities for the people involved (*high confidence*). Planned relocation will be increasingly required as climate change undermines habitability, especially for coastal areas (*medium confidence*). Full participation of those affected, ensuring human rights-based approaches, preserving cultural, emotional and spiritual bonds to place, and dedicated governance structures and associated funding are associated with improved outcomes (*high confidence)*. Improving the feasibility of planned relocation and resettlement is a high priority for managing climate risks *(high confidence*).

CCB FEASIB.1 Scope

The Paris Climate Agreement marked a significant shift for the IPCC AR6 assessment towards a systematic exploration of climate solutions and a suite of linked adaptation and mitigation options (IPCC, 2018; IPCC, 2019). This shift was first evidenced in SR1.5, whose plenary-approved outline sought to define " Feasibility refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined, and increase when enabling conditions are strengthened". Based on this mandate, SR1.5 identified (with *high confidence*) rapid and far-reaching transitions in four systems: energy, land and other ecosystems, urban and infrastructure (including transport and buildings) and industrial systems, necessary to enable pathways to limit average global warming to 1.5°C compared to pre-industrial temperatures (Bazaz et al., 2018; IPCC, 2018). This was deepened for terrestrial systems in SRCCL, while SROCC added additional evidence from ocean and cryosphere systems. The assessment includes the interactions between carbon dioxide removal and adaptation outcomes: compared to previous Assessment Reports, it is clear that the ambitious temperature targets agreed upon in Paris in 2015 will require at least some carbon dioxide removal (CDR), i.e. all 1.5°C pathways feature annual removals at Gigaton level (Rogelj et al., 2018). This necessitates assessing the interactions of CDR with adaptation.

This feasibility assessment of adaptation options is situated within four system transitions identified in SR1.5 (de Coninck et al., 2018). In this report, feasibility refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined, and increase when enabling conditions are strengthened. Twenty-two key adaptation options have been identified in AR6, across these system transitions, and mapped against representative key risks at global scale (Chapter 16) (Figure 1).

This cross-chapter box first presents the methodology for the feasibility assessment of adaptation options (section 2); findings of the FA (section 3); presents S&Ts of adaptation for mitigation options and mitigation for adaptations (section 4); and knowledge gaps (section 5).

There has been growing research emphasis on synthesising adaptation literature through meta-reviews of adaptation research (Sietsma et al., 2021), adaptation readiness (Ford et al., 2015; Ford et al., 2017); adaptation progress (Araos et al., 2016a); adaptation barriers and enablers (Biesbroek et al., 2013; Eisenack et al., 2014; Barnett et al., 2015); and adaptation outcomes (Owen, 2020) [Cross-Chapter Box ADAPT in Chapter 1]. In particular, understanding which adaptation options are effective, to what risks, and under what conditions, is particularly challenging given the lack of a clearly defined, globally agreed upon adaptation goal and disagreement on the metrics to assess effectiveness (Berrang-Ford et al., 2019; Singh et al., 2021b) [Ch 17, Sec 17.5.2 on Successful adaptation]. Effectiveness studies often use metrics such as proportion of population amount of population exposure reduced or conduct cost-benefit analyses of specific options, which lend themselves well to infrastructural options (e.g. effectiveness of seawalls in reducing SLR exposure in coastal cities) but do not translate well to 'soft' adaptation options such as uptake of climate services or changing building codes.

Systems transitions RKRs	Energy Systems Transitions	Land and Ecosystems Transitions	Urband & Infrastructure Systems Transitions	Overarching Adapatation Options
Risk to coastal socio-ecological systems		• Coastal defence and hardening • Sustainable aquaculture		
Risk to terrestrial and ocean ecosystems		• Integrated coastal zone management including wetland, mangrove conservation • Sustainable forest management and conservation, reforestation and afforestation • Biodiversity management and ecosystem connectivity		• Social safety nets • Risk spreading and sharing • Risk spreading and sharing • Climate services, including EWS • Disaster risk management • Population health and health systems • Human migration and displacement • Planned relocation and resettlement
Risks associated with critical physical infrastructure, networks, and services	• Resilient power infrastructure • Improved power reliability		• Green infrastructure & ecosystem services • Sustainable land-use & urban planning	
Risk to living standards and equity		• Livelihood diversification		
Risk to human health				
Risk to food security		• Improved cropland management(including integrated soil management, conservation agriculture) • Efficient livestock systems (including improved grazing land management) Agroforestry		
Risk to water security	• Improve water use efficiency	• Water use efficiency and water resource management	• Sustainable urban water management	
Risk to peace and migration				

Figure Cross-Chapter Box FEASIB.1: Feasibility assessment option mapped against Representative Key Risks (RKRs)

CCB FEASIB.2 Methodology: feasibility assessment of adaptation options across key system transitions

Multi-dimensional feasibility of adaptation options is assessed across six dimensions. This multidimensional framework goes beyond technical or economic feasibility alone to capture how adaptation is mediated by the political environment, sociocultural norms (Evans et al., 2016), cognitive and motivational factors (van Valkengoed and Steg, 2019), economic incentives and benefits (Masud et al., 2017), and ecological conditions (Biesbroek et al., 2013).

The six feasibility dimensions are underpinned by a set of twenty indicators. Each adaptation option is scored as having high, medium or low evidence on barriers based on a review of literature published from 2018 onwards (pre-2018 literature is expected to be covered by SR1.5 but in some cases pre-2018 literature was added where relevant literature was found) that reports studies that are 1.5°C-relevant. Further details and motivations for this methodology can be found in (Singh et al., 2020c)."

The scoring process is undertaken by one author and reviewed by at least two more authors to ensure robustness and geographical coverage. While the literature does not support an assessment at different temperature levels or an assessment of how feasibility can change over time, some examples on these spatial and temporal aspects are detailed below.

CCB FEASIB.3 Findings: feasibility assessment of adaptation options across key system transitions

The following sections outline the findings of a 1.5°C-relevant feasibility assessment of adaptation options by the four system transitions. A synoptic summary of the findings of the multi-dimensional feasibility is shown at the end of this section in Figure Cross-Chapter Box FEASIB.2. The full line of sight can be found in Supplementary Material (SM).

CCB FEASIB.3.1 Energy systems transitions

The adaptation options assessed for energy system transitions are resilient power infrastructure, water management, focused on water efficiency and cooling, for all types of generation source, and reliable power systems. Since SR1.5, there has not been significant change in the feasibility of the first two options as they continue to be implemented successfully, allowing for power generation to maintain or increase its reliability during extreme weather events (high confidence) (Zhang et al., 2018) (Ali and Kumar, 2016; DeNooyer et al., 2016). As in the case of SR1.5, these options are not sufficient for the far-reaching transformations required in the energy sector, which tend to focus on technological transitions from a fossil-based to a renewable energy regime (Erlinghagen and Markard, 2012; Muench et al., 2014; Brand and von Gleich, 2015; Monstadt and Wolff, 2015; Child and Breyer, 2017; Hermwille et al., 2017). The main difference from SR1.5 is that resilient power infrastructure now includes distributed generation utilities, such as microgrids, as there is increasing evidence of its role in reducing vulnerability, especially within underserved populations (high confidence).

The option for resilient power infrastructure is considered for all types of power generation sources, and transmission and distribution systems. There is robust evidence and high agreement for the high feasibility of the economic and technological dimensions as the technologies have been used and their cost effectiveness is high, although the latter is dependent upon the generation source and location of each specific generation plant. There is medium institutional feasibility (medium evidence, medium agreement) as there are insufficient policies for resilient infrastructure, although there is high acceptability for these options.

The option of efficient water use and management also has high feasibility for the economic, technological and environmental dimensions (robust evidence, high agreement), as this option also has proven that technology and efficient water use can make operations more efficient and cost effective as well as have positive effects on the environment, especially in drought-stricken regions. There is high political acceptability, existence of water use policies, regulations and supporting institutional frameworks to ensure compliance (Ali and Kumar, 2016; DeNooyer et al., 2016; Zhang et al., 2018). There is medium evidence and high agreement for the medium feasibility of the socio-cultural dimension, especially given the evidence of resilience in distributed generation systems and independent microgrids.

Since AR5, the reliability of power systems has gained interest due to the numerous service disruptions during extreme weather events. As with resilient power systems, there is increasing evidence of the feasibility of increased reliability for both existing power plants, independently of the generation source, and for rural landscapes. The option has high confidence (robust evidence, high agreement) for the high feasibility of the technological and social dimensions. As with previous options, the technological means exist to create redundancy in power generation, transmission and distribution systems and their implementation ensures the continuous functionality of emergency services, such as communications, health, and water pumping, amongst others, in urban, peri-urban and rural landscapes (high confidence). There is high feasibility for the economic, technical and socio-cultural dimensions (the latter more prominently for decentralized systems), and medium feasibility for institutional and geophysical dimensions.

For the three options, some of the indicators within the institutional, social and geophysical dimensions have limited evidence as they haven't been the focus of research. For example, when discussing the social co-benefits of energy reliable systems of efficient water use, literature doesn't focus on intergenerational or gender issues separately from the broad range of social co-benefits the options provide, but, for example, highlight the need for electricity for communications and health centers.

CCB FEASIB.3.2 Land and ecosystems

CCB FEASIB.3.2.1 Coastal defence & hardening

There is *medium agreement* and *robust evidence* regarding the feasibility of coastal defense and hardening as adaptation options in some circumstances, which here includes hard engineering solutions and grey coastal infrastructure. Economic and social factors potentially limit the feasibility of these options as they require large investments (both construction, maintenance and monitoring) (Hamin et al., 2018; Magnan and Duvat, 2018; Morris et al., 2018; Morris et al., 2019; Nicholls et al., 2019; Hanley et al., 2020b) (CCP2.3). While these costs present challenges for rural areas, coastal defense structures may still be cost-effective in some areas, such as those with larger economies (Aerts, 2018; Lincke and Hinkel, 2018; Tiggeloven et al., 2020; Vousdoukas et al., 2020; Lima and Coelho, 2021)). Strong yet transparent and inclusive governance is key, suggesting that these measures can occasionally fail to adequately balance competing stakeholder interests. Consequently, they may disproportionately benefit wealthier people and exacerbate existing vulnerability (Kind et al., 2017; O'Donnell, 2019; Ratter et al., 2019; Siders and Keenan, 2020; Siriwardane-de Zoysa, 2020). They are also potentially maladaptive in that they are not flexible or robust in response to a changing climate (Antunes do Carmo, 2018; Hamin et al., 2018; Morris et al., 2019; Baills et al., 2020; Foti et al., 2020; Hanley et al., 2020b) and can have negative impacts on the local environment, habitats, ecosystems and services, and communities (Mills et al., 2016; Morris et al., 2018; Morris et al., 2019; Foti et al., 2020; Hanley et al., 2020b).

Recent projects have focused on improving adaptability and increasing ecological and social sustainability, by combining both hard engineering and 'softer' nature-based solutions (Morris et al., 2019; Scheres and Schüttrumpf, 2019; Schoonees et al., 2019; Van Loon-Steensma and Vellinga, 2019; Du et al., 2020; Foti et al., 2020; Winters et al., 2020; Ghiasian et al., 2021; Joy and Gopinath, 2021; Tanaya et al., 2021; Waryszak et al., 2021). For example, coastal defense might involve a combination of 'stabilizing' ecosystems (e.g. seagrasses, mangroves, salt marsh) and hard human-made structures. Such coastal defense 'mixed' structures can be part of an Integrated Coastal Zone Management (ICZM) strategy, which is covered as a separate option below.

CCB FEASIB.3.2.2 Sustainable aquaculture

There is *medium evidence* with *medium agreement* on the feasibility of sustainable aquaculture as an adaptation measure. Sustainable aquaculture (e.g. Integrated Multi-Tropic Aquaculture, polyculture, aquaponics, mangrove-integrated culture) can have socio-economic benefits for vulnerable communities and small-scale fisheries (Ahmed, 2018; Blasiak et al., 2019; Mustafa et al., 2021; Thomas et al., 2021; Xuan et al., 2021). Nevertheless, caution is important to guarantee that access to fish supply of local and vulnerable communities is not affected (Chan et al., 2019; Galappaththi et al., 2020). Access to financial resources is often a barrier to implementation, although sustainable aquaculture can increase employment opportunities that are increasingly gender equitable (Alleway et al., 2018; Leakhena et al., 2018; Valenti et al., 2018; Gopal et al., 2020), as well as increasing the resilience of coastal livelihoods to climate change (Shaffril et al., 2017; Blasiak and Wabnitz, 2018). Technological, institutional and socio-cultural factors can form barriers to the feasibility of sustainability of aquaculture (e.g. (Ahmed et al., 2018; Blasiak et al., 2019; Galappaththi et al., 2019; Boyd et al., 2020; Osmundsen et al., 2020; Stentiford et al., 2020; Mustapha et al., 2021; Xuan et al., 2021).

Sustainable aquaculture depends on healthy ecosystems (Sampantamit et al., 2020; Stentiford et al., 2020; Qurani et al., 2021). At the same time, its implementation can increase or regenerate ecosystem services, enhance ecosystem's adaptive capacity (Shaffril et al., 2017; Freduah et al., 2018; Custódio et al., 2020; Bricknell et al., 2021; Mustafa et al., 2021) and protect nursery grounds and habitats for fish and other important organisms (i.e., many commercial species are associated with mangroves). It may also prevent ecosystem degradation such as deforestation, enhancing land-use potential (Ahmed et al., 2018; Stentiford et al., 2020; Turolla et al., 2020; Mustafa et al., 2021).

Environmental as well as economic aspects are key when assessing the sustainability of aquaculture practices (Ahmed et al., 2018; Aubin et al., 2019; Bohnes et al., 2019; Galappaththi et al., 2019; Boyd et al., 2020; Galappaththi et al., 2020; Osmundsen et al., 2020; Stentiford et al., 2020; Thomas et al., 2021). A global picture of where sustainable aquaculture is possible is clearly desirable (FAO, 2018; Galappaththi et al., 2019; Bricknell et al., 2021), yet there are few new references to physical feasibility. Adaptation options for existing sustainable aquaculture need to be developed, along with institutional arrangements such as education and technical exchange, focused on developing sustainable industries (Section 8.6.2.3). Sustainable agriculture is likely to receive strong support from many countries but may experience resistance for several reasons (e.g., competition with existing industries, debates over tolerance to aesthetic changes to coastlines). Literature on this area is growing and potential barriers at the government and political levels are significant (e.g. (Jayanthi et al., 2018; Blasiak et al., 2019; Hargan et al., 2020; Osmundsen et al., 2020; Stentiford et al., 2020; Mustafa et al., 2021; Qurani et al., 2021).

CCB FEASIB.3.2.3 Integrated coastal zone management

Salt marsh management, re-vegetation of shorelines, community-based coastal adaptation, and ecosystem-based adaptation, among other approaches implemented in coastal areas (which are considered to be part of ICZM, "soft measures") were considered in this assessment. There is robust evidence and high agreement that ICZM increases ecological and adaptive capacity to climate change (Villamizar et al., 2017; Antunes do Carmo, 2018; Hamin et al., 2018; Le Cornu et al., 2018; Propato et al., 2018; Romañach et al., 2018; Rosendo et al., 2018; Warnken and Mosadeghi, 2018; Morecroft et al., 2019; Morris et al., 2019; Alves et al., 2020; Donatti et al., 2020; Erftemeijer et al., 2020; Foti et al., 2020; Gómez Martín et al., 2020; Hanley et al., 2020b; Jones et al., 2020b; Krauss and Osland, 2020; O'Mahony et al., 2020; Perera-Valderrama et al., 2020; Cantasano et al., 2021).

Diverse socio-economic co-benefits have been identified, including integration of tourism activities, increased educational opportunities for the reduction in storm damage, maintenance of ecosystems and their services, increasing adaptive capacities of institutions (Romañach et al., 2018; Mestanza-Ramón et al., 2019; Morris et al., 2019; Donatti et al., 2020; Ellison et al., 2020; Erftemeijer et al., 2020; Gómez Martín et al., 2020; Hanley et al., 2020a; Jones et al., 2020b; Martuti et al., 2020; Perera-Valderrama et al., 2020; Telave and Chandankar, 2021); as well as environmental and geophysical co-benefits aspects, including mitigation potential and hazard risk reduction (Propato et al., 2018; Romañach et al., 2018; Ellison et al., 2020; Erftemeijer et al., 2020; Hanley et al., 2020a; Jones et al., 2020b; Martuti et al., 2020; Cantasano et al., 2021).

ICZM measures are generally more cost-effective or affordable than "hard-engineering" measures (Antunes do Carmo, 2018; Morecroft et al., 2019; Morris et al., 2019; Donatti et al., 2020; Erftemeijer et al., 2020; Hanley et al., 2020a; Jones et al., 2020b), but the costs for its implementation is a barrier, especially in low income countries (Lamari et al., 2016; Villamizar et al., 2017; Rosendo et al., 2018; Mestanza-Ramón et al., 2019; Barragán Muñoz, 2020; Botero and Zielinski, 2020; Caviedes et al., 2020; Martuti et al., 2020; Lin et al., 2021). The implementation of ICZM measures requires a strong institutional framework, where all relevant stakeholders (especially representatives of local communities) are part of the decision-making process (Pérez-Cayeiro and Chica-Ruiz, 2015; Lamari et al., 2016; Hassanali, 2017; Antunes do Carmo, 2018; Hamin et al., 2018; Phillips et al., 2018; Romañach et al., 2018; Rosendo et al., 2018; Warnken and Mosadeghi, 2018; Mestanza-Ramón et al., 2019; Morecroft et al., 2019; Morris et al., 2019; Walsh, 2019; Barragán Muñoz, 2020; Caviedes et al., 2020; Donatti et al., 2020; Ellison et al., 2020; Martuti et al., 2020; O'Mahony et al., 2020; Perera-Valderrama et al., 2020). This aspect is mentioned as a key challenge in developing countries (Pérez-Cayeiro and Chica-Ruiz, 2015; Villamizar et al., 2017; Rosendo et al., 2018; Alves et al., 2020). Similarly, incorporating gender issues explicitly into ICZM is generally recommended, also because women are key knowledge holders in coastal communities; however, this is rarely done in practice, which may lead to suboptimal or unequal outcomes (Nguyen Mai and Dang Hoang, 2018; Hoegh-Guldberg and al., 2019; Pearson et al., 2019; Barreto et al., 2020). The perception that building "hard" infrastructure (i.e. coastal defense and hardening) is a more efficient way of reducing coastal risk than the implementation of "soft" or NBS measures has been challenged in recent studies (Magnan and Duvat, 2018).

CCB FEASIB.3.2.4 Agroforestry

There is *robust evidence* and *high agreement* that agroforestry systems can increase ecological and adaptive capacity (Schoeneberger et al., 2012; Smith et al., 2013; Minang et al., 2014; Apuri et al., 2018; Kmoch et al., 2018; IPCC, 2019; Jordon et al., 2020). Benefits include preservation of ecosystems services, such as water provision and soil conservation, more efficient use of limited land, alleviation of land degradation, prevention of desertification and improved agricultural output. Agroforestry solutions also result in co-benefits in the water-energy-land-food nexus, with observed positive outcomes in soil management, crop diversification, water efficiency and alternative sources of energy (De Beenhouwer et al., 2013; Elagib and Al-Saidi, 2020). Further, they can have social and economic benefits and positive synergies between adaptation and mitigation (Section 8.6.2.2) (Coulibaly et al., 2017; Hernández-Morcillo et al., 2018; Tschora and Cherubini, 2020; Duffy et al., 2021).

When locally adapted to fine-scale ecological and social variation, agroforestry initiatives can improve household income, and provide regular employment and sustainable livelihood to local communities, thereby strengthening peoples' resilience to cope with adverse impacts of changing climate conditions (Coe et al., 2014; Ogada et al., 2020; Sharma et al., 2020; Sollen-Norrlin et al., 2020; Awazi et al., 2021). However, (Cechin et al., 2021) question the financial viability of agroforestry systems, especially in the case of smallholders in agrarian reform settlements, struggling with high upfront costs. Similarly, insufficient financial support was found to be a major constraint for the implementation of broader agroforestry initiatives in South East Asia and Africa (Sections 8.5.2 and 8.6.2.1) (Dhyani et al., 2021; Williams et al., 2021).

Over the last decade, agroforestry schemes have grown in acceptability and political support, most notably observed in their broad inclusion in countries' Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). Governance and institutional arrangements, however, have not been conducive to broader implementation of agroforestry initiatives at the landscape level (Dhyani et al., 2021; Williams et al., 2021). *Medium evidence* with *medium agreement* suggests that economic and cultural barriers may explain difficulties with the implementation of agroforestry systems (Coe et al., 2014; Quandt et al., 2017; Cedamon et al., 2018; Hernández-Morcillo et al., 2018; Ghosh-Jerath et al., 2021). Also, unclear land tenure and ownership issues, together with inappropriate mapping and databases for monitoring vegetation, continue to hinder the adoption of broader agroforestry strategies, particularly in remote areas and tropical forests (Martin et al., 2020).
Notably, agroforestry practices are often part of indigenous and local knowledge (Santoro et al., 2020), and so far, most literature refers to the evaluation of existing agroforestry practices or autonomous adaptation, with few studies evaluating the effects of targeted interventions, especially in low and middle income countries (Miller, 2020; Castle et al., 2021).

CCB FEASIB.3.2.5 Sustainable forest management and conservation, reforestation and afforestation
There is *robust evidence* and *medium agreement* supporting the overall feasibility of forest-based adaptation options. Regarding its economic feasibility, some studies (Nabuurs et al., 2017; Chow et al., 2019; Seddon et al., 2020a) highlight that the net benefits of measures such as reforestation, sustainable forest management and ecosystem restoration outweigh the costs of implementation and maintenance. Yet, another strand of literature observes that limited access to financial resources is a major constraint to reforestation and adaptive management initiatives, especially in the face of upfront investment costs and alternative, more profitable land uses, like agriculture (Bustamante et al., 2019; Ota et al., 2020; Seddon et al., 2020b). In countries with extensive rural areas where forests provide for local communities, government support together with private investments and long-term assurances of maintenance, are considered fundamental for the long-term viability of forest conservation strategies (Bustamante et al., 2019; Seddon et al., 2020b). In rural areas, smallholders can diversify their livelihood and increase household income as a result of improved local forest governance (Bustamante et al., 2019; Fleischman et al., 2020; Ota et al., 2020) Similarly, ecosystem restoration has been found to reduce poverty and improve social inclusion and participation, given that ecosystems can be managed jointly and in traditional ways (Woroniecki et al., 2019). *Robust evidence* (*high agreement*) links forest-based adaptation to job creation, improved health and recreational benefits, most notably for indigenous, rural and remote communities (Muricho et al., 2019; Rahman et al., 2019; Ambrosino et al., 2020; Bhattarai, 2020; Ota et al., 2020; von Holle et al., 2020; Tagliari et al., 2021). However (Chausson et al., 2020), note that still today frameworks for assessing the cost-effectiveness of adaptation strategies continue to be tailored to conventional, engineered interventions, which fail to capture the broader array of material and non-material benefits that sustainable forest management might bring.

Forest-based solutions enjoy wide local, regional and international support (Lange et al., 2019; Chausson et al., 2020; Seddon et al., 2020b), and most countries have the basic regulatory framework for environmental protection. However, lack of institutional capacity, deficient inter-agency coordination, and insufficient staff and budget continue to limit broader implementation of forest-based adaptation measures. Limited technical capacity, insufficient production and supply of seeds and seedlings, long transport distances and immature supply chains have also been identified as significant barriers that hinder the expansion of forest-based initiatives (Bustamante et al., 2019; Nunes et al., 2020).

There is *robust evidence* and *medium agreement* that forest-based solutions support ecosystems' capacity to adapt to climate change, including better regulation of microclimate, increased groundwater recharge, improved quality of air and water, reduced soil erosion, improved and climate-adapted biodiversity habitats, expansion of biomass, as well as continuous provision of renewable wood products (Nabuurs et al., 2017; Chow et al., 2019; Lochhead et al., 2019; Shannon et al., 2019; Weng et al., 2019; von Holle et al., 2020; Dooley et al., 2021; Forster et al., 2021; Tagliari et al., 2021). In well designed systems, adaptation and mitigation can then go hand in hand, as in climate smart forestry. What is more, adaptive forest management is already being tested in climate smart forestry pilots in several temperate regions (Nabuurs et al., 2017). However, large afforestation and non-native monoculture plantations may negatively impact non-forest ecosystems, such as grasslands, shrublands, and peatlands, their water resources and biodiversity (Seddon et al., 2019; Seddon et al., 2020a; Seddon et al., 2020b). Similarly, the International Resource Panel (2019) warns that restoration may also imply trade-offs with other ecological and societal goals.

Regarding risk reduction potential, reforestation and afforestation strategies are found to protect in-land infrastructure from landslides and coastal infrastructure from storm surges (Seddon et al., 2020a; Seddon et al., 2020b), together with offering a cheaper solution than engineered grey solutions (Chausson et al., 2020). Land availability is a limiting factor for expanding forest-based solutions (Morecroft et al., 2019; Ontl et al., 2020). However, there is *high agreement* and *robust evidence* that reforestation, environmental conservation and nature-based solutions result in increased carbon sinks (Griscom et al., 2017; Nabuurs et al., 2017; de Coninck et al., 2018; Fuss et al., 2018; Favretto et al., 2020; Forster et al., 2021). Some authors argue that primary ecosystems and native forests contain larger stocks of carbon than tree plantations (Seddon et al., 2019; Fleischman et al., 2020; Seddon et al., 2020a), while another strain of literature finds that net sequestration rate is lower in mature primary forests than in younger managed forests with their associated wood value chains (Cowie et al., 2021; Forster et al., 2021; Gundersen et al., 2021). There is *robust evidence* and *high agreement* that reforestation and ecosystem-based strategies result in hazard risk reduction potential. Environmental restoration can be an effective climate change adaptation alternative, reducing susceptibility to extreme events, improving ecological capacities and increasing overall ecosystems' resilience (Chapter 8, Box 9.7) (Nunes et al., 2020). However, too much reliance on reforestation and green alternatives might increase water shortages and wildfires (Seddon et al., 2019; Fleischman et al., 2020).

CCB FEASIB.3.2.6 Biodiversity management and ecosystem connectivity

There is *robust evidence* and *medium agreement* supporting the overall feasibility of biodiversity management and ecosystem connectivity as adaptation options. With respect to its economic feasibility, financial constraints continue to hinder broader implementation of biodiversity-based solutions (Lausche et al., 2013; Chausson et al., 2020; Jones et al., 2020a).(Seddon et al., 2020a) highlights that only five percent of climate finance goes towards adaptation strategies, and only one percent is destined to disaster risk management including nature-based solutions and biodiversity management. Government support via subsidies and fiscal transfers is critical for broader biodiversity management interventions. In addition, REDD+ initiatives have been promoted as a profitable mechanism to advance biodiversity conservation strategies while reducing carbon emissions. As far as ecosystem connectivity is concerned, its feasibility will strongly depend on the existence of a regulatory framework that appropriately balances property rights, environmental regulations and monetary incentives to ensure landowners' willingness to participate and maintain ecosystem corridors (Jones et al., 2020b). The demands of commodity-based economies, favouring extractive land-uses, present serious barriers to upscaling biodiversity-based adaptation interventions (Seddon et al., 2020a). In addition, integrated assessments have shown how biodiversity-based solutions can deliver jobs from landscape restoration or income from wildlife tourism and how those benefits are fairly distributed (Chausson et al., 2020).

Legal and regulatory instruments are not perceived as major barriers to biodiversity management and ecosystem connectivity projects (Lausche et al., 2013; D'Aloia et al., 2019). A challenge that biodiversity-based measures still face is less acceptance among decision-makers because their efficiency and cost-benefit ratio are difficult to determine and most of the measures are only effective in the long-term (Lange et al., 2019). Methodologies to determine cost-effectiveness vary substantially between studies, in part because these analyses must be tailored to the social-ecological context in order to be meaningful for local governance. This makes it challenging to capture and synthesize the full economic benefits of biodiversity-based solutions in comparison to alternatives (Chausson et al., 2020). In all, biodiversity and nature-based solutions have gained considerable political traction, with the greatest emphasis on the role of ecosystems as carbon sinks (Lange et al., 2019; Chausson et al., 2020; Seddon et al., 2020a).

Several social co-benefits are found to follow from biodiversity management strategies, including improved community health, recreational activities, eco-tourism, in addition to educational, spiritual and scientific benefits (Lausche et al., 2013; Worboys et al., 2016; Seddon et al., 2020a). (Lavorel et al., 2020) show how the benefits of biodiversity management are co-produced by harnessing ecological and social capital to promote resilient ecosystems with high connectivity and functional diversity. Furthermore, (Chausson et al., 2020) note how properly implemented nature-based solutions, including biodiversity management, can strengthen social networks and foster a sense of place, supporting virtuous cycles of community engagement to sustain interventions over time.

There is *high agreement* and *robust evidence* supporting the ecological capacity enhancement of biodiversity-based and ecosystem connectivity strategies (Thompson et al., 2017; Lavorel et al., 2020). Forest management that favors mixed-species rather than non-native monocultures can promote the resilience of timber production and carbon storage while also benefiting biodiversity (Chausson et al., 2020). Similarly, monocultures have been found to impoverish biodiversity and hold less resilient carbon stocks than natural and semi-natural forests (Seddon et al., 2020a).

There is a *relatively high agreement* that ecosystem connectivity has the potential to improve the adaptive capacity of both ecological systems and humans. (Krosby et al., 2010), for example, found that planting trees in short distances could increase the probability of range shifts in species that depend on the habitat those trees provide. Likewise, connectivity conservation has benefits for climate change mitigation (Lausche et al., 2013), but empirical evidence of the adaptation benefits for humans is scant. More recently, it has been found that biodiversity conservation reduces the risk of zoonotic diseases when it provides additional habitats for species and reduces the potential contact between wildlife, livestock and humans (Van Langevelde et al., 2020). Ecosystem-based approaches have been promoted to address the risk of increased zoonotic diseases, including the conservation of wildlife corridors (Gibb et al., 2020).

Despite abundant literature on the necessity to implement ecosystem connectivity strategies, many policy recommendations are mostly discursive and not supported by evidence. There is a lack of specificity when referring to the actors that should intervene in the design, implementation and evaluation of policies. What is more, most of the literature comes from the natural sciences and is concerned with co-benefits to wildlife and nature, with very little elaboration on the socio-economic co-benefits for humans.

CCB FEASIB.3.2.7 Improved cropland management

Improved cropland management, which includes agricultural adaptation strategies such as integrated soil management, no/reduced tillage, conservation agriculture, planting of stress-resistant or early maturing crop varieties, and mulching, has high economic and environmental feasibility (*robust evidence, high agreement*) (AGEGNEHU and AMEDE, 2017; Lalani et al., 2017; Schulte et al., 2017; Thierfelder et al., 2017; Aryal et al., 2018a; Mayer et al., 2018; Prestele et al., 2018; Sova et al., 2018; Gonzalez-Sanchez et al., 2019; Lunduka et al., 2019; McFadden et al., 2019; Shah and Wu, 2019; TerAvest et al., 2019; Adams et al., 2020; Aryal et al., 2020a; Debie, 2020; Mutuku et al., 2020; Somasundaram et al., 2020; Du et al., 2021). Despite higher initial costs in some cases, the economic feasibility of improved cropland management is high through improved productivity, higher net-returns, reduced input costs (Aryal, 2020 #6850}(Mottaleb et al., 2017; Keil et al., 2019; Lunduka et al., 2019; McFadden et al., 2019; Parihar et al., 2020). Self-efficacy is shown to be the most important predictor in technical and non-technical adaptation behaviour (Zobeidi et al., 2021), while subsidies, extension services, training, commercial custom-hire services and strong social connections such as farmer networks are among the factors supporting adoption among farmers (Section 8.5.2.3) (Aryal et al., 2015a; Aryal et al., 2015b; Kannan and Ramappa, 2017; Bedeke et al., 2019; Acevedo et al., 2020). In some regions and for some practices, technological feasibility is constrained by cost, and inadequate information and technical know-how on particular practices and their benefits and tradeoffs, indicating medium feasibility (Khatri-Chhetri et al., 2016; Bhatta et al., 2017; Dougill et al., 2017; Kannan and Ramappa, 2017; Aryal et al., 2018a; Sova et al., 2018; Findlater et al., 2019). Delays between actions and tangible benefits can reduce public and private acceptability and uptake of improved cropland management practices (e.g. (Dougill et al., 2017) in Malawi).

There remain institutional and financial barriers to improved cropland management such as lack of comprehensive policies, inadequate mainstreaming into national policy priorities (e.g. (Amjath-Babu et al., 2019) and (Reddy et al., 2020) in South Asia), fragmentation across different sectors (Dougill et al., 2017) in Malawi), and inadequate access to credit (Aryal et al., 2018c) in India). Adoption of improved cropland management practices is often strongly mediated by gender: structural barriers such as unequal access to land, machinery, inputs, and extension and credit services, constrain adoption by female farmers (Aryal et al., 2018b; Aryal et al., 2018c). (Mponela et al., 2016; Van Hulst and Posthumus, 2016; Ntshangase et al., 2018; Aryal et al., 2020b; Somasundaram et al., 2020). Improved cropland management practices have social and ecological co-benefits in terms of better health, education and food security (Agarwal, 2017; Farnworth et al., 2017; Hörner and Wollni, 2020) and better soil health and ecosystem functioning (AGEGNEHU and AMEDE, 2017; Mottaleb et al., 2017; Thierfelder et al., 2017; Zomer et al., 2017; Sarkar et al., 2018; Gonzalez-Sanchez et al., 2019; Shah and Wu, 2019; Du et al., 2020; Mutuku et al., 2020; Somasundaram et al., 2020).

There is *robust evidence* (*medium agreement*) that improved cropland management can have mitigation co-benefits but the exact quantity of emissions reductions and increased removals depend on agro-ecosystem type, climatic factors and cropping practices (VandenBygaart, 2016; Han et al., 2018; Mayer et al., 2018; Prestele et al., 2018; Singh et al., 2018a; Sommer et al., 2018; Gonzalez-Sanchez et al., 2019; Ogle et al., 2019; Shah and Wu, 2019; Adams et al., 2020; Aryal et al., 2020a; Li et al., 2020; Wang et al., 2020; Shang et al., 2021).

CCB FEASIB.3.2.8 Efficient livestock systems

Enhancing the production efficiency of livestock systems, through for example, improved livestock diets, enhanced animal health, breeding and manure management, can contribute to adaptation and mitigation (Ericksen and Crane, 2018; Accatino et al., 2019; Paul et al., 2020)IPCC WGIII AR6 Section 7.4.3). While the technological and ecological feasibility of improving livestock production systems is high (i.e. measures are technically well established, with different options applicable to a range of livestock production systems and ecological conditions), there are multiple context-specific barriers to adoption. These include a lack of coordinated policy support or governance, potentially high implementation costs and limited access to finance, inadequate advisory, knowledge exchange or infrastructural capacity (Escarcha et al., 2018; Paul et al., 2020), the potential land requirements and associated ecological impacts of adjusting livestock management, lack of context specific research (Pardo and del Prado, 2020), and socio-cultural barriers limiting access by women or low-income groups to better breeds or feed varieties (Luqman et al., 2018; Salmon et al., 2018) as well as women losing influence in the household in some contexts when farms intensify (Tavenner and Crane, 2018). In dryland livestock systems in Ethiopia and Kenya, (Ericksen and Crane, 2018) find that low governance capacities to implement improved grazing regimes and prevent overgrazing constrain improved grassland management.

CCB FEASIB.3.2.9 Water use efficiency and water resource management

There is high technological feasibility (*robust evidence, high agreement*) to improve water use efficiency as well as manage water resources at basin and field scales. These approaches include rainwater harvesting, drip irrigation, laser land leveling, drainage management and stubble retention (Dasgupta and Roy, 2017; Khatri-Chhetri et al., 2017; Rahman et al., 2017; Adham et al., 2018; Darzi-Naftchali and Ritzema, 2018; Terêncio et al., 2018; Velasco-Muñoz et al., 2018; Sojka et al., 2019). There is *high evidence (medium agreement*) that such measures have socio-economic co-benefits and improve adaptive capacities through improved water supply (e.g. through rainwater harvesting , increased infiltration, or integrated watershed management),, and sustainable water demand management (e.g. reduction of evaporation loss). There is *medium evidence* (*high agreement*) of the option's economic feasibility due to water and energy cost savings enhanced by low-cost monitoring systems in some cases (Kodali and Sarjerao, 2017; Viani et al., 2017). Implementation costs vary widely, with landforming and irrigation infrastructure requiring substantial up-front investment, while mulches and cover crops are low cost practices. Water management and use efficiency is currently constrained by governance and institutional factors such as inadequate institutional capacities to prepare for changing water availability, especially in the long term, unsustainable and unequal water use and sharing practices, particularly across boundaries, and fragmented, and siloed resource management approaches (Lardizabal, 2015; Margerum and Robinson, 2015; Singh et al., 2020a).

CCB FEASIB.3.2.10 Livelihood diversification

Livelihood diversification is a key coping and adaptive strategy to climatic and non-climatic risks (Gautam and Andersen, 2016; Asfaw et al., 2018)Liu, 2015 #1681}(Goulden et al., 2013; Makate et al., 2016; Orchard et al., 2016; Nyantakyi-Frimpong, 2017; Schuhbauer et al., 2017; Kihila, 2018; Radel et al., 2018; Tian and Lemos, 2018; Buechler and Lutz-Ley, 2019; Salam and Bauer, 2020). There is high evidence (medium agreement) that diversifying livelihoods improves incomes and reduces socio-economic vulnerability, but depending on livelihood type, opportunities, and local context, feasibility changes (Section 8.5.1) (Barrett, 2013; Martin and Lorenzen, 2016; Sina et al., 2019). Livelihood diversification has positive and negative outcomes for adaptive capacity, especially in ecologically and resource-stressed regions (for e.g.(Anderson et al., 2017; Woodhouse and McCabe, 2018; Rosyida et al., 2019; Ojea et al., 2020), with diversification predominantly out of rural farm-based livelihoods on the rise (Rigg and Oven, 2015; Shackleton et al., 2015; Ober and Sakdapolrak, 2020). Key barriers to livelihood diversification include socio-cultural and institutional barriers (including social networks (Goulden et al., 2013) as well as inadequate resources and livelihood opportunities that hinder the full adaptive possibilities of existing livelihood diversification practices (Shackleton et al., 2015; Nightingale, 2017; Bhowmik et al., 2021; Rahut et al., 2021). Autonomous diversification in the absence of more equitable and harmonised efforts at regional and national scales to facilitate sustainable diversification can further skew development indicators at the subnational scale in favour of local elites, increased inequality, and environmental degradation (Ford et al., 2014; Wilson, 2014; Alobo Loison, 2015; Tanner et al., 2015; Gautam and Andersen, 2016; Baird and Hartter, 2017; Torell et al., 2017; Asfaw et al., 2018; Woodhouse and McCabe, 2018; Brown et al., 2019; Rosyida et al., 2019; Sani Ibrahim et al., 2019; Ojea et al., 2020; Salam and Bauer, 2020). Livelihood diversification can be facilitated in key technical areas (Shackleton et al., 2015; Brown et al., 2017; Schuhbauer et al., 2017) including regulatory frameworks (Butler et al., 2020) (limited but robust evidence), as well institutional support through funding and more localised research on interaction among and between enablers and barriers concerning specific local diversification options (Barrett, 2013; Herrero et al., 2016; Martin and Lorenzen, 2016; Sina et al., 2019) in the case of pastoral communities).

CCB FEASIB.3.3 Urban and infrastructure system transitions

CCB FEASIB.3.3.1 Sustainable land-use & urban planning

Urban planning is a medium feasibility option to support adaptation by prioritizing it in city plans, such as land-use planning, transportation (Liang et al., 2020), and health and social services (Carter et al., 2015; Araos et al., 2016b); by procuring the design and construction of resilient infrastructure; by promoting community-based adaptation through community-based design and implementation of adaptation activities (Archer, 2016); and by protecting and integrating biodiversity and ecosystem services into city planning. Research since SR 1.5 documents the challenging high costs of infrastructure (Georgeson et al., 2016; Woodruff et al., 2018); potential loss of municipal revenue in the case of managed retreat (Shi and Varuzzo, 2020; Siders and Keenan, 2020); and the fraught causal connection between planning and the reduction of socioeconomic vulnerability (Keenan et al., 2018; Anguelovski et al., 2019a; Elliott, 2019; Paganini, 2019; Shokry et al., 2020). However, adaptation benefits could potentially outweigh costs (Carey, 2020); the financial viability of green infrastructure (Meerow, 2019; Zhang et al., 2019; Van Oijstaeijen et al., 2020; Ossola and Lin, 2021); and availability of technical expertise, although the inequitable planning processes and distribution of those resources remains a significant concern (Serre and Heinzlef, 2018; Szewrański et al., 2018; Fitzgibbons and Mitchell, 2019; Hasan et al., 2019; Heikkinen et al., 2019; Colven, 2020; Goetz et al., 2020; Goh, 2020).

Structural disincentives and institutional arrangements create challenges for planning even where political willingness may be high (Di Gregorio et al., 2019; DuPuis and Greenberg, 2019; Shi, 2019; Zen et al., 2019; Rasmussen et al., 2020). Social resistance may significantly delay or block progress entirely, as vulnerable communities have responded negatively in cases adaptive urban and land-use planning leads to perceived "resilience gentrification" (Keenan et al., 2018; Anguelovski et al., 2019a), if residents do not perceive themselves as included in the crafting of plans (Araos, 2020; Rasmussen et al., 2020), if the options such as managed retreat are perceived as culturally unacceptable (Ajibade, 2019; Koslov, 2019; Siders, 2019), or if wealthier and advantaged residents benefit from planning at the expense of socially vulnerable groups (Chu and Michael, 2018; Chu et al., 2018; Fainstein, 2018; Rosenzweig et al., 2018; Pelling and Garschagen, 2019; Ranganathan and Bratman, 2021). Nonetheless, potential social co-benefits related to health and education are high (Raymond et al., 2017; Spaans and Waterhout, 2017; Klinenberg, 2018; Keeler et al., 2019; Meerow, 2019). Finally, the option is highly feasible in relation to ecological and geophysical characteristics, as urban and land-use planning's primary tool is to manipulate the built environment and natural spaces to protect and reduce the vulnerability of residents.

CCB FEASIB.3.3.2 Green infrastructure & ecosystem services

Urban green infrastructure and ecosystem services have high feasibility to support climate adaptation and mitigation efforts in cities, for example to reduce flood exposure and attenuate the urban heat island (Perrotti and Stremke, 2018; Belčáková et al., 2019; De la Sota et al., 2019; Stefanakis, 2019). While green infrastructure options are cost-effective and provide co-benefits in terms of ecosystem services such as improved air quality or other health benefits (Depietri and McPhearson, 2017; Morris et al., 2018; Reguero et al., 2018; Escobedo et al., 2019; Filazzola et al., 2019; Hewitt et al., 2020b; Venter et al., 2020; Nieuwenhuijsen, 2021) (*robust evidence, high agreement*), there remains a need for systematically assessing co-benefits, particularly for flood risk management (Alves, 2019 (Alves et al., 2019; Stefanakis, 2019) and sustainable material flow analysis (Perrotti and Stremke, 2018). Moreover, while once neglected, rapidly increasing attention has been paid to the equity and justice dimensions of planning and implementing green infrastructure initiatives, such as inclusion of citizens in decision-making or the allocation of benefits and impacts of projects (Anguelovski et al., 2019b; Buijs et al., 2019; Langemeyer et al., 2020; Venter et al., 2020)

Institutional barriers constrain the feasibility of urban green infrastructure (medium confidence), such as policy resistance to shift priorities from grey to green infrastructure (e.g. Johns 2019 in Canada) or siloed governance structures (Willems et al., 2021). Further social and political acceptability of green infrastructure is constrained by lack of confidence in efficacy (Thorne et al., 2018) or issues of accessibility (Biernacka and Kronenberg, 2018).

For flood management, a mix of green, blue and grey infrastructures are found effective with grey infrastructure reducing the risk of flooding and green infrastructure yielding multiple co-benefits (Alves et al., 2019; Gu et al., 2019; Webber et al., 2020) but catchment-wide solutions are advocated as the best performing strategy (Webber et al., 2020). Recognising and addressing a full range of ecosystem disturbances and disasters over a larger urban spatial scale (Vargas-Hernández and Zdunek-Wielgołaska, 2021) are crucial for planning green infrastructure based solutions. In some cases, low impact development interventions yield effective flood management outcomes but are adequate only for small flood peaks (Pour et al., 2020), with the major challenge being identifying best practices. Nature-based strategies (NBS) hold significant potential to achieve mitigation and adaptation goals in comparison to traditional approaches, but more research is necessary to understand their effectiveness, distribution, implementation at scale, cost-benefit and integration with spatial dimensions of planning (Davies et al., 2019; Dorst et al., 2019; Zwierzchowska et al., 2019; Hobbie and Grimm, 2020).

CCB FEASIB.3.3.3 Sustainable urban water management (blue infrastructure interventions e.g. lake/river restoration; rainwater harvesting)

Governments across scales can support urban sustainable water management with high feasibility by undertaking projects to recycle wastewater and runoff from worsening storms, with implications for decarbonization and adaptation. Green infrastructure, for example, has shown the high potential to reduce water use footprints and to save potable water for consumption (Liu and Jensen, 2018), and contributing to a "circular" water system in cities (Oral et al., 2020). Supportive governance can yield positive outcomes such as improved water security (Jensen and Nair, 2019); and there is *medium evidence* and *high agreement* that participation, such as involving informal settlement residents in water management can improve social inclusion (Pelling et al., 2018; Williams et al., 2018; Leigh and Lee, 2019; Sletto et al., 2019). Green infrastructure can support the planning of "sponge cities," such as in China, wherein large areas of green space, permeable surfaces, and sustainable water sourcing combine to purify urban runoff, attenuate peak runoff, and conserve water for consumption (Chan et al., 2018; Nguyen et al., 2019). Similar approaches in Dutch cities focus on designing and planning for the capturing, storing, and draining of storm water (Dai et al., 2018). Nonetheless, some interventions suffer from uncertainties in design, planning, and financing (Nguyen et al., 2019). As drought becomes more severe in some regions, physical barriers in the form of reduced availability of water may become pressing (Singh et al., 2021a)}.

Deployment of decentralised water management, through effective local governance frameworks, is an important water management strategy (Herslund and Mguni, 2019; Leigh and Lee, 2019) but in general, insufficient institutional learning and capacity is a critical barrier for the uptake of sustainable urban water management practices (Krueger et al., 2019; Adem Esmail and Suleiman, 2020). Transnational networks of cities for sharing best practices in water supply and storm runoff treatment also hold the potential to scale sustainable management (Feingold et al., 2018). In rapidly growing large urban areas, sustainable water management faces challenges of institutional heterogeneity (Chu et al., 2018), scalar mismatch; particularly between river basin and city scales (van den Brandeler et al., 2019) and equity and justice concerns (Chu et al., 2018; Pelling et al., 2018). Finally, assessing the vulnerability of urban water infrastructures at city-scale remains an important knowledge gap (Dong et al., 2020).

CCB FEASIB.3.4 Overarching adaptation options

CCB FEASIB.3.4.1 Social safety nets

Social safety nets meet development goals (e.g. poverty alleviation, accessible education and health services) and are increasingly being reconfigured to build adaptive capacities of the most vulnerable (Coirolo et al., 2013; Aleksandrova, 2020; Bowen et al., 2020; Fischer, 2020; Mueller et al., 2020). They include a range of policy and market-based instruments such as public works programmes and conditional or unconditional cash transfers, in-kind transfers; and insurance schemes (Centre, 2019; Aleksandrova, 2020). While there is *high evidence (medium agreement)* that social safety nets can build adaptive capacities, reduce socio-economic vulnerability, and reduce risk linked to hazards (Fischer, 2020; Mueller et al., 2020); macroeconomic, institutional, and regulatory barriers such as limited state resources, underdeveloped credit and insurance markets, and leakages constraint feasibility (Singh et al., 2018c; Hansen et al., 2019; Aleksandrova, 2020; Lykke Strøbech and Bordon Rosa, 2020). Social safety nets have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion, and food security (Section 8.6) (Castells-Quintana et al., 2018; Ulrichs et al., 2019; Mueller et al., 2020) but these positive outcomes are constrained by inadequate regional inclusiveness (e.g. limited access in certain remote, rural areas - (Singh et al., 2018b; Aleksandrova, 2020; Lykke Strøbech and Bordon Rosa, 2020); or focus on rural areas overlooks urban vulnerable groups (Coirolo et al., 2013).

CCB FEASIB.3.4.2 Risk spreading and sharing

There is high confidence on risk spreading and sharing, most commonly arranged through insurance, as an adaptation option, but high to medium feasibility depending on context (e.g. developed vs. developing countries)Technological, economic, and institutional feasibility is high, as insurance can spread risk, provide a buffer against the impact of climate-hazards, support recovery and reduce the financial burden on governments, households, and businesses (Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017; Kousky et al., 2021). Insurance can shift the mobilization of financial resources away from ad hoc post-event payments, where funding is often unpredictable and delayed, towards more strategic approaches that are set up in advance of disastrous events (Surminski et al., 2016). By pricing risk, insurance can provide incentives for investments and behavior that reduce vulnerability and exposure (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Shapiro, 2016; Jenkins et al., 2017). Socio-cultural barriers, such as social inclusiveness, socio-cultural acceptability and gender equity, constraints feasibility (Bageant and Barrett, 2017; Budhathoki et al., 2019). Insurance can provide disincentives for reducing risk through the transfer of the risk spatially and temporally; can distort incentives for adaptation strategies if the pricing is too low (moral hazard); is often unaffordable, poorly understood, and not widely utilized in developing nations even when subsidized; and can lead to maladaptation (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016; Müller et al., 2017; Tesselaar et al., 2020). Insurance can reinforce exposure and vulnerability through underwriting a return to the 'status-quo' rather than enabling adaptive behaviour (e.g. through 'no-betterment' principles) (Collier and Cox, 2021). (Surminski et al., 2016) raise concern that for low income nations and in the absence of global support, insurance shifts responsibility to those least responsible for climate change.

CCB FEASIB.3.4.3 Disaster risk management

There is robust evidence (high agreement) that DRM aids adaptation decision-making, particularly where it is demand-driven, context-specific and supported by strong institutions, good governance, strong local engagement, and trust across actors (Hasan et al., 2019; Kim and Marcouiller, 2020; Peng et al., 2020; Smucker et al., 2020; Uddin et al., 2020; Webb, 2020; Ali et al., 2021; Anderson and Renaud, 2021; Glantz and Pierce, 2021; Ji and Lee, 2021; Villeneuve, 2021). These conditions are rarely met, and therefore DRM is often constrained by institutional factors that may even increase vulnerability (Booth et al., 2020; Islam et

al., 2020a; Islam et al., 2020b; Marchezini, 2020; Goryushina, 2021; Mena and Hilhorst, 2021). The feasibility of DRM continues to be constrained by limited coordination across levels of government lack of transparency and accountability, poor communication, and a preference for top-down DRM processes that can undermine local institutions and perpetuate uneven power relationships (Atanga, 2020; Booth et al., 2020; Bordner et al., 2020; Bronen et al., 2020; Goryushina, 2021; Mena and Hilhorst, 2021; Son et al., 2021; Yumagulova et al., 2021). However, local integration of worldviews, belief systems and Local and Indigenous Knowledge into DRM activities improves feasibility (Bordner et al., 2020; Cuaton and Su, 2020; Hosen et al., 2020; Sharma and Sharma, 2021), including disability-inclusive and gender-focused DRM (Ruszczyk et al., 2020; Crawford et al., 2021). Data access and availability continues to challenge DRM despite advances in data analytics, especially in rapidly growing informal settlements, including population estimates and limited mobility data (Goniewicz and Burkle, 2019; Marchezini, 2020).
Moves towards community-based and ecosystem-based DRM are promising but uneven (Klein et al., 2019; Seebauer et al., 2019; Almutairi et al., 2020; Bordner et al., 2020; Hosen et al., 2020; Murti et al., 2020; Sharma and Sharma, 2021), and may increase vulnerability if they fail to address underlying, structural determinants of vulnerability, particularly among marginalised groups and by gender (Sections 8.4.4 and 8.4.5) (Seleka et al., 2017; Hossen et al., 2019; Ramalho, 2019; Atanga, 2020; Cuaton and Su, 2020; Gartrell et al., 2020; Kenney and Phibbs, 2020; Khalil et al., 2020; Ngin et al., 2020; Ruszczyk et al., 2020; Webb, 2020; Ali et al., 2021; Geekiyanage et al., 2021; Villeneuve, 2021).

CCB FEASIB.3.4.4 Climate services, including EWS

There is robust evidence (high agreement) that climate services aid adaptation decision-making and build adaptive capacity, particularly where they are demand-driven and context-specific (Vaughan et al., 2018; Bruno Soares and Buontempo, 2019; Daniels et al., 2020; Hewitt et al., 2020a; Findlater et al., 2021). Climate service interventions are constrained by low capacity, inadequate institutions, difficulties in maintaining systems beyond pilot project stage (Vincent et al., 2017; Tall et al., 2018; Bruno Soares and Buontempo, 2019), and poor mapping between climate services and existing user capacities and demands (Williams et al., 2020) (robust evidence, high agreement). Metrics to assess outcomes of climate services remain project-based and insufficiently capture longer-term economic and non-economic benefits of interventions (Tall et al., 2018; Parton et al., 2019; Perrels, 2020). The technical feasibility of climate services is relatively strong and growing (Vaughan et al., 2016; Kihila, 2017; Findlater et al., 2021) but they can be made more inclusive by focussing on addressing uneven uptake based on location or gender (Amegnaglo et al., 2017; Daly and Dessai, 2018; Tall et al., 2018; Alexander and Dessai, 2019; Vaughan et al., 2019; Gumucio et al., 2020) and a more balanced focus on uptake rather than data production alone (Dorward et al., 2021; Findlater et al., 2021) that values co-production and different knowledge systems (Daniels et al., 2020; Martínez-Barón et al., 2021).

CCB FEASIB.3.4.5 Population health and health systems

Climate change will exacerbate existing health challenges. Strong health systems can protect and promote the health of a population in the face of known and unexpected stressors and pressures (Watts et al., 2021), including climate change. The building blocks of strong health systems engender climate resilience, strong leadership and governance, and effective coordination across sectors, to prioritize the needs of the most vulnerable (Ebi et al., 2020). Options for enhancing current health services include providing access to safe water and sanitation, improving food security, enhancing access to essential services such as vaccinations, developing or strengthening integrated surveillance systems, and changing the timing and location of specific vector-control measures (WHO, 2015; Haines and Ebi, 2019). These measures can reduce the health system's vulnerability to climate change, especially if combined with iterative management that incorporates monitoring of (and resilience against) climate change impacts (Hanefeld et al., 2018; Haines and Ebi, 2019; Linares et al., 2020; Rudolph et al., 2020) (medium evidence, high agreement).

Health system can provide sufficient and high quality healthcare to all where capacity is well-developed, and where options are aligned with national priorities, engage local to international communities, and address the needs of particularly vulnerable regions and population groups (Hanefeld et al., 2018; Austin et al., 2019; Nuzzo et al., 2019; Sheehan and Fox, 2020). Microeconomic feasibility and socio-economic vulnerability reduction potential are high where a system's capacity is well-developed. Macroeconomic feasibility poses a significant challenge in low income settings, with many governments projected to require international climate finance for health systems which is not currently available (WHO, 2019; Watts et al., 2021), and where adequate household-level financial security is a cross-cutting barrier (Paudel and Pant, 2020). Risk mitigation potential is high where capacity is well developed, for example through technologies to monitor and alter environmental conditions (Lock-Wah-Hoon et al., 2020; Kouis et al., 2021; Ligsay et al., 2021). Social co-benefits of mainstreaming health and climate change are also present, such as the inclusion of environmental health in medical education curricula training programmes (Kligler et al., 2021). There is growing recognition that lack of institutional capacity and low availability of resources represent major barriers to health system adaptation options, particularly for health systems struggling to manage current health risks (Ebi et al., 2018; Brooke-Sumner et al., 2019; Chersich and Wright, 2019; Gilfillan, 2019; Negev et al., 2019; Hussey and Arku, 2020), for neglected populations (Hanefeld et al., 2018; Negev et al., 2019), and where there are conflicting mandates or poor coordination across ministries (Austin et al., 2019; Fox et al., 2019; Gilfillan, 2019; Kendrovski and Schmoll, 2019; Sheehan and Fox, 2020). Barriers to adapting health systems to climate change include lack of institutional funding, staff, and data access (Austin et al., 2019; Schramm et al., 2020; Opoku et al., 2021), inadequate resources for evaluation and management of adaptation (Pascal et al., 2021), competing stakeholder goals, and costly technology (Negev et al., 2021). Within the healthcare community, surveillance systems generally lack ways to integrate climate observation data, as well as expertise to critically evaluate these data, limiting their ability to plan and prepare for climate hazards and hospital-associated vulnerabilities (Runkle et al., 2018; Chersich and Wright, 2019; Liao et al., 2019). Although understanding on health vulnerability is growing (Berry et al., 2018), knowledge on the health effects of climate change among health practitioners remains limited (Ebi et al., 2018; Brooke-Sumner et al., 2019; Chersich and Wright, 2019; Fox et al., 2019; Liao et al., 2019; Albright et al., 2020). Mechanisms to ensure transparency and accountability of implementing, monitoring, and evaluating adaptation within the health sector are lacking, across scales and contexts (Gostin and Friedman, 2017; Huynh and Stringer, 2018; Parry et al., 2019).

CCB FEASIB.3.4.6 Human migration and displacement

Much climate-related migration is associated with labour migration. Rural-urban migrant networks are important channels for remittances and knowledge that help build resilience to hazards in sending areas (Bragg et al., 2018; Obokata and Veronis, 2018; Semenza and Ebi, 2019; Maharjan et al., 2020; Porst et al., 2020). Whether migration reduces vulnerability for migrants depends on levels of control over the migration decision and assets such as wealth education of the migrant household (Thober et al., 2018; Cattaneo, 2019; Hoffmann et al., 2020; Maharjan et al., 2020; Sedova and Kalkuhl, 2020). Individuals from households of all levels of wealth migrate. However, poorer households do so with lower levels of choice and often more likely under duress, and in these cases migration can undermine wellbeing (Suckall et al., 2016; Mallick et al., 2017; Nawrotzki and DeWaard, 2018; Natarajan et al., 2019). In some cases, migration can increase poverty in sending communities (Jacobson et al., 2019).Women in the sending community can experience an increase or decrease in the vulnerability depending on context (Banerjee et al., 2018; Banerjee et al., 2019; Goodrich et al., 2019; Maharjan et al., 2020; Rao et al., 2020; Singh and Basu, 2020; Singh et al., 2020b). Migration has been highly politicised, and climate-related immigration has been conceptualised in public and media discourse as a potential threat which limit adaptation feasibility (Telford, 2018; Honarmand Ebrahimi and Ossewaarde, 2019; McLeman, 2019; Wiegel et al., 2019; Hauer et al., 2020). Existing international agreements provide potential frameworks for climate-related migration to benefit adaptive capacity and sustainable development (Warner, 2018; Kälin, 2019). However, agreements to facilitate temporary or circular migration and remittances are often informal and limited in scope (Webber and Donner, 2017; Margaret and Matias, 2020) and migrant receiving areas, particularly urban areas, can be better assisted to prepare for population change (Deshpande et al., 2019; Adger et al., 2020; Hauer et al., 2020). Policies and planning are lacking that would ensure that positive migration outcomes for sending and receiving areas and the migrants themselves (Wrathall et al., 2019; Adger et al., 2020; de Salles Cavedon-Capdeville et al., 2020; Hughes, 2020).

Investing in building in situ adaptive capacity through climate resilient development is a precondition to supporting high agency migration (). Migration only tends to occur when adaptation in situ has been exhausted and thresholds for living with risk have been crossed (Sections 8.2.2.1, 8.4.4, 8.4.5) (McLeman, 2018; Adams and Kay, 2019; Semenza and Ebi, 2019). The financial, emotional and social costs of leaving are high (Adams and Kay, 2019; McNamara et al., 2021), there are environmental, health and wellbeing risks in destination areas (Schwerdtle et al., 2018; Schwerdtle et al., 2020) and existential threats to identity and citizenship (Oakes, 2019; Piguet, 2019; Desai et al., 2021). In receiving areas, without appropriate policies to ensure equitable provision of services, there can be socio-cultural barriers to in-migration where there is the perception of a loss caused by new arrivals, although outcomes are mixed (Koubi et al., 2018; Linke et al., 2018; Spilker et al., 2020; Petrova, 2021).

CCB FEASIB.3.4.7 Planned relocation and resettlement

Few climate-related planned resettlement and relocation initiatives have taken place. However, initial findings, and experience from past development and disaster-related resettlement programmes, show that when implemented in a top-down manner and without the full participation of those affected, resettlement increases vulnerability by undermining livelihoods, negatively impacting health, community cohesion and emotional and psychological wellbeing (Wilmsen and Webber, 2015; Dannenberg et al., 2019; Piggott-McKellar et al., 2019; Tabe, 2019; Ajibade et al., 2020; Henrique and Tschakert, 2020; Desai et al., 2021). Planned relocation could also redistribute vulnerability for those who do not move (Thomas and Benjamin, 2018; Mach et al., 2019; Piggott-McKellar et al., 2019; Johnson et al., 2021; Maldonado et al., 2021) and vulnerability generally is reproduced along existing social cleavages often worsening inequality (See and Wilmsen, 2020). Approaches that foreground participation; non-material and socio-cultural factors, livelihoods, and local power dynamics can be addressed and adjusted to prevent planned relocation from reproducing inequality (See and Wilmsen, 2020; Alverio et al., 2021).

There is inadequate institutional capacity to enable movement relocation with global and national policies identified as too abstract and lacking guidance on ensuring equity (Mortreux et al., 2018; Kelman et al., 2019; Ajibade et al., 2020; Hauer et al., 2020; Alverio et al., 2021). Lack of institutional capacity can lead to resettlements being stalled indefinitely. Climate-related resettlement can be facilitated by novel institutional structures that expand the definition of disaster to include slow onset events, adaptive management frameworks that facilitate a continuum of responses from supporting communities to community relocation and approaches that incorporate existing power dynamics (Bronen and Chapin, 2013; See and Wilmsen, 2020). In 2018, the Fiji Government provided a framework for climate change related relocation and equipped communities with rights in the planned relocation process (McMichael and Katonivualiku, 2020). However, even with guidelines in place, local socio-cultural dynamics complicate planning, and relocation should take place only after cost-benefit analysis of all available adaptation options (Jolliffe, 2016).(Bronen and Chapin, 2013; Albert et al., 2017; Mortreux et al., 2018). At a local level, issues around land tenure, a lack of financial support, dedicated governance frameworks and complex planning processes delay action (Albert et al., 2017). Funding for climate-related resettlement is currently not readily available, exacerbated by a lack of appropriate mechanisms through which to deliver that funding (Boston et al., 2021). For example, planned relocation projects cannot access disaster relief funds in the US because of the slow onset nature of the impacts (Bronen and Chapin, 2013).

Without consultation relocated people can experience significant financial and emotional distress as cultural and spiritual bonds to place and livelihoods are disrupted (Neef et al., 2018; Roy et al., 2018; Piggott-McKellar et al., 2019; Bertana, 2020; McMichael and Katonivualiku, 2020; McMichael et al., 2021) - However, in some places, where climate risks are acute, political acceptance for planned relocation is high (e.g. (McNamara, 2015; Roy et al., 2018) in Kiribati). Socio-cultural feasibility can be improved by participatory approaches, and where possible, moving within ancestral lands (McNamara, 2015). In this case, voluntary planned relocation can represent the assertion of people living in an area to preserve land and community-based social, cultural and spiritual ties.

A summary of feasible options to enable four 1.5C-relevant system transitions is presented in Figure Cross-Chapter Box FEASIB.2.

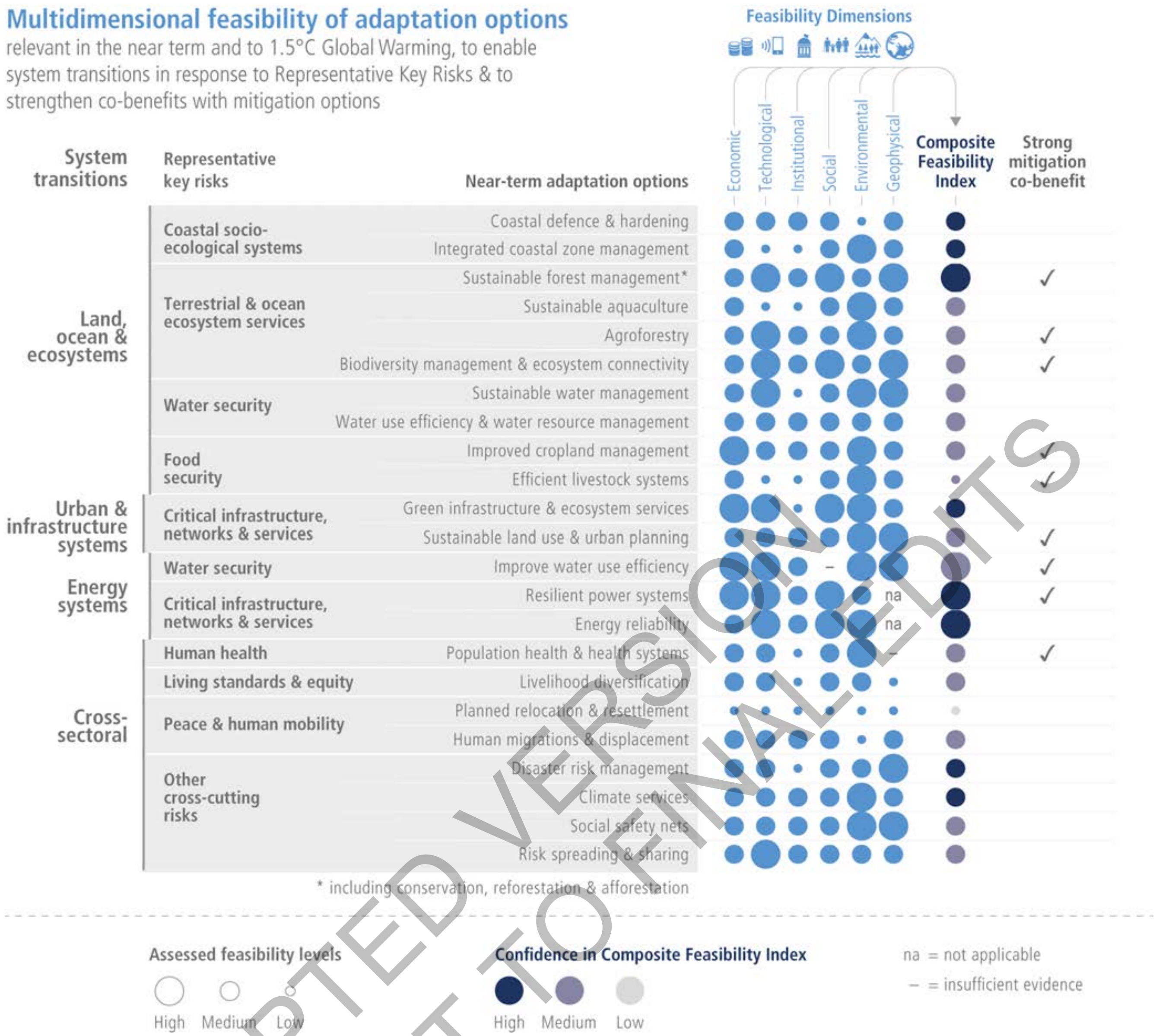
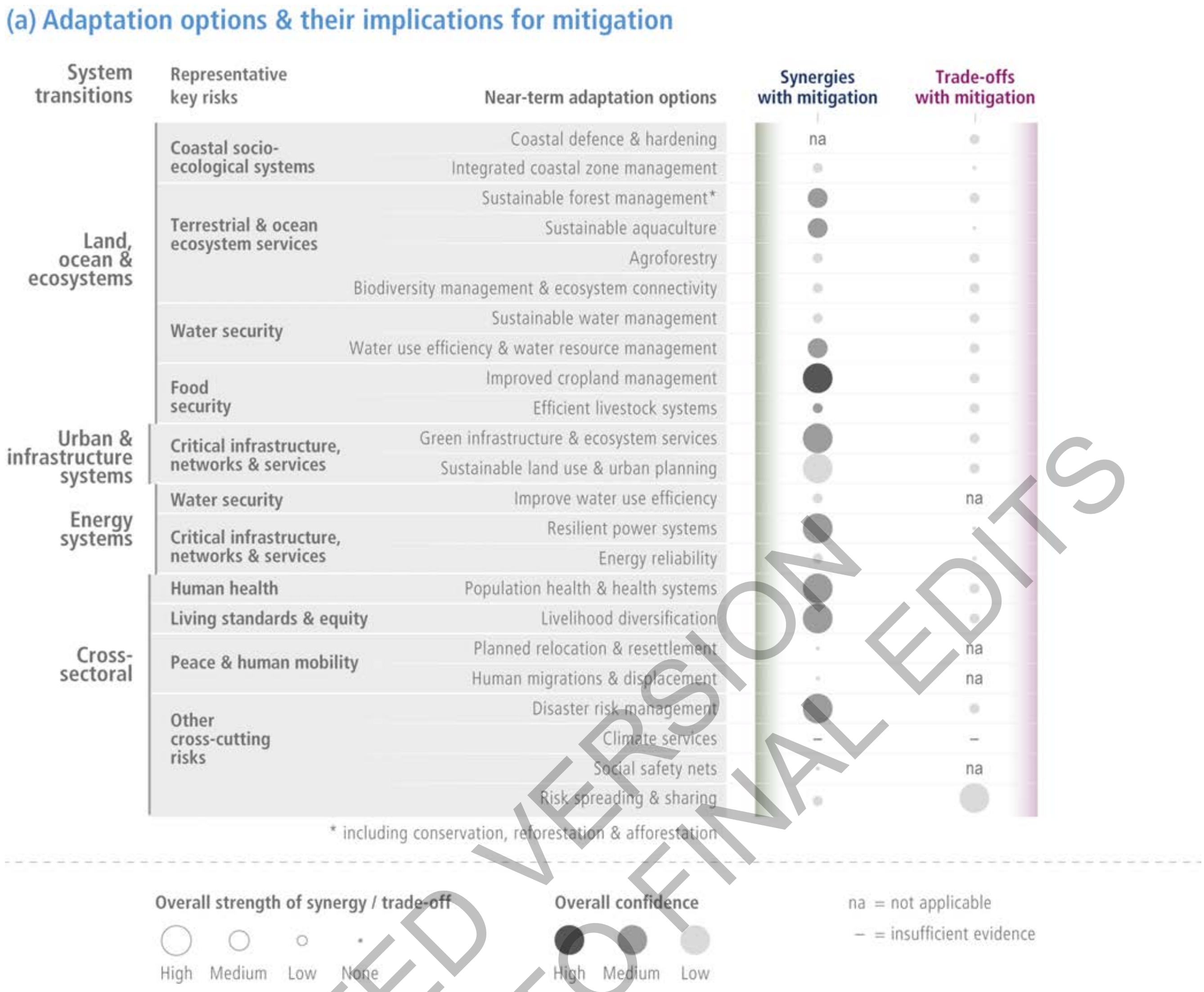


Figure Cross-Chapter Box FEASIB.2: Multi-dimensional feasibility.

CCB FEASIB.4 Synergies and Trade-offs

The feasibility assessment focuses on individual options. However, systems transitions necessitate assessing how mitigation and adaptation options *interact* to mediate overall feasibility. To capture these linkages, this section reports synergies and trade-offs of a) adaptation options for mitigation, and b) mitigation options for adaptation (following (de Coninck et al., 2018) as outcome of an iterative assessment between WG2 and WG3 authors. Also assessed are synergies and tradeoffs of adaptation with the SDGs following (Roy et al., 2018) (which was done for mitigation alone).


(a) Adaptation options & their implications for mitigation
System transitions
Representative key risks
Near-term adaptation options
Synergies with mitigation
Trade-offs with mitigation
Land, ocean & ecosystems
Coastal socio-ecological systems
Coastal defence & hardening
Integrated coastal zone management
Terrestrial & ocean ecosystem services
Sustainable forest management*
Sustainable aquaculture
Agroforestry
Biodiversity management & ecosystem connectivity
Water security
Sustainable water management
Water use efficiency & water resource management
Food security
Improved cropland management
Efficient livestock systems
Urban & infrastructure systems
Critical infrastructure, networks & services
Green infrastructure & ecosystem services
Sustainable land use & urban planning
Energy systems
Water security
Improve water use efficiency
Critical infrastructure, networks & services
Resilient power systems
Energy reliability
Cross-sectoral
Human health
Population health & health systems
Living standards & equity
Livelihood diversification
Peace & human mobility
Planned relocation & resettlement
Human migrations & displacement
Other cross-cutting risks
Disaster risk management
Climate services
Social safety nets
Risk spreading & sharing
na
na
na
na
na
–
–
* including conservation, reforestation & afforestation
Overall strength of synergy / trade-off
High
Medium
Low
None
Overall confidence
High
Medium
Low
na = not applicable
– = insufficient evidence

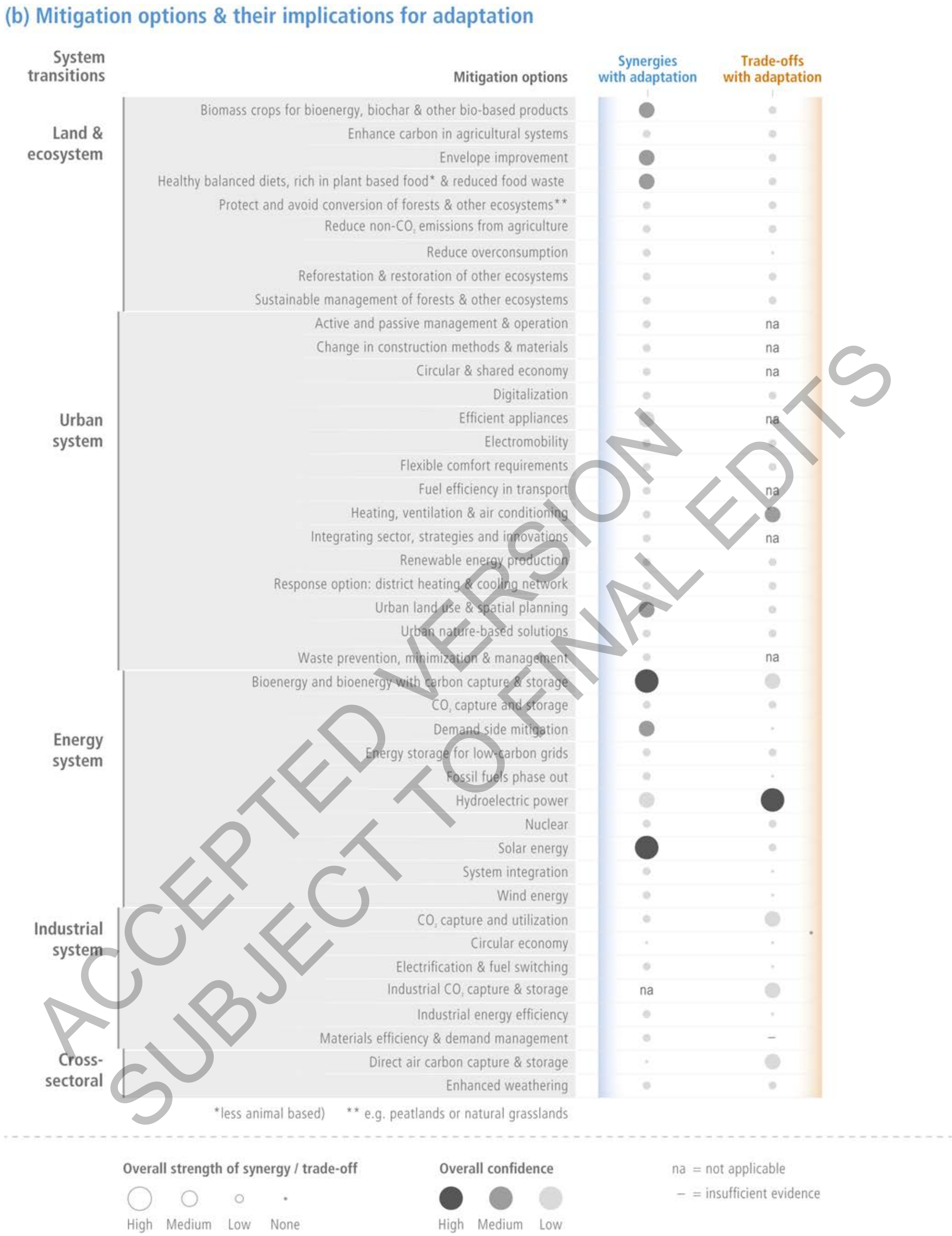


Figure Cross-Chapter Box FEASIB.3: Synergies and trade-offs. This figure shows a) adaptation options synergies and trade-offs with mitigation and b) mitigation options synergies and trade-offs with adaptation. The size of the circle denotes the strength of the synergy or trade-offs with big circles meaning strong synergy or trade-off and small circles denoting a weak synergy or trade-off.

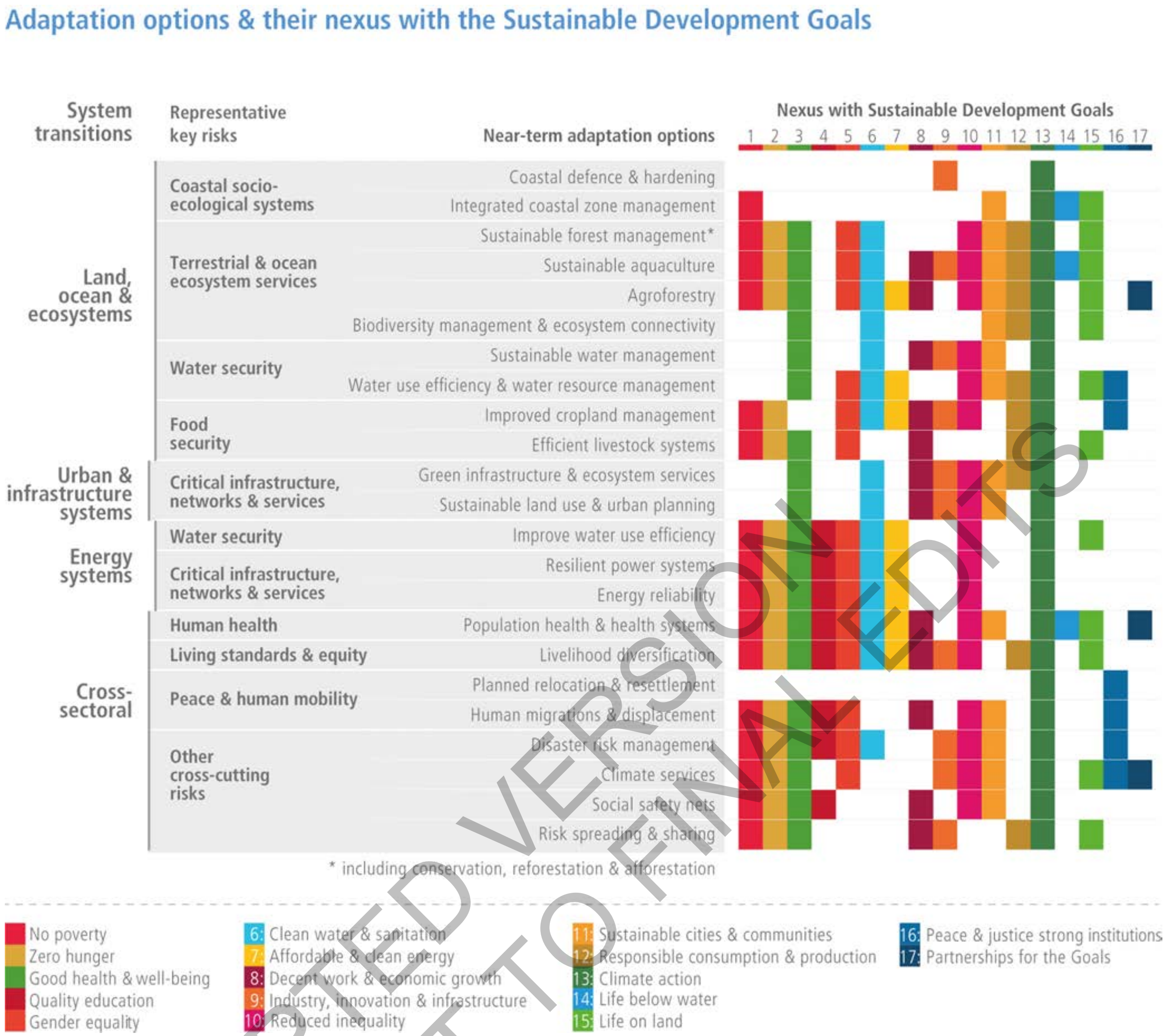


Figure Cross-Chapter Box FEASIB.4: Adaptation options and their nexus with the Sustainable Development Goals.

CCB FEASIB.5 Knowledge Gaps

Despite the progress in new evidence since the SR1.5, there remain several knowledge gaps for the assessment of adaptation and mitigation options. They are found within the Figure Cross-Chapter Box FEASIB.2 through the NE (no evidence) or LE (low evidence).

Within energy system transitions, resilient power infrastructure has knowledge gaps on indicators of transparency and accountability potential, socio-cultural acceptability, social and regional inclusiveness and intergenerational equity.

Under land and ecosystem system transitions, gaps include limited evidence for some of the institutional and socio-cultural feasibility dimensions indicators of Integrated Coastal Zone Management. Specifically, there is lack of evidence for transparency and accountability potential and for gender and intergenerational equity. For coastal defense and hardening, there is no or limited evidence on the indicators of employment and productivity enhancement, legal and regulatory acceptability, transparency and accountability potential, social and regional inclusiveness, benefits for gender equity, intergenerational equity and land use change enhancement potential. Sustainable aquaculture has knowledge gaps for the indicators of macroeconomic viability, legal and regulatory acceptability, transparency and accountability potential, social and regional inclusiveness, intergenerational equity and land use change enhancement potential. The geographical feasibility for migration and relocation is still an emerging area of research, however, there is limited evidence to assess this specific dimension.

The option of reforestation, afforestation, protection of forests and wild areas and their resources, biodiversity management and conservation has knowledge gaps for the indicators of risk mitigation potential, legal and regulatory feasibility and social and regional inclusiveness. The option of improved cropland management has no or limited evidence for the indicators of legal and regulatory feasibility, transparency and accountability potential and hazard risk reduction potential. Efficient livestock systems has no evidence for political acceptability and legal and regulatory feasibility and limited evidence for overall institutional feasibility. Agroforestry has knowledge gaps for employment and productivity enhancement, transparency and accountability potential and intergenerational equity. There is also limited evidence for the economic and technical feasibility dimensions for ecosystem connectivity.

For urban and infrastructure systems, the option of green infrastructure and ecosystem services has limited evidence for macroeconomic viability, employment and productivity enhancement and political acceptability. Sustainable water management has gaps for macroeconomic viability, employment and productivity enhancement, and transparency and accountability potential.

For overarching options, the main knowledge gaps identified are socio-cultural acceptability for social safety nets. While the evidence on resettlement, relocation and migration is large and growing, there is disagreement on several indicators, marking the need for more evidence synthesis. Geophysical feasibility for resettlement, relocation and migration has limited evidence, but is an emerging area of research.

In general, throughout most of the options, there is significantly less literature from the regions of Central and South America and West and Central Asia, as compared to other world regions.

References

Accatino, F. et al., 2019: Trade-offs and synergies between livestock production and other ecosystem services. *Agricultural Systems*, **168**, 58-72, doi:10.1016/j.agsy.2018.08.002.

Acevedo, M. et al., 2020: A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nature Plants*, **6**, 1231-1241, doi:10.1038/s41477-020-00783-z.

Adams, A. M. et al., 2020: Long-term effects of integrated soil fertility management practices on soil chemical properties in the Sahel. *Geoderma*, **366**, 114207, doi:10.1016/j.geoderma.2020.114207.

Adams, H. and S. Kay, 2019: Migration as a human affair: Integrating individual stress thresholds into quantitative models of climate migration. *Environmental Science and Policy*, **93**, 129-138, doi:10.1016/j.envsci.2018.10.015.

Adem Esmail, B. and L. Suleiman, 2020: Analyzing Evidence of Sustainable Urban Water Management Systems: A Review through the Lenses of Sociotechnical Transitions. *Sustainability*, **12**(11), doi:10.3390/su12114481.

Adger, W. N. et al., 2020: Urbanization, Migration, and Adaptation to Climate Change. *One Earth*, **3**, 396-399, doi:10.1016/j.oneear.2020.09.016.

Adham, A. et al., 2018: A GIS-based approach for identifying potential sites for harvesting rainwater in the Western Desert of Iraq. *International Soil and Water Conservation Research*, **6**(4), 297-304, doi:https://doi.org/10.1016/j.iswcr.2018.07.003.

Aerts, J. C. J. H., 2018: A Review of Cost Estimates for Flood Adaptation.

Agarwal, P. K. (ed.), Impact of Pesticide : An Overview A comparative economic analysis of SRI and traditional method of Paddy Cultivation View project ECONOMIC APPRAISAL OF SOYBEAN CULTIVATION IN MADHYA PRADESH INDIA; ISSUES. OF GROWTH AND SUSTAINABILITY View project.

AGEGNEHU, G. and T. AMEDE, 2017: Integrated Soil Fertility and Plant Nutrient Management in Tropical Agro-Ecosystems: A Review. Soil Science Society of China, 662-680 pp.

Ahmed, B., 2018: Who takes responsibility for the climate refugees? *International Journal of Climate Change Strategies and Management*, **10**, 5-26, doi:10.1108/IJCCSM-10-2016-0149.

Ahmed, N. et al., 2018: Blue-Green Water Nexus in Aquaculture for Resilience to Climate Change. *Reviews in Fisheries Science and Aquaculture*, **26**, 139-154, doi:10.1080/23308249.2017.1373743.

Ajibade, I., 2019: Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. *Climatic Change*, doi:10.1007/s10584-019-02535-1.

Ajibade, I., M. Sullivan and M. Haeffner, 2020: Why climate migration is not managed retreat: Six justifications. *Global Environmental Change*, **65**, 102187, doi:10.1016/J.GLOENVCHA.2020.102187.

Albert, S. et al., 2017: Winners and losers as mangrove, coral and seagrass ecosystems respond to sea-level rise in Solomon Islands. *Environmental Research Letters*, **12**, 94009.

Albright, K., P. Shah, M. Santodomingo and J. Scandlyn, 2020: Dissemination of information about climate change by state and local public health departments: United states, 2019-2020. *American Journal of Public Health*, **110**, 1184-1190, doi:10.2105/AJPH.2020.305723.
Aleksandrova, M., 2020: Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries. *Climate and Development*, **12**, 511-520, doi:10.1080/17565529.2019.1642180.
Alexander, M. and S. Dessai, 2019: What can climate services learn from the broader services literature? *Climatic Change*, **157**, 133-149, doi:10.1007/s10584-019-02388-8.
Ali, B. and A. Kumar, 2016: Development of life cycle water footprints for gas-fired power generation technologies. *Energy Conversion and Management*, **110**, 386-396, doi:https://doi.org/10.1016/j.enconman.2015.12.048.
Ali, T. et al., 2021: Integrating Indigenous perspectives and community-based disaster risk reduction: A pathway for sustainable Indigenous development in Northern Pakistan. *International Journal of Disaster Risk Reduction*, **59**, 102263, doi:https://doi.org/10.1016/j.ijdrr.2021.102263.
Alleway, H. K. et al., 2018: The Ecosystem Services of Marine Aquaculture: Valuing Benefits to People and Nature. *BioScience*, **69**, 59-68, doi:10.1093/biosci/biy137.
Almutairi, A., M. Mourshed and R. F. M. Ameen, 2020: Coastal community resilience frameworks for disaster risk management. Springer, 595-630 pp.
Alobo Loison, S., 2015: Rural Livelihood Diversification in Sub-Saharan Africa: A Literature Review. *The Journal of Development Studies*, **51**, 1125-1138, doi:10.1080/00220388.2015.1046445.
Alverio, G. N., S. H. Hoagland, E. C. d. Perez and K. J. Mach, 2021: The role of international organizations in equitable and just planned relocation. *Journal of Environmental Studies and Sciences*, 1-12, doi:10.1007/S13412-021-00698-X.
Alves, A. et al., 2019: Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of Environmental Management*, **239**, 244-254, doi:https://doi.org/10.1016/j.jenvman.2019.03.036.
Alves, B., D. B. Angnuureng, P. Morand and R. Almar, 2020: A review on coastal erosion and flooding risks and best management practices in West Africa: what has been done and should be done. *Journal of Coastal Conservation*, **24**, 38, doi:10.1007/s11852-020-00755-7.
Ambrosino, C. et al., 2020: Integrating Climate Adaptation, Poverty Reduction, and Environmental Conservation in Kwale County, Kenya. Springer International Publishing, 1-19 pp.
Amegnaglo, C. J. et al., 2017: Contingent valuation study of the benefits of seasonal climate forecasts for maize farmers in the Republic of Benin, West Africa. *Climate Services*, **6**, 1-11, doi:https://doi.org/10.1016/j.cliser.2017.06.007.
Amjath-Babu, T. S., P. K. Aggarwal and S. Vermeulen, 2019: Climate action for food security in South Asia? Analyzing the role of agriculture in nationally determined contributions to the Paris agreement. *Climate Policy*, **19**, 283-298, doi:10.1080/14693062.2018.1501329.
Anderson, C. C. and F. G. Renaud, 2021: A review of public acceptance of nature-based solutions: The 'why', 'when', and 'how' of success for disaster risk reduction measures. *Ambio*, **50**(8), 1552-1573, doi:10.1007/s13280-021-01502-4.
Anderson, S. C. et al., 2017: Benefits and risks of diversification for individual fishers. *Proceedings of the National Academy of Sciences of the United States of America*, **114**, 10797-10802, doi:10.1073/pnas.1702506114.
Anguelovski, I. et al., 2019a: New scholarly pathways on green gentrification: What does the urban 'green turn' mean and where is it going? *Progress in Human Geography*, **43**, 1064-1086, doi:10.1177/0309132518803799.
Anguelovski, I., C. Irazábal-Zurita and J. J. T. Connolly, 2019b: Grabbed Urban Landscapes: Socio-spatial Tensions in Green Infrastructure Planning in Medellín. *International Journal of Urban and Regional Research*, **43**, 133-156, doi:10.1111/1468-2427.12725.
Antunes do Carmo, J. S., 2018: Climate Change, Adaptation Measures, and Integrated Coastal Zone Management: The New Protection Paradigm for the Portuguese Coastal Zone. Coastal Education Research Foundation Inc., 687-703 pp.
Apuri, I., K. Peprah and G. T. W. Achana, 2018: Climate change adaptation through agroforestry: The case of Kassena Nankana West District, Ghana. *Environmental Development*, **28**, 32-41, doi:10.1016/j.envdev.2018.09.002.
Araos, M., 2020: Democracy Underwater: Public Participation and Technical Expertise in Climate Infrastructure Planning in New York City. *Social Science Research Network*.
Araos, M., S. E. Austin, L. Berrang-Ford and J. D. Ford, 2016a: Public health adaptation to climate change in large cities: A global baseline. *International Journal of Health Services*, **46**, 53-78, doi:10.1177/0020731415621458.
Araos, M. et al., 2016b: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science & Policy*, **66**, 375-382, doi:10.1016/j.envsci.2016.06.009.
Archer, D., 2016: Building urban climate resilience through community-driven approaches to development. *International Journal of Climate Change Strategies and Management*, **8**, 654-669, doi:10.1108/IJCCSM-03-2014-0035.
Aryal, J. P. et al., 2018a: Adoption of multiple climate-smart agricultural practices in the Gangetic plains of Bihar, India. *International Journal of Climate Change Strategies and Management*, **10**, 407-427, doi:10.1108/IJCCSM-02-2017-0025.

Aryal, J. P., M. B. Mehrotra, M. L. Jat and H. S. Sidhu, 2015a: Impacts of laser land leveling in rice–wheat systems of the north–western indo-gangetic plains of India. *Food Security*, **7**, 725-738, doi:10.1007/s12571-015-0460-y.
Aryal, J. P. et al., 2018b: Factors determining the adoption of laser land leveling in the irrigated rice–wheat system in Haryana, India. *Journal of Crop Improvement*, **32**, 477-492, doi:10.1080/15427528.2018.1457584.
Aryal, J. P., D. B. Rahut, S. Maharjan and O. Erenstein, 2018c: Factors affecting the adoption of multiple climate-smart agricultural practices in the Indo-Gangetic Plains of India. *Natural Resources Forum*, **42**, 141-158, doi:10.1111/1477-8947.12152.
Aryal, J. P., T. B. Sapkota, M. L. Jat and D. K. Bishnoi, 2015b: On-farm economic and environmental impact of zero-tillage wheat: A case of North-West India. *Experimental Agriculture*, **51**, 1-16, doi:10.1017/S001447971400012X.
Aryal, J. P. et al., 2020a: Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environment, Development and Sustainability*, **22**, 5045-5075, doi:10.1007/s10668-019-00414-4.
Aryal, J. P., T. B. Sapkota, D. B. Rahut and M. L. Jat, 2020b: Agricultural sustainability under emerging climatic variability: the role of climate-smart agriculture and relevant policies in India. *International Journal of Innovation and Sustainable Development*, **14**, 219-245.
Asfaw, S., G. Pallante and A. Palma, 2018: Diversification Strategies and Adaptation Deficit: Evidence from Rural Communities in Niger. *World Development*, **101**, 219-234, doi:10.1016/j.worlddev.2017.09.004.
Atanga, R. A., 2020: The role of local community leaders in flood disaster risk management strategy making in Accra. *International Journal of Disaster Risk Reduction*, **43**, doi:10.1016/j.ijdrr.2019.101358.
Aubin, J. et al., 2019: Implementing ecological intensification in fish farming: definition and principles from contrasting experiences. *Reviews in Aquaculture*, **11**, 149-167, doi:10.1111/raq.12231.
Austin, S. E. et al., 2019: Enabling local public health adaptation to climate change. *Social Science and Medicine*, **220**, 236-244, doi:10.1016/j.socscimed.2018.11.002.
Awazi, N. P., M. N. Tchamba and L. F. Temgoua, 2021: Climate-Smart Practices of Smallholder Farmers in Cameroon Confronted with Climate Variability and Change: The Example of Agroforestry. *Agricultural Research*, **10**, 83-96, doi:10.1007/s40003-020-00477-0.
Bageant, E. R. and C. B. Barrett, 2017: Are There Gender Differences in Demand for Index-Based Livestock Insurance? *Journal of Development Studies*, **53**, 932-952, doi:10.1080/00220388.2016.1214717.
Baills, A., M. Garcin and T. Bulteau, 2020: Assessment of selected climate change adaptation measures for coastal areas. *Ocean and Coastal Management*, **185**, 105059, doi:10.1016/j.ocecoaman.2019.105059.
Baird, T. D. and J. Hartter, 2017: Livelihood diversification, mobile phones and information diversity in Northern Tanzania. *Land Use Policy*, **67**, 460-471, doi:10.1016/j.landusepol.2017.05.031.
Banerjee, S. et al., 2018: Assessing vulnerability of remittance-recipient and nonrecipient households in rural communities affected by extreme weather events: Case studies from S outh-W est. *Wiley Online Library*, **25**, doi:10.1002/psp.2157.
Banerjee, S., A. Hussain, S. Tuladhar and A. Mishra, 2019: Building capacities of women for climate change adaptation: Insights from migrant-sending households in Nepal. *Climatic Change*, **157**, 587-609, doi:10.1007/S10584-019-02572-W.
Barnett, J. et al., 2015: From barriers to limits to climate change adaptation: Path dependency and the speed of change. *Ecology and Society*, **20**, doi:10.5751/ES-07698-200305.
Barragán Muñoz, J. M., 2020: Progress of coastal management in Latin America and the Caribbean. *Ocean and Coastal Management*, **184**, 105009, doi:10.1016/j.ocecoaman.2019.105009.
Barreto, G. C., M. Di Domenico and R. P. Medeiros, 2020: Human dimensions of marine protected areas and small-scale fisheries management: A review of the interpretations. *Marine Policy*, **119**, 104040, doi:https://doi.org/10.1016/j.marpol.2020.104040.
Barrett, S., 2013: Local level climate justice? Adaptation finance and vulnerability reduction. *Global Environmental Change*, **23**(6), 1819-1829, doi:https://doi.org/10.1016/j.gloenvcha.2013.07.015.
Bazaz, A. et al. (eds.), Summary for Urban Policymakers – What the IPCC Special Report on 1.5C Means for Cities.
Bedeke, S. et al., 2019: Adoption of climate change adaptation strategies by maize-dependent smallholders in Ethiopia. *NJAS - Wageningen Journal of Life Sciences*, **88**, 96-104, doi:https://doi.org/10.1016/j.njas.2018.09.001.
Belčáková, I., M. Świąder and M. Bartyna-Zielińska, 2019: The Green Infrastructure in Cities as A Tool for Climate Change Adaptation and Mitigation: Slovakian and Polish Experiences. *Atmosphere*, **10**(9), doi:10.3390/atmos10090552.
Berrang-Ford, L. et al., 2019: Tracking global climate change adaptation among governments. *Nature Climate Change*, **9**, 440-449, doi:10.1038/s41558-019-0490-0.
Berry, P. et al., 2018: Assessing health vulnerabilities and adaptation to climate change: A review of international progress. MDPI AG.
Bertana, A., 2020: The role of power in community participation: Relocation as climate change adaptation in Fiji. *Environment and Planning C: Politics and Space*, **38**(5), 902-919, doi:10.1177/2399654420909394.
Bhatta, G. D. et al., 2017: Agricultural innovation and adaptation to climate change: empirical evidence from diverse agro-ecologies in South Asia. *Environment, Development and Sustainability*, **19**, 497-525, doi:10.1007/s10668-015-9743-x.

Bhattarai, B., 2020: How do gender relations shape a community's ability to adapt to climate change? Insights from Nepal's community forestry. *Climate and Development*, **12**, 876-887, doi:10.1080/17565529.2019.1701971.
Bhowmik, J., H. M. Irfanullah and S. A. Selim, 2021: Empirical evidence from Bangladesh of assessing climate hazard-related loss and damage and state of adaptive capacity to address them. *Climate Risk Management*, **31**, 100273, doi:10.1016/j.crm.2021.100273.
Biernacka, M. and J. Kronenberg, 2018: Classification of institutional barriers affecting the availability, accessibility and attractiveness of urban green spaces. *Urban Forestry & Urban Greening*, **36**, 22-33, doi:https://doi.org/10.1016/j.ufug.2018.09.007.
Biesbroek, G. R., J. E. M. Klostermann, C. J. A. M. Termeer and P. Kabat, 2013: On the nature of barriers to climate change adaptation. *Regional Environmental Change*, **13**, 1119-1129, doi:10.1007/s10113-013-0421-y.
Blasiak, R. and C. C. C. Wabnitz, 2018: Aligning fisheries aid with international development targets and goals. *Marine Policy*, **88**, 86-92, doi:10.1016/j.marpol.2017.11.018.
Blasiak, R. et al., 2019: Towards greater transparency and coherence in funding for sustainable marine fisheries and healthy oceans. *Marine Policy*, **107**, 103508, doi:10.1016/j.marpol.2019.04.012.
Bohnes, F. A., M. Z. Hauschild, J. Schlundt and A. Laurent, 2019: Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture*, **11**, 1061-1079, doi:https://doi.org/10.1111/raq.12280.
Booth, L. et al., 2020: Simulating synergies between Climate Change Adaptation and Disaster Risk Reduction stakeholders to improve management of transboundary disasters in Europe. *International Journal of Disaster Risk Reduction*, **49**, 101668, doi:https://doi.org/10.1016/j.ijdrr.2020.101668.
Bordner, A. S., C. E. Ferguson and L. Ortolano, 2020: Colonial dynamics limit climate adaptation in Oceania: Perspectives from the Marshall Islands. *Global Environmental Change*, **61**, 102054, doi:https://doi.org/10.1016/j.gloenvcha.2020.102054.
Boston, J., A. Panda and S. Surminski, 2021: Designing a funding framework for the impacts of slow-onset climate change — insights from recent experiences with planned relocation. *Current Opinion in Environmental Sustainability*, **50**, 159-168, doi:10.1016/j.cosust.2021.04.001.
Botero, C. M. and S. Zielinski, 2020: The implementation of a world-famous tourism ecolabel triggers political support for beach management. *Tourism Management Perspectives*, **35**, 100691, doi:10.1016/j.tmp.2020.100691.
Bowen, T. et al., 2020: Adaptive Social Protection: Building Resilience to Shocks. *Adaptive Social Protection: Building Resilience to Shocks*, doi:10.1596/978-1-4648-1575-1.
Boyd, C. E. et al., 2020: Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *Journal of the World Aquaculture Society*, **51**, 578-633, doi:https://doi.org/10.1111/jwas.12714.
Bragg, C. et al., 2018: Remittances as aid following major sudden-onset natural disasters. *Disasters*, **42**, 3-18, doi:10.1111/DISA.12229.
Brand, U. and A. von Gleich, 2015: Transformation toward a Secure and Precaution-Oriented Energy System with the Guiding Concept of Resilience – Implementation of Low-Exergy Solutions in Northwestern Germany. *Energies*, **8**, 6995-7019, doi:10.3390/en8076995.
Bricknell, I. R. et al., 2021: Resilience of cold water aquaculture: a review of likely scenarios as climate changes in the Gulf of Maine. *Reviews in Aquaculture*, **13**, 460-503, doi:10.1111/RAQ.12483.
Bronen, R. and F. S. Chapin, 2013: Adaptive governance and institutional strategies for climate-induced community relocations in Alaska. *Proceedings of the National Academy of Sciences*, **110**, 9320-9325, doi:10.1073/pnas.1210508110.
Bronen, R. et al., 2020: Usteq: integrating indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation. *Polar Geography*, **43**(2-3), 188-205, doi:10.1080/1088937X.2019.1679271.
Brooke-Sumner, C. et al., 2019: 'Doing more with Less': A qualitative investigation of perceptions of South African health service managers on implementation of health innovations. *Health Policy and Planning*, **34**, 132-140, doi:10.1093/heapol/czz017.
Brown, B., I. Nuberg and R. Llewellyn, 2017: Negative evaluation of conservation agriculture: perspectives from African smallholder farmers. *International Journal of Agricultural Sustainability*, **15**, 467-481, doi:10.1080/14735903.2017.1336051.
Brown, P. R. et al., 2019: Constraints to the capacity of smallholder farming households to adapt to climate change in South and Southeast Asia. *Climate and Development*, **11**, 383-400, doi:10.1080/17565529.2018.1442798.
Bruno Soares, M. and C. Buontempo, 2019: Challenges to the sustainability of climate services in Europe. *WIREs Climate Change*, **10**(4), e587, doi:https://doi.org/10.1002/wcc.587.
Budhathoki, N. K., J. A. Lassa, S. Pun and K. K. Zander, 2019: Farmers' interest and willingness-to-pay for index-based crop insurance in the lowlands of Nepal. *Land Use Policy*, **85**, 1-10, doi:10.1016/j.landusepol.2019.03.029.
Buechler, S. and A. Lutz-Ley, 2019: Livelihoods with multiple stressors: Gendered youth decision-making under global change in rural Northwest Mexico. *Environment and Planning E: Nature and Space*, **3**(4), 1096-1119, doi:10.1177/2514848619878603.
Buijs, A. et al., 2019: Mosaic governance for urban green infrastructure: Upscaling active citizenship from a local government perspective. *Urban Forestry and Urban Greening*, **40**, 53-62, doi:10.1016/J.UFUG.2018.06.011.

Bustamante, M. M. C. et al., 2019: Ecological restoration as a strategy for mitigating and adapting to climate change: lessons and challenges from Brazil. Springer Netherlands, 1249-1270 pp.
Butler, J. R. A. et al., 2020: How Feasible Is the Scaling-Out of Livelihood and Food System Adaptation in Asia-Pacific Islands? *Frontiers in Sustainable Food Systems*, **4**, 43, doi:10.3389/fsufs.2020.00043.
Cantasano, N. et al., 2021: Can ICZM Contribute to the Mitigation of Erosion and of Human Activities Threatening the Natural and Cultural Heritage of the Coastal Landscape of Calabria? *Sustainability*, **13**, doi:10.3390/su13031122.
Carey, J., 2020: Core Concept: Managed retreat increasingly seen as necessary in response to climate change's fury. *Proceedings of the National Academy of Sciences*, **117**, 202008198, doi:10.1073/pnas.2008198117.
Carter, J. G. et al., 2015: Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, **95**, 1-66, doi:10.1016/j.progress.2013.08.001.
Castells-Quintana, D., M. d. P. Lopez-Uribe and T. K. J. McDermott, 2018: Adaptation to climate change: A review through a development economics lens. *World Development*, **104**, 183-196, doi:10.1016/j.worlddev.2017.11.016.
Castle, S. E. et al., 2021: The impacts of agroforestry interventions on agricultural productivity, ecosystem services, and human well-being in low- and middle-income countries: A systematic review. *Campbell Systematic Reviews*, **17**, e1167, doi:10.1002/CL2.1167.
Cattaneo, C., 2019: Migrant networks and adaptation. *Nature Climate Change*, **9**, 907-908, doi:10.1038/s41558-019-0646-y.
Caviedes, V., P. Arenas-Granados and J. M. Barragán-Muñoz, 2020: Regional public policy for Integrated Coastal Zone Management in Central America. *Ocean and Coastal Management*, **186**, 105114, doi:10.1016/j.ocecoaman.2020.105114.
Cechin, A., V. da Silva Araújo and L. Amand, 2021: Exploring the synergy between Community Supported Agriculture and agroforestry: Institutional innovation from smallholders in a brazilian rural settlement. *Journal of Rural Studies*, **81**, 246-258, doi:10.1016/j.jrurstud.2020.10.031.
Cedamon, E., I. Nuberg, B. H. Pandit and K. K. Shrestha, 2018: Adaptation factors and futures of agroforestry systems in Nepal. *Agroforestry Systems*, **92**, 1437-1453, doi:10.1007/s10457-017-0090-9.
Centre, F. a. R. C. R. C. C. (ed.), Managing climate risks through social protection Reducing rural poverty and building resilient agricultural livelihoods. Rome. ISBN 9789251318843.
Chan, C. Y. et al., 2019: Prospects and challenges of fish for food security in Africa. Elsevier B.V., 17-25 pp.
Chan, F. K. S. et al., 2018: "Sponge City" in China—A breakthrough of planning and flood risk management in the urban context. *Land Use Policy*, **76**, 772-778, doi:10.1016/J.LANDUSEPOL.2018.03.005.
Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, **26**, 6134-6155, doi:10.1111/gcb.15310.
Chersich, M. F. and C. Y. Wright, 2019: Climate change adaptation in South Africa: a case study on the role of the health sector. BioMed Central Ltd.
Child, M. and C. Breyer, 2017: Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems. *Energy Policy*, **107**, 11-26, doi:10.1016/j.enpol.2017.04.022.
Chow, J., T. Khanom, R. Hossain and J. Khadim, 2019: Forest Management for Climate Change Adaptation in Bangladesh. Springer, Cham, 39-50 pp.
Chu, E. and K. Michael, 2018: Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. *SAGE journal*
31(1), 139-156, doi:https://doi.org/10.1177%2F0956247818814449.
Chu, E., T. Schenk and J. Patterson, 2018: The Dilemmas of Citizen Inclusion in Urban Planning and Governance to Enable a 1.5 °C Climate Change Scenario. *Urban Planning*, **3**, 128-140, doi:10.17645/up.v3i2.1292.
Coe, R., F. Sinclair and E. Barrios, 2014: Scaling up agroforestry requires research 'in' rather than 'for' development. *Current Opinion in Environmental Sustainability*, **6**, 73-77, doi:10.1016/j.cosust.2013.10.013.
Coirolo, C., S. Commins, I. Haque and G. Pierce, 2013: Climate change and social protection in bangladesh: Are existing programmes able to address the impacts of climate change? *Development Policy Review*, **31**, o74-o90, doi:10.1111/dpr.12040.
Collier, S. J. and S. Cox, 2021: Governing urban resilience: Insurance and the problematization of climate change. *Economy and Society*, **50**(2), 275-296, doi:10.1080/03085147.2021.1904621.
Colven, E., 2020: Thinking beyond success and failure: Dutch water expertise and friction in postcolonial Jakarta. *Environment and Planning C: Politics and Space*, **38**, 961-979, doi:10.1177/2399654420911947.
Coulibaly, J. Y., B. Chiputwa, T. Nakelse and G. Kundhlande, 2017: Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agricultural Systems*, **155**, 52-69, doi:10.1016/j.agsy.2017.03.017.
Cowie, A. L. et al., 2021: Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *GCB Bioenergy*, **13**(8), 1210-1231, doi:https://doi.org/10.1111/gcbb.12844.
Crawford, T. et al., 2021: Disability inclusive disaster risk reduction with culturally and linguistically diverse (CALD) communities in the Hawkesbury-Nepean region: A co-production approach. *International Journal of Disaster Risk Reduction*, **63**, 102430, doi:https://doi.org/10.1016/j.ijdrr.2021.102430.
Cuaton, G. P. and Y. Su, 2020: Local-indigenous knowledge on disaster risk reduction: Insights from the Mamanwa indigenous peoples in Basey, Samar after Typhoon Haiyan in the Philippines. *International Journal of Disaster Risk Reduction*, **48**, 101596, doi:https://doi.org/10.1016/j.ijdrr.2020.101596.

Custódio, M., S. Villasante, R. Calado and A. I. Lillebø, 2020: Valuation of Ecosystem Services to promote sustainable aquaculture practices. *Reviews in Aquaculture*, **12**, 392-405, doi:https://doi.org/10.1111/raq.12324.
D'Aloia, C. C. et al., 2019: Coupled Networks of Permanent Protected Areas and Dynamic Conservation Areas for Biodiversity Conservation Under Climate Change. *Frontiers in Ecology and Evolution*, **7**, 27, doi:10.3389/fevo.2019.00027.
Dai, L., R. Wörner and H. F. M. W. van Rijswick, 2018: Rainproof cities in the Netherlands: approaches in Dutch water governance to climate-adaptive urban planning. *International Journal of Water Resources Development*, **34**, 652-674, doi:10.1080/07900627.2017.1372273.
Daly, M. and S. Dessai, 2018: Examining the Goals of the Regional Climate Outlook Forums: What Role for User Engagement? *Weather, Climate, and Society*, **10**(4), 693-708, doi:10.1175/WCAS-D-18-0015.1.
Daniels, E. et al., 2020: Refocusing the climate services lens: Introducing a framework for co-designing “transdisciplinary knowledge integration processes” to build climate resilience. *Climate Services*, **19**, 100181, doi:https://doi.org/10.1016/j.cliser.2020.100181.
Dannenberg, A. L., H. Frumkin, J. J. Hess and K. L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: public health implications. *Climatic Change*, **153**(1), 1-14, doi:10.1007/s10584-019-02382-0.
Darzi-Naftchali, A. and H. Ritzema, 2018: Integrating Irrigation and Drainage Management to Sustain Agriculture in Northern Iran. *Sustainability*, **10**(6), doi:10.3390/su10061775.
Dasgupta, S. and J. Roy, 2017: Analysing energy intensity trends and decoupling of growth from energy use in Indian manufacturing industries during 1973–1974 to 2011–2012. *Energy Efficiency*, **10**, 925-943, doi:10.1007/s12053-016-9497-9.
Davies, C. M. et al., 2019: Potential of precision livestock farming in small ruminant farming systems. Wageningen Academic Publishers, 717 p. pp.
De Beenhouwer, M., R. Aerts and O. Honnay, 2013: A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. *Agriculture, Ecosystems & Environment*, **175**, 1-7, doi:https://doi.org/10.1016/j.agee.2013.05.003.
de Coninck, H. et al. (eds.), Strengthening and Implementing the Global Response. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthen.
De la Sota, C., V. J. Ruffato-Ferreira, L. Ruiz-García and S. Alvarez, 2019: Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain. *Urban Forestry & Urban Greening*, **40**, 145-151, doi:https://doi.org/10.1016/j.ufug.2018.09.004.
de Salles Cavedon-Capdeville, F. et al., 2020: Climate Change, Extreme Events and Human Mobility in Latin America: Exploring the Links Through National Laws and Policies.
Debie, E., 2020: Multi-criteria evaluation of soil conservation practices to sustainable cropland management in northwest highlands of Ethiopia. *Authorea Preprints*, doi:10.22541/AU.159221547.73795848.
DeNooyer, T. A., J. M. Peschel, Z. Zhang and A. S. Stillwell, 2016: Integrating water resources and power generation: The energy-water nexus in Illinois. *Applied Energy*, **162**, 363-371, doi:10.1016/j.apenergy.2015.10.071.
Depietri, Y. and T. McPhearson, 2017: Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction.
Desai, B. et al., 2021: Addressing the human cost in a changing climate. *Science*, **372**, 1284-1287, doi:10.1126/SCIENCE.ABH4283.
Deshpande, T., K. Michael and K. Bhaskara, 2019: Barriers and enablers of local adaptive measures: a case study of Bengaluru’s informal settlement dwellers. *Local Environment*, **24**, 167-179, doi:10.1080/13549839.2018.1555578.
Dhyani, S. et al., 2021: Agroforestry to achieve global climate adaptation and mitigation targets: Are south asian countries sufficiently prepared? MDPI AG, 303 pp.
Di Gregorio, M. et al., 2019: Multi-level governance and power in climate change policy networks. *Global Environmental Change*, **54**, 64-77, doi:10.1016/j.gloenvcha.2018.10.003.
Donatti, C. I. et al., 2020: Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. *Climatic Change*, **158**, 413-433, doi:10.1007/s10584-019-02565-9.
Dong, X. et al., 2020: Vulnerability of urban water infrastructures to climate change at city level. *Resources, Conservation and Recycling*, **161**, doi:10.1016/J.RESCONREC.2020.104918.
Dooley, K., E. Harrould-Kolieb and A. Talberg, 2021: Carbon-dioxide Removal and Biodiversity: A Threat Identification Framework. *Global Policy*, **12**, 34-44, doi:10.1111/1758-5899.12828.
Dorst, H., A. van der Jagt, R. Raven and H. Runhaar, 2019: Urban greening through nature-based solutions – Key characteristics of an emerging concept. *Sustainable Cities and Society*, **49**, 101620, doi:https://doi.org/10.1016/j.scs.2019.101620.
Dorward, P., G. Clarkson, S. Poskitt and R. Stern, 2021: Putting the farmer at the center of climate services. *One Earth*, **4**(8), 1059-1061, doi:https://doi.org/10.1016/j.oneear.2021.08.004.
Dougill, A. J. et al., 2017: Mainstreaming conservation agriculture in Malawi: Knowledge gaps and institutional barriers. *Journal of Environmental Management*, **195**, 25-34, doi:10.1016/j.jenvman.2016.09.076.

Du, S. et al., 2020: Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. *Global Environmental Change*, **61**, 102037, doi:https://doi.org/10.1016/j.gloenvcha.2020.102037.
Du, X., J. Jian, C. Du and R. D. Stewart, 2021: Conservation management decreases surface runoff and soil erosion. *International Soil and Water Conservation Research*, doi:https://doi.org/10.1016/j.iswcr.2021.08.001.
Duffy, C. et al., 2021: Agroforestry contributions to smallholder farmer food security in Indonesia. *Agroforestry Systems 2021 95:6*, **95**, 1109-1124, doi:10.1007/S10457-021-00632-8.
DuPuis, E. M. and M. Greenberg, 2019: The right to the resilient city: progressive politics and the green growth machine in New York City. *Journal of Environmental Studies and Sciences*, **9**, 352-363, doi:10.1007/s13412-019-0538-5.
Ebi, K. L. et al., 2018: Stress testing the capacity of health systems to manage climate change-related shocks and stresses. *International Journal of Environmental Research and Public Health*, **15**, doi:10.3390/ijerph15112370.
Ebi, K. L. et al., 2020: Transdisciplinary Research Priorities for Human and Planetary Health in the Context of the 2030 Agenda for Sustainable Development. *International Journal of Environmental Research and Public Health*, **17**(23), doi:10.3390/ijerph17238890.
Eisenack, K. et al., 2014: Explaining and overcoming barriers to climate change adaptation. *Nature Climate Change*, **4**, 867-872, doi:10.1038/nclimate2350.
Elagib, N. A. and M. Al-Saidi, 2020: Balancing the benefits from the water–energy–land–food nexus through agroforestry in the Sahel. Elsevier B.V., 140509 pp.
Elliott, R., 2019: 'Scarier than another storm': values at risk in the mapping and insuring of US floodplains. *British Journal of Sociology*, **70**, 1067-1090, doi:10.1111/1468-4446.12381.
Ellison, A. M., A. J. Felson and D. A. Friess, 2020: Mangrove Rehabilitation and Restoration as Experimental Adaptive Management. *Frontiers in Marine Science*, **7**, 327, doi:10.3389/fmars.2020.00327.
Erftemeijer, P. L. A. et al., 2020: Mangrove planting on dredged material: Three decades of nature-based coastal defence along a causeway in the Arabian Gulf. *Marine and Freshwater Research*, **71**, 1062-1072, doi:10.1071/MF19289.
Ericksen, P. and T. Crane (eds.), The feasibility of low emissions development interventions for the East African livestock sector: Lessons from Kenya and Ethiopia The feasibility of low emissions development interventions for the East African livestock sector: Lessons from Kenya and Ethiopia. International Livestock Research Institute. ISBN 9291465429.
Erlinghagen, S. and J. Markard, 2012: Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change. *Energy Policy*, **51**, 895-906, doi:10.1016/j.enpol.2012.09.045.
Escarcha, J. F., J. A. Lassa and K. K. Zander, 2018: Livestock under climate change: A systematic review of impacts and adaptation. *Climate*, **6**, 54, doi:10.3390/cli6030054.
Escobedo, F. J. et al., 2019: Urban forests, ecosystem services, green infrastructure and nature-based solutions: Nexus or evolving metaphors? *Urban Forestry and Urban Greening*, **37**, 3-12, doi:10.1016/J.UFUG.2018.02.011.
Evans, L. S. et al., 2016: Structural and Psycho-Social Limits to Climate Change Adaptation in the Great Barrier Reef Region. *PLOS ONE*, **11**, e0150575.
Fainstein, S. S., 2018: Resilience and justice: planning for New York City. *Urban Geography*, 1-8, doi:10.1080/02723638.2018.1448571.
FAO (ed.), The State of World Fisheries and Aquaculture 2018. Rome, Italy, 227 pp.
Farnworth, C. R. et al., 2017: Gender and inorganic nitrogen: what are the implications of moving towards a more balanced use of nitrogen fertilizer in the tropics? *International Journal of Agricultural Sustainability*, **15**, 136-152, doi:10.1080/14735903.2017.1295343.
Favretto, N. et al., 2020: Delivering Climate-Development Co-Benefits through Multi-Stakeholder Forestry Projects in Madagascar: Opportunities and Challenges. *Land*, **9**, 157, doi:10.3390/land9050157.
Feingold, D., S. Koop and K. van Leeuwen, 2018: The City Blueprint Approach: Urban Water Management and Governance in Cities in the U.S. *Environmental Management*, **61**, 9-23, doi:10.1007/S00267-017-0952-Y.
Filazzola, A., N. Shrestha and J. S. MacIvor, 2019: The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta-analysis. *Journal of Applied Ecology*, **56**, 2131-2143, doi:10.1111/1365-2664.13475.
Findlater, K., S. Webber, M. Kandlikar and S. Donner, 2021: Climate services promise better decisions but mainly focus on better data. *Nature Climate Change*, **11**(9), 731-737, doi:10.1038/s41558-021-01125-3.
Findlater, K. M., M. Kandlikar and T. Satterfield, 2019: Misunderstanding conservation agriculture: Challenges in promoting, monitoring and evaluating sustainable farming. *Environmental Science and Policy*, **100**, 47-54, doi:10.1016/j.envsci.2019.05.027.
Fischer, H. W., 2020: Policy innovations for pro-poor climate support: social protection, small-scale infrastructure, and active citizenship under India's MGNREGA. *Climate and Development*, **12**, 689-702, doi:10.1080/17565529.2019.1676690.
Fitzgibbons, J. and C. Mitchell, 2019: Just urban futures? Exploring equity in "100 Resilient Cities". *World Development*, **122**, 648-659, doi:10.1016/j.worlddev.2019.06.021.
Fleischman, F. et al., 2020: Pitfalls of Tree Planting Show Why We Need People-Centered Natural Climate Solutions. *BioScience*, **70**, 947-950, doi:10.1093/biosci/biaa094.

Ford, J. D. et al., 2015: Adaptation tracking for a post-2015 climate agreement. *Nature Climate Change*, **5**, 967-969, doi:10.1038/nclimate2744.
Ford, J. D., J. Labbé, M. Flynn and M. Araos, 2017: Readiness for climate change adaptation in the Arctic: a case study from Nunavut, Canada. *Climatic Change*, **145**, 85-100, doi:10.1007/s10584-017-2071-4.
Ford, J. D. et al., 2014: Adapting to the Effects of Climate Change on Inuit Health. *American Journal of Public Health*, **104**, e9-e17, doi:10.2105/AJPH.2013.301724.
Forster, E. J., J. R. Healey, C. Dymond and D. Styles, 2021: Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. *Nature Communications*, **12**(1), 3831, doi:10.1038/s41467-021-24084-x.
Foti, E., R. E. Musumeci and M. Stagnitti, 2020: Coastal defence techniques and climate change: a review. *Rendiconti Lincei*, **31**, 123-138, doi:10.1007/s12210-020-00877-y.
Fox, M. et al., 2019: Integrating public health into climate change policy and planning: State of practice update. MDPI AG.
Freduah, G., P. Fidelman and T. F. Smith, 2018: Mobilising adaptive capacity to multiple stressors: Insights from small-scale coastal fisheries in the Western Region of Ghana. *Geoforum*, **91**, 61-72, doi:10.1016/j.geoforum.2018.02.026.
Fuss, S. et al., 2018: Negative emissions – Part 2: Costs, potentials and side effects. *Environmental Research Letters*, **13**, 063002, doi:10.1088/1748-9326/aabf9f.
Galappaththi, E. K., J. D. Ford and E. M. Bennett, 2019: A framework for assessing community adaptation to climate change in a fisheries context. Elsevier Ltd, 17-26 pp.
Galappaththi, E. K. et al., 2020: Climate change adaptation in aquaculture. *Reviews in Aquaculture*, **12**, 2160-2176, doi:10.1111/raq.12427.
García Romero, H. and A. Molina (eds.), Agriculture and Adaptation to Climate Change: The Role of Insurance in Risk Management: The Case of Colombia. Washington DC, USA, Inter-American Development Bank (IDB), 49 pp.
Gartrell, A., E. Calgaro, G. Goddard and N. Saorath, 2020: Disaster experiences of women with disabilities: Barriers and opportunities for disability inclusive disaster risk reduction in Cambodia. *Global Environmental Change*, **64**, 102134, doi:https://doi.org/10.1016/j.gloenvcha.2020.102134.
Gautam, Y. and P. Andersen, 2016: Rural livelihood diversification and household well-being: Insights from Humla, Nepal. *Journal of Rural Studies*, **44**, 239-249, doi:10.1016/j.jrurstud.2016.02.001.
Geekiyanage, D., K. Keraminiyage, T. Fernando and T. Jayawickrama, 2021: Factors influencing acceptance or rejection regarding being the host community for post-disaster resettlements in developing countries. *International Journal of Disaster Risk Reduction*, **53**, 101973, doi:10.1016/J.IJDRR.2020.101973.
Georgeson, L., M. Maslin, M. Poessinouw and S. Howard, 2016: Adaptation responses to climate change differ between global megacities. *Nature Climate Change*, **6**, 584-588, doi:10.1038/nclimate2944.
Ghiasian, M. et al., 2021: Dissipation of wave energy by a hybrid artificial reef in a wave simulator: implications for coastal resilience and shoreline protection. *Limnology and Oceanography: Methods*, **19**(1), 1-7, doi:https://doi.org/10.1002/lom3.10400.
Ghosh-Jerath, S. et al., 2021: Pathways of Climate Change Impact on Agroforestry, Food Consumption Pattern, and Dietary Diversity Among Indigenous Subsistence Farmers of Sauria Paharia Tribal Community of India: A Mixed Methods Study. *Frontiers in Sustainable Food Systems*, **0**, 174, doi:10.3389/FSUFS.2021.667297.
Gibb, R., L. H. V. Franklinos, D. W. Redding and K. E. Jones, 2020: Ecosystem perspectives are needed to manage zoonotic risks in a changing climate. *The BMJ*, **371**, doi:10.1136/bmj.m3389.
Gilfillan, D., 2019: The health sector's role in governance of climate change adaptation in Myanmar. *Climate and Development*, **11**, 574-584, doi:10.1080/17565529.2018.1510364.
Glaas, E., E. C. H. Keskitalo and M. Hjerpe, 2017: Insurance sector management of climate change adaptation in three Nordic countries: the influence of policy and market factors. *Journal of Environmental Planning and Management*, **60**, 1601-1621, doi:10.1080/09640568.2016.1245654.
Glantz, M. H. and G. E. Pierce, 2021: Forecast Hesitancy: Why are People Reluctant to Believe, Accept, or Respond to Various Weather, Water, and Climate Hazard-Related Forecasts? *International Journal of Disaster Risk Science*, **12**(4), 600-609, doi:10.1007/s13753-021-00353-7.
Goetz, E. G., R. A. Williams and A. Damiano, 2020: Whiteness and Urban Planning. Routledge, 142-156 pp.
Goh, K., 2020: Flows in formation: The global-urban networks of climate change adaptation. *Urban Studies*, **57**, 2222-2240, doi:10.1177/0042098018807306.
Gómez Martín, E., M. Máñez Costa and K. Schwerdtner Máñez, 2020: An operationalized classification of Nature Based Solutions for water-related hazards: From theory to practice. *Ecological Economics*, **167**, 106460, doi:10.1016/j.ecolecon.2019.106460.
Goniewicz, K. and F. M. Burkle, 2019: Challenges in Implementing Sendai Framework for Disaster Risk Reduction in Poland. *International Journal of Environmental Research and Public Health*, **16**(14), doi:10.3390/ijerph16142574.
Gonzalez-Sanchez, E. J. et al., 2019: Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. *Soil and Tillage Research*, **190**, 22-30, doi:10.1016/j.still.2019.02.020.
Goodrich, C. G., A. Prakash and P. B. Udas, 2019: Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. *Environmental Development*, **31**, 1-8, doi:10.1016/J.ENVDEV.2019.01.001.

Gopal, N. et al., 2020: Expanding the horizons for women in fisheries and aquaculture. *Gender, Technology and Development*, **24**, 1-9, doi:10.1080/09718524.2020.1736353.
Goryushina, E. M., 2021: Challenges of the Sendai Framework for Disaster Risk Reduction Adaption in Russia. *IOP Conference Series: Earth and Environmental Science*, **720**(1), 012101, doi:10.1088/1755-1315/720/1/012101.
Gostin, L. O. and E. A. Friedman, 2017: Global Health: A Pivotal Moment Of Opportunity And Peril. *Health Affairs*, **36**(1), 159-165, doi:10.1377/hlthaff.2016.1492.
Goulden, M. C., W. N. Adger, E. H. Allison and D. Conway, 2013: Limits to Resilience from Livelihood Diversification and Social Capital in Lake Social–Ecological Systems. *Annals of the Association of American Geographers*, **103**, 906-924, doi:10.1080/00045608.2013.765771.
Griscom, B. W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114**, 11645-11650, doi:10.1073/pnas.1710465114.
Gu, L. et al., 2019: The contribution of internal climate variability to climate change impacts on droughts. *Science of The Total Environment*, **684**, 229-246, doi:https://doi.org/10.1016/j.scitotenv.2019.05.345.
Gumucio, T., J. Hansen, S. Huyer and T. van Huysen, 2020: Gender-responsive rural climate services: a review of the literature. *Climate and Development*, **12**(3), 241-254, doi:10.1080/17565529.2019.1613216.
Gundersen, P. et al., 2021: Old-growth forest carbon sinks overestimated. *Nature*, **591**(7851), E21-E23, doi:10.1038/s41586-021-03266-z.
Haines, A. and K. Ebi, 2019: The Imperative for Climate Action to Protect Health. *New England Journal of Medicine*, **380**, 263-273, doi:10.1056/nejmra1807873.
Hamin, E. et al., 2018: Pathways to Coastal Resiliency: The Adaptive Gradients Framework. *Sustainability*, **10**, 2629, doi:10.3390/su10082629.
Han, D. et al., 2018: Large soil organic carbon increase due to improved agronomic management in the North China Plain from 1980s to 2010s. *Global Change Biology*, **24**, 987-1000, doi:10.1111/gcb.13898.
Hanefeld, J. et al., 2018: Towards an understanding of resilience: Responding to health systems shocks. *Health Policy and Planning*, **33**, 355-367, doi:10.1093/heapol/czx183.
Hanley, M. E., T. J. Bouma and H. L. Mossman, 2020a: The gathering storm: Optimizing management of coastal ecosystems in the face of a climate-driven threat. *Annals of Botany*, **125**, 197-212, doi:10.1093/aob/mcz204.
Hanley, M. E., T. J. Bouma and H. L. Mossman, 2020b: The gathering storm: Optimizing management of coastal ecosystems in the face of a climate-driven threat. Oxford University Press, 197-212 pp.
Hansen, J. et al., 2019: Climate risk management and rural poverty reduction. *Agricultural Systems*, **172**, 28-46, doi:10.1016/j.agsy.2018.01.019.
Hargan, K. E. et al., 2020: Understanding the fate of shrimp aquaculture effluent in a mangrove ecosystem: Aiding management for coastal conservation. *Journal of Applied Ecology*, **57**, 754-765, doi:https://doi.org/10.1111/1365-2664.13579.
Hasan, M. R., M. Nasreen and M. A. Chowdhury, 2019: Gender-inclusive disaster management policy in Bangladesh: A content analysis of national and international regulatory frameworks. Elsevier Ltd.
Hassanali, K., 2017: Challenges in mainstreaming climate change into productive coastal sectors in a Small Island State – The case of Trinidad and Tobago. *Ocean and Coastal Management*, **142**, 136-142, doi:10.1016/j.ocecoaman.2017.04.001.
Hauer, M. E. et al., 2020: Sea-level rise and human migration. *Nature Reviews Earth & Environment*, **1**, 28-39, doi:10.1038/s43017-019-0002-9.
Heikkinen, M., T. Ylä-Anttila and S. Juhola, 2019: Incremental, reformistic or transformational: what kind of change do C40 cities advocate to deal with climate change? *Journal of Environmental Policy and Planning*, **21**, 90-103, doi:10.1080/1523908X.2018.1473151.
Henrique, K. P. and P. Tschakert, 2020: Pathways to urban transformation: From dispossession to climate justice. *Progress in Human Geography*, **0**(0), 0309132520962856, doi:10.1177/0309132520962856.
Hermwille, L., W. Obergassel, H. E. Ott and C. Beuermann, 2017: UNFCCC before and after Paris – what's necessary for an effective climate regime? *Climate Policy*, **17**, 150-170, doi:10.1080/14693062.2015.1115231.
Hernández-Morcillo, M. et al., 2018: Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science & Policy*, **80**, 44-52, doi:10.1016/j.envsci.2017.11.013.
Herrero, M. et al., 2016: Climate change and pastoralism: impacts, consequences and adaptation. *Rev. Sci. Tech. Off. Int. Epiz*, **35**, 417-433, doi:10.20506/rst/35.2.2533.
Herslund, L. and P. Mguni, 2019: Examining urban water management practices – Challenges and possibilities for transitions to sustainable urban water management in Sub-Saharan cities. *Sustainable Cities and Society*, **48**, doi:10.1016/J.SCS.2019.101573.
Hewitt, C. D. et al., 2020a: Making Society Climate Resilient: International Progress under the Global Framework for Climate Services. *Bulletin of the American Meteorological Society*, **101**(2), E237-E252, doi:10.1175/BAMS-D-18-0211.1.
Hewitt, C. N., K. Ashworth and A. R. MacKenzie, 2020b: Using green infrastructure to improve urban air quality (GI4AQ). *Ambio*, **49**, 62-73, doi:10.1007/S13280-019-01164-3.
Hobbie, S. E. and N. B. Grimm, 2020: Nature-based approaches to managing climate change impacts in cities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190124, doi:10.1098/rstb.2019.0124.

Hoegh-Guldberg, O. and e. al. (eds.), The Ocean as a Solution to Climate Change: Five Opportunities for Action.
Hoffmann, R. et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change 2020 10:10*, **10**, 904-912, doi:10.1038/s41558-020-0898-6.
Honarmand Ebrahimi, S. and M. Ossewaarde, 2019: Not a security issue: How policy experts de-politicize the climate change-migration nexus. *Social Sciences*, **8**, 214, doi:10.3390/socsci8070214.
Hörner, D. and M. Wollni, 2020: RTG 1666 GlobalFood Transformation of Global Agri-Food Systems: Trends, Driving Forces, and Implications for Developing Countries Does Integrated Soil Fertility Management increase returns to land and labor? Plot-level evidence from Ethiopia.
Hosen, N., H. Nakamura and A. Hamzah, 2020: Adaptation to Climate Change: Does Traditional Ecological Knowledge Hold the Key? *Sustainability*, **12**(2), doi:10.3390/su12020676.
Hossen et al., 2019: Governance Challenges in Addressing Climatic Concerns in Coastal Asia and Africa. *Sustainability*, **11**, 2148, doi:10.3390/su11072148.
Hughes, S., 2020: Principles, drivers, and policy tools for just climate change adaptation in legacy cities. *Environmental Science and Policy*, **111**, 35-41, doi:10.1016/j.envsci.2020.05.007.
Hussey, L. K. and G. Arku, 2020: Are we ready for it? Health systems preparedness and capacity towards climate change-induced health risks: perspectives of health professionals in Ghana. *Climate and Development*, **12**, 170-182, doi:10.1080/17565529.2019.1610350.
Huynh, L. T. M. and L. C. Stringer, 2018: Multi-scale assessment of social vulnerability to climate change: An empirical study in coastal Vietnam. *Climate Risk Management*, **20**, 165-180, doi:https://doi.org/10.1016/j.crm.2018.02.003.
IPCC (ed.), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,.
IPCC, 2019: Climate Change and Land: an IPCC special report. *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, 1-864.
Islam, S., C. Chu and J. C. R. Smart, 2020a: Challenges in integrating disaster risk reduction and climate change adaptation: Exploring the Bangladesh case. *International Journal of Disaster Risk Reduction*, **47**, doi:10.1016/j.ijdrr.2020.101540.
Islam, S., C. Chu, J. C. R. Smart and L. Liew, 2020b: Integrating disaster risk reduction and climate change adaptation: a systematic literature review. Taylor and Francis Ltd., 255-267 pp.
Jacobson, C., S. Crevello, C. Chea and B. Jarihani, 2019: When is migration a maladaptive response to climate change? *Regional Environmental Change*, **19**, 101-112, doi:10.1007/s10113-018-1387-6.
Jayanthi, M., S. Thirumurthy, M. Muralidhar and P. Ravichandran, 2018: Impact of shrimp aquaculture development on important ecosystems in India. *Global Environmental Change*, **52**, 10-21, doi:https://doi.org/10.1016/j.gloenvcha.2018.05.005.
Jenkins, K., S. Surminski, J. Hall and F. Crick, 2017: Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. *Science of The Total Environment*, **595**, 159-168, doi:10.1016/j.scitotenv.2017.03.242.
Jensen, O. and S. Nair, 2019: Integrated urban water management and water security: A comparison of Singapore and Hong Kong. *Water (Switzerland)*, **11**, doi:10.3390/W11040785.
Ji, H. and D. Lee, 2021: Disaster risk reduction, community resilience, and policy effectiveness: the case of the Hazard Mitigation Grant Program in the United States. *Disasters*, **45**, 378-402, doi:10.1111/disa.12424.
Jin, J., W. Wang and X. Wang, 2016: Farmers' Risk Preferences and Agricultural Weather Index Insurance Uptake in Rural China. *International Journal of Disaster Risk Science*, **7**, 366-373, doi:10.1007/s13753-016-0108-3.
Johnson, K., S. Mortensen, C. Gueguen-Teil and A. R. Torre, 2021: Displaced by climate and disaster-induced relocations: Experiences of cascading displacement in Fiji and the Philippines. *Disasters*, doi:10.1111/DISA.12475.
Jolliffe, J., 2016: Economic dimensions of relocation as an adaptation strategy to climate change: A case study of the Narikoso Relocation Project, Fiji.
Jones, H. P. et al., 2020a: Global hotspots for coastal ecosystem-based adaptation. *PLOS ONE*, **15**, e0233005, doi:10.1371/journal.pone.0233005.
Jones, K. W., K. Powlen, R. Roberts and X. Shinbrot, 2020b: Participation in payments for ecosystem services programs in the Global South: A systematic review. *Ecosystem Services*, **45**, 101159, doi:10.1016/j.ecoser.2020.101159.
Jordon, M. W. et al., 2020: Implications of Temperate Agroforestry on Sheep and Cattle Productivity, Environmental Impacts and Enterprise Economics. A Systematic Evidence Map. *Forests 2020, Vol. 11, Page 1321*, **11**, 1321, doi:10.3390/F11121321.
Joy, A. and A. Gopinath, 2021: The Application of Reefs in Shoreline Protection, 295-315 pp.
Joyette, A. R. T., L. A. Nurse and R. S. Pulwarty, 2015: Disaster risk insurance and catastrophe models in risk-prone small Caribbean islands. *Disasters*, **39**, 467-492, doi:10.1111/disa.12118.
Kälin, W., 2019: The Global Compact on Migration: A Ray of Hope for Disaster-Displaced Persons. *International Journal of Refugee Law*, **30**, 664-667, doi:10.1093/ijrl/eey047.

Kannan, E. and K. B. Ramappa, 2017: Analysis of farm-level adoption of soil nutrient management technology by paddy farmers in Karnataka, India. *Environment, Development and Sustainability*, **19**, 2317-2331, doi:10.1007/s10668-016-9858-8.
Keeler, B. L. et al., 2019: Social-ecological and technological factors moderate the value of urban nature. Nature Publishing Group, 29-38 pp.
Keenan, J. M., T. Hill and A. Gumber, 2018: Climate gentrification: From theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters*, **13**, doi:10.1088/1748-9326/aabb32.
Keil, A., A. Mitra, A. K. Srivastava and A. McDonald, 2019: Social inclusion increases with time for zero-tillage wheat in the Eastern Indo-Gangetic Plains. *World Development*, **123**, 104582, doi:10.1016/j.worlddev.2019.06.006.
Kelman, I. et al., 2019: Does climate change influence people's migration decisions in Maldives? *Climatic Change*, **153**, 285-299, doi:10.1007/s10584-019-02376-y.
Kendrovski, V. and O. Schmoll, 2019: Priorities for protecting health from climate change in the WHO European Region: recent regional activities. Springer Verlag, 537-545 pp.
Kenney, C. and S. Phibbs, 2020: Indigenous Peoples and Climate Change: Situating Culture, Identity, and Place in Climate Change Risk Mitigation and Resilience. In: *Handbook of Climate Change Management: Research, Leadership, Transformation* [Leal Filho, W., J. Luetz and D. Ayal (eds.)]. Springer International Publishing, Cham, pp. 1-27. ISBN 978-3-030-22759-3.
Khalil, M. B., B. C. Jacobs, K. McKenna and N. Kuruppu, 2020: Female contribution to grassroots innovation for climate change adaptation in Bangladesh. *Climate and Development*, **12**(7), 664-676, doi:10.1080/17565529.2019.1676188.
Khatri-Chhetri, A., P. K. Aggarwal, P. K. Joshi and S. Vyas, 2017: Farmers' prioritization of climate-smart agriculture (CSA) technologies. *Agricultural Systems*, **151**, 184-191, doi:10.1016/j.agsy.2016.10.005.
Khatri-Chhetri, A., J. P. Aryal, T. B. Sapkota and R. Khurana, 2016: Economic benefits of climate-smart agricultural practices to smallholder farmers in the Indo-Gangetic Plains of India. *Current Science*, **110**, 1251-1256, doi:10.18520/cs/v110/i7/1251-1256.
Kihila, J. M., 2017: Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review. *Climate and Development*, 1-11, doi:10.1080/17565529.2017.1318739.
Kihila, J. M., 2018: Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review. Taylor and Francis Ltd., 406-416 pp.
Kim, H. and D. W. Marcouiller, 2020: Making sense of resilience planning and policy in the pursuit of sustainable development and disaster risk reduction. *Climate and Development*, **12**, 228-240, doi:10.1080/17565529.2019.1613215.
Kind, J., W. J. Wouter Botzen and J. C. J. H. Aerts, 2017: Accounting for risk aversion, income distribution and social welfare in cost-benefit analysis for flood risk management. *WIREs Climate Change*, **8**, e446, doi:https://doi.org/10.1002/wcc.446.
Klein, J. A. et al., 2019: An integrated community and ecosystem-based approach to disaster risk reduction in mountain systems. *Environmental Science and Policy*, **94**, 143-152, doi:10.1016/j.envsci.2018.12.034.
Kligler, B. et al., 2021: The impact of integrating environmental health into medical school curricula: a survey-based study. *BMC Medical Education*, **21**(1), 40, doi:10.1186/s12909-020-02458-x.
Klinenberg, E., 2018: *Palaces for the people : how social infrastructure can help fight inequality, polarization, and the decline of civic life*. ISBN 9781524761165 1524761168 9781524761172 1524761176 9781984822413 1984822411.
Kmoch, L., T. Pagella, M. Palm and F. Sinclair, 2018: Using local agroecological knowledge in climate change adaptation: A study of tree-based options in Northern Morocco. *Sustainability (Switzerland)*, **10**, 3719, doi:10.3390/su10103719.
Kodali, R. K. and B. S. Sarjerao (eds.), A low cost smart irrigation system using MQTT protocol. 2017 IEEE Region 10 Symposium (TENSYMP), 14-16 July 2017, 1-5 pp.
Koslov, L., 2019: Avoiding Climate Change: "Agnostic Adaptation" and the Politics of Public Silence. *Annals of the American Association of Geographers*, **109**, 568-580, doi:10.1080/24694452.2018.1549472.
Koubi, V. et al., 2018: The determinants of environmental migrants' conflict perception. *cambridge.org*.
Kouis, P. et al., 2021: The MEDEA childhood asthma study design for mitigation of desert dust health effects: implementation of novel methods for assessment of air pollution exposure and lessons learned. *BMC Pediatrics*, **21**(1), 13, doi:10.1186/s12887-020-02472-4.
Kousky, C., H. Wiley and L. Shabman, 2021: Can Parametric Microinsurance Improve the Financial Resilience of Low-Income Households in the United States? *Economics of Disasters and Climate Change*, doi:10.1007/s41885-021-00088-1.
Krauss, K. W. and M. J. Osland, 2020: Tropical cyclones and the organization of mangrove forests: A review. *Annals of Botany*, **125**, 213-234, doi:10.1093/aob/mcz161.
Krosby, M., J. Tewksbury, N. M. Haddad and J. Hoekstra, 2010: Ecological Connectivity for a Changing Climate. *Conservation Biology*, **24**, 1686-1689, doi:10.1111/j.1523-1739.2010.01585.x.
Krueger, E., P. S. C. Rao and D. Borchardt, 2019: Quantifying urban water supply security under global change. *Global Environmental Change*, **56**, 66-74, doi:10.1016/J.GLOENVCHA.2019.03.009.

Lalani, B., P. Dorward and G. Holloway, 2017: Farm-level Economic Analysis - Is Conservation Agriculture Helping the Poor? *Ecological Economics*, **141**, 144-153, doi:10.1016/j.ecolecon.2017.05.033.
Lamari, M., J. Bouchard, J. Jacob and L. Poulin-Larivière, 2016: Monitoring and Evaluation of Climate Change Adaptation in Coastal Zones: Overview of the Indicators in Use. Springer, 3-20 pp.
Lange, W. et al., 2019: Ecosystem-Based Approaches for Disaster Risk Reduction and Climate Change Adaptation in Rio de Janeiro State. Springer, Cham, 345-359 pp.
Langemeyer, J. et al., 2020: Creating urban green infrastructure where it is needed – A spatial ecosystem service-based decision analysis of green roofs in Barcelona. *Science of the Total Environment*, **707**, 135487, doi:10.1016/j.scitotenv.2019.135487.
Lardizabal, C. C., 2015: Basin Comanagement Plans – A Participative Approach to Water Governance: A Case Study in Honduras, Central America. *Sustainability of Integrated Water Resources Management: Water Governance, Climate and Ecohydrology*, 345-363, doi:10.1007/978-3-319-12194-9_19.
Lashley, J. G. and K. Warner, 2015: Evidence of demand for microinsurance for coping and adaptation to weather extremes in the Caribbean. *Climatic Change*, **133**, 101-112, doi:10.1007/s10584-013-0922-1.
Lausche, B. et al. (eds.), The Legal Aspects of Connectivity Conservation A Concept Paper.
Lavorel, S., B. Locatelli, M. J. Colloff and E. Bruley, 2020: Co-producing ecosystem services for adapting to climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**, doi:10.1098/rstb.2019.0119.
Le Cornu, E. et al., 2018: Spatial management in small-scale fisheries: A potential approach for climate change adaptation in Pacific Islands. *Marine Policy*, **88**, 350-358, doi:https://doi.org/10.1016/j.marpol.2017.09.030.
Leakhena, C. et al., 2018: Aiming for Improved Gender Equity in Cambodian Aquaculture.
Leigh, N. G. and H. Lee, 2019: Sustainable and resilient urban water systems: The role of decentralization and planning. *Sustainability (Switzerland)*, **11**, doi:10.3390/SU11030918.
Li, Z. et al., 2020: Biochar-supported nanoscale zero-valent iron as an efficient catalyst for organic degradation in groundwater. *Journal of Hazardous Materials*, **383**, doi:10.1016/j.jhazmat.2019.121240.
Liang, Y., M. Du, X. Wang and X. Xu, 2020: Planning for urban life: A new approach of sustainable land use plan based on transit-oriented development. *Evaluation and Program Planning*, **80**, 101811, doi:10.1016/j.evalprogplan.2020.101811.
Liao, W. et al., 2019: Preparing the next generation of health professionals to tackle climate change: Are China's medical students ready? *Environmental Research*, **168**, 270-277, doi:10.1016/j.envres.2018.10.006.
Ligsay, A., O. Telle and R. Paul, 2021: Challenges to Mitigating the Urban Health Burden of Mosquito-Borne Diseases in the Face of Climate Change. *Int J Environ Res Public Health*, **18**(9), doi:10.3390/ijerph18095035.
Lima, M. and C. Coelho, 2021: Integrated Methodology for Physical and Economic Assessment of Coastal Interventions Impacts. *Journal of Modeling and Optimization*, **13**, 22-43, doi:10.32732/jmo.2021.13.1.22.
Lin, T. Y., V. M. V. Onselen and L. P. Vo, 2021: Coastal erosion in Vietnam: Case studies and implication for integrated coastal zone management in the Vietnamese south-central coastline. *IOP Conference Series: Earth and Environmental Science*, **652**, 012009, doi:10.1088/1755-1315/652/1/012009.
Linares, C. et al., 2020: Impacts of climate change on the public health of the Mediterranean Basin population - Current situation, projections, preparedness and adaptation. Academic Press Inc.
Lincke, D. and J. Hinkel, 2018: Economically robust protection against 21st century sea-level rise. *Global Environmental Change*, **51**, 67-73, doi:https://doi.org/10.1016/j.gloenvcha.2018.05.003.
Linke, A., F. Witmer, J. O. L.-E. … and u. 2018, 2018: The consequences of relocating in response to drought: human mobility and conflict in contemporary Kenya. *iopscience.iop.org*, doi:10.1088/1748-9326/aad8cc.
Linnerooth-Bayer, J. and S. Hochrainer-Stigler, 2015: Financial instruments for disaster risk management and climate change adaptation. *Climatic Change*, **133**, 85-100, doi:10.1007/s10584-013-1035-6.
Liu, L. and M. B. Jensen, 2018: Green infrastructure for sustainable urban water management: Practices of five forerunner cities. *Cities*, **74**, 126-133, doi:10.1016/j.cities.2017.11.013.
Lochhead, K., S. Ghafghazi, V. LeMay and G. Q. Bull, 2019: Examining the vulnerability of localized reforestation strategies to climate change at a macroscale. *Journal of Environmental Management*, **252**, 109625, doi:10.1016/j.jenvman.2019.109625.
Lock-Wah-Hoon, J. et al., 2020: Exploring Vector-Borne Disease Surveillance and Response Systems in Beijing, China: A Qualitative Study from the Health System Perspective. *Int J Environ Res Public Health*, **17**(22), doi:10.3390/ijerph17228512.
Lunduka, R. W., K. I. Mateva, C. Magorokosho and P. Manjeru, 2019: Impact of adoption of drought-tolerant maize varieties on total maize production in south Eastern Zimbabwe. *Climate and Development*, **11**, 35-46, doi:10.1080/17565529.2017.1372269.
Luqman, M. et al., 2018: Socio-Economic Impacts of Agro-Forestry on Livelihoods of Rural Households in Southern Region of the Punjab, Pakistan. *Sarhad Journal of Agriculture*, **34**, doi:http://dx.doi.org/10.17582/journal.sja/2018/34.4.880.887.
Lykke Strøbech, H. and A. Bordon Rosa, 2020: Addressing the risk of Maladaptation in Social Protection: The case of World Food Programme.
Mach, K. J. et al., 2019: Managed retreat through voluntary buyouts of flood-prone properties. **5**, doi:10.1126/SCIADV.AAX8995.

Magnan, A. K. and V. K. E. Duvat, 2018: Unavoidable solutions for coastal adaptation in Reunion Island (Indian Ocean). *Environmental Science and Policy*, **89**, 393-400, doi:10.1016/j.envsci.2018.09.002.

Maharjan, A. et al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, **6**, doi:10.1007/S40641-020-00153-Z.

Makate, C., R. Wang, M. Makate and N. Mango, 2016: Crop diversification and livelihoods of smallholder farmers in Zimbabwe: Adaptive management for environmental change. *SpringerPlus*, **5**, 1-18, doi:10.1186/s40064-016-2802-4.

Maldonado, J. et al., 2021: Addressing the challenges of climate-driven community-led resettlement and site expansion: knowledge sharing, storytelling, healing, and collaborative coalition building. *Journal of Environmental Studies and Sciences*, 1-11, doi:10.1007/S13412-021-00695-0.

Mallick, B., B. Ahmed, J. V.-. Environments and u. 2017, 2017: Living with the risks of cyclone disasters in the south-western coastal region of Bangladesh. *mdpi.com*, doi:10.3390/environments4010013.

Marchezini, V., 2020: "What is a Sociologist Doing Here?" An Unconventional People-Centered Approach to Improve Warning Implementation in the Sendai Framework for Disaster Risk Reduction. *International Journal of Disaster Risk Science*, **11**(2), 218-229, doi:10.1007/s13753-020-00262-1.

Margaret, D. and S. Matias, 2020: Climate humanitarian visa: international migration opportunities as post-disaster humanitarian intervention. *Climatic Change*, **160**, 143-156, doi:10.1007/s10584-020-02691-9.

Margerum, R. D. and C. J. Robinson, 2015: Collaborative partnerships and the challenges for sustainable water management. *Current Opinion in Environmental Sustainability*, **12**, 53-58, doi:10.1016/j.cosust.2014.09.003.

Martin, G. et al., 2020: Potential of multi-species livestock farming to improve the sustainability of livestock farms: A review. *Agricultural Systems*, **181**, 102821, doi:10.1016/j.agsy.2020.102821.

Martin, S. M. and K. Lorenzen, 2016: Livelihood Diversification in Rural Laos. *World Development*, **83**, 231-243, doi:10.1016/j.worlddev.2016.01.018.

Martínez-Barón, D. et al., 2021: Strengthening the climate services chain in Central America.

Martuti, N. K. T., R. Pribadi, W. A. B. N. Sidiq and D. P. Mutiatari, 2020: Community-Based Integrated Coastal Management Strategy in Tugurejo Subdistrict, Semarang. Atlantis Press, 73-80 pp.

Masud, M. M. et al., 2017: Adaptation barriers and strategies towards climate change: Challenges in the agricultural sector. *Journal of Cleaner Production*, **156**, 698-706, doi:https://doi.org/10.1016/j.jclepro.2017.04.060.

Mayer, A., Z. Hausfather and W. Silver, 2018: The potential of agricultural land management to contribute to lower global surface temperatures. *Science Advances*, **4**, doi:10.1126/sciadv.aaq0932.

McFadden, J., D. Smith, S. Wechsler and S. Wallander (eds.), Development, Adoption, and Management of Drought-Tolerant Corn in the United States.

McLeman, R., 2018: Migration and displacement risks due to mean sea-level rise. *Bulletin of the Atomic Scientists*, **74**(3), 148-154, doi:10.1080/00963402.2018.1461951.

McLeman, R., 2019: International migration and climate adaptation in an era of hardening borders. *Nature Climate Change 2019 9:12*, **9**, 911-918, doi:10.1038/s41558-019-0634-2.

McMichael, C. et al., 2021: Rising seas, immobilities, and translocality in small island states: case studies from Fiji and Tuvalu. *Population and Environment*, **43**(1), 82-107, doi:10.1007/s11111-021-00378-6.

McMichael, C. and M. Katonivualiku, 2020: Thick temporalities of planned relocation in Fiji. *Geoforum*, **108**, 286-294, doi:https://doi.org/10.1016/j.geoforum.2019.06.012.

McNamara, K. E., 2015: Cross-border migration with dignity in Kiribati. *Forced Migration Review*, **49**, 62.

McNamara, K. E., R. Westoby and A. Chandra, 2021: Exploring climate-driven non-economic loss and damage in the Pacific Islands. *Current Opinion in Environmental Sustainability*, **50**, 1-11, doi:10.1016/j.cosust.2020.07.004.

Meerow, S., 2019: A green infrastructure spatial planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities. *Environmental Research Letters*, **14**, doi:10.1088/1748-9326/ab502c.

Mena, R. and D. Hilhorst, 2021: The (im)possibilities of disaster risk reduction in the context of high-intensity conflict: the case of Afghanistan. *Environmental Hazards*, **20**(2), 188-208, doi:10.1080/17477891.2020.1771250.

Mestanza-Ramón, C., M. S. Capa, H. F. Saavedra and J. R. Paredes, 2019: Integrated coastal zone management in continental Ecuador and Galapagos Islands: Challenges and opportunities in a changing tourism and economic context. *Sustainability*, **11**, 6386, doi:10.3390/su11226386.

Miller, F., 2020: Exploring the consequences of climate-related displacement for just resilience in Vietnam. *Urban Studies*, **57**, 1570-1587, doi:10.1177/0042098019830239.

Mills, M. et al., 2016: Reconciling Development and Conservation under Coastal Squeeze from Rising Sea Level. *Conservation Letters*, **9**, 361-368, doi:10.1111/conl.12213.

Minang, P. A. et al., 2014: Prospects for agroforestry in REDD+ landscapes in Africa. Elsevier, 78-82 pp.

Monstadt, J. and A. Wolff, 2015: Energy transition or incremental change? Green policy agendas and the adaptability of the urban energy regime in Los Angeles. *Energy Policy*, **78**, 213-224, doi:10.1016/j.enpol.2014.10.022.

Morecroft, M. D. et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366**, doi:10.1126/science.aaw9256.

Morris, R. et al., 2019: Developing a nature-based coastal defence strategy for Australia. *Australian Journal of Civil Engineering*, **17**, 167-176, doi:10.1080/14488353.2019.1661062.

Morris, R. L., T. M. Konlechner, M. Ghisalberti and Stephen E. Swearer, 2018: From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. Blackwell Publishing Ltd, 1827-1842 pp.

Mortreux, C. et al., 2018: Political economy of planned relocation: A model of action and inaction in government responses. *Global Environmental Change*, **50**, 123-132, doi:10.1016/j.gloenvcha.2018.03.008.
Mottaleb, K. A. et al., 2017: Benefits of the development and dissemination of climate-smart rice: ex ante impact assessment of drought-tolerant rice in South Asia. *Mitigation and Adaptation Strategies for Global Change*, **22**, 879-901, doi:10.1007/s11027-016-9705-0.
Mponela, P. et al., 2016: Determinants of integrated soil fertility management technologies adoption by smallholder farmers in the Chinyanja Triangle of Southern Africa. *Land Use Policy*, **59**, 38-48, doi:10.1016/j.landusepol.2016.08.029.
Mueller, V., C. Gray, S. Handa and D. Seidenfeld, 2020: Do social protection programs foster short-term and long-term migration adaptation strategies? *Environment and Development Economics*, **25**, 135-158, doi:10.1017/S1355770X19000214.
Muench, S., S. Thuss and E. Guenther, 2014: What hampers energy system transformations? The case of smart grids. *Energy Policy*, **73**, 80-92, doi:10.1016/j.enpol.2014.05.051.
Müller, B., L. Johnson and D. Kreuer, 2017: Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change*, **46**, 23-33, doi:10.1016/j.gloenvcha.2017.06.010.
Muricho, D. N., D. J. Otieno, W. Oluoch-Kosura and M. Jirström, 2019: Building pastoralists' resilience to shocks for sustainable disaster risk mitigation: Lessons from West Pokot County, Kenya. *International Journal of Disaster Risk Reduction*, **34**, 429-435, doi:10.1016/j.ijdrr.2018.12.012.
Murti, R., S. L. Mathez-Stiefel, V. R. Garcia and S. Rist, 2020: Engaging national policy makers in ecosystem based disaster risk reduction through social learning: Lessons from workshops in Africa, oceania, Latin America and the Caribbean. Elsevier Ltd.
Mustafa, S. et al., 2021: Technological applications and adaptations in aquaculture for progress towards sustainable development and seafood security. *{IOP} Conference Series: Earth and Environmental Science*, **718**, 12041, doi:10.1088/1755-1315/718/1/012041.
Mustapha, U. F., A.-W. Alhassan, D.-N. Jiang and G.-L. Li, 2021: Sustainable aquaculture development: a review on the roles of cloud computing, internet of things and artificial intelligence (CIA). *Reviews in Aquaculture*, **n/a**, doi:https://doi.org/10.1111/raq.12559.
Mutuku, E. A. et al., 2020: Maize production under combined Conservation Agriculture and Integrated Soil Fertility Management in the sub-humid and semi-arid regions of Kenya. *Field Crops Research*, **254**, 107833, doi:10.1016/j.fcr.2020.107833.
Nabuurs, G.-J. et al., 2017: By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. *Forests*, **8**(12), doi:10.3390/f8120484.
Natarajan, N., K. B.-E. a. P. … and u. 2019, 2019: Climate change adaptation and precarity across the rural–urban divide in Cambodia: Towards a 'climate precarity'approach. *journals.sagepub.com*, **2**, 899-921, doi:10.1177/2514848619858155.
Nawrotzki, R. J. and J. DeWaard, 2018: Putting trapped populations into place: climate change and inter-district migration flows in Zambia. *Regional Environmental Change*, **18**, 533-546, doi:10.1007/S10113-017-1224-3.
Neef, A. et al., 2018: Climate adaptation strategies in Fiji: The role of social norms and cultural values. *World Development*, **107**, 125-137, doi:https://doi.org/10.1016/j.worlddev.2018.02.029.
Negev, M. et al., 2021: Regional lessons from the COVID-19 outbreak in the Middle East: From infectious diseases to climate change adaptation. *Sci Total Environ*, **768**, 144434, doi:10.1016/j.scitotenv.2020.144434.
Negev, M. et al., 2019: Adaptation of health systems to climate-related migration in Sub-Saharan Africa: Closing the gap. *International Journal of Hygiene and Environmental Health*, **222**, 311-314, doi:10.1016/j.ijheh.2018.10.004.
Ngin, C., J. H. Grayman, A. Neef and N. Sanunsilp, 2020: The role of faith-based institutions in urban disaster risk reduction for immigrant communities. *Natural Hazards*, **103**(1), 299-316, doi:10.1007/s11069-020-03988-9.
Nguyen Mai, T. H. and T. Dang Hoang, 2018: Gender role in mangrove resource management: case study in Trieu Phong district of Quang Tri province, Vietnam. *Journal of Vietnamese Environment*, **9 (2)**, doi:https://doi.org/10.13141/jve.vol9.no2.pp92-98.
Nguyen, T. T. et al., 2019: Implementation of a specific urban water management - Sponge City. *Science of the Total Environment*, **652**, 147-162, doi:10.1016/J.SCITOTENV.2018.10.168.
Nicholls, R., J. Hinkel, D. Lincke and T. D. van der Pol, 2019: Global Investment Costs for Coastal Defense Through the 21st Century. *World Bank Policy Research Working Paper Series*.
Nieuwenhuijsen, M. J., 2021: Green Infrastructure and Health. *Annual Review of Public Health*, **42**(1), 317-328, doi:10.1146/annurev-publhealth-090419-102511.
Nightingale, A. J., 2017: Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, **84**, 11-20, doi:10.1016/j.geoforum.2017.05.011.
Ntshangase, N. L., B. Muroyiwa and M. Sibanda, 2018: Farmers' perceptions and factors influencing the adoption of no-till conservation agriculture by small-scale farmers in Zashuke, KwaZulu-Natal province. *Sustainability (Switzerland)*, **10**, 555, doi:10.3390/su10020555.
Nunes, S. et al., 2020: Challenges and opportunities for large-scale reforestation in the Eastern Amazon using native species. Elsevier B.V., 118120 pp.
Nuzzo, J. B. et al., 2019: What makes health systems resilient against infectious disease outbreaks and natural hazards? Results from a scoping review. *BMC Public Health*, **19**, doi:10.1186/s12889-019-7707-z.

Nyantakyi-Frimpong, H., 2017: Agricultural diversification and dietary diversity: A feminist political ecology of the everyday experiences of landless and smallholder households in northern Ghana. *Geoforum*, **86**, 63-75, doi:10.1016/j.geoforum.2017.09.003.
O'Donnell, T., 2019: Contrasting land use policies for climate change adaptation: A case study of political and geo-legal realities for Australian coastal locations. *Land Use Policy*, **88**, doi:10.1016/J.LANDUSEPOL.2019.104145.
O'Mahony, C., S. Gray, J. Gault and V. Cummins, 2020: ICZM as a framework for climate change adaptation action – Experience from Cork Harbour, Ireland. *Marine Policy*, **111**, 102223, doi:10.1016/j.marpol.2015.10.008.
O'Hare, P., I. White and A. Connelly, 2016: Insurance as maladaptation: Resilience and the 'business as usual' paradox. *Environment and Planning C: Government and Policy*, **34**, 1175-1193, doi:10.1177/0263774X15602022.
Oakes, R., 2019: Culture, climate change and mobility decisions in Pacific Small Island Developing States. *Population and Environment*, **40**, 480-503, doi:10.1007/s11111-019-00321-w.
Ober, K. and P. Sakdapolrak, 2020: Whose climate change adaptation 'barriers'? Exploring the coloniality of climate change adaptation policy assemblages in Thailand and beyond. *Singapore Journal of Tropical Geography*, **41**(1), 86-104, doi:https://doi.org/10.1111/sjtg.12309.
Obokata, R. and L. Veronis, 2018: Transnational approaches to remittances, risk reduction, and disaster relief : Evidence from post-Typhoon Haiyan experiences of Filipino immigrants in Canada. *Routledge Handbook of Environmental Displacement and Migration*, 270-276, doi:10.4324/9781315638843-21.
Ogada, M. J. et al., 2020: Climate-smart agriculture, household income and asset accumulation among smallholder farmers in the Nyando basin of Kenya. *World Development Perspectives*, **18**, 100203-100203, doi:10.1016/j.wdp.2020.100203.
Ogle, S. M. et al., 2019: Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions. *Scientific Reports*, **9**, 1-8, doi:10.1038/s41598-019-47861-7.
Ojea, E., S. E. Lester and D. Salgueiro-Otero, 2020: Adaptation of Fishing Communities to Climate-Driven Shifts in Target Species. Cell Press, 544-556 pp.
Ontl, T. A. et al., 2020: Forest Management for Carbon Sequestration and Climate Adaptation. *Journal of Forestry*, **118**, 86-101, doi:10.1093/jofore/fvz062.
Opoku, S. K., W. L. Filho, F. Hubert and O. Adejumo, 2021: Climate Change and Health Preparedness in Africa: Analysing Trends in Six African Countries. *International Journal of Environmental Research and Public Health*, **18**(9), doi:10.3390/ijerph18094672.
Oral, H. V. et al., 2020: A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. *Blue-Green Systems*, **2**, 112-136, doi:10.2166/BGS.2020.932.
Orchard, S. E., L. C. Stringer and C. H. Quinn, 2016: Mangrove system dynamics in Southeast Asia: linking livelihoods and ecosystem services in Vietnam. *Regional Environmental Change*, **16**(3), 865-879, doi:10.1007/s10113-015-0802-5.
Osmundsen, T. C. et al., 2020: The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. *Global Environmental Change*, **60**, 102025, doi:https://doi.org/10.1016/j.gloenvcha.2019.102025.
Ossola, A. and B. B. Lin, 2021: Making nature-based solutions climate-ready for the 50 °C world. Elsevier Ltd, 151-159 pp.
Ota, L., J. Herbohn, N. Gregorio and S. Harrison, 2020: Reforestation and smallholder livelihoods in the humid tropics. *Land Use Policy*, **92**, 104455, doi:10.1016/j.landusepol.2019.104455.
Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071, doi:https://doi.org/10.1016/j.gloenvcha.2020.102071.
Paganini, Z., 2019: Underwater: Resilience, racialized housing, and the national flood insurance program in Canarsie, Brooklyn. *Geoforum*, **104**, 25-35, doi:10.1016/j.geoforum.2019.06.003.
Pardo, G. and A. del Prado, 2020: Guidelines for small ruminant production systems under climate emergency in Europe. *Small Ruminant Research*, **193**, 106261, doi:10.1016/j.smallrumres.2020.106261.
Parihar, C. M. et al., 2020: Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. *Soil and Tillage Research*, **202**, 104653, doi:10.1016/j.still.2020.104653.
Parry, L. et al., 2019: The (in)visible health risks of climate change. *Social Science & Medicine*, **241**, 112448, doi:https://doi.org/10.1016/j.socscimed.2019.112448.
Parton, K. A., J. Crean and P. Hayman, 2019: The value of seasonal climate forecasts for Australian agriculture. *Agricultural Systems*, **174**, 1-10, doi:https://doi.org/10.1016/j.agsy.2019.04.005.
Pascal, M. et al., 2021: Evolving heat waves characteristics challenge heat warning systems and prevention plans. *International Journal of Biometeorology*, doi:10.1007/s00484-021-02123-y.
Patel, R., G. Walker, M. Bhatt and V. Pathak, 2017: The Demand for Disaster Microinsurance for Small Businesses in Urban Slums: The Results of Surveys in Three Indian Cities. *PLOS Currents Disasters*, **9**.
Paudel, U. and K. P. Pant, 2020: Estimation of household health cost and climate adaptation cost with its health related determinants: empirical evidences from western Nepal. *Heliyon*, **6**(11), e05492, doi:https://doi.org/10.1016/j.heliyon.2020.e05492.

Paul, S. et al., 2020: Development of an indicator based composite measure to assess livelihood sustainability of shifting cultivation dependent ethnic minorities in the disadvantageous Northeastern region of India. *Ecological Indicators*, **110**, 105934, doi:https://doi.org/10.1016/j.ecolind.2019.105934.
Pearson, J., K. E. McNamara and P. D. Nunn, 2019: Gender-specific perspectives of mangrove ecosystem services: Case study from Bua Province, Fiji Islands. *Ecosystem Services*, **38**, 100970, doi:https://doi.org/10.1016/j.ecoser.2019.100970.
Pelling, M. and M. Garschagen, 2019: Put equity first in climate adaptation. Nature Publishing Group, 327-329 pp.
Pelling, M. et al., 2018: Africa's urban adaptation transition under a 1.5° climate. *Current Opinion in Environmental Sustainability*, **31**, 10-15, doi:10.1016/j.cosust.2017.11.005.
Peng, L. L. H. et al., 2020: Cooling effects of block-scale facade greening and their relationship with urban form. *Building and Environment*, **169**, 106552, doi:https://doi.org/10.1016/j.buildenv.2019.106552.
Perera-Valderrama, S. et al., 2020: Increasing marine ecosystems conservation linking marine protected areas and integrated coastal management in southern Cuba. *Ocean and Coastal Management*, **196**, 105300, doi:10.1016/j.ocecoaman.2020.105300.
Pérez-Cayeiro, M. L. and J. A. Chica-Ruiz, 2015: Evaluation of a programme of integrated coastal zone management: The Ecoplata Programme (Uruguay). *Marine Policy*, **51**, 527-535, doi:10.1016/j.marpol.2014.09.008.
Perrels, A., 2020: Quantifying the uptake of climate services at micro and macro level. *Climate Services*, **17**, 100152, doi:https://doi.org/10.1016/j.cliser.2020.100152.
Perrotti, D. and S. Stremke, 2018: Can urban metabolism models advance green infrastructure planning? Insights from ecosystem services research. *https://doi.org/10.1177/2399808318797131*, **47**(4), 678-694, doi:10.1177/2399808318797131.
Petrova, K., 2021: Natural hazards, internal migration and protests in Bangladesh. *Journal of Peace Research*, **58**, 33-49, doi:10.1177/0022343320973741.
Phillips, M. R., A. L. Jones and T. Thomas, 2018: Climate Change, Coastal Management and Acceptable Risk: Consequences for Tourism. *Journal of Coastal Research*, **85**, 1411-1415, doi:10.2112/SI85-283.1.
Piggott-McKellar, A. E., K. E. McNamara, P. D. Nunn and S. T. Sekinini, 2019: Moving people in a changing climate: Lessons from two case studies in Fiji. *Social Sciences*, **8**, 133, doi:10.3390/socsci8050133.
Piguet, E., 2019: Climatic Statelessness: Risk Assessment and Policy Options. *Population and Development Review*, **45**(4), 865-883, doi:https://doi.org/10.1111/padr.12295.
Porst, L., P. S.-. Population, S. a. Place and u. 2020, 2020: Gendered translocal connectedness: Rural–urban migration, remittances, and social resilience in Thailand. *Wiley Online Library*, **26**, doi:10.1002/psp.2314.
Pour, S. H. et al., 2020: Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges. *Sustainable Cities and Society*, **62**, 102373, doi:https://doi.org/10.1016/j.scs.2020.102373.
Prestele, R. et al., 2018: A spatially explicit representation of conservation agriculture for application in global change studies. *Global Change Biology*, **24**, 4038-4053, doi:10.1111/gcb.14307.
Propato, M., J. S. Clough and A. Polaczyk, 2018: Evaluating the costs and benefits of marsh-management strategies while accounting for uncertain sea-level rise and ecosystem response. *PLOS ONE*, **13**, e0200368, doi:10.1371/journal.pone.0200368.
Quandt, A., H. Neufeldt and J. T. McCabe, 2017: The role of agroforestry in building livelihood resilience to floods and drought in semiarid Kenya. *Ecology and Society*, **22**, 10, doi:10.5751/ES-09461-220310.
Qurani, I. Z., N. I. Fawzi, R. Fadilah and W. Kismorodati, 2021: Empowering Fish-Farmer through Coastal Field School: Towards Sustainable Aquaculture Practice. *IOP Conference Series: Earth and Environmental Science*, **750**, 12054, doi:10.1088/1755-1315/750/1/012054.
Radel, C., B. Schmook, L. Carte and S. Mardero, 2018: Toward a Political Ecology of Migration: Land, Labor Migration, and Climate Change in Northwestern Nicaragua. *World Development*, **108**, 263-273, doi:10.1016/j.worlddev.2017.04.023.
Rahman, A. T. M. S. et al., 2017: Drought analysis and its implication in sustainable water resource management in Barind area, Bangladesh. *Journal of the Geological Society of India*, **89**(1), 47-56, doi:10.1007/s12594-017-0557-3.
Rahman, S., M. S. Islam, M. N. H. Khan and M. Touhiduzzaman, 2019: Climate change adaptation and disaster risk reduction (DRR) through coastal afforestation in South-Central Coast of Bangladesh. *Management of Environmental Quality: An International Journal*, **30**, 498-517, doi:10.1108/MEQ-01-2018-0021.
Rahut, D. B., J. P. Aryal and P. Marenya, 2021: Understanding climate-risk coping strategies among farm households: Evidence from five countries in Eastern and Southern Africa. **769**, 145236.
Ramalho, J., 2019: Worlding aspirations and resilient futures: Framings of risk and contemporary city-making in Metro Cebu, the Philippines. *Asia Pacific Viewpoint*, **60**, 24-36, doi:10.1111/apv.12208.
Ranganathan, M. and E. Bratman, 2021: From Urban Resilience to Abolitionist Climate Justice in Washington, DC. *Antipode*, **53**(1), 115-137, doi:https://doi.org/10.1111/anti.12555.
Rao, N. et al., 2020: Managing risk, changing aspirations and household dynamics: Implications for wellbeing and adaptation in semi-arid Africa and India. *World Development*, **125**, 104667, doi:10.1016/J.WORLDDEV.2019.104667.

Rasmussen, D., M. Oppenheimer, R. E. Kopp and R. Shwom, 2020: The political complexity of coastal flood risk reduction: lessons for climate adaptation public works in the U.S. *Earth and Space Science Open Archive*, doi:https://doi.org/10.1002/essoar.10502705.3.
Ratter, B., A. Hennig and Zahid, 2019: Challenges for shared responsibility – Political and social framing of coastal protection transformation in the Maldives. *DIE ERDE – Journal of the Geographical Society of Berlin*, **150**, doi:10.12854/erde-2019-426.
Raymond, C. M. et al., 2017: A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science and Policy*, **77**, 15-24, doi:10.1016/j.envsci.2017.07.008.
Reddy, V. R., T. Chiranjeevi and G. Syme, 2020: Inclusive sustainable intensification of agriculture in West Bengal, India: policy and institutional approaches. *International Journal of Agricultural Sustainability*, **18**, 70-83, doi:10.1080/14735903.2019.1698489.
Reguero, B. G. et al., 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLOS ONE*, **13**(4), e0192132, doi:10.1371/journal.pone.0192132.
Rigg, J. and K. Oven, 2015: Building liberal resilience? A critical review from developing rural Asia. *Global Environmental Change*, **32**, 175-186, doi:https://doi.org/10.1016/j.gloenvcha.2015.03.007.
Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, **8**, 325-332, doi:10.1038/s41558-018-0091-3.
Romañach, S. S. et al., 2018: Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean & Coastal Management*, **154**, 72-82, doi:10.1016/j.ocecoaman.2018.01.009.
Rosendo, S., L. Celliers and M. Mechisso, 2018: Doing more with the same: A reality-check on the ability of local government to implement Integrated Coastal Management for climate change adaptation. *Marine Policy*, **87**, 29-39, doi:10.1016/j.marpol.2017.10.001.
Rosenzweig, C. et al., 2018: Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network. Cambridge University Press, xvii-xlii pp.
Rosyida, I., W. Ullah, A. Helmi and M. Sasaoka, 2019: Adapting livelihoods to the impacts of tin mining in Indonesia: options and constraints. **6**, 1302-1313.
Roy, J. et al., 2018: Sustainable development, poverty eradication and reducing inequalities. In: Global warming of 1.5° C.
Rudolph, L., N. Maizlish, S. North and K. Dervin, 2020: A Public Health Learning Collaborative on Climate Change for Urban Health Departments, 2016-2018. *Public Health Reports*, **135**, 189-201, doi:10.1177/0033354920902468.
Runkle, J. et al., 2018: Population Health Adaptation Approaches to the Increasing Severity and Frequency of Weather-Related Disasters Resulting From our Changing Climate: A Literature Review and Application to Charleston, South Carolina. Springer, 439-452 pp.
Ruszczyk, H. A. et al., 2020: Empowering women through participatory action research in community-based disaster risk reduction efforts. *International Journal of Disaster Risk Reduction*, **51**, 101763, doi:https://doi.org/10.1016/j.ijdrr.2020.101763.
Salam, S. and S. Bauer, 2020: Rural non-farm economy and livelihood diversification strategies: evidence from Bangladesh. *GeoJournal*, 1-13, doi:10.1007/s10708-020-10269-2.
Salmon, G. et al., 2018: Trade-offs in livestock development at farm level: Different actors with different objectives. *Global Food Security*, **17**, 103-112, doi:10.1016/j.gfs.2018.04.002.
Sampantamit, T. et al., 2020: Aquaculture Production and Its Environmental Sustainability in Thailand: Challenges and Potential Solutions. *Sustainability*, **12**, doi:10.3390/su12052010.
Sani Ibrahim, S., H. Ozdeser and B. Cavusoglu, 2019: Financial inclusion as a pathway to welfare enhancement and income equality: Micro-level evidence from Nigeria. *Development Southern Africa*, **36**, 390-407, doi:10.1080/0376835X.2018.1498766.
Santoro, A., M. Venturi, R. Bertani and M. Agnoletti, 2020: A Review of the Role of Forests and Agroforestry Systems in the FAO Globally Important Agricultural Heritage Systems (GIAHS) Programme. *Forests 2020, Vol. 11, Page 860*, **11**, 860, doi:10.3390/F11080860.
Sarkar, D. et al., 2018: Can sustainability of maize-mustard cropping system be achieved through balanced nutrient management? *Field Crops Research*, **225**, 9-21, doi:10.1016/j.fcr.2018.05.018.
Scheres, B. and H. Schüttrumpf, 2019: Enhancing the Ecological Value of Sea Dikes.
Schoeneberger, M. et al., 2012: Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. *Journal of Soil and Water Conservation*, **67**, 128A-136A, doi:10.2489/jswc.67.5.128A.
Schoonees, T. et al., 2019: Hard Structures for Coastal Protection, Towards Greener Designs. *Estuaries and Coasts*, **42**, 1709-1729, doi:10.1007/s12237-019-00551-z.
Schramm, P. J. et al., 2020: How Indigenous Communities Are Adapting To Climate Change: Insights From The Climate-Ready Tribes Initiative. *Health Affairs*, **39**(12), 2153-2159, doi:10.1377/hlthaff.2020.00997.
Schuhbauer, A. et al., 2017: How subsidies affect the economic viability of small-scale fisheries. *Marine Policy*, **82**, 114-121, doi:https://doi.org/10.1016/j.marpol.2017.05.013.
Schulte, L. A. et al., 2017: Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands. *Proceedings of the National Academy of Sciences of the United States of America*, **114**, 11247-11252, doi:10.1073/pnas.1620229114.

Schwerdtle, P., K. Bowen and C. McMichael, 2018: The health impacts of climate-related migration. *BMC Medicine 2018 16:1*, **16**, 1-7, doi:10.1186/S12916-017-0981-7.
Schwerdtle, P., C. McMichael, I. M.-E. … and u. 2020, 2020: Health and migration in the context of a changing climate: a systematic literature assessment. *iopscience.iop.org*, doi:10.1088/1748-9326/ab9ece.
Seddon, N. et al., 2020a: Understanding the value and limits of nature-based solutions to climate change and other global challenges. Royal Society Publishing.
Seddon, N. et al., 2020b: Global recognition of the importance of nature-based solutions to the impacts of climate change. *Global Sustainability*, **3**, doi:10.1017/sus.2020.8.
Seddon, N. et al., 2019: Grounding nature-based climate solutions in sound biodiversity science. Nature Publishing Group, 84-87 pp.
Sedova, B. and M. Kalkuhl, 2020: Who are the climate migrants and where do they go? Evidence from rural India. *World Development*, **129**, 104848, doi:10.1016/j.worlddev.2019.104848.
See, J. and B. Wilmsen, 2020: Just adaptation? Generating new vulnerabilities and shaping adaptive capacities through the politics of climate-related resettlement in a Philippine coastal city. *Global Environmental Change*, **65**, 102188, doi:10.1016/J.GLOENVCHA.2020.102188.
Seebauer, S., S. Ortner, P. Babcicky and T. Thaler, 2019: Bottom-up citizen initiatives as emergent actors in flood risk management: Mapping roles, relations and limitations. *Journal of Flood Risk Management*, **12**, doi:10.1111/jfr3.12468.
Seleka, M., B. Lough, E. Combaz and M. L. Seleka, 2017: African Young Graduates and Scholars Conference Paper.
Semenza, J. C. and K. L. Ebi, 2019: Climate change impact on migration, travel, travel destinations and the tourism industry. *Journal of Travel Medicine*, **26**, doi:10.1093/jtm/taz026.
Serre, D. and C. Heinzlef, 2018: Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks. *International Journal of Disaster Risk Reduction*, **30**, 235-243, doi:10.1016/j.ijdrr.2018.02.018.
Shackleton, S. et al., 2015: Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *Wiley Interdisciplinary Reviews: Climate Change*, **6**, 321-344, doi:10.1002/wcc.335.
Shaffril, H. A. M., A. Abu Samah and J. L. D'Silva, 2017: Adapting towards climate change impacts: Strategies for small-scale fishermen in Malaysia. *Marine Policy*, **81**, 196-201, doi:10.1016/j.marpol.2017.03.032.
Shah, F. and W. Wu, 2019: Soil and Crop Management Strategies to Ensure Higher Crop Productivity within Sustainable Environments. *Sustainability*, **11**, 1485, doi:10.3390/su11051485.
Shang, Z. et al., 2021: Can cropland management practices lower net greenhouse emissions without compromising yield? *Global Change Biology*, **n/a**, doi:https://doi.org/10.1111/gcb.15796.
Shannon, P. D. et al., 2019: Adaptation strategies and approaches for forested watersheds. Elsevier B.V., 51-64 pp.
Shapiro, S., 2016: The realpolitik of building codes: overcoming practical limitations to climate resilience. *Building Research & Information*, **44**, 490-506, doi:10.1080/09613218.2016.1156957.
Sharma, H., D. Kumar, L. . and K. S. Pant, 2020: Agroforestry- A sustainable Tool for Climate Change Adaptation and Mitigation. *Agricultural Reviews*, doi:10.18805/ag.r-1924.
Sharma, R. and R. Sharma, 2021: Community Based Flood Risk Management: Local Knowledge and Actor's Involvement Approach from Lower Karnali River Basin of Nepal. *Journal of Geoscience and Environment Protection*, **9**(6), 35-65, doi:10.4236/GEP.2021.96003.
Sheehan, M. C. and M. A. Fox, 2020: Early Warnings: The Lessons of COVID-19 for Public Health Climate Preparedness. *International Journal of Health Services*, **50**, 264-270, doi:10.1177/0020731420928971.
Shi, L., 2019: Promise and paradox of metropolitan regional climate adaptation. *Environmental Science and Policy*, **92**, 262-274, doi:10.1016/j.envsci.2018.11.002.
Shi, L. and A. M. Varuzzo, 2020: Surging seas, rising fiscal stress: Exploring municipal fiscal vulnerability to climate change. *Cities*, **100**, doi:10.1016/j.cities.2020.102658.
Shokry, G., J. J. Connolly and I. Anguelovski, 2020: Understanding climate gentrification and shifting landscapes of protection and vulnerability in green resilient Philadelphia. *Urban Climate*, **31**, 100539, doi:10.1016/j.uclim.2019.100539.
Siders, A. R., 2019: Social justice implications of US managed retreat buyout programs. *Climatic Change*, **152**, 239-257, doi:10.1007/s10584-018-2272-5.
Siders, A. R. and J. M. Keenan, 2020: Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. *Ocean and Coastal Management*, **183**, 105023, doi:10.1016/j.ocecoaman.2019.105023.
Sietsma, A. J., J. D. Ford, M. W. Callaghan and J. C. Minx, 2021: Progress in climate change adaptation research. *Environmental Research Letters*, **16**, 54038, doi:10.1088/1748-9326/abf7f3.
Sina, D., A. Y. Chang-Richards, S. Wilkinson and R. Potangaroa, 2019: What does the future hold for relocated communities post-disaster? Factors affecting livelihood resilience. *International Journal of Disaster Risk Reduction*, **34**, 173-183, doi:10.1016/j.ijdrr.2018.11.015.
Singh, B. P., R. Setia, M. Wiesmeier and A. Kunhikrishnan, 2018a: Agricultural management practices and soil organic carbon storage. Elsevier, 207-244 pp.
Singh, C. and R. Basu, 2020: Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural–urban continuum in India. *The Geographical Journal*, **186**, 87-102, doi:10.1111/geoj.12328.

Singh, C. et al., 2020a: Assessing the feasibility of climate change adaptation options in the water sector: Examples from rural and urban landscapes. *Water Security*, **11**, 100071, doi:10.1016/j.wasec.2020.100071.
Singh, C. et al., 2018b: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and Development*, **10**, 389-405, doi:10.1080/17565529.2017.1318744.
Singh, C. et al., 2020b: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Climatic Change*, doi:10.1007/s10584-020-02762-x.
Singh, C., G. Jain, V. Sukhwani and R. Shaw, 2021a: Losses and damages associated with slow-onset events: urban drought and water insecurity in Asia. *Current Opinion in Environmental Sustainability*, **50**, 72-86, doi:https://doi.org/10.1016/j.cosust.2021.02.006.
Singh, C., M. Madhavan, J. Arvind and A. Bazaz, 2021b: Climate change adaptation in Indian cities: A review of existing actions and spaces for triple wins. *Urban Climate*, **36**, 100783, doi:https://doi.org/10.1016/j.uclim.2021.100783.
Singh, C., A. Rahman, A. Srinivas and A. Bazaz, 2018c: Risks and responses in rural India: Implications for local climate change adaptation action. *Climate Risk Management*, **21**, 52-68, doi:10.1016/j.crm.2018.06.001.
Singh, D. et al., 2020c: A review on feedstocks, production processes, and yield for different generations of biodiesel. Elsevier Ltd.
Siriwardane-de Zoysa, R., 2020: Beyond the wall: Dyking as an object of everyday governance in the Bay of Manila, Philippines. *Marine Policy*, **112**, 103661, doi:https://doi.org/10.1016/j.marpol.2019.103661.
Sletto, B., S. Tabory and K. Strickler, 2019: Sustainable urban water management and integrated development in informal settlements: The contested politics of co-production in Santo Domingo, Dominican Republic. *Global Environmental Change*, **54**, 195-202, doi:10.1016/J.GLOENVCHA.2018.12.004.
Smith, J., B. D. Pearce and M. S. Wolfe, 2013: Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? *Renewable Agriculture and Food Systems*, **28**(1), 80-92, doi:10.1017/S1742170511000585.
Smucker, T. A., M. Oulu and R. Nijbroek, 2020: Foundations for convergence: Sub-national collaboration at the nexus of climate change adaptation, disaster risk reduction, and land restoration under multi-level governance in Kenya. *International Journal of Disaster Risk Reduction*, **51**, 101834, doi:https://doi.org/10.1016/j.ijdrr.2020.101834.
Sojka, M. et al., 2019: Sustainable Water Management in Agriculture—The Impact of Drainage Water Management on Groundwater Table Dynamics and Subsurface Outflow. *Sustainability*, **11**(15), doi:10.3390/su11154201.
Sollen-Norrlin, M., B. B. Ghaley and N. L. Rintoul, 2020: Agroforestry Benefits and Challenges for Adoption in Europe and Beyond. *Sustainability*, **12**(17), doi:10.3390/su12177001.
Somasundaram, J. et al., 2020: No-Till Farming and Conservation Agriculture in South Asia–Issues, Challenges, Prospects and Benefits. *Critical Reviews in Plant Sciences*, **39**, 236-279, doi:10.1080/07352689.2020.1782069.
Sommer, R., B. K. Paul, J. Mukalama and J. Kihara, 2018: Reducing losses but failing to sequester carbon in soils – the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. *Agriculture, Ecosystems and Environment*, **254**, 82-91, doi:10.1016/j.agee.2017.11.004.
Son, H. N., A. Kingsbury and H. T. Hoa, 2021: Indigenous knowledge and the enhancement of community resilience to climate change in the Northern Mountainous Region of Vietnam. *Agroecology and Sustainable Food Systems*, **45**(4), 499-522, doi:10.1080/21683565.2020.1829777.
Sova, C. A. et al., 2018: Bringing the Concept of Climate-Smart Agriculture to Life. *Bringing the Concept of Climate-Smart Agriculture to Life*, doi:10.1596/31064.
Spaans, M. and B. Waterhout, 2017: Building up resilience in cities worldwide–Rotterdam as participant in the 100 Resilient Cities Programme. *Cities*, **61**, 109-116.
Spilker, G., Q. Nguyen, V. Koubi and T. Böhmelt, 2020: Attitudes of urban residents towards environmental migration in Kenya and Vietnam. *Nature Climate Change*, **10**, 622-627, doi:10.1038/s41558-020-0805-1.
Stefanakis, A. I., 2019: The Role of Constructed Wetlands as Green Infrastructure for Sustainable Urban Water Management. *Sustainability*, **11**(24), doi:10.3390/su11246981.
Stentiford, G. D. et al., 2020: Sustainable aquaculture through the One Health lens. *Nature Food*, **1**, 468-474, doi:10.1038/s43016-020-0127-5.
Suckall, N., E. Fraser, P. F.-C. a. Development and u. 2017, 2016: Reduced migration under climate change: Evidence from Malawi using an aspirations and capabilities framework. *Taylor & Francis*, **9**, 298-312, doi:10.1080/17565529.2016.1149441.
Surminski, S., L. M. Bouwer and J. Linnerooth-Bayer, 2016: How insurance can support climate resilience. *Nature Climate Change*, **6**, 333-334, doi:10.1038/nclimate2979.
Szewrański, S. et al., 2018: Socio-Environmental Vulnerability Mapping for Environmental and Flood Resilience Assessment: The Case of Ageing and Poverty in the City of Wrocław, Poland. Wiley-Blackwell, 592-597 pp.
Tabe, T., 2019: Climate Change Migration and Displacement: Learning from Past Relocations in the Pacific. *Social Sciences*, **8**(7), doi:10.3390/socsci8070218.
Tagliari, M. M. et al., 2021: Collaborative management as a way to enhance Araucaria Forest resilience. Associacao Brasileira de Ciencia Ecologica e Conservacao, 131-142 pp.

Tall, A., J. Y. Coulibaly and M. Diop, 2018: Do climate services make a difference? A review of evaluation methodologies and practices to assess the value of climate information services for farmers: Implications for Africa. *Climate Services*, **11**, 1-12, doi:https://doi.org/10.1016/j.cliser.2018.06.001.
Tanaya, T. et al., 2021: Improvement of the coral growth and cost- effectiveness of hybrid infrastructure by an innovative breakwater design in Naha Port, Okinawa, Japan. *Coastal Engineering Journal*, doi:10.1080/21664250.2021.1889823.
Tanner, T. et al., 2015: Livelihood resilience in the face of climate change. Nature Publishing Group, 23-26 pp.
Tavenner, K. and T. A. Crane, 2018: Gender power in Kenyan dairy: cows, commodities, and commercialization. *Agriculture and Human Values*, **35**(3), 701-715, doi:10.1007/s10460-018-9867-3.
Telave, A. B. and S. R. Chandankar, 2021: Integrated coastal zone management: An Indian perspective-A Review. *Ecology, Environment and Conservation*, S162-S167.
Telford, A., 2018: A threat to climate-secure European futures? Exploring racial logics and climate-induced migration in US and EU climate security discourses. *Geoforum*, **96**, 268-277, doi:https://doi.org/10.1016/j.geoforum.2018.08.021.
TerAvest, D., P. R. Wandschneider, C. Thierfelder and J. P. Reganold, 2019: Diversifying conservation agriculture and conventional tillage cropping systems to improve the wellbeing of smallholder farmers in Malawi. *Agricultural Systems*, **171**, 23-35, doi:10.1016/j.agsy.2019.01.004.
Terêncio, D. P. S. et al., 2018: Rainwater harvesting in catchments for agro-forestry uses: A study focused on the balance between sustainability values and storage capacity. *Science of The Total Environment*, **613-614**, 1079-1092, doi:https://doi.org/10.1016/j.scitotenv.2017.09.198.
Tesselaar, M., W. J. W. Botzen and J. C. J. H. Aerts, 2020: Impacts of climate change and remote natural catastrophes on EU flood insurance markets: An analysis of soft and hard reinsurance markets for flood coverage. *Atmosphere*, **11**, doi:10.3390/atmos11020146.
Thierfelder, C. et al., 2017: How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. *Food Security*, **9**, 537-560, doi:10.1007/s12571-017-0665-3.
Thober, J., N. Schwarz and K. Hermans, 2018: Agent-based modeling of environment-migration linkages: A review. *Ecology and Society*, **23**, doi:10.5751/ES-10200-230241.
Thomas, A. and L. Benjamin, 2018: Policies and mechanisms to address climate-induced migration and displacement in Pacific and Caribbean small island developing states. *International Journal of Climate Change Strategies and Management*, **10**, 86-104, doi:10.1108/IJCCSM-03-2017-0055.
Thomas, M. et al., 2021: When more is more: taking advantage of species diversity to move towards sustainable aquaculture. *Biological Reviews*, **96**, 767-784, doi:https://doi.org/10.1111/brv.12677.
Thompson, P. L., B. Rayfield and A. Gonzalez, 2017: Loss of habitat and connectivity erodes species diversity, ecosystem functioning, and stability in metacommunity networks. *Ecography*, **40**, 98-108, doi:10.1111/ecog.02558.
Thorne, C. R. et al., 2018: Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management. *Journal of Flood Risk Management*, **11**(S2), S960-S972, doi:https://doi.org/10.1111/jfr3.12218.
Tian, Q. and M. C. Lemos, 2018: Household Livelihood Differentiation and Vulnerability to Climate Hazards in Rural China. *World Development*, **108**, 321-331, doi:10.1016/j.worlddev.2017.10.019.
Tiggeloven, T. et al., 2020: Global-scale benefit--cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. *Natural Hazards and Earth System Sciences*, **20**, 1025-1044, doi:10.5194/nhess-20-1025-2020.
Torell, E., C. McNally, B. Crawford and G. Majubwa, 2017: Coastal Livelihood Diversification as a Pathway Out of Poverty and Vulnerability: Experiences from Tanzania. *Coastal Management*, **45**(3), 199-218, doi:10.1080/08920753.2017.1303718.
Tschora, H. and F. Cherubini, 2020: Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. *Global Ecology and Conservation*, **22**, doi:10.1016/J.GECCO.2020.E00919.
Turolla, E., G. Castaldelli, E. A. Fano and E. Tamburini, 2020: Life Cycle Assessment (LCA) Proves that Manila Clam Farming (Ruditapes Philippinarum) is a Fully Sustainable Aquaculture Practice and a Carbon Sink.
Uddin, M. S., C. E. Haque and M. N. Khan, 2020: Good governance and local level policy implementation for disaster-risk-reduction: actual, perceptual and contested perspectives in coastal communities in Bangladesh. *Disaster Prevention and Management: An International Journal*, **30**, 94-111, doi:10.1108/DPM-03-2020-0069.
Ulrichs, M., R. Slater and C. Costella, 2019: Building resilience to climate risks through social protection: from individualised models to systemic transformation. *Disasters*, **43**, S368-S387, doi:10.1111/disa.12339.
Valenti, W. C., J. M. Kimpara, B. d. L. Preto and P. Moraes-Valenti, 2018: Indicators of sustainability to assess aquaculture systems. *Ecological Indicators*, **88**, 402-413, doi:https://doi.org/10.1016/j.ecolind.2017.12.068.
van den Brandeler, F., J. Gupta and M. Hordijk, 2019: Megacities and rivers: Scalar mismatches between urban water management and river basin management. *Journal of Hydrology*, **573**, 1067-1074, doi:https://doi.org/10.1016/j.jhydrol.2018.01.001.
Van Hulst, F. J. and H. Posthumus, 2016: Understanding (non-) adoption of Conservation Agriculture in Kenya using the Reasoned Action Approach. *Land Use Policy*, **56**, 303-314, doi:10.1016/j.landusepol.2016.03.002.

Van Langevelde, F. et al. (eds.), The link between biodiversity loss and the increasing spread of zoonotic diseases Policy Department for Economic, Scientific and Quality of Life Policies Directorate-General for Internal Policies.
Van Loon-Steensma, J. M. and P. Vellinga, 2019: How "wide green dikes" were reintroduced in The Netherlands: a case study of the uptake of an innovative measure in long-term strategic delta planning. *Journal of Environmental Planning and Management*, **62**, 1525-1544, doi:10.1080/09640568.2018.1557039.
Van Oijstaeijen, W., S. Van Passel and J. Cools, 2020: Urban green infrastructure: A review on valuation toolkits from an urban planning perspective. *Journal of Environmental Management*, **267**, 110603, doi:10.1016/j.jenvman.2020.110603.
van Valkengoed, A. M. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, **9**, 158-163, doi:10.1038/s41558-018-0371-y.
VandenBygaart, A. J., 2016: The myth that no-till can mitigate global climate change. Elsevier B.V., 98-99 pp.
Vargas-Hernández, J. G. and J. Zdunek-Wielgołaska, 2021: Urban green infrastructure as a tool for controlling the resilience of urban sprawl. *Environment, Development and Sustainability*, **23**(2), 1335-1354, doi:10.1007/s10668-020-00623-2.
Vaughan, C., L. Buja, A. Kruczkiewicz and L. Goddard, 2016: Identifying research priorities to advance climate services. *Climate Services*, **4**, 65-74, doi:10.1016/j.cliser.2016.11.004.
Vaughan, C., S. Dessai and C. Hewitt, 2018: Surveying Climate Services: What Can We Learn from a Bird's-Eye View? *Weather, Climate, and Society*, **10**, 373-395, doi:10.1175/WCAS-D-17-0030.1.
Vaughan, C. et al., 2019: Evaluating agricultural weather and climate services in Africa: Evidence, methods, and a learning agenda. *WIREs Climate Change*, **10**(4), e586, doi:https://doi.org/10.1002/wcc.586.
Velasco-Muñoz, J. F., J. A. Aznar-Sánchez, L. J. Belmonte-Ureña and M. J. López-Serrano, 2018: Advances in Water Use Efficiency in Agriculture: A Bibliometric Analysis. *Water*, **10**(4), doi:10.3390/w10040377.
Venter, Z. S. et al., 2020: Green Apartheid: Urban green infrastructure remains unequally distributed across income and race geographies in South Africa. *Landscape and Urban Planning*, **203**, 103889, doi:10.1016/j.landurbplan.2020.103889.
Viani, F., M. Bertolli, M. Salucci and A. Polo, 2017: Low-Cost Wireless Monitoring and Decision Support for Water Saving in Agriculture. *IEEE Sensors Journal*, **17**(13), 4299-4309, doi:10.1109/JSEN.2017.2705043.
Villamizar, A. et al., 2017: Climate adaptation in South America with emphasis in coastal areas: the state-of-the-art and case studies from Venezuela and Uruguay. *Climate and Development*, **9**, 364-382, doi:10.1080/17565529.2016.1146120.
Villeneuve, M., 2021: Building a roadmap for inclusive disaster risk reduction in Australian communities. *Progress in Disaster Science*, **10**, 100166, doi:https://doi.org/10.1016/j.pdisas.2021.100166.
Vincent, K. et al., 2017: Identifying climate services needs for national planning: insights from Malawi. *Climate Policy*, **17**(2), 189-202, doi:10.1080/14693062.2015.1075374.
von Holle, B., S. Yelenik and E. S. Gornish, 2020: Restoration at the landscape scale as a means of mitigation and adaptation to climate change. *Current Landscape Ecology Reports*, **5**, 85-97, doi:10.1007/s40823-020-00056-7.
Vousdoukas, M. I. et al., 2020: Economic motivation for raising coastal flood defenses in Europe. *Nature Communications*, **11**, 2119, doi:10.1038/s41467-020-15665-3.
Walsh, C., 2019: Integration of expertise or collaborative practice?: Coastal management and climate adaptation at the Wadden Sea. *Ocean and Coastal Management*, **167**, 78-86, doi:10.1016/j.ocecoaman.2018.10.004.
Wang, X. et al., 2020: Cutting carbon footprints of vegetable production with integrated soil - crop system management: A case study of greenhouse pepper production. *Journal of Cleaner Production*, **254**, 120158, doi:10.1016/j.jclepro.2020.120158.
Warner, K., 2018: Coordinated approaches to large-scale movements of people: contributions of the Paris Agreement and the Global Compacts for migration and on refugees. *Population and Environment*, **39**, 384-401, doi:10.1007/S11111-018-0299-1.
Warnken, J. and R. Mosadeghi, 2018: Challenges of implementing integrated coastal zone management into local planning policies, a case study of Queensland, Australia. *Marine Policy*, **91**, 75-84, doi:10.1016/j.marpol.2018.01.031.
Waryszak, P. et al., 2021: Combining gray and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defenses. *Coastal Engineering Journal*, 1-16, doi:10.1080/21664250.2021.1920278.
Watts, N. et al., 2021: The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *Lancet*, **397**(10269), 129-170, doi:10.1016/s0140-6736(20)32290-x.
Webb, J., 2020: What difference does disaster risk reduction make? Insights from Vanuatu and tropical cyclone Pam. *Regional Environmental Change*, **20**, doi:10.1007/s10113-020-01584-y.
Webber, J. L. et al., 2020: Is green infrastructure a viable strategy for managing urban surface water flooding? *Urban Water Journal*, **17**(7), 598-608, doi:10.1080/1573062X.2019.1700286.
Webber, S. and S. D. Donner, 2017: Climate service warnings: cautions about commercializing climate science for adaptation in the developing world. *Wiley Interdisciplinary Reviews: Climate Change*, **8**, e424, doi:10.1002/wcc.424.
Weng, W., L. Costa, M. K. B. Lüdeke and D. C. Zemp, 2019: Aerial river management by smart cross-border reforestation. *Land Use Policy*, **84**, 105-113, doi:10.1016/j.landusepol.2019.03.010.
WHO, 2015: Operational framework for building climate resilient health systems. *World Health Organisation*, 56.

WHO, 2019: *2018 WHO health and climate change survey report: Tracking global progress*.

Wiegel, H., I. Boas, J. W.-W. I. Reviews and u. 2019, 2019: A mobilities perspective on migration in the context of environmental change. *Wiley Online Library*, **10**, doi:10.1002/wcc.610.

Willems, J. J., A. V. Kenyon, L. Sharp and A. Molenveld, 2021: How actors are (dis)integrating policy agendas for multi-functional blue and green infrastructure projects on the ground. *Journal of Environmental Policy & Planning*, **23**(1), 84-96, doi:10.1080/1523908X.2020.1798750.

Williams, D. S., M. M. Costa, L. Celliers and C. Sutherland, 2018: Informal settlements and flooding: Identifying strengths andweaknesses in local governance for water management. *Water (Switzerland)*, **10**, doi:10.3390/W10070871.

Williams, D. S. et al., 2020: A method of assessing user capacities for effective climate services. *Climate Services*, **19**, 100180, doi:https://doi.org/10.1016/j.cliser.2020.100180.

Williams, P. A. et al., 2021: Feasibility assessment of climate change adaptation options across Africa: An evidence-based review. *Environmental Research Letters*, **16**, 73004, doi:10.1088/1748-9326/ac092d.

Wilmsen, B. and M. Webber, 2015: What can we learn from the practice of development-forced displacement and resettlement for organised resettlements in response to climate change? *Geoforum*, **58**, 76-85, doi:10.1016/j.geoforum.2014.10.016.

Wilson, N. J., 2014: The Politics of Adaptation: Subsistence Livelihoods and Vulnerability to Climate Change in the Koyukon Athabascan Village of Ruby, Alaska. *Human Ecology*, **42**, 87-101, doi:10.1007/s10745-013-9619-3.

Winters, M. A., B. Leslie, E. B. Sloane and T. W. Gallien, 2020: Observations and Preliminary Vulnerability Assessment of a Hybrid Dune-Based Living Shoreline.

Wolfrom, L. and M. Yokoi-Arai, 2015: Financial instruments for managing disaster risks related to climate change. *OECD Journal: Financial Market Trends*, **2015**, 25-47, doi:10.1787/fmt-2015-5jrqdkpxk5d5.

Woodhouse, E. and J. T. McCabe, 2018: Well-being and conservation: diversity and change in visions of a good life among the Maasai of northern Tanzania. *Ecology and Society, Published online: Mar 26, 2018 | doi:10.5751/ES-09986-230143*, **23**, doi:10.5751/ES-09986-230143.

Woodruff, S., T. K. BenDor and A. L. Strong, 2018: Fighting the inevitable: infrastructure investment and coastal community adaptation to sea level rise. *System Dynamics Review*, **34**, 48-77, doi:10.1002/sdr.1597.

Worboys, G. L. et al. (eds.), CONNECTIVITY CONSERVATION AREA GUIDELINES [DEFINITION, TYPES, SELECTION CRITERIA AND GOVERNANCE] ADVANCED DRAFT, MAY 2016.

Woroniecki, S., C. Wamsler and E. Boyd, 2019: The promises and pitfalls of ecosystem-based adaptation to climate change as a vehicle for social empowerment. *Ecology and Society*, **24**(2), doi:10.5751/ES-10854-240204.

Wrathall, D. J. et al., 2019: Meeting the looming policy challenge of sea-level change and human migration. *Nature Climate Change 2019 9:12*, **9**, 898-901, doi:10.1038/s41558-019-0640-4.

Xuan, B. B., E. D. Sandorf and Q. T. K. Ngoc, 2021: Stakeholder perceptions towards sustainable shrimp aquaculture in Vietnam. *Journal of Environmental Management*, **290**, 112585, doi:https://doi.org/10.1016/j.jenvman.2021.112585.

Yumagulova, L. et al., 2021: The role of disaster volunteering in Indigenous communities. *Environmental Hazards*, **20**(1), 45-62, doi:10.1080/17477891.2019.1657791.

Zen, I. S., A. Q. Al-Amin and B. Doberstein, 2019: Mainstreaming climate adaptation and mitigation policy: Towards multi-level climate governance in Melaka, Malaysia. Elsevier B.V.

Zhang, C., L. Zhong and J. Wang, 2018: Decoupling between water use and thermoelectric power generation growth in China. *Nature Energy*, **3**, 792-799, doi:10.1038/s41560-018-0236-7.

Zhang, Z., S. Meerow, J. P. Newell and M. Lindquist, 2019: Enhancing landscape connectivity through multifunctional green infrastructure corridor modeling and design. *Urban Forestry and Urban Greening*, **38**, 305-317, doi:10.1016/j.ufug.2018.10.014.

Zobeidi, T. et al., 2021: Factors affecting smallholder farmers' technical and non-technical adaptation responses to drought in Iran. *Journal of Environmental Management*, **298**, 113552, doi:https://doi.org/10.1016/j.jenvman.2021.113552.

Zomer, R. J., D. A. Bossio, R. Sommer and L. V. Verchot, 2017: Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Scientific Reports*, **7**, 1-8, doi:10.1038/s41598-017-15794-8.

Zwierzchowska, I. et al., 2019: Introducing nature-based solutions into urban policy – facts and gaps. Case study of Poznań. *Land Use Policy*, **85**, 161-175, doi:https://doi.org/10.1016/j.landusepol.2019.03.025.

[END CROSS-CHAPTER BOX FEASIB HERE]

Cross-Chapter Paper 1: Biodiversity Hotspots

Cross-Chapter Paper Leads: Mark John Costello (New Zealand/Ireland/Norway), Mariana M. Vale (Brazil)

Cross-Chapter Paper Authors: Wolfgang Kiessling (Germany), Shobha Maharaj (Germany/Trinidad and Tobago), Jeff Price (United Kingdom), Gautam Hirak Talukdar (India)

Cross-Chapter Paper Contributing Authors: Heath Beckett (South Africa), Will Darwall (United Kingdom), Anindita Debnath (India), Eleanor Devenish-Nelson (United Kingdom), Yimnang Golbuu (Palau), Kerry-Anne Grey (South Africa) Tamlin Jefferson (New Zealand/United Kingdom), Rhosanna Jenkins (United Kingdom), Adam Kocsis (Germany/Hungary), Stella Manes (Brazil), Guy Midgley (South Africa), David Schoeman (Australia), Pablo A. Tedesco (France)

Cross-Chapter Paper Review Editor: Andreas Fischlin (Switzerland)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Geographic areas that are exceptionally rich in species, ecologically distinct and/or show high endemism (species occurring in that defined geographic area and nowhere else), are broadly recognised as biodiversity hotspots and prioritised for conservation. Here, we assess the impacts and vulnerability to climate change of terrestrial, freshwater and marine regions considered to be biodiversity hotspots. {CCP1.1}

Species in biodiversity hotspots already show changes in response to climate change (*high confidence*[1]). The animal and plant species assessed have been shifting their geographic ranges from low to high latitudes in response to climate warming on land and in the ocean (*very high confidence*). On land, climate change-induced shifts towards higher elevations are also common in biodiversity hotspots (*high confidence*); while in the ocean climate-induced shifts to greater water depths are little studied. In the ocean, abrupt mortality of habitat-forming species on coral reefs and kelp forests, especially following heatwaves, are increasing in frequency in biodiversity hotspots (*high confidence*). {CCP1.2.1, 1.2.2, 1.2.4}

All biodiversity hotspots are impacted, to differing degrees, by human activities (*very high confidence*), Climate change impacts are compounded by other anthropogenic impacts, including habitat loss and fragmentation, hunting, fishing and its bycatch, over-exploitation, water abstraction, nutrient enrichment, pollution, human introduction of invasive species, pests and diseases, all of which reduce climate resilience (*very high confidence*), complicating the attribution of observed changes to climate change. {CCP1.2.1}

Observed climate velocities are approximately 20% lower inside than outside of terrestrial and freshwater biodiversity hotspots, but 69% higher inside than outside marine hotspots (*high confidence*). In spite of the lower climate velocities inside terrestrial hotspots, these areas are projected not to serve as effective climate refugia from the effects of global warming, especially for endemic species (unique to a hotspot) (*medium confidence*). The greater climate velocities inside marine hotspots exposes their species to greater climate-induced pressures inside than outside hotspots (*high confidence*). The differences between temperatures inside and outside of hotspots narrow with increasing warming (*medium confidence*). {CCP1.2.2}

The risk of species extinction increases with warming in all climate change projections for native species studied in hotspots (*high confidence*), being about ten-times greater for endemic species from 1.5°C to 3°C above pre-industrial levels (*medium confidence*). Of the 6,116 projections for more than 2,700 species assessed in biodiversity hotspots, ~44% were found to be at high extinction risk, and ~24% at very high extinction risk due to climate change (*medium confidence*). Very high extinction risk in biodiversity hotspots due to climate change is more common for endemic species than other native species (*high confidence*). For these endemic species, considering all scenarios and time periods evaluated, ~100% on islands, ~84% on mountains, ~12% on continents (*high confidence*) and ~54% in the ocean (notably the Mediterranean) (*low confidence*) are projected to be threatened with extinction due to climate change. With further warming, increasingly high risks of local and global extinctions are projected in biodiversity hotspots from climate-related stressors (*high confidence*). {CCP1.2.1, Figure CCP1.7, Figure CCP1.6}

Adaptation options could enhance the persistence of biodiversity in hotspots (*high confidence*). Noting that over 3 billion people live within biodiversity hotspots, reduction of existing (non-climatic) pressures due to human activities is critical for building resilience within hotspots. Adaptation options for biodiversity (e.g., expanding fully protected areas, restoration and sustainable use practices) are as applicable inside as outside biodiversity hotspots (*high confidence*). Nevertheless, the protection of biodiversity hotspots is key to prevent a substantial global biodiversity decline from climate change {CCP 1.3, Table CCP1.2, 2.6, 3.6, Cross-Chapter Box NATURAL in Chapter 2}.

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

CCP1.1 Point of Departure

Biodiversity hotspots are geographic areas with an exceptionally high richness of species, including rare and endemic species. Such hotspots have deep evolutionary roots and are concentrated in areas where past climatic variability was moderate (Enquist et al., 2019; Brown et al., 2020; Trew and Maclean, 2021). An important limitation of the biodiversity hotspot concept is that there may be species highly threatened with extinction which do not occur within what has traditionally been classified as a hotspot (Grenyer et al., 2006). Thus, biodiversity hotspot assessments need to be paralleled by assessments of highly endangered species, and the threats they face.

Many studies have proposed biodiversity hotspots based on different criteria, taxa and geographic contexts (e.g., Myers et al., 2000; Mittermeier et al., 2004; Mittermeier et al., 2011; Williams et al., 2011; Noss et al., 2015; Asaad et al., 2017). A coherent comparative assessment of all such schemes is beyond the scope of this chapter but is provided in recent reviews (Asaad et al., 2017; Jefferson and Costello, 2019). We base this assessment on the "WWF Global 200" areas of conservation importance (Olson and Dinerstein, 2002). These 238 ecoregions have been used in a previous climate risk assessment (Warren et al., 2018b) and cover terrestrial, freshwater and marine environments (Table CCP1.1, Figures CCP1.1, CCP1.2). In addition we included the terrestrial "biodiversity hotspots" as defined by Myers et al. (2000) and extended later (Table CCP1.1; Mittermeier et al., 2011; Williams et al., 2011; Noss et al., 2015). This assessment thus covers the "Global 200" (hereafter G200) and "Myers" biodiversity hotspots rather than particular species or ecological systems such as rainforests, coral reefs or the deep sea. Such systems are assessed in Chapters 2 and 3. Chapters 2 and 3 also cover observed and projected impacts, changes in ecosystem functioning, and species extinction risks at a global level.

Biodiversity hotspots have not been explicitly covered in the Fifth Assessment Report (IPCC, 2014) (hereafter AR5). Thus, the point of departure is AR4 (Parry et al., 2007), which assessed that climate change exacerbates biodiversity risks in hotspots and that 15-40% of endemic species (species only occurring in one region) were projected to become extinct at 3.5°C global warming (Fischlin et al., 2007). Risks of extinction are assessed using the guidelines in Chapter 2, with species projected to lose 80% of its range or abundance being classified as at very high risk of extinction and those projected to lose 50% being at high risk of extinction (Chapter 2, Fig. 2.8 for definitions and a global overview).

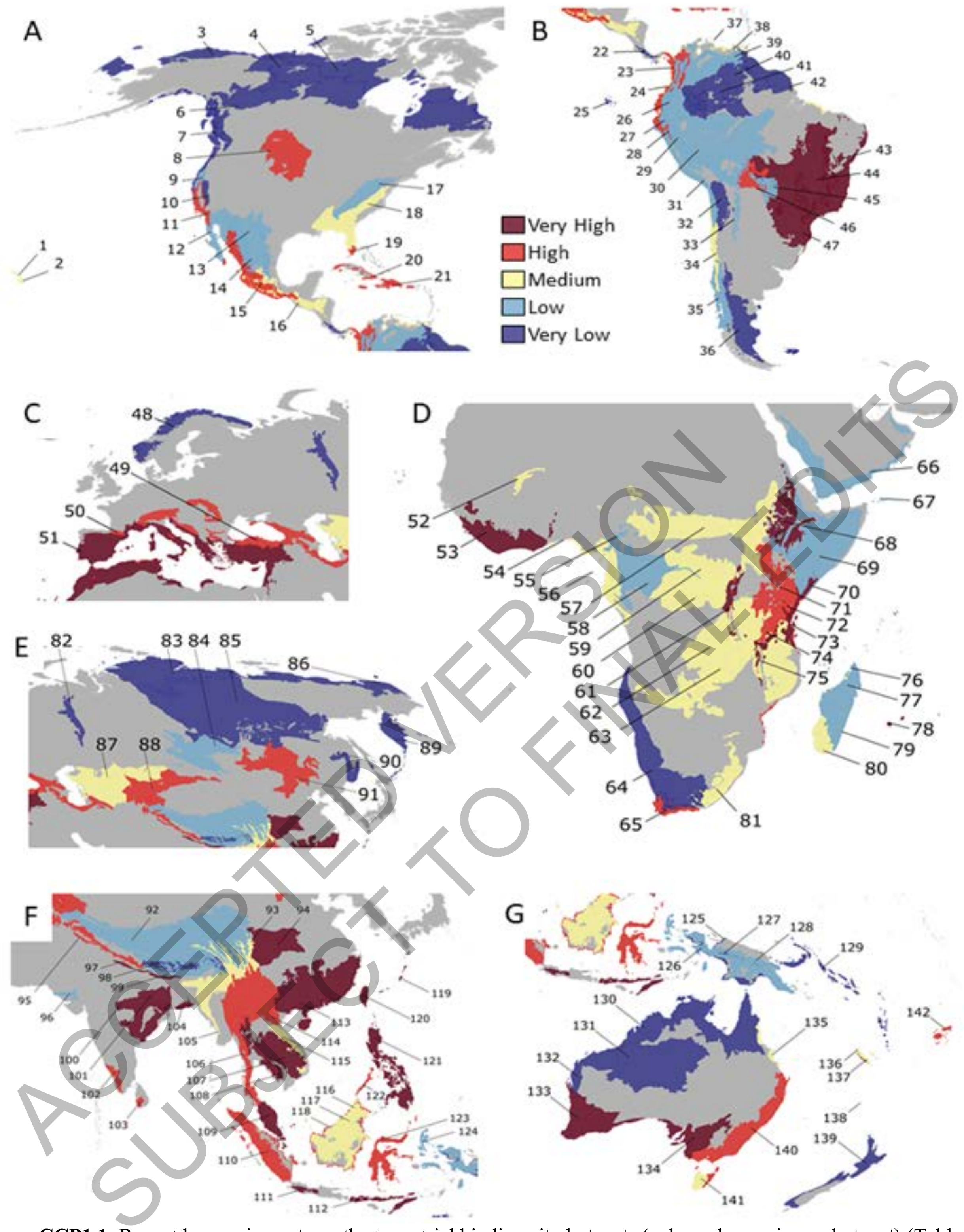


Figure CCP1.1: Recent human impacts on the terrestrial biodiversity hotspots (coloured, grey is non hotspot) (Table SMCCP1.1). Impacts are scaled in five equal 20% categories. A, North and Central America, B, South America, ,C, Europe and North Africa, ,D, Africa and Arabia, E, North Asia, ,F, Southeast Asia, G, Southeast Asian archipelagos, Australia and New Zealand. See Table CCP1.1 for key to hotspot numbers.

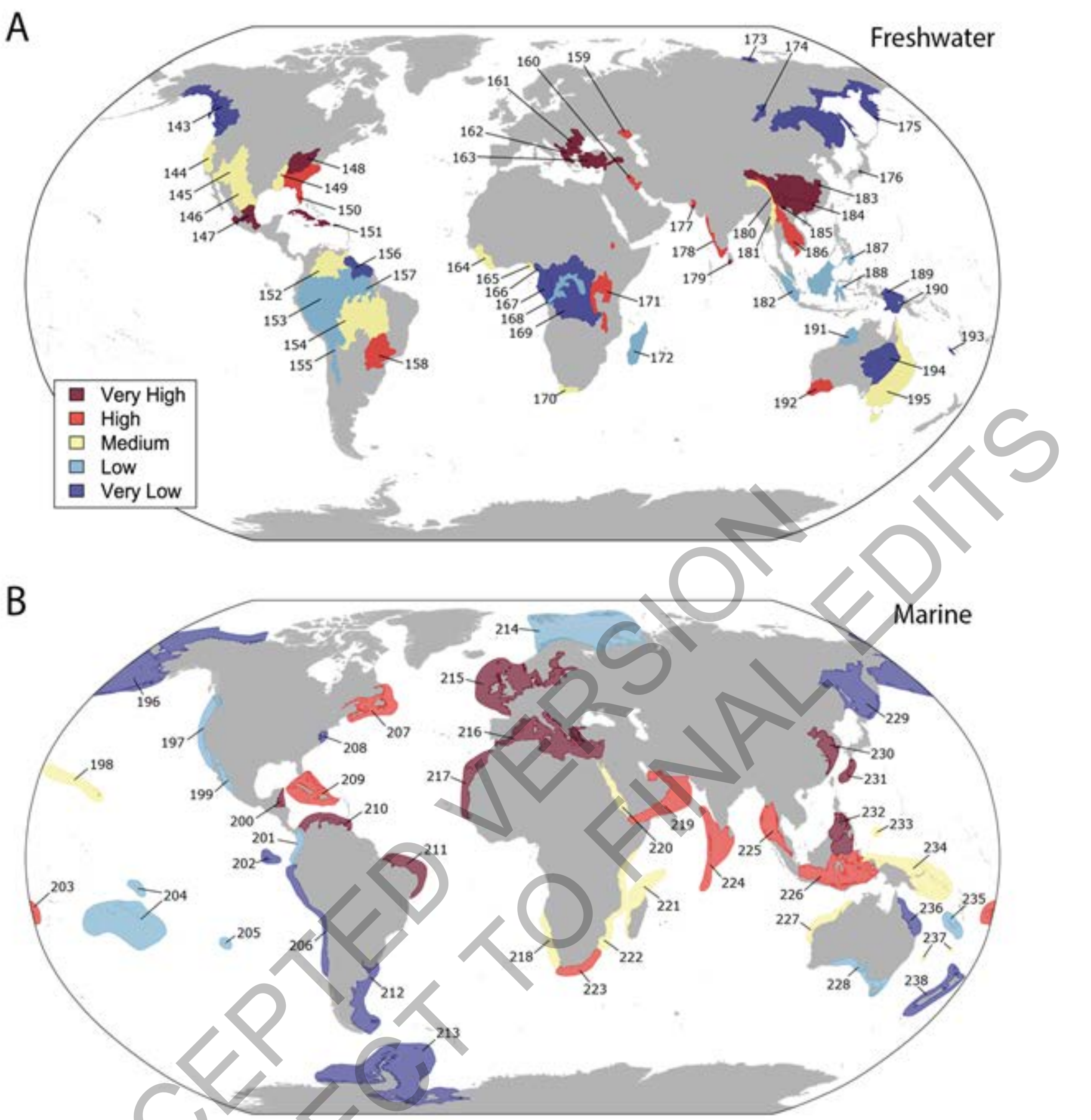


Figure CCP1.2: Recent human impacts from multiple factors on (A) freshwater hotspots since 2000 based on Janse et al. (2015) and (B) marine hotspots based on Halpern et al. (2015). Human impacts in terrestrial and freshwater habitats refer to the remaining wilderness. Marine impacts represent land-based, fishing, climate change and ocean-based stressors. Impacts are scaled into five equal 20% categories. See Table CCP1.1 for the key to hotspot numbers.

Table CCP1.1: List of biodiversity hotspots names from (Olson and Dinerstein, 2002) as mapped in Figures CCP1.1 (terrestrial, black text) and CCP1.2 (freshwater and marine in green and blue text respectively). Hotspots containing islands (> 100km2) are indicated with an asterisk.

1 Hawaii Moist Forest *	81 Drakensberg Montane Woodlands & Grasslands	161 Danube River Delta
2 Hawaii Dry Forest *	82 Ural Mountains Taiga & Tundra	162 Balkan Rivers & Streams *
3 Alaskan North Slope Coastal Tundra *	83 Taimyr and Russian Coastal Tundra *	163 Anatolian Freshwater
4 Canadian Boreal Taiga *	84 Altai-Sayan Montane Forests	164 Upper Guinea Rivers & Streams *
5 Canadian Low Arctic Tundra *	85 Central and Eastern Siberian Taiga	165 Niger River Delta *
6 Muskwa/Slave Lake Boreal Forests	86 Chukhote Coastal Tundra *	166 Cameroon Crater Lakes
7 Pacific Temperate Rainforests*	87 Central Asian Deserts	167 Gulf of Guinea Rivers & Streams *

8 Northern Prairies	88 Middle Asian Montane Woodlands and Steppe	168 Congo River and Flooded Forests
9 Klamath-Siskiyou Coniferous Forests	89 Kamchatka Taiga & Grasslands *	169 Congo Basin Piedmont Rivers & Streams
10 Sierra Nevada Coniferous Forests	90 Russian Far East Broadleaf & Mixed Forests *	170 Cape Rivers & Streams
11 California Chaparral & Woodlands *	91 Daurian/Mongolian Steppe	171 Rift Valley Lakes
12 Sonoran-Baja Deserts*	92 Tibetan Plateau Steppe	172 Madagascar Freshwater Ecosystem *
13 Chihuahuan-Tehuacan Deserts	93 Hengduan Shan Conifer Forests	173 Lena River Delta
14 Sierra Madre Oriental & Occidental Pine-Oak	94 Southwest China Temperate Forests	174 Lake Baikal
15 Southern Mexican Dry Forests *	95 Western Himalayan Temperate Forests	175 Russian Far East Rivers & Wetlands *
16 Mesoamerican Pine-Oak Forests	96 Rann of Kutch Flooded Grasslands	176 Lake Biwa *
17 Appalachian & Mixed Mesophytic Forests	97 Terai-Duar Savannas & Grasslands	177 Indus River Delta *
18 Southeastern Conifer and Broadleaf Forests *	98 Eastern Himalayan Alpine Meadows	178 Western Ghats Rivers & Streams
19 Everglades Flooded Grasslands	99 Eastern Himalayan Broadleaf and Conifer Forests	179 Southwestern Sri Lanka Rivers *
20 Greater Antillean Moist Forests *	100 Eastern Deccan Plateau Moist Forests *	180 Salween River
21 Greater Antillean Pine Forests *	101 Chhota-Nagpur Dry Forests	181 Lake Inle
22 Talamancan-Isthmian Pacific Forests	102 Southwestern Ghats Moist Forest	182 Sundaland Rivers & Swamps *
23 Choco-Darien Moist Forests *	103 Sri Lankan Moist Forest *	183 Yangtze River & Lakes
24 South American Pacific Mangroves*	104 Sundarbans Mangroves	184 Xi Jiang Rivers & Streams
25 Galapagos Islands Scrub *	105 Naga-Manapuri-Chin Hills Moist Forests *	185 Yunnan Lakes & Streams
26 Northern Andean Páramo	106 Kayah-Karen/Tenasserim Moist Forests	186 Mekong River *
27 Northern Andean Montane Forests	107 Indochina Dry Forests *	187 Philippines Freshwater *
28 Tumbesian-Andean Valleys Dry Forests *	108 Cardamom Mountains Moist Forests *	188 Central Sulawesi Lakes *
29 Napo Moist Forests	109 Peninsular Malaysia Lowland& Montane Forests *	189 New Guinea Rivers & Streams *
30 Southwestern Amazonian Moist Forests	110 Sumatran Islands Lowland and Montane Forests *	190 Lakes Kutubu & Sentani *
31 Atacama-Sechura Deserts	111 Western Java Montane Forests *	191 Kimberley Rivers & Streams
32 Central Andean Dry Puna	112 Nusu Tenggara Dry Forests *	192 Southwest Australia Rivers & Streams
33 Central Andean Yungas	113 Southeast China-Hainan Moist Forests	193 New Caledonia Rivers & Streams *
34 Chilean Matorral	114 North Indochina Subtropical Moist Forests	194 Central Australian Freshwater *
35 Valdivian Temp. Rain Forests Juan Fernandez *	115 Annamite Range Moist Forests	195 Eastern Australia Rivers & Streams
36 Patagonian Steppe*	116 Kinabalu Montane Shrublands *	196 Bering Sea *
37 Amazon-Orinoco-Southern Caribbean Mangroves *	117 Borneo Lowland and Montane Forests *	197 California Current *
38 Coastal Venezuela Montane Forests	118 Greater Sundas Mangroves *	198 Hawaiian Marine *
39 Llanos Savannas	119 Nansei Shoto Archipelago Forests *	199 Gulf of California *
40 Guianan Highlands Moist Forests	120 Taiwan Montane Forests *	200 Mesoamerican Reef *
41 Rio Negro-Jurua Moist Forests	121 Philippines Moist Forests *	201 Panama Bight *
42 Guianan Moist Forests	122 Palawan Moist Forests *	202 Galapagos Marine *
43 Atlantic Dry Forests	123 Sulawesi Moist Forests *	203 Fiji Barrier Reef *
44 Cerrado Woodlands & Savannas	124 Moluccas Moist Forests *	204 Tahitian Marine *
45 Pantanal Flooded Savannas	125 New Guinea Mangroves *	205 Rapa Nui *
46 Chiquitano Dry Forests	126 Southern New Guinea Lowland Forests *	206 Humboldt Current *

47 Atlantic Forests*	127 Central Range Subalpine Grasslands *	207 Grand Banks *
48 Fenno-Scandia Alpine Tundra & Taiga *	128 New Guinea Montane Forests *	208 Chesapeake Bay
49 Caucasus-Anatolian-Hyrcanian Temp. Forests	129 Solomons-Vanuatu-Bismarck Moist Forests *	209 Greater Antillean Marine *
50 European-Mediterranean Montane Forests	130 Northern Australia & Trans-Fly Savannas *	210 Southern Caribbean Sea *
51 Mediterranean Forests, Woodlands, Scrub *	131 Great Sandy-Tanami-Central Ranges Desert	211 Northeast Brazil Shelf Marine *
52 Sudd-Sahelian Flooded Grasslands & Savannas	132 Carnavon Xeric Shrubs *	212 Patagonian Southwest Atlantic *
53 Guinean Moist Forests	133 Southwestern Australia Forests & Scrub *	213 Antarctic Peninsula and Weddell Sea *
54 Gulf of Guinea Mangroves *	134 Southern Australia Mallee and Woodlands *	214 Barents-Kara Seas *
55 Cameroon Highlands Forests *	135 Queensland Tropical Forests *	215 Northeast Atlantic Shelf Marine *
56 Congolian Coastal Forests *	136 New Caledonia Moist Forests *	216 Mediterranean Sea *
57 Sudanian Savannas	137 New Caledonia Dry Forests	217 Canary Current *
58 Western Congo Basin Moist Forests	138 Lord Howe and Norfolk Island Forests *	218 Benguela Current
59 Northeastern Congo Basin Moist Forests	139 New Zealand Temperate Forests *	219 Arabian Sea *
60 Central Congo Basin Moist Forests	140 Eastern Australia Temperate Forests *	220 Red Sea *
61 Albertine Rift Montane Forests	141 Tasmanian Temperate Rainforests *	221 West Madagascar Marine *
62 Central and Eastern Miombo Woodlands	142 Southern Pacific Islands Forests *	222 East African Marine *
63 Zambezian Flooded Savannas	143 Gulf of Alaska Coastal Rivers*	223 Agulhas Current
64 Namib-Karoo-Kaokoveld Deserts & Shrublands *	144 Pacific Northwest Coastal Rivers	224 Maldives-Chagos-Lakshadweep Atolls *
65 Fynbos	145 Colorado River	225 Andaman Sea *
66 Arabian Highlands Woodlands and Shrublands *	146 Chihuahuan Freshwater	226 Banda-Flores Sea *
67 Socotra Island Desert *	147 Mexican Highland Lakes	227 Western Australia Marine *
68 Ethiopian Highlands	148 Mississippi Piedmont Rivers & Streams	228 Southern Australian Marine
69 Horn of Africa Acacia Savannas	149 Lower Mississippi River	229 Okhotsk Sea *
70 East African Coastal Forests *	150 Southeastern Rivers & Stream s*	230 Yellow Sea *
71 East African Moorlands	151 Greater Antillean Freshwater *	231 Nansei Shoto *
72 Eastern Arc Montane Forests	152 Orinoco River & Flooded Forests	232 Sulu-Sulawesi Seas
73 East African Mangroves *	153 Upper Amazon Rivers & Streams	233 Palau Marine *
74 East African Acacia Savannas	154 Brazilian Shield Amazonian Rivers & Streams	234 Bismarck-Solomon Seas
75 Southern Rift Montane Woodlands	155 High Andean Lakes	235 New Caledonia Barrier Reef *
76 Madagascar Mangroves *	156 Guianan Freshwater	236 Great Barrier Reef *
77 Madagascar Dry Forests *	157 Amazon River & Flooded Forests *	237 Lord Howe-Norfolk Islands Marine
78 Seychelles and Mascarenes Moist Forests *	158 Upper Parana Rivers & Streams	238 New Zealand Marine *
79 Madagascar Forests & Shrublands *	159 Volga River Delta	
80 Madagascar Spiny Thicket *	160 Mesopotamian Delta and Marshes *	

CCP1.2 Assessment

Specific hotspot numbers (H) are indicated in this chapter text to aid their identification in Table CCP1.1 and Figures CCP1.1 and CCP1.2.

CCP1.2.1 Global Perspective

CCP1.2.1.1 Observed Impacts

CCP1.2.1.1.1 Observed climatic hazards

Terrestrial and freshwater hotspots have been warming less over the last 50 years than non-hotspot areas, whereas marine hotspots have been warming more (Kocsis et al., 2021). The warming inside terrestrial hotspots is 0.91°C (Myers) and 1.04°C (G200), respectively, while for freshwater hotspots it is 0.89°C, compared to a +1.08°C warming outside (Kocsis et al., 2021). In contrast, mean annual sea surface temperatures in the G200 marine biodiversity hotspots have warmed 41% more than the regions outside (0.53 *vs* 0.38°C) (Kocsis et al., 2021). Thus, terrestrial biodiversity hotspots have been warming slightly less, and marine hotspots considerably more than non-hotspots (*medium confidence*).

Climate velocity, the direction and pace of movement in climate variables (typically temperature) in space, is key to understanding the origin and fate of biodiversity hotspots under climate change (Loarie et al., 2009; Burrows et al., 2011). Climate trajectories generally predict the direction and pace of past and future species range shifts (Pinsky et al., 2013; Brito-Morales et al., 2018) although there are exceptions (Fuchs et al., 2020). Spatial patterns of climate trajectories show regions where species are expected to leave, pass through, and/or arrive under climate change (Burrows et al., 2014). Regions of high climate velocities are those with low topographic relief on land, particularly flooded grasslands and deserts (Loarie et al., 2009), and tropical as well as offshore and polar sea regions (Burrows et al., 2011; Burrows et al., 2014; García Molinos et al., 2016; Brito-Morales et al., 2018; Brito-Morales et al., 2020).

On millennial time scales, some areas of low climate velocity have more endemic species and can be considered climate refugia, at least on land (Sandel et al., 2011) and, for marine species, around Antarctica (H213) (Costello et al., 2010). This suggests that if these areas are subject to increased velocities they may lose species which may not be able to disperse fast enough to cope with the pace of climate change (*medium confidence*) (Sandel et al., 2011; Brito-Morales et al., 2018).

Climate velocities are 47% (Myers), 29% (G200, terrestrial) and 10% (G200, freshwater) lower inside than outside biodiversity hotspots, respectively (Kocsis et al., 2021), but are 69% higher inside marine hotspots than outside (*medium confidence*). Climate velocities from 1970 to 2019 ranged from 3-4 km/decade (terrestrial and freshwater) to ~11 km/decade in marine (Kocsis et al., 2021).

For terrestrial and freshwater hotspots, the highest climate velocities are in central South America, including the Amazon (H153, 154) (Figure CCP1.3). Terrestrial hotspots also have high velocities in the Arctic (H196, 214) and east of the Caspian Sea, while freshwater hotspots have low velocities in eastern European Mediterranean and eastern Australia.

Marine hotspots have a wider range of climate velocities than terrestrial and freshwater environments (Figure CCP1.3), being faster in equatorial, Mediterranean (H216), Baltic (H215), North and Okhotsk (H229), and Arctic hotspots (H196, 214), and slow in the Antarctic hotspot (H213). Marine species tend to follow climate velocities more closely than terrestrial species (*high confidence*) (Sunday et al., 2012; Pinsky et al., 2019; Lenoir et al., 2020). The reasons may be smaller thermal safety margins in the seas or greater human impacts on land impeding species range shifts. Climate velocities are particularly fast in equatorial seas (Figure CCP1.3; Burrows et al., 2011), which are therefore expected to be source areas for species shifting their ranges towards the subtropics (Burrows et al., 2014). The subtropics are then source areas of species that shift to temperate latitudes and so forth, such that observed impacts in marine biodiversity hotspots are largely attributable to species range shifts (*high confidence*) (Pecl et al., 2017). Because marine climate velocities are significantly greater within than outside hotspots, marine hotspots are especially prone to species redistributions (*medium confidence*) (Figure CCP1.3; Kocsis et al., 2021).

While species from lower latitudes may shift their geographic ranges into higher latitudes to adapt to changing climate, there are no species to replace low latitude species. Thus, as already observed in the oceans around the equator, the loss of species in low latitudes will continue with future climate warming (*high confidence*) (Yasuhara et al., 2020; Chaudhary et al., 2021). The issue also extends to altitudinal ranges in terrestrial environments, with species moving to higher elevations where surface area generally declines with increasing elevation, and mountaintop species may have nowhere to go (Flousek et al., 2015; Freeman et al., 2018; Kidane et al., 2019).

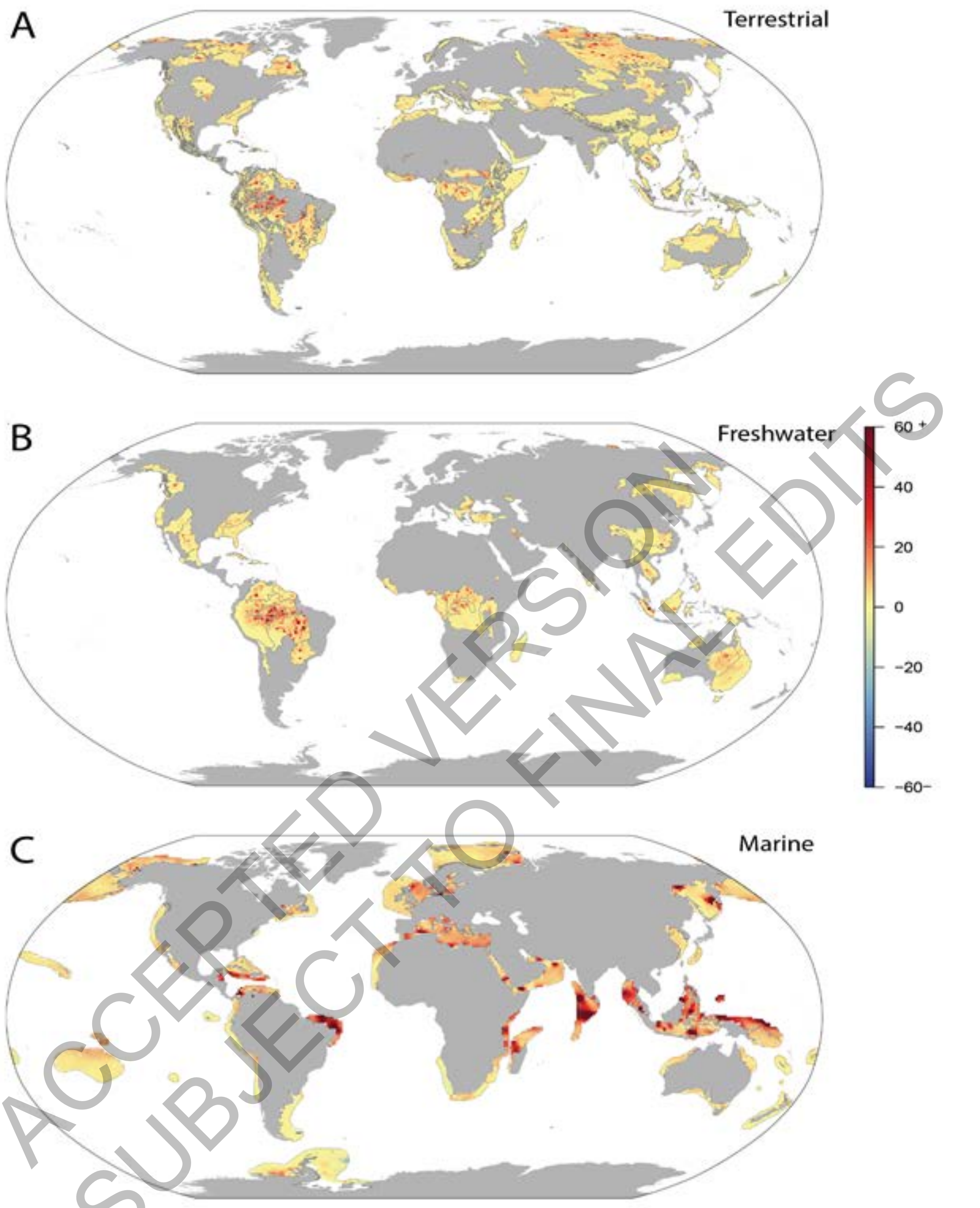


Figure CCP1.3: Climate velocities in terrestrial (A), freshwater (B) and marine (C) hotspots between 1970-2019. Values are presented in km/decade and derived using VoCC (García Molinos et al., 2019) from gridded temperature data, sea-surface temperatures for marine (Rayner et al., 2003) and near surface air temperatures on land and freshwater (Harris et al., 2020). Positive and negative velocities indicate warming and cooling, respectively.

CCP1.2.1.1.2 Observed impacts on biodiversity

Although the conservation status has only been assessed globally for about 6% of all species (Costello, 2019) and most confirmed extinctions and threatened species are terrestrial, a higher proportion of freshwater species are threatened, which is reflected in the higher proportion of freshwater hotspots impacted by humans (Collen et al., 2014; Costello, 2015; Harrison et al., 2018). The rate of species endemicity is exceptionally high in freshwater biogeographic realms (i.e., large regions of distinct species composition and endemicity), at 89-96% for fish in all but one realm, compared to 11-98% for terrestrial vertebrate groups (Leroy et al., 2019) and 17-84% for marine realms (Costello et al., 2017). Already, one third of wetlands have been lost and 9,000 freshwater species threatened with extinction without considering the effects of climate change (Darwall et al., 2018), and only 13% of world rivers were recently classified as least impacted (Su et al., 2021).

Globally, observed climate-driven changes in biodiversity are typically of species distributions shifting to higher latitudes (*virtually certain*) (Lenoir et al., 2020, Ch.2, Ch. 3.4). Since the 1950s, marine species richness has shifted poleward in the northern hemisphere, increased in mid-latitudes, and declined at the equator in concert with ocean warming (*medium confidence*) (Chaudhary et al., 2021). Climate-driven altitudinal shifts are common on land (*high confidence*) (Lenoir and Svenning, 2015; Steinbauer et al., 2018), and depth shifts in the ocean may occur but are little studied (*low confidence*) (Burrows et al., 2019; Jorda et al., 2020). While climate-induced range expansions can be viewed as opportunities for increasing regional biodiversity, range contractions adversely affect biodiversity through regional extirpations (*high confidence*) (Cahill et al., 2013; Chaudhary et al., 2021).

Both of the two climate change associated global species extinctions to date support the predictions that endemic species on mountains and islands are at the greatest risk of extinction (Manes et al., 2021). The golden toad (*Bufo periglenes*) became extinct after some years of decline associated with changes in climate warming and precipitation in the Talamancan-Isthmian Pacific Forests biodiversity hotspot (H22) (Section 2.4.2.2; Pounds et al., 1999; Cahill et al., 2013). The Bramble Cays Melomys, a rodent endemic to an island between Australia and Papua New Guinea closely related to a mainland Australian species, became extinct due to habitat loss arising from climate change related sea-level rise and cyclone activity (Chapter11; Fulton, 2017; Roycroft et al., 2021).

CCP1.2.1.2 Projected Impacts

CCP1.2.1.2.1 Projected climatic hazards

Comparison of climate warming projected for air and sea temperature shows biodiversity hotspots will continue to experience the greatest net increases in temperature at higher northern hemisphere latitudes; particularly in tundra regions (Figures CCP1.4, CCP1.5, Table CCP1.1). Generally, terrestrial and freshwater hotspots are projected to continue to warm more than marine (Figure CCP1.3). Predicted actual temperatures are projected to continue to be the highest in the tropics, indicating where there are more thermally stressful conditions for more species (*high confidence*) (Stuart-Smith et al., 2015; Stuart-Smith et al., 2017; Foster et al., 2018; Waldock et al., 2019). By the end of this century, all terrestrial biodiversity hotspots in central and south America, Africa, India and southern and eastern Asia (including the Indo-west Pacific islands) are projected to experience climates unprecedented in their species' evolutionary history (*medium confidence*) (Williams et al., 2007).

Based on WGI Atlas data (Gutiérrez et al., 2021), global warming is projected to affect terrestrial hotspots less than non-hotspot areas: 80% less for Myers and 95-96% less for G200 terrestrial and freshwater hotspots at global warming of 1.5-3°C (*medium confidence*) (Kocsis et al., 2021). In contrast, warming is projected to be 12-13% greater inside than outside marine hotspots (*medium confidence*) (Kocsis et al., 2021). Precipitation is generally projected to increase more in terrestrial and freshwater biodiversity hotspots compared to outside them (*low confidence*) (Kocsis et al., 2021). The exception is Myers hotspots, which are projected to have, on average, ~28% less precipitation at 1.5°C warming, but ~33% more at 2°C, and ~65% more at 3°C (*low confidence*). However, precipitation changes are often difficult to assess as many hotspots cover large areas, with some areas projected to be wetter and some drier with wide differences between different climate models.

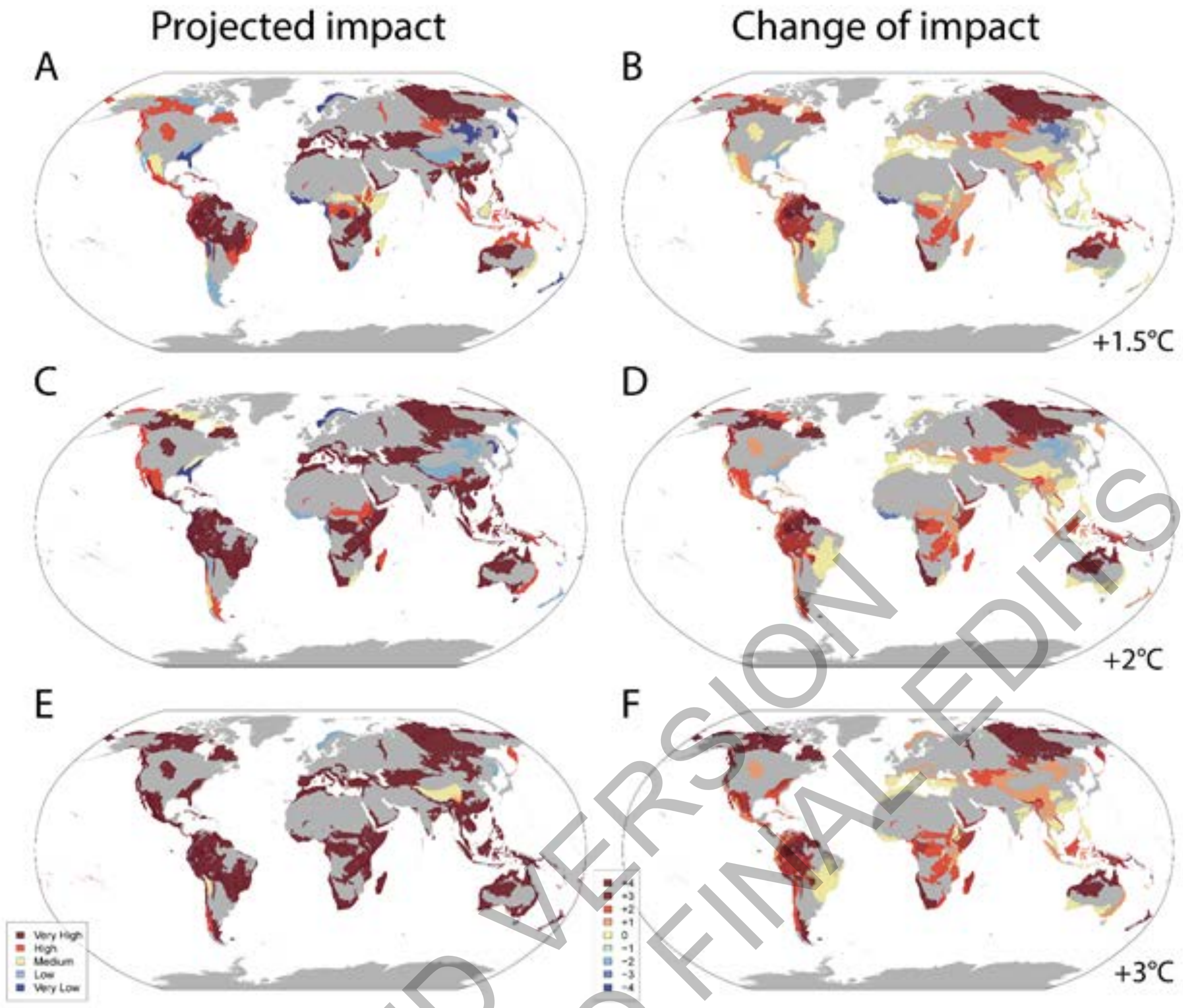


Figure CCP1.4: Projected loss of climatically suitable area in terrestrial biodiversity hotspots for a global average of 1.5°C (upper row, A-B), 2°C (middle, C-D) and 3°C (lower E-F). Left-hand column displays the projected human impact using the five equal 20% categories of present-day impact (Figure CCP1.1). The right-hand column indicates the changes of impact categories compared to present day-impact. See Table SMCCP1.1 for more details.

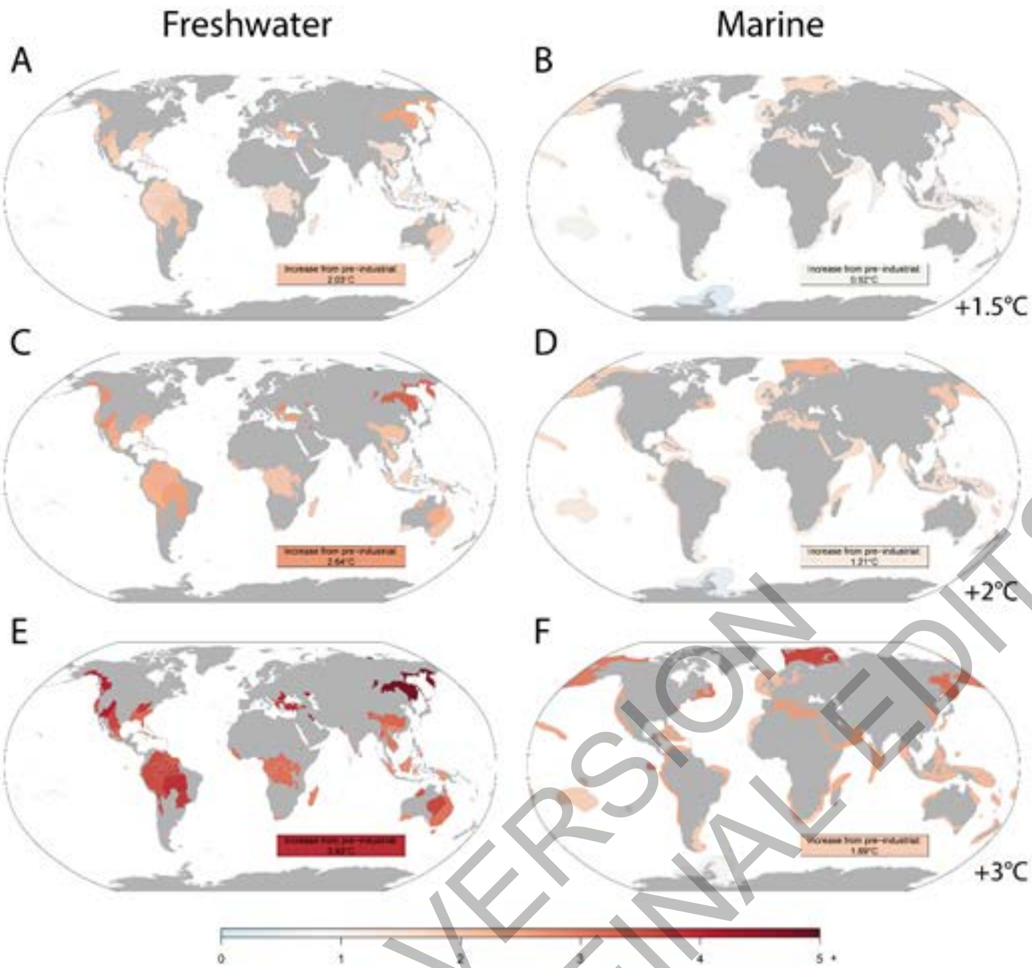


Figure CCP1.5: Projected future warming in °C for freshwater (left column, near-surface air temperature, panels A, C and E) and marine (right column as sea surface temperature, panels B, D and F) hotspots for a global average warming of +1.5°C (A, B), +2°C (C, D) and +3°C (E, F) compared to pre-industrial conditions. Values in text boxes in the Figures indicate temperature increase from present-day (2005-2014) settings. Projected temperatures were calculated with averages of multi-model, yearly means across Shared Socioeconomic Pathways (SSP) 1.26 (only for +1.5°C), SSP2-45, SSP3-70 and SSP5-85.

CCP1.2.1.2.2 Projected impacts on biodiversity

Biodiversity hotspots are expected to be especially vulnerable to climate change because their endemic species have smaller geographic ranges (*high confidence*) (Sandel et al., 2011; Brown et al., 2020; Manes et al., 2021). Manes et al. (2021) reviewed over 8,000 projections of climate change impacts on biodiversity in 232 studies, including 6,116 projections on endemic, native and introduced species in terrestrial (200 studies), freshwater (14 studies) and marine (34 studies) environments in biodiversity hotspots. Only half of the hotspots had studies on climate change impacts. All measures of biodiversity were found to be negatively impacted by projected climate change, i.e., species abundance, diversity, area, physiology, and fisheries catch potential (*medium confidence*). However, introduced species' responses were neutral to positive (*medium confidence*). Land areas were projected to be more negatively affected by climate warming than marine. Land plants, insects, birds, reptiles, and mammals were all projected to be negatively affected (*medium confidence*), as well as fish, coral reef, benthic, planktonic and other marine species (*medium confidence*).

Of the 6,116 projections for more than 2,700 species assessed in biodiversity hotspots, ~44% were found to be at high extinction risk, and ~24% at very high extinction risk due to climate change (Manes et al., 2021) (*medium confidence*). Risks of extinction were estimated based on the projections for all warming levels combined, showing that endemic species were about 2.7 times more at very high risk of extinction compared to non-endemic native species (Manes et al., 2021). Extinction risks were highest for endemic species of both land and ocean (*medium confidence*), and were higher for those living on islands (~100%, *medium confidence*) and mountains (~84%, *medium confidence*) than in the ocean (~54%, *low evidence, medium* *agreement*; *low confidence*) and on continents (~12%, *robust evidence, medium agreement*; *medium confidence*) (Figure CCP1.6). Extinction risks for non-endemic natives were ~20% for both terrestrial and marine species, with introduced species projected to become more rather than less invasive. At 1.5°C warming, ~2% of both terrestrial and marine species and at 3°C, ~20% and ~32% respectively, were projected to be at very high risk of extinction in the hotspots (Figure CCP1.6). Thus, a doubling of warming results in a roughly tenfold increase in species at very high extinction risk.

Manes et al. (2021) found that any benefits to species (e.g., range or abundance increase) were projected to be localised and transient (e.g., Arctic, H196, 214). This and previous assessments indicate that while climate change varies spatially and taxa may respond differently, a loss of biodiversity is projected across all terrestrial hotspots (*high confidence*) (Foden et al., 2013; Warren et al., 2018a; Manes et al., 2021). Abrupt changes across species assemblages may occur under all scenarios: in 9% of assemblages at 1.75°C and 35% at 4.4°C on both land and sea (Trisos et al., 2020). However, species losses may be reduced if species have thermal microclimate refugia and behavioural thermoregulation, or greater due to extreme events, such as heatwaves.

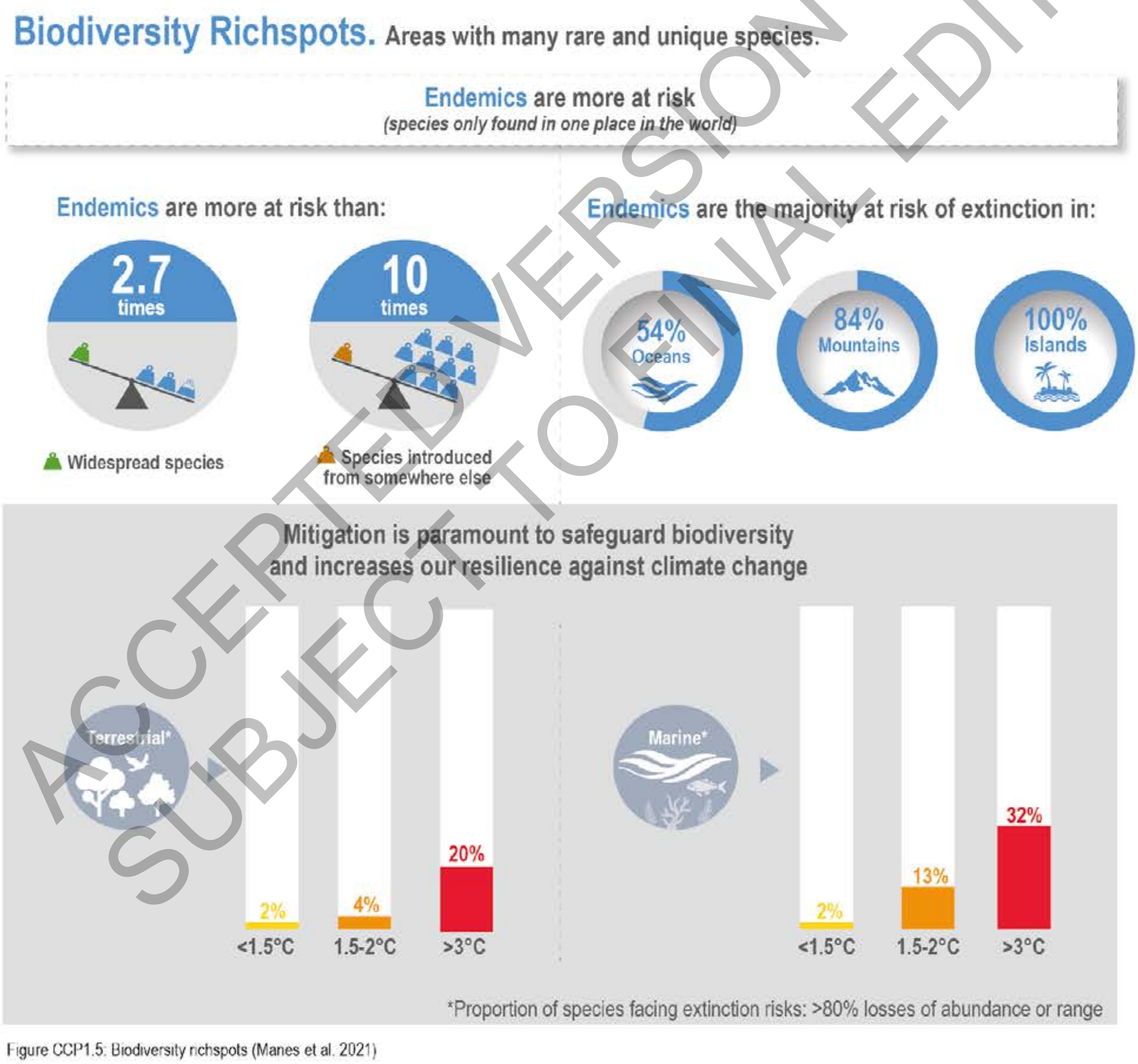


Figure CCP1.6: A summary of the projected risks of species extinction at global warming levels of < 1.5 ºC, 1.5 – 2.0 ºC, and > 3°C in terrestrial and marine biodiversity hotspots. Data from Manes et al. (2021).

CCP1.2.1.3 Compounding and Cascading Effects

All biodiversity hotspots are already impacted, to differing degrees, by human activities (*high confidence*) (Table CCP1.1, Figures CCP1.1, CCP1.2, Myers et al., 2000; Le Roux et al., 2019). At present, over three billion people live within the terrestrial and (catchments of) freshwater biodiversity hotspots, many of which border marine hotspots (WGII Atlas; Figures CCP1.1, CCP1.2; Table SMCCP1.1). Thus, climate change impacts on biodiversity hotspots are compounded by other anthropogenic impacts, increasing the vulnerability and reducing the resilience of biodiversity to climate change (*very high confidence*). Projections of changing climate alone may overestimate or underestimate the impacts on biodiversity (*medium evidence, high agreement*). The additional risk of the combined effects of climate change and other impacts (e.g., land-use change, overhunting, pollution and invasive species) on species has been raised since the Third Assessment Report. The terrestrial hotspots projected to be most affected by global warming are, in general, those already being impacted by loss of habitat due to land use change (Figure CCP1.4; Table SMCCP1.1) (Warren et al., 2018a). This remains a trend in the recent literature, although most studies still address only one stressor (Titeux et al., 2016). For example, Mantyka-Pringle et al. (2015) show that when the interaction between projected climate change and habitat loss is taken into account, the extinction risk of birds and mammals in 15–32% of terrestrial biodiversity hotspots changes. Similarly, Bellard et al. (2014b) found different results when examining the impact of climate change, invasive species and land use change independently, as opposed to synergistically. When combining those three impacts they identified the Atlantic Forest (H47), Cape Floristic Region (H65) and Polynesia-Micronesia (H1, 2, 138, 139, 142) as particularly vulnerable.

In a global assessment of the threat of climate change to river fish biodiversity, Tedesco et al. (2013) projected that current extinction rates of species may be 7% greater due to climate change (*low confidence*). The main threat is due to the effects of drought and reduced river flows, which would be 18 times greater than without climate change. However, just 20 of the 110 river basins studied would experience sufficient climate-driven water loss to cause fish extinctions by 2090. Moreover, the present rates of species loss due to present human activities are 130 times greater than those projected by likely by future climate change (*medium confidence*) (Tedesco et al., 2013).

Marine systems are also vulnerable to cumulative human impacts, which can be direct (e.g., pollution, overfishing) and indirect (altered food webs) (*very high confidence*) (Halpern et al., 2008; Halpern et al., 2015). The marine hotspots most currently threatened by non-climate related human impacts are all situated in the northern hemisphere, specifically along the northern European, Mediterranean, and Asian coasts, where the overlap of overfishing and pollution is especially large (Halpern et al., 2008; Halpern et al., 2015; Ramírez et al., 2018), part B in Figure CCP1.2). Although there is a strong overlap of non-climatic and climatic impacts in marine ecosystems (Blowes et al., 2019; Bowler et al., 2020), the effects suggest that climate change impacts are most severe in tropical and northern high latitude seas (*high confidence*) (Doney et al., 2012; Gattuso et al., 2015; Cheung et al., 2018; IPCC, 2019b). Temperature-driven range-shifts and range-expansions are projected to also lead to cascading effects on marine biodiversity through ecological interactions (*high confidence*) (Pecl et al., 2017; Vergés et al., 2019). Cascading effects may be especially pronounced in temperate reefs, where tropicalisation may lead to arrival of herbivorous fish and predators previously absent (Vergés et al., 2019). However, how these indirect effects of climate change on species may change food webs and ecosystem function, including carbon sequestration, is unknown. Direct and indirect human impacts due to fisheries and pollution can also lead to cascading effects that may be additive with climate impacts on biodiversity. Destruction of marine biogenic habitats due to trawling and dredging, and loss of large proportions of marine megafauna, particularly fish, mammals, birds and reptiles, alters food webs and reduces resilience to additional disturbances, such as due to climate change (*medium evidence, high agreement*) (Brander, 2007; Wernberg et al., 2011; Ramírez et al., 2017; Cheung et al., 2018; Bates et al., 2019; Costello, in press).

The following sections report observed and projected climate change impacts on terrestrial, freshwater and marine environments.

CCP1.2.2 Terrestrial

The 177 terrestrial hotspots assessed here (including 142 G200) cover ca. 61,000,000 km^2 (41% of global land area), with a 37% overlap with freshwater hotspots (Table CCP1.1, Figure CCP1.2). They include wet and dry forests, woodland and scrub, highlands, mangroves, deserts, steppe, savanna, grasslands, moorlands and tundra. Over 77% of publications on climate change impacts on hotspots since AR5 have been on terrestrial ecosystems, most of it on projected (as opposed to observed) impacts (Manes et al., 2021).

CCP1.2.2.1 Observed Impacts

There is *high confidence* that climate change has already had impacts in North American hotspots. Phenological and range shifts have been reported for bird and mammal species within the boreal forest hotspot (Davidson et al., 2020), and earlier egg laying in birds in tundra hotspots (H3, 5) owing to changes in snowmelt (Grabowski et al., 2013). Woody vegetation is already shifting north into the tundra (Larsen et al., 2014).

In Central and South America, observed impacts within Mesoamerica (H15, 16) and the Tropical Andes hotspots (H26, 27, 28, 32, 33) comprise upward altitudinal range shifts of birds, frogs, beetles and butterflies (Narins and Meenderink, 2014; Molina-Martínez et al., 2016; Moret et al., 2016; Freeman et al., 2018) (*medium confidence*). A shift of the Guianan-Amazon mangroves (H37) to higher grounds inland was attributed to the effects of observed sea-level rise (*low confidence*) (Cohen et al., 2018).

In Europe, the Mediterranean hotspot (H216) has seen increases in wildfires and droughts attributed to anthropogenic climate change (Gudmundsson et al., 2017; Barbero et al., 2020), and range shifts in birds have been observed at higher elevations (*medium confidence*) (Tellería, 2020).

In Africa, multiple lines of evidence suggest woody plants are increasing in area, density and cover in previously lightly wooded savanna and grassland hotspots (H65, H82) (Poulsen and Hoffman, 2015; Stevens et al., 2017). Significant vulture and cheetah range reductions in these hotspots are at least partially attributable to bush encroachment (Nghikembua et al., 2016; Wolter et al., 2016; Santangeli et al., 2018). Thus, climate-driven bush encroachment has adversely affected unique mammal and bird diversity (*robust evidence, medium agreement, medium confidence*). Warming and drying trends have historically been shown to reduce the range of the Ethiopian Wolf, and they interact with land-use pressures in the Ethiopian hotspot (H68) (Sintayehu, 2018) and plant species richness in the Cape Fynbos (H65) of southern Africa by reducing post-wildfire recruitment (*low confidence*) (Slingsby et al., 2017).

Observed impacts in Asia were mostly restricted to the Himalaya (H95, 98, 99), Sundaland (H109, 110, 111, 112, 117, 118) and Indo-Burma (H105, 106, 107, 114, 115) hotspots, showing negative impacts through increased invasion by exotic plants, decreased suitable area for endemic species and significant changes in phenology (*medium confidence*) (Telwala et al., 2013; Braby et al., 2014; Padalia et al., 2015; Lamsal et al., 2017). In the Central Asian mountain landscape (H87), studies have shown increased aridity induced by climate change impacts on several shrub species (Seim et al., 2016). Some positive effects were observed for native species in terms of an increase of suitable habitat (*limited evidence, low agreement*) (Priti et al., 2016; Tang et al., 2017; Rathore et al., 2019).

In Australia, climate change has been implicated in: drought-induced canopy dieback across a range of forest and woodland types due to decades of declining rainfall in the southwestern hotspot (H133); fires in the palaeo-endemic pencil pine forests (Tasmania H142); declines in vertebrates in the Australian Wet Tropics World Heritage Area, which overlaps with the eastern part of the Northern Australia hotspot (H131), related to warming and increased length of the dry season; and declines in grass and increases in shrubs in the Bogong High Plains (*high confidence*) (Hoffmann et al., 2019). The Australian Alps have seen increased species diversity following retreat of the snow line (Slatyer, 2010), replacement of long-lived trees by short-lived shrubs following multiple wildfires (Zylstra, 2018), and changing ecological interactions due to climate-related snow loss, drought and fires (*high confidence*) (Hoffmann et al., 2019). While warming is allowing mangroves to expand their range in coastal hotspots of Asia and Australia (Ward et al., 2016; Hughes et al., 2019a), drought and associated salinity stress has killed mangroves in northern Australia hotspots (Chapter 11, Babcock et al., 2019).

Approximately 76% of biodiversity hotspots within this assessment either contain, or, are comprised of islands >100 km^2 (Table CCP1.1). However, just 0.08% of these hotspots were represented in post-AR5 literature examining climate change impacts on terrestrial biodiversity. Most observed impacts were assessed with *low evidence*, but *high agreement*, and focus on plants and insects. Impacts described included abundance changes and extirpations (Jenouvrier et al., 2014), altitudinal range shifts (Koide et al., 2017), increased invasive alien species' abundance and extent in Madagascar (H76, 77), Balearic (H51) and Pacific Islands (Ghulam, 2014; Silva-Rocha et al., 2015; Goulding et al., 2016; Dawson et al., 2017), increased temperature affecting physiology, body size and behaviour of frogs in the Caribbean (H20) (Narins and Meenderink, 2014) and phenological alterations (Fontúrbel et al., 2018). One positive observation was the high resilience to recovery of intact forest ecosystems to tropical cyclones within Caribbean (H20) and Pacific islands (*medium confidence*) (Keppel et al., 2014; Marler, 2014; Shiels et al., 2014).

CCP1.2.2.2 Projected Impacts

Most terrestrial species in biodiversity hotspots in North America have been projected to be negatively impacted by climate change (*medium evidence, medium agreement*, *medium confidence*). About ~80% of projections for assessed species showed a negative impact of climate change climate change, with ~25% at very high risk of extinction (Figure CCP1.7; Manes et al., 2021). Alterations to vegetation that would have ecosystem-wide impacts, such as a shift from oak-dominated forests to predominantly hickory and maple species in the Appalachian Forests (H17) (Ma et al., 2016) or the continued shrinking of tundra ecosystems, have also been projected. Range shifts have been projected for a variety of plants (Beltrán et al., 2014; Riordan and Rundel, 2014) and vertebrate taxa (Warren et al., 2014; Stralberg et al., 2015; McKelvy and Burbrink, 2017). Sizeable range loss, which particularly affects endemic species, is projected with higher levels of climate change. Adaptation in the agricultural sector poses an additional risk to remaining wildlife habitat (e.g., wine in California: Roehrdanz and Hannah, 2016; Figure CCP1.9, CCP1.8).

In Central and South America, risks have been assessed in at least twenty-four terrestrial hotspots, especially within the Atlantic Forest, Cerrado, Mesoamerica and the Caribbean, the most studied hotspots in the world in terms of climate change impacts (H47, 44, 15, 16, 20, respectively) (Manes et al., 2021). About 85% of projections for assessed species showed a negative impact of climate change (*high confidence*), with ~26% of projections predicting species extinctions (Figure CCP1.7; Manes et al., 2021). Projected impacts include contraction or loss of species' geographic range, loss of diversity and high species turnover (*high confidence*). Most studies had focused on vertebrates and plants in the Atlantic Forest (H47) and Cerrado (H44) (Loyola et al., 2014; de Oliveira et al., 2015; Vale et al., 2018; Vasconcelos et al., 2018; Hidasi-Neto et al., 2019; Lima et al., 2019; Lourenço-de-Moraes et al., 2019; Vasconcelos and Prado, 2019; Velazco et al., 2019). Several insect species are projected to lose suitable climatic conditions, including Cerrado (H44) moths (Khormi and Kumar, 2014). There were projected negative impacts on vegetation such as rupestrian grasslands in Cerrado (H44) (Fernandes et al., 2018) and tropical and temperate forests in hotspots in Mesoamerica (H15, H16) (Mendoza-Ponce et al., 2018; Mendoza-Ponce et al., 2019). Endemic species face consistent risks of decrease in suitable habitat in the Atlantic Forest (H47) (Vale et al., 2018), Cerrado (H44) (Vasconcelos, 2014), Tumbes-Chocó-Magdalena (H28, H23) (Hermes et al., 2018), and Mesoamerica (H15, H16) (Garcia et al., 2014; Ramírez-Amezcua et al., 2016). Climate change may also benefit invasive plant species in terms of range expansion (Wang et al., 2017) and physiology (de Faria et al., 2018) in the region (Figure CCP1.8).

In European biodiversity hotspots, about 75% of projections for assessed species showed a negative impact of climate change, with ~30% at very high risk of extinction (*medium confidence*) (Figure CCP1.7; Manes et al., 2021). These threats are projected to be worse under higher levels of warming. Increased wildfire size and frequency is projected to have a strong effect on, the Mediterranean basin (H216) ecosystems (*medium confidence*) (Lozano et al., 2017). Range reductions have been projected for endemic plants (Pérez-García et al., 2013; Casazza et al., 2014), reptiles (Ahmadi et al., 2019), birds (Abolafya et al., 2013) and insects (Sánchez-Guillén et al., 2013) (*medium confidence*).

In African biodiversity hotspots, about 80% of projections for assessed species showed a negative impact of climate change, with ~10% at very high risk of extinction, especially of endemic species including birds, plants, bees across several taxa and hotspots if warming exceeds 2°C (*high confidence*) (Figure CCP1.7;

Figure CCP1.10; Huntley and Barnard, 2012; Kuhlmann et al., 2012; Baker et al., 2015; Lee and Barnard, 2016; Young et al., 2016; Hannah et al., 2020; Manes et al., 2021).

In Asia, there is a bias in studies towards Indo-Burma (H105, 106, 107, 114, 115), followed by Himalaya (H95, 98, 99) and South-East Asian montane tropical and temperate forests. About ~70% of projections for assessed species showed a negative impact of climate change, with ~30% at very high risk of extinction (*medium confidence*) (Figure CCP1.7; Manes et al., 2021) (). Impacts include species' range changes, habitat loss for endemic plants, expansion of invasive species, decreased connectivity and overall species richness decline (*high confidence*) (DasGupta and Shaw, 2013; Telwala et al., 2013; Sridhar et al., 2014; Zomer et al., 2014; Ali and Begum, 2015; Aryal et al., 2016). A projected decrease in habitat suitability for large species like the Asiatic Black Bear is of concern as alternative habitats are outside protected areas, and may lead to human-wildlife conflicts (Farashi and Erfani, 2018). The few positive impacts of climate change were projected as increases in suitable habitat and distribution range for a few endangered plants and mammals (*medium confidence*) (Banag et al., 2015; Shrestha et al., 2018). Animals benefiting from increased fruit and seed production in Southeast Asian forests during warm El Nino cycles were also projected to increase with climate warming (Figure CCP1.8; Corlett, 2011).

All projections for assessed species in Australia and New Zealand terrestrial biodiversity hotspots showed a negative impact of climate change, with half at very high risk of extinction (*low confidence*) (Figure CCP1.7; Manes et al., 2021) (). Observed impacts in the Australian Alps were projected to continue under future climate change (Zylstra, 2018). The Northern Australia savanna (H131) may experience increased rainfall and carbon dioxide due to climate change (Scheiter et al., 2015), and exotic grasses are projected to reduce their range under climate warming (Gallagher et al., 2009). In Australian tropical wet forests, ground-living vertebrates may be more sensitive than arboreal species to unstable climates (Scheffers et al., 2017). Bellard et al. (2016) projected losses of land due to sea-level rise in the East Australian Forest hotspot (H140), and González-Orozco et al. (2016) projected the contraction of eucalyptus species towards the coast of the Southwest Australia hotspot (H134), exposing them to sea-level rise. In New Zealand forests (H139), native plants may be replaced by more fire-resistant introduced species following climate-change related fires (*low confidence*) (Perry et al., 2014). While forest growth is projected to potentially increase due to carbon dioxide fertilization, this may be compromised by drought (*low confidence*) (Ausseil et al., 2013). Seed production in native New Zealand beech forests is projected to increase due to climate warming, fuelling the abundance of invasive rats and stoats, which then predate native species and lead to loss of endemic fauna and flora (*medium confidence*) (Figure CCP1.8; Tompkins et al., 2013, Ch. 11).

About 80% of projections for assessed terrestrial species within insular biodiversity hotspots showed a negative impact of climate change, with ~50% at very high risk of extinction, including 100% of endemic species (*medium confidence*) (Figure CCP1.7; Manes et al., 2021). In addition to habitat loss and species range reductions, changes in precipitation may be a major driver impacting tropical and subtropical island species (*medium confidence*) (Maharaj and New, 2013; Harter et al., 2015; Struebig et al., 2015; Vogiatzakis et al., 2016; Maharaj et al., 2018). Compared to continents, island species are projected to undergo greater impacts from spatial change, especially birds and amphibians (*high confidence*) (Box CCP1.1; Fortini et al., 2015; Holmes et al., 2015; Manes et al., 2021,). Of all biodiversity hotspots, island species face the highest proportion of extirpation risk at high elevations due to decreasing habitat area (e.g., Brown et al., 2015) and at low elevations from sea-level rise, habitat loss and introduced species (*medium confidence*) (Figure CCP1.11; Bellard et al., 2014a).

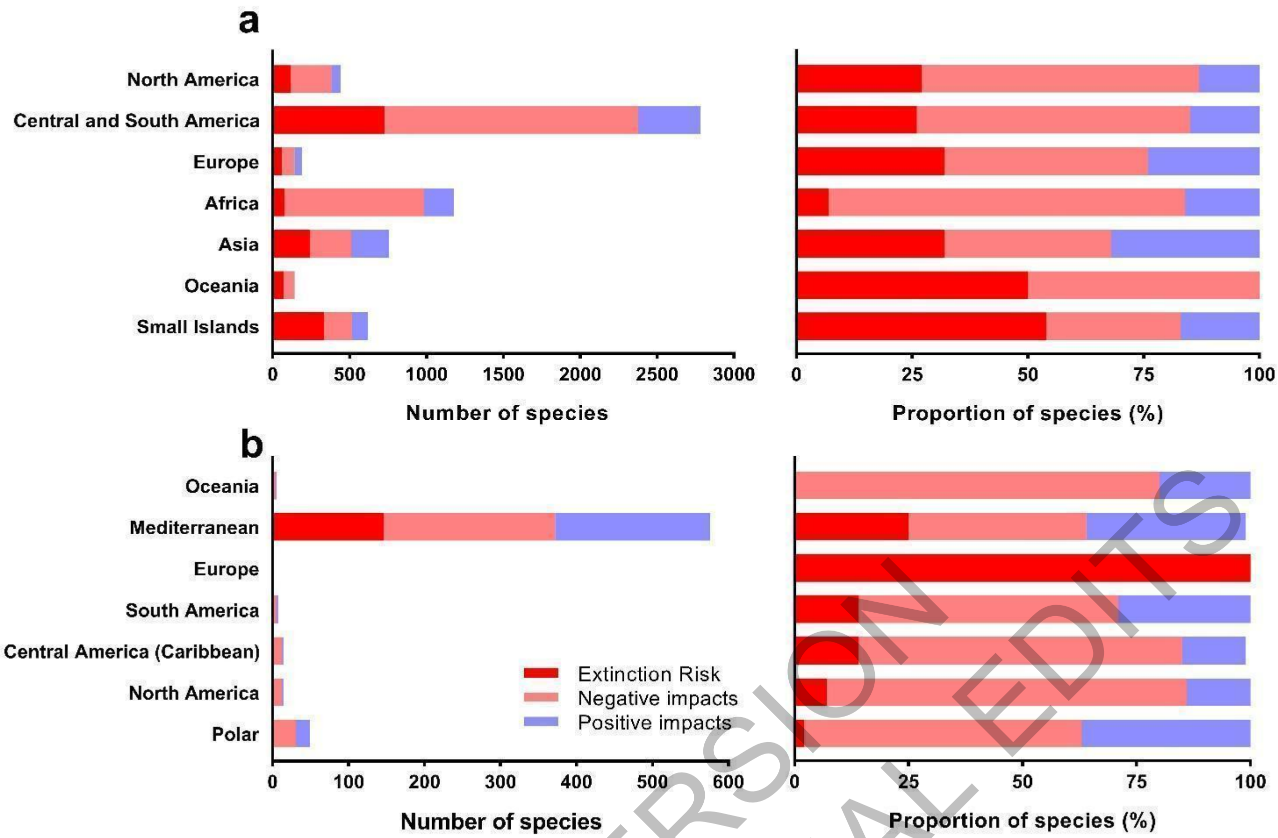


Figure CCP1.7: The projected impacts of climate change on species in 232 studies (a) terrestrial and (b) marine hotspots (adapted from Manes et al., 2021), showing the number and percentage of species showing positive and negative responses to climate change, and threatened with extinction. Note Oceania includes Australia, New Zealand, Wallacea, New Guinea, New Caledonia, Polynesia and Micronesia and overlaps with the global Small Islands category, which excludes Australia. The "small Islands" category represents oceanic and continent associated small islands, and thus overlaps with Oceania and continental data.

Figure CCP1.8: Terrestrial biodiversity hotspots in the Americas, Asia and New Zealand. Photos by Denis Costello (top four), Mariana M. Vale (Brazil), and Mark Costello (other three).

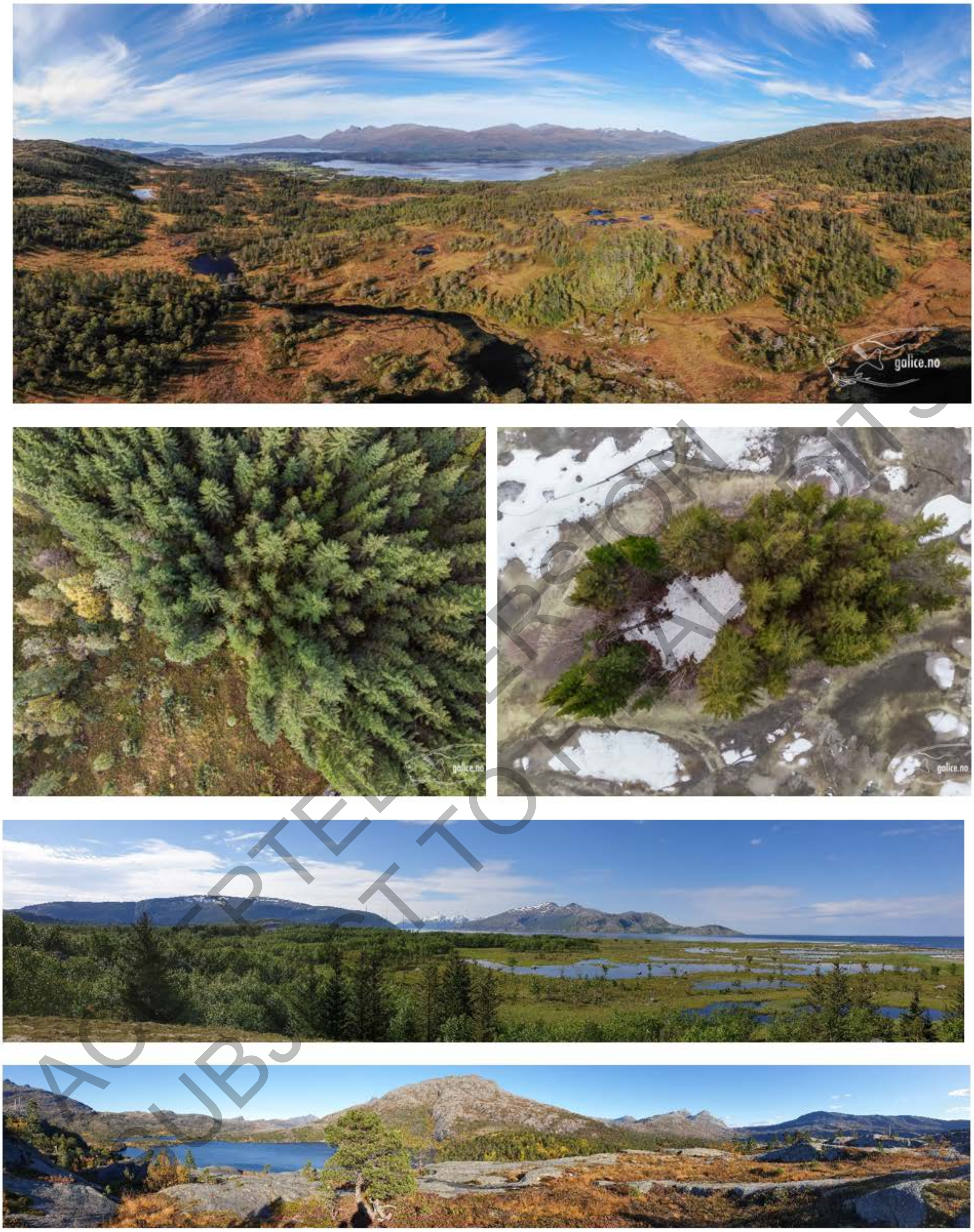


Figure CCP1.9: Polar and boreal biodiversity hotspots in the Arctic (Norway) taiga. Photos by Galice Hormeau (top three) and Mark Costello (bottom two).

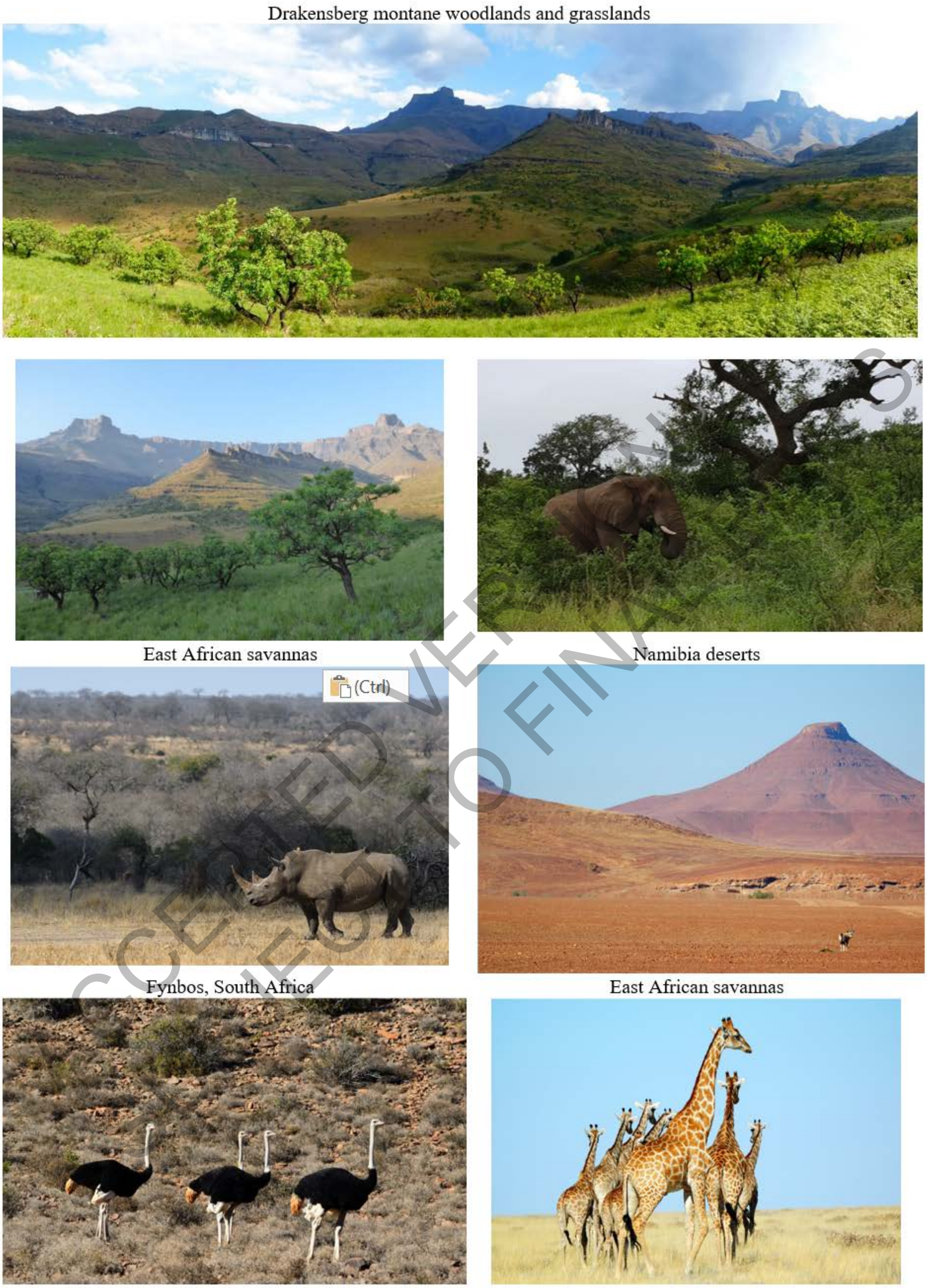


Figure CCP1.10: African biodiversity hotspots. Photos by Denis Costello (top two), Mark Costello (with elephant), Frank Zachos (lower four).

Figure CCP1.11: Island biodiversity hotspots. Photos by Galice Hormeau (top two) and Mark Costello (other four).

CCP1.2.3 Freshwater

The 53 hotspots in freshwater ecosystems assessed here cover ca. 32,830,000 km^2 (17% of global freshwater habitats and 22% of the global land area), with a 68% overlap with terrestrial ecosystems (Table CCP1.1, Figure CCP.2). They include lakes, rivers, and streams (Figure CCP1.12).

CCP1.2.3.1 Observed Impacts

An analysis of trends in 190 river basins in Australia found that stream-flows have been declining, including in the Central Australian (H194) and Kimberley (H191) hotspots, due to greater terrestrial plant uptake of water in response to climate-related increases in carbon dioxide (*low confidence*) (Ukkola et al., 2016). We did not find any other publications providing evidence of impacts of climate change on freshwater biodiversity within the hotspots. Whether this is because freshwater temperatures tend to be cooler due to inputs from groundwater and/or mountain streams (Knouft and Ficklin, 2017), resilience of freshwater species, or lack of research is unclear.

CCP1.2.3.2 Projected Impacts

Cold-water species are projected to lose habitat in Canada and this may apply in the Alaskan river (H143) and Russian Far East Lake Inle (H181) hotspots (*medium confidence*) (Comte et al., 2013). Water abstraction is significant in the Colorado river hotspot (H145) and reduces its resilience to climate change effects on flow rates (Grafton et al., 2013).

In South America, in the Brazilian Amazon hotspot (H153, 154, 157) half the assessed fish species were considered sensitive to increased temperatures and reduced oxygen due to climate change (*low confidence*) (Frederico et al., 2016), and the use of protected areas was recommended to reduce the impacts of deforestation and water pollution (Jézéquel et al., 2020). El Nino related floods have led to declines in numbers of caiman, a top predator in the Brazilian Paraná river hotspot (H158), which indicates that increased floods due to climate change may reduce its population and alter food webs (*low confidence*) (Herrera et al., 2015).

In Europe, including the Mediterranean freshwater hotspots, climate change is projected to result in reduced river flow, low oxygen in summer, salinity incursions, further eutrophication and spread of invasive species, compromising the survival of native biodiversity (*medium confidence*) (Moss et al., 2009). The longer growth season in the boreal and Arctic latitudes is projected to aid the invasion of exotic species, and increase lake stratification resulting in lower oxygen below the hypolimnion (*medium confidence*). In addition, strict cold-water species are projected to lose suitable habitat (Moss et al., 2009). An analysis of 1,648 species of freshwater fish, amphibians, turtles, plants, molluscs, crayfish and dragonflies, projected ~6% of common and ~77% of rare species would lose 90% of their geographic range (*low confidence*) (Markovic et al., 2014). Even if some species may be able to spread to other areas and follow the climate, Markovic et al. (2014) projected a loss of species, especially molluscs, from the south-eastern Mediterranean, including the Balkan biodiversity hotspot (H162) (*medium confidence*). Similarly, within Europe, Mediterranean fish (Jarić et al., 2019) and insects (Conti et al., 2014) are the most threatened by climate warming, droughts and floods. The fish species of the Danube river delta hotspot (H161) are less susceptible to climate change than in the Balkans (H162) and Anatolian (H163) hotspots. The rest of Europe, from the Iberian Peninsula to Scandinavia is not classified as a biodiversity hotspot. Thus, the areas where freshwater biodiversity is most threatened by climate change in Europe are in two of the three hotspots (*high confidence*).

The African Rift Valley Lakes (H171), including Lakes Tanganyika and Turkana, are suffering from climate change influenced drought, potentially impacting freshwater biodiversity (*medium confidence*) (Dudgeon et al., 2006). Africa and Madagascar (H172) are projected to see a climate-driven 10% reduction in freshwater flow that is projected to threaten the survival of ~9% of freshwater dependent fish and birds (*low confidence*) (Thieme et al., 2010). Climate change is projected to increase the extinction vulnerability of most freshwater fish in the western South Africa Cape hotspot (H170) (*low confidence*) (Shelton et al., 2018).

In Asia, although climate change impacts on the Yangtze (H183) and Mekong river (H186) biodiversity hotspots have not been reported, they are subject to the range of human impacts of over-exploitation, pollution, water abstraction, altered flow regimes, habitat loss, and spread of invasive species which makes them more vulnerable to climate effects (*medium confidence*) (Dudgeon et al., 2006). The release of water from shrinking glaciers in Asia to some extent protects downstream freshwaters against drought, but half of these glaciers are projected to disappear by 2100 (*medium confidence*) (Pritchard, 2019).

In Australia, the Murray-Darling river basin occupies much of the Eastern Rivers hotspot (H195) and climate related drought exacerbated by water abstraction is projected to drive declines in freshwater birds, fish and invertebrates (*high confidence*) (Grafton et al., 2013). However, a national scale analysis projected that climate change would cause freshwater species range shifts, but no losses of species in this hotspot (*low confidence*) (James et al., 2017, Chapter 11).

Figure CCP1.12: Photographs of freshwater biodiversity hotspots. Photos by Will Darwall, Pablo Tedesco, and Mark Costello (bottom row).

CCP1.2.4 Marine

The 43 hotspots in marine ecosystems cover 46,600,000 km^2, representing 9% of the ocean area (Table CCP1.1, Figure CCP1.2). They include coral reef ecosystems, kelp forests, seagrass meadows, polar, and upwelling zones (Figures CCP1.13, CCP1.14).

CCP1.2.4.1 Observed Impacts

Observed impacts attributable to climate change are strongly biased geographically, with most data from the temperate Northern Hemisphere, followed by subtropical to temperate Australia and few long-term data in the tropics (Poloczanska et al., 2013; Poloczanska et al., 2016). Marine heatwaves have increased over the past century, causing mass mortalities in the hotspots of the Mediterranean (H216), Great Barrier Reef (H236), western and southern Australia (H227, 228), north-west Atlantic (H207), and north-east Pacific (H197) (*high confidence*) (Hobday et al., 2018; Oliver et al., 2018). The shift of thousands of species from equatorial latitudes since the 1950s has been attributed to climate warming (*medium confidence*) (Chaudhary et al., 2021).

Climate-change related hazards, particularly marine heat events, have caused widespread coral bleaching and mass mortalities as the time between consecutive bleaching events decreases (*high confidence*) (IPCC, 2018; Bindoff et al., 2019; IPCC, 2019b). Coral reefs in some Indian Ocean hotspots (H230, 234) already exhibit net loss of coral reefs (*low confidence*) (Perry et al., 2018). While coral bleaching is a visible symptom of heat stress, warming has also induced restructuring of associated fish and invertebrate communities in the Great Barrier Reef (H236) (*medium confidence*) (Stuart-Smith et al., 2018).

Although the number of coral species that are both exposed and vulnerable to climate hazards is greatest in the central Indo-Pacific, the proportion of corals at risk is greater in the lower diversity Caribbean hotspots (H209) (*medium confidence*) (Foden et al., 2013). Some reef corals may acclimate to heatwaves (*low confidence*) (DeCarlo et al., 2019), and some have expanded their latitudinal ranges polewards (*high confidence*), up to 14 km/yr in the northwest Pacific (Yamano et al., 2011). Although future latitudinal expansions may be limited by winter light availability (Muir et al., 2015) new coral reefs are already emerging in Japan (Kumagai et al., 2018).

The Mediterranean Sea hotspot (H216) is negatively affected by climate change (*high confidence*) (Cross-Chapter Paper 4). Species entering via the Suez Canal from the Red Sea (H220) are facilitated by warming and lead to profound community changes (*high confidence*) (Yeruham et al., 2015; Rilov, 2016; Vasilakopoulos et al., 2017; Givan et al., 2018; Bianchi et al., 2019). In contrast, the more open coastal seas of both coasts of North America have had increasing species richness since the 1970s (Batt et al., 2017).

Kelp forests are in decline in mid-latitudes due to warming and associated increased herbivory (*medium confidence*) (Section 3.4.2.3, Chapter 11). South and south-eastern (H228), and south-western (H227) Australia have experienced a climate-related decline of kelp forests (Wernberg et al., 2011; Vergés et al., 2016; Wernberg et al., 2016). West Australia (H227) has been affected by extreme climate events leading to tropicalisation characterised by the replacement of kelp and sessile invertebrates by algal turfs and warm-water fish species (Wernberg et al., 2013; Wernberg et al., 2016). Australia's Great Barrier Reef (H236), kelp forests, seagrass meadows, and mangroves (due to drought), have suffered mortalities due to climate change (*medium confidence*) (Babcock et al., 2019). Climate warming driven changes in seaweed assemblages have been reported not only in Australia, but in the marine biodiversity hotspots of Atlantic Canada, Japan, Mediterranean, New Zealand (Laffoley and Baxter, 2016; Thomsen et al., 2019; Thomsen and South, 2019), and California (H207, 231, 216, 238, 199) (Arafeh-Dalmau et al., 2019; McPherson et al., 2021). However, while climate change is having measurable effects on kelp, the dominant effects on kelp projected to 2025 are fishing, through its effects on herbivores and predators (*medium confidence*) (Steneck et al., 2002). Although fishing affected Atlantic cod in the Barents Sea (H214) and Gulf of Maine (H207) biodiversity hotspots, so did climate change, but negatively and positively, respectively (Kjesbu et al., 2014; Pershing et al., 2015).

Range expansions out of the Nansei Shoto (H231) hotspot south of Japan led to the replacement of temperate kelp forests by tropical coral and herbivorous fishes on Japanese coasts (Kumagai et al., 2018). The Yellow Sea (H230) is one of the most exploited marine hotspots, with decreasing ecosystem services compounded by climate change but *low confidence* for climate change contributing substantially to ecological degradation (Wang et al., 2016; Song and Duan, 2019).

Upwelling systems are best known for bringing nutrients to the surface that stimulate phytoplankton blooms, which in turn support important fisheries (Section 3.4.2.11). However, this deep water also tends to be low in oxygen, which can be further depleted by respiration and surface warming. Prolonged marine heatwaves in this Californian hotspot (H197) drove major shifts in the geographic range of birds, mammals, fish, crustaceans, molluscs and other species, and toxic algal blooms (Sanford et al., 2019).

In both the Antarctic (H213) and Arctic (H196, 214), the loss of ice impacts on the behaviour and foraging ability of marine mammals and birds (Doney et al., 2012). The retreat of sea-ice in the Bering Sea (H196) hotspot has been followed by a reorganisation of the seabed and fish communities, a northward shift in species, and greater species' biomass and richness (Mueter and Litzow, 2008; Grebmeier et al., 2018). In the Eurasian Arctic (H214), species richness has similarly been increasing (Węsławski et al., 2011; Kortsch et al., 2012; Certain and Planque, 2015; Fossheim et al., 2015; Węsławski et al., 2018) as has phytoplankton productivity (Arrigo et al., 2008). The distribution of krill has already contracted with ocean warming in the Southern Ocean (*medium confidence*) (Cox et al., 2018; Atkinson et al., 2019).

CCP1.2.4.2 Projected Impacts

Tropical extirpations, as already underway (CCP1.2.4.1), are projected to reduce hotspot diversity especially in the Coral Triangle (H226, 232, 234), Maldives (H224), and to a lesser extent in the Caribbean (H200, H210) (Jones and Cheung, 2015; García Molinos et al., 2016), and Persian Gulf (H219) (Wabnitz et al., 2018). Paleo evidence supports projections of tropical biodiversity loss under high global warming (*high confidence*) (Kiessling et al., 2012; Yasuhara et al., 2020).

Warm-water coral reefs are expected to decline with 1.5ºC warming (*very high confidence*) (King et al., 2017; Bindoff et al., 2019) leading to systems with reduced biodiversity and structural complexity (*high confidence*) (Chapters 3 and 11, Box 11.2). In the Coral Triangle, marine heatwaves are projected to have the same effect as an added mean annual 0.5°C SST increase (McManus et al., 2020). While some corals may survive in deep 'mesophotic' reefs (Laverick and Rogers, 2019), the shallow coral reefs of today appear unlikely to last the century if climate warming continues without mitigation (*high confidence*) (Hughes et al., 2018a; Hughes et al., 2018b; IPCC, 2018; Bindoff et al., 2019; Hughes et al., 2019b).

In temperate shelf seas, ocean acidification may lead to increases of fleshy algae at the expense of calcifying algae (*low confidence*) (Zunino et al., 2017). However, seagrass has been projected to decline (Chefaoui et al., 2018) and increase (Zunino et al., 2017) in the Mediterranean Sea hotspot (H216). Kelp forests are expected to decline in the northwest Atlantic (Grand Banks, H207), whereas gains and losses are approximately balanced in the Northeast Atlantic Shelf (H215) under RCP 8.5 (Assis et al., 2018; Wilson et al., 2019), but leading to impoverished benthic assemblages (*medium confidence*) (Teagle and Smale, 2018).

Projected climate caused changes in biodiversity in coastal upwelling regions are uncertain. While productivity in the California Current (H197) system is projected to increase with future climate change, non-linear plankton responses and uncertain interactions with food-web dynamics hinder predictions of ecosystem responses (Xiu et al., 2018). In addition, this hotspot is projected to suffer from ocean acidification by 2050 (Gruber et al., 2012).

Around Antarctica (H213), almost half of all species are endemic (Costello et al., 2010), and warming during this century is projected to cause a reduction in suitable thermal environment for 79% of its species given continued warming (RCP8.5) (*low confidence*) (Basher and Costello, 2016; Griffiths et al., 2017). The previously mentioned declines in Southern Ocean krill due to climate change contribute to projected declines in baleen whales there (Tulloch et al., 2019).

Species richness in the northern polar hotspots is expected to increase substantially (*high confidence*) (Cheung et al., 2015). However, population sizes of presently occurring native species are expected to decline, especially in the Barents Sea (H214) (Koenigstein et al., 2018). Ocean acidification is projected to continue globally, and while its impact is uncertain and projected to be less than the effect of warming, it may lead to changes in marine food webs due to varying effects on marine species (Terhaar et al., 2020). Hotspots in temperate latitudes are projected to have assemblages modified by immigration from the tropics and emigration to polar waters. Where land barriers and other geographical limits to range shifts occur, limited dispersal and habitat fragmentation may also limit the capacity of species to track climate velocities such as in the Baltic Sea (H215) (Jonsson et al., 2018), Mediterranean Sea (H216) (Burrows et al., 2014; Arafeh-Dalmau et al., 2021), and Antarctica (H213) (*medium confidence*) (Cristofari et al., 2018).

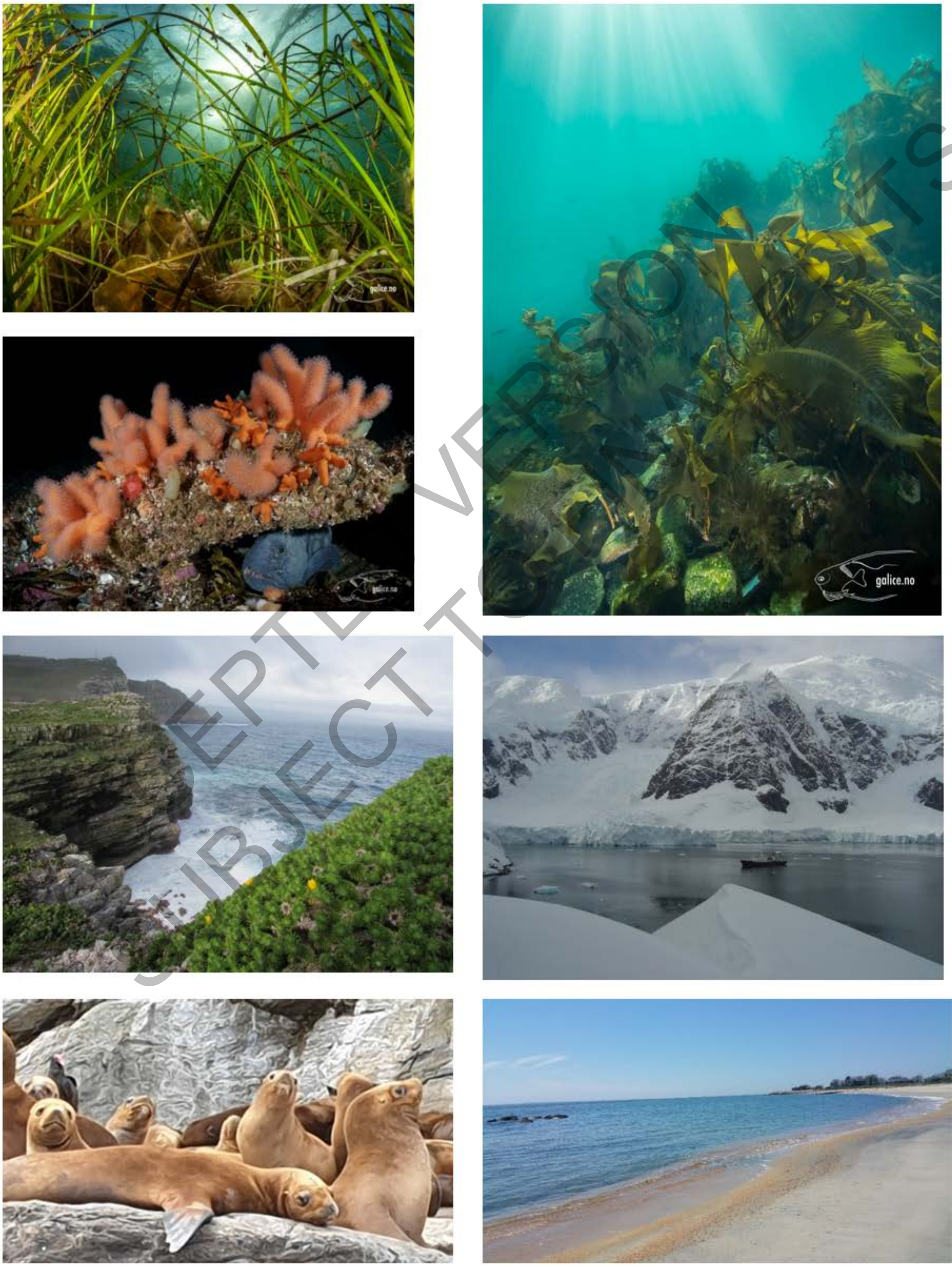


Figure CCP1.13: High latitude marine biodiversity hotspots. North-east Atlantic temperate seagrass beds, soft-corals, and kelp forests in Norway (photos by Galice Hormeau). South African fynbos and Agulhas current and Antarctic Peninsula and Weddell Sea (photos by Denis Costello). In the Americas, the Humboldt Current Chile and Chesapeake Bay (photos by Mark Costello).

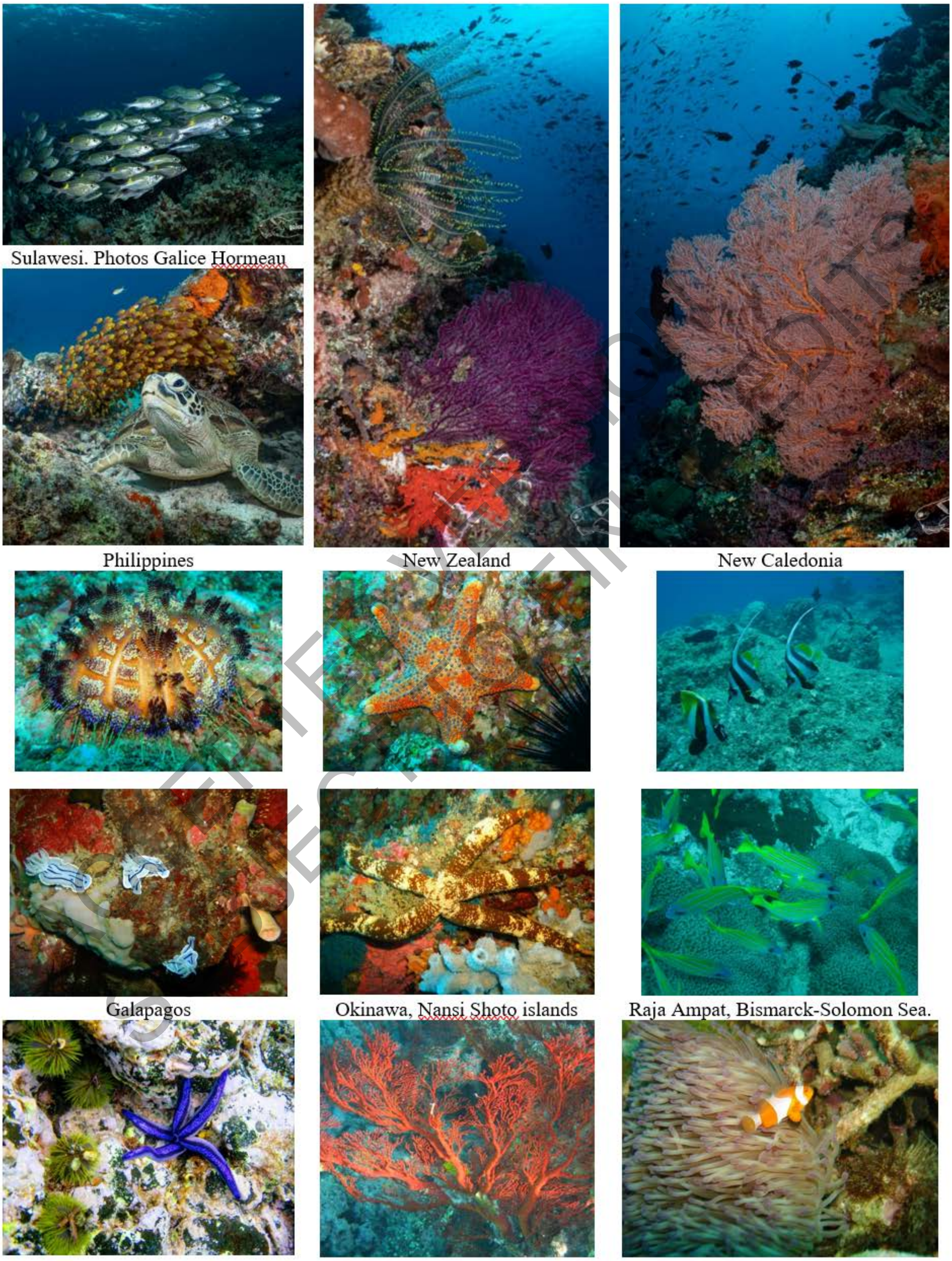


Figure CCP1.14: Species in island coral and rocky reef biodiversity richspots. Photos by Galice Hormeau (top four Sulawesi), and Mark Costello (other nine).

CCP1.3 Adaptation and Solutions

Terrestrial, freshwater and coastal marine ecosystems are impacted by the three billion people that currently live in in biodiversity hotspots (WGII Atlas). At the same time, biodiversity in hotspots supports the livelihoods of the local communities. The suite of adaptation options for biodiversity are as applicable inside as outside hotspots (Table CCP1.2). However, autonomous adaptation options are more limited in hotspots, due to, for example, high endemism within hotspots, the fact that hotspots have evolved in isolation, their species often have narrow thermal tolerances, or lack connectivity (e.g., mountaintops and islands) (*high confidence*). In addition, many of these hotspots are now faced with widespread fragmentation and habitat degradation (*high confidence*) (Table SMCCP1.1).

Because projected changes in biodiversity increase disproportionately with warming, climate change mitigation is the primary action to conserve biodiversity within hotspots. If global warming is kept within the 1.5°C limit of the Paris Agreement, just ~4% of endemic species in biodiversity hotspots would be threatened with extinction from climate change. However, at the current commitments there is projected to be ~3°C warming by 2100 and ~20% and ~32% for terrestrial and marine species, respectively, fall into the category of very high extinction risk (Figure CCP1.6; Manes et al., 2021).

Although mitigation can sharply reduce extinction risk associated with climate change (*high confidence*), it cannot reduce all of the risk, nor the risk associated with other drivers that can have a compound effect with climate change. Thus, in addition to mitigation, the literature consistently calls for reducing current non-climate impacts (e.g., habitat conversion, over-exploitation, hunting, fishing, wildfire, pollution, human introduced invasive species) in order to increase biodiversity resilience to climate change (*very high confidence*) (e.g., Mantyka-Pringle et al., 2015; Warren et al., 2018a; Costello, in press). The main strategies to increase resilience rely on the combination of well-planned protected areas, restoration of degraded areas, and the sustainable use of biodiversity (*high confidence*) (Chapter 2; Section 3.6; Table CCP1.2; IPCC, 2019a; Pörtner et al., 2021) . On land, creating corridors for species is key for facilitating species movements (*high confidence*) (McGuire et al., 2016; Heikkinen et al., 2020; Pörtner et al., 2021). Habitat protection has numerous co-benefits, including potential climate mitigation through carbon storage and sequestration, in addition to climatic regulation (Alkama and Cescatti, 2016; Mackey et al., 2020), and pandemic prevention (Cross-Chapter Box COVID in Chapter 7; Allen et al., 2017; Dobson et al., 2020,).

Active relocation of endangered species to areas where they may be safer from predation and human impacts, as already practised for a few charismatic fauna, is expensive and fraught with complex regulations and concerns over impacts on native species (Brodie et al., 2021). Therefore, managed relocation of species threatened by climate change is questionable for most species.

Healthier marine ecosystems are more resilient to additional stressors, such as storms and climate change (*high confidence*) (Isbell et al., 2015; Duffy et al., 2016; Roberts et al., 2017; Bates et al., 2019; Mariani et al., 2020; Donovan et al., 2021; Costello, in press). Extinction risk is lower when populations are larger and more genetically diverse, individuals are larger and older, and seabed habitats (e.g., coral, kelp, seagrass) are flourishing as occurs in marine reserves (*high confidence*) (Costello, 2014; Roberts et al., 2017; Bates et al., 2019; Costello, in press). Similarly, global fish biomass may be less affected from climate change if biodiversity is greater (Duffy et al., 2016). Thus, a network of reserves representative of global biodiversity, helps attenuate the effects of climate change (*medium confidence*), e.g. by having more abundant fish and top predator populations (Roberts et al., 2017; Beyer et al., 2018; Carter et al., 2020; Sala et al., 2021). However, the impacts of marine heatwaves on corals across marine reserves illustrates that enhanced resilience is not enough to protect against extreme and future climate change conditions (*high confidence*) (Bruno et al., 2018; Hughes et al., 2018a; Kleypas et al., 2021).

Mangroves occupy the interface of terrestrial, freshwater and marine environments, dominate in eight hotspots (Table CCP1.1) and are connected to or integral habitats within one-third of all terrestrial and freshwater, and two-thirds of marine, hotspots (Figures CCP1.1, 2). A global analysis of sediment cores from mangroves indicated that mangroves seem to be able to accrete sediment at levels of sea-level rise projected under low emission scenarios, but may decline at their seaward edge under high emission scenarios (*high confidence*) (Saintilan et al., 2020, Section 3.4.2, Cross-Chapter Box SLR in Chapter 3). However, even if this seaward erosion occurs, the expansion of mangroves inland due to sea-level rise will increase carbon sequestration, because they capture carbon from seawater and freshwater runoff, in addition to photosynthesis, into their underlying sediments. If coastal management permits the expansion of mangroves inland with rising sea level, this will increase carbon sequestration because mangroves capture and preserve more carbon in their sediments than other terrestrial and marine forests and biomes (*high confidence*) (Table CCP1.2; Alongi, 2020; Goldstein et al., 2020; Lovelock and Reef, 2020; Saintilan et al., 2020).

On land, fragmentation and habitat degradation are particularly pervasive, imposing hard limits to adaptation of terrestrial and freshwater ecosystems (Ibisch et al., 2016; Lenoir et al., 2020; Mechler et al., 2020). Thus, the protection of existing natural habitats coupled with the restoration of the surrounding non-protected habitat can increase the effectiveness of adaptation strategies in terrestrial and freshwater hotspots (*very high confidence*) (Table CCP1.2; IPCC, 2019a; Jung et al., 2021) . Additionally, strategic allocation of new protected areas within gaps across elevational and climatic gradients could enhance biodiversity conservation across hotspots. This would align with target 3 of the Convention on Biological Diversity's post-2020 global biodiversity framework, and could include underrepresented climate and elevation spaces as well as potential climate refugia currently not under protection (Pörtner et al., 2021). In terrestrial ecosystems, restoration initiatives can help sustain biodiversity, improve resilience in a changing climate, and avoid maladaptation by selecting appropriate native species to be planted (Cross-Chapter Box BIOECONOMY in Chapter 5; Gann et al., 2019). In freshwater ecosystems, conservation needs catchment level management of human activities (Saunders et al., 2002; Dudgeon et al., 2006) (Chapter 11, Box 11.6) especially as 37% of the terrestrial biodiversity hotspots overlap with freshwater (Figure CCP1.2), and 23% border marine hotspots (Olson and Dinerstein, 2002).

Protecting biodiversity hotspots is a pragmatic way to conserve biodiversity that is representative of a substantive fraction of genetic and species diversity on Earth (Mittermeier et al., 2011) while achieving co-benefits (Bonan, 2016; Sala et al., 2021). Protecting hotspots also helps protect important ecosystem services. In a global ranking of areas that combine biodiversity conservation while maximizing carbon retention and water quality regulation, for example, the terrestrial and freshwater hotspots assessed here ranked high (41st and 34th on average, respectively, on a scale of 100) (Jung et al., 2021). The solutions needed to reverse biodiversity decline are well known and articulated in numerous international agreements and goals, such as the Convention of Biological Diversity Aichi Targets, the United Nations' Sustainable Development Goals, the Nationally Determined Contributions under the Paris Agreement, the International Union for Nature Conservation's Bonn Restoration Challenge, and the Ramsar Convention on Wetland Conservation. Thus, expanding and enhancing protection of a worldwide network of fully protected areas and protection and restoration of non-protected areas representative of the biodiversity hotspots — inclusive of marine, freshwater and terrestrial environments, is a highly recommended adaptation strategy to increase resilience of biodiversity to climate change (Brito-Morales et al., 2018). However, adaptation strategies alone cannot protect biodiversity from climate impacts without complementary and concomitant reduction of greenhouse gas emissions.

Table CCP1.2: Examples of adaptation actions that benefit the conservation of biodiversity and climate change mitigation.

Actions	Terrestrial	Freshwater	Marine
Protect biodiversity hotspots	Protect native forests, bush, and grasslands	Stop pollution and sedimentation into streams, rivers, ponds, lakes	Ban seabed trawling and dredging
	Control introduction and spread of invasive species and pests		
Increase connectivity	Use riverbank and hedgerow corridors to connect protected native habitats		Already connected
	Reduce habitat and species loss outside protected areas to add species dispersal (corridors)		
Outside biodiversity hotspots	Environmentally sustainable agriculture, tourism, and other land and freshwater uses		Environmentally sustainable aquaculture, fisheries, tourism
Restoration and recovery	Actively rehabilitate old mines, quarries and industrial lands	Stabilise riverbanks. Remove weirs and artificial barriers to fish migration.	Ban removal of marine life and habitat, and fishing in selected areas to allow passive recovery of habitats,

	Reintroduce extirpated native species		natural population structure, and food webs
Reduce erosion, soil loss, and flooding	Preserve, reduce degradation, and restore habitats to enable uplands to absorb rainfall and reduce flash floods. Protect sand-dune systems from erosion due to human and farm animal trampling. Set aside land for salt marshes and mangroves to buffer against river and seawater flooding. Link estuarine and upriver protected areas to provide more wildlife habitat and absorb storm surges and floods.		
Urban development	Concentrate development to more cost efficiently manage transport and waste management infrastructure	Limit upland development where it may affect freshwater quality	Avoid construction in areas at risk of sea level rise and associated storm surges.
Greenhouse gas mitigation	Prevent deforestation; Reforestation (especially mangroves); Revegetation; Fewer farm mammals. Minimise release of greenhouse gases from soils.	Expand wetlands to capture and deposit carbon in soils.	Limit seabed disturbance by trawling and dredging that releases CO_2 and CH_4. Eliminate fishery subsidies, and remove tax breaks on fuel for fishing boats.
Carbon sequestration and preservation	Allow biodiversity to flourish and capture CO_2 from the air and sequester it in biomass, soils and sediments.		
	Manage forestry to maximise in situ food web biomass.	Manage fisheries to maximise in situ food web biomass.	
Social	Communicate information on the benefits of adaptation measures to the public		
Political and economic	Provide leadership and governance of mitigation and adaptation measures, including through regulations and economic incentives that guide the transition to a low carbon emissions economy		
Scientific	Address data gaps and make monitoring data and its meaning rapidly available to society so that the public and policy makers are informed of trends in biodiversity and related factors, including climate variables, extreme weather related events, threatened and invasive species, natural habitats, and their relationships.		
	Conduct research to improve understanding of cause-effect relationships regarding environmental factors and biodiversity trends, including in nature conservation, forestry, agriculture, fisheries and food production sectors, and improve projections of consequences of management action and inaction		

[START BOX CCP1.1 HERE]

Box CCP1.1: Climate Change and Terrestrial Biodiversity Hotspots on Small Islands

Despite covering approximately 2% of the Earth's land area, islands harbour more than 20% of extant terrestrial species (Wetzel et al., 2013). Islands have disproportionately higher rates of endemism and threat when compared to continents, with 80% of historical extinctions (since 1500 AD) having occurred on islands (*high confidence*) (Taylor and Kumar, 2016; Spatz et al., 2017; Dueñas et al., 2021). Current climate change projections suggest that insular species are particularly sensitive, and even at mild warming levels, substantial losses are expected (*high confidence*) (Pouteau and Birnbaum, 2016; Taylor and Kumar, 2016; Dawson et al., 2017; Manes et al., 2021). Given islands' characteristic high endemicity, current high threat levels and the fact that islands host almost half of all species currently considered to be at risk of extinction, at especially higher warming levels (*high confidence*) (Taylor and Kumar, 2016; Spatz et al., 2017) — further losses could contribute disproportionately to global biodiversity decline (*medium evidence, high agreement*) (Harter et al., 2015; Pouteau and Birnbaum, 2016; Manes et al., 2021).

The high vulnerability of terrestrial biodiversity on islands to global change can be explained by a number of limitations, characteristic of both islands and insular species. Older, isolated islands tend to have fewer species and lower functional redundancy but higher proportion of endemism (Pouteau and Birnbaum, 2016; Médail, 2017). Many of these islands contain species with inherently high sensitivity to environmental change (narrow habitat ranges, small population sizes, low genetic diversity and poor adaptive, dispersal and defensive capabilities) (Harter et al., 2015). Unlike continental environments, insular species often have limited opportunities for autonomous adaptation from not having enough geographic space to shift their ranges to track suitable climatic conditions (*high confidence*) (Fortini et al., 2015; Manes et al., 2021). Local extinction risks are amplified by even small losses of habitat due to global change including human-induced disturbances, extreme events, sea-level rise (Chapter 15; Cross-Chapter Box SLR in Chapter 3) and invasive species.

However, some insular species may be resilient to climate change (*low confidence*). Intact island forests, for example, have shown rapid recovery rates after tropical cyclones, despite high levels of initial damage, especially in the Caribbean (*medium confidence*) (Luke et al., 2016; Richardson et al., 2018). Additionally, many Mediterranean islands are 'disturbance adapted', with continued persistence of some single-island endemic plants, despite exposure to multiple threats (Vogiatzakis et al., 2016). This continued persistence has been attributed, at least partially, to climate refugia, oceanic buffering, and high habitat heterogeneity within topographically complex mountainous regions (Chapter 15, Table 15.1; Pouteau and Birnbaum, 2016; Médail, 2017). However, this climate resilience may not be sustained under climate change, especially when coupled with habitat degradation (*high confidence*) (Wiens, 2016).

Adaptation strategies depend on the ability to project future impacts from climate change, but this is hampered by lack of fine-scale climate data especially for developing small island nations. There is a paucity of robust impacts-based modelling output for terrestrial biodiversity from these islands due to the wide, chronic unavailability of Regional Climate Model (RCM) data premised on the most recent suite of scenarios (RCPs and especially SSPs) *(medium evidence*, *high agreement*) (Gutiérrez et al., 2021, Ch.15.8; Pörtner et al., 2021; WMO, 2021). Additionally, realistic assessments of changing climate on such small ecosystems require further RCM downscaling and verification to sub-island resolutions of < 5 km. Furthermore, widely used statistically (bias-corrected) downscaled data at sub-5 km resolutions such as WorldClim are often unsuitable due to limited spatial and temporal resolutions of observation station data from small islands (Maharaj and New, 2013; Gutiérrez et al., 2021), and higher errors associated with statistical downscaling and locations with complex topography and coastlines (Fick and Hijmans, 2017; Lanzante et al., 2018). Widespread unavailability of such data constrains accurate simulations of climatic variation within the small-scale mountainous and coastal regions of islands, associated with climate refugia and high habitat heterogeneity (*high confidence*) (Balzan et al., 2018). This is a key element contributing to the continued delay in development of robust adaptation strategies towards not only biodiversity conservation but other important cross-sectoral issues (*medium confidence*) (Robinson, 2020b).

Due to islands' limited size and isolation, conventional conservation measures focused on expanding protected areas, dispersal corridors and buffer zones are of limited effectiveness on islands (*high confidence*) (Vogiatzakis et al., 2016). Instead, multifaceted, locally-driven holistic climate-smart strategies across mosaics of human-impacted, often heavily degraded and fragmented landscapes are required. These should ideally be long-term, flexible and sustainable solutions that incorporate social and biocultural knowledge as well as economic co-benefits to island communities in order to 'buy time' (Betzold, 2015; Robinson, 2020a). Examples include ecosystem-based approaches such as ridge-to-reef management (Table CCP1.2.4; Struebig et al., 2015; Ferreira et al., 2019), which incorporates conservation partnerships among lands inside and outside protected areas to increase connectivity and reduce land-use impacts, while building on the interconnections among terrestrial, freshwater, coastal and marine ecosystems. Such strategies require raising awareness of biodiversity values among local communities, and cross-sectoral planning and policy at both island, regional and trans-boundary scales. These lend to private-public partnerships, increasing the potential of solutions reaching beyond protected areas boundaries and affecting socio-political change (*high confidence*) (Scobie, 2016).

Limited terrain, natural, economic and data resources across small developing-nation islands mean that unconstrained habitat destruction and degradation cannot be sustained, as this harms both people and the biodiversity upon which they depend. This limitation of resources compromises climate adaptation — which is often further complicated by varying governance and states of economic development (Petzold and Magnan, 2019). With changing climate conditions, there is an increased urgency to re-think how progress can be measured, and to create opportunities building on synergies between disaster risk reduction, food security and social justice – so that islands can most benefit from their natural resources and biodiversity in a sustained manner (Box 15.2; Section 15.3.4.4).

[END BOX CCP1.1 HERE]

[START FAQCCP1.! HERE]

FAQ CCP1.1: Why are biodiversity hotspots important?

Biodiversity hotspots are regions that are exceptionally rich in species, ecologically unique and which may contain geographically restricted species. They are thus priority targets for nature conservation.

Recognizing that the Convention on Biological Diversity definition of biodiversity includes the variation within and between species and of ecosystems, different schemes have been applied to define hotspots, leading to hundreds of different areas being proposed as hotspots. However, all identify a set of priority areas that cover a small portion of the Earth, but house an exceptionally high proportion of its biodiversity. Because biodiversity underpins all life on Earth, these hotspots have significant global value as they contain species and habitats that are found nowhere else. Their loss would mean loss of species and habitats that provide wild and farmed food, medicine and other materials, and services such as climate regulation, pollination and water purification, all of which maintain the health of the ecosystems we depend upon.

Healthy ecosystems, with flourishing biodiversity in natural conditions, are more resilient to disturbances, whether natural or human in origin. Environmentally sustainable development inside and outside hotspots could help reverse human impacts on biodiversity. The hotspots also capture and store carbon, thereby helping to mitigate climate change. Prioritization of protecting biodiversity in hotspots thus benefits nature conservation and helps mitigate climate change. A global network of protected areas and restoration initiatives inside biodiversity hotspots can also help increase resilience to the effects of climate change on biodiversity.

[END FAQ CCP1.1 HERE]

[START FAQ CCP1.2 HERE]

FAQ CCP1.2: How can society ensure conservation of biodiversity in climate policies?

To reduce the effects of climate change on biodiversity it is first essential to address direct human impacts that are already leading to a loss of biodiversity. This can be achieved by protecting biodiversity in conservation areas, restoring biodiversity everywhere possible and promoting sustainable development. Climate policies should thus integrate with policies to protect and restore nature.

Avoiding further loss of biodiversity is implicit in sustainable development. This needs to happen on land, rivers, lakes and in the oceans. It is especially important in "biodiversity hotspots" (FAQ-CCP1.1) and protected areas. Hence calls by the International Union for the Conservation of Nature (IUCN), Convention on Biological Diversity, United Nations Sustainable Development Goals and scientific community to increase the size and connectivity of fully protected areas (which aim to have biodiversity in a near natural condition) and include in them the biodiversity hotspots, need to be immediately implemented.

Five of the Sustainable Development Goals (SDGs) are life on land, life below water, good health and well-being, food security, and climate action. They underpin and interact with many other SDGs. Healthy ecosystems play a role in mitigating greenhouse gas emissions, not only protecting areas to prevent the release of carbon through land conversion activities but also restoring otherwise degraded land. The United Nations has declared 2021- 2030 as the Decade of Restoration, and the Decade of the Oceans. Restoration means actively or passively allowing habitat to return to its natural state (e.g., grassland, forest, peatland, oyster beds), including replanting native vegetation. This can benefit the recovery of biodiversity, help remove carbon dioxide from the atmosphere, and improve the delivery of nature's contributions to people such as climate regulation, water purification, pollination and pest and disease control. Thus, protecting biodiversity helps to meet two SDGs directly, and three indirectly.

On land, the loss of natural forests and grasslands not only means a loss of carbon and many of their associated species, but exposes soils to erosion, affecting food production, and can affect the climate by altering the water-cycle. Sustainable development, even within hotspots, involves active restoration of natural biodiversity, reducing poaching and trafficking of wildlife (UN SDG 15), and needs to include agriculture. This includes working to ensure biodiverse soils, and supporting healthy pollinator populations. Biodiversity includes not only wild species but also the genetic diversity, including crops and wild crop relatives. These wild relatives may contain important genes that could help farmed crops survive better in a changed climate. At least some of these wild relatives come from areas designated as hotspots. In the ocean, sustainable development means reducing pollution, carefully managed aquaculture development, increased protected areas (from the present 2.5% of the ocean area), enforcement of fisheries regulations, and removal of fishery subsidies that perpetuate over-fishing within Exclusive Economic Zones and on the High Seas (UN SDG 14). Generally, the use of freshwaters, both rivers, lakes and groundwaters, has not been sustainable and needs to restore biodiversity and water quality by eliminating pollution, and better management of abstraction, river flows, fishing and invasive species. Thus, as is the case with land and oceans, climate policies must prioritize the restoration of freshwater biodiversity, and reduction of the current negative impacts of human activities.

[END FAQ CCP1.2 HERE]

References

Abolafya, M., O. Onmuş, Ç. H. Şekercioğlu and R. Bilgin, 2013: Using Citizen Science Data to Model the Distributions of Common Songbirds of Turkey Under Different Global Climatic Change Scenarios. *PLOS ONE*, **8**(7), e68037, doi:10.1371/journal.pone.0068037.

Ahmadi, M. et al., 2019: Extinction risks of a Mediterranean neo-endemism complex of mountain vipers triggered by climate change. *Scientific Reports*, **9**(1), 6332, doi:10.1038/s41598-019-42792-9.

Ali, K. and H. A. Begum, 2015: A comparative assessment of climate change effect on some of the important tree species of Hindu-Kush Himalayas, using predictive modelling techniques. *International Journal of Advanced Research*, **3**(5), 1230-1240, doi:10.15242/IICBE.C0415015.

Alkama, R. and A. Cescatti, 2016: Biophysical climate impacts of recent changes in global forest cover. *Science*, **351**(6273), 600-604, doi:10.1126/science.aac8083.

Allen, T. et al., 2017: Global hotspots and correlates of emerging zoonotic diseases. *Nature Communications*, **8**(1), 1124, doi:10.1038/s41467-017-00923-8.

Alongi, D. M., 2020: Global Significance of Mangrove Blue Carbon in Climate Change Mitigation. *Sci*, **2**(3), 67, doi:10.3390/sci2030067.

Arafeh-Dalmau, N. et al., 2021: Incorporating climate velocity into the design of climate-smart networks of marine protected areas. *Methods in Ecology and Evolution*, **in press**, doi:doi.org/10.1111/2041-210X.13675.

Arafeh-Dalmau, N. et al., 2019: Extreme marine heatwaves alter kelp forest community near its equatorward distribution limit. *Frontiers in Marine Science*, **6**(499), doi:10.3389/fmars.2019.00499.

Arrigo, K. R., G. van Dijken and S. Pabi, 2008: Impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters*, **35**(19), doi:10.1029/2008gl035028.

Aryal, A. et al., 2016: Predicting the distributions of predator (snow leopard) and prey (blue sheep) under climate change in the Himalaya. *Ecology and Evolution*, **6**(12), 4065-4075, doi:10.1002/ece3.2196.

Asaad, I., C. J. Lundquist, M. V. Erdmann and M. J. Costello, 2017: Ecological criteria to identify areas for biodiversity conservation. *Biological Conservation*, **213**, 309-316, doi:10.1016/j.biocon.2016.10.007.

Assis, J., M. B. Araújo and E. A. Serrão, 2018: Projected climate changes threaten ancient refugia of kelp forests in the North Atlantic. *Global Change Biology*, **24**(1), e55-e66, doi:10.1111/gcb.13818.

Atkinson, A. et al., 2019: Krill (Euphausia superba) distribution contracts southward during rapid regional warming. *Nature Climate Change*, **9**(2), 142-147, doi:10.1038/s41558-018-0370-z.

Ausseil, A.-G. E. et al., 2013: Climate regulation in New Zealand: contribution of natural and managed ecosystems. In: *Ecosystem services in New Zealand–conditions and trends* [Dymond, J. R. (ed.)]. Manaaki Whenua Press, Lincoln, pp. 386-399.

Babcock, R. C. et al., 2019: Severe continental-scale impacts of climate change are happening now: Extreme climate events impact marine habitat forming communities along 45% of Australia's coast. *Frontiers in Marine Science*, **6**(411), doi:10.3389/fmars.2019.00411.

Baker, D. J. et al., 2015: Assessing climate change impacts for vertebrate fauna across the West African protected area network using regionally appropriate climate projections. *Diversity and Distributions*, **21**(9), 991-1003, doi:10.1111/ddi.12337.

Balzan, M. V., M. Potschin-Young and R. Haines-Young, 2018: Island ecosystem services: insights from a literature review on case-study island ecosystem services and future prospects. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **14**(1), 71-90, doi:10.1080/21513732.2018.1439103.

Banag, C. et al., 2015: Bioclimatic niches of selected endemic Ixora species on the Philippines: predicting habitat suitability due to climate change. *Plant Ecology*, **216**(9), 1325-1340, doi:10.1007/s11258-015-0512-6.

Barbero, R. et al., 2020: Attributing Increases in Fire Weather to Anthropogenic Climate Change Over France. *Frontiers in Earth Science*, **8**(104), doi:10.3389/feart.2020.00104.

Basher, Z. and M. J. Costello, 2016: The past, present and future distribution of a deep-sea shrimp in the Southern Ocean. *PeerJ*, **4**, e1713, doi:10.7717/peerj.1713.

Bates, A. E. et al., 2019: Climate resilience in marine protected areas and the 'Protection Paradox'. *Biological Conservation*, **236**, 305-314, doi:10.1016/j.biocon.2019.05.005.

Batt, R. D. et al., 2017: Gradual changes in range size accompany long-term trends in species richness. *Ecology Letters*, **20**(9), 1148-1157, doi:10.1111/ele.12812.

Bellard, C., C. Leclerc and F. Courchamp, 2014a: Impact of sea level rise on the 10 insular biodiversity hotspots. *Global Ecology and Biogeography*, **23**(2), 203-212, doi:10.1111/geb.12093.

Bellard, C., C. Leclerc, B. D. Hoffmann and F. Courchamp, 2016: Vulnerability to climate change and sea-level rise of the 35th biodiversity hotspot, the Forests of East Australia. *Environmental Conservation*, **43**(1), 79-89, doi:10.1017/S037689291500020X.

Bellard, C. et al., 2014b: Vulnerability of biodiversity hotspots to global change. *Global Ecology and Biogeography*, **23**(12), 1376-1386, doi:10.1111/geb.12228.

Beltrán, B. J. et al., 2014: Effects of climate change and urban development on the distribution and conservation of vegetation in a Mediterranean type ecosystem. *International Journal of Geographical Information Science*, **28**(8), 1561-1589, doi:10.1080/13658816.2013.846472.

Betzold, C., 2015: Adapting to climate change in small island developing states. *Climatic Change*, **133**(3), 481-489, doi:10.1007/s10584-015-1408-0.

Beyer, H. L. et al., 2018: Risk-sensitive planning for conserving coral reefs under rapid climate change. *Conservation Letters*, **11**(6), e12587, doi:10.1111/conl.12587.

Bianchi, C. N. et al., 2019: Abrupt change in a subtidal rocky reef community coincided with a rapid acceleration of sea water warming. *Diversity*, **11**(11), 215, doi:10.3390/d11110215.

Bindoff, N. L., W. L. Cheung and J. G. Kairo, 2019: Changing ocean, marine ecosystems, and dependent communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. S. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)], pp. 65-72. ISBN 0906-7590.

Blowes, S. A. et al., 2019: The geography of biodiversity change in marine and terrestrial assemblages. *Science*, **366**(6463), 339-345, doi:10.1126/science.aaw1620.

Bonan, G. B., 2016: Forests, Climate, and Public Policy: A 500-Year Interdisciplinary Odyssey. *Annual Review of Ecology, Evolution, and Systematics*, **47**(1), 97-121, doi:10.1146/annurev-ecolsys-121415-032359.

Bowler, D. E. et al., 2020: Mapping human pressures on biodiversity across the planet uncovers anthropogenic threat complexes. *People and Nature*, **2**(2), 380-394, doi:10.1002/pan3.10071.

Braby, M. F., C. Bertelsmeier, C. Sanderson and B. M. Thistleton, 2014: Spatial distribution and range expansion of the Tawny Coster butterfly, Acraea terpsicore (Linnaeus, 1758) (Lepidoptera: Nymphalidae), in South-East Asia and Australia. *Insect Conservation and Diversity*, **7**(2), 132-143, doi:10.1111/icad.12038.

Brander, K. M., 2007: Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(50), 19709-19714, doi:10.1073/pnas.0702059104.

Brito-Morales, I. et al., 2018: Climate velocity can inform conservation in a warming world. *Trends Ecol. Evol.*, **33**(6), 441-457, doi:10.1016/j.tree.2018.03.009.

Brito-Morales, I. et al., 2020: Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. *Nature Climate Change*, **10**(6), 576-581, doi:10.1038/s41558-020-0773-5.

Brodie, J. F. et al., 2021: Global policy for assisted colonization of species. *Science*, **372**(6541), 456-458.

Brown, K. A. et al., 2015: Predicting plant diversity patterns in Madagascar: Understanding the effects of climate and land cover change in a biodiversity hotspot. *PLOS ONE*, **10**(4), e0122721, doi:10.1371/journal.pone.0122721.

Brown, S. C. et al., 2020: Persistent Quaternary climate refugia are hospices for biodiversity in the Anthropocene. *Nature Climate Change*, **10**(3), 244-248, doi:10.1038/s41558-019-0682-7.

Bruno, J. F. et al., 2018: Climate change threatens the world's marine protected areas. *Nature Climate Change*, **8**, 499–503.

Burrows, M. T. et al., 2019: Ocean community warming responses explained by thermal affinities and temperature gradients. *Nature Climate Change*, **9**(12), 959-963, doi:10.1038/s41558-019-0631-5.

Burrows, M. T. et al., 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334**(6056), 652-655, doi:10.1126/science.1210288.

Burrows, M. T. et al., 2014: Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**(7493), 492-+, doi:10.1038/nature12976.

Cahill, A. E. et al., 2013: How does climate change cause extinction? *Proceedings of the Royal Society B: Biological Sciences*, **280**(1750), doi:10.1098/rspb.2012.1890.

Carter, A. L. et al., 2020: Assessing opportunities to support coral reef climate change refugia in MPAs: A case study at the Revillagigedo Archipelago. *Marine Policy*, **112**, 103769, doi:10.1016/j.marpol.2019.103769.

Casazza, G. et al., 2014: Climate change hastens the urgency of conservation for range-restricted plant species in the central-northern Mediterranean region. *Biological Conservation*, **179**, 129-138, doi:10.1016/j.biocon.2014.09.015.

Certain, G. and B. Planque, 2015: Biodiversity baseline for large marine ecosystems: an example from the Barents Sea. *ICES Journal of Marine Science*, **72**(6), 1756-1768, doi:10.1093/icesjms/fsv040.

Chaudhary, C., A. J. Richardson, D. S. Schoeman and M. J. Costello, 2021: Global warming is causing a more pronounced dip in marine species richness around the equator. *Proceedings of the National Academy of Sciences*, **118**(15), e2015094118, doi:10.1073/pnas.2015094118.

Chefaoui, R. M., C. M. Duarte and E. A. Serrão, 2018: Dramatic loss of seagrass habitat under projected climate change in the Mediterranean Sea. *Global Change Biology*, **24**(10), 4919-4928, doi:10.1111/gcb.14401.

Cheung, W. W. L., R. D. Brodeur, T. A. Okey and D. Pauly, 2015: Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progress in Oceanography*, **130**, 19-31, doi:10.1016/j.pocean.2014.09.003.

Cheung, W. W. L., M. C. Jones, G. Reygondeau and T. L. Frölicher, 2018: Opportunities for climate-risk reduction through effective fisheries management. *Global Change Biology*, **24**(11), 5149-5163, doi:10.1111/gcb.14390.

Cohen, M. C. L. et al., 2018: Decadal-scale dynamics of an Amazonian mangrove caused by climate and sea level changes: Inferences from spatial–temporal analysis and digital elevation models. *Earth Surf. Process. Landforms*, **43**(14), 2876-2888, doi:10.1002/esp.4440.

Collen, B. et al., 2014: Global patterns of freshwater species diversity, threat and endemism. *Glob Ecol Biogeogr*, **23**(1), 40-51, doi:10.1111/geb.12096.

Comte, l., L. Buisson, M. Daufresne and G. Grenouillet, 2013: Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. *Freshwater Biology*, **58**(4), 625-639, doi:10.1111/fwb.12081.

Conti, L., A. Schmidt-Kloiber, G. Grenouillet and W. Graf, 2014: A trait-based approach to assess the vulnerability of European aquatic insects to climate change. *Hydrobiologia*, **721**(1), 297-315, doi:10.1007/s10750-013-1690-7.
Corlett, R. T., 2011: Impacts of warming on tropical lowland rainforests. *Trends Ecol. Evol.*, **26**(11), 606-613, doi:10.1016/j.tree.2011.06.015.
Costello, M. J., 2014: Long live Marine Reserves: A review of experiences and benefits. *Biological Conservation*, **176**, 289-296, doi:10.1016/j.biocon.2014.04.023.
Costello, M. J., 2015: Biodiversity: the known, unknown, and rates of extinction. *Current biology : CB*, **25**(9), R368-371, doi:10.1016/j.cub.2015.03.051.
Costello, M. J., 2019: Unhelpful inflation of threatened species. *Science*, **365**(6451), 332-333, doi:10.1126/science.aay3467.
Costello, M. J., in press: Biodiversity conservation through protected areas supports healthy ecosystems and resilience to climate change and other disturbances. In: *Imperiled: The Encyclopedia of Conservation. Reference Module in Earth Systems and Environmental Sciences* [Goldstein, M. I. and D. A. DellaSala (eds.)]. Elsevier, Amsterdam. ISBN 9780124095489.
Costello, M. J. et al., 2010: A census of marine biodiversity knowledge, resources, and future challenges. *PLOS ONE*, **5**(8), e12110, doi:10.1371/journal.pone.0012110.
Costello, M. J. et al., 2017: Marine biogeographic realms and species endemicity. *Nature Communications*, **8**(1), 1057, doi:10.1038/s41467-017-01121-2.
Cox, M. J. et al., 2018: No evidence for a decline in the density of Antarctic krill Euphausia superba Dana, 1850, in the Southwest Atlantic sector between 1976 and 2016. *Journal of Crustacean Biology*, **38**(6), 656-661, doi:10.1093/jcbiol/ruy072.
Cristofari, R. et al., 2018: Climate-driven range shifts of the king penguin in a fragmented ecosystem. *Nature Climate Change*, **8**(3), 245-251, doi:10.1038/s41558-018-0084-2.
Darwall, W. et al., 2018: The Alliance for Freshwater Life: A global call to unite efforts for freshwater biodiversity science and conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **28**(4), 1015-1022, doi:10.1002/aqc.2958.
DasGupta, R. and R. Shaw, 2013: Cumulative impacts of human interventions and climate change on mangrove ecosystems of south and southeast asia: An overview. *Journal of Ecosystems*, **2013**, 15, doi:10.1155/2013/379429.
Davidson, S. C. et al., 2020: Ecological insights from three decades of animal movement tracking across a changing Arctic. *Science*, **370**(6517), 712-715, doi:10.1126/science.abb7080.
Dawson, W. et al., 2017: Global hotspots and correlates of alien species richness across taxonomic groups. *Nature Ecology & Evolution*, **1**(7), 0186, doi:10.1038/s41559-017-0186.
de Faria, A., M. Marabesi, M. Gaspar and M. França, 2018: The increase of current atmospheric CO2 and temperature can benefit leaf gas exchanges, carbohydrate content and growth in C4 grass invaders of the Cerrado biome. *Plant Physiology and Biochemistry*, **127**, 608-616, doi:10.1016/j.plaphy.2018.04.042.
de Oliveira, G. et al., 2015: Conservation biogeography of the Cerrado's wild edible plants under climate change: Linking biotic stability with agricultural expansion. *American journal of botany*, **102**(6), 870-877, doi:10.3732/ajb.1400352.
DeCarlo, T. M. et al., 2019: Acclimatization of massive reef-building corals to consecutive heatwaves. *Proceedings. Biological sciences*, **286**(1898), 20190235, doi:10.1098/rspb.2019.0235.
Dobson, A. P. et al., 2020: Ecology and economics for pandemic prevention. *Science*, **369**(6502), 379-381, doi:10.1126/science.abc3189.
Doney, S. C. et al., 2012: Climate change impacts on marine ecosystems. *Annual Review of Marine Science*, **4**, 11-37, doi:10.1146/annurev-marine-041911-111611.
Donovan, M. K. et al., 2021: Local conditions magnify coral loss after marine heatwaves. *Science*, **372**(6545), 977-980, doi:10.1126/science.abd9464.
Dudgeon, D. et al., 2006: Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, **81**(2), 163-182, doi:10.1017/s1464793105006950.
Dueñas, M.-A., D. J. Hemming, A. Roberts and H. Diaz-Soltero, 2021: The threat of invasive species to IUCN-listed critically endangered species: A systematic review. *Global Ecology and Conservation*, **26**, e01476, doi:10.1016/j.gecco.2021.e01476.
Duffy, J. E. et al., 2016: Biodiversity enhances reef fish biomass and resistance to climate change. *Proceedings of the National Academy of Science (USA)*, **113**(22), 6230-6235, doi:10.1073/pnas.1524465113.
Enquist, B. J. et al., 2019: The commonness of rarity: Global and future distribution of rarity across land plants. *Science Advances*, **5**(11), eaaz0414, doi:10.1126/sciadv.aaz0414.
Farashi, A. and M. Erfani, 2018: Modeling of habitat suitability of Asiatic black bear (Ursus thibetanus gedrosianus) in Iran in future. *Acta Ecologica Sinica*, **38**(1), 9-14, doi:10.1016/j.chnaes.2017.07.003.
Fernandes, G. W. et al., 2018: The deadly route to collapse and the uncertain fate of Brazilian rupestrian grasslands. *Biodiversity and Conservation*, **27**(10), 2587-2603, doi:10.1007/s10531-018-1556-4.
Ferreira, M. T. et al., 2019: Implications of climate change to the design of protected areas: The case study of small islands (Azores). *PLOS ONE*, **14**(6), e0218168, doi:10.1371/journal.pone.0218168.
Fick, S. E. and R. J. Hijmans, 2017: WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, **37**(12), 4302-4315, doi:10.1002/joc.5086.

Fischlin, A. et al., 2007: Ecosystems their properties goods and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. v. d. Linden and C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, pp. 211-272.
Flousek, J., T. Telenský, J. Hanzelka and J. Reif, 2015: Population Trends of Central European Montane Birds Provide Evidence for Adverse Impacts of Climate Change on High-Altitude Species. *PLOS ONE*, **10**(10), e0139465, doi:10.1371/journal.pone.0139465.
Foden, W. B. et al., 2013: Identifying the world's most climate change vulnerable species: A systematic trait-based assessment of all birds, amphibians and corals. *PLOS ONE*, **8**(6), e65427, doi:10.1371/journal.pone.0065427.
Fontúrbel, F. E., A. Lara, D. Lobos and C. Little, 2018: The cascade impacts of climate change could threaten key ecological interactions. *Ecosphere*, **9**(12), e02485, doi:10.1002/ecs2.2485.
Fortini, L. B. et al., 2015: Large-Scale Range Collapse of Hawaiian Forest Birds under Climate Change and the Need 21st Century Conservation Options. *PLOS ONE*, **10**(10), e0140389, doi:10.1371/journal.pone.0140389.
Fossheim, M. et al., 2015: Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change*, **5**, 673, doi:10.1038/nclimate2647.
Foster, G. L., P. Hull, D. J. Lunt and J. C. Zachos, 2018: Placing our current 'hyperthermal' in the context of rapid climate change in our geological past. *Philosophical Transactions of the Royal Society A*, **376**(2130), 20170086, doi:10.1098/rsta.2017.0086.
Frederico, R. G., J. D. Olden and J. Zuanon, 2016: Climate change sensitivity of threatened, and largely unprotected, Amazonian fishes. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **26**(S1), 91-102, doi:10.1002/aqc.2658.
Freeman, B. G., M. N. Scholer, V. Ruiz-Gutierrez and J. W. Fitzpatrick, 2018: Climate change causes upslope shifts and mountaintop extirpations in a tropical bird community. *Proceedings of the National Academy of Sciences*, **115**(47), 11982-11987, doi:10.1073/pnas.1804224115.
Fuchs, H. L. et al., 2020: Wrong-way migrations of benthic species driven by ocean warming and larval transport. *Nature Climate Change*, **10**, 1052–1056, doi:10.1038/s41558-020-0894-x.
Fulton, G. R., 2017: The Bramble Cay melomys: the first mammalian extinction due to human-induced climate change. *Pacific Conservation Biology*, **23**(1), 1-3, doi:10.1071/PCV23N1_ED.
Gallagher, R. V., L. Hughes and M. R. Leishman, 2009: Phenological trends among Australian alpine species: using herbarium records to identify climate-change indicators. *Australian Journal of Botany*, **57**(1), 1-9, doi:10.1071/BT08051.
Gann, G. D. et al., 2019: International principles and standards for the practice of ecological restoration. Second edition. *Restoration Ecology*, **27**(S1), S1-S46, doi:10.1111/rec.13035.
Garcia, J. et al., 2014: Intake, grazing time and performance of steers supplemented in Brachiaria decumbens pastures during the dry season. *Semina: Ciências Agrárias*, **35**(4), 2095-2106, doi:10.5433/1679-0359.2014v35n4p2095.
García Molinos, J. et al., 2016: Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, **6**(1), 83-88, doi:10.1038/nclimate2769.
García Molinos, J., D. S. Schoeman, C. J. Brown and M. T. Burrows, 2019: VoCC: An r package for calculating the velocity of climate change and related climatic metrics. *Methods in Ecology and Evolution*, **10**(12), 2195-2202, doi:10.1111/2041-210X.13295.
Gattuso, J.-P. et al., 2015: Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science*, **349**(6243), doi:10.1126/science.aac4722.
Ghulam, A., 2014: Monitoring tropical forest degradation in Betampona Nature Reserve, Madagascar using multisource remote sensing data fusion. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **7**(12), 4960-4971, doi:10.1109/JSTARS.2014.2319314.
Givan, O., D. Edelist, O. Sonin and J. Belmaker, 2018: Thermal affinity as the dominant factor changing Mediterranean fish abundances. *Global Change Biology*, **24**(1), e80-e89, doi:10.1111/gcb.13835.
Goldstein, A. et al., 2020: Protecting irrecoverable carbon in Earth's ecosystems. *Nature Climate Change*, **10**(4), 287-295, doi:10.1038/s41558-020-0738-8.
González-Orozco, C. E. et al., 2016: Phylogenetic approaches reveal biodiversity threats under climate change. *Nature Climate Change*, **6**, 1110, doi:10.1038/nclimate3126.
Goulding, W., P. T. Moss and C. A. McAlpine, 2016: Cascading effects of cyclones on the biodiversity of Southwest Pacific islands. *Biological Conservation*, **193**, 143-152, doi:10.1016/j.biocon.2015.11.022.
Grabowski, M. M. et al., 2013: Do Arctic-nesting birds respond to earlier snowmelt? A multi-species study in north Yukon, Canada. *Polar Biology*, **36**(8), 1097-1105, doi:10.1007/s00300-013-1332-6.
Grafton, R. Q. et al., 2013: Global insights into water resources, climate change and governance. *Nature Climate Change*, **3**, 315-321, doi:10.1038/nclimate1746.
Grebmeier, J. M., K. E. Frey, L. W. Cooper and M. Kędra, 2018: Trends in benthic macrofaunal populations, seasonal sea ice persistence, and bottom water temperatures in the Bering Strait region. *Oceanography*, **31**(2), 136-151, doi:10.5670/oceanog.2018.224.
Grenyer, R. et al., 2006: Global distribution and conservation of rare and threatened vertebrates. *Nature*, **444**(7115), 93-96, doi:10.1038/nature05237.

Griffiths, H. J., A. J. S. Meijers and T. J. Bracegirdle, 2017: More losers than winners in a century of future Southern Ocean seafloor warming. *Nature Climate Change*, **7**, 749, doi:10.1038/nclimate3377.
Gruber, N. et al., 2012: Rapid Progression of Ocean Acidification in the California Current System. *Science*, **337**(6091), 220-223, doi:10.1126/science.1216773.
Gudmundsson, L., S. I. Seneviratne and X. Zhang, 2017: Anthropogenic climate change detected in European renewable freshwater resources. *Nature Climate Change*, **7**(11), 813-816, doi:10.1038/nclimate3416.
Gutiérrez, J. M. et al., IPCC WGI Interactive Atlas, Cambridge University Press. Available at: https://interactive-atlas.ipcc.ch/.
Halpern, B. S. et al., 2015: Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications*, **6**, 7615, doi:10.1038/ncomms8615.
Halpern, B. S. et al., 2008: A global map of human impact on marine ecosystems. *Science*, **319**(5865), 948-952, doi:10.1126/science.1149345.
Hannah, L. et al., 2020: 30% land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography*, **43**(7), 943-953, doi:10.1111/ecog.05166.
Harris, I., T. J. Osborn, P. Jones and D. Lister, 2020: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, **7**(1), 109, doi:10.1038/s41597-020-0453-3.
Harrison, I. et al., 2018: The freshwater biodiversity crisis. *Science*, **362**(6421), 1369-1369, doi:10.1126/science.aav9242.
Harter, D. E. V. et al., 2015: Impacts of global climate change on the floras of oceanic islands – Projections, implications and current knowledge. *Perspectives in Plant Ecology, Evolution and Systematics*, **17**(2), 160-183, doi:10.1016/j.ppees.2015.01.003.
Heikkinen, R. K. et al., 2020: Fine-grained climate velocities reveal vulnerability of protected areas to climate change. *Scientific Reports*, **10**(1), 1678, doi:10.1038/s41598-020-58638-8.
Hermes, C., G. Segelbacher and H. M. Schaefer, 2018: A framework for prioritizing areas for conservation in tropical montane cloud forests. *Écoscience*, **25**(1), 97-108, doi:10.1080/11956860.2017.1419787.
Herrera, J., A. Solari and L. O. Lucifora, 2015: Unanticipated effect of climate change on an aquatic top predator of the Atlantic rainforest. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **25**(6), 817-828, doi:10.1002/aqc.2536.
Hidasi-Neto, J. et al., 2019: Climate change will drive mammal species loss and biotic homogenization in the Cerrado Biodiversity Hotspot. *Perspectives in Ecology and Conservation*, **17**(2), 57-63, doi:10.1016/j.pecon.2019.02.001.
Hobday, A. J. et al., 2018: Categorizing and naming marine heatwaves. *Oceanography*, **31**(2), 162-173, doi:10.5670/oceanog.2018.205.
Hoffmann, A. A. et al., 2019: Impacts of recent climate change on terrestrial flora and fauna: Some emerging Australian examples. *Austral Ecol.*, **44**(1), 3-27, doi:10.1111/aec.12674.
Holmes, I., K. McLaren and B. Wilson, 2015: Niche modeling for management-ready information in little-studied, threatened frog species assemblages. *Journal for Nature Conservation*, **28**, 26-34, doi:10.1016/j.jnc.2015.08.005.
Hughes, L., A. Dean, W. Steffen and M. Rice, 2019a: *This is what climate change looks like*. Climate Council of Australia. Available at: https://www.climatecouncil.org.au/wp-content/uploads/2019/09/This-is-What-Climate-Change-Looks-Like.pdf.
Hughes, T. P. et al., 2018a: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, **359**(6371), 80-83, doi:10.1126/science.aan8048.
Hughes, T. P. et al., 2019b: Global warming impairs stock–recruitment dynamics of corals. *Nature*, **568**(7752), 387-390, doi:10.1038/s41586-019-1081-y.
Hughes, T. P. et al., 2018b: Global warming transforms coral reef assemblages. *Nature*, **556**(7702), 492-496, doi:10.1038/s41586-018-0041-2.
Huntley, B. and P. Barnard, 2012: Potential impacts of climatic change on southern African birds of fynbos and grassland biodiversity hotspots. *Diversity and Distributions*, **18**(8), 769-781, doi:10.1111/j.1472-4642.2012.00890.x.
Ibisch, P. L. et al., 2016: A global map of roadless areas and their conservation status. *Science*, **354**(6318), 1423-1427, doi:doi:10.1126/science.aaf7166.
IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, 1132 pp.
IPCC, 2018: *Global warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. IPCC Special Report.
IPCC, 2019a: Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL). In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL)*

[Shukla, P. R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (eds.)]. IPCC with World Meteorological Organisation (WMO), and United Nations Environmental Program (UNEP), Geneva, Switzerland, pp. 1542, In press.

IPCC, 2019b: Summary for Policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D. C. R., V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (ed.)], pp. in press. ISBN 1354-1013.

Isbell, F. et al., 2015: Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, **526**, 574, doi:10.1038/nature15374.

James, C. S. et al., 2017: Sink or swim? Potential for high faunal turnover in Australian rivers under climate change. *Journal of Biogeography*, **44**(3), 489-501, doi:10.1111/jbi.12926.

Janse, J. H. et al., 2015: GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems. *Environmental Science & Policy*, **48**, 99-114, doi:10.1016/j.envsci.2014.12.007.

Jarić, I. et al., 2019: Susceptibility of European freshwater fish to climate change: Species profiling based on life-history and environmental characteristics. *Global Change Biology*, **25**(2), 448-458, doi:10.1111/gcb.14518.

Jefferson, T. and M. J. Costello, 2019: Hotspots of marine biodiversity. In: *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. ISBN 978-0-12-409548-9.

Jenouvrier, S. et al., 2014: Projected continent-wide declines of the emperor penguin under climate change. *Nature Climate Change*, **4**(8), 715-718, doi:10.1038/nclimate2280.

Jézéquel, C. et al., 2020: Freshwater fish diversity hotspots for conservation priorities in the Amazon Basin. *Conservation Biology*, **34**(4), 956-965, doi:10.1111/cobi.13466.

Jones, M. C. and W. W. L. Cheung, 2015: Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES Journal of Marine Science*, **72**(3), 741–752, doi:10.1093/icesjms/fsu172.

Jonsson, P. R. et al., 2018: High climate velocity and population fragmentation may constrain climate-driven range shift of the key habitat former *Fucus vesiculosus*. *Diversity and Distributions*, **24**(7), 892-905, doi:10.1111/ddi.12733.

Jorda, G. et al., 2020: Ocean warming compresses the three-dimensional habitat of marine life. *Nature Ecology & Evolution*, **4**(1), 109-114, doi:10.1038/s41559-019-1058-0.

Jung, M. et al., 2021: Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nature Ecology & Evolution*, doi:10.1038/s41559-021-01528-7.

Keppel, G., C. Morrison, J.-Y. Meyer and H. J. Boehmer, 2014: Isolated and vulnerable: the history and future of Pacific Island terrestrial biodiversity. *Pacific Conservation Biology*, **20**(2), 136-145, doi:10.1071/PC140136.

Khormi, H. M. and L. Kumar, 2014: Climate change and the potential global distribution of Aedes aegypti: spatial modelling using GIS and CLIMEX. *Geospat Health*, **8**(2), 405-415, doi:10.4081/gh.2014.29.

Kidane, Y. O., M. J. Steinbauer and C. Beierkuhnlein, 2019: Dead end for endemic plant species? A biodiversity hotspot under pressure. *Global Ecology and Conservation*, **19**, e00670, doi:10.1016/j.gecco.2019.e00670.

Kiessling, W. et al., 2012: Equatorial decline of reef corals during the last Pleistocene interglacial. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(52), 21378-21383, doi:10.1073/pnas.1214037110.

King, A. D., D. J. Karoly and B. J. Henley, 2017: Australian climate extremes at 1.5 °C and 2 °C of global warming. *Nature Climate Change*, **7**(6), 412-416, doi:10.1038/nclimate3296.

Kjesbu, O. S. et al., 2014: Synergies between climate and management for Atlantic cod fisheries at high latitudes. *Proceedings of the National Academy of Sciences*, **111**(9), 3478-3483, doi:10.1073/pnas.1316342111.

Kleypas, J. et al., 2021: Designing a blueprint for coral reef survival. *Biological Conservation*, **257**, 109107, doi:10.1016/j.biocon.2021.109107.

Knouft, J. H. and D. L. Ficklin, 2017: The Potential Impacts of Climate Change on Biodiversity in Flowing Freshwater Systems. *Annual Review of Ecology, Evolution, and Systematics*, **48**(1), 111-133, doi:10.1146/annurev-ecolsys-110316-022803.

Kocsis, Á. T., Q. Zhao, M. J. Costello and W. Kiessling, 2021: Not all biodiversity richspots are climate refugia. *Biogeosciences Discuss.*, **2021**, 1-18, doi:10.5194/bg-2021-179.

Koenigstein, S. et al., 2018: Forecasting future recruitment success for Atlantic cod in the warming and acidifying Barents Sea. *Global Change Biology*, **24**(1), 526-535, doi:10.1111/gcb.13848.

Koide, D., K. Yoshida, C. C. Daehler and D. Mueller-Dombois, 2017: An upward elevation shift of native and non-native vascular plants over 40 years on the island of Hawai'i. *Journal of Vegetation Science*, **28**(5), 939-950, doi:10.1111/jvs.12549.

Kortsch, S. et al., 2012: Climate-driven regime shifts in Arctic marine benthos. *Proceedings of the National Academy of Sciences*, **109**(35), 14052-14057, doi:10.1073/pnas.1207509109.

Kuhlmann, M., D. Guo, R. Veldtman and J. Donaldson, 2012: Consequences of warming up a hotspot: species range shifts within a centre of bee diversity. *Diversity and Distributions*, **18**(9), 885-897, doi:10.1111/j.1472-4642.2011.00877.x.

Kumagai, N. H. et al., 2018: Ocean currents and herbivory drive macroalgae-to-coral community shift under climate warming. *Proceedings of the National Academy of Sciences*, **115**, 8990-8995, doi:10.1073/pnas.1716826115.

Laffoley, D. D. A. and J. Baxter, 2016: *Explaining ocean warming: Causes, scale, effects and consequences*. IUCN Gland, Switzerland. ISBN 2831718066.

Lamsal, P., L. Kumar and K. Atreya, 2017: Historical evidence of climatic variability and changes, and its effect on high-altitude regions: insights from Rara and Langtang, Nepal. *International Journal of Sustainable Development & World Ecology*, **24**(6), 471-484, doi:10.1080/13504509.2016.1198939.
Lanzante, J. R. et al., 2018: Some Pitfalls in Statistical Downscaling of Future Climate. *Bulletin of the American Meteorological Society*, **99**(4), 791-803, doi:10.1175/BAMS-D-17-0046.1.
Larsen, J. N. et al., 2014: Polar regions. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.
Laverick, J. H. and A. D. Rogers, 2019: Mesophotic Coral Ecosystems. In: *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. ISBN 978-0-12-409548-9.
Le Roux, J. J. et al., 2019: Recent Anthropogenic Plant Extinctions Differ in Biodiversity Hotspots and Coldspots. *Current Biology*, **29**(17), 2912-2918.e2912, doi:10.1016/j.cub.2019.07.063.
Lee, A. T. K. and P. Barnard, 2016: Endemic birds of the Fynbos biome: a conservation assessment and impacts of climate change. *Bird Conservation International*, **26**(1), 52-68, doi:10.1017/S0959270914000537.
Lenoir, J. et al., 2020: Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, **4**(1044-1059), doi:10.1038/s41559-020-1198-2.
Lenoir, J. and J. C. Svenning, 2015: Climate-related range shifts – a global multidimensional synthesis and new research directions. *Ecography*, **38**(1), 15-28, doi:10.1111/ecog.00967.
Leroy, B. et al., 2019: Global biogeographical regions of freshwater fish species. *Journal of Biogeography*, **NA**(0), doi:10.1111/jbi.13674.
Lima, A. A. d., M. C. Ribeiro, C. E. d. V. Grelle and M. P. Pinto, 2019: Impacts of climate changes on spatio-temporal diversity patterns of Atlantic Forest primates. *Perspectives in Ecology and Conservation*, **17**(2), 50-56, doi:10.1016/j.pecon.2019.04.004.
Loarie, S. R. et al., 2009: The velocity of climate change. *Nature*, **462**(7276), 1052-1055.
Lourenço-de-Moraes, R. et al., 2019: Climate change will decrease the range size of snake species under negligible protection in the Brazilian Atlantic Forest hotspot. *Scientific Reports*, **9**(1), 8523, doi:10.1038/s41598-019-44732-z.
Lovelock, C. E. and R. Reef, 2020: Variable Impacts of Climate Change on Blue Carbon. *One Earth*, **3**(2), 195-211, doi:10.1016/j.oneear.2020.07.010.
Loyola, R. D. et al., 2014: Clade-specific consequences of climate change to amphibians in Atlantic Forest protected areas. *Ecography*, **37**(1), 65-72, doi:10.1111/j.1600-0587.2013.00396.x.
Lozano, O. M. et al., 2017: Assessing climate change impacts on wildfire exposure in Mediterranean areas. *Risk Analysis*, **37**(10), 1898-1916, doi:10.1111/risa.12739.
Luke, D., K. McLaren and B. Wilson, 2016: Short-term Dynamics and the Effects of Biotic and Abiotic Factors on Plant Physiognomic Groups in a Hurricane-impacted Lower Montane Tropical Forest. *Biotropica*, **48**(3), 332-341, doi:10.1111/btp.12288.
Ma, W. et al., 2016: Fundamental shifts of central hardwood forests under climate change. *Ecological Modelling*, **332**, 28-41, doi:10.1016/j.ecolmodel.2016.03.021.
Mackey, B. et al., 2020: Understanding the importance of primary tropical forest protection as a mitigation strategy. *Mitig Adapt Strateg Glob Change*, **25**(5), 763-787, doi:10.1007/s11027-019-09891-4.
Maharaj, S. et al., 2018: Assessing protected area effectiveness within the Caribbean under changing climate conditions: A case study of the small island, Trinidad. *Land Use Policy*, **81**, 185-193.
Maharaj, S. S. and M. New, 2013: Modelling individual and collective species responses to climate change within Small Island States. *Biological Conservation*, **167**, 283-291, doi:10.1016/j.biocon.2013.08.027.
Manes, S. et al., 2021: Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, **257**, 109070, doi:10.1016/j.biocon.2021.109070.
Mantyka-Pringle, C. S. et al., 2015: Climate change modifies risk of global biodiversity loss due to land-cover change. *Biological Conservation*, **187**, 103-111, doi:10.1016/j.biocon.2015.04.016.
Mariani, G. et al., 2020: Let more big fish sink: Fisheries prevent blue carbon sequestration—half in unprofitable areas. *Science Advances*, **6**(44), eabb4848, doi:10.1126/sciadv.abb4848.
Markovic, D. et al., 2014: Europe's freshwater biodiversity under climate change: distribution shifts and conservation needs. *Diversity and Distributions*, **20**(9), 1097-1107, doi:10.1111/ddi.12232.
Marler, T. E., 2014: Pacific island tropical cyclones are more frequent and globally relevant, yet less studied. *Frontiers in Environmental Science*, **2**(42), doi:10.3389/fenvs.2014.00042.
McGuire, J. L. et al., 2016: Achieving climate connectivity in a fragmented landscape. *Proceedings of the National Academy of Sciences*, **113**(26), 7195-7200, doi:10.1073/pnas.1602817113.
McKelvy, A. and F. Burbrink, 2017: Ecological divergence in the yellow-bellied kingsnake (Lampropeltis calligaster) at two North American biodiversity hotspots. *Molecular Phylogenetics and Evolution*, **106**, 61-72, doi:10.1016/j.ympev.2016.09.006.

McManus, L. C. et al., 2020: Extreme temperature events will drive coral decline in the Coral Triangle. *Global Change Biology*, **26**(4), 2120-2133, doi:10.1111/gcb.14972.
McPherson, M. L. et al., 2021: Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave. *Communications Biology*, **4**(1), 298, doi:10.1038/s42003-021-01827-6.
Mechler, R. et al., 2020: Loss and Damage and limits to adaptation: recent IPCC insights and implications for climate science and policy. *Sustainability Science*, **15**(4), 1245-1251, doi:10.1007/s11625-020-00807-9.
Médail, F., 2017: The specific vulnerability of plant biodiversity and vegetation on Mediterranean islands in the face of global change. *Regional Environmental Change*, **17**(6), 1775-1790, doi:10.1007/s10113-017-1123-7.
Mendoza-Ponce, A. et al., 2018: Identifying effects of land use cover changes and climate change on terrestrial ecosystems and carbon stocks in Mexico. *Global Environmental Change*, **53**, 12-23, doi:10.1016/j.gloenvcha.2018.08.004.
Mendoza-Ponce, A., R. O. Corona-Núñez, L. Galicia and F. Kraxner, 2019: Identifying hotspots of land use cover change under socioeconomic and climate change scenarios in Mexico. *Ambio*, **48**(4), 336-349, doi:10.1007/s13280-018-1085-0.
Mittermeier, R. A. et al., 2004: *Hotspots revisited*. Cemex, Mexico City, 392 pp. ISBN 9686397779.
Mittermeier, R. A. et al., 2011: Global biodiversity conservation: The critical role of hotspots. In: *Biodiversity Hotspots: Distribution and Protection of Conservation Priority Areas* [Zachos, F. E. and J. C. Habel (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 3-22. ISBN 978-3-642-20992-5.
Molina-Martínez, A. et al., 2016: Changes in butterfly distributions and species assemblages on a Neotropical mountain range in response to global warming and anthropogenic land use. *Diversity and Distributions*, **22**(11), 1085-1098, doi:10.1111/ddi.12473.
Moret, P., M. d. l. Á. Aráuz, M. Gobbi and Á. Barragán, 2016: Climate warming effects in the tropical Andes: first evidence for upslope shifts of Carabidae (Coleoptera) in Ecuador. *Insect Conservation and Diversity*, **9**(4), 342-350, doi:10.1111/icad.12173.
Moss, B. et al., 2009: Climate change and the future of freshwater biodiversity in Europe: a primer for policy-makers. *Freshwater Reviews*, **2**(2), 103-131, doi:10.1608/FRJ-2.2.1.
Mueter, F. J. and M. A. Litzow, 2008: Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications*, **18**(2), 309-320, doi:10.1890/07-0564.1.
Muir, P. R., C. C. Wallace, T. Done and J. D. Aguirre, 2015: Limited scope for latitudinal extension of reef corals. *Science*, **348**(6239), 1135-1138, doi:10.1126/science.1259911.
Myers, N. et al., 2000: Biodiversity hotspots for conservation priorities. *Nature*, **403**(6772), 853-858, doi:10.1038/35002501.
Narins, P. M. and S. W. F. Meenderink, 2014: Climate change and frog calls: long-term correlations along a tropical altitudinal gradient. *Proceedings of the Royal Society B: Biological Sciences*, **281**(1783), 20140401, doi:doi:10.1098/rspb.2014.0401.
Nghikembua, M., J. Harris, T. Tregenza and L. Marker, 2016: Spatial and Temporal Habitat Use by GPS Collared Male Cheetahs in Modified Bushland Habitat. *Open Journal of Forestry*, **Vol.06No.04**, 12, doi:10.4236/ojf.2016.64022.
Noss, R. F. et al., 2015: How global biodiversity hotspots may go unrecognized: lessons from the North American Coastal Plain. *Diversity and Distributions*, **21**(2), 236-244, doi:10.1111/ddi.12278.
Oliver, E. C. J. et al., 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9**(1), 1324, doi:10.1038/s41467-018-03732-9.
Olson, D. M. and E. Dinerstein, 2002: The Global 200: Priority ecoregions for global conservation. *Annals of the Missouri Botanical garden*, **89**(2), 199-224, doi:10.2307/3298564.
Padalia, H., V. Srivastava and S. P. S. Kushwaha, 2015: How climate change might influence the potential distribution of weed, bushmint (Hyptis suaveolens)? *Environmental Monitoring and Assessment*, **187**(4), 210, doi:10.1007/s10661-015-4415-8.
Parry, M. et al. (eds.), 2007: *Climate Change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC*, vol. 4, Cambridge University Press. ISBN 0521880106.
Pecl, G. T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355**(6332), doi:10.1126/science.aai9214.
Pérez-García, N., X. Font, A. Ferré and J. Carreras, 2013: Drastic reduction in the potential habitats for alpine and subalpine vegetation in the Pyrenees due to twenty-first-century climate change. *Regional Environmental Change*, **13**(6), 1157-1169, doi:10.1007/s10113-013-0427-5.
Perry, C. T. et al., 2018: Loss of coral reef growth capacity to track future increases in sea level. *Nature*, **558**(7710), 396-400, doi:10.1038/s41586-018-0194-z.
Perry, G. L., J. M. Wilmshurst and M. S. McGlone, 2014: Ecology and long-term history of fire in New Zealand. *New Zealand Journal of Ecology*, **38**(2), 1.
Pershing, A. J. et al., 2015: Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, **350**(6262), 809-812, doi:10.1126/science.aac9819.
Petzold, J. and A. K. Magnan, 2019: Climate change: thinking small islands beyond Small Island Developing States (SIDS). *Climatic Change*, **152**(1), 145-165, doi:10.1007/s10584-018-2363-3.
Pinsky, M. L. et al., 2019: Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, **569**(7754), 108-111, doi:10.1038/s41586-019-1132-4.

Pinsky, M. L. et al., 2013: Marine taxa track local climate velocities. *Science*, **341**(6151), 1239-1242, doi:10.1126/science.1239352.

Poloczanska, E. S. et al., 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3**, 919-925, doi:10.1038/nclimate1958.

Poloczanska, E. S. et al., 2016: Responses of marine organisms to climate change across oceans. *Frontiers in Marine Science*, **3**(62), doi:10.3389/fmars.2016.00062.

Pörtner, H.-O. et al., 2021: *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change*. IPBES secretariat, Bonn, Germany,. Available at: https://zenodo.org/record/4923212/export/hx (accessed 2021/06/10/16:24:01).

Poulsen, Z. C. and M. T. Hoffman, 2015: Changes in the distribution of indigenous forest in Table Mountain National Park during the 20th Century. *South African Journal of Botany*, **101**, 49-56, doi:10.1016/j.sajb.2015.05.002.

Pounds, J. A., M. P. L. Fogden and J. H. Campbell, 1999: Biological response to climate change on a tropical mountain. *Nature*, **398**(6728), 611-615, doi:10.1038/19297.

Pouteau, R. and P. Birnbaum, 2016: Island biodiversity hotspots are getting hotter: vulnerability of tree species to climate change in New Caledonia. *Biological Conservation*, **201**, 111-119, doi:10.1016/j.biocon.2016.06.031.

Pritchard, H. D., 2019: Asia's shrinking glaciers protect large populations from drought stress. *Nature*, **569**(7758), 649-654, doi:10.1038/s41586-019-1240-1.

Priti, H., N. A. Aravind, R. Uma Shaanker and G. Ravikanth, 2016: Modeling impacts of future climate on the distribution of Myristicaceae species in the Western Ghats, India. *Ecological Engineering*, **89**, 14-23, doi:10.1016/j.ecoleng.2016.01.006.

Ramírez-Amezcua, Y., V. W. Steinmann, E. Ruiz-Sanchez and O. R. Rojas-Soto, 2016: Mexican alpine plants in the face of global warming: potential extinction within a specialized assemblage of narrow endemics. *Biodiversity and conservation*, **25**(5), 865-885, doi:10.1007/s10531-016-1094-x.

Ramírez, F., I. Afán, L. S. Davis and A. Chiaradia, 2017: Climate impacts on global hot spots of marine biodiversity. *Science Advances*, **3**(2), e1601198, doi:10.1126/sciadv.1601198.

Ramírez, F. et al., 2018: Spatial congruence between multiple stressors in the Mediterranean Sea may reduce its resilience to climate impacts. *Scientific Reports*, **8**(1), 14871, doi:10.1038/s41598-018-33237-w.

Rathore, P., A. Roy and H. Karnatak, 2019: Modelling the vulnerability of Taxus wallichiana to climate change scenarios in South East Asia. *Ecological Indicators*, **102**, 199-207, doi:10.1016/j.ecolind.2019.02.020.

Rayner, N. A. et al., 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres*, **108**(D14), doi:10.1029/2002JD002670.

Richardson, B., M. Richardson and G. González, 2018: Responses of two litter-based invertebrate communities to changes in canopy cover in a forest subject to hurricanes. *Forests*, **9**(6), 309, doi:10.3390/f9060309.

Rilov, G., 2016: Multi-species collapses at the warm edge of a warming sea. *Scientific Reports*, **6**, 36897, doi:10.1038/srep36897.

Riordan, E. C. and P. W. Rundel, 2014: Land Use Compounds Habitat Losses under Projected Climate Change in a Threatened California Ecosystem. *PLOS ONE*, **9**(1), e86487, doi:10.1371/journal.pone.0086487.

Roberts, C. M. et al., 2017: Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences*, **114**(24), 6167-6175, doi:10.1073/pnas.1701262114.

Robinson, S.-a., 2020a: Climate change adaptation in SIDS: A systematic review of the literature pre and post the IPCC Fifth Assessment Report. *WIREs Climate Change*, **11**(4), e653, doi:10.1002/wcc.653.

Robinson, S.-a., 2020b: A richness index for baselining climate change adaptations in small island developing states. *Environmental and Sustainability Indicators*, **8**, 100065, doi:10.1016/j.indic.2020.100065.

Roehrdanz, P. R. and L. Hannah, 2016: Climate change, California wine, and wildlife habitat. *Journal of Wine Economics*, **11**(1), 69-87, doi:10.1017/jwe.2014.31.

Roycroft, E. et al., 2021: Museum genomics reveals the rapid decline and extinction of Australian rodents since European settlement. *Proceedings of the National Academy of Sciences*, **118**(27), e2021390118, doi:10.1073/pnas.2021390118.

Saintilan, N. et al., 2020: Thresholds of mangrove survival under rapid sea level rise. *Science*, **368**(6495), 1118-1121, doi:10.1126/science.aba2656.

Sala, E. et al., 2021: Protecting the global ocean for biodiversity, food and climate. *Nature*, **592**(7854), 397-402, doi:10.1038/s41586-021-03371-z.

Sánchez-Guillén, R. A. et al., 2013: Climate-induced range shifts and possible hybridisation consequences in insects. *PLOS ONE*, **8**(11), e80531, doi:10.1371/journal.pone.0080531.

Sandel, B. et al., 2011: The influence of late Quaternary climate-change velocity on species endemism. *Science*, **334**(6056), 660-664, doi:10.1126/science.1210173.

Sanford, E. et al., 2019: Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. *Scientific Reports*, **9**(1), 4216, doi:10.1038/s41598-019-40784-3.

Santangeli, A., O. Spiegel, P. Bridgeford and M. Girardello, 2018: Synergistic effect of land-use and vegetation greenness on vulture nestling body condition in arid ecosystems. *Scientific Reports*, **8**(1), 13027, doi:10.1038/s41598-018-31344-2.

Saunders, D. L., J. J. Meeuwig and A. C. J. Vincent, 2002: Freshwater protected areas: Strategies for conservation. *Conservation Biology*, **16**(1), 30-41, doi:10.1046/j.1523-1739.2002.99562.x.
Scheffers, B. R. et al., 2017: Vertical (arboreality) and horizontal (dispersal) movement increase the resilience of vertebrates to climatic instability. *Global Ecology and Biogeography*, **26**(7), 787-798, doi:10.1111/geb.12585.
Scheiter, S., S. I. Higgins, J. Beringer and L. B. Hutley, 2015: Climate change and long-term fire management impacts on Australian savannas. *New Phytologist*, **205**(3), 1211-1226, doi:10.1111/nph.13130.
Scobie, M., 2016: Policy coherence in climate governance in Caribbean Small Island Developing States. *Environmental Science & Policy*, **58**, 16-28, doi:10.1016/j.envsci.2015.12.008.
Seim, A. et al., 2016: Climate change increases drought stress of juniper trees in the mountains of Central Asia. *PLOS ONE*, **11**(4), e0153888, doi:10.1371/journal.pone.0153888.
Shelton, J. M. et al., 2018: Vulnerability of Cape Fold Ecoregion freshwater fishes to climate change and other human impacts. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **28**(1), 68-77, doi:10.1002/aqc.2849.
Shiels, A. B., G. González and M. R. Willig, 2014: Responses to canopy loss and debris deposition in a tropical forest ecosystem: Synthesis from an experimental manipulation simulating effects of hurricane disturbance. *Forest Ecology and Management*, **332**, 124-133.
Shrestha, U. B. et al., 2018: Potential impact of climate change on the distribution of six invasive alien plants in Nepal. *Ecological Indicators*, **95**, 99-107, doi:10.1016/j.ecolind.2018.07.009.
Silva-Rocha, I. et al., 2015: Snakes on the Balearic Islands: An Invasion Tale with Implications for Native Biodiversity Conservation. *PLOS ONE*, **10**(4), e0121026, doi:10.1371/journal.pone.0121026.
Sintayehu, D. W., 2018: Impact of climate change on biodiversity and associated key ecosystem services in Africa: a systematic review. *Ecosystem Health and Sustainability*, **4**(9), 225-239, doi:10.1080/20964129.2018.1530054.
Slatyer, R., 2010: Climate change impacts on Australia's alpine ecosystems. *The ANU Undergraduate Research Journal*, **2**, 1-17, doi:10.22459/aurj.02.2010.05.
Slingsby, J. A. et al., 2017: Intensifying postfire weather and biological invasion drive species loss in a Mediterranean-type biodiversity hotspot. *Proc Natl Acad Sci U S A*, **114**(18), 4697-4702, doi:10.1073/pnas.1619014114.
Song, J. and L. Duan, 2019: Chapter 18 - The Yellow Sea. In: *World Seas: an Environmental Evaluation (Second Edition)* [Sheppard, C. (ed.)]. Academic Press, pp. 395-413. ISBN 978-0-08-100853-9.
Spatz, D. R. et al., 2017: Globally threatened vertebrates on islands with invasive species. *Science Advances*, **3**(10), e1603080, doi:10.1126/sciadv.1603080.
Sridhar, V. et al., 2014: CLIMEX simulated predictions of Oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) geographical distribution under climate change situations in India. *Current Science*, **106**, 1702-1710.
Steinbauer, M. J. et al., 2018: Accelerated increase in plant species richness on mountain summits is linked to warming. *Nature*, **556**, 231-234, doi:10.1038/s41586-018-0005-6.
Steneck, R. S. et al., 2002: Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environmental Conservation*, **29**(4), 436-459.
Stevens, N., C. E. R. Lehmann, B. P. Murphy and G. Durigan, 2017: Savanna woody encroachment is widespread across three continents. *Global Change Biology*, **23**(1), 235-244, doi:10.1111/gcb.13409.
Stralberg, D. et al., 2015: Conservation of future boreal forest bird communities considering lags in vegetation response to climate change: a modified refugia approach. *Diversity and Distributions*, **21**(9), 1112-1128, doi:10.1111/ddi.12356.
Struebig, M. et al., 2015: Targeted conservation to safeguard a biodiversity hotspot from climate and land-cover change. *Current Biology*, **25**(3), 372-378, doi:10.1016/j.cub.2014.11.067.
Stuart-Smith, R. D., C. J. Brown, D. M. Ceccarelli and G. J. Edgar, 2018: Ecosystem restructuring along the Great Barrier Reef following mass coral bleaching. *Nature*, **560**(7716), 92-96, doi:10.1038/s41586-018-0359-9.
Stuart-Smith, R. D. et al., 2015: Thermal biases and vulnerability to warming in the world's marine fauna. *Nature*, **528**, 88, doi:10.1038/nature16144.
Stuart-Smith, R. D., G. J. Edgar and A. E. Bates, 2017: Thermal limits to the geographic distributions of shallow-water marine species. *Nature Ecology & Evolution*, **1**(12), 1846-1852, doi:10.1038/s41559-017-0353-x.
Su, G. et al., 2021: Human impacts on global freshwater fish biodiversity. *Science*, **371**(6531), 835-838, doi:10.1126/science.abd3369.
Sunday, J. M., A. E. Bates and N. K. Dulvy, 2012: Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, **2**(9), 686–690.
Tang, C. Q. et al., 2017: Potential effects of climate change on geographic distribution of the Tertiary relict tree species Davidia involucrata in China. *Scientific Reports*, **7**, 43822, doi:10.1038/srep43822.
Taylor, S. and L. Kumar, 2016: Global Climate Change Impacts on Pacific Islands Terrestrial Biodiversity: A Review. *Tropical Conservation Science*, **9**(1), 203-223, doi:10.1177/194008291600900111.
Teagle, H. and D. A. Smale, 2018: Climate-driven substitution of habitat-forming species leads to reduced biodiversity within a temperate marine community. *Diversity and Distributions*, **24**(10), 1367-1380, doi:10.1111/ddi.12775.
Tedesco, P. A. et al., 2013: A scenario for impacts of water availability loss due to climate change on riverine fish extinction rates. *Journal of Applied Ecology*, **50**(5), 1105-1115, doi:doi:10.1111/1365-2664.12125.
Tellería, J. L., 2020: Long-term altitudinal change in bird richness in a Mediterranean mountain range: habitat shifts explain the trends. *Regional Environmental Change*, **20**(2), 69, doi:10.1007/s10113-020-01657-y.

Telwala, Y., B. W. Brook, K. Manish and M. K. Pandit, 2013: Climate-induced elevational range shifts and increase in plant species richness in a himalayan biodiversity epicentre. *PLOS ONE*, **8**(2), e57103, doi:10.1371/journal.pone.0057103.
Terhaar, J., L. Kwiatkowski and L. Bopp, 2020: Emergent constraint on Arctic Ocean acidification in the twenty-first century. *Nature*, **582**(7812), 379-383, doi:10.1038/s41586-020-2360-3.
Thieme, M. L., B. Lehner, R. Abell and J. Matthews, 2010: Exposure of Africa's freshwater biodiversity to a changing climate. *Conservation Letters*, **3**(5), 324-331, doi:10.1111/j.1755-263X.2010.00120.x.
Thomsen, M. S. et al., 2019: Local extinction of bull kelp (Durvillaea spp.) due to a marine heatwave. *Frontiers in Marine Science*, **6**(84), doi:10.3389/fmars.2019.00084.
Thomsen, M. S. and P. M. South, 2019: Communities and attachment networks associated with primary, secondary and alternative foundation species; a case study of stressed and disturbed stands of southern bull kelp. *Diversity*, **11**(4), 56, doi:10.3390/d11040056.
Titeux, N. et al., 2016: Biodiversity scenarios neglect future land-use changes. *Global Change Biology*, **22**(7), 2505-2515, doi:10.1111/gcb.13272.
Tompkins, D. M., A. E. Byrom and R. P. Pech, 2013: Predicted responses of invasive mammal communities to climate-related changes in mast frequency in forest ecosystems. *Ecological Applications*, **23**(5), 1075-1085, doi:10.1890/12-0915.1.
Trew, B. T. and I. M. D. Maclean, 2021: Vulnerability of global biodiversity hotspots to climate change. *Global Ecology and Biogeography*, **30**(4), 768-783, doi:10.1111/geb.13272.
Trisos, C. H., C. Merow and A. L. Pigot, 2020: The projected timing of abrupt ecological disruption from climate change. *Nature*, **580**(7804), 496-501, doi:10.1038/s41586-020-2189-9.
Tulloch, V. J. D. et al., 2019: Future recovery of baleen whales is imperiled by climate change. *Global Change Biology*, **25**(4), 1263-1281, doi:10.1111/gcb.14573.
Ukkola, A. M. et al., 2016: Reduced streamflow in water-stressed climates consistent with CO2 effects on vegetation. *Nature Climate Change*, **6**, 75-78, doi:10.1038/nclimate2831.
Vale, M. M., T. V. Souza, M. A. S. Alves and R. Crouzeilles, 2018: Planning protected areas network that are relevant today and under future climate change is possible: the case of Atlantic Forest endemic birds. *PeerJ*, **6**, e4689, doi:10.7717/peerj.4689.
Vasconcelos, T. d. S., 2014: Tracking climatically suitable areas for an endemic Cerrado snake under climate change. *Natureza & Conservação*, **12**(1), 47-52, doi:10.4322/natcon.2014.009.
Vasconcelos, T. S., B. T. M. do Nascimento and V. H. M. Prado, 2018: Expected impacts of climate change threaten the anuran diversity in the Brazilian hotspots. *Ecology and Evolution*, **8**(16), 7894-7906, doi:10.1002/ece3.4357.
Vasconcelos, T. S. and V. H. M. Prado, 2019: Climate change and opposing spatial conservation priorities for anuran protection in the Brazilian hotspots. *Journal for Nature Conservation*, **49**, 118-124, doi:10.1016/j.jnc.2019.04.003.
Vasilakopoulos, P., D. E. Raitsos, E. Tzanatos and C. D. Maravelias, 2017: Resilience and regime shifts in a marine biodiversity hotspot. *Scientific Reports*, **7**(1), 13647, doi:10.1038/s41598-017-13852-9.
Velazco, S. J. E., F. Villalobos, F. Galvão and P. De Marco Júnior, 2019: A dark scenario for Cerrado plant species: Effects of future climate, land use and protected areas ineffectiveness. *Diversity and Distributions*, **25**(4), 660-673, doi:10.1111/ddi.12886.
Vergés, A. et al., 2016: Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. *Proceedings of the National Academy of Sciences*, **113**(48), 13791-13796, doi:10.1073/pnas.1610725113.
Vergés, A. et al., 2019: Tropicalisation of temperate reefs: Implications for ecosystem functions and management actions. *Functional Ecology*, **33**(6), 1000-1013, doi:10.1111/1365-2435.13310.
Vogiatzakis, I. N., A. M. Mannion and D. Sarris, 2016: Mediterranean island biodiversity and climate change: the last 10,000 years and the future. *Biodiversity and Conservation*, **25**(13), 2597-2627, doi:10.1007/s10531-016-1204-9.
Wabnitz, C. C. C. et al., 2018: Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. *PLOS ONE*, **13**(5), e0194537, doi:10.1371/journal.pone.0194537.
Waldock, C. et al., 2019: The shape of abundance distributions across temperature gradients in reef fishes. *Ecology Letters*, **22**(4), 685-696, doi:10.1111/ele.13222.
Wang, C.-J., J.-Z. Wan and Z.-X. Zhang, 2017: Expansion potential of invasive tree plants in ecoregions under climate change scenarios: an assessment of 54 species at a global scale. *Scandinavian Journal of Forest Research*, **32**(8), 663-670, doi:10.1080/02827581.2017.1283049.
Wang, Q. et al., 2016: Temporal evolution of the Yellow Sea ecosystem services (1980–2010). *Heliyon*, **2**(3), e00084, doi:10.1016/j.heliyon.2016.e00084.
Ward, R. D., D. A. Friess, R. H. Day and R. A. MacKenzie, 2016: Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosystem Health and Sustainability*, **2**(4), e01211, doi:10.1002/ehs2.1211.
Warren, D. L., A. N. Wright, S. N. Seifert and H. B. Shaffer, 2014: Incorporating model complexity and spatial sampling bias into ecological niche models of climate change risks faced by 90 California vertebrate species of concern. *Diversity and Distributions*, **20**(3), 334-343, doi:10.1111/ddi.12160.
Warren, R. et al., 2018a: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5 degrees C rather than 2 degrees C. *Science*, **360**(6390), 791-+, doi:10.1126/science.aar3646.

Warren, R. et al., 2018b: The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Climatic Change*, **147**(3-4), 395-409, doi:10.1007/s10584-018-2158-6.
Wernberg, T. et al., 2016: Climate-driven regime shift of a temperate marine ecosystem. *Science*, **353**(6295), 169-172, doi:10.1126/science.aad8745.
Wernberg, T. et al., 2011: Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. *Journal of Experimental Marine Biology and Ecology*, **400**(1), 7-16, doi:10.1016/j.jembe.2011.02.021.
Wernberg, T. et al., 2013: An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change*, **3**(1), 78-82, doi:10.1038/nclimate1627.
Węsławski, J. M., K. Dragańska-Deja, J. Legeżyńska and W. Walczowski, 2018: Range extension of a boreal amphipod Gammarus oceanicus in the warming Arctic. *Ecology and Evolution*, **8**(15), 7624-7632, doi:10.1002/ece3.4281.
Węsławski, J. M. et al., 2011: Climate change effects on Arctic fjord and coastal macrobenthic diversity—observations and predictions. *Marine Biodiversity*, **41**(1), 71-85, doi:10.1007/s12526-010-0073-9.
Wetzel, F. T., H. Beissmann, D. J. Penn and W. Jetz, 2013: Vulnerability of terrestrial island vertebrates to projected sea-level rise. *Global Change Biology*, **19**(7), 2058-2070, doi:10.1111/gcb.12185.
Wiens, J. J., 2016: Climate-related local extinctions are already widespread among plant and animal species. *PLOS Biology*, **14**(12), e2001104, doi:10.1371/journal.pbio.2001104.
Williams, J. W., S. T. Jackson and J. E. Kutzbach, 2007: Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences*, **104**(14), 5738-5742, doi:10.1073/pnas.0606292104.
Williams, K. J. et al., 2011: Forests of East Australia: The 35th Biodiversity Hotspot. In: *Biodiversity Hotspots: Distribution and Protection of Conservation Priority Areas* [Zachos, F. E. and J. C. Habel (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 295-310. ISBN 978-3-642-20992-5.
Wilson, K. L., M. A. Skinner and H. K. Lotze, 2019: Projected 21st-century distribution of canopy-forming seaweeds in the Northwest Atlantic with climate change. *Diversity and Distributions*, **25**(4), 582-602, doi:10.1111/ddi.12897.
WMO, 2021: *State of the Climate in Latin America and the Caribbean 2020*. World Meteorological Organization (WMO), 32 pp. ISBN 978-92-63-11272-9.
Wolter, K., W. Neser, M. T. Hirschauer and A. Camiña, 2016: Cape Vulture Gyps coprotheres breeding status in southern Africa: monitoring results from 2010–2014. *Ostrich*, **87**(2), 119-123.
Xiu, P., F. Chai, E. N. Curchitser and F. S. Castruccio, 2018: Future changes in coastal upwelling ecosystems with global warming: The case of the California Current System. *Scientific Reports*, **8**(1), 2866, doi:10.1038/s41598-018-21247-7.
Yamano, H., K. Sugihara and K. Nomura, 2011: Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophysical Research Letters*, **38**(4), doi:10.1029/2010GL046474.
Yasuhara, M. et al., 2020: Past and future decline of tropical pelagic biodiversity. *Proceedings of the National Academy of Sciences*, **117**(23), 12891-12896, doi:10.1073/pnas.1916923117.
Yeruham, E., G. Rilov, M. Shpigel and A. Abelson, 2015: Collapse of the echinoid Paracentrotus lividus populations in the Eastern Mediterranean—result of climate change? *Scientific Reports*, **5**, 13479, doi:10.1038/srep13479.
Young, A. J., D. Guo, P. G. Desmet and G. F. Midgley, 2016: Biodiversity and climate change: Risks to dwarf succulents in Southern Africa. *Journal of Arid Environments*, **129**, 16-24, doi:10.1016/j.jaridenv.2016.02.005.
Zomer, R. J. et al., 2014: Projected climate change impacts on spatial distribution of bioclimatic zones and ecoregions within the Kailash Sacred Landscape of China, India, Nepal. *Climatic Change*, **125**(3), 445-460, doi:10.1007/s10584-014-1176-2.
Zunino, S., D. M. Canu, V. Bandelj and C. Solidoro, 2017: Effects of ocean acidification on benthic organisms in the Mediterranean Sea under realistic climatic scenarios: A meta-analysis. *Regional Studies in Marine Science*, **10**, 86-96, doi:10.1016/j.rsma.2016.12.011.
Zylstra, P. J., 2018: Flammability dynamics in the Australian Alps. *Austral Ecol.*, **43**(5), 578-591, doi:10.1111/aec.12594.

Cross-Chapter Paper 2: Cities and Settlements by the Sea

Cross-Chapter Paper Leads: Bruce Glavovic (New Zealand/South Africa), Richard Dawson (United Kingdom), Winston Chow (Singapore)

Cross-Chapter Paper Authors: Matthias Garschagen (Germany), Marjolijn Haasnoot (The Netherlands), Chandni Singh (India), Adelle Thomas (Bahamas)

Cross-Chapter Paper Contributing Authors: Jeroen Aerts (The Netherlands), Sophie Blackburn (United Kingdom), David Catt (USA), Eric Chu (USA), William Solecki (USA), Stijn-Temmerman (Belgium), Gundula Winter (Germany)

Cross-Chapter Paper Review Editor: Soojeong Myeong (Republic of Korea)

Cross-Chapter Paper Scientist: David Catt (USA)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Cities and settlements by the sea (C&S) are on the frontline of climate change – they face amongst the highest climate-compounded risks but are a key source of innovations in climate resilient development (*high confidence*[1]) {Sections 6.1, 6.2; Chapter 7, Box 15.2; Cross-Chapter Box –COVID in Chapter 7; Cross-Chapter Box –SLR in Chapter 3; CCP2.2; SMCCP2.1; WGI Section 12.4.10.2}.

Much of the world's population, economic activities and critical infrastructure are concentrated near the sea (*high confidence*), with nearly 11% of the global population, or 896 million people, already living on low-lying coasts directly exposed to interacting climate- and non-climate coastal hazards (*very high confidence*) {CCP2.1}. Low-lying C&S are experiencing adverse climate impacts that are superimposed on extensive and accelerating anthropogenic coastal change (*very high confidence*) {WGI Section 12.4.10.2; Sections 6.1, 6.2; CCP2.2, SMCCP2.1}. Depending on coastal C&S characteristics, continuing existing patterns of coastal development will worsen exposure and vulnerability (*high confidence*) {CCP2.1}. With accelerating sea level rise (SLR) and worsening climate-driven risks in a warming world, prospects for achieving the Sustainable Development Goals (SDGs) and charting Climate Resilient Development (CRD) pathways are dismal (*high confidence*) {CCP2.3, CCP2.4; Chapter 16, 18}. However, coastal C&S are also the source of SDG and CRD solutions because they are centres of innovation with long histories of place-based livelihoods, many of which are globally connected through maritime trade and exchange (*medium confidence*) {CCP2.4}.

Regardless of climate and socio-economic scenarios, many C&S face severe disruption to coastal ecosystems and livelihoods by 2050 – and across all C&S by 2100 and beyond – caused by compound and cascading risks, including submergence of some low-lying island states (*very high confidence*) {CCP2.1; CCP2.2; SROCC SPM, Chapter 4; Section 6.2}.

There is *high confidence* that projected climate risks will increase with (i) exposure to climate- and ocean-driven hazards manifest at the coast, such as heat waves, droughts, pluvial floods, and impacts due to SLR, tropical cyclones, marine and land heatwaves, and ocean acidification; (ii) with increasing vulnerability driven by inequity, and (iii) increasing exposure driven by urban growth in at-risk locations. Compounded and cascading climate risks, such as to coastal C&S infrastructure and supply chain networks, are also expected to increase {Section 6.2.7; CCP2.2}. These risks are acute for C&S on subsiding and/or low-lying small islands, the Arctic, and open, estuarine and deltaic coasts (*high confidence*) {CCP2.2; Table SMCCP2.1}. By 2050, more than a billion people located in low-lying C&S will be at risk from coast-specific climate hazards, influenced by coastal geomorphology, geographical location and adaptation action (*high confidence*). Between US$7-14 trillion of coastal infrastructure assets will be exposed by 2100, depending on warming levels and socio-economic development trajectories (*medium confidence*) {CCP2.1}. Historically rare extreme sea level events will occur annually by 2100, with some atolls being uninhabitable by 2050. Coastal flood risk rapidly increases in coming decades, and could increase by 2–3 orders of magnitude by 2100 in the absence of effective adaptation and mitigation, with severe impacts on coast-dependent livelihoods and socio-ecological systems (*high confidence*) {SROCC SPM; Chapter 4}. Impacts reach far beyond C&S e.g., damage to ports severely compromising global supply chains and maritime trade with local-global geo-political and economic ramifications. Global investment costs to accommodate port growth and adapt to SLR amount to USD223-768 billion before 2050, presenting opportunities for C&S by the sea to build climate resilience (*medium evidence, high agreement*) {CCP2.1; CCP2.2; Cross-Chapter Box SLR in Chapter 3}. Severely accelerated SLR resulting from rapid continental ice mass-loss would bring impacts forward by decades, and adaptation would need to occur much faster and at much greater scale than ever done in the past (*medium confidence*).

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

A mix of interventions is necessary to manage coastal risks and build resilience over time. An adaptation pathways approach sets out near-term 'low-regret' actions that align with societal goals, and facilitates implementation of a locally appropriate sequence of interventions in the face of uncertain climate and development futures, and enables necessary transformation (*high confidence*) {CCP2.3; Cross-Chapter Box DEEP in Chapter 17, Cross-Chapter Box SLR in Chapter 3}

A mix of infrastructural, nature-based, institutional and socio-cultural interventions are needed to reduce the multifaceted risk facing C&S, including vulnerability reducing measures, avoidance (i.e., disincentivising developments in high-risk areas), hard- and soft-protection, accommodation, advance (i.e., building up and out to sea) and retreat (i.e., landward movement of people and development) (*very high confidence*) {CCP2.3}. Depending on the C&S archetype, technical limits for hard protection may be reached beyond 2100 under high emission scenarios, with socio-economic and governance barriers reached before then (*medium confidence*). Hard protection can, however, set up lock-in of assets and people to risks and, in some cases, may reach limits, due to technical and financial constraints, by 2100 or sooner depending on the scenario, local SLR effects and community tolerance thresholds (*medium confidence*). Where sufficient space and adequate habitats are available, nature-based solutions can help to reduce coastal hazard risks and provide other benefits, but biophysical limits may be reached before end-century (*medium confidence*). Accommodation is easier, faster and cheaper to implement than hard protection, but limits may be reached by 2100, or sooner in some settings. An adaptation pathways planning approach demonstrates how the solution space can expand or shrink depending on the type and timing of adaptation interventions {CCP1.3.1.2}. As SLR is relentless on human timescales, the solution space will shrink without adoption of an adaptation pathways planning approach (*high confidence*). Due to long implementation lead times and the need to avoid maladaptive lock-in, especially in localities facing rapid SLR and climate-compounded risk, adaptation will be more successful if timely action is taken accounting for long-term (committed) SLR; and if this is underpinned by sustained and ambitious mitigation to slow greenhouse gas emission rates (*high confidence*) {CCP2.3; CCP2.4; Cross-Chapter Box SLR in Chapter 3}.

Individual and collective choices founded on public-centred values and norms, as well as pro-social behaviour, help to foster climate resilient coastal development in C&S (*high confidence*) {CCP2.4.1}.

The effectiveness of different approaches (e.g., awareness and education, market-based and legal strategies) is mediated by how well they address contextual and psycho-social factors influencing adaptation choices in coastal C&S (*medium confidence*). Adaptation options accounting for risk perceptions and aligning with public values are more likely to be socio-culturally acceptable, and consequently facilitate pro-social behavioural change {CCP2.4.1}.

Locally appropriate institutional capabilities, including regulatory provisions and finances dedicated to maintaining healthy coastal social-ecological systems, build adaptive capacity in C&S by the sea (*high confidence*) {CCP2.4}.

Implementing integrated multi-level coastal zone governance, pre-emptive planning, enabling behavioural change, and alignment of financial resources with a wide set of values, will provide C&S with greater flexibility to open up the solution space to adapt to climate change (*high confidence*) {CCP2.4.4}. Insufficient financial resources are a key constraint for coastal adaptation, particularly in the Global South (*high confidence*). Engaging the private sector in coastal adaptation action with a range of financial tools is crucial to address the coastal adaptation funding gap (*high confidence*). Considering the full range of economic and non-economic values will improve adaptation effectiveness and equity across C&S archetypes (*high confidence*). Aligning adaptation in C&S with socio-economic development, infrastructure maintenance, and COVID-19 recovery investments will provide additional co-benefits {CCP2.4.2}. Urgency is also driven by the need to avoid lock-in to new and additional risk, e.g., avoid C&S sprawl into fragile ecosystems and the most exposed coastal localities {CCP2.3}.

Realising global aspirations for climate resilient development depend on the extent to which coastal C&S institutionalise key enabling conditions and chart place-based adaptation pathways to close the coastal adaptation gap, and take urgent action to mitigate greenhouse gas emissions (*medium confidence*) {CCP2.4, Table CCP2.1}.

Since AR5, extensive adaptation planning has been undertaken, but there has not been widespread effective implementation - giving rise to a ‘coastal adaptation gap’ (*high confidence*). To date, most interventions have been reactive, reliant on protective works alone (*high confidence*). Effectiveness of alternative interventions differs among C&S archetypes, while their feasibility is influenced by geomorphology, socio-economic conditions as well cultural, political and institutional considerations (*very high confidence*). Mismatches between adaptation needs and patterns of physical development are commonplace in many coastal C&S, with especially adverse impacts on poor and marginalised communities in the global North and South (*high confidence*). Overcoming this gap is key to transitioning towards CRD (*medium confidence*). Under higher warming levels and higher SLR, increasingly dichotomous coastal futures will become more entrenched (*medium confidence*), with stark differences between more urbanised, resource-rich coastal C&S dependent on hard protection, and more rural, resource-poor C&S facing displacement and migration {CCP2.3; CCP2.4, Chapter 18}.

Coastal adaptation innovators adopt more flexible, anticipatory and integrative strategies, combining technical and non-technical interventions that account for uncertainties, and facilitate effective resolution of conflicting interests and worldviews (*limited evidence, high agreement*) {CCP2.3; CCP2.4; Chapter 17, 18; Cross-Chapter Box DEEP in Chapter 17}. Moreover, a core set of critical enablers is foundational for C&S to chart CRD pathways. These include building and strengthening governance capabilities to tackle complex problems; taking a long-term perspective in making short-term decisions; enabling more effective coordination across scales, sectors and policy domains; reducing injustice, inequity, and social vulnerability; and unlocking the productive potential of coastal conflict while strengthening local democracy (*medium evidence, high agreement*) {Table CCP2.1, Table CCP2.2}.

C&S play a pivotal role in global aspirations to implement the Paris Agreement, advance the SDGs, and foster CRD. Progress towards these ends depends on the extent to which C&S mobilise urgent and transformational changes to institutionalise enabling conditions; close the coastal adaptation gap by addressing the drivers and root causes of exposure and vulnerability to climate-compounded coastal hazard risks; and drastically reduce greenhouse gas emissions (*medium confidence*) {CCP2.4; Chapter 18}

CCP2.1 Context of Cities and Settlements by the Sea

CCP2.1.1 Introduction and Context

This CCP examines the distinctive roles played by Cities and Settlements (C&S) by the sea in vulnerability and coastal hazard risk reduction, adaptation, resilience, and sustainability in a changing climate. The paper builds upon evidence from AR5 (Wong et al., 2014), the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Magnan et al., 2019; Oppenheimer et al., 2019) and draws material from across WGII AR6 (especially Chapters 3, 6, 9-15). It differs from the sea level rise (SLR) focused analysis of urban areas in SROCC (Section 4.3) through a more integrated assessment that distinguishes between archetypal coastal C&S (CCP2.1.2); sectoral risks to C&S by the sea, (CCP2.2); responses to address these risks (CCP2.3); and enabling conditions and lessons learned (CCP2.4).

We define 'cities and settlements' as concentrated human habitation centres, whether small or large, rural or urban (Chapter 6.1.3). We highlight the unique exposure and vulnerability of coastal C&S resulting from rapid urbanisation at the narrow land-sea interface, concentration of economic activity and at-risk people, many with long-standing cultural ties to the coast and dependence on coastal ecosystems that are prone to climate change impacts (*high confidence*) (He and Silliman, 2019; Lau et al., 2019; Oppenheimer et al., 2019; Sterzel et al., 2020).

Presently, coastal C&S population exposure to ocean-driven impacts from SLR, and other climate-driven impacts is considerable by any measure (Buddemeier et al., 2008; Barragán and de Andrés, 2015; Kay and Alder, 2017; Haasnoot et al., 2019; McMichael et al., 2020; Sterzel et al., 2020). In 2020, almost 11% of global population – 896 million people – resided in C&S within the Low Elevation Coastal Zone (LECZ, coastal areas below 10 m of elevation above sea level that are hydrologically connected to the sea) (Haasnoot et al., 2021b), and potentially increases beyond 1 billion by 2050 (Oppenheimer et al., 2019). Infrastructural and economic assets worth US$6,500-US$11,000 billion are also exposed in the 1-in-100-year floodplain for C&S of all sizes (Neumann et al., 2015; Muis et al., 2016; Brown et al., 2018; Andrew et al., 2019; Kulp and Strauss, 2019; Kirezci et al., 2020; Thomas et al., 2020; Haasnoot et al., 2021b; Hooijer and Vernimmen, 2021).

Further, coastal cities located at higher elevations (e.g., São Paulo, Brazil), or distantly located inland along tidal-influenced rivers (e.g., the Recife Metropolitan Region, Brazil) also have populations and infrastructure exposed to climate impacts. As such, the inclusion of C&S beyond the LECZ is warranted when assessing climate impacts and associated exposure, vulnerabilities and risks. The coastal zone includes some of the world's largest, most densely populated megacities, as well as the fastest-growing urban areas. However, vast coastal areas are sparsely populated, with population in these regions concentrated in smaller C&S, including along subsiding shorelines and in deltas (Nicholls and Small, 2002; McGranahan et al., 2007; Merkens et al., 2018; Edmonds et al., 2020; Nicholls et al., 2021). From this wider perspective, climate change impacts on the coast directly or indirectly affect a large portion of the global population, economic activity and associated critical infrastructure. Some estimates suggest 23-37% of the global population lives within 100 km of the shoreline (Nicholls and Small, 2002; Shi and Singh, 2003; Christopher Small and Joel E. Cohen, 2004; McMichael et al., 2020).

C&S by the sea are thus on the 'frontline' of action to adapt to climate change, mitigate greenhouse gas emissions, and chart climate resilient development (CRD) pathways for several distinct reasons. First, home to a concentrated (and growing) portion of the world's population, many coastal C&S are simultaneously exposed and vulnerable to climate-compounded hazards as well as being centres of creativity and innovation (Glavovic, 2013; Crescenzi and Rodríguez-Pose, 2017; Druzhinin et al., 2021; Mariano et al., 2021; Storbjörk and Hjerpe, 2021). Second, people in C&S by the sea rely on coastal ecosystems, many of which are highly sensitive to climate change impacts that compound non-climate risks and increase the precarity of coastal livelihoods (Lu et al., 2018; He and Silliman, 2019; Thrush et al., 2021). Third, coastal C&S are linked together through a network of ports and harbours that underpin global trade and exchange but are prone to climate change impacts, especially SLR, with significant implications for global CRD prospects (Becker et al., 2018; Christodoulou et al., 2019; Walsh et al., 2019; Hanson and Nicholls, 2020). For these reasons, this paper assesses responses, enabling conditions and lessons learned for addressing climate change in C&S by the sea.

CCP2.1.2 Urbanisation in Coastal Systems: Coastal City and Settlement Archetypes

This assessment uses an archetype framework categorizing coastal C&S according to geomorphological characteristics, urban growth, economic resources, and inequalities (Figure CCP2.1). We use three broadly defined coastal settlement geomorphologies in each row: open coasts (a coast with sediment without river mouths), and two transitional coastal zones with river mouths: estuaries (a wetland receiving sediment from both fluvial and marine sources, which is affected by tide, wave, and river processes), and deltas (a wetland where fluvial sediment is supplied and deposited more rapidly than it can be redistributed by basin processes such as waves and tides) (Bhattacharya, 1978; Barragán and de Andrés, 2015; Kay and Alder, 2017; Haasnoot et al., 2019; Sterzel et al., 2020). Small island C&S are not singled out in this typology because their coastlines often include the geomorphic features listed above, or require a different adaptation approach at larger spatial scales (Haasnoot et al., 2019). Several coastal C&S have a combination of two typologies e.g., Maputo-Matola, Mozambique, and Mumbai, India, having both open and transitional riverine coasts, and can be classed as mixed. We also acknowledge several coastal C&S may have areas sited in mountainous topography that abruptly rise from the coast (e.g., along the Mediterranean), but generally these cities have narrow densely populated coastal shelfs exhibiting these three archetypal categories (Blackburn et al., 2019). Arctic settlements are addressed separately in this CCP.

Coastal C&S within these geomorphological categories are further distinguished according to higher or lower rates of urban growth and inequality – which can be estimated through population growth from national census data, or areal extent of urban development (CEIC); as well as relative urban inequalities estimated by Gini Coefficient data and urban-rural poverty rates (OECD, 2018; OECD, 2020). Combining geomorphological and socio-economic data accounts for urban-rural interconnections and differences; with levels of capital generation, diversity of economic functions and human development indices having previously been used to discern cultural, economic, administrative and political differences between cities and their hinterland (Blackburn et al., 2019; Rocle et al., 2020). For instance, the ecological, cultural and economic footprint of tertiary sectors e.g., coastal tourism associated with the Australian Great Barrier Reef stretches far beyond the nearest onshore settlement of Cairns (Bohnet and Pert, 2010; Brodie and Pearson, 2016).

Some caveats are warranted. First, locating a specific city or settlement in a particular archetype does not account for future reclassification due to growth or shifts in development trajectories. Second, significant socio-economic, political and governance variations exist within many C&S, c.f., impoverished informal settlements alongside wealthy neighbourhoods in cities like Cape Town and São Paulo (also see Table SMCCP2.1). Third, this archetype framework does not explicitly reveal important interconnections between coastal C&S and their hinterlands, or between particular C&S through maritime trade or other economic, socio-cultural and geopolitical inter-dependencies. Notwithstanding these caveats, these archetypes reveal differentiated physical impacts and socio-economic conditions, as well as the variable challenges and opportunities arising for addressing climate change impacts and projected risk, which, depending on coastal type, C&S size, and resource availability, help to inform efforts to adapt and chart CRD for each archetype (Sánchez-Arcilla et al., 2016; Rocle et al., 2020; Sterzel et al., 2020).

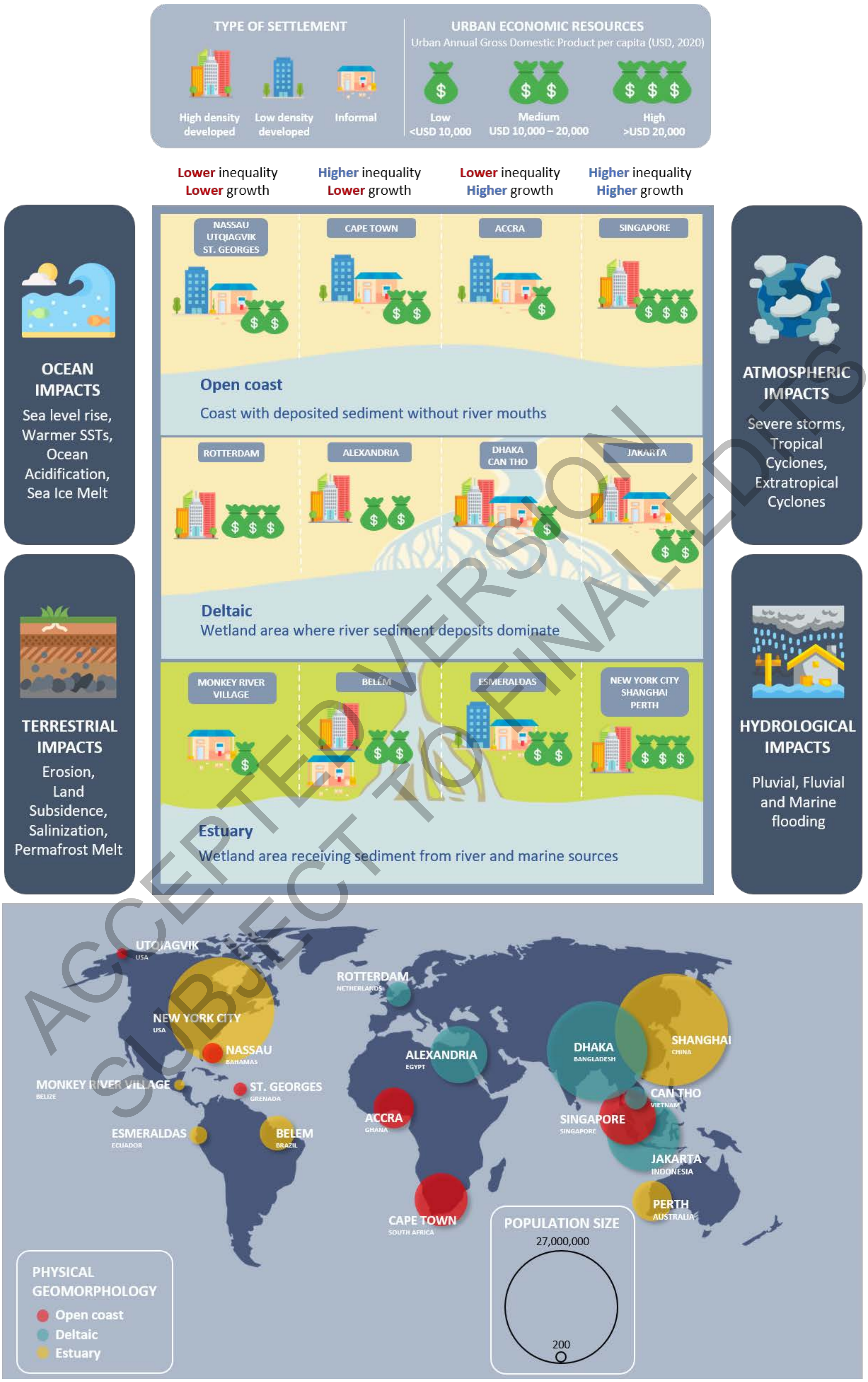

TYPE OF SETTLEMENT
High density developed
Low density developed
Informal
URBAN ECONOMIC RESOURCES
Urban Annual Gross Domestic Product per capita (USD, 2020)
Low <USD 10,000
Medium USD 10,000 – 20,000
High >USD 20,000
Lower inequality Lower growth
Higher inequality Lower growth
Lower inequality Higher growth
Higher inequality Higher growth
OCEAN IMPACTS
Sea level rise, Warmer SSTs, Ocean Acidification, Sea Ice Melt
TERRESTRIAL IMPACTS
Erosion, Land Subsidence, Salinization, Permafrost Melt
ATMOSPHERIC IMPACTS
Severe storms, Tropical Cyclones, Extratropical Cyclones
HYDROLOGICAL IMPACTS
Pluvial, Fluvial and Marine flooding
NASSAU UTQIAGVIK ST. GEORGES
CAPE TOWN
ACCRA
SINGAPORE
Open coast
Coast with deposited sediment without river mouths
ROTTERDAM
ALEXANDRIA
DHAKA CAN THO
JAKARTA
Deltaic
Wetland area where river sediment deposits dominate
MONKEY RIVER VILLAGE
BELEM
ESMERALDAS
NEW YORK CITY SHANGHAI PERTH
Estuary
Wetland area receiving sediment from river and marine sources
UTQIAGVIK USA
NEW YORK CITY USA
NASSAU BAHAMAS
MONKEY RIVER VILLAGE BELIZE
ST. GEORGES GRENADA
ESMERALDAS ECUADOR
BELEM BRAZIL
ROTTERDAM NETHERLANDS
ALEXANDRIA EGYPT
ACCRA GHANA
CAPE TOWN SOUTH AFRICA
DHAKA BANGLADESH
SHANGHAI CHINA
CAN THO VIETNAM
SINGAPORE SINGAPORE
JAKARTA INDONESIA
PERTH AUSTRALIA
POPULATION SIZE
27,000,000
200
PHYSICAL GEOMORPHOLOGY
Open coast
Deltaic
Estuary

Figure CCP2.1: Archetypal C&S affected by ocean, terrestrial, geological, atmospheric and hydrological hazards driven by climate change. Coastal C&S are grouped by physical geomorphology along estuary, deltaic, or open coasts (Barragán and de Andrés, 2015; Kay and Alder, 2017; Haasnoot et al., 2019). C&S are also classified according to relative inequality (e.g., urban Gini coefficient or poverty rates) and growth rates (e.g., recent population growth and increasing density of urban form or built-up area over the past decade) (OECD, 2018; CEIC; OECD, 2020). Settlement types (e.g., informal, low-density or high-density developments) and economic resources (e.g., urban per capita GDP) are also reflected in their respective categories. The bottom map shows the location, 2020 population size, and geomorphological types.

CCP2.2 Climate Change Risks to Cities and Settlements by the Sea

Coastal C&S are at the forefront of climate risk (FAQ CCP2.1). The dynamic interaction between ocean- and climate-drivers and varied coastal geographies influences the character of coastal risks, including many that are unique to C&S by the sea. The interaction of coastal hazards with exposure and vulnerability is differentiated by coastal archetypes, leading to distinct climate change-compounded risks, and associated responses (Figure CCP2.2; Section 1.3.1.2; Simpson et al. (2021)).

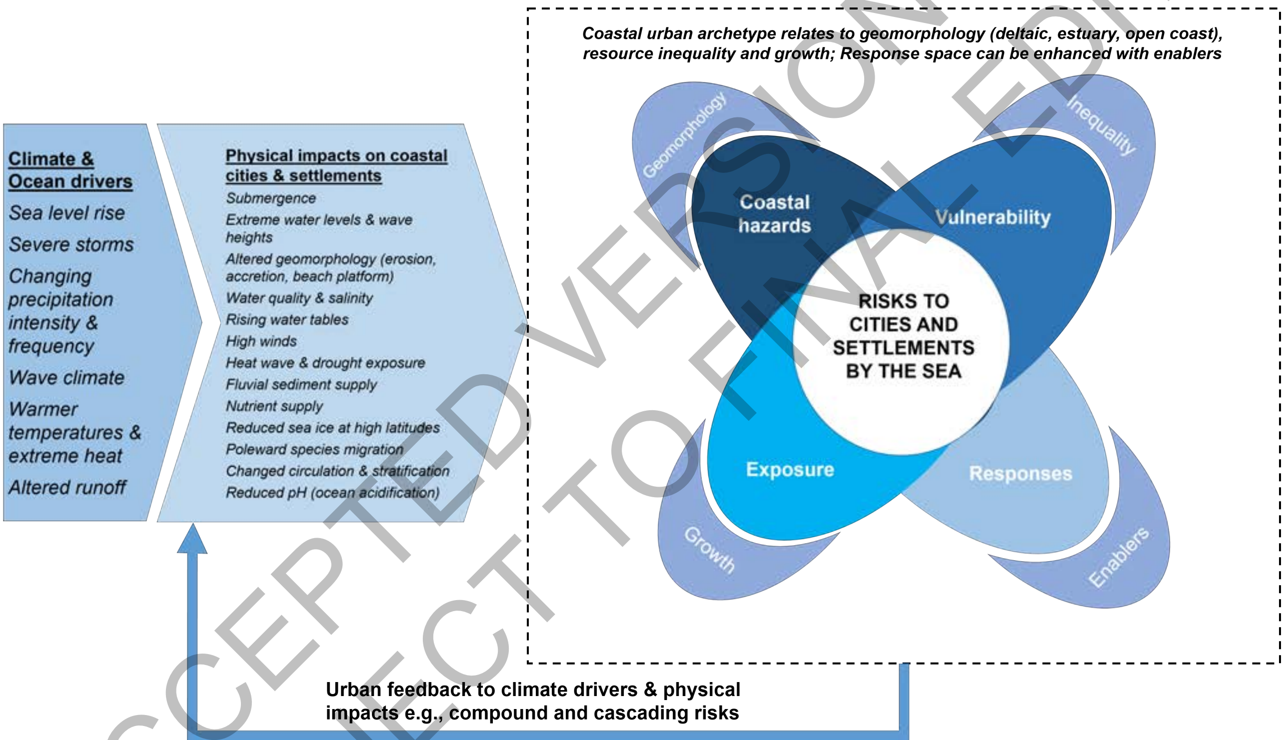


Figure CCP2.2: Schematic of how climate- and ocean-drivers (from WGI Chapter 12.4.10.2) and consequential physical impacts on coastal C&S influence risks assessed in (CCP2.2; Figure based on Simpson et al. (2021) and Section 1.3.1.2). These risks to C&S by the sea are shaped and mediated by adaptation interventions aimed at reducing vulnerability and exposure to coastal hazards given settlement archetypes, as well as by expanding the space for responses to risk via enabling conditions assessed in (CCP2.4). Note that exposure to coastal hazard is controlled chiefly by underlying coastal C&S geomorphology, and changes in coastal hazards and urban growth, including population and infrastructure growth; vulnerability is controlled, for example, by socio-economic development and inequality; and responses that shape risks assessed in (CCP2.3) can be enhanced by enabling conditions, including behavioural change, conducive finance, and prudent governance.

Overall, interactions between climatic and non-climatic drivers of coastal change are increasing the frequency and intensity of many coastal hazards, with settlement archetypes and the wider coastal zone subject to escalating risk (*high confidence*) (Figure CCP2.2; Table SMCCP2.1 for examples of selected coastal C&S). Risks can vary markedly between different archetypes. C&S sited on deltaic and estuarine coasts face additional risks of pluvial flooding compared to open coasts; while greater vulnerabilities arise in coastal settlements with higher inequalities.

Risks to C&S by the sea were extensively covered in SROCC (Oppenheimer et al., 2019) and also in WGII Chapter 3, 6 and regional chapters; in this paper, specific risks to livelihoods, activities, built environment, and ecosystems are assessed in detail in Supplementary Material SMCCP2.1. The ocean- and climate-impact drivers influencing these risks are assessed in WG1 (Section 12.4.10.2), which include extreme heat, pluvial floods from increasing rainfall intensity, coastal erosion and coastal flood driven by increasing SLR, and tropical cyclone storm surges (*high confidence*). Further, Arctic coastal settlements are particularly exposed to climate change due to sea ice retreat as well as from permafrost melt (*high confidence*).

Without adaptation, risks to land and people in coastal C&S from pluvial- and coastal-flooding will *very likely*[2] increase substantially by 2100 and *likely* beyond as a result of SLR, with significant impacts even under RCP2.6 (Neumann et al., 2015; Muis et al., 2016; Brown et al., 2018; Nicholls et al., 2018; Kulp and Strauss, 2019; Oppenheimer et al., 2019; Kirezci et al., 2020; Haasnoot et al., 2021b). Across these studies, by 2100, 158-510 million people and US$7,919-US$12,739 billion assets under RCP4.5, and 176-880 million people and US$8,813-US$14,178 billion assets under RCP8.5, will be within the 1-in-100-year floodplain (*very high confidence*). There is *medium confidence* that accelerated SLR will increase shoreline erosion globally, although biophysical feedbacks will allow many coastlines to maintain relatively stable morphology if room exists to accommodate mangroves in estuarine and deltaic coasts, and beach movement along open coasts (Kench et al., 2015; McLean and Kench, 2015; Perkins et al., 2015; Richards and Friess, 2016; CCC, 2017; Duncan et al., 2018; Luijendijk et al., 2018; Mentaschi et al., 2018; Schuerch et al., 2018; Ghosh et al., 2019; Masselink et al., 2020; Toimil et al., 2020; Vousdoukas et al., 2020b). Limiting emissions to RCP2.6 (corresponding to a mean post-industrial global temperature increase of 1.5-2C) significantly reduces future SLR risks (Hinkel et al., 2014; Brown et al., 2018; Nicholls et al., 2018; Schinko et al., 2020). For example, by 2100 the population at risk of permanent submergence increases by 26% under RCP2.6 compared with 53% under RCP8.5 (median values from Kulp and Strauss (2019).

There is *high confidence* about regionally differentiated but considerable global sectoral impacts in coastal C&S arising from exposure to hazards. Tangible impacts include damage, loss of life, loss of livelihoods, especially fisheries and tourism (Tessler et al., 2015; Avelino et al., 2018; Hoegh-Guldberg et al., 2018; Seekamp et al., 2019; Arabadzhyan et al., 2020); negative impacts on health and wellbeing, especially under extreme events (McIver et al., 2016; Bakkensen and Mendelsohn, 2019; Bindoff et al., 2019; Pugatch, 2019); and involuntary displacement and migration (Hauer, 2017; Davis et al., 2018; Neef et al., 2018; Boas et al., 2019; McLeman et al., 2021). Intangible impacts include psychological impacts due to extreme events, such as heat-waves, flooding, droughts, and tropical cyclones; heightened inequality in coastal archetypes with systematic gender/ethnicity/structural vulnerabilities; and loss of things of personal or cultural value, and sense of place or connection, including existential risk of the demise of nations due to submergence (Allison and Bassett, 2015; Barnett, 2017; Schmutter et al., 2017; Weir et al., 2017; Farbotko et al., 2020; Hauer et al., 2020; Hoffmann et al., 2020; Bell et al., 2021). Impacts extend beyond the coastal zone, for example disruption to ports and supply chains, with major geopolitical and economic ramifications from the C&S to global scale (*very high confidence*) (Becker et al., 2018; Camus et al., 2019; Christodoulou et al., 2019; Walsh et al., 2019; Hanson and Nicholls, 2020; Yang and Ge, 2020; Izaguirre et al., 2021; León-Mateos et al., 2021; Ribeiro et al., 2021).

Many coastal C&S have densely built physical infrastructure and assets that are exposed and vulnerable to climate change-compounded coastal hazards. There is *high confidence* that SLR, land subsidence, poorly regulated coastal development, and the rise of asset values are major drivers of future risk in all coastal archetypes and, without adaptation, built environment risks, especially in archetypes with high exposure due to rapid growth, are expected to rise considerably in this century across all RCPs (Koks et al., 2019; Magnan et al., 2019; Oppenheimer et al., 2019; Abadie et al., 2020; Nicholls et al., 2021). Archetypes with more

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

informal settlements are often disproportionally exposed to coastal risks (Roy et al., 2016; Hallegatte et al., 2017; Bangalore et al., 2019).

There is *high confidence* that loss of coastal ecosystem services will increase risks to all coastal C&S archetypes that include reduced provisioning of materials and food (e.g., wood, fishery habitat) (Kok et al., 2021), amelioration of coastal hazards (e.g., attenuation of storm surges, waves, and containing erosion) (Section 2.3.2.3; Godfroy et al., 2019; Schoutens et al., 2019; Zhu et al., 2020b), climate change mitigation (through carbon sequestration) (Macreadie et al., 2017; Rovai et al., 2018; Ward, 2020), water quality regulation (nutrient, pollutant and sediment retention and cycling) (Wilson et al., 2018; Zhao et al., 2018), and recreation and tourism (Pueyo-Ros et al., 2018).

Most studies of coastal C&S focus on adaptation to a single or limited set of risks, but there is *high confidence* that compound and cascading risks significantly alter C&S risk profiles (Nicholls et al., 2015; Estrada et al., 2017; Edmonds et al., 2020; Eilander et al., 2020; Yin et al., 2020; Ghanbari et al., 2021). Extreme events can lead to cascading infrastructure failures that cause damage and economic losses well beyond the coastal zone (Haraguchi and Kim, 2016; Kishore et al., 2018; Rey et al., 2019; So et al., 2019), and have forced evacuation of C&S and small islands (Look et al., 2019; Thomas and Benjamin, 2020). These risks are exacerbated by non-climate drivers, e.g., compound and cascading impacts arising from exposure to tropical cyclones and COVID-19 that threaten population health and hamper pandemic responses (Salas et al., 2020; Shultz et al., 2020a; Shultz et al., 2020b). There is emerging evidence (*low confidence*) from individual coastal C&S, and regional case studies (e.g., in Europe, Australia, and the U.S.), illustrating the increasing influence of compound risks on vulnerability due to accelerating climate change (Wahl et al., 2015; Xu et al., 2019; Kirezci et al., 2020).

Figure CCP2.3 shows that ocean-driven coastal risks to people, land, and infrastructure in East and Southeast Asia are highest compared to other regions, even for low levels of projected SLR. However, risks facing coastal C&S are high across the globe, especially under higher SLR projections (*high confidence*). Without adaptation, the population at-risk to a 100-year coastal flood increases by ~20% if current global mean sea level rises by 0.15m relative to current levels; this at-risk population doubles at 0.75m rise in mean sea level, and triples at 1.4m. Simultaneously, coastal C&S are projected to experience shoreline retreat, with coastlines having more than 100 m retreat increasing ~165% if current mean sea levels rise between 0.23-0.53 m. Ocean-driven flooding in coastal C&S is also projected to disrupt flights by up to three orders of magnitude per year in selected coastal C&S as mean sea level increases. Typically, larger risks correspond with archetypes associated with higher inequality and high growth rates, especially in deltas, leading to larger vulnerability and exposure respectively under higher warming levels.

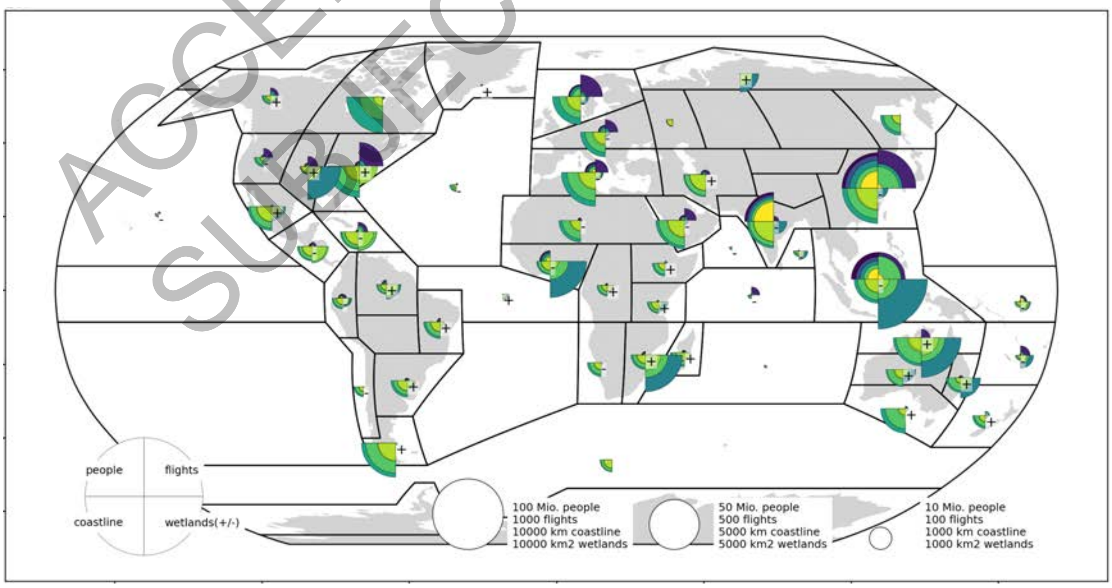


Figure CCP2.3: Map of coastal C&S risks according to IPCC regions, showing risks to people from a 100-year coastal flood event (*100.000) (Haasnoot et al., 2021b), risks to loss of coastal land (length of coast with more than 100 m retreat) (Vousdoukas et al., 2020b), risks to the built environment (airports at risk indicated by number of flights disrupted (Yesudian and Dawson, 2021)) and risk to wetlands (± indicates positive or negative area change) (Schuerch et al., 2018). Risks are reported against global mean sea level rise relative to 2020, depending on data availability.

CCP2.3 Adaptation in Cities and Settlements by the Sea

CCP2.3.1 Introduction

This section extends SROCC Chapter 4 (Oppenheimer et al., 2019), which focused on SLR, and draws from Chapters 6 and 9-15 to cover all C&S archetypes. Adaptation interventions span psycho-social (e.g., awareness raising), economic (e.g., insurance), physical (e.g., retreat), technical (e.g., sea walls) and natural dimensions (e.g., wetland restoration) (Nicholls et al., 2015). Adaptation strategies for coastal C&S are typically classified in terms of protect, accommodate, advance, and retreat, which are used below.

Some coastal cities have adapted to meters of SLR in the past, indicating that adaptation is feasible (Esteban et al., 2020a), but future adaptation options are influenced by variations in projected socio-economic conditions and rates of SLR (Cross-Chapter Box SLR in Chapter 3). To date, interventions are typically implemented reactively in response to extreme events (*high confidence*); but leading adaptors are increasingly proactive (*medium confidence*) (Araos et al., 2016; Dulal, 2019; Dedekorkut-Howes et al., 2020), and those that move from previously rigid to more adaptive and flexible solutions, using an adaptation pathways approach that keeps options open in the face of uncertainty, have improved climate risk management (*high confidence*) (Sections 9.9.4; 10.5; 11.7; 12.5.5; 13.2; 14.7; 15.5; Cross-Chapter Box DEEP in Chapter 17; Walker et al., 2013; Marchau et al., 2019).

The effectiveness of different strategies and interventions is mediated by physical coastal features for hard adaptation measures, and by the scope and depth of soft adaptation measures, e.g., the coverage extent of social safety nets for urban poor (Section 6.3). Their feasibility is also shaped by socio-economic, cultural, political and institutional factors, e.g., social acceptance of measures (CCP2.2, SMCCP2.2.4). Together, response effectiveness and feasibility shape the solution space for mediating risks (Section 1.3.1.2; Figure CCP2.3; Simpson et al., 2021;), which is achieved chiefly through governance interventions e.g., laws and regulations (Haasnoot et al., 2020). Access to financial resources expands the solution space, most notably for some resource-rich coastal archetypes (CCP2.4.2; Table SMCCP2.1; Sections 3.6, 14.7), but rapid population growth and unfolding climate-driven impacts can increase risks (Haasnoot et al., 2021a) especially for small island and poorer C&S (*high confidence*) (Section 15.3; Magnan and Duvat (2020).

CCP2.3.2 Protection of Coastal Cities and Settlements

CCP2.3.2.1 Hard Engineering Measures

Hard engineering protection measures are commonly used to reduce coastal flooding, and to drain or store excess water from intense precipitation. Many coastal cities, in particular densely populated and high resource archetypes, have planned and are planning to continue a protection-based strategy, comprising e.g., breakwaters, sea walls and/or dikes, which could be raised or complemented with large barriers or with 'super-levees' enabling construction on top of them (*high confidence*) (Table SMCCP2.1; Takagi et al., 2016; Haasnoot et al., 2019; Hall et al., 2019; Esteban et al., 2020b)).

Protection is effective in the short- to medium-term for many coastal cities, and can be cost-effective in the 21st Century (section CCP2.4.2), but residual risk remains because protection can fail. Even under RCP8.5, technical limits to hard protection may only be reached after 2100 in many regions, but socio-economic and institutional barriers may be reached before then (Hinkel et al., 2018). With progressive SLR, protection eventually becomes unaffordable and impractical (Strauss et al., 2021). Combining hard engineering measures with nature-based solutions, spatial planning and early warning systems, can help to contain residual risk (Du et al., 2020). Protective works do not prevent salinisation and higher groundwater levels (Alves et al., 2020), and can lead to loss of coastal habitat (Cross-Chapter Box SLR in Chapter 3; Achete et al. (2017); Cooper et al. (2020)). Hard protection measures also create long-term path-dependency as they last for decades and attract new development, locking in impact and exposure as C&S grow, with the expectation of ongoing protection (Chapter 3; Di Baldassarre et al., 2015; Gibbs, 2016; Griggs and Patsch, 2019; Siders, 2019a).

CCP2.3.2.2 Soft Engineering and Sediment-based Measures

Sediment-based interventions e.g., beach nourishment, aim to limit coastal erosion and flood risk and have become a widely applied strategy especially in open coast archetypal C&S; in part because there is less impact on adjacent beaches and coastal ecology, and lower construction and maintenance costs compared to hard protection (*high confidence*) (Parkinson and Ogurcak, 2018). In addition, it is considered a flexible strategy under more rapid SLR conditions (Kabat et al., 2009; Stive et al., 2013), and can be applied in the form of a mega-nourishment strategy wherein natural currents distribute sand along the coast (Stive et al., 2013; de Schipper et al., 2021). However, there are limits to this strategy due to environmental impacts, costs, and the availability of potential and permitted sand reserves which may be unable to keep up with higher rates of SLR (Parkinson and Ogurcak, 2018; Haasnoot et al., 2019; Harris et al., 2021; Staudt et al., 2021). Simultaneously, other socio-economic needs (e.g., damming rivers, or for building and transport infrastructure) may compete for sand as a limited resource (Torres et al., 2017; Bendixen et al., 2019). Regional and global governance provisions (e.g., spatial reservations for sand mining; international frameworks for distribution) could improve long-term feasibility (Torres et al., 2017; Parkinson and Ogurcak, 2018; Bendixen et al., 2019; Haasnoot et al., 2019).

CCP2.3.2.3 Nature-based Measures

Nature-based measures, such as retaining mangroves and marshes, have been successful in reducing deaths and damage due to storm surges (*high agreement, medium evidence*) (Das and Vincent, 2009; Saleh and Weinstein, 2016; Narayan et al., 2017; Triyanti et al., 2017; Hochard et al., 2019; del Valle et al., 2020), and across the USA reportedly provide USD23.2 billion yr-1 in storm protection services (Saleh and Weinstein, 2016). They are also a cost-effective strategy (*medium confidence*) that provide C&S with additional co-benefits through ecosystem services (*high confidence*) (Cross-Chapter Box NATURAL in Chapter 2; Section 2.2.4; Narayan et al., 2016; Depietri and McPhearson, 2017; Morris et al., 2018; Reguero et al., 2018; Chausson et al., 2020; Du et al., 2020; NIES and ISME, 2020; Reguero et al., 2020; Sudmeier-Rieux et al., 2021).

Nature-based measures can reduce inland propagation of extreme sea levels (high tides, storm surges) (*high agreement*) (Godfroy et al., 2019; James et al., 2020; Zhu et al., 2020b), with vertical reduction in water levels ranging from 5-50cm/km behind large mangroves and marshes (Stark et al., 2015; Van Coppenolle and Temmerman, 2020). They also attenuate wind-driven waves and reduce shoreline erosion (*high agreement*), and this can be as much as 90% over stretches of 10-100 meters for dense mangrove and marsh vegetation (*medium evidence*) (Li et al., 2014; Möller et al., 2014; Vuik et al., 2016; Vuik et al., 2018; Godfroy et al., 2019; Zhu et al., 2020a) and up to 40% for dunes (Feagin et al., 2019). Coral reefs on average reduce wave energy by 97% (Ferrario et al., 2014). Seagrass meadows attenuate wind waves to a lesser extent, and are only effective in water <0.2 m deep (Ondiviela et al., 2014; Narayan et al., 2016; Morris et al., 2019).

Within limits, coastal ecosystems can respond to rising sea-level through sediment accretion and lateral inland movement (Kirwan et al., 2016; Schuerch et al., 2018). Nature-based measures have greatest potential in coastal deltas and estuaries, where human populations are exposed but large ecosystems, like mangroves and marshes, can be conserved and restored (Menéndez et al., 2020; Van Coppenolle and Temmerman, 2020). Their feasibility depends on physical, ecological, institutional, and socio-economic conditions that are typically locality-dependent (Temmerman and Kirwan, 2015; Arkema et al., 2017); space may not be available in certain places (e.g., intensive urbanization on the shoreline), or these measures may conflict with other human demands for scarce land (Tian et al., 2016). Successful nature-based measures require site-specific knowledge and science-based design, pilot monitoring, and adaptive upscaling (Evans et al., 2017; Nesshöver et al., 2017), and more rigorous understanding of long-term performance, maintenance and costs (Kumar et al., 2021).

Nature-based measures are increasingly implemented in combination with hard protection measures (Hu et al., 2019; Schoonees et al., 2019; Morris et al., 2020; Oanh et al., 2020). They can reduce dike failure and increase design life where sediment accretion allows wetlands to respond to SLR (Jongman, 2018; Vuik et al., 2019; Zhu et al., 2020a). There is *high agreement* that a hybrid strategy combining hard and soft protect strategies is more effective and less costly under many circumstances; and there is *limited evidence* that technical limits will be encountered with such a strategy for low-lying C&S built on soft or permeable soil or with high exposure to monsoons and river discharges (Spalding et al., 2014; Sutton-Grier et al., 2015; Pontee et al., 2016; Morris et al., 2018; Reguero et al., 2018; Du et al., 2020; Morris et al., 2020; Seddon et al., 2020; Waryszak et al., 2021).

CCP2.3.3 Accommodation of the Built Environment

The most effective solution for limiting the growth of climate risks in C&S by the sea is to avoid new development in coastal locations prone to major flooding and/or SLR impacts (*very high confidence*) (Cross-Chapter Box SLR in Chapter 3; Oppenheimer et al., 2019; Doberstein et al., 2019). For existing C&S accommodation includes biophysical and institutional responses to reduce exposure and/or vulnerability of coastal residents, human activities, ecosystems and the built environment, enabling continued habitation of coastal C&S (Oppenheimer et al., 2019). Next to hard protection, accommodation is the most widely used adaptation strategy across all archetypes to date (*high confidence*) (Sayers et al., 2015; Olazabal et al., 2019; Le, 2020). Measures include elevation or flood-proofing of houses and other infrastructure (Garschagen, 2015; Aerts et al., 2018; Buchori et al., 2018; Jamero et al., 2018; Tamura et al., 2019), spatial planning (e.g. Duy et al. (2018)), amphibious building designs (Nilubon et al., 2016), increasing water storage and/or drainage capacity within C&S (Chan et al., 2018), early warning systems and disaster responses (Hissel et al., 2014), and slum upgrading (Jain et al., 2017; Olthuis et al., 2020).

Raising land, or individual buildings, can avert flooding and can be done artificially or as nature-based interventions through river diversion and control in estuarine and deltaic archetypes (Nittrouer et al., 2012; Auerbach et al., 2015; Day et al., 2016; Sánchez-Arcilla et al., 2016; Hiatt et al., 2019; Cornwall, 2021). Nature-based land elevation is limited by sediment supply and can address SLR rates of up to 10mm/yr (Kleinhans et al., 2010; Kirwan et al., 2016; IPCC, 2019). It also assumes that existing land-use patterns permit land raising (e.g., in rural or newly developed areas (Scussolini et al., 2017). Artificial land raising can achieve significant elevations and be implemented over a large spatial scale (Esteban et al., 2015; Esteban et al., 2019). Raising land can be cost beneficial for small areas, or where lower safety levels are satisfactory, but protection is usually more economical for larger areas, though both strategies are often combined (Lendering et al., 2020).

Accommodation measures can be very effective for current conditions and small changes in SLR (Laurice Jamero et al., 2017; Scussolini et al., 2017; Oppenheimer et al., 2019; Du et al., 2020; Haasnoot et al., 2021a), and buy time to prepare for more significant changes in sea level and other climate compounded coastal hazards. However, limits to this strategy occur comparatively soon in some locations, possibly requiring protection in the medium-term, and retreat in the long run and beyond 2100, particularly in scenarios of dramatic SLR (Oppenheimer et al., 2019). For the foreseeable future, accommodation can play an important role in combination with protective measures, to form hybrid interventions, with higher effectiveness than either approach in isolation (Du et al., 2020). Accommodation can play an increasingly important role where hard protection is neither technically nor financially viable; but detailed studies about expected trends of accommodation are lacking (Oppenheimer et al., 2019).

CCP2.3.4 Advance

An advance strategy creates new land by building seaward, which can reduce risk for the hinterland and the newly elevated land, either by land reclamation through land-filling or polderisation through planting of vegetation to support natural land accretion (Wang et al., 2014; Sengupta et al., 2018). Advance has occurred in all archetypes (*high confidence*); from open coasts (e.g., Singapore) and small atolls (e.g., Hulhumalé in the Maldives) (Hinkel et al., 2018; Brown et al., 2020) to cities on estuaries (e.g., Rotterdam) and deltas (e.g., Shanghai Sengupta et al. (2020)), and mountainous coasts (e.g., Hong Kong SAR, China). Earth observations show between 14,000-33,700 km^2 of land has been gained in coastal areas over the past 30 years, the dominant drivers being urban development and activities like fish farming (Donchyts et al., 2016; Zhang et al., 2017; Mentaschi et al., 2018). Advancing seawards through large floating structures may be a viable option in future (Wang et al., 2019; Setiadi et al., 2020; Wang and Wang, 2020), but is at an experimental stage, and, so far, only applied in calm water within a city as part of an accommodate strategy (Scussolini et al., 2017; Penning-Rowsell, 2020; Storbjörk and Hjerpe, 2021).

Advance is seen as an attractive option to adapt to SLR in growing cities that are already densely populated and have limited available land for safe development, with a moderate to high adaptive capacity. But advance can have significant negative impacts on coastal ecosystems and livelihoods, requires substantial financial and material resources and time to build, and may be subject to land subsidence (Jeuken et al., 2014; Garschagen et al., 2018; Brown et al., 2019; NYCEDC, 2019; Oppenheimer et al., 2019; Sengupta et al., 2020; Bendixen et al., 2021).

CCP2.3.5 Retreat

Retreat is a strategy to reduce exposure and eventually risks facing coastal C&S by moving people, assets and activities out of coastal hazard zones (Oppenheimer et al., 2019). This includes adaptive migration, involuntary displacement, and planned relocation of population and assets from the coast (Section 7.2.6; Cross-Chapter Box CB-MIGRATE in Chapter 7).

Planned relocation in coastal C&S with high hazard exposure and climate impacts is already occurring and has been increasing in frequency (*medium confidence*) (Hino et al., 2017; Mortreux et al., 2018), with some small islands purchasing land in other countries to facilitate movement (Klepp, 2018). In the Arctic, the pressure to relocate away from the coast is expected to rise given the interacting effects of permafrost thaw and coastal erosion. Native villages in Alaska are already relocating (Ristroph, 2017; Ristroph, 2019). Involuntary resettlement may be a secondary effect of large-scale hard coastal protection projects, or inner-city river and canal regulation. In Jakarta, for example, a new giant seawall project involves resettling coastal households along large parts of the coastline (Garschagen et al., 2018).

Increased migration is to be expected across different climate scenarios, but there is *limited evidence* and *medium agreement* about the scale of climate-induced migration at the coast (Oppenheimer et al., 2019) (Chapter 16, RKR on peace). Planned relocation is expected to rise in C&S in response to SLR and other coastal hazards (*high agreement, medium evidence*) (Siders et al., 2019). Relocation has predominantly been reactive to date, but increased attention is being given to pre-emptive resettlement and the potential pathways and necessary governance, finance and institutional arrangements to support this strategy (Ramm et al., 2018; Lawrence et al., 2020; Haasnoot et al., 2021a). There is *limited evidence* about the costs of planned relocation and retreat more generally (Oppenheimer et al., 2019).

Retreat can effectively reduce the exposure of urban residents to coastal hazards and provide opportunity for re-establishment of ecosystems services (*very high confidence*) (Song et al., 2018; Carey, 2020; Hindsley and Yoskowitz, 2020; Lincke et al., 2020; Lincke and Hinkel, 2021). But there is *high confidence* that it can sever cultural ties to the coast (Reimann et al., 2018) and can lead to negative and inequitable socio-economic effects for resettled communities if not planned and implemented in ways that are inclusive, just and address cultural, place-attachment and livelihood considerations (Ajibade, 2019; Adger et al., 2020; Carey, 2020; Jain et al., 2021; Johnson et al., 2021), and the rights and practices of Indigenous People (Nakashima et al., 2018; Ristroph, 2019; Mohamed Shaffril et al., 2020). If planned well ahead and aligned with social goals, pathways to managed retreat can achieve positive outcomes and provide opportunities for transformation of coastal C&S (Haasnoot et al., 2021a; Mach and Siders, 2021). There is *medium confidence* that the availability of suitable and affordable land, and appropriate financing, is a major bottleneck for planned relocation (Alexander et al., 2012; Ong et al., 2016; Hino et al., 2017; Fisher and Goodliffe, 2019; Hanna et al., 2019; Buser, 2020; Doberstein et al., 2020), particularly in very dense mega-urban areas (Ajibade, 2019) and crowded small islands (Neise and Revilla Diez, 2019; Weber et al., 2019; Kool et al., 2020; Lincke et al., 2020)

CCP2.3.6 Adaptation Pathways

No single adaptation intervention comprehensively addresses coastal risks and enables CRD. An adaptation pathways approach can facilitate long-term thinking, foresee maladaptive consequences and lock-ins, and address dynamic risk in the face of relentless and potentially high SLR; and frame adaptation as a series of manageable steps over time (Cross-Chapter Box DEEP in Chapter 17; Figure CCP2.4; Haasnoot et al.

(2019)). A portfolio of hard, soft and nature-based interventions can be used to implement strategies to protect, accommodate, retreat, and advance, individually or in combination.

The strategy, and portfolio of interventions, can be adjusted in response to new information about SLR and other climate risks according to economic, environmental, social, institutional, technical or other objectives. In cases of rapid SLR, it may be necessary to implement a short-term protection strategy to buy time to implement more transformative and enduring strategies (*high confidence*) (Du et al., 2020; Lawrence et al., 2020; Morris et al., 2020; Haasnoot et al., 2021a). There is *high agreement* that combining and sequencing adaptation interventions can reduce risk over time (Du et al., 2020; Morris et al., 2020). Phasing interventions can help to spread costs and minimise regret (de Ruig et al., 2019), provided that options are kept open to adjust to changing conditions (Buurman and Babovic, 2016; Haasnoot et al., 2019; Hall et al., 2019).

Many megacities plan to continue a protection strategy (Table SMCCP2.1). This becomes increasingly costly, institutionally challenging, and requires space possibly facilitated through local relocation. There is *high agreement* that many C&S are locked-in to a self-reinforcing pathway: coastal defences have a long lifetime and attract people and assets that require further protection (Gralepois et al., 2016; Bubeck et al., 2017; Welch et al., 2017; Di Baldassarre et al., 2018; Jongman, 2018). Transitioning to alternative pathways may involve major transfer and sunk costs (e.g., Gralepois et al. (2016)), but these may prove to be less costly in the long-term. Because of considerable inertia in the built form of cities, such transitions are more likely to be successful and aligned with societal goals if embedded early into C&S planning and development processes that enable transformational change and CRD (Sections 6.4.8; 11.7; 13.11; Box 18.1; Ürge-Vorsatz et al., 2018; Siders 2019b).

In islands, hybrid options of nature-based (where space and environmental conditions allow) and protect measures (on wealthy, already densely populated islands) could reduce risk for low SLR in the next few decades (Section 15.5). Where feasible, retreat is a compelling option to reduce risk (Figure CCP2.4). With higher rates and levels of SLR in the medium- to long-term, financial, governance and material barriers may differentiate resource-rich islands and more rural islands, leading to a dichotomy between which islands retreat or can rely on protection for a period of time.

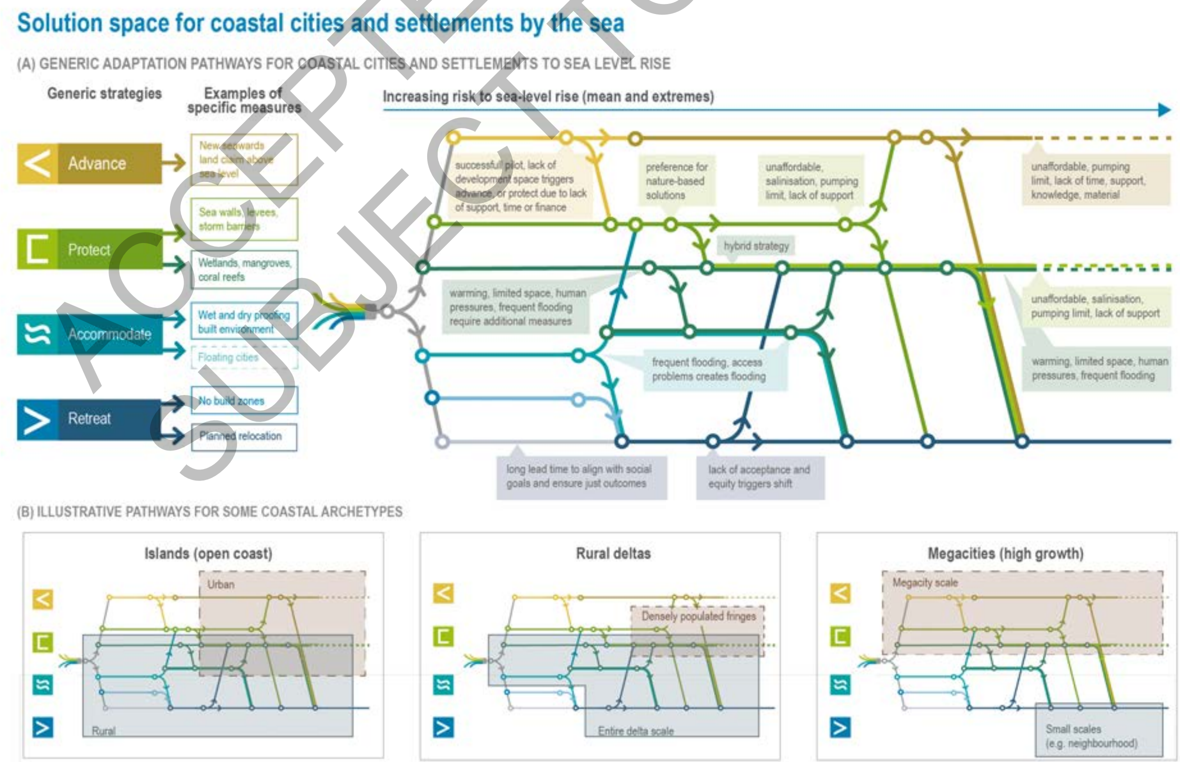


Figure CCP2.4: Generic adaptation pathways for coastal C&S (a) and the typical solution space with illustrative pathways for three coastal archetypes (b). As risk increases under rising sea levels, solutions need to be combined or sequenced in order contain risk. Pathways involve different trade-offs. Based on Table SMCCP2.1 - 2.3; Chapters 11 and 13, Magnan and Duvat (2020); Lawrence et al. (2020); Haasnoot et al. (2019). Depending on local conditions, archetype and risk tolerance, alternative pathways are needed and possible to contain risk. Dashed lines indicate uncertainty in pathway (a). Dashed and plain borders are used for illustrating various local situations within each archetype (b).

CCP2.4 Enabling Conditions and Lessons Learned

Here we distil enabling conditions and lessons learned from C&S archetypes adapting to coastal risk (Table SMCCP2.1; Table SMCCP2.2; Sections 6.4; 9.9.4; 10.5; 10.6; 11.7; 11.8; 12.5.5; 13.6.2; 14.7.2; 15.6).

CCP2.4.1 Enabling Behavioural Change

Changing behaviours and practices are a critical enabler of adaptation in coastal C&S. Behavioural enablers include using economic, informational, socio-cultural, and psychological incentives to motivate adaptation actions (van Valkengoed and Steg, 2019; Gibbs, 2020): e.g., leveraging Indigenous Knowledge and Local Knowledge (IKLK) and religious beliefs to incentivise adaptation (Hiwasaki et al., 2014; Ford et al., 2015); implementing subsidies/bans to incentivise sustainable aquaculture (Condie et al., 2014; Krause et al., 2020); providing localized flood warnings and forecasts to inform individual risk perceptions and risk management (Bruine de Bruin et al., 2014; Gibbs, 2020), or incentivise risk insurance (Bradt, 2019).

There is *high evidence* with *medium agreement* that public attitudes and perceptions of climate risks significantly influence individual adaptation behaviour across all coastal archetypes (Bradt, 2019; Buchanan et al., 2019; Javeline et al., 2019). Information on climate risks and impacts (e.g., flood warnings, SLR projections) strongly shapes public perceptions of climate risks. It is most effective at incentivising and enabling adaptation behaviour if provided at meaningful spatial and temporal scales, with guidance about how to interpret the information (*medium evidence, high agreement*) (Gibbs (2020); Cools et al. (2016)). Further, there is *medium evidence, high agreement* that integrating climate information with existing knowledge systems, such as local norms and beliefs and IKLK, is critical to improve public acceptability and develop context-specific solutions (Ford et al., 2015).

A second key enabler of coastal adaptation behaviour is self-efficacy or belief in one's capacity to undertake adaptation. There is *medium evidence, high agreement* that high risk perception is in itself insufficient to motivate people to undertake adaptation (Fox-Rogers et al., 2016; Roder et al., 2019; Gibbs, 2020) and needs to be supplemented with supportive policy and financial provisions to enable adaptation Fox-Rogers et al. (2016).

Third, there is *medium evidence* on how trust in state-led, planned adaptation measures can hinder or enable individual adaptation (van Valkengoed and Steg, 2019; Schneider et al., 2020). As an enabler, trust in early warnings can mitigate flood risk by incentivising evacuation (Binh et al., 2020) and high trust can help overcome uncertainty attached to projected climate impacts and/or adaptation decisions (Frederiksen, 2014). As a barrier, low trust can disincentivise adaptation, e.g., willingness to pay for flood insurance (Roder et al., 2019) or public support for managed retreat (Hanna et al., 2020). Paradoxically, high trust in existing adaptation measures can reduce people's perceived need for ongoing adaptation (e.g., levees potentially reducing individual flood-proofing actions). Adaptation decisions also manifest 'single-action bias' with modest-cost adaptation actions in the present disincentivising further adaptation (Buchanan et al., 2019).

Several tools to incentivise adaptation behaviour are being tested around the world – e.g., nudges and boosts[2] are being experimented with to shape individual risk beliefs and demand for flood insurance (Bradt, 2019); ordinances are being used to ban, authorise or limit certain activities (Herrick, 2018); subsidies and financial support being used to incentivise adaptation such as subsidised beach nourishment (McNamara et al., 2015); and zoning restrictions and building codes restrict or guide climate-resilient infrastructural development Schneider et al. (2020). Overall, the literature affirms that behavioural interventions are more readily taken up if they are: aligned with cultural practices, norms, and beliefs; on temporal scales within peoples' planning horizons; and build upon relationships of trust and legitimacy (Donner and Webber, 2014; Herrick, 2018; Schneider et al., 2020).

CCP2.4.2 Finance

Lack of financial resources is a key constraint affecting all coastal archetypes (*high confidence*) (Table SMCCP2.2). Adaptation to coastal hazards is costly – the global costs of protecting coastal areas with levees (annual investment and maintenance costs) are estimated at US$12–71 billion in 2100 with SLR up to 1.2m (Hinkel et al., 2014). Broadly speaking, it is cost-effective to contain coastal hazard risk in the short- to medium-term in densely populated wealthy localities by using protective works but such measures are unaffordable in dispersed poorer coastal C&S (Lincke and Hinkel, 2018).

Archetypes with high adaptive capacity may currently have financial resources to meet adaptation needs, but such funding may be unsustainable in the long-term. In Catalonia, while public funds are currently used to finance beach nourishment, these costs will increase with SLR and it is unclear if public finance will remain a feasible source (Hinkel et al., 2018). Even in relatively richer municipalities, financing adaptation is constrained by other urban priorities (Bisaro and Hinkel, 2018). In Europe, shifting responsibilities from national governments to transnational and local actors has resulted in reduced national budgets for coastal adaptation investment and increased pressure on local authorities to raise public funds for adaptation without alienating electoral bases (Bisaro and Hinkel, 2018).

Locations in the Global South have limited public budgets allocated to coastal adaptation and may rely on international donor aid (Donner et al., 2016; Araos et al., 2017). Such aid is often inconsistent and short-term, which limits long-term maintenance of knowledge, equipment and infrastructure needed to sustain adaptation measures beyond initial funding periods (Weiler et al., 2018; Thomas et al., 2020), with resultant negative consequences in places as different as Kiribati (Donner and Webber, 2014) and Bangladesh (Hinkel et al., 2018). Donor-funded adaptation programs aimed at promoting behavioural change, e.g., through coastal planning or new decision-making systems, require enduring training and institutional capacity, which is difficult to upkeep after aid is depleted. Donor funding is often project-based and there are few avenues available to fund additional permanent and long-term staff needed to bolster climate change institutions. Without funding to support additional staff, existing institutions often lack the human capacity and resources needed for coastal adaptation (Ziervogel and Parnell, 2014).

C&S in the Global South also face financial challenges in addressing loss and damage due to climate-induced slow-onset and extreme events. Financial support to address both quantifiable damages and non-economic losses through measures such as climate resilient reconstruction after extreme weather events, and national and local level emergency contingency funds, is lacking and has been an issue of contention in international policy arenas (Bahinipati et al., 2017; Wewerinke-Singh and Salili, 2020; Martyr-Koller et al., 2021).

While coastal adaptation has largely been viewed as the responsibility of governments, private finance is increasingly recognized as necessary to help close the coastal adaptation funding gap (Ware and Banhalmi-Zakar, 2020). Financial arrangements for coastal adaptation measures that align public actor and private investor interests are suitable for a range of budgets, from US$10,000-100 million (Bisaro and Hinkel, 2018). Private equity instruments that involve real estate development companies have already been successfully implemented and are most effective in urban areas with high-value real estate development (Chiang and Ling, 2017). Public-private partnership equity instruments that engage construction and real estate developers have been successful for small- to medium-scale infrastructural projects. While public-private partnership bonds and public bonds have potential to align public actors and private investors, such instruments require de-risking of coastal adaptation through enabling economic policy instruments, such as concessional loans (Bisaro and Hinkel, 2018).

Explicitly identifying the benefits, or goods and services, that are provided by coastal adaptation is critical to supplement limited government funds and engage a broader set of financial tools and actors (Woodruff et al., 2020). Matching goods and services provided by particular adaptation strategies to specific beneficiaries helps identify the range of fair and equitable financial tools. In the Netherlands, public funding through state, regional and local entities have independent tax revenue systems to provide the funding needed to maintain flooding infrastructure (Hinkel et al., 2018).

Given the high costs of coastal adaptation, benefit to cost ratios (BCR) are often used to determine the value of investing in adaptation. BCR are high for urbanized coastal areas with high concentrations of assets (13% of the world's coastline), covering 90% of global coastal floodplain population and 96% of assets in the global coastal floodplain (Lincke and Hinkel, 2018). A global assessment shows BCR for investing in flood protection up to ~120 (Tiggeloven et al., 2020). For Europe, at least 83% of flood damages could be avoided by elevating dikes along ~23-32% of Europe's coastline and BCR vary from 8.3 to 14.9, with higher ratios for higher concentration pathways (Section 13.2) (Vousdoukas et al., 2020a). Globally 40% of damages can be reduced with levees of 1m and costs lower than avoided damage (Tamura et al., 2019). For a mix of expensive storm surge barriers, nature-based solutions and flood proofing measures for New York City, Aerts et al. (2014) found BCRs <1 for the current situation, but >2 for a SLR scenario of +1m.

However, BCR values may be low and adaptation investment may not be financially viable for small coastal settlements, less densely populated poorer coasts, or isolated communities *(medium confidence).* Considering BCR of protection and coastal migration across a range of SLR and SSP scenarios for the 21st century, a higher BCR was found for protection of only 3% of the global coastline protecting 78% of the coastal population and 92% of global coastal floodplain assets, while for the remaining coasts, coastal migration was estimated to be optimal in terms of economic costs (Lincke and Hinkel, 2021). Considering coastal migration as part of the solution space could lower global costs in investment and maintenance for SLR protection by a factor of 2-4 in the 21st century but would result in large land losses and high levels of migration for South and South-east Asia in particular and, in relative terms, small island nations would suffer most. The need to consider place attachment, community relationships, livelihoods and the spiritual and cultural significance of settlements limit the application of BCR as a tool for coastal adaptation decisions in these contexts (Thomas and Benjamin, 2020). Moreover, there is limited knowledge on trade-offs, including BCR, of alternative adaptation options and pathways at global to regional scale, in particular over the long-term (beyond 2100).

Even where BCR is high, finance may be inaccessible as it is challenging to convert the long-term benefits of adaptation into the revenue streams that may be needed to initially finance adaptation investments (Hinkel et al., 2018). For example, in Ho Chi Minh City, Vietnam, despite high BCR, high costs of flood protection (US$1.4-2.6 billion) have prevented such adaptation measures from being implemented (Hinkel et al., 2018; Cao et al., 2021). Moreover, drawing from places as distinct as small communities in Fiji (Neef et al., 2018) and Belize (Karlsson and Hovelsrud, 2015), and megacities like New York City and Shanghai (Oppenheimer et al., 2019), BCR provides only a limited view and consideration of feasibility, effectiveness, efficiency, equity, culture, politics and power, and attachment to place, is more likely to foster CRD (*high confidence*).

CCP2.4.3 Governance

An array of climate and non-climate perils (Le Cozannet et al., 2017), present coastal communities and their governing authorities with immense governance and institutional challenges that will get progressively more difficult as sea level rises (*high confidence*) (Wallace, 2017; Leal Filho et al., 2018; Oppenheimer et al., 2019). Yet a study of public provisions for coastal adaptation in 136 of the largest coastal port-urban agglomerations across 68 countries found no policy implementation in 50% of the cases; in 85% of cases, adaptation actions are not framed by current impacts or future risks; and formal efforts are recent and concentrated in more developed settings (Olazabal et al., 2019; Olazabal and Ruiz De Gopegui, 2021) - underscoring a persistent coastal adaptation gap. Translating these challenges into enabling governance conditions is difficult but instructive lessons are being learned, and summarized (from Table SMCCP2.4) for archetypal C&S in Tables CCP2.1, 2.2.

We start with a synopsis of governance settings within which coastal adaptation and CRD choices are made, and spotlight factors hindering and enabling translation of adaptation into practice. Then, building upon and extending the SROCC analysis of enablers and lessons learned in responding to SLR (Oppenheimer et al., 2019), we assess key governance challenges, related enablers and lessons learned (Tables CCP2.1, CCP2.2).

Governance arrangements and practices are embedded in the socio-political and institutional fabric of coastal C&S. Consequently, barriers and enablers for adapting to climate change at the coast, and charting pathways for CRD, reflect more general constraints and opportunities (*high confidence*) (Meerow, 2017; Rocle and Salles, 2018; Rosendo et al., 2018; Di Giulio et al., 2019; Hölscher et al., 2019; Van Assche et al., 2020; Williams et al., 2020). Local level action is often constrained; 231 cities in the USA report weak leadership, lack of funding and staffing, and low political will (Fu, 2020). A meta-analysis of coastal municipal planning documents in Australia shows few localities have moved beyond risk assessment (Bradley et al., 2015). Coastal C&S tend to prefer strategies that protect and accommodate existing coastline assets, i.e., a 'fix and forget' approach (Gibbs, 2015), rather than enduring proactive adaptation (Cooper and Pile, 2014).

Many C&S, especially in the Global South, already face high exposure to coastal risks, and development constraints associated with poverty and socioeconomic inequality, lack of transparent resource allocation mechanisms, and low political will (*high confidence*) (Di Giulio et al., 2019; Nagy et al., 2019; Pasquini, 2020; Lehmann et al., 2021). Research from across South America notes inadequate regulatory frameworks, missing data and information, widespread coastal ecosystem degradation, and complex interactions between natural disasters and civil conflict (Villamizar et al., 2017; Nagy et al., 2019). Coastal climate risks in the Global South are often compounded by ongoing land-use management conflicts and other pressures including informal land uses, unregulated and/or inadequate infrastructure/building development, public health priorities such as combating Dengue Fever, inadequate income diversification, low education levels, and political marginalization of communities historically not represented in the urban development process (Barbi and Ferreira, 2014; Salik et al., 2015; Cabral et al., 2017; Goh, 2019). There are also entrenched socio-economic inequalities leading to the maldistribution of adaptation actions and benefits in the Global North (Gould and Lewis, 2018; Keenan et al., 2018; Ranganathan and Bratman, 2019; Yumagulova, 2020; Long et al., 2021).

To address the myriad governance challenges attributed to low awareness, low skills, scalar mismatches, and high socioeconomic inequality and coastal vulnerability, post-AR5 research highlights enablers of more innovative approaches to bridge capacity, policy, and financial deficits (Reiblich et al., 2019) and facilitate more proactive implementation of coastal adaptation actions (Table SMCCP2.2; Fu, 2020). A survey of NGOs, state and local government across Alaska, Florida, and Maryland in the USA found that perceived risk, uncertainty, and trust in support for climate adaptation varied across two stages of adaptation – support for the development of plans and willingness to allocate human and financial resources to implement plans (Kettle and Dow, 2016). To bridge this gap, Cinner et al. (2018) suggest the need to build capacity across five domains: the assets that people can draw upon in times of need; the flexibility to change strategies and interventions; the ability to organize and act collectively; learning to recognize and respond to change (especially as important thresholds are approached); and the agency to determine whether to change or not, and then take prudent action).

Effective and accountable local leadership can help to mobilize capacities, resources, and climate awareness within coastal C&S. Strong leadership is associated with agenda-setting authorities and the ability to navigate complex institutional interests towards more strategic planning efforts (*high confidence*) (Ferguson et al., 2013; Anguelovski et al., 2014; Chu et al., 2017; Valdivieso and Andersson, 2018; Fink, 2019; Ndebele-Murisa et al., 2020). Policy leadership can positively influence the motivation and initiative of municipal officers (Lassa and Nugraha, 2014; Wijaya et al., 2020); whilst local leadership is needed integrate coastal management, disaster management and climate adaptation mandates (Rosendo et al., 2018).

Inclusive decision-making arrangements can enable participation, local ownership, and further equity in crafting coastal adaptation plans and policies (Chu et al., 2016). Inclusion of diverse stakeholders can help improve awareness of adaptation needs; help to bridge existing social inequalities in decision-making about adaption needs, options and outcomes; close the gap between formal and informal institutions, and engage Indigenous forms of decision-making, which often associate climate risks with livelihood, housing, and employment stressors (Ziervogel et al., 2016; Fayombo, 2020). For example, research from Pacific Island States (Nunn et al., 2017) and coastal Arctic zones (Romero Manrique et al., 2018) highlight the need to engage with Indigenous environmental knowledge. Case studies from Indonesia, Philippines, and Timor-Leste show that IKLK and customary laws can support environmental awareness, strengthen social cohesion, and help communities to better respond to climate impacts (Hiwasaki et al., 2015). Research from coastal Cambodia shows that inclusive governance arrangements can target empowerment of the most vulnerable groups to facilitate better adaptation behavior and mainstream adaption knowledge through both formal and informal education at the community level (Ung et al., 2016).

The law is key to governing climate risks in C&S, including regulating exposure to coastal hazards; facilitating accountable decision-making, funding arrangements, liabilities, and resolving disputes; and securing human rights (*high confidence*) (Setzer and Vanhala, 2019; Averill, 2020). But it has limits and can be an adaptation enabler and barrier (Green et al., 2015; Cosens et al., 2017; Craig et al., 2017; DeCaro et al., 2017). Contemporary legal practice has not enabled effective adaptation in part because SLR affects compensable property rights that are secured by the law and which generally trump concerns about public safety, resilience and sustainability (Reiblich et al., 2019). Private property rights can be used as both a sword and a shield to privilege dominant interests, by undermining land use policies, plans and implementation efforts intended to promote integrated coastal management and risk reduction (O'Donnell et al., 2019; Reiblich et al., 2019). Climate change litigation has proliferated over the last decade (Setzer and Vanhala, 2019), addressing, among other things, failures to prepare for or adapt to climate change, and to secure human rights (Peel and Osofsky, 2018). Reflexive and adaptive law that accounts for the distinctive features of coastal hazard risk, and associated governance imperatives, builds coastal C&S adaptive capacity and resilience (*high confidence*) (Garmestani and Benson, 2013; Cosens et al., 2017; DeCaro et al., 2017). Procedural justice, due process, and use of substantive standards instead of rules, provide legal stability and enable adaptation (Craig et al., 2017). Coastal adaptation efforts are ultimately implemented through C&S actions that are enabled or constrained by prevailing legislative, executive and judicial provisions and practices, which differ significantly across jurisdictions (He, 2018). In practice, the 'coastal lawscape' is made up of interconnected cultural-normative, political and legal systems that need to be understood holistically to enable coastal adaptation in C&S (O'Donnell, 2021).

Tables CCP2.1 and CCP2.2 summarise key insights about key governance challenges facing archetypal coastal C&S around the world, and associated critical enablers and lessons learned to address climate change-compounded coastal hazard risk (based on synthesis of Table SMCCP2.3).

Table CCP2.1: Governance challenges and critical enablers for addressing coastal hazard risk in C&S

Key governance challenges	Critical enablers for C&S to address coastal hazard risk
Complexity: Climate change compounds non-climatic hazard risks facing coastal C&S in interconnected, dynamic and emergent ways for which there are no simple solutions.	Draw on **multiple knowledge systems** to co-design and co-produce more acceptable, effective and enduring responses.
	Build **governance capacity** to tackle complex problems.
Time horizon and uncertainty: The future is uncertain, but climate change will continue for generations and cannot be addressed by short-term (e.g., 1-10 years) responses alone.	Adopt a **long-term view** but take action now. **Keep options open** to adjust responses as climate risk escalates and circumstances change
	Avoid new development commitments in exposed locations. Enable managed retreat in most at-risk locations by **anticipatory actions**, e.g., secure funds, legal provisions for buy-outs, resettlement, etc.
Cross-scale and cross-domain coordination: Decisions bound by jurisdictional and sectoral boundaries fail to address linkages within and between coastal ecosystems and C&S facing interconnected climate change compounded impacts and risk.	Develop networks and linkages within and between different governance scales and levels, and across policy domains and sectors, to improve **coordination**, build trust and legitimise decisions.
	Build **shared understanding** and enable locally appropriate responses through experimentation, innovation and social learning.
Equity and social vulnerability: Climate change compounds everyday inequity and vulnerability in coastal C&S, making it difficult to disentangle and address social drivers and root causes of risk.	Recognise political realities and **prioritise vulnerability**, justice and equity concerns to enable just, impactful and enduring outcomes.
	Strengthen **community capabilities** to respond to coastal hazard risk, using external assistance and government support if necessary.
Social conflict: Coastal C&S will be the focal point of contending views about appropriate climate responses; and face the challenge of avoiding destructive conflict and realising its productive potential.	Design and facilitate **tailor-made participation processes**, involving stakeholders early and consistently from negotiating responses to implementation.
	Create **safe arenas of engagement** for inclusive, informed and meaningful deliberation and collaborative problem-solving.

Table CCP2.2: Lessons learned from efforts to address coastal hazard risk

Lessons to address governance challenges and unlock enablers	**Archetypal C&S initiatives, constraints aside**
Complexity: Multiple knowledge systems – Reveal dynamic complexity drawing on multiple sources of locally relevant evidence – Use and integrate local, Indigenous and scientific knowledge – Include marginalised voices and knowledges of vulnerable groups, women, young people, etc. – Build shared understanding through storytelling – Bridge gaps between science, policy and practice by experimenting with novel approaches and working across organisational, sectoral and institutional boundaries	**Seychelles (0.1mill; open coast):** Science-policy-local knowledge partnerships to co-produce usable information for decision-making. **Dhaka, Bangladesh (21mill; delta):** Climate change is national priority. Partnering with Netherlands to develop long-term data plans. **Jakarta, Indonesia (10.8mill; delta):** Community-based efforts to foster mutual assistance and self-organisation. **Utqiagvik (formerly Barrow) Alaska, USA (0.04 mill; Arctic, open coast):** Using local knowledge and historical precedent of transformative change to integrate local and scientific knowledge.
Complexity: Governance capacity – Joined-up visionary leadership is key, e.g., cabinet- and C&S-level commitments to long-term implementation – Translate political will into substantial dedicated budgets to build government capacity to tackle complex problems – Use flexible approaches to build resilience, e.g., independent agency alongside traditional administrative bodies – Counter deadlocks due to short-term priorities and vested interests with long-term perspective, considering plausible scenarios and incentivising novel solutions – Translate national requirements into local action with enabling provisions for tailored local policy and practice – Tackle emergent problems by setting up enduring monitoring and lesson-learning processes – Governance arrangements reconcile competing interests in inclusive, timely and legitimate manner – Make visible and reflect on underlying reasons for policy actions / inaction, including values, attitudes and taken for granted habits influencing problem-solving capability	**Singapore (5.6mill; open coast):** Integrated approach across Ministries committing to long-term adaptation (and mitigation goals) by 2030. **Rotterdam, Netherlands (0.65mill; delta):** Delta Programme, supported by law, administrative arrangements, and €1bill pa budget to 2029. **Florianopolis, Santa Catarina island, Brazil (1.2mill; mixed):** Building knowledge hub via public-private-civil society partnerships. **Nassau, Bahamas (0.275mill; open coast, small island):** Identifying responsibilities, accessing funding, and preparing adaptation plans drawing on evidence-based studies. **Shanghai (27mill; estuary), China:** Contain risk by combining long-term planning, political will, and national and municipal provisions, and technical capability. **Can Tho City, Vietnam (0.4 mill; delta):** Engage international donors and research community.
Time horizon and uncertainty: Long-term view – Establish national policies and guidance with long-term view (e.g., 100 years) that enables action now – Develop shared medium- (10-50 years) to long-term vision (100+ years) – Use adaptation pathways approach to make short-term decisions consistent with long-term goals – Meaningfully involve stakeholders, e.g., involve representatives in decision-making – Address power imbalances and human development needs, e.g., in goal-setting and process design – Reconcile divergent perspectives through tailored responses	**Napier (65k), Hawkes Bay (178.6k; open coast), New Zealand:** National law compels local authorities to take 100-year perspective; 2100 Strategy accounts for dynamic complexity and uncertain future through adaptation pathways. **Shanghai, China (27mill; estuary):** Plans up to 2100, strong national and municipal focus on climate change, and access to technical expertise. **Dhaka, Bangladesh (21mill; delta):** Long term adaptation plans through to 2100.
Time horizon and uncertainty: Avoidance and anticipatory action – Avoid development in exposed localities using spatial plans – Use window of opportunity created by extreme events – Prepare pre-event plans and tailor risk reduction and resilience building post-disaster – Reveal political pressures and opposition that hamper efforts to address intolerable risk and unacceptable impacts	**Rotterdam, Netherlands (0.65mill; delta):** Delta Programme promotes 'living with water', allowing and managing urban flooding. **Napier (65k), Hawkes Bay, New Zealand (178.6k, open coast):** Regulatory provisions discourage new development in high-risk locations; strategy sequences adaptation interventions. **Florianopolis, Santa Catarina island, Brazil (1.2mill; mixed):** Research reveals unregulated ad hoc development in at-risk locations preventing effective adaptation.
Cross-scale and cross-domain coordination: Coordination – Collaborative projects involve state and non-state actors	**Seychelles (0.1mill; open coast, small island):** Cross-sectoral and institutional collaboration to improve use of limited financial resources; and

– Multi-lateral agreements, e.g., between neighbouring countries, coastal regions and C&S – Connect people, organizations and communities through boundary spanning organizations – Leadership by central actors with capable teams is key – Mobilise the capabilities of communities and non-state actors – Address policy inconsistencies and clarify roles and responsibilities – Secure national and regional resources to support local efforts – Use measures to promote interaction, deliberation and coordination to manage spill-over effects – Strengthen linkages between formal (e.g., regulatory) and informal (e.g., traditions and rituals) institutions, e.g., through information sharing – Use spatial coordination mechanisms, e.g., land-use planning, to translate national and regional provisions into local competencies	community-based and ecosystem-based adaptation to bridge adaptation and mitigation and improve coordination. **Florianopolis, Santa Catarina island, Brazil (1.2mill; mixed):** Effective local climate action hampered by governance constraints and weak federal leadership. **Cape Town, South Africa (4.6mill; mixed):** Multi-level climate governance advanced at local-provincial level, but political turf-battles hamper national-provincial-local progress.
Cross-scale and cross-domain coordination: Shared understanding – Prioritise social learning and shared understanding, e.g., accessible information to all, irrespective of education, language, etc. – Account for local history, culture and politics through engagement, experimentation and innovation – Generate socio-economic, livelihood and climate-development co-benefits – Leverage national and trans-national community and local authority networks	**Cape Town, South Africa (4.6mill; mixed):** Capable local leaders collaborate with researchers in municipality-initiated community-based adaptation. Translating plans into action challenging given 'everyday' vulnerability exacerbated by climate change impacts. **New York City, USA (23.5mill; mixed):** State and city government work with communities to build adaptive capacity and resilience, drawing on technical capabilities but many challenges.
Equity and social vulnerability: Address vulnerability – Expose drivers and root causes of injustice, structural inequity and vulnerability – Link human development concerns, risk reduction, resilience and adaptation – Raise awareness and public support for actions that are just and equitable – Understand discriminatory drivers (e.g., on racial grounds) of coastal land-use patterns and risk – Address barriers facing marginalised groups – Use inclusive planning, decision-making and implementation processes that give voice to vulnerable people	**Cape Town, South Africa (4.6mill; mixed):** Adaptation framed by apartheid legacy; focus on reducing vulnerability, public safety and securing critical infrastructure and community assets. **Maputo-Matola, Mozambique (3mill; mixed):** Livelihood opportunities compromised by ecological degradation compelling community DIY coping in face of severe poverty and vulnerability, and weak governance and institutional capacity, and reliance on donors. **New York City, USA (23.5mill; estuary):** Hurricane Sandy (2012) focused attention on climate risk and plight of exposed and vulnerable people, and sparked adaptation action.
Equity and social vulnerability: Community capabilities – Raise vulnerability and risk awareness and understanding, build community capability and leverage external support by working with professionals, academics, local NGOs, journalists and activists – Secure rights of vulnerable groups through court action where necessary – Integrate traditional community responses with local government efforts – Ensure gender equity, e.g., representation on planning and decision-making bodies	**Monkey River village, Belize (200 people; estuary):** Remote Indigenous community capacity to tackle erosion enabled by interventions by researchers, journalists and local NGOs to secure media and political attention after hurricane damage. **Accra, Ghana (2.5mill; delta):** Household adaptation mediated by local government flood mitigation efforts; need better early warning and maintain local stormwater to prevent flooding. **Lagos, Nigeria (14 mill; open coast):** Building adaptive capacity to overcome 'everyday' vulnerability and poverty severely challenging.
Social conflict: Tailor-made participation – Create opportunities for integrative and inclusive solutions – Use conflict resolution mechanisms	**Napier (65k), Hawkes Bay, New Zealand (178.6k people, open coast):** Collaboration between local authorities and Indigenous People (Māori), involving stakeholders, led to co-designed

– Appoint independent facilitators / mediators and involve officials as 'bureaucratic activists' to improve inclusivity and iterative and reflexive engagement – Align informal participatory processes with statutory processes and government practices – Sustain engagement by securing resources for local use, and aligning activities with political and bureaucratic cycles – Involve historically disadvantaged and socially vulnerable groups, e.g., accessible meeting locations / venues, local languages and culturally appropriate meeting protocols – Involve local leaders who will champion adaptation and help mainstream findings into C&S decision-making – Inclusive processes help address conflict and drivers of vulnerability, and promote just adaptation	long-term strategy with implementation commitment. **Manila, Philippines (14mill; open coast):** Metro-wide planning and infrastructure provisions that foster climate justice and resilience explored; with community-based actions.
Social conflict: Safe arenas of engagement – Use flexible and enabling processes based in local institutions that are robust and fair, supported by governing authorities – Attend to local social dynamics and reduce elite domination – Use local and Indigenous knowledge and science – Use institutional improvisation to address local concerns – Use trusted independent facilitators – Incentivise participation by disadvantaged groups – Focus on improving risk literacy, optimism and capacity for joint problem-solving – Use joint, collaborative activities to facilitate public dialogue, and secure institutional support for action – Enable ongoing deliberation and social learning – Make continual adjustments as circumstances change, e.g., build shared understanding about locally relevant thresholds beyond which alternative courses of action need to be actioned.	**Napier (65k), Hawkes Bay, New Zealand (178.6k people, open coast):** Active involvement of local communities, Indigenous People (Māori) and research community to co-produce fit-for-purpose long-term coastal hazard risk strategy. **Rotterdam, Netherlands (0.65mill; delta):** Delta Programme institutionalised multi-level adaptation governance with strong accountability mechanisms. **Greater London, UK (8.9mill; estuary):** Long-term provisions for at-risk Thames Estuary, including major protective works, embedded in Greater London Spatial Development Plan and London Climate Change Partnership championed by strategic leadership, and supported by the public and strong technical capability.

In sum, prospects for addressing climate risk in archetypal coastal C&S around the world depend on the extent to which societal choices, and associated governance processes and practices, address the drivers and root causes of exposure and social vulnerability (*very high confidence*). Coastal C&S are more able to address these challenges when authorities work with local communities, and vulnerable groups in particular, and with stakeholders from the local to national level and beyond, to chart adaptation pathways that enable sustained reduction in the exposure and vulnerability of those most at risk *(very high confidence)* (Cross-Chapter Box SLR in Chapter 3; Magnan et al., 2019; Oppenheimer et al., 2019). Unlocking potential enablers for locally appropriate and effective adaptation is difficult because many drivers and root causes of coastal risk are historically and institutionally embedded *(high confidence)* (Thomas et al., 2019). Charting credible, salient and legitimate adaptation pathways is consequently a struggle in reconciling divergent worldviews, values and interests (Sovacool, 2018; Mendenhall et al., 2020; Bowden et al., 2021a; Bowden et al., 2021b). Unlocking the productive potential of conflict is foundational for transitioning towards pathways that foster CRD *(high confidence)* (Abrahams and Carr, 2017; Harris et al., 2018; Sharifi, 2020). But this can be especially challenging for low-lying coastal C&S characterised by degraded coastal ecosystems susceptible to climate change impacts as well as pronounced inequity and governance constraints *(high confidence)* (Esteban et al., 2017; Jones et al., 2020).

CCP2.4.4 Enabling Climate Resilient Development for Cities and Settlements by the Sea

The above critical enablers, and lessons learned from around the world, establish a strong foundation for charting pathways for CRD in coastal C&S. These pathways will necessarily vary in different C&S, and synergies and commonalities within different coastal archetypes can be leveraged. Pivotal is recognition of the narrow window of time remaining to translate embryonic risk assessment and adaptation planning into concerted implementation efforts. C&S by the sea could be the centres of innovation that lead the way to advancing SDGs through to 2030, and CRD beyond this decade (see Section 2.1.1).

This CCP shows that a range of adaptation solutions; hard and soft protection, nature-based measures, accommodate, advance, retreat, and behavioural change will need to be implemented as an integrated and sequenced portfolio of responses if coastal C&S are to contain the adverse risks of climate change (*high confidence*). The effectiveness and feasibility of any intervention, at a given moment, to reduce a particular climate-compounded coastal hazard risk, or combination of risks, depend upon the settlement archetype; including its geomorphological, cultural, economic, technical, institutional, and political features, and historical development trajectory. Coastal C&S will benefit from developing flexible adaptation pathways - sequences of adaptation strategies and intervention options - to navigate a dynamic solution space that changes in response to climate and other drivers of change, and is also shaped by human development choices, and socio-economic, technological and institutional change.

There is no silver bullet or panacea. But developing locally appropriate, yet flexible, pathways for CRD will help coastal communities address escalating risks and uncertainty (Cross-Chapter Box DEEP in Chapter 17). Effective pathways are based on robust integrated information about dynamic coastal hazard risk and plausible interventions. However, their successful implementation requires multi-scale governance arrangements and practices able to bridge different administrative and sectoral capacities in the coastal zone; effective and accountable leadership; and inclusive decision-making arrangements to enable participation, manage conflicts and trade-offs; engender local ownership, and promote equity and justice in coastal adaptation plans and policies. Further, the feasibility of adaptation strategies and interventions, especially those entailing changing behaviours and practices, is increased by recognising and incorporating peoples' values and beliefs and Indigenous and Local knowledge systems, as well as the voices of women and vulnerable groups.

Coastal C&S are on the frontline of observed climate change impacts and future risk (*high confidence*). Difficult choices will be made as climate- and ocean-driven extremes become more frequent. In the next few decades, many coastal regions and C&S will have the opportunity to take actions to avoid and reduce risk, through incremental as well as more transformative interventions. Under higher levels of global warming, decisions will need to be made faster or respond to higher levels of SLR (*high confidence*) (Cross-Chapter Box SLR in Chapter 3). This is particularly challenging in coastal C&S characterised by inertia and path-dependency of development choices, with long lead times for adaptation planning and implementation, and the long design life and societal impact of many interventions. Given the risks assessed in coastal C&S, the scale of climate impacts globally will depend to a large extent on whether coastal settlements develop and implement pre-emptive and flexible adaptation pathways, and whether significant and timely reduction in greenhouse gas emissions is achieved in C&S and globally *(high confidence).*

[START FAQ CCP2.1 HERE]

FAQ CCP2.1: Why are coastal cities and settlements by the sea especially at risk in a changing climate, and which cities are most at risk?

Coastal cities and settlements (C&S) by the sea face much greater risk than comparable inland C&S because they concentrate a large portion of global population and economic activity whilst being exposed and vulnerable to a range of climate- and ocean-compounded hazard risk driven by climate change. Coastal C&S range from small settlements along waterways and estuaries, to small island states with maritime populations and/or beaches and atolls that are major tourist attractions, to large cities that are major transport and financial hubs in coastal deltas, and mega-cities and even mega-regions with several coastal mega-cities.

The concentration of people, economic activity and infrastructure dynamically interact with coast-specific hazards magnifying the exposure of these C&S to climate risks. While large inland cities and coastal settlements can be exposed to climate-driven hazards, such as urban heat islands and air pollution, the latter are also subject to distinctive ocean-driven hazards, such as rising sea levels, exposure to tropical cyclones and storm surges, flooding from extreme tides, and land subsidence from decreased sediment deposition along coastal deltas and estuaries. With climate change increasing the intensity and frequency of hazards under all future warming levels, the risks to lives, livelihoods and property are especially acute in C&S by the sea.

Coastal cities are diverse in shape, size, growth patterns and trajectories, and access to cultural, financial, and ecosystem resources and services. Along deltaic and estuarine archetypes, cities most vulnerable to a changing climate have relatively high levels of poverty and inequality, in terms access to resources and ecosystem services, and large populations and dense built environments translating into higher exposure to coastal climate risks.

These climate risks at the coast can also be magnified by compounding and cascading effects due to non-climate drivers directly affecting vulnerable peri- and ex-urban areas inland. These risks include disruption to transport supply chains and energy infrastructure from airports and power plants sited along coastal areas, as occurred in New York City, USA, during Hurricane Sandy in 2012. The impacts can be felt around the world through globalized economic and geopolitical linkages, e.g., through maritime trade and port linkages.

For open coasts, settlements on low-lying small island states and the Arctic are especially vulnerable to climate change, and sea level rise impacts in particular, well before 2100. While the economic risks may not compare to the scale of those faced in coastal megacities with high per capita GDP, the existential risks to some nations and an array of distinctive livelihoods, cultural heritage, and ways-of-life in these settlements are great, even with modest sea level rise.

[END FAQ CCP2.1 HERE]

[START FAQ CCP2.2 HERE]

FAQ CCP2.2: What actions can be taken by coastal cities and settlements to reduce climate change risk?

Sea level rise responds to climate change over long timeframes and will continue even after successful mitigation. However, rapid global mitigation of greenhouse gases significantly reduces risks to coastal C&S, and crucially buys time for adaptation.

Appropriate actions to reduce climate change risks on coastal C&S depend on the scale and speed of coastal change interacting with unfolding local circumstances – reflecting the hazards, exposure, vulnerability, and response to risks.

'Hard' protection, like dikes and seawalls, can reduce risks of flooding for several metres of sea-level rise in some coastal C&S. These are most cost-effective for densely populated cities and some islands but may be unaffordable for poorer regions. Although these measures reduce the likelihood of coastal flooding, residual risk remains, and hard protection typically has negative consequences for natural systems. In low-lying protected coastal zones, draining river and excess water will increasingly be hampered, requiring pumping eventually or transferring to alternative strategies.

Whereas structures can disrupt natural beach morphology processes, sediment-based protection replenishes beaches. These have lower impact on adjacent beaches and coastal ecology and lower costs for construction and maintenance compared to hard structures. Another form of 'soft' protection involves establishing, rehabilitating and preserving coastal ecosystems, like marshes, mangroves, seagrass, coral reefs and dunes, providing 'soft' protection against storm surges, reducing coastal erosion, and offering additional benefits including food, materials, and carbon sequestration. However, these are less effective where there is limited space in the coastal zone, limited sediment supply, and under higher rates of sea level rise.

Coastal settlements can 'avoid' new flood and erosion risk by preventing development in areas exposed to current and future coastal hazards. Where development already exists, settlements can 'accommodate' climate change impacts through, among other things, land use zoning, raising ground or buildings above storm surge levels, installing flood proofing measures within and outside properties, and early warning systems. Improving the capacity of urban drainage, incorporating nature-based solutions within urban areas, and managing land upstream of settlements to reduce runoff from the hinterland, reduces the risk of compound flood events. More radically, land can also be reclaimed from the sea, which offers opportunities for further development but has impacts on the natural system and wider implications for the trajectory of development.

Coastal risks and impacts such as floods, loss of fisheries or tourism, or salinization of groundwater, require people to change behaviour to adapt, such as diversifying livelihoods or moving away from low-lying areas. Currently most of these practices are reactive and help people adjust to/cope with current impacts. While a critical part of coastal adaptation, changing behaviour is most likely when enabled by supportive policies and financial structures, and alignment with socio-cultural values and worldviews.

Where risks are very high, or resources are insufficient to manage risks, submergence or erosion of coastal C&S will be inevitable, requiring 'retreat' from the coastline. This is the outlook for millions of people in coming decades, including those living in river deltas, Arctic communities, small islands, and low-lying small settlements in poor and wealthy nations. Whilst the impacts of retreat on communities can be devastating, the prospect of many C&S and even whole nations being permanently inundated in coming centuries underscores the imperative for urgent action.

Crucial to making choices about how to mitigate greenhouse gas emissions, and adapt to climate change in coastal C&S, is to establish institutions and governance practices supporting climate resilient development – a mix and sequence of mitigation and adaptation actions - that are fair, just, and inclusive as well as technically and economically effective across successive generations.

[END FAQ CCP2.2 HERE]

[START FAQ CCP2.3 HERE]

FAQ CCP2.3: Considering the wide-ranging and interconnected climate and development challenges coastal cities and settlements face, how can more climate resilient development pathways be enabled?

Coastal C&S are on the frontline of the climate change challenge. They are the interface of three interconnected realities. First, they are critical nodes of global trade, economic activity and coast-dependent livelihoods, all of which are highly and increasingly exposed to climate- and ocean-driven hazards (FAQ CCP2.1). Second, coastal C&S are also sites where some of the most pressing development challenges are at play (e.g., trade-offs between expanding critical built infrastructure while protecting coastal ecosystems, high economic growth coupled with high inequality in some coastal megacities). Third, coastal C&S are also centres of innovation and creativity, thus presenting a tremendous opportunity for climate action through a range of infrastructural, nature-based, institutional, and behavioural solutions (FAQ CCP2.2). Given these three realities of high climate change risks, rapid but contested and unequal development trajectories, and high potential for innovative climate action, C&S are key to charting pathways for Climate Resilient Development.

Three key levers can enable pathways that are climate-resilient and meet goals of inclusive, sustainable development. One is to enable climate resilient development is flexible, proactive, and transparent governance systems, built on a bedrock of accountable local leadership, evidence-based decision-making, even under uncertainty, and inclusive institutions that consider different stakeholder voices and knowledge systems. Another key enabler is acknowledging the socio-cultural and psychological barriers to climate action and incentivising people to change lifestyles and behaviours that are pro-climate and aligned with community-oriented values and norms. In practice, coastal C&S are experimenting with different strategies to change practices and behaviours, such as using subsidies and zoning policies, tax rebates and public awareness campaigns, to promote individual and collective action. Finally, enabling climate resilient development needs dedicated, short- and long-term financing to reorient current trajectories of unsustainable and unequal development towards climate mitigation and adaptation action that reduces current and predicted losses and damages, especially in highly vulnerable coasts, such as the small island states, the

Arctic and low-lying C&S. Currently, adaptation finance is concentrated in coastal megacities and tends to be deployed in risk-proofing high-value waterfront properties or key infrastructures. Addressing these finance imbalances (globally, regionally, and sub-nationally) remains a critical barrier to inclusive climate resilient coastal development.

Notwithstanding the many interconnected challenges faced, from more frequent and intense extreme events to the COVID-19 pandemic, many coastal C&S are experimenting with ways to pivot towards climate resilient development. Critical enablers have been identified and lesson learned which, if translated into practice, will enhance the prospects for advancing the SDGs and charting pathways for Climate Resilient Development that are appropriate to local contexts and foster human well-being and planetary health.

References

Abadie, L. M. et al., 2020: Comparing urban coastal flood risk in 136 cities under two alternative sea-level projections: RCP 8.5 and an expert opinion-based high-end scenario. *Ocean & Coastal Management*, **193**, 105249, doi:https://doi.org/10.1016/j.ocecoaman.2020.105249.

Abrahams, D. and E. R. Carr, 2017: Understanding the Connections Between Climate Change and Conflict: Contributions From Geography and Political Ecology. *Current Climate Change Reports*, **3** (4), 233-242, doi:10.1007/s40641-017-0080-z.

Achete, F., M. van der Wegen, J. A. Roelvink and B. Jaffe, 2017: How can climate change and engineered water conveyance affect sediment dynamics in the San Francisco Bay-Delta system? *Climatic Change*, **142** (3), 375-389, doi:10.1007/s10584-017-1954-8.

Adger, W. N. et al., 2020: Urbanization, Migration, and Adaptation to Climate Change. *One Earth*, **3** (4), 396-399, doi:https://doi.org/10.1016/j.oneear.2020.09.016.

Aerts, J. C. et al., 2018: Pathways to resilience: adapting to sea level rise in Los Angeles. *Annals of the New York Academy of Sciences*, **1427** (1), 1-90, doi:doi:10.1111/nyas.13917.

Aerts, J. C. J. H. et al., 2014: Evaluating Flood Resilience Strategies for Coastal Megacities. *Science*, **344** (6183), 473-475, doi:10.1126/science.1248222.

Ajibade, I., 2019: Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. *Climatic Change*, **157** (2), 299-317, doi:10.1007/s10584-019-02535-1.

Alexander, K. S., A. Ryan and T. G. Measham, 2012: Managed retreat of coastal communities: understanding responses to projected sea level rise. *Journal of Environmental Planning and Management*, **55** (4), 409-433, doi:10.1080/09640568.2011.604193.

Allison, E. H. and H. R. Bassett, 2015: Climate change in the oceans: Human impacts and responses. *Science*, **350** (6262), 778-782, doi:10.1126/science.aac8721.

Alves, B., D. B. Angnuureng, P. Morand and R. Almar, 2020: A review on coastal erosion and flooding risks and best management practices in West Africa: what has been done and should be done. *Journal of Coastal Conservation*, **24** (3), 38, doi:10.1007/s11852-020-00755-7.

Andrew, N. L. et al., 2019: Coastal proximity of populations in 22 Pacific Island Countries and Territories. *PLoS One*, **14** (9), e0223249, doi:10.1371/journal.pone.0223249.

Anguelovski, I., E. Chu and J. Carmin, 2014: Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South. *Global Environmental Change*, **27**, 156-167, doi:https://doi.org/10.1016/j.gloenvcha.2014.05.010.

Arabadzhyan, A. et al., 2020: Climate change, coastal tourism, and impact chains – a literature review. *Current Issues in Tourism*, 1-36, doi:10.1080/13683500.2020.1825351.

Araos, M. et al., 2016: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science & Policy*, **66**, 375-382, doi:10.1016/j.envsci.2016.06.009.

Araos, M. et al., 2017: Climate change adaptation planning for Global South megacities: the case of Dhaka. *Journal of Environmental Policy & Planning*, **19** (6), 682-696, doi:10.1080/1523908X.2016.1264873.

Arkema, K. K. et al., 2017: Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Annals of the New York Academy of Sciences*, **1399** (1), 5-26, doi:10.1111/nyas.13322.

Auerbach, L. W. et al., 2015: Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. *Nature Climate Change*, **5**, 153, doi:10.1038/nclimate2472
https://www.nature.com/articles/nclimate2472#supplementary-information.

Avelino, J. E. et al., 2018: Survey tool for rapid assessment of socio-economic vulnerability of fishing communities in Vietnam to climate change. *Geosciences*, **8** (12), 452, doi:https://doi.org/10.3390/geosciences8120452.

Averill, M., 2020: Climate Litigation: Ethical Implications and Societal Impacts. *Denver Law Review*, **85** (4), 899.

Bahinipati, C. S., U. Rajasekar, A. Acharya and M. Patel, 2017: Flood-induced Loss and Damage to Textile Industry in Surat City, India. *Environment and Urbanization ASIA*, **8** (2), 170-187, doi:10.1177/0975425317714903.

Bakkensen, L. A. and R. O. Mendelsohn, 2019: Global Tropical Cyclone Damages and Fatalities Under Climate Change: An Updated Assessment. In: Hurricane Risk [Collins, J. M. and K. Walsh (eds.)]. Springer International Publishing, Cham, 179-197.

Bangalore, M., A. Smith and T. Veldkamp, 2019: Exposure to Floods, Climate Change, and Poverty in Vietnam. *Economics of Disasters and Climate Change*, **3** (1), 79-99, doi:10.1007/s41885-018-0035-4.

Barbi, F. and L. d. C. Ferreira, 2014: Risks and political responses to climate change in Brazilian coastal cities. *Journal of Risk Research*, **17** (4), 485-503, doi:10.1080/13669877.2013.788548.

Barnett, J., 2017: The dilemmas of normalising losses from climate change: Towards hope for Pacific atoll countries. *Asia Pacific Viewpoint*, **58** (1), 3-13, doi:10.1111/apv.12153.

Barragán, J. M. and M. de Andrés, 2015: Analysis and trends of the world's coastal cities and agglomerations. *Ocean & Coastal Management*, **114**, 11-20, doi:10.1016/j.ocecoaman.2015.06.004.

Becker, A., A. K. Y. Ng, D. McEvoy and J. Mullett, 2018: Implications of climate change for shipping: Ports and supply chains. *WIREs Climate Change*, **9** (2), e508, doi:10.1002/wcc.508.

Bell, A. R. et al., 2021: Migration towards Bangladesh coastlines projected to increase with sea-level rise through 2100. *Environmental Research Letters*, **16** (2), 024045, doi:10.1088/1748-9326/abdc5b.
Bendixen, M. et al., 2021: Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward. *One Earth*, **4** (8), 1095-1111, doi:https://doi.org/10.1016/j.oneear.2021.07.008.
Bendixen, M. et al., 2019: Promises and perils of sand exploitation in Greenland. *Nature Sustainability*, **2** (2), 98-104, doi:10.1038/s41893-018-0218-6.
Bhattacharya, J., 1978: Deltas and estuaries. In: Sedimentology. Springer Berlin Heidelberg, Berlin, Heidelberg, 310-322.
Bindoff, N. et al., 2019: Changing ocean, marine ecosystems, and dependent communities. In: IPCC special report on the ocean and cryosphere in a changing climate.
Binh, P. T., X. Zhu, R. A. Groeneveld and E. C. van Ierland, 2020: Risk communication, women's participation and flood mitigation in Vietnam: An experimental study. *Land Use Policy*, **95**, 104436, doi:https://doi.org/10.1016/j.landusepol.2019.104436.
Bisaro, A. and J. Hinkel, 2018: Mobilizing private finance for coastal adaptation: A literature review. *WIREs Climate Change*, **9** (3), e514, doi:10.1002/wcc.514.
Blackburn, S., M. Pelling and C. Marques, 2019: Megacities and the Coast: Global Context and Scope for Transformation. In: Coasts and Estuaries. Elsevier, 661-669.
Boas, I. et al., 2019: Climate migration myths. *Nature Climate Change*, **9** (12), 901-903, doi:10.1038/s41558-019-0633-3.
Bohnet, I. C. and P. L. Pert, 2010: Patterns, drivers and impacts of urban growth—A study from Cairns, Queensland, Australia from 1952 to 2031. *Landscape and Urban Planning*, **97** (4), 239-248, doi:10.1016/j.landurbplan.2010.06.007.
Bowden, V., D. Nyberg and C. Wright, 2021a: Truth and power: deliberation and emotions in climate adaptation processes. *Environmental Politics*, **30** (5), 708-726, doi:10.1080/09644016.2020.1850972.
Bowden, V., D. Nyberg and C. Wright, 2021b: "We're Going Under": The Role of Local News Media in Dislocating Climate Change Adaptation. *Environmental Communication*, **15** (5), 625-640, doi:10.1080/17524032.2021.1877762.
Bradley, M., I. van Putten and M. Sheaves, 2015: The pace and progress of adaptation: Marine climate change preparedness in Australia's coastal communities. *Marine Policy*, **53**, 13-20, doi:https://doi.org/10.1016/j.marpol.2014.11.004.
Bradt, J., 2019: Comparing the effects of behaviorally informed interventions on flood insurance demand: an experimental analysis of 'boosts' and 'nudges'. *Behavioural Public Policy*, 1-31, doi:10.1017/bpp.2019.31.
Brodie, J. and R. G. Pearson, 2016: Ecosystem health of the Great Barrier Reef: Time for effective management action based on evidence. *Estuarine, Coastal and Shelf Science*, **183**, 438-451, doi:10.1016/j.ecss.2016.05.008.
Brown, S. et al., 2018: Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, **6** (3), 583-600, doi:10.1002/2017ef000738.
Brown, S. et al., 2020: Land raising as a solution to sea-level rise: An analysis of coastal flooding on an artificial island in the Maldives. *Journal of Flood Risk Management*, **13** (S1), e12567, doi:10.1111/jfr3.12567.
Brown, S. I., M. E. Dickson, P. S. Kench and R. J. Bergillos, 2019: Modelling gravel barrier response to storms and sudden relative sea-level change using XBeach-G. *Marine Geology*, **410**, 164-175, doi:10.1016/j.margeo.2019.01.009.
Bruine de Bruin, W., G. Wong-Parodi and M. G. Morgan, 2014: Public perceptions of local flood risk and the role of climate change. *Environment Systems and Decisions*, **34** (4), 591-599, doi:10.1007/s10669-014-9513-6.
Bubeck, P. et al., 2017: Explaining differences in flood management approaches in Europe and in the USA – a comparative analysis. *Journal of Flood Risk Management*, **10** (4), 436-445, doi:https://doi.org/10.1111/jfr3.12151.
Buchanan, M. K., M. Oppenheimer and A. Parris, 2019: Values, bias, and stressors affect intentions to adapt to coastal flood risk: a case study from New York City. *Weather, Climate, and Society*, **11** (4), 809-821, doi:10.1175/WCAS-D-18-0082.1.
Buchori, I. et al., 2018: Adaptation to coastal flooding and inundation: Mitigations and migration pattern in Semarang City, Indonesia. *Ocean & Coastal Management*, **163**, 445-455, doi:https://doi.org/10.1016/j.ocecoaman.2018.07.017.
Buddemeier, R. W. et al., 2008: Coastal typology: An integrative "neutral" technique for coastal zone characterization and analysis. *Estuarine, Coastal and Shelf Science*, **77** (2), 197-205, doi:10.1016/j.ecss.2007.09.021.
Buser, M., 2020: Coastal Adaptation Planning in Fairbourne, Wales: lessons for Climate Change Adaptation. *Planning Practice & Research*, **35** (2), 127-147, doi:10.1080/02697459.2019.1696145.
Buurman, J. and V. Babovic, 2016: Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society*, **35** (2), 137-150, doi:10.1016/j.polsoc.2016.05.002.
Cabral, P. et al., 2017: Assessing Mozambique's exposure to coastal climate hazards and erosion. *International Journal of Disaster Risk Reduction*, **23**, 45-52, doi:https://doi.org/10.1016/j.ijdrr.2017.04.002.
Camus, P. et al., 2019: Probabilistic assessment of port operation downtimes under climate change. *Coastal Engineering*, **147**, 12-24, doi:https://doi.org/10.1016/j.coastaleng.2019.01.007.

Cao, A. et al., 2021: Decoupled formal and informal flooding adaptation and conflicts in coastal cities: A case study of Ho Chi Minh City. *Ocean & Coastal Management*, **209**, 105654, doi:https://doi.org/10.1016/j.ocecoaman.2021.105654.
Carey, J., 2020: Core Concept: Managed retreat increasingly seen as necessary in response to climate change's fury. *Proceedings of the National Academy of Sciences*, **117** (24), 13182-13185, doi:10.1073/pnas.2008198117.
CCC, 2017: *Managing the coast in a changing climate*. Committee on Climate Change, London.
CEIC. 2021: Census and Economic Information Center. [Available at: https://www.ceicdata.com/en]
Chan, F. K. S. et al., 2018: Towards resilient flood risk management for Asian coastal cities: Lessons learned from Hong Kong and Singapore. *Journal of Cleaner Production*, **187**, 576-589, doi:https://doi.org/10.1016/j.jclepro.2018.03.217.
Chausson, A. et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, **26** (11), 6134-6155, doi:10.1111/gcb.15310.
Chiang, Y.-C. and T.-Y. Ling, 2017: Exploring Flood Resilience Thinking in the Retail Sector under Climate Change: A Case Study of an Estuarine Region of Taipei City. *Sustainability*, **9** (9), 1650.
Christodoulou, A., P. Christidis and H. Demirel, 2019: Sea-level rise in ports: a wider focus on impacts. *Maritime Economics & Logistics*, **21** (4), 482-496, doi:10.1057/s41278-018-0114-z.
Christopher Small and Joel E. Cohen, 2004: Continental Physiography, Climate, and the Global Distribution of Human Population. *Current Anthropology*, **45** (2), 269-277, doi:10.1086/382255.
Chu, E., I. Anguelovski and J. Carmin, 2016: Inclusive approaches to urban climate adaptation planning and implementation in the Global South. *Climate Policy*, **16** (3), 372-392, doi:10.1080/14693062.2015.1019822.
Chu, E., I. Anguelovski and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**, 378-387, doi:https://doi.org/10.1016/j.cities.2016.10.016.
Cinner, J. E. et al., 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, **8** (2), 117-123, doi:10.1038/s41558-017-0065-x.
Condie, H. M., A. Grant and T. L. Catchpole, 2014: Incentivising selective fishing under a policy to ban discards; lessons from European and global fisheries. *Marine Policy*, **45** (C), 287-292.
Cools, J., D. Innocenti and S. O'Brien, 2016: Lessons from flood early warning systems. *Environmental Science & Policy*, **58**, 117-122, doi:https://doi.org/10.1016/j.envsci.2016.01.006.
Cooper, J. A. G., M. C. O'Connor and S. McIvor, 2020: Coastal defences versus coastal ecosystems: A regional appraisal. *Marine Policy*, **111**, 102332, doi:https://doi.org/10.1016/j.marpol.2016.02.021.
Cooper, J. A. G. and J. Pile, 2014: The adaptation-resistance spectrum: A classification of contemporary adaptation approaches to climate-related coastal change. *Ocean & Coastal Management*, **94**, 90-98, doi:https://doi.org/10.1016/j.ocecoaman.2013.09.006.
Cornwall, W., 2021: Unleashing Big Muddy. *Science*, **372** (6540), 334-337, doi:10.1126/science.abj1040.
Cosens, B. A. et al., 2017: The role of law in adaptive governance. *Ecology and Society*, **22** (1), doi:10.5751/ES-08731-220130.
Craig, R. K. et al., 2017: Balancing stability and flexibility in adaptive governance: an analysis of tools available in U.S. environmental law. *Ecology and Society*, **22** (2), doi:10.5751/ES-08983-220203.
Crescenzi, R. and A. Rodríguez-Pose, 2017: The Geography of Innovation in China and India. *International Journal of Urban and Regional Research*, **41** (6), 1010-1027, doi:https://doi.org/10.1111/1468-2427.12554.
Das, S. and J. R. Vincent, 2009: Mangroves protected villages and reduced death toll during Indian super cyclone. *Proceedings of the National Academy of Sciences*, **106** (18), 7357-7360, doi:10.1073/pnas.0810440106.
Davis, K. F., A. Bhattachan, P. D'Odorico and S. Suweis, 2018: A universal model for predicting human migration under climate change: examining future sea level rise in Bangladesh. *Environmental Research Letters*, **13** (6), doi:10.1088/1748-9326/aac4d4.
Day, J. W. et al., 2016: Large infrequently operated river diversions for Mississippi delta restoration. *Estuarine, Coastal and Shelf Science*, **183**, 292-303, doi:https://doi.org/10.1016/j.ecss.2016.05.001.
de Ruig, L. T. et al., 2019: An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles. *Science of The Total Environment*, **678**, 647-659, doi:https://doi.org/10.1016/j.scitotenv.2019.04.308.
de Schipper, M. A. et al., 2021: Beach nourishment has complex implications for the future of sandy shores. *Nature Reviews Earth & Environment*, **2** (1), 70-84, doi:10.1038/s43017-020-00109-9.
DeCaro, D. A. et al., 2017: Legal and institutional foundations of adaptive environmental governance. *Ecology and Society*, **22** (1), doi:10.5751/ES-09036-220132.
Dedekorkut-Howes, A., E. Torabi and M. Howes, 2020: When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding. *Journal of Environmental Planning and Management*, **63** (12), 2102-2143, doi:10.1080/09640568.2019.1708709.
del Valle, A., M. Eriksson, O. A. Ishizawa and J. J. Miranda, 2020: Mangroves protect coastal economic activity from hurricanes. *Proceedings of the National Academy of Sciences*, **117** (1), 265-270, doi:10.1073/pnas.1911617116.
Depietri, Y. and T. McPhearson, 2017: Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In: Nature-Based Solutions to Climate Change Adaptation in

Urban Areas: Linkages between Science, Policy and Practice [Kabisch, N., H. Korn, J. Stadler and A. Bonn (eds.)]. Springer International Publishing, Cham, 91-109.
Di Baldassarre, G. et al., 2018: Hess Opinions: An interdisciplinary research agenda to explore the unintended consequences of structural flood protection. *Hydrol. Earth Syst. Sci.*, **22** (11), 5629-5637, doi:10.5194/hess-22-5629-2018.
Di Baldassarre, G. et al., 2015: Debates—Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resources Research*, **51** (6), 4770-4781, doi:https://doi.org/10.1002/2014WR016416.
Di Giulio, G. M. et al., 2019: Bridging the gap between will and action on climate change adaptation in large cities in Brazil. *Regional Environmental Change*, **19** (8), 2491-2502, doi:10.1007/s10113-019-01570-z.
Doberstein, B., J. Fitzgibbons and C. Mitchell, 2019: Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience. *Natural Hazards*, **98** (1), 31-50, doi:10.1007/s11069-018-3529-z.
Doberstein, B., A. Tadgell and A. Rutledge, 2020: Managed retreat for climate change adaptation in coastal megacities: A comparison of policy and practice in Manila and Vancouver. *Journal of Environmental Management*, **253**, 109753, doi:https://doi.org/10.1016/j.jenvman.2019.109753.
Donchyts, G. et al., 2016: Earth's surface water change over the past 30 years. *Nature Climate Change*, **6**, 810-813, doi:10.1038/nclimate3111.
Donner, S. D., M. Kandlikar and S. Webber, 2016: Measuring and tracking the flow of climate change adaptation aid to the developing world. *Environmental Research Letters*, **11** (5), 054006, doi:10.1088/1748-9326/11/5/054006.
Donner, S. D. and S. Webber, 2014: Obstacles to climate change adaptation decisions: a case study of sea-level rise and coastal protection measures in Kiribati. *Sustainability Science*, **9** (3), 331-345, doi:10.1007/s11625-014-0242-z.
Druzhinin, A., A. Mikhaylov and A. Lialina, 2021: Coastal Regions of Russia: Migration Attractiveness and Innovation Performance. *Quaestiones Geographicae*, **40** (2), 5-18, doi:doi:10.2478/quageo-2021-0019.
Du, S. et al., 2020: Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. *Global Environmental Change*, **61**, 102037, doi:https://doi.org/10.1016/j.gloenvcha.2020.102037.
Dulal, H. B., 2019: Cities in Asia: how are they adapting to climate change? *Journal of Environmental Studies and Sciences*, **9** (1), 13-24.
Duncan, C. et al., 2018: Satellite remote sensing to monitor mangrove forest resilience and resistance to sea level rise. *Methods in Ecology and Evolution*, **9** (8), 1837-1852, doi:https://doi.org/10.1111/2041-210X.12923.
Duy, P. N. et al., 2018: Urban Resilience to Floods in Coastal Cities: Challenges and Opportunities for Ho Chi Minh City and Other Emerging Cities in Southeast Asia. *Journal of Urban Planning and Development*, **144** (1), 05017018, doi:doi:10.1061/(ASCE)UP.1943-5444.0000419.
Edmonds, D. A., R. L. Caldwell, E. S. Brondizio and S. M. O. Siani, 2020: Coastal flooding will disproportionately impact people on river deltas. *Nature Communications*, **11** (1), 4741, doi:10.1038/s41467-020-18531-4.
Eilander, D. et al., 2020: The effect of surge on riverine flood hazard and impact in deltas globally. *Environmental Research Letters*, **15** (10), 104007, doi:10.1088/1748-9326/ab8ca6.
Esteban, M. et al., 2019: Adaptation to sea level rise on low coral islands: Lessons from recent events. *Ocean & Coastal Management*, **168**, 35-40, doi:https://doi.org/10.1016/j.ocecoaman.2018.10.031.
Esteban, M., M. Onuki, I. Ikeda and T. Akiyama, 2015: Chapter 29 - Reconstruction Following the 2011 Tohoku Earthquake Tsunami: Case Study of Otsuchi Town in Iwate Prefecture, Japan. In: Handbook of Coastal Disaster Mitigation for Engineers and Planners [Esteban, M., H. Takagi and T. Shibayama (eds.)]. Butterworth-Heinemann, Boston, 615-631.
Esteban, M. et al., 2020a: Adaptation to sea level rise: Learning from present examples of land subsidence. *Ocean & Coastal Management*, **189**, 104852, doi:https://doi.org/10.1016/j.ocecoaman.2019.104852.
Esteban, M. et al., 2017: Awareness of coastal floods in impoverished subsiding coastal communities in Jakarta: Tsunamis, typhoon storm surges and dyke-induced tsunamis. *International Journal of Disaster Risk Reduction*, **23**, 70-79, doi:https://doi.org/10.1016/j.ijdrr.2017.04.007.
Esteban, M. et al., 2020b: Adapting ports to sea-level rise: empirical lessons based on land subsidence in Indonesia and Japan. *Maritime Policy & Management*, **47** (7), 937-952, doi:10.1080/03088839.2019.1634845.
Estrada, F., W. J. W. Botzen and R. S. J. Tol, 2017: A global economic assessment of city policies to reduce climate change impacts. *Nature Climate Change*, **7** (6), 403-406, doi:10.1038/nclimate3301.
Evans, A. J. et al., 2017: Stakeholder priorities for multi-functional coastal defence developments and steps to effective implementation. *Marine Policy*, **75**, 143-155, doi:https://doi.org/10.1016/j.marpol.2016.10.006.
Farbotko, C. et al., 2020: Relocation planning must address voluntary immobility. *Nature Climate Change*, **10** (8), 702-704, doi:10.1038/s41558-020-0829-6.
Fayombo, O. O., 2020: Discursive constructions underlie and exacerbate the vulnerability of informal urban communities to the impacts of climate change. *Climate and Development*, 1-13, doi:10.1080/17565529.2020.1765133.
Feagin, R. A. et al., 2019: The role of beach and sand dune vegetation in mediating wave run up erosion. *Estuarine, Coastal and Shelf Science*, **219**, 97-106, doi:https://doi.org/10.1016/j.ecss.2019.01.018.
Ferguson, B. C. et al., 2013: The enabling institutional context for integrated water management: Lessons from Melbourne. *Water Research*, **47** (20), 7300-7314, doi:https://doi.org/10.1016/j.watres.2013.09.045.

Ferrario, F. et al., 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, **5**, 3794.
Fink, J. H., 2019: Contrasting governance learning processes of climate-leading and -lagging cities: Portland, Oregon, and Phoenix, Arizona, USA. *Journal of Environmental Policy & Planning*, **21** (1), 16-29, doi:10.1080/1523908X.2018.1487280.
Fisher, K. and R. Goodliffe, 2019: Adaptive Coastal Management at Three Sites in East Anglia. In: *Coastal Management 2019*, [Hardiman, N. and I. o. C. Engineers (eds.)], 245-258, doi:10.1680/cm.65147.245.
Ford, J. D., G. McDowell and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5**, 1046, doi:10.1038/nclimate2723
https://www.nature.com/articles/nclimate2723#supplementary-information.
Fox-Rogers, L. et al., 2016: Is there really "nothing you can do"? Pathways to enhanced flood-risk preparedness. *Journal of Hydrology*, **543**, 330-343, doi:https://doi.org/10.1016/j.jhydrol.2016.10.009.
Frederiksen, M., 2014: Trust in the face of uncertainty: a qualitative study of intersubjective trust and risk. *International Review of Sociology*, **24** (1), 130-144, doi:10.1080/03906701.2014.894335.
Fu, X., 2020: Measuring local sea-level rise adaptation and adaptive capacity: A national survey in the United States. *Cities*, **102**, 102717, doi:https://doi.org/10.1016/j.cities.2020.102717.
Garmestani, A. S. and M. H. Benson, 2013: A Framework for Resilience-based Governance of Social-Ecological Systems. *Ecology and Society*, **18** (1), doi:10.5751/ES-05180-180109.
Garschagen, M., 2015: Risky Change? Vietnam's Urban Flood Risk Governance between Climate Dynamics and Transformation. *Pacific Affairs*, **88** (3), 599-621, doi:10.5509/2015883599.
Garschagen, M., G. A. K. Surtiari and M. Harb, 2018: Is Jakarta's new flood risk reduction strategy transformational? *Sustainability*, **10** (8), 2934, doi:https://doi.org/10.3390/su10082934.
Ghanbari, M. et al., 2021: Climate Change and Changes in Compound Coastal-Riverine Flooding Hazard Along the U.S. Coasts. *Earth's Future*, **9** (5), e2021EF002055, doi:https://doi.org/10.1029/2021EF002055.
Ghosh, M. K., L. Kumar and P. Kibet Langat, 2019: Geospatial modelling of the inundation levels in the Sundarbans mangrove forests due to the impact of sea level rise and identification of affected species and regions. *Geomatics, Natural Hazards and Risk*, **10** (1), 1028-1046, doi:10.1080/19475705.2018.1564373.
Gibbs, M. T., 2015: Pitfalls in developing coastal climate adaptation responses. *Climate Risk Management*, **8**, 1-8, doi:https://doi.org/10.1016/j.crm.2015.05.001.
Gibbs, M. T., 2016: Why is coastal retreat so hard to implement? Understanding the political risk of coastal adaptation pathways. *Ocean & Coastal Management*, **130**, 107-114, doi:https://doi.org/10.1016/j.ocecoaman.2016.06.002.
Gibbs, M. T., 2020: The two-speed coastal climate adaptation economy in Australia. *Ocean & Coastal Management*, **190**, 105150, doi:https://doi.org/10.1016/j.ocecoaman.2020.105150.
Glavovic, B. C., 2013: Coastal innovation paradox. *Sustainability*, **5** (3), 912-933, doi:https://doi.org/10.3390/su5030912.
Godfroy, M., V. Vuik, E. van Berchum and B. Jonkman, 2019: Quantifying Wave Attenuation by Nature-based Solutions in the Galveston Bay. In: *Coastal Structures 2019*, 1008-1019, doi:https://doi.org/10.18451/978-3-939230-64-9_101.
Goh, K., 2019: Urban Waterscapes: The Hydro-Politics of Flooding in a Sinking City. *International Journal of Urban and Regional Research*, **43** (2), 250-272, doi:10.1111/1468-2427.12756.
Gould, K. A. and T. L. Lewis, 2018: From Green Gentrification to Resilience Gentrification: An Example from Brooklyn1. *City & Community*, **17** (1), 12-15, doi:10.1111/cico.12283.
Gralepois, M. et al., 2016: Is flood defense changing in nature? Shifts in the flood defense strategy in six European countries. *Ecology and Society*, **21** (4).
Green, O. O. et al., 2015: Barriers and bridges to the integration of social–ecological resilience and law. *Frontiers in Ecology and the Environment*, **13** (6), 332-337, doi:https://doi.org/10.1890/140294.
Griggs, G. and K. Patsch, 2019: The Protection/Hardening of California's Coast: Times Are Changing. *Journal of Coastal Research*, **35** (5), 1051-1061, doi:10.2112/jcoastres-d-19a-00007.1.
Haasnoot, M. et al., 2020: Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, **20** (2), 37, doi:10.1007/s10113-020-01623-8.
Haasnoot, M. et al., 2019: Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. *Environmental Research Communications*, doi:10.1088/2515-7620/ab1871.
Haasnoot, M., J. Lawrence and A. K. Magnan, 2021a: Pathways to coastal retreat. *Science*, **372** (6548), 1287-1290, doi:10.1126/science.abi6594.
Haasnoot, M. et al., 2021b: Long-term sea-level rise necessitates a commitment to adaptation: A first order assessment. *Climate Risk Management*, **34**, doi:https://doi.org/10.1016/j.crm.2021.100355.
Hall, J. W., H. Harvey and L. J. Manning, 2019: Adaptation thresholds and pathways for tidal flood risk management in London. *Climate Risk Management*, **24**, 42-58, doi:https://doi.org/10.1016/j.crm.2019.04.001.
Hallegatte, S., A. Vogt-Schilb, M. Bangalore and J. Rozenberg, 2017: *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*. Climate Change and Development Series, World Bank, Washington, DC.
Hanna, C., I. White and B. Glavovic, 2019: Managed Retreat in Practice: Mechanisms and Challenges for Implementation. Oxford University Press, doi:10.1093/acrefore/9780199389407.013.350.

Hanna, C., I. White and B. Glavovic, 2020: The Uncertainty Contagion: Revealing the Interrelated, Cascading Uncertainties of Managed Retreat. *Sustainability*, **12** (2), 736, doi:https://doi.org/10.3390/su12020736.
Hanson, S. E. and R. J. Nicholls, 2020: Demand for Ports to 2050: Climate Policy, Growing Trade and the Impacts of Sea-Level Rise. *Earth's Future*, **8** (8), e2020EF001543, doi:https://doi.org/10.1029/2020EF001543.
Haraguchi, M. and S. Kim, 2016: Critical infrastructure interdependence in New York City during Hurricane Sandy. *International Journal of Disaster Resilience in the Built Environment*, **7** (2), 133-143, doi:10.1108/IJDRBE-03-2015-0015.
Harris, B. D. et al., 2021: Establishment of soil strength in a nourished wetland using thin layer placement of dredged sediment. *PLoS One*, **16** (5), e0251420, doi:10.1371/journal.pone.0251420.
Harris, L. M., E. K. Chu and G. Ziervogel, 2018: Negotiated resilience. *Resilience*, **6** (3), 196-214, doi:10.1080/21693293.2017.1353196.
Hauer, M. E., 2017: Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change*, **7**, 321, doi:10.1038/nclimate3271
https://www.nature.com/articles/nclimate3271#supplementary-information.
Hauer, M. E. et al., 2020: Sea-level rise and human migration. *Nature Reviews Earth & Environment*, **1** (1), 28-39, doi:10.1038/s43017-019-0002-9.
He, Q. and B. R. Silliman, 2019: Climate Change, Human Impacts, and Coastal Ecosystems in the Anthropocene. *Current Biology*, **29** (19), R1021-R1035, doi:https://doi.org/10.1016/j.cub.2019.08.042.
He, X., 2018: Legal and Policy Pathways of Climate Change Adaptation: Comparative Analysis of the Adaptation Practices in the United States, Australia and China. *Transnational Environmental Law*, **7** (2), 347-373, doi:10.1017/S2047102518000092.
Herrick, C. N., 2018: Self-Identity and Sense of Place: Some Thoughts Regarding Climate Change Adaptation Policy Formulation. *Environmental Values*, **27** (1), 81-102, doi:10.3197/096327118X15144698637531.
Hiatt, M. et al., 2019: Drivers and impacts of water level fluctuations in the Mississippi River delta: Implications for delta restoration. *Estuarine, Coastal and Shelf Science*, **224**, 117-137, doi:https://doi.org/10.1016/j.ecss.2019.04.020.
Hindsley, P. and D. Yoskowitz, 2020: Global change—Local values: Assessing tradeoffs for coastal ecosystem services in the face of sea level rise. *Global Environmental Change*, **61**, 102039, doi:https://doi.org/10.1016/j.gloenvcha.2020.102039.
Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8** (7), 570-578, doi:10.1038/s41558-018-0176-z.
Hinkel, J. et al., 2014: Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, **111** (9), 3292-3297.
Hino, M., C. B. Field and K. J. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, **7** (5), 364-370, doi:10.1038/nclimate3252.
Hissel, F. et al., 2014: Early warning and mass evacuation in coastal cities. *Coastal Engineering*, **87**, 193-204, doi:https://doi.org/10.1016/j.coastaleng.2013.11.015.
Hiwasaki, L., E. Luna, Syamsidik and J. A. Marçal, 2015: Local and indigenous knowledge on climate-related hazards of coastal and small island communities in Southeast Asia. *Climatic Change*, **128** (1), 35-56, doi:10.1007/s10584-014-1288-8.
Hiwasaki, L., E. Luna, Syamsidik and R. Shaw, 2014: Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. *International Journal of Disaster Risk Reduction*, **10**, 15-27, doi:https://doi.org/10.1016/j.ijdrr.2014.07.007.
Hochard, J. P., S. Hamilton and E. B. Barbier, 2019: Mangroves shelter coastal economic activity from cyclones. *Proceedings of the National Academy of Sciences*, **116** (25), 12232-12237, doi:10.1073/pnas.1820067116.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M.I.Gomis, E. Lonnoy, T.Maycock, M.Tignor and T. Waterfield (eds.)]. In Press.
Hoffmann, R. et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nature Climate Change*, **10** (10), 904-912, doi:10.1038/s41558-020-0898-6.
Hölscher, K., N. Frantzeskaki, T. McPhearson and D. Loorbach, 2019: Tales of transforming cities: Transformative climate governance capacities in New York City, U.S. and Rotterdam, Netherlands. *Journal of Environmental Management*, **231**, 843-857, doi:https://doi.org/10.1016/j.jenvman.2018.10.043.
Hooijer, A. and R. Vernimmen, 2021: Global LiDAR land elevation data reveal greatest sea-level rise vulnerability in the tropics. *Nature Communications*, **12** (1), 3592, doi:10.1038/s41467-021-23810-9.
Hu, H. et al., 2019: Synthesized trade-off analysis of flood control solutions under future deep uncertainty: An application to the central business district of Shanghai. *Water Research*, **166**, 115067, doi:https://doi.org/10.1016/j.watres.2019.115067.

IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanka, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. In press.
Izaguirre, C. et al., 2021: Climate change risk to global port operations. *Nature Climate Change*, **11** (1), 14-20, doi:10.1038/s41558-020-00937-z.
Jain, G., C. Singh, K. Coelho and T. Malladi, 2017: *Long-term implications of humanitarian responses: the case of Chennai*. IIED Working Paper, IIED, London.
Jain, G., C. Singh and T. Malladi, 2021: (Re)creating disasters
a case of post-disaster resettlements in Chennai. In: Rethinking Urban Risk and Resettlement in the Global South [Jain, G., C. Johnson and A. Lavell (eds.)]. UCL Press, 269-289.
Jamero, M. L., M. Onuki, M. Esteban and N. Tan, 2018: Community-based adaptation in low-lying islands in the Philippines: challenges and lessons learned. *Regional Environmental Change*, **18** (8), 2249-2260, doi:10.1007/s10113-018-1332-8.
James, R. K. et al., 2020: Tropical Biogeomorphic Seagrass Landscapes for Coastal Protection: Persistence and Wave Attenuation During Major Storms Events. *Ecosystems*, doi:10.1007/s10021-020-00519-2.
Javeline, D., T. Kijewski-Correa and A. Chesler, 2019: Does it matter if you "believe" in climate change? Not for coastal home vulnerability. *Climatic Change*, **155** (4), 511-532, doi:10.1007/s10584-019-02513-7.
Jeuken, A., M. Haasnoot, T. Reeder and P. Ward, 2014: Lessons learnt from adaptation planning in four deltas and coastal cities. *Journal of Water and Climate Change*, **6** (4), 711-728, doi:10.2166/wcc.2014.141.
Johnson, C., G. Jain and A. Lavell, Eds., 2021: Rethinking Urban Risk and Resettlement in the Global South. UCL Press,
Jones, H. P. et al., 2020: Global hotspots for coastal ecosystem-based adaptation. *PLoS One*, **15** (5), e0233005, doi:10.1371/journal.pone.0233005.
Jongman, B., 2018: Effective adaptation to rising flood risk. *Nature Communications*, **9** (1), 1986, doi:10.1038/s41467-018-04396-1.
Kabat, P. et al., 2009: Dutch coasts in transition. *Nature Geoscience*, **2** (7), 450.
Karlsson, M. and G. K. Hovelsrud, 2015: Local collective action: Adaptation to coastal erosion in the Monkey River Village, Belize. *Global Environmental Change*, **32**, 96-107, doi:https://doi.org/10.1016/j.gloenvcha.2015.03.002.
Kay, R. and J. Alder, 2017: *Coastal planning and management*. CRC Press.
Keenan, J. M., T. Hill and A. Gumber, 2018: Climate gentrification: from theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters*, **13** (5), 054001, doi:10.1088/1748-9326/aabb32.
Kench, P. S. et al., 2015: Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll. *Geology*, **43** (6), 515-518, doi:10.1130/g36555.1.
Kettle, N. P. and K. Dow, 2016: The Role of Perceived Risk, Uncertainty, and Trust on Coastal Climate Change Adaptation Planning. *Environment and Behavior*, **48** (4), 579-606, doi:10.1177/0013916514551049.
Kirezci, E. et al., 2020: Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific Reports*, **10** (1), 11629, doi:10.1038/s41598-020-67736-6.
Kirwan, M. L. et al., 2016: Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change*, **6**, 253, doi:10.1038/nclimate2909.
Kishore, N. et al., 2018: Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine*, **379** (2), 162-170, doi:10.1056/NEJMsa1803972.
Kleinhans, M. G., H. J. T. Weerts and K. M. Cohen, 2010: Avulsion in action: Reconstruction and modelling sedimentation pace and upstream flood water levels following a Medieval tidal-river diversion catastrophe (Biesbosch, The Netherlands, 1421–1750AD). *Geomorphology*, **118** (1), 65-79, doi:https://doi.org/10.1016/j.geomorph.2009.12.009.
Klepp, S., 2018: Framing Climate Change Adaptation from a Pacific Island Perspective–The Anthropology of Emerging Legal Orders. *Sociologus*, **68** (2), 149-170, doi:https://doi.org/10.3790/soc.68.2.149.
Kok, S. et al., 2021: The potential of nature-based flood defences to leverage public investment in coastal adaptation: Cases from the Netherlands, Indonesia and Georgia. *Ecological Economics*, **179**, 106828, doi:https://doi.org/10.1016/j.ecolecon.2020.106828.
Koks, E. E. et al., 2019: A global multi-hazard risk analysis of road and railway infrastructure assets. *Nature Communications*, **10** (1), 2677, doi:10.1038/s41467-019-10442-3.
Kool, R., J. Lawrence, M. Drews and R. Bell, 2020: Preparing for Sea-Level Rise through Adaptive Managed Retreat of a New Zealand Stormwater and Wastewater Network. *Infrastructures*, **5** (11), doi:https://doi.org/10.3390/infrastructures5110092.
Krause, G. et al., 2020: Visualizing the social in aquaculture: How social dimension components illustrate the effects of aquaculture across geographic scales. *Marine Policy*, **118**, 103985, doi:https://doi.org/10.1016/j.marpol.2020.103985.
Kulp, S. A. and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, **10** (1), 4844, doi:10.1038/s41467-019-12808-z.
Kumar, P. et al., 2021: Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations. *Science of The Total Environment*, **784**, 147058, doi:https://doi.org/10.1016/j.scitotenv.2021.147058.

Lassa, J. A. and E. Nugraha, 2014: From shared learning to shared action in building resilience in the city of Bandar Lampung, Indonesia. *Environment and Urbanization*, **27** (1), 161-180, doi:10.1177/0956247814552233.
Lau, J. D., C. C. Hicks, G. G. Gurney and J. E. Cinner, 2019: What matters to whom and why? Understanding the importance of coastal ecosystem services in developing coastal communities. *Ecosystem Services*, **35**, 219-230, doi:https://doi.org/10.1016/j.ecoser.2018.12.012.
Laurice Jamero, M. et al., 2017: Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change*, **7** (8), 581-586, doi:10.1038/nclimate3344.
Lawrence, J. et al., 2020: Implementing Pre-Emptive Managed Retreat: Constraints and Novel Insights. *Current Climate Change Reports*, **6** (3), 66-80, doi:10.1007/s40641-020-00161-z.
Le Cozannet, G. et al., 2017: Sea level change and coastal climate services: The way forward. *Journal of Marine Science and Engineering*, **5** (4), 49.
Le, T. D. N., 2020: Climate change adaptation in coastal cities of developing countries: characterizing types of vulnerability and adaptation options. *Mitigation and adaptation strategies for global change*, **25** (5), 739-761, doi:10.1007/s11027-019-09888-z.
Leal Filho, W. et al., 2018: Fostering coastal resilience to climate change vulnerability in Bangladesh, Brazil, Cameroon and Uruguay: a cross-country comparison. *Mitigation and adaptation strategies for global change*, **23** (4), 579-602, doi:10.1007/s11027-017-9750-3.
Lehmann, M. et al., 2021: The way forward: Supporting climate adaptation in coastal towns and small cities. *Ocean & Coastal Management*, **212**, 105785, doi:https://doi.org/10.1016/j.ocecoaman.2021.105785.
Lendering, K. T., S. N. Jonkman, M. van Ledden and J. K. Vrijling, 2020: Defend or raise? Optimising flood risk reduction strategies. *Journal of Flood Risk Management*, **13** (S1), e12553, doi:10.1111/jfr3.12553.
León-Mateos, F., A. Sartal, L. López-Manuel and M. A. Quintás, 2021: Adapting our sea ports to the challenges of climate change: Development and validation of a Port Resilience Index. *Marine Policy*, **130**, 104573, doi:https://doi.org/10.1016/j.marpol.2021.104573.
Li, X. et al., 2014: The impact of the change in vegetation structure on the ecological functions of salt marshes: the example of the Yangtze estuary. *Regional Environmental Change*, **14** (2), 623-632, doi:10.1007/s10113-013-0520-9.
Lincke, D. and J. Hinkel, 2018: Economically robust protection against 21st century sea-level rise. *Global Environmental Change*, **51**, 67-73, doi:10.1016/j.gloenvcha.2018.05.003.
Lincke, D. and J. Hinkel, 2021: Coastal Migration due to 21st Century Sea-Level Rise. *Earth's Future*, **9** (5), e2020EF001965, doi:https://doi.org/10.1029/2020EF001965.
Lincke, D. et al., 2020: The effectiveness of setback zones for adapting to sea-level rise in Croatia. *Regional Environmental Change*, **20** (2), 46, doi:10.1007/s10113-020-01628-3.
Long, N., P. Cornut and V. Kolb, 2021: Strategies for adapting to hazards and environmental inequalities in coastal urban areas: what kind of resilience for these territories? *Nat. Hazards Earth Syst. Sci.*, **21** (3), 1087-1100, doi:10.5194/nhess-21-1087-2021.
Look, C., E. Friedman and G. Godbout, 2019: The Resilience of Land Tenure Regimes During Hurricane Irma: How Colonial Legacies Impact Disaster Response and Recovery in Antigua and Barbuda. *Journal of Extreme Events*, **06** (01), 1940004, doi:10.1142/s2345737619400049.
Lu, Y. et al., 2018: Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability. *Environmental Pollution*, **239**, 670-680, doi:https://doi.org/10.1016/j.envpol.2018.04.016.
Luijendijk, A. et al., 2018: The State of the World's Beaches. *Sci Rep*, **8** (1), 6641, doi:10.1038/s41598-018-24630-6.
Mach, K. J. and A. R. Siders, 2021: Reframing strategic, managed retreat for transformative climate adaptation. *Science*, **372** (6548), 1294-1299, doi:10.1126/science.abh1894.
Macreadie, P. I. et al., 2017: Can we manage coastal ecosystems to sequester more blue carbon? *Frontiers in Ecology and the Environment*, **15** (4), 206-213, doi:10.1002/fee.1484.
Magnan, A. K. and V. K. E. Duvat, 2020: Towards adaptation pathways for atoll islands. Insights from the Maldives. *Regional Environmental Change*, **20** (4), 119, doi:10.1007/s10113-020-01691-w.
Magnan, A. K. et al., 2019: Integrative Cross-Chapter Box on Low-lying Islands and Coasts. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. In Press.
Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen and S. W. Popper, 2019: *Decision Making under Deep Uncertainty: From Theory to Practice*. Decision Making under Deep Uncertainty: From Theory to Practice, Springer International Publishing, Cham, 1-405 pp.
Mariano, C., M. Marino, G. Pisacane and G. Sannino, 2021: Sea Level Rise and Coastal Impacts: Innovation and Improvement of the Local Urban Plan for a Climate-Proof Adaptation Strategy. *Sustainability*, **13** (3), 1565.
Martyr-Koller, R. et al., 2021: Loss and damage implications of sea-level rise on Small Island Developing States. *Current Opinion in Environmental Sustainability*, **50**, 245-259, doi:https://doi.org/10.1016/j.cosust.2021.05.001.
Masselink, G., E. Beetham and P. Kench, 2020: Coral reef islands can accrete vertically in response to sea level rise. *Science Advances*, **6** (24), eaay3656, doi:10.1126/sciadv.aay3656.

McGranahan, G., D. Balk and B. Anderson, 2007: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, **19** (1), 17-37, doi:10.1177/0956247807076960.
McIver, L. et al., 2016: Health Impacts of Climate Change in Pacific Island Countries: A Regional Assessment of Vulnerabilities and Adaptation Priorities. *Environmental health perspectives*, **124** (11), 1707-1714, doi:10.1289/ehp.1509756.
McLean, R. and P. Kench, 2015: Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *WIREs Climate Change*, **6** (5), 445-463, doi:10.1002/wcc.350.
McLeman, R. et al., 2021: Conceptual framing to link climate risk assessments and climate-migration scholarship. *Climatic Change*, **165** (1), 24, doi:10.1007/s10584-021-03056-6.
McMichael, C., S. Dasgupta, S. Ayeb-Karlsson and I. Kelman, 2020: A review of estimating population exposure to sea-level rise and the relevance for migration. *Environmental Research Letters*, doi:10.1088/1748-9326/abb398.
McNamara, D. E., S. Gopalakrishnan, M. D. Smith and A. B. Murray, 2015: Climate Adaptation and Policy-Induced Inflation of Coastal Property Value. *PLoS One*, **10** (3), e0121278, doi:10.1371/journal.pone.0121278.
Meerow, S., 2017: Double exposure, infrastructure planning, and urban climate resilience in coastal megacities: A case study of Manila. *Environment and Planning A: Economy and Space*, **49** (11), 2649-2672, doi:10.1177/0308518x17723630.
Mendenhall, E. et al., 2020: Climate change increases the risk of fisheries conflict. *Marine Policy*, **117**, 103954, doi:https://doi.org/10.1016/j.marpol.2020.103954.
Menéndez, P. et al., 2020: The Global Flood Protection Benefits of Mangroves. *Scientific Reports*, **10** (1), 4404, doi:10.1038/s41598-020-61136-6.
Mentaschi, L. et al., 2018: Global long-term observations of coastal erosion and accretion. *Scientific Reports*, **8** (1), 12876, doi:10.1038/s41598-018-30904-w.
Merkens, J.-L. et al., 2018: Regionalisation of population growth projections in coastal exposure analysis. *Climatic Change*, **151** (3), 413-426, doi:10.1007/s10584-018-2334-8.
Mohamed Shaffril, H. A. et al., 2020: Systematic literature review on adaptation towards climate change impacts among indigenous people in the Asia Pacific regions. *Journal of Cleaner Production*, **258**, 120595, doi:https://doi.org/10.1016/j.jclepro.2020.120595.
Möller, I. et al., 2014: Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience*, **7**, 727, doi:10.1038/ngeo2251
https://www.nature.com/articles/ngeo2251#supplementary-information.
Morris, R. L., A. Boxshall and S. E. Swearer, 2020: Climate-resilient coasts require diverse defence solutions. *Nature Climate Change*, **10** (6), 485-487, doi:10.1038/s41558-020-0798-9.
Morris, R. L. et al., 2019: Kelp beds as coastal protection: wave attenuation of Ecklonia radiata in a shallow coastal bay. *Annals of Botany*, **125** (2), 235-246, doi:10.1093/aob/mcz127.
Morris, R. L., T. M. Konlechner, M. Ghisalberti and Stephen E. Swearer, 2018: From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Global Change Biology*, **24** (5), 1827-1842, doi:10.1111/gcb.14063.
Mortreux, C. et al., 2018: Political economy of planned relocation: A model of action and inaction in government responses. *Global Environmental Change*, **50**, 123-132, doi:https://doi.org/10.1016/j.gloenvcha.2018.03.008.
Muis, S. et al., 2016: A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, **7** (1), 11969, doi:10.1038/ncomms11969.
Nagy, G. J. et al., 2019: Climate vulnerability, impacts and adaptation in Central and South America coastal areas. *Regional Studies in Marine Science*, **29**, 100683, doi:https://doi.org/10.1016/j.rsma.2019.100683.
Nakashima, D., J. T. Rubis and I. Krupnik, 2018: Indigenous Knowledge for Climate Change Assessment and Adaptation: Introduction. In: Indigenous Knowledge for Climate Change Assessment and Adaptation [Nakashima, D., I. Krupnik and J. T. Rubis (eds.)]. Cambridge University Press, Cambridge, 1-20.
Narayan, S. et al., 2016: The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLoS One*, **11** (5), e0154735, doi:10.1371/journal.pone.0154735.
Narayan, S. et al., 2017: The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. *Scientific Reports*, **7** (1), 9463, doi:10.1038/s41598-017-09269-z.
Ndebele-Murisa, M. R. et al., 2020: City to city learning and knowledge exchange for climate resilience in southern Africa. *PLoS One*, **15** (1), e0227915, doi:10.1371/journal.pone.0227915.
Neef, A. et al., 2018: Climate adaptation strategies in Fiji: The role of social norms and cultural values. *World Development*, **107**, 125-137, doi:https://doi.org/10.1016/j.worlddev.2018.02.029.
Neise, T. and J. Revilla Diez, 2019: Adapt, move or surrender? Manufacturing firms' routines and dynamic capabilities on flood risk reduction in coastal cities of Indonesia. *International Journal of Disaster Risk Reduction*, **33**, 332-342, doi:https://doi.org/10.1016/j.ijdrr.2018.10.018.
Nesshöver, C. et al., 2017: The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of The Total Environment*, **579**, 1215-1227, doi:https://doi.org/10.1016/j.scitotenv.2016.11.106.
Neumann, B., A. T. Vafeidis, J. Zimmermann and R. J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding--a global assessment. *PLoS One*, **10** (3), e0118571, doi:10.1371/journal.pone.0118571.

Nicholls, R. J. et al., 2018: Stabilization of global temperature at 1.5C and 2.0C: implications for coastal areas. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376** (2119), 20160448, doi:doi:10.1098/rsta.2016.0448.
Nicholls, R. J., R. J. Dawson and S. A. Day, 2015: *Broad Scale Coastal Simulation: New Techniques to Understand and Manage Shorelines in the Third Millennium*. Broad Scale Coastal Simulation: New Techniques to Understand and Manage Shorelines in the Third Millennium, 1-398 pp.
Nicholls, R. J. et al., 2021: A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, **11** (4), 338-342, doi:10.1038/s41558-021-00993-z.
Nicholls, R. J. and C. Small, 2002: Improved estimates of coastal population and exposure to hazards released. *Eos, Transactions American Geophysical Union*, **83** (28), 301-305, doi:https://doi.org/10.1029/2002EO000216.
NIES and ISME. Tropical Coastal Ecosystems Portal (TroCEP). [Available at, accessed 5/11/2020]
Nilubon, P., W. Veerbeek and C. Zevenbergen, 2016: Amphibious Architecture and Design: A Catalyst of Opportunistic Adaptation? – Case Study Bangkok. *Procedia - Social and Behavioral Sciences*, **216**, 470-480, doi:https://doi.org/10.1016/j.sbspro.2015.12.063.
Nittrouer, J. A. et al., 2012: Mitigating land loss in coastal Louisiana by controlled diversion of Mississippi River sand. *Nature Geoscience*, **5** (8), 534-537, doi:10.1038/ngeo1525.
Nunn, P. D., J. Runman, M. Falanruw and R. Kumar, 2017: Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. *Regional Environmental Change*, **17** (4), 959-971, doi:10.1007/s10113-016-0950-2.
NYCEDC, 2019: *Lower Manhattan Climate Resilience Study*. New York City Economic Development Corporation [Available at: https://edc.nyc/project/lower-manhattan-coastal-resiliency].
O'Donnell, T., 2021: Coastal Lawscape: A framework for understanding the complexities of climate change adaptation. *Marine Policy*, **129**, 104532, doi:https://doi.org/10.1016/j.marpol.2021.104532.
O'Donnell, T., T. F. Smith and S. Connor, 2019: Research Handbook on Climate Change Adaptation Policy. In: Property rights and land use planning on the Australian coast. Edward Elgar Publishing.
Oanh, P. T., M. Tamura, N. Kumano and Q. V. Nguyen, 2020: Cost-Benefit Analysis of Mixing Gray and Green Infrastructures to Adapt to Sea Level Rise in the Vietnamese Mekong River Delta. *Sustainability*, **12** (24), 10356.
OECD, 2018: Income inequality and poverty in cities. In: OECD Regions and Cities at a Glance 2018. OECD Publishing, Paris.
OECD, 2020: *OECD Regions and Cities at a Glance 2020*.
Olazabal, M. and M. Ruiz De Gopegui, 2021: Adaptation planning in large cities is unlikely to be effective. *Landscape and Urban Planning*, **206**, 103974, doi:https://doi.org/10.1016/j.landurbplan.2020.103974.
Olazabal, M. et al., 2019: A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, **14** (12), 124056, doi:10.1088/1748-9326/ab5532.
Olthuis, K., P.-B. Tartas and C. Zevenbergen, 2020: Design Guidelines for Upgrading Living Conditions in Wetslums. Singapore, Springer Singapore, 1-18.
Ondiviela, B. et al., 2014: The role of seagrasses in coastal protection in a changing climate. *Coastal Engineering*, **87**, 158-168, doi:https://doi.org/10.1016/j.coastaleng.2013.11.005.
Ong, J. M. et al., 2016: Challenges in Build-Back-Better Housing Reconstruction Programs for Coastal Disaster Management: Case of Tacloban City, Philippines. *Coastal Engineering Journal*, **58** (01), 1640010, doi:10.1142/S0578563416400106.
Oppenheimer, M. et al., 2019: Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer (eds.)]. In press.
Parkinson, R. W. and D. E. Ogurcak, 2018: Beach nourishment is not a sustainable strategy to mitigate climate change. *Estuarine, Coastal and Shelf Science*, **212**, 203-209.
Pasquini, L., 2020: The urban governance of climate change adaptation in least-developed African countries and in small cities: the engagement of local decision-makers in Dar es Salaam, Tanzania, and Karonga, Malawi. *Climate and Development*, **12** (5), 408-419, doi:10.1080/17565529.2019.1632166.
Peel, J. and H. M. Osofsky, 2018: A Rights Turn in Climate Change Litigation? *Transnational Environmental Law*, **7** (1), 37-67, doi:10.1017/S2047102517000292.
Penning-Rowsell, E., 2020: Floating architecture in the landscape: climate change adaptation ideas, opportunities and challenges. *Landscape Research*, **45** (4), 395-411, doi:10.1080/01426397.2019.1694881.
Perkins, M. J. et al., 2015: Conserving intertidal habitats: What is the potential of ecological engineering to mitigate impacts of coastal structures? *Estuarine, Coastal and Shelf Science*, **167**, 504-515, doi:https://doi.org/10.1016/j.ecss.2015.10.033.
Pontee, N., S. Narayan, M. W. Beck and A. H. Hosking, 2016: Nature-based solutions: lessons from around the world. *Proceedings of the Institution of Civil Engineers - Maritime Engineering*, **169** (1), 29-36, doi:10.1680/jmaen.15.00027.
Pueyo-Ros, J., X. Garcia, A. Ribas and R. M. Fraguell, 2018: Ecological Restoration of a Coastal Wetland at a Mass Tourism Destination. Will the Recreational Value Increase or Decrease? *Ecological Economics*, **148**, 1-14, doi:https://doi.org/10.1016/j.ecolecon.2018.02.002.

Pugatch, T., 2019: Tropical storms and mortality under climate change. *World Development*, **117**, 172-182, doi:https://doi.org/10.1016/j.worlddev.2019.01.009.
Ramm, T. D., C. S. Watson and C. J. White, 2018: Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. *Environmental Science & Policy*, **87**, 92-101, doi:https://doi.org/10.1016/j.envsci.2018.06.001.
Ranganathan, M. and E. Bratman, 2019: From Urban Resilience to Abolitionist Climate Justice in Washington, DC. *Antipode*, doi:10.1111/anti.12555.
Reguero, B. G. et al., 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS One*, **13** (4), e0192132, doi:10.1371/journal.pone.0192132.
Reguero, B. G. et al., 2020: Financing coastal resilience by combining nature-based risk reduction with insurance. *Ecological Economics*, **169**, 106487, doi:https://doi.org/10.1016/j.ecolecon.2019.106487.
Reiblich, J. et al., 2019: Bridging climate science, law, and policy to advance coastal adaptation planning. *Marine Policy*, **104**, 125-134, doi:https://doi.org/10.1016/j.marpol.2019.02.028.
Reimann, L. et al., 2018: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications*, **9** (1), 4161, doi:10.1038/s41467-018-06645-9.
Rey, T. et al., 2019: Coastal Processes and Influence on Damage to Urban Structures during Hurricane Irma (St-Martin & St-Barthélemy, French West Indies). *Journal of Marine Science and Engineering*, **7** (7), 215, doi:https://doi.org/10.3390/jmse7070215.
Ribeiro, A. S. et al., 2021: Flooding Conditions at Aveiro Port (Portugal) within the Framework of Projected Climate Change. *Journal of Marine Science and Engineering*, **9** (6), 595.
Richards, D. R. and D. A. Friess, 2016: Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences*, **113** (2), 344-349, doi:10.1073/pnas.1510272113.
Ristroph, E. B., 2017: When Climate Takes a Village: Legal Pathways toward the Relocation of Alaska Native Villages. *Climate Law*, **7** (4), 259-289, doi:https://doi.org/10.1163/18786561-00704003.
Ristroph, E. B., 2019: Improving Justice and Avoiding Colonization in Managing Climate Change Related Disasters: A Case Study of Alaska Native Villages. *American Indian Law Journal*, **7** (2), 5.
Rocle, N. et al., 2020: Paving the way to coastal adaptation pathways: An interdisciplinary approach based on territorial archetypes. *Environmental Science & Policy*, **110**, 34-45, doi:https://doi.org/10.1016/j.envsci.2020.05.003.
Rocle, N. and D. Salles, 2018: "Pioneers but not guinea pigs": experimenting with climate change adaptation in French coastal areas. *Policy Sciences*, **51** (2), 231-247, doi:10.1007/s11077-017-9279-z.
Roder, G., P. Hudson and P. Tarolli, 2019: Flood risk perceptions and the willingness to pay for flood insurance in the Veneto region of Italy. *International Journal of Disaster Risk Reduction*, **37**, 101172, doi:https://doi.org/10.1016/j.ijdrr.2019.101172.
Romero Manrique, D., S. Corral and Â. Guimarães Pereira, 2018: Climate-related displacements of coastal communities in the Arctic: Engaging traditional knowledge in adaptation strategies and policies. *Environmental Science & Policy*, **85**, 90-100, doi:https://doi.org/10.1016/j.envsci.2018.04.007.
Rosendo, S., L. Celliers and M. Mechisso, 2018: Doing more with the same: A reality-check on the ability of local government to implement Integrated Coastal Management for climate change adaptation. *Marine Policy*, **87**, 29-39, doi:https://doi.org/10.1016/j.marpol.2017.10.001.
Rovai, A. S. et al., 2018: Global controls on carbon storage in mangrove soils. *Nature Climate Change*, **8** (6), 534-538, doi:10.1038/s41558-018-0162-5.
Roy, M., S. Cawood, M. Hordijk and D. Hulme, 2016: *Urban Poverty and Climate Change*. Routledge advances in climate change research, Routledge.
Salas, R. N., J. M. Shultz and C. G. Solomon, 2020: The Climate Crisis and Covid-19 — A Major Threat to the Pandemic Response. *New England Journal of Medicine*, **383** (11), e70, doi:10.1056/NEJMp2022011.
Saleh, F. and M. P. Weinstein, 2016: The role of nature-based infrastructure (NBI) in coastal resiliency planning: A literature review. *Journal of Environmental Management*, **183**, 1088-1098, doi:https://doi.org/10.1016/j.jenvman.2016.09.077.
Salik, K. M., S. Jahangir, W. u. Z. Zahdi and S. u. Hasson, 2015: Climate change vulnerability and adaptation options for the coastal communities of Pakistan. *Ocean & Coastal Management*, **112**, 61-73, doi:https://doi.org/10.1016/j.ocecoaman.2015.05.006.
Sánchez-Arcilla, A. et al., 2016: Managing coastal environments under climate change: Pathways to adaptation. *Science of The Total Environment*, **572**, 1336-1352, doi:https://doi.org/10.1016/j.scitotenv.2016.01.124.
Sayers, P., C. Walsh and R. Dawson, 2015: Climate impacts on flood and coastal erosion infrastructure. *Infrastructure Asset Management*, **2** (2), 69-83, doi:10.1680/iasma.14.00040.
Schinko, T. et al., 2020: Economy-wide effects of coastal flooding due to sea level rise: a multi-model simultaneous treatment of mitigation, adaptation, and residual impacts. *Environmental Research Communications*, **2** (1), 015002, doi:10.1088/2515-7620/ab6368.
Schmutter, K., M. Nash and L. Dovey, 2017: Ocean acidification: assessing the vulnerability of socioeconomic systems in Small Island Developing States. *Regional Environmental Change*, **17** (4), 973-987, doi:doi:10.1007/s10113-016-0949-8.
Schneider, P. et al., 2020: A rising tide of adaptation action: Comparing two coastal regions of Aotearoa-New Zealand. *Climate Risk Management*, **30**, 100244, doi:https://doi.org/10.1016/j.crm.2020.100244.

Schoonees, T. et al., 2019: Hard Structures for Coastal Protection, Towards Greener Designs. *Estuaries and coasts*, **42** (7), 1709-1729, doi:10.1007/s12237-019-00551-z.
Schoutens, K. et al., 2019: How effective are tidal marshes as nature-based shoreline protection throughout seasons? *Limnology and Oceanography*, **64** (4), 1750-1762, doi:https://doi.org/10.1002/lno.11149.
Schuerch, M. et al., 2018: Future response of global coastal wetlands to sea-level rise. *Nature*, **561** (7722), 231-234, doi:10.1038/s41586-018-0476-5.
Scussolini, P. et al., 2017: Adaptation to Sea Level Rise: A Multidisciplinary Analysis for Ho Chi Minh City, Vietnam. *Water Resources Research*, **53** (12), 10841-10857, doi:10.1002/2017wr021344.
Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190120, doi:doi:10.1098/rstb.2019.0120.
Seekamp, E., M. Jurjonas and K. Bitsura-Meszaros, 2019: Influences on coastal tourism demand and substitution behaviors from climate change impacts and hazard recovery responses. *Journal of Sustainable Tourism*, **27** (5), 629-648, doi:10.1080/09669582.2019.1599005.
Sengupta, D., R. Chen and M. E. Meadows, 2018: Building beyond land: An overview of coastal land reclamation in 16 global megacities. *Applied Geography*, **90**, 229-238, doi:https://doi.org/10.1016/j.apgeog.2017.12.015.
Sengupta, D., R. Chen, M. E. Meadows and A. Banerjee, 2020: Gaining or losing ground? Tracking Asia's hunger for 'new' coastal land in the era of sea level rise. *Science of The Total Environment*, **732**, 139290, doi:https://doi.org/10.1016/j.scitotenv.2020.139290.
Setiadi, R., J. Baumeister, P. Burton and J. Nalau, 2020: Extending Urban Development on Water: Jakarta Case Study. *Environment and Urbanization ASIA*, **11** (2), 247-265, doi:10.1177/0975425320938539.
Setzer, J. and L. C. Vanhala, 2019: Climate change litigation: A review of research on courts and litigants in climate governance. *WIREs Climate Change*, **10** (3), e580, doi:https://doi.org/10.1002/wcc.580.
Sharifi, A., 2020: Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. *Journal of Cleaner Production*, **276**, 122813, doi:https://doi.org/10.1016/j.jclepro.2020.122813.
Shi, H. and A. Singh, 2003: Status and Interconnections of Selected Environmental Issues in the Global Coastal Zones. *AMBIO: A Journal of the Human Environment*, **32** (2), 145-152, 8.
Shultz, J. M., C. Fugate and S. Galea, 2020a: Cascading Risks of COVID-19 Resurgence During an Active 2020 Atlantic Hurricane Season. *JAMA*, **324** (10), 935-936, doi:10.1001/jama.2020.15398.
Shultz, J. M. et al., 2020b: Superimposed threats to population health from tropical cyclones in the prevaccine era of COVID-19. *The Lancet Planetary Health*, **4** (11), e506-e508, doi:10.1016/S2542-5196(20)30250-3.
Siders, A. R., 2019a: Managed Retreat in the United States. *One Earth*, **1** (2), 216-225, doi:https://doi.org/10.1016/j.oneear.2019.09.008.
Siders, A. R., 2019b: Social justice implications of US managed retreat buyout programs. *Climatic Change*, **152** (2), 239-257, doi:10.1007/s10584-018-2272-5.
Siders, A. R., M. Hino and K. J. Mach, 2019: The case for strategic and managed climate retreat. *Science*, **365** (6455), 761, doi:10.1126/science.aax8346.
Simpson, N. P. et al., 2021: A framework for complex climate change risk assessment. *One Earth*, **4** (4), 489-501, doi:https://doi.org/10.1016/j.oneear.2021.03.005.
So, S., B. Juarez, A. Valle-Levinson and M. E. Gillin, 2019: Storm surge from Hurricane Irma along the Florida Peninsula. *Estuarine, Coastal and Shelf Science*, **229**, 106402, doi:https://doi.org/10.1016/j.ecss.2019.106402.
Song, J. et al., 2018: Does planned retreat matter? Investigating land use change under the impacts of flooding induced by sea level rise. *Mitigation and adaptation strategies for global change*, **23** (5), 703-733, doi:10.1007/s11027-017-9756-x.
Sovacool, B. K., 2018: Bamboo Beating Bandits: Conflict, Inequality, and Vulnerability in the Political Ecology of Climate Change Adaptation in Bangladesh. *World Development*, **102**, 183-194, doi:https://doi.org/10.1016/j.worlddev.2017.10.014.
Spalding, M. D. et al., 2014: Coastal Ecosystems: A Critical Element of Risk Reduction. *Conservation Letters*, **7** (3), 293-301, doi:https://doi.org/10.1111/conl.12074.
Stark, J., T. Van Oyen, P. Meire and S. Temmerman, 2015: Observations of tidal and storm surge attenuation in a large tidal marsh. *Limnology and Oceanography*, **60** (4), 1371-1381, doi:10.1002/lno.10104.
Staudt, F. et al., 2021: The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. *Journal of Coastal Conservation*, **25** (2), 34, doi:10.1007/s11852-021-00801-y.
Sterzel, T. et al., 2020: Typology of coastal urban vulnerability under rapid urbanization. *PLoS One*, **15** (1), e0220936, doi:10.1371/journal.pone.0220936.
Stive, M. J. F. et al., 2013: A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. *Journal of Coastal Research*, 1001-1008, doi:10.2112/JCOASTRES-D-13-00070.1.
Storbjörk, S. and M. Hjerpe, 2021: Climate-proofing coastal cities: What is needed to go from envisioning to enacting multifunctional solutions for waterfront climate adaptation? *Ocean & Coastal Management*, **210**, 105732, doi:https://doi.org/10.1016/j.ocecoaman.2021.105732.
Strauss, B. H. et al., 2021: Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. *Nature Communications*, **12** (1), 2720, doi:10.1038/s41467-021-22838-1.

Sudmeier-Rieux, K. et al., 2021: Scientific evidence for ecosystem-based disaster risk reduction. *Nature Sustainability*, doi:10.1038/s41893-021-00732-4.

Sutton-Grier, A. E., K. Wowk and H. Bamford, 2015: Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, **51**, 137-148.

Takagi, H., M. Esteban, T. Mikami and D. Fujii, 2016: Projection of coastal floods in 2050 Jakarta. *Urban Climate*, **17**, 135-145, doi:https://doi.org/10.1016/j.uclim.2016.05.003.

Tamura, M., N. Kumano, M. Yotsukuri and H. Yokoki, 2019: Global assessment of the effectiveness of adaptation in coastal areas based on RCP/SSP scenarios. *Climatic Change*, **152** (3), 363-377, doi:10.1007/s10584-018-2356-2.

Temmerman, S. and M. L. Kirwan, 2015: Building land with a rising sea. *Science*, **349** (6248), 588-589.

Tessler, Z. D. et al., 2015: Profiling risk and sustainability in coastal deltas of the world. *Science*, **349** (6248), 638, doi:10.1126/science.aab3574.

Thomas, A. et al., 2020: Climate Change and Small Island Developing States. *Annual Review of Environment and Resources*, **45** (1), 1-27, doi:10.1146/annurev-environ-012320-083355.

Thomas, A. and L. Benjamin, 2020: Non-economic loss and damage: lessons from displacement in the Caribbean. *Climate Policy*, **20** (6), 715-728, doi:10.1080/14693062.2019.1640105.

Thomas, K. et al., 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565, doi:https://doi.org/10.1002/wcc.565.

Thrush, S. F. et al., 2021: Cumulative stressors reduce the self-regulating capacity of coastal ecosystems. *Ecological Applications*, **31** (1), e02223, doi:https://doi.org/10.1002/eap.2223.

Tian, B., W. Wu, Z. Yang and Y. Zhou, 2016: Drivers, trends, and potential impacts of long-term coastal reclamation in China from 1985 to 2010. *Estuarine, Coastal and Shelf Science*, **170**, 83-90, doi:https://doi.org/10.1016/j.ecss.2016.01.006.

Tiggeloven, T. et al., 2020: Global-scale benefit–cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. *Nat. Hazards Earth Syst. Sci.*, **20** (4), 1025-1044, doi:10.5194/nhess-20-1025-2020.

Toimil, A. et al., 2020: Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment. *Earth-Science Reviews*, **202**, 103110, doi:https://doi.org/10.1016/j.earscirev.2020.103110.

Torres, A., J. Brandt, K. Lear and J. Liu, 2017: A looming tragedy of the sand commons. *Science*, **357** (6355), 970, doi:10.1126/science.aao0503.

Triyanti, A., M. Bavinck, J. Gupta and M. A. Marfai, 2017: Social capital, interactive governance and coastal protection: The effectiveness of mangrove ecosystem-based strategies in promoting inclusive development in Demak, Indonesia. *Ocean & Coastal Management*, **150**, 3-11, doi:https://doi.org/10.1016/j.ocecoaman.2017.10.017.

Ung, M., I. Luginaah, R. Chuenpagdee and G. Campbell, 2016: Perceived self-efficacy and adaptation to climate change in coastal Cambodia. *Climate*, **4** (1), 1, doi:https://doi.org/10.3390/cli4010001.

Ürge-Vorsatz, D. et al., 2018: Locking in positive climate responses in cities. *Nature Climate Change*, **8** (3), 174-177, doi:10.1038/s41558-018-0100-6.

Valdivieso, P. and K. P. Andersson, 2018: What motivates local governments to invest in critical infrastructure? Lessons from Chile. *Sustainability*, **10** (10), 3808, doi:https://doi.org/10.3390/su10103808.

Van Assche, K., A.-K. Hornidge, A. Schlüter and N. Vaidianu, 2020: Governance and the coastal condition: Towards new modes of observation, adaptation and integration. *Marine Policy*, **112**, 103413, doi:https://doi.org/10.1016/j.marpol.2019.01.002.

Van Coppenolle, R. and S. Temmerman, 2020: Identifying Ecosystem Surface Areas Available for Nature-Based Flood Risk Mitigation in Coastal Cities Around the World. *Estuaries and coasts*, **43** (6), 1335-1344, doi:10.1007/s12237-020-00718-z.

van Valkengoed, A. M. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, **9** (2), 158-163, doi:10.1038/s41558-018-0371-y.

Villamizar, A. et al., 2017: Climate adaptation in South America with emphasis in coastal areas: the state-of-the-art and case studies from Venezuela and Uruguay. *Climate and Development*, **9** (4), 364-382, doi:10.1080/17565529.2016.1146120.

Vousdoukas, M. I. et al., 2020a: Economic motivation for raising coastal flood defenses in Europe. *Nature Communications*, **11** (1), 2119, doi:10.1038/s41467-020-15665-3.

Vousdoukas, M. I. et al., 2020b: Sandy coastlines under threat of erosion. *Nature Climate Change*, **10** (3), 260-263, doi:10.1038/s41558-020-0697-0.

Vuik, V., B. W. Borsje, P. W. J. M. Willemsen and S. N. Jonkman, 2019: Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. *Ocean & Coastal Management*, **171**, 96-110, doi:https://doi.org/10.1016/j.ocecoaman.2019.01.010.

Vuik, V., S. N. Jonkman, B. W. Borsje and T. Suzuki, 2016: Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coastal Engineering*, **116**, 42-56, doi:https://doi.org/10.1016/j.coastaleng.2016.06.001.

Vuik, V. et al., 2018: Assessing safety of nature-based flood defenses: Dealing with extremes and uncertainties. *Coastal Engineering*, **139**, 47-64, doi:https://doi.org/10.1016/j.coastaleng.2018.05.002.

Wahl, T. et al., 2015: Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, **5** (12), 1093-1097, doi:10.1038/nclimate2736.

Walker, W. E., M. Haasnoot and J. H. Kwakkel, 2013: Adapt or perish: a review of planning approaches for adaptation under deep uncertainty. *Sustainability*, **5** (3), 955-979.

Wallace, B., 2017: A framework for adapting to climate change risk in coastal cities. *Environmental Hazards*, **16** (2), 149-164, doi:10.1080/17477891.2017.1298511.

Walsh, C. et al., 2019: Trade and trade-offs: Shipping in changing climates. *Marine Policy*, **106**, 103537, doi:https://doi.org/10.1016/j.marpol.2019.103537.

Wang, C. M. and B. T. Wang, 2020: Floating Solutions for Challenges Facing Humanity. Singapore, Springer Singapore, 3-29, doi:10.1007/978-981-15-5144-4_1.

Wang, G., Y. Goldfeld and N. Drimer, 2019: Expanding coastal cities – Proof of feasibility for modular floating structures (MFS). *Journal of Cleaner Production*, **222**, 520-538, doi:https://doi.org/10.1016/j.jclepro.2019.03.007.

Wang, W., H. Liu, Y. Li and J. Su, 2014: Development and management of land reclamation in China. *Ocean & Coastal Management*, **102**, 415-425, doi:https://doi.org/10.1016/j.ocecoaman.2014.03.009.

Ward, R. D., 2020: Carbon sequestration and storage in Norwegian Arctic coastal wetlands: Impacts of climate change. *Science of The Total Environment*, **748**, 141343, doi:https://doi.org/10.1016/j.scitotenv.2020.141343.

Ware, D. and Z. Banhalmi-Zakar, 2020: Strategies for governments to help close the coastal adaptation funding gap. *Ocean & Coastal Management*, **198**, 105223, doi:https://doi.org/10.1016/j.ocecoaman.2020.105223.

Waryszak, P. et al., 2021: Combining gray and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defenses. *Coastal Engineering Journal*, 1-16, doi:10.1080/21664250.2021.1920278.

Weber, E., P. Kissoon and C. Koto, 2019: Moving to dangerous places. In: Dealing with climate change on small islands: Towards effective and sustainable adaptation [Klöck, C. and M. Fink (eds.)]. Universitätsverlag Göttingen, Göttingen.

Weiler, F., C. Klöck and M. Dornan, 2018: Vulnerability, good governance, or donor interests? The allocation of aid for climate change adaptation. *World Development*, **104**, 65-77, doi:https://doi.org/10.1016/j.worlddev.2017.11.001.

Weir, T., L. Dovey and D. Orcherton, 2017: Social and cultural issues raised by climate change in Pacific Island countries: an overview. *Regional Environmental Change*, **17** (4), 1017-1028, doi:10.1007/s10113-016-1012-5.

Welch, A. C., R. J. Nicholls and A. N. Lázár, 2017: Evolving deltas: Coevolution with engineered interventions. *Elementa: Science of the Anthropocene*, **5**, doi:10.1525/elementa.128.

Wewerinke-Singh, M. and D. H. Salili, 2020: Between negotiations and litigation: Vanuatu's perspective on loss and damage from climate change. *Climate Policy*, **20** (6), 681-692, doi:10.1080/14693062.2019.1623166.

Wijaya, N., V. Nitivattananon, R. P. Shrestha and S. M. Kim, 2020: Drivers and Benefits of Integrating Climate Adaptation Measures into Urban Development: Experience from Coastal Cities of Indonesia. *Sustainability*, **12** (2), 750, doi:https://doi.org/10.3390/su12020750.

Williams, D. S., S. Rosendo, O. Sadasing and L. Celliers, 2020: Identifying local governance capacity needs for implementing climate change adaptation in Mauritius. *Climate Policy*, **20** (5), 548-562, doi:10.1080/14693062.2020.1745743.

Wilson, B. J. et al., 2018: Declines in Plant Productivity Drive Carbon Loss from Brackish Coastal Wetland Mesocosms Exposed to Saltwater Intrusion. *Estuaries and coasts*, **41** (8), 2147-2158, doi:10.1007/s12237-018-0438-z.

Wong, P. P. et al., 2014: Coastal systems and low-lying areas. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L.L.White (eds.)]. Cambridge Univeristy Press, Cambridge, United Kingdom
New York, NY, USA, 361-409.

Woodruff, S. C., M. Mullin and M. Roy, 2020: Is coastal adaptation a public good? The financing implications of good characteristics in coastal adaptation. *Journal of Environmental Planning and Management*, **63** (12), 2082-2101, doi:10.1080/09640568.2019.1703656.

Xu, H., K. Xu, J. Lian and C. Ma, 2019: Compound effects of rainfall and storm tides on coastal flooding risk. *Stochastic Environmental Research and Risk Assessment*, **33** (7), 1249-1261, doi:10.1007/s00477-019-01695-x.

Yang, Y.-C. and Y.-E. Ge, 2020: Adaptation strategies for port infrastructure and facilities under climate change at the Kaohsiung port. *Transport Policy*, **97**, 232-244, doi:https://doi.org/10.1016/j.tranpol.2020.06.019.

Yesudian, A. N. and R. J. Dawson, 2021: Global analysis of sea level rise risk to airports. *Climate Risk Management*, **31**, 100266, doi:https://doi.org/10.1016/j.crm.2020.100266.

Yin, J. et al., 2020: Flood Risks in Sinking Delta Cities: Time for a Reevaluation? *Earth's Future*, **8** (8), e2020EF001614, doi:https://doi.org/10.1029/2020EF001614.

Yumagulova, L., 2020: Disrupting the riskscapes of inequities: a case study of planning for resilience in Canada's Metro Vancouver region. *Cambridge Journal of Regions, Economy and Society*, **13** (2), 293-318, doi:10.1093/cjres/rsaa029.

Zhang, J., F. Su and Z. Ding, 2017: Sea Reclamation Status of Countries around the South China Sea from 1975 to 2010. *Sustainability*, **9** (6), 878.

Zhao, Q. et al., 2018: Effects of water and salinity regulation measures on soil carbon sequestration in coastal wetlands of the Yellow River Delta. *Geoderma*, **319**, 219-229, doi:https://doi.org/10.1016/j.geoderma.2017.10.058.
Zhu, L. et al., 2020a: Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies. *Coastal Engineering*, **160**, 103737, doi:https://doi.org/10.1016/j.coastaleng.2020.103737.
Zhu, Z. et al., 2020b: Historic storms and the hidden value of coastal wetlands for nature-based flood defence. *Nature Sustainability*, **3** (10), 853-862, doi:10.1038/s41893-020-0556-z.
Ziervogel, G., A. Cowen and J. Ziniades, 2016: Moving from adaptive to transformative capacity: Building foundations for inclusive, thriving, and regenerative urban settlements. *Sustainability*, **8** (9), 955, doi:https://doi.org/10.3390/su8090955.
Ziervogel, G. and S. Parnell, 2014: Tackling barriers to climate change adaptation in South African coastal cities. In: Adapting to climate change. Springer, 57-73.

Cross-Chapter Paper 3: Deserts, Semi-Arid Areas and Desertification

Cross-Chapter Paper Leads: Alisher Mirzabaev (Uzbekistan), Lindsay C. Stringer (United Kingdom)

Cross-Chapter Paper Authors: Tor A. Benjaminsen (Norway), Patrick Gonzalez (USA), Rebecca Harris (Australia), Mostafa Jafari (Iran), Nicola Stevens (South Africa), Cristina Maria Tirado (Spain/USA), Sumaya Zakieldeen (Sudan)

Cross-Chapter Paper Contributing Authors: Elena Abraham (Argentina), Dulce Flores-Renteria (Mexico), Houda Ghazi (Morocco), Pierre Hiernaux (France), Margot Hurlbert (Canada), Oksana Lipka (Russian Federation), Nausheen Mazhar (Pakistan), Nicholas Middleton (United Kingdom), Uriel Safriel (Israel), Ranjay K. Singh (India), Fei Wang (China)

Cross-Chapter Paper Review Editor: Taha Zatari (Saudi Arabia)

Cross-Chapter Paper Scientist: Asmita Bhardwaj (India)

Date of Draft: 1 October 2021

Note: TSU Compiled Version

Table of Contents

Executive Summary

Introduction

This cross-chapter paper on "Deserts, semi-arid areas and desertification" updates and extends Chapter 3 on "Desertification" in the IPCC Special Report on Climate Change and Land (SRCCL). It assesses new information and links it to the findings across the chapters of Working Group 2's contribution as well as relevant chapters of Working Group 1's contribution to the IPCC Sixth Assessment Report (AR6), with an added focus on deserts which were outside the scope of the SRCCL.

Where are we now: Observed impacts and adaptation responses

Deserts and semi-arid areas have already been affected by climate change, with some areas experiencing increases in aridity. Mixed trends of decreases and increases in vegetation productivity have been observed, depending on the time period, geographic region, detection methods used and vegetation type under consideration (*high confidence*[1]). These changes have had varying and location-specific impacts on biodiversity, and have altered ecosystem carbon balance, water availability and the provision of ecosystem services (*high confidence*). There is no evidence, however, of a global trend in dryland expansion based on analyses of vegetation patterns, precipitation and soil moisture, with overall, more greening than drying in drylands since the 1980s (*medium confidence*). Deserts and semi-arid areas host unique biodiversity, rich cultural heritage and provide globally valuable ecosystem services. They are also highly vulnerable to climate change. The vitality of natural ecosystems in arid and semi-arid regions greatly depends on water availability, as they are highly sensitive to changes in precipitation and potential evapotranspiration {3.1.2; 3.2.1}, as well as to land management practices. Multiple lines of evidence from 1920-2015 indicate that surface warming of 1.2ºC-1.3ºC over global drylands (Section 1.1.1) exceeded the 0.8ºC-1.0ºC warming over humid lands. From 1982 to 2015, unsustainable land use and climate change combined caused desertification of 6% of the global dryland area, while 41% showed significant increases in vegetation productivity (greening) and 53% of the area had no notable change, although greening rates are slowing or declining in some locations. Greening may cause biodiversity loss and ecosystem service degradation in relation to livelihood systems {3.2.2}. Observed trends in deserts and semi-arid areas have led to varying impacts on flora, fauna, soil, nutrient cycling, the carbon cycle and water resources. Ecological changes in dryland ecosystems detected and attributed primarily to climate change include tree mortality and losses of mesic tree species at specific sites in the African Sahel particularly during the droughts of the 1970s and 80s, and in North Africa from 1970 to 2007 (CCP4.3.2); and losses of bird species in the Mojave Desert of North America from 1908 to 2016 (CCP4.3.2). In contrast, growth in herbaceous vegetation production has increased in some drylands since the 1980s. Widespread woody encroachment has occurred in many shrublands and savannas in Africa, Australia, North America and South America, due to a combination of land use change, changes in rainfall, fire suppression, and CO_2 fertilization {3.2.1, 3.2.2} which, together with unsustainable management, alters biodiversity and reduces ecosystem services such as water availability and grazing potential.

The impacts of climate change have affected the ecosystem services that humans can harness from drylands, with largely negative implications for livelihoods, human health and wellbeing, particularly in deserts and semi-arid areas with lower adaptive capacities (*high confidence*). Ecosystem degradation (Section 16.5.2.3.1) and desertification threaten the abilities of both natural and human systems to adapt to climate change (*high confidence*) {3.1.1}. Changes in desert and semi-arid ecosystem services most acutely affect people who are directly dependent on naatural resources for their livelihoods and survival. These groups also often have lower capacities to adapt, particularly given structural limitations of some drylands where healthcare, sanitation, infrastructure and efficient markets are lacking, reinforcing existing inequalities (*high confidence*) {3.2.1, 3.2.2}. In rural drylands in tropical and Mediterranean areas, human populations are steadily expanding with mixed implications for ecosystem services under climate change, while rapid

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

urbanisation in new and existing dryland megacities put additional pressure on water ecosystem services (*high confidence*). Impacts resulting from consumption of dryland ecosystem services elsewhere, alongside other teleconnections associated with health, trade, conflict and migration, mean that dryland adaptive capacities have far reaching implications for other locations, while other locations affect dryland adaptation options {3.1.1; 3.4}.

Where are we going? Risks and adaptation under warming pathways

Some drylands will expand by 2100, while others will shrink (*high confidence*). Climate change affects drylands through increased temperatures and more irregular rainfall, with important differences between areas with different rainfall distributions linked to the dominant climate systems in each location (Chapter 9). Projections are nevertheless uncertain and not well supported by observed trends, while different methodological approaches and indices exhibit different strengths and weaknesses (*medium confidence*). A fundamental methodological challenge is how to attribute projected impacts to climate change when background climate variability in drylands is so high. Some projections show aridity (as measured by the aridity index) to expand substantially on all continents except Antarctica. Expansion of arid regions is probable in southwest North America, the northern fringe of Africa, southern Africa and Australia. The main areas of semi-arid expansion are *likely*[2] to occur on the north side of the Mediterranean, southern Africa and North and South America. India, parts of northern China, eastern equatorial Africa and the southern Saharan regions are projected to have shrinking drylands. Under RCP 8.5, aridity zones could expand by one-quarter of the 1990 area by 2100, increasing to over half the global terrestrial area. Lower greenhouse gas emissions, under RCP 4.5, could limit expansion to one-tenth of the 1990 area by 2100. Nevertheless, the utility of the aridity index in delineating dryland biomes is limited under an increasing CO_2 environment (*medium confidence*) and how well the index fits observed trends has been questioned in recent research. The impacts of climate change on sand and dust storm activity are projected to be substantial, however, there is large regional variability in terms of rainfall seasonality, land management practices, as well as differences in rates of change and the scales at which the projections are undertaken. The characteristics and speed of human responses and adaptations also affect future risks and impacts (*high confidence*). Increased temperature and rainfall variability will significantly change the inter-annual variability in the global carbon cycle which is strongly influenced by the world's drylands and the ways they are managed (*medium confidence*). Increased variability of precipitation would generally contribute to increased vulnerability for people in drylands, intensifying the challenges that people living in deserts and semi-arid areas will face for their sustainable development (*medium confidence*) {3.3.1, 3.3.2}.

Contributions of adaptation measures to climate resilient development

Drivers of desert expansion and greening are numerous, are attributed to environmental and human processes and differ across dryland types, yet a suite of adaptations can help to address human drivers of change, support resilience and build the adaptive capacity of dryland people (*medium confidence*). Deserts and semi-arid areas have a rich cultural heritage, Indigenous knowledge, and local knowledge which enrich and influence sustainability and land use globally. Growing research evidence and experience highlight the necessary features of an enabling environment for dryland adaptation (Section 8.5.2). Key enablers include supportive policies, institutions and governance approaches that strengthen the adaptive capacities of dryland farmers, pastoralists and other dryland resource users (*high confidence*), addressing drivers (proximate and underlying) as well as symptoms of desertification. For instance, the skills and capacities held by the mobile and adaptive approach of pastoralists may provide lessons for society at large in adapting to climate change and dealing with increased uncertainty. Such a policy would stand in contrast to previous attempts at settling pastoralists. There is a persistent gap in terms of scaling-up already known good practices, combining nature-based, land-based, and ecosystem-based approaches that facilitate sustainable land management, with contextually appropriate and responsible governance systems (e.g., including those supporting communal land tenure arrangements and Indigenous knowledge) (*medium*

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range

confidence). Land based adaptations can help manage dryland changes including sand and dust storms and desertification (*high confidence*), while technological options linked to water management draw from both traditional practices and new innovations. Adequate financing and investment is required to harness multiple benefits for managing the impacts of climate change and desertification whilst accelerating progress towards sustainable development in deserts and semi-arid areas {3.4}.

CCP3.1 Introduction

CCP3.1.1 Concepts, Definitions and Scope

Deserts and semi-arid areas are in 'drylands', which comprise hyper-arid, arid, semi-arid and dry sub-humid areas (Figure CCP3.1). Drylands cover about 45-47% of the global land area (Prăvălie, 2016; Koutroulis, 2019) and are home to about 3 billion people residing primarily in semi-arid and dry sub-humid areas (van der Esch et al., 2017). Drylands host unique, rich biodiversity (Maestre et al., 2015) and provide important ecosystem services (Bidak et al., 2015; Lu et al., 2018), while dryland people have a rich cultural and historical heritage. Rural human populations are growing in some Mediterranean and tropical drylands, while many are rapidly urbanizing (Guengant Jean-Pierre, 2003; Tabutin and Schoumaker, 2004; Denis and Moriconi-Ebrard, 2009), with varying impacts on ecosystem services and adaptive capacities. In recent decades, 6% of global megacities have been established in arid areas and 2% in hyper-arid desert areas (Cherlet et al., 2018), with many of these areas suffering from severe water security challenges (Stringer et al., 2021). Dryland inhabitants in many developing countries are also experiencing poverty (Section 16.1.4.3), hunger, poor health, land degradation, and economic and political marginalisation (Mbow et al., 2019; Mirzabaev et al., 2019), which sometimes limits their access to common pool resources. These challenges, together with a weak enabling environment, threaten opportunities to adapt to climate change.

The terms "desert" and "desertification" are subject to various interpretations due to the diverse components, processes and states they denote. Recognizing "land degradation" as a contested and perceptual term (Blaikie and Brookfield, 1987; Behnke and Mortimore, 2016; Robbins, 2020), this cross-chapter paper, defines land degradation as "a negative trend in land condition, caused by direct or indirect human-induced processes including climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans" (Olsson et al., 2019). Desertification is land degradation in arid, semi-arid, and dry sub-humid areas (UNCCD, 1994). Following the above definitions, desertification is more common in arid and semi-arid climates than in hyper-arid climates. When desertification does occur in arid and hyper-arid ecosystems it is often in oases and irrigated cultivated lands (Ezcurra, 2006; Dilshat et al., 2015). Hyper-arid areas, except wetlands such as oases, wadis and riverbanks, are excluded in the United Nations Convention to Combat Desertification (UNCCD) definition of desertification used here, yet many of the world's deserts are in hyper-arid areas. Hyper-arid areas are therefore included when discussing deserts but not when discussing desertification. Deserts are not the end point in a desertification process (Ezcurra, 2006), and there is robust evidence of desertification in deserts, mostly driven by human activities and climate variability, expressed as loss of biological productivity, ecological integrity or value to humans to below their natural levels (Moridnejad et al., 2015).

Interactions between climate change and desertification in drylands create challenges for both ecosystem and human resilience, affecting ecosystem services, biodiversity, food security, human health and wellbeing (Reed and Stringer, 2016). Dryland livelihoods that heavily rely on natural ecosystems face pressures including high population growth rates, weak or poor governance, low investment, unemployment and poverty, market distortions and underestimates of the value of drylands (Stringer et al., 2017; Bawden, 2018). These pressures intersect with broader societal challenges such as conflict and civil unrest (Okpara et al., 2015; Almer et al., 2017), which together, can contribute to human displacement (Section 16.2.3.8) in some drylands (Warner, 2010; Abel et al., 2019). Nevertheless, evidence linking conflict with climate change and desertification is weak (Benjaminsen et al., 2012) and data are insufficient to draw robust conclusions.

Drylands yield important opportunities for adapting to and mitigating climate change. They offer abundant solar energy which could support mitigation efforts, opportunities for cultural and nature-based tourism, rich plant biodiversity in some areas (e.g. Namibia), and extensive Indigenous knowledge and experience of adapting to dynamic climates (Christie et al., 2014; Stringer et al., 2017), e.g. across West Asia and North Africa (Louhaichi and Tastad, 2010; Hussein, 2011). Improved understanding of challenges and opportunities in drylands can be achieved by transdisciplinary, multi-scale and inter-sectoral approaches encompassing links between physical, biological and socioeconomic, and institutional systems (Reynolds et al., 2007; Stringer et al., 2017).

Chapter 3 of the IPCC Special Report on Climate Change and Land (SRCCL) focused on desertification, but links between climate change and deserts, desertification and semi-arid areas have not been extensively considered in recent IPCC assessment cycles. AR5 noted that desertification contributes to atmospheric dust production, identifying desertification as needing consideration within climate change mitigation and adaptation governance and decision-making (Boucher et al., 2013; Myhre et al., 2013). This cross-chapter paper focuses on environmental and human aspects, finding that climate change impacts will intensify the challenges faced by dryland populations in advancing sustainable development. However, viable options exist for adapting to climate change, reducing desertification and supporting progress towards the Sustainable Development Goals (SDGs), particularly by combining modern science, Indigenous knowledge, and local knowledge, as well as livelihood and land management strategies that enable land-based adaptation, mitigation and nature-based solutions (Section 16.3.2.3).

CCP3.1.2 Key Measurement Challenges and Observed Dryland Dynamics

Maps of dryland extent commonly employ a climate-based approach measured using the aridity index (AI), or consider the extent of dryland vegetation. The two approaches sometimes do not demarcate the same geographical areas as being drylands, particularly when projecting future changes (Stringer et al., 2021). Dryland dynamics therefore need to be viewed specifically in relation to the definitions and measurements being used. From 1982 to 2015, unsustainable land use and climate change combined caused desertification of 6% of the global dryland area, while 41% showed significant greening (i.e. increased vegetation productivity), and 53% of the area had no notable change (Figure CCP3.1; Burrell et al., 2020);). In contrast Yuan et al. (2019) conclude that during 1999-2015, trends of vegetation production reversed globally and in drylands, showing extensive declines. Thus, while overall greening has occurred, this trend now appears to be declining. Analyses of vegetation, soil, and physical characteristics of over 50 000 sample points in drylands around the world indicate that aridification causes ecological degradation at three successive thresholds: vegetation decline at aridity index = 0.56, soil disruption at aridity index = 0.3, and loss of plant cover at aridity index = 0.2 (Berdugo et al., 2020). Drylands nevertheless show different dynamics depending on the index used and the variables assessed.

Based on the AI, some drylands are projected to expand and others to contract due to climate change. However, there is no evidence of a global trend in dryland expansion based on vegetation patterns, precipitation and soil moisture, based on the satellite record from the 1980s to the present (*medium confidence*). The AI will also be of limited use under a changing CO_2 environment due to higher water use efficiency by some plants (Mirzabaev et al., 2019), and it overvalues the role of potential evapotranspiration (PET) relative to rainfall. It also does not account for CO_2 impacts on evapotranspiration, and seasonality in rainfall and evapotranspiration. Higher annual PET because of increased temperatures will have little impact if temperature and actual evapotranspiration are not rising during the period of vegetation growth (Stringer et al., 2021).

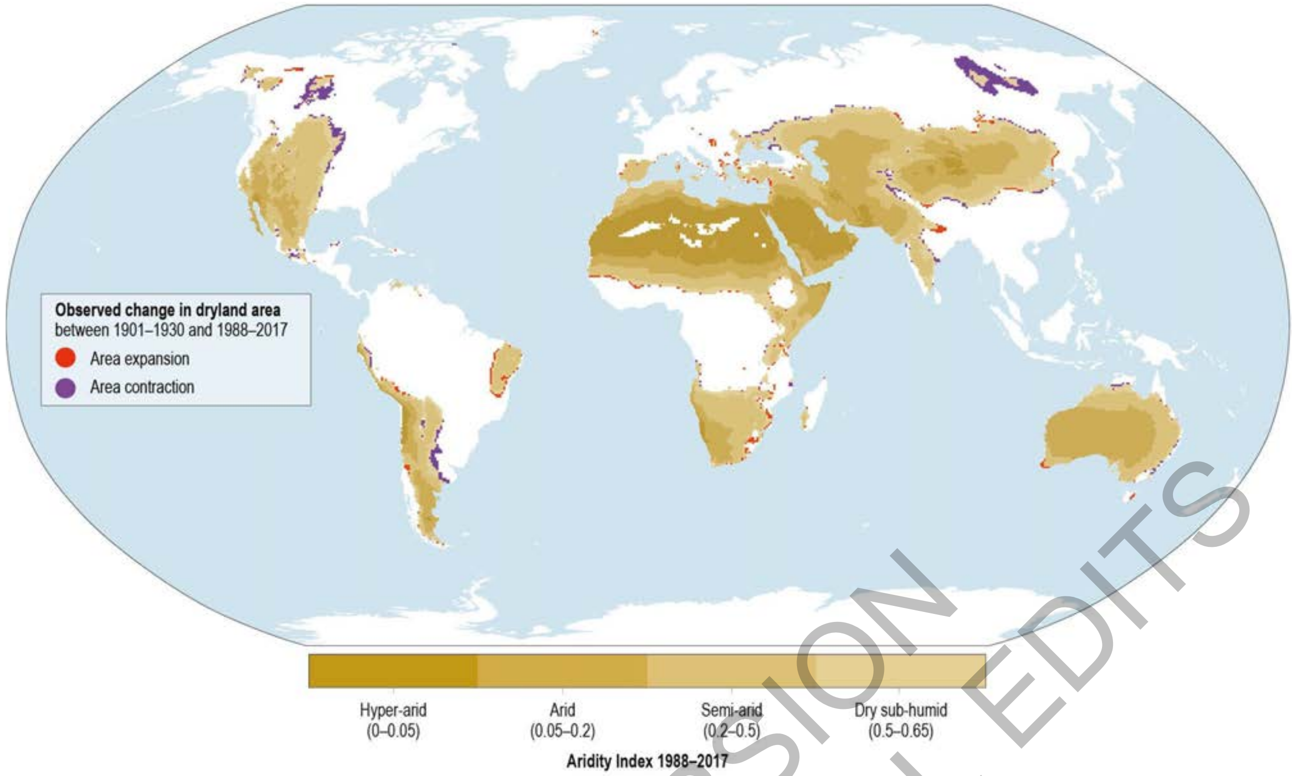


Figure CCP3.1: Aridity zone extent and observed changes in dryland areas as defined by the Aridity Index. Aridity zones, according to UNESCO (1979) and UNEP (1992) classifications, defined by the aridity index (AI), consider the ratio of average annual precipitation to potential evapotranspiration: (i) dry sub-humid ($0.5 \leq AI < 0.65$), (ii) semi-arid ($0.2 \leq AI < 0.5$), (iii) arid ($0.05 \leq AI < 0.2$) and (iv) hyper-arid ($AI < 0.05$). Drylands include land with AI < 0.65, humid lands are those with AI >0.6. Drylands include land with AI < 0.65, humid lands are those with AI >0.65 (UNEP, 1992). Deserts represent a major part of the hyper-arid and arid zones. The aridity zones are shown for climate in the period 1988-2017 and changes in dryland area (combined area of four aridity zones) are shown between the periods 1901-1930 and 1988-2017, based on climate time series at 50 km spatial resolution (Harris et al., 2020). The AI has various limitations in assessing dryland expansion and different indices highlight different areas and different changes. This is known as the aridity paradox (Greve et al., 2019). See SRCCL Section 3.2.1 (Mirzabaev et al., 2019) for an in-depth analysis of limitations, and Stringer et al. (2021) for a summary of different measures and indices used in the literature.

CCP3.2 Observed Impacts of Climate Change Across Sectors and Regions

CCP3.2.1 Observed Impacts on Natural Systems in Arid and Semi-arid Areas

CCP3.2.1.1 Temperature and Rainfall

Significant warming has occurred across drylands globally (WGI, 2021). Surface warming (from 1920-2015) of 1.2ºC-1.3ºC in global drylands has exceeded the 0.8ºC-1.0ºC warming over humid lands (Huang et al., 2017). As measured by the AI, this has expanded the area of drylands by ~4% from 1948-2004 (Ji et al., 2015; Spinoni et al., 2015; Huang et al., 2016). However, as mentioned in Figure CCP3.1, the AI has various limitations in assessing drylands expansion. Increases in potential evapotranspiration have exceeded increases in precipitation in the last half of the period 1901-2017 (Pan et al., 2021). Observations from the Sahel demonstrated that temperature seasonality changes differ from rainfall seasonality changes (Guichard et al., 2015), and there has been an increase in surface water and groundwater recharge in the Sahel since the 1980s, referred to as "the Sahel paradox" (Favreau et al., 2009; Gardelle et al., 2010; Descroix et al., 2013; Wendling et al., 2019). Research from the USA suggests that historical soil moisture levels can contribute to such variability (Heisler-White et al., 2009). Studies from the Middle East show rising temperatures and declining rainfall trends (ESCWA, 2017), with most decreasing aridity trends in north Sudan and most increasing aridity trends in eastern Arabia over the period 1948-2018 (Sahour et al., 2020).

CCP3.2.1.2 Ecosystem Processes

Semi-arid ecosystems have a disproportionately large role in the global carbon cycle, driving trends and inter-annual variability of the global carbon sink (Alstrom et al., 2015). These systems are highly sensitive to annual precipitation and temperature variations (*high confidence*) (Alstrom et al., 2015, Poulter et al., 2014). The positive trend in semi-arid regions is consistent with widespread woody encroachment and increased vegetation greenness (Andela et al., 2013; Piao et al., 2019; Piao et al., 2020) driven by CO_2 fertilisation and rainfall increases (Sitch et al., 2015; Piao et al., 2020), although some trends are complicated by irrigation practices (He et al., 2019). Increases in temperature and drought diminish this trend through reduced vegetation productivity and increased vegetation mortality (Brandt et al., 2016; Ma et al., 2016; Fernández-Martínez et al., 2019; Maurer et al., 2020) with indications that this trend is declining or reversing in some locations (Yuan et al., 2019; Wang et al., 2020).

Changed climates have increased water constraints of vegetation growth most notably in the Mediterranean (CCP1.2.3.2, CCP4.2.1) and west and central Asia (Jiao et al., 2021). Climate change and elevated CO_2 have both increased and decreased vegetation sensitivity to rainfall throughout drylands, with the degree of variation shaped by region, land-use and vegetation traits (Haverd et al., 2017; Abel et al., 2021). Mineral nitrogen production in drylands may become increasingly decoupled from consumption by plants over prolonged dry periods, and more extreme hydrological events can drive multiple changes to nutrient cycling (Manzoni et al., 2019). Soil biocrusts (composed of lichens, bryophytes and soil microorganisms) which contribute to dryland ecosystem function including carbon uptake and soil stabilisation (Reed et al., 2019), are sensitive to warming and altered rainfall in a shift in biocrust communities of mosses and lichens in favour of early successional cyanobacteria-dominated biocrusts (Escolar et al., 2012; Reed et al., 2012), which can increase surface albedo (Rutherford et al., 2017).

CCP3.2.1.3 Vegetation Changes

CCP3.2.1.4 Woody Cover Increase

Dryland ecosystems have shown mixed trends of decreases and increases in vegetation and biodiversity, depending on the time period, geographic region, and vegetation type assessed (see Table CCP3.1 for examples of observed environmental changes and impacts in drylands and the role of climate change and non-climatic factors in causing these changes).

Increases in shrub cover in arid deserts and shrublands have been recorded in the North American drylands (Caracciolo et al., 2016; Archer et al., 2017; Chambers et al., 2019), the Namib desert (Rohde et al., 2019), the Karoo (Ward et al., 2014; Masubelele et al., 2015b), north and central Mexico (Pérez-Sánchez et al., 2011; Báez et al., 2013; Castillón et al., 2015; Sosa et al., 2019), large parts of the West African Sahel with some local exceptions (Brandt et al., 2016), and in Central Asia (Jia et al., 2015; Li et al., 2015; Deng et al., 2016; Jiao et al., 2016; Wang et al., 2016). Increasing woodiness in the Namib is consistent with an increase in rainfall extremes and westward expansion of convective rainfall (Haensler et al., 2010; Rohde et al., 2019). Increasing rainfall and rising CO_2 concentrations (which improves water use efficiency) benefits some shrubs (Polley et al., 1997; Morgan et al., 2004; Donohue et al., 2013). Together with changes in land use (Hoffman et al., 2018), improved land management (Reij et al., 2005) and improved irrigation (He et al., 2019) this contributes to woody cover increases. Extensive woody encroachment has been recorded in savannas (measured between 1920-2015, over the past century) in Africa (2.4% woody cover increase/decade), Australia (1% increase/decade), and South America (8% increase/decade) (O'Connor et al., 2014; Stevens et al., 2016; Skowno et al., 2017; Venter et al., 2018; Zhang et al., 2019). Following drought in the Sahel (1968-1973 and 1982-1984), a rainfall increase since the mid-1990s has been linked to increases of woody cover between 1992-2011/2012 (Brandt et al., 2016; Brandt et al., 2017; Brandt et al., 2019). See SRCCL section 3.2.1.1 for an evaluation of NDVI and remote sensing approaches used in these studies. Tree regeneration by farmers has also increased woody cover, particularly next to villages (*high confidence*) (Reij et al., 2005; Reij and Garrity, 2016; Brandt et al., 2018). Otherwise, savanna encroachment has been attributed to combinations of increased rainfall (Venter et al., 2018; Zhang et al., 2019), warming (Venter et al., 2018) and CO_2 fertilisation (Kgope et al., 2010; Bond and Midgley, 2012; Buitenwerf et al., 2012; Stevens et al., 2016; Quirk et al., 2019) interacting with changing land use (Archer et al., 2017; Venter et al., 2018) where herbivory and fire regimes are altered (O'Connor et al., 2014; Archer et al., 2017;see also discussion on fire and herbivory in Section 2.4.3.1.2). In some cases, woody increase has been balanced locally by changes in runoff (Trichon et al., 2018), or by land clearing and fuel wood harvesting, as seen in western Niger, northern Nigeria, and at the periphery of major towns (Montagné et al., 2016).

CCP3.2.1.5 Tree Death and Woody Cover Decline

Field measurements have also detected tree mortality and loss of mesic tree species at some Sahel sites during drought periods (Gonzalez et al., 2012; Kusserow, 2017; Brandt et al., 2018; Ibrahim et al., 2018; Trichon et al., 2018; Zwarts et al., 2018; Bernardino et al., 2020; Zida et al., 2020) and a reduction of mesic species in favour of drought-tolerant species (*high confidence*) (Hänke et al., 2016; Kusserow, 2017; Ibrahim et al., 2018; Trichon et al., 2018; Dendoncker et al., 2020; Zida et al., 2020b), with attribution to climate change (Gonzalez et al., 2012). Furthermore, vegetation productivity per unit of rainfall showed a net decline of 4% in the period 2000-2015 across drylands globally, with the greatest net declines in Africa (16%) and Asia (33%) (Abel et al., 2021), but with location-specific increases in vegetation-rainfall sensitivity, e.g. in southern and eastern Africa and parts of the Sahel. Furthermore, NDVI declines were reported across the Sahel from 1999 to 2015 (Yuan et al., 2019; Zida et al., 2020a). However, field site monitoring showed a strong regeneration of the decimated woody populations except on shallow soil where the runoff system had evolved towards a web of gullies (Hiernaux et al., 2009a; Trichon et al., 2018; Wendling et al., 2019) .

Other site-specific impacts include tree mortality in south-western Morocco (Le Polain de Waroux and Lambin, 2012), mortality of *Austrocedrus* and *Nothofagus* forests in the dry Patagonia forest-steppe (Rodríguez-Catón et al., 2019), and a tree range contraction of *Aloidendron dichotmum* in Southern Africa (Foden et al., 2007b). In Morocco, tree mortality was most highly correlated to an increase in aridity, measured by the Palmer Drought Severity Index (PDSI), which showed a statistically significant increase since 1900 due to climate change (Dai et al., 2004; Esper et al., 2007; Dai, 2011).

In deserts of the south-western United States, a drought since 2000, mainly due to climate change (Williams et al., 2020), together with land use change, invasive plant species, and wildfire (Syphard et al., 2017), has led to reductions in native desert plant species (Defalco et al., 2010; Conver et al., 2017) and perennial vegetation cover (Munson et al., 2016a; Munson et al., 2016b). An increase in invasive exotic grasses has increased wildfires in these desert ecosystems in which fire had been rare (Brooks and Matchett, 2006; Abatzoglou and Kolden, 2011; Hegeman et al., 2014; Horn and St. Clair, 2017). In the Mojave Desert in the United States, a loss of bird biodiversity has also been detected and attributed to increased aridity caused by climate change (Iknayan and Beissinger, 2018; Riddell et al., 2019).

CCP3.2.1.6 Change in Herbaceous Cover

Changes in aridity (Rudgers et al., 2018) have caused some expansion of dominant grasses (often invasive) into desert shrublands. The spread of invasive *Bromus tectorum* may be enhanced by altered precipitation and freeze-thaw cycles (*low confidence*) (Collins and Xia, 2015; Rudgers et al., 2018). Arid grassland has expanded (between 10-100 km) into the eastern Karoo, South Africa (*high confidence*) (du Toit et al., 2015; Masubelele et al., 2015a; Masubelele et al., 2015b). Observations from 100-year-old grazing trials demonstrate that the increase in grassiness is a product of shift in rainfall seasonality and an increase in rainfall (Du Toit and O'Connor, 2014; du Toit et al., 2015; Masubelele et al., 2015a; Masubelele et al., 2015b; du Toit et al., 2018). These changes are causing an increase in fire frequency in these seldom burnt areas (du Toit et al., 2015). The Sahara Desert was suggested to have expanded 10% from 1902 to 2013 (Thomas and Nigam, 2018), although herbaceous vegetation production has increased in general in the Sahel since the dry 1980s (Eklundh and Olsson, 2003; Anyamba and Tucker, 2005; Herrmann et al., 2005; Hutchinson et al., 2005; Olsson et al., 2005; Fensholt et al., 2006; Dardel et al., 2014; Hiernaux et al., 2016; Stith et al., 2016; Benjaminsen and Hiernaux, 2019; Hiernaux and Assouma, 2020).

Trends of land degradation (Section 16.4.1.2) and desertification (as demonstrated by loss of cover or reduced vegetation productivity) as an impact of changing climatic trends have been reported in Burkina Faso (Zida et al., 2020), the north-western regions of China during 1975-1990 (Zhang et al., 2020) in Afghanistan (Savage et al., 2009), Iran (Mahmoudi et al., 2011; Kamali et al., 2017), Argentina (Barbosa et al., 2015) and India (Javed et al., 2012). Encroachment, re-greening and an increase of unpalatable plant species into rangeland areas (e.g. in East Africa and southern Africa's Kalahari) all contribute to dryland degradation through the loss of open ecosystems and their services (Reed et al., 2015; Le et al., 2016; Chen et al., 2019b).

Table CCP3.1: Observed ecological changes in drylands.
[INSERT TABLE CCP3.1 HERE]

CCP3.2.1.7 Sand and Dust Storms

Soil dust emissions are highly sensitive to changing climate conditions but also to changing land use and management practices (*high confidence*). Distinguishing between the effects of these drivers is not straightforward, even in well-documented locations (Middleton, 2019). There is *limited evidence and low agreement* about the impacts of climate change on sand and dust storms (SDS), with studies pointing to either substantial increases (+300%) or decreases (-60%) (Boucher et al., 2013). Current climate models cannot adequately model the impact of climate change on SDS activity (Mirzabaev et al., 2019). However, there is *high confidence* that land degradation, loss of vegetative cover, and drying of water bodies in semi-arid and arid areas will contribute to sand and dust activity (Mirzabaev et al., 2019).

Sand and dust storms remain a major concern for desert areas under conditions of climate change and desertification (Middleton, 2017). Only about 20% of deserts are covered by sand, but desert sand and dust storms provide an important feedback mechanism to climate (Pu and Ginoux, 2017), with literature showing that some areas have very frequent dust days (Figure CCP3.2; Ginoux et al., 2012). In some locations such as the USA, desert dust can be deposited downwind on snowpacks, hastening snowmelt and altering river hydrology (Painter et al., 2010). Deserts and other natural dryland surfaces produced 75-90% of atmospheric dust globally in the early 21st century, with the remainder from agricultural and other land dominated by human land use (Ginoux et al., 2012; Stanelle et al., 2014).

Recent changes in dust emissions and their attributions vary geographically. Warming in Iran over the period 1951–2013 has been associated with an increased frequency of dust events (Alizadeh-Choobari and Najafi, 2018) and a trend (2000–2014) towards increased fine atmospheric mineral dust concentrations in the US southwest has been linked to increasing aridity (Hand et al., 2017). Conversely, increases in rainfall, soil moisture, and vegetation linked to changes in circulation strength of the Indian summer monsoon since 2002 have led to a substantial reduction of dust in the Thar Desert and surrounding region, showing agreement with findings from the Sahel and the West African Monsoon (Kergoat et al., 2017). A decreasing trend in the number and intensity of SDS in spring (2007-2016) in East Asia has also responded to higher precipitation and soil moisture, related to a decrease in the intensity of the polar vortex, favouring higher vegetation cover during the period studied (An et al., 2018). Global climate change, transboundary movement of aeolian material by atmospheric flows from Central Asia, dynamics of the Caspian Sea regime, erosion, salinization, as well as the loss of land as a result of the placement of industrial facilities have expanded the land area prone to desertification in Russia. Desertification has been observed to some extent in 27 sub-regions of the Russian Federation on territory of more than 100 million hectares (Kust et al., 2011; also recently confirmed by National Report, 2019). Eastern and south-eastern regions of Kalmykia, Russia, serve as dust sources, while dust and sand masses from the areas of the Black Land sometimes move far beyond to parts of Rostov, Astrakhan, Volgograd, and Stavropol regions. Agricultural land in these areas can become covered with dust and sand 10 cm or more thick, with negative impacts on yields (Tsymbarovich et al., 2020). High dust day frequency is occurring also in the High Latitude Dust (HLD) source areas not reported in Figure CCP3.2 such as in Iceland, Patagonia, Canada, Alaska, and based on *in situ* measurements in Antarctica (Dagsson-Waldhauserová et al., 2014; Bullard et al., 2016; Dagsson-Waldhauserova and Meinander, 2019; Bachelder et al., 2020). Active HLD dust sources cover at least 500,000 km^2 and produce at least 5% of global dust budget (Bullard et al., 2016). HLD has negative impacts on the cryosphere via albedo changes and snow/ice melting (Boy, 2019; Dagsson-Waldhauserova and Meinander, 2019).

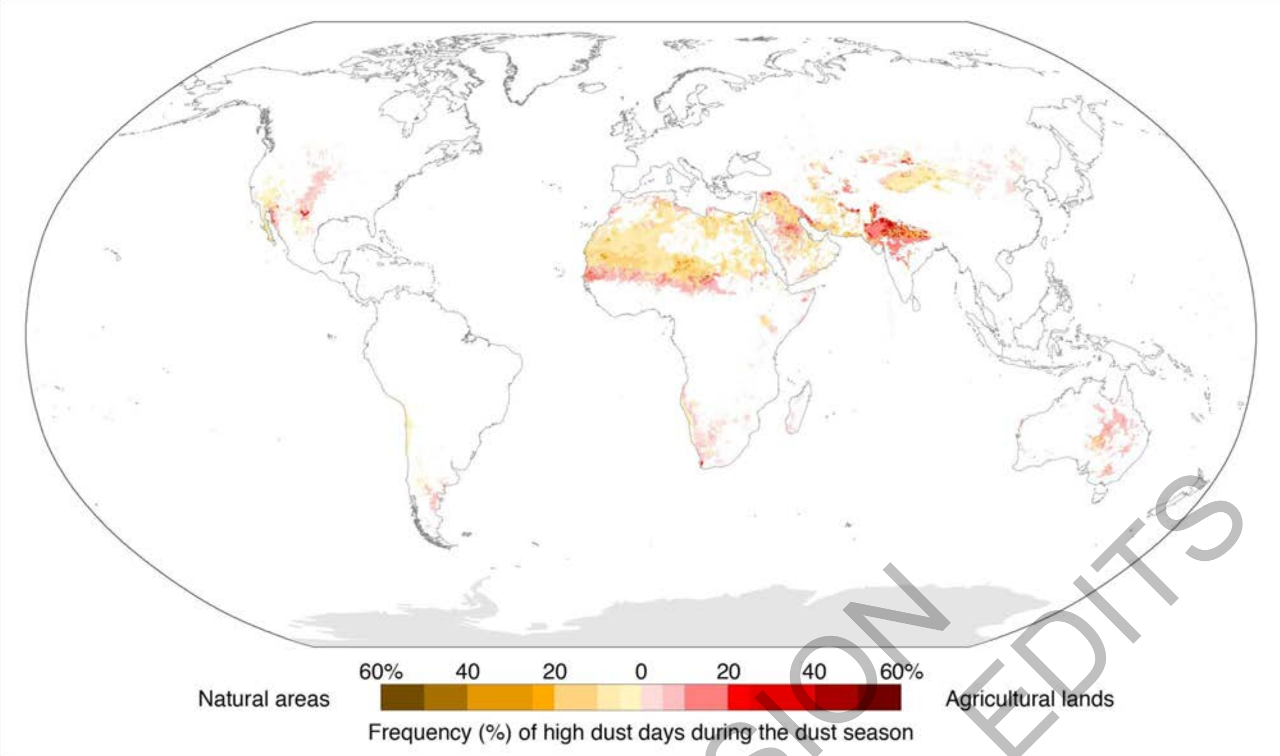


Figure CCP3.2: Frequency of high dust days (dust optical depth >0.2) during the dust season, based on 2003-2009 remote sensing, the most recent data analysed, and divided into areas primarily in agriculture and areas dominated by natural land cover (Ginoux et al., 2012). Dust seasons: Africa (North), Year-round; Africa (South), September-February; America (North), March-May; America (South), December-February), Asia, March-May; Australia, September-February.

CCP3.2.1.8 Water Scarcity

Climate change and desertification have been linked to water loss (Bayram and Öztürk, 2014; Schwilch et al., 2014; Mohamed et al., 2016), decreases in water quantity for irrigation, and contamination of surface water bodies (Middleton, 2017). Increased runoff in areas in the Sahel with shallow soils increased water flows to lakes and the recharge of water tables (Favreau et al., 2009; Gardelle et al., 2010; Descroix et al., 2013; Kaptué et al., 2015; Gal et al., 2017). Water scarcity (Section 16.5.2.3.7) was among the first impacts of climate change recognized in North African countries such as Morocco which have extensive dryland areas, with countries such as Turkey, Libya, USA and China carrying out large-scale water transfer projects (Sternberg, 2016; Stringer et al., 2021). The decrease in water availability in Morocco was substantial in terms of both surface water supply (Rochdane et al., 2012; Choukri et al., 2020) and groundwater (Bahir et al., 2020), threatening agricultural production.

CCP3.2.2 Observed Impacts of Climate Change on Human Systems in Desert and Semi-Arid Areas

Climate change and desertification, alongside other drivers of degradation, reduce dryland ecosystem services, leading to losses of biodiversity, water, food, and impacts on human health (CCP4.2.3, WG2) and well-being *(high confidence*) (Mirzabaev et al., 2019) resulting in disruption to the economic structures and cultural practices of affected communities (Elhadary, 2014; Middleton, 2017).

CCP3.2.2.1 Sand and Dust Storms

Desertification and SDS can cause substantial socioeconomic damage in drylands (UNEP, 1992; Opp et al., 2021) over both the short and long term. Short-term impacts occur on health, food production systems, infrastructure (damaging buildings, energy systems, and communications), transport and related economic productivity, air and road traffic, and costs are incurred in clearing sand and dust from deposition areas (Mirzabaev et al., 2019). In the Arab region increasing frequency of SDS events is projected to further exacerbate water scarcity and drought (ESCWA, 2017). Longer-term costs include loss of ecosystem services, biodiversity and habitat, chronic health problems, soil erosion and reduced soil quality (particularly through nutrient losses and deposition of pollutants), and disruption of global climate regulation (Middleton, 2018; Allahbakhshi et al., 2019). Dust deposition nevertheless can offer environmental and economic benefits, bringing important nutrients that improve and sustain soil fertility (Marticorena et al., 2017). Preventing and reducing SDS entails upfront investment costs but full cost-benefit analyses of different measures compared to the costs of inaction are scarce and need to consider the likely frequency and magnitude of SDS events (Tozer and Leys, 2013).

CCP3.2.2.2 Human Health

Potential impacts of climate change, recurrent droughts and desertification on human health in drylands include: higher risks from water scarcity (linked to deteriorating surface and ground water quality and water-borne diseases; Stringer et al., 2021), food insecurity and malnutrition (Section 16.2.3.3) in the absence of sufficient imports; respiratory, cardiovascular and infectious diseases caused by SDS (Mirzabaev et al., 2019), potential displacement and migration and mental health consequences (Chapter 7; Stringer et al., 2021) and heat stress (Dunne et al., 2013; Zhao et al., 2015; Russo et al., 2016). SDS negatively impact human health through various pathways, causing respiratory, cardiovascular diseases and facilitating infections (*high confidence*) (Díaz et al., 2017; Goudarzi et al., 2017; Allahbakhshi et al., 2019; Münzel et al., 2019). SDS can cause mortality and injuries related to transport accidents (Goudie, 2014). Research from China suggests that prenatal exposure to SDS can affect children's cognitive function (Li et al., 2018). The pollutants that are entrained and ingested or inhaled closely link to the land management strategies in source areas.

Droughts (TS.2.6 L, AR6, WGI) are among the natural hazards with the highest adverse impacts on human populations (Mishra and Singh, 2010). Although droughts just represented 4% of hazard events, their impacts amounted to 31% of affected people (29 million) (Louvain, 2019). Drought exposure relates to a higher risk of undernutrition (Section 16.5.2.3.6), among vulnerable populations (Kumar, 2016), particularly children (IFPRI, 2016) for whom the impacts can lead to lifelong consequences through stunted growth, impaired cognitive ability and reduced future educational and work performance (UNICEF/WHO/WBG, 2019). The corresponding costs of children stunting in terms of lost economic growth can be of the order of 7% of per capita income in developing countries (Galasso and Wagstaff, 2018).

CCP3.2.2.3 Agro-ecological Food Systems, Livelihoods and Food Security

Rising temperatures, variation in rainfall patterns and frequent extreme weather events associated with climate change have adversely affected agro-ecological food systems and pastoral systems in some drylands (Section 16.3.2.6Zhu et al., 2013; Amin et al., 2018), especially in developing countries (Haider and Adnan, 2014; Ahmed et al., 2016; ur Rahman et al., 2018) where desertification is a key challenge to agricultural livelihoods. Recurrent droughts in recent decades, coupled with wind erosion (particularly of fine sediment which gives soil its water holding capacity and nutrients), affected vast areas in Argentina, leading to land abandonment and agricultural fields being covered by sand and invasive plants (Abraham et al., 2016). Temperature increases have contributed to reduced wheat yields in arid, semi-arid and dry sub-humid zones of Pakistan (Sultana et al., 2019). Agricultural production in the drylands of South Punjab is experiencing irreversible impacts since the grain formation phase has become swifter with a warmer climate, leading to improper growth and reduced yields (Rasul et al., 2011).

Aslam et al. (2018) regard climate change impacts to be particularly threatening to the livestock sector, water and food security and the economy beyond agriculture in South Punjab, particularly as yields decrease. In the livestock sector across global drylands (TS.4.3.2.10, AR 6, WGI), observed impacts include reduction of plant cover in rangelands, reduced livestock and crop yields, loss of biodiversity and increased land degradation and soil nutrient loss (Van de Steeg, 2012; Mganga et al., 2015; Ahmed et al., 2016; Mohamed et al., 2016; Eldridge and Beecham, 2018) as well as injury and livestock death due to SDS. This is particularly worrisome for traditional pastoralists who find themselves with fewer safety nets and limited adaptive capacities than in the past, particularly where mobility, access and tenure rights are becoming restricted (Section 16.3.2.6; Box CCP3.1) and where use of technologies such as mobile phones can result in mixed effects, as found in Morocco (Vidal-González and Nahhass, 2018). Observed SDS impacts can increase food production costs and threaten sustainability more generally (Middleton, 2017).

Woody-plant encroachment and greening may be masking underlying land degradation processes and losses of ecosystem services, livelihood and adaptation options in pastoral livelihood systems (Reed et al., 2015; Chen et al., 2019a). Woody encroachment alters ecosystem services, particularly in rangelands, resulting in reduction of grass cover, hindering livestock production (Anadón et al. 2014), reducing water availability (Honda and Durigan 2016, Stringer et al., 2021) but increasing availability of wood (Mograbi et al., 2019).

[START BOX CCP3.1 HERE]

Box CCP3.1: Pastoralism and Climate Change

Pastoralism is a livestock keeping system based on the herding of animals. Migrations often take place over long distances to track variable and unpredictable plant growth that tends to be patchy in space and variable in time (Homewood, 2018). Pastoralism has a considerably lower carbon budget than other livestock-keeping systems, with research on pastoralism in the Sahel concluding that this system may be carbon neutral (Assouma et al., 2019), despite contributing directly to greenhouse gas emissions via methane enteric emissions and indirectly through faeces-driven CO_2, CH_4 and N_2O emissions during mineralisation (Assouma et al., 2017). Efforts to sedentarize and villagize pastoralists can lead to land degradation and higher overall emissions from the sector (Section 16.3.2.6).

Pastoralists migrate with their animals in some of the most remote and marginal environments on the planet. Globally, mobile pastoralists number about 200 million households and use about 25% of the Earth's landmass (Dong, 2016). Many pastoralists operate in non-equilibrial environments that are unstable, fluctuating and generally uncertain, and driven more by climatic variation than livestock numbers and grazing pressure (Behnke et al., 1993). Examples of such systems are grazing areas in the dry tropics (Sandford, 1983; Turner, 1993; Sullivan and Rohde, 2002; Benjaminsen et al., 2006; Hiernaux et al., 2016), and rangelands in the Arctic (Behnke, 2000; Tyler et al., 2008; Benjaminsen et al., 2015; Marin et al., 2020).

Over many generations, pastoralists have accumulated practical experience and knowledge to cope with uncertainty and value variability (Krätli and Schareika, 2010), mainly through a mobile and flexible approach. While pastoralists are also at risk of climate change impacts, they may be better able to adapt to a changing climate than other land users (Davies and Nori, 2008; Krätli and Schareika, 2010; Jones and Gutzler, 2016).

While pastoralists possess substantial adaptive capacity as a result of their Indigenous knowledge, this has been under pressure during the last few decades through continued loss of livestock corridors (essential to mobility) and pastures in general due to competing land-uses such as farming, mining, crop expansion and the establishment or extension of protected areas (Thébaud and Batterbury, 2001; Brockington, 2002; Benjaminsen and Ba, 2009; Upton, 2014; Johnsen, 2016; Tappan, 2016; Homewood, 2018; Weldemichel and Lein, 2019; Bergius et al., 2020). Many of these competing land uses erect fences and exclude other uses, while property rights often privilege sedentary farming.

Modern states have typically tried to settle pastoralists and confine their movements within clearly defined boundaries, claiming that pastoral land-use is neither ecologically sustainable nor economically productive. Based on such negative and often flawed views, stall-feeding and ranching are often presented by policymakers as successful models of livestock keeping in contrast to the pastoral way of life (Steinfeld et al., 2006; Chatty, 2007).

Current pressures and processes of pastoral change are spatially variable and complex, and tend to result in further economic and political marginalization of pastoralists, with adverse effects on livelihoods and landscapes. With climate change, which is projected to lead to higher temperatures and more frequent fluctuations in precipitation, maintaining flexibility and resilience in pastoral land use is essential. However, current processes of marginalization, in addition to increased insecurity in some drylands (e.g. the Sahel), make pastoralists more vulnerable, and constrain them from fully employing their adaptive capacities

(Davies and Nori, 2008). The skills and capacities held by pastoralists may, however, offer lessons for society at large in its struggle to adapt to climate change and deal with increased uncertainty (Davies and Nori, 2008; Scoones, 2009; Nori and Scoones, 2019).

[END BOX CCP3.1 HERE]

CCP3.2.2.4 Gender Differentiated Impacts

Impacts of desertification, climate change, and environmental degradation, as well as vulnerability and capacity to adapt, are gendered. Differences are determined by socially structured gender-specific roles and responsibilities, ownership of, access to and control over natural resources and technology, decision making, and capacity to cope and adapt to long-term changes (Mirzabaev et al., 2019; Cross-Chapter Box GENDER in Chapter 18). Assessments of the gender dimension of desertification and climate change impacts and responses are scarce, and highly context specific. For example, in many lower income countries, rural women produce most of the household food, and are responsible for food preparation and collecting fuelwood and water from increasingly distant sources (Mekonnen et al., 2017; Droy, 2020). Drought and water scarcity particularly affect women and girls in drylands because they need to spend more time and energy collecting water and fuelwood, have less time for education or income generating activities, and may be more exposed to violence (Sommer et al., 2014) and less able to migrate as an adaptation option. Women are also commonly excluded from family and community decision making on actions to address desertification and climate change, yet their engagement in climate adaptation is critical. International policy efforts are currently seeking to better recognise and address this challenge (Okpara et al., 2019).

CCP3.2.2.5 Climate Change, Migration and Conflict

Dryland populations pursuing traditional land-based livelihood options are generally mobile due to a highly fluctuating resource base (Box CCP3.1). Many rural dwellers in drylands also move to urban areas for seasonal work which can have positive impacts in terms of remittances. While reasons for migration vary and can be positive or negative, oppression and human rights abuses, lack of livelihood opportunities and food insecurity tend to be among the main push factors, while emerging opportunities at the rural-urban nexus present lucrative pull factors (Cross-Chapter Box MIGRATE in Chapter 7). In a survey in Libya in 2016, 80% of migrants interviewed said they had left home because of economic hardship (Hochleithner and Exner, 2018), which in drylands under water scarcity linked to climate change, would be exacerbated.

Causes of migration and violent conflict need to be seen in a wider historical, agrarian, political, economic and environmental context, in a multi-scalar perspective integrating levels of analysis from the local to the global (Glick Schiller, 2015). Quantitative studies tend to conclude that climate change has so far not significantly impacted migration including in drylands (Owain and Maslin, 2018), although with some disagreement (Lima et al., 2016; Missirian and Schlenker, 2017). In a study of the climate change-migration-conflict interface, Abel et al. (2019) found limited empirical evidence supporting a link between climatic shocks, conflict and asylum-seeking for the period 2006–2015 from 157 countries. The authors found evidence of such a link for the period 2010–2012 relating to some countries affected by the Arab Spring and concluded that the impact of climate on conflict and migration is limited to specific time periods and contexts.

The same lack of general causality is largely concluded on the specific link between climate change and conflict (Buhaug et al., 2014; Buhaug et al., 2015; von Uexkull et al., 2016; Koubi, 2019), but a minority of quantitative studies argue for a stronger causal association (Hsiang et al., 2013). Mach et al. (2019) found considerable agreement among experts that climate variability and change have influenced the risk of organized armed conflict within countries, but they also agreed that other factors, such as state capacity and level of socioeconomic development, played a much larger role. These factors also play a role in determining adaptation possibilities and in shaping the enabling environment (Section 8.5.2).

Qualitative case studies tend to frame conflict and migration within a larger political, economic and historical context. A number of studies from African drylands find that land dispossession is a key driver of both migration and conflict resulting from large-scale resource extraction or land encroachment often associated with processes of elite capture and marginalization (Benjaminsen and Ba, 2009; Benjaminsen et al., 2009; Cross, 2013; Glick Schiller, 2015; Nyantakyi-Frimpong and Bezner Kerr, 2017; Obeng-Odoom, 2017; Bergius et al., 2020). By undermining livelihoods, exacerbating poverty, and setting rural population groups adrift, land dispossession in the Sahel may lead to increased migration to urban areas, to rural sites of non-farm employment (e.g. mines) (Chevrillon-Guibert et al., 2019) or out of the country. In addition, it may lead to other types of reactions including violent resistance (Oliver-Smith, 2010; Cavanagh and Benjaminsen, 2015; Hall et al., 2015) as already seen in the Sahel in terms of the emergence of jihadist armed groups (Benjaminsen and Ba, 2019). Major drivers of the current crisis in Mali include decades of bureaucratic mismanagement and widespread corruption, the spill-over of jihadist groups from Algeria after the civil war there in the 1990s and the current civil war in Libya. Climate change has played a marginal role as a driver of conflicts in the Sahel (Benjaminsen et al., 2012; Benjaminsen and Hiernaux, 2019) but has potential to exacerbate the situation in the future with regards to migration and conflict (Owain and Maslin, 2018).

CCP3.3 Future Projections

CCP3.3.1 Projected Changes and Risks in Natural Systems

CCP3.3.1.1 Temperature

Globally, warming rates have been twice as high in drylands compared to humid lands, because the sparse vegetation cover and lower soil moisture of dryland ecosystems amplify temperature and aridity increases (Huang et al., 2016). This enhanced warming is expected to continue in the future. Surface warming over drylands is projected to reach ~6.5°C (~3.5°C) under the high RCP8.5 (low-moderate RCP4.5) emissions scenario by the end of this century, relative to the historical period (1961-1990) (Huang et al., 2016; Huang et al., 2017). Exploring the spatial variations between the aeolian desertification response in selected climate change scenarios, Wang et al. (2017) reported that temperature rise could trigger aeolian desertification in West Asia, Central China and Mongolia. The number of extremely hot days with temperatures above 40°C is projected to increase considerably across the Arab region by the end of the 21st century (ESCWA, 2017).

CCP3.3.1.2 Rainfall, Evaporation and Drought

Drylands are highly sensitive to changes in precipitation and evapotranspiration. Potential evapotranspiration (PET) is projected to increase in all regions globally, under all RCPs, as a result of increasing temperatures and surface water vapour deficit (Mirzabaev et al., 2019). Simulations based on coupled land surface, energy and water and vegetation models in the Central Sahel showed a strong response of the water budget. Under +2°C and +4°C warming scenarios, decreased evapotranspiration, runoff and drainage were found for all scenarios except those with the highest precipitation (Léauthaud et al., 2015).

Globally, soil moisture declined over the 20th century (Gu et al., 2019), a trend that is projected to continue under all emissions scenarios (WGI AR6). Projected drier soils can further amplify aridity through feedbacks with land surface temperature, relative humidity and precipitation (Berg et al., 2016).

Drought conditions (frequency, severity and duration) are expected to substantially worsen in global drylands, driven by a higher saturation threshold and more intense and frequent dry spells under rising temperatures (Liu et al., 2019a; Liu et al., 2019b). In a +1.5°C world, historical 50-year droughts (based on the Standardised Precipitation-Evapotranspiration Index (SPEI)) could occur twice as frequently across 58% of global landmasses relative to the 1976–2005 period, an area that increases to 67% under 2°C warming (Gu et al., 2020). Multi-year drought events of magnitudes exceeding historical baselines will increase by 2050 in countries with drylands including Australia, Brazil, Spain, Portugal, and the USA (Jenkins and Warren, 2015). The magnitude of drought stress in different regions differs depending on the metric used. Projections based on the Palmer Drought Severity Index (PDSI) suggest drought stress will increase by more than 70% globally, while a substantially lower estimate of 37% is found when precipitation minus evapotranspiration (P-E) is used (Swann et al., 2016). However, the two metrics agree on increasing drought stress in regions with more robust decreases in precipitation, such as southern North America (Section 14.4.3.1), north-eastern South America (Section 12.3.1.1) and southern Europe (Section 13.1.3; Swann et al., 2016).

CCP3.3.1.3 Aridity

Studies based on the AI (the ratio of annual potential evapotranspiration to precipitation), almost always project conditions of increasing aridity under climate change, and associated widespread expansion of drylands (Huang et al., 2016). The limitations of the AI are widely reported (Mirzabaev et al., 2019), with alternative indices that consider different variables including the Ecohydrological Index, PDSI, Standardised Precipitation Index and SPEI (Stringer et al., 2021). AI projections indicate potentially severe aridification in the Amazon, Australia, Chile, the Mediterranean region, northern, southern and west Africa, south-western United States, and South America (*medium confidence*) (Feng and Fu, 2013; Greve and Seneviratne, 2015; Jones and Gutzler, 2016; Park et al., 2018). However, the AI does not incorporate potential changes to plant transpiration under increasing CO_2 concentration and therefore overestimates drought conditions and aridity. Additionally, it does not reflect seasonality in rainfall and evapotranspiration, which is important in regions where temperature and actual evapotranspiration are not increasing during the wet season when vegetation growth is occurring. Mirzabaev et al. (2019) concluded that while aridity will increase in some places (*high confidence*), there is insufficient evidence to suggest a global change in dryland aridity (*medium confidence*). Nevertheless, a comparison of several metrics of aridity showed robust aridity increases are projected for several hotspots such as the Mediterranean region and South Africa (Greve et al., 2019). Under RCP8.5, aridity zones could expand by one-quarter of the 1990 area by 2100, increasing to over half of the global terrestrial area (Huang et al., 2016; Lickley and Solomon, 2018). Lower greenhouse gas emissions, under RCP4.5, could limit expansion to one-tenth of the 1990 area by 2100 (Huang et al., 2016). Aridity could expand substantially on all continents except Antarctica (Huang et al., 2016), with expansion first manifesting in the Mediterranean region, southern Africa, southern South America, and western Australia (Lickley and Solomon, 2018). In the Northern Hemisphere, aridity zones could expand poleward as much as 11 degrees of latitude (Rajaud and Noblet-Ducoudré, 2017). By 2100, the population of dryland areas could increase by 700 million people and, under RCP8.5, three billion people might live in areas with a 25% or greater increase in aridity (Lickley and Solomon, 2018). Many studies point to an increasing dryland area based on the AI, but there is low agreement on the actual amount and area of change (Feng and Fu, 2013; Scheff and Frierson, 2015; Huang et al., 2017). The inconsistency between studies is largely due to the substantial internal climate variability in regional precipitation. Changes in annual precipitation have been shown to range from -30% to 25% over drylands. Consistent changes in precipitation are only found at high latitudes, while total PET is projected to increase over most land areas (Feng and Fu, 2013). This leads to more consistent, widespread drying in the tropics, subtropics and mid-latitudes in most models (Feng and Fu, 2013; Cook et al., 2014; Scheff and Frierson, 2015; Zhao and Dai, 2015).

CCP3.3.1.4 Dryland Extent

Global dryland area (based on the AI) is projected to expand by ~10% by 2100 compared to 1961-1990 under a high emission scenario (Chapter 12, WGI). However, there are significant regional differences in the drivers of dryland expansion and subsequent estimates of change in dryland extent. Subtropical drylands are projected to expand as the climate in these regions shifts from temperate to subtropical and aridity increases in currently sub-humid subtropical regions, resulting in the loss of temperature-controlled seasonal cycles (Schlaepfer et al., 2017). Observed and projected warming and drying trends are most severe in transitional climate regions between dry and wet climates, with some exceptions (Nkrumah et al., 2019), which are often highly populated agricultural regions with fragile ecosystems (Cheng and Huang, 2016). In contrast, P-E predicts decreasing drought stress across temperate Asia and central Africa (Swann et al., 2016). Expansion of arid regions is anticipated in southwest North America, the northern fringe of Africa, southern Africa and Australia. The main areas of semi-arid expansion are expected to occur in the north side of the Mediterranean, southern Africa and North and South America. In contrast, India, eastern equatorial Africa and other areas of the southern Saharan regions are projected to have shrinking drylands (Biasutti and Giannini, 2006; Biasutti, 2013; Rowell et al., 2016). Future projections may underestimate dryland expansion, since the Coupled Model Intercomparison Project (CMIP) 5 models underestimate historical warming (Huang et al., 2016) and overestimate precipitation over drylands, particularly in the semi-arid and dry sub-humid regions (Ji et al., 2015). However, estimates vary depending on the metric used (Swann et al., 2016; Berg et al., 2017b). Studies based on off-line aridity and drought metrics (calculated from model output of precipitation, evapotranspiration or temperature) project strong surface drying trends (Cook et al., 2014; Scheff and Frierson, 2015; Zhao and Dai, 2015), while projections based on total soil water availability from CMIP5 models show weaker and less extensive drying (Berg et al., 2017a). In contrast, projections in southern Africa may overestimate future drying, with systematic rainfall biases being found in the present-day climatology in models that simulate extreme future drying (Munday and Washington, 2019). Improvements in projections of future changes in aridity require better understanding of seasonality, land hydrology, and the feedbacks between projected soil moisture decrease on land surface temperature, relative humidity and precipitation (Huang et al., 2016).

Higher dust emissions are consistent with climate change projections indicating an expansion in the global area of drylands (Feng and Fu, 2013; Huang et al., 2016) and increased drought risk (Cook et al., 2014; Xu et al., 2019), but future trends in dust event frequency and intensity as a result of climate change are uncertain and will vary geographically (Jia, 2019). Combined effects of climate change and anthropogenic activities are projected to increase sand encroachment and extreme dust storms (Omar Asem and Roy, 2010; Sharratt et al., 2015; Pu and Ginoux, 2017) as a result of increased aridity, accelerating soil erosion (Section 4.4.8; Sharratt et al., 2015) and loss of biomass (Sharratt et al., 2015; Middleton and Kang, 2017). Shifts in dust storm timings are also projected in some regions (Hand et al., 2016). Dustiness is projected to increase in the southern US Great Plains in the late 21st century under the RCP8.5 climate change scenario but decrease over the northern Great Plains (Pu and Ginoux, 2017). A declining trend in dust emission and transport from the Sahara under RCP8.5 was detected by Evan et al. (2016) but regional climate model experiments conducted by Ji et al. (2018) under the same scenario indicated that overall dust loadings would increase by the end of the 21st century over West Africa. New dust sources may emerge with changing climate conditions, as Bhattachan et al. (2012) indicate for the Kalahari Desert in southern Africa, due to vegetation loss and dune remobilization. There is overall *low confidence* on future atmospheric dust loads at the global and regional scale. Models of future dust emissions are limited by the low accuracy of models of present anthropogenic dust emissions, which range from 10% and 60% of the total atmospheric dust load (Webb and Pierre, 2018). A global compilation of data from sedimentary archives (ice cores), remote sensing, airborne sediment sampling and meteorological station data estimated that anthropogenic dust emissions have at least doubled over the past 250 years (Hooper and Marx, 2018). While future emissions of natural dust sources are projected to decrease (Mahowald et al., 2006) or remain stable (Ashkenazy et al., 2012), when sources of human emissions are included, projections of future atmospheric dust loads suggest that emissions may increase (Stanelle et al., 2014).

The relative contribution of albedo and evapotranspiration to regional trends in surface temperature (Charney, 1975) remains unresolved, and may be determined by different mechanisms in different systems, depending on site-specific conditions such as snow coverage, vegetation and soil moisture (Yu et al., 2017). For example, the vegetation-albedo feedback mechanism may dominate in the Arctic (Blok et al., 2011; te Beest et al., 2016), while the vegetation-evaporation feedback may drive change in other regions. Actions that increase forest cover across Africa could thus, theoretically, moderate projected future temperature increases (Wu et al., 2016; Diba et al., 2018), but with potentially negative effects on biodiversity (Chapter 2). Soil drying exacerbates atmospheric aridity, which causes more soil drying in a self-reinforcing land–atmosphere feedback that could intensify under RCP8.5 (Zhou et al., 2019).

Changes to the composition, structure and functioning of natural communities in deserts and dryland ecosystems are key risks resulting from water stress, drought intensity and continued habitat degradation, greater frequency of wildfire, biodiversity loss and the spread of invasive species (Hurlbert et al., 2019). Not all these stresses occur at the same time in a particular environment, with some areas more exposed to e.g. wildfire than others, especially in areas with high amounts of dry herbaceous biomass. Grassland composition may shift as C3 plants are replaced by C4 species, which have higher optimal temperatures and higher water use efficiency (although seasonality of precipitation also plays a role) (Knapp et al., 2020). Many desert species have morphological, physiological and/or behavioural adaptations to cope with climatic extremes, including rapid regeneration following droughts (Boudet, 1977; Hiernaux and Le Houérou, 2006), leaf dropping during the dry season to reduce water loss (Santos et al., 2014), alongside long histories of adaptation to climate change (Brooks et al., 2005; Ballouche and Rasse, 2007), while many animals live near their physiological limits (Vale and Brito, 2015). Substantial ecological effects may occur when extreme events such as heatwaves or droughts are superimposed on the warming trend, pushing species beyond their physiological and mortality thresholds (Hoover et al., 2015; Harris et al., 2018).

Climate change increases risks of continued range retractions of Karoo succulents in South Africa (Young et al., 2016), dry argan woodlands in Morocco (Alba-Sánchez et al., 2015), epiphytic cacti in Brazil (Cavalcante and Duarte, 2019; Cavalcante et al., 2020) and other plant species exposed to higher aridity. Projected increases in heat and aridity could increase mortality of trees and shrubs in Sonoran Desert ecosystems in the United States (Munson et al., 2012; Munson et al., 2016b), reduce sagebrush in arid ecosystems of the western United States (Renwick et al., 2018), and contribute to the replacement of perennial grasses with xeric shrubs in the south-western United States (Bestelmeyer et al., 2018). CO_2 fertilization and warmer conditions, combined with changes in timing and availability of moisture, could increase invasive grasses and wildfire in desert ecosystems of Australia and the south-western United States where wildfire has historically been absent or infrequent (Abatzoglou and Kolden, 2011; Horn and St. Clair, 2017; Klinger and Brooks, 2017; Syphard et al., 2017). Trends of woody encroachment may continue in some North American and African drylands or at least not reverse (Higgins and Scheiter, 2012; Caracciolo et al., 2016). Impacts of woody encroachment on drylands may show a slight increase in carbon, but a decline in water and huge negative impacts on biodiversity, with a tendency for open ecosystem species to be most affected (Archer et al., 2017). Expansion of grasses into these arid shrublands has the potential to transform them rapidly, especially through the acceleration of the fire cycle (Bradley et al., 2016). While the impact of increased aridity may be offset by changing water use efficiency by plants under high CO_2 concentrations, limiting the expansion of dryland ecosystems (Swann et al., 2016; Mirzabaev et al., 2019), increased plant growth in response to elevated CO_2, which results in increased water consumption, may counteract this. Increased water use efficiency is therefore not expected to counterbalance increased evaporative demand (Chapter 8). There is *medium confidence* that succulent species will be particularly vulnerable to increased heat and aridity due to reduced physiological performance, loss of seed banks, lower germination rates and increased mortality (Table CCP3.1; Musil et al., 2005; Aragón-Gastélum et al., 2014; Shryock et al., 2014; Martorell et al., 2015; Carrillo-Angeles et al., 2016; Aragón-Gastélum et al., 2017; Koźmińska et al., 2019).

CCP3.3.2 Projected Impacts on Human Systems

Across many drylands, human-induced causes of desertification, SDS, climate change and unsustainable land use, are projected to become more pronounced over the next several decades with global consequences. Future climate changes with increasing frequency, intensity and scales of droughts and heatwaves, are projected to further exacerbate the vulnerability and risk to humans from desertification (Hurlbert et al., 2019).

Sand and dust storms exert a wide range of impacts on people, within deserts and semi-deserts but also outside dryland environments because of long-range dust transport (Middleton, 2017). Research on the economic impacts of SDS is lacking, while studies that have been conducted lack consistency in data collection methods and analysis (Middleton, 2019). Although projections are rarely modelled, estimated economic damages of increased dust-related health impacts and mortality under RCP8.5 could total $47 billion/year additional to the 1986-2005 value of $13 billion/year in southwest USA (Allahbakhshi et al., 2019).

Projected impacts of climate change on the risk of food insecurity are a particular concern for the developing world drylands (Chapter 16, WGI; Mirzabaev et al., 2019), potentially leading to breakdown of food production systems, including crops, livestock, and fisheries, as well as disruptions in food supply chains and distribution (Myers et al., 2017; Lewis and Mallela, 2018). Developing country drylands are particularly vulnerable due to a higher share of populations with lower income, lower physical access to nutritious food, social discrimination as well as other environmental factors that link to climate change. For example, countries such as Somalia, Yemen and Sudan faced recent and resurging challenges from an increase in desert locusts, the effects of which in 2020 extended from East Africa through the Arabian Peninsula and Iran as far as India and Pakistan. Meynard et al. (2020) note that under climate change, some areas suffering from previous outbreaks may see changes in formation of swarms of *Schistocerca gregaria*. Salih et al. (2020) recognise that attributing the 2020 swarms as a single event to climate change remains challenging, but highlight that projected temperature and rainfall increases in deserts and strong tropical cycles can create conditions conducive to the development, aggregation, outbreak and survival of locusts. Mandumbu et al. (2017) highlight how crop parasites such as *Striga spp.* in southern Africa may benefit from higher temperatures and rainfall activating dormant seeds, while high winds aid their dispersal. Combined with increasing risks of erosion and soil fertility losses (*Striga* is able to tolerate drought and a low nitrogen environment), this can have important impacts on the yields of key dryland crops such as maize and pearl millet.

Human responses can exacerbate desertification processes under climate change conditions, even in deserts. Exploitation of mineral resources (e.g. lithium mining in Chile's Atacama Desert) can cause human population changes as people flock to the area for work (Liu et al., 2019), increasing vulnerability due to e.g. soil erosion and salinisation, as well as increasing pressure on potable water for human consumption (Stringer et al., 2021) and exhausting aquifers. Salinisation is projected to increase in the drylands due to climate change impacts in future (Mirzabaev et al., 2019). For example, in India, about 7 million ha arable land area is currently salt-affected (Sharma et al., 2015; Sharma and Singh, 2015). It is projected that unsustainable use of marginal quality waters in irrigation and neglect of drainage, combined with climate change impacts, will accelerate land salinization in India, rendering another 9 million ha area salty and less productive by 2050 (ICAR-CSSRI, 2015). This has important cost implications given that annually, 16.84 million tonnes of farm production valued at INR 230.19 billion is already lost in India due to salinity and associated problems (Sharma and Singh, 2015). The literature further shows evidence of desertification of oases and irrigated lands in parts of northern China's drylands (Wang et al., 2020), the Indian subcontinent's deserts, as well as the Mesopotamian Arabian Desert (Ezcurra, 2006; Dilshat et al., 2015).

CCP3.4 Adaptations and Responses

Adaptations to climate change impacts in human systems vary depending on exposure to risks, types of risks and responses, underlying social vulnerabilities and adaptive capacities, including access to resources, the extent of adaptation responses and the potential of these responses to reduce risk/vulnerability (Chapter 16 ; Singh and Chudasama 2021). Adaptations tend to be applied locally, tackling symptoms of the problem and proximate drivers (e.g. of desertification), rather than distant or external drivers (Morris et al., 2016; Adenle and Ifejika Speranza, 2021). Different groups require different kinds of supports and levers to enable them to follow adaptive pathways (Stringer et al., 2020; Møller et al., 2017) and face different barriers and limits to adaptation (Chapter 18, WG2). What constitutes an incremental adaptation in one location may be transformational in another. Spatial patterns of dryland resilience and adaptive capacity can be partly explained by access to livelihood capitals (Mazhar et al., 2021) and are shaped by prevailing structures and power dynamics. Supportive policies, institutions and good governance approaches can strengthen the adaptive capacities of dryland farmers, pastoralists and other resource users (*high confidence*) (Stringer et al., 2017). Table CCP3.2 provides examples of illustrative adaptation options responding to major challenges of climate change and desertification in deserts and semi-arid areas. Some adaptations present no-regrets options while others tackle desertification and/ or climate changes to different extents.

Table CCP3.2: Synthesis of adaptation measures and responses to risks in deserts and semi-arid areas. Appropriateness of measures is context dependent and some adaptations will be incremental or even maladaptive in some dryland contexts while being transformational in other locations.
[INSERT TABLE CCP3.2 HERE]

Adaptations to climate change, desertification, drought management (Section 17.2.2.2) and sustainable development activities largely overlap in drylands, pointing to synergies between them (Reichhuber et al., 2019). For example, support for communal and flexible land tenure could bring about benefits across multiple dimensions, while attention to water as a limiting factor in drylands can link to multiple SDGs (Stringer et al., 2021) as well as adaptations in natural systems, where improved forecasting and anticipatory science and management can be appropriate (Bradford et al., 2018). Currently, more than 125 countries around the world, particularly in drylands, are setting land degradation neutrality (LDN) targets. LDN and its hierarchical response mechanisms of avoiding, reducing and reversing land degradation, can provide an overarching resilience-based framework for adaptation at the national level (Mirzabaev et al., 2019; Orr et al., 2017b; Cowie et al., 2018) and support biodiversity conservation (Akhtar-Schuster et al., 2017). However, achieving LDN will require a transparent decision and prioritisation process (Dallimer and Stringer, 2018), anchored in a socio-ecological systems approach (Okpara et al., 2018), with investment in all dimensions of an enabling environment, including inclusive policies and regulations, sustainable institutions, accessible finance and effective science-policy communications and interactions (Verburg et al., 2019; Allen et al., 2020). LDN calls for integrated land use planning to ensure land uses are optimized at a landscape scale to help balance competition for limited land resources and harness multiple benefits (Cowie et al., 2018, Verburg et al., 2019), recognising that adaptations present synergies and trade-offs along various dimensions of sustainable development such as poverty reduction, enhancing food security and human health or providing improved access to clean energy, land water, and finance (see Section 8.6). Distributional effects of adaptation options also may vary between different socio-economic groups within countries or locally among communities, pushing social justice concerns to the fore (Section 8.4). Measures promoting particular adaptations need to take into account such consequences as well as the potential for some adaptations to become maladaptive at scale.

Natural systems are also able to adapt to climate change, be adapted and become more resilient to desertification. For example, the root network architecture of the hyper-arid Negev Desert acacia trees has enabled them to withstand intensive cultivation and climate-change driven desertification (Winter et al., 2015) while vegetation-induced sand mounds ("coppice dunes") in the Arabian Desert have reduced desertification through reducing wind erosion and enriching sand desert land with water and nutrients (Quets et al., 2017). Vegetation cover of psammophyte shrub species (in the "desert oasis transitional area") surrounding the Dunhuang Oasis (northwest China) reduces oasis land degradation risk by reducing sand grain size and velocity of winds from the aeolian desert (Zhang et al., 2007); while land use planning in Israel's Negev Desert taking a 'sharing' approach between cultivation and urbanization has helped to minimise the external degrading effects of adjacent desert land ecosystems (Portnov and Safriel, 2004). Scholars are nevertheless questioning the wider suitability of tree planting in drylands, given concerns for water availability and other ecosystem services (Veldman et al., 2015; Bond et al., 2019; Veldman et al., 2019). How natural dryland systems are managed following disturbances such as wildfire is important too. van den Elsen et al. (2020) found that establishing vegetation and mulch cover after a fire in a Mediterranean dryland ecosystem reduced soil erosion, helping maintain soil fertility and nutrients. However, different management objectives require different adaptations. For example, adaptation measures that reduce land degradation through reforestation could increase vulnerability to fire if they exclude ecologically sound fire management or are based on plant species that are fire prone. Combinations of different land management practices and governance approaches tackling a range of different stresses appear to best support sustainability and adaptation over the long term (van den Elsen et al., 2020).

Collective action can facilitate the implementation of adaptation responses and help tackle challenges associated with upscaling of successful land-based adaptations (Thomas et al., 2018). However, a lack of coordination between stakeholders and across sectors can be problematic (Amiraslani et al., 2018), showing the importance of multi-stakeholder engagement (De Vente et al., 2016). Multi-stakeholder engagement is recognized as an essential part of desertification control, as well as vital in tackling climate change (Reed and Stringer, 2016), with participation taking place to different extents in different drylands according to the prevailing governance system. In China, the Grain for Green programme is an example of a large-scale ecological restoration programme securing local engagement through payments for ecosystem services (Kong et al., 2021), while transdisciplinary stakeholder engagement involving researchers and central and local governments in the Heihe River Basin in China's arid and semi-arid northwest, using an interdisciplinary 'web' approach, enabled basin restoration. Multi-stakeholder efforts saw improvement in the condition of Juyan Lake and the surrounding catchment, increasing both the lake surface area and groundwater in downstream locations (Liu et al., 2019).

In the short- to medium-term, monitoring, prediction and early warning can support adaptation and e.g. help reduce negative impacts of SDS by mobilising emergency responses. Daily dust forecasts enable preparation to minimise risks from sand/dust storms to both human and natural systems (e.g. the WMO Sand and Dust Storm Warning Advisory and Assessment System: https://sds-was.aemet.es/forecast-products/dust-forecasts). Preparedness and emergency response procedures benefit from covering diverse sectors, such as public health surveillance, hospital services, air and ground transportation services, water and sanitation, food production systems and public awareness, suggesting the need for a coherent, multi-sector governance approach. Longer-term actions include prioritizing sustainable land management (Middleton and Kang, 2017), based on Indigenous knowledge and local knowledge, and modern science (Verner, 2012), along with the investment of financial and human capital in supporting these measures. Devolved adaptation finance in dryland areas of e.g. Kenya (Nyangena and Roba, 2017) and Mali (Hesse, 2016) has yielded promising insights, highlighting the importance of climate information services and local government support for community prioritisation of adaptation activities. Such actions can enable substantial benefits for poor and marginalised men and women. Among international institutional measures, a global coalition to combat SDS was launched at the United Nations Convention to Combat Desertification Conference of Parties (UNCCD COP14) in 2019, which could help to better mobilize a global response to SDS. Similarly, there have been calls for increased investment in regional institutions such as the Desert Locust Control Organisation for Eastern Africa to both pre-empt and tackle locust plagues (Salih et al., 2020), requiring trans-boundary cooperation.

There is *high agreement* and *robust evidence* that shifting emphasis to proactive risk mitigation, including solutions for drought, flooding erosion and dust management, instead of exclusive focus on disaster management, reduces vulnerability and improves adaptive capacity (Section 16.4.3.2 and 16.5.2.3.4; Sivakumar, 2005; Grobicki et al., 2015; Wieriks and Vlaanderen, 2015; Aguilar-Barajas et al., 2016; Runhaar et al., 2016; Wilhite and Pulwarty, 2018; Wilhite, 2019). It also underscores the LDN response hierarchy avoid > reduce > reverse (Orr et al., 2017a). Nevertheless, *ex ante* drought and flood risk mitigation has been adopted in limited dryland settings, despite that it is preferable to increase preparedness before it happens, provide incentives for adaptation instead of insurance, provide insurance instead of relief, and provide relief instead of regulation (Sivakumar, 2005). Yet, providing disaster relief is often more publicly visible and politically expedient, despite its social, economic and environmental challenges. The absence of proactive risk mitigation and resulting crisis management increases vulnerability, increases reliance on government support, reduces self-reliance and increases costs (Grobicki et al., 2015; Wilhite, 2019), as well as hindering progress towards the SDGs. In the case of drought and flooding, major obstacles for the transition from reactive management to proactive drought risk mitigation include path dependencies and lack of knowledge about relative costs and benefits of reactive versus proactive approaches. This lack of information can deter large-scale and long-term investments into proactive approaches (Mirzabaev, 2016).

A range of risk mitigation and adaptation measures can be taken, to address drought, desertification and other climate change-related challenges in deserts and semi-arid areas, some of which can be both proactive and reactive. These include *inter alia*:

i) Policies, public advocacy, and social media campaigns that improve water use efficiency, especially in agriculture and industry, which can foster behavioural changes and reduce water consumption (Yusa et al., 2015; Tsakiris, 2017; Booysen et al., 2019),

ii) Integrating access to insurance, financial services, savings programs, and cash transfers into policies to increase the effectiveness of e.g. drought responses. Such efforts can result in significant cost savings (Berhane et al., 2014; Bazza et al., 2018 ; Guimarães Nobre et al., 2019),

iii) Development of robust early warning systems that provide information and improve knowledge surrounding drought and SDS to enable early recovery (Wilhite, 2019), considering also vulnerability and impact assessments (i.e. who is at greatest risk),

iv) Water management and storage, including using methods that draw on Indigenous knowledge (Stringer et al., 2021), water transfers, and trade, all of which can reduce costs and provide timely adaptations to drought, supporting agricultural productivity and rural livelihoods (Harou et al., 2010; Hurlbert, 2018),

v) Restoration, reclamation, and landscape heterogeneity strategies, promoting ecosystem resilience to wind erosion and dust abatement (Duniway et al., 2019) as well as restoring important ecosystem services at a catchment scale,

vi) Prevention of soil erosion, provision of dust abatement and enhanced biodiversity by changing grazing techniques (e.g. rotational grazing), facilitating herd mobility, protecting rangeland areas from fragmentation, promoting common tenure and access rights on grazing land, enabling rapid post fire restoration efforts, minimum tillage, sustainable land management, integrated landscape management, planting and caring for non-irrigated indigenous trees and other vegetation (Middleton and Kang, 2017); and

vii) Creation of drought tolerant food crops through participatory plant breeding (Grobicki et al., 2015) and investment in research and development of drought resistant varieties (Basu et al., 2017; Mottaleb et al., 2017; Dar et al., 2020), alongside adjusted planting and harvesting periods (Frischen et al., 2020). Similar to other adaptations, the net economic benefits of *ex ante* resilient plant development far outweigh the research investment (Basu et al., 2017; Mottaleb et al., 2017; Dar et al., 2020).

Many of these measures can also support climate change mitigation efforts in drylands. Uptake of adaptation measures is often grounded in clear communications and information provision to support behavioural changes, taking into account local risk aversion and risk perceptions (Zeweld et al., 2018; Jellason et al., 2019). Building capacity by improving the knowledge base and access to information as well as to financial and other resources, encourages vulnerable economic sectors and people to adopt more self-reliant measures that promote more integrated and sustainable use of natural resources *(high confidence*) (Sivakumar, 2005; Wieriks and Vlaanderen, 2015; Aguilar-Barajas et al., 2016; Middleton and Kang, 2017; Wilhite, 2019). Engaging natural resource users as active participants in planning and technology adoption using extension services, financial grants and services geared to the local area, can build resilience and drive changes in practices (Webb and Pierre, 2018), while approaches such as Integrated Water Resources Management (IWRM) can support adaptation and drought risk management, including in dryland urban megacities (Stringer et al., 2021) and in deserts and semi-arid areas where precipitation trends remain stable yet other pressures on water are growing (Reichhuber et al., 2019).

[START FAQ CCP3.1 HERE]

FAQ CCP3.1: How has climate change already affected drylands and why are they so vulnerable?

Human-caused climate change has so far had mixed effects across the drylands, leading to fewer trees and less biodiversity in some areas and increased grass and tree cover in others. In those dryland areas with increasing aridity, millions of people face difficulties in maintaining their livelihoods particularly where there is water scarcity.

Drylands include the hottest and most arid areas on Earth. Human-caused climate change has been intensifying this heat and aridity in some places, increasing temperatures more across global drylands than in humid areas. In areas which are hotter and drier, tree death has occurred and in some locations bird species have been lost. Climate change has reduced rainfall in some dryland areas and increased rainfall in other areas. Increased rainfall, combined with the plant-fertilizing effect of more carbon dioxide in the atmosphere, can increase grass and shrub production in dryland areas. Because water is scarce in drylands and aridity limits the productivity of agriculture, millions of people living in drylands have faced severe difficulties in maintaining their livelihoods. This challenge is exacerbated by non-climate change factors, such as low levels of infrastructure, remoteness, and limited livelihood options that are less dependent on scarce natural resources. High temperatures in drylands increase the vulnerability of people to potential heat-related illnesses and deaths from heat under continued climate change.

[END FAQ CCP3.1 HERE]

[START FAQ CCP3.2 HERE]

FAQ CCP3.2: How will climate change impact the world's drylands and their people?

Climate change is projected to lead to higher temperatures across global drylands. Many drylands also risk more irregular rainfall leading to increased irregularity in crop yields, and increased water insecurity where less rainfall is projected, which may have profound implications for both dryland ecosystems and their human inhabitants.

There is, however, considerable uncertainty about the changes that may occur in drylands in the future and how people and ecosystems will be affected. In some drylands, higher temperatures and declining rainfall have increased aridity. However, this is not a global trend as many drylands are experiencing increases in vegetation cover and rainfall. Both the amount of rainfall and its seasonality have changed in many dryland areas, associated with natural variability and warming.

Most climate models project increased rainfall in tropical drylands, but more variability. High natural climatic variability in drylands makes predictions uncertain. Understanding future impacts is further complicated by many interacting factors such as land use change and urbanisation that affect the condition of drylands. Future trends in sand and dust storm activity are also uncertain and will not be the same everywhere, but there will likely be increases in some regions (e.g. the United States) in the long-term. The impacts of climate change in deserts and semi-arid areas may have substantial implications globally: for agriculture, biodiversity, health, trade and poverty, as well as potentially, for conflicts and migration. Increasing temperatures and more irregular rainfall are expected to affect soil and water and contribute to tree death and loss of biodiversity. In other places, woody encroachment onto savannas may increase, in response to the combination of land use change, changes in rainfall, fire suppression, and CO_2 fertilization. Crop yields are projected to decline in some areas, with adverse impacts on food security. The potential for conflicts and migration is primarily associated with socioeconomic development, while links to climate change remain uncertain and lack evidence.

[END FAQ CCP3.2 HERE]

[START FAQ CCP3.3 HERE]

FAQ CCP3.3: What can be done to support sustainable development in desert and semi-arid areas, given projected climate changes?

Water is a major limiting factor in drylands. Many efforts to support sustainable development aim to improve water availability, access and quality, ranging from large engineering solutions that move or desalinise water; to herders' migrations with their animals to locations that have water; to land management and water harvesting practices that conserve water and support land cover. These solutions draw on Indigenous knowledge, local knowledge and innovative science, and can help to address multiple Sustainable Development Goals.

Different desert and semi-arid areas can benefit from different incremental and transformational solutions to move toward sustainable development under climate change. In some dryland areas facing critical water shortages, transformational adaptations may be needed - for example, large-scale water desalination when they have access to sea water, despite high energy use and negative environmental impacts of waste brine. In dryland agricultural areas across the world, incremental adaptations include water conservation measures, use of improved crop varieties or increasing herd mobility. What counts as a transformational change in some places may be incremental in others. Often solutions can target multiple development goals. For example, water harvesting can make water available during drought, buffering water scarcity impacts, while also supporting food production, agricultural livelihoods and human health. Land based approaches, e.g. restoration of grassland, shrubland, and savanna ecosystems, are important for ensuring ecological integrity, soil protection and preventing livelihoods from being undermined as a result of growing extreme weather events. It is important that policies, investments and interventions that aim to support sustainable development take into account which groups are likely to be most affected by climate change. Those people directly dependent on natural resources for their survival are generally most vulnerable but least able to adapt. The capacity to translate local and Indigenous knowledge and experience into actions can require external support. Governments and other stakeholders can help by investing in early warning systems, providing climate information, realigning policies and incentives for sustainable management, investing in supporting infrastructures, alongside developing alternative livelihood options that are less exposed and sensitive to climate change. Involving all relevant stakeholders is important. For example, in China the Grain for Green programme secured local engagement by paying people to manage the environment more sustainably. At a global level important groups have emerged to cooperate and offer solutions around issues such as sand and dust storms, and integrated drought management. Efforts are needed across all scales from local to global to support sustainable development in desert and semi-arid areas, given projected climate changes.

Large Tables

Table CCP3.1: Observed ecological changes in drylands.

Region	**Observed change**	**Climate change factors**	**Attribution to climate change**	**Non-climate change factors**	**Confidence in observed change**	**References**
Hyper arid						
Asian hyper arid regions (Gobi)	Loss of shallow rooted desert plants	Increase in extreme warm temperatures			*Medium*	Li et al. (2015)
North America - Mojave Desert	Loss of mesic bird species	Decreased rainfall	Yes. Analyses of causal factors find decreased rainfall more important than non-climate factors.	Livestock, human-ignited fires	*Medium*	Iknayan and Beissinger (2018); Riddell et al. (2019)
	Decline of desert tortoise (*Gopherus agassizii*) population 90% from 1993 to 2012 at one site in the Mojave	Decreased rainfall				Lovich et al. (2014)
	Reduced perennial vegetation cover, including trees and cacti, in the Mojave and Sonoran deserts of the southwestern United States	Increased temperature, decreased rainfall, wildfire		Land use change, invasive plant species	*High*	Defalco et al. (2010); Munson et al. (2016b); Conver et al. (2017)
Arid						
African Sahel	Woody cover increase in parts of the Sahel	Increase in rainfall since the mid-1990s (compared to 1968-1993)and increased CO_2		Restoration planting Agroforestry	*High*	

	Increase in grass production across Sahel	Increases in rainfall since the mid-1990s (compared to 1968-1993) and increased CO_2			*Medium*	Hiernaux et al. (2009a); Hiernaux et al. (2009b); Dardel et al. (2014); Venter et al. (2018); Zhang et al. (2018); Brandt et al. (2019); Bernardino et al. (2020)
	Decline of mesic tree species at field sites across the Sahel	Decreased rainfall from 1901 to 2002 increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.	Land clearing for cropland expansion, Increase pressure on wood resources (rural demography, urbanization)	*High*	Gonzalez (2001); Wezel and Lykke (2006); Maranz (2009); Gonzalez et al. (2012); Hänke et al. (2016); Kusserow (2017); Ibrahim et al. (2018); Zida et al. (2020b)
	Increased tree mortality at field sites across the Sahel	Decreased rainfall from 1901 to 2002, increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.	Agricultural expansion, modified runoff on shallow soils	*High*	Helldén (1984); Gonzalez, (2001); Wezel and Lykke (2006); Maranz (2009); Vincke et al. (2010); Hänke et al. (2016); Trichon et al. (2018); Zwarts et al. (2018); Wendling et al. (2019); Bernardino et al. (2020); Zida et al. (2020a)
	Latitudinal biome shift of the Sahel	Decreased rainfall, increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.		*High*	Boudet (1977); Tucker and Nicholson (1999); Gonzalez, (2001); Hiernaux and Le Houérou (2006); Hiernaux et al. (2009a); Maranz (2009); Gonzalez et al. (2012)
Namib desert	Increase in woody plant cover and a shift of mesic	Increase in amount of fog from westward			*Medium*	Morgan et al. (2004); Haensler et al. (2010); Donohue et al. (2013); Rohde et al. (2019)

	species into more arid regions	expansion of convective rainfall and increase in number of extreme rainfall events. Elevated CO2 and warming effects on the Bengula upwelling system				
Southern Africa - Nama-Karoo		Shifting rainfall seasonality (debate if its cyclical or directional); elevated CO2			*Medium*	Du Toit and O'Connor (2014); du Toit et al. (2015); Masubelele et al. (2015a); Masubelele et al. (2015b)
	Eastern Karoo has experienced a significant increase in the end of the growing season length	Shift in rainfall seasonality and increase in MAP			*Low*	Davis-Reddy (2018)
	Woody encroachment has been observed throughout the Nama-Karoo in valley bottoms, ephemeral stream banks and the slopes of Karoo hills.	Rising concentration of CO_2		Changing land use and herbivore management	*Medium*	Polley et al. (1997); Morgan et al. (2004); Donohue et al. (2013); Ward et al. (2014); Masubelele et al. (2015a); Hoffman et al. (2018)
Southern Africa - Succulent Karoo	*Succulent Karoo*: Range shift in tree aloe *Aloidendron dichotomum* with mortality in the warmer and drier range and increase in recruitment in the cooler southern range, populations have positive growth rates, possibly due to warming, although this finding has been challenged	Warming and drying			*Medium*	Foden et al. (2007a); Jack et al. (2016)
Northern Africa - Morocco	Increased vulnerability of oasis's, and reduced ecosystem service provision	High temperature and reduced precipitation		Agricultural growth, high population growth	*Medium*	Karmaoui et al. (2014)

		causing soil and water salinization, drying up of surface water. Hot winds and sandstorms.		and unregulated and indiscriminate land development		
	Reduced surface water availability	Increased temperature and reduced precipitation		High demand (population growth) and landuse change	*Medium*	Rochdane et al. (2012); Choukri et al. (2020)
	Reduction of resilience of *Abies pinasapo- Cedrus atlantica* forests to subsequent droughts	Successive droughts			*Medium*	Navarro-Cerrillo et al. (2020)
North American drylands	Drought adapted species are increasing in Chihuahuan deserts	Increase in aridity and increased inter-annual variation in climate trends			*Medium*	Collins and Xia (2015); Rudgers et al. (2018)
	Widespread woody plant encroachment. *Prosopis sp* encroachment in arid desert regions (Chihuahuan and Sonoran Desert) at a rate of ~3% per decade.	Increasing temperature, elevated CO_2 and changing rainfall		Fire suppression and altered grazing/browsing regimes,	*High*	Caracciolo et al. (2016); Archer et al. (2017)
	Plant desert community shift changes the albedo through the reduction in dark biocrusts	Warming and drought			*Medium*	Rutherford et al. (2000)
South Chihuahuan Desert - North and central Mexico	Shrub encroachment of grassland (*Berberis trifoliolata, Ephedra aspera, Larrea tridentata*) changes on dominant species in shrub areas loss of less resistant shrubby species (*Leucophyllum laevigatum, Lindleya mespiloides, Setchellanthus caeruleu*). Shrub encroachment of mesic and temperate areas	Decreased rainfall, increase in temperature and increase CO_2		Urban growth, mechanized agriculture, and changes in land use	*High*	Pérez-Sánchez et al. (2011); Castillón et al. (2015); Sosa et al. (2019)

	Shifts on soil microbial community to more abundant in fungi (Ascomycota and Pleosporales)	decreased rainfall and increase in temperature		changes in land use	*Low*	Vargas-Gastélum et al. (2015)
	Limited ecological connectivity of shrubby populations	decreased rainfall + increase in temperature			*Medium*	Sosa et al. (2019)
	Loss of Cacti species (*Echinocactus platyacanthus, Pediocactus bradyi, Coryphantha werdermannii, Astrophytum*) due to decline in physiological performance, loss of seed banks and lower germination rates	decreased rainfall + increase in temperature		Cattle grazing, looting	*High*	Aragón-Gastélum et al. (2014); Shryock et al. (2014); Martorell et al. (2015); Carrillo-Angeles et al. (2016); Aragón-Gastélum et al. (2018)
Arid and semi-arid territories in Argentina	Decreases in vegetation indexes	Decreased rainfall		human-induced land degradation	*Low*	Barbosa et al. (2015)
Argentina Chaco Region	Dryland salinity	changes in rainfall		Land use change Overexploitation of water resources	*Medium*	Amdan et al. (2013); Marchesini et al. (2017)
South America Arid Diagonal	Marked reduction in streamflow from the Andes mountain "water towers" due to the persistent reduction in precipitation."	Decrease in precipitation in the upper Andes. The unprecedented 10-year extreme dry period has been called the "Mega-drought			*High*	Bianchi et al. (2017); Rivera and Penalba (2018); Masiokas et al. (2019); Rodríguez-Morales et al. (2019)
South American Andes	Extensive glacier retreat across the Andes	Increasing sub-continental temperature and regional reduction in snow precipitation			*High*	Dussaillant et al. (2019); Falaschi et al. (2019); Masiokas et al. (2019)

Patagonian Andes	Widespread tree mortality of *Austrocedrus* and *Nothofagus* forests in the dry ecotone forest-steppe across Patagonia	Increase in extreme drought events			*High*	Rodríguez-Catón et al. (2019)
	Increase in elevation of the upper-forest *Nothofagus* treeline across Patagonia	Increase in temperature and duration of the growing season at high elevation in the Patagonian Andes			*High*	(Srur et al. (2016); Srur et al. (2018)
Central Asian arid lands	Shrub encroachment into arid grasslands within the past 10 years	Temperature of central Asian arid regions experienced a sharp increase since 1997 and has been in a state of high variability since then			*Medium*	Li et al. (2015)
Loess Plateau, China	Widespread vegetation greening in the Loess Plateau region; soil moisture declining widely, and deficit in forests and orchards. The runoff of the Yellow River is declining	Significant warming, slight increase in precipitation.		The land use and cover change, ecological restoration, mainly induced by Grain for Green Project	*High*	Jia et al. (2015); Wang et al. (2015); Deng et al. (2016); Jiao et al. (2016)
The Three-River Source Region of the Tibetan Plateau, China	The runoff increases, the total water storage and groundwater increasing. NPP increase	The precipitation increasing and evapotranspiration (ET) slight decreasing		Grassland protection	*High*	Xu et al. (2019)
Semi-arid						
Australian arid lands	Widespread greening	Elevated CO2			*Medium*	Donohue et al. (2013)
African savanna	Doubling of tree cover from 1940 – 2010 in South Africa changing land use), and 20% increase in spread of woody	Warming, elevated CO_2, altered rainfall regimes		Removal of mega-herbivores, fire suppression,	*High*	Skowno et al. (2017); Stevens et al. (2017); Venter et al. (2018); García Criado et al. 2020)

	areas into previously open areas in the last 20 years			changed herbivore regime		
African savanna	Widespread increase in tree cover across Africa with only 3 countries across continent experiencing a net decline in tree cover	Warming, changing rainfall, mention of CO_2		Fire suppression	*High*	Venter et al. (2018)
African savanna	Biodiversity responses to changes in vegetation structure (woody encroachment) causing declines in functional groups that are open area specialists. Records in birds, rodents, termites, mammals, insects.	Woody encroachment			*Medium*	Blaum et al. (2007); Blaum et al. (2009); Sirami and Monadjem (2012); Gray and Bond (2013); Péron and Altwegg (2015); Smit and Prins (2015)
African semi-arid regions (savanna)	Reduced tourism experience due to woody encroachment	Woody encroachment			*Low*	Gray and Bond (2013)
North American drylands – sagebrush steppes	Sagebrush steppes are being invaded by non-native grasses	Increase in temperature and favourable climates			*High*	Bradley et al. (2016); Hufft and Zelikova (2016); Chambers (2018)
	Shrub encroachment,(*Prosopis glandulosa, Juniper ashei* and *Juniper pinchotti)* is occurring in the semi-arid grasslands of the southern great plains at a rate of ~8% per decade	Increasing temperature, elevated CO2 and changing rainfall		Fire suppression and altered grazing/browsing regimes	*High*	Caracciolo et al. (2016); Archer et al. (2017)
	Woody encroachment in sagebrush steppes (cold deserts) (*Juniper occidentalis*) at a rate of 2% per decade	a) Warming and associated decline in snowpack b) Less precipitation falling as snow and an increase in the rain fraction in winter.			*High*	Chambers et al. (2014); Mote et al. (2018)

Central Mexico	Desertification (as decreases in vegetation indexes).	decreased rainfall + increase in temperature		Land use change and intensification	*Medium*	Becerril-Pina et al. (2015); Noyola-Medrano and Martínez-Sías (2017)
Chinese drylands	Widespread greening trend of vegetation in China over the last three decades; regional difference	Warming, CO_2 increase. 1) Rising atmospheric CO2 concentration and nitrogen deposition are identified as the most likely causes of the greening trend in China, explaining 85% and 41% of the average growing-season LAI trend. 2) Negative impacts of climate change in north China and Inner Mongolia and the positive impact in the Qinghai-Xizang plateau		Ecological protection	*Medium*	Piao et al. (2015)
Dry sub-humid						
African mesic savannas	Forest expansion into mesic savannas	Increases rainfall, elevated CO_2		Fire suppression	*Medium*	Baccini et al. (2017); Aleman et al. (2018)
South American cerrado	8% rate of woody cover increase	Elevated Co2		Fire exclusion	*High*	Stevens et al. (2017); Rosan et al. (2019)
South American cerrado	Expansion of forest into cerrado	Elevated CO2		Fire exclusion	*High*	Passos et al. (2018); Rosan et al. (2019)
Australian savannas	2% rate of woody cover increase and greening of drylands				*High*	Donohue et al. (2013); Stevens et al. (2017); Bernardino et al. (2020)

Table CCP3.2: Synthesis of adaptation measures and responses to risks in deserts and semi-arid areas. Appropriateness of measures is context dependent and some adaptations will be incremental or even maladaptive in some dryland contexts while being transformational in other locations.

Challenge	**Adaptation Measures and Responses**	**References**
Soil erosion	Rainwater harvesting and soil conservation, grass reseeding, agroforestry. Use of different breeds of grazing animals, altered livestock rotation systems, use of new crop varieties, development of management strategies that reduce the risk of wildfire.	Eldridge and Beecham (2018)
Overgrazing	Modification of production and management systems that involve diversification of livestock animals and crops, integration of livestock systems with forestry and crop production, and changing the timing and locations of farm operations. Improved breeds and feeding strategies and adoption of improved breeds for households without cows (both economic & environmental gain).	Kattumuri et al. (2015), Shikuku et al. (2017)
Clearing of natural vegetation	Carbon sequestration through decreasing vegetation clearing rates, reversal through revegetation, targeting for higher-yielding crops with better climate change adapted varieties, and improvement of land and water management Agroforestry role in addressing various on-farm adaptation needs besides fulfilling many roles in AFOLU-related mitigation pathways (assets and income from carbon, wood energy, improved soil fertility and enhancement of local climate conditions; it provides ecosystem services and reduces human impacts on natural forests). Implementation of co-benefits strategies including provision of incentives across multiple scales and time frames, fostering multidimensional communication networks and promoting long-term integrated impact assessment. Achievement of triple-wins in SSA through provision of development benefits by making payments for forest services to smallholder farmers, mitigation benefits by increasing carbon storage, and adaptation benefits by creating opportunities for livelihood diversification.	Kattumuri et al. (2017), Mbow et al. (2014), Suckall et al. (2014)
Invasive species and woody encroachment	Cliamte change is projected to facilitate the spread of invasive species. Invaive species can have profound impacts on dryland ecosystems functioning leading to the loss of biodiversity. Biomass harvesting and selective clearing; utilising intense fires to manage encroachment, combined browsing and fire management. Rewilding in open ecosystems and reintroduction of mega-herbivores (e.g. in parts of Africa) to counter negative impact of woody encroachment. Chemical removal of undesirable encroached woody species	Mirzabaev et al. (2019); Davies and Nori (2008); Stafford et al. (2017); Cromsigt et al. (2018); Ding and Eldridge (2019)
Droughts	Pro-active drought risk mitigation vs reactive crisis management approaches. Promoting collective action in livestock management, optimizing livestock policies and feed subsidies. interventions in livestock markets during drought onset. Expanding sustainable irrigation and shifting to drought-resistant crops and crop varieties. Environmentally sustainable sea water desalination. Promoting behavioural changes for more efficient residential water use. Moving away from water-intensive agricultural practices in arid areas. Harvesting rainwater by local communities; empowering women and engagement in local climate adaptation planning, community	Morton and Barton (2002); Abebe et al. (2008); Alary et al. (2014); Catley et al. (2014); Mohamed et al. (2016)

	based early warning systems, IRWM, water governance benchmarking, and exploration of palaeo channels as freshwater sources using remote sensing	
Grassland and savanna degradation	Prescribed fire and tree cutting, invasive plant removal, grazing management, reintroduction of grasses and forbs, restoration of soil disturbance.	For review see Buisson et al. (2019)
Rangeland degradation (decreasing fodder quality or yield, invasion by fodder poor value species/refusals)	Promote herd local and regional mobility during the growing season to avoid intense grazing pressure on growing annual herbaceous vegetation of rangelands near settlements, water points, market. Moderate grazing facilitates grass tillering and herbaceous flora diversity. Ecological restoration of grazing ecosystems by sowing a mixture of zone-typical dominant species and life forms of plants on severely degraded land. Clearance of invasives. Ecological restoration of arid ecosystems by sowing a mixture of zone-typical dominant species and life forms of fodder plants with partial (ribbon) treatment of pasture lands. Ecological restoration of secondary salted irrigated soils using halophytes.	De Vries and Djitèye (1982); Hiernaux et al. (1994); Hiernaux and Le Houérou (2006); Reed et al. (2015)
Poor livestock productivity (reproduction/dairy/meat) in relation with poor seasonal nutrition	Promote seasonal-regional herd mobility to optimise the use of complementary fodder resources (rangelands, browses, crop residues). Implies institutionalized communal access, community agreements and infrastructures (water points, livestock path, grazing reserves, access to education, health care, markets for transhumant population). Cross state boundary mobility implies international agreements such as promoted by N'djamena meeting (Declaration 2013)	Turner (1993); Schlecht et al. (2004); Fernández-Rivera et al. (2005); Bonnet and Herault (2011); Hiernaux et al. (2016)
	Promote strategic supplementation of reproductive and young animals by the end of dry and early wet season. Secondary effect on excretion quantity/ quality to manure croplands.	Many trials in research stations and on farm: for example Sangaré et al. (2002a); Sangaré et al. (2002b); Osbahr et al. (2011); Sanogo (2011)
Decrease trend in cropland soil fertility	Rotational corralling of livestock in field during the dry season (and on cleared fallow the following year in the wet season) to ensure maximum retrieval of organic matter and nutrients from faeces and urine deposited. Application or mineral N and P fertilisers as placed (per poquet) microdoses (50-80 kg/ha) to intensify staple crop production. Impact on soil fertility, rain use efficiency, vegetation cover, organic matter production and recycling. Legume association with cereals (millet-cowpea; Sorghum-groundnut). Adapting cultivars and cropping techniques (calendar, fertilisation)	Pieri (1989); Breman et al. (2001); Gandah et al. (2003); Manlay et al. (2004); Abdoulaye and Sanders (2005); Reij et al. (2005); Akponikpe (2008); Bagayoko et al. (2011); Bationo et al. (2011); Hiernaux et al. (2009b); Sendzimir et al. (2011); Turner and Hiernaux (2015); Weston et al. (2015; Reij and Garrity (2016)
Salinisation and groundwater depletion	Indigenous and scientific adaptive practices to cope with salinity. Farmers in waterlogged saline areas harness sub-surface drainage, salt tolerant crop varieties, land-shaping techniques and agroforestry to adapt to salinity and waterlogging risks. Locally adapted crops and landraces, and the traditional tree- and animal-based means to sustain livelihoods	Sengupta (2002); Buechler and Mekala (2005); Wassmann et al. (2009); Singh (2010); Jnandabhiram and Sailen Prasad

	in face of salinisation. Climate change is projected to increase the salinization of groundwaters. Current unsustainable use of groundwaters is already leading to their depletion in some dryland areas.	(2012); Manga et al. (2015); Sharma and Singh (2015); Gupta and Dagar (2016); Nikam et al. (2016); Bundela et al. (2017); Sharma and Singh (2017); Patel et al. (2020); Singh et al. (2020b); Sharma, (2016); Mirzabaev et al. (2019)
Sand and dust storms	Use of live windbreaks or shelterbelts, protection of the loose soil particles through the use of crop residues or plastic sheets or chemical adhesives, increasing the cohesion of soil particles by mechanical tillage operations or soil mulching. Use of perennial plant species that have the ability to trap sediments (sand and fallen dust) and form sandy mound around it, such as *Haloxylon salicornicum*, *Cyperus conglomerates*, *Lycium shawii*, and *Nitraria retusa*. In Sahel: promote herbaceous (not woody plants) to trap sand annuals such as Colocynthis vulgaris, Chrozophora senegalensis, Farsetia ramosissima, perennials such as Cyperus conglomeratus, Leptadenia hastate. In Sahel: leaving at least part of the crop residues (stalks) laid down on the soil during the dry season (100kg dry matter per hectare has already significant effect on wind erosion, many trials on Millet in Niger). Trampling by grazing livestock improves the partial burying of the residues. Improve monitoring, prediction and early warning. Monitoring, prediction and early warning to mobilize emergency responses for human systems & prioritize long-term sustainable land management measures. Establishment of a Global Dust-Health Early Warning System (building on the SDS-WAS initiative). Multi-sectoral preparedness and response including public health, hospital services, air and ground transportation and communication services	Ahmed et al. (2016); Al-Hemoud et al. (2017); Sivakumar (2005); Hiernaux et al. (2009a); Hiernaux et al. (2016); Pierre et al. (2018); Lamers et al. (1995); Michels et al. (1998); Bielders et al. (2004),UNEP (2016); UNEP (1992)

References

Abatzoglou, J. T. and C. A. Kolden, 2011: Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangeland Ecology & Management*, **64**(5), 471-478, doi:https://doi.org/10.2111/REM-D-09-00151.1.

Abdoulaye, T. and J. H. Sanders, 2005: Stages and determinants of fertilizer use in semiarid African agriculture: the Niger experience. **32**(2), 167-179, doi:10.1111/j.0169-5150.2005.00011.x.

Abebe, D. et al., 2008: Impact of a commercial destocking relief intervention in Moyale district, southern Ethiopia. *Disasters*, **32**, 167-189, doi:10.1111/j.1467-7717.2007.01034.x.

Abel, C. et al., 2021: The human–environment nexus and vegetation–rainfall sensitivity in tropical drylands. *Nature Sustainability*, **4**(1), 25-32, doi:10.1038/s41893-020-00597-z.

Abel, G. J., M. Brottrager, J. Crespo Cuaresma and R. Muttarak, 2019: Climate, conflict and forced migration. *Global Environmental Change*, **54**, 239-249, doi:https://doi.org/10.1016/j.gloenvcha.2018.12.003.

Abraham, E. M., J. Guevara, R. J. Candia and N. D. Soria, 2016: *Dust storms, drought and desertification in the Southwest of Buenos Aires Province, Argentina*. vol. 48, 221-241 pp.

Aguilar-Barajas, I. et al., 2016: Drought policy in Mexico: a long, slow march toward an integrated and preventive management model. *Water Policy*, **18**(S2), 107-121, doi:10.2166/wp.2016.116.

Ahmed, M., N. Al-Dousari and A. Al-Dousari, 2016: The role of dominant perennial native plant species in controlling the mobile sand encroachment and fallen dust problem in Kuwait. *Arabian Journal of Geosciences*, **9**(2), 134, doi:10.1007/s12517-015-2216-6.

Akhtar-Schuster, M. et al., 2017: Unpacking the concept of land degradation neutrality and addressing its operation through the Rio Conventions. *Journal of Environmental Management*, **195**, 4-15, doi:https://doi.org/10.1016/j.jenvman.2016.09.044.

Akponikpe, P. B. I., 2008: Millet response to water and soil fertility management in the Sahelian Niger: Experiments and modelling. . Université catholique de Louvain, Louvain-la-Neuve, Belgium, 168 pp.

Al-Hemoud, A. et al., 2017: Socioeconomic effect of dust storms in Kuwait. *Arabian Journal of Geosciences*, **10**(1), 18, doi:10.1007/s12517-016-2816-9.

Alary, V. et al., 2014: Livelihood strategies and the role of livestock in the processes of adaptation to drought in the Coastal Zone of Western Desert (Egypt). *Agricultural Systems*, **128**, 44-54, doi:https://doi.org/10.1016/j.agsy.2014.03.008.

Alba-Sánchez, F., J. A. López-Sáez, D. Nieto-Lugilde and J.-C. Svenning, 2015: Long-term climate forcings to assess vulnerability in North Africa dry argan woodlands. *Applied Vegetation Science*, **18**(2), 283-296, doi:10.1111/avsc.12133.

Aleman, J. C., M. A. Jarzyna and A. C. Staver, 2018: Forest extent and deforestation in tropical Africa since 1900. *Nat Ecol Evol*, **2**(1), 26-33, doi:10.1038/s41559-017-0406-1.

Alizadeh-Choobari, O. and M. S. Najafi, 2018: Extreme weather events in Iran under a changing climate. *Climate Dynamics*, **50**(1), 249-260, doi:10.1007/s00382-017-3602-4.

Allahbakhshi, K., D. Khorasani-Zavareh, R. Khani Jazani and Z. Ghomian, 2019: Preparedness components of health systems in the Eastern Mediterranean Region for effective responses to dust and sand storms: a systematic review. *F1000Research*, **8**, 146-146, doi:10.12688/f1000research.17543.1.

Almer, C., J. Laurent-Lucchetti and M. Oechslin, 2017: Water scarcity and rioting: Disaggregated evidence from Sub-Saharan Africa. *Journal of Environmental Economics and Management*, **86**, 193-209, doi:https://doi.org/10.1016/j.jeem.2017.06.002.

Amdan, M. L. et al., 2013: Onset of deep drainage and salt mobilization following forest clearing and cultivation in the Chaco plains (Argentina). *Water Resources Research*, **49**(10), 6601-6612, doi:10.1002/wrcr.20516.

Amin, A. et al., 2018: Regional climate assessment of precipitation and temperature in Southern Punjab (Pakistan) using SimCLIM climate model for different temporal scales. *Theoretical and Applied Climatology*, **131**(1), 121-131, doi:10.1007/s00704-016-1960-1.

Amiraslani, F., A. Caiserman, F. Amiraslani and A. Caiserman, 2018: Multi-Stakeholder and Multi-Level Interventions to Tackle Climate Change and Land Degradation: The Case of Iran. *Sustainability*, **10**(6), 2000-2000, doi:10.3390/su10062000.

An, L. et al., 2018: Temporal and spatial variations in sand and dust storm events in East Asia from 2007 to 2016: Relationships with surface conditions and climate change. *Science of The Total Environment*, **633**, 452-462, doi:https://doi.org/10.1016/j.scitotenv.2018.03.068.

Andela, N. et al., 2013: Global changes in dryland vegetation dynamics (1988–2008) assessed by satellite remote sensing: comparing a new passive microwave vegetation density record with reflective greenness data. *Biogeosciences*, **10**(10), 6657-6676.

Anyamba, A. and C. J. Tucker, 2005: Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003. *Journal of Arid Environments*, **63**(3), 596-614, doi:10.1016/J.JARIDENV.2005.03.007.

Aragón-Gastélum, J. L. et al., 2017: Seedling survival of three endemic and threatened Mexican cacti under induced climate change. *Plant Species Biology*, **32**(1), 92-99, doi:10.1111/1442-1984.12120.

Aragón-Gastélum, J. L. et al., 2018: Potential impact of global warming on seed bank, dormancy and germination of three succulent species from the Chihuahuan Desert. *Seed Science Research*, **28**(4), 312-318.

Aragón-Gastélum, J. L. et al., 2014: Induced climate change impairs photosynthetic performance in Echinocactus platyacanthus, an especially protected Mexican cactus species. *Flora-Morphology, Distribution, Functional Ecology of Plants*, **209**(9), 499-503.
Archer, S. R. et al., 2017: Woody Plant Encroachment: Causes and Consequences. In: *Rangeland Systems: Processes, Management and Challenges* [Briske, D. D. (ed.)]. Springer International Publishing, Cham, pp. 25-84. ISBN 978-3-319-46709-2.
Ashkenazy, Y., H. Yizhaq and H. Tsoar, 2012: Sand dune mobility under climate change in the Kalahari and Australian deserts. *Climatic Change*, **112**(3-4), 901-923, doi:10.1007/s10584-011-0264-9.
Aslam, A. Q. et al., 2018: Integrated climate change risk assessment and evaluation of adaptation perspective in southern Punjab, Pakistan. *Science of The Total Environment*, **628-629**, 1422-1436, doi:https://doi.org/10.1016/j.scitotenv.2018.02.129.
Assouma, M. H. et al., 2019: Contrasted seasonal balances in a Sahelian pastoral ecosystem result in a neutral annual carbon balance. *Journal of Arid Environments*, **162**, 62-73, doi:https://doi.org/10.1016/j.jaridenv.2018.11.013.
Assouma, M. H. et al., 2017: Livestock induces strong spatial heterogeneity of soil CO2, N2O and CH4 emissions within a semi-arid sylvo-pastoral landscape in West Africa. *Journal of Arid Land*, **9**(2), 210-221, doi:10.1007/s40333-017-0001-y.
Baccini, A. et al., 2017: Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science*, **358**(6360), 230-234, doi:10.1126/science.aam5962.
Bachelder, J. et al., 2020: Chemical and microphysical properties of wind-blown dust near an actively retreating glacier in Yukon, Canada. *Aerosol Science and Technology*, **54**(1), 2-20, doi:10.1080/02786826.2019.1676394.
Báez, S. et al., 2013: Effects of experimental rainfall manipulations on Chihuahuan Desert grassland and shrubland plant communities. *Oecologia*, **172**(4), 1117-1127, doi:10.1007/s00442-012-2552-0.
Bagayoko, M. et al., 2011: Microdose and N and P fertilizer application rates for pearl millet in West Africa. *African Journal of Agricultural Research*, **6**, 1141-1150.
Bahir, M., S. Ouhamdouch, D. Ouazar and N. El Moçayd, 2020: Climate change effect on groundwater characteristics within semi-arid zones from western Morocco. *Groundwater for Sustainable Development*, **11**, 100380, doi:https://doi.org/10.1016/j.gsd.2020.100380.
Ballouche, A. and M. Rasse, 2007: L'homme, artisan des paysages de savane. *Pour la science*,(358), 56-61.
Barbosa, H. A., T. V. Lakshmi Kumar and L. R. M. Silva, 2015: Recent trends in vegetation dynamics in the South America and their relationship to rainfall. *Natural Hazards*, **77**(2), 883-899, doi:10.1007/s11069-015-1635-8.
Basu, S., J. Jongerden and G. Ruivenkamp, 2017: Development of the drought tolerant variety Sahbhagi Dhan: exploring the concepts commons and community building. *International Journal of the Commons*, **11**(1), 144, doi:10.18352/ijc.673.
Bationo, J. et al., 2011: Comparative Analysis of the Current and Potential Role of Legumes in Integrated Soil Fertility Management in West and Central Africa. . In: *Fighting Poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management.* [Bationo A., W. B., Okeyo J.M., Maina F., Kihara J. and U. Mokwunye (ed.)]. Springer Dordrecht, Netherlands, pp. 117-150. ISBN 9789400715356.
Bawden, R., 2018: Global Change and Its Consequences for the World's Arid Lands. In: *Climate Variability Impacts on Land Use and Livelihoods in Drylands* [Gaur, M. K. and V. R. Squires (eds.)]. Springer International Publishing, Cham, pp. 59-71. ISBN 978-3-319-56681-8.
Bayram, H. and A. B. Öztürk, 2014: Global Climate Change, Desertification, and Its Consequences in Turkey and the Middle East. In: *Global Climate Change and Public Health* [Pinkerton, K. E. and W. N. Rom (eds.)]. Springer New York, New York, NY, pp. 293-305. ISBN 978-1-4614-8417-2.
Bazza, M., M. Kay and C. Knutson, 2018 *Drought Characteristics and Management in North Africa and the Near East* Food and Agriculture Organisation of the United Nations (FAO), Rome, Italy, 266 pp. Available at: http://www.fao.org/3/CA0034EN/ca0034en.pdf (Accessed on: 5.11.2020).
Becerril-Pina, R. et al., 2015: Assessing desertification risk in the semi-arid highlands of central Mexico. *Journal of Arid Environments*, **120**, 4-13.
Behnke, R., 2000: Equilibrium and non-equilibrium models of livestock population dynamics in pastoral Africa: Their relevance to Arctic grazing systems. *Rangifer*, **20**, doi:10.7557/2.20.2-3.1509.
Behnke, R. H. and M. Mortimore, 2016: The End of Desertification? : Disputing Environmental Change in the Drylands, 1st ed., Springer Berlin Heidelberg : Imprint: Springer,, Berlin, Heidelberg, 1 online resource (VIII, 560 pages 117 illustrations, 541 illustrations in color pp.
Benjaminsen, T. A., K. Alinon, H. Buhaug and J. T. Buseth, 2012: Does climate change drive land-use conflicts in the Sahel? *Journal of Peace Research*, **49**(1), 97-111, doi:10.1177/0022343311427343.
Benjaminsen, T. A. and B. Ba, 2009: Farmer–herder conflicts, pastoral marginalisation and corruption: a case study from the inland Niger delta of Mali. *Geographical Journal*, **175**(1), 71-81.
Benjaminsen, T. A. and B. Ba, 2019: Why do pastoralists in Mali join jihadist groups? A political ecological explanation. *The Journal of Peasant Studies*, **46**(1), 1-20, doi:10.1080/03066150.2018.1474457.
Benjaminsen, T. A. and P. Hiernaux, 2019: From Desiccation to Global Climate Change: A History of the Desertification Narrative in the West African Sahel, 1900-2018. *Global Environment*, **12**(1), 206-236, doi:10.3197/ge.2019.120109.

Benjaminsen, T. A., F. P. Maganga and J. M. Abdallah, 2009: The Kilosa Killings: Political Ecology of a Farmer–Herder Conflict in Tanzania. *Development and Change*, **40**(3), 423-445, doi:10.1111/j.1467-7660.2009.01558.x.
Benjaminsen, T. A., H. Reinert, E. Sjaastad and M. N. Sara, 2015: Misreading the Arctic landscape: A political ecology of reindeer, carrying capacities, and overstocking in Finnmark, Norway. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography*, **69**(4), 219-229, doi:10.1080/00291951.2015.1031274.
Benjaminsen, T. A. et al., 2006: Land Reform, Range Ecology, and Carrying Capacities in Namaqualand, South Africa. *Annals of the Association of American Geographers*, **96**(3), 524-540, doi:10.1111/j.1467-8306.2006.00704.x.
Berdugo, M. et al., 2020: Global ecosystem thresholds driven by aridity. *Science*, **367**(6479), 787-790, doi:10.1126/science.aay5958.
Berg, A. et al., 2016: Land–atmosphere feedbacks amplify aridity increase over land under global warming. *Nature Climate Change*, **6**(9), 869-874.
Berg, A., J. Sheffield and P. C. Milly, 2017a: Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, **44**(1), 236-244.
Berg, A., J. Sheffield and P. C. D. Milly, 2017b: Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, **44**(1), 236-244, doi:10.1002/2016GL071921.
Bergius, M., T. A. Benjaminsen, F. Maganga and H. Buhaug, 2020: Green economy, degradation narratives, and land-use conflicts in Tanzania. *World Development*, **129**, 104850, doi:https://doi.org/10.1016/j.worlddev.2019.104850.
Berhane, G. et al., 2014: Can Social Protection Work in Africa? The Impact of Ethiopia's Productive Safety Net Programme. *Economic Development and Cultural Change*, **63**(1), 1-26, doi:10.1086/677753.
Bernardino, P. N. et al., 2020: Uncovering Dryland Woody Dynamics Using Optical, Microwave, and Field Data—Prolonged Above-Average Rainfall Paradoxically Contributes to Woody Plant Die-Off in the Western Sahel. *Remote Sensing*, **12**(14), 2332.
Bestelmeyer, B. T. et al., 2018: The Grassland–Shrubland Regime Shift in the Southwestern United States: Misconceptions and Their Implications for Management. *BioScience*, **68**(9), 678-690, doi:10.1093/biosci/biy065.
Bhattachan, A. et al., 2012: The Southern Kalahari: a potential new dust source in the Southern Hemisphere? *Environmental Research Letters*, **7**(2), 024001.
Bianchi, L. O. et al., 2017: A regional water balance indicator inferred from satellite images of an Andean endorheic basin in central-western Argentina. *Hydrological Sciences Journal*, **62**(4), 533-545.
Biasutti, M., 2013: Forced Sahel rainfall trends in the CMIP5 archive. *Journal of Geophysical Research: Atmospheres*, **118**(4), 1613-1623, doi:10.1002/jgrd.50206.
Biasutti, M. and A. Giannini, 2006: Robust Sahel drying in response to late 20th century forcings. *Geophysical Research Letters*, **33**(11), doi:10.1029/2006GL026067.
Bidak, L. M., S. A. Kamal, M. W. A. Halmy and S. Z. Heneidy, 2015: Goods and services provided by native plants in desert ecosystems: Examples from the northwestern coastal desert of Egypt. *Global ecology and conservation*, **3**, 433-447.
Bielders, C., L., R. Jean-Louis and M. Karlheinz, 2004: L'érosion éolienne dans le Sahel nigérien : influence des pratiques culturales actuelles et méthodes de lutte. *Science et changements planétaires / Sécheresse*, **15**(1), 19-32.
Blaikie, P. M. and H. C. Brookfield, 1987: *Land degradation and society*, 1st Edition ed., Methuen, London ; New York, 296 pp. ISBN 9780416401509.
Blaum, N., E. Rossmanith, A. Popp and F. Jeltsch, 2007: Shrub encroachment affects mammalian carnivore abundance and species richness in semiarid rangelands. *Acta Oecologica*, **31**(1), 86-92, doi:https://doi.org/10.1016/j.actao.2006.10.004.
Blaum, N. et al., 2009: Changes in arthropod diversity along a land use driven gradient of shrub cover in savanna rangelands: identification of suitable indicators. *Biodiversity and Conservation*, **18**(5), 1187-1199.
Blok, D. et al., 2011: The response of Arctic vegetation to the summer climate: relation between shrub cover, NDVI, surface albedo and temperature. *Environmental Research Letters*, **6**(3), 035502, doi:10.1088/1748-9326/6/3/035502.
Bond, W. J. and G. F. Midgley, 2012: Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **367**(1588), 601-612, doi:10.1098/rstb.2011.0182.
Bond, W. J., N. Stevens, G. F. Midgley and C. E. R. Lehmann, 2019: The Trouble with Trees: Afforestation Plans for Africa. *Trends in Ecology & Evolution*, **34**(11), 963-965, doi:https://doi.org/10.1016/j.tree.2019.08.003.
Bonnet, B. and D. Herault, 2011: Gouvernance du foncier pastorale et changement climatique au Sahel. *Revue des questions foncières (Land Tenure Journal)*, **2**, 157-187.
Booysen, M. J., M. Visser and R. Burger, 2019: Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data. *Water Research*, **149**, 414-420, doi:10.1016/j.watres.2018.11.035.
Boucher, O. et al., 2013: Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 571-658. ISBN 9781107057991.
Boudet, G., 1977: Désertification ou remontée biologique au Sahel. *Cahiers ORSTOM, série biologie*, **12**(4), 293-300.

Boy, M., 2019: *Interactions between the atmosphere, cryosphere, and ecosystems at northern high latitudes*. vol. 19, 2015 pp.
Bradford, J. B. et al., 2018: Anticipatory natural resource science and management for a changing future. *Frontiers in Ecology and the Environment*, **16**(5), 295-303, doi:https://doi.org/10.1002/fee.1806.
Bradley, B. A., C. A. Curtis and J. C. Chambers, 2016: Bromus Response to Climate and Projected Changes with Climate Change. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications* [Germino, M. J., J. C. Chambers and C. S. Brown (eds.)]. Springer International Publishing, Cham, pp. 257-274. ISBN 978-3-319-24930-8.
Brandt, M. et al., 2016: Assessing woody vegetation trends in Sahelian drylands using MODIS based seasonal metrics. *Remote Sensing of Environment*, **183**, 215-225, doi:https://doi.org/10.1016/j.rse.2016.05.027.
Brandt, M. et al., 2019: Changes in rainfall distribution promote woody foliage production in the Sahel. *Communications Biology*, **2**(1), doi:10.1038/s42003-019-0383-9.
Brandt, M. et al., 2018: Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands. *Nature Geoscience*, **11**(5), 328-333, doi:https://doi.org/10.1038/s41561-018-0092-x.
Brandt, M. et al., 2017: Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. *Nature Ecology & Evolution*, **1**(4), 0081, doi:10.1038/s41559-017-0081.
Breman, H., J. J. R. Groot and H. v. Keulen, 2001: Resource limitations in Sahelian agriculture. *Global environmental change : human and policy dimensions*, **11**(1), 59-68.
Brockington, D., 2002: *Fortress Conservation. The Preservation of the Mkomazi Game Reserve Tanzania*. James Currey, Oxford, UK. ISBN 9780852554173.
Brooks, M. L. and J. R. Matchett, 2006: Spatial and temporal patterns of wildfires in the Mojave Desert, 1980–2004. *Journal of Arid Environments*, **67**, 148-164, doi:https://doi.org/10.1016/j.jaridenv.2006.09.027.
Brooks, N. et al., 2005: The climate-environment-society nexus in the Sahara from prehistoric times to the present day. *The Journal of North African Studies*, **10**(3-4), 253-292.
Buechler, S. and G. D. Mekala, 2005: Local responses to water resource degradation in India: Groundwater farmer innovations and the reversal of knowledge flows. *The Journal of Environment & Development*, **14**(4), 410-438.
Buhaug, H., T. Benjaminsen, E. Sjaastad and O. Theisen, 2015: Climate variability, food production shocks, and violent conflict in Sub-Saharan Africa. *Environmental Research Letters*, **10**, 125015, doi:10.1088/1748-9326/10/12/125015.
Buhaug, H. et al., 2014: One effect to rule them all? A comment on climate and conflict. *Climatic Change*, **127**(3-4), 391-397, doi:10.1007/s10584-014-1266-1.
Buisson, E. et al., 2019: Resilience and restoration of tropical and subtropical grasslands, savannas, and grassy woodlands. *Biological Reviews*, **94**(2), 590-609, doi:10.1111/brv.12470.
Buitenwerf, R., W. J. Bond, N. Stevens and W. S. W. Trollope, 2012: Increased tree densities in South African savannas: >50 years of data suggests CO2 as a driver. *Global Change Biology*, **18**(2), 675-684, doi:10.1111/j.1365-2486.2011.02561.x.
Bullard, J. E. et al., 2016: High-latitude dust in the Earth system. *Reviews of Geophysics*, **54**(2), 447-485, doi:https://doi.org/10.1002/2016RG000518.
Bundela, D. S., A. L. Pathan and R. Raju 2017: *Performance evaluation of sub-surface drainage systems in Haryana and to implement interventions for improving operational performance and impact. I*. CAR-CSSRI Annual Report (2017-18), ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, India 36-38 pp. Available at: https://cssri.res.in/poxumyse/2018/07/Annual-Report-2017-18.pdf.
Burrell, A. L., J. P. Evans and M. G. De Kauwe, 2020: Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. *Nature Communications*, **11**(1), doi:10.1038/s41467-020-17710-7.
Caracciolo, D., E. Istanbulluoglu, L. V. Noto and S. L. Collins, 2016: Mechanisms of shrub encroachment into Northern Chihuahuan Desert grasslands and impacts of climate change investigated using a cellular automata model. *Advances in Water Resources*, **91**, 46-62, doi:https://doi.org/10.1016/j.advwatres.2016.03.002.
Carrillo-Angeles, I. G. et al., 2016: Niche breadth and the implications of climate change in the conservation of the genus Astrophytum (Cactaceae). *Journal of Arid Environments*, **124**, 310-317.
Castillón, E. E. et al., 2015: Classification and ordination of main plant communities along an altitudinal gradient in the arid and temperate climates of northeastern Mexico. *The Science of Nature*, **102**(9-10), 59, doi:10.1007/s00114-015-1306-3.
Catley, A., B. Admassu, G. Bekele and D. Abebe, 2014: Livestock mortality in pastoralist herds in Ethiopia and implications for drought response. *Disasters*, **38**(3), 500-516, doi:10.1111/disa.12060.
Cavalcante, A., A. Duarte and J. Ometto, 2020: Modeling the potential distribution of Epiphyllum phyllanthus (L.) Haw. under future climate scenarios in the Caatinga biome. *Anais da Academia Brasileira de Ciências*, **92**, doi:10.1590/0001-3765202020180836.
Cavalcante, A. and A. S. Duarte, 2019: Modeling the Distribution of Three Cactus Species of the Caatinga Biome in Future Climate Scenarios. *International journal of ecology and environmental sciences*, **45**, 191-203.
Cavanagh, C. J. and T. A. Benjaminsen, 2015: Guerrilla agriculture? A biopolitical guide to illicit cultivation within an IUCN Category II protected area. *The Journal of Peasant Studies*, **42**(3-4), 725-745, doi:10.1080/03066150.2014.993623.

Chambers, D. P., 2018: Using kinetic energy measurements from altimetry to detect shifts in the positions of fronts in the Southern Ocean. *Ocean Science*, **14**(1), 105-116, doi:10.5194/os-14-105-2018.
Chambers, J. C. et al., 2014: Resilience to Stress and Disturbance, and Resistance to Bromus tectorum L. Invasion in Cold Desert Shrublands of Western North America. *Ecosystems*, **17**(2), 360-375, doi:10.1007/s10021-013-9725-5.
Chambers, J. C. et al., 2019: Operationalizing Resilience and Resistance Concepts to Address Invasive Grass-Fire Cycles. *Frontiers in Ecology and Evolution*, **7**(185), doi:10.3389/fevo.2019.00185.
Charney, J. G., 1975: *Dynamics of deserts and drought in the Sahel**. **101**, 193-202 pp. Available at: https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.49710142802.
Chatty, D., 2007: Mobile Peoples: Pastoralists and Herders at the Beginning of the 21st Century. *Reviews in Anthropology*, **36**(1), 5-26, doi:10.1080/00938150601177538.
Chen, C. et al., 2019a: China and India lead in greening of the world through land-use management. *Nature Sustainability*, **2**(2), 122-129, doi:10.1038/s41893-019-0220-7.
Chen, H., T. Li and Q. Wang, 2019b: Ten years of algal biofuel and bioproducts: gains and pains. *Planta*, **249**(1), 195-219, doi:10.1007/s00425-018-3066-8.
Cheng, S. and J. Huang, 2016: Enhanced soil moisture drying in transitional regions under a warming climate. *Journal of Geophysical Research: Atmospheres*, **121**(6), 2542-2555, doi:10.1002/2015jd024559.
Cherlet, M. et al., 2018: *World atlas of desertification rethinking land degradation and sustainable land management*. ISBN 9789279753503 9279753509.
Chevrillon-Guibert, R., L. Gagnol and G. Magrin, 2019: Les ruées vers l'or au Sahara et au nord du Sahel. Ferment de crise ou stabilisateur? *Hérodote*,(1), 193-215.
Choukri, F. et al., 2020: Distinct and combined impacts of climate and land use scenarios on water availability and sediment loads for a water supply reservoir in northern Morocco. *International Soil and Water Conservation Research*, doi:https://doi.org/10.1016/j.iswcr.2020.03.003.
Christie, I. T., E. H. Fernandes, H. R. Messerli and L. D. Twining-Ward, 2014: *Tourism in Africa : harnessing tourism for growth and improved livelihoods*. Africa development forum, World Bank Group., Washington, DC.
Collins, S. and Y. Xia, 2015: *Long-Term Dynamics and Hotspots of Change in a Desert Grassland Plant Community*. vol. 185, E30-E43 pp.
Conver, J. L., T. Foley, D. E. Winkler and D. E. Swann, 2017: Demographic changes over >70 yr in a population of saguaro cacti (Carnegiea gigantea) in the northern Sonoran Desert. *Journal of Arid Environments*, **139**, 41-48, doi:https://doi.org/10.1016/j.jaridenv.2016.12.008.
Cook, B. I., J. E. Smerdon, R. Seager and S. Coats, 2014: Global warming and 21st century drying. *Climate Dynamics*, **43**(9-10), 2607-2627, doi:10.1007/s00382-014-2075-y.
Cowie, A. L. et al., 2018: Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science & Policy*, **79**, 25-35, doi:10.1016/J.ENVSCI.2017.10.011.
Cromsigt, J. et al., 2018: Trophic rewilding as a climate change mitigation strategy? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **373**, 20170440, doi:10.1098/rstb.2017.0440.
Cross, H., 2013: Labour and underdevelopment? Migration, dispossession and accumulation in West Africa and Europe. *Review of African Political Economy*, **40**(136), 202-218, doi:10.1080/03056244.2013.794727.
Dagsson-Waldhauserová, P., Ó. Arnalds and H. Olafsson, 2014: Long-term variability of dust events in Iceland (1949-2011). *Atmospheric Chemistry and Physics*, **14**, 13411-13422.
Dagsson-Waldhauserova, P. and O. Meinander, 2019: Editorial: Atmosphere—Cryosphere Interaction in the Arctic, at High Latitudes and Mountains With Focus on Transport, Deposition, and Effects of Dust, Black Carbon, and Other Aerosols. *Frontiers in Earth Science*, **7**(337), doi:10.3389/feart.2019.00337.
Dai, A., 2011: Drought Under Global Warming: A Review. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 45-65, doi:10.1002/wcc.81.
Dai, A., K. Trenberth and T. T. Qian, 2004: A Global Dataset of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming. *JOURNAL OF HYDROMETEOROLOGY*, **5**, 1117-1130, doi:10.1175/JHM-386.1.
Dar, M. H. et al., 2020: Drought Tolerant Rice for Ensuring Food Security in Eastern India. *Sustainability*, **12**(6), 2214.
Dardel, C. et al., 2014: Re-greening Sahel: 30years of remote sensing data and field observations (Mali, Niger). *Remote Sensing of Environment*, **140**, 350-364, doi:https://doi.org/10.1016/j.rse.2013.09.011.
Davies, J. and M. Nori, 2008: Managing and mitigating climate change through pastoralism.
Davis-Reddy, C., 2018: Assessing vegetation dynamics in response to climate variability and change across sub-Saharan Africa. Stellenbosch University, Stellenbosch, South Africa.
De Vente, J. et al., 2016: How does the context and design of participatory decision making processes affect their outcomes? Evidence from sustainable land management in global drylands. *Ecology and Society*, **21**(2), doi:10.5751/es-08053-210224.
De Vries, F. P. and M. Djitèye, 1982: *La productivité des pâturages sahéliens: une étude des sols, des végétations et de l'exploitation de cette ressource naturelle*. Pudoc. ISBN 9022008061.
Defalco, L. A., T. C. Esque, S. J. Scoles-Sciulla and J. Rodgers, 2010: Desert wildfire and severe drought diminish survivorship of the long-lived Joshua tree (Yucca brevifolia; Agavaceae). *American Journal of Botany*, **97**(2), 243-250, doi:10.3732/ajb.0900032.

Dendoncker, M. et al., 2020: 50 years of woody vegetation changes in the Ferlo (Senegal) assessed by high-resolution imagery and field surveys. *Regional Environmental Change*, **20**(4), 137, doi:10.1007/s10113-020-01724-4.

Deng, Q. et al., 2016: Assessing the impacts of tillage and fertilization management on nitrous oxide emissions in a cornfield using the DNDC model. *Journal of Geophysical Research: Biogeosciences*, **121**(2), 337-349.

Denis, E. and F. Moriconi-Ebrard, 2009: La croissance urbaine en Afrique de l'Ouest. *La Chronique du CEPED*,(57), 1-5.

Descroix, L. et al., 2013: Impact of Drought and Land – Use Changes on Surface – Water Quality and Quantity: The Sahelian Paradox. InTech.

Díaz, J. et al., 2017: Saharan dust intrusions in Spain: Health impacts and associated synoptic conditions. *Environmental Research*, **156**, 455-467, doi:https://doi.org/10.1016/j.envres.2017.03.047.

Diba, I., M. Camara, A. Sarr and A. Diedhiou, 2018: Potential Impacts of Land Cover Change on the Interannual Variability of Rainfall and Surface Temperature over West Africa. *Atmosphere*, **9**(376), 1-32, doi:doi:10.3390/atmos9100376.

Dilshat, A. et al., 2015: Study on the expansion of cultivated land and its human driving forces in typical arid area oasis: a case study of Charchan Oasis in Xinjiang. *Area Research and Development*, **34**, 132-136.

Ding, J. and D. J. Eldridge, 2019: Contrasting global effects of woody plant removal on ecosystem structure, function and composition. *Perspectives in Plant Ecology, Evolution and Systematics*, **39**, 125460, doi:https://doi.org/10.1016/j.ppees.2019.125460.

Dong, S., 2016: Overview: Pastoralism in the World. pp. 1-37. ISBN 978-3-319-30730-5.

Donohue, R. J., M. L. Roderick, T. R. McVicar and G. D. Farquhar, 2013: Impact of CO ₂ fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters*, **40**(12), 3031-3035, doi:10.1002/grl.50563.

Droy, B., Bonnet, Cabrit,Coronel,Lambert, Loireau,Requier-Desjardins, Amsallem, 2020: Gender issues in dryland areas. Women as key stakeholders in combating desertification. *Les dossiers thématiques du CSFD. N°13. CSFD/Agropolis Intern., Montpellier, France.* , 52 pp

du Toit, J. C. O., T. G. O'Connor and L. Van den Berg, 2015: Photographic evidence of fire-induced shifts from dwarf-shrub- to grass-dominated vegetation in Nama-Karoo. *South African Journal of Botany*, **101**, 148-152, doi:https://doi.org/10.1016/j.sajb.2015.06.002.

Du Toit, J. C. O. and T. G. O'Connor, 2014: Changes in rainfall pattern in the eastern Karoo, South Africa, over the past 123 years. *Water SA*, **40**(3), 453-453, doi:10.4314/wsa.v40i3.8.

du Toit, J. C. O., T. Ramaswiela, M. J. Pauw and T. G. O'Connor, 2018: Interactions of grazing and rainfall on vegetation at Grootfontein in the eastern Karoo. *African Journal of Range & Forage Science*, **35**(3-4), 267-276, doi:10.2989/10220119.2018.1508072.

Duniway, M. C. et al., 2019: Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. *Ecosphere*, **10**(3), e02650, doi:10.1002/ecs2.2650.

Dunne, J. P., R. J. Stouffer and J. G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3**(6), 563-566, doi:10.1038/nclimate1827.

Dussaillant, I. et al., 2019: South American Andes elevation changes from 2000 to 2018, links to GeoTIFFs. *Supplement to: Dussaillant, I et al. (2019): Two decades of glacier mass loss along the Andes. Nature Geoscience, 12(10), 802-808, https://doi.org/10.1038/s41561-019-0432-5*, PANGAEA. Available at: https://doi.org/10.1594/PANGAEA.903618.

Eklundh, L. and L. Olsson, 2003: Vegetation index trends for the African Sahel 1982–1999. *Geophysical Research Letters*, **30**(8), doi:10.1029/2002gl016772.

Eldridge, D. J. and G. Beecham, 2018: The Impact of Climate Variability on Land Use and Livelihoods in Australia's Rangelands. In: *Climate Variability Impacts on Land Use and Livelihoods in Drylands* [Gaur, M. K. and V. R. Squires (eds.)]. Springer International Publishing, Cham, pp. 293-315. ISBN 978-3-319-56681-8.

Elhadary, Y. A. E., 2014: Examining drivers and indicators of the recent changes among pastoral communities of butana locality, gedarif State, Sudan. *American Journal of Sociological Research*, **4**(3), 88-101, doi:10.5923/j.sociology.20140403.04.

Escolar, C., I. Martínez, M. A. Bowker and F. T. Maestre, 2012: Warming reduces the growth and diversity of biological soil crusts in a semi-arid environment: implications for ecosystem structure and functioning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **367**(1606), 3087-3099.

ESCWA, U. N. E. a. S. C. f. W. A., 2017: Arab Climate Change Assessment Report – Main Report (Beirut). E/ESCWA/SDPD/2017/RICCAR/Report.

Esper, J. et al., 2007: Long-term drought severity variations in Morocco. *Geophysical Research Letters - GEOPHYS RES LETT*, **34**, doi:10.1029/2007GL030844.

Ezcurra, E., 2006: *Global deserts outlook*. UNEP/Earthprint. ISBN 9280727222.

Falaschi, D. et al., 2019: Brief communication: Collapse of 4 Mm3 of ice from a cirque glacier in the Central Andes of Argentina. *The Cryosphere*, **13**(3), 997-1004, doi:10.5194/tc-13-997-2019.

Favreau, G. et al., 2009: Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review. **45**, doi:10.1029/2007wr006785.

Feng, S. and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmospheric Chemistry and Physics*, **13**(19), 10081-10094, doi:10.5194/acp-13-10081-2013.

Fensholt, R., I. Sandholt, S. Stisen and C. Tucker, 2006: Analysing NDVI for the African continent using the geostationary meteosat second generation SEVIRI sensor. *Remote Sensing of Environment*, **101**(2), 212-229, doi:https://doi.org/10.1016/j.rse.2005.11.013.
Fernández-Martínez, M. et al., 2019: Global trends in carbon sinks and their relationships with CO2 and temperature. *Nature Climate Change*, **9**(1), 73-79, doi:10.1038/s41558-018-0367-7.
Fernández-Rivera, S. et al., 2005: *Nutritional constraints to grazing ruminants in the millet-cowpea- livestock farming system of the Sahel*. International Livestock Research Institute (ILRI), Nairobi, Kenya, 157–182 pp. Available at: https://cgspace.cgiar.org/handle/10568/50886. Accesed on 5.11.2020.
Foden, W. et al., 2007a: A changing climate is eroding the geographical range of the Namib Desert tree Aloe through population declines and dispersal lags: Namib Desert trees feel the heat of climate change. *Diversity and Distributions - DIVERS DISTRIB*, **13**, 645-653, doi:10.1111/j.1472-4642.2007.00391.x.
Foden, W. et al., 2007b: A changing climate is eroding the geographical range of the Namib Desert tree Aloe through population declines and dispersal lags. *Diversity and Distributions*, **13**(5), 645-653, doi:10.1111/j.1472-4642.2007.00391.x.
Frischen, J. et al., 2020: Drought Risk to Agricultural Systems in Zimbabwe: A Spatial Analysis of Hazard, Exposure, and Vulnerability. *Sustainability*, **12**(3), 752.
Gal, L. et al., 2017: The paradoxical evolution of runoff in the pastoral Sahel: analysis of the hydrological changes over the Agoufou watershed (Mali) using the KINEROS-2 model. *Hydrology and Earth System Sciences*, **21**(9), 4591-4613, doi:10.5194/hess-21-4591-2017.
Gandah, M. et al., 2003: Strategies to optimize allocation of limited nutrients to sandy soils of the Sahel: a case study from Niger, west Africa. *Agriculture, Ecosystems & Environment*, **94**(3), 311-319, doi:https://doi.org/10.1016/S0167-8809(02)00035-X.
García Criado, M. et al., 2020: Woody plant encroachment intensifies under climate change across tundra and savanna biomes. *Global Ecology and Biogeography*, **29**(5), 925-943, doi:10.1111/geb.13072.
Gardelle, J., P. Hiernaux, L. Kergoat and M. Grippa, 2010: Less rain, more water in ponds: a remote sensing study of the dynamics of surface waters from 1950 to present in pastoral Sahel (Gourma region, Mali). *Hydrology and Earth System Sciences*, **14**(2), 309-324, doi:10.5194/hess-14-309-2010.
Ginoux, P. et al., 2012: Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Reviews of Geophysics*, **50**(3), doi:10.1029/2012RG000388.
Glick Schiller, N., 2015: Explanatory frameworks in transnational migration studies: the missing multi-scalar global perspective. *Ethnic and Racial Studies*, **38**, doi:10.1080/01419870.2015.1058503.
Gonzalez, P., 2001: Desertification and shift of forest species in the West African Sahel. *Climate Research - CLIMATE RES*, **17**, 217-228, doi:10.3354/cr017217.
Gonzalez, P., C. J. Tucker and H. Sy, 2012: Tree Density and Species Decline in the African Sahel Attributable to Climate. *Journal of Arid Environments - J ARID ENVIRON*, **78**, doi:10.1016/j.jaridenv.2011.11.001.
Goudarzi, G. et al., 2017: Health risk assessment of exposure to the Middle-Eastern Dust storms in the Iranian megacity of Kermanshah. *Public Health*, **148**, 109-116, doi:https://doi.org/10.1016/j.puhe.2017.03.009.
Goudie, A. S., 2014: Desert dust and human health disorders. *Environment International*, **63**, 101-113, doi:10.1016/J.ENVINT.2013.10.011.
Gray, E. F. and W. J. Bond, 2013: Will woody plant encroachment impact the visitor experience and economy of conservation areas? *Koedoe*, **55**(1), doi:10.4102/koedoe.v55i1.1106.
Greve, P., M. Roderick, A. Ukkola and Y. Wada, 2019: The aridity Index under global warming. *Environmental Research Letters*, **14**(12), 124006, doi:https://doi.org/10.1088/1748-9326/ab5046.
Greve, P. and S. I. Seneviratne, 2015: Assessment of future changes in water availability and aridity. *Geophysical Research Letters*, **42**(13), 5493-5499, doi:10.1002/2015gl064127.
Grobicki, A., F. MacLeod and F. Pischke, 2015: Integrated policies and practices for flood and drought risk management. *Water Policy*, **17**(S1), 180-194, doi:http://dx.doi.org/10.2166/wp.2015.009.
Gu, H. et al., 2019: Hypoxia aggravates the effects of ocean acidification on the physiological energetics of the blue mussel *Mytilus edulis*. *Marine Pollution Bulletin*, **149**, 110538, doi:10.1016/j.marpolbul.2019.110538.
Gu, L. et al., 2020: Projected increases in magnitude and socioeconomic exposure of global droughts in 1.5 and 2° C warmer climates. *Hydrology and Earth System Sciences*, **24**(1), 451-472.
Guengant Jean-Pierre, B. M., Quesnel André (coord.), Gendreau Francis (ed.), Lututala M. (ed.) 2003: *Dynamique des populations, disponibilités en terres et adaptation des régimes fonciers : le cas du Niger*. ITA;: FAO ; CICRED, Rome; Paris 144 p pp. Available at: https://www.documentation.ird.fr/hor/fdi:010032613.
Guimarães Nobre, G. et al., 2019: Financing agricultural drought risk through ex-ante cash transfers. *Science of The Total Environment*, **653**, 523-535, doi:10.1016/j.scitotenv.2018.10.406.
Gupta, S. and J. Dagar, 2016: Agroforestry for ecological restoration of salt-affected lands. In: *Innovative Saline Agriculture*. Springer, pp. 161-182.
Haensler, A., S. Hagemann and D. Jacob, 2010: Will the southern African west coast fog be affected by climate change? *Erdkunde*, **65**(3), doi:10.3112/erdkunde.2011.03.04.
Haider, S. and S. Adnan, 2014: Classification and assessment of aridity over Pakistan provinces (1960-2009). *International Journal of Environment*, **3**(4), 24-35.

Hall, R. et al., 2015: Resistance, acquiescence or incorporation? An introduction to land grabbing and political reactions 'from below'. *The Journal of Peasant Studies*, **42**(3-4), 467-488, doi:10.1080/03066150.2015.1036746.
Hand, J. L., T. Gill and B. Schichtel, 2017: Spatial and seasonal variability in fine mineral dust and coarse aerosol mass at remote sites across the United States. *Journal of Geophysical Research: Atmospheres*, **122**(5), 3080-3097.
Hänke, H., L. Börjeson, K. Hylander and E. Enfors-Kautsky, 2016: Drought tolerant species dominate as rainfall and tree cover returns in the West African Sahel. *Land Use Policy*, **59**, 111-120, doi:https://doi.org/10.1016/j.landusepol.2016.08.023.
Harou, J. J. et al., 2010: Economic consequences of optimized water management for a prolonged, severe drought in California. *Water Resources Research*, **46**(5), doi:10.1029/2008wr007681.
Harris, D. L. et al., 2018: Coral reef structural complexity provides important coastal protection from waves under rising sea levels. *Science Advances*, **4**(2), eaao4350, doi:10.1126/sciadv.aao4350.
Harris, I., T. J. Osborn, P. Jones and D. Lister, 2020: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, **7**(1), doi:10.1038/s41597-020-0453-3.
Haverd, V., A. Ahlström, B. Smith and J. G. Canadell, 2017: Carbon cycle responses of semi-arid ecosystems to positive asymmetry in rainfall. *Global change biology*, **23**(2), 793-800.
He, B., S. Wang, L. Guo and X. Wu, 2019: Aridity change and its correlation with greening over drylands. *Agricultural and Forest Meteorology*, **278**, 107663, doi:https://doi.org/10.1016/j.agrformet.2019.107663.
Hegeman, E. E., B. G. Dickson and L. J. Zachmann, 2014: Probabilistic models of fire occurrence across National Park Service units within the Mojave Desert Network, USA. *Landscape Ecology*, **29**(9), 1587-1600, doi:10.1007/s10980-014-0078-z.
HEISLER-WHITE, J. L. et al., 2009: Contingent productivity responses to more extreme rainfall regimes across a grassland biome. *Global Change Biology*, **15**(12), 2894-2904, doi:https://doi.org/10.1111/j.1365-2486.2009.01961.x.
Helldén, U., 1984: Drought impact monitoring. A remote sensing study of desertification in Kordofan, Sudan. *Rapporter och Notiser-Lunds Universitets Naturgeografiska Institution (Sweden)*.
Herrmann, S. M., A. Anyamba and C. J. Tucker, 2005: Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environmental Change*, **15**(4), 394-404, doi:https://doi.org/10.1016/j.gloenvcha.2005.08.004.
Hesse, C., 2016: *Decentralising climate finance to reach the most vulnerable*. IIED, London. Available at: https://pubs.iied.org/pdfs/G04103.pdf.
Hiernaux, P. and M. H. Assouma, 2020: Adapting pastoral breeding to global changes in West and Central tropical Africa: Review of ecological views. *Revue d'élevage et de médecine vétérinaire des pays tropicaux*, **73**(3).
Hiernaux, P., C. Dardel, L. Kergoat and E. Mougin, 2016: Desertification, Adaptation and Resilience in the Sahel: Lessons from Long Term Monitoring of Agro-ecosystems. In: *The End of Desertification? : Disputing Environmental Change in the Drylands* [Behnke, R. and M. Mortimore (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 147-178. ISBN 978-3-642-16014-1.
Hiernaux, P. et al., 2009a: Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). *Journal of Hydrology*, **375**(1), 103-113, doi:https://doi.org/10.1016/j.jhydrol.2009.01.043.
Hiernaux, P. and H. N. Le Houérou, 2006: Les parcours du Sahel. *Science et changements planétaires/Sécheresse*, **17**(1), 51-71.
Hiernaux, P. et al., 2009b: Sahelian rangeland response to changes in rainfall over two decades in the Gourma region, Mali. *Journal of Hydrology*, **375**(1-2), 114-127.
Hiernaux, P. H. Y., M. I. Cissé, L. Diarra and P. N. De Leeuw, 1994: Fluctuations saisonnières de la feuillaison des arbres et des buissons sahéliens. Conséquences pour la quantification des ressources fourragères. *AGROPASTORALISME* **47 (1)**.
Higgins, S. I. and S. Scheiter, 2012: Atmospheric CO2 forces abrupt vegetation shifts locally, but not globally. *Nature*, **488**(7410), 209-212, doi:10.1038/nature11238.
Hochleithner, S. and A. Exner, 2018: *Outmigration, development, and global environmental change: A review and discussion of case studies from the West African Sahel*. **Working Paper No. 15**, Swedish International Centre for Local Democracy.
Hoffman, T. M., A. Skowno, W. Bell and S. Mashele, 2018: Long-term changes in land use, land cover and vegetation in the Karoo drylands of South Africa: implications for degradation monitoring. *African Journal of Range & Forage Science*, **35**(3-4), 209-221, doi:10.2989/10220119.2018.1516237.
Homewood, K., 2018: Pastoralism. *The International Encyclopedia of Anthropology*, 1-10, doi:https://doi.org/10.1002/9781118924396.wbiea1559.
Hooper, J. and S. Marx, 2018: A global doubling of dust emissions during the Anthropocene? *Global and Planetary Change*, **169**, 70-91, doi:https://doi.org/10.1016/j.gloplacha.2018.07.003.
Hoover, D. L., M. C. Duniway and J. Belnap, 2015: Pulse-drought atop press-drought: unexpected plant responses and implications for dryland ecosystems. *Oecologia*, **179**(4), 1211-1221, doi:10.1007/s00442-015-3414-3.
Horn, K. J. and S. B. St. Clair, 2017: Wildfire and exotic grass invasion alter plant productivity in response to climate variability in the Mojave Desert. *Landscape Ecology*, **32**(3), 635-646, doi:10.1007/s10980-016-0466-7.
Hsiang, S. M., M. Burke and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341**(6151).

Huang, J. et al., 2016: Global semi-arid climate change over last 60 years. *Climate Dynamics*, **46**(3), 1131-1150, doi:10.1007/s00382-015-2636-8.
Huang, J. et al., 2017: Drylands face potential threat under 2 °C global warming target. *Nature Climate Change*, **7**(6), 417-422, doi:10.1038/nclimate3275.
Hufft, R. A. and T. J. Zelikova, 2016: Ecological Genetics, Local Adaptation, and Phenotypic Plasticity in Bromus tectorum in the Context of a Changing Climate. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications* [Germino, M. J., J. C. Chambers and C. S. Brown (eds.)]. Springer International Publishing, Cham, pp. 133-154. ISBN 978-3-319-24930-8.
Hurlbert, M. et al., 2019: Risk management and decision making in relation to sustainable development. In: *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
Hurlbert, M. A., 2018: *Adaptive Governance of Disaster: Drought and Flood in Rural Areas*. Springer International Publishing. ISBN 978-3-319-57800-2.
Hussein, I. A. E., 2011: Desertification process in Egypt. In: *Coping with Global Environmental Change, Disasters and Security: Threats, Challenges, Vulnerabilities and Risks* [Brauch, H. G., U. Oswald Spring, C. Mesjasz, J. Grin, P. Kameri-Mbote, B. Chourou, P. Dunay and J. Brikmann (ed.)]. Springer, Berlin, Germany, pp. 863–874
Hutchinson, C., S. Herrmann, T. Maukonen and J. Weber, 2005: Introduction: The "Greening" of the Sahel. *Journal of Arid Environments - J ARID ENVIRON*, **63**, 535-537, doi:10.1016/j.jaridenv.2005.03.002.
Ibrahim, Y. Z., H. Balzter and J. Kaduk, 2018: Land degradation continues despite greening in the Nigeria-Niger border region. *Global Ecology and Conservation*, **16**, e00505, doi:https://doi.org/10.1016/j.gecco.2018.e00505.
ICAR-CSSRI, 2015: *ICAR-CSSRI Vision 2050*. ICAR-Central Soil Salinity Research, Karnal, Haryana, India. Available at: https://cssri.res.in/download/vision_2050_cssri_karnal/?wpdmdl=3031.
IFPRI, 2016. : *Global Nutrition Report 2016: From Promise to Impact: Ending Malnutrition by 2030. Washington, D.C.* International Food Policy Research Institute. . Available at: https://www.ifpri.org/publication/global-nutrition-report-2016-promise-impact-ending-malnutrition-2030. Accessed on 6.11.2020.
Iknayan, K. J. and S. R. Beissinger, 2018: Collapse of a desert bird community over the past century driven by climate change. *Proceedings of the National Academy of Sciences*, **115**(34), 8597, doi:10.1073/pnas.1805123115.
Jack, S. L., M. T. Hoffman, R. F. Rohde and I. Durbach, 2016: Climate change sentinel or false prophet? The case of Aloe dichotoma. *Diversity and Distributions*, **22**(7), 745-757, doi:10.1111/ddi.12438.
Javed, A., S. Jamal and M. Y. Khandey, 2012: Climate change induced land degradation and socio-economic deterioration: a remote sensing and GIS based case study from Rajasthan, India.
Jellason, N. P., R. N. Baines, J. S. Conway and C. C. Ogbaga, 2019: Climate change perceptions and attitudes to smallholder adaptation in Northwestern Nigerian Drylands. *Social Sciences*, **8**(2), 31.
Ji, M., J. Huang, Y. Xie and J. Liu, 2015: Comparison of dryland climate change in observations and CMIP5 simulations. *Advances in Atmospheric Sciences*, **32**(11), 1565-1574, doi:10.1007/s00376-015-4267-8.
Ji, Z., G. Wang, M. Yu and J. S. Pal, 2018: Potential climate effect of mineral aerosols over West Africa: Part II—contribution of dust and land cover to future climate change. *Climate Dynamics*, **50**(7), 2335-2353, doi:10.1007/s00382-015-2792-x.
Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot,, 2019: *Land–climate interactions. In: Climate Change and Land* [[P.R. Shukla, J. S., E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley (ed.)]. IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems Intergovernmental Panel for Climate Change. Available at: https://www.ipcc.ch/srccl/cite-report/.
Jia, H. et al., 2015: Field monitoring of a LID-BMP treatment train system in China. *Environmental monitoring and assessment*, **187**(6), 1-18.
Jiao, Q. et al., 2016: Impacts of Re-Vegetation on Surface Soil Moisture over the Chinese Loess Plateau Based on Remote Sensing Datasets. *Remote Sensing*, **8**(2), 156.
Jiao, W. et al., 2021: Observed increasing water constraint on vegetation growth over the last three decades. *Nature Communications*, **12**(1), 3777, doi:10.1038/s41467-021-24016-9.
Jnandabhiram, C. and B. Sailen Prasad, 2012: Water stress effects on leaf growth and chlorophyll content but not the grain yield in traditional rice (Oryza sativa Linn.) genotypes of Assam, India II. Protein and proline status in seedlings under PEG induced water stress. *American Journal of Plant Sciences*, **2012**.
Johnsen, K. I., 2016: Land-use conflicts between reindeer husbandry and mineral extraction in Finnmark, Norway: contested rationalities and the politics of belonging. *Polar Geography*, **39**(1), 58-79, doi:10.1080/1088937X.2016.1156181.
Jones, S. M. and D. S. Gutzler, 2016: Spatial and Seasonal Variations in Aridification across Southwest North America. *Journal of Climate*, **29**(12), 4637-4649, doi:10.1175/jcli-d-14-00852.1.
Kamali, B., D. Houshmand Kouchi, H. Yang and K. C. Abbaspour, 2017: Multilevel drought hazard assessment under climate change scenarios in semi-arid regions—A case study of the Karkheh river basin in Iran. *Water*, **9**(4), 241.
Kaptué, A. T., L. Prihodko and N. P. Hanan, 2015: On regreening and degradation in Sahelian watersheds. *Proc Natl Acad Sci U S A*, **112**(39), 12133-12138, doi:10.1073/pnas.1509645112.

Karmaoui, A., M. Messouli, Y. M. Khebiza and I. Ifaadassan, 2014: Environmental vulnerability to climate change and anthropogenic impacts in dryland,(pilot study: Middle Draa Valley, South Morocco. *Journal of Earth Science & Climatic Change*,(S11), 1, doi:10.4172/2157-7617.S11-0.
Kattumuri, R., D. Ravindranath and T. Esteves, 2015: Local adaptation strategies in semi-arid regions: study of two villages in Karnataka, India. Clim. Dev. 5529, 1–14. doi:https://doi.org/10.1080/17565529.2015.1067179.
Kattumuri, R., D. Ravindranath and T. Esteves, 2017: Local adaptation strategies in semi-arid regions: study of two villages in Karnataka, India. *Climate and Development*, **9**(1), 36-49, doi:https://doi.org/10.1080/17565529.2015.1067179.
Kergoat, L., F. Guichard, C. Pierre and C. Vassal, 2017: Influence of dry-season vegetation variability on Sahelian dust during 2002–2015. *Geophysical Research Letters*, **44**(10), 5231-5239, doi:10.1002/2016gl072317.
Kgope, B. S., W. J. Bond and G. F. Midgley, 2010: Growth responses of African savanna trees implicate atmospheric [CO2] as a driver of past and current changes in savanna tree cover. *Austral Ecology*, **35**(4), 451-463, doi:10.1111/j.1442-9993.2009.02046.x.
Klinger, R. and M. Brooks, 2017: Alternative pathways to landscape transformation: invasive grasses, burn severity and fire frequency in arid ecosystems. *Journal of Ecology*, **105**(6), 1521-1533, doi:10.1111/1365-2745.12863.
Kong, Z.-H., L. Stringer, J. Paavola and Q. Lu, 2021: Situating China in the Global Effort to Combat Desertification. *Land*, **10**(7), 702.
Koubi, V., 2019: Climate Change and Conflict. *Annual Review of Political Science*, **22**(1), 343-360, doi:10.1146/annurev-polisci-050317-070830.
Koutroulis, A. G., 2019: Dryland changes under different levels of global warming. *Science of The Total Environment*, **655**, 482-511, doi:https://doi.org/10.1016/j.scitotenv.2018.11.215.
Koźmińska, A. et al., 2019: Responses of succulents to drought: comparative analysis of four Sedum (Crassulaceae) species. *Scientia Horticulturae*, **243**, 235-242, doi:10.1016/j.scienta.2018.08.028.
Krätli, S. and N. Schareika, 2010: Living Off Uncertainty: The Intelligent Animal Production of Dryland Pastoralists. *The European Journal of Development Research*, **22**(5), 605-622, doi:10.1057/ejdr.2010.41.
Kumar, M., 2016: Impact of climate change on crop yield and role of model for achieving food security. *Environmental Monitoring and Assessment*, **188**(8), 465, doi:10.1007/s10661-016-5472-3.
Kusserow, H., 2017: Desertification, resilience, and re-greening in the African Sahel – a matter of the observation period? *Earth Syst. Dynam.*, **8**(4), 1141-1170, doi:10.5194/esd-8-1141-2017.
Kust, G. S., O. V. Andreeva and D. V. Dobrynin, 2011: Desertification assessment and mapping in the Russian Federation. *Arid Ecosystems*, **1**(1), 14-28, doi:10.1134/S2079096111010057.
Lamers, J. P., K. Michels and P. R. Feil, 1995: Wind erosion control using windbreaks and crop residues: local knowledge and experimental results. *Der Tropenlandwirt-Journal of Agriculture in the Tropics and Subtropics*, **96**(1), 87-96.
Le Polain de Waroux, Y. and E. Lambin, 2012: Monitoring degradation in arid and semi-arid forests and woodlands: The case of the argan woodlands (Morocco). *Applied Geography*, **32**, 777-786, doi:10.1016/j.apgeog.2011.08.005.
Le, Q. B., E. Nkonya and A. Mirzabaev, 2016: *Biomass productivity-based mapping of global land degradation hotspots*. Economics of land degradation and improvement–A global assessment for sustainable development, 55 pp. ISBN 9783319191676.
Léauthaud, C. et al., 2015: Revisiting historical climatic signals to better explore the future: prospects of water cycle changes in Central Sahel. *Proceedings of the International Association of Hydrological Sciences*, **371**, 195-201.
Lewis, S. C. and J. Mallela, 2018: A multifactor risk analysis of the record 2016 Great Barrier Reef bleaching. *Bulletin of the American Meteorological Society*, **99**(1), S144-S149, doi:10.1175/BAMS-D-17-0074.1.
Li, Z., L. Chen, M. Li and J. Cohen, 2018: Prenatal exposure to sand and dust storms and children's cognitive function in China: a quasi-experimental study. *The Lancet. Planetary health*, **2**(5), e214-e222, doi:10.1016/S2542-5196(18)30068-8.
Li, Z. et al., 2015: Potential impacts of climate change on vegetation dynamics in Central Asia. *Journal of Geophysical Research: Atmospheres*, **120**(24), 12345-12356, doi:10.1002/2015jd023618.
Lickley, M. and S. Solomon, 2018: Drivers, timing and some impacts of global aridity change. *Environmental Research Letters*, **13**, doi:10.1088/1748-9326/aae013.
Lima, M., D. A. Christie, M. C. Santoro and C. Latorre, 2016: Coupled socio-environmental changes triggered indigenous aymara depopulation of the semiarid Andes of Tarapacá-Chile during the late 19th-20th centuries. *PLoS One*, **11**(8), e0160580.
Liu, J. et al., 2019: On knowledge generation and use for sustainability. *Nature Sustainability*, **2**(2), 80-82, doi:10.1038/s41893-019-0229-y.
Louhaichi, M. and A. Tastad, 2010: The Syrian Steppe: Past Trends, Current Status, and Future Priorities. *Rangelands*, **32**(2), 2-7, 6, doi:10.2111/1551-501X-32.2.2.
Louvain, C., 2019: Natural disasters 2018. *Centre for Research on the Epidemiology of Disasters CRED: Brussels, Belgium*, 8.
Lovich, J. E. et al., 2014: Climatic variation and tortoise survival: has a desert species met its match? *Biological Conservation*, **169**, 214-224, doi:10.1016/j.biocon.2013.09.027.
Lu, N. et al., 2018: Research advances in ecosystem services in drylands under global environmental changes. *Current Opinion in Environmental Sustainability*, **33**, 92-98, doi:https://doi.org/10.1016/j.cosust.2018.05.004.

Ma, J., H. Hung and R. W. Macdonald, 2016: The influence of global climate change on the environmental fate of persistent organic pollutants: a review with emphasis on the Northern Hemisphere and the Arctic as a receptor. *Global and Planetary Change*, **146**, 89-108, doi:10.1016/j.gloplacha.2016.09.011.

Mach, K. J. et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193-197, doi:10.1038/s41586-019-1300-6.

Maestre, F. T. et al., 2015: Increasing aridity reduces soil microbial diversity and abundance in global drylands. *Proceedings of the National Academy of Sciences*, **112**(51), 201516684-201516684, doi:10.1073/pnas.1516684112.

Mahmoudi, P., D. Kalim and M. R. Amirmoradi (eds.), Investigation of Iran Vulnerability Trend to Desertification with approach of climate change. Second International Conference on Environmental Science and Development IPCBEE; IACSIT Press: Singapore, 63-67 pp.

Mandumbu, R., C. Mutengwa, S. Mabasa and E. Mwenje, 2017: Predictions of the Striga scourge under new climate in Southern Africa. *J Biol Sci*, **17**, 192-201.

Manga, V., A. K. Jukanti and R. Bhatt (eds.), Adaptation and selection of crop varieties for hot arid climate of Rajasthan.

Manlay, R. J. et al., 2004: Spatial carbon, nitrogen and phosphorus budget of a village in the West African savanna—I. Element pools and structure of a mixed-farming system. **79**(1), 55-81, doi:10.1016/s0308-521x(03)00053-2.

Manzoni., A., Porporato. EIn: D'Odorico P., Porporato., Wilkinson Runyan 2019: Ecohydrological and Stoichiometric Controls on Soil Carbon and Nitrogen Dynamics in Drylands. . *Dryland Ecohydrology. Springer, Cham.*

Maranz, S., 2009: Tree mortality in the African Sahel indicates an anthropogenic ecosystem displaced by climate change. *Journal of Biogeography*, **36**(6), 1181-1193, doi:10.1111/j.1365-2699.2008.02081.x.

Marchesini, V. A., R. Giménez, M. D. Nosetto and E. G. Jobbágy, 2017: Ecohydrological transformation in the Dry Chaco and the risk of dryland salinity: Following Australia's footsteps? *Ecohydrology*, **10**(4), e1822, doi:10.1002/eco.1822.

Marin, A. et al., 2020: Productivity beyond density: A critique of management models for reindeer pastoralism in Norway. *Pastoralism*, **10**(1), 9, doi:10.1186/s13570-020-00164-3.

Martorell, C., D. M. Montañana, C. Ureta and M. C. Mandujano, 2015: Assessing the importance of multiple threats to an endangered globose cactus in Mexico: Cattle grazing, looting and climate change. *Biological conservation*, **181**, 73-81.

Masiokas, M. H. et al., 2019: Streamflow variations across the Andes (18°-55°S) during the instrumental era. *Scientific reports*, **9**(1), 17879-17879, doi:10.1038/s41598-019-53981-x.

Masubelele, M. L., M. T. Hoffman and W. J. Bond, 2015a: Biome stability and long-term vegetation change in the semi-arid, south-eastern interior of South Africa: A synthesis of repeat photo-monitoring studies. *South African Journal of Botany*, **101**, 139-147, doi:https://doi.org/10.1016/j.sajb.2015.06.001.

Masubelele, M. L., M. T. Hoffman and W. J. Bond, 2015b: A repeat photograph analysis of long-term vegetation change in semi-arid South Africa in response to land use and climate. *Journal of Vegetation Science*, **26**(5), 1013-1023, doi:10.1111/jvs.12303.

Maurer, G. E. et al., 2020: Sensitivity of primary production to precipitation across the United States. *Ecology letters*, **23**(3), 527-536.

Mbow, C. et al., 2019: Food Security. In: *An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Mbow, C. et al., 2014: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability*, **6**, 8-14, doi:https://doi.org/10.1016/j.cosust.2013.09.002.

Mekonnen, D., E. Bryan, T. Alemu and C. Ringler, 2017: Food versus fuel: examining tradeoffs in the allocation of biomass energy sources to domestic and productive uses in Ethiopia. *Agricultural Economics*, **48**(4), 425-435, doi:10.1111/agec.12344.

Meynard, C. N., M. Lecoq, M.-P. Chapuis and C. Piou, 2020: On the relative role of climate change and management in the current desert locust outbreak in East Africa. *Global Change Biology*, **26**(7), 3753-3755, doi:10.1111/gcb.15137.

Mganga, K. Z., N. K. R. Musimba and D. M. Nyariki, 2015: Combining Sustainable Land Management Technologies to Combat Land Degradation and Improve Rural Livelihoods in Semi-arid Lands in Kenya. *Environmental Management*, **56**(6), 1538-1548, doi:10.1007/s00267-015-0579-9.

Michels, K., J. P. A. Lamers and A. Buerkert, 1998: EFFECTS OF WINDBREAK SPECIES AND MULCHING ON WIND EROSION AND MILLET YIELD IN THE SAHEL. **34**(4), 449-464, doi:10.1017/s0014479798004050.

Middleton, N., 2018: Rangeland management and climate hazards in drylands: dust storms, desertification and the overgrazing debate. *Natural Hazards*, **92**(1), 57-70, doi:10.1007/s11069-016-2592-6.

Middleton, N., 2019: Variability and trends in dust storm frequency on decadal timescales: Climatic drivers and human impacts. *Geosciences*, **9**(6), 261, doi:https://doi.org/10.3390/geosciences9060261.

Middleton, N. and U. Kang, 2017: Sand and Dust Storms: Impact Mitigation. *Sustainability*, **9**(6), 1053-1053, doi:10.3390/su9061053.

Middleton, N. J., 2017: Desert dust hazards: A global review. *Aeolian Research*, **24**, 53-63, doi:10.1016/J.AEOLIA.2016.12.001.

Mirzabaev, A. et al., 2019: Desertification. In: *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. IPCC.
Mirzabaev, G. a., 2016: Benefits of action and costs of inaction: Drought mitigation and preparedness–a literature review. . *World Meteorological Organization and Global Water Partnership. Integrated Drought Management Programme Working Paper No. 1, Geneva, Switzerland*.
Mishra, A. K. and V. P. Singh, 2010: A Review of Drought Concepts. *Journal of Hydrology*, **, 391,** , 202-216., doi:https://doi.org/10.1016/j.jhydrol.2010.07.012.
Missirian, A. and W. Schlenker, 2017: Asylum applications respond to temperature fluctuations. *Science (New York, N.Y.)*, **358**(6370), 1610-1614, doi:10.1126/science.aao0432.
Mohamed, N., B. Abdou, H. Mohamed Fadul and S. Zakieldeen, 2016: Ecological Zones Degradation Analysis in Central Sudan during a Half Century Using Remote Sensing and GIS. *Advances in Remote Sensing*, **5**(04), 355-371, doi:10.4236/ars.2016.54025.
Montagné, P. et al. (eds.), Bois-énergie domestique, démographie et urbanisation : situation après vingt-cinq années de gestion forestière des néo-communs au Sud-Niger.
Morgan, J. A. et al., 2004: Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO2. *Oecologia*, **140**(1), 11-25, doi:10.1007/s00442-004-1550-2.
Moridnejad, A., N. Karimi and P. A. Ariya, 2015: Newly desertified regions in Iraq and its surrounding areas: Significant novel sources of global dust particles. *Journal of Arid Environments*, **116**, 1-10.
Morton, J. and D. Barton, 2002: Destocking as a Drought–mitigation Strategy: Clarifying Rationales and Answering Critiques. *Disasters*, **26**(3), 213-228, doi:10.1111/1467-7717.00201.
Mote, P. W. et al., 2018: Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science*, **1**(1), 2, doi:10.1038/s41612-018-0012-1.
Mottaleb, K. A. et al., 2017: Benefits of the development and dissemination of climate-smart rice: ex ante impact assessment of drought-tolerant rice in South Asia. *Mitigation and Adaptation Strategies for Global Change*, **22**(6), 879-901, doi:10.1007/s11027-016-9705-0.
Munday, C. and R. Washington, 2019: Controls on the Diversity in Climate Model Projections of Early Summer Drying over Southern Africa. *Journal of Climate*, **32**(12), 3707-3725, doi:10.1175/jcli-d-18-0463.1.
Munson, S. M., A. L. Long, C. S. A. Wallace and R. H. Webb, 2016a: Cumulative drought and land-use impacts on perennial vegetation across a North American dryland region. *Applied Vegetation Science*, **19**(3), 430-441, doi:https://doi.org/10.1111/avsc.12228.
Munson, S. M. et al., 2016b: Decadal shifts in grass and woody plant cover are driven by prolonged drying and modified by topo-edaphic properties. *Ecological Applications*, **26**(8), 2480-2494, doi:10.1002/eap.1389.
Munson, S. M. et al., 2012: Forecasting climate change impacts to plant community composition in the Sonoran Desert region. *Global Change Biology*, **18**(3), 1083-1095, doi:10.1111/j.1365-2486.2011.02598.x.
Münzel, T., J. Lelieveld, S. Rajagopalan and A. Daiber, 2019: Contribution of airborne desert dust to air quality and cardiopulmonary disease. *European Heart Journal*, doi:10.1093/eurheartj/ehz216.
Musil, C. F., U. Schmiedel and G. F. Midgley, 2005: Lethal effects of experimental warming approximating a future climate scenario on southern African quartz-field succulents: a pilot study. *New Phytologist*, **165**(2), 539-547, doi:10.1111/j.1469-8137.2004.01243.x.
Myers, S. S. et al., 2017: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annual Review of Public Health*, **38**(1), 259-277, doi:10.1146/annurev-publhealth-031816-044356.
Myhre, G. D. et al., 2013: Anthropogenic and Natural Radiative Forcing. [Stocker, T. F. D., Q. G., K. Plattner, M. Tignor, S. K. Allen, A. J. Boschung, N. Y., X. V., Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Navarro-Cerrillo, R. M. et al., 2020: Competition modulates the response of growth to climate in pure and mixed Abies pinsapo subsp. Maroccana forests in northern Morocco. *Forest Ecology and Management*, **459**, 117847, doi:https://doi.org/10.1016/j.foreco.2019.117847.
Nikam, V. R., R. Singh and A. Chinchmalatpure, 2016: Salt tolerant varieties: A biological intervention to manage saline and sodic environment and sustain livelihoods. *Journal of Soil Salinity and Water Quality*, **8**(1), 37-44.
Nkrumah, F. et al., 2019: Recent Trends in the Daily Rainfall Regime in Southern West Africa. *Atmosphere*, **10**(12), 741.
Nori, M. and I. Scoones, 2019: Pastoralism, uncertainty and resilience: global lessons from the margins. *Pastoralism*, **9**(1), 1-7.
Noyola-Medrano, C. and V. A. Martínez-Sías, 2017: Assessing the progress of desertification of the southern edge of Chihuahuan Desert: A case study of San Luis Potosi Plateau. *Journal of Geographical Sciences*, **27**(4), 420-438, doi:10.1007/s11442-017-1385-5.
Nyangena, J. and A. W. Roba, 2017: *Funding adaptation in Kenya's drylands* International Institute of Environment and Development (IIED), London, United Kingdom. Available at: https://pubs.iied.org/pdfs/17418IIED.pdf.

Nyantakyi-Frimpong, H. and R. Bezner Kerr, 2017: Land grabbing, social differentiation, intensified migration and food security in northern Ghana. *The Journal of Peasant Studies*, **44**(2), 421-444, doi:10.1080/03066150.2016.1228629.
O'Connor, T. G., J. R. Puttick and M. T. Hoffman, 2014: Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science*, **31**(2), 67-88, doi:10.2989/10220119.2014.939996.
Obeng-Odoom, F., 2017: Unequal access to land and the current migration crisis. *Land Use Policy*, **62**, 159-171, doi:https://doi.org/10.1016/j.landusepol.2016.12.024.
Okpara, U. T., L. C. Stringer and M. Akhtar-Schuster, 2019: Gender and land degradation neutrality: A cross-country analysis to support more equitable practices. *Land Degradation & Development*, **30**(11), 1368-1378, doi:10.1002/ldr.3326.
Okpara, U. T., L. C. Stringer, A. J. Dougill and M. D. Bila, 2015: Conflicts about water in Lake Chad: Are environmental, vulnerability and security issues linked? *Progress in Development Studies*, **15**(4), 308-325, doi:10.1177/1464993415592738.
Oliver-Smith, A., 2010: *Defying displacement: Grassroots resistance and the critique of development*. University of Texas Press, Austin.
Olsson, L. et al., 2019: Land Degradation. In: *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
Olsson, L., L. Eklundh and J. Ardö, 2005: A recent greening of the Sahel—trends, patterns and potential causes. *Journal of Arid Environments*, **63**(3), 556-566, doi:https://doi.org/10.1016/j.jaridenv.2005.03.008.
Omar Asem, S. and W. Y. Roy, 2010: Biodiversity and climate change in Kuwait. *International Journal of Climate Change Strategies and Management*, **2**(1), 68-83, doi:10.1108/17568691011020265.
Opp, C., M. Groll, H. Abbasi and M. A. Foroushani, 2021: Causes and Effects of Sand and Dust Storms: What Has Past Research Taught Us? A Survey. *Journal of Risk and Financial Management*, **14**(7), 326.
Orr, B. et al. (eds.), Scientific conceptual framework for land degradation neutrality. A report of the science-policy interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany.
Orr, B. J. et al., 2017b: *Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface*. Bonn, Germany. Available at: https://www.unccd.int/sites/default/files/documents/2017-08/LDN_CF_report_web-english.pdf.
Osbahr, H., P. Dorward, R. Stern and S. Cooper, 2011: SUPPORTING AGRICULTURAL INNOVATION IN UGANDA TO RESPOND TO CLIMATE RISK: LINKING CLIMATE CHANGE AND VARIABILITY WITH FARMER PERCEPTIONS. *Experimental Agriculture*, **47**(2), 293-316, doi:10.1017/S0014479710000785.
Owain, E. L. and M. A. Maslin, 2018: Assessing the relative contribution of economic, political and environmental factors on past conflict and the displacement of people in East Africa. *Palgrave Communications*, **4**(1), 47-47, doi:10.1057/s41599-018-0096-6.
Painter, T. H. et al., 2010: Response of Colorado River runoff to dust radiative forcing in snow. *Proceedings of the National Academy of Sciences*, **107**(40), 17125-17130, doi:10.1073/pnas.0913139107.
Pan, N. et al., 2021: Rapid increase of potential evapotranspiration weakens the effect of precipitation on aridity in global drylands. *Journal of Arid Environments*, **186**, 104414, doi:https://doi.org/10.1016/j.jaridenv.2020.104414.
Park, C.-E. et al., 2018: Keeping global warming within 1.5 °C constrains emergence of aridification. *Nature Climate Change*, **8**(1), 70-74, doi:10.1038/s41558-017-0034-4.
Passos, F. B. et al., 2018: Savanna turning into forest: concerted vegetation change at the ecotone between the Amazon and "Cerrado" biomes. *Brazilian Journal of Botany*, **41**(3), 611-619, doi:10.1007/s40415-018-0470-z.
Patel, S. K., A. Sharma and G. S. Singh, 2020: Traditional agricultural practices in India: an approach for environmental sustainability and food security. *Energy, Ecology and Environment*, **5**(4), 253-271, doi:10.1007/s40974-020-00158-2.
Pérez-Sánchez, R. M., E. Jurado, L. Chapa-Vargas and J. Flores, 2011: Seed germination of Southern Chihuahuan Desert plants in response to elevated temperatures. *Journal of Arid Environments*, **75**(10), 978-980, doi:https://doi.org/10.1016/j.jaridenv.2011.04.020.
Péron, G. and R. Altwegg, 2015: Twenty-five years of change in southern African passerine diversity: nonclimatic factors of change. **21**(9), 3347-3355, doi:10.1111/gcb.12909.
Piao, S. et al., 2019: Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth & Environment*, **1**, 14 - 27.
Piao, S. et al., 2020: Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth & Environment*, **1**(1), 14-27, doi:10.1038/s43017-019-0001-x.
Piao, S. et al., 2015: Detection and attribution of vegetation greening trend in China over the last 30 years. *Global Change Biology*, **21**(4), 1601-1609, doi:10.1111/gcb.12795.
Pieri, C., 1989: *Fertilité des terres de savanes: bilan de trente ans de recherche et de développement agricole au sud du Sahara*. Ministère de la Coopération, CIRAD-IRAT, , Paris, France, 444 pp.
Pierre, C. et al., 2018: Impact of Agropastoral Management on Wind Erosion in Sahelian Croplands. *Land Degradation & Development*, **29**(3), 800-811, doi:10.1002/ldr.2783.
Polley, H., H. S. Mayeux, H. B. Johnson and C. R. Tischler, 1997: *Viewpoint: Atmospheric CO2, Soil Water, and Shrub/Grass Ratios on Rangelands*. vol. 50.

Portnov, B. A. and U. N. Safriel, 2004: Combating desertification in the Negev: dryland agriculture vs. dryland urbanization. *Journal of Arid Environments*, **56**(4), 659-680, doi:https://doi.org/10.1016/S0140-1963(03)00087-9.
Prăvălie, R., 2016: Drylands extent and environmental issues. A global approach. *Earth-Science Reviews*, **161**, 259-278, doi:https://doi.org/10.1016/j.earscirev.2016.08.003.
Pu, B. and P. Ginoux, 2017: Projection of American dustiness in the late 21st century due to climate change. *Scientific Reports*, **7**(1), 5553-5553, doi:10.1038/s41598-017-05431-9.
Quets, J. J. et al., 2017: Emergence, survival, and growth of recruits in a desert ecosystem with vegetation-induced dunes (nebkhas): A spatiotemporal analysis. *Journal of arid environments*, **139**.
Quirk, J., C. Bellasio, D. Johnson and D. Beerling, 2019: Response of photosynthesis, growth and water relations of a savannah-adapted tree and grass grown across high to low CO2. *Annals of botany*, **124**, 77-90, doi:10.1093/aob/mcz048.
Rajaud, A. and N. d. Noblet-Ducoudré, 2017: Tropical semi-arid regions expanding over temperate latitudes under climate change. *Climatic Change*, **144**(4), 703-719, doi:10.1007/s10584-017-2052-7.
Rasul, G., Chaudhry, Q. Z. , A. Mahmood and K. W. Hyder, 2011: Effect of Temperature Rise on Crop Growth & Productivity. *Pakistan Journal of Meteorology* **8 (5)**.
Reed, M. S. and L. C. Stringer, 2016: *Land degradation, desertification, and climate change : anticipating, assessing, and adapting to future change*. Routledge, 184-184 pp. ISBN 9781849712712.
Reed, M. S. et al., 2015: Reorienting land degradation towards sustainable land management: Linking sustainable livelihoods with ecosystem services in rangeland systems. *Journal of Environmental Management*, **151**, 472-485, doi:https://doi.org/10.1016/j.jenvman.2014.11.010.
Reed, S. C. et al., 2012: Changes to dryland rainfall result in rapid moss mortality and altered soil fertility. *Nature Climate Change*, **2**(10), 752-755, doi:10.1038/nclimate1596.
Reed, S. C., M. Delgado-Baquerizo and S. Ferrenberg, 2019: Biocrust science and global change. *New Phytologist*, **223**(3), 1047-1051, doi:https://doi.org/10.1111/nph.15992.
Reichhuber, A. et al., 2019: *The Land-Drought Nexus: Enhancing the Role of Land-Based Interventions in Drought Mitigation and Risk Management*. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD), UNCCD, Bonn. Available at: https://knowledge.unccd.int/sites/default/files/2019-08/03EP_UNCCD_SPI_2019_Report_2.pdf.
Reij, C. and D. Garrity, 2016: Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. *Biotropica*, **48**(6), 834-843, doi:10.1111/btp.12390.
Reij, C., G. Tappan and A. Belemvire, 2005: Changing land management practices and vegetation on the Central Plateau of Burkina Faso (1968–2002). *Journal of Arid Environments*, **63**(3), 642-659, doi:https://doi.org/10.1016/j.jaridenv.2005.03.010.
Renwick, K. M. et al., 2018: Multi-model comparison highlights consistency in predicted effect of warming on a semi-arid shrub. *Global Change Biology*, **24**(1), 424-438, doi:10.1111/gcb.13900.
Reynolds, J. F. et al., 2007: Global Desertification: Building a Science for Dryland Development. *Science*, **316**(5826), 847-851, doi:10.1126/science.1131634.
Riddell, E. A. et al., 2019: Cooling requirements fueled the collapse of a desert bird community from climate change. *Proceedings of the National Academy of Sciences*, **116**(43), 21609-21615, doi:10.1073/pnas.1908791116.
Rivera, J. A. and O. C. Penalba, 2018: Spatio-temporal assessment of streamflow droughts over Southern South America: 1961–2006. *Theoretical and Applied Climatology*, **133**(3), 1021-1033, doi:10.1007/s00704-017-2243-1.
Robbins, P., 2020: Political ecology : a critical introduction (Wiley Blackwell).
Rochdane, S. et al., 2012: Climate Change Impacts on Water Supply and Demand in Rheraya Watershed (Morocco), with Potential Adaptation Strategies. **4**(4), 28-44, doi:10.3390/w4010028.
Rodríguez-Catón, M., R. Villalba, A. Srur and A. P. Williams, 2019: Radial Growth Patterns Associated with Tree Mortality in Nothofagus pumilio Forest. *Forests*, **10**(6), 489.
Rodríguez-Morales, M. et al., 2019: Ecohydrology of the Venezuelan páramo: water balance of a high Andean watershed. *Plant Ecology & Diversity*, **12**(6), 573-591, doi:10.1080/17550874.2019.1673494.
Rohde, R. F. et al., 2019: Vegetation and climate change in the Pro-Namib and Namib Desert based on repeat photography: Insights into climate trends. *Journal of Arid Environments*, **165**, 119-131, doi:https://doi.org/10.1016/j.jaridenv.2019.01.007.
Rosan, T. M. et al., 2019: Extensive 21st-Century Woody Encroachment in South America's Savanna. *Geophysical Research Letters*, **46**(12), 6594-6603, doi:10.1029/2019gl082327.
Rowell, D. P., C. A. Senior, M. Vellinga and R. J. Graham, 2016: Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? *Climatic Change*, **134**(4), 621-633, doi:https://doi.org/10.1007/s10584-015-1554-4.
Rudgers, J. A. et al., 2018: Climate sensitivity functions and net primary production: A framework for incorporating climate mean and variability. *Ecology*, **99**(3), 576-582, doi:10.1002/ecy.2136.
Runhaar, H. A. C. et al., 2016: Prepared for climate change? A method for the ex-ante assessment of formal responsibilities for climate adaptation in specific sectors. *Regional Environmental Change*, **16**(5), 1389-1400, doi:10.1007/s10113-015-0866-2.
Russo, S., A. F. Marchese, J. Sillmann and G. Immé, 2016: When will unusual heat waves become normal in a warming Africa? *Environmental Research Letters*, **11**(5), 054016.

Rutherford, M. C., L. Powrie and R. Roberts, 2000: *Plant Biodiversity: Vulnerability and Adaptation Assessment*. South Afr. Ctry. Study Clim. Change Natl. Bot. Inst. Claremont South Afr.

Rutherford, W. A. et al., 2017: Albedo feedbacks to future climate via climate change impacts on dryland biocrusts. *Scientific Reports*, **7**(1), 44188, doi:10.1038/srep44188.

Sahour, H., M. Vazifedan and F. Alshehri, 2020: Aridity trends in the Middle East and adjacent areas. *Theoretical and Applied Climatology*, 1-16.

Salih, A. A. M., M. Baraibar, K. K. Mwangi and G. Artan, 2020: Climate change and locust outbreak in East Africa. *Nature Climate Change*, **10**(7), 584-585, doi:10.1038/s41558-020-0835-8.

Sandford, S., 1983: *Management of pastoral development in the Third World*. Wiley, Chichester West Sussex ; New York

Sangaré, M. et al., 2002a: Influence of dry season supplementation for cattle on soil fertility and millet (Pennisetum glaucum L.) yield in a mixed crop/livestock production system of the Sahel. *Nutrient Cycling in Agroecosystems*, **62**(3), 209-217, doi:10.1023/A:1021237626450.

Sangaré, M., S. Fernández-Rivera, P. Hiernaux and V. Pandey, 2002b: Effect of groundnut cake and P on millet stover utilisation and nutrient excretion by sheep. *Tropical agriculture*.

Sanogo, O. M., 2011: Le lait, de l'or blanc ? Amélioration de la productivité des exploitations mixtes cultures-élevage à travers une meilleure gestion et alimentation des vaches laitières dans la zone de Koutiala, Mali. Wageningen Univ, Netherlands, 158 p. pp.

Santos, M. G. et al., 2014: Caatinga, the Brazilian dry tropical forest: can it tolerate climate changes? *Theoretical and Experimental Plant Physiology*, **26**(1), 83-99, doi:10.1007/s40626-014-0008-0.

Savage, M. et al., 2009: *Socio-economic impacts of climate change in Afghanistan*. Stockholm Environment Institute, Oxford, UK. Available at: https://www.weadapt.org/sites/weadapt.org/files/legacy-new/placemarks/files/5345354491559sei-dfid-afghanistan-report-1-.pdf. Accessed on 5.11.2020.

Scheff, J. and D. M. W. W. Frierson, 2015: Terrestrial aridity and its response to greenhouse warming across CMIP5 climate models. *Journal of Climate*, **28**(14), 5583-5600, doi:10.1175/JCLI-D-14-00480.1.

Schlecht, E., P. Hiernaux, F. Achard and M. D. Turner, 2004: Livestock related nutrient budgets within village territories in western Niger. **68**(3), 199-211, doi:10.1023/b:fres.0000019453.19364.70.

Schwilch, G., H. P. Liniger and H. Hurni, 2014: Sustainable Land Management (SLM) Practices in Drylands: How Do They Address Desertification Threats? *Environmental Management*, **54**(5), 983-1004, doi:10.1007/s00267-013-0071-3.

Scoones, I., 2009: Climate Change and the Challenge of Non-equilibrium Thinking. *IDS Bulletin*, **35**, 114-119, doi:10.1111/j.1759-5436.2004.tb00144.x.

Sendzimir, J., C. P. Reij and P. Magnuszewski, 2011: Rebuilding resilience in the Sahel: regreening in the Maradi and Zinder regions of Niger. *Ecology and society*, **16**(3).

Sengupta, N., 2002: Traditional vs modern practices in salinity control. Econ Pol Weekly 37(13): 1247- 1254. *Econ Pol Weekly* **37(13)** 1247- 1254.

Sharma, D. K. et al., 2015: *Assessment of production and monetary losses from salt-affected soils in India*. ICAR-Central Soil Salinity Research Institute.

Sharma, D. K. and A. Singh, 2015: Salinity research in India: Achievements, challenges and future prospects. *Water and Energy International*.

Sharma, P. and A. Singh, 2017: ICAR-Central Soil Salinity Research Institute Annual Report 2016-17.

Sharma, P. C., M.J. Kaledhonkar, K. Thiimmappa, and S.K. Chaudhari,, 2016: *Reclamation of waterlogged saline soils through subsurface drainage technology.* ICAR-CSSRI/Karnal/ Technology Folder/ 2016/02, ICAR-CSSRI, Karnal, Haryana Available at: https://krishi.icar.gov.in/jspui/bitstream/123456789/3676/1/Reclamation%20of%20Waterlogged.pdf.

Sharratt, B. et al., 2015: Implications of climate change on wind erosion of agricultural lands in the Columbia Plateau. *Weather and Climate Extremes*, **10**, 20-31.

Shikuku, K. M. et al., 2017: Prioritizing climate-smart livestock technologies in rural Tanzania: A minimum data approach. *Agricultural Systems*, **151**, 204-216, doi:https://doi.org/10.1016/j.agsy.2016.06.004.

Shryock, D. F., T. C. Esque and L. Hughes, 2014: Population viability of Pediocactus bradyi (Cactaceae) in a changing climate. *Am J Bot*, **101**(11), 1944-1953, doi:10.3732/ajb.1400035.

Singh, R. K., E. Redoña, and L. Refuerzo, , 2010: Plant breeding, genetics and biotechnology. . In: *In: Abiotic Stress Adaptation in Plants: Physiological, Molecular and Genomic Foundation, pp. 387–415. DOI 10.1007/978-90-481-3112-9_18.* [Pareek A, S. K. S., H.J. Bohnert, and Govindjee, (eds.), (ed.)]. Springer, pp. pp. 387–415. ISBN ISBN 978-90-481-3111-2.

Singh, R. K. et al., 2020b: Perceived Climate Variability and Compounding Stressors: Implications for Risks to Livelihoods of Smallholder Indian Farmers. *Environmental Management*, 1-19.

Sirami, C. and A. Monadjem, 2012: Changes in bird communities in Swaziland savannas between 1998 and 2008 owing to shrub encroachment. *Diversity and Distributions*, **18**(4), 390-400, doi:10.1111/j.1472-4642.2011.00810.x.

Sitch, S. et al., 2015: Recent trends and drivers of regional sources and sinks of carbon dioxide. *Biogeosciences*, **12**(3), 653-679.

Sivakumar, M. V. K., 2005: Impacts of Sand Storms/Dust Storms on Agriculture. Springer-Verlag, Berlin/Heidelberg, pp. 159-177.

Skowno, A. L. et al., 2017: Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers. *Global Change Biology*, **23**(6), 2358-2369, doi:10.1111/gcb.13529.
Smit, I. P. J. and H. H. T. Prins, 2015: Predicting the Effects of Woody Encroachment on Mammal Communities, Grazing Biomass and Fire Frequency in African Savannas. *PLOS ONE*, **10**(9), e0137857, doi:10.1371/journal.pone.0137857.
Sommer, M., S. Ferron, S. Cavill and S. House, 2014: Violence, gender and WASH: spurring action on a complex, under-documented and sensitive topic. *Environment and Urbanization*, **27**(1), 105-116, doi:10.1177/0956247814564528.
Sosa, V. et al., 2019: Climate change and conservation in a warm North American desert: effect in shrubby plants. *PeerJ*, **7**, e6572, doi:https://doi.org/10.7717/peerj.6572.
Spinoni, J. et al., 2015: Towards identifying areas at climatological risk of desertification using the Köppen-Geiger classification and FAO aridity index. *International Journal of Climatology*, **35**(9), 2210-2222, doi:10.1002/joc.4124.
Srur, A. M. et al., 2016: Establishment of Nothofagus pumilio at upper treelines across a precipitation gradient in the northern Patagonian Andes. *Arctic, Antarctic, and Alpine Research*, **48**(4), 755-766, doi:https://doi.org/10.1657/AAAR0016-015.
Srur, A. M. et al., 2018: Climate and Nothofagus pumilio Establishment at Upper Treelines in the Patagonian Andes. *Frontiers in Earth Science*, **6**(57), doi:10.3389/feart.2018.00057.
Stafford, W. et al., 2017: The economics of landscape restoration: Benefits of controlling bush encroachment and invasive plant species in South Africa and Namibia. *Ecosystem Services*, **27**, 193-202, doi:https://doi.org/10.1016/j.ecoser.2016.11.021.
Stanelle, T. et al., 2014: Anthropogenically induced changes in twentieth century mineral dust burden and the associated impact on radiative forcing. *Journal of Geophysical Research: Atmospheres*, **119**(23), 13,526-513,546, doi:10.1002/2014jd022062.
Steinfeld, H. et al., 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agriculture Organization of the United Nations, Rome, Italy. Available at: http://www.fao.org/3/a0701e/a0701e00.htm. Accessed on 5.11.2020.
Sternberg, T., 2016: Water megaprojects in deserts and drylands. *International Journal of Water Resources Development*, **32**(2), 301-320.
Stevens, N., B. Erasmus, S. Archibald and W. Bond, 2016: Woody encroachment over 70 years in South African savannahs: Overgrazing, global change or extinction aftershock? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**, 20150437, doi:10.1098/rstb.2015.0437.
Stevens, N., C. E. R. Lehmann, B. P. Murphy and G. Durigan, 2017: Savanna woody encroachment is widespread across three continents. *Global Change Biology*, **23**(1), 235-244, doi:10.1111/gcb.13409.
Stith, M. et al., 2016: A Quantitative Evaluation of the Multiple Narratives of the Recent Sahelian Regreening*. *Weather, Climate, and Society*, **8**(1), 67-83, doi:10.1175/wcas-d-15-0012.1.
Stringer, L. et al., 2021: Climate change impacts on water security in global drylands. *One Earth*, **4**(6), 851-864.
Stringer, L. C. et al., 2017: A New Dryland Development Paradigm Grounded in Empirical Analysis of Dryland Systems Science. *Land Degradation & Development*, **28**(7), 1952-1961, doi:10.1002/ldr.2716.
Suckall, N., E. Tompkins and L. Stringer, 2014: Identifying trade-offs between adaptation, mitigation and development in community responses to climate and socio-economic stresses: Evidence from Zanzibar, Tanzania. *Applied Geography*, **46**, 111-121.
Sullivan, S. and R. Rohde, 2002: On non-equilibrium in arid and semi-arid grazing systems. *Journal of Biogeography*, **29**(12), 1595-1618, doi:10.1046/j.1365-2699.2002.00799.x.
Sultana, P. et al., 2019: Transforming local natural resource conflicts to cooperation in a changing climate: Bangladesh and Nepal lessons. *Climate Policy*, **19**(sup1), S94-S106, doi:10.1080/14693062.2018.1527678.
Swann, A. L., F. M. Hoffman, C. D. Koven and J. T. Randerson, 2016: Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. *Proc Natl Acad Sci U S A*, **113**(36), 10019-10024, doi:10.1073/pnas.1604581113.
Syphard, A. D., J. E. Keeley and J. T. Abatzoglou, 2017: Trends and drivers of fire activity vary across California aridland ecosystems. *Journal of Arid Environments*, **144**, 110-122, doi:https://doi.org/10.1016/j.jaridenv.2017.03.017.
Tabutin, D. and B. Schoumaker, 2004: La démographie de l'Afrique au sud du Sahara des années 1950 aux années 2000. *Population*, **59**(3), 521, doi:10.3917/popu.403.0521.
Tappan, G. G., Cushing, W.M., Cotil- lon, S.E., Mathis, M.L., Hutchinson, J.A., and Dalsted, K.J., , 2016: West Africa land use land cover time series: U.S. Geological Survey data release.
te Beest, M., J. Sitters, C. B. Ménard and J. Olofsson, 2016: Reindeer grazing increases summer albedo by reducing shrub abundance in Arctic tundra. *Environmental Research Letters*, **11**(12), 125013, doi:10.1088/1748-9326/aa5128.
Thébaud, B. and S. Batterbury, 2001: Sahel pastoralists: opportunism, struggle, conflict and negotiation. A case study from eastern Niger. *Global Environmental Change*, **11**(1), 69-78, doi:https://doi.org/10.1016/S0959-3780(00)00046-7.

Thomas, N. and S. Nigam, 2018: Twentieth-Century Climate Change over Africa: Seasonal Hydroclimate Trends and Sahara Desert Expansion. *Journal of Climate*, **31**(9), 3349-3370, doi:10.1175/JCLI-D-17-0187.1.

Thomas, R. et al., 2018: A framework for scaling sustainable land management options. *Land Degradation & Development*, **29**(10), 3272-3284, doi:https://doi.org/10.1002/ldr.3080.

Trichon, V., P. Hiernaux, R. Walcker and E. Mougin, 2018: The persistent decline of patterned woody vegetation: The tiger bush in the context of the regional Sahel greening trend. *Global Change Biology*, **24**(6), 2633-2648, doi:10.1111/gcb.14059.

Tsakiris, G., 2017: Facets of Modern Water Resources Management: Prolegomena. *Water Resources Management*, **31**(10), 2899-2904, doi:10.1007/s11269-017-1742-2.

Tsymbarovich, P. et al., 2020: Soil erosion: An important indicator for the assessment of land degradation neutrality in Russia. *International Soil and Water Conservation Research*, **8**(4), 418-429, doi:https://doi.org/10.1016/j.iswcr.2020.06.002.

Tucker, C. J. and S. E. Nicholson, 1999: Variations in the size of the Sahara Desert from 1980 to 1997. *Ambio*, 587-591.

Turner, M., 1993: Overstocking the Range: A Critical Analysis of the Environmental Science of Sahelian Pastoralism. *Economic Geography*, **69**(4), 402-421, doi:10.2307/143597.

Turner, M. D. and P. Hiernaux, 2015: The effects of management history and landscape position on inter-field variation in soil fertility and millet yields in southwestern Niger. *Agriculture, Ecosystems & Environment*, **211**, 73-83, doi:https://doi.org/10.1016/j.agee.2015.05.010.

Tyler, N., M. Forchhammer and N. Øritsland, 2008: Nonlinear effects of climate and density in the dynamics of a fluctuating population of reindeer. *Ecology*, **89**, 1675-1686, doi:10.1890/07-0416.1.

UNCCD, 1994: *Elaboration of an international convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa*. Paris, 1-58 pp.

UNEP, 1992: *World Atlas of Desertification*. UNEP. ISBN 0340555122.

United Nations Educational, Scientific and Cultural Organization, 1979: Map of the world distribution of arid regions. UNESCO Paris.

Upton, C., 2014: The new politics of pastoralism: Identity, justice and global activism. *Geoforum*, **54**, 207-216, doi:https://doi.org/10.1016/j.geoforum.2013.11.011.

ur Rahman, M. H. et al., 2018: Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. *Agricultural and Forest Meteorology*, **253**, 94-113.

Vale, C. G. and J. C. Brito, 2015: Desert-adapted species are vulnerable to climate change: Insights from the warmest region on Earth. *Global Ecology and Conservation*, **4**, 369-379, doi:https://doi.org/10.1016/j.gecco.2015.07.012.

Van de Steeg, J., Tibbo, M. , 2012: Livestock and climate change in the Near East Region: measures to adapt and mitigate climate change *Regional Office for the Near East [Corporate Author] RNE [Corporate Author]; FAO, Cairo (Egypt).*

Vargas-Gastélum, L. et al., 2015: Impact of seasonal changes on fungal diversity of a semi-arid ecosystem revealed by 454 pyrosequencing. *FEMS Microbiology Ecology*, **91**(5), doi:10.1093/femsec/fiv044.

Veldman, J. W. et al., 2019: Comment on “The global tree restoration potential&#x201d. *Science*, **366**(6463), eaay7976, doi:doi:10.1126/science.aay7976.

Veldman, J. W. et al., 2015: Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *BioScience*, **65**(10), 1011-1018, doi:10.1093/biosci/biv118.

Venter, Z. S., M. D. Cramer and H. J. Hawkins, 2018: Drivers of woody plant encroachment over Africa. *Nature Communications*, **9**(1), 2272, doi:10.1038/s41467-018-04616-8.

Verner, 2012: Adaptation to a Changing Climate in the Arab Countries: A Case for Adaptation Governance and Leadership in Building Climate Resilience. *MENA development report. Washington, DC. World Bank.* .

Vidal-González, P. and B. Nahhass, 2018: The use of mobile phones as a survival strategy amongst nomadic populations in the Oriental region (Morocco). *GeoJournal*, **83**(5), 1079-1090, doi:10.1007/s10708-017-9823-6.

Vincke, C., I. Diedhiou and M. Grouzis, 2010: Long term dynamics and structure of woody vegetation in the Ferlo (Senegal). *Journal of Arid Environments*, **74**, 268-276, doi:10.1016/j.jaridenv.2009.08.006.

von Uexkull, N., M. Croicu, H. Fjelde and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proc Natl Acad Sci U S A*, **113**(44), 12391-12396, doi:10.1073/pnas.1607542113.

Wang, D. W., T. C. Gouhier, B. A. Menge and A. R. Ganguly, 2015: Intensification and spatial homogenization of coastal upwelling under climate change. *Nature*, **518**(7539), 390-394, doi:10.1038/nature14235.

Wang, S. et al., 2020: Recent global decline of CO2 fertilization effects on vegetation photosynthesis. *Science*, **370**(6522), 1295-1300.

Wang, X., T. Hua, L. Lang and W. Ma, 2017: Spatial differences of aeolian desertification responses to climate in arid Asia. *Global and Planetary Change*, **148**, 22-28.

Wang, Y., X. Yan and Z. Wang, 2016: A preliminary study to investigate the biogeophysical impact of desertification on climate based on different latitudinal bands. *International Journal of Climatology*, **36**(2), 945-955, doi:10.1002/joc.4396.

Ward, D., M. T. Hoffman and S. J. Collocott, 2014: A century of woody plant encroachment in the dry Kimberley savanna of South Africa. *African Journal of Range & Forage Science*, **31**(2), 107-121, doi:10.2989/10220119.2014.914974.

Warner, K., 2010: Global environmental change and migration: Governance challenges. *Global Environmental Change*, **20**(3), 402-413, doi:https://doi.org/10.1016/j.gloenvcha.2009.12.001.
Wassmann, R. et al., 2009: Chapter 3 Regional Vulnerability of Climate Change Impacts on Asian Rice Production and Scope for Adaptation. In: *Advances in Agronomy*. Academic Press, pp. 91-133. ISBN 0065-2113.
Webb, N. P. and C. Pierre, 2018: Quantifying Anthropogenic Dust Emissions. *Earth's Future*, **6**(2), 286-295, doi:10.1002/2017ef000766.
Weldemichel, T. G. and H. Lein, 2019: "Fencing is our last stronghold before we lose it all." A political ecology of fencing around the Maasai Mara National Reserve, Kenya. *Land Use Policy*, **87**, 104075, doi:https://doi.org/10.1016/j.landusepol.2019.104075.
Wendling, V. et al., 2019: Drought-induced regime shift and resilience of a Sahelian ecohydrosystem. *Environmental Research Letters*, **14**(10), 105005, doi:10.1088/1748-9326/ab3dde.
Weston, P., R. Hong, C. Kaboré and C. A. Kull, 2015: Farmer-Managed Natural Regeneration Enhances Rural Livelihoods in Dryland West Africa. *Environmental Management*, **55**(6), 1402-1417, doi:10.1007/s00267-015-0469-1.
Wezel, A. and A. M. Lykke, 2006: Woody vegetation change in Sahelian West Africa: evidence from local knowledge. *Environment, Development and Sustainability*, **8**(4), 553-567, doi:10.1007/s10668-006-9055-2.
Wieriks, K. and N. Vlaanderen, 2015: Water-related disaster risk reduction: time for preventive action! Position paper of the High Level Experts and Leaders Panel (HELP) on water and disasters. *Water Policy*, **17**(S1), 212-219, doi:10.2166/wp.2015.011.
Wilhite, D. A., 2019: Integrated drought management: moving from managing disasters to managing risk in the Mediterranean region. *Euro-Mediterranean Journal for Environmental Integration*, **4**(1), 42, doi:10.1007/s41207-019-0131-z.
Wilhite, D. A. and R. S. Pulwarty, 2018: *Drought and Water Crises: Integrating Science, Management, and Policy*, Second Edition ed., CRC Press. ISBN 9781138035645.
Williams, A. P. et al., 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science (New York, N.Y.)*, **368**(6488), 314-318.
Winter, J. M., P. J.-F. Yeh, X. Fu and E. A. B. Eltahir, 2015: Uncertainty in modeled and observed climate change impacts on American Midwest hydrology. *Water Resources Research*, **51**(5), 3635-3646, doi:10.1002/2014wr016056.
Wu, M. et al., 2016: Vegetation–climate feedbacks modulate rainfall patterns in Africa under future climate change. *Earth Syst. Dynam.*, **7**(3), 627-647, doi:10.5194/esd-7-627-2016.
Xu, L., N. Chen and X. Zhang, 2019: Global drought trends under 1.5 and 2 C warming. *International Journal of Climatology*, **39**(4), 2375-2385.
Yu, Y. et al., 2017: Observed positive vegetation-rainfall feedbacks in the Sahel dominated by a moisture recycling mechanism. *Nature Communications*, **8**(1), 1873, doi:10.1038/s41467-017-02021-1.
Yuan, W. et al., 2019: Increased atmospheric vapor pressure deficit reduces global vegetation growth. *Science Advances*, **5**(8), eaax1396, doi:10.1126/sciadv.aax1396.
Yusa, A. et al., 2015: Climate Change, Drought and Human Health in Canada. *International journal of environmental research and public health*, **12**(7), 8359-8412, doi:10.3390/ijerph120708359.
Zeweld, W. et al., 2018: Impacts of Socio-Psychological Factors on Actual Adoption of Sustainable Land Management Practices in Dryland and Water Stressed Areas. *Sustainability*, **10**(9), 2963.
Zhang, C., X. Wang, J. Li and T. Hua, 2020: Identifying the effect of climate change on desertification in northern China via trend analysis of potential evapotranspiration and precipitation. *Ecological Indicators*, **112**, 106141, doi:https://doi.org/10.1016/j.ecolind.2020.106141.
Zhang, R., L. Xie and Z. Yan, 2019: Ecological study on biomineralization in *Pinctada fucata*. In: *Biomineralization Mechanism of the Pearl Oyster, Pinctada fucata* [Zhang, R., L. Xie and Z. Yan (eds.)]. Springer Singapore, Singapore, pp. 661-694. ISBN 978-981-13-1459-9.
Zhang, W. et al., 2018: Impacts of the seasonal distribution of rainfall on vegetation productivity across the Sahel. *Biogeosciences*, **15**(1), 319-330, doi:10.5194/bg-15-319-2018.
Zhang, X. et al., 2007: Detection of human influence on twentieth-century precipitation trends. *Nature*, **448**(7152), 461-465, doi:10.1038/nature06025.
Zhao, T. and A. Dai, 2015: The Magnitude and Causes of Global Drought Changes in the Twenty-First Century under a Low–Moderate Emissions Scenario. *Journal of Climate*, **28**(11), 4490-4512, doi:10.1175/jcli-d-14-00363.1.
Zhao, Y. et al., 2015: Estimating heat stress from climate-based indicators: present-day biases and future spreads in the CMIP5 global climate model ensemble. *Environmental Research Letters*, **10**, 084013, doi:10.1088/1748-9326/10/8/084013.
Zhou, S. et al., 2019: Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. *Proceedings of the National Academy of Sciences*, **116**(38), 18848, doi:10.1073/pnas.1904955116.
Zhu, T. et al., 2013: Climate change impacts and adaptation options for water and food in Pakistan: scenario analysis using an integrated global water and food projections model. *Water International*, **38**(5), 651-669, doi:10.1080/02508060.2013.830682.

Zida, W. A., B. A. Bationo and J.-P. Waaub, 2020: Re-greening of agrosystems in the Burkina Faso Sahel: greater drought resilience but falling woody plant diversity. *Environmental Conservation*, **47**(3), 174-181, doi:10.1017/S037689292000017X.
Zida, W. A., B. A. Bationo and J.-P. Waaub, 2020b: Re-greening of agrosystems in the Burkina Faso Sahel: greater drought resilience but falling woody plant diversity. *Environmental Conservation*, **47**(3), 174-181, doi:10.1017/S037689292000017X.
Zida, W. A., F. Traoré, B. A. Bationo and J.-P. Waaub, 2020a: Dynamics of woody plant cover in the Sahelian agroecosystems of the northern region of Burkina Faso since the 1970s–1980s droughts. *Canadian Journal of Forest Research*, **50**(7), 659-669, doi:10.1139/cjfr-2019-0247.
Zwarts, L., R. G. Bijlsma and J. van der Kamp, 2018: Large decline of birds in Sahelian rangelands due to loss of woody cover and soil seed bank. *Journal of Arid Environments*, **155**, 1-15, doi:https://doi.org/10.1016/j.jaridenv.2018.01.013.

Cross-Chapter Paper 4: Mediterranean Region

Cross-Chapter Paper Leads: Elham Ali (Egypt), Wolfgang Cramer (France)

Cross-Chapter Paper Authors: Jofre Carnicer (Spain), Elena Georgopoulou (Greece), Nathalie Hilmi (Monaco), Gonéri Le Cozannet (France), Piero Lionello (Italy)

Cross-Chapter Paper Contributing Authors: Ahmed Abdelrehim (Egypt), Mine Cinar (USA), Islam Abou El-Magd (Egypt), Shekoofeh Farahmand (Iran), François Gemenne (Belgium), Lena Reimann (Germany), Alain Safa (France), Sergio Vicente-Serrano (Spain), Francesca Spagnuolo (Italy), Duygu Sevgi Sevilgen (Monaco), Samuel Somot (France), Rémi Thiéblemont (France), Cristina Tirado (USA), Yves Tramblay (France)

Cross-Chapter Paper Review Editors: Karim Hilmi (Morocco), Marta Rivera-Ferre (Spain)

Cross-Chapter Paper Scientist: Duygu Sevgi Sevilgen (Monaco)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

The Mediterranean Region hosts exceptional biological diversity and socio-cultural richness originating from three continents. The nature of the semi-enclosed Mediterranean Sea and the complex topography imply unique physiographic and ecological features. The region has undergone continuous change in human activities during several millennia, and it now hosts more than 500 million people with a high concentration of urban settlements and industrial infrast`ructure close to sea level. The region is the world's leading tourist destination and one of its busiest shipping routes. Climate change strongly interacts with other environmental problems in the Mediterranean Basin, resulting from urbanisation, land use change, overfishing, pollution, biodiversity loss and degradation of land and marine ecosystems. {CCP4.1.1}

Previous IPCC reports have never assessed the Mediterranean region as an entity – but they have nevertheless shown that virtually all parts of it are vulnerable and face significant risks due to climate change. Identified regional key risks include increased water scarcity (notably in the South and East) and droughts (in the North), coastal risks due to flooding, erosion and saltwater intrusions, wildfire, terrestrial and marine ecosystem losses, as well as risks to food production and security, human health, well-being and the cultural heritage. {CCP4.1.2}

Surface temperature in the Mediterranean region is now 1.5°C above pre-industrial level, with a corresponding increase in high-temperature extreme events (*high confidence*[1]). Trends in precipitation are variable across the basin (*low confidence*). Droughts have become more frequent and intense, especially in the North Mediterranean (*high confidence*). The sea surface has warmed by 0.29-0.44°C per decade since the early 1980s with stronger trends in the Eastern Basin. Sea level has risen by 1.4±0.2 mm yr^{-1} during the 20th century (2.8±0.1 mm yr^{-1} over 1993-2018) (*high confidence*). Ocean acidity is increasing (*medium confidence*). {CCP4.1.3}

A growing number of observed impacts across the entire basin are now being attributed to climate change, along with major roles of other forcings of environmental change (*medium to high confidence*). These impacts include multiple consequences of longer and/or more intensive heat waves, droughts, floods, ocean acidification and sea-level rise, such as cascading impacts on marine and terrestrial ecosystems as well as on land and sea use (agriculture, forestry, fisheries, tourism, recreation etc.) and human health. {CCP4.1.4}

During the 21st century, climate change is projected to intensify throughout the region. Air and sea temperature and their extremes (notably heat waves) are *likely*[2] to continue to increase more than the global average (*high confidence*). The projected annual mean warming on land at the end of the century is in the range from 0.9 to 5.6°C compared to the last two decades of the 20th century, depending on the emission scenario (*high confidence*). Precipitation will *likely* decrease in most areas by 4% to 22%, depending on the emission scenario (*medium confidence*). Rainfall extremes will *likely* increase in the northern part of the region (*high confidence*). Droughts will become more prevalent in many areas (*high confidence*). {CCP4.1.3}

Mediterranean sea-level is projected to rise further during the coming decades and centuries (*high confidence*), *likely* reaching 0.15 to 0.33 m in 2050, and 0.3 to 0.6 m for SSP1-1.9 and 0.6 to 1.1 m for SSP5-8.5 in 2100 (relative to 1995-2014) (*medium confidence*). Higher values cannot be excluded (*low confidence*) and the process is irreversible at the scale of centuries to millennia (*high confidence*).

---

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

Coastal flood risks will increase in low-lying areas along 37% of the Mediterranean coastline that currently host 42 million people. The number of people exposed to sea-level rise is projected to increase up to 2050, especially in the Southern and Eastern Mediterranean region, and may reach up to 130% compared to present in 2100 (*medium confidence*). Coastal settlements, world heritage sites and ecosystems are at longer-term risk from sustained sea-level rise over at least the coming three centuries (*high confidence*). {CCP4.1.3, CCP4.2, CCP4.3, SMCCP4.4}

Due to its particular combination of multiple strong climate hazards and high vulnerability, the Mediterranean region is a hotspot for highly interconnected climate risks. The main economic sectors in the region (agriculture, fisheries, forestry, tourism) are highly vulnerable to climatic hazards, while socio-economic vulnerability is also considerable. The low-lying areas are the most vulnerable areas for coastal climate-related risks (e.g. sea level rise, floods, erosion) and other consequent risks (e.g. saltwater intrusion and agriculture damage) (*high confidence*). Climate change threatens water availability, reducing river low flows and annual runoff by 5-70%, reducing hydropower capacity (*high confidence*). Yields of rain-fed crops may decrease by 64% in some locations (*high confidence*). Ocean warming and acidification will impact marine ecosystems, with uncertain consequences on fisheries (*low confidence*). Desertification will affect additional areas, notably in the South and South-East (*medium confidence*). Burnt area of forests may increase by 96-187% under 3°C, depending on fire management (*low confidence*). Beyond 3°C, 13-30% of the Natura 2000 protected area and 15-23% of Natura 2000 sites could be lost due to climate-driven habitat change (*medium confidence*). {CCP4.2, CCP4.3}

The adaptive capacity of ecosystems and human systems is expected to encounter hard limits due to the interacting, cumulative and cascading effects of droughts, heat waves, sea-level rise, ocean warming and acidification (*high confidence*). Coastal protection can reduce risks from sea-level rise in some regions, but the costs of such interventions and their consequences for coastal ecosystems are high (*medium confidence*) {CCP4.4.1}. There is *low confidence* in the feasibility of adaptation options to sea-level rise beyond 2100 or for large Antarctic ice melting. {CCP4.4.5}

Progress towards achievement of the UN Sustainable Development Goals differs strongly between Mediterranean sub-regions, with north-western countries having stronger resilience than southern and eastern countries (*high confidence*). To equitably enhance regional adaptive capacity and sustainable development, while safeguarding the rights of the most vulnerable people, regional cooperation can be strengthened with a focus on the link between adaptation, costs and financial limitation and climate justice (*high confidence*). Cooperative policies across multiple various sectors, involving all user groups and considering all regional and sectorial differences may enhance sustainable resource use in the region (*high confidence*). {CCP4.4.6}

Sharing and co-production of knowledge can support climate adaptation practices and enhance sustainability in the Mediterranean region (*medium* to *high confidence*). Currently incomplete knowledge of climate impacts and risks in the southern and eastern part of the basin hinders the implementation of adaptation measures, creating a need for implementable plans with enhanced and cooperative research and monitoring capacities between the north and south/east countries (*high agreement*). {CCP4.4}

CCP4.1 Climate Change in the Mediterranean Basin

CCP4.1.1 The Mediterranean Sea, Land and People

The Mediterranean Basin, known for its exceptional environmental and socio-cultural richness, comprises the semi-enclosed Mediterranean Sea and the countries and regions bordering it[3], which belong to Europe, Asia and Africa (Figure CCP4.1). The region has a unique historical and environmental identity (Abulafia, 2011), despite undeniable variations in the environment, socio-economic conditions and cultural traditions. The countries in the Mediterranean Basin hosted approx. 542 million people in 2020, a number which is expected to increase to 657 million in 2050 and 694 million in 2100. In 1950, only 23.7% of the Mediterranean population lived in countries of the South, this number has increased to 41.2% in 2000, 46.3% in 2020, and is projected to reach 55.5% in 2050 and 64.6% in 2100 (UN DESA, 2019).

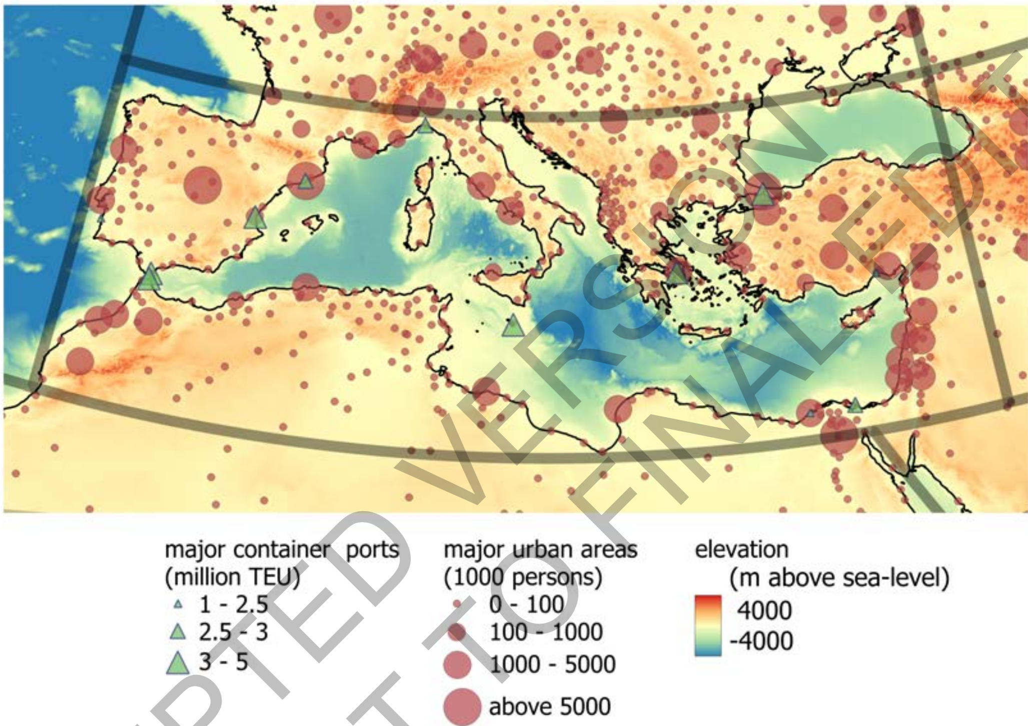


Figure CCP4.1: The Mediterranean region: Topography and bathymetry (colour bar in meters), main urban areas (population in thousands for 2020 from www.naturalearthdata.com), container ports (millions of TEU twenty-foot container equivalent units in 2017, from International Association of Ports and Harbours) and borders of the AR6-WGI Mediterranean region.

CCP4.1.2 Main Findings from Previous Assessments

All previous assessments of climate change for the Mediterranean Basin and its sub-regions indicate ongoing warming of the atmosphere and the sea, as well as projected warming and changes in rainfall (Stocker et al., 2013; Cherif et al., 2020). The projected increase in climate hazards, in combination with high regional vulnerability and exposure make it a prominent 'climate change hotspot' (Giorgi, 2006), with a large number of vulnerable natural systems and socio-economic sectors (Field et al., 2014; MedECC, 2020). In addition to high temperatures, the main risk factor identified is drought, generally expected to increase in the region, significant already at global warming of only 1.5°C, reaching, for higher warming levels, intensities unprecedented during the past 10ka (Hoegh-Guldberg et al., 2018). In southern Europe and North Africa, groundwater recharge and soil water content consequently decline, especially during summer (Kovats et al., 2014; Niang et al., 2014).

[3] By tradition, also Portugal and Jordan are considered Mediterranean countries, despite having no Mediterranean coastline

With the changing climate, marine ecosystems have already undergone changes in structure, including the spread of tropical species from the Atlantic Ocean and the Red Sea (*high confidence*) and mass mortality in at least 25 invertebrate species, threatening, along with ocean acidification, marine ecosystems, including seagrass meadows (Hoegh-Guldberg et al., 2014; Nurse et al., 2014; Pörtner et al., 2014; Wong et al., 2014). Endemic marine species are at higher risk of extinction due to limited possibilities to migrate northward (Kovats et al., 2014; Poloczanska et al., 2014; Balzan et al., 2020). Southern and Eastern Mediterranean coastal systems with narrow dune belts and often rapid urbanization are vulnerable to both warming and sea-level rise (Seneviratne et al., 2012; Wong et al., 2014; Balzan et al., 2020).

Most Mediterranean land ecosystems are impacted negatively by drier conditions, causing the ranges of many endemic species to shrink, and the health and growth rates of trees to decline (Kovats et al., 2014; Niang et al., 2014; Nurse et al., 2014; Settele et al., 2014). Climate change is expected to increase wildfire risk in the region (Kovats et al., 2014), although earlier estimates of burnt area have been reduced in the most recent assessments to approx. 40-100%, considering that prevention and mitigation actions have successfully reduced this risk so far (Balzan et al., 2020). Wetlands and mountain summits are hotspots for biodiversity loss and extinctions (*medium confidence*) (Jiménez Cisneros et al., 2014; Nurse et al., 2014; IPBES, 2018a; IPBES, 2018b; Balzan et al., 2020). Along with unsustainable land use practices, climate change is projected to increase soil erosion in semi-arid areas (Jiménez Cisneros et al., 2014).

The increasing water scarcity was found to be a significant threat to agriculture (Jiménez Cisneros et al., 2014; Kovats et al., 2014; Niang et al., 2014; Mrabet et al., 2020). Associated with increased extreme temperatures, the Mediterranean is expected to become less attractive for tourism (Kovats et al., 2014; Nurse et al., 2014; Wong et al., 2014; Dos Santos et al., 2020). Several critical risks for human health increase due to climate change, including heat waves and vector-borne diseases (Kovats et al., 2014; Nurse et al., 2014; Linares et al., 2020). Adaptation options have been identified for many risks (buildings, water management, coastal protection etc.) (Murray et al., 2012; Revi et al., 2014; Wong et al., 2014). There are synergies between adaptation and mitigation, e.g. renewable energies or nature-based solutions focused on the conservation and restoration of ecosystems (Nurse et al., 2014; Hoegh-Guldberg et al., 2018; Vafeidis et al., 2020).

CCP4.1.3 Observed and Projected Climate Change

The Mediterranean Basin is located in a transition zone between mid-latitude and subtropical atmospheric circulation regimes, with large topographic gradients. The analysis of observed climate changes and their impacts is strongly affected by the imbalance of observations between northern and southern countries, where available time series often have not allowed to reconstruct past climate evolution over a sufficiently long-time scale (Cramer et al., 2018).

Since the 1980s, Mediterranean atmospheric warming has exceeded global average rates (*high confidence*) (WGI AR6 Chapter 11; Lionello and Scarascia, 2018; Cherif et al., 2020). Future annual and summer warming rates are projected to be 20% and 50% larger than the global annual average, respectively. Summer warming is projected to be particularly strong in the north (Figure CCP4.2, WGI AR6 Chapter 11;Mariotti et al., 2015; Lionello and Scarascia, 2018). Temperature extremes and heat waves have increased in intensity, number, and length during recent decades, particularly in summer, and are projected to continue increasing (*high confidence*) (WGI AR6 Chapter 11Zittis et al., 2016; Hoegh-Guldberg et al., 2018; Cherif et al., 2020).

Sea surface temperatures have increased in recent decades (*high confidence*), with regional variation between +0.29 and +0.44°C per decade (Darmaraki et al., 2019a) and stronger trends in the eastern basin (Iona et al., 2018; Pastor et al., 2019), involving the whole upper mixed layer (Rivetti et al., 2017). Towards the end of the 21st century, ocean warming in the range 0.8-3.8°C is projected near the surface (*high confidence*), 0.8-3.0°C at intermediate depth and 0.15-0.18°C in deeper waters (Darmaraki et al., 2019b; Soto-Navarro et al., 2020). The duration and intensity of marine heat waves have increased (*high confidence*) (Darmaraki et al., 2019a) and both parameters are projected to continue increasing in the future (Galli et al., 2017). Under RCP8.5, at least one long-lasting marine heat wave is projected for every year by 2100, up to three months longer and about four times more intense than present day events (WGI AR6 Chapter 9) (Darmaraki et al., 2019b). Salinity is projected to increase, with anomalies from +0.48 to +0.89 psu at the end of the century (*medium confidence*) (WGI AR6 Chapter 9; Adloff et al., 2015).

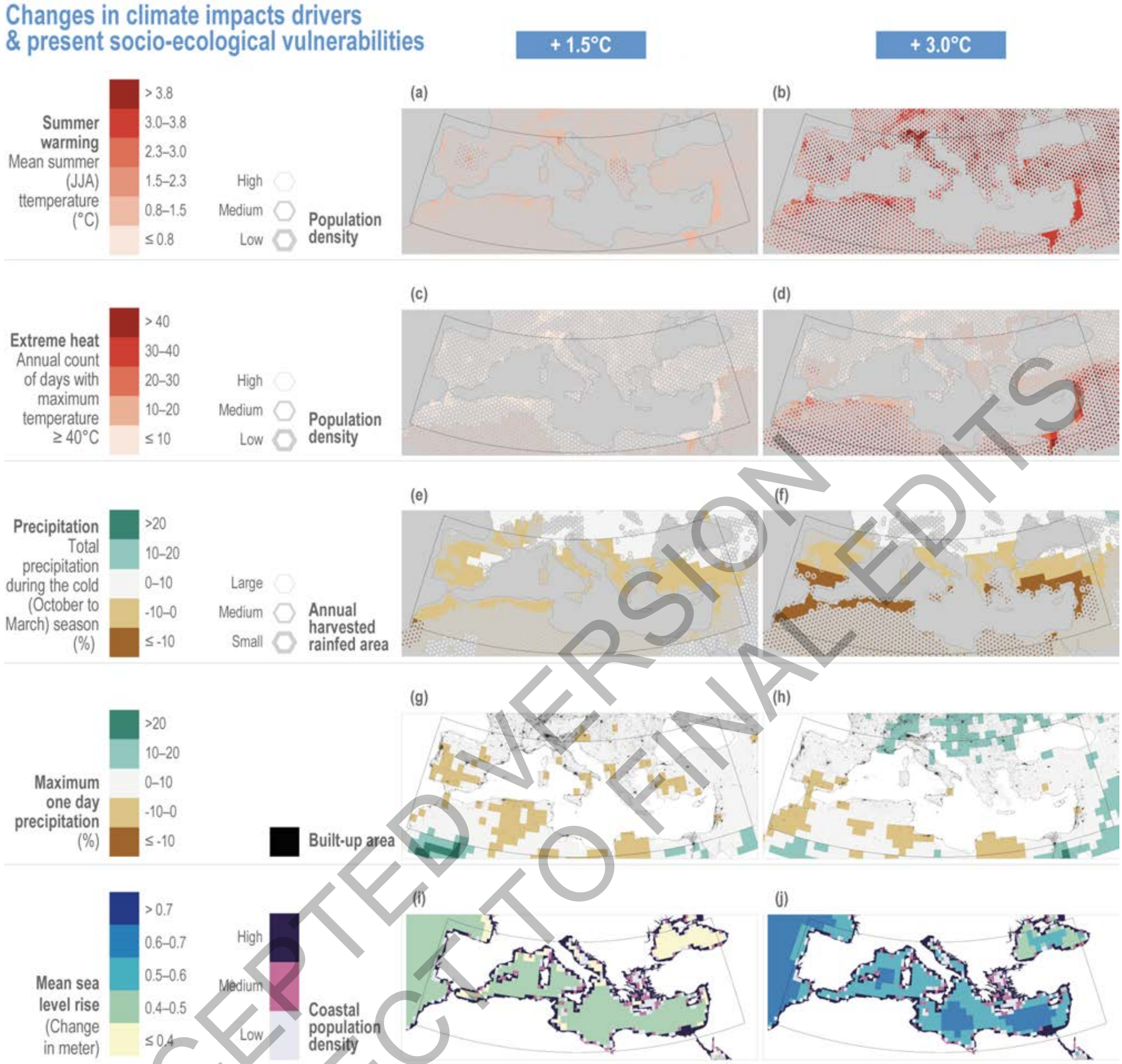


Figure CCP4.2: Changes in climate impact drivers with respect to the 1995-2014 period for 1.5°C (left column) and 3°C (right column) global warming: mean summer (June to August) temperature (°C, a, b), number of days with maximum temperature above 40°C (days, c, d), total precipitation during the cold (October to March) season (%, e, f)) and 1-day maximum precipitation (mm, g, h). Values based on CMIP6 global projections and SSP5 8.5 (source: Annex I: Atlas).

Observed trends in annual precipitation are significant only in some areas and some periods, and they are stationary on the long term throughout the region (*medium confidence*) (WGI AR6 Chapter 11, Figure CCP4.3; Harris et al., 2014; Lionello and Scarascia, 2018; Vicente-Serrano et al., 2020). Precipitation is projected to decrease (*high confidence* for global warming levels above 2°C) (Figure CCP4.2) by approximately 4% per 1°C global warming, for all seasons in the central and southern basin, and mostly in summer in the north (Mariotti et al., 2015; Hertig and Tramblay, 2017; Lionello and Scarascia, 2018). Precipitation extremes have increased in some northern areas (*medium confidence*), and are projected to increase in the north (*high confidence* for global warming levels above 2°C), potentially accompanied by an increase in of flash floods (Llasat et al., 2016), with no change in the south (*low confidence*) (WGI AR6 ATLAS, Figures CCP4.2 and CCP4.3; Tramblay and Somot, 2018; Lionello and Scarascia, 2020). These trends enhance the gradient between northern (already characterized by more intense events) and southern areas (where extreme precipitation events are comparatively milder) (Giorgi et al., 2014; Jacob et al., 2014; Vautard et al., 2014; Lionello and Scarascia, 2020).

Widespread increase of evaporative demand and some decrease of precipitation explain the drying of the Mediterranean region during recent decades (*high confidence*) (Chapter 11, Figure CCP4.3) (Spinoni et al., 2015; Gudmundsson and Seneviratne, 2016; Spinoni et al., 2017; Stagge et al., 2017; Caloiero et al., 2018). Droughts are projected to become more severe, more frequent and longer under moderate emission scenarios, and strongly enhanced under severe emission scenarios (*high confidence*) (WGI AR6 Chapter 11) (Hertig and Tramblay, 2017; Lehner et al., 2017; Ruosteenoja et al., 2018; Spinoni et al., 2018b; Grillakis, 2019; Lionello and Scarascia, 2020).

No trends in mid-latitude cyclones crossing the Mediterranean basin have been detected for recent decades (Lionello et al., 2016). For Mediterranean hurricanes ("medicanes"), no observed trends are known because of insufficient monitoring. In the future, mid-latitude cyclones and medicanes are projected to decrease in frequency, but medicane intensity will *likely* increase (Cavicchia et al., 2014; Nissen et al., 2014; Romera et al., 2017).

Mediterranean waters have acidified since the pre-industrial period, more rapidly than the global ocean, due to faster ventilation times (*high confidence*) (Palmiéri et al., 2015). Acidification is projected to continue (*virtually certain*) (WGI AR6 Chapter 11), with a pH decrease that might reach -0.46 in a high emission scenario (Goyet et al., 2016).

Mediterranean mean sea level has risen by 1.4±0.2 mm yr^{-1} during the 20th century (Wöppelmann and Marcos, 2012) and accelerated to 2.4±0.5 mm yr^{-1} for 1993 to 2012 (Bonaduce et al., 2016) and 3.4 mm yr^{-1} for 1990 to 2009 in the northwest (*medium confidence*) (Calvo et al., 2011). The accelerating trend is robust, although different methods and time horizons yield slightly different rates of change (Meyssignac et al., 2011; Cazenave et al., 2018; von Schuckmann et al., 2020). For 2150, sea level is *likely* to reach 0.52 m [0.32-0.81] for SSP1-1.9, to 1.22 [0.91-1.78] for SSP5-8.5 relative to 1996-2014 (*medium confidence*) (WGI AR6 Chapter 9; Figure FAQ-CCP4.2, SMCCP4.4), with uncertain variation between sub-basins (Slangen et al., 2017). Melting processes in Greenland and Antarctica could result in even higher levels (*low confidence*, WGI AR6 Chapter 9; Cross-Chapter Box SLR in Chapter 3).

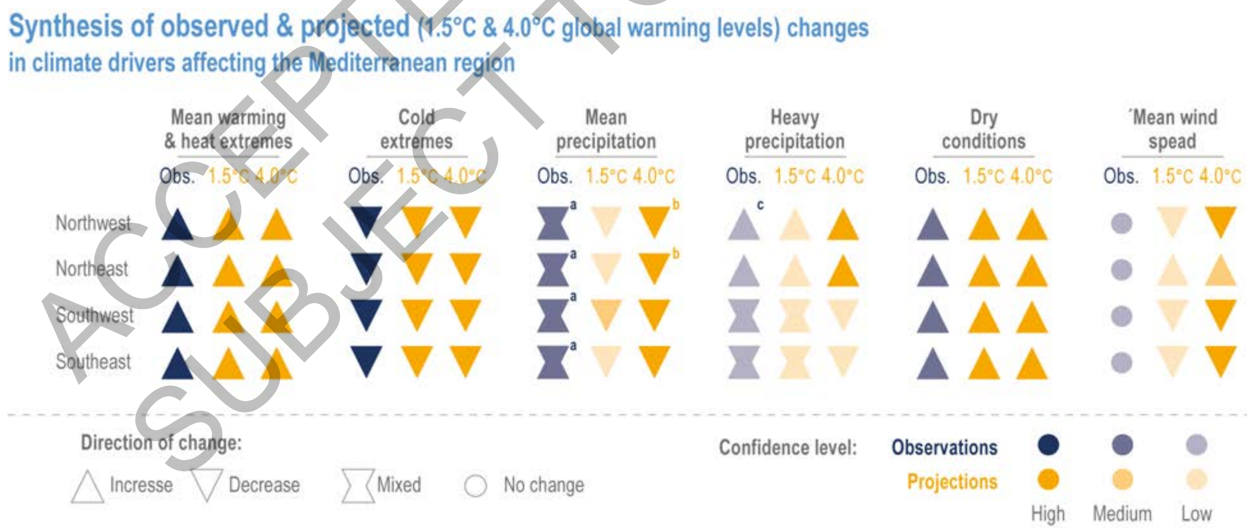


Figure CCP4.3: Observed and projected (at global warming levels of 1.5°C and 3°C) direction of change of climate drivers and confidence levels for Mediterranean land sub-regions. [a] The magnitude and sign of trends depend substantially on time period and study region. Although precipitation is highly variable, it is stationary on the long term for the whole region. [b] Marginal increase in winter at the northern boundary of the subregions. [c] There are subregional differences, with no change or even decrease over Iberia.

The Mediterranean Basin includes within small distances a large variety of climatic conditions that are *likely* to shift northward with global warming. Consequently, ecoregions will be exposed to potentially unsuitable conditions: more arid climate for Mediterranean forests of North-Africa, more subtropical climate and temperate climate for mountain forests of the Balkans and of the Alps, respectively, and Mediterranean climate for the temperate forests of North Anatolia (Figure CCP4.4; Lelieveld et al., 2012; Simpson et al., 2014).

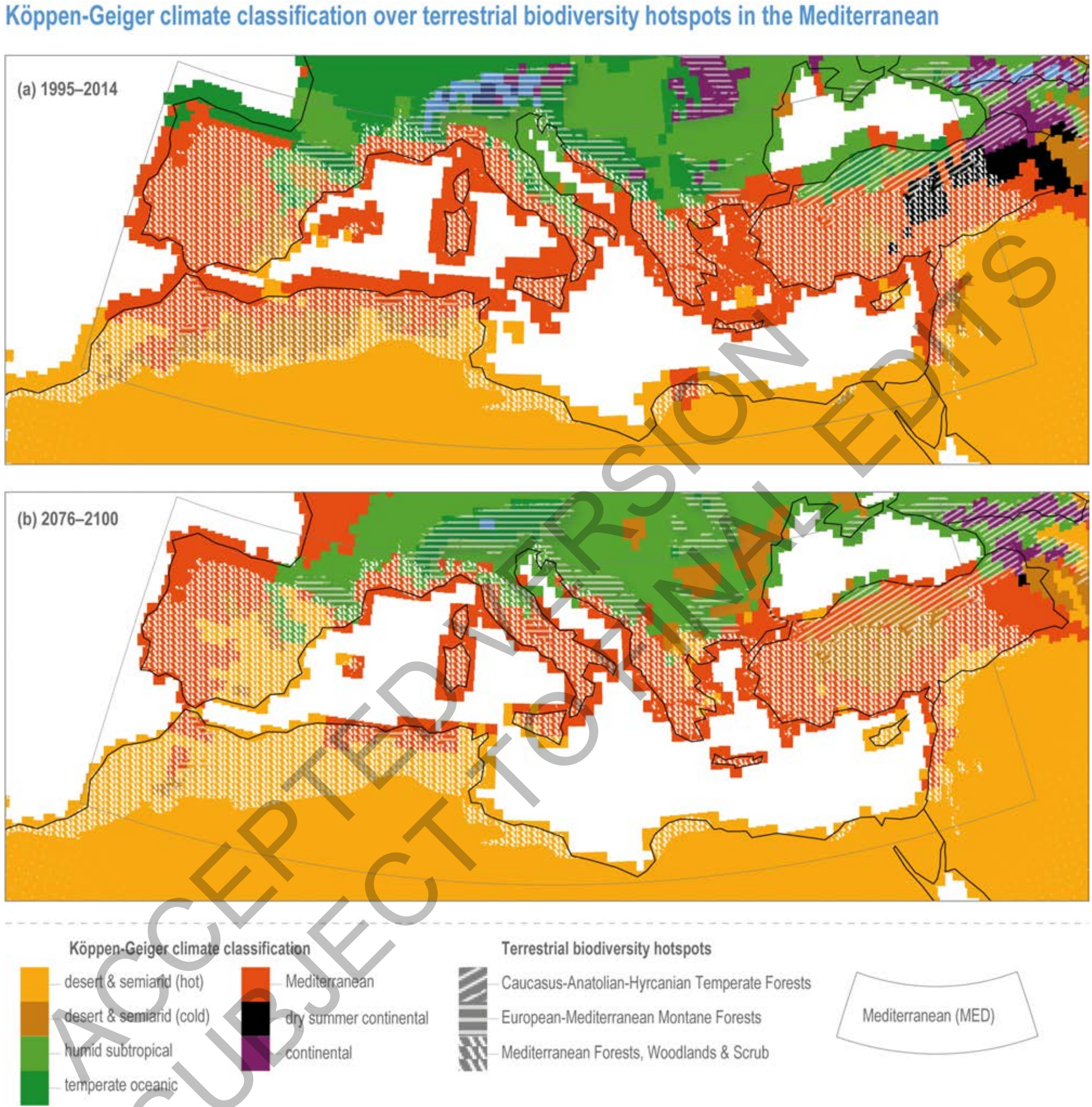


Figure CCP4.4: Climate and natural land ecosystems in the Mediterranean Basin, based on Köppen-Geiger climate types, for the AR6 baseline climate (panel a, 1985-2014) and future climate (panel b, 2076-2100, A1FI scenario, corresponding to global warming of approximately 4°C), based on (Rubel and Kottek, 2010) with the three biodiversity hot spots.

CCP4.1.4 Detection and Attribution of Climate Change Impacts

New evidence published since AR5 confirms that climate change is increasingly affecting many systems and sectors in the Mediterranean region (*high confidence*) (Figure CCP4.5; Chapter 9, 13 and 16). There is *high confidence* that climate change has worsened heat waves and droughts (CCP4.1.3;Lionello et al., 2014; Caloiero et al., 2018; Mathbout et al., 2018; Spinoni et al., 2019), and *medium to high confidence* that heat waves are impacting marine (Rivetti et al., 2014; Tsikliras and Stergiou, 2014; Stergiou et al., 2016; Corrales et al., 2017), freshwater and terrestrial ecosystems (Peñuelas et al., 2018; Bartsch et al., 2020; Carosi et al., 2021), as well as agriculture (El-Maayar and Lange, 2013; Ortas and Lal, 2013; Ponti et al., 2014; Garcia-Mozo et al., 2015; Moore and Lobell, 2015; Oteros et al., 2015; Di Lena et al., 2018) and fisheries (Fortibuoni et al., 2015; Givan et al., 2018; IPBES, 2018a). Heat waves have also increased thermal discomfort, especially in urban area (WGI AR6 Chapters 10 and 12; Zinzi and Carnielo, 2017). Despite increasing wildfire hazard, forest fires are generally decreasing in the European part of the basin, due to more efficient risk management (*medium confidence*) (Turco et al., 2016; Turco et al., 2017). Mixed trends of increasing and decreasing flash and river floods across the Mediterranean are reported, but there is *low confidence* in their attribution to climate change (Mediero et al., 2014; Baahmed et al., 2015; Gaume et al., 2016; Paprotny et al., 2018; Blöschl et al., 2019; Vicente-Serrano et al., 2019).

Flooding, erosion and salinization are significant observed impacts in coastal regions, especially where subsidence is significant, such as in the region of Thessaloniki in Greece or the eastern Nile Delta in Egypt (Raucoules et al., 2008; Frihy et al., 2010), with only *low confidence* in attribution to climate change so far (SMCCP4.1). Coastal urbanisation and engineering protection are expanding in the Mediterranean, resulting in substantial impacts on coastal biodiversity (Masria et al., 2015; Carranza et al., 2020).

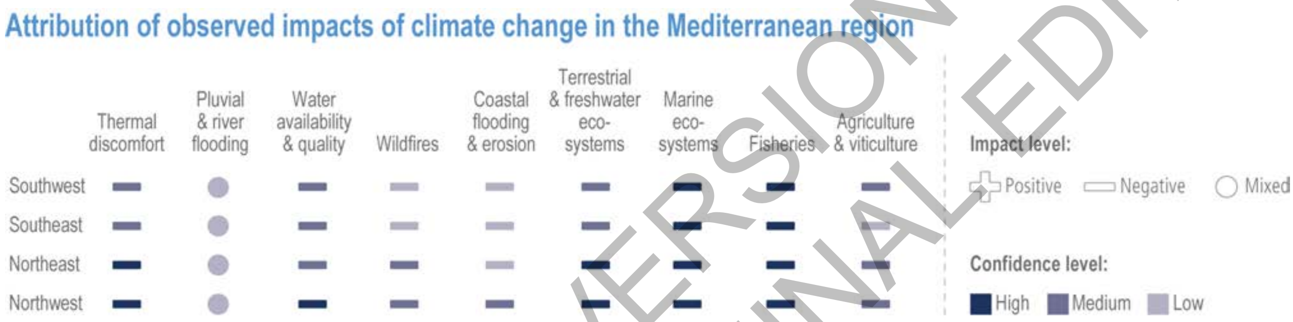


Figure CCP4.5: Attribution of observed impacts of climate change in the Mediterranean region (see SMCCP4.1 for supporting references).

The attribution of impacts displays little variability across sub-regions, but confidence in attribution to climate change is higher in the north, due to the larger number of observations and studies in Europe. While land use and fisheries are still major non-climatic drivers of changing hazards and biodiversity losses (Aguilera et al., 2015; Turco et al., 2016; IPBES, 2018a; IPBES, 2018b; Tramblay et al., 2019; Vicente-Serrano et al., 2019), impacts of climate change are now being observed in all parts of the Mediterranean region (*high confidence*).

CCP4.2 Vulnerability of Mediterranean Countries to Climate Change

CCP4.2.1 The Specific Vulnerability of Mediterranean countries

The Mediterranean region is predominantly vulnerable to the impacts of warming, notably prolonged and stronger heat waves, and increased drought in an already dry climate, and risk of coastal flooding (Section CCP4.1). Southern and Eastern countries are generally more vulnerable than countries in the north. Several countries (Tunisia, Algeria and Libya) are below the water scarcity threshold set by the Food and Agriculture Organization of the United Nations (FAO), others (Morocco) are close to the threshold for severe water stress. Uncertainties regarding the timing, duration, intensity and interval between extreme climatic events put some sectors such as agriculture and tourism at particular risk in the Mediterranean region (Section CCP4.3; Kallis, 2008; Kutiel, 2019).

CCP4.2.2 Economic Vulnerability

All Mediterranean countries are vulnerable to climate change across most socio-economic sectors. In low-income countries of the basin a 1.1-point reduction of Gross Domestic Product (GDP) could occur as a consequence of 1°C rise warming (Radhouane, 2013). In Morocco, GDP impacts of climate change could be

-3% to +0.4% by 2050 relative to 2003 (Ouraich and Tyner, 2018). In MENA countries, approx. 10-13 % of GDP loss in MENA are projected for an increase in global mean temperature of 4.8°C in 2100 (Kompas et al., 2018). In southern Europe, mean labour productivity loss would shrink by approx. 2% under 2°C warming, along with a GDP loss of 0.1% in 2030s, reaching 0.4% in the 2080s (Szewczyk et al., 2018).

Freshwater resources are vulnerable to climate change and growing demand, notably from agriculture (Section 4.1.3; Gudmundsson et al., 2017; Zabalza-Martínez et al., 2018; Masseroni et al., 2020). The share of GDP and population exposed to high or very high water stress in MENA countries are 71% and 61%, respectively, compared to 22% and 36% in the world (World Bank, 2018). Freshwater resources are also vulnerable to sea-level rise and associated salinization (Ali and El-Magd, 2016; Wassef and Schüttrumpf, 2016; Twining-Ward et al., 2018). Due to the impact of climate change on water supplies (-14% to -6%), MENA countries are projected to experience high losses in GDP by 2050 (World Bank, 2016).

The agricultural sector is important for most Mediterranean economies, both in terms of GDP and employment, with its share of the total GDP in the region at 6.7% in 2016 (Kutiel, 2019). Water stress in southern countries is largely driven by growing demand from agriculture, with a potential water deficit of 28-47% in 2030 (Sebri, 2017). In Spain, eleven out of fifteen river basin districts are under water stress due to demand from agriculture (Vargas and Paneque, 2019). In Greece, the largest agricultural region (Thessaly) where 70% of the irrigation water comes from groundwater, is under water stress (Gemitzi and Lakshmi, 2018). Water scarcity and high dependence on rain-fed agriculture make MENA countries vulnerable to warming and reduced rainfall, associated with high irrigation requirements (Dhehibi et al., 2015; Fader et al., 2016; World Bank, 2016; Asseng et al., 2018; World Bank, 2018), exacerbated by poverty and political instability (Price, 2017). For cropping systems in MENA countries, the Nile Valley and the western parts of North Africa on the Atlas Mountains are classified as the areas with highest vulnerability (ESCWA, 2017).

As MENA countries are net food importers, they are not only vulnerable to climate change on food production in the Mediterranean region, but also by the climate impacts on food production elsewhere, e.g. in China and Russia (Waha et al., 2017). The agri-food sector in the Mediterranean region is also important for global food security because several large producing countries in the region, such as France, Italy and Morocco, are net exporters of many essential micronutrients to low and lower-middle income countries. Changing quantity and quality of production would have direct (availability) and indirect (price signals) impacts on their trade partners.

The economic value of fisheries in the Mediterranean Sea is over 3.4 billion USD (Randone et al., 2017) with about 76250 fishing vessels in 2019 (FAO, 2020), most of them (about 62%) in the eastern and central Mediterranean (FAO, 2018). Total employment on-board fishing vessels is 202,000 and six countries, i.e. Tunisia, Algeria, Turkey, Italy, Greece and Egypt, account for approximately 82 percent of total employment (FAO, 2020). About 78% of the fish stocks in the Mediterranean are currently fished at unsustainable levels (Galli et al., 2015). The share of stocks in overexploitation has decreased from 88% in 2012 to 75% in 2018 (FAO, 2020). Nearly half of the catches consist of small pelagic species (anchovies, sardines, herrings), which are very vulnerable to increased seawater temperatures (FAOSTAT, 2019). Turkey is particularly sensitive to climate change in the fisheries sector (Turan et al., 2016; Hidalgo et al., 2018). Fisheries in northern countries are less vulnerable because they have a greater capacity to adapt (i.e. more assets, flexibility, learning potential, and social organization), while southern countries are more vulnerable (Ding et al., 2017). The reduction of fish availability directly impacts the income of employees, e.g. in the Italian fisheries industry (Tulone et al., 2019).

Mediterranean forests are diverse and play a major ecological and social role through significant ecosystem services, including wood, but also the recreational value and production of non-wood goods such as mushrooms (Ding et al., 2016; Peñuelas et al., 2017; Gauquelin et al., 2018; Herrero et al., 2019). Many forests grow at the dry margin of their distribution area, therefore projected drier conditions will affect their productivity and health (Doblas-Miranda et al., 2017; Dorado-Liñán et al., 2019; Sangüesa-Barreda et al., 2019). Vulnerability to wildfire is a significant matter of concern, particularly in the northern and south-western Mediterranean region (Ager et al., 2014; Gomes da Costa et al., 2020). In Córdoba (Spain), for example, fire suppression costs have increased by 66-87% in the last decade (Molina et al., 2019).

The Mediterranean region accounts for one third of global tourism with 330 million tourists in 2016 (Tovar-Sánchez et al., 2019). Before the COVID-19 crisis, international tourist arrivals were assumed to increase by 60% between 2015 and 2030 and reach 500 million then. In 2015, tourism supported 15% of the total employment in the region (Randone et al., 2017). France, Spain, Italy and Greece are the top tourist destinations (UNWTO, 2016), but the highest growth was in Turkey, Croatia and Albania during 1995-2015 (MGI, 2017). The tourism industry is vulnerable to climate change, particularly in low income countries (Dogru et al., 2016; Dogru et al., 2019). Coastal tourism in the region generates 300 billion USD annually followed by marine tourism (110 billion USD) (Radhouane, 2013; Randone et al., 2017).

By providing around 550,000 jobs in the Mediterranean region, the maritime transport and trade industry comprises approximately 20-40% of GDP. As a hub for trade, the Mediterranean, with approximately 600 ports of different sizes, accounts for 25% of all international seaborne trade, including 22% of its oil trade. In the region, the shift to green energy to combat climate change would significantly influence the structure of foreign trade in terms of commodities and maritime energy transport flows (Manoli, 2021).

CCP4.2.3 Social and Human Vulnerability

With population growth, food demand in the region increases and will continue to do so, while regional food production on land and from the sea is threatened by climate change, creating the need for additional import. In MENA countries, livestock production has increased by 25% in 1993-2013, causing animal feed imports to increase to about 32% of the total food import in 2014 (FAO, 2018), thereby increasing food-import dependence of southern countries (INRA, 2015; Saladini et al., 2018). Sharp increases in international food prices since 2007 have caused inflation, trade deficits, fiscal pressure, increased poverty as well as political instability, all affecting food supply, notably in the South and East of the region (Harrigan, 2011; Kamrava and Babar, 2012; Ferragina and Canitano, 2015; Paciello, 2015).

Heat waves and other climatic extremes affect densely populated urban centres and coastal regions, causing health risks for vulnerable groups, in particular those who live in poverty with substandard housing (Paz et al., 2016; Scortichini et al., 2018; Rohat et al., 2019). Nights with temperatures higher than 23°C have been increase health risks (Royé, 2017). Human health is also vulnerable to other risks altered by climate change, either directly through droughts, floods, fires etc., or indirectly through impacts on disease vectors, air pollution, water quality, and food security (Negev et al., 2015). Cases of dengue fever were recently reported from several countries, and there is an apparent threat of outbreaks transmitted by *Aedes* mosquitoes in the northern Mediterranean (Semenza et al., 2016; Semenza and Suk, 2017). The most vulnerable to climate impacts are the elderly, pregnant women, children, the chronically ill, the obese and people with cognitive impairment (Linares et al., 2015; Paravantis et al., 2017).

One third of the Mediterranean population (about 150 million people) currently lives close to the sea, often in growing urban regions and with infrastructure vulnerable to sea-level rise (Cross-Chapter Box SLR in Chapter 3; Briche et al., 2016; UN DESA, 2017). Future exposure to sea-level rise is related to demographic growth. All Shared Socio-Economic Pathways (SSP) project an increase of coastal population in the Mediterranean region to 2050. By 2100, coastal population could grow by up to 130%, mostly in the south, but it could also drop by 20% for SSP1 (Reimann et al., 2018b). Overall, countries in the South-Eastern Mediterranean are most vulnerable to coastal risks, but the exposure is also high in the Northern Mediterranean (Satta et al., 2017).

In terms of the number of people, Egypt, Libya, Morocco and Tunisia are the most exposed countries to sea-level rise (World Bank, 2014), and this difference is projected to increase under SSP2-4 (Reimann et al., 2018a). Among MENA countries, Egypt is particularly exposed with several coastal cities at risk of inundation (Frihy et al., 2010; Solyman and Abdel Monem, 2020; Elshinnawy and Almaliki, 2021). In the Nile Delta, between 1500 and 2600 km^2 of land are projected to be exposed to flooding by 2100 by a sea-level rise of 0.75 m (median sea-level rise scenario for SSP5-85) and additional subsidence up to 0.25 m, threatening around 6.3 million residents (Figure CCP4.6; Ali and El-Magd, 2016; Solyman and Abdel Monem, 2020). Basin-wide economic losses are estimated at US$5 billion assuming a rise of sea levels by 1.26 m in 2100 (Frihy et al., 2010; World Bank, 2014).

The Mediterranean area is characterized by high human mobility, mostly within countries but also between them (Cross-Chapter Box MIGRATE in Chapter 7; Charef and Doraï, 2016; Ben Youssef et al., 2017). In 2017, the value of remittances from migrants was about 16% of southern Mediterranean countries' exports to the EU (Alcidi et al., 2019). Impacts of recent climate change, notably drought and their effects on human livelihoods and vulnerability, may have contributed to migration decisions, although there is debate about the relative importance (Kelley et al., 2015; Fröhlich, 2016; Hamed et al., 2018; Ash and Obradovich, 2020). One study of five MENA countries estimated that extreme climate events account for about 10 to 20 % of migration, with an expected increase of the role of environmental factors in the future as climatic conditions deteriorate further (Wodon et al., 2014).

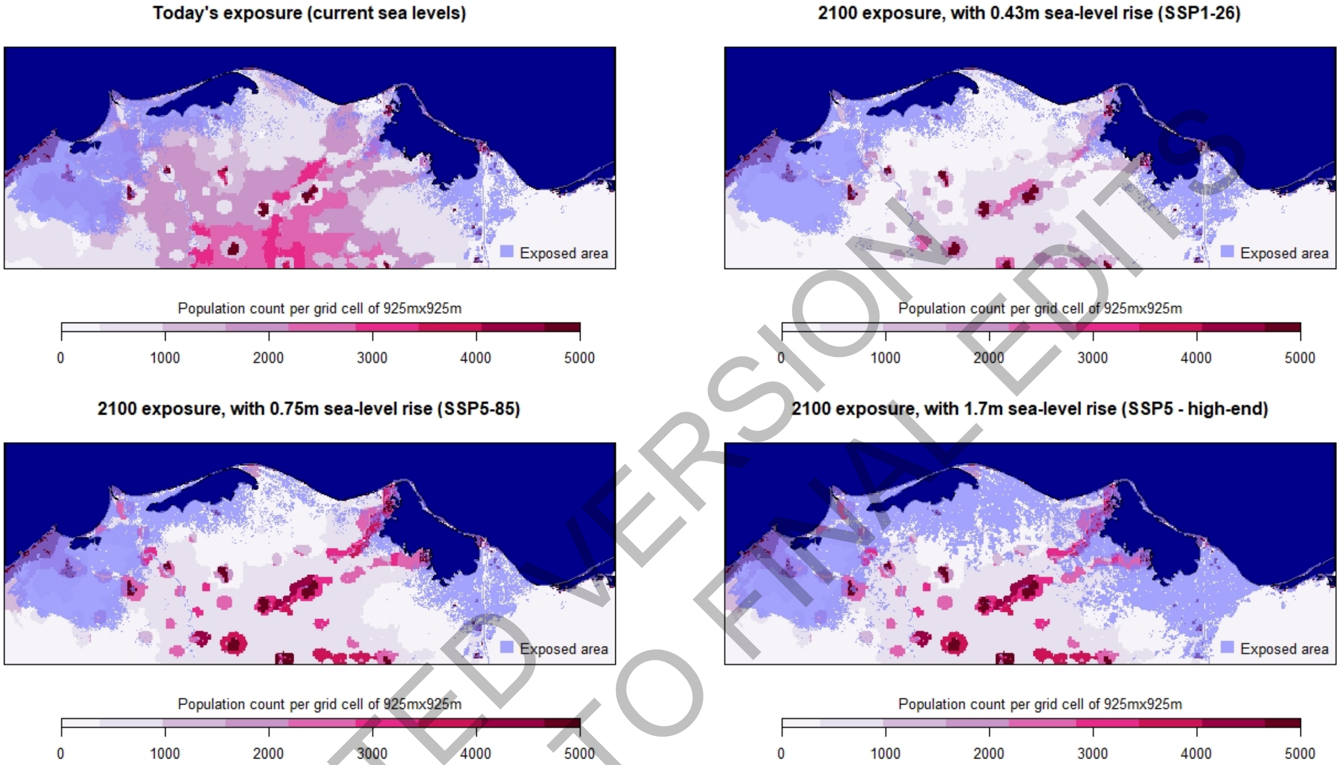


Figure CCP4.6: Present-day and projected exposure to sea-level rise in the Nile delta, due to sea-level change and land subsidence. A: Current exposure; B: Exposure for 2°C of global warming by 2100; C: Exposure for 3°C of global warming by 2100; D: Exposure for a high-end sea-level rise scenario involving additional mass losses from Antarctica ice-sheet (Frihy et al., 2010; Ali and El-Magd, 2016; Kulp and Strauss, 2019); sea-level scenarios from AR6-WG1-Ch9; see supplementary material for additional details.

Improved sharing and co-production of knowledge can support climate adaptation practices, ensure their implementation, and thereby reduce vulnerability (Nguyen et al., 2019), e.g. in the water sector (Iglesias and Garrote, 2015; Iglesias et al., 2018) and notably river management (Tàbara et al., 2018). The individual perception of climate risks is also a component of vulnerability (Nguyen et al., 2016). Understanding the gap between perceptions and scientific evidence, and increasing risk perception and awareness, will be crucial to promote adaptive responses both at the individual and the collective level throughout the Mediterranean Basin (Macias et al., 2015; Bodoque et al., 2016; Cramer et al., 2018).

CCP4.3 Projected Climate Risks in the Mediterranean Basin

CCP4.3.1 Ocean Systems

With warming, marine primary production is projected to decrease in the western and increase in the eastern Mediterranean Sea (Macias et al., 2015). The diversity of copepods (species which dominate the meso-zooplankton communities feeding Mediterranean fishes) is projected to decline over most of the Mediterranean, albeit with regional variation (Benedetti et al., 2018). Total marine biomass (and fishery potential) is projected to increase in the south-eastern Mediterranean, whereas significant decreases are most likely in the west (Moullec et al., 2019). The projected increase of marine heat waves in the Mediterranean Sea will add additional pressures on coastal and marine ecosystems. Warm-water fish species are expected to move northwards, while cold-water species will decline, and invasions of thermal-tolerant tropical species will increase (*high confidence*) (Lloret et al., 2015; Corrales et al., 2018). Fish species richness is predicted to increase in the eastern and decrease in the western Mediterranean by 2050, but by 2100 the cooler areas in the North will become a 'cul-de-sac' for many species (Albouy et al., 2013; Burrows et al., 2014). Out of 75 endemic fish species, 14 are projected to go extinct, almost all of them benthic and demersal species (Ben Rais Lasram et al., 2010). The abundance of small and medium-sized pelagic fish (e.g. European anchovy) is projected to decline by 15-33% by 2100 (Stergiou et al., 2016; Raybaud et al., 2017).

Heat waves will *likely* cause increasing mass mortality events of benthic species, mostly invertebrate organisms such as corals, sponges, bivalves, ascidians and bryozoans, increasing the risks of abrupt collapse of endemic species (Kersting et al., 2013; Rivetti et al., 2014; Rivetti et al., 2017; Garrabou et al., 2019; Garrabou et al., 2021). Deep water corals live near their upper thermal tolerance and further warming can thus reduce their biotic potential and long-term survival (Brooke et al., 2013; Nannini et al., 2015; Yasuhara and Danovaro, 2016; Marchini et al., 2019), although there are some exceptions (Naumann et al., 2013) and also knowledge gaps (Maier et al., 2019). Warming has been shown to severely reduce the metabolism of some Mediterranean coral species (Gori et al., 2016). In summary, the observed shift in marine ecosystems observed since 1980 is projected to continue and intensify, resulting in very high risks for marine ecosystems between 1.5°C to 2°C GWL (Figure CCP4.8; Chapter 3, 13 and CCP1; Manes et al., 2021).

CCP4.3.2 Coastal Systems

Sea-level rise is at the origin of multiple risks for low-lying areas in the Mediterranean Basin, such as the further increase in flooding at high-tide in some locations such as Venice (*high confidence*) (AR6 WGII Chapter 13;Cid et al., 2016; Pomaro et al., 2017). Currently, 37% of coastal areas are at moderate to high risk from coastal erosion and flooding (Satta et al., 2017). Due to rapid urban development, many coastal assets are directly exposed to projected sea-level rise and coastal hazards, with limited adaptation options and resilience of beaches (Section CCP4.2;Brown et al., 2016; Jiménez et al., 2017).

The Mediterranean is a micro-tidal sea, where storms may hit the coast during several hours or longer and and not only during high tides (Le Cozannet et al., 2015; Sánchez-Arcilla et al., 2016; Sierra et al., 2016; Sayol and Marcos, 2018). Projected changes of winds, storms and waves are small, and confidence in these changes is limited by the quality of climate models applied to the Mediterranean (Calafat et al., 2014; Androulidakis et al., 2015; Vousdoukas et al., 2017). Overall, sea-level rise is projected to increase the risk of coastal flooding despite the potential slight reductions of marine storms (*high confidence*) (Lionello et al., 2017; Vousdoukas et al., 2017). Risks of erosion and flooding will be amplified with climate change, particularly in river deltas (Figure CCP4.6;Ali and El-Magd, 2016), on low-lying floodplains, on sandy beaches around the basin and in many coastal cities (Satta et al., 2017). Impacts are projected to increase non-linearly during the 21st century with higher sea-level rise, because coastal flooding will progressively change from overtopping to overflow, high-tide flooding and ultimately permanent flooding and shoreline retreat (*high confidence*) (Le Cozannet et al., 2015; Sánchez-Arcilla et al., 2016; Sierra et al., 2016; Antonioli et al., 2017; Anzidei et al., 2017; Ciro Aucelli et al., 2017; Enríquez et al., 2017; Jiménez et al., 2017; Sayol and Marcos, 2018). These risks may be amplified further in areas with poor storm water management and sealed urban surfaces (Llasat et al., 2013; Gaume et al., 2016).

Combined with storm surges, sea-level rise may disrupt Mediterranean port operations (Sánchez-Arcilla et al., 2016; Sierra et al., 2016), with risks depending on adaptation, physical protection measures and basin depth. Risks for deep ports are more limited (Sierra et al., 2017), while low-depth small harbours, common in the Mediterranean, could be significantly affected (Sierra et al., 2016). Sea-level rise may enhance sandy beach erosion and thereby impact recreation and tourism (Bitan and Zviely, 2018; Rizzetto, 2020), magnifying coastal degradation and pollution (Enríquez et al., 2017; Gössling et al., 2018).

CCP4.3.3 Inland Ecosystems

Beyond 3°C GWL, 13-30% of the Mediterranean Natura 2000 protected area and 15 to 23% of Natura 2000 sites are projected to change towards more arid ecosystem types (Barredo et al., 2016). Biodiversity and ecosystem services would be exposed to degradation of wetland hydrology, which could affect 19-32% of localities under a 1.5 to 2°C GWL (48-73% under higher warming), particularly in Spain, Portugal, Morocco and Algeria (Lefebvre et al., 2019) and a substantial shrinking of terrestrial and freshwater ecosystem habitats, in particular in Mediterranean islands (Chapters 2 and 4; CCP1).

Increased aridity impacts forest ecosystems (Costa-Saura et al., 2017; García Sánchez et al., 2018). Increasing heat waves, combined with drought and land-use change, reduce fuel moisture, thereby increasing fire risk, extending the duration of fire seasons and increasing the likelihood of large, severe fires (*high confidence*) (EEA, 2017; Lozano et al., 2017; Peñuelas et al., 2017; Varela et al., 2019). Fires impact vegetation recovery after abandonment, thus transforming landscapes (González-De Vega et al., 2016). At warming levels of 1.5°C, 2°C and 3°C, burnt area in Mediterranean Europe could increase by 40-54%, 62-87% and 96-187%, respectively (Turco et al., 2018b), although changes are highly site-dependant and also affected by management (Caon et al., 2014; Wu et al., 2015; Parra and Moreno, 2018; Brotons and Duane, 2019; Hinojosa et al., 2019).

Desertification occurs in large parts of the region, generally due to unsustainable land use (Peñuelas et al., 2017). Increasing drought is projected to exacerbate desertification in North Africa and, under high warming, also southern Spain. In some areas, sclerophyllous vegetation could replace deciduous forests (Guiot and Cramer, 2016). Increasing temperatures and drought could trigger dieback for some forest species such as Mediterranean oak (Sánchez-Salguero et al., 2020), potentially also in combination with biotic factors such as pathogens (Matías et al., 2019).

CCP4.3.4 Water, Agriculture and Food Production

River runoff and low flows are expected to decrease (possibly by 12-15% or more) in most locations due to reduced precipitation (Giuntoli et al., 2015; Roudier et al., 2016; Andrew and Sauquet, 2017; Gosling et al., 2017; Marchane et al., 2017; Marcos-Garcia et al., 2017; Marx et al., 2018; Yeste et al., 2021). Groundwater recharge is projected to decrease due to reduced recharge (AR6 WG1 Chapter 11; Koutroulis et al., 2016; Guyennon et al., 2017; Braca et al., 2019; Calvache et al., 2020). Water levels in lakes and availability of reservoirs are expected to decline by up to 45% in 2100 (Koutroulis et al., 2016; Masia et al., 2018; Okkan and Kirdemir, 2018; Braca et al., 2019; Tramblay et al., 2020). The largest freshwater lake in the basin, Lake Beyşehir (Turkey), could dry out after 2070 (Bucak et al., 2017). In northern Africa, surface water availability is projected to be reduced by 5-40% in 2030-2065 and by 7-55% in 2066-2095 from 1976-2005 (Tramblay et al., 2018), with decreases of runoff by 10-63% by mid-century in Morocco and Tunisia (Marchane et al., 2017; Dakhlaoui et al., 2020). Reduced summer river flows and increasing water temperatures will constrain freshwater-cooled thermoelectric (including nuclear) power plants and hydropower plants, with possible reductions of production in the northern Mediterranean by 6-33% under 2°C and by 20-60% beyond 3°C warming (Lobanova et al., 2016; Solaun and Cerdá, 2017; Payet-Burin et al., 2018; Tobin et al., 2018).These findings confirm the AR6 WG1 Chapter 8 statement that drought duration and frequencies and water scarcity are projected to increase drastically between 1.5°C and 2°C of GWLs.

Climate change will *likely* reduce crop yields in many areas (Table CCP4.1), mainly due to higher temperatures affecting crop phenology and the shortening of the crop growing season (*high confidence*). Additional irrigation will be needed for most crops, although the shortening of the growing season could reduce irrigation needs in some cases (Saadi et al., 2015). Irrigation needs could increase by 25% in northern and two-fold in south-eastern Mediterranean (Fader et al., 2016), with arid southern areas at risk of insufficient water resources by 2100. The use of supplemental irrigation for winter wheat could become more common in northern Mediterranean (Saadi et al., 2015; Ruiz-Ramos et al., 2018).

Seawater intrusion is projected to cause additional risks in coastal aquifers, with severe impacts on agricultural productivity (Ali and El-Magd, 2016; Wassef and Schüttrumpf, 2016; Pulido-Velazquez et al., 2018; Twining-Ward et al., 2018; Omran and Negm, 2020). While elevated atmospheric CO_2 concentration could be positive for photosynthesis and cereal yields (Dixit et al., 2018; Ben-Asher et al., 2019; Kapur et al., 2019; Kheir et al., 2019), the net outcome for agricultural production is highly uncertain (Moriondo et al., 2016). The projected yield losses will *likely* reduce farm revenues, e.g., in Morocco (Ouraich and Tyner, 2018), in Egypt (Abd El-Azeem, 2020), Greece (Georgopoulou et al., 2017) and Israel (Zelingher et al., 2019). Given the growing water demand from agriculture and other users and the increasing competition over water resources, adaptation efforts for water supply need to be enhanced (Guyennon et al., 2017; Zabalza-Martínez et al., 2018).

Table CCP4.1: Projected risks for crop production in the Mediterranean Basin

Crop	Projected risk
Cereals and rice	Under 2°C warming and beyond, rain-fed wheat yield in most locations could decline by 2-59%, depending on agricultural practices (Chourghal et al., 2016; Dettori et al., 2017; Iocola et al., 2017; Brouziyne et al., 2018; Kheir et al., 2019). Under 1.5-3°C warming and reduced rainfall, yield decreases are also projected for maize (Georgopoulou et al., 2017; Iocola et al., 2017) and barley (Bouregaa, 2019; Cammarano et al., 2019), mainly due to the shortening of the crop growing season by up to 30 days due to higher temperatures (Saadi et al., 2015; Bird et al., 2016; Waha et al., 2017; Bouregaa, 2019). In Tunisia, cereal production may decrease by 0.79% with a 1% decrease in precipitation (Zouabi and Peridy, 2015). Reductions of rice yields in parts of the region are projected in the absence of adaptation, e.g. by 6-20% in southern France and Italy in 2070 under RCP8.5 (Bregaglio et al., 2017).
Olives	Higher temperatures and more frequent extreme heat events around flowering will *likely* affect phenology. While suitable areas for olive cultivation could extend northward and to higher elevations under the A1B scenario in 2036-2065 (Tanasijevic et al., 2014), negative consequences for several countries are expected, including southern Spain (Gabaldón-Leal et al., 2017; Arenas-Castro et al., 2020) and Tunisia (Ouessar, 2017) under 2°C warming. Under 1.5-2°C GWL, olive yields in northern Mediterranean locations could decrease by up to 21% (Brilli et al., 2019; Fraga et al., 2020). A 3°C warming could cause a 15-64% drop of production of rain-fed olives in Algeria (Bouregaa, 2019).
Vegetables	Yields could decline by up to 45% under current irrigation in some areas by 2050 under the A1B scenario (Zhao et al., 2015; Georgopoulou et al., 2017), while a lower availability of irrigation water would lead to further losses (Saadi et al., 2015) or even to non-viability of crops in some locations, e.g., in Tunisia beyond 2°C warming (Bird et al., 2016).
Fruit trees	Flowering of many fruit trees may be delayed, and chilling accumulation may be threatened. In Spain, under the A2 scenario, apples at maturity could be of inferior quality from mid-century, while after 2070 28-72% of the years could have winters not fulfilling chilling requirements (Funes et al., 2016; Rodríguez et al., 2019) Similar threats for other fruit trees were found beyond 3°C GWL (Funes et al., 2016; Rodríguez et al., 2019).
Grapevines and orchards	Climate change could advance bud break and flowering, shortening the growing season by 20-35 days after 2060 under RCP8.5 (Fraga et al., 2016; Ramos, 2017; Leolini et al., 2018; Ramos et al., 2018) and shifting maturation under high summer temperatures, thus affecting grape quality. Higher temperatures may increase evapotranspiration and therefore water deficit (Ramos et al., 2018). Some locations may suffer from high winter temperatures, causing a lack of chilling accumulation and finally a missed bud-break (Leolini et al., 2018). Early maturation may result in unbalanced wine quality through higher sugar and lower acids in the grape must after 2050 under RCP8.5 (Fraga et al., 2016; Koufos et al., 2018). Negative impacts of climate change on table quality vines and wine grape production in southern Europe after 2040 under RCP8.5 have been projected (Cardell et al., 2019).
Dates	Irrigation requirements for date palms in Tunisia under RCP8.5 could increase by 34% in 2050 from present to sustain date production (Haj-Amor et al., 2020), with adverse effects on groundwater resources.

Climate-driven change in pelagic production (Section CCP4.3.1), together with overfishing, will *likely* increase risks for fishery landings (Hidalgo et al., 2018). By 2060, more than 20% of exploited fishes and invertebrates currently found in eastern Mediterranean could become locally extinct (Jones and Cheung, 2015; Cheung et al., 2016; Balzan et al., 2020). Thermophilic and/or thermal-tolerant tropical species may increasingly dominate the catch composition (Moullec et al., 2019), creating possible opportunities depending on technology and consumer acceptance of new species (Hidalgo et al., 2018). Warming and acidification may weaken mussel shells, negatively impacting shellfish aquaculture (Martinez et al., 2018). High losses of clawed lobster production by the end of the century are projected under RCP4.5 (Boavida-Portugal et al., 2018). For much of the region, fisheries revenue may decrease by 15-30% by 2050 relative to 2000 under RCP8.5 (Lam et al., 2016).

Overall, reduced crop yields and fishery landings, combined with other factors such as rapid population growth and urbanization, increasing competition for water, and changing lifestyles, will *likely* impact food security, particularly in North Africa and the Middle East (Jobbins and Henley, 2015).

CCP4.3.5 Human Health and Cultural Heritage

Warming is projected to impact human health, mostly through increased intensity, frequency and duration of heat waves (*high confidence*) (Guerreiro et al., 2018; Jacob et al., 2018; Rohat et al., 2019; Smid et al., 2019). Under current socio-economic conditions, 53-93 million more people could be exposed to high or very high heat stress in northern Mediterranean by 2050 (Gasparrini et al., 2017; Rohat et al., 2019) and heat-related excess mortality could increase by more than 6-fold above 3°C GWL (Gasparrini et al., 2017; Rohat et al., 2019). In MENA countries, the mortality risk of the elderly in 2100 could be 8-20 times higher under RCP8.5 compared to 1951-2005, and still 3-7 times higher under RCP4.5 (Ahmadalipour and Moradkhani, 2018). Deaths attributable to high temperatures in the northern Mediterranean could increase by 18-20,000 in 2050 (50,000 in 2100) under RCP8.5 (1.4 and 2.6 times lower under RCP4.5) (Kendrovski et al., 2017).

Climate change and variability may also influence the emergence of vector-, food- and water-borne diseases (Negev et al., 2015). Under RCP8.5, the epidemic potential of dengue fever in southern Europe is projected to increase by 2100 (Liu-Helmersson et al., 2019), as well as the risk of infections by West Nile virus in 2050 under A1B (Semenza et al., 2016). Climate-induced diseases could reduce labour productivity in the region by 2060, particularly in MENA countries (Dellink et al., 2019). Overall, there is still uncertainty in projections of the future severity and distribution of diseases because of climate change due to the complex interactions between hosts, pathogens and vectors. Reductions in fruit and vegetable consumption as a result of climate change on food availability could lead to more than 20,000 deaths in 2050 under RCP8.5 from diseases caused by malnutrition (Springmann et al., 2016).

Extreme high temperatures, hot days and nights and consequently cooling degree days will likely increase (*high confidence*) (Spinoni et al., 2018a; Coppola et al., 2021), with specific cooling needs in cities possibly increasing by 50-278% under 2°C GWL and 134-375% beyond 3°C GWL (Cellura et al., 2018). Urban heat island effects will further increase cooling needs (Salvati et al., 2017; Zinzi and Carnielo, 2017). Higher temperatures will increase thermal and chemical stress on materials used in many ancient buildings and sculptures, such as marble, stone and masonry (Bonazza et al., 2009; Leissner et al., 2015).

Many studies project a decrease of climatic comfort for tourism in the Mediterranean by 2071 to 2100, particularly during summer (Grillakis et al., 2016; Jacob et al., 2018; Braki and Anagnostopoulou, 2019). There is adaptive potential in the extension of the period with favourable climatic conditions for urban tourism in Mediterranean cities (Scott et al., 2016). Water scarcity may create additional constraints for tourism (Köberl et al., 2016).

Cultural heritage sites in the region face risks from coastal flooding, with 37 out of 49 cultural World Heritage Sites today facing risk from a 100-year flood, and 42 of them from coastal erosion (Reimann et al., 2018b). Sea-level rise will increase these risks (*high confidence*) (Lionello, 2012; Rizzi et al., 2017; Reimann et al., 2018b; Ravanelli et al., 2019; Tagliapietra et al., 2019). By 2100, 47 of the 49 UNESCO sites are projected to be at risk from coastal flooding or erosion (Reimann et al., 2018b). Beyond 2100, sea levels are committed to rise further and represent an existential threat for the high number of coastal cultural heritage located in the Mediterranean (AR6 WGI Chapter 9; Chapter 13; Cross-Chapter Box SLR in Chapter 3; Marzeion and Levermann, 2014).

CCP4.3.6 Synthesis of Key Risks

For the Mediterranean Basin, all currently projected pathways of climate change will exacerbate climate-related risks in multiple systems and economic sectors, and for human health and well-being, amplifying current pressures on local ecosystems, economies and human well-being (Figures CCP4.7 and CCP4.8; Cramer et al., 2018; MedECC, 2020). While the majority of these risks apply across the entire region, many are specific for certain sub-regions or locations.

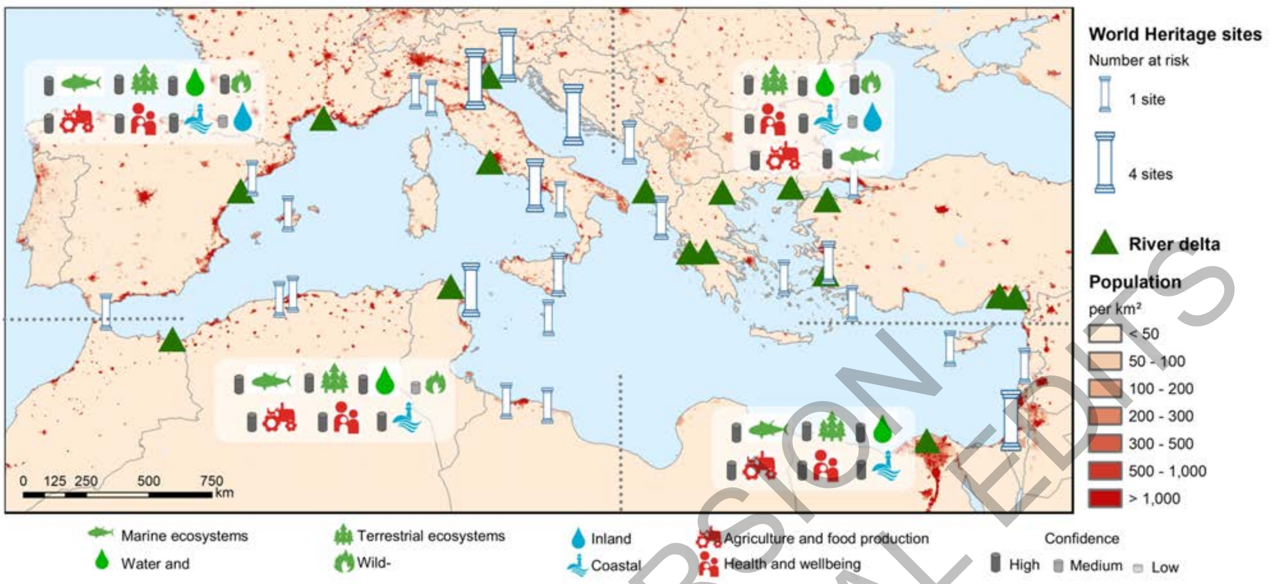


Figure CCP4.7: Key risks in the Mediterranean and their location for SSP5-RCP8.5 by 2100 across the Mediterranean region for SSP5-RCP8.5 by 2100 (Sections CCP4.3.2-6 and Table SMCCP4.2a & b for details). Risks to world cultural heritage sites from flooding or erosion due to sea-level rise in multiple locations (section CCP4.3.5) and Mediterranean river deltas are hotspots of vulnerability to climate change (Section CCP4.3.2). The population exposed to risks is mapped for an SSP5-8.5 pathway. Adaptation can reduce these risks (Section CCP4.4) (based on: Reimann et al., 2018a; Reimann et al., 2018b; Wolff et al., 2018).

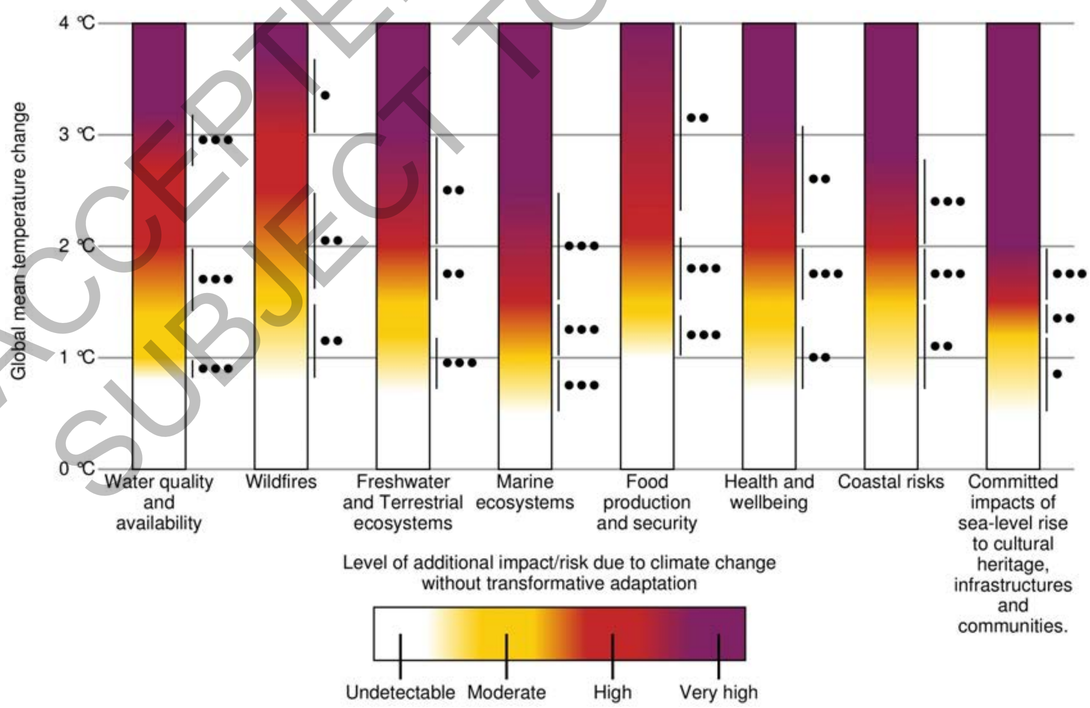


Figure CCP4.8: Summary of key risks for the Mediterranean (Sections CCP4.3.2-8 and Supplementary Tables SMCCP4.2a-h for details). Coastal risks include one burning ember displaying additional risks due to climate change as specific GWL are exceeded (Coastal risks), and one burning ember describing additional risks due to committed sea-level rise at timescales of centuries and millennia for long living infrastructure and cultural heritage (AR6 WGI Chapter 9; Marzeion et al., 2014; Marzeion and Levermann, 2014; Clark et al., 2016; see SMCCP4.2h).

CCP4.4 Adaptation and Sustainable Development in the Mediterranean Basin

CCP4.4.1 Ocean and Coastal Systems

Adaptation options for climate change impacts on marine ecosystems and fisheries include improving and enlarging the regional network of marine protected areas, transnational management of marine food resources, sustainable fishery practices, developing collaborative monitoring, research and managing knowledge platforms for fisheries (Bjørkan et al., 2020; Raicevich et al., 2020) and sustainable aquaculture (Ehlers, 2016; Lacroix, 2016).

Adaptation options to sea-level rise in the Mediterranean include nature-based solutions, such as beach and shore nourishment, dune restoration, or ecosystem-based adaptation and restoration in low-lying coasts, lagoons, estuaries and delta (Aragonés et al., 2015; Aspe et al., 2016; Loizidou et al., 2016; Danovaro et al., 2018). Engineering plays a major role for coastal adaptation too, through breakwaters, seawalls, dykes, surge barriers and submerged breakwaters (Sancho-García et al., 2013; Becchi et al., 2014; Balouin et al., 2015; Masria et al., 2015; Tsoukala et al., 2015; Bouvier et al., 2017). Many engineering-based coastal adaptation imply large residual impacts to coastal ecosystems (*high confidence*) (Micheli et al., 2013; Masria et al., 2015; Cooper et al., 2016; Bonnici et al., 2018). A sea surface height control dam at the Strait of Gibraltar has been proposed for mitigating sea-level rise in the Mediterranean, but this would *likely* involve major impacts on ecosystems and fisheries (Gower, 2015).

CCP4.4.2 Inland Ecosystems

In forests, adaptation to impacts of warming and drought may involve multiple forest management strategies such as thinning (Fernández-de-Uña et al., 2015; Giuggiola et al., 2016; Aldea et al., 2017; del Río et al., 2017; Gleason et al., 2017; Lechuga et al., 2017; Vilà-Cabrera et al., 2018), increasing the share of drought-tolerant species and provenances (Hlásny et al., 2014; Calvo et al., 2016), or promoting mixed-species stands (Ruiz-Benito et al., 2014; Guyot et al., 2016; Sánchez-Pinillos et al., 2016; del Río et al., 2017; Jactel et al., 2017; Ratcliffe et al., 2017).

Adaptation options to increased fire risks include improved planning of residential development such as to avoid inevitable wildfire (Schoennagel et al., 2017; Samara et al., 2018), improved fire suppression capacities and strategies (Brotons et al., 2013; Regos et al., 2014; Khabarov et al., 2016; Turco et al., 2018a; Turco et al., 2018b), managing and planning landscape matrix schemes to reduce fire risk (de Rigo et al., 2017; Erdős et al., 2018), thinning, slash management and prescribed burning techniques (Fernandes et al., 2016; Khabarov et al., 2016; Regos et al., 2016; Fernandes, 2018; Piqué and Domènech, 2018; Samara et al., 2018; Vilà-Cabrera et al., 2018; Duane et al., 2019), as well as understory grazing (Varga et al., 2016; Vilà-Cabrera et al., 2018).

Adaptation of forest management generally requires improved monitoring systems of forest condition and natural disturbances (Hlásny et al., 2014; Hengeveld et al., 2015; Maes et al., 2015), supported by participatory forest management and planning processes and local self-governance mechanisms (Bouriaud et al., 2013; Bouriaud et al., 2015).

For freshwater ecosystems, adaptation options include hydrological and land use planning at basin scale, which can be complemented with local conservation and restoration efforts, and the preservation of natural flow variability of rivers and streams (Aspe et al., 2016; Loizidou et al., 2016; Cid et al., 2017; Menció and Boix, 2018; Morant et al., 2020).

CCP4.4.3 Water Management, Agriculture and Food Security

Adaptation options to address water shortages at the national scale include transboundary resource management (Escriva-Bou et al., 2017; Pulido-Velazquez et al., 2018), promoting fair, equitable and sustainable water trade in international markets (Johansson et al., 2016; Lee et al., 2019), regional, national and basin-scale management plans for water resources (Wilhite et al., 2014; Paneque, 2015; Urquijo et al., 2015; Estrela and Sancho, 2016; Vargas and Paneque, 2019), improved groundwater monitoring and strategic management (Pulido-Velazquez et al., 2020) and economic instruments to manage water demand (prices policies, markets and subsidies).

Technical options include the reduction of losses in water distribution networks for drinking water and irrigation (Burak and Margat, 2016; Fader et al., 2016), desalinization, often combined with generation of electricity (Papanicolas et al., 2016; Bonanos et al., 2017; Jones et al., 2019), artificial recharge of groundwater and subterranean dams (Djuma et al., 2017; De Giglio et al., 2018; Missimer and Maliva, 2018; Baena-Ruiz et al., 2020), and waste water reuse (Kalavrouziotis et al., 2015; Barba-Suñol et al., 2018; Cherfouh et al., 2018). On the demand side, options include changing diet and water consumption patterns (Blas et al., 2016; Gul et al., 2017; Blas et al., 2018) and enhancing water use efficiency in the tourism and food sector (Hadjikakou et al., 2013; Moresi, 2014).

In the agriculture sector improved efficiency of irrigation practices can be achieved by changing surface water irrigation for other techniques and shifting to more sustainable practices (Mrabet et al., 2012; Benlhabib et al., 2014; Boari et al., 2015; Ćosić et al., 2015; Guilherme et al., 2015; Iglesias and Garrote, 2015; Cantore et al., 2016; Triberti et al., 2016; AbdAllah et al., 2018; Billen et al., 2018; Iglesias et al., 2018; Malek and Verburg, 2018; Vargas and Paneque, 2019). Overall, the region could save 35% of water resources by improved irrigation techniques (Fader et al., 2016). However, maladaptive drip irrigation subsidies and developments can also result in the unsustainable use of groundwater resources and excessive agriculture intensification, indicating the need for careful strategic planning, regulation and monitoring of these options (Venot et al., 2017). In the livestock sector, adaptation options for heat wave-induced mortality of animals include the choice of more resistant genetic provenances (Rojas-Downing et al., 2017).

Other adaptation options in the agricultural sector include agroecological techniques that increase the water retention capacity of soils (mulching, zero tillage, reduced tillage etc.) (Aguilera et al., 2013a; Aguilera et al., 2013b; Almagro et al., 2016; Sanz-Cobena et al., 2017; Tomaz et al., 2017; Bhakta et al., 2019; García-Tejero et al., 2020) and promoting crop diversification, adapting the crop calendar, and the use of new varieties adapted to evolving conditions. Many of these strategies for more sustainable production are also intended to address the food security risks and import dependence in the region. Other options are to manage nitrogen resources, food demand, change diets and reduce food waste (Billen et al., 2018; Schils et al., 2018; Billen et al., 2019; Garnier et al., 2019; Aguilera et al., 2020; Lassaletta et al., 2021).

CCP4.4.4 Human Health

In the Mediterranean region, adapting to increasing heat wave impacts involves local urban health adaptation plans, as well as increasing the capacity of the healthcare systems (Fernandez Milan and Creutzig, 2015; Larsen, 2015; Paz et al., 2016; Liotta et al., 2018; Reckien et al., 2018; Tsiros et al., 2018). Local urban adaptation strategies need to be integrative and address the housing and infrastructure, the increase and design of urban green areas, the education and awareness-raising of the most vulnerable communities, the implementation of early warning systems for extreme events and the surveillance of climate-change induced diseases, the strengthening of local emergency and healthcare services, and the general strengthening adaptive capacity of the community and of the local institutions.

CCP4.4.5 Limits to Adaptation, Equity and Climate Justice

There is low confidence that the Mediterranean region can adapt to rapid sea-level rise for the case of rapid Antarctic ice-sheets collapse, even in regions with high capabilities to adapt such as the northwest Mediterranean (Poumadère et al., 2008). Residual coastal risks are still largely unquantified. For moderate levels of sea-level rise, it is *unlikely* that these changes alone exceed the technical limits to coastal adaptation over the 21st century (Hinkel et al., 2018). Beyond 2100, continued sea-level rise may require managed retreat in low-lying Mediterranean areas, particularly in deltas area such as the Nile (Figure CCP4.6). There is little knowledge on the potential for adaptation at these timescales.

Regional adaptation initiatives occur in a highly asymmetric geographic context characterized by contrasting demographic, environmental and socioeconomic trends in the southern, eastern and northern parts of the Mediterranean Basin (Pausas and Fernández-Muñoz, 2012). Adaptation plans in Mediterranean countries are also limited by a lack of effective regional governance schemes (with the partial exception of European countries subjected to the European directives and strategies), hampering the effective implementation of regionally harmonized adaptation strategies, plans and quantitative targets (UNEP/MAP, 2016; Sachs et al., 2019). Adaptation to sea-level rise is essentially limited by social barriers along urban coasts in the northwest Mediterranean at present (Hinkel et al., 2018), while the adaptation dilemma involving economic and financial barriers are greater in peri-urban, rural and natural areas, as well as in the southern and eastern Mediterranean. In addition, limited regional monitoring of risks and adaptation options hampers adaptation in domains and sectors (Cramer et al., 2018).

In the Mediterranean region, vulnerability is strongly affected by equity: people most vulnerable to the effects of climate change are the elderly, especially women (Iñiguez et al., 2016; Achebak et al., 2018) and children, who are often strongly affected by climate change (Watts et al., 2019). An increase of heat waves poses a significant health risk especially for young children living in urban areas (UNICEF, 2014; Perera, 2017; Royé, 2017) and for elderly women, in particular those affected by other conditions such as respiratory diseases (Sellers, 2016; Achebak et al., 2018). Children and future generations in the eastern Mediterranean countries are those most at risk of food insecurity, in both quantity and quality (Prosperi et al., 2014). In the region many children are particularly vulnerable due to scarcity of drinking water and food, aggravated by droughts and flooding (Philipsborn and Chan, 2018). The potential for adaptation and preparation to vector-borne diseases and other health risks, expected to increase with climate change, differs among Mediterranean countries (Negev et al., 2015). Climate change in the Mediterranean region also impacts some groups disproportionately (e.g. poor farmers, urban migrants, seasonal workers) and livelihoods (Waha et al., 2017), favouring mobility and migration (Nori and Farinella, 2020).

To safeguard the rights of the most vulnerable people in the Mediterranean region, climate adaptation plans and measures must be designed by taking into account the cost of adaptation (Watts et al., 2019) and also that some adaptation options can have side and residual effects, by favouring some countries/groups over others. Climate-just adaptation options are those that promote fair solutions for all and take into account region-specific socio-economic and geopolitical variabilities and vulnerabilities, such as the lack of inclusive and participatory approaches (Iglesias and Garrote, 2015) and pre-existing vulnerabilities, as in the case of Palestine (Jarrar, 2015) and Syria (Gleick, 2014).

CCP4.4.6 Pathways for Sustainable Development

Climate-resilient sustainable development pathways are trajectories that combine adaptation and mitigation to realize the goal of sustainable development through iterative, continually evolving socioecological processes (Chapters 1, 18; Denton et al., 2014). Transformative adaptation can be promoted through social and political processes, identifying the enabling conditions and strategies that facilitate structural changes (UNEP/MAP, 2016; Ramieri et al., 2018; EC, 2020; UNEP/MAP and Plan Bleu, 2020). Among the main options is the ongoing structural change in the renewable energy system in this region, the production of renewable biological resources, measures towards increased water irrigation efficiency, for behavioural changes in multiple sectors, and improved regional governance (Table CCP4.2;Cramer et al., 2018).

Table CCP4.2: Transformative adaptation and mitigation options for climate resilient sustainable development in the Mediterranean Basin

Code	Sector	Transformative option	References
T1	Energy, transport and tourism	National plans and regulations to decarbonise fuel sources and electricity grids on the supply side, for reducing energy demand and increasing efficiency and converting transport systems from fossil fuels to electricity	UNEP/MAP (2016); Bastianin et al. (2017); EEA (2018a); EEA (2018b); OME (2018); CMI and EC (2019); EEA (2019); Sachs et al. (2019); EC, (2020); Simionescu et al. (2020)
T2	Energy	Deployment of large-scale Mediterranean transboundary renewable energy infrastructures and interconnections. Transboundary energy market integration schemes.	EIB and IRENA (2015); Tagliapietra (2018); CMI and EC (2019); Zappa et al. (2019); CMI and EC (2020)

T3	Energy	Definition of "Important Projects of Common European Interest" (IPCEI) pooling financial resources and funding large-scale innovation projects across borders in the Mediterranean. Green hydrogen projects in Mediterranean North Africa (especially Morocco) have already been suggested as strategic actions.	CMI and EC (2019); CMI and EC (2020)
T4	Energy-Finance	EU Renewable Energy Financing Mechanisms including calls for proposals to new renewable energy projects, including joint projects with third Mediterranean countries, joint support schemes, innovative technology projects or other projects that contribute to the enabling framework of the Renewable Directive 2018/2001. The mechanism can provide resources from payments by Member States, European Union funds (European Green Deal Investment Plan, the Sustainable Finance Strategy, the Just Transition Fund, Connecting Europe Facility) or private sector contributions.	CMI and EC (2019); CMI and EC (2020)
T5	Water	Improving efficiency of irrigation practices, including changing surface water irrigation for other techniques, use of remote sensing in intensive agriculture, optimization of irrigation practices and other approaches. The Mediterranean region could save 35% of water by implementing improved irrigation techniques	Iglesias et al. (2011); Boari et al. (2015); Ćosić et al. (2015); Dhehibi et al. (2015); Guilherme et al. (2015); Iglesias and Garrote (2015); Cantore et al. (2016); Fader et al. (2016); Iglesias et al. (2017); Kang et al. (2017); AbdAllah et al. (2018); Iglesias et al. (2018); Malek and Verburg (2018); Vargas and Paneque (2019)
T6	Water	Improvement of water resource availability and quality. Desalinization and co-generation of electricity and potable water in integrated Concentration Solar Power (CSP) plants. Reduce climate impacts on nitrate and other pollutant concentrations through improved agriculture and fertilizer management	Abufayed and El-Ghuel (2001); Elimelech and Phillip (2011); Aguilera et al. (2015); Papanicolas et al. (2016); Bonanos et al. (2017); Cramer et al. (2018); Jones et al. (2019); Lange (2019)
T7	Water	Reduce/control water demand and use through efficiency management and/or modernization in irrigation	Sanchis-Ibor et al. (2016); UNEP/MAP (2016)
T8	Water	Water demand management. Behavioural shifts in consumption and diet choice. Diet type influences the amount of water needed to produce and process food. Food waste implies the waste of the water used in the production cycle.	Blas et al. (2016); Gul et al. (2017); Blas et al. (2018)
T9	Water	Adaptation by increasing water trade in international markets (commodity markets)	Antonelli et al. (2012); Hoekstra and Mekonnen (2012); Johansson et al. (2016); Lee et al. (2019)
T10	Food and fisheries	Changing diets, managing food demand and reducing food waste. Reductions in the demand for livestock products	Bajželj et al. (2014); Havlík et al. (2014); Tilman and Clark (2014); Westhoek et al. (2014); Herrero et al. (2016); van Sluisveld et al. (2016)
T11	Food and fisheries	Shift to more sustainable fishery practices. Collaborative monitoring, research and managing knowledge platforms	Bjørkan et al. (2020); Raicevich et al. (2020)

T12	Human conflict, displacement, migration and security	Implementation of more effective Mediterranean regional policies and institutional frameworks for human rights protection, management of transboundary human migration, resolution of political and armed conflicts, increased internal displacements, and food security	UNEP/MAP (2016)
T13	Finance	Enhanced Mediterranean transnational governance and financial bilateral and multilateral capacity. Increased finance for regional cooperation and development (above current levels, 8300 million US$ yr^{-1}).	UNEP/MAP (2016); Midgley et al. (2018); Fosse et al. (2019)
T14	Coastal	Nature based solutions aiming at reducing future coastal risks by restoring a buffer zone in coastal areas (e.g., through managed realignment), leaving space for sediments and coastal ecosystems, thus reducing the hazard and exposure to coastal flooding and erosion.	Pranzini et al. (2015)

There also are risks for non-linear climate change impacts in key socioeconomic and environmental processes, which could promote reactive changes and forced transformations (Table CCP4.3).

Table CCP4.3: Non-linear processes that could force reactive changes and social transformations for climate resilient sustainable development in the Mediterranean Basin. Non-linearity implies the absence of straight-line relationship between the independent variable and the response variable. In other words, changes in the output do not change in direct proportion to changes in the independent variable and the form of the relationship is often described applying non-linear mathematical models. Gradual changes induced by climate warming in thermal exposure or rainfall availability can induce non-linear effects on social and ecological response variables.

Code	**Sector**	**Processes**	**References**
P1	Agriculture and migration	Adverse non-linear impacts of temperature on agricultural productivity can induce non-linear effect on human migration. The temperature–migration relationship is non-linear and resembles the nonlinear temperature–yield relationship. These relationships affect mostly agriculture-dependent countries and especially people in those countries whose livelihoods depend on agriculture	Reuveny (2007); Schlenker and Roberts (2009); Cai et al. (2016)
P3	All societal sectors	The increase in climatic impacts and catastrophic events is associated with non-linear changes in economic and social impacts	Burke et al. (2014); Burke et al. (2015); Carleton and Hsiang (2016); Hsiang et al. (2017); Prahl et al. (2018); Coronese et al. (2019)
P4	All economic sectors	Non-linear temperature effects on labour conditions	Burke et al. (2014); Graff Zivin and Neidell (2014); Burke et al. (2015); Somanathan et al. (2018)
P5	All economic sectors	Non-linear temperature effects on GDP. Higher temperature may reduce GDP in Mediterranean agricultural countries more than non-agricultural countries. Extreme heat over 30°C significantly reduce GDP of agricultural countries but not the non-agricultural ones. GDP is a main determinant of international migration. Nonlinear relationship between GDP and temperature in agricultural countries provide an indirect evidence for the agricultural linkage between temperature and migration.	Dell et al. (2012); Burke et al. (2014); Burke et al. (2015); Cai et al. (2016)

P6	All societal sectors	Non-linear effects of temperature on human conflict	Baylis (2015); Burke et al. (2018); Koubi (2018); Baylis (2020)
P7	Food, health and demography	In low-income areas of the Mediterranean Basin and sub-Saharan Africa regions higher poverty rates, malnutrition and elevated infant mortality are coupled with higher fertility, implying a higher rate of population growth that in turn can generate more poverty. These demographic cycles can in turn interact with climatic impacts and conflict-induced displacement and migration processes.	Vörösmarty et al. (2000); Barrios et al. (2006); Reuveny (2007); Hsiang et al. (2013); Ghimire et al. (2015); Brzoska and Fröhlich (2016); Cai et al. (2016); Cattaneo and Peri (2016); Grecequet et al. (2017); Waha et al. (2017); WFP (2017); Livi Bacci (2018); Raineri (2018); Scott et al. (2020)
P8	Energy	Non-linear effects of increased temperatures on energy demand and supply. High temperatures provoke demand surges while straining supply and transmission	Carleton and Hsiang (2016)
P9	Industry	Non-linear effects of temperature on industrial production	Hsiang and Meng (2015)

In the Mediterranean Basin, indicators for progress towards the Sustainable Development Goals (SDG) show multiple directions of transformative change (Sachs et al., 2019). In some sectors, such as energy, there are general positive trends in sustainability (UNEP/MAP, 2016), but there also are significant imbalances between northern and southern shores of the basin for most SDGs. Over the coming decades the Mediterranean Basin will *likely* experience sustained growth in renewable energy investments, accompanied by a shift in regional geographical patterns of energy demand (OME, 2018). But future developmental pathways, solution space and feasible system transformations could be constrained by multiple factors for several SDGs, such as social conflicts, lack of regional governance, limited action capacity and financial constraints (Figure CCP4.9, Table CCP4.3).

Figure CCP4.9: Differences in present day SDG indicator values between northern (blue) and southern (gold) Mediterranean countries. Yellow-shaded areas indicate better indicator values for the SDG descriptor. Red-shaded areas indicate poor performance on SDG values. Details on calculations and indicators in Table SMCCP4.3.

CCP4.4.7 Governance and Finance for Sustainable Development

Several multilateral institutions are managing international environmental governance in the Mediterranean Sea, including, i) the Barcelona Convention or Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (established under the United Nations Environment Programme; UNEP), ii) the General Fisheries Commission for the Mediterranean (GFCM, a subsidiary of the FAO), and iii) the ACCOBAMS (Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea, also under the UNEP). These institutions act cooperatively pursuing synergies and greater effectiveness (Lacroix, 2016). The Mediterranean Action Plan (MAP) under the Barcelona Convention System involves 21 Mediterranean countries and the European Union and promotes the Mediterranean Strategy for Sustainable Development (MSSD), coordinated by the Mediterranean Commission on Sustainable Development (MCSD) (UNEP/MAP, 2016). MAP is primarily financed by national governments and the EU. Its financial capacity for regional environmental governance remains limited, with available annual funds in the range of 5-10 million Euro (Humphrey and Lucas, 2015).

Bilateral public climate finance in the Mediterranean area includes loans by multilateral development banks, bilateral official development aid, and international climate funds projects (Midgley et al., 2018; Tagliapietra, 2018). Bilateral public and private financial resources invested in international climate finance in southern Mediterranean countries are two orders of magnitude greater than the existing multilateral regional governance programmes for the environment (EC, 2018; Midgley et al., 2018; Fosse et al., 2019). The Mediterranean Strategy for Sustainable Development (MSSD) is a tool for enhancing the governance of environmental issues, proposing the biannual reporting by the national parties of a set of quantitative indicators, including the commitments and obligations under the UNFCCC climate agreement, and other climate change mitigation and adaptation policy actions.

Existing legal and institutional structures can facilitate coordination and collaboration across scales (DeCaro et al., 2017). Legislative mechanisms, such as the rules governing water uses in time of drought, already exist in some Mediterranean countries, but they might not be suitable to cope with irreversible changes (e.g. the depletion of groundwater aquifers) or be flexible enough to respond to the needs of water users under a changing climate (Nanni, 2012). Although legislation can be recognized as a tool in support of adaptive water management, there is a need of better coordination among the various legal provisions that define institutional roles and set out the mechanisms for the management of water resources across different scales (regional/national/sub-national) and sectors (agriculture, industry, urban, energy).

[START FAQ CCP4.1 HERE]

FAQ CCP4.1: Is the Mediterranean Basin a "climate change hotspot"?

Is the Mediterranean "a geographical area characterized by high vulnerability and exposure to climate change"? Climate change projections for the Mediterranean Basin indicate with very high consistency that the region will experience higher temperatures, less rainfall during the coming decades and continued sea-level rise. Given that summers are already comparatively dry, these factors together will likely cause substantially drier and hotter conditions as well as coastal flooding, impacting people directly but also harming ecosystems on land and in the ocean.

For the Mediterranean Basin, climate models consistently project regional warming at rates about 20% above global means and reduced rainfall (-12% for global warming of 3°C). While it is not the region with the highest rate of expected warming on Earth, the Mediterranean Basin is considered particular in comparison to most other regions due to the high exposure and vulnerability of human societies and ecosystems to these changes: a "climate change hotspot".

Rising temperatures trigger large evaporation of water from all wet surfaces, notably the sea, lakes, rivers but also from soils. Along with decreasing rainfall, this evaporation leads to shrinking water resources on land, drier soils, reduced river flow and significantly longer and more intensive drought spells. Since the Mediterranean climate is already relatively dry and warm in the summer, any additional drought (and also heat) will affect plants, animals and people significantly, and ultimately entire societies and economies.

In general, increasing temperatures and more intensive heatwaves in the basin threaten human well-being, economic activities and also many ecosystems on land and in the ocean. Extreme rainfall events, which despite the lower total rainfall are expected to increase in intensity and frequency in some regions, generate significant risks for infrastructure and people through flash floods. Warming also affects the ocean and its ecosystems, jointly with acidification caused by atmospheric carbon dioxide. Finally, sea-level rise, currently accelerating as a consequence of global ice loss, threatens coastal ecosystems, historical sites and a growing human population.

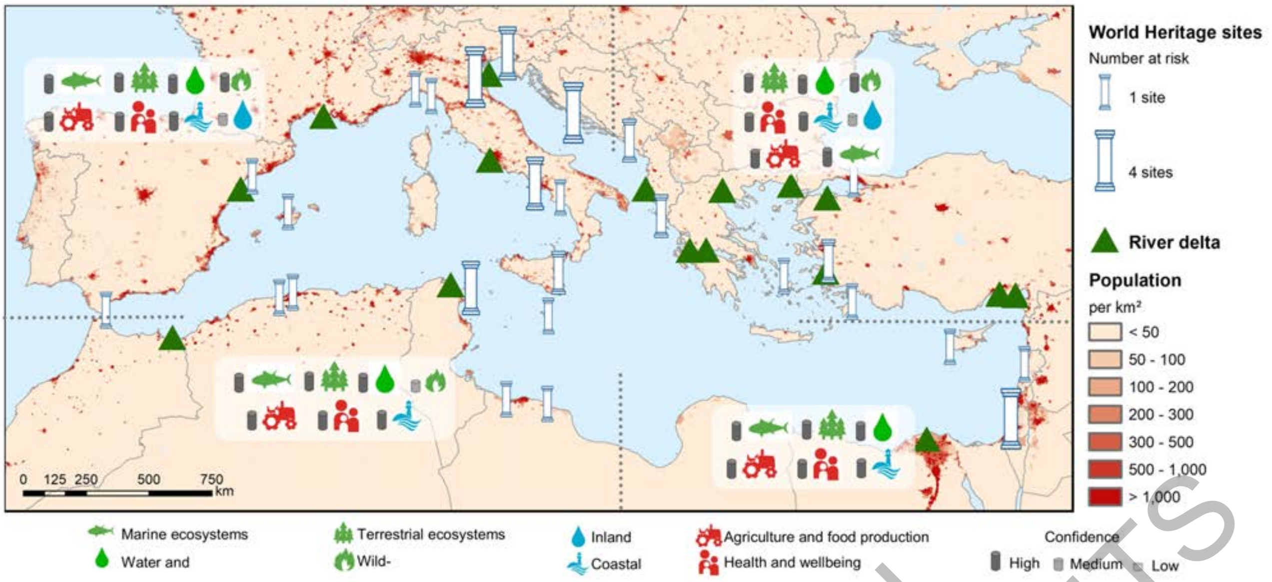


Figure FAQ CCP4.1.1: Key risks across the Mediterranean region by 2100. The symbols above the map highlight risks enhanced by climate change which apply to the entire region with *high confidence*. Other risks are localized in the map (for details, see CCP4).

Risks associated with projected climate change are particularly high for people and ecosystems in the Mediterranean Basin due to the unique combination of many factors, including:

i) a large and growing urban population exposed to heat waves, with limited access to air conditioning,
ii) a large and growing number of people living in settlements impacted by rising sea level,
iii) important and increasing water shortages, experienced by 180 million people today already,
iv) growing demand for water by agriculture for on irrigation,
v) high economic dependency on tourism, which is likely to suffer from increasing heat but also from the consequences of international emission reduction policies on aviation and cruise-ship travel,
vi) loss of ecosystems in the ocean, wetlands, rivers and also uplands, many of which are already endangered by unsustainable practices (e.g. overfishing, land use change).

[END FAQ CCP4.1 HERE]

[START FAQ CCP4.2 HERE]

FAQ CCP4.2: Can Mediterranean countries adapt to sea-level rise?

The rates of observed and projected sea-level rise in the Mediterranean are similar to the Northeast Atlantic, potentially reaching 1.1 m at the end of the present century. Erosion, flooding and the impacts of salinization are projected to be particularly severe due to the special conditions of the coastal zones in the region. Beyond a few tens of centimeters, adaptation to sea-level rise will require very large investments and may be impossible in some regions.

Sea level in the Mediterranean has been rising by only 1.4 mm yr^{-1} during the 20th century, more recently by 2.4±0.5mm yr^{-1} from 1993 to 2012, and it is bound to continue rising in the future. Future rates are projected to be similar to the global mean (within an uncertainty of 10-20 cm), potentially reaching 1.1 m or more around 2100 in the event of 3°C of global warming (Figure FAQ-CCP4.2; SMCCP4.4). Due to the ongoing ice loss in Greenland and Antarctica, this trend is expected to continue in coming centuries. Sea-level rise already impacts extreme coastal waters around the Mediterranean and it is projected to increase coastal flooding, erosion and salinization risks. These impacts would affect agriculture, fisheries and aquaculture, urban development, port operations, tourism, cultural sites, and many coastal ecosystems.

Most of the Mediterranean Sea is a micro-tidal environment, which means that the difference between regular high and mean water levels (astronomical tides) is very small. Storm surges and waves can produce coastal floods that persist for several hours, causing particularly large impacts on sandy coasts and eventually also on coastal infrastructure. Mediterranean coasts are also characterized by narrow sandy beaches that are highly valuable for coastal ecosystems and tourism. These beaches are projected to be increasingly affected by erosion and eventually disappear where sedimentary stocks are small.

Overall, Mediterranean low-lying areas of significant width occur along 37% of the coastline and currently host 42 million inhabitants. The coastal population growth projected until 2050 mostly occurs in southern Mediterranean countries, with Egypt, Libya, Morocco and Tunisia being the most exposed countries to future sea-level rise. The area at risk also hosts 49 cultural World Heritage Sites, including the city of Venice and the early Christian monuments of Ravenna. The Mediterranean also includes areas subjected to sinking of the land (subsidence), including the eastern Nile delta (Egypt) and the Thessaloniki flood plain (Greece), where local relative sea-level rise can exceed 1 cm yr^{-1} today.

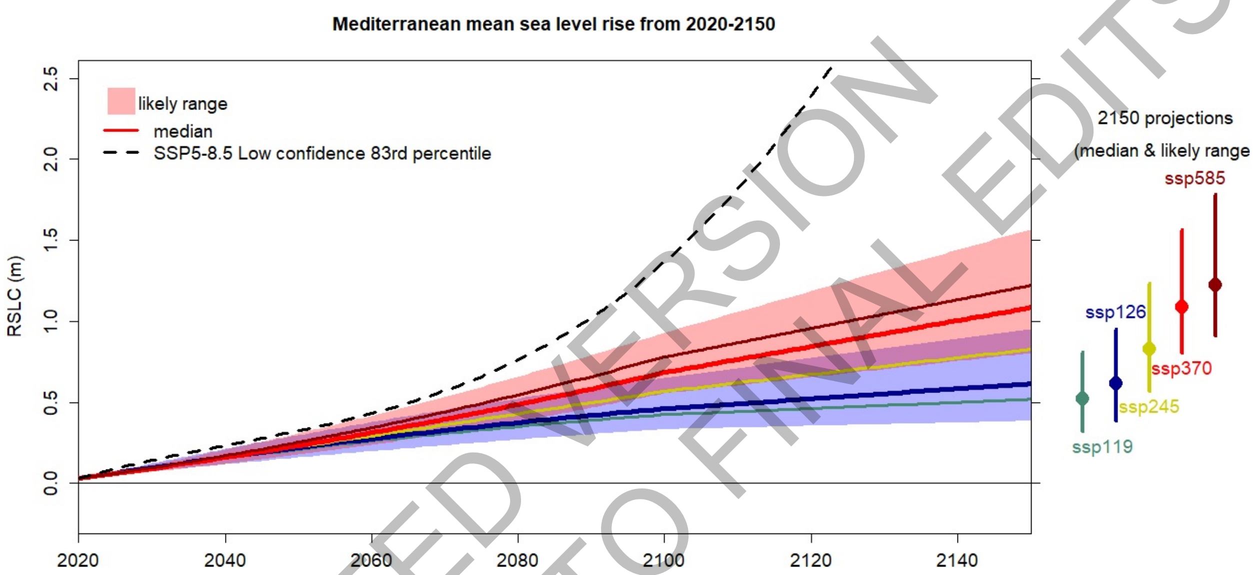


Figure FAQ CCP4.2.1: Mediterranean sea level projections. These projections translate the global estimates in WGI AR6 Chapter 9 to the Mediterranean basin. They assume that sea-level change in the Mediterranean continues to be forced by Atlantic sea-level change seen at the Gibraltar Strait (Section CCP4.1) and thus follow the global mean beyond 2100. Vertical ground motions induced by glacial isostatic adjustments are also included, but not those due to other natural or anthropogenic processes such as tectonics or groundwater extractions. Intra-basin sea-level changes are not included. Data available as supplementary material.

Adaptation to sea-level rise in the Mediterranean includes engineering or soft/ecosystem-based protection, accommodation and retreat or managed realignment. Despite various limitations, adaptation already happens today to some extent, as for example the coastal flood and erosion protections along the subsiding Nile delta coast. Only massive coastal protection and other sustainable development policies could reduce the growing number of people exposed to sea-level rise by 20%, it appears therefore likely that the number of people exposed could increase by up to 130% by 2100.

Without drastic mitigation of climate change, sea-level rise is projected to accelerate and will require additional coastal engineering protection projects (e.g. dikes or groins). Despite their efficiency for the few next decades, these engineering options have also adverse impacts for coastal ecosystems and may not ensure that the recreative value of Mediterranean coasts can be sustained (see Chapter 13 Box on Venice on the movable barriers protecting the Venice Lagoon). Among nature-based solutions, there are immediate benefits of restoring dunes and coastal wetlands to restore a buffer zone between coastal infrastructure and the sea and therefore reduce coastal risks (Cross-Chapter Box SLR in Chapter 3). Yet, this kind of protection is not feasible everywhere, facing its limits particularly in urbanized areas. The limits for adaptation in the Mediterranean to further acceleration of sea-level rise have stimulated ideas of large-scale geoengineering projects such as surface height control dams at Gibraltar. However, such projects come with unknown risks for humans and ecosystems.

[END FAQ CCP4.2 HERE]

[START FAQ CCP4.3 HERE]

FAQ CCP4.3: What is the link between climate change and human migration in the Mediterranean Basin?

Climate change already influences conflict and migrations occurring within countries or regions. However, climate is only one of the multiple factors affecting conflict and migration decisions across countries and regions. It is currently not possible to attribute particular conflicts or migrations to climate change and also in the future migration will most likely depend on economic, social and governance context.

The Mediterranean Sea is the world's most dangerous place for migrants, with more than 20,000 deaths reported since 2014. Although empirical evidence indicates that migration related to climate impacts is mostly internal to national borders, climate change is likely to contribute to migration in the Mediterranean Basin as one out of several factors. Climate impacts contribute to migration flows particularly by affecting the economic and political drivers of migration.

Many migrants attempting to cross the Mediterranean to Europe originate from sub-Saharan Africa, a region heavily affected by climate change. In West Africa for example, migration decisions are heavily influenced by perceptions of climate change and of its economic impact on resources and income. However, projections are uncertain, because climate impacts in Africa might both increase human suffering and thus enhance mobility, but they could also limit mobility of people through lack of financial resources.

The impacts of climate change on conflicts and security are increasingly documented, especially in Africa. Climate impacts may not in itself have caused social and political unrest but can contribute to them. The conflict in Syria has occurred after the drought that marred the country in the years before, but there is no evidence for direct causal linkage. There is however significant agreement that food insecurity and land degradation, which can be induced by climate change, are major drivers of political upheavals and instability in northern and sub-Saharan Africa.

[END FAQ CCP4.3 HERE]

References

Abd El-Azeem, S. A. E.-M. M., 2020: Impacts of climate change on microbial activity in agricultural Egyptian soils. In: *Climate Change Impacts on Agriculture and Food Security in Egypt: Land and Water Resources—Smart Farming—Livestock, Fishery, and Aquaculture* [Ewis Omran, E.-S. and A. M. Negm (eds.)]. Springer International Publishing, Cham, pp. 97-114. ISBN 978-3-030-41629-4.

AbdAllah, A. M., K. O. Burkey and A. M. Mashaheet, 2018: Reduction of plant water consumption through anti-transpirants foliar application in tomato plants (*Solanum lycopersicum* L.). *Scientia Horticulturae*, **235**, 373-381, doi:10.1016/j.scienta.2018.03.005.

Abufayed, A. A. and M. K. A. El-Ghuel, 2001: Desalination process applications in Libya. *Desalination*, **138**(1), 47-53, doi:10.1016/S0011-9164(01)00243-0.

Abulafia, D., 2011: *The Great Sea: A Human History of the Mediterranean*. Oxford University Press, Oxford, United Kingdom, 816 pp. ISBN 978-0-713-99934-1.

Achebak, H., D. Devolder and J. Ballester, 2018: Heat-related mortality trends under recent climate warming in Spain: A 36-year observational study. *PLoS Medicine*, **15**(7), e1002617, doi:10.1371/journal.pmed.1002617.

Adloff, F. et al., 2015: Mediterranean Sea response to climate change in an ensemble of twenty first century scenarios. *Climate Dynamics*, **45**(9-10), 2775-2802, doi:10.1007/s00382-015-2507-3.

Ager, A. A. et al., 2014: Wildfire risk estimation in the Mediterranean area. *Environmetrics*, **25**(6), 384-396, doi:10.1002/env.2269.

Aguilera, E. et al., 2020: Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. *Agricultural Systems*, **181**, 102809, doi:10.1016/j.agsy.2020.102809.

Aguilera, E., L. Lassaletta, A. Gattinger and B. S. Gimeno, 2013a: Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment*, **168**, 25-36, doi:10.1016/j.agee.2013.02.003.

Aguilera, E. et al., 2013b: The potential of organic fertilizers and water management to reduce N_2O emissions in Mediterranean climate cropping systems. A review. *Agriculture, Ecosystems & Environment*, **164**, 32-52, doi:10.1016/j.agee.2012.09.006.

Aguilera, R., R. Marce and S. Sabater, 2015: Detection and attribution of global change effects on river nutrient dynamics in a large Mediterranean basin. *Biogeosciences*, **12**(13), 4085-4098, doi:10.5194/bg-12-4085-2015.

Ahmadalipour, A. and H. Moradkhani, 2018: Escalating heat-stress mortality risk due to global warming in the Middle East and North Africa (MENA). *Environment International*, **117**, 215-225, doi:10.1016/j.envint.2018.05.014.

Albouy, C. et al., 2013: Projected climate change and the changing biogeography of coastal Mediterranean fishes. *Journal of Biogeography*, **40**(3), 534-547, doi:10.1111/jbi.12013.

Alcidi, C., N. Laurentsyeva and A. W. Ahmad Yar, 2019: *Legal Migration Pathways Across The Mediterranean: Achievements, Obstacles And The Way Forward*. EMNES Policy Paper Nº 009, Euro-Mediterranean Network for Economic Studies (EMNES), 38 pp. Available at: https://euromed-economists.org/download/legal-migration-pathways-across-the-mediterranean-achievements-obstacles-and-the-way-forward/ (accessed 25/10/2020).

Aldea, J. et al., 2017: Thinning enhances the species-specific radial increment response to drought in Mediterranean pine-oak stands. *Agricultural and Forest Meteorology*, **237-238**, 371-383, doi:10.1016/j.agrformet.2017.02.009.

Ali, E. M. and I. A. El-Magd, 2016: Impact of human interventions and coastal processes along the Nile Delta coast, Egypt during the past twenty-five years. *The Egyptian Journal of Aquatic Research*, **42**(1), 1-10, doi:10.1016/j.ejar.2016.01.002.

Almagro, M. et al., 2016: Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems. *Mitigation and Adaptation Strategies for Global Change*, **21**(7), 1029-1043, doi:10.1007/s11027-013-9535-2.

Andrew, J. T. and E. Sauquet, 2017: Climate change impacts and water management adaptation in two Mediterranean-climate watersheds: Learning from the Durance and Sacramento rivers. *Water*, **9**(2), 126, doi:10.3390/w9020126.

Androulidakis, Y. S. et al., 2015: Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions. *Dynamics of Atmospheres and Oceans*, **71**, 56-82, doi:10.1016/j.dynatmoce.2015.06.001.

Antonelli, M., R. Roson and M. Sartori, 2012: Systemic input-output computation of green and blue virtual water 'flows' with an illustration for the Mediterranean region. *Water Resources Management*, **26**(14), 4133-4146, doi:10.1007/s11269-012-0135-9.

Antonioli, F. et al., 2017: Sea-level rise and potential drowning of the Italian coastal plains: Flooding risk scenarios for 2100. *Quaternary Science Reviews*, **158**, 29-43, doi:10.1016/j.quascirev.2016.12.021.

Anzidei, M. et al., 2017: Flooding scenarios due to land subsidence and sea-level rise: a case study for Lipari Island (Italy). *Terra Nova*, **29**(1), 44-51, doi:10.1111/ter.12246.

Aragonés, L. et al., 2015: Beach nourishment impact on *Posidonia oceanica*: Case study of Poniente Beach (Benidorm, Spain). *Ocean Engineering*, **107**, 1-12, doi:10.1016/j.oceaneng.2015.07.005.

Arenas-Castro, S., J. F. Gonçalves, M. Moreno and R. Villar, 2020: Projected climate changes are expected to decrease the suitability and production of olive varieties in southern Spain. *Science of The Total Environment*, **709**, 136161, doi:10.1016/j.scitotenv.2019.136161.

Ash, K. and N. Obradovich, 2020: Climatic stress, internal migration, and Syrian civil war onset. *Journal of Conflict Resolution*, **46**, 3-31.

Aspe, C., A. Gilles and M. Jacqué, 2016: Irrigation canals as tools for climate change adaptation and fish biodiversity management in Southern France. *Regional Environmental Change*, **16**(7), 1975-1984, doi:10.1007/s10113-014-0695-8.
Asseng, S. et al., 2018: Can Egypt become self-sufficient in wheat? *Environmental Research Letters*, **13**(9), 094012, doi:10.1088/1748-9326/aada50.
Baahmed, D., L. Oudin and M. Errih, 2015: Current runoff variations in the Macta catchment (Algeria): is climate the sole factor? *Hydrological Sciences Journal*, **60**(7-8), 1331-1339, doi:10.1080/02626667.2014.975708.
Baena-Ruiz, L. et al., 2020: Summarizing the impacts of future potential global change scenarios on seawater intrusion at the aquifer scale. *Environmental Earth Sciences*, **79**(5), 99, doi:10.1007/s12665-020-8847-2.
Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4**(10), 924-929, doi:10.1038/nclimate2353.
Balouin, Y., F. Longueville and Y. Colombet, 2015: Video monitoring of soft coastal defenses at the Lido of Sete, France. In: *3ème Conférence Méditerranéenne Côtière et Maritime*, 25 - 27 November 2015, Ferrare, Italy, doi:10.5150/cmcm.2015.038.
Balzan, M. V. et al., 2020: Ecosystems. In: *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 323-468.
Barba-Suñol, O. et al. (eds.), 2018: Reuse of treated waste water in the Mediterranean and impacts on territories. 8th World Water Forum, March 2018, Brasilia, Brasil, 20 pp.
Barredo, J. I., G. Caudullo and A. Dosio, 2016: Mediterranean habitat loss under future climate conditions: Assessing impacts on the Natura 2000 protected area network. *Applied Geography*, **75**, 83-92, doi:10.1016/j.apgeog.2016.08.003.
Barrios, S., L. Bertinelli and E. Strobl, 2006: Climatic change and rural–urban migration: The case of sub-Saharan Africa. *Journal of Urban Economics*, **60**(3), 357-371, doi:10.1016/j.jue.2006.04.005.
Bartsch, S. et al., 2020: Impact of precipitation, air temperature and abiotic emissions on gross primary production in Mediterranean ecosystems in Europe. *European Journal of Forest Research*, **139**(1), 111-126, doi:10.1007/s10342-019-01246-7.
Bastianin, A., M. Galeotti and M. Manera, 2017: Oil supply shocks and economic growth in the Mediterranean. *Energy Policy*, **110**, 167-175, doi:10.1016/j.enpol.2017.08.004.
Baylis, P., 2015: *Temperature and Temperament: Evidence from a Billion Tweets*. Energy Institute at Haas working papers, Energy Institute At Haas, 59 pp. Available at: https://pdfs.semanticscholar.org/68e0/6ebd51a8631cb1014c6d4f256af89951c612.pdf (accessed 08/11/2020).
Baylis, P., 2020: Temperature and temperament: Evidence from Twitter. *Journal of Public Economics*, **184**, 104161, doi:10.1016/j.jpubeco.2020.104161.
Becchi, C., I. Ortolani, A. Muir and S. Cannicci, 2014: The effect of breakwaters on the structure of marine soft-bottom assemblages: A case study from a North-Western Mediterranean basin. *Marine Pollution Bulletin*, **87**(1), 131-139, doi:10.1016/j.marpolbul.2014.08.002.
Ben-Asher, J., T. Yano, M. Aydın and A. Garcia y Garcia, 2019: Enhanced growth rate and reduced water demand of crop due to climate change in the Eastern Mediterranean region. In: *Climate Change Impacts on Basin Agro-ecosystems* [Watanabe, T., S. Kapur, M. Aydın, R. Kanber and E. Akça (eds.)]. Springer, Cham, Switzerland, pp. 269-293. ISBN 9783030010362.
Ben Rais Lasram, F. et al., 2010: The Mediterranean Sea as a 'cul-de-sac' for endemic fishes facing climate change. *Global Change Biology*, **16**(12), 3233-3245, doi:10.1111/j.1365-2486.2010.02224.x.
Ben Youssef, A., M. Arouri and C. V. Nguyen, 2017: *Is internal migration a way to cope with climate change? Evidence from Egypt*. Working Papers 1099, Economic Research Forum. Available at: https://ideas.repec.org/p/erg/wpaper/1099.html.
Benedetti, F., F. Guilhaumon, F. Adloff and S.-D. Ayata, 2018: Investigating uncertainties in zooplankton composition shifts under climate change scenarios in the Mediterranean Sea. *Ecography*, **41**(2), 345-360, doi:10.1111/ecog.02434.
Benlhabib, O. et al., 2014: How can we improve Mediterranean cropping systems? *Journal of Agronomy and Crop Science*, **200**(5), 325-332, doi:10.1111/jac.12066.
Bhakta, I., S. Phadikar and K. Majumder, 2019: State-of-the-art technologies in precision agriculture: a systematic review. *Journal of the Science of Food and Agriculture*, **99**(11), 4878-4888, doi:10.1002/jsfa.9693.
Billen, G. et al., 2019: Opening to distant markets or local reconnection of agro-food systems? Environmental consequences at regional and global scales. In: *Agroecosystem Diversity* [Lemaire, G., P. C. D. F. Carvalho, S. Kronberg and S. Recous (eds.)]. Academic Press, pp. 391-413. ISBN 9780128110508.
Billen, G., J. Le Noë and J. Garnier, 2018: Two contrasted future scenarios for the French agro-food system. *Science of The Total Environment*, **637-638**, 695-705, doi:10.1016/j.scitotenv.2018.05.043.
Bird, D. N. et al., 2016: Modelling climate change impacts on and adaptation strategies for agriculture in Sardinia and Tunisia using AquaCrop and value-at-risk. *Science of The Total Environment*, **543**, 1019-1027, doi:10.1016/j.scitotenv.2015.07.035.
Bitan, M. and D. Zviely, 2018: Lost value assessment of bathing beaches due to sea level rise: a case study of the Mediterranean coast of Israel. *Journal of Coastal Conservation*, **23**(4), 773-783, doi:10.1007/s11852-018-0660-7.

Bjørkan, M. et al., 2020: When Fishermen Take Charge: The Development of a Management Plan for the Red Shrimp Fishery in Mediterranean Sea (NE Spain). In: *Collaborative Research in Fisheries: Co-creating Knowledge for Fisheries Governance in Europe* [Holm, P., M. Hadjimichael, S. Linke and S. Mackinson (eds.)]. Springer, Cham, Switzerland, pp. 159-178. ISBN 978-3-030-26784-1.

Blas, A., A. Garrido and B. Willaarts, 2018: Food consumption and waste in Spanish households: Water implications within and beyond national borders. *Ecological Indicators*, **89**, 290-300, doi:10.1016/j.ecolind.2018.01.057.

Blas, A., A. Garrido and B. A. Willaarts, 2016: Evaluating the water footprint of the Mediterranean and American diets. *Water*, **8**(10), 14, doi:10.3390/w8100448.

Blöschl, G. et al., 2019: Changing climate both increases and decreases European river floods. *Nature*, **573**(7772), 108-111, doi:10.1038/s41586-019-1495-6.

Boari, F., A. Donadio, M. I. Schiattone and V. Cantore, 2015: Particle film technology: A supplemental tool to save water. *Agricultural Water Management*, **147**, 154-162, doi:10.1016/j.agwat.2014.07.014.

Boavida-Portugal, J. et al., 2018: Climate change impacts on the distribution of coastal lobsters. *Marine Biology*, **165**(12), 186, doi:10.1007/s00227-018-3441-9.

Bodoque, J. M. et al., 2016: Improvement of resilience of urban areas by integrating social perception in flash-flood risk management. *Journal of Hydrology*, **541**, 665-676, doi:10.1016/j.jhydrol.2016.02.005.

Bonaduce, A. et al., 2016: Sea-level variability in the Mediterranean Sea from altimetry and tide gauges. *Climate Dynamics*, **47**(9), 2851-2866, doi:10.1007/s00382-016-3001-2.

Bonanos, A. M., M. C. Georgiou, E. Guillen and C. N. Papanicolas, 2017: CSP+D: The case study at the PROTEAS facility. *AIP Conference Proceedings*, **1850**(1), 170001, doi:10.1063/1.4984564.

Bonazza, A. et al., 2009: Climate change impact: Mapping thermal stress on Carrara marble in Europe. *Science of The Total Environment*, **407**(15), 4506-4512, doi:10.1016/j.scitotenv.2009.04.008.

Bonnici, L. et al., 2018: Of rocks and hard places: Comparing biotic assemblages on concrete jetties versus natural rock along a microtidal Mediterranean shore. *Journal of Coastal Research*, **34**(5), 1136-1148, 1113.

Bouregaa, T., 2019: Impact of climate change on yield and water requirement of rainfed crops in the Setif region. *Management of Environmental Quality: An International Journal*, **30**(4), 851-863, doi:10.1108/MEQ-06-2018-0110.

Bouriaud, L. et al., 2015: Institutional factors and opportunities for adapting European forest management to climate change. *Regional Environmental Change*, **15**(8), 1595-1609, doi:10.1007/s10113-015-0852-8.

Bouriaud, L. et al., 2013: Governance of private forests in Eastern and Central Europe: An analysis of forest harvesting and management rights. *Annals of Forest Research*, **56**(1), doi:10.15287/afr.2013.54.

Bouvier, C., Y. Balouin and B. Castelle, 2017: Video monitoring of sandbar-shoreline response to an offshore submerged structure at a microtidal beach. *Geomorphology*, **295**, 297-305, doi:10.1016/j.geomorph.2017.07.017.

Braca, G. et al., 2019: Evaluation of national and regional groundwater resources under climate change scenarios using a GIS-based water budget procedure. *Rendiconti Lincei. Scienze Fisiche e Naturali*, **30**(1), 109-123, doi:10.1007/s12210-018-00757-6.

Braki, E. and C. Anagnostopoulou, 2019: The impacts of climate change on tourism in the mediterranean region. In: *XXXIIème Colloque International de l'AIC - Climatic Change, Variability and Climatic Risks*, 29 May - 1 June 2019, Thessaloniki, Greece, pp. 537-542.

Bregaglio, S. et al., 2017: Identifying trends and associated uncertainties in potential rice production under climate change in Mediterranean areas. *Agricultural and Forest Meteorology*, **237-238**, 219-232, doi:10.1016/j.agrformet.2017.02.015.

Briche, E., N. Martin and S. Dahech, 2016: Observation systems and urban climate modelling. In: *The Mediterranean Region under Climate Change: A Scientific Update* [Thiébault, S., J.-P. Moatti, V. Ducrocq, E. Gaume, F. Dulac, E. Hamonou, Y.-J. Shin, J. Guiot, W. Cramer, G. Boulet, J.-F. Guégan, R. Barouki, I. Annesi-Maesano, P. Marty, E. Torquebiau, J. F. Soussana, Y. Aumeeruddy-Thomas, J.-L. Chotte and D. Lacroix (eds.)]. IRD Éditions, Marseille, France, pp. 445-453. ISBN 9782709922203.

Brilli, L. et al., 2019: Carbon sequestration capacity and productivity responses of Mediterranean olive groves under future climates and management options. *Mitigation and Adaptation Strategies for Global Change*, **24**(3), 467-491, doi:10.1007/s11027-018-9824-x.

Brooke, S. et al., 2013: Temperature tolerance of the deep-sea coral *Lophelia pertusa* from the southeastern United States. *Deep Sea Research Part II: Topical Studies in Oceanography*, **92**, 240-248, doi:10.1016/j.dsr2.2012.12.001.

Brotons, L. et al., 2013: How fire history, fire suppression practices and climate change affect wildfire regimes in Mediterranean landscapes. *PLoS ONE*, **8**(5), e62392, doi:10.1371/journal.pone.0062392.

Brotons, L. and A. Duane, 2019: Correspondence: Uncertainty in climate-vegetation feedbacks on fire regimes challenges reliable long-term projections of burnt area from correlative models. *Fire*, **2**(1), 8.

Brouziyne, Y. et al., 2018: Modeling sustainable adaptation strategies toward a climate-smart agriculture in a Mediterranean watershed under projected climate change scenarios. *Agricultural Systems*, **162**, 154-163, doi:10.1016/j.agsy.2018.01.024.

Brown, S., R. J. Nicholls, J. A. Lowe and J. Hinkel, 2016: Spatial variations of sea-level rise and impacts: An application of DIVA. *Climatic Change*, **134**(3), 403-416, doi:10.1007/s10584-013-0925-y.

Brzoska, M. and C. Fröhlich, 2016: Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migration and Development*, **5**(2), 190-210, doi:10.1080/21632324.2015.1022973.

Bucak, T. et al., 2017: Future water availability in the largest freshwater Mediterranean lake is at great risk as evidenced from simulations with the SWAT model. *Science of The Total Environment*, **581-582**, 413-425, doi:10.1016/j.scitotenv.2016.12.149.

Burak, S. and J. Margat, 2016: Water management in the Mediterranean region: Concepts and policies. *Water Resources Management*, **30**(15), 5779-5797, doi:10.1007/s11269-016-1389-4.

Burke, M. et al., 2014: Incorporating climate uncertainty into estimates of climate change Impacts. *The Review of Economics and Statistics*, **97**(2), 461-471, doi:10.1162/REST_a_00478.

Burke, M. et al., 2018: Higher temperatures increase suicide rates in the United States and Mexico. *Nature Climate Change*, **8**(8), 723-729, doi:10.1038/s41558-018-0222-x.

Burke, M., S. M. Hsiang and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**(7577), 235-239, doi:10.1038/nature15725.

Burrows, M. T. et al., 2014: Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**(7493), 492-495, doi:10.1038/nature12976.

Cai, R., S. Feng, M. Oppenheimer and M. Pytlikova, 2016: Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management*, **79**, 135-151, doi:10.1016/j.jeem.2016.06.005.

Calafat, F. M. et al., 2014: The ability of a barotropic model to simulate sea level extremes of meteorological origin in the Mediterranean Sea, including those caused by explosive cyclones. *Journal of Geophysical Research-Oceans*, **119**(11), 7840-7853, doi:10.1002/2014jc010360.

Caloiero, T., S. Veltri, P. Caloiero and F. Frustaci, 2018: Drought analysis in Europe and in the Mediterranean Basin using the Standardized Precipitation Index. *Water*, **10**(8), doi:10.3390/w10081043.

Calvache, M. L., C. Duque and D. Pulido-Velazquez, 2020: Summary Editorial: Impacts of global change on groundwater in Western Mediterranean countries. *Environmental Earth Sciences*, **79**(24), 531, doi:10.1007/s12665-020-09261-3.

Calvo, E. et al., 2011: Effects of climate change on Mediterranean marine ecosystems: the case of the Catalan Sea. *Climate Research*, **50**(1), 1-29, doi:10.3354/cr01040.

Calvo, L., V. Hernández, L. Valbuena and A. Taboada, 2016: Provenance and seed mass determine seed tolerance to high temperatures associated to forest fires in *Pinus pinaster*. *Annals of Forest Science*, **73**(2), 381-391, doi:10.1007/s13595-015-0527-0.

Cammarano, D. et al., 2019: The impact of climate change on barley yield in the Mediterranean basin. *European Journal of Agronomy*, **106**, 1-11, doi:10.1016/j.eja.2019.03.002.

Cantore, V. et al., 2016: Combined effect of deficit irrigation and strobilurin application on yield, fruit quality and water use efficiency of "cherry" tomato (*Solanum lycopersicum* L.). *Agricultural Water Management*, **167**, 53-61, doi:10.1016/j.agwat.2015.12.024.

Caon, L., V. R. Vallejo, C. J. Ritsema and V. Geissen, 2014: Effects of wildfire on soil nutrients in Mediterranean ecosystems. *Earth-Science Reviews*, **139**, 47-58, doi:10.1016/j.earscirev.2014.09.001.

Cardell, M. F., A. Amengual and R. Romero, 2019: Future effects of climate change on the suitability of wine grape production across Europe. *Regional Environmental Change*, **19**(8), 2299-2310, doi:10.1007/s10113-019-01502-x.

Carleton, T. A. and S. M. Hsiang, 2016: Social and economic impacts of climate. *Science*, **353**(6304), aad9837, doi:10.1126/science.aad9837.

Carosi, A., L. Ghetti and M. Lorenzoni, 2021: The role of climate changes in the spread of freshwater fishes: Implications for alien cool and warm-water species in a Mediterranean Basin. *Water*, **13**(3), 347.

Carranza, M. L. et al., 2020: Urban expansion depletes cultural ecosystem services: an insight into a Mediterranean coastline. *Rendiconti Lincei. Scienze Fisiche e Naturali*, **31**(1), 103-111, doi:10.1007/s12210-019-00866-w.

Cattaneo, C. and G. Peri, 2016: The migration response to increasing temperatures. *Journal of Development Economics*, **122**, 127-146, doi:10.1016/j.jdeveco.2016.05.004.

Cavicchia, L., H. von Storch and S. Gualdi, 2014: Mediterranean tropical-like cyclones in present and future climate. *Journal of Climate*, **27**(19), 7493-7501, doi:10.1175/jcli-d-14-00339.1.

Cazenave, A. et al., 2018: Global sea-level budget 1993-present. *Earth System Science Data*, **10**(3), 1551-1590, doi:10.5194/essd-10-1551-2018.

Cellura, M., F. Guarino, S. Longo and G. Tumminia, 2018: Climate change and the building sector: Modelling and energy implications to an office building in southern Europe. *Energy for Sustainable Development*, **45**, 46-65, doi:10.1016/j.esd.2018.05.001.

Charef, M. and K. Doraï, 2016: Human migration and climate change in the Mediterranean region. In: *The Mediterranean Region under Climate Change: A Scientific Update* [Thiébault, S., J.-P. Moatti, V. Ducrocq, E. Gaume, F. Dulac, E. Hamonou, Y.-J. Shin, J. Guiot, W. Cramer, G. Boulet, J.-F. Guégan, R. Barouki, I. Annesi-Maesano, P. Marty, E. Torquebiau, J. F. Soussana, Y. Aumeeruddy-Thomas, J.-L. Chotte and D. Lacroix (eds.)]. IRD Éditions, Marseille, France, pp. 439-444. ISBN 9782709922203.

Cherfouh, R., Y. Lucas, A. Derridj and P. Merdy, 2018: Long-term, low technicality sewage sludge amendment and irrigation with treated wastewater under Mediterranean climate: impact on agronomical soil quality. *Environmental Science and Pollution Research*, **25**(35), 35571-35581, doi:10.1007/s11356-018-3463-3.

Cherif, S. et al., 2020: Drivers of change. In: *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 59-180.
Cheung, W. W. L. et al., 2016: Structural uncertainty in projecting global fisheries catches under climate change. *Ecological Modelling*, **325**, 57-66, doi:10.1016/j.ecolmodel.2015.12.018.
Chourghal, N., J. P. Lhomme, F. Huard and A. Aidaoui, 2016: Climate change in Algeria and its impact on durum wheat. *Regional Environmental Change*, **16**(6), 1623-1634, doi:10.1007/s10113-015-0889-8.
Cid, A. et al., 2016: Long-term changes in the frequency, intensity and duration of extreme storm surge events in southern Europe. *Climate Dynamics*, **46**(5), 1503-1516, doi:10.1007/s00382-015-2659-1.
Cid, N. et al., 2017: High variability is a defining component of Mediterranean-climate rivers and their biota. *Water*, **9**(1), doi:10.3390/w9010052.
Ciro Aucelli, P. P. et al., 2017: Coastal inundation risk assessment due to subsidence and sea level rise in a Mediterranean alluvial plain (Volturno coastal plain – southern Italy). *Estuarine, Coastal and Shelf Science*, **198**, 597-609, doi:10.1016/j.ecss.2016.06.017.
Clark, P. U. et al., 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, **6**(4), 360-369, doi:10.1038/nclimate2923.
CMI and EC, 2019: *"Clean Energy for all Europeans" Package: Implications and Opportunities for the Mediterranean. Briefing paper*. Center for Mediterranean Integration (CMI) and European Commission (EC), 63 pp. Available at: https://www.cmimarseille.org/knowledge-library/briefing-paper-eu-clean-energy-all-europeans-package-use-southern-and-eastern (accessed 03/11/2020).
CMI and EC, 2020: *CMI Mediterranean Forum on Energy and Climate Change Insights*. Center for Mediterranean Integration (CMI) and European Commission (EC), 6 pp. Available at: https://www.cmimarseille.org/knowledge-library/cmi-mediterranean-forum-energy-and-climate-change-insights (accessed 03/11/2020).
Cooper, J. A. G., M. C. O'Connor and S. McIvor, 2016: Coastal defences versus coastal ecosystems: A regional appraisal. *Marine Policy*, **111**, 102332, doi:10.1016/j.marpol.2016.02.021.
Coppola, E. et al., 2021: Assessment of the European Climate Projections as Simulated by the Large EURO-CORDEX Regional and Global Climate Model Ensemble. *Journal of Geophysical Research: Atmospheres*, **126**(4), e2019JD032356, doi:10.1029/2019JD032356.
Coronese, M. et al., 2019: Evidence for sharp increase in the economic damages of extreme natural disasters. *Proceedings of the National Academy of Sciences*, **116**(43), 21450, doi:10.1073/pnas.1907826116.
Corrales, X. et al., 2018: Future scenarios of marine resources and ecosystem conditions in the Eastern Mediterranean under the impacts of fishing, alien species and sea warming. *Scientific Reports*, **8**(1), 14284, doi:10.1038/s41598-018-32666-x.
Corrales, X. et al., 2017: Hindcasting the dynamics of an Eastern Mediterranean marine ecosystem under the impacts of multiple stressors. *Marine Ecology Progress Series*, **580**, 17-36, doi:10.3354/meps12271.
Ćosić, M. et al., 2015: Effect of irrigation regime and application of kaolin on yield, quality and water use efficiency of sweet pepper. *Agricultural Water Management*, **159**, 139-147, doi:10.1016/j.agwat.2015.05.014.
Costa-Saura, J. M., A. Trabucco, D. Spano and S. Mereu, 2017: Environmental filtering drives community specific leaf area in Spanish forests and predicts relevant changes under future climatic conditions. *Forest Ecology and Management*, **405**, 1-8, doi:10.1016/j.foreco.2017.09.023.
Cramer, W. et al., 2018: Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, **8**(11), 972-980, doi:10.1038/s41558-018-0299-2.
Dakhlaoui, H., J. Seibert and K. Hakala, 2020: Sensitivity of discharge projections to potential evapotranspiration estimation in Northern Tunisia. *Regional Environmental Change*, **20**(2), 34, doi:10.1007/s10113-020-01615-8.
Danovaro, R. et al., 2018: Limited impact of beach nourishment on macrofaunal recruitment/settlement in a site of community interest in coastal area of the Adriatic Sea (Mediterranean Sea). *Marine Pollution Bulletin*, **128**, 259-266, doi:10.1016/j.marpolbul.2018.01.033.
Darmaraki, S., S. Somot, F. Sevault and P. Nabat, 2019a: Past variability of Mediterranean sea marine heatwaves. *Geophysical Research Letters*, **46**, 9813– 9823, doi:10.1029/2019GL082933.
Darmaraki, S. et al., 2019b: Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics*, **53**(3), 1371-1392, doi:10.1007/s00382-019-04661-z.
De Giglio, O. et al., 2018: The aquifer recharge: an overview of the legislative and planning aspect. *Annali di igiene: medicina preventiva e di comunità*, **30**(1), 34-43, doi:10.7416/ai.2018.2193.
de Rigo, D. et al., 2017: *Forest fire danger extremes in Europe under climate change: variability and uncertainty. PESETA III project - Climate Impacts and Adaptation in Europe, focusing on Extremes, Adaptation and the 2030s. Task 11 - Forest fires. Final report*. JRC Technical Reports, Publications Office of the European Union, Luxembourg, 71 pp.
DeCaro, D. A. et al., 2017: Legal and institutional foundations of adaptive environmental governance. *Ecology and Society*, **22**(1), doi:10.5751/ES-09036-220132.
del Río, M. et al., 2017: A review of thinning effects on Scots pine stands. From growth and yield to new challenges under global change. *Forest Systems*, **26**(2), 19, doi:10.5424/fs/2017262-11325.
Dell, M., B. F. Jones and B. A. Olken, 2012: Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, **4**(3), 66-95, doi:10.1257/mac.4.3.66.

Dellink, R., E. Lanzi and J. Chateau, 2019: The sectoral and regional economic consequences of climate change to 2060. *Environmental and Resource Economics*, **72**(2), 309-363, doi:10.1007/s10640-017-0197-5.
Denton, F. et al., 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131. ISBN 9781107058071.
Dettori, M., C. Cesaraccio and P. Duce, 2017: Simulation of climate change impacts on production and phenology of durum wheat in Mediterranean environments using CERES-Wheat model. *Field Crops Research*, **206**, 43-53, doi:10.1016/j.fcr.2017.02.013.
Dhehibi, B., A. Frija, R. Telleria and A. A. Aw-Hassan, 2015: The effect of trade liberalization on the sustainability of agricultural sectors in Egypt and Tunisia: A new framework based on TFP growth structure. In: *Building Sustainable Agriculture for Food Security in the Euro-Mediterranean Area: Challenges and Policy Options* [Paciello, M. C. (ed.)]. Edizioni Nuova Cultura, Rome, Italy, pp. 179-205. ISBN 9788868125080.
Di Lena, B., O. Silvestroni, V. Lanari and A. Palliotti, 2018: Climate change effects on cv. Montepulciano in some wine-growing areas of the Abruzzi region (Italy). *Theoretical and Applied Climatology*, doi:10.1007/s00704-018-2545-y.
Ding, H., A. Chiabai, S. Silvestri and P. A. L. D. Nunes, 2016: Valuing climate change impacts on European forest ecosystems. *Ecosystem Services*, **18**, 141-153, doi:10.1016/j.ecoser.2016.02.039.
Ding, Q., X. Chen, R. Hilborn and Y. Chen, 2017: Vulnerability to impacts of climate change on marine fisheries and food security. *Marine Policy*, **83**, 55-61, doi:10.1016/j.marpol.2017.05.011.
Dixit, P. N., R. Telleria, A. N. Al Khatib and S. F. Allouzi, 2018: Decadal analysis of impact of future climate on wheat production in dry Mediterranean environment: A case of Jordan. *Science of The Total Environment*, **610-611**, 219-233, doi:10.1016/j.scitotenv.2017.07.270.
Djuma, H. et al., 2017: The impact of a check dam on groundwater recharge and sedimentation in an ephemeral stream. *Water*, **9**(10), doi:10.3390/w9100813.
Doblas-Miranda, E. et al., 2017: A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: Beyond drought effects. *Global and Planetary Change*, **148**, 42-54, doi:10.1016/j.gloplacha.2016.11.012.
Dogru, T., U. Bulut and E. S. Turk, 2016: Efficacy of gain index in predicting the economic impacts of climate change to tourism receipts in the Mediterranean Basin. In: *2013 TTRA, Travel and Tourism Research Association: Advancing Tourism Research Globally*, 20 - 22 June 2013, Kansas City, MO, USA, pp. 5.
Dogru, T., E. A. Marchio, U. Bulut and C. Suess, 2019: Climate change: Vulnerability and resilience of tourism and the entire economy. *Tourism Management*, **72**, 292-305, doi:10.1016/j.tourman.2018.12.010.
Dorado-Liñán, I. et al., 2019: Geographical adaptation prevails over species-specific determinism in trees' vulnerability to climate change at Mediterranean rear-edge forests. *Global Change Biology*, **25**(4), 1296-1314, doi:10.1111/gcb.14544.
Dos Santos, M. et al., 2020: Development. In: *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 469-492.
Duane, A. et al., 2019: Adapting prescribed burns to future climate change in Mediterranean landscapes. *Science of The Total Environment*, **677**, 68-83, doi:10.1016/j.scitotenv.2019.04.348.
EC, 2018: *A Modern Budget for a Union that Protects, Empowers and Defends The Multiannual Financial Framework for 2021-2027*, European Commission, Brussels, Belgium, 31 pp. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A321%3AFIN (accessed 28/10/2020).
EC, 2020: *Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people*, European Commission, Brussles, Belgium, 26 pp. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0562&from=en (accessed 03/11/2020).
EEA, 2017: *Climate change, impacts and vulnerability in Europe 2016: An indicator-based report*. European Environment Agency. Publications Office of the European Union, Luxembourg, 424 pp. Available at: https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016 (accessed 15/10/2020).
EEA, 2018a: *Renewable energy in Europe - 2018: Recent growth and knock-on effects*. European Environment Agency. Publications Office of the European Union, Luxembourg, 80 pp. Available at: https://www.eea.europa.eu/publications/renewable-energy-in-europe-2018 (accessed 03/11/2020).
EEA, 2018b: *Sharing adaptation information across Europe*. European Environment Agency. Publications Office of the European Union, Luxembourg, 72 pp. Available at: https://www.eea.europa.eu/publications/sharing-adaptation-information-across-europe (accessed 15/10/2020).
EEA, 2019: *Trends and projections in Europe 2019: Tracking progress towards Europe's climate and energy targets*. European Environment Agency. Publications Office of the European Union, Luxembourg, 114 pp. Available at: https://www.eea.europa.eu/publications/trends-and-projections-in-europe-1 (accessed 02/11/2020).

Ehlers, P., 2016: Blue growth and ocean governance - how to balance the use and the protection of the seas. *WMU Journal of Maritime Affairs*, **15**(2), 187-203, doi:10.1007/s13437-016-0104-x.
EIB and IRENA, 2015: *Evaluating Renewable Energy Manufacturing Potential in the Mediterranean Partner Countries. Final Report*. European Investment Bank (EIB) and International Renewable Energy Agency (IRENA), 172 pp. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/femip_study_evaluating_renewable_energy_manufacturing_potential_en.pdf (accessed 01/11/2020).
El-Maayar, M. and M. A. Lange, 2013: A methodology to infer crop yield response to climate variability and change using long-term observations. *Atmosphere*, **4**, 365-382, doi:10.3390/atmos4040365.
Elimelech, M. and W. A. Phillip, 2011: The future of seawater desalination: Energy, technology, and the environment. *Science*, **333**(6043), 712, doi:10.1126/science.1200488.
Elshinnawy, I. A. and A. H. Almaliki, 2021: Vulnerability assessment for sea level rise impacts on coastal systems of Gamasa Ras El Bar area, Nile Delta, Egypt. *Sustainability*, **13**(7), 3624.
Enríquez, A. R. et al., 2017: Changes in beach shoreline due to sea level rise and waves under climate change scenarios: application to the Balearic Islands (western Mediterranean). *Natural Hazards and Earth System Sciences*, **17**(7), 1075-1089, doi:10.5194/nhess-17-1075-2017.
Erdős, L. et al., 2018: Habitat heterogeneity as a key to high conservation value in forest-grassland mosaics. *Biological Conservation*, **226**, 72-80, doi:10.1016/j.biocon.2018.07.029.
Escriva-Bou, A., M. Pulido-Velazquez and D. Pulido-Velazquez, 2017: Economic value of climate change adaptation strategies for water management in Spain's Jucar basin. *Journal of Water Resources Planning and Management*, **143**(5), 04017005, doi:10.1061/(ASCE)WR.1943-5452.0000735.
ESCWA, 2017: *Arab Climate Change Assessment Report – Main Report*. United Nations Economic and Social Commission for Western Asia (ESCWA), Beirut, Lebanon, 334 pp. Available at: https://www.unescwa.org/sites/default/files/pubs/pdf/riccar-main-report-2017-english_0.pdf.
Estrela, T. and T. A. Sancho, 2016: Drought management policies in Spain and the European Union: from traditional emergency actions to drought management plans. *Water Policy*, **18**(S2), 153-176, doi:10.2166/wp.2016.018.
Fader, M. et al., 2016: Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrology and Earth System Sciences*, **20**(2), 953-973, doi:10.5194/hess-20-953-2016.
FAO, 2018: *The state of the Mediterranean and Black Sea fisheries 2018*. Food and Agriculture Organization of the United Nations (FAO) - General Fisheries Commission for the Mediterranean, Rome, Italy. Available at: http://www.fao.org/3/CA2702EN/ca2702en.pdf (accessed 31/10/2020).
FAO, 2020: *The State of Mediterranean and Black Sea Fisheries 2020*. General Fisheries Commission for the Mediterranean, Rome, Italy.
FAOSTAT, 2019: Food Balance Sheets, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. Available at: http://www.fao.org/faostat/en/#data/FBS (accessed 30/07/2020).
Fernandes, P. M., 2018: Scientific support to prescribed underburning in southern Europe: What do we know? *Science of The Total Environment*, **630**, 340-348, doi:10.1016/j.scitotenv.2018.02.214.
Fernandes, P. M., A. M. G. Barros, A. Pinto and J. A. Santos, 2016: Characteristics and controls of extremely large wildfires in the western Mediterranean Basin. *Journal of Geophysical Research: Biogeosciences*, **121**(8), 2141-2157, doi:10.1002/2016JG003389.
Fernández-de-Uña, L., I. Cañellas and G. Gea-Izquierdo, 2015: Stand competition determines how different tree species will cope with a warming climate. *PLoS ONE*, **10**(3), e0122255, doi:10.1371/journal.pone.0122255.
Fernandez Milan, B. and F. Creutzig, 2015: Reducing urban heat wave risk in the 21st century. *Current Opinion in Environmental Sustainability*, **14**, 221-231, doi:10.1016/j.cosust.2015.08.002.
Ferragina, E. and G. Canitano, 2015: Geopolitical implications of water and food security in Southern and Eastern Mediterranean countries. In: *Building Sustainable Agriculture for Food Security in the Euro-Mediterranean Area: Challenges and Policy Options* [Paciello, M. C. (ed.)], pp. 33-59. ISBN 9788868125080.
Field, C. B. et al., 2014: Technical Summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94. ISBN 9781107058163.
Fortibuoni, T. et al., 2015: Climate impact on Italian fisheries (Mediterranean Sea). *Regional Environmental Change*, **15**(5), 931-937, doi:10.1007/s10113-015-0781-6.
Fosse, J., K. Petrick, S. Klarwein and K. Moukaddem, 2019: *Tracking and enhancing international private climate finance in the Southern-Mediterranean Region*. Union for the Mediterranean (UfM), Barcelona, Spain, 58 pp. Available at: https://ufmsecretariat.org/wp-content/uploads/2019/09/Private-Climate-Finance-Tracking-and-enhancing-international-private-climate-finance-in-the-Southern-Mediterranean-Region.pdf (accessed 02/11/2020).

Fraga, H., I. García de Cortázar Atauri, A. C. Malheiro and J. A. Santos, 2016: Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Global Change Biology*, **22**(11), 3774-3788, doi:10.1111/gcb.13382.

Fraga, H., J. G. Pinto, F. Viola and J. A. Santos, 2020: Climate change projections for olive yields in the Mediterranean Basin. *International Journal of Climatology*, **40**(2), 769-781, doi:10.1002/joc.6237.

Frihy, O. E. S., E. A. Deabes, S. M. Shereet and F. A. Abdalla, 2010: Alexandria-Nile Delta coast, Egypt: update and future projection of relative sea-level rise. *Environmental Earth Sciences*, **61**(2), 253-273, doi:10.1007/s12665-009-0340-x.

Fröhlich, C. J., 2016: Climate migrants as protestors? Dispelling misconceptions about global environmental change in pre-revolutionary Syria. *Contemporary Levant*, **1**, 38-50.

Funes, I. et al., 2016: Future climate change impacts on apple flowering date in a Mediterranean subbasin. *Agricultural Water Management*, **164**, 19-27, doi:10.1016/j.agwat.2015.06.013.

Gabaldón-Leal, C. et al., 2017: Impact of changes in mean and extreme temperatures caused by climate change on olive flowering in southern Spain. *International Journal of Climatology*, **37**(S1), 940-957, doi:10.1002/joc.5048.

Galli, A., M. Halle and N. Grunewald, 2015: Physical limits to resource access and utilisation and their economic implications in Mediterranean economies. *Environmental Science & Policy*, **51**, 125-136, doi:10.1016/j.envsci.2015.04.002.

Galli, G., C. Solidoro and T. Lovato, 2017: Marine heat waves hazard 3D maps and the risk for low motility organisms in a warming Mediterranean Sea. *Frontiers in Marine Science*, **4**, 136, doi:10.3389/fmars.2017.00136.

Garcia-Mozo, H., J. Oteros and C. Galan, 2015: Phenological changes in olive (*Olea europaea* L.) reproductive cycle in southern Spain due to climate change. *Annals of Agricultural and Environmental Medicine*, **22**(3), 421-428, doi:10.5604/12321966.1167706.

García-Tejero, I. F. et al., 2020: Conservation agriculture practices to improve the soil water management and soil carbon storage in Mediterranean rainfed agro-ecosystems. In: *Soil Health Restoration and Management* [Meena, R. S. (ed.)]. Springer, Singapore, pp. 203-230. ISBN 9789811385698.

García Sánchez, F., W. D. Solecki and C. Ribalaygua Batalla, 2018: Climate change adaptation in Europe and the United States: A comparative approach to urban green spaces in Bilbao and New York City. *Land Use Policy*, **79**, 164-173, doi:10.1016/j.landusepol.2018.08.010.

Garnier, J. et al., 2019: Long-term changes in greenhouse gas emissions from French agriculture and livestock (1852–2014): From traditional agriculture to conventional intensive systems. *Science of The Total Environment*, **660**, 1486-1501, doi:10.1016/j.scitotenv.2019.01.048.

Garrabou, J. et al., 2019: Collaborative database to track mass mortality events in the Mediterranean Sea. *Frontiers in Marine Science*, **6**, 2775, doi:papers3://publication/doi/10.3389/fmars.2019.00707.

Garrabou, J. et al., 2021: Sliding toward the collapse of Mediterranean coastal marine rocky ecosystems. In: *Ecosystem Collapse and Climate Change* [Canadell, J. G. and R. B. Jackson (eds.)]. Springer International Publishing, Cham, pp. 291-324. ISBN 978-3-030-71330-0.

Gasparrini, A. et al., 2017: Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health*, **1**(9), e360-e367, doi:10.1016/S2542-5196(17)30156-0.

Gaume, E. et al., 2016: Mediterranean extreme floods and flash floods. In: *The Mediterranean Region under Climate Change: A Scientific Update* [Thiébault, S., J.-P. Moatti, V. Ducrocq, E. Gaume, F. Dulac, E. Hamonou, Y.-J. Shin, J. Guiot, W. Cramer, G. Boulet, J.-F. Guégan, R. Barouki, I. Annesi-Maesano, P. Marty, E. Torquebiau, J. F. Soussana, Y. Aumeeruddy-Thomas, J.-L. Chotte and D. Lacroix (eds.)]. IRD Éditions, Marseille, France, pp. 133-144. ISBN 9782709922203.

Gauquelin, T. et al., 2018: Mediterranean forests, land use and climate change: a social-ecological perspective. *Regional Environmental Change*, **18**(3), 623-636, doi:10.1007/s10113-016-0994-3.

Gemitzi, A. and V. Lakshmi, 2018: Evaluating renewable groundwater stress with GRACE data in Greece. *Groundwater*, **56**(3), 501-514, doi:10.1111/gwat.12591.

Georgopoulou, E. et al., 2017: Climate change impacts and adaptation options for the Greek agriculture in 2021–2050: A monetary assessment. *Climate Risk Management*, **16**, 164-182, doi:10.1016/j.crm.2017.02.002.

Ghimire, R., S. Ferreira and J. H. Dorfman, 2015: Flood-induced displacement and civil conflict. *World Development*, **66**, 614-628, doi:10.1016/j.worlddev.2014.09.021.

Giorgi, F., 2006: Climate change hot-spots. *Geophysical Research Letters*, **33**(8), doi:https://doi.org/10.1029/2006GL025734.

Giorgi, F. et al., 2014: Changes in extremes and hydroclimatic regimes in the CREMA ensemble projections. *Climatic Change*, **125**(1), 39-51, doi:10.1007/s10584-014-1117-0.

Giuggiola, A. et al., 2016: Improvement of water and light availability after thinning at a xeric site: which matters more? A dual isotope approach. *New Phytologist*, **210**(1), 108-121, doi:10.1111/nph.13748.

Giuntoli, I., J. P. Vidal, C. Prudhomme and D. M. Hannah, 2015: Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models. *Earth System Dynamics*, **6**(1), 267-285, doi:10.5194/esd-6-267-2015.

Givan, O., D. Edelist, O. Sonin and J. Belmaker, 2018: Thermal affinity as the dominant factor changing Mediterranean fish abundances. *Global Change Biology*, **24**(1), E80-E89, doi:10.1111/gcb.13835.

Gleason, K. E. et al., 2017: Competition amplifies drought stress in forests across broad climatic and compositional gradients. *Ecosphere*, **8**(7), e01849, doi:10.1002/ecs2.1849.
Gleick, P. H., 2014: Water, drought, climate change, and conflict in Syria. *Weather, Climate, and Society*, **6**(3), 331-340, doi:10.1175/WCAS-D-13-00059.1.
Gomes da Costa, H. et al., 2020: *European wildfire danger and vulnerability under a changing climate: Towards integrating risk dimensions*. Publications Office of the European Union, Luxembourg.
González-De Vega, S., J. De las Heras and D. Moya, 2016: Resilience of Mediterranean terrestrial ecosystems and fire severity in semiarid areas: Responses of Aleppo pine forests in the short, mid and long term. *Science of The Total Environment*, **573**, 1171-1177, doi:10.1016/j.scitotenv.2016.03.115.
Gori, A. et al., 2016: Physiological response of the cold-water coral *Desmophyllum dianthus* to thermal stress and ocean acidification. *PeerJ*, **4**, e1606, doi:10.7717/peerj.1606.
Gosling, S. N. et al., 2017: A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1°C, 2°C and 3°C. *Climatic Change*, **141**(3), 577-595, doi:10.1007/s10584-016-1773-3.
Gössling, S., C. M. Hall and D. Scott, 2018: Coastal and Ocean Tourism. In: *Handbook on Marine Environment Protection - Science, Impacts and Sustainable Management* [Salomon, M. and T. Markus (eds.)]. Springer, Cham, Switzerland, pp. 773-790. ISBN 9783319601564.
Gower, J., 2015: A sea surface height control dam at the Strait of Gibraltar. *Natural Hazards*, **78**(3), 2109-2120, doi:10.1007/s11069-015-1821-8.
Goyet, C. et al., 2016: Thermodynamic forecasts of the Mediterranean Sea acidification. *Mediterranean Marine Science*, **17**(2), 508-518, doi:10.12681/mms.1487.
Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics*, **32**(1), 1-26, doi:10.1086/671766.
Grecequet, M., J. DeWaard, J. J. Hellmann and G. J. Abel, 2017: Climate vulnerability and human migration in global perspective. *Sustainability*, **9**(5), doi:10.3390/su9050720.
Grillakis, M. G., 2019: Increase in severe and extreme soil moisture droughts for Europe under climate change. *Science of The Total Environment*, **660**, 1245-1255, doi:10.1016/j.scitotenv.2019.01.001.
Grillakis, M. G., A. G. Koutroulis and I. K. Tsanis, 2016: The 2°C global warming effect on summer European tourism through different indices. *International Journal of Biometeorology*, **60**(8), 1205-1215, doi:10.1007/s00484-015-1115-6.
Gudmundsson, L. and S. I. Seneviratne, 2016: Anthropogenic climate change affects meteorological drought risk in Europe. *Environmental Research Letters*, **11**(4), 044005, doi:10.1088/1748-9326/11/4/044005.
Gudmundsson, L., S. I. Seneviratne and X. Zhang, 2017: Anthropogenic climate change detected in European renewable freshwater resources. *Nature Climate Change*, **7**, 813, doi:10.1038/nclimate3416.
Guerreiro, S. B. et al., 2018: Future heat-waves, droughts and floods in 571 European cities. *Environmental Research Letters*, **13**(3), 034009, doi:10.1088/1748-9326/aaaad3.
Guilherme, M. R. et al., 2015: Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: A review. *European Polymer Journal*, **72**, 365-385, doi:10.1016/j.eurpolymj.2015.04.017.
Guiot, J. and W. Cramer, 2016: Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Science*, **354**(6311), 465-468, doi:10.1126/science.aah5015.
Gul, M., M. G. Akpinar and R. F. Ceylan, 2017: Water use efficiency of urban households in the Mediterranean region of Turkey. *Desalination and Water Treatment*, **76**, 364-368, doi:10.5004/dwt.2017.20445.
Guyennon, N., F. Salerno, I. Portoghese and E. Romano, 2017: Climate change adaptation in a Mediterranean semi-arid catchment: Testing managed aquifer recharge and increased surface reservoir capacity. *Water*, **9**(9), 689, doi:10.3390/w9090689.
Guyot, V. et al., 2016: Tree diversity reduces pest damage in mature forests across Europe. *Biology Letters*, **12**(4), 20151037, doi:10.1098/rsbl.2015.1037.
Hadjikakou, M., J. Chenoweth and G. Miller, 2013: Estimating the direct and indirect water use of tourism in the eastern Mediterranean. *Journal of Environmental Management*, **114**, 548-556, doi:10.1016/j.jenvman.2012.11.002.
Haj-Amor, Z., T. Kumar Acharjee, L. Dhaouadi and S. Bouri, 2020: Impacts of climate change on irrigation water requirement of date palms under future salinity trend in coastal aquifer of Tunisian oasis. *Agricultural Water Management*, **228**, 105843, doi:10.1016/j.agwat.2019.105843.
Hamed, Y. et al., 2018: Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. *Euro-Mediterranean Journal for Environmental Integration*, **3**, 25.
Harrigan, J., 2011: *Food Security in the Middle East and North Africa (MENA) and sub-Saharan Africa: A Comparative Analysis.* CEI Working Paper Series No. 2011-5, Center for Economic Institutions, Institute of Economic Research, Hitotsubashi University. Available at: https://ideas.repec.org/p/hit/hitcei/2011-5.html (accessed 04/11/2020).
Harris, I., P. D. Jones, T. J. Osborn and D. H. Lister, 2014: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology*, **34**(3), 623-642, doi:10.1002/joc.3711.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111**(10), 3709, doi:10.1073/pnas.1308044111.
Hengeveld, G. M. et al., 2015: The landscape-level effect of individual-owner adaptation to climate change in Dutch forests. *Regional Environmental Change*, **15**(8), 1515-1529, doi:10.1007/s10113-014-0718-5.
Herrero, C. et al., 2019: Predicting mushroom productivity from long-term field-data series in Mediterranean *Pinus pinaster* Ait. forests in the context of climate change. *Forests*, **10**(3), 206, doi:10.3390/f10030206.
Herrero, M. et al., 2016: Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, **6**(5), 452-461, doi:10.1038/nclimate2925.
Hertig, E. and Y. Tramblay, 2017: Regional downscaling of Mediterranean droughts under past and future climatic conditions. *Global and Planetary Change*, **151**, 36-48, doi:10.1016/j.gloplacha.2016.10.015.
Hidalgo, M., V. Mihneva, M. Vasconcellos and M. Bernal, 2018: Climate change impacts, vulnerabilities and adaptations: Mediterranean Sea and the Black Sea marine fisheries. In: *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options* [Barange, M., T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith and F. Poulain (eds.)]. Food and Agriculture Organization of the United Nations (FAO), Rome, pp. 628. ISBN 978-92-5-130607-9.
Hinkel, J. et al., 2018: The ability of societies to adapt to twenty-firstcentury sea-level rise. *Nature Climate Change*, **8**(7), 570-578, doi:10.1038/s41558-018-0176-z.
Hinojosa, M. B. et al., 2019: Drought and its legacy modulate the post-fire recovery of soil functionality and microbial community structure in a Mediterranean shrubland. *Global Change Biology*, **25**(4), 1409-1427, doi:10.1111/gcb.14575.
Hlásny, T. et al., 2014: Climate change increases the drought risk in Central European forests: What are the options for adaptation? *Central European Forestry Journal*, **60**(1), doi:10.2478/forj-2014-0001.
Hoegh-Guldberg, O. et al., 2014: The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731. ISBN 9781107058163.
Hoegh-Guldberg, O. et al., 2018: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, G. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)], pp. In press. ISBN 9789291691517.
Hoekstra, A. Y. and M. M. Mekonnen, 2012: The water footprint of humanity. *Proceedings of the National Academy of Sciences*, **109**(9), 3232, doi:10.1073/pnas.1109936109.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356**(6345), 1362, doi:10.1126/science.aal4369.
Hsiang, S. M., M. Burke and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341**(6151), 1235367, doi:10.1126/science.1235367.
Hsiang, S. M. and K. C. Meng, 2015: Tropical economics. *American Economic Review*, **105**(5), 257-261, doi:10.1257/aer.p20151030.
Humphrey, S. and S. Lucas, 2015: *Outcome Evaluation of Barcelona Convention/United Nations Environment Programme - Mediterranean Action Plan (UNEP-MAP) Five Year Programme of Work 2010-2014*. Evaluation Office UNEP/MAP. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/273/Outcome_Evaluation_of_Barcelona_Convention_UNEP_MAP_Five_Year_Programme_of_Work_2010-2014.pdf (accessed 28/10/2020).
Iglesias, A. and L. Garrote, 2015: Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management*, **155**, 113-124, doi:10.1016/j.agwat.2015.03.014.
Iglesias, A. et al., 2011: Re-thinking water policy priorities in the Mediterranean region in view of climate change. *Environmental Science & Policy*, **14**(7), 744-757, doi:10.1016/j.envsci.2011.02.007.
Iglesias, A., B. Sánchez, L. Garrote and I. López, 2017: Towards adaptation to climate change: Water for rice in the coastal wetlands of Doñana, Southern Spain. *Water Resources Management*, **31**(2), 629-653, doi:10.1007/s11269-015-0995-x.
Iglesias, A., D. Santillán and L. Garrote, 2018: On the barriers to adaption to less water under climate change: Policy choices in Mediterranean countries. *Water Resources Management*, **32**(15), 4819-4832, doi:10.1007/s11269-018-2043-0.
Iñiguez, C. et al., 2016: Temperature in summer and children's hospitalizations in two Mediterranean cities. *Environmental Research*, **150**, 236-244, doi:10.1016/j.envres.2016.06.007.
INRA, 2015: *Addressing Agricultural Import Dependence in the Middle East - North Africa Region through the year 2050. Short summary of the study - October 2015*. Institut National de la Recherche Agronomique (INRA), Paris,

France, 1-8 pp. Available at: https://www.inrae.fr/sites/default/files/pdf/addressing-agricultural-import-dependence-in-the-middle-east-north-africa-region-through-to-the-year-2050-doc.pdf (accessed 02/11/2020).
Iocola, I. et al., 2017: Can conservation tillage mitigate climate change impacts in Mediterranean cereal systems? A soil organic carbon assessment using long term experiments. *European Journal of Agronomy*, **90**, 96-107, doi:10.1016/j.eja.2017.07.011.
Iona, A. et al., 2018: Mediterranean Sea climatic indices: monitoring long-term variability and climate changes. *Earth System Science Data*, **10**(4), 1829-1842, doi:10.5194/essd-10-1829-2018.
IPBES, 2018a: *The IPBES regional assessment report on biodiversity and ecosystem services for Africa* [Archer, E., L. Dziba, K. J. Mulongoy, M. A. Maoela and M. Walters (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany, 492 pp. (accessed 22/09/2020).
IPBES, 2018b: *The IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia* [Rounsevell, M., M. Fischer, A. Torre-Marin Rando and A. Mader (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany, 892 pp. (accessed 22/09/2020).
Jacob, D. et al., 2018: Climate impacts in Europe under +1.5°C global warming. *Earth's Future*, **6**(2), 264-285, doi:10.1002/2017ef000710.
Jacob, D. et al., 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, **14**(2), 563-578, doi:10.1007/s10113-013-0499-2.
Jactel, H. et al., 2017: Tree diversity drives forest stand resistance to natural disturbances. *Current Forestry Reports*, **3**(3), 223-243, doi:10.1007/s40725-017-0064-1.
Jarrar, S., 2015: No Justice, No Adaptation: The politics of climate change adaptation in Palestine. *La balsa di piedra*,(10), 26.
Jiménez Cisneros, B. E. et al., 2014: Freshwater Resources. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269. ISBN 9781107058071.
Jiménez, J. A. et al., 2017: Impacts of sea-level rise-induced erosion on the Catalan coast. *Regional Environmental Change*, **17**(2), 593-603, doi:10.1007/s10113-016-1052-x.
Jobbins, G. and G. Henley, 2015: *Food in an uncertain future: the impacts of climate change on food security and nutrition in the Middle East and North Africa*. Overseas Development Institute / World Food Programme. Available at: https://www.preventionweb.net/files/46974_46974odiwfpimpactofcconfnsinmena201.pdf.
Johansson, E. L., M. Fader, J. W. Seaquist and K. A. Nicholas, 2016: Green and blue water demand from large-scale land acquisitions in Africa. *Proceedings of the National Academy of Sciences*, **113**(41), 11471, doi:10.1073/pnas.1524741113.
Jones, E. et al., 2019: The state of desalination and brine production: A global outlook. *Science of The Total Environment*, **657**, 1343-1356, doi:10.1016/j.scitotenv.2018.12.076.
Jones, M. C. and W. W. L. Cheung, 2015: Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES Journal of Marine Science*, **72**(3), 741-752, doi:10.1093/icesjms/fsu172.
Kalavrouziotis, I. K. et al., 2015: Current status in wastewater treatment, reuse and research in some mediterranean countries. *Desalination and Water Treatment*, **53**(8), 2015-2030, doi:10.1080/19443994.2013.860632.
Kallis, G., 2008: Droughts. *Annual Review of Environment and Resources*, **33**(1), 85-118, doi:10.1146/annurev.environ.33.081307.123117.
Kamrava, M. and Z. Babar, 2012: *Food Security and Food Sovereignty in the Middle East*. Food Security and Food Sovereignty in the Middle East - Summary Report No.6, Center for International and Regional Studies (CIRS), Doha, Qatar, 40 pp. Available at: https://cirs.georgetown.edu/research/research-initiatives/food-security-and-food-sovereignty-middle-east/summary-report (accessed 04/11/2020).
Kang, S. et al., 2017: Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. *Agricultural Water Management*, **179**, 5-17, doi:10.1016/j.agwat.2016.05.007.
Kapur, B. et al., 2019: Interactive effects of elevated CO_2 and climate change on wheat production in the Mediterranean region. In: *Climate Change Impacts on Basin Agro-ecosystems* [Watanabe, T., S. Kapur, M. Aydın, R. Kanber and E. Akça (eds.)]. Springer, Cham, Switzerland, pp. 245-268. ISBN 9783030010362.
Kelley, C. P. et al., 2015: Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences*, **112**, 3241.
Kendrovski, V. et al., 2017: Quantifying projected heat mortality impacts under 21st-century warming conditions for selected European countries. *International Journal of Environmental Research and Public Health*, **14**(7), 729, doi:10.3390/ijerph14070729.
Kersting, D. K., N. Bensoussan and C. Linares, 2013: Long-term responses of the endemic reef-builder *Cladocora caespitosa* to Mediterranean warming. *PLoS ONE*, **8**(8), e70820, doi:papers3://publication/doi/10.1371/journal.pone.0070820.

Khabarov, N. et al., 2016: Forest fires and adaptation options in Europe. *Regional Environmental Change*, **16**(1), 21-30, doi:10.1007/s10113-014-0621-0.
Kheir, A. M. S. et al., 2019: Impacts of rising temperature, carbon dioxide concentration and sea level on wheat production in North Nile delta. *Science of The Total Environment*, **651**, 3161-3173, doi:10.1016/j.scitotenv.2018.10.209.
Köberl, J., F. Prettenthaler and D. N. Bird, 2016: Modelling climate change impacts on tourism demand: A comparative study from Sardinia (Italy) and Cap Bon (Tunisia). *Science of The Total Environment*, **543**, 1039-1053, doi:10.1016/j.scitotenv.2015.03.099.
Kompas, T., V. H. Pham and T. N. Che, 2018: The effects of climate change on GDP by country and the global economic gains from complying with the Paris Climate Accord. *Earth's Future*, **6**(8), 1153-1173, doi:10.1029/2018EF000922.
Koubi, V., 2018: Exploring the relationship between climate change and violent conflict. *Chinese Journal of Population Resources and Environment*, **16**(3), 197-202, doi:10.1080/10042857.2018.1460957.
Koufos, G. C., T. Mavromatis, S. Koundouras and G. V. Jones, 2018: Response of viticulture-related climatic indices and zoning to historical and future climate conditions in Greece. *International Journal of Climatology*, **38**(4), 2097-2111, doi:10.1002/joc.5320.
Koutroulis, A. G. et al., 2016: Cross sectoral impacts on water availability at +2°C and +3°C for east Mediterranean island states: The case of Crete. *Journal of Hydrology*, **532**, 16-28, doi:10.1016/j.jhydrol.2015.11.015.
Kovats, R. S. et al., 2014: Europe. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1267-1326. ISBN 9781107058163.
Kulp, S. A. and B. H. Strauss, 2019: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, **10**(1), 4844, doi:10.1038/s41467-019-12808-z.
Kutiel, H., 2019: Climatic uncertainty in the Mediterranean Basin and its possible relevance to important economic sectors. *Atmosphere*, **10**(1), doi:10.3390/atmos10010010.
Lacroix, D., 2016: Adapting to global change in the Mediterranean Sea. In: *The Mediterranean Region under Climate Change: A Scientific Update* [Thiébault, S., J.-P. Moatti, V. Ducrocq, E. Gaume, F. Dulac, E. Hamonou, Y.-J. Shin, J. Guiot, W. Cramer, G. Boulet, J.-F. Guégan, R. Barouki, I. Annesi-Maesano, P. Marty, E. Torquebiau, J. F. Soussana, Y. Aumeeruddy-Thomas, J.-L. Chotte and D. Lacroix (eds.)]. IRD Éditions, Marseille, France, pp. 91-92. ISBN 978270992255.
Lam, V. W. Y., W. W. L. Cheung, G. Reygondeau and U. R. Sumaila, 2016: Projected change in global fisheries revenues under climate change. *Scientific Reports*, **6**(1), 32607, doi:10.1038/srep32607.
Lange, M. A., 2019: Impacts of climate change on the Eastern Mediterranean and the Middle East and North Africa region and the water-energy nexus. *Atmosphere*, **10**(8), 22, doi:10.3390/atmos10080455.
Larsen, L., 2015: Urban climate and adaptation strategies. *Frontiers in Ecology and the Environment*, **13**(9), 486-492, doi:10.1890/150103.
Lassaletta, L. et al., 2021: Nitrogen dynamics in cropping systems under Mediterranean climate: a systemic analysis. *Environmental Research Letters*, **16**(7), 073002, doi:10.1088/1748-9326/ac002c.
Le Cozannet, G. et al., 2015: Evaluating uncertainties of future marine flooding occurrence as sea-level rises. *Environmental Modelling & Software*, **73**, 44-56, doi:10.1016/j.envsoft.2015.07.021.
Lechuga, V. et al., 2017: Managing drought-sensitive forests under global change. Low competition enhances long-term growth and water uptake in *Abies pinsapo*. *Forest Ecology and Management*, **406**, 72-82, doi:10.1016/j.foreco.2017.10.017.
Lee, S. H., R. H. Mohtar and S. H. Yoo, 2019: Assessment of food trade impacts on water, food, and land security in the MENA region. *Hydrology and Earth System Sciences*, **23**(1), 557-572, doi:10.5194/hess-23-557-2019.
Lefebvre, G. et al., 2019: Predicting the vulnerability of seasonally-flooded wetlands to climate change across the Mediterranean Basin. *Science of The Total Environment*, **692**, 546-555, doi:10.1016/j.scitotenv.2019.07.263.
Lehner, F. et al., 2017: Projected drought risk in 1.5°C and 2°C warmer climates. *Geophysical Research Letters*, **44**(14), 7419-7428, doi:10.1002/2017gl074117.
Leissner, J. et al., 2015: Climate for culture: assessing the impact of climate change on the future indoor climate in historic buildings using simulations. *Heritage Science*, **3**(1), 38, doi:10.1186/s40494-015-0067-9.
Lelieveld, J. et al., 2012: Climate change and impacts in the Eastern Mediterranean and the Middle East. *Climatic Change*, **114**(3), 667-687, doi:10.1007/s10584-012-0418-4.
Leolini, L. et al., 2018: Late spring frost impacts on future grapevine distribution in Europe. *Field Crops Research*, **222**, 197-208, doi:10.1016/j.fcr.2017.11.018.
Linares, C. et al., 2020: Health. In: *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 493-514.

Linares, C., R. Sánchez, I. J. Mirón and J. Díaz, 2015: Has there been a decrease in mortality due to heat waves in Spain? Findings from a multicity case study. *Journal of Integrative Environmental Sciences*, **12**(2), 153-163, doi:10.1080/1943815X.2015.1062032.
Lionello, P., 2012: The climate of the Venetian and North Adriatic region: Variability, trends and future change. *Physics and Chemistry of the Earth, Parts A/B/C*, **40-41**, 1-8, doi:10.1016/j.pce.2012.02.002.
Lionello, P. et al., 2014: The climate of the Mediterranean region: research progress and climate change impacts. *Regional Environmental Change*, **14**(5), 1679-1684, doi:10.1007/s10113-014-0666-0.
Lionello, P., D. Conte, L. Marzo and L. Scarascia, 2017: The contrasting effect of increasing mean sea level and decreasing storminess on the maximum water level during storms along the coast of the Mediterranean Sea in the mid 21st century. *Global and Planetary Change*, **151**, 80-91, doi:10.1016/j.gloplacha.2016.06.012.
Lionello, P. and L. Scarascia, 2018: The relation between climate change in the Mediterranean region and global warming. *Regional Environmental Change*, **18**(5), 1481-1493, doi:10.1007/s10113-018-1290-1.
Lionello, P. and L. Scarascia, 2020: The relation of climate extremes with global warming in the Mediterranean region and its north versus south contrast. *Regional Environmental Change*, **20**(1), 31, doi:10.1007/s10113-020-01610-z.
Lionello, P. et al., 2016: Objective climatology of cyclones in the Mediterranean region: A consensus view among methods with different system identification and tracking criteria. *Tellus, Series A: Dynamic Meteorology and Oceanography*, **68**(1), doi:10.3402/tellusa.v68.29391.
Liotta, G. et al., 2018: Social interventions to prevent heat-related mortality in the older adult in Rome, Italy: A quasi-experimental study. *International Journal of Environmental Research and Public Health*, **15**(4), doi:10.3390/ijerph15040715.
Liu-Helmersson, J., J. Rocklöv, M. Sewe and Å. Brännström, 2019: Climate change may enable *Aedes aegypti* infestation in major European cities by 2100. *Environmental Research*, **172**, 693-699, doi:10.1016/j.envres.2019.02.026.
Livi Bacci, M., 2018: *Future Demographic Trends and Scenarios*. Food & Migration: Understanding the Geopolitical Nexus in the Euro-Mediterranean, Barilla Center for Food & Nutrition (BCFN), Parma, Italy, 19-27 pp. Available at: https://www.datocms-assets.com/4084/1512237431-food-and-migration-macrogeo-barilla-cfn.pdf (accessed 08/11/2020).
Llasat, M. C. et al., 2013: Towards a database on societal impact of Mediterranean floods within the framework of the HYMEX project. *Natural Hazards and Earth System Sciences*, **13**(5), 1337-1350, doi:10.5194/nhess-13-1337-2013.
Llasat, M. C. et al., 2016: Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia. *Journal of Hydrology*, **541**, 24-37, doi:10.1016/j.jhydrol.2016.05.040.
Lloret, J. et al., 2015: How a multidisciplinary approach involving ethnoecology, biology and fisheries can help explain the spatio-temporal changes in marine fish abundance resulting from climate change. *Global Ecology and Biogeography*, **24**(4), 448-461, doi:10.1111/geb.12276.
Lobanova, A. et al., 2016: Impacts of changing climate on the hydrology and hydropower production of the Tagus River basin. *Hydrological Processes*, **30**(26), 5039-5052, doi:10.1002/hyp.10966.
Loizidou, M., C. Giannakopoulos, M. Bindi and K. Moustakas, 2016: Climate change impacts and adaptation options in the Mediterranean basin. *Regional Environmental Change*, **16**(7), 1859-1861, doi:10.1007/s10113-016-1037-9.
Lozano, O. M. et al., 2017: Assessing climate change impacts on wildfire exposure in Mediterranean areas. *Risk Analysis*, **37**(10), 1898-1916, doi:10.1111/risa.12739.
Macias, D. M., E. Garcia-Gorriz and A. Stips, 2015: Productivity changes in the Mediterranean Sea for the twenty-first century in response to changes in the regional atmospheric forcing. *Frontiers in Marine Science*, **2**(79), doi:10.3389/fmars.2015.00079.
Maes, J. et al., 2015: More green infrastructure is required to maintain ecosystem services under current trends in land-use change in Europe. *Landscape Ecology*, **30**(3), 517-534, doi:10.1007/s10980-014-0083-2.
Maier, C., M. G. Weinbauer and J.-P. Gattuso, 2019: Fate of Mediterranean scleractinian cold-water corals as a result of global climate change. A synthesis. In: *Mediterranean Cold-Water Corals: Past, Present and Future: Understanding the Deep-Sea Realms of Coral* [Orejas, C. and C. Jiménez (eds.)]. Springer International Publishing, Cham, pp. 517-529. ISBN 978-3-319-91608-8.
Malek, Ž. and P. H. Verburg, 2018: Adaptation of land management in the Mediterranean under scenarios of irrigation water use and availability. *Mitigation and Adaptation Strategies for Global Change*, **23**(6), 821-837, doi:10.1007/s11027-017-9761-0.
Manes, S. et al., 2021: Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, **257**, 109070, doi:https://doi.org/10.1016/j.biocon.2021.109070.
Manoli, P., 2021: *Economic Linkages across the Mediterranean: Trends on trade, investments and energy*. ELIAMEP Policy Paper, **20**, Hellenic Foundation for European and Foreign Policy (ELIAMEP), Athens, Greece, 20 pp. Available at: https://www.eliamep.gr/wp-content/uploads/2021/01/Policy-paper-52-Manoli-final.pdf.
Marchane, A. et al., 2017: Climate change impacts on surface water resources in the Rheraya catchment (High Atlas, Morocco). *Hydrological Sciences Journal*, **62**(6), 979-995, doi:10.1080/02626667.2017.1283042.
Marchini, A. et al., 2019: Intertidal Mediterranean coralline algae habitat is expecting a shift toward a reduced growth and a simplified associated fauna under climate change. *Frontiers in Marine Science*, **6**, 106, doi:10.3389/fmars.2019.00106.

Marcos-Garcia, P., A. Lopez-Nicolas and M. Pulido-Velazquez, 2017: Combined use of relative drought indices to analyze climate change impact on meteorological and hydrological droughts in a Mediterranean basin. *Journal of Hydrology*, **554**, 292-305, doi:10.1016/j.jhydrol.2017.09.028.
Mariotti, A., Y. Pan, N. Zeng and A. Alessandri, 2015: Long-term climate change in the Mediterranean region in the midst of decadal variability. *Climate Dynamics*, **44**(5), 1437-1456, doi:10.1007/s00382-015-2487-3.
Martinez, M. et al., 2018: Measuring the effects of temperature rise on Mediterranean shellfish aquaculture. *Ecological Indicators*, **88**, 71-78, doi:10.1016/j.ecolind.2018.01.002.
Marx, A. et al., 2018: Climate change alters low flows in Europe under global warming of 1.5, 2, and 3 °C. *Hydrology and Earth System Sciences*, **22**(2), 1017-1032, doi:10.5194/hess-22-1017-2018.
Marzeion, B. and A. Levermann, 2014: Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environmental Research Letters*, **9**(3), 034001, doi:10.1088/1748-9326/9/3/034001.
Masia, S. et al., 2018: Assessment of irrigated agriculture vulnerability under climate change in Southern Italy. *Water*, **10**(2), 209, doi:10.3390/w10020209.
Masria, A., M. Iskander and A. Negm, 2015: Coastal protection measures, case study (Mediterranean zone, Egypt). *Journal of Coastal Conservation*, **19**(3), 281-294, doi:10.1007/s11852-015-0389-5.
Masseroni, D. et al., 2020: 65-year changes of annual streamflow volumes across Europe with a focus on the Mediterranean basin. *Hydrol. Earth Syst. Sci. Discuss.*, **2020**, 1-16, doi:10.5194/hess-2020-21.
Mathbout, S. et al., 2018: Observed changes in daily precipitation extremes at annual timescale over the Eastern Mediterranean during 1961-2012. *Pure and Applied Geophysics*, **175**(11), 3875-3890, doi:10.1007/s00024-017-1695-7.
Matías, L., M. Abdelaziz, O. Godoy and L. Gómez-Aparicio, 2019: Disentangling the climatic and biotic factors driving changes in the dynamics of Quercus suber populations across the species' latitudinal range. *Diversity and Distributions*, **25**(4), 524-535, doi:10.1111/ddi.12873.
MedECC, 2020: Summary for Policymakers. In: *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 11-40.
Mediero, L., D. Santillán, L. Garrote and A. Granados, 2014: Detection and attribution of trends in magnitude, frequency and timing of floods in Spain. *Journal of Hydrology*, **517**, 1072-1088, doi:10.1016/j.jhydrol.2014.06.040.
Menció, A. and D. Boix, 2018: Response of macroinvertebrate communities to hydrological and hydrochemical alterations in Mediterranean streams. *Journal of Hydrology*, **566**, 566-580, doi:10.1016/j.jhydrol.2018.09.040.
Meyssignac, B. et al., 2011: Two-dimensional reconstruction of the Mediterranean sea level over 1970–2006 from tide gage data and regional ocean circulation model outputs. *Global and Planetary Change*, **77**(1), 49-61, doi:10.1016/j.gloplacha.2011.03.002.
MGI, 2020: Tourism in the Mediterranean, Mediterranean Growth Initiative. Available at: https://www.mgi.online/content/2017/8/4/tourism-in-the-mediterranean.
Micheli, F. et al., 2013: Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: Assessing current pressures and opportunities. *PLoS ONE*, **8**(12), e79889, doi:10.1371/journal.pone.0079889.
Midgley, A. et al., 2018: *International Public Climate Finance in the Mediterranean*. Union for the Mediterranean (UfM), Barcelona, Spain, 52 pp. Available at: https://ufmsecretariat.org/wp-content/uploads/2018/12/UfM-Climate-Finance-Study-2018.pdf (accessed 03/11/2020).
Missimer, T. M. and R. G. Maliva, 2018: Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. *Desalination*, **434**, 198-215, doi:10.1016/j.desal.2017.07.012.
Molina, J. R., A. González-Cabán and F. Rodríguez y Silva, 2019: Potential effects of climate change on fire behavior, economic susceptibility and suppression costs in Mediterranean ecosystems: Córdoba Province, Spain. *Forests*, **10**(8), 679, doi:10.3390/f10080679.
Moore, F. C. and D. B. Lobell, 2015: The fingerprint of climate trends on European crop yields. *Proceedings of the National Academy of Sciences of the United States of America*, **112**(9), 2670-2675, doi:10.1073/pnas.1409606112.
Morant, D. et al., 2020: Carbon metabolic rates and GHG emissions in different wetland types of the Ebro Delta. *PLoS ONE*, **15**(4), e0231713, doi:10.1371/journal.pone.0231713.
Moresi, M., 2014: Assessment of the life cycle greenhouse gas emissions in the food industry, 53-62 pp.
Moriondo, M. et al., 2016: Heat stress and crop yields in the Mediterranean basin: impact on expected insurance payouts. *Regional Environmental Change*, **16**(7), 1877-1890, doi:10.1007/s10113-015-0837-7.
Moullec, F. et al., 2019: An end-to-end model reveals losers and winners in a warming Mediterranean Sea. *Frontiers in Marine Science*, **6**(345), doi:10.3389/fmars.2019.00345.
Mrabet, R., R. Moussadek, A. Fadlaoui and E. van Ranst, 2012: Conservation agriculture in dry areas of Morocco. *Field Crops Research*, **132**, 84-94, doi:10.1016/j.fcr.2011.11.017.
Mrabet, R. et al., 2020: Food. In: *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 237-264.
Murray, V. et al., 2012: Case Studies. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C. B., V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach,

G.-K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 487-542. ISBN 9781107025066.

Nanni, M., 2012: Legislation as a tool in support of adaptive water management in response to climate change. *Water International*, **37**(6), 628-639, doi:10.1080/02508060.2012.714966.

Nannini, M., L. De Marchi, C. Lombardi and F. Ragazzola, 2015: Effects of thermal stress on the growth of an intertidal population of *Ellisolandia elongata* (Rhodophyta) from N-W Mediterranean Sea. *Marine Environmental Research*, **112**(Pt B), 11-19, doi:10.1016/j.marenvres.2015.05.005.

Naumann, M. S., C. Orejas and C. Ferrier-Pagès, 2013: High thermal tolerance of two Mediterranean cold-water coral species maintained in aquaria. *Coral Reefs*, **32**(3), 749-754, doi:10.1007/s00338-013-1011-7.

Negev, M. et al., 2015: Impacts of climate change on vector borne diseases in the Mediterranean Basin — Implications for preparedness and adaptation policy. *International Journal of Environmental Research and Public Health*, **12**(6), 6745-6770, doi:10.3390/ijerph120606745.

Nguyen, T. P. L. et al., 2016: Perceptions of present and future climate change impacts on water availability for agricultural systems in the Western Mediterranean Region. *Water*, **8**(11), 523, doi:10.3390/w8110523.

Nguyen, T. P. L., G. Seddaiu and P. P. Roggero, 2019: Declarative or procedural knowledge? Knowledge for enhancing farmers' mitigation and adaptation behaviour to climate change. *Journal of Rural Studies*, **67**, 46-56, doi:10.1016/j.jrurstud.2019.02.005.

Niang, I. et al., 2014: Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265. ISBN 9781107058163.

Nissen, K. M., G. C. Leckebusch, J. G. Pinto and U. Ulbrich, 2014: Mediterranean cyclones and windstorms in a changing climate. *Regional Environmental Change*, **14**(5), 1873-1890, doi:10.1007/s10113-012-0400-8.

Nori, M. and D. Farinella, 2020: Rural World, Migration, and Agriculture in Mediterranean EU: An Introduction. In: *Migration, Agriculture and Rural Development: IMISCOE Short Reader* [Nori, M. and D. Farinella (eds.)]. Springer, Cham, pp. 1-16. ISBN 978-3-030-42863-1.

Nurse, L. A. et al., 2014: Small Islands. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1613-1654. ISBN 9781107058163.

Okkan, U. and U. Kirdemir, 2018: Investigation of the behavior of an agricultural-operated dam reservoir under RCP scenarios of AR5-IPCC. *Water Resources Management*, **32**(8), 2847-2866, doi:10.1007/s11269-018-1962-0.

OME, 2018: *Mediterranean Energy Perspectives 2018*. Observatoire Méditerranéen de l'Energie (OME), Paris, France. Available at: https://www.ome.org/mep-2018-2/ (accessed 16/10/2020).

Omran, E.-S. E. and A. M. Negm, 2020: Introduction. In: *Climate Change Impacts on Agriculture and Food Security in Egypt: Land and Water Resources—Smart Farming—Livestock, Fishery, and Aquaculture* [Ewis Omran, E.-S. and A. M. Negm (eds.)]. Springer International Publishing, Cham, pp. 3-19. ISBN 978-3-030-41629-4.

Ortas, I. and R. Lal, 2013: Food security and Climate Change in West Asia and North Africa. In: *Climate Change and Food Security in West Asia and North Africa* [Sivakumar, M. V. K., R. Lal, R. Selvaraju and I. Hamdan (eds.)]. Springer, Dordrecht, Netherlands, Heidelberg, Germany, New York, NY, USA and London, United Kingdom, pp. 423. ISBN 9789400767508.

Oteros, J. et al., 2015: Variations in cereal crop phenology in Spain over the last twenty-six years (1986-2012). *Climatic Change*, **130**(4), 545-558, doi:10.1007/s10584-015-1363-9.

Ouessar, M., 2017: Climate change vulnerability of olive oil groves in dry areas of Tunisia: Case study in the Governorate of Médenine. In: *Rethinking Resilience, Adaptation and Transformation in a Time of Change* [Yan, W. and W. Galloway (eds.)]. Springer, Cham, Switzerland, pp. 41-52. ISBN 9783319501710.

Ouraich, I. and W. E. Tyner, 2018: Moroccan agriculture, climate change, and the Moroccan Green Plan: A CGE analysis. *African Journal of Agricultural and Resource Economics*, 13(4), 307-330. Available at: http://ageconsearch.umn.edu/record/284990/files/3.-Ouraich-Tyner.pdf (accessed 2018-12).

Paciello, M. C. (ed.), 2015: *Building Sustainable Agriculture for Food Security in the Euro-Mediterranean Area: Challenges and Policy Options*, Edizioni Nuova Cultura, Rome, Italy, 334 pp. ISBN 9788868125080.

Palmiéri, J. et al., 2015: Simulated anthropogenic CO_2 storage and acidification of the Mediterranean Sea. *Biogeosciences*, **12**(3), 781-802, doi:10.5194/bg-12-781-2015.

Paneque, P., 2015: Drought management strategies in Spain. *Water*, **7**(12), doi:10.3390/w7126655.

Papanicolas, C. N. et al., 2016: CSP cogeneration of electricity and desalinated water at the Pentakomo field facility. *AIP Conference Proceedings*, **1734**(1), 100008, doi:10.1063/1.4949196.

Paprotny, D., A. Sebastian, O. Morales-Nápoles and S. N. Jonkman, 2018: Trends in flood losses in Europe over the past 150 years. *Nature Communications*, **9**(1), 1985, doi:10.1038/s41467-018-04253-1.

Paravantis, J. et al., 2017: Mortality associated with high ambient temperatures, heatwaves, and the urban heat island in Athens, Greece. *Sustainability*, **9**(4), doi:10.3390/su9040606.
Parra, A. and J. M. Moreno, 2018: Drought differentially affects the post-fire dynamics of seeders and resprouters in a Mediterranean shrubland. *Science of The Total Environment*, **626**, 1219-1229, doi:10.1016/j.scitotenv.2018.01.174.
Pastor, F., J. A. Valiente and J. L. Palau, 2019: Sea surface temperature in the Mediterranean: Trends and spatial patterns (1982–2016). In: *Meteorology and Climatology of the Mediterranean and Black Seas* [Vilibić, I., K. Horvath and J. L. Palau (eds.)]. Springer, Cham, Switzerland, pp. 297-309. ISBN 9783030119584.
Pausas, J. G. and S. Fernández-Muñoz, 2012: Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Climatic Change*, **110**(1), 215-226, doi:10.1007/s10584-011-0060-6.
Payet-Burin, R., F. Bertoni, C. Davidsen and P. Bauer-Gottwein, 2018: Optimization of regional water - power systems under cooling constraints and climate change. *Energy*, **155**, 484-494, doi:10.1016/j.energy.2018.05.043.
Paz, S., M. Negev, A. Clermont and M. S. Green, 2016: Health aspects of climate change in cities with Mediterranean climate, and local adaptation plans. *International Journal of Environmental Research and Public Health*, **13**(4), doi:10.3390/ijerph13040438.
Peñuelas, J. et al., 2017: Impacts of global change on Mediterranean forests and their services. *Forests*, **8**(12), 463, doi:10.3390/f8120463.
Peñuelas, J. et al., 2018: Assessment of the impacts of climate change on Mediterranean terrestrial ecosystems based on data from field experiments and long-term monitored field gradients in Catalonia. *Environmental and Experimental Botany*, **152**, 49-59, doi:10.1016/j.envexpbot.2017.05.012.
Perera, F. P., 2017: Multiple threats to child health from fossil fuel combustion: Impacts of air pollution and climate change. *Environmental Health Perspectives*, **125**(2), 141-148, doi:10.1289/EHP299.
Philipsborn, R. P. and K. Chan, 2018: Climate change and global child health. *Pediatrics*, **141**(6), e20173774, doi:10.1542/peds.2017-3774.
Piqué, M. and R. Domènech, 2018: Effectiveness of mechanical thinning and prescribed burning on fire behavior in *Pinus nigra* forests in NE Spain. *Science of The Total Environment*, **618**, 1539-1546, doi:10.1016/j.scitotenv.2017.09.316.
Poloczanska, E. S. et al., 2014: Cross-Chapter Box on Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 123-127. ISBN 9781107058071.
Pomaro, A., L. Cavaleri and P. Lionello, 2017: Climatology and trends of the Adriatic Sea wind waves: analysis of a 37-year long instrumental data set. *International Journal of Climatology*, **37**(12), 4237-4250, doi:10.1002/joc.5066.
Ponti, L., A. P. Gutierrez, P. M. Ruti and A. Dell'Aquila, 2014: Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers. *Proceedings of the National Academy of Sciences*, 201314437, doi:10.1073/pnas.1314437111.
Pörtner, H.-O. et al., 2014: Ocean Systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484. ISBN 9781107058071.
Poumadère, M., C. Mays, G. Pfeifle and A. T. Vafeidis, 2008: Worst case scenario as stakeholder decision support: a 5- to 6-m sea level rise in the Rhone delta, France. *Climatic Change*, **91**(1), 123, doi:10.1007/s10584-008-9446-5.
Prahl, B. F. et al., 2018: Damage and protection cost curves for coastal floods within the 600 largest European cities. *Scientific Data*, **5**(1), 180034, doi:10.1038/sdata.2018.34.
Pranzini, E., L. Wetzel and A. T. Williams, 2015: Aspects of coastal erosion and protection in Europe. *Journal of Coastal Conservation*, **19**(4), 445-459, doi:10.1007/s11852-015-0399-3.
Price, R., 2017: *Climate change and stability inNorth Africa*. K4D Helpdesk Report, Institute of Development Studies, Brighton, UK, 18 pp. Available at: http://opendocs.ids.ac.uk/opendocs/handle/123456789/13489 (accessed 26/10/2020).
Prosperi, P. et al., 2014: Sustainability and Food & Nutrition Security: A Vulnerability Assessment Framework for the Mediterranean Region. *SAGE Open*, **4**(2), 2158244014539169, doi:10.1177/2158244014539169.
Pulido-Velazquez, D. et al., 2018: Integrated assessment of future potential global change scenarios and their hydrological impacts in coastal aquifers – a new tool to analyse management alternatives in the Plana Oropesa-Torreblanca aquifer. *Hydrology and Earth System Sciences*, **22**(5), 3053-3074, doi:10.5194/hess-22-3053-2018.
Pulido-Velazquez, D. et al., 2020: Using the turnover time index to identify potential strategic groundwater resources to manage droughts within continental Spain. *Water*, **12**(11), 3281.

Radhouane, L., 2013: Climate change impacts on North African countries and on some Tunisian economic sectors. *Journal of Agriculture and Environment for International Development (JAEID)*, **107**(1), 101-113, doi:10.12895/jaeid.20131.123.

Raicevich, S. et al., 2020: The Italian Job: Navigating the (Im)Perfect Storm of Participatory Fisheries Research in the Northern Adriatic Sea. In: *Collaborative Research in Fisheries: Co-creating Knowledge for Fisheries Governance in Europe* [Holm, P., M. Hadjimichael, S. Linke and S. Mackinson (eds.)]. Springer, Cham, Switzerland, pp. 121-140. ISBN 978-3-030-26784-1.

Raineri, L., 2018: *Routes of Trans-Mediterranean Migration*. Food & Migration: Understanding the Geopolitical Nexus in the Euro-Mediterranean, Barilla Center for Food & Nutrition (BCFN), Parma, Italy, 57-62 pp. Available at: https://www.datocms-assets.com/4084/1512237431-food-and-migration-macrogeo-barilla-cfn.pdf (accessed 08/11/2020).

Ramieri, E. et al., 2018: *Adaptation policies and knowledge base in transnational regions in Europe*. European Topic Centre on Climate Change impacts, Vulnerability and Adaptation (ETC/CCA) Technical Paper 2018/4, **4**, European Environment Agency, Bologna, Italy, 170 pp. Available at: https://www.eionet.europa.eu/etcs/etc-cca/products/etc-cca-reports/tp_4-2018/@@download/file/ETC-CCA%20Paper%20-%20Final%20version_2018%2012%2008_2.pdf (accessed 16/10/2020).

Ramos, M., G. Jones and J. Yuste, 2018: Phenology of Tempranillo and Cabernet-Sauvignon varieties cultivated in the Ribera del Duero DO: observed variability and predictions under climate change scenarios. *OENO One*, **52**(1), doi:10.20870/oeno-one.2018.52.1.2119.

Ramos, M. C., 2017: Projection of phenology response to climate change in rainfed vineyards in north-east Spain. *Agricultural and Forest Meteorology*, **247**, 104-115, doi:10.1016/j.agrformet.2017.07.022.

Randone, M., G. Di Carlo and M. Costantini, 2017: *Reviving the Economy of the Mediterranean Sea: Actions for a Sustainable Future* [Karavellas, D. and P. Lombardi (eds.)]. WWF, World Wildlife Fund, Mediterranean Marine Initiative, Rome, Italy, 64 pp. Available at: https://www.wwf.fr/sites/default/files/doc-2017-09/170927_rapport_reviving_mediterranean_sea_economy.pdf (accessed 27/10/2020).

Ratcliffe, S. et al., 2017: Biodiversity and ecosystem functioning relations in European forests depend on environmental context. *Ecology Letters*, **20**(11), 1414-1426, doi:10.1111/ele.12849.

Raucoules, D. et al., 2008: Ground deformation detection of the greater area of Thessaloniki (Northern Greece) using radar interferometry techniques. *Natural Hazards and Earth System Sciences*, **8**(4), 779-788, doi:10.5194/nhess-8-779-2008.

Ravanelli, R. et al., 2019: Sea level rise scenario for 2100 A.D. for the archaeological site of Motya. *Rendiconti Lincei. Scienze Fisiche e Naturali*, doi:10.1007/s12210-019-00835-3.

Raybaud, V., M. Bacha, R. Amara and G. Beaugrand, 2017: Forecasting climate-driven changes in the geographical range of the European anchovy (*Engraulis encrasicolus*). *ICES Journal of Marine Science*, **74**(5), 1288-1299, doi:10.1093/icesjms/fsx003.

Reckien, D. et al., 2018: How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *Journal of Cleaner Production*, **191**, 207-219, doi:10.1016/j.jclepro.2018.03.220.

Regos, A. et al., 2016: Synergies between forest biomass extraction for bioenergy and fire suppression in Mediterranean Ecosystems: Insights from a storyline-and-simulation approach. *Ecosystems*, **19**(5), 786-802, doi:10.1007/s10021-016-9968-z.

Regos, A. et al., 2014: Using unplanned fires to help suppressing future large fires in Mediterranean forests. *PLoS ONE*, **9**(4), e94906, doi:10.1371/journal.pone.0094906.

Reimann, L., J.-L. Merkens and A. T. Vafeidis, 2018a: Regionalized Shared Socioeconomic Pathways: narratives and spatial population projections for the Mediterranean coastal zone. *Regional Environmental Change*, **18**(1), 235-245, doi:10.1007/s10113-017-1189-2.

Reimann, L. et al., 2018b: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications*, **9**(1), 4161, doi:10.1038/s41467-018-06645-9.

Reuveny, R., 2007: Climate change-induced migration and violent conflict. *Political Geography*, **26**(6), 656-673, doi:10.1016/j.polgeo.2007.05.001.

Revi, A. et al., 2014: Urban Areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612. ISBN 9781107058071.

Rivetti, I. et al., 2017: Anomalies of the upper water column in the Mediterranean Sea. *Global and Planetary Change*, **151**, 68-79, doi:10.1016/j.gloplacha.2016.03.001.

Rivetti, I. et al., 2014: Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea. *PLoS ONE*, **9**(12), e115655, doi:10.1371/journal.pone.0115655.

Rizzetto, F., 2020: Effects of climate change on the morphological stability of the Mediterranean coasts: Consequences for tourism. In: *Climate Change, Hazards and Adaptation Options: Handling the Impacts of a Changing Climate* [Leal Filho, W., G. J. Nagy, M. Borga, P. D. Chávez Muñoz and A. Magnuszewski (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 761-775. ISBN 9783030374259.

Rizzi, J. et al., 2017: Assessing storm surge risk under future sea-level rise scenarios: a case study in the North Adriatic coast. *Journal of Coastal Conservation*, **21**(4), 453-471, doi:10.1007/s11852-017-0517-5.
Rodríguez, A. et al., 2019: Chilling accumulation in fruit trees in Spain under climate change. *Natural Hazards and Earth System Sciences*, **19**(5), 1087-1103, doi:10.5194/nhess-19-1087-2019.
Rohat, G. et al., 2019: Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe. *Global and Planetary Change*, **172**, 45-59, doi:10.1016/j.gloplacha.2018.09.013.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163, doi:10.1016/j.crm.2017.02.001.
Romera, R. et al., 2017: Climate change projections of medicanes with a large multi-model ensemble of regional climate models. *Global and Planetary Change*, **151**, 134-143, doi:10.1016/j.gloplacha.2016.10.008.
Roudier, P. et al., 2016: Projections of future floods and hydrological droughts in Europe under a +2°C global warming. *Climatic Change*, **135**(2), 341-355, doi:10.1007/s10584-015-1570-4.
Royé, D., 2017: The effects of hot nights on mortality in Barcelona, Spain. *International Journal of Biometeorology*, **61**(12), 2127-2140, doi:10.1007/s00484-017-1416-z.
Rubel, F. and M. Kottek, 2010: Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift*, **19**(2), 135-141, doi:10.1127/0941-2948/2010/0430.
Ruiz-Benito, P. et al., 2014: Diversity increases carbon storage and tree productivity in Spanish forests. *Global Ecology and Biogeography*, **23**(3), 311-322, doi:10.1111/geb.12126.
Ruiz-Ramos, M. et al., 2018: Adaptation response surfaces for managing wheat under perturbed climate and CO_2 in a Mediterranean environment. *Agricultural Systems*, **159**, 260-274, doi:10.1016/j.agsy.2017.01.009.
Ruosteenoja, K. et al., 2018: Seasonal soil moisture and drought occurrence in Europe in CMIP5 projections for the 21st century. *Climate Dynamics*, **50**(3), 1177-1192, doi:10.1007/s00382-017-3671-4.
Saadi, S. et al., 2015: Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield. *Agricultural Water Management*, **147**, 103-115, doi:10.1016/j.agwat.2014.05.008.
Sachs, J. et al., 2019: *Sustainable Development Report 2019*. Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York, NY, USA. Available at: https://sdgindex.org/reports/sustainable-development-report-2019/ (accessed 16/10/2020).
Saladini, F. et al., 2018: Linking the water-energy-food nexus and sustainable development indicators for the Mediterranean region. *Ecological Indicators*, **91**, 689-697, doi:10.1016/j.ecolind.2018.04.035.
Salvati, A., H. Coch Roura and C. Cecere, 2017: Assessing the urban heat island and its energy impact on residential buildings in Mediterranean climate: Barcelona case study. *Energy and Buildings*, **146**, 38-54, doi:10.1016/j.enbuild.2017.04.025.
Samara, T., D. Raptis and I. Spanos, 2018: Fuel treatments and potential fire behavior in peri-urban forests in Northern Greece. *Environments*, **5**(7), doi:10.3390/environments5070079.
Sánchez-Arcilla, A. et al., 2016: A review of potential physical impacts on harbours in the Mediterranean Sea under climate change. *Regional Environmental Change*, **16**(8), 2471-2484, doi:10.1007/s10113-016-0972-9.
Sánchez-Pinillos, M., L. Coll, M. De Cáceres and A. Ameztegui, 2016: Assessing the persistence capacity of communities facing natural disturbances on the basis of species response traits. *Ecological Indicators*, **66**, 76-85, doi:10.1016/j.ecolind.2016.01.024.
Sánchez-Salguero, R. et al., 2020: Shifts in growth responses to climate and exceeded drought-vulnerability thresholds characterize dieback in two Mediterranean deciduous oaks. *Forests*, **11**(7), 714.
Sanchis-Ibor, C., M. García-Mollá and L. Avellà-Reus, 2016: Effects of drip irrigation promotion policies on water use and irrigation costs in Valencia, Spain. *Water Policy*, **19**(1), 165-180, doi:10.2166/wp.2016.025.
Sancho-García, A., J. Guillén and E. Ojeda, 2013: Storm-induced readjustment of an embayed beach after modification by protection works. *Geo-Marine Letters*, **33**, 159–172, doi:10.1007/s00367-012-0319-6.
Sangüesa-Barreda, G. et al., 2019: Droughts and climate warming desynchronize Black pine growth across the Mediterranean Basin. *Science of The Total Environment*, **697**, 133989, doi:10.1016/j.scitotenv.2019.133989.
Sanz-Cobena, A. et al., 2017: Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. *Agriculture, Ecosystems & Environment*, **238**, 5-24, doi:10.1016/j.agee.2016.09.038.
Satta, A., M. Puddu, S. Venturini and C. Giupponi, 2017: Assessment of coastal risks to climate change related impacts at the regional scale: The case of the Mediterranean region. *International Journal of Disaster Risk Reduction*, **24**, 284-296, doi:10.1016/j.ijdrr.2017.06.018.
Sayol, J. M. and M. Marcos, 2018: Assessing flood risk under sea level rise and extreme sea levels scenarios: Application to the Ebro delta (Spain). *Journal of Geophysical Research: Oceans*, **123**(2), 794-811, doi:10.1002/2017jc013355.
Schils, R. et al., 2018: Cereal yield gaps across Europe. *European Journal of Agronomy*, **101**, 109-120, doi:10.1016/j.eja.2018.09.003.
Schlenker, W. and M. J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences*, **106**(37), 15594, doi:10.1073/pnas.0906865106.

Schoennagel, T. et al., 2017: Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences*, **114**(18), 4582, doi:10.1073/pnas.1617464114.
Scortichini, M. et al., 2018: The inter-annual variability of heat-related mortality in nine European cities (1990–2010). *Environmental Health*, **17**(1), 66, doi:10.1186/s12940-018-0411-0.
Scott, D., M. Rutti, B. Amelung and M. Tang, 2016: An inter-comparison of the Holiday Climate Index (HCI) and the Tourism Climate Index (TCI) in Europe. *Atmosphere*, **7**(6), 80, doi:10.3390/atmos7060080.
Scott, M. et al., 2020: Climate disruption and planning: Resistance or retreat? *Planning Theory & Practice*, **21**(1), 125-154, doi:10.1080/14649357.2020.1704130.
Sebri, M., 2017: Bridging the Maghreb's water gap: from rationalizing the virtual water trade to enhancing the renewable energy desalination. *Environment, Development and Sustainability*, **19**(5), 1673-1684, doi:10.1007/s10668-016-9820-9.
Sellers, S., 2016: *Gender and Climate Change: A Closer Look at Existing Evidence*. Global Gender and Climate Alliance, 51 pp. Available at: https://wedo.org/wp-content/uploads/2016/11/GGCA-RP-FINAL.pdf (accessed 07/11/2020).
Semenza, J. C. and J. E. Suk, 2017: Vector-borne diseases and climate change: a European perspective. *FEMS Microbiology Letters*, **365**(2), doi:10.1093/femsle/fnx244.
Semenza, J. C. et al., 2016: Climate change projections of West Nile virus infections in Europe: implications for blood safety practices. *Environmental Health*, **15**(1), S28, doi:10.1186/s12940-016-0105-4.
Seneviratne, S. I. et al., 2012: Changes in Climate Extremes and their Impacts on the Natural Physical Environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C. B., V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 109-230. ISBN 9781107025066.
Settele, J. et al., 2014: Terrestrial and Inland Water Systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359. ISBN 9781107058071.
Sierra, J. P. et al., 2016: Vulnerability of Catalan (NW Mediterranean) ports to wave overtopping due to different scenarios of sea level rise. *Regional Environmental Change*, **16**(5), 1457-1468, doi:10.1007/s10113-015-0879-x.
Sierra, J. P. et al., 2017: Modelling the impact of climate change on harbour operability: The Barcelona port case study. *Ocean Engineering*, **141**, 64-78, doi:10.1016/j.oceaneng.2017.06.002.
Simionescu, M., W. Strielkowski and M. Tvaronavičienė, 2020: Renewable energy in final energy consumption and income in the EU-28 Countries. *Energies*, **13**, 2280, doi:10.3390/en13092280.
Simpson, I. R., R. Seager, T. A. Shaw and M. Ting, 2014: Mediterranean summer climate and the importance of Middle East topography. *Journal of Climate*, **28**(5), 1977-1996, doi:10.1175/JCLI-D-14-00298.1.
Slangen, A. B. A. et al., 2017: A review of recent updates of sea-level projections at global and regional scales. *Surveys in Geophysics*, **38**(1), 385-406, doi:10.1007/s10712-016-9374-2.
Smid, M. et al., 2019: Ranking European capitals by exposure to heat waves and cold waves. *Urban Climate*, **27**, 388-402, doi:10.1016/j.uclim.2018.12.010.
Solaun, K. and E. Cerdá, 2017: The impact of climate change on the generation of hydroelectric power - A case study in Southern Spain. *Energies*, **10**(9), 1343, doi:10.3390/en10091343.
Solyman, A. and T. Abdel Monem, 2020: Mapping Egypt vulnerability to sea level rise scenarios. In: *Climate Change Impacts on Agriculture and Food Security in Egypt: Land and Water Resources—Smart Farming—Livestock, Fishery, and Aquaculture* [Ewis Omran, E.-S. and A. M. Negm (eds.)]. Springer International Publishing, Cham, pp. 183-201. ISBN 978-3-030-41629-4.
Somanathan, E., R. Somanathan, A. Sudarshan and M. Tewari, 2018: *The Impact of Temperature on Productivity and Labor Supply: Evidence from Indian Manufacturing*. Becker Friedman Institute, Chicago, IL, USA, 70 pp. Available at: https://bfi.uchicago.edu/wp-content/uploads/BFI-WP_2018-69.pdf (accessed 08/11/2020).
Soto-Navarro, J. et al., 2020: Evolution of Mediterranean Sea water properties under climate change scenarios in the Med-CORDEX ensemble. *Climate Dynamics*, **54**(3), 2135-2165, doi:10.1007/s00382-019-05105-4.
Spinoni, J. et al., 2019: A new global database of meteorological drought events from 1951 to 2016. *Journal of Hydrology: Regional Studies*, **22**, 100593, doi:10.1016/j.ejrh.2019.100593.
Spinoni, J., G. Naumann and J. V. Vogt, 2017: Pan-European seasonal trends and recent changes of drought frequency and severity. *Global and Planetary Change*, **148**, 113-130, doi:10.1016/j.gloplacha.2016.11.013.
Spinoni, J., G. Naumann, J. V. Vogt and P. Barbosa, 2015: The biggest drought events in Europe from 1950 to 2012. *Journal of Hydrology: Regional Studies*, **3**, 509-524, doi:10.1016/j.ejrh.2015.01.001.
Spinoni, J. et al., 2018a: Changes of heating and cooling degree-days in Europe from 1981 to 2100. *International Journal of Climatology*, **38**(S1), e191-e208, doi:10.1002/joc.5362.
Spinoni, J. et al., 2018b: Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, **38**(4), 1718-1736, doi:10.1002/joc.5291.

Springmann, M. et al., 2016: Global and regional health effects of future food production under climate change: a modelling study. *The Lancet*, **387**(10031), 1937-1946, doi:10.1016/S0140-6736(15)01156-3.
Stagge, J. H., D. G. Kingston, L. M. Tallaksen and D. M. Hannah, 2017: Observed drought indices show increasing divergence across Europe. *Scientific Reports*, **7**(1), 14045, doi:10.1038/s41598-017-14283-2.
Stergiou, K. I. et al., 2016: Trends in productivity and biomass yields in the Mediterranean Sea Large Marine Ecosystem during climate change. *Environmental Development*, **17**, 57-74, doi:10.1016/j.envdev.2015.09.001.
Stocker, T. F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Szewczyk, W., J. C. Ciscar, I. Mongelli and A. Soria, 2018: *JRC PESETA III project: Economic integration and spillover analysis*. Union, P. O. o. t. E., Luxembourg, 49 pp.
Tàbara, J. D. et al., 2018: Exploring institutional transformations to address high-end climate change in Iberia. *Sustainability*, **10**(1), 161, doi:10.3390/su10010161.
Tagliapietra, D. et al., 2019: Bioerosion effects of sea-level rise on the Doge's Palace water doors in Venice (Italy). *Facies*, **65**(3), 34, doi:10.1007/s10347-019-0577-0.
Tagliapietra, S., 2018: *The euro-mediterranean energy relationship: a fresh perspective*. Policy Briefs 27839, Bruegel, Brussels, Belgium. Available at: https://www.bruegel.org/2018/10/the-euro-mediterranean-energy-relationship-a-fresh-perspective/ (accessed 28/10/2020).
Tanasijevic, L. et al., 2014: Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. *Agricultural Water Management*, **144**, 54-68, doi:10.1016/j.agwat.2014.05.019.
Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515**(7528), 518-522, doi:10.1038/nature13959.
Tobin, I. et al., 2018: Vulnerabilities and resilience of European power generation to 1.5 degrees C, 2 degrees C and 3 degrees C warming. *Environmental Research Letters*, **13**(4), doi:10.1088/1748-9326/aab211.
Tomaz, A., C. A. Pacheco and J. M. Coleto Martinez, 2017: Influence of cover cropping on water uptake dynamics in an irrigated Mediterranean vineyard. *Irrigation and Drainage*, **66**(3), 387-395, doi:10.1002/ird.2115.
Tovar-Sánchez, A., D. Sánchez-Quiles and A. Rodríguez-Romero, 2019: Massive coastal tourism influx to the Mediterranean Sea: The environmental risk of sunscreens. *Science of The Total Environment*, **656**, 316-321, doi:10.1016/j.scitotenv.2018.11.399.
Tramblay, Y., L. Jarlan, L. Hanich and S. Somot, 2018: Future scenarios of surface water resources availability in North African dams. *Water Resources Management*, **32**(4), 1291-1306, doi:10.1007/s11269-017-1870-8.
Tramblay, Y. et al., 2020: Challenges for drought assessment in the Mediterranean region under future climate scenarios. *Earth-Science Reviews*, **210**, 103348, doi:10.1016/j.earscirev.2020.103348.
Tramblay, Y. et al., 2019: Detection and attribution of flood trends in Mediterranean basins. *Hydrology and Earth System Sciences*, **23**(11), 4419-4431, doi:10.5194/hess-23-4419-2019.
Tramblay, Y. and S. Somot, 2018: Future evolution of extreme precipitation in the Mediterranean. *Climatic Change*, **151**(2), 289-302, doi:10.1007/s10584-018-2300-5.
Triberti, L., A. Nastri and G. Baldoni, 2016: Long-term effects of crop rotation, manure and mineral fertilisation on carbon sequestration and soil fertility. *European Journal of Agronomy*, **74**, 47-55, doi:10.1016/j.eja.2015.11.024.
Tsikliras, A. C. and K. I. Stergiou, 2014: Mean temperature of the catch increases quickly in the Mediterranean Sea. *Mar Ecol Prog Ser*, **515**, 281-284, doi:10.3354/meps11005.
Tsiros, I. X. et al., 2018: An assessment to evaluate potential passive cooling patterns for climate change adaptation in a residential neighbourhood of a Mediterranean coastal city (Athens, Greece). *International Journal of Global Warming*, **16**(2), 181-208, doi:10.1504/IJGW.2018.094557.
Tsoukala, V. K., V. Katsardi, K. Hadjibiros and C. I. Moutzouris, 2015: Beach erosion and consequential impacts due to the presence of harbours in sandy beaches in Greece and Cyprus. *Environmental Processes*, **2**(1), 55-71, doi:10.1007/s40710-015-0096-0.
Tulone, A. et al., 2019: What are the effects of sea warming on the fishing industry? *Economia Agro-Alimentare / Food Economy*, **21**(2), 217-233, doi:10.3280/ECAG2019-002003.
Turan, C., D. Erguden and M. Gürlek, 2016: Climate change and biodiversity effects in Turkish seas. *Natural and Engineering Sciences*, **1**(2), 15-24.
Turco, M. et al., 2016: Decreasing fires in Mediterranean Europe. *PLoS ONE*, **11**(3), e0150663, doi:10.1371/journal.pone.0150663.
Turco, M. et al., 2018a: Skilful forecasting of global fire activity using seasonal climate predictions. *Nature Communications*, **9**(1), 2718, doi:10.1038/s41467-018-05250-0.
Turco, M. et al., 2018b: Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nature Communications*, **9**(1), 3821, doi:10.1038/s41467-018-06358-z.
Turco, M. et al., 2017: On the key role of droughts in the dynamics of summer fires in Mediterranean Europe. *Scientific Reports*, **7**(1), 81, doi:10.1038/s41598-017-00116-9.
Twining-Ward, T. et al., 2018: *Climate Change Adaptation in the Arab States - Best practices and lessons learned*. Bangkok Regional Hub (BRH), United Nations Development Programme (UNDP), Bangkok, Thailand, 90 pp. Available at:

https://www.undp.org/content/dam/undp/library/Climate%20and%20Disaster%20Resilience/Climate%20Change/Arab-States-CCA.pdf (accessed 02/11/2020).
UN DESA, 2017: World Population Prospects 2017, United Nations, Department of Economic and Social Affairs, Population Dynamics. Available at: https://population.un.org/wup/.
UN DESA, World Population Prospects 2019, United Nations, Department of Economic and Social Affairs, Population Dynamics. Available at: https://population.un.org/wpp/DataQuery/.
UNEP/MAP, 2016: *Mediterranean Strategy for Sustainable Development 2016-2025*. Valbonne. Plan Bleu, Regional Activity Centre, 84 pp. Available at: https://planbleu.org/sites/default/files/publications/mssd_2016-2025_final.pdf (accessed 31/10/2020).
UNEP/MAP and Plan Bleu, 2020: *State of the Environment and Development (SoED) in the Mediterranean*. State of the Environment and Development in the Mediterranean, United Nations Environment Programme (UNEP), Nairobi, Kenya, 342 pp. Available at: https://planbleu.org/wp-content/uploads/2020/10/SoED-Full-Report.pdf (accessed 07/11/2020).
UNICEF, 2014: *The Challenges of Climate Change: Children on the front line*. UNICEF Office of Research, Insight, I., Florence, Italy, 123 pp. Available at: https://www.unicef-irc.org/publications/716-the-challenges-of-climate-change-children-on-the-front-line.html (accessed 07/11/2020).
UNWTO, W. T. O., 2016: UNWTO Tourism Trends Snapshot: Tourism in the Mediterranean, 2015 edition. 12 pp. Available at: https://www.e-unwto.org/doi/epdf/10.18111/9789284416929 (accessed 27/10/2020).
Urquijo, J., L. De Stefano and A. La Calle, 2015: Drought and exceptional laws in Spain: the official water discourse. *International Environmental Agreements: Politics, Law and Economics*, **15**(3), 273-292, doi:10.1007/s10784-015-9275-8.
Vafeidis, A. T. et al., 2020: Managing future risks and building socio-ecological resilience in the Mediterranean. In: *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., J. Guiot and K. Marini (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 539-588.
van Sluisveld, M. A. E., S. H. Martínez, V. Daioglou and D. P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309-319, doi:10.1016/j.techfore.2015.08.013.
Varela, V. et al., 2019: Projection of forest fire danger due to climate change in the French Mediterranean region. *Sustainability*, **11**(16), 4284, doi:10.3390/su11164284.
Varga, A. et al., 2016: Changing year-round habitat use of extensively grazing cattle, sheep and pigs in East-Central Europe between 1940 and 2014: Consequences for conservation and policy. *Agriculture, Ecosystems & Environment*, **234**, 142-153, doi:10.1016/j.agee.2016.05.018.
Vargas, J. and P. Paneque, 2019: Challenges for the integration of water resource and drought-risk management in Spain. *Sustainability*, **11**(2), 308, doi:10.3390/su11020308.
Vautard, R. et al., 2014: The European climate under a 2°C global warming. *Environmental Research Letters*, **9**(3), 034006 (034011pp), doi:10.1088/1748-9326/9/3/034006.
Venot, J.-P., M. Kuper and M. Zwarteveen (eds.), 2017: *Drip Irrigation for Agriculture. Untold stories of efficiency, innovation and development*, Routledge, 358 pp.
Vicente-Serrano, S. M. et al., 2020: Long-term variability and trends in meteorological droughts in Western Europe (1851–2018). *International Journal of Climatology*, **n/a**(n/a), doi:10.1002/joc.6719.
Vicente-Serrano, S. M. et al., 2019: Climate, irrigation, and land cover change explain streamflow trends in countries bordering the Northeast Atlantic. *Geophysical Research Letters*, **46**(19), 10821-10833, doi:10.1029/2019GL084084.
Vilà-Cabrera, A., L. Coll, J. Martínez-Vilalta and J. Retana, 2018: Forest management for adaptation to climate change in the Mediterranean basin: A synthesis of evidence. *Forest Ecology and Management*, **407**, 16-22, doi:10.1016/j.foreco.2017.10.021.
von Schuckmann, K. et al., 2020: Copernicus Marine Service Ocean State Report, Issue 4. *Journal of Operational Oceanography*, **13**(sup1), S1-S172, doi:10.1080/1755876X.2020.1785097.
Vörösmarty, C. J., P. Green, J. Salisbury and R. B. Lammers, 2000: Global water resources: Vulnerability from climate change and population growth. *Science*, **289**(5477), 284, doi:10.1126/science.289.5477.284.
Vousdoukas, M. I. et al., 2017: Extreme sea levels on the rise along Europe's coasts. *Earth's Future*, **5**(3), 304-323, doi:10.1002/2016ef000505.
Waha, K. et al., 2017: Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. *Regional Environmental Change*, **17**(6), 1623-1638, doi:10.1007/s10113-017-1144-2.
Wassef, R. and H. Schüttrumpf, 2016: Impact of sea-level rise on groundwater salinity at the development area western delta, Egypt. *Groundwater for Sustainable Development*, **2-3**, 85-103, doi:10.1016/j.gsd.2016.06.001.
Watts, N. et al., 2019: The 2019 report of The *Lancet* Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *The Lancet*, **394**(10211), 1836-1878, doi:10.1016/S0140-6736(19)32596-6.
Westhoek, H. et al., 2014: Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change*, **26**, 196-205, doi:10.1016/j.gloenvcha.2014.02.004.

WFP, 2017: *Annual Performance Report for 2016*. World Food Programme (WFP), Rome, Italy, 176 pp. Available at: https://documents.wfp.org/stellent/groups/public/documents/eb/wfp291465.pdf (accessed 08/11/2020).
Wilhite, D. A., M. V. K. Sivakumar and R. Pulwarty, 2014: Managing drought risk in a changing climate: The role of national drought policy. *Weather and Climate Extremes*, **3**, 4-13, doi:10.1016/j.wace.2014.01.002.
Wodon, Q., A. Liverani, G. Joseph and N. Bougnoux (eds.), 2014: *Climate Change and Migration: Evidence from the Middle East and North Africa*, The World Bank, Washington DC, 287 pp.
Wolff, C. et al., 2018: A Mediterranean coastal database for assessing the impacts of sea-level rise and associated hazards. *Scientific Data*, **5**, 180044, doi:10.1038/sdata.2018.44.
Wong, P. P. et al., 2014: Coastal Systems and Low-Lying Areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, M. D. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409. ISBN 9781107058071.
Wöppelmann, G. and M. Marcos, 2012: Coastal sea level rise in southern Europe and the nonclimate contribution of vertical land motion. *Journal of Geophysical Research-Oceans*, **117**, doi:10.1029/2011JC007469.
World Bank, 2014: *Turn Down the Heat: Confronting the New Climate Normal*. World Bank, Washington, DC, USA, 320 pp. Available at: http://documents.worldbank.org/curated/en/317301468242098870/pdf/927040v20WP00O0ull0Report000English.pdf.
World Bank, 2016: *High and Dry: Climate Change, Water, and the Economy*. World Bank, Washington, DC, USA, 69 pp. Available at: https://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy (accessed 31/10/2020).
World Bank, 2018: *Beyond Scarcity: Water Security in the Middle East and North Africa, MENA Development Report*. World Bank, Washington, DC, USA. Available at: http://hdl.handle.net/10986/27659 (accessed 02/11/2020).
Wu, M. et al., 2015: Sensitivity of burned area in Europe to climate change, atmospheric CO_2 levels, and demography: A comparison of two fire-vegetation models. *Journal of Geophysical Research: Biogeosciences*, **120**(11), 2256-2272, doi:10.1002/2015JG003036.
Yasuhara, M. and R. Danovaro, 2016: Temperature impacts on deep-sea biodiversity. *Biological Reviews*, **91**(2), 275-287, doi:10.1111/brv.12169.
Yeste, P. et al., 2021: Projected hydrologic changes over the north of the Iberian Peninsula using a Euro-CORDEX multi-model ensemble. *Science of The Total Environment*, **777**, 146126, doi:10.1016/j.scitotenv.2021.146126.
Zabalza-Martínez, J. et al., 2018: The influence of climate and land-cover scenarios on dam management strategies in a high water pressure catchment in Northeast Spain. *Water*, **10**(11), 1668, doi:10.3390/w10111668.
Zappa, W., M. Junginger and M. van den Broek, 2019: Is a 100% renewable European power system feasible by 2050? *Applied Energy*, **233-234**, 1027-1050, doi:10.1016/j.apenergy.2018.08.109.
Zelingher, R. et al., 2019: Economic impacts of climate change on vegetative agriculture markets in Israel. *Environmental and Resource Economics*, **74**(2), 679-696, doi:10.1007/s10640-019-00340-z.
Zhao, G. et al., 2015: The implication of irrigation in climate change impact assessment: a European-wide study. *Global Change Biology*, **21**(11), 4031-4048, doi:10.1111/gcb.13008.
Zinzi, M. and E. Carnielo, 2017: Impact of urban temperatures on energy performance and thermal comfort in residential buildings. The case of Rome, Italy. *Energy and Buildings*, **157**, 20-29, doi:10.1016/j.enbuild.2017.05.021.
Zittis, G., P. Hadjinicolaou, M. Fnais and J. Lelieveld, 2016: Projected changes in heat wave characteristics in the eastern Mediterranean and the Middle East. *Regional Environmental Change*, **16**(7), 1863-1876, doi:10.1007/s10113-014-0753-2.
Zouabi, O. and N. Peridy, 2015: Direct and indirect effects of climate on agriculture: an application of a spatial panel data analysis to Tunisia. *Climatic Change*, **133**(2), 301-320, doi:10.1007/s10584-015-1458-3.

Cross-Chapter Paper 5: Mountains

Cross-Chapter Paper Leads: Carolina Adler (Switzerland/Chile/Australia), Philippus Wester (Nepal/The Netherlands)

Cross-Chapter Paper Authors: Indra Bhatt (India), Christian Huggel (Switzerland), Gregory Insarov (Russian Federation), Michael Morecroft (United Kingdom), Veruska Muccione (Switzerland/Italy), Anjal Prakash (India)

Cross-Chapter Paper Contributing Authors: Irasema Alcántara-Ayala (Mexico), Simon K. Allen (Switzerland/New Zealand), Maaike Bader (Germany), Sophie Bigler (Switzerland), James Camac (Australia), Ritodhi Chakraborty (New Zealand/India), Aida Cuni Sanchez (Norway/Spain), Nicolás Cuvi (Ecuador), Fabian Drenkhan (Peru/Germany), Abid Hussain (Nepal/Pakistan), Amina Maharjan (Nepal), Robert Marchant (United Kingdom), Graham McDowell (Canada/USA), Samuel Morin (France), Laura Niggli (Switzerland), Ana Ochoa (Ecuador), Avash Pandey (Nepal), Julio Postigo (USA/Peru), Estelle Razanatsoa (South Africa/Madagascar), Valeria M. Rudloff (Chile), Christopher Scott (USA), Madison Stevens (Canada), Daithi Stone (New Zealand), Jessica Thorn (United Kingdom/Namibia), James Thornton (Switzerland/United Kingdom), Daniel Viviroli (Switzerland), Saskia Werners (The Netherlands)

Cross-Chapter Paper Review Editor: Georg Kaser (Austria)

Cross-Chapter Paper Scientist: Valeria M. Rudloff (Chile)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Mountains are highly significant regions in the context of climate change and sustainable development, at the intersection of accelerated warming and a large population depending directly or indirectly on them. They are regions of high biological and cultural diversity and provide vital goods and services to people living in and around mountain regions and in downstream areas. Building on the IPCC's Fifth Assessment Report (AR5), Chapter 2 "High Mountain Areas" of the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), and the IPCC Working Group I contribution to AR6, this Cross-Chapter Paper (CCP) assesses new evidence on observed and projected climate change impacts in mountain regions, their associated key risks and adaptation measures.

Observed changes, their impacts, and adaptation responses in mountains

Climate change impacts in mountains and their attribution to human influence have increased in recent decades with observable and serious consequences for people and ecosystems in many mountain regions (*high confidence*[1]). Observed changes include increasing temperatures, changing seasonal weather patterns, reductions in snow cover extent and duration at low elevation, loss of glacier mass, increased permafrost thaw, and an increase in the number and size of glacier lakes (*high confidence*). {CCP5.2.7, Figure CCP5.4, SROCC Chapter 2, WGI Section 9.5}

The spatial distributions of many plant species have shifted to higher elevations in recent decades, consistent with rising temperatures across most mountain regions (*high confidence*). Around two-thirds of treeline ecotones have also shifted upwards in recent decades, though these shifts are not ubiquitous and slower than expected based on rising temperatures (*high confidence*). Impacts on biological communities and animal species are also increasingly being reported, with species of lower elevations increasing in mountain regions, creating more homogeneous vegetation and increasing risks to mountain top species (*medium confidence*). {CCP5.2.1; Chapter 2.4}

Climate and cryosphere change have negatively affected the water cycle in mountains, including variable timing of glacier- and snow-melt stream discharge (*high confidence*). These changes have variable impacts on water availability for people and economies, contributing to increasing tensions or conflicts over water resources, especially in seasonally dry regions (*medium confidence*). Mountains are an essential source of freshwater for large, and growing populations; the number of people largely or fully dependent on water from mountains has increased worldwide from ~0.6 billion in the 1960s to ~2 billion in the past decade and globally two-thirds of irrigated agriculture depends on essential runoff contributions from the mountains. {CCP5.2.2; Figure CCP5.2; SROCC Chapter 2; 4.2.2.3; 4.4.4.1}

Climate change-driven changes in precipitation, river flow regimes and landslides affect the production and use of energy in mountain regions, in particular hydropower (*high confidence*). Billions of USD in investment and assets of energy production are exposed to changing mountain hazards. Combined effects of climate change, hydropower development and other human interventions have exacerbated water security problems and social injustice (*medium confidence*). {CCP5.2.2, SROCC Chapter 2}

Observed climate-driven impacts on mountain ecosystem services, agriculture and pastoralism are largely negative in most mountain regions (*medium confidence*). Agriculture has been negatively affected through increased exposure to hazards such as droughts and floods, changes in the onset of seasons, the timing and availability of water, increasing pests and decreasing pollinator diversity, which in turn have negatively influenced overall production, dietary diversity and nutritional value (*medium confidence*). Negative climate impacts on pastoralism, such as drought induced degradation of rangelands and pastures, have affected livestock productivity and livelihood of pastoralists, while other non-climatic factors such as

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

land-use change and management also play a role (*medium confidence*). {CCP5.2.3; CCP5.2.5; Table CCP5.2; SROCC Section 2.3.1.3.2; SROCC Section 2.3.7}

While contributing to poverty reduction in some mountain regions, there is *limited evidence* of adaptations effectively contributing to remediating the underlying social determinants of vulnerability such as gender and ethnicity (*medium confidence*). Exposure and vulnerability exacerbate the negative effects of climate impacts on livelihoods, and intertwines with power imbalances, gender and other inequalities (*medium confidence*). {CCP5.2.7; CCP5.3.2.2}

Observed changes in seasonality (timing and extent) are negatively affecting mountain winter tourism and recreation (*high confidence*), and variably affect tourism and recreation activities in other seasons (*medium confidence*). For winter activities such as skiing, diminishing snow at lower elevations has challenged their operating conditions (*medium confidence*), increasing the demand for and dependence on snow management measures such as snow-making (*high confidence*). Climate-induced hazards are negatively affecting some climbing, mountaineering, and hiking routes (*medium confidence*). In some regions, options to change routes or shift seasons to reduce hazard exposure have been employed as adaptation strategies, with variable outcomes (*medium confidence).* In some cases, higher temperatures and extreme heatwave conditions at lower elevations have made some mountain destinations more appealing, increasing the potential for summer visitation demand (*medium confidence*). {CCP5.2.5; Table CCP5.2; SROCC Ch2.3.5}

Climate-related hazards, such as flash floods and landslides, have contributed to an increase in disasters affecting a growing number of people in mountain regions and further downstream (*high confidence*). The resulting number of disasters has increased, however there is *limited evidence* that this is due to changes in the underlying hazard processes, pointing mainly to increasing levels of exposure (*medium confidence*). {CCP5.2.6; CCP5.2.7; CCP5.3.2.1}.

Adaptation responses to climate-driven impacts in mountain regions vary significantly in terms of goals and priorities, scope, depth and speed of implementation, governance and modes of decision-making, and the extent of financial and other resources to implement them (*high confidence*). Observed adaptation responses in mountains are largely incremental and mainly focus on early warning systems and the diversification of livelihood strategies in smallholder agriculture, pastoralism, and tourism. However, there is *limited evidence* of the feasibility and long-term effectiveness of these measures to address climate-related impacts and related losses and damages, including in cities and settlements experiencing changing demographics. {CCP5.2.4; CCP5.2.7.2}

Projected impacts, key risks and limits to adaptation in mountains

Increasing temperatures will continue to induce changes in mountain regions throughout the 21st century, with expected negative consequences for mountain cryosphere, biodiversity, ecosystem services and human wellbeing (*very high confidence*). Many low elevation and small glaciers around the world will lose most of their total mass at 1.5°C GWL (*high confidence*). A large majority of endemic mountain species will be at risk of extinction; regions heavily relying on glacier- and snow-melt for irrigation will face erratic water supply and increased food insecurity, whereas agriculture in some regions might see positive changes. Damages and losses from water related hazards such as floods and landslides are projected to increase considerably between 1.5 and 3° GWL. {CCP5.3.1}

Projected changes in hazards, such as floods and landslides, as well as changes in the water cycle, will lead to severe risk consequences for people, infrastructure and the economy in many mountain regions (*high confidence*). These risks will be more pervasive and also increase more rapidly in South and Central Asia and Northwestern South America. However, nearly all mountain regions will face at least moderate and some regions even high risks at around 2°C GWL (*medium confidence*). {CCP5.3.2.1, CCP5.3.2.2; 16.B.4}

There is an increasing risk of local and global species extinctions where they are not able to move to higher elevations or other cooler locations (*high confidence*), with risks from extreme events such as wildfire potentially exacerbating those risks (*medium confidence*). The topographic variation in mountains may mean that some species can survive in cooler microclimates with aspect as well as elevation.

Mountain regions may act as refugia for some species from lower elevations, if they can move into them. This may enable some species to persist in a region, although it can present a threat to cold-adapted species, including endemics, which may be outcompeted (*high confidence*); invasive non-native species may become an increasing problem in some places. {CCP5.3.2.3, Box CCP5.1; CCP1.2.2.1; 2.6.6; 16.6.3.1}

Climate change is projected to lead to profound changes and irreversible losses in mountain regions with negative consequences for ways of life and cultural identity (*medium confidence*). Intangible losses and loss of cultural values will become increasingly more widespread in mountain regions mainly driven by a decline in snow and ice and an increase in intangible harm to people from hazards (*medium confidence*). However, there is *limited evidence* on the magnitude of the consequences. {CCP5.3.2.4; 16.5.2.1; 16.5.2.3.7}

Options for future adaptation and climate resilient sustainable development in mountains

The current pace, depth and scope of adaptation is insufficient to address future risks in mountain regions, particularly at higher warming levels (*high confidence*). While the incremental nature of most implemented adaptations will not be sufficient to reduce severe risk consequences, options exist which offer practical and timely prospects to address risks before limits to adaptation are reached or exceeded. Reducing climate risks will depend on addressing the root causes of vulnerability, which include poverty, marginalization, and inequitable gender dynamics *(high confidence*). {CCP5.4.1, Figure CCP5.7; CCP5.4.2, Cross-Chapter Box DEEP in Chapter 17; Cross-Chapter Box LOSS in Chapter 17; 17.3, 17.6}

Adaptation decision-making processes that engage with and incorporate people's concerns and values and address multiple risks are more robust than those with a narrow focus on single risks (*medium confidence*). Risk management strategies that better integrate the adaptation needs of all affected sectors, account for different risk perceptions and build on multiple and diverse knowledge systems, including Indigenous knowledge and local knowledge, are important enabling conditions to reduce risk severity (*medium confidence*). {CCP5.2.6, CCP5.4.2; 17.3; 17.4; Cross-Chapter Box PROGRESS in Chapter 17; Cross-Chapter Box DEEP in Chapter 17}

Regional cooperation and transboundary governance in mountain regions, supported by multi-scale knowledge networks and monitoring programmes, enable long-term adaptation actions where risks transcend boundaries and jurisdictions (*medium confidence*). Collectively, they show potential to form an important component of the adaptation solution space in mountains. There are increasing calls for more ambitious climate action in mountains, providing impetus for stronger cooperation within and across mountain regions, and downstream areas (*medium confidence*). {CCP5.4.2; CCP5.4.3}

With warming above 1.5°C, the need for adaptation to address key risks in mountains becomes increasingly urgent (*high confidence*). Pathways and system transitions that strengthen climate-resilient sustainable mountain development are starting to receive attention, but current levels of resourcing are substantially insufficient to support timely action. {CCP5.4.2; CCP5.4.3; CCP5.5; 18.1; 18.2}

CCP5.1 Point of Departure

Mountains are an extensive and significant *typological region* (Section 1.3.3 and AR6 Glossary) in the context of climate change and sustainable development, with a large population directly or indirectly depending on mountains. These are areas of high biological and cultural diversity that provide vital goods and services – such as water, food, energy, minerals, medicinal plants, tourism and recreation, and aesthetic and spiritual values – to people living in and around these mountain regions and in downstream areas. Mountain regions are hotspots of climate related losses in, for example, ecosystems, landscapes, culture, and habitability, and while mountain people are adaptive, resourceful, and independent, they live in highly fragile environments and in some regions under challenging socioeconomic circumstances that enhance their vulnerability to climate change (Alfthan et al., 2018).

Chapter 2 "High Mountain Areas" (Hock et al., 2019) of the IPCC Special Report on the Ocean and the Cryosphere in a Changing Climate (SROCC), presented an assessment of observed changes in the high mountain cryosphere, their resulting impacts in-situ and further downstream, and the state of adaptation responses to these impacts. Before SROCC, the last time climate change in mountain regions were systematically assessed in IPCC reports was in Chapter 5 of the Second Assessment Report (SAR) (Beniston et al., 1996). Projections made at the time for climate-related changes in mountain regions were expected towards the middle and the second half of the twenty-first century, rather than as early as the past decades (Haeberli and Beniston, 2021), underscoring the striking pace of change already observed in mountain regions.

Whereas SROCC focused on impacts from a changing climate on high mountain cryosphere, this Cross-Chapter Paper (CCP) on "Mountains" synthesizes key relevant content from across the AR6 WGII report with a broader scope on the impacts and adaptation to climate change in mountain regions as defined for this assessment (Figure CCP5.1, SMCCP5.1). It provides a wider assessment of the solutions space and consequences for sustainable development due to climate change in mountain regions and downstream areas.

To define the geographical scope of the assessment in this CCP and to quantify the human population residing within these regions, the mountain characterization given by Kapos et al. (2000) (Figure CCP5.1a and SMCCP5.1), minus Antarctica, Svalbard and Greenland (which fall under the assessment scope of CCP6 Polar Regions), was employed. This characterization is consistent with the mountain region extents used in the AR6 WGI report (see AR6 WGI Atlas) and yields a global mountainous area of 31.74 million km^2, which corresponds to approximately 23.5% of the global land surface. In 2015, a total of 1.28 billion people resided in mountain regions as delineated for this CCP (SMCCP5.1).

The scope of the assessment presented in this CCP covers observed and projected climate change impacts in mountains, present, emerging and future key risks and observed adaptation responses, leading to an exploration of the adaptation solution space and climate-resilient development (pathways) in mountains. Section 5.2 presents observed impacts and adaptation responses by synthesizing information on mountains in the sectorial and regional chapters of WGII AR6, additional supporting evidence found in the literature, a Detection and Attribution assessment (SMCCP5.2) and a reanalysis of the mountain literature collected and synthesised in the Global Adaptation Mapping Initiative (GAMI) (SMCCP5.3). Section 5.3 presents an assessment of future key risks in mountains drawing from the regional and sectorial chapters and a key risks assessment for this CCP (SMCCP5.4). Section 5.4 explores the solution space for future adaptation opportunities and constraints as well as climate resilient development in mountains. This CCP concludes with key assessment limitations and knowledge gaps and prospects to address these gaps in Section 5.5.

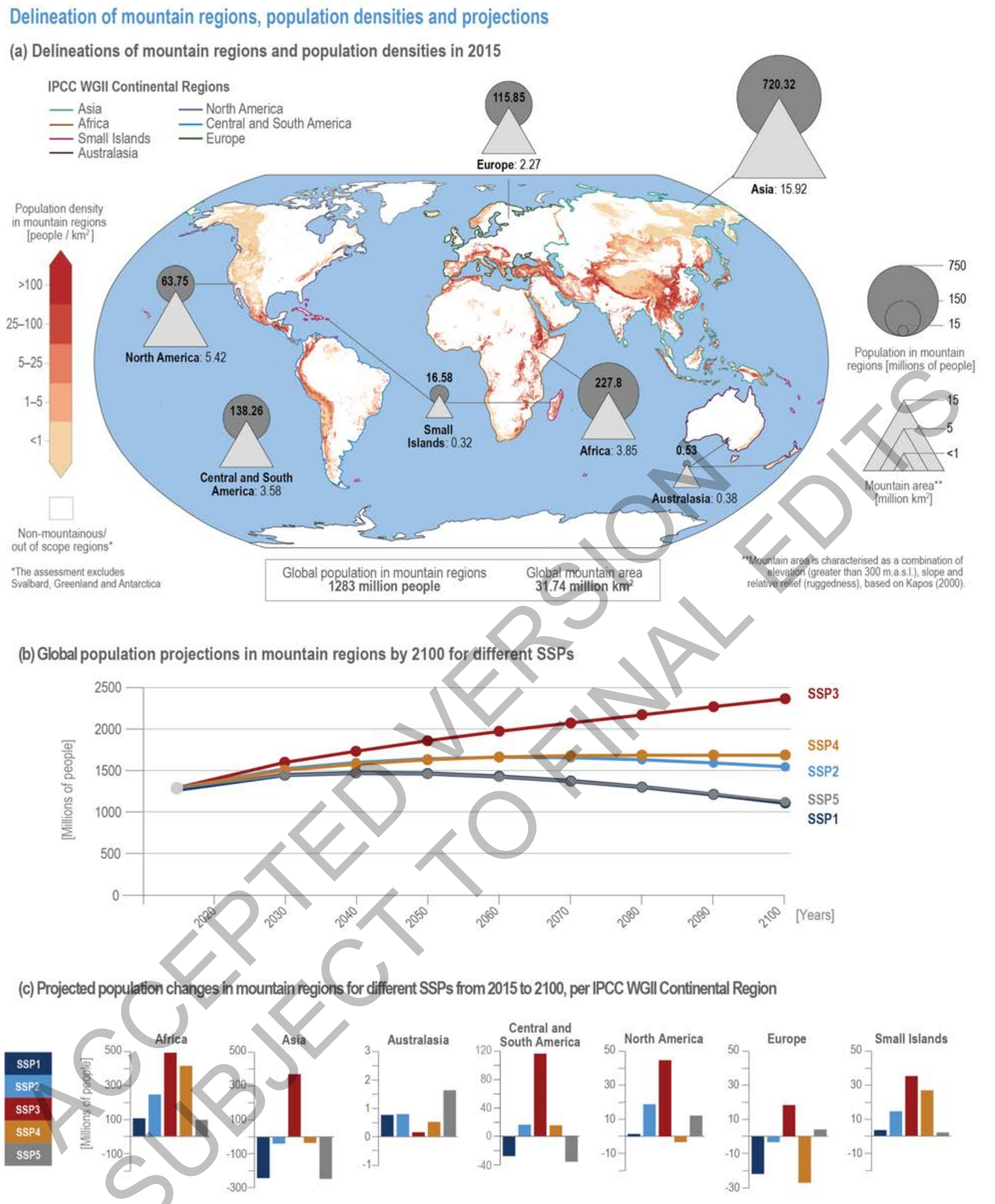


Figure CCP5.1: Delineation of mountain regions in CCP Mountains, population numbers and densities in 2015, and their projections to 2100. a) Population in mountain regions in 2015 aggregated per IPCC WGII Continental Regions, considering population densities, mountain areas and total population in mountain regions. b) Population projections in mountain regions by 2100 for different Shared Socioeconomic Pathways (SSP) scenarios. c) Projected changes in population in mountain regions from 2015 to 2100 across five different SSP scenarios, per IPCC WGII Continental Region (see SMCCP5.1 and Tables SMCCP5.1-5.4).

CCP5.2 Observed Impacts and Adaptation in Mountain Social-Ecological Systems

CCP5.2.1 Ecosystems and Ecosystem Services

Changes in climate over short distances in mountains are reflected in large ecological gradients. AR5 reported new evidence that plant species of mid and low elevations were starting to colonise high elevations in mountains. Since AR5, new studies have been published (e.g. Steinbauer et al., 2018; Payne et al., 2020), including in some previously less well studied areas such as the Andes (e.g. Morueta-Holme et al., 2015; Báez et al., 2016) and parts of Asia (e.g. Telwala et al., 2013; Artemov, 2018). There is now *high confidence* that many plant species distributions have shifted to higher elevations in recent decades, consistent with climatic warming (Sections 2.4.2; 10.4.2.1.1; 13.3.1.1). In recent years publications have also started to show similar trends in some animal species include those on birds (Freeman et al., 2018; Bani et al., 2019; Lehikoinen et al., 2019) and snails (Baur and Baur, 2013). Other climatic variables besides temperature can also affect elevational limits of species (Section 2.4.2) and sometimes in contrasting ways to temperature, for example increasing precipitation can allow some species to occur at lower elevations in dry climates (Crimmins et al., 2011; Coals et al., 2018). Tsai et al. (2015) reported large changes in the montane bird community in Taiwan which they link to changes in weather patterns including more severe typhoons. Changes in the amplitude and frequency of bank vole population waves in the Ilmen Nature Reserve, Middle Urals can be linked to a longer frost-free periods (Kiseleva, 2020).

There are interactions with land use, for example a decrease in forest cover can exacerbate the effects of rising temperatures (Guo et al., 2018). In contrast, Bhatta et al. (2018) showed a downward shift of species assemblages in Langtang National Park, Nepal, most likely related to interactions with land use, especially reduced grazing. Where glaciers are retreating, new areas become available for pioneer species to colonise and new communities to form (Cuesta et al., 2019; Hock et al., 2019; Muhlfeld et al., 2020). The risk of extreme events such as wildfire, drought, floods and landslips is increasing in a wide range of places as a result of climate change and the evidence of the disturbance they cause to ecosystems has grown in recent decades (Section 2.3.1, Box CCP5.1). The impacts of such extreme events may be larger than those of incremental changes.

For species at lower elevations, mountains may represent refugia to which they can retreat. In this respect, Elsen et al. (2018) have highlighted the importance of protecting areas along elevational gradients. This applies in freshwater as well as terrestrial habitats with mountain streams acting as potential refugia (Isaak et al., 2016). In contrast, species restricted to the highest elevations are increasingly at risk, including from competition with colonising species (Britton et al., 2016; Winkler et al., 2016). Mountain top species are often separated from potential new habitat by large areas with unsuitable climates and tropical mountain species often have particularly narrow thermal tolerance and limited dispersal capacity (Polato et al., 2018).

The risks posed by non-native species may increase with climate change (Carboni et al., 2018; Shrestha et al., 2018; Thapa et al., 2018). Koide et al. (2017) found that non-native plant species on Hawaii were moving to higher elevations, whereas native species distributions were retracting at their lower elevational limit. Dainese et al. (2017) found that non- native plant species spread to higher elevations approximately twice as fast as native species. Following recent climate warming, invasive bamboo *Phyllostachys edulis* and *Phyllostachys bambusoides* (Poaceae) in Japan has shifted northward and upslope in the last three decades (Takano et al., 2017). New evidence has shown that variations in microclimate, with topography and cold groundwater seeps, can provide micro-refugia small areas of locally suitable conditions where cold adapted species can survive (Bramer et al., 2018; Muhlfeld et al., 2020) (Section 2.6.2). Some alpine species have thrived in recent years, and the range of microclimates may partly explain this (Rumpf et al., 2018).

Treeline elevation is linked to temperature (Paulsen and Körner, 2014) but may also be affected by water supply (Sigdel et al., 2018; Lu et al., 2021) and land management. A recent summary of treeline shifts worldwide found that 67% of studied alpine treelines had shifted upwards while 33% remained stable (based on 142 published studies); 88.8% of the 143 undisturbed alpine treelines across the northern Hemisphere had shifted upwards (Hansson et al., 2021; Lu et al., 2021). Since AR5, new evidence of shifting treeline ecotones has emerged for a wide variety of species in different locations including in Siberia (Pospelova et al., 2017), various parts of the Ural Mountains (Shiyatov and Mazepa, 2015; Zolotareva and Zolotarev, 2017; Sannikov et al., 2018), in Canadian Rocky Mountains (Trant et al., 2020) and Himalaya (Tiwari and Joshi, 2015; Chakraborty et al., 2016; Gaire, 2016; Yadava et al., 2017). Recent studies of treelines that have not or hardly shifted include the Himalaya (Singh et al., 2015; Sigdel et al., 2018), eastern Tibetan Plateau (Wang et al., 2020), and the Andes (Lutz et al., 2014). Migration rates are not proceeding as fast as warming climate, implying other processes also limit treeline ecotone response (e.g. Sigdel et al., 2020; Lu et al., 2021).

Whether treeline shifts occur, and if so at what rate, depends on a range of factors including: land use (especially livestock grazing and fire), species interactions, wildfires, and climatic stress factors (wind, frost, drought, excess or shortage of snow) interacting with tree population processes (viable seed production, dispersal, seedling establishment, clonal propagation, growth, dieback, mortality). Differences in treeline shifts between North- and South-facing slopes have been demonstrated in the Rocky Mountains (Elliott and Cowell, 2015). Grigorieva and Moiseev (2018) showed that significant factors limiting the number of seedlings and shoots are the snow depth, the topsoil temperature dependent on it, and the degree of competition from the parental tree stand and grass–shrub vegetation. There is also an influence of land use and management in many mountains around the world. Suwal et al. (2016) found that elevational shifts in Himalayan silver fir in Nepal were larger when areas were protected from management. Similarly, Lutz et al. (2014) found faster treeline shifts in the Peruvian Andes in protected areas than that in other areas, where cattle grazing and fires are more frequent. Treeline ecotones can also change independent of climate change if land use changes (Vitali et al., 2019; Körner, 2020).

Changes in community composition are also happening within ecosystem types. Duque et al. (2015) showed a change in the composition of north Andean forests, and Feeley et al. (2013) in that of forests up to 2800 m in Costa Rica. In both cases the proportion of species adapted to warmer conditions increased, driven primarily by patterns of mortality, indicating that the changes in composition are mostly via range retractions, rather than range shifts or expansions. An analysis of 200 forest inventory plots in the Andes likewise indicated a widespread, though not ubiquitous, thermophilization of the tree species' composition (Fadrique et al., 2018). Within a period of eight years (2003–2010), significant shifts in communities of vascular plants, butterflies and birds were found in Switzerland (Roth et al., 2014). At lower elevations, communities of all species groups changed towards warm-dwelling species, corresponding to an average uphill shift of 8 m, 38 m and 42 m in plant, butterfly and bird communities, respectively. However, rates of community changes decreased with elevation in plants and butterflies, while bird communities shifted towards warm-dwelling species at all elevations (Roth et al., 2014).

Changes in mountain biodiversity and ecosystems have a wide range of impacts on ecosystem services and effects on people. Some mountain ecosystems, particularly those with peatlands or forests are important carbon stores and climate change presents a risk to these in some locations (Dwire et al., 2018) (Sections 2.4.3.8; 2.4.4.4; 2.4.4.5). Palomo (2017) identified a wide range of threats to the lives, livelihoods and culture of mountain people as a consequence of the impacts of climate change on ecosystems. However, impacts are very heterogeneous between locations, even within the same region and ecosystem type (for example mountain forests in Europe; Mina et al. (2017) and are not necessarily all negative. As well as changes in services, other impacts on humans from a changing climate may be mediated through species and ecosystems, for example changes in vector distribution shifting disease incidence into higher elevation areas (Escobar et al., 2016).

[START BOX CCP5.1 HERE]

Box CCP5.1: Wildfires and Mountain Ecosystems

Mountain ecosystems have long been known to be highly sensitive to the direct impacts of climatic warming and drying (Beniston et al., 1994; Nogués-Bravo, 2009; Gottfried et al., 2012; Guisan et al., 2019). Furthermore, wildfires in these ecosystems, as with many others (Sections 2.4.4.2 and 2.5.3.2), are also expected to increase (Abatzoglou et al., 2019). This is because the occurrence and severity of fire is governed by four fundamental processes that are intricately linked to climate: 1) fuel biomass growth; 2) fuel moisture and type; 3) ignition source; and 4) favourable weather conditions for fire spread (Bradstock, 2010).

In temperate and tropical mountain ecosystems, increases in fire activity are potentially linked to changing climate on most continents, including Europe (Dupire et al., 2017), North America (Westerling, 2016; Halofsky et al., 2020; Burke et al., 2021), South America (Román-Cuesta et al., 2014), Africa (Hemp, 2005), Asia (Tian et al., 2014) and Australia (Bradstock et al., 2014; Abram et al., 2021). In these ecosystems, fire frequency, severity and extent (i.e. the fire regime) are increasing because of climate-induced impacts on fuel moisture (Gergel et al., 2017; Littell et al., 2018), vegetation composition (i.e. fuel types) (Camac et al., 2017; Prichard et al., 2017; Zylstra, 2018), fire-conducive weather patterns and the length of fire seasons (Westerling, 2016; Fill et al., 2019; Di Virgilio et al., 2020).

Fire in mountain ecosystems alters many ecological processes and ecosystem services across all elevational zones, from foothill montane forests to the high elevation alpine (treeless) zones (Turner et al., 2003; Williams et al., 2008; Oliveras et al., 2014; Rocca et al., 2014; Oliveras et al., 2018). However, the magnitude of short-term and long-term fire impacts depends on the degree of novelty of future fire regimes and the capacity of species to adapt to change (Camac et al., 2017; Archibald et al., 2018; Camac et al., 2021).

Montane and subalpine ecosystems have variable ecological responses to fire that are ultimately influenced by long-term, historical fire regimes and the evolutionary forces that have governed post-fire regeneration strategies of the biota. Two contrasting strategies in temperate forests are illustrated here. SE Australian mountain ash (*Eucalyptus regnans*) forests are adapted to a high severity fire regime, consisting of infrequent (>100 years), large stand-replacing wildfires (Bowman et al., 2016). Mountain ash is a long-lived obligate seeder but is slow to reach reproductive maturity (>20 years; Bowman et al., 2016). As such, natural post-fire regeneration takes decades to centuries to recover to pre-fire conditions, and if fire recurs before reproductive maturity is reached, the species can be eliminated. By contrast, ponderosa pine (*Pinus ponderosa*) forests of the SW United States have evolved with a low- or mixed-severity fire regime, where fire is frequent (5-25 year), low intensity, less likely to kill the dominant stand, and thus, allow faster post-fire recovery (Prichard et al., 2017). However, post-fire recovery times in this ecosystem are also becoming longer due to a century of effective fire suppression shifting the fire regime to one which is more infrequent, high-intensity, extensive and stand replacing (Prichard et al., 2017).

Above the treeline, fire is less common than in foothill forests. Post-fire recovery times also tend to be shorter (Williams et al., 2008; Camac et al., 2013; Verrall and Pickering, 2019) because of the dual influences of the low flammability traits coupled with most alpine plant species exhibiting strong resprouting strategies that have evolved in response to harsh climate conditions (Körner, 2003). However, fires in alpine treeless landscapes can still have long-term and catastrophic impacts on fire-sensitive vegetation types such as ground-water dependent wetlands dominated by hygrophilous plants and peat soils (De Roos et al., 2018). Similar impacts can be severe on long-lived, slow growing vegetation such as coniferous heathlands (Bowman et al., 2019), and highly restricted and threatened fauna (e.g. Mountain pygmy possum) that depend on these plant communities (Gibson et al., 2018). Such fires have even been found to have significantly impact subalpine treeline mortality rates (Fairman et al., 2017), and in some cases have resulted in treelines shifting to lower elevations (e.g. Hemp, 2005).

The long-term implications of a warmer global climate, coupled with more frequent and/or severe fires in mountain ecosystems, are expected to be transformative for mountain biota. Fire sensitive montane forests, such as Australia's alpine ash (*Eucalyptus delegatensis*) are expected to become highly susceptible to population collapse and local extinction as intervals between fire events contract and become too short for species to reach reproductive maturity (Bowman et al., 2014; Enright et al., 2015) – an impact that will *likely* be further exacerbated by recruitment failure caused by post-fire drought and moisture deficiencies (Davies et al., 2019; Halofsky et al., 2020; Rodman et al., 2020). Fire and climate change are also *likely* to act synergistically in mountainous ecosystems, via positive feedbacks that increase fire frequency by changing vegetation composition to more flammable fuel types, and thus increasing landscape susceptibility to future fire (Camac et al., 2017; Tepley et al., 2018; Zylstra, 2018; Lucas and Harris, 2021). More frequent fires in these ecosystems will also exacerbate native and exotic species invasions (Catford et al., 2009; McDougall et al., 2011; Gottfried et al., 2012; Kueffer et al., 2013), faunal population declines (Ward et al., 2020), poor air quality (de la Barrera et al., 2018; Burke et al., 2021), soil erosion and landslide risk (de la Barrera et al., 2018), and reduce freshwater catchment volumes and quality (Rust et al., 2018; Niemeyer et al., 2020), all of which will impact negatively on human health and wellbeing (Ebi et al., 2021).

Taking this evidence together, there is a significant risk of wildfire exacerbating other impacts of climate change on already vulnerable ecosystems in many mountain regions (*medium confidence*).

[END BOX CCP5.1 HERE]

CCP5.2.2 Water and Energy

CCP5.2.2.1 Water

Water is a fundamental source of life in mountain regions; it is also a central element and 'connector' in coupled natural-human systems and bears diverse meanings in different socio-cultural contexts, including in indigenous ontologies (Boelens, 2014). Water is also a key component connecting upstream mountains and downstream lowlands (Salzmann et al., 2016; Di Baldassarre et al., 2018; Encalada et al., 2019). Mountains are of paramount importance as water towers for people in the mountains and for around 2 billion people living in connected lowland areas (Immerzeel et al., 2020; Viviroli et al., 2020).

Mountain river systems are especially sensitive to, and affected by, climate change and continuing anthropogenic disturbance, including water pollution, hydropower development, water withdrawals for agriculture and human consumption, and biodiversity loss and ecosystem changes (Honda and Durigan, 2016; Encalada et al., 2019; Bissenbayeva et al., 2021; Chen et al., 2021) (*high confidence*). The effect of climate and cryosphere change in mountains on downstream water and river systems has been studied and quantified for many regions worldwide (Barnett et al., 2005; Huss, 2011; Lutz et al., 2014; O'Neel et al., 2015; Huss and Hock, 2018). Comprehensive approaches focusing on both water demand and supply aspects provide regionally or locally specified information on water availability, scarcity and security (Buytaert et al., 2014; Drenkhan et al., 2015; Brunner et al., 2019) (Chapter 4). Present and potential future hotspot regions of water scarcity that rely heavily on mountainous water sources include Central Asia, South Asia, tropical and subtropical western South America, and southwestern North America (*robust evidence, medium agreement*) (Kummu et al., 2016; Biemans et al., 2019; Immerzeel et al., 2020; Viviroli et al., 2020).

Figure CCP5.2 represents different levels of dependences of lowland areas on mountain water. At a global scale, 68% of irrigated agricultural areas in lowlands depend on essential runoff contributions from the mountains. The dependence of lowland populations on essential mountain runoff contributions increased by a factor of more than three from the 1960s to the 2000s, with increases of up to ten-fold in some major river catchments (Viviroli et al., 2020).

Many mountain regions have one or more cryosphere components (glaciers, permafrost and perennial or seasonal snow), and the mountain cryosphere is among the natural systems most sensitive to climate change worldwide (*high confidence*). The SROCC assessed a decline in all cryosphere components due to climate change over the past decades, i.e. for low-elevation snow cover (*high confidence*), permafrost (*high confidence*), and glaciers (*very high confidence*) (Hock et al., 2019). More recent studies using globally more complete data sets show a considerably higher glacier mass loss (267 ±16 Gt yr^{-1}) for 2000-2019 as compared to a (*very likely*[2]) range of 123 ±24 Gt yr^{-1} for 2006-2015 in SROCC, with a mass loss acceleration of 48 ±16 Gt per year and decade over 2000-2019 (Hugonnet et al., 2021). Assessment conclusions in SROCC found with *high confidence* that glacier shrinkage and snow cover changes over the past two decades has led to changes in the amount and timing of runoff in many mountain regions (Hock et al., 2019).

The effects of climate and environmental changes in upstream areas on downstream water quantity and quality, including nutrient, pollutant, heavy metals and sediment flux, have only been assessed in a limited number of catchments (Rakhmatullaev et al., 2009; Dong et al., 2015; Milner et al., 2017; Ilyashuk et al., 2018; Lane et al., 2019; Li et al., 2020; Chen et al., 2021). Groundwater contributions to streamflow are highly variable in mountains, but can be substantial (up to 70 to 80% or more) during low-flow periods (Frisbee et al., 2011; Baraer et al., 2015; Gordon et al., 2015; Käser and Hunkeler, 2016; Somers et al.,

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

2019). Groundwater may provide some resilience to loss of melt water from glacier and snow decline but in the longer term groundwater recharge and contribution to streamflow is expected to decrease with ongoing climate change (*medium confidence*) (Somers and McKenzie, 2020). In some mountain regions springs are a particularly important source of water, e.g. in the Himalayan region where large populations depend on them. Observations indicate reduction of water provision from springs in recent years in the Himalaya, caused by multiple causal factors (human interventions, climatic) (section 10.4.4.).

Both small-scale interventions (e.g. livestock grazing in sensitive high-elevation wetlands) as well as high-investment interventions (e.g. hydropower dams and plants) in upstream regions can strongly affect water availability, river connectivity, biodiversity and catchment management (Anderson et al., 2018; Ramsar Convention on Wetlands, 2018; Encalada et al., 2019), and are often contested and have led to conflict (*medium evidence, high agreement*) (Drenkhan et al., 2015; French et al., 2015). Climate change often exacerbates tensions or conflicts between different users over water at local, national and transboundary or regional scales; many tensions and social or political conflicts are documented, especially in seasonally dry regions; where large power inequalities among users exists; where clear and established regulations are lacking; and especially also in transboundary settings (e.g. Central Asia, Hindu-Kush-Himalaya, Andes) (Carey et al., 2014; Bocchiola et al., 2017; Yapiyev et al., 2017; Hock et al., 2019; Mukherji et al., 2019).

Water plays a fundamental role in climate change adaptation in mountains. A majority of documented adaptation efforts in mountain regions address water-related aspects (precipitation variability and extremes, including drought, water availability, floods) (McDowell et al., 2019; McDowell et al., 2020) (*high confidence*). This is a robust finding across different mountain regions and adaptation project and program types, and also in line with findings for cryosphere change related adaptation as reported in SROCC (Hock et al., 2019). Water also plays a role for adaptation in other sectors such as agriculture, disaster management and tourism and recreation (McDowell et al., 2019). There is *high confidence* that water conservation efforts, also including restoration and protection of particularly vulnerable areas (e.g., wetlands), and increase of efficiency in water use, are robust, low-regret adaptation measures.

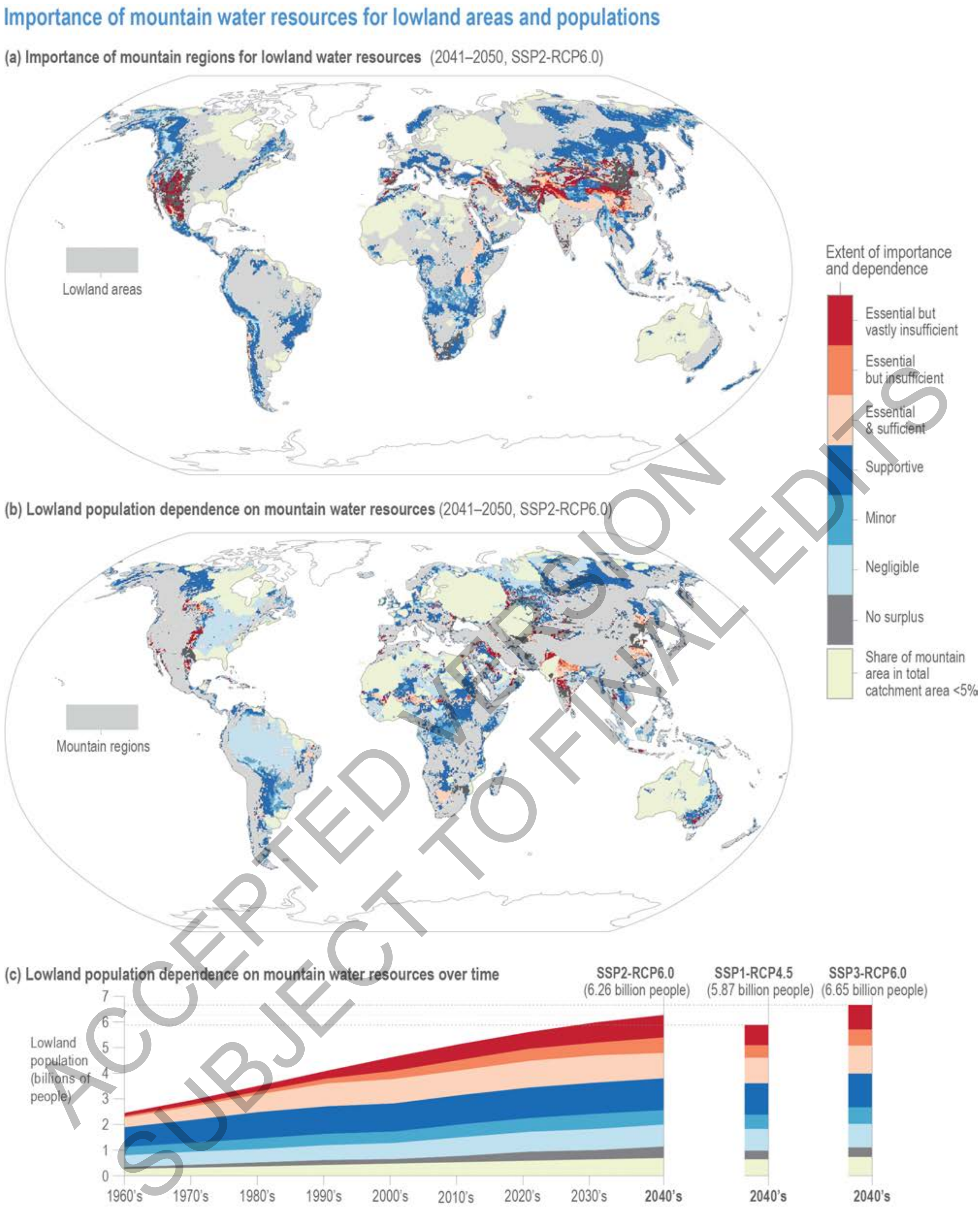


Figure CCP5.2: Dependence of land surface areas and population on mountain water resources 1961–2050. Results are shown as decadal averages for lowland population in each category of dependence on mountain water from no surplus and negligible to essential; a) map of global mountain regions and their differentiated importance for lowland water resources; b) map of lowland population and their differentiated dependence on mountain water resources, both for the scenario combination SSP2-RCP6.0 and for the time period 2041-2050; c) number of lowland population and their differentiated dependence on mountain water resources from the 1960's to the 2040's for three different scenario combinations (based on Viviroli et al., 2020).

CCP5.2.2.2 Energy

Increasing temperatures and variability in precipitation and river flow affect energy availability and use in mountain regions. Mountain peoples, more so than national or global populations, are dependent on local sources of energy, accentuating climate adaptation cost and barriers (*medium evidence, high agreement*) while also offering opportunities for mountain-specific solutions (*medium evidence, high agreement*). In mountain regions, inadequate infrastructure (Tiwari et al., 2018), remoteness, and reliance on traditional forms of energy that may be difficult to diversify (Dhakal et al., 2019), exacerbating impacts of climate change on energy use and demand.

A review of the renewable energy transition in the context of adaptation across global mountain regions, including hydropower, wind, solar and biomass, shows that observed climate change impacts on these energy sources include altered seasonality, timing as related to snow and glacial melt runoff (30.9% of analysed cases), variable or declining precipitation and runoff (26.4%), increased flooding (15.5%), altered wind patterns (8.2%), and other/not specified effects (19.1%) (Scott et al., 2019). Combined effects of climate change, hydropower development and further anthropogenic effects in upstream mountain basins, have increased and are expected to further negatively affect several aspects of ecosystem functions and water security (e.g. negative effects on river geometry, water chemistry, sediment transport, fish composition and migration) (Anderson et al., 2018; Encalada et al., 2019; Lepcha et al., 2021) (*high confidence*).

With respect to hydropower, mountains have a unique role for the production of renewable energy for large downstream populations, but it also comes with important trade-offs affecting mountain ecosystems and populations (*high confidence*) (Farinotti et al., 2019; Viviroli et al., 2020; Vaidya et al., 2021). Climate change requires adaptation in the hydropower sector; for instance, some advocate for increased water storage in dams and the importance of mountains for pumped hydropower storage systems (Gurung et al., 2016; Hunt et al., 2020), while others emphasize adaptive water management (Gaudard et al., 2014; Caruso et al., 2017b). An example is multi-purpose use of water strategies where water management storage is designed to accommodate different uses, including hydropower, agriculture, and flood risk reduction (Haeberli et al., 2016a; Drenkhan et al., 2019) (Section 12.6.3). Hydropower is also particularly exposed to glacier and snow decline (Schaefli et al., 2019), and is subject to risks from extreme events (Rangecroft et al., 2013; Schwanghart et al., 2016; Mishra et al., 2020; Shugar et al., 2021), social and political opposition (Ahlers et al., 2015; Díaz et al., 2017) and the resulting financial uncertainty for hydropower investors. There is still *limited evidence* on how climate change impacts wind, solar and biomass energy production, and use.

Overall, synergies between adaptation to climate change and renewable energy transition can be successfully generated where benefit-sharing improves local involvement and support, adaptive capacity is enhanced, local health and livelihoods supported, Sustainable Development Goals (SDGs) met, and environmental justice considered and sustainable mountain development pursued (*high agreement, medium evidence*).

CCP5.2.3 Food, Fibre, and Other Mountain Ecosystem Products

There is *high confidence* that climate change is largely negatively impacting on food, fibre and other ecosystem products, including agriculture (Porter et al., 2014; Ingxay et al., 2015; Upgupta et al., 2015; Chirwa et al., 2017; Rojas-Downing et al., 2017; Chitale et al., 2018; Pretzsch et al., 2018; Barberán et al., 2019; Sultan et al., 2019; Huang and Hao, 2020; Godde et al., 2021), and ecosystem services (Grêt-Regamey and Weibel, 2020) across many different mountainous region e.g. Africa (Bondé et al., 2019; Musakwa et al., 2020), Asia (Guo et al., 2018; Sunderland and Vasquez, 2020), Europe (Nair, 2019), North America (Hupp et al., 2015; Prevéy et al., 2020), South America (Herman-Mercer et al., 2020) (Section 5.4, 5.4.1, 5.5.1, 5.6.2, 5.7, 5.11.1.1).

Ecosystem products are vital to support the livelihoods and economic prospects for communities living in and around mountains (Figure CCP5.3). For instance, collection and trade of caterpillar fungus contributed to 53.3 - 64.5% annual household cash income in Nepal (Shrestha and Bawa, 2014; Shrestha et al., 2019); 40-80% in Bhutan (Thapa et al., 2018); 60-78% in Uttarakhand, India (Laha et al., 2018; Yadav et al., 2019) (Section 5.7.1). Livelihood support from ecosystem products in Southern Malawi region (Pullanikkatil et al., 2020), south-western Ethiopian mountains (Nischalke et al., 2017) and Southern China (Min et al., 2017), Himalayan mountains (Nepal et al., 2018), South Africa (Ngwenya et al., 2019) is reported. Additionally, the sacredness of mountains in different religions and cultures is widely acknowledged (Ceruti, 2019; Benedetti et al., 2021).

Climate change and associated impacts on multiple ecosystem services and related products (timber production, carbon sequestration, biodiversity and protection against natural hazards) have been observed across European mountains, e.g. in central Iberian Mountains (Spain), Western and Eastern Alps (France, Austria) and Dinaric Mountains (Slovenia) (Mina et al., 2017). Dumont et al. (2015) demonstrated that climate change negatively affects the forage nitrogen (N) content by 8% but increase the total non-structural carbohydrate content by 25% in European mountains. Positive impacts have been reported on mushroom productivity in the mountains of Spain (Karavani et al., 2018) (Section 5.7.3.3), yet negative impacts on the *Ophiocordyceps* in the Himalayan region (Hopping et al., 2018), likewise on apple production in Himachal Pradesh, India, which declined by 9.4 tonnes per hectare in the past two decades (Das, 2021). Shifts in crop wild relatives richness from south to north, and increase in the numbers of threatened taxa with an increase of 1.5 and 3^0C temperature rise, have been observed in European mountains (Phillips et al., 2017).

Medicinal and aromatic plants and their secondary metabolites are also observed to be affected by climate change (Das et al., 2016; Zhang et al., 2019a) *(medium confidence)*. Phenological changes like early flowering and reduced vegetative phase are negatively affecting the productivity of such plants (Harish et al., 2012; Gaira et al., 2014; Maikhuri et al., 2018). While increasing atmospheric temperature and CO_2 are reported to improve the biomass of *Gynostemmapentaphyllum* (Chang et al., 2016) (Section 5.7.3.3), they adversely affect its antioxidant compounds/activity, health-promoting properties and phytochemical content (Gairola et al., 2010; Das et al., 2016; Kumar et al., 2020). Experimental trials have shown that when medicinal plants are stressed by drought there is an increase in phytochemical content, either by decreasing biomass or by increasing actual production of the metabolites (Selmar and Kleinwächter, 2013; Al-Gabbiesh et al., 2015) *(medium confidence)*. Strong effects of climatic and non-climatic factors have been observed to affect the distribution of selected medicinal plants species in northern Thailand (Tangjitman et al., 2015), as well as in Egypt, Sub-Saharan Africa, Spain, Central Himalaya, China, Nepal, with some species at risk of being lost (Munt et al., 2016; Yan et al., 2017; Brunette et al., 2018; Chitale et al., 2018; Zhao et al., 2018; Applequist et al., 2020). Negative climate-related impacts on the distribution range of forty one medicinal plant species have been predicted for Spanish and Asian mountains (Munt et al., 2016) (Section5.7.3.3), and decreasing size of fruits of *Myrica esculenta* in Himalaya (Shah and Tewari, 2016).

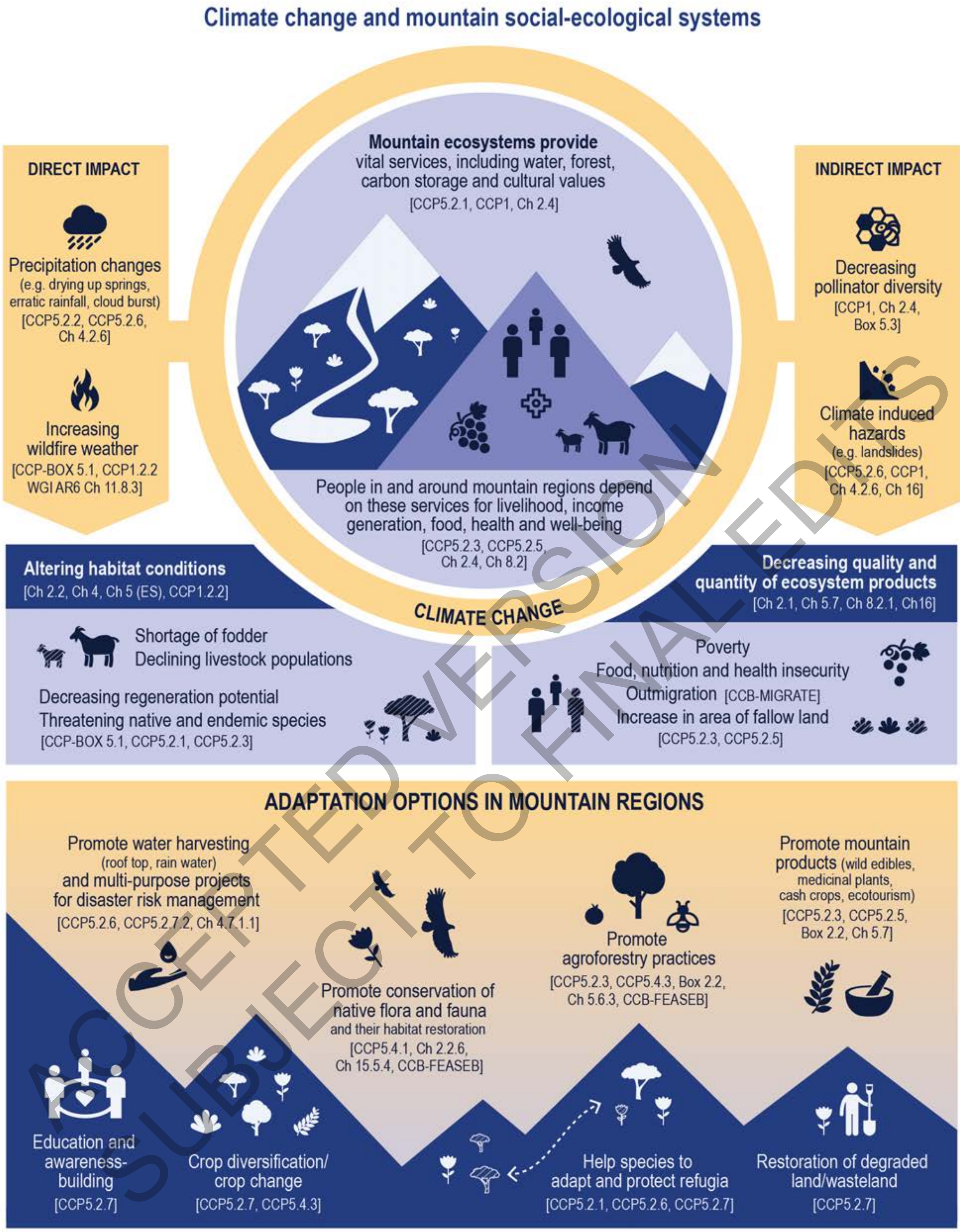


Figure CCP5.3: Impact of climate change on mountain social-ecological systems, including ecosystem services and products, livelihoods of mountain people and examples of adaptation options to address direct and indirect impacts.

CCP5.2.4 Cities, Settlements and Key Infrastructure

Mountain settlements and people are globally distributed and represent a significant proportion of the total global population that is exposed to the effects of climate change (Section CCP5.1, SMCCP5.1). Cities with one or several million inhabitants located in mountainous environments or at high elevations are predominantly found in Latin America e.g., in El Alto and La Paz (Bolivia), Quito (Ecuador), Mexico City (Mexico) and Bogotá (Colombia); Asia e.g., Kabul (Afghanistan), Kathmandu (Nepal), Srinagar (India), Peshawar (Pakistan), Quetta (Pakistan), Xining and Kunming (China), and Dehradun (India); and in Africa e.g., Harare (Zimbabwe) and Addis Ababa (Ethiopia) (Wang and Lu, 2018; Balderas Torres et al., 2021; Ehrlich et al., 2021). Mountain regions also host many settlements with fewer than 500,000 inhabitants (Alfthan et al., 2016). In many cases, particularly in developing countries, portions of the population also reside in informal and low-income settlements (French et al., 2021), where rates of poverty and inequality exacerbate their vulnerability and exposure to climate-related hazards such as landslides (Alfthan et al. 2018) (Section CCP5.2.5.1), environmental pollution or even pandemic diseases (Marazziti et al., 2021).

In many mountain regions, particularly in developing countries, the increasing urban population has put considerable pressure on water services and basic amenities for urban dwellers (Singh et al., 2021), for example in cities such as La Paz (Kinouchi et al., 2019), which are regions already under pressure due to the negative effects of climate change coupled with poor water availability and governance (Chapter 4; Section CCP5.2.2.1; FAQ CCP5.1; Hock et al. (2019). In many areas of the Hindu Kush Himalaya (HKH) region, water demand far exceeds municipal supply and people often cope with water insecurity in myriad ways (Bharti et al., 2020; Sharma et al., 2020; Singh et al., 2020), such as turning to inter-basin water transfers and deep pumping to supply their water needs (Ojha et al., 2020). Additionally, the influx of migrants, tourists and retirees, combined with the growth of the incumbent population, places considerable stress on urban infrastructure to supply adequate clean water and sewage disposal (Prakash and Molden, 2020), which is also observable in other regions (Chapter 4; Section 6.4.7; Case Study 6.1 in Chapter 6). Energy provision in and around mountain settlements, is another key sector affected by climate-related impacts (Hock et al., 2019) (CCP5.2.2.2), and which bear relevance for the adaptation prospects for urban mountain settlements (*medium confidence*).

CCP5.2.5 Mountain Communities, Livelihoods, Health and Wellbeing

People living in and around mountain regions strongly depend on the ecosystem functions, services and resources available in these areas for their livelihoods, health and wellbeing. Overall, subsistence agriculture and livestock remain key sources of livelihood in many mountain regions (FAO, 2019), with non-agricultural income sources such as remittances, small businesses, medicinal plants, wage labour and tourism also contributing to these economies (Montanari and Koutsoyiannis, 2014; Palomo, 2017; Minta et al., 2018). This section provides an illustrative overview of key reported observed impacts and adaptation responses to climate change on mountain communities (Table CCP5.1), and livelihood activities and economic sectors such as agriculture and pastoralism, and tourism and recreation (Table CCP5.2), reported since AR5.

Table CCP5.1: Overview of key observed impacts and adaptation on mountain communities – livelihoods and poverty; migration, habitability, and displacement; health and wellbeing.

Overview of key observed impacts and adaptation on mountain communities		References and relevant AR6 WGII Sections
Mountain livelihoods and poverty		
Impacts	• In some mountain regions, the incidence of poverty can be higher compared to other areas, with observed impacts of climate change intensifying the deterioration of socio-economic conditions that support livelihoods, thereby exacerbating already existing conditions of non-climate related vulnerabilities and livelihood insecurity (*medium confidence*).	Gioli et al. (2019); Tiwari and Joshi (2012); Rasul and Hussain (2015); Hussain et al. (2019); McDowell and Hess (2012); FAO (2015); FAO (2019); Shrestha et al. (2015); Motschmann et al. (2020a); Section 8.3
Responses and adaptation	• Diversification of livelihoods through the integration of drought-resilient livestock and crops and changes in farming practices (i.e. water management or migration of crops from low to high land) with some shifting to non-agricultural livelihood options, reported for cases such as in the HKH, the Andes, Rwenzori mountains of Uganda and Simien Mountains of Ethiopia.	Ashraf et al. (2014); Hussain et al. (2016a); Skarbø and VanderMolen (2016); Nkuba et al. (2020); Yohannes et al. (2020); CCP5.4.1

	Overview of key observed impacts and adaptation on mountain communities	**References and relevant AR6 WGII Sections**
Migration, habitability and displacement		
Impacts	• There is growing evidence of links between climate change impacts and migration and mobility through a complex web of causal links (*medium confidence*). In mountain contexts, migration and mobility are indirectly impacted by climate change through adverse effects on mountain livelihoods that are dependent on mountain ecosystem services.	Wrathall et al. (2014); Hunter et al. (2015); Brandt et al. (2016); Mastrorillo et al. (2016); Gautam (2017); Sagynbekova (2017); Cattaneo et al. (2019); Maharjan et al. (2020)
	• Extreme events are resulting in temporary and in some cases permanent displacement of populations in mountains (*medium confidence*), with hazards such as floods and mass movement (avalanche, flood, landslide) leading to population displacements e.g., in Afghanistan, Pakistan, Peru, Thailand, and Uganda.	Iribarren Anacona et al. (2015); Stäubli et al. (2018); IDMC (2020); Wang et al. (2020)
	• Cases of entire settlements either abandoned or relocated due to prolonged slow onset events such as water shortage, drought, and heat stress have been reported.	Mueller et al. (2014); Nawrotzki and DeWaard (2016); Prasain (2018)
	• In contrast, place attachment is increasingly cited as one of the reasons for the immobility choices for some people. However, in some cases, vulnerability to climatic events contribute to the in-migration decisions of vulnerable populations exposed to hazards from downstream to upland areas.	Adams (2016); Dandy et al. (2019); Khanian et al. (2019); Islam et al. (2020)
Responses and adaptations	• Migration, in turn, is often cited as a risk management strategy, where migration can lead to the diversification of livelihood options, improves access to information and resources, and expands social networks, all of which can support households in their capacity to adapt to climate change impacts • Migration is often gendered, with men migrating and leaving women to manage households at origin. Women's capacities are often constrained due to institutional barriers and social norms, resulting in low adaptive capacity and increased vulnerability to hazards. Capacity-building interventions strengthens adaptation capacity as well as links to access institutional support (*medium confidence*).	Banerjee et al. (2018); Banerjee et al. (2019); Siddiqui et al. (2019); Maharjan et al. (2020); Maharjan et al. (2021)
Health and wellbeing		
Impacts	• Direct links between climate change and health in mountain regions are reported in terms of physical injury or fatality due to exposure to climate-related hazards such as floods or landslides, or exposure to vector-borne diseases such as malaria or dengue fever reported at higher elevations with warming temperatures (*medium confidence*), such as in Mexico, Nepal, Ethiopia, and Colombia.	Dantés et al. (2014); Siraj et al. (2014); Dhimal et al. (2015); Wu et al. (2016); Equihua et al. (2017); Alfthan et al. (2018); Gilgel et al. (2019); Chapter 7
	• Indirect impacts to health by climate change are linked to water-borne diseases and pathogens associated with floods and droughts.	Table 7.6
	• Whilst reports on the ongoing challenges associated with the COVID-19 pandemic are emerging in relation to their compounding impacts on adaptive capacities, there is *limited evidence* to assess those effects with respect to other climate-related impacts on health.	Baiker et al. (2020); Cross-Chapter Box COVID in Chapter 7
	• Mental health issues associated with climate-related impacts are reported with respect to climate anxiety and ecological grief and their effects on the wellbeing of individuals. For example, the grief and loss associated with changes in glaciated landscapes, such as the 'death' of the Okjökull glacier in Iceland. However, there is *limited evidence* on mountain-specific cases and experiences that would allow for an assessment of the broader and longer-term impacts to mental health associated with a changing climate in the mountains.	Trombley et al. (2017); Cunsolo and Ellis (2018); Clayton (2020); Sideris (2020)
	• Other heightened vulnerability to climate-related impacts on health and wellbeing are also experienced by specific groups, for example	Furberg et al. (2011); Section 7.1.7.2

Overview of key observed impacts and adaptation on mountain communities		References and relevant AR6 WGII Sections
	Sami pastoralists facing changes in mountain snow cover that negatively affect their reindeer herding, a key activity for their identity and spiritual health.	
Responses and adaptations	• Approximately a fifth of observed adaptations reported in the GAMI mountain re-analysis address health and wellbeing as an aspect of vulnerability. This includes raising communities' awareness of and coping strategies climate change-induced health issues.	Furu and Van (2013); Section CCP5.4.1

Table CCP5.2: Overview of key observed impacts and adaptation on select livelihood activities and economic sectors – mountain agriculture and pastoralism; and tourism and recreation.

Overview of key observed impacts and adaptation on select livelihood activities and economic sectors		References and relevant AR6 WGII Sections
Mountain Agriculture and Pastoralism		
Impacts	• Changes in temperature and seasonal precipitation patterns are affecting the timing and availability of water for agricultural activities (*high confidence*), e.g. in the Bolivian Andes, Andean-Amazon foothills of Colombia, Ecuador, and Peru, High Atlas of Morocco, the Hindu Kush Himalaya (HKH), and Golestan province of Iran.	Rangecroft et al. (2013); Kaboosi and Kordjazi (2017); Hussain et al. (2018); Kalbali et al. (2019); Zkhiri et al. (2019); Beltrán-Tolosa et al. (2020); Torres-Batlló and Martí-Cardona (2020)
	• Changes in temperature and seasonal precipitation patterns are reported to affect nutrient depletion of soils and increased incidence of pest attacks in crops, e.g. in cases in the HKH and in Peru, however there is generally *limited evidence* on directs links to climate-related changes in mountain regions, specifically.	Oliver-Smith (2014); Hussain et al. (2016b)
	• Climate-induced hazards such as erratic precipitation (rain, snow and hail), floods, droughts and landslides have negatively affected the stable supply and transport of agricultural products in and out of remote mountain areas, such as in the Peruvian Altiplano and HKH.	Hussain et al. (2016b); Gonzales-Valero (2018); Thapa and Hussain (2020)
	• Warming temperatures and changes in timing of seasons and frost conditions needed for seeding of certain tree crops, are impacting lower elevation mountain areas, such as in Oman.	Buerkert et al. (2020)
	• Drought conditions are negatively affecting mountain grasslands (*medium confidence*), as reported in cases in Tyrol (Austria), Nepal, Afghanistan, Pakistan and China, which can contribute to a decline in agrobiodiversity.	Ashraf et al. (2014); Zomer et al. (2014b); Grüneis et al. (2018); Adhikari et al. (2019); Chaudhary et al. (2020); Hussain and Qamar (2020)
	• In some cases, climate-related hazards are leading to outmigration in mountain areas, with indirect negative impacts on labour deficits to support agricultural practices and productivity in mountain areas (*medium confidence*), e.g. in Ghana, Tanzania, Thailand and HKH.	Warner and Afifi (2014); Wester et al. (2019)
	• Positive impacts (favourable growing conditions) are reported for the production of some fruits and vegetables in Gilgit-Baltistan province of Pakistan, and for the production of traditional crops (e.g. local beans) in the Karnali region of Nepal.	Hussain et al. (2016b); Thapa and Hussain (2020)
	• Impacts on pastoralism include changes in growing conditions associated with warming temperatures and declining precipitation, which in turn leads to negative impacts on livestock productivity, food security and livelihoods of pastoralist communities, including drought-induced degradation of rangelands (*medium confidence*) e.g. in mountainous areas of Mongolia, Tanzania, Nepal, and Ethiopia, which exacerbate impoverished conditions for pastoral communities.	Batima et al. (2013); Rasul et al. (2014); Gentle and Thwaites (2016); Kimaro et al. (2018); Mekuyie et al. (2018); Tiwari et al. (2020)

Overview of key observed impacts and adaptation on select livelihood activities and economic sectors		References and relevant AR6 WGII Sections
Responses and adaptations	• Recharging groundwater and adopting rainwater harvesting (including appropriate tillage methods to improve soil moisture), restoration and rehabilitation of land, diversification of agricultural crops (including introduction of stress resistant crop varieties), promotion of in situ (protected areas, conservation areas) and ex situ (nurseries, gene banks, home gardens) conservation strategies, afforestation and agro-forestry.	Sections 4.7.1.1; 5.6.3; Cross-Chapter Box FEASIB in Chapter 18
	• Local knowledge is being used to help maintain the productive and cultural value of mountain agriculture and pastoralism, such as in the French and Italian Alps, Western Himalaya in India, and mountains in northern Morocco.	Fassio et al. (2014); Kmoch et al. (2018); Das (2021)
	• Ecosystem-based and community-based adaptation are contributing to supporting the diversity and complementarily of management options, permaculture, and local capacities to adapt and support ecosystem functions vital for agrobiodiversity (*medium confidence*).	Reid (2016); Grêt-Regamey and Weibel (2020); Cross-Chapter Box NATURAL in Chapter 2
Tourism and Recreation		
Impacts	• Since SROCC, the literature on climate change impacts on ski winter tourism has remained dominated by studies focused on future climate change impacts and projected risks due to decreasing seasonal snow reliability (see CCP5.3.1), most relevant when considering snow management and in particular snowmaking.	Hock et al. (2019); Sauri and Llurdés (2020); AR6 WG1 Sections 9.5.3 and 12.4.10.4
	• Climate-induced hazards in mountains, such as rockfalls, are negatively affecting access to some climbing, mountaineering, and hiking routes in summer (*medium confidence*), with cases mainly reported in the European Alps.	Hock et al. (2019); Mourey et al. (2019); Mourey et al. (2020)
	• Higher temperatures and extreme heatwave conditions at lower elevations have made some mountain destinations more appealing for human comfort, increasing the potential summer visitation demand and opportunities for tourism and recreation in mountains, such as in the European Alps and the Catalan Pyrenees (*medium confidence*). However, there is *limited evidence* reported for similar trends in mountain regions outside of Europe.	Serquet and Rebetez (2011); March et al. (2014); Pröbstl-Haider et al. (2015); Steiger et al. (2016); Juschten et al. (2019a); Juschten et al. (2019b)
Responses and adaptation	• Diversification of tourism activities to non-snow activities is reported as an adaptation approach to maintain economic viability in some winter ski areas, partly due to the high cost of running snowmaking infrastructure in winter e.g. in the Pyrenees (Europe) and Australian Alps.	Morrison and Pickering (2013); Sauri and Llurdés (2020)
	• In some cases, managing the availability and demand for water resources used for snowmaking is reported, with destination and large-scale governance highlighted as critical aspects for managing trade-offs, including overcoming conflicts arising from competing demands for environmental resources and land use, e.g. in the French Alps and in Scandinavia.	Demiroglu et al. (2019); Gerbaux et al. (2020)
	• For snow management, there are examples of dedicated climate services designed to enable better-informed decision making on appropriate long-term adaptation e.g. through a dedicated Copernicus Climate Change Service, or real-time early warning systems.	Köberl et al. (2021); Morin et al. (2021)
	• Barriers to adaptation strategies such as snowmaking, for instance in Switzerland, have been linked to perceived economic constrains to their implementation, as well as the social acceptability of these measures.	Matasci et al. (2014); Moser and Baulcomb (2020)
	• Adaptation options to limit exposure to hazards in hiking, climbing or mountaineering activities, include shifting the seasonal timing for practicing these activities, or changing routes entirely.	Hock et al. (2019); Mourey et al. (2019); Mourey et al. (2020)

Overview of key observed impacts and adaptation on select livelihood activities and economic sectors	References and relevant AR6 WGII Sections
• In some cases, such as in Bolivia, Peru, and New Zealand, and more recently reported in the French Alps, 'last chance' tourism has increased the appeal of some mountain destinations, resulting in visitation demand to witness the effects of climate change on iconic mountain landscape features such as glaciers.	Hock et al. (2019); Salim and Ravanel (2020)

Other sections in this CCP provide detailed assessments that synthesise impacts and adaptation on the detection and attribute of impacts to anthropogenic climate change (CCP5.2.7), projected impacts and key risks (CCP5.3), and adaptation responses to reduce those key risks (CCP5.4.1).

CCP5.2.6 Natural Hazards and Disasters

Climate and weather-related disasters in mountain regions have increased over the last three decades (*medium confidence*). Disaster frequency shows increasing trends in the Hindu Kush Himalaya, the Andes and mountain regions in Africa, whereas no clear trends for the European Alps and Central Asia are observed (*medium confidence*) (Froude and Petley, 2018; Stäubli et al., 2018).

Floods, debris flows, landslides and avalanches are the most frequent hazards affecting the highest number of people in mountain regions (*medium confidence*) (Stäubli et al., 2018). Landslides count amongst the deadliest hazards globally with over 150,000 reported fatalities for the period 1995-2014 (Haque et al., 2019). There is *high confidence* that the number of fatalities from landslides has increased globally over the past twenty years (Froude and Petley, 2018; Haque et al., 2019), but there is *limited evidence* that this is due to changes in landslide event frequency and/or magnitude. Infrastructure expansion on unstable terrain can increase disaster risk (Zimmermann and Keiler, 2015; Huggel et al., 2019; Kirschbaum et al., 2019; Schauwecker et al., 2019; Terzi et al., 2019; Motschmann et al., 2020a; Shugar et al., 2021). A study from western Nepal concludes that the exposure of people and infrastructure has been the main cause of disasters (Muñoz-Torrero Manchado et al., 2021). Decreasing numbers of fatalities from disasters resulting from decreasing vulnerabilities have been reported in Europe and North America (see Section 13.2.2.1*)* (Gariano and Guzzetti, 2016; Strouth and McDougall, 2021). Evidence from Africa suggests that disasters from climate induced natural hazards in mountain areas are often due to droughts, pests and changes to rainfall and associated impacts on smallholder farmers' agricultural livelihoods (Shikuku et al., 2017).

Characteristics of natural hazards in mountain areas have been largely explored and evidence suggests that conditions favouring cascading impacts are a common feature (*high confidence*) (Section 8.2.1.1) (Zimmermann and Keiler, 2015; Huggel et al., 2019; Kirschbaum et al., 2019; Schauwecker et al., 2019; Terzi et al., 2019; Motschmann et al., 2020a; Shugar et al., 2021). Compound and cascading impacts have affected people, ecosystems and infrastructure and generate significant spillovers across numerous sectors, resulting in destructive impacts (Nones and Pescaroli, 2016; Kirschbaum et al., 2019; Schauwecker et al., 2019).

Most adaptation responses to natural hazards in mountain regions are reactive and autonomous to specific climate stimuli or post-disaster recovery (*robust evidence, medium agreement*) (McDowell et al., 2019; Rasul et al., 2020). Hard structural measures such as dikes, dam reservoirs and embankments have largely been employed to contain the hazards alongside early warning systems, zonation and land management (Sections 4.4.1.3, 10.3, 12.5.3, 13.2.2). Awareness raising, preparedness and disaster response plans are increasingly used in the context of more unpredictable hazard trends (see Cross-Chapter Box DEEP in Chapter 17) (Allen et al., 2016; Allen et al., 2018; Hovelsrud et al., 2018). Ecosystem based adaptations (EbA) are widely implemented to mitigate risks from shallow landslides (e.g. afforestation and. reforestation and improved forest management), floods (e.g. river restoration and renaturation) (Renaud et al., 2016; Klein et al., 2019b) and droughts (e.g. adapting watershed) (Renaud et al., 2016; Klein et al., 2019b; Palomo et al., 2021).

Evidence from different mountain regions show that adaptation and risk reduction efforts are less successful if they focus on hazards or risks, without considering diverse risk and value perceptions of affected people (*medium confidence*) (French et al., 2015; Allen et al., 2018; Hovelsrud et al., 2018; Kadetz and Mock, 2018; Klein et al., 2019b). Previous experience and local social contexts of exposure to climate-related disasters affect the perception of people and influence the patterns associated with disaster risk management and associated coping strategies (*high confidence*) (see SROCC Chapter 2) (Kaul and Thornton, 2014; Shijin and Dahe, 2015; Landeros-Mugica et al., 2016; Wirz et al., 2016; Carey et al., 2017; Adler et al., 2019).

Important synergies exist between disaster risk reduction, climate change adaptation and sustainable development in mountain regions (*medium confidence*) (Zimmermann and Keiler, 2015), where the multiple and diverse perceptions of risk and risk tolerance to natural hazards are relevant considerations (Schneiderbauer et al., 2021). Global agreements for integrated disaster risk management and climate change adaptation (Alcántara-Ayala et al., 2017), including the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015), the SDGs (UN, 2015), the Paris Agreement (UNFCCC, 2015) and the New Urban Agenda-Habitat III (UN, 2016) create opportunities for synergies to address disaster risks (see also Section 6.3). Although these agreements are well established in the international agendas, there is *limited evidence* of their implementation to address disaster risk reduction and adaptation in mountains (Alcántara-Ayala et al., 2017).

CCP5.2.7 Synthesis of Observed Impacts and Attribution and Observed Adaptation

CCP5.2.7.1 Observed Impacts and Attribution to Anthropogenic Climate Change

The assessment of observed impacts identified a large number of impacts across all major mountain regions of the world and for a large variety of systems, based on more than 300 references (see SMCCP5.2). The literature was assessed, and results classified on a per regions and systems basis. Confidence statements on detection and attribution are based on expert judgement following IPCC guidelines (see Section 1.3.4), building on evidence from multiple sources in the literature (Mach et al., 2017) (see SMCCP5.2). Figure CCP5.4 provides an overview of the assessment results.

Climate change impacts have been documented in mountains of all continents. A wide range of human and natural systems have been affected by climate change to date, including the cryosphere, water resources, terrestrial and aquatic ecosystems, agriculture, tourism, energy production, infrastructure, health and life, migration, disasters and community and cultural values. The confidence levels for detection of impacts are generally in the range of medium to high. The contribution of climate change to the detected impact varies depending on the affected system, and climatic and non-climatic drivers. The highest levels of confidence for attribution of detected impacts to anthropogenic climate change is assigned to the cryosphere. More generally, those impacts are more strongly driven by increasing temperatures and show higher confidence for attribution than those impacts mainly driven by precipitation changes. The level of contribution of climate change to observed impacts is predominantly medium or high, indicating the high sensitivity of natural and human systems in mountains to climate change. Furthermore, the vast majority of detected impacts imply negative impacts on natural and human systems (*high confidence*).

Local knowledge plays an important role in documenting impacts of climate change in mountain regions. Since IPCC AR5 the evidence of meaningful climate change impacts being reported using local knowledge sources has increased substantially (*high confidence*). Similarly, important regional gaps present in the IPCC AR5 have been addressed here (e.g. Africa), resulting in a much more comprehensive and regionally balanced assessment and perspective.

Furthermore, the science of attributing negative impacts of climate change to anthropogenic emissions or even individual polluters is becoming increasingly important for climate litigation (Marjanac et al., 2017; McCormick et al., 2017; Otto et al., 2017; Setzer and Vanhala, 2019) and there is emerging evidence that mountains are becoming sites of litigation cases, with cases for instance in Peru, Colombia, and India (UNEP, 2017). Recent studies put litigation cases such as the Lliuya vs RWE case on risk of glacier lake floods in Peru in a broader context of differentiated responsibilities and justice (Huggel et al., 2020b).

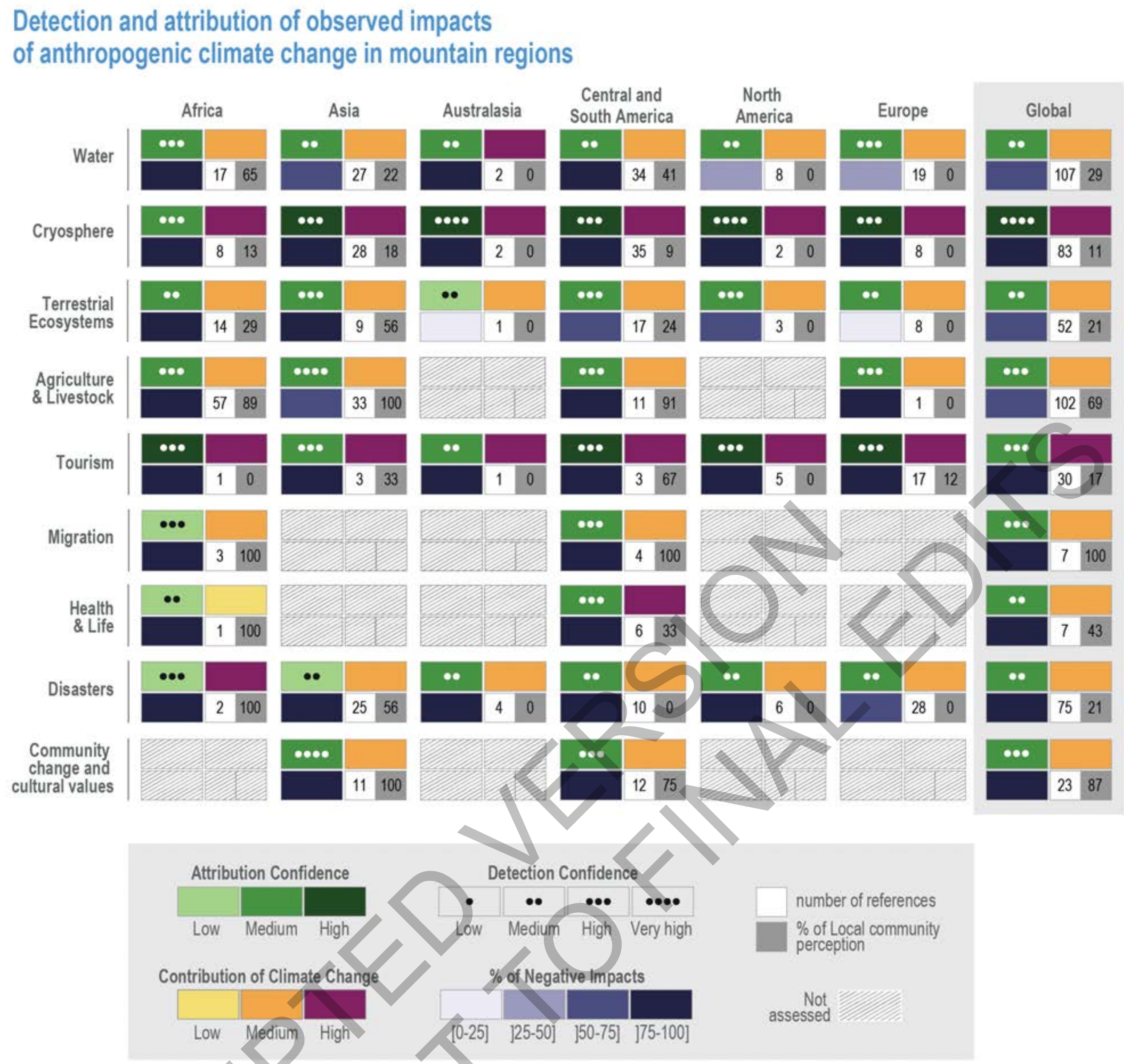


Figure CCP5.4: Synthesis of detection and attribution of impacts of anthropogenic climate change on different natural and human systems in mountain regions. For each system and region assessed, the level of confidence for detection and for attribution to anthropogenic climate change is indicated. Also indicated is how strong the contribution of climate change is to the observed changes, considering climatic and non-climatic causal factors. Observed impacts were analysed in terms of negative impacts (e.g. economic or non-economic damages, losses, contribution to increasing risks for society), where the numbers refer to the percentage of references indicating negative impacts for a given impact. The percentage of local community perception indicates the percentage of all literature references for a given system and region that account for local knowledge. The number of references refers to the total number of literature references considered for an impact to a specific system and region. "Not assessed" refers to *limited evidence* in the literature (see SMCCP5.2 and Table SMCCP5.5-5.14).

CCP5.2.7.2 Synthesis of Observed Adaptation

Extending from recent assessments of observed adaptation in high mountain areas (Hock et al., 2019; McDowell et al., 2019) new evidence for the geographically larger space for mountains assessed in this CCP is available from a mountain specific re-analysis of the GAMI dataset, which contains 423 articles reporting adaptation in mountains (Berrang-Ford et al., 2021; McDowell et al., 2021b) (SMCCP5.3), some of which also include those reported in section CCP5.2. In these articles, adaptation measures in mountains are reported from all regions worldwide, with predominance from Asia and Africa. Of all reported adaptations, 91% involve individuals or households, frequently engaged in smallholder agriculture and/or pastoralism; local governments are also often involved (31%) and sub-national or local civil society actors (29%) while private sector involvement remains scarce (below 10%). Food, fibre and other ecosystem products (76%) and poverty, livelihoods and sustainable development (55%) are by far most often involved in reported adaptation in mountains, followed by water and sanitation (28%) and health, well-being and communities (26%) (McDowell et al., 2021b) (SMCCP5.3.2).

Adaptation measures most commonly found include farming-related changes (e.g. resilient or drought-tolerant crop varieties, irrigation techniques, crop storage, and livestock insurance schemes), infrastructure development, Indigenous knowledge, community-based capacity building, and ecosystem-based adaptation (McDowell et al., 2021b) (SMCCP5.3.2) (*high confidence*). Nature-based solutions (NbS) are an adaptation component in NDC's of many mountain countries around the world (UNEP, 2021). Furthermore, Indigenous knowledge and local knowledge are often reported as informing adaptation efforts, and Indigenous Peoples, marginalized people and gender issues are recognized in several national adaptation strategies but autonomous responses are often insufficiently understood (Mishra et al., 2019).

The GAMI based re-analysis for mountains indicates that food security (75%), poverty (47%), consumption and production (36%), terrestrial and freshwater ecosystem services (19%) and clean water and sanitation (18%) are important aspects of vulnerability that adaptations address, with an emphasis on responses to climate-related shocks and stressors (McDowell et al., 2021b) (SMCCP5.2). The re-analysis also shows that more than 80% of adaptations in mountains are behavioural/cultural in nature, and more than 50% ecosystem-based, or technological or infrastructural.

About a third of the assessed adaptation activities are in the planning and early implementation stage, and around one-fifth in a stage of advanced implementation (McDowell et al., 2021b) (SMCCP5.3.2). Several lines of evidence converge, indicating that most observed adaptation in mountains is incremental in nature and not transformative (*high confidence*) (Mishra et al., 2019 ; McDowell et al., 2021b) (SMCCP5.3.2). Nevertheless, some adaptation measures such as NbS were found to bear important transformative potential in mountains if different knowledge types are combined, and community engagement and ecosystem management processes are in place (Palomo et al., 2021).

Overall, and consistent with findings in SROCC, there are still limited systematic monitoring and evaluation processes implemented to track adaptation progress, and there is *limited evidence* and prevailing uncertainties on the extent to which observed adaptation efforts reduce risks (Hock et al., 2019; McDowell et al., 2021b; UNEP, 2021) (SMCCP5.3.2).

Limits to adaptation are found in a majority (>80%) of the assessed adaptation studies; around half of the studies reported soft limits and less than a third identified both hard and soft limits to adaptation (McDowell et al., 2021b) (SMCCP5.3.2) (*high confidence*). Soft limits are frequently related to governance, economics, and social/cultural constraints, and can be overcome in principle through targeted efforts to address social conditions that impede adaptation planning and action. Hard limits are more frequently described as biophysical, such as precipitous declines in water supply. Examples of adaptation limits include lack of access to credit and markets, fixed livelihoods, insufficient awareness of climate risk, poor access to technology, and the erosion of existing skills and knowledge, social inequities, lack of trust and social cohesion, inequitable gender norms, and perceptions of conflict or scarcity. Furthermore, land tenure insecurity, poor integration of adaptation programmes across governing scales, and lack of decision-making power among vulnerable groups, along with inadequate funding for government-implemented adaptation programmes are reported to limit adaptation (Mishra et al., 2019; McDowell et al., 2021b) (SMCCP5.3.2). Hard limits imply that further adaptation action is unfeasible, ineffective, or unacceptable, resulting in inevitable losses and damages in mountain areas (Huggel et al., 2019) (*medium evidence, medium agreement*).

Overall, adaptation in mountain regions is taking place in various ways, in different sectors, scales, levels, quality, and effectiveness (*high confidence*). Most responses are incremental, with asymmetries of power among state, institutions and individuals, costs or capital requirements of adaptation, lack of coordinated planning, resistance to institutional change, household risk aversion, and lack of access to information inhibiting more transformational responses (SMCCP5.3.2). Aside from poverty reduction, there is *limited evidence* of adaptations effectively remediating the underlying social determinants of vulnerability (e.g. gender, ethnic identity).

CCP5.3 Projected Impacts and Risks in Mountains

CCP5.3.1 Synthesis of Projected Impacts

Declines and extinctions have been projected in a range of montane plants and animal species, including rare endemic species and subspecies due to climate change (*medium evidence, high agreement*) (Li et al., 2017; Ashrafzadeh et al., 2019; Brunetti et al., 2019; Zhang et al., 2019b; Manes et al., 2021). Up to 84% of endemic mountain species are found to be at risk of extinction (Manes et al., 2021). By using a simple model, Helmer et al. (2019) predict a large-scale contraction in the next 25 years of alpine ecosystems above tropical mountains cloud forest in the Andes due to tree invasion. Topographic complexity can smoothen and delay transition of montane forests in terms of size and composition for warming up to 3°C GWL (Albrich et al., 2020).

Hydrological changes will determine how some ecosystems change, more than changes in temperature. For example, (Dwire et al., 2018) found that changes in riparian areas, wetlands and forests were likely under climate change in the Blue Mountains, Oregon, USA, as a result of altered snowpack, hydrologic regimes, drought and wildfire. In the Bolivian Cordillera Real, wetland cover variations were associated with increases in precipitation extreme events and glacier melting over the 1984-2011 period but might be reversed with predicted future decrease in both total precipitations and glacier run-off (Dangles et al., 2017). About 30% of the wetland area in the Great Xing'an Mountains, northeastern China has been projected to disappear by 2050, with this value doubling by 2100 under CGCM3-B1 scenario (Liu et al., 2011).

Climate change impacts on food, fibre and ecosystem products will be highly variable across mountain regions (*medium confidence*) (Briner et al., 2013; Rasul and Hussain, 2015; Mina et al., 2017; Palomo, 2017; Said et al., 2019; Xenarios et al., 2019) (Sections 10.4; 12.3; 13.5; 14.4). In some regions, tree crops that are cultivated at certain elevations may reach the limit of their agroclimatic plasticity, for instance for crop types that require winter chills and where projected growing conditions would be too warm (Buerkert et al., 2020). In the European Alps, agricultural production in some areas may benefit from temperature rises, as total productivity in grasslands is projected to increase (Mitter et al., 2015; Grüneis et al., 2018), whereas some areas in Asia and South America heavily depended on glacier- and snow fed irrigation will be at risk of food insecurity (Rasul and Molden, 2019). In a study in the Eastern Pamir, (Mętrak et al., 2017) found that summer droughts and water changes lead to functional transformations of the wetland ecosystems which can affect food security of the local population. Climate change affects the phenology of plants (Harish et al., 2012; Gaira et al., 2014; Maikhuri et al., 2018), secondary metabolites (Chang et al., 2016; Kumar et al., 2020), and pharmacological properties of medicinal plants (Gairola et al., 2010; Das et al., 2016).

Water resources in mountains and dependent lowlands will continue to be strongly impacted by climate change throughout the 21st century (*high confidence*). The difference in impacts will be particularly strong for regions that highly depend on glacier and snow melt, and in pronounced dry seasons (*high confidence*), regions including Central Asia, South Asia, tropical and subtropical western South America, and southwestern North America (Huss and Hock, 2018; Hock et al., 2019; Immerzeel et al., 2020). Glaciers are expected to continue to lose mass throughout the 21st century, with higher mass loss under high emission scenarios (AR6 WGI Chapter 9). Many low elevation and small glaciers around the world will lose most of their total mass at 1.5°C GWL (*high confidence*) (Marzeion et al., 2018; Vuille et al., 2018; Hock et al., 2019; Zekollari et al., 2020) (WGI 9.5). For tropical and mid-latitude mountains, around half of the current ice mass can be preserved under low-emission scenarios, while two-thirds up to more than 90% will be lost under high emission scenarios compared to the 2000's (*medium confidence*) (Schauwecker et al., 2017; Vuille et al., 2018; Hock et al., 2019) (WGI 9.5). Strong differences in impacts between the emission scenarios are also assessed for decline in snow depth or mass at lower elevation [10 to 40% for RCP2.6 and 50 to 90% for RCP 8.5 by the end of the century (Hock et al., 2019)]. However, limitations in long-term climate, glaciological and hydrological monitoring data adds uncertainty to current understanding and adaptation support, e.g. when peak water is reached in different mountain catchments (Salzmann et al., 2014; Hock et al., 2019). Furthermore, context specific socio-cultural and economic factors can magnify, or moderate impacts related to hydrological change (McDowell et al., 2021a).

The dependence of lowland populations on mountain water resources will grow by mid-century across several climate and socio-economic scenarios, and several seasonally dry or semi-arid mountain regions (e.g. parts of South Asia, North America) are projected to be highly dependent (*medium confidence*) (Viviroli et al., 2020) (Figure CCP5.2). Changing sediment, nutrient and pollutant flows due to climatic and non-climatic drivers will impact populations and economic sectors (*medium evidence, high agreement*). Hydropower in all mountain regions will experience higher flux of water and sediment in some seasons, but lower water flow with demands from other water uses (e.g., irrigation) (Chevallier et al., 2011) in other seasons (Beniston and Stoffel, 2014; Gaudard et al., 2014; Majone et al., 2016; Caruso et al., 2017a; Caruso et al., 2017b; Patro et al., 2018). Recharge from groundwater and its buffer function is expected to decrease on the longer term (Somers and McKenzie, 2020). Glacier and snow depth or mass decline will impact current hydropower facilities and production in various complex ways, requiring changes in hydropower management, with further potential for evidence informed solutions (Gaudard et al., 2014; Schaefli, 2015; Schaefli et al., 2019). On the other hand, deglaciation in mountain regions opens topographic space and thus potential for additional long-term hydropower development and production (Haeberli et al., 2016a), with an estimated additional production of up to several hundred terawatt-hour per year, a potentially important contribution to national energy supplies, in particular in the High Mountain Asia region (Farinotti et al., 2019). However, water supply from glacier melt will decrease once source glaciers pass peak discharge (Huss and Hock, 2018), and the areas with available sediment will grow as glaciers shrink, posing potential risks to downstream populations and assets (Lane et al., 2019) (*high confidence*).

Since SROCC (Hock et al., 2019), several new studies have addressed projected impacts of future climate change on snow reliability in ski resorts, complementing previous findings or bridging existing knowledge gaps for winter tourism. This includes, in particular, new studies for China (An et al., 2019; Fang et al., 2019), showing that average ski seasons are projected to shorten (-4 to -61% for RCP4.5; -6 to -79% RCP8.5 in the 2050s) along with increases in snowmaking water demand (27 to 51% for RCP4.5; 46 to 80% for RCP8.5 in the 2050s), with large differences across the country. Changes in future snow reliability are projected across Europe at the national or pan-European scale (Demiroglu et al., 2019; Steiger and Scott, 2020; Morin et al., 2021), highlighting strong contrasts at the local (across ski resorts size and/or elevation range, or local social or environmental context) and continental scales. Higher latitude and high elevation locations generally exhibit delayed declines in snow reliability compared to lower latitude and lower-elevation locations (*high confidence*), consistent with assessment conclusions reached in SROCC (Hock et al., 2019). In general, climate change impacts and risks to ski tourism are found to be spatially heterogeneous, within and across local and international markets, with potential for significant disruptions to related socio-economic sectors due to a growing mismatch between ski area supply and skier demand in the coming decades (Fang et al., 2019; Hock et al., 2019; Steiger et al., 2020a) (*high confidence*). These disruptions are plausible, even though a fraction of current ski resorts could technically be able to operate under comparatively favourable locations (elevation, latitude) and operating models (business models, socio-cultural assets and conditions, governance) (Steiger et al., 2020b).

Severe damage and disruptions to people and infrastructure from floods are projected to increase in Northwestern South America (NWS), South Asia (SAS), Tibetan Plateau (TIB) and Central Asia (WCA) between 1.5°C to 3°C GWL mainly driven by river floods and an increase in the number of glacial lakes with high potential for outburst (*high confidence*) (Drenkhan et al., 2019; Motschmann et al., 2020b; Furian et al., 2021; Zheng et al., 2021). For example, the formation of new lakes at the foot of steep icy peaks largely extends the hazard zones with respect to the earlier situation without lakes (Haeberli et al., 2016b). Projected changes in ice and snow-melt, as well as seasonal increases in extreme rainfall and permafrost thaw, will favour chain reactions and cascading processes which can have devastating downstream effects well beyond the site of the original event (Cui and Jia, 2015; Beniston et al., 2018; Terzi et al., 2019; Vaidya et al., 2019; Shugar et al., 2021) (*high confidence*). The incidence of disasters is projected to increase in the future due to some hazards becoming more pervasive, with an increase in the exposure of people and infrastructure with future environmental and socio-economic changes either contributing to reduce or enhance these disaster risks (Klein et al., 2019b) (*medium confidence*).

CCP5.3.2 Key Risks Across Sectors and Regions

Key risks are derived from the detection and attribution assessment (CCP5.2.7) and from the projected impact and risks (CCP5.3.1). The assessment is informed by evidence in the regional and sectoral chapters and supports the key risk assessment in Chapter 16. Four key risks (KR1 to KR4) have been identified in this CCP and are presented in Sections CCP5.3.2.1-CCP5.3.2.4 (see SMCCP5.4 for methodology and references).

CCP5.3.2.1 KR1: People and Infrastructures at Risks from Landslides and Floods

The amount of people and infrastructure at risk of landslides will increase in regions where the frequency and intensity of rainfall events is projected to rise (Gariano and Guzzetti, 2016; Haque et al., 2019). Extreme precipitation in major mountain regions is projected to increase leading to consequences such as floods and landslides (AR6 WGI TS, *medium confidence*). Rain-on-snow events which can accelerate all flood stages and result in widespread consequence for societies are projected to increase between 2-4°C GWL (but decrease afterwards) (SROCC Chapter 2; WG I Chapter 12). There is *high confidence* that glacial retreat, slope instabilities and heavy precipitation will affect landslides and flood activities although for landslides there are considerable uncertainties in the direction of change (Patton et al., 2019) (AR6 WGI Chapter 12).

Future risk consequences which are considered severe include for example an increase of 10-20% compared to present of the population exposed to landslides activities in certain regions (e.g. High Mountain Asia) (Kirschbaum et al., 2020). This does not consider the expected increase in landslide activity relating to glacier and permafrost changes (Picarelli et al., 2021) (see SROCC Chapter 2) and therefore it is expected to be a conservative estimate. Other severe consequences are on average a projected twofold increase in the number of people exposed to inland flooding between 2°C and 4°C with highest increases in South Asia, Southeast Asia and South America (*high confidence* in the direction of change and *medium confidence* in the absolute values because based on global studies) (Hirabayashi et al., 2013; Allen et al., 2016; Arnell and Gosling, 2016; Zheng et al., 2021). Therefore, high to very high risks are expected between 2°C and 4°C GWL in several mountain regions (Figure CCP5.5 red and violet shaded bars). Many regions are projected to experience high risks due to the timing (potentially for severe consequences to happen sooner rather than later), the magnitude in terms of number of people and infrastructure affected) and the persistence of hazard conditions (Figure CCP5.5, AR6 WGI Chapter 12). Comparatively, more severe risks consequences are expected under SSP3 and/or SSP4 given the high population projections in certain regions compared to SSP1 (Kirschbaum et al., 2020) (see Figure CCP5.1) (*medium confidence*).

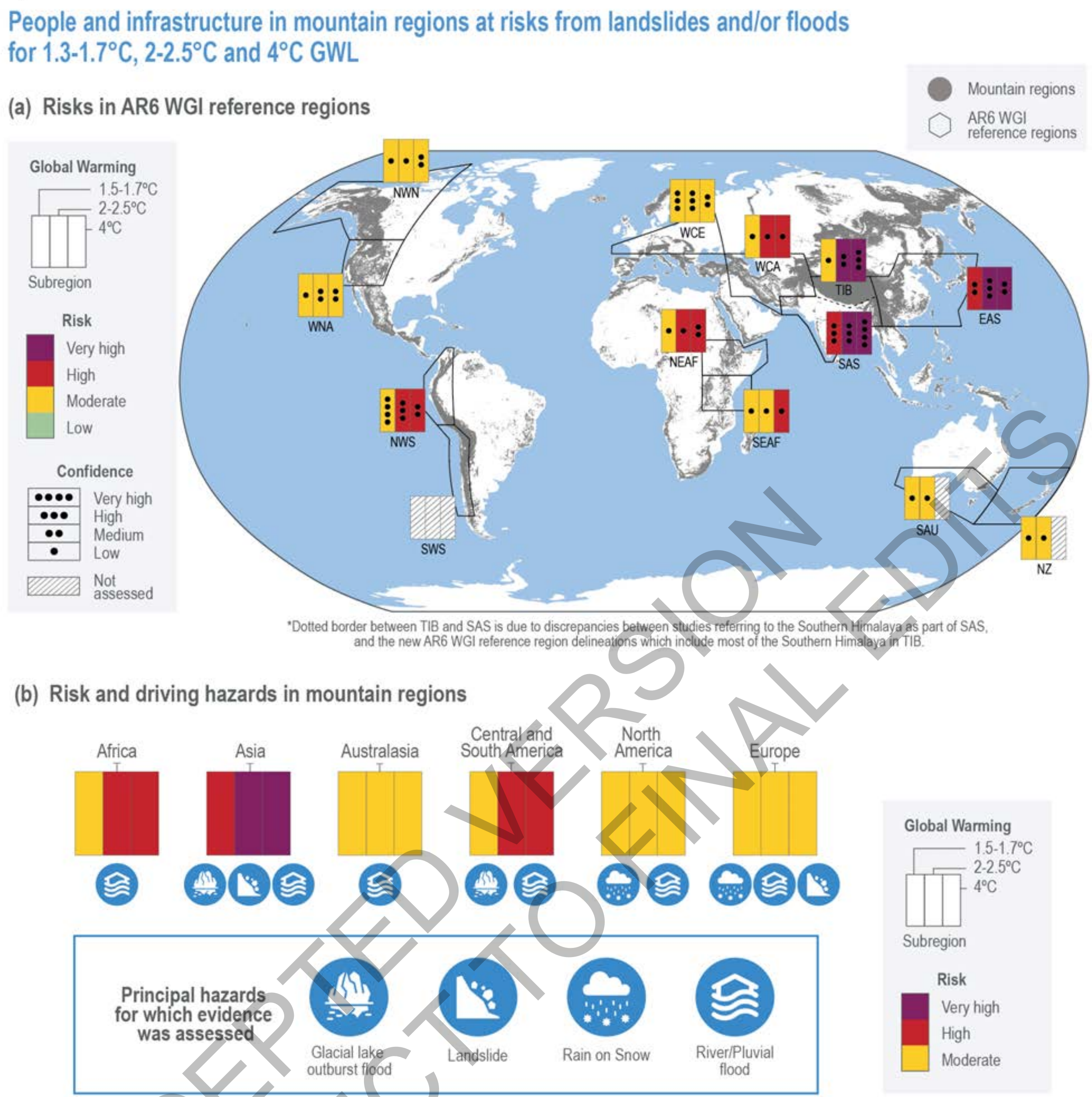


Figure CCP5.5: People and infrastructure in mountain regions at risk from landslides and/or floods for various Global Warming Levels (GWLs). Panel a) shows the level of risk assessed per AR6 WGI reference regions (see AR6 WGI Atlas). For some mountain regions, there is limited evidence to adequately assess the level of risks against GWLs, therefore this is labelled as "not assessed". Panel b) shows the level of risk aggregated at the continent scale and the principal hazards for which evidence was available and assessed. Methodological details and traceability are provided in SMCCP5.4, Figure SMCCP5.1, Table SMCCP5.15 and SMCCP5.17.

CCP5.3.2.2 KR2: Risks to Livelihoods and the Economy from Changing Water Resources

KR2 encompasses the relative and absolute dependency on water resources for economic activities and livelihood sustainment in mountain regions and in the lowlands. Particularly affected by changes in water resources will be regions with (seasonally) high dependence on snow and glacier melt, i.e. arid and semi-arid zones in the Andes, Central Asia and the Upper Indus Basin (Huss et al., 2017; Huss and Hock, 2018; Viviroli et al., 2020) (Section CCP5.3.1).

Consequences that are considered severe refer to the magnitude (number of people and economic activities affected), the timing (increase of water stress as early as mid-century in several regions) and the likelihood (severe risk consequences are more *likely* where high population density is projected) (see Figure CCP5.1,

Figure CCP5.6, Section 4.2.2.3) (Fuhrer et al., 2014; Wijngaard et al., 2018; Biemans et al., 2019; Immerzeel et al., 2020; Viviroli et al., 2020) (*high confidence*). Severe consequences are that by mid-century more than a half of agriculture regions equipped for irrigation are projected to be dependent on mountain runoff and could therefore be unsustainably using blue water (e.g. water from river, lakes and aquifers) (Viviroli et al., 2020) or that the number of people being water stressed will increase by 50% to 100% in areas already water stressed today (Munia et al., 2020). Hotspot regions are those with large lowland populations depending on essential mountain water resource contributions and include river catchments such as Ganges, Brahmaputra, Meghna, Yangtze, Nile, Niger, Indus, Euphrates-Tigris or Pearl (Viviroli et al., 2020) (*high confidence*) (see Figure CCP5.6). Limited governance and integrated management of water resources, power and gender inequalities and level of disruption of local community practices also contribute to make risks more severe (*medium confidence*) (Lynch, 2012; Boelens, 2014; Wijngaard et al., 2018; Scott et al., 2019; Immerzeel et al., 2020). Consequences for hydropower are comparatively less severe than for agriculture and domestic/municipal use although this depends on region and timing (see also Section 5.2.2.2). For example, a study shows low risk to hydropower production in High Mountain Asia until the end of the century and even for warming levels beyond 3°C (Mishra et al., 2020) *(robust evidence, moderate agreement).*

Large scale and transformative interventions can reduce the high-end impacts of changing water resources and in particular the risks of water scarcity (see Section CCP5.4.1). These interventions have long lead times, are costly and may face institutional constraints (see Section 4.5.3), resulting in adaptation shortfall. Therefore, high to very high-risk levels cannot be excluded in regions where other key risks characteristics such as magnitude, timing and likelihood are assessed as high due to potential losses (e.g. in many Asian regions, see Figure CC5.6, SMCCP5.4 and Table SMCCP5.16).

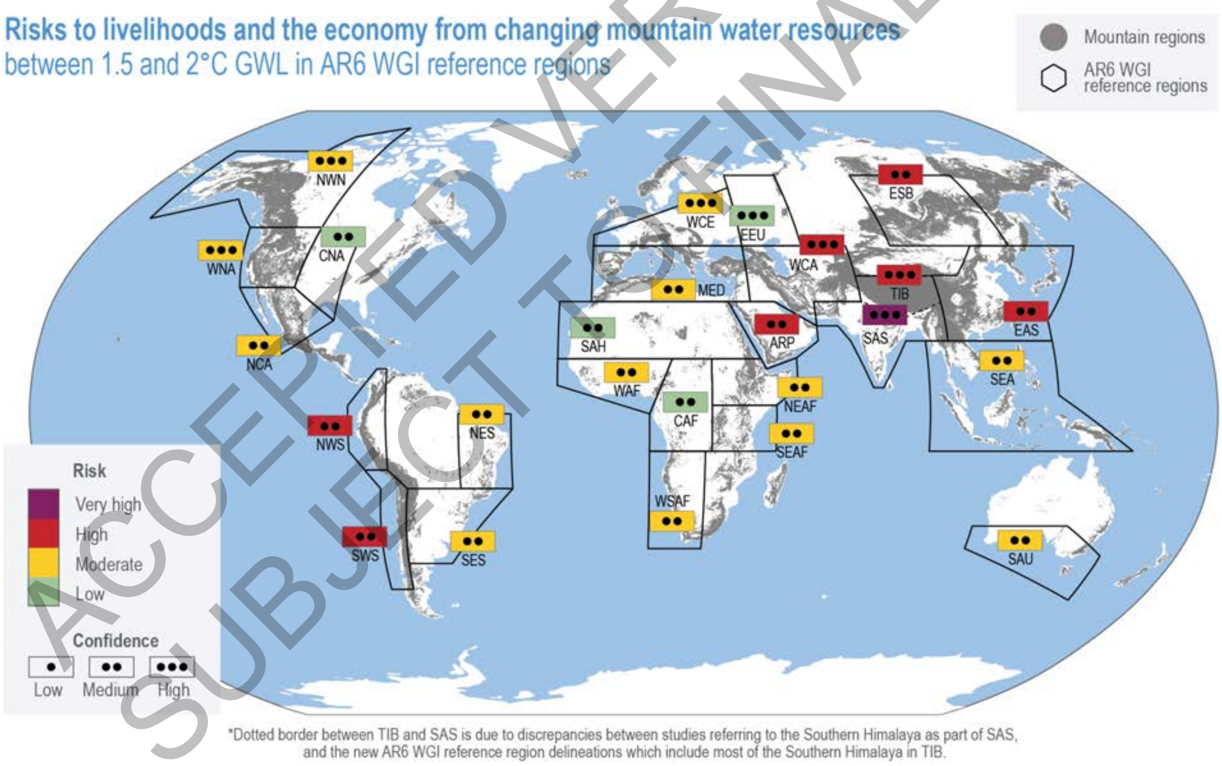


Figure CCP5.6: Risk levels assessed per AR6 WGI reference regions (see AR6 WGI Atlas). The majority of studies assessed focus on impacts up to mid-century (2030-2060) and for RCP-2.6, RCP-4.5 and RCP-6.0, which was converted into the corresponding warming level range 1.5-2.0°C GWL (see Cross-Chapter Box CLIMATE in Chapter 1). Methodological details are provided in Section SMCCP5.4, Figure SMCCP5.1, Table SMCCP5.16 and SMCCP5.18. Due to the *limited evidence* available to determine risks against high Global Warming Levels (GLWs), and the relatively high uncertainties associated with future irrigation trends for the second half of the century (see e.g. Viviroli et al., 2020), assessment of risks associated with GLWs greater than 2.0°C GWL was not conducted.

CCP5.3.2.3 KR3: Risks of Ecosystem Change and Species Extinction

Risks to mountain ecosystems and the services they provide to people are varied in magnitude, timing, likelihood and potential to adapt and place specific (see Table SMCCP5.19). However, many mountain ecosystems are already showing impacts of climate change (CCP5.3.1), reflecting the strong influence climate has in many situations and indicative that risks are large, immediate and will *likely* increase in the near as well as long-term. There is *robust evidence (high agreement*) of vegetation zones and individual species shifting to higher elevations (Section 5.2.1; Chapter 2.4) and projections indicate that current will continue and accelerate at higher rates of warming (*medium evidence, high agreement*) (Section 2.5).

Many mountain species are at risk of range contraction and ultimately extinction if dispersal at the upper range limit is slower than losses due to mortality at the lower range limit (observed for trees in the Neotropics; (Feeley et al., 2013; Duque et al., 2015), or if mountains are not high enough to allow species to move to higher elevations. Ramirez-Villegas et al. (2014) modelled 11,012 species of birds and vascular plants in the Andes, finding large decreases by 2050 (SRES-A2 scenario); in absence of dispersal 10% of species could become extinct. Even assuming unlimited dispersal, most of the Andean endemics would become severely threatened. Other modelling studies have also projected declines in a range of communities and species, including rare endemics (Zomer et al., 2014a; Rashid et al., 2015; Bitencourt et al., 2016; Li et al., 2017; Rehnus et al., 2018; Ashrafzadeh et al., 2019; Zhang et al., 2019b; Cuesta et al., 2020; Hoffmann et al., 2020).

Many treelines will continue to shift to higher elevations with increasing temperatures (Chhetri and Cairns, 2018), although very few are changing as fast as climate change (Liang et al., 2016; Hansson et al., 2021) and some are not moving or even shifting to lower elevations (CCP5.2.1). If treelines fail to shift uphill, this presents a risk for species of the upper-montane forest that experience range contraction at their lower range limit but lack a suitable habitat to expand into beyond their upper range limit (Rehm and Feeley, 2015). Changes in phenology can also present risks to species and ecosystems (Chapter 2), including a potential desynchronization of mutualistic relationship such as pollination and increased freezing damage due to premature emergence from winter dormancy. In European broadleaved trees, for example, the upper elevational limits of different species involve a trade-off between maximizing growing season length and limiting the risk of spring freezing damage (Vitasse et al., 2012; Körner and Spehn, 2016).

A wide range of mechanisms can cause changes within ecological communities, some of which are hard to predict but there are an increasing number of studies illustrating some of the risks which are expected to be most common. If treelines shift upwards, this presents a risk for alpine species, which cannot compete with trees. This may lead to extinction of alpine species on mountains where there is insufficient room for the alpine zone to shift uphill. Shifts in species distributions, and in particular shifts in ecosystem types, can cause changes in ecosystem function, which may in turn have cascading impacts on people, for example leading to increased exposure to diseases such as malaria at high elevation (Section 2.4.2.7.2) as vector distribution changes and wider impacts on ecosystem services (Section 2.5.3) such as water supply, flood alleviation and food.

CCP5.3.2.4 KR4: Risk of Intangible Losses and the Loss of Cultural Values

The risk of intangible losses and loss of cultural values is associated with the decline of ice and snow cover and temperature increase, as well as the increase in intangible harm from hazards such as floods and droughts (*high agreement, medium evidence*) (Diemberger et al., 2015; Jurt et al., 2015; Vuille et al., 2018; Tschakert et al., 2019; Vander Naald, 2020). Losses are intangible because they characterise aspects which are difficult to quantify, i.e. loss of identity, loss of self-reliance, loss of rituals and traditions and place attachment (Allison, 2015; Baul and McDonald, 2015; Motschmann et al., 2020a; Schneiderbauer et al., 2021). A global systematic analysis of case studies shows that this risk is more prevalent in the Andes, the Himalaya and the Alps (Tschakert et al., 2019). Often mentioned across studies is the loss of intrinsic memories and culture related to changes in world heritage landscapes and iconic sites (Jurt et al., 2015; Sherry et al., 2018; Bosson et al., 2019). Changes in the hazard landscapes are also reported to contribute to the loss of peace of mind and loss of well-being (Diemberger et al., 2015). Overall, there is *limited evidence but medium agreement* that the risk of intangible losses and the loss of cultural identity will rapidly increase and that consequences will go from reversible damage to irreversible losses (Tschakert et al., 2019).

CCP5.4 Options for Adaptation and Climate Resilient Development Pathways

CCP5.4.1 Synthesis of Adaptation Responses to Reducing (Key) Risks

More than half of the studies having a focus on mountains (423 articles) extracted from the GAMI dataset report that adaptation responses are contributing to reducing climate risks (Berrang-Ford et al., 2021; McDowell et al., 2021b) (see SMCCP5.3.2). However, the extent of adaptation in terms of time (i.e. speed), the scale of change (i.e. scope) and its depth (i.e. degree to which a change is substantial) is low in mountain regions, with the level of agreement across studies varying from one region to the other (*medium confidence*) (Figure CCP5.7, SMCCP5.3.2). In regions where risk levels remain moderate, a low adaptation extent might be sufficient to constrain risks (see Figure CCP5.5 and Figure 5.6; Section 16.3.2.5).

Adaptation responses in mountains are mainly incremental changes from existing practices (*high confidence*) (McDowell et al., 2019; Rasul et al., 2020; McDowell et al., 2021b), signalling that the potential of current and planned adaptation responses to reduce risks in the future will not be adequate to mitigate high to very high risks. For example, measures to contain floods or landslides (KR1) are designed with specific magnitudes and types in mind often assuming stationarity of return periods (Montanari and Koutsoyiannis, 2014; Gariano and Guzzetti, 2016). In the case of events showing decreasing return periods, risk mitigation standards need to be elevated to provide for more protection in the future (Felder et al., 2018; François et al., 2019). The portfolio of adaptation options to mitigate risks from changing water resources (KR2) is large but challenging and includes integrated catchment management, implementation of multiple use of water strategies, improved water governance (including community based and participatory water governance), overcoming power inequalities among users and sectors, and balancing economic pressure and sustainable development (*high confidence*) (Bekchanov and Lamers, 2016; Yapiyev et al., 2017; Jalilov et al., 2018; Drenkhan et al., 2019; Allen et al., 2020; Aggarwal et al., 2021; Huang et al., 2021) (SMCCP5.3.2). There is *limited evidence* on the effectiveness of adaptation responses to reduce the severity of ecosystem change (KR3) (also see Section 16.3.1). Prevention rather than control and eradication efforts can contribute to curbing biological invasions of alien species in the short turn, whereas colonisation by native trees following land use abandonment can be more effective in the long run (Carboni et al., 2018). Reducing intensified grazing, agricultural expansion, and conservation management in buffer zones of protected areas can limit the altitudinal range shift of endemic species (Kidane et al., 2019).

EbA has been effective in mountain regions to reduce risks from floods (e.g. restoration of buffer zones and floodplains) and landslides (e.g. protective forests) (Muccione and Daley, 2016; Klein et al., 2019b; Lavorel et al., 2019). Ecosystem based measures have been implemented for water management purposes to supply clean water and improve water quality (see Section 4.5.2.1). Furthermore, they provide scope for conservation and improvement of habitats, e.g. forest ecosystems (Nagel et al., 2017; Lamborn and Smith, 2019) (*high agreement, medium evidence*). However, repeated, and recurrent disturbances that increase recovery times can reduce the effectiveness of EbA (Sebald et al., 2019; Scheidl et al., 2020) (*medium confidence*).

Adaptation in mountain areas is currently constrained predominantly by soft limits related to existing social, economic, and political conditions (*high confidence*) (Gioli et al., 2014; Sansilvestri et al., 2016). Progress in overcoming soft limits is currently minimal due to insufficient engagement with socio-economic and political issues in existing adaptation (*medium confidence*) (McDowell et al., 2019; McDowell et al., 2021b) (Sections 8.4.5.3, Cross-Chapter Box LOSS in Chapter 17). This is expected to lead to an expansion of residual risks as risk severity increases (McDowell et al., 2021b).

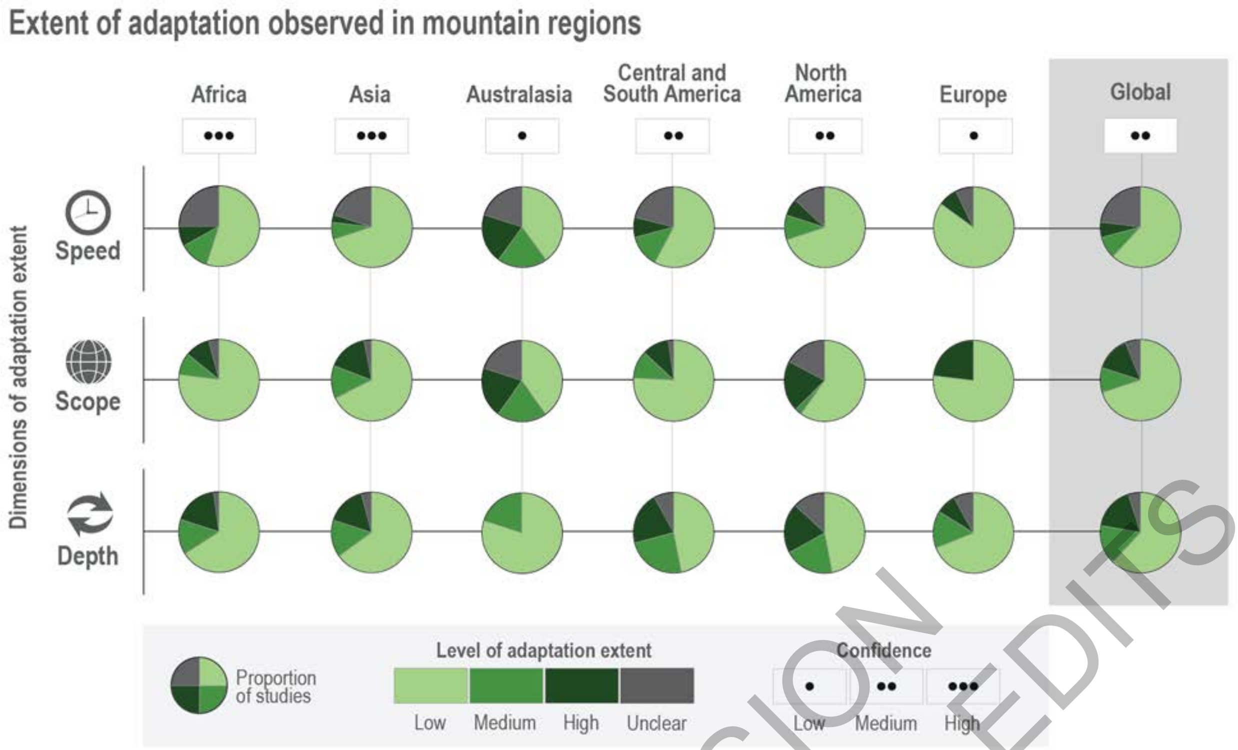


Figure CCP5.7: Extent of planned and implemented adaptation actions observed in mountain regions shown in terms of three dimensions: i) speed (timeframe within which adaptations are being implemented), ii) scope (the scale of changes observed from the adaptation action), and iii) its depth (i.e., degree to which a change reflects something new) (see Section 16.3.2.5). The data are obtained from the Global Adaptation Mapping Initiative (GAMI) re-analysis for mountains (see SMCCP5.3.2 and Berrang-Ford et al., 2021; McDowell et al., 2021b).

CCP5.4.2 Challenges, Opportunities and the Solution Space for Adaptation in Mountains

The effects of climate change on mountain environments pose significant challenges for people, ecosystems, and sustainable development, with issues such as difficult access, environmental sensitivity, and socio-economic marginalization making adaptation particularly complex. Furthermore, varied and dynamic biophysical characteristics as well as high socio-cultural diversity preclude one-size-fits-all responses; adaptation planning and action in mountains rooted in context-specific socio-ecological and climatic realities are more effective (Hock et al., 2019; Lavorel et al., 2019; McDowell et al., 2020) (*high confidence*). Despite these challenges, there is growing evidence of opportunities for advancing effective responses to climate risks in mountain areas (McDowell et al., 2020) (Section 16.3; Cross-Chapter Box NATURAL in Chapter 2).

The solution space for adaptation represents a realm of possibility for addressing climate risks; it is shaped by both socio-economic and climatic factors that influence who adapts, when they adapt, and how they adapt to climate change (Haasnoot et al., 2020) (Sections 1.5.1 and 17.4). The space includes both planned and autonomous responses (Hock et al., 2019; McDowell et al., 2019). Autonomous response can be appropriate when local resilience is high (Mishra et al., 2019; Ford et al., 2020); however, many mountain communities continue to face socio-economic challenges that constrain their adaptive capacity (*high confidence*). Planned adaptations are a critical component of the solution space, although external interventions can also reinforce, redistribute, or create new vulnerabilities when they proceed without sincere engagement with local communities (Eriksen et al., 2021). The solution space also evolves as social and climatic conditions change and can be capped by social and biophysical limits to adaptation that render further responses to climate change inaccessible, unfeasible, or ineffectual. Such limits are already observed and are *likely* to become more widespread as climatic stressors move beyond historical experience (IPCC, 2018; Hock et al., 2019; McDowell et al., 2020) (Section 17.3; Cross-Chapter Box DEEP in Chapter 17) (*high confidence*).

Evidence shows the significant potential of adaptation actions such as Nature-based Solutions or multiple use of water approaches but with a need to carefully evaluate environmental, economic and social co-benefits, trade-offs (Yang et al., 2016; Drenkhan et al., 2019; Lavorel et al., 2019; McDowell et al., 2019; Palomo et al., 2021) (*high agreement, medium confidence*). The potential for adaptation to contribute to sustainable development and transformative change in mountains is also becoming increasingly evident (Palomo et al., 2021) (*medium confidence*), yet there is currently *limited evidence* with respect to the long-term effectiveness of adaptations in achieving such outcomes (Balsiger et al., 2020). To better achieve the adaptation potential in mountains, adaptation finance and private sector inclusion and contribution are key enablers (Mishra et al., 2019; UNEP, 2021) (*high confidence*).

There is increasing recognition that inclusive and comprehensive adaptation approaches can be more successful (Allen et al., 2018; Hock et al., 2019; Huggel et al., 2020a; Huggel et al., 2020b) (*medium evidence, high agreement*). Stakeholders such as local communities and government entities often prioritize different dimensions of climate related risks (López et al., 2017; McDowell et al., 2020). Adaptation initiatives that identify locally-relevant climate stressors and risks through knowledge co-production have the potential to be more acceptable and effective (*medium evidence, high agreement*) (Huggel et al., 2015; Muccione et al., 2016; Allen et al., 2018; Quincey et al., 2018; Balsiger et al., 2020; McDowell et al., 2020; McDowell et al., 2021b) (Cross Chapter Box DEEP in Chapter 17). However, tenable co-production requires recognition of the validity and integrity of diverse knowledges systems, including those held by Indigenous Peoples and local communities, as well as the provision of sufficient time and resources for meaningful engagement between stakeholder groups (Howarth and Monasterolo, 2016; Bremer and Meisch, 2017; Schoolmeester and Verbist, 2018; McDowell et al., 2019; Ford et al., 2020). Power imbalances and knowledge politics continue to impede the inclusion of historically underrepresented voices in adaptation planning and action(Ojha et al., 2016; Mills-Novoa et al., 2017). Citizen science plays an additional role in facilitating the inclusion of multiple knowledges (Buytaert et al., 2014; Dickerson-Lange et al., 2016; Tellman et al., 2016; Njue et al., 2019).

Progress in addressing climate risks requires targeting the root causes of vulnerability, which are often socio-economic in origin and can include poverty, marginalization, and inequitable gender dynamics (Ribot, 2014; Carey et al., 2017; Shukla et al., 2018; McDowell et al., 2019) (*high confidence*). Promoting resilience in many mountain regions requires responses that address the social determinants of susceptibility to harm. Context-specific manifestations of such determinants (and leverage points for positive action) can be identified through participatory processes with affected populations, with action on social determinants of climate change vulnerability having important co-benefits for equity, justice, and sustainability. Addressing the root causes of vulnerability can also resolve soft limits to adaptation, thereby increasing the solution space (McDowell et al., 2020).

There is growing evidence of the potential for coordination and monitoring networks to overcome existing data deficiencies, to fill knowledge gaps, and to streamline implementation, all of which currently impede adaptation in mountains (Salzmann et al., 2014; Muccione et al., 2016; Ryan and Bustos, 2019; McDowell et al., 2020; Shahgedanova et al., 2021; Thornton et al., 2021; Price et al., Accepted/In press). Furthermore, there is increasing evidence that key conventions related to mountains, such as the Alpine Climate Board (SROCC 2.4), provide opportunities for accelerating adaptation efforts through mainstreaming responses into other policies aimed at addressing climate-related risks (Balsiger et al., 2020) (*medium confidence*). Regional cooperation among countries and transboundary landscape and river basin governance initiatives are an important mechanism for advancing adaptation in mountains (Molden et al., 2017; Mishra et al., 2019; Balsiger et al., 2020) (*high agreement, medium evidence*), particularly as many mountain ranges and mountain ecosystem services are transboundary in nature.

Access to major adaptation support programs such as through the UNFCCC, national governments, multi- and bi-lateral aid arrangements, the private sector, and non-governmental organizations (NGOs) has been relatively limited to support adaptation action in mountain regions, indicating significant unutilized support options for increasing the solution space in mountains (McDowell et al., 2020). Enhanced uptake of available support and funding could help to ease the adaptation burden for mountain communities. This will require addressing soft limits to adaptation, which currently constrain the ability of actors to identify, access, and mobilize resources for planned adaptations (McDowell et al., 2020).

More inclusive adaptation approaches, engagement with the root causes of vulnerability, improved coordination and monitoring activities, and upscaling of support for adaptation are key enablers and are indicative of a substantial solution space for adaptation in mountains regions (*high confidence*). However, trajectories of climate change and the prospect of hard limits to adaptation, which are often biophysical in origin, portend climate futures that could overwhelm adaptation efforts. Success therefore hinges on increasing the quality and quantity of adaptation efforts, including through transformative action, as well as enhanced mitigation efforts, consistent with the recommendations of IPCC SR 1.5C (IPCC 2018) (Cross-Chapter Box PROGRESS in Chapter 17).

CCP5.4.3 Climate Resilient and Sustainable Development in Mountains

With accelerating warming and compounding risks increasing above 1.5ºC warming, the need for climate resilient development in mountains is evident, and intricately linked to achieving the SDGs and equity (*high confidence*). In this context, Chapter 18 draws attention to climate resilient development pathways (CRDP), as processes that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation and mitigation. Pathways that strengthen climate-resilient sustainable mountain development are starting to receive attention (Chelleri et al., 2016; Trabacchi and Stadelmann, 2016; AlpineConvention, 2021). This section treats four domains of emerging evidence related to climate resilient development in mountains: 1) climate actions that support both adaptation and mitigation; 2) Indigenous knowledge and local knowledge in support of climate resilient development; 3) climate resilient development in climate policy and planning; and 4) mainstreaming of climate action into development pathways.

Nature-based Solutions (NbS) can be pursued in mountains that will mitigate climate change and its impacts while at the same time contributing to improving livelihoods, social and economic well-being, and sustainable environmental management *(high confidence).* A global review of 93 Nature-based Solutions in mountains, such as afforestation, protection of existing forests, agroforestry and climate smart agriculture, confirm the potential of NbS for change towards sustainable trajectories (Palomo et al., 2021). Agroforestry is widely cited for delivering on food security as well as increasing resilience and mitigating climate change (Mbow et al., 2014; Amadu et al., 2020; Gidey et al., 2020). Also, the prudent use of biomass for wood-based bioenergy in mountains can mitigate the impacts of climate change, reduce vulnerability to disturbance events such as fires, and enhance rural socioeconomic development (Beeton and Galvin, 2017). Yet, there can be trade-offs contingent upon place-based and context-specific social and environmental factors, such as between the use of bio-energy, agricultural production and conservation concerns (Beeton and Galvin, 2017). Evidence from the world's mountains highlights the importance of cross-scale partnerships and interdisciplinary, bottom-up approaches that facilitate stakeholders in envisioning locally tailored, climate-resilient and sustainable development pathways (Chelleri et al., 2016; Capitani et al., 2019; Klein et al., 2019b; Pandey et al., 2021).

Mountains are the home of many cultures and diverse Indigenous knowledge and local knowledge (systems), which can and do provide strong support for place-based integrated adaptation and mitigation strategies (Merino et al., 2019). Indigenous knowledge and local knowledge reinforce community adaptive capacity, yet governance structures and processes, including the deliberate design and implementation of climate policy, can constrain that capacity from being realised (Hill, 2013; McDowell et al., 2014; Wyborn et al., 2015; Klepp and Chavez-Rodriguez, 2018; Lavorel et al., 2019) (*high confidence)*. Communities, particularly poor and remote mountain communities, are vulnerable to climate change and there is a need for capacity building in research, policy development and implementation for pursuing climate resilient development (Manton and Stevenson, 2014). Climatic stressors and socio-economic changes are changing traditional genderscapes in mountain communities (Goodrich et al., 2019). There is increasing evidence on the roles that gendered diversity in knowledge, institutions, and everyday practices can play in addressing barriers and creating opportunities for achieving resilience, adaptive capacity and sustainability in societies (Gioli et al., 2014; Ravera et al., 2016; Su et al., 2017; Udas et al., 2018; Goodrich et al., 2019; Sujakhu et al., 2019).

Concerning climate policy and planning for climate resilient development in mountains, a review of mountain specific priorities in the National Adaptation Programmes of Action (NAPA) submitted to the UNFCCC shows that countries have prioritized improving agricultural outputs by introducing climate smart crops and upgrading and building climate resilient irrigation infrastructure (UNFCCC, 2020c). Countries that have submitted their NAPs to the UNFCCC have prioritized improving ecosystem resilience through conserving agro-biodiversity in mountains. Countries have also focused on achieving food security in mountain regions and laying the foundations for food availability, stability, access and safety amidst increasing climate risks (UNFCCC, 2020a).

In the Nationally Determined Contributions (NDCs) where mountain regions are specifically mentioned, countries have prioritized climate resilient solutions, including, developing a low carbon green economy through implementing low carbon transport systems and encouraging sustainable waste management practices, as well as developing infrastructure for climate resilient agriculture, the sustainable management of forests and the conservation of biodiversity. Several countries have specifically pledged to build climate resilient mountain infrastructure taking into account future climate uncertainties. Countries have also identified the need for capacity building of national stakeholders and have pledged to provide relevant climate information (UNFCCC, 2020b).

Similar pledges are announced in formal institutional arrangements such as the Alpine Convention and the Carpathian Convention. The Alpine Convention's climate action plan prioritises reaching climate-neutral and climate resilient Alps by 2050. For this, implementation pathways on specific sectors have been identified ensuring coherence to global and regional goals such as the Paris agreement, SDGs, EU legislations and climate laws (AlpineConvention, 2021). Likewise, the Carpathian Convention's working group on climate change has presented a long-term vision towards combating climate change thorough amending the article of the convention to focus specifically on climate change adaptation and mitigation (CarpathianConvention, 2020).

Sustainable and climate resilient mountain development is predicated on effective and timely climate action building on cross-scalar partnerships among researchers, stakeholders, and decision makers to jointly identify desired futures and pathways and assess trade-offs and synergies between climate action and the SDGs (Klein et al., 2019a; Pandey et al., 2021) (*high agreement, medium evidence*). Understanding of the complexity of mountain ecosystems as well as path-dependency from earlier and current decisions is of critical importance for the sustainable future of mountain regions (Satyal et al., 2017; Chanapathi and Thatikonda, 2020; Berkey et al., 2021). Framing pathways through questions such as "to whom or to what is climate action positive" and "which trade-off should be accepted, and why" can serve as a tool for addressing sustainable development goals, while avoiding lock-ins or unsustainable path dependencies (Chelleri et al., 2016). Increasingly, climate action is mainstreamed into sustainable development, which signifies a shift from climate policy as an end-point to a continuing process for managing change and facilitating long-term sustainable development. The Ethiopian government's Climate Resilient Green Economy (CRGE) strategy is an example of such a shift (Simane and Bird, 2017) as are emerging initiatives to build-back-greener in response to COVID-19 impacts (Schipper et al., 2020).

CCP5.5 Key Assessment Limitations and Relevant Knowledge Gaps

The assessment presented in this CCP has several limitations, principally in terms of the amount, often fragmented and biased geographic coverage, or lack of relevant thematic scope covered in the literature published since AR5 and SROCC. Key assessment limitations and relevant knowledge gaps identified in this CCP fall within the following broad categories: 1) detection and attribution of observed impacts to climate change; 2) limitations and uncertainties associated with predictive models of projected impacts and risks; 3) integrated and systems-oriented research on mountain ecosystem services and their limits under climate change; and 4) measurable tracking of adaptation action implemented in mountain regions and their suitability for addressing climate risks. These are summarised in Table CCP5.3. While these limitations and assessment-relevant gaps in knowledge offer important caveats for the interpretation of this assessment, they also highlight prospects to address and improve the evidence basis in future assessments.

Table CCP5.3: Summary of key assessment-relevant knowledge gaps and limitations identified in CCP5.

Key assessment-relevant knowledge gaps and limitations	Relevant WGII report sections
Detection and attribution of observed impacts to climate change	

Key assessment-relevant knowledge gaps and limitations		Relevant WGII report sections
Limited amount and scope of literature available on impacts for assessment of detection and attribution to climate change.	• While there is *high confidence* on the links between future impacts and risks associated with climate change, there is *medium evidence* available on robust detection and attribution of past changes in mountain regions. • Considerable assessment gaps exist given the limited scope (temporal, spatial, or thematic coverage) and number of published studies reporting data and information that capture how mountains social-ecological systems function, and their trends over the past decades, that may be applicable for detection and attribution of changes to climatic change. • Additionally, there are limitations in current methodologies to include and account for other knowledges with respect to detection and attribution of impacts to climate change in mountain regions (e.g. Chakraborty and Sherpa, 2021).	CCP5.2.7; Figure CCP5.4; SMCCP5.2.
Consequences of shifting treelines and their interactions with other ecosystem functions	• The net effects of ongoing climate change with treeline advance and vegetation change on ecosystem carbon exchange, or possible effects on mountain hydrology, remain unresolved in the literature. • Uncertainties remain regarding effects to ecosystem-level carbon storage, given that above-ground biomass is higher in forests than in alpine vegetation and (new) trees may change soil carbon fluxes, for instance by introducing new soil organisms, thereby increasing soil carbon flux (e.g. Tonjer et al., 2021). • Short- and long-term effects of combined warming and changed species cover on mountain soils are complex and insufficiently quantified (Hagedorn et al., 2019).	CCP5.2.1; CCP1-Biodiversity Hotspots
Limitations and uncertainties associated with predictive models of projected impacts and risks		
Shared socioeconomic pathways (SSPs)	• There are relevant knowledge gaps in the understanding of future vulnerabilities in mountain social-ecological systems in relation to highly variable and dynamic trends in projected demographic change, socio-economic development pathways, and demands for resources.	CCP5.3.1; SMCCP5.1
Species distribution models (SDM)	• Species distribution models (SDMs), which rely on statistical correlations between occurrence records and environmental variables to make spatially explicit predictions, are commonly used to project climate change impacts on mountain ecosystems (Guisan et al., 2017). • However, they are associated with some limitations that can limit their utility to derive reliable predictions of future mountain vegetation distributions, and therefore ability to provide a sound basis for mountain nature conservation and climate change adaptation. • In particular, they only indicate the potential future species distributions based on the static relationships between species and predictors in the calibration data; in reality, vegetation dynamics will be heavily modulated by phenomena that are commonly overlooked by such models like changing species interactions and competition due to variance in response rates amongst different species, dispersal limitations, and demographic processes (Scherrer et al., 2020). • In addition, SDMs are often limited by data availability and therefore tend to omit several environmental factors known to be important for plants such as soil formation processes, disturbances (e.g. rockfalls, avalanches), and microclimatic conditions (Scherrer et al., 2011; Enright, 2014; Mod et al., 2015; Bråthen et al., 2018). • More complex dynamic and process-based models are available, but still rarely represent all potentially influential vegetation co-variates; applying both model types in conjunction demonstrates potential (Horvath et al., 2021).	CCP5.2.1
Quantifiable estimates of monetary costs and potential material losses	• There is *limited evidence* on climate-related risks to economic sectors that are vital for mountain regions, specifically on quantifiable estimates of monetary costs and potential material losses for economic sectors and communities in mountains, adjacent lowlands, and other regions dependent on these economic activities.	CCP5.3.1

Key assessment-relevant knowledge gaps and limitations		Relevant WGII report sections
Other model limitations	• Ecological models which could allow to better forecast the effectiveness of EbA as NbS, under different climate scenarios, are not fully developed (Seddon et al., 2020).	CCP5.4
Integrated and systems-oriented research on mountain ecosystem services and their limits under climate change		
Water	• Few assessment-relevant integrative studies are available in the published literature that address relevant aspects of water security, beyond water availability from glacier-fed meltwater, or snow, groundwater, other water stores, such as wetlands, sediments, etc. Likewise, few studies address seasonality with respect to a more systems-oriented approach to supply (e.g. water availability) and demand (irrigated agriculture, and other multiple uses and user groups).	CCP5.2.2 Chapter 4
Measurable tracking of adaptation action implemented in mountain regions and their suitability for addressing climate risks		
Conditions under which adaptation interventions work against stated goals	• Few studies report on how adaptation measures and programmes function in mountainous contexts that yield the outcomes reported (McDowell et al., 2020). • Despite transformative processes, to date there is *limited evidence* of how knowledge co-production activities support the planning and implementation of successful adaptations in mountain areas.	CCP5.4.2
Metrics and heuristics for tracking effectiveness	• Adaptation responses to intangible losses and loss of cultural values are reported and take different forms as demonstrated in studies from different world regions (de la Riva et al., 2013; Wang and Qin, 2015; Vander Naald, 2020). However, there is *limited evidence* on their adequacy for addressing increasing losses, which remains largely unexplored in the available literature.	CCP5.3.2.4; Section 4.4.3.3
Methods and frameworks for monitoring and evaluation	• Regarding adaptation efforts and effectiveness, there are considerable gaps in adequate monitoring and appropriate evaluation of successful implementation of diverse adaptation measures. • Across mountain areas, integrated monitoring of key environmental and socio-economic variables, including international efforts for the acquisition and sharing of data, offers prospects for supporting the tracking of impacts and adaptation responses, including community-based monitoring initiatives (Shahgedanova et al., 2021; Thornton et al., 2021).	Section 17.5; CCP5.4.2
Feasibility and suitability of adaptation options for managing climate risks	• The feasibility of adaptation options for managing risks, for example those that could facilitate systems transitions with respect to energy, remains largely unexplored in the literature, with *limited evidence* on how projected climate change could impact prospects to develop wind, solar or biomass energy production and use in mountain contexts. • Given assessments on observed adaptation (Section CCP5.2) and adaptation responses (Section CCP5.4), few studies report a 'systems approach' to the study and evaluation of adaptations that combine all relevant aspects of the risk framework (i.e. hazards, exposure, and vulnerabilities), including how synergies and trade-offs are considered in context for managing risks. • There is *limited evidence* of the feasibility and long-term effectiveness of adaptation measures to address climate-related impacts and related losses and damages in cities and settlements experiencing changing demographics.	CCP5.2.2.2; CCP5.4.2; CCP5.4.3

[START FAQ CCP5.1 HERE]

FAQ CCP5.1: How is freshwater from mountain regions affected by climate change, and what are the consequences for people and ecosystems?

Sources of freshwater from mountains such as rainfall, snow and glacier melt, and groundwater are all strongly affected by climate change, leading to important changes in water supply in terms of quantity, and *partly quality, and timing (e.g. shifts and changes in seasonality). In many cases, the effects on ecosystems and people are negative, e.g. creating or exacerbating ecosystem degradation, water scarcity, or competition or conflict over water.*

River flow is a main source of freshwater both in mountain regions and downstream areas. Various sources contribute to it, including rainfall, snow and glacier melt, and groundwater. Climate change affects these different sources in different ways. Climate change affects rainfall patterns such as long-term increase or decrease, seasonal shifts or changes in rainfall intensity. Rising temperatures strongly influence snow and glacier melt generated river discharge; the snowmelt season starts earlier, less snow mass is available for melt, and snowmelt contribution to river flow thus decreases over the year. Whether rising temperatures produce meltwater from glaciers depends on the state and characteristics of the glaciers and the catchment basin. The concept of 'peak water' implies that first, as glaciers shrink in response to a warmer climate, more meltwater is released until a turning point (peak water) after which glaciers melt and thus its contribution to river flow decreases. In many mountain regions worldwide, glaciers and their basins have already passed peak water, and the runoff contribution of glaciers is on the decline. Glacier shrinkage not only influences river discharge but also water quality. In the Andes of Peru, for instance, it has been observed that retreating glaciers expose bedrock, resulting in more acid water because of minerals that dissolve from the rock. Mountain ecosystems are also affected by changing freshwater availability. For instance, high-elevation wetlands in the tropical Andes critically depend on glacier meltwater during the dry season and the disappearance of this freshwater source results in ecosystem degradation.

The effect of climate change on groundwater in mountains is insufficiently understood. Infiltrating water from glaciers and snowmelt plays an important role in groundwater recharge. Groundwater recharge is expected to decrease with continued climate change in several mountain regions. In the Himalaya many springs have already been observed to decline.

The availability of freshwater is a function of water supply and water demand, with the latter being determined by sectors such as agriculture, energy, industry, or domestic use, as well as by competition between these sectors. Formal and informal water extraction and use prevail, and competition includes issues of inequalities, and power relations and asymmetry. Consequently, the effects of climate change on water resources, people and ecosystems are strongly modulated and often exacerbated by socio-economic development and related water resource management. For example, increasing frequency and intensity of droughts in the European Alps, combined with decline and seasonal shifts of river runoff from snow and glacier melt, is expected to result in growing competition between different sectors, such as hydropower, agriculture, and tourism. Similar developments are projected or have already been observed in many other mountain regions. This situation calls for strengthening and improving negotiation formats for water management that are transparent, equal, and socially and environmentally just. Management of water demand and strategies that entail multiple uses of water will become increasingly important in this context.

[END FAQ CCP5.1 HERE]

[START FAQ CCP5.2 HERE]

FAQ CCP5.2: Are people in mountain regions, and further downstream, facing more severe risks to water-related disasters due to climate change, and how are they coping?

Mountain regions have always been affected by either too much or too little water. Because of climate change, hazards are changing rapidly and becoming even more unpredictable. Whether or not these changes will result in more disasters locally and further downstream depends on several factors, not least the fact that more people are settling in exposed locations. People in mountains have a history of developing skills to live in a dangerous and dynamic environment, which will be invaluable in the future when combined with inclusive and long-term disaster risk reduction measures.

Water-related hazards in mountains include rainfall (pluvial) and river (fluvial) floods, extreme rainfall-induced landslides, debris flows, ice and snow avalanches and droughts. When people are exposed and vulnerable to these hazards, there is potential for them to result in disasters. Floods and landslides in mountains contribute to, and count amongst the most devastating disasters globally, often resulting in significant losses such as high numbers of fatalities and damages. Climate change may change rainfall frequency/intensity distributions, potentially leading to floods and droughts. Climate change may also lead to shifts in precipitation type, with more precipitation falling as rain than snow in the future., which further impacts both short- and long-term water storage, and therefore impacts downstream ecosystems and cities.

Although climate change directly affects water-related hazards, studies indicate that above and beyond natural hazards, disaster risk and disasters are influenced to a major extent by vulnerability and exposure. This is of relevance in mountains, where disaster risk is influenced by population growth, induced displacements, land-use changes and inefficient water distribution systems. For example, current trends suggest that more people are settling in exposed locations, with more infrastructure being built and activities such as tourism and recreation being promoted, exacerbating this exposure.

Experiences in dealing with water-related disasters provide a basis from which to build adequate responses to increasing risks in the future. For example, upgrading infrastructure such as dams and embankments can help address water shortages, but diversification of income-generating activities, such as subsistence farming moving away from certain drought-sensitive crops, can also help.

The risk perceptions of people also shape their behaviours in coping with disaster risks. For example, based on their longstanding observations and local knowledge, communities in the southern part of the Peruvian Andes identified the shrinking of glaciers, more frequent and intense extreme weather events, more extreme temperatures, and shortened rainy seasons as key challenges. The recognition of local knowledge is key to address these challenges, as well as provide a basis for the transformation of current systems. A lack of community involvement and participation in decision making on how to addresses disaster risk can contribute to a mismatch between perceptions and behaviours towards those risks, and the actions needed to reduce losses. Therefore, measures which are flexible, address the objectives and needs of all those affected by disasters and bring long term benefits have more chances of being successful in dealing with future disaster risks.

[END FAQ CCP5.2 HERE]

[START FAQ CCP5.3 HERE]

FAQ CCP5.3: Is climate change a risk to mountain species and ecosystems, and will this affect people?

Treeline position, bioclimatic zones and species ranges move up in elevation as the climate warms, increasing the risk of extinction for species isolated on mountaintops as a result of exceeding their physiological limits, loss of habitat or competition from colonising species. Additionally, climate change may alter the quality and quantity of food and natural products on which the livelihood of many mountain communities depends.

Mountain regions cover about a quarter of the Earth's land surface, scattered around the globe and may support a wide range of climates within short horizontal distances. Mountains have experienced above-average warming, and this trend is expected to continue. Mountains provide a variety of goods for people, are home to many Indigenous Peoples and are attractive for tourism and recreational activities. Mountain regions support many different ecosystems and some are very species rich. Mountain regions can be vast and diverse, and climate change and impacts on ecosystems vary greatly depending on location.

With increasing average global temperature, the climatic conditions under which plants and animals can thrive are shifting to higher elevations. Movement of some plant taxa toward mountaintops, has been observed in the past decades. However, for species restricted to the highest elevations, there is nowhere to move to, meaning they are increasingly at risk of extinction. Climatic conditions may exceed the physiological limits for species and the habitat may become unsuitable for others. There is also a risk from competition with colonizing native species and invading non-native species, spreading to higher elevations and some species cannot move quickly enough to keep pace with the change in climate. The most vulnerable species are those that reproduce and disperse slowly and those that are isolated on the mountaintops, including endemic species, which may face global extinction. In other cases species will be lost from some parts of their current range. Mountains can however allow other species to survive in areas where they would not otherwise do so, because of small scale variations in climate with elevation or different aspects of slopes.

Changes in snow cover and snow duration are related to changes in temperature and precipitation and are also critical for plants and animals. In particular, glacier retreat and changing snow patterns affect both streamflow dynamics (including extremes) and soil moisture conditions and can cause moisture shortages during the growing season. Change of snow patterns can critically affect animal movements in mountains. Other processes creating stresses on mountain ecosystems are direct human impacts, such as the influence of grazing, tourism, air pollution and nitrogen deposition on alpine vegetation. In some cases, these impacts can be so large on the goods and services provided by alpine ecosystems, that they can overshadow the effects of climate change or exacerbate its effects.

In many mountain regions, multiple sources of evidence point to tree expansions into treeless area above (and in some cases below) the forest belt. This may increase forest productivity at the upper treeline. Treelines have moved up in the last 30-100 years in many mountain regions, including e.g. Andes, Urals and Altai. At the same time, since the 1990s, treelines responses in different parts of the Himalaya have been highly variable, in some places advancing upslope, in others demonstrating little change, and in others moving downward. This can be explained by site-specific complex interactions of the positive effect of warming on tree growth, drought stress, change in snow precipitation, land-use change, especially grazing, and other factors. Treelines are affected by land use and management around the globe and changing land-use practices can supersede climate change effects in some mountain regions. An upward shift in elevation of bioclimatic zones, decreases in area of the highest elevation zones, and an expansion of the lower zones can be expected by mid-century, for examples in regions such as the Himalaya.

In some regions, the livelihoods of many local mountain communities depend on access to firewood, pastures, edible plants and mushrooms, medicinal and aromatic plants. Climate change can alter the quality and quantity of these ecosystem services; however, the degree and direction of change are context specific. The appeal and feasibility of mountains for tourism and recreation activities are also affected by climate change.

[END FAQ CCP5.3 HERE]

[START FAQ CCP5.4 HERE]

FAQ CCP5.4: What type of adaptation options are feasible to address the impacts of climate change in mountain regions under different levels of warming, and what are their limits?

The feasibility of adaptation to address risks in mountain regions is influenced by numerous factors, many of which are unique to mountain people and their environment. Adaptation efforts in mountains are mainly made of small steps and largely autonomous. Robust and flexible adaptation measures have a better chance to address risks, but eventually large systemic transformation will be needed for higher levels of warming. Empirical evidence on "what works and what does not work" is largely absent, but urgently needed.

The term feasibility refers to climate goals and adaptation options that are possible and desirable. Feasibility is influenced by factors such as economic viability, availability of technical resources, institutional support, social capital, ecological and adaptive capacity, and biophysical conditions. Establishing the feasibility of options under changing climatic and socio-economic conditions is not an easy task – mostly because even present feasibility is difficult to assess in mountains, due to a lack of systematic information on opportunities and challenges of adaptation in practice.

Underlying environmental conditions such as limited space, shallow soils, exposure to numerous hazards, climate-sensitive ecosystems and isolation make it particularly difficult to implement adaptation at scales relevant for implementation. Common adaptation options are often implemented at the individual, household or community scale. These options are incremental and have generated observable results and outcomes. Adaptation actions that involve partial changes that do not dramatically alter established practices and behaviours seem to have better chances of being implemented than systemic or structural changes. Formal or planned adaptation efforts which are more institutionally driven are only a small proportion of observed adaptation in mountains regions. Where adaptation options are implemented, they are often not only targeting climate change, but an array of other issues, priorities, and pressures experienced by and in those communities (e.g. livelihood diversification in farming practices).

Whether or not adaptation options are feasible does not say much about their effectiveness, i.e. the degree to which adaptation has been or will be successful in reducing the risks of negative impacts. Adaptation is difficult to disentangle from other factors that contribute to both increasing and decreasing risks. Since adaptation in mountains is often autonomous and unplanned, measuring its effectiveness is complex and missed by more conventional, formal, or structured monitoring and evaluation frameworks.

Evidence suggests that promising measures being taken in mountains are those that are robust under uncertain futures, allow for adaptive planning and management, and respond to multiple interests and purposes. For example, multi-purpose water reservoirs can alleviate multiple stressors and address several risks such as those from natural hazards and water shortages. Capacity building and awareness-raising can go a long way to ensure that these measures are also socially acceptable if combined with more structural and systemic changes. Indeed, transformations are happening slowly in mountains and it is unlikely that small steps and incremental measures will be able to cope with more severe and pervasive risks.

Overall, empirical evidence on the effectiveness of adaptation to reducing risk is largely missing but is urgently needed to better understand what works and what does not work under certain circumstances.

[END FAQ CCP5.4 HERE]

[START FAQ CCP5.5 HERE]

FAQ CCP5.5: Why regional cooperation and transboundary governance is needed for sustainable mountain development?

Regional cooperation and transboundary governance are key to managing our vast mountain resources because they do not necessarily share political boundaries. Mountain countries need to come together, share data and information, form joint management committees, bring in policies and take decisions that benefit all countries equitably. Lack of cooperation may lead to missing important opportunities to address climate risks and adequately manage mountain resources, which can cause potential social unrest and spark conflict within and between countries.

Mountains are climate change hotspots that are highly susceptible to climate change. Due to rapidly changing climatic conditions, climate change is one of the major issues that would benefit from regional cooperation. The transboundary management of mountains means shared legal and institutional frameworks for sharing the benefits and costs of managing the mountain ranges across boundaries, be it local or district jurisdictions within countries or indeed across national boundaries.

The IPCC's Special Report on Oceans and Cryosphere refers to governance as an "effort to establish, reaffirm or change formal and informal institutions at all scales to negotiate relationships, resolve social conflicts and realise mutual gains". Governance is an act of governments, NGOs, private sectors, and civil society in establishing rules and norms for restricting the use of common goods. "Institutions can guide, constrain, and shape human interaction through direct control, incentives, and processes of socialisation". How do we apply the definitions of governance and institutions in the context of mountains? Since governance not only refers to government, which is a formal arm of the state, it also talks about other agencies such as community organizations, non-profit or businesses that play a vital role in society and influences individual or collective decisions and help in preventing the overexploitation of its resources.

To comprehend the processes of governance in mountain areas, we need to recognize how each of these agencies add to the enduring task of enabling and managing change at the system level but also to preserving social structure and reconciling disputes. For the sustainable and resilient development of mountain regions, governance mechanisms may be different than those applied for managing other resources such as coastal zones or rivers. This is also because mountains are mostly transboundary and do not necessarily follow political boundaries. Mountain governance, therefore, is about managing the resources across political boundaries for the benefit of all countries. This includes downstream countries that also rely on these resources such as water, silt, and other resources from these mountain regions. These include high rangelands, biodiversity hotspots, forests, glaciers etc.

There are several examples of regional cooperation around the governance of shared resources in mountains. Some examples come from the Arctic (bottom-up and science-based evolution of Arctic cooperation), South-East Europe (regionalisation of environmental benefits) and the Hindu Kush Himalaya region (inter-governmental scientific institution for research and data sharing). Mountains share resources and therefore, their management will benefit from cooperation between countries. Transboundary cooperation is not only needed to address transboundary climate risks and regional adaptation to climate change in mountains, but also to work across countries to reduce greenhouse gas emissions.

[END FAQ CCP5.5 HERE]

References

Abatzoglou, J. T., A. P. Williams and R. Barbero, 2019: Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophysical Research Letters*, **46**(1), doi:10.1029/2018GL080959.

Abram, N. J. et al., 2021: Connections of climate change and vari-ability to large and extreme forest fires in southeast Australia. *Communications Earth and Environment*, **2**, doi:10.1038/s43247-020-00065-8.

Adams, H., 2016: Why populations persist: mobility, place attachment and climate change. *Population and Environment*, **37**, 429–448, doi:10.1007/s11111-015-0246-3.

Adhikari, L., S. Tuladhar, A. Hussain and K. Aryal, 2019: Are Traditional Food Crops Really 'Future Smart Foods?'A Sustainability Perspective. *Sustainability*, **11**(19), 5236, doi:10.3390/su11195236.

Adler, C., C. Huggel, B. Orlove and A. Nolin, 2019: Climate change in the mountain cryosphere: impacts and responses. *Regional Environmental Change*, **19**(5), 1225-1228, doi:10.1007/s10113-019-01507-6.

Aggarwal, A. et al., 2021: Adaptation to climate change induced water stress in major glacierized mountain regions. *Climate and Development*, 1-13, doi:10.1080/17565529.2021.1971059.

Ahlers, R. et al., 2015: Framing hydropower as green energy: assessing drivers, risks and tensions in the Eastern Himalayas. *Earth System Dynamics*, **6**(1), 195–204, doi:10.5194/esd-6-195-2015.

Al-Gabbiesh, A., M. Kleinwächter and D. Selmar, 2015: Influencing the contents of secondary metabolites in spice and medicinal plants by deliberately applying drought stress during their cultivation. *Jordan Journal of Biological Sciences*, **147**(3379), 1-10.

Albrich, K., W. Rammer and R. Seidl, 2020: Climate change causes critical transitions and irreversible alterations of mountain forests. *Global Change Biology*, **26**(7), 4013-4027, doi:10.1111/gcb.15118.

Alcántara-Ayala, I., V. Murray, P. Daniels and G. McBean, 2017: International Council for Science (ICSU)—On the Future Challenges for the Integration of Science into International Policy Development for Landslide Disaster Risk Reduction. In: *Advancing Culture of Living with Landslide* [Sassa, K., M. Mikoš and Y. Yin (eds.)]. Springer, Cham, Switzerland, pp. 143-154. ISBN 9783319594699.

Alfthan, B. et al., 2018: *Mountain Adaptation Outlook Series – Synthesis Report*. United Nations Environment Programme, and GRID-Arendal, Nairobi, Kenya, Vienna, Austria, and Arenda, Norway, 51 pp. ISBN 9788277011806.

Alfthan, B. et al., 2016: *Waste Management Outlook for Mountain Regions – Sources and Solutions*. United Nations Environment Programme, GRID-Arendal and ISWA, Nairobi, Kenya, Vienna, Austria, and Arenda, Norway, 51 pp. ISBN 9788277011585.

Allen, S. et al., 2020: *Building Transformative Institutional Adaptive Capacity: Assessing The Potential Contribution of PPCR to Build a Climate Resilient Water Governance Framework in The Plurinational State of Bolivia*. Inter-American Development Bank Available at: https://publications.iadb.org/en/building-transformative-institutional-adaptive-capacity-assessing-potential-contribution-ppcr-build (accessed 30/08/2021).

Allen, S. K. et al., 2018: Translating the concept of climate risk into an assessment framework to inform adaptation planning: Insights from a pilot study of flood risk in Himachal Pradesh, Northern India. *Environmental Science & Policy*, **87**, 1-10, doi:10.1016/j.envsci.2018.05.013.

Allen, S. K. et al., 2016: Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. *Natural Hazards*, **84**(3), 1741-1763, doi:10.1007/s11069-016-2511-x.

Allison, E. A., 2015: The spiritual significance of glaciers in an age of climate change. *WIREs Climate Change*, **6**(5), 493-508, doi:10.1002/wcc.354.

AlpineConvention, 2021: *CLIMATE ACTION PLAN 2.0*. Permanent Secretariat of the Alpine Convention, Innsbruck, Austria. Available at: https://www.alpconv.org/en/home/news-publications/publications-multimedia/detail/climate-action-plan-20/.

Amadu, F. O., D. C. Miller and P. E. McNamara, 2020: Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. *Ecological Economics*, **167**(C), 106443, doi:10.1016/j.ecolecon.2019.106443.

Anderson, E. P. et al., 2018: Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Science Advances*, **4**(1), eaao1642, doi:10.1126/sciadv.aao1642.

Applequist, W. L. et al., 2020: Scientists' warning on climate change and medicinal plants. *Planta medica*, **86**(01), 10-18.

Archibald, S. et al., 2018: Biological and geophysical feedbacks with fire in the Earth system. *Environmental Research Letters*, **13**(3), 033003, doi:10.1088/1748-9326/aa9ead.

Arnell, N. W. and S. N. Gosling, 2016: The impacts of climate change on river flood risk at the global scale. *Climatic Change*, **134**(3), 387-401, doi:10.1007/s10584-014-1084-5.

Artemov, I. A., 2018: Changes in the Altitudinal Distribution of Alpine Plants in Katunskiy Biosphere Reserve (Central Altai) Revealed on the Basis of Multiyear Monitoring Data. *Contemporary Problems of Ecology*, **11**(1), 1-12, doi:10.1134/S1995425518010018.

Ashraf, M., J. K. Routray and M. Saeed, 2014: Determinants of farmers' choice of coping and adaptation measures to the drought hazard in northwest Balochistan, Pakistan. *Natural hazards*, **73**(3), 1451-1473, doi:10.1007/s11069-014-1149-9.

Ashrafzadeh, M. R., A. A. Naghipour, M. Haidarian and I. Khorozyan, 2019: Modeling the response of an endangered flagship predator to climate change in Iran. *Mammal Research*, **64**, 39-51, doi:10.1007/s13364-018-0384-y.
Báez, S., L. Jaramillo, F. Cuesta and D. A. Donoso, 2016: Effects of climate change on Andean biodiversity: a synthesis of studies published until 2015. *Neotropical Biodiversity*, **2**(1), 181-194, doi:10.1080/23766808.2016.1248710.
Baiker, J. R. et al., 2020: How the COVID-19 pandemic is teaching us to tackle the climate crisis, PLOS Collections. Available at: https://collectionsblog.plos.org/how-the-covid-19-pandemic-is-teaching-us-to-tackle-the-climate-crisis/.
Balderas Torres, A., S. Angón Rodríguez, A. Sudmant and G. A., 2021: *Adapting to climate change in mountain cities: Lessons from Xalapa, Mexico*. Coalition for Urban Transitions, London and Washington, DC. Available at: https://urbantransitions.global/publications.
Balsiger, J., E. Dupuits and A. Scolobig, 2020: *International Experience in Transboundary Mountain Governance: Insights for Andean Cooperation*. Institute for Environmental Governance and Territorial Development, University of Geneva, Geneva, Switzerland, 124 pp. Available at: https://archive-ouverte.unige.ch/unige:145756 (accessed 10/12/2020).
Banerjee, S., R. Black, A. Mishra and D. Kniveton, 2018: Assessing vulnerability of remittance-recipient and non-recipient households in rural communities affected by extreme weather events: Case studies from south-west China and north-east India. *Population, Space and Place*, **25**(2), e2157, doi:10.1002/psp.2157.
Banerjee, S., A. Hussain, S. Tuladhar and A. Mishra, 2019: Building capacities of women for climate change adaptation: Insights from migrant-sending households in Nepal'. *Climatic Change*, **157**, 587-609, doi:10.1007/s10584-019-02572-w.
Bani, L. et al., 2019: Winners and losers: How the elevational range of breeding birds on Alps has varied over the past four decades due to climate and habitat changes. *Ecology and Evolution*, **9**(3), 1289-1305, doi:10.1002/ece3.4838.
Baraer, M. et al., 2015: Contribution of groundwater to the outflow from ungauged glacierized catchments: a multi-site study in the tropical Cordillera Blanca, Peru. *Hydrological Processes*, **29**(11), 2561-2581, doi:10.1002/hyp.10386.
Barberán, R. M. et al., 2019: Vulnerability to climate change of smallholder cocoa producers in the province of Manabí, Ecuador. *Revista Facultad Nacional de Agronomía Medellín*, **72**(1), 8707-8716, doi:10.15446/rfnam.v72n1.72564.
Barnett, T. P., J. C. Adam and D. P. Lettenmaier, 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, **438**(7066), 303–309, doi:10.1038/nature04141.
Batima, P., L. Natsagdorj and N. Batnasan, 2013: Vulnerability of Mongolia's pastoralists to climate extremes and changes. In: *Climate Change and Vulnerability and Adaptation* [Leary, N., C. Conde, J. Kulkarni, A. Nyong, J. Adejuwon, V. Barros, I. Burton, R. Lasco and J. Pulhin (eds.)]. Routledge, London, United Kingdom, pp. 67-87. ISBN 9781315067179.
Baul, T. and M. A. McDonald, 2015: Integration of Indigenous knowledge in addressing climate change. *Indian journal of traditional knowledge*, **1**, 20-27.
Baur, B. and A. Baur, 2013: Snails keep the pace: shift in upper elevation limit on mountain slopes as a response to climate warming. *Canadian journal of zoology*, **91**(8), 596-599, doi:10.1139/cjz-2013-0036.
Beeton, T. A. and K. A. Galvin, 2017: Wood-based bioenergy in western Montana: the importance of understanding path dependence and local context for resilience. *Ecology Society*, **22**(2), 9, doi:10.5751/ES-09157-220209.
Bekchanov, M. and J. P. A. Lamers, 2016: Economic costs of reduced irrigation water availability in Uzbekistan (Central Asia). *Regional Environmental Change*, **16**(8), 2369-2387, doi:10.1007/s10113-016-0961-z.
Beltrán-Tolosa, L. M. et al., 2020: Action needed for staple crops in the Andean-Amazon foothills because of climate change. *Mitigation and Adaptation Strategies for Global Change*, **25**(6), 1103-1127, doi:10.1007/s11027-020-09923-4.
Benedetti, Y., E. Kapsalis, F. Morelli and V. Kati, 2021: Sacred oak woods increase bird diversity and specialization: Links with the European Biodiversity Strategy for 2030. *Journal of Environmental Management*, **294**, 112982, doi:10.1016/j.jenvman.2021.112982.
Beniston, M. et al., 2018: The European mountain cryosphere: a review of its current state, trends, and future challenges. *The Cryosphere*, **12**(2), 759-794, doi:10.5194/tc-12-759-2018.
Beniston, M. et al., 1996: Impacts of climate change on mountain regions. In: *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses* [Watson, R. T., M. C. Zinyowera and R. H. Moss (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 191-213. ISBN 052156431X.
Beniston, M., M. Rebetez, F. Giorgi and M. R. Marinucci, 1994: An analysis of regional climate change in Switzerland. *Theoretical and Applied Climatology*, **49**, 135–159, doi:10.1007/BF00865530.
Beniston, M. and M. Stoffel, 2014: Assessing the impacts of climatic change on mountain water resources. *Science of The Total Environment*, **493**, 1129-1137, doi:10.1016/j.scitotenv.2013.11.122.
Berkey, J. K., R. T. Belote, C. T. Maher and A. Larson, 2021: Structural diversity and development in active fire regime mixed-conifer forests. *Forest Ecology Management*, **479**, 118548, doi:10.1016/j.foreco.2020.118548.
Berrang-Ford, L. et al., 2021: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, In press, doi:10.21203/rs.3.rs-100873/v1.

Bharti, N. et al., 2020: Dynamics of urban water supply management of two Himalayan towns in India. *Water Policy*, **22**(s1), 65-89, doi:10.2166/wp.2019.203.
Bhatta, K. P., J.-A. Grytnes and O. R. Vetaas, 2018: Downhill shift of alpine plant assemblages under contemporary climate and land-use changes. *Ecosphere*, **9**(1), e02084, doi:10.1002/ecs2.2084.
Biemans, H. et al., 2019: Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, **2**(7), 594-601, doi:10.1038/s41893-019-0305-3.
Bissenbayeva, S., J. Abuduwaili, A. Saparova and T. Ahmed, 2021: Long-term variations in runoff of the Syr Darya River Basin under climate change and human activities. *Journal of Arid Land*, **13**(1), 56-70, doi:10.1007/s40333-021-0050-0.
Bitencourt, C., A. Rapini, L. Santos Damascena and P. De Marco Junior, 2016: The worrying future of the endemic flora of a tropical mountain range under climate change. *Flora - Morphology, Distribution, Functional Ecology of Plants*, **218**, 1-10, doi:10.1016/j.flora.2015.11.001.
Bocchiola, D., M. G. Pelosi and A. Soncini, 2017: Effects of hydrological changes on cooperation in transnational catchments: the case of the Syr Darya. *Water International*, **42**(7), 852-873, doi:10.1080/02508060.2017.1376568.
Boelens, R., 2014: Cultural politics and the hydrosocial cycle: Water, power and identity in the Andean highlands. *Geoforum*, **57**, 234-247, doi:10.1016/j.geoforum.2013.02.008.
Bondé, L. et al., 2019: Variability and estimating in fruiting of shea tree (Vitellaria paradoxa CF Gaertn) associated to climatic conditions in West Africa: implications for sustainable management and development. *Plant Production Science*, **22**(2), 143-158.
Bosson, J. B., M. Huss and E. Osipova, 2019: Disappearing World Heritage Glaciers as a Keystone of Nature Conservation in a Changing Climate. *Earth's Future*, **7**(4), 469-479, doi:10.1029/2018EF001139.
Bowman, D. M. J. S., A. Bliss, C. J. W. Bowman and L. D. Prior, 2019: Fire caused demographic attrition of the Tasmanian palaeoendemic conifer Athrotaxis cupressoides. *Austral Ecology*, **44**(8), 1322-1339, doi:10.1111/aec.12789.
Bowman, D. M. J. S. et al., 2014: Abrupt fire regime change may cause landscape-wide loss of mature obligate seeder forests. *Global Change Biology*, **20**(3), 1008-1015, doi:10.1111/gcb.12433.
Bowman, D. M. J. S., G. J. Williamson, L. D. Prior and B. P. Murphy, 2016: The relative importance of intrinsic and extrinsic factors in the decline of obligate seeder forests. *Global Ecology and Biogeography*, **25**(10), 1166-1172, doi:10.1111/geb.12484.
Bradstock, R. et al., 2014: Divergent responses of fire to recent warming and drying across south-eastern Australia. *Global Change Biology*, **20**(5), 1412-1428, doi:10.1111/gcb.12449.
Bradstock, R. A., 2010: A biogeographic model of fire regimes in Australia: current and future implications. *Global Ecology and Biogeography*, **19**(2), 145-158, doi:10.1111/j.1466-8238.2009.00512.x.
Bramer, I. et al., 2018: Advances in monitoring and modelling climate at ecologically relevant scales. In: *Advances in Ecological Research* [Bohan, D. A., A. J. Dumbrell, G. Woodward and M. Jackson (eds.)]. Elsevier, San Diego, California, USA, pp. 101-161. ISBN 9780128139493.
Brandt, R., R. Kaenzig and S. Lachmuth, 2016: Migration as a Risk Management Strategy in the Context of Climate Change: Evidence from the Bolivian Andes. In: *Migration, Risk Management and Climate Change: Evidence and Policy Responses* [Milan, A., B. Schraven, K. Warner and N. Cascone (eds.)]. Springer, Cham, Switzerland, pp. 43-61. ISBN 9783319429229.
Bråthen, K. A., V. T. González and N. G. Yoccoz, 2018: Gatekeepers to the effects of climate warming? Niche construction restricts plant community changes along a temperature gradient. *Perspectives in Plant Ecology, Evolution and Systematics*, **30**, 71-81, doi:10.1016/j.ppees.2017.06.005Get.
Bremer, S. and S. Meisch, 2017: Co-production in climate change research: reviewing different perspectives. *Wiley Interdisciplinary Reviews: Climate Change*, **8**(6), e482, doi:10.1002/wcc.482.
Briner, S., C. Elkin and R. Huber, 2013: Evaluating the relative impact of climate and economic changes on forest and agricultural ecosystem services in mountain regions. *Journal of Environmental Management*, **129**, 414-422, doi:10.1016/j.jenvman.2013.07.018.
Britton, A. J. et al., 2016: Climate, pollution and grazing drive long-term change in moorland habitats. *Applied Vegetation Science*, **20**(2), 194-203, doi:10.1111/avsc.12260.
Brunette, M., R. Bourke, M. Hanewinkel and R. Yousefpour, 2018: Adaptation to climate change in forestry: A multiple correspondence analysis (MCA). *Forests*, **9**(1), 20, doi:ff10.3390/f9010020.
Brunetti, M. et al., 2019: Phylogeography and species distribution modelling of Cryptocephalus barii (Coleoptera: Chrysomelidae): is this alpine endemic species close to extinction? *ZooKeys*, **856**, 3-25, doi:10.3897/zookeys.856.32462.
Brunner, M. I. et al., 2019: Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. *Science of The Total Environment*, **666**, 1033-1047, doi:10.1016/j.scitotenv.2019.02.169.
Buerkert, A., E. Fernandez, B. Tietjen and E. Luedeling, 2020: Revisiting climate change effects on winter chill in mountain oases of northern Oman. *Climatic Change*, **162**(3), 1399-1417, doi:10.1007/s10584-020-02862-8.
Burke, M. et al., 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of united States of America, PNAS*, **118**(2), e2011048118, doi:10.1073/pnas.2011048118.

Buytaert, W. et al., 2014: Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, **2**, 1-21, doi:10.3389/feart.2014.00026.
Camac, J. S. et al., 2021: Predicting species and community responses to global change using struc-tured expert judgement: An Australian mountain ecosystems case study. *Global Change Biology*, 1-15, doi:10.1111/gcb.15750.
Camac, J. S. et al., 2017: Climatic warming strengthens a positive feedback between alpine shrubs and fire. *Global Change Biology*, **23**(8), doi:10.1111/gcb.13614.
Camac, J. S. et al., 2013: Post-fire regeneration in alpine heathland: Does fire severity matter? *Austral Ecology*, **38**(2), 199-207, doi:10.1111/j.1442-9993.2012.02392.x.
Capitani, C. et al., 2019: Views from two mountains: Exploring climate change impacts on traditional farming communities of Eastern Africa highlands through participatory scenarios. *Sustainability Science*, **14**(1), 191-203, doi:10.1007/s11625-018-0622-x.
Carboni, M. et al., 2018: Simulating plant invasion dynamics in mountain ecosystems under global change scenarios. *Global change biology*, **24**(1), 289-302, doi:10.1111/gcb.13879.
Carey, M. et al., 2014: Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru). *Journal of Hydrology*, **518, Part A**, 60-70, doi:10.1016/j.jhydrol.2013.11.006.
Carey, M. et al., 2017: Impacts of Glacier Recession and Declining Meltwater on Mountain Societies. *Annals of the American Association of Geographers*, **107**(2), 350-359, doi:10.1080/24694452.2016.1243039.
CarpathianConvention, 2020: *Long-term Vision 2030 towards combating climate change in the Carpathians*. Carpathian Convention Working Group on Climate Change. Sixth Meeting of the Conference of the Parties to the Framework Convention on the Protection and Sustainable Development of the Carpathians. Available at: http://www.carpathianconvention.org/tl_files/carpathiancon/Downloads/03%20Meetings%20and%20Events/COP/2020_COP6_Online/official%20documents/CC%20COP6%20DOC10_Long_Term_Vision_2030_FINAL%20DRAFT.pdf.
Caruso, B., S. Newton, R. King and C. Zammit, 2017a: Modelling climate change impacts on hydropower lake inflows and braided rivers in a mountain basin. *Hydrological sciences journal*, **62**(6), 928-946, doi:10.1080/02626667.2016.1267860.
Caruso, B. S., R. King, S. Newton and C. Zammit, 2017b: Simulation of Climate Change Effects on Hydropower Operations in Mountain Headwater Lakes, New Zealand. *River Research and Applications*, **33**(1), 147-161, doi:10.1002/rra.3056.
Catford, J. A., R. Jansson and C. Nilsson, 2009: Reducing redundancy in invasion ecol-ogy by integrating hypotheses into a single theoretical framework. *Diversity and Distributions*, **15**, 22-40, doi:10.1111/j.1472-4642.2008.00521.x.
Cattaneo, C. et al., 2019: Human Migration in the Era of Climate Change. *Review of Environmental Economics and Policy*, **13**, 2, doi:10.1093/reep/rez008.
Ceruti, M. C., 2019: Practical Spirituality and Journey with Sacred Mountains. In: *Practical Spirituality and Human Development*. Springer, pp. 495-509.
Chakraborty, A., P. K. Joshi and K. Sachdeva, 2016: Predicting distribution of major forest tree species to potential impacts of climate change in the central Himalayan region. *Ecological engineering*, **97**, 593-609, doi:10.1016/j.ecoleng.2016.10.006.
Chakraborty, R. and P. Y. Sherpa, 2021: From climate adaptation to climate justice: Critical reflections on the IPCC and Himalayan climate knowledges. *Climatic Change*, **167**(3), 49, doi:10.1007/s10584-021-03158-1.
Chanapathi, T. and S. Thatikonda, 2020: Evaluation of sustainability of river Krishna under present and future climate scenarios. *Science of The Total Environment*, **738**, 140322, doi:10.1016/j.scitotenv.2020.140322.
Chang, J. D. et al., 2016: Effects of elevated CO2 and temperature on Gynostemma pentaphyllum physiology and bioactive compounds. *Journal of Plant Physiology*, **196**, 41-52, doi:10.1016/j.jplph.2016.02.020.
Chaudhary, P. et al., 2020: Threats, Drivers, and Conservation Imperative of Agrobiodiversity. *The Journal of Agriculture and Environment*, **21**, 44-61.
Chelleri, L., G. Minucci and E. Skrimizea, 2016: Does community resilience decrease social–ecological vulnerability? Adaptation pathways trade-off in the Bolivian Altiplano. *Regional Environmental Change*, **16**, 2229-2241, doi:10.1007/s10113-016-1046-8.
Chen, M. et al., 2021: Climatic, land cover, and anthropogenic controls on dissolved organic matter quantity and quality from major alpine rivers across the Himalayan-Tibetan Plateau. *Science of The Total Environment*, **754**, 142411, doi:10.1016/j.scitotenv.2020.142411.
Chevallier, P., B. Pouyaud, W. Suarez and T. Condom, 2011: Climate change threats to environment in the tropical Andes: glaciers and water resources. *Regional Environmental Change*, **11**, 179-187, doi:10.1007/s10113-010-0177-6.
Chhetri, P. K. and D. M. Cairns, 2018: Low recruitment above treeline indicates treeline stability under changing climate in Dhorpatan Hunting Reserve, Western Nepal. *Physical Geography*, **39**(4), 329-342, doi:10.1080/02723646.2018.1428266.

Chirwa, P. W., L. Mahamane and G. Kowero, 2017: Forests, people and environment: some African perspectives. *Southern Forests: a Journal of Forest Science*, **79**(2), 79-85, doi:10.2989/20702620.2017.1295347.
Chitale, V., R. Silwal and M. Matin, 2018: Assessing the Impacts of Climate Change on Distribution of Major Non-Timber Forest Plants in Chitwan Annapurna Landscape, Nepal. *Resources*, **7**(4), 66, doi:10.3390/resources7040066.
Clayton, S., 2020: Climate anxiety: Psychological responses to climate change. *Journal of Anxiety Disorders*, **74**, 102263, doi:10.1016/j.janxdis.2020.102263.
Coals, P. et al., 2018: Elevation patterns of plant diversity and recent altitudinal range shifts in Sinai's high-mountain flora. *Journal of vegetation science*, **29**(2), 255-264, doi:10.1111/jvs.12618.
Crimmins, S. M. et al., 2011: Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science*, **331**(6015), 324-327, doi:10.1126/science.1199040.
Cuesta, F. et al., 2019: New land in the Neotropics: a review of biotic community, ecosystem, and landscape transformations in the face of climate and glacier change. *Regional Environmental Change*, **19**(6), 1623-1642, doi:10.1007/s10113-019-01499-3.
Cuesta, F. et al., 2020: Thermal niche traits of high alpine plant species and communities across the tropical Andes and their vulnerability to global warming. *Journal of Biogeography*, **47**(2), 408-420.
Cui, P. and Y. Jia, 2015: Mountain hazards in the Tibetan Plateau: research status and prospects. *National Science Review*, **2**(4), 397-399, doi:10.1093/nsr/nwv061.
Cunsolo, A. and N. R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8**(4), 275-281, doi:10.1038/s41558-018-0092-2.
Dainese, M. et al., 2017: Human disturbance and upward expansion of plants in a warming climate. *Nature Climate Change*, **7**(8), 577-580, doi:0.1038/nclimate3337.
Dandy, J. et al., 2019: Leaving home: place attachment and decisions to move in the face of environmental change. *Regional Environmental Change* **19**, 615-620, doi:10.1007/s10113-019-01463-1.
Dangles, O. et al., 2017: Ecosystem sentinels for climate change? Evidence of wetland cover changes over the last 30 years in the tropical Andes. *PLoS One*, **12**(5), e0175814, doi:10.1371/journal.pone.0175814.
Dantés, H. G., J. A. Farfán-Ale and E. Sarti, 2014: Epidemiological Trends of Dengue Disease in Mexico (2000–2011): A Systematic Literature Search and Analysis. *PLOS Neglected Tropical Diseases*, **8**(11), e3158, doi:10.1371/journal.pntd.0003158.
Das, M., V. Jain and S. Malhotra, 2016: Impact of climate change on medicinal and aromatic plants: Review. *Indian Journal of Agricultural* **86**(11), 1375-1382.
Das, P. V., 2021: People's climate knowledge versus scientists' climate knowledge: a study of apple farming communities in Western Himalayas, India. *GeoJournal*, 1-12.
Davies, K. T. et al., 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, **116**(13), 6193-6198, doi:10.1073/pnas.1815107116.
de la Barrera, F. et al., 2018: Megafires in Chile 2017: Monitoring multiscale environmental impacts of burned ecosystems. *Sci Total Environ*, **637-638**, 1526-1536, doi:10.1016/j.scitotenv.2018.05.119.
de la Riva, M. V. d. l., A. Lindner and J. Pretzsch, 2013: Assessing adaptation – Climate change and indigenous livelihood in the Andes of Bolivia. *Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS)*, **114**(2), 109-122.
De Roos, S., D. Turner, A. Lucieer and D. M. J. S. Bowman, 2018: Using Digital Surface Models from UAS Imagery of Fire Damaged Sphagnum Peatlands for Monitoring and Hydrological Restoration. *Drones*, **2**(4), 45, doi:10.3390/drones2040045.
Demiroglu, O. C., L. Lundmark, J. Saarinen and D. K. Müller, 2019: The last resort? Ski tourism and climate change in Arctic Sweden. *Journal of Tourism Futures*, **6**(1), 91-101, doi:10.1108/JTF-05-2019-0046.
Dhakal, S. et al., 2019: Meeting Future Energy Needs in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People* [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer, Cham, Switzerland, pp. 167-207. ISBN 9783319922881.
Dhimal, M., B. Ahrens and U. Kuch, 2015: Climate Change and Spatiotemporal Distributions of Vector-Borne Diseases in Nepal – A Systematic Synthesis of Literature. *PLOS ONE*, **10**(6), e0129869, doi:10.1371/journal.pone.0129869.
Di Baldassarre, G. et al., 2018: Water shortages worsened by reservoir effects. *Nature Sustainability*, **1**, 617-622, doi:10.1038/s41893-018-0159-0.
Di Virgilio, G. et al., 2020: Climate Change Significantly Alters Future Wildfire Mitigation Opportunities in Southeastern Australia. *Geophysical Research Letters*, **47**(15), e2020GL088893, doi:10.1029/2020GL088893.
Díaz, P., C. Adler and A. Patt, 2017: Do stakeholders' perspectives on renewable energy infrastructure pose a risk to energy policy implementation? A case of a hydropower plant in Switzerland. *Energy Policy*, **108**, 21-28, doi:10.1016/j.enpol.2017.05.033.
Dickerson-Lange, S. et al., 2016: Challenges and successes in engaging citizen scientists to observe snow cover: from public engagement to an educational collaboration. *Journal of Science Communication*, **15**(1), 1-14, doi:10.22323/2.15010201.

Diemberger, H., A. Hovden and E. T. Yeh, 2015: The honour of the snow-mountains is the snow: Tibetan livelihoods in a changing climate. In: *The High-Mountain Cryosphere: Environmental Changes and Human Risks* [Huggel, C., M. Carey, J. Clague and A. Kääb (eds.)]. Cambridge University Press, pp. 249-271. ISBN 9781107588653.
Dong, Z. et al., 2015: New insights into trace elements deposition in the snow packs at remote alpine glaciers in the northern Tibetan Plateau, China. *Science of The Total Environment*, **529**, 101-113, doi:10.1016/j.scitotenv.2015.05.065.
Drenkhan, F. et al., 2015: The changing water cycle: climatic and socioeconomic drivers of water-related changes in the Andes of Peru. *Wiley Interdisciplinary Reviews: Water*, **2**(6), 715-733, doi:10.1002/wat2.1105.
Drenkhan, F., C. Huggel, L. Guardamino and W. Haeberli, 2019: Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin. *Science of the Total Environment*, **665**, 465-483, doi:10.1016/j.scitotenv.2019.02.070.
Dumont, B. et al., 2015: A meta-analysis of climate change effects on forage quality in grasslands: specificities of mountain and M editerranean areas. *Grass and Forage Science*, **70**(2), 239-254, doi:10.1111/gfs.12169.
Dupire, S., T. Curt and S. Bigot, 2017: Spatio-temporal trends in fire weather in the French Alps. *Science of the Total Environment*, **595**, 801-817, doi:10.1016/j.scitotenv.2017.04.027.
Duque, A., P. R. Stevenson and K. J. Feeley, 2015: Thermophilization of adult and juvenile tree communities in the northern tropical Andes. *Proceedings of the National Academy of Sciences*, **112**(34), 10744-10749, doi:10.1073/pnas.1506570112.
Dwire, K. A., S. Mellmann-Brown and J. T. Gurrieri, 2018: Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. *Climate Services*, **10**, 44-52, doi:10.1016/j.cliser.2017.10.002.
Ebi, K. L. et al., 2021: Extreme weather and climate change: population health and health system implications. *Annual Review of Public Health Volume*, **42**, 293-315, doi:10.1146/annurev-publhealth-012420-105026.
Ehrlich, D., M. Melchiorri and C. Capitani, 2021: Population Trends and Urbanisation in Mountain Ranges of the World. *Land*, **10**(3), 255, doi:10.3390/land10030255.
Elliott, G. P. and C. M. Cowell, 2015: Slope aspect mediates fine-scale tree establishment patterns at upper treeline during wet and dry periods of the 20th century. *Arctic, Antarctic, and Alpine Research*, **47**(4), 681-692, doi:10.1657/AAAR0014-025.
Elsen, P. R., W. B. Monahan and A. M. Merenlender, 2018: Global patterns of protection of elevational gradients in mountain ranges. *Proceedings of the National Academy of Sciences*, **115**(23), 6004-6009, doi:10.1073/pnas.1720141115.
Encalada, A. C. et al., 2019: A global perspective on tropical montane rivers. *Science*, **365**(6458), 1124-1129, doi:10.1126/science.aax1682.
Enright, N. J., 2014: Introduction to the special virtual issue on climate change. *Plant Ecology*, **215**, 1-2, doi:10.1007/s11258-013-0284-9.
Enright, N. J. et al., 2015: Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, **13**(5), 265-272, doi:10.1890/140231.
Equihua, M. et al., 2017: Establishment of Aedes aegypti (L.) in mountainous regions in Mexico: Increasing number of population at risk of mosquito-borne disease and future climate conditions. *Acta Tropica*, **166**, 316-327, doi:10.1016/j.actatropica.2016.11.014.
Eriksen, S. et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383, doi:10.1016/j.worlddev.2020.105383.
Escobar, L. E. et al., 2016: Declining prevalence of disease vectors under climate change. *Scientific reports*, **6**, 39150, doi:10.1038/srep39150.
Fadrique, B. et al., 2018: Widespread but heterogeneous responses of Andean forests to climate change. *Nature*, **564**(7735), 207-212, doi:10.1038/s41586-018-0715-9.
Fairman, T. A., L. T. Bennett, S. Tupper and C. R. Nitschke, 2017: Frequent wildfires erode tree persistence and alter stand structure and initial composition of a fire-tolerant sub-alpine forest. *Journal of Vegetation Science* **28**(6), 1151-1165, doi:10.1111/jvs.12575.
Fang, Y., D. Scott and R. Steiger, 2019: The impact of climate change on ski resorts in China. *International Journal of Biometeorology*, doi:10.1007/s00484-019-01822-x.
FAO, 2015: *Mapping the vulnerability of mountain peoples to food insecurity* [Romeo, R., A. Vita, R. Testolin and T. Hofer (eds.)]. Food and Agriculture Organization of the United Nations, Rome, Italy, 66 pp. ISBN 9789251089934.
FAO, 2019: *Mountain agriculture: Opportunities for harnessing Zero Hunger in Asia* [Li, X., M. El Solh and K. H. M. Siddique (eds.)]. Food and Agricultural Organization of the United Nations, Bangkok, Thailand, 278 pp. ISBN 9789251316801.
Farinotti, D. et al., 2019: Large hydropower and water-storage potential in future glacier-free basins. *Nature*, **575**(7782), 341-344, doi:10.1038/s41586-019-1740-z.
Fassio, G., L. M. Battaglini, V. Porcellana and P. P. Viazzo, 2014: The Role of the Family in Mountain Pastoralism—Change and Continuity. *Mountain Research and Development*, **34**(4), 336-343, doi:10.1659/MRD-JOURNAL-D-14-00019.1.

Feeley, K. J. et al., 2013: Compositional shifts in Costa Rican forests due to climate-driven species migrations. *Global Change Biology*, **19**(11), 3472-3480, doi:10.1111/gcb.12300.
Felder, G. et al., 2018: From global circulation to local flood loss: Coupling models across the scales. *Science of the Total Environment*, **635**, 1225-1239, doi:10.1016/j.scitotenv.2018.04.170.
Fill, J. M., C. N. Davis and R. M. Crandall, 2019: Climate change lengthens southeastern USA light-ning-ignited fire seasons. *Global Change Bioloiy*, **25**(10), 3562– 3569, doi:10.1111/gcb.14727.
Ford, J. D. et al., 2020: The Resilience of Indigenous Peoples to Environmental Change. *One Earth*, **2**(6), 532-543, doi:10.1016/j.oneear.2020.05.014.
François, B., K. E. Schlef, S. Wi and C. M. Brown, 2019: Design considerations for riverine floods in a changing climate – A review. *Journal of Hydrology*, **574**, 557-573, doi:10.1016/j.jhydrol.2019.04.068.
Freeman, B. G., M. N. Scholer, V. Ruiz-Gutierrez and J. W. Fitzpatrick, 2018: Climate change causes upslope shifts and mountaintop extirpations in a tropical bird community. *Proceedings of the National Academy of Sciences*, **115**(47), 11982-11987, doi:10.1073/pnas.1804224115.
French, A., J. Barandiarán and C. Rampini, 2015: Contextualizing conflict. Vital water and competing values in glaciated environments. In: *The High-Mountain Cryosphere. Environmental Changes and Human Risk* [Huggel, C., M. Carey, J. J. Clague and A. Kääb (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 315-336. ISBN 9781107588653.
French, M., A. Trundle, I. Korte and C. Koto, 2021: Climate Resilience in Urban Informal Settlements: Towards a Transformative Upgrading Agenda. *Climate Resilient Urban Areas*, 129-153, doi:10.1007/978-3-030-57537-3_7.
Frisbee, M. D. et al., 2011: Streamflow generation in a large, alpine watershed in the southern Rocky Mountains of Colorado: Is streamflow generation simply the aggregation of hillslope runoff responses? *Water Resources Research*, **47**(6), doi:10.1029/2010WR009391.
Froude, M. J. and D. N. Petley, 2018: Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Science*, **18**(8), 2161-2181, doi:10.5194/nhess-18-2161-2018.
Fuhrer, J., P. Smith and A. Gobiet, 2014: Implications of climate change scenarios for agriculture in alpine regions - A case study in the Swiss Rhone catchment. *Science of the Total Environment*, **493**, 1232-1241, doi:10.1016/j.scitotenv.2013.06.038.
Furberg, M., B. Evengard and M. Nilsson, 2011: Facing the limit of resilience: perceptions of climate change among reindeer herding Sami in Sweden. *Global Health Action*, **4**(1), 8417, doi:10.3402/gha.v4i0.8417.
Furian, W., D. Loibl and C. Schneider, 2021: Future glacial lakes in High Mountain Asia: an inventory and assessment of hazard potential from surrounding slopes. *Journal of Glaciology*, **67**(264), 653-670, doi:10.1017/jog.2021.18.
Furu, P. and D. K. Van, 2013: Health Impacts of Climate and Environmental Change: Awareness and Challenges to Adaptation. In: *On the Frontiers of Climate and Environmental Change* [Bruun, O. and T. Casse (eds.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 195-217. ISBN 978-3-642-35803-6 978-3-642-35804-3.
Gaira, K. S., R. S. Rawal, B. Rawat and I. D. Bhatt, 2014: Impact of climate change on the flowering of Rhododendron arboreum in central Himalaya, India. *Current Science*, 1735-1738.
Gaire, N. P., 2016: Climate Trend and Treeline Dynamics in Nepal Himalaya. Ph.D. thesis. Tribhuvan University, Institute of Science and Technology, Kirtipur , Nepal.
Gairola, S., N. M. Shariff and A. Bhatt, 2010: Influence of climate change on production of secondary chemicals in high altitude medicinal plants: issues needs immediate attention. *Journal of Medicinal Plants Research*, **4**(18), 1825-1829.
Gariano, S. L. and F. Guzzetti, 2016: Landslides in a changing climate. *Earth-Science Reviews*, **162**, 227-252, doi:10.1016/j.earscirev.2016.08.011.
Gaudard, L. et al., 2014: Climate change impacts on hydropower in the Swiss and Italian Alps. *Science of The Total Environment*, **493**, 1211-1221, doi:10.1016/j.scitotenv.2013.10.012.
Gautam, Y., 2017: Seasonal migration and livelihood resilience in the face of climate change in Nepal. *Mountain Research and Development*, **37**(4), 436-445, doi:10.1659/MRD-JOURNAL-D-17-00035.1.
Gentle, P. and R. Thwaites, 2016: Transhumant Pastoralism in the Context of Socioeconomic and Climate Change in the Mountains of Nepal. *Mountain Research and Development*, **36**(2), 173-182, doi:10.1659/MRD-JOURNAL-D-15-00011.1.
Gerbaux, M. et al., 2020: Snow reliability and water availability for snowmaking in the ski resorts of the Isère département (French Alps), under current and future climate conditions. *Journal of Alpine Research*, **108**, 1, doi:10.4000/rga.6724.
Gergel, D. R. et al., 2017: Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change*, **141**, 287–299, doi:10.1007/s10584-017-1899-y.
Gibson, R. K., L. Broome and M. F. Hutchinson, 2018: Susceptibility to climate change via effects on food resources: the feeding ecology of the endangered mountain pygmy-possum (Burramys parvus). *Wildlife Research*, **45**(6), 539-550, doi:10.1071/WR17186.
Gidey, T., T. S. Oliveira, J. Crous-Duran and J. H. Palma, 2020: Using the yield-SAFE model to assess the impacts of climate change on yield of coffee (Coffea arabica L.) under agroforestry and monoculture systems. *Agroforestry Systems*, **94**(1), 57-70, doi:10.1007/s10457-019-00369-5.

Gilgel, A. W., T. Terefe and M. Asfaw, 2019: Assessment and Projection of Climate Change Impacts on Malaria Distribution in Ethiopia: Case of Combolcha and Debark Districts. *International Journal of Research in Environmental Science*, **5**(4), 20-42, doi:10.20431/2454-9444.0504003.
Gioli, G., T. Khan, S. Bisht and J. Scheffran, 2014: Migration as an Adaptation Strategy and its Gendered Implications: A Case Study From the Upper Indus Basin. *Mountain Research and Development*, **34**(3), 255-265, doi:10.1659/MRD-JOURNAL-D-13-00089.1.
Gioli, G. et al., 2019: Understanding and Tackling Poverty and Vulnerability in Mountain Livelihoods in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment* [Wester, P., A. Mishra, A. Mukherji and A. Shrestha (eds.)]. Springer, Cham, Switzerland, pp. 421-455. ISBN 9783319922881.
Godde, C. M. et al., 2021: Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, **28**, 100488, doi:10.1016/j.gfs.2020.100488.
Gonzales-Valero, W., 2018: Hazards to food caloric availability and coverage per capita due to climate change in the Puno region, Peruvian Altiplano: Challenges in food security and sovereignty. *Food and Energy Security*, **7**(2), e00134, doi:10.1002/fes3.134.
Goodrich, C. G., A. Prakash and P. B. Udas, 2019: Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. *Environmental Development*, **31**, 1-8, doi:10.1016/j.envdev.2019.01.001.
Gordon, R. P. et al., 2015: Sources and pathways of stream generation in tropical proglacial valleys of the Cordillera Blanca, Peru. *Journal of Hydrology*, **522**, 628-644, doi:10.1016/j.jhydrol.2015.01.013.
Gottfried, M. et al., 2012: Continent-wide response of mountain vegetation to climate change. *Nature Climate Change*, **2**(2), 111-115, doi:10.1038/nclimate1329.
Grêt-Regamey, A. and B. Weibel, 2020: Global assessment of mountain ecosystem services using earth observation data. *Ecosystem Services*, **46**, doi:10.1016/j.ecoser.2020.101213.
Grigorieva, A. V. and P. A. Moiseev, 2018: Peculiarities and Determinants of Regeneration of Siberian Larch on the Upper Limit of Its Growth in the Urals. *Contemporary Problems of Ecology*, **11**, 13-25, doi:10.1134/S1995425518010031.
Grüneis, H. et al., 2018: Why do we not pick the low-hanging fruit? Governing adaptation to climate change and resilience in Tyrolean mountain agriculture. *Land Use Policy*, **79**, 386-396, doi:10.1016/j.landusepol.2018.08.025.
Guisan, A., W. Thuiller and N. E. Zimmermann, 2017: *Habitat suitability and distribution model with applications in R*. Cambridge University Press, 462 pp. ISBN 9781139028271.
Guisan, A. A. et al., 2019: Climate change impacts on mountain biodiversity. In: *Biodiversity and Climate ChangeTransforming the Biosphere* [Lovejoy, T. E. and L. Hannah (eds.)]. Yale University Press, pp. 221-233. ISBN 9780300206111.
Guo, F., J. Lenoir and T. C. Bonebrake, 2018: Land-use change interacts with climate to determine elevational species redistribution. *Nature communications*, **9**, 1315, doi:10.1038/s41467-018-03786-9.
Gurung, A. B. et al., 2016: Rethinking pumped storage hydropower in the European Alps. *Mountain Research and Development*, **36**(2), 222–232, doi:10.1659/MRD-JOURNAL-D-15-00069.1.
Haasnoot, M. et al., 2020: Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, **20**, 37, doi:10.1007/s10113-020-01623-8.
Haeberli, W. and M. Beniston, 2021: Icy mountains in a warming world: Revisiting science from the end of the 1990s in the early 2020s. *Ambio*, **50**, 1130–1132, doi:10.1007/s13280-021-01513-1.
Haeberli, W. et al., 2016a: New lakes in deglaciating high-mountain regions – Opportunities and risks. *Climatic Change*, **139**(2), 201-214, doi:10.1007/s10584-016-1771-5.
Haeberli, W., Y. Schaub and C. Huggel, 2016b: Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, **293**(Part B), 405-417, doi:10.1016/j.geomorph.2016.02.009.
Hagedorn, F., K. Gavazov and J. M. Alexander, 2019: Above- And belowground linkages shape responses of mountain vegetation to climate change. *Science*, **365**, 1119-1123., doi:10.1126/science.aax4737.
Halofsky, J. E., D. L. Peterson and B. J. Harvey, 2020: Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, **16**, 4, doi:10.1186/s42408-019-0062-8.
Hansson, A., P. Dargusch and J. Shulmeister, 2021: A review of modern tree-line migration, the factors controlling it and the implications for carbon storage. *Journal of Mountain Science*, **18**(2), 291-306, doi:10.1007/s11629-020-6221-1.
Haque, U. et al., 2019: The human cost of global warming: Deadly landslides and their triggers (1995–2014). *Science of The Total Environment*, **682**, 673-684, doi:10.1016/j.scitotenv.2019.03.415.
Harish, B. S., S. B. Dandin, K. Umesha and H. M. Pallavi, 2012: Impact of climate change on Medicinal Plants - A review. *Ancient Science of life*, **32**(5), 23, doi:10.4103/0257-7941.111986.
Helmer, E. H. et al., 2019: Neotropical cloud forests and páramo to contract and dry from declines in cloud immersion and frost. *PloS ONE*, **14**(4), e0213155, doi:10.1371/journal.pone.0213155.
Hemp, A., 2005: Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Global Change Biology*, **11**(7), 1013-1023, doi:10.1111/j.1365-2486.2005.00968.x.

Herman-Mercer, N. M., R. A. Loehman, R. C. Toohey and C. Paniyak, 2020: Climate-and disturbance-driven changes in subsistence berries in coastal Alaska: Indigenous knowledge to inform ecological inference. *Human Ecology*, **48**(1), 85-99.
Hill, M., 2013: Adaptive Capacity of Water Governance: Cases From the Alps and the Andes. *Mountain Research and Development*, **33**(3), 248, doi:10.1659/MRD-JOURNAL-D-12-00106.1.
Hirabayashi, Y. et al., 2013: Global flood risk under climate change. *Nature Climate Change*, **3**(9), 816-821, doi:10.1038/nclimate1911.
Hock, R. et al., 2019: High Mountain Areas. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H. O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. 133-202.
Hoffmann, D., M. F. de Vasconcelos and G. Wilson Fernandes, 2020: The fate of endemic birds of eastern Brazilian mountaintops in the face of climate change. *Perspectives in Ecology and Conservation*, **18**(4), 257-266, doi:10.1016/j.pecon.2020.10.005.
Honda, E. A. and G. Durigan, 2016: Woody encroachment and its consequences on hydrological processes in the savannah. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1703), 20150313, doi:10.1098/rstb.2015.0313.
Hopping, K. A., S. M. Chignell and E. F. Lambin, 2018: The demise of caterpillar fungus in the Himalayan region due to climate change and overharvesting. *Proceedings of the National Academy of Sciences*, **115**(45), 11489-11494, doi:10.1073/pnas.1811591115.
Horvath, P. et al., 2021: Improving the representation of high-latitude vegetation distribution in dynamic global vegetation models. *Biogeosciences*, **18**(1), 95-112, doi:10.5194/bg-18-95-2021.
Hovelsrud, G. K., M. Karlsson and J. Olsen, 2018: Prepared and flexible: Local adaptation strategies for avalanche risk. *Cogent Social Sciences*, **4**(1), 1460899, doi:10.1080/23311886.2018.1460899.
Howarth, C. and I. Monasterolo, 2016: Understanding barriers to decision making in the UK energy-food-water nexus: The added value of interdisciplinary approaches. *Environmental Science & Policy*, **61**, 53-60, doi:10.1016/j.envsci.2016.03.014.
Huang, J. and H. Hao, 2020: Effects of climate change and crop planting structure on the abundance of cotton bollworm, Helicoverpa armigera (Hübner)(Lepidoptera: Noctuidae). *Ecology and Evolution*, **10**(3), 1324-1338, doi:10.1002/ece3.5986.
Huang, Z. et al., 2021: Global assessment of future sectoral water scarcity under adaptive inner-basin water allocation measures. *Science of The Total Environment*, **783**, 146973, doi:10.1016/j.scitotenv.2021.146973.
Huggel, C. et al., 2020a: Anthropogenic climate change and glacier lake outburst flood risk: local and global drivers and responsibilities for the case of lake Palcacocha, Peru. *Natural Hazards and Earth System Sciences*, **20**(8), 2175-2193, doi:10.5194/nhess-20-2175-2020.
Huggel, C. et al., 2020b: Glacier Lake 513, Peru: Lessons for early warning service development. *World Meterological Organization (WMO) Bulletin*, **69**(1), 45-52.
Huggel, C. et al., 2019: Loss and Damage in the mountain cryosphere. *Regional Environmental Change*, **19**, 1387–1399, doi:10.1007/s10113-018-1385-8.
Huggel, C. et al., 2015: A framework for the science contribution in climate adaptation: Experiences from science-policy processes in the Andes. *Environmental Science & Policy*, **47**, 80-94, doi:10.1016/j.envsci.2014.11.007.
Hugonnet, R. et al., 2021: Accelerated global glacier mass loss in the early twenty-first century. *Nature*, **592**(7856), 726-731, doi:10.1038/s41586-021-03436-z.
Hunt, J. D. et al., 2020: Mountain Gravity Energy Storage: A new solution for closing the gap between existing short- and long-term storage technologies. *Energy*, **190**, 116419, doi:10.1016/j.energy.2019.116419.
Hunter, L. M., J. K. Luna and R. M. Norton, 2015: The Environmental Dimensions of Migration. *Annual Review of Sociology*, **41**, 377-397, doi:10.1146/annurev-soc-073014-112223.
Hupp, J., M. Brubaker, K. Wilkinson and J. Williamson, 2015: How are your berries? Perspectives of Alaska's environmental managers on trends in wild berry abundance. *International journal of circumpolar health*, **74**(1), 28704.
Huss, M., 2011: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. *Water Resources Research*, **47**(7), W07511, doi:10.1029/2010WR010299.
Huss, M. et al., 2017: Toward mountains without permanent snow and ice. *Earth's Future*, **5**(5), 418-435, doi:10.1002/2016EF000514.
Huss, M. and R. Hock, 2018: Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, **8**(2), 135-140, doi:10.1038/s41558-017-0049-x.
Hussain, A., N. K. Agrawal and I. Leikanger, 2016a: Action for Adaptation: Bringing climate change science to policy makers - a synthesis report of a conference held in Islamabad on 23–25 July 2015. *Food Security*, **8**, 285-289, doi:10.1007/s12571-015-0529-7.
Hussain, A. et al., 2019: Climate Change Perspective in Mountain Area: Impacts and Adaptations in Naltar Valley, Western Himalaya, Pakistan. *Fresenius Environmental Bulletin*, **28**(9), 312-320.
Hussain, A. and F. M. Qamar, 2020: Dual challenge of climate change and agrobiodiversity loss in mountain food systems in the Hindu-Kush Himalaya. *One Earth*, doi:10.1016/j.oneear.2020.10.016.

Hussain, A., G. Rasul, B. Mahapatra and S. Tuladhar, 2016b: Household food security in the face of climate change in the Hindu-Kush Himalayan region. *Food Security*, **8**(5), 921-937, doi:10.1007/s12571-016-0607-5.
Hussain, A. et al., 2018: Climate change-induced hazards and local adaptations in agriculture: a study from Koshi River Basin, Nepal. *Natural Hazards*, **91**(3), 1365-1383, doi:10.1007/s11069-018-3187-1.
IDMC, 2020: *Internal displacement index 2020 report*. Internal Displacement Monitoring Centre, Geneva, Switzerland. Available at: https://www.internal-displacement.org/global-report/grid2020/.
Ilyashuk, B. P. et al., 2018: Rock glaciers in crystalline catchments: Hidden permafrost-related threats to alpine headwater lakes. *Global Change Biology*, **24**(4), 1548-1562, doi:10.1111/gcb.13985.
Immerzeel, W. W. et al., 2020: Importance and vulnerability of the world's water towers. *Nature*, **577**, 364-369, doi:10.1038/s41586-019-1822-y.
Ingxay, P., S. Yokoyama and I. Hirota, 2015: Livelihood factors and household strategies for an unexpected climate event in upland northern Laos. *Journal of Mountain Science*, **12**(2), 483-500, doi:10.1007/s11629-013-2879-y.
IPCC, 2018: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. Intergovernmental Panel on Climate Change, Geneva, Switserland.
Iribarren Anacona, P., A. Mackintosh and K. Norton, 2015: Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia: Lessons for GLOF risk management. *Science of The Total Environment*, **527-528**, 1-11, doi:10.1016/j.scitotenv.2015.04.096.
Isaak, D. J. et al., 2016: Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. *Proceedings of the National Academy of Sciences*, **113**(16), 4374-4379, doi:10.1073/pnas.1522429113.
Islam, R., S. Schech and U. Saikia, 2020: Climate change events in the Bengali migration to the Chittagong Hill Tracts (CHT) in Bangladesh. *Climate and Development*, 1-11, doi:10.1080/17565529.2020.1780191.
Jalilov, S.-M., S. A. Amer and F. A. Ward, 2018: Managing the water-energy-food nexus: Opportunities in Central Asia. *Journal of Hydrology*, **557**, 407-425, doi:10.1016/j.jhydrol.2017.12.040.
Jurt, C. et al., 2015: Cultural values of glaciers. In: *The High Mountain Cryosphere: Environmental Changes and Human Risks* [Huggel, C., M. Carey, J. J. Clague and A. Kääb (eds.)]. Cambridge University Press, pp. 90-106. ISBN 9781107588653.
Juschten, M. et al., 2019a: Out of the City Heat—Way to Less or More Sustainable Futures? *Sustainability*, **11**, 214, doi:10.3390/su11010214.
Juschten, M., A. Jiricka-Pürrer, W. Unbehaun and R. Hössinger, 2019b: The Mountains Are Calling! An Extended Tpb Model for Understanding Metropolitan Residents' Intentions to Visit Nearby Alpine Destinations in Summer. *Tourism Management*, **75**, 293-306, doi:10.1016/j.tourman.2019.05.014.
Kaboosi, K. and M. Kordjazi, 2017: The effect of climate change on meteorological parameters and drought in Golestan province. *Iran-Water Resources Research*, **13**(3), 205-213.
Kadetz, P. and N. B. Mock, 2018: Chapter 9 - Problematizing vulnerability: Unpacking gender, intersectionality, and the normative disaster paradigm. In: *Creating Katrina, Rebuilding Resilience* [Zakour, M. J., N. B. Mock and P. Kadetz (eds.)]. Butterworth-Heinemann, pp. 215-230. ISBN 978-0-12-809557-7.
Kalbali, E., S. Ziaee, M. Mardani Najafabadi and M. Zakerinia, 2019: Assessment of Climate Change Impacts on Optimum Cropping Pattern: A Case Study of Ghareso Basin in Golestan Province. *Iran-Water Resources Research*, **15**(3), 251-271.
Kapos, V. et al., 2000: Developing a map of the world's mountain forests. In: *Forests in sustainable mountain development: a state of knowledge report for 2000. Task Force on Forests in Sustainable Mountain Development* [Price, M. F. and N. Butt (eds.)]. CABI, Wallingford, United Kingdom, pp. 4-18. ISBN 9780851994468.
Karavani, A. et al., 2018: Effect of climatic and soil moisture conditions on mushroom productivity and related ecosystem services in Mediterranean pine stands facing climate change. *Agricultural and Forest Meteorology*, **248**, 432-440, doi:10.1016/j.agrformet.2017.10.024.
Käser, D. and D. Hunkeler, 2016: Contribution of alluvial groundwater to the outflow of mountainous catchments. *Water Resources Research*, **52**(2), 680-697, doi:10.1002/2014WR016730.
Kaul, V. and T. F. Thornton, 2014: Resilience and adaptation to extremes in a changing Himalayan environment. *Regional Environmental Change*, **14**(2), 683-698, doi:10.1007/s10113-013-0526-3.
Khanian, M., B. Serpoush and N. Gheitarani, 2019: Balance between place attachment and migration based on subjective adaptive capacity in response to climate change: the case of Famenin County in Western Iran. *Climate and Development*, **11**(1), 69-82, doi:10.1080/17565529.2017.1374238.
Kidane, Y. O., M. J. Steinbauer and C. Beierkuhnlein, 2019: Dead end for endemic plant species? A biodiversity hotspot under pressure. *Global Ecology and Conservation*, **19**, e00670-e00670, doi:10.1016/j.gecco.2019.e00670.
Kimaro, E. G., S. M. Mor and J.-A. L. M. L. Toribio, 2018: Climate change perception and impacts on cattle production in pastoral communities of northern Tanzania. *Pastoralism*, **8**(1), 19, doi:10.1186/s13570-018-0125-5.

Kinouchi, T. et al., 2019: Water security in high mountain cities of the Andes under a growing population and climate change: A case study of La Paz and El Alto, Bolivia. *Water Security*, **6**, 100025, doi:10.1016/j.wasec.2019.100025.
Kirschbaum, D., S. B. Kapnick, T. Stanley and S. Pascale, 2020: Changes in Extreme Precipitation and Landslides Over High Mountain Asia. *Geophysical Research Letters*, **47**(4), 1-9, doi:10.1029/2019GL085347.
Kirschbaum, D. et al., 2019: The State of Remote Sensing Capabilities of Cascading Hazards Over High Mountain Asia. *Frontiers in Earth Science*, **7**, 197, doi:10.3389/feart.2019.00197.
Kiseleva, N. V., 2020: Long-term Population Dynamics of the Bank Vole in the Ilmen Nature Reserve. *Russian Journal of Ecology*, **51**(2), 188-194, doi:10.1134/S1067413620020071.
Klein, J. A. et al., 2019a: Catalyzing Transformations to Sustainability in the World's Mountains. *Earth's Future*, **7**(5), 547-557, doi:10.1029/2018EF001024.
Klein, J. A. et al., 2019b: An integrated community and ecosystem-based approach to disaster risk reduction in mountain systems. *Environmental Science & Policy*, **94**, 143-152, doi:10.1016/j.envsci.2018.12.034.
Klepp, S. and L. Chavez-Rodriguez (eds.), 2018: *A Critical Approach to Climate Change Adaptation. Discourses, Policies and Practices*, Routledge, 302 pp.
Kmoch, L., T. Pagella, M. Palm and F. Sinclair, 2018: Using local agroecological knowledge in climate change adaptation: a study of tree-based options in Northern Morocco. *Sustainability*, **10**(10), 3719.
Köberl, J. et al., 2021: The demand side of climate services for real-time snow management in Alpine ski resorts: Some empirical insights and implications for climate services development. *Climate Services*, **22**, 100238, doi:10.1016/j.cliser.2021.100238.
Koide, D., K. Yoshida, C. C. Daehler and D. Mueller-Dombois, 2017: An upward elevation shift of native and non-native vascular plants over 40 years on the island of Hawai'i. *Journal of vegetation science*, **28**(5), 939-950, doi:10.1111/jvs.12549.
Körner, C., 2003: *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*. Springer, Berlin, Germany, 349 pp. ISBN 9783642189708.
Körner, C., 2020: Climatic Controls of the Global High Elevation Treelines. In: *Encyclopedia of the World's Biomes* [Goldstein, M. I. and D. A. DellaSala (eds.)]. Elsevier, USA, pp. 275-281. ISBN 9780128160978.
Körner, C. and E. Spehn, 2016: Alpine Ökosysteme. In: *Brennpunkt Klima Schweiz. Grundlagen, Folgen und Perspektiven.* [Mittler, M. and S. Hosi (eds.)]. Akademien der Wissenschaften Schweiz, Bern, Switzerland, pp. 96-99.
Kueffer, C. et al., 2013: Plant Invasions into Mountain Protected Areas: Assessment, Prevention and Control at Multiple Spatial Scales. In: *Plant Invasions in Protected Areas* [Foxcroft, L., P. Pyšek, D. Richardson and P. Genovesi (eds.)]. Springer, Dordrecht, pp. 89-113. ISBN 9789400777507.
Kumar, R. et al., 2020: Elevated CO2 and temperature influence key proteins and metabolites associated with photosynthesis, antioxidant and carbon metabolism in Picrorhiza kurroa. *Journal of Proteomics*, **219**, 103755, doi:10.1016/j.jprot.2020.103755.
Kummu, M. et al., 2016: The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*, **6**, 38495, doi:10.1038/srep38495.
Laha, A., R. Badola and S. A. Hussain, 2018: Earning a Livelihood from Himalayan Caterpillar Fungus in Kumaon Himalaya: Opportunities, Uncertainties, and Implications. *Mountain Research and Development*, **38**, 323, doi:10.1659/MRD-JOURNAL-D-17-00063.1.
Lamborn, C. C. and J. W. Smith, 2019: Human perceptions of, and adaptations to, shifting runoff cycles: A case-study of the Yellowstone River (Montana, USA). *Fisheries Research*, **216**, 96-108, doi:10.1016/j.fishres.2019.04.005.
Landeros-Mugica, K., J. Urbina-Soria and I. Alcántara-Ayala, 2016: The good, the bad and the ugly: on the interactions among experience, exposure and commitment with reference to landslide risk perception in México. *Natural Hazards*, **80**(3), 1515-1537, doi:10.1007/s11069-015-2037-7.
Lane, S. N. et al., 2019: Making stratigraphy in the Anthropocene: climate change impacts and economic conditions controlling the supply of sediment to Lake Geneva. *Scientific Reports*, **9**, 8904, doi:10.1038/s41598-019-44914-9.
Lavorel, S. et al., 2019: Mustering the power of ecosystems for adaptation to climate change. *Environmental Science & Policy*, **92**, 87-97, doi:10.1016/j.envsci.2018.11.010.
Lehikoinen, A. et al., 2019: Declining population trends of European mountain birds. *Global Change Biology*, **25**(2), 577-588, doi:10.1111/gcb.14522.
Lepcha, P. T., P. K. Pandey and P. Ranjan, 2021: Hydrological significance of Himalayan surface water and its management considering anthropogenic and climate change aspects. *IOP Conference Series: Materials Science and Engineering*, **1020**, 012013, doi:10.1088/1757-899X/1020/1/012013.
Li, D., Z. Li, Y. Zhou and X. Lu, 2020: Substantial Increases in the Water and Sediment Fluxes in the Headwater Region of the Tibetan Plateau in Response to Global Warming. *Geophysical Research Letters*, **47**(11), e2020GL087745, doi:10.1029/2020GL087745.
Li, J. et al., 2017: Assessing vulnerability of giant pandas to climate change in the Qinling Mountains of China. *Ecology and Evolution*, **7**(11), 4003-4015, doi:10.1002/ece3.2981.
Liang, E. et al., 2016: Species interactions slow warming-induced upward shifts of treelines on the Tibetan Plateau. *Proceedings of the National Academy of Sciences*, **113**(16), 4380, doi:10.1073/pnas.1520582113.

Littell, J. S., D. McKenzie, H. Y. Wan and S. A. Cushman, 2018: Climate change and fu-ture wildfire in the western United States: An ecological approach to nonstationarity. *Earth's Future*, **6**(8), 1097-1111, doi:10.1029/2018EF000878.
Liu, H. et al., 2011: Predicting the wetland distributions under climate warming in the Great Xing'an Mountains, northeastern China. *Ecological Research*, **26**(3), 605–613, doi:10.1007/s11284-011-0819-2.
López, S., J.-K. Jung and M. F. López, 2017: A hybrid-epistemological approach to climate change research: Linking scientific and smallholder knowledge systems in the Ecuadorian Andes. *Anthropocene*, **17**, 30-45, doi:10.1016/j.ancene.2017.01.001.
Lu, X. et al., 2021: Mountain treelines climb slowly despite rapid climate warming. *Global Ecology and Biogeography*, **30**, 305–315, doi:10.1111/geb.13214.
Lucas, J. and R. M. B. Harris, 2021: Changing Climate Suitability for Dominant Eucalyptus Species May Affect Future Fuel Loads and Flammability in Tasmania. *Fire*, **4**(1), 1, doi:10.3390/fire4010001.
Lutz, A. F., W. W. Immerzeel, A. B. Shrestha and M. F. P. Bierkens, 2014: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, **4**(7), 587-592, doi:10.1038/nclimate2237.
Lynch, B. D., 2012: Vulnerabilities, competition and rights in a context of climate change toward equitable water governance in Peru's Rio Santa Valley. *Global Environmental Change*, **22**(2), 364-373, doi:10.1016/j.gloenvcha.2012.02.002.
Mach, K. J., M. D. Mastrandrea, P. T. Freeman and C. B. Field, 2017: Unleashing expert judgment in assessment. *Global Environmental Change*, **44**, 1-14, doi:10.1016/j.gloenvcha.2017.02.005.
Maharjan, A. et al., 2020: Migration and Household Adaptation in Climate-Sensitive Hotspots in South Asia. *Current Climate Change Reports*, **6**, 1-16, doi:10.1007/s40641-020-00153-z.
Maharjan, A. et al., 2021: Can labour migration help households adapt to climate change? Evidence from four river basins in South Asia. *Climate and Development*, doi:10.1080/17565529.2020.1867044.
Maikhuri, R. K. et al., 2018: Assessment of climate change impacts and its implications on medicinal plants-based traditional healthcare system in Central Himalaya, India. *Iranian Journal of Science and Technology, Transactions A: Science*, **42**(4), 1827-1835.
Majone, B., F. Villa, R. Deidda and A. Bellin, 2016: Impact of climate change and water use policies on hydropower potential in the south-eastern Alpine region. *Science of the Total Environment*, **543**, 965-980, doi:10.1016/j.scitotenv.2015.05.009.
Manes, S. et al., 2021: Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, **257**, 109070, doi:10.1016/j.biocon.2021.109070.
Manton, M. J. and L. A. Stevenson, 2014: Future Directions for Climate Research in Asia and the Pacific. In: *Climate in Asia and the Pacific* [Manton, M. J. and L. A. Stevenson (eds.)]. Springer, Netherlands, pp. 289-307. ISBN 9789400773387.
Marazziti, D. et al., 2021: Climate change, environment pollution, COVID-19 pandemic and mental health. *Science of The Total Environment*, **773**, 145182, doi:10.1016/j.scitotenv.2021.145182.
March, H., D. Saurí and J. C. Llurdés, 2014: Perception of the effects of climate change in winter and summer tourist areas: the Pyrenees and the Catalan and Balearic coasts, Spain. *Regional Environmental Change*, **14**(3), 1189-1201, doi:10.1007/s10113-013-0561-0.
Marjanac, S., L. Patton and J. Thornton, 2017: Acts of God, human influence and litigation. *Nature Geoscience*, **10**(9), 616-619, doi:10.1038/ngeo3019.
Marzeion, B., G. Kaser, F. Maussion and N. Champollion, 2018: Limited influence of climate change mitigation on short-term glacier mass loss. . *Nature Climate Change*, **8**, 305–308, doi:10.1038/s41558-018-0093-1.
Mastrorillo, M. et al., 2016: The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change,* **39**, 155-169, doi:10.1016/j.gloenvcha.2016.04.014.
Matasci, C., S. Kruse, N. Barawid and P. Thalmann, 2014: Exploring barriers to climate change adaptation in the Swiss tourism sector. *Mitigation and Adaptation Strategies for Global Change*, **19**(8), 1239-1254, doi:10.1007/s11027-013-9471-1.
Mbow, C., M. van Noordwijk, R. Prabhu and T. Simons, 2014: Knowledge gaps and research needs concerning agroforestry's contribution to sustainable development goals in Africa. *Current Opinion in Environmental Sustainability*, **6**, 162-170, doi:10.1016/j.cosust.2013.11.030.
McCormick, S. et al., 2017: Science in litigation, the third branch of U.S. climate policy. *Science*, **357**(6355), 979-980, doi:10.1126/science.aao0412.
McDougall, K. L. et al., 2011: Plant Invasions in Mountains: Global Les-sons for Better Management. *Mountain Research and Development*, **31**(4), 380-387, doi:10.1659/MRD-JOURNAL·D-11.QOOS2.1.
McDowell, G. et al., 2020: From needs to actions: prospects for planned adaptations in high mountain communities. *Climatic Change*, **16**, 953-972, doi:10.1007/s10584-020-02920-1.
McDowell, G. et al., 2019: Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change? *Global Environmental Change*, **54**, 19-30, doi:10.1016/j.gloenvcha.2018.10.012.
McDowell, G. et al., 2021a: Lived experiences of "peak water" in the high mountains of Nepal and Peru. *Climate and Development*, 1–14, doi:10.1080/17565529.2021.1913085.

McDowell, G., E. Stephenson and J. Ford, 2014: Adaptation to climate change in glaciated mountain regions. *Climatic Change*, **126**(1), 77-91, doi:10.1007/s10584-014-1215-z.
McDowell, G. et al., 2021b: Closing the adaptation gap in mountains. *Mountain Research and Development*, In Press, doi:10.1659/MRD-JOURNAL-D-21-00033.1.
McDowell, J. Z. and J. J. Hess, 2012: Accessing adaptation: Multiple stressors on livelihoods in the Bolivian highlands under a changing climate. *Global Environmental Change*, **22**(2), 342-352, doi:10.1016/j.gloenvcha.2011.11.002.
Mekuyie, M., A. Jordaan and Y. Melka, 2018: Understanding resilience of pastoralists to climate change and variability in the Southern Afar Region, Ethiopia. *Climate Risk Management*, **20**, 64-77, doi:10.1016/j.crm.2018.02.004.
Merino, V. M., D. Sietz, F. Jost and U. Berger, 2019: Archetypes of climate vulnerability: a mixed-method approach applied in the Peruvian Andes. *Climate and Development*, **11**(5), 418-434, doi:10.1080/17565529.2018.1442804.
Mętrak, M. et al., 2017: Nature's patchwork: How water sources and soil salinity determine the distribution and structure of halophytic plant communities in arid environments of the Eastern Pamir. *PLOS ONE*, **12**(3), e0174496, doi:10.1371/journal.pone.0174496.
Mills-Novoa, M. et al., 2017: Bringing the Hydrosocial Cycle into Climate Change Adaptation Planning: Lessons from Two Andean Mountain Water Towers. *Annals of the American Association of Geographers*, **107**(2), 393–402, doi:10.1080/24694452.2016.1232618.
Milner, A. M. et al., 2017: Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, **114**(37), 9770-9778, doi:10.1073/pnas.1619807114.
Min, S., J. Huang, J. Bai and H. Waibel, 2017: Adoption of intercropping among smallholder rubber farmers in Xishuangbanna, China. *International Journal of Agricultural Sustainability*, **15**(3), 223-237, doi:10.1080/14735903.2017.1315234.
Mina, M. et al., 2017: Future ecosystem services from European mountain forests under climate change. *Journal of Applied Ecology*, **54**(2), 389-401, doi:10.1111/1365-2664.12772.
Minta, M. et al., 2018: Land use and land cover dynamics in Dendi-Jeldu hilly-mountainous areas in the central Ethiopian highlands. *Geoderma*, **314**, 27-36, doi:10.1016/j.geoderma.2017.10.035.
Mishra, A. et al., 2019: Adaptation to Climate Change in the Hindu Kush Himalaya: Stronger Action Urgently Needed. In: *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People* [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer, Cham, Switzerland, pp. 457-490. ISBN 9783319922881.
Mishra, S. K. et al., 2020: Differential Impact of Climate Change on the Hydropower Economics of Two River Basins in High Mountain Asia. *Frontiers in Environmental Science*, **8**, 26, doi:10.3389/fenvs.2020.00026.
Mitter, H., C. Heumesser and E. Schmid, 2015: Spatial modeling of robust crop production portfolios to assess agricultural vulnerability and adaptation to climate change. *Land Use Policy*, **46**, 75-90, doi:10.1016/j.landusepol.2015.01.010.
Mod, H. K., P. C. le Roux, A. Guisan and M. Luoto, 2015: Biotic interactions boost spatial models of species richness. *Ecography*, **38**(9), 913-921, doi:10.1111/ecog.01129.
Molden, D. et al., 2017: Advancing regional and transboundary cooperation in the conflict-prone Hindu Kush-Himalaya. *Mountain Research and Development*, **37**(4), 502-508, doi:10.1659/MRD-JOURNAL-D-17-00108.1.
Montanari, A. and D. Koutsoyiannis, 2014: Modeling and mitigating natural hazards: Stationarity is immortal! *Water Resources Research*, **50**(12), 9748-9756, doi:10.1002/2014wr016092.
Morin, S. et al., 2021: Pan-European meteorological and snow indicators of climate change impact on ski tourism. *Climate Services*, **22**, 100215, doi:10.1016/j.cliser.2021.100215.
Morrison, C. and C. M. Pickering, 2013: Perceptions of climate change impacts, adaptation and limits to adaption in the Australian Alps: the ski-tourism industry and key stakeholders. *Journal of Sustainable Tourism*, **21**(2), 173-191, doi:10.1080/09669582.2012.681789.
Morueta-Holme, N. et al., 2015: Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt. *Proceedings of the National Academy of Sciences*, **112**(41), 12741-12745, doi:10.1073/pnas.1509938112.
Moser, D. J. and C. Baulcomb, 2020: Social Perspectives on Climate Change Adaptation, Sustainable Development, and Artificial Snow Production: A Swiss Case Study Using Q Methodology. *Environmental Science & Policy*, **104**, 98-106, doi:10.1016/j.envsci.2019.10.001.
Motschmann, A. et al., 2020a: Losses and damages connected to glacier retreat in the Cordillera Blanca, Peru. *Climatic Change*, **162**(2), 1-22, doi:10.1007/s10584-020-02770-x.
Motschmann, A., C. Huggel, R. Muñoz and A. Thür, 2020b: Towards integrated assessments of water risks in deglaciating mountain areas: water scarcity and GLOF risk in the Peruvian Andes. *Geoenvironmental Disasters*, **7**(26), 1–18, doi:10.1186/s40677-020-00159-7.
Mourey, J., C. Perrin-Malterre and L. Ravanel, 2020: Strategies Used by French Alpine Guides to Adapt to the Effects of Climate Change. *Journal of Outdoor Recreation and Tourism*, **29**, 100278, doi:10.1016/j.jort.2020.100278.
Mourey, J. et al., 2019: Access Routes to High Mountain Huts Facing Climate-Induced Environmental Changes and Adaptive Strategies in the Western Alps since the 1990s. *Norwegian Journal of Geography*, **73**(4), 215-228, doi:10.1080/00291951.2019.1689163.
Muccione, V. and B. Daley, 2016: The Role of Ecosystem-based Adaptation in the Swiss Mountains. In: *Climate Change Adaptation Strategies – An Upstream-downstream Perspective* [Salzmann, N., C. Huggel, S. U. Nussbaumer and G. Ziervogel (eds.)]. Springer, Cham, Switzerland, pp. 161-177. ISBN 9783319407739.

Muccione, V., N. Salzmann and C. Huggel, 2016: Scientific Knowledge and Knowledge Needs in Climate Adaptation Policy: A Case Study of Diverse Mountain Regions. *Mountain Research and Development*, **36**(3), 364-375, doi:10.1659/MRD-JOURNAL-D-15-00016.1.
Mueller, V., C. Gray and K. Kosec, 2014: Heat stress increases long-term human migration in rural Pakistan. *Nature Climate Change*, **4**, 182-185, doi:10.1038/nclimate2103.
Muhlfeld, C. C. et al., 2020: Specialized meltwater biodiversity persists despite widespread deglaciation. *Proceedings of the National Academy of Sciences*, **117**(22), 12208-12214, doi:10.1073/pnas.2001697117.
Mukherji, A. et al., 2019: Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: a review. *Regional Environmental Change*, **19**, 1311-1326, doi:10.1007/s10113-019-01484-w.
Munia, H. A. et al., 2020: Future transboundary water stress and its drivers under climate change: A global study. *Earth's Future*, **8**(7), e2019EF001321, doi:10.1029/2019EF001321.
Muñoz-Torrero Manchado, A. et al., 2021: Three decades of landslide activity in western Nepal: Unique insights into trends and climate drivers.
Munt, D. D., P. Muñoz-Rodríguez, I. Marques and J. C. M. Saiz, 2016: Effects of climate change on threatened Spanish medicinal and aromatic species: predicting future trends and defining conservation guidelines. *Israel Journal of Plant Sciences*, **63**(4), 309-319, doi:10.1080/07929978.2016.1258257.
Musakwa, W., E. Mpofu and N. A. Nyathi, 2020: Local community perceptions on landscape change, ecosystem services, climate change, and livelihoods in Gonarezhou National Park, Zimbabwe. *Sustainability*, **12**(11), 4610.
Nagel, L. M. et al., 2017: Adaptive Silviculture for Climate Change: A National Experiment in Manager-Scientist Partnerships to Apply an Adaptation Framework. *Journal of Forestry*, **115**(3), 167-178, doi:10.5849/jof.16-039.
Nair, K. P., 2019: Utilizing crop wild relatives to combat global warming. *Advances in Agronomy*, **153**, 175-258.
Nawrotzki, R. J. and J. DeWaard, 2016: Climate shocks and the timing of migration from Mexico. *Population and Environment*, **38**, 72-100, doi:10.1007/s11111-016-0255-x.
Nepal, M. et al., 2018: Valuing Cultural Services of the Kailash Sacred Landscape for Sustainable Management. *Sustainability*, **10**(10), 3638, doi:10.3390/su10103638.
Ngwenya, S. J., E. Torquebiau and J. W. H. Ferguson, 2019: Mountains as a critical source of ecosystem services: the case of the Drakensberg, South Africa. *Environment, Development and Sustainability*, **21**(2), 1035-1052, doi:10.1007/s10668-017-0071-1.
Niemeyer, R. J., K. D. Bladon and R. D. Woodsmith, 2020: Long-term hydrologic recovery after wildfire and post-fire forest management in the interior Pacific North-west. *Hydrological Processes*, **34**, 1182– 1197, doi:10.1002/hyp.13665.
Nischalke, S. M. et al., 2017: Forgotten Forests? Food Potential of Ancient Coffee Forests and Agroforestry Systems in the Southwestern Ethiopian Mountains, Seen Through a Gender Lens. *Mountain Research and Development*, **37**(3), 254-262, doi:10.1659/MRD-JOURNAL-D-16-00096.1.
Njue, N. et al., 2019: Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. *Science of The Total Environment*, **693**, 133531, doi:10.1016/j.scitotenv.2019.07.337.
Nkuba, M. R. et al., 2020: Influence of Indigenous Knowledge and Scientific Climate Forecasts on Arable Farmers' Climate Adaptation Methods in the Rwenzori region, Western Uganda. *Environmental Management*, **65**, 500-516, doi:10.1007/s00267-020-01264-x.
Nogués-Bravo, D., 2009: Predicting the past distribution of species climatic niches. *Global Ecology and Biogeography*, **18**(5), 521-531, doi:10.1111/j.1466-8238.2009.00476.x.
Nones, M. and G. Pescaroli, 2016: Implications of cascading effects for the EU Floods Directive. *International Journal of River Basin Management*, **14**(2), 195-204, doi:10.1080/15715124.2016.1149074.
O'Neel, S. et al., 2015: Icefield-to-Ocean Linkages across the Northern Pacific Coastal Temperate Rainforest Ecosystem. *BioScience*, **65**(5), 499-512, doi:10.1093/biosci/biv027.
Ojha, H. et al., 2020: Scarcity Amidst Plenty: Lower Himalayan Cities Struggling for Water Security. *Water*, **12**(2), 567, doi:10.3390/w12020567.
Ojha, H. R. et al., 2016: Policy without politics: technocratic control of climate change adaptation policy making in Nepal. *Climate Policy*, **16**(4), 415-433, doi:10.1080/14693062.2014.1003775.
Oliver-Smith, A., 2014: Climate change adaptation and disaster risk reduction in Highland Peru. In: *Adapting to Climate Change* [Glavovic, B. and G. Smith (eds.)]. Springer, Dordrecht, Netherlands, pp. 77-100. ISBN 9789401786317.
Oliveras, I., L. O. Anderson and Y. Malhi, 2014: Application of remote sensing to understanding fire regimes and biomass burning emissions of the tropical Andes. *Global Biogeochemical Cycles*, **28**(4), 480-496.
Oliveras, I. et al., 2018: Fire effects and ecological recovery pathways of tropical montane cloud forests along a time chronosequence. *Global change biology*, **24**(2), 758-772.
Otto, F. E. L. et al., 2017: Assigning historic responsibility for extreme weather events. *Nature Climate Change*, **7**, 757–759, doi:10.1038/nclimate3419.
Palomo, I., 2017: Climate Change Impacts on Ecosystem Services in High Mountain Areas: A Literature Review. *Mountain Research and Development*, **37**(2), 179-187, doi:10.1659/MRD-JOURNAL-D-16-00110.1.
Palomo, I. et al., 2021: Assessing nature-based solutions for transformative change. *One Earth*, **4**(5), 730-741, doi:10.1016/j.oneear.2021.04.013.

Pandey, A., A. Prakash and S. E. Werners, 2021: Matches, mismatches and priorities of pathways from a climate-resilient development perspective in the mountains of Nepal. *Environmental Science and Policy*, **125**, 135-145, doi:10.1016/j.envsci.2021.08.013.
Patro, E. R., C. De Michele and F. Avanzi, 2018: Future perspectives of run-of-the-river hydropower and the impact of glaciers? shrinkage: The case of Italian Alps. *Applied Energy*, **231**, 699-713, doi:10.1016/j.apenergy.2018.09.063.
Patton, A. I., S. L. Rathburn and D. M. Capps, 2019: Landslide response to climate change in permafrost regions. *Geomorphology*, **340**, 116-128, doi:10.1016/j.geomorph.2019.04.029.
Paulsen, J. and C. Körner, 2014: A climate-based model to predict potential treeline position around the globe. *Alpine Botany*, **124**(1), 1-12.
Payne, D. et al., 2020: Nature and People in the Andes, East African Mountains,European Alps, and Hindu Kush Himalaya: CurrentResearch and Future Directions. *Mountain Research and Development*, **40**(2), A1-A14, doi:10.1659/MRD-JOURNAL-D-19-00075.1.
Phillips, J. et al., 2017: Climate change and national crop wild relative conservation planning. *Ambio*, **46**(6), 630-643.
Picarelli, L., S. Lacasse and K. K. S. Ho, 2021: The Impact of Climate Change on Landslide Hazard and Risk. In: *Understanding and Reducing Landslide Disaster Risk* [Sassa, K., M. Mikoš, S. Sassa, P. T. Bobrowsky, K. Takara and K. Dang (eds.)]. Springer, Cham, pp. 131-141. ISBN 9783030601966.
Polato, N. R. et al., 2018: Narrow thermal tolerance and low dispersal drive higher speciation in tropical mountains. *Proceedings of the National Academy of Sciences*, **115**(49), 12471-12476, doi:10.1073/pnas.1809326115.
Porter, J. R. et al., 2014: Food security and food production systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.
Pospelova, E. B., I. N. Pospelov and M. V. Orlov, 2017: Climate Change in Eastern Taimyr over the Last 80 Years and the Warming Impact on Biodiversity and Ecosystem Processes in Its Territory. *Nature Conservation Research*, **2**(3), 48-60, doi:10.24189/ncr.2017.040.
Prakash, A. and D. Molden (eds.), 2020: *Water in Himalayan Towns: Lessons for Adaptive Water Governance*, IWA, London, United Kingdom, 204 pp. ISBN 9781789061901.
Prasain, S., 2018: Climate change adaptation measure on agricultural communities of Dhye in Upper Mustang, Nepal. *Climatic Change*, **148**(1), 279-291, doi:10.1007/s10584-018-2187-1.
Pretzsch, H. et al., 2018: Wood density reduced while wood volume growth accelerated in Central European forests since 1870. *Forest Ecology and Management*, **429**, 589-616, doi:10.1016/j.foreco.2018.07.045.
Prevéy, J. S. et al., 2020: Climate change shifts in habitat suitability and phenology of huckleberry (Vaccinium membranaceum). *Agricultural and forest meteorology*, **280**, 107803.
Price, M. F., T. Schaaf and M. R. Cárdenas Tomažič, Accepted/In press: Mountain research in UNESCO's Man and the Biosphere Programme: The first five decades. *eco.mont*, **13**, 90-98, doi:10.1553/eco.mont-13-sis90.
Prichard, S. J., C. S. Stevens-Rumann and P. F. Hessburg, 2017: Tamm Review: Shift-ing global fire regimes: Lessons from reburns and research needs. *Forest Ecology and Management*, **395**, 217-233, doi:10.1016/j.foreco.2017.03.035.
Pröbstl-Haider, U., W. Haider, V. Wirth and B. Beardmore, 2015: Will Climate Change Increase the Attractiveness of Summer Destinations in the European Alps? A Survey of German Tourists. *Journal of Outdoor Recreation and Tourism*, **11**, 44-57, doi:10.1016/j.jort.2015.07.003.
Pullanikkatil, D. et al., 2020: Unsustainable trade-offs: provisioning ecosystem services in rapidly changing Likangala River catchment in southern Malawi. *Environment, Development and Sustainability*, **22**(2), 1145-1164, doi:10.1007/s10668-018-0240-x.
Quincey, D. et al., 2018: The changing water cycle: the need for an integrated assessment of the resilience to changes in water supply in High-Mountain Asia. *Wiley Interdisciplinary Reviews: Water*, **5**(1), e1258, doi:10.1002/wat2.1258.
Rakhmatullaev, S. et al., 2009: Groundwater resources use and management in the Amu Darya River Basin (Central Asia). *Environ Earth Science*, **59**, 1183, doi:10.1007/s12665-009-0107-4.
Ramirez-Villegas, J. et al., 2014: Using species distributions models for designing conservation strategies of Tropical Andean biodiversity under climate change. *Journal for Nature Conservation*, **22**(5), 391-404, doi:10.1016/j.jnc.2014.03.007.
Ramsar Convention on Wetlands, 2018: *Global Wetland Outlook: State of the World's Wetlands and their Services to People*. Ramsar Convention Secretariat, Gland, Switzerland, 84 pp. Available at: https://medwet.org/publications/ramsar-global-wetland-outlook-2018/ (accessed 03/11/2020).
Rangecroft, S. et al., 2013: Climate Change and Water Resources in Arid Mountains: An Example from the Bolivian Andes. *AMBIO*, **42**(7), 852-863, doi:10.1007/s13280-013-0430-6.
Rashid, I. et al., 2015: Projected climate change impacts on vegetation distribution over Kashmir Himalayas. *Climatic Change*, **132**(4), 601-613, doi:10.1007/s10584-015-1456-5.
Rasul, G. and A. Hussain, 2015: Sustainable food security in the mountains of Pakistan: Towards a policy framework. *Ecology of food and nutrition*, **54**(6), 625-643, doi:10.1080/03670244.2015.1052426.

Rasul, G. et al., 2014: *Towards a framework for achieving food security in the mountains of Pakistan*. International Centre for Integrated Mountain Development, Kathmandu, Nepal, 22 pp. ISBN 9789291153305.
Rasul, G. and D. Molden, 2019: The Global Social and Economic Consequences of Mountain Cryospheric Change. *Frontiers in Environmental Science*, **7**(91), doi:10.3389/fenvs.2019.00091.
Rasul, G., B. Pasakhala, A. Mishra and S. Pant, 2020: Adaptation to mountain cryosphere change: issues and challenges. *Climate and Development*, **12**(4), 297-309, doi:10.1080/17565529.2019.1617099.
Ravera, F. et al., 2016: Gender perspectives in resilience, vulnerability and adaptation to global environmental change. *Ambio*, **45**(3), 235-247, doi:10.1007/s13280-016-0842-1.
Rehm, E. M. and K. J. Feeley, 2015: The inability of tropical cloud forest species to invade grasslands above treeline during climate change: potential explanations and consequences. *Ecography*, **38**(12), 1167-1175, doi:10.1111/ecog.01050.
Rehnus, M. et al., 2018: Alpine glacial relict species losing out to climate change: the case of the fragmented mountain hare population (Lepus timidus) in the Alps. *Global Change Biology*, **24**(7), 3236-3253.
Reid, H., 2016: Ecosystem-and community-based adaptation: learning from community-based natural resource management. *Climate and Development*, **8**(1), 4-9, doi:10.1080/17565529.2015.1034233.
Renaud, F. G., U. Nehren, K. Sudmeier-Rieux and M. Estrella, 2016: Developments and Opportunities for Ecosystem-Based Disaster Risk Reduction and Climate Change Adaptation. In: *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice* [Renaud, F. G., K. Sudmeier-Rieux, M. Estrella and U. Nehren (eds.)]. Springer International Publishing, Cham, pp. 1-20. ISBN 978-3-319-43633-3.
Ribot, J., 2014: Cause and response: vulnerability and climate in the Anthropocene. *The Journal of Peasant Studies*, **41**(5), 667-705, doi:10.1080/03066150.2014.894911.
Rocca, M. E., P. M. Brown, L. H. MacDonald and C. M. Carrico, 2014: Climate change impacts on fire regimes and key ecosystem services in Rocky Mountain forests. *Forest Ecology and Management*, **327**, 290-305, doi:10.1016/j.foreco.2014.04.005.
Rodman, K. C. et al., 2020: A changing climate is snuffing out post-fire recovery in montane forests. *Global Ecology and Biogeography*, **29**(11), 2039-2051, doi:10.1111/geb.13174.
Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan and S. A. Woznicki, 2017: Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, **16**, 145-163, doi:10.1016/j.crm.2017.02.001.
Román-Cuesta, R. M. et al., 2014: Synchronous fire activity in the tropical high An-des: an indication of regional climate forcing. *Global Change Biology*, **20**(6), 1929-1942, doi:10.1111/gcb.12538.
Roth, T., M. Plattner and V. Amrhein, 2014: Plants, Birds and Butterflies: Short-Term Responses of Species Communities to Climate Warming Vary by Taxon and with Altitude. *PLoS ONE* **9**(1), e82490, doi:10.1371/journal.pone.0082490.
Rumpf, S. B. et al., 2018: Range dynamics of mountain plants decrease with elevation. *Proceedings of the National Academy of Sciences*, **115**(8), 1848, doi:10.1073/pnas.1713936115.
Rust, A. J., T. S. Hogue, S. Saxe and J. McCray, 2018: Post-fire water-quality response in the western United States. *International Journal of Wildland Fire*, **27**(3), 203-216, doi:10.1071/WF17115.
Ryan, D. and E. Bustos, 2019: Knowledge gaps and climate adaptation policy: a comparative analysis of six Latin American countries. *Climate Policy*, **19**(10), 1297-1309, doi:10.1080/14693062.2019.1661819.
Sagynbekova, L., 2017: Environment, rural livelihoods and labour migration. A case study in central Kyrgyzstan. *Mountain Research and Development*, **37**(4), 456-463, doi:10.1659/MRD-JOURNAL-D-17-00029.1.
Said, M., H. C. Komakech, L. K. Munishi and A. N. N. Muzuka, 2019: Evidence of climate change impacts on water, food and energy resources around Kilimanjaro, Tanzania. *Regional Environmental Change*, **19**, 2521–2534, doi:10.1007/s10113-019-01568-7.
Salim, E. and L. Ravanel, 2020: Last chance to see the ice: visitor motivation at Montenvers-Mer-de-Glace, French Alps. *Tourism Geographies*, doi:10.1080/14616688.2020.1833971.
Salzmann, N., C. Huggel, S. U. Nussbaumer and G. Ziervogel (eds.), 2016: *Climate Change Adaptation Strategies – An Upstream-downstream Perspective*, Springer, Cham, Switzerland, 292 pp. ISBN 9783319407715.
Salzmann, N., C. Huggel, M. Rohrer and M. Stoffel, 2014: Data and knowledge gaps in glacier, snow and related runoff research – A climate change adaptation perspective. *Journal of Hydrology*, **518**, 225-234, doi:10.1016/j.jhydrol.2014.05.058.
Sannikov, S. N., N. V. Tantsyrev and I. V. Petrova, 2018: Invasion of Siberian Pine Populations in Mountain Tundra in the Northern Urals. *Contemporary Problems of Ecology*, **11**(4), 396-405, doi:10.1134/S1995425518040078.
Sansilvestri, R., N. Frascaria-Lacoste and J. Fernández-Manjarrés, 2016: One option, two countries, several strategies: subjacent mechanisms of assisted migration implementation in Canada and France: Implementation issues of assisted migration. *Restoration Ecology*, **24**(4), 489-498, doi:10.1111/rec.12343.
Satyal, P. et al., 2017: A new Himalayan crisis? Exploring transformative resilience pathways. *Environmental Development*, **23**, 47-56, doi:10.1016/j.envdev.2017.02.010.
Sauri, D. and J. C. Llurdés, 2020: Climate Change and Adaptation Strategies of Spanish Catalan Alpine Ski Resorts. *Journal of Alpine Research*, **108**, 1, doi:10.4000/rga.6796.
Schaefli, B., 2015: Projecting hydropower production under future climates: a guide for decision-makers and modelers to interpret and design climate change impact assessments. *WIREs Water*, **2**(4), 271-289, doi:10.1002/wat2.1083.

Schaefli, B. et al., 2019: The role of glacier retreat for Swiss hydropower production. *Renewable Energy*, **132**, 615-627, doi:10.1016/j.renene.2018.07.104.
Schauwecker, S. et al., 2019: Anticipating cascading effects of extreme precipitation with pathway schemes - Three case studies from Europe. *Environment International*, **127**, 291-304, doi:10.1016/j.envint.2019.02.072.
Schauwecker, S. et al., 2017: The freezing level in the tropical Andes, Peru: an indicator for present and future glacier extents. *Journal of Geophysical Research: Atmospheres*, **122**(10), 5172-5189, doi:10.1002/2016JD025943.
Scheidl, C. et al., 2020: The influence of climate change and canopy disturbances on landslide susceptibility in headwater catchments. *Science of The Total Environment*, **742**, 140588, doi:10.1016/j.scitotenv.2020.140588.
Scherrer, D., S. Schmid and C. Körner, 2011: Elevational species shifts in a warmer climate are overestimated when based on weather station data. *International Journal of Biometeorology*, **55**(4), 645-654, doi:10.1007/s00484-010-0364-7.
Scherrer, D. et al., 2020: Competition and demography rather than dispersal limitation slow down upward shifts of trees' upper elevation limits in the Alps. *Journal of Ecology*, **108**(6), 2416-2430, doi:10.1111/1365-2745.13451
Schipper, E. L. F. et al., 2020: Turbulent transformation: abrupt societal disruption and climate resilient development. *Climate and Development*, 1-8, doi:10.1080/17565529.2020.1799738.
Schneiderbauer, S. et al., 2021: Risk perception of climate change and natural hazards in global mountain regions: A critical review. *Science of The Total Environment*, **784**, 146957, doi:10.1016/j.scitotenv.2021.146957.
Schoolmeester, T. and K. Verbist (eds.), 2018: *The Andean Glacier and Water Atlas - The Impact of Glacier Retreat on Water Resources*, UNESCO and GRID-Arendal, Paris, France and Arendal, Norway, 77 pp. ISBN 9789231002861.
Schwanghart, W. et al., 2016: Uncertainty in the Himalayan energy–water nexus: estimating regional exposure to glacial lake outburst floods. *Environmental Research Letters*, **11**, 074005, doi:10.1088/1748-9326/11/7/074005.
Scott, C. A. et al., 2019: Water in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People* [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer, Cham, Switzerland, pp. 257-299. ISBN 9783319922881.
Sebald, J. et al., 2019: The effects of forest cover and disturbance on torrential hazards: large-scale evidence from the Eastern Alps. *Environmental Research Letters*, **14**, 11, doi:10.6084/m9.figshare.9758891.v1.
Seddon, N. et al., 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190120, doi:10.1098/rstb.2019.0120.
Selmar, D. and M. Kleinwächter, 2013: Influencing the product quality by deliberately applying drought stress during the cultivation of medicinal plants. *Industrial Crops and Products*, **42**, 558-566, doi:10.1016/j.indcrop.2012.06.020.
Serquet, G. and M. Rebetez, 2011: Relationship between Tourism Demand in the Swiss Alps and Hot Summer Air Temperatures Associated with Climate Change. *Climatic Change*, **108**(1), 291-300, doi:10.1007/s10584-010-0012-6.
Setzer, J. and L. C. Vanhala, 2019: Climate change litigation: a review of research on courts and litigants in climate government. *WIREs Climate Change*, **10**(3), e580, doi:10.1002/wcc.580.
Shah, S. and A. Tewari, 2016: Limited impact of climate change on seed maturation time in Myrica esculenta Buch-Ham. Ex. D. Don in Himalayan region. *International Journal of Environment, Agriculture and Biotechnology*, **1**(4), 713-717, doi:10.22161/ijeab/1.4.13.
Shahgedanova, M. et al., 2021: Mountain Observatories: Status and Prospects for Enhancing and Connecting a Global Community. *Mountain Research and Development*, **41**(2), doi:10.1659/MRD-JOURNAL-D-20-00054.1.
Sharma, G. et al., 2020: Water management systems of two towns in the Eastern Himalaya: case studies of Singtam in Sikkim and Kalimpong in West Bengal states of India. *Water Policy*, **22**, 107-129, doi:10.2166/wp.2019.229.
Sherry, J., A. Curtis, E. Mendham and E. Toman, 2018: Cultural landscapes at risk: Exploring the meaning of place in a sacred valley of Nepal. *Global Environmental Change*, **52**(July), 190-200, doi:10.1016/j.gloenvcha.2018.07.007.
Shijin, W. and Q. Dahe, 2015: Mountain inhabitants' perspectives on climate change, and its impacts and adaptation based on temporal and spatial characteristics analysis: a case study of Mt. Yulong Snow, Southeastern Tibetan Plateau. *Environmental Hazards*, **14**(2), 122-136, doi:10.1080/17477891.2014.1003776.
Shikuku, K. M. et al., 2017: Smallholder farmers' attitudes and determinants of adaptation to climate risks in East Africa. *Climate Risk Management*, **16**, 234-245, doi:10.1016/j.crm.2017.03.001.
Shiyatov, S. G. and V. S. Mazepa, 2015: Contemporary expansion of Siberian larch into the mountain tundra of the Polar Urals. *Russian Journal of Ecology*, **46**(6), 495-502, doi:10.1134/S1067413615060168.
Shrestha, A. B. et al., 2015: The Himalayan Climate and Water Atlas: impact of climate change on water resources in five of Asia's major river basins. *The Himalayan Climate and Water Atlas: impact of climate change on water resources in five of Asia's major river basins.*
Shrestha, U. B. and K. S. Bawa, 2014: Economic contribution of Chinese caterpillar fungus to the livelihoods of mountain communities in Nepal. *Biological Conservation*, **177**, 194-202, doi:10.1016/j.biocon.2014.06.019.
Shrestha, U. B., K. R. Dhital and A. P. Gautam, 2019: Economic dependence of mountain communities on Chinese caterpillar fungus Ophiocordyceps sinensis (yarsagumba): a case from western Nepal. *Oryx*, **53**(2), 256-264, doi:10.1017/S0030605317000461.

Shrestha, U. B. et al., 2018: Potential impact of climate change on the distribution of six invasive alien plants in Nepal. *Ecological Indicators*, **95**, 99-107, doi:10.1016/j.ecolind.2018.07.009.
Shugar, D. H. et al., 2021: A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science*, **373**(6552), 300-306, doi:10.1126/science.abh4455.
Shukla, R., K. Sachdeva and P. K. Joshi, 2018: Demystifying vulnerability assessment of agriculture communities in the Himalayas: a systematic review. *Natural Hazards*, **91**(1), 409-429, doi:10.1007/s11069-017-3120-z.
Siddiqui, T. et al., 2019: Migration in the Hindu Kush Himalaya: Drivers, Consequences, and Governance. In: *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People* [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer, Cham, Switzerland, pp. 517-544. ISBN 9783319922881.
Sideris, L. H., 2020: Grave Reminders: Grief and Vulnerability in the Anthropocene. *Religions*, **11**(6), 293, doi:10.3390/rel11060293.
Sigdel, S. R. et al., 2020: Tree-to-tree interactions slow down Himalayan treeline shifts as inferred from tree spatial patterns. *Journal of Biogeography*, **47**, 1816-1826, doi:10.1111/jbi.13840.
Sigdel, S. R. et al., 2018: Moisture-mediated responsiveness of treeline shifts to global warming in the Himalayas. *Global change biology*, **24**(11), 5549-5559, doi:10.1111/gcb.14428.
Simane, B. and N. Bird, 2017: Enhancing Adaptation and Mitigation Activities Through Effective Climate Change Financing Policy in Ethiopia. In: *Climate Change Adaptation in Africa* [Leal Filho, W., S. Belay, J. Kalangu, W. Menas, P. Munishi and K. Musiyiwa (eds.)]. Springer, Cham, Switzerland, pp. 435-445. ISBN 9783319495200.
Singh, D. et al., 2021: Ensuring Domestic Water Security for Cities Under Rapid Urbanisation and Climate Change Risks. In: *Exploring Synergies and Trade-offs between Climate Change and the Sustainable Development Goals* [Venkatramanan, V., S. Shah and R. Prasad (eds.)]. Springer, Singapore, pp. 213-229. ISBN 9789811573019.
Singh, N., J. Ram, A. Tewari and R. P. Yadav, 2015: Phenological events along the elevation gradient and effect of climate change on Rhododendron arboreum Sm. in Kumaun Himalaya. *Current Science*, **108**(1), 106-110.
Singh, S., K. Shrestha, M. Hamal and A. Prakash, 2020: Perform or wither: role of water users' associations in municipalities of Nepal. *Water Policy*, **22**(s1), 90-106, doi:10.2166/wp.2019.051.
Siraj, A. S. et al., 2014: Altitudinal changes in malaria incidence in highlands of Ethiopia and Colombia. *Science*, **343**(6175), 1154-1158, doi:10.1126/science.1244325.
Skarbø, K. and K. VanderMolen, 2016: Maize migration: key crop expands to higher altitudes under climate change in the Andes. *Climate and Development*, **8**(3), 245-255, doi:10.1080/17565529.2015.1034234.
Somers, L. D. and J. M. McKenzie, 2020: A review of groundwater in high mountain environments. *WIREs Water*, **7**(6), e1475, doi:10.1002/wat2.1475.
Somers, L. D. et al., 2019: Groundwater Buffers Decreasing Glacier Melt in an Andean Watershed—But Not Forever. *Geophysical Research Letters*, **46**(22), 13016-13026, doi:10.1029/2019GL084730.
Stäubli, A. et al., 2018: Analysis of weather- and climate-related disasters in mountain regions using different disaster databases. In: *Climate Change, Extreme Events and Disaster Risk Reduction* [Mal, S., R. Singh and C. Huggel (eds.)]. Springer, Cham, Switzerland, pp. 17-41. ISBN 9783319564692.
Steiger, R., B. Abegg and L. Jänicke, 2016: Rain, Rain, Go Away, Come Again Another Day. Weather Preferences of Summer Tourists in Mountain Environments. *Atmosphere*, **7**(5), 63, doi:10.3390/atmos7050063.
Steiger, R., A. Damm, F. Prettenthaler and U. Pröbstl-Haider, 2020a: Climate change and winter outdoor activities in Austria. *Journal of Outdoor Recreation and Tourism*, **100330**, In Press, doi:10.1016/j.jort.2020.100330.
Steiger, R., E. Posch, G. Tappeiner and J. Walde, 2020b: The impact of climate change on demand of ski tourism - a simulation study based on stated preferences. *Ecological Economics*, **170**, 106589, doi:10.1016/j.ecolecon.2019.106589.
Steiger, R. and D. Scott, 2020: Ski tourism in a warmer world: Increased adaptation and regional economic impacts in Austria. *Tourism Management*, **77**, 104032, doi:10.1016/j.tourman.2019.104032.
Steinbauer, M. J. et al., 2018: Accelerated increase in plant species richness on mountain summits is linked to warming. *Nature*, **556**, 231-234, doi:10.1038/s41586-018-0005-6.
Strouth, A. and S. McDougall, 2021: Historical Landslide Fatalities in British Columbia, Canada: Trends and Implications for Risk Management. *Frontiers in Earth Science* **9**, 22, doi:10.3389/feart.2021.606854.
Su, Y. et al., 2017: Gendered Responses to Drought in Yunnan Province, China. *Mountain Research and Development*, **37**(1), 24-34, doi:10.1659/MRD-JOURNAL-D-15-00041.1.
Sujakhu, N. M. et al., 2019: Assessing the livelihood vulnerability of rural indigenous households to climate changes in central Nepal, Himalaya. *Sustainability*, **11**(10), 2977, doi:10.3390/su11102977.
Sultan, B., D. Defrance and T. Iizumi, 2019: Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Scientific reports*, **9**, 12834, doi:10.1038/s41598-019-49167-0.
Sunderland, T. C. and W. Vasquez, 2020: Forest conservation, rights, and diets: Untangling the issues. *Frontiers in Forests and Global Change*, **3**, 29.
Suwal, M. K. et al., 2016: Land-use change under a warming climate facilitated upslope expansion of Himalayan silver fir (Abies spectabilis (D. Don) Spach). *Plant Ecology*, **217**, 993-1002, doi:10.1007/s11258-016-0624-7.
Takano, K. T. et al., 2017: Detecting latitudinal and altitudinal expansion of invasive bamboo Phyllostachys edulis and Phyllostachys bambusoides (Poaceae) in Japan to project potential habitats under 1.5°C–4.0°C global warming. *Ecology and Evolution*, **7**(23), 9848–9859, doi:10.1002/ece3.3471.

Tangjitman, K. et al., 2015: Potential impact of climatic change on medicinal plants used in the Karen women's health care in northern Thailand. *Songklanakarin Journal of Science and Technology*, **37**(3), 369-379.
Tellman, B., J. E. Saiers and O. A. R. Cruz, 2016: Quantifying the impacts of land use change on flooding in data-poor watersheds in El Salvador with community-based model calibration. *Regional Environmental Change*, **16**(4), 1183-1196, doi:10.1007/s10113-015-0841-y.
Telwala, Y., B. W. Brook, K. Manish and M. K. Pandit, 2013: Climate-Induced Elevational Range Shifts and Increase in Plant Species Richness in a Himalayan Biodiversity Epicentre. *PLoS ONE*, **8**(2), e57103, doi:10.1371/journal.pone.0057103.
Tepley, A. J. et al., 2018: Influences of fire–vegetation feedbacks and post-fire recovery rates on forest landscape vulnerability to altered fire regimes. *Journal of Ecology*, **106**(5), 1925-1940, doi:10.1111/1365-2745.12950.
Terzi, S. et al., 2019: Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation. *Journal of Environmental Management*, **232**, 759-771, doi:10.1016/j.jenvman.2018.11.100.
Thapa, S. et al., 2018: Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. *PloS one*, **13**(4), e0195752, doi:10.1371/journal.pone.0195752.
Thapa, S. and A. Hussain, 2020: Climate change and high-altitude food security: a small-scale study from the Karnali region in Nepal. *Climate and Development*, 1-12.
Thornton, J. M. et al., 2021: Toward a definition of Essential Mountain Climate Variables. *One Earth*, **4**, 805-827, doi:10.1016/j.oneear.2021.05.005.
Tian, X.-r., F.-j. Zhao, L.-f. Shu and M.-y. Wang, 2014: Changes in forest fire danger for south-western China in the 21st century. *International Journal of Wildland Fire*, **23**, 185-195, doi:10.1071/WF13014.
Tiwari, K. R. et al., 2020: Vulnerability of Pastoralism: A Case Study from the High Mountainsof Nepal. *Sustainability*, **12**(7), 2737, doi:10.3390/su12072737.
Tiwari, P. C. and B. Joshi, 2012: Natural and socio-economic factors affecting food security in the Himalayas. *Food Security*, **4**(2), 195-207, doi:10.1007/s12571-012-0178-z.
Tiwari, P. C. and B. Joshi, 2015: Climate Change and Rural Out-migration in Himalaya. *Change and Adaptation in Socio-Ecological Systems*, **2**(1), 8-25, doi:10.1515/cass-2015-0002.
Tiwari, P. C., A. Tiwari and B. Joshi, 2018: Urban growth in Himalaya: understanding the process and options for sustainable development. *Journal of Urban and Regional Studies on Contemporary India*, **4**(2), 15–27.
Tonjer, L. R. et al., 2021: Expanding forests in alpine regions: space-for-time indicates a corresponding shift in belowground fungal communities. *Authorea*, doi:10.22541/au.161065834.45838723/v1.
Torres-Batlló, J. and B. Martí-Cardona, 2020: Precipitation trends over the southern Andean Altiplano from 1981 to 2018. *Journal of Hydrology*, **590**, 125485.
Trabacchi, C. and M. Stadelmann, 2016: Making Climate Resilience a Private Sector Business: Insights from the Agricultural Sector in Nepal. In: *Climate Change Adaptation Strategies - An Upstream-downstream Perspective* [Salzmann, N., C. Huggel, S. Nussbaumer and G. Ziervogel (eds.)]. Springer, Cham, Switzerland, pp. 213-238. ISBN 9783319407739.
Trant, A., E. Higgs and B. M. Starzomski, 2020: A century of high elevation ecosystem change in the Canadian Rocky Mountains. *Scientific Reports*, 9698, doi:10.1038/s41598-020-66277-2.
Trombley, J., S. Chalupka and L. Anderko, 2017: Climate change and mental health. *American Journal of Nursing*, **117**(4), 44-52, doi:10.1097/01.NAJ.0000515232.51795.fa.
Tsai, C.-F. et al., 2015: Species turnover in tropical montane forest avifauna links to climatic correlates. *Global Ecology and Conservation*, **3**, 541-552, doi:10.1016/j.gecco.2015.01.008.
Tschakert, P. et al., 2019: One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change*, **55**, 58-72, doi:10.1016/j.gloenvcha.2018.11.006.
Turner, M. G., W. H. Romme and D. B. Tinker, 2003: Surprises and lessons from the 1988 Yellowstone fires. *Frontiers in Ecology and the Environment*, **1**(7), 351-358, doi:10.1890/1540-9295(2003)001[0351:SALFTY]2.0.CO;2.
Udas, P. B., A. Prakash and C. G. Goodrich, 2018: Gendered Vulnerabilities in Diaras. Struggling with Floods in the Gandak River Basin *Review of Women's Studies*, **53**(17), 46-54.
UN, 2015: *Transforming our world: the 2030 agenda for sustainable development*, **A/RES/70/1**, United Nations, New York, NY, USA, 35 pp. Available at: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf (accessed 31/10/2020).
UN (ed.), 2017: New Urban Agenda - Habitat III. Housing and Sustainable Urban Development (Habitat III), Quito, Ecuador, United Nations, 52 pp. ISBN 9789211327311.
UNEP, 2017: *The Status of Climate Change Litigation – A Global Review*. United Nations Environment Programme, Nairobi, Kenya, 41 pp. ISBN 9789280736564.
UNEP, 2021: *Adaptation Gap Report 2020*. United Nations Environment Programme, Nairobi, Kenya. Available at: https://www.unep.org/resources/adaptation-gap-report-2020.
UNFCCC, 2015: *Adoption of the Paris agreement, COP 21, Paris, France*. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.
UNFCCC, 2020: National Adaptation Plans, United Nations Framework Convention on Climate Change. Available at: https://www4.unfccc.int/sites/NAPC/News/Pages/national_adaptation_plans.aspx.

UNFCCC, 2020: NDC Registry (interim), United Nations Framework Convention on Climate Change. Available at: https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx.
UNFCCC, 2020: Submitted NAPAs, United Nations Framework Convention on Climate Change. Available at: https://unfccc.int/topics/resilience/workstreams/national-adaptation-programmes-of-action/napas-received.
UNISDR, 2015: *Disaster Risk reduction and resilience in the 2030 agenda for sustainable development*. Geneva, Switzerland. Available at: https://www.undrr.org/publication/disaster-risk-reduction-and-resilience-2030-agenda-sustainable-development.
Upgupta, S. et al., 2015: Climate change impact and vulnerability assessment of forests in the Indian Western Himalayan region: A case study of Himachal Pradesh, India. *Climate Risk Management*, **10**, 63-76, doi:10.1016/j.crm.2015.08.002.
Vaidya, R. A. et al., 2021: The role of hydropower in South Asia's energy future. *International Journal of Water Resources Development*, **37**(3), 367-391, doi:10.1080/07900627.2021.1875809.
Vaidya, R. A. et al., 2019: Disaster Risk Reduction and Building Resilience in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People* [Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.)]. Springer, Cham, Switzerland, pp. 389-419. ISBN 9783319922881.
Vander Naald, B., 2020: Examining tourist preferences to slow glacier loss: evidence from Alaska. *Tourism Recreation Research*, **45**(1), 107-117, doi:10.1080/02508281.2019.1606978.
Verrall, B. and C. M. Pickering, 2019: Recovery of subalpine grasslands 15 years after landscape level fires. *Australian Journal of Botany*, **67**(5), 425-436, doi:10.1071/BT19020.
Vitali, A. et al., 2019: Pine recolonization dynamics in Mediterranean human-disturbed treeline ecotones. *Forest Ecology and Management*, **435**, 28-37, doi:10.1016/j.foreco.2018.12.039.
Vitasse, Y. et al., 2012: Tree recruitment of European tree species at their current upper elevational limits in the Swiss Alps. *Journal of Biogeography*, **39**(8), 1439-1449, doi:10.1111/j.1365-2699.2012.02697.x.
Viviroli, D. et al., 2020: Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, doi:10.1038/s41893-020-0559-9.
Vuille, M. et al., 2018: Rapid decline of snow and ice in the tropical Andes – Impacts, uncertainties and challenges ahead. *Earth-Science Reviews*, **176**, 195-213, doi:10.1016/j.earscirev.2017.09.019.
Wang, C., B. Gao, Z. Weng and Y. Tian, 2020: Primary causes of total hamlet abandonment for different types of hamlets in remote mountain areas of China. A case study of Shouning country, Fujian province. *Land Use Policy*, **95**, 104627, doi:10.1016/j.landusepol.2020.104627.
Wang, S. and D. Qin, 2015: Mountain inhabitants' perspectives on climate change, and its impacts and adaptation based on temporal and spatial characteristics analysis: a case study of Mt. Yulong Snow, Southeastern Tibetan Plateau. *Environmental Hazards*, **14**(2), 122-136, doi:10.1080/17477891.2014.1003776.
Wang, Z. and C. Lu, 2018: Urban land expansion and its driving factors of mountain cities in China during 1990–2015. *Journal of Geographical Sciences*, **28**(8), 1152-1166, doi:10.1007/s11442-018-1547-0.
Ward, M. et al., 2020: Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology and Evolution*, **4**(10), 1321-1326, doi:10.1038/s41559-020-1251-1.
Warner, K. and T. Afifi, 2014: Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. *Climate and Development*, **6**(1), 1-17.
Wester, P., A. Mishra, A. Mukherji and A. B. Shrestha (eds.), 2019: *The Hindu Kush Himalaya assessment: mountains, climate change, sustainability and people*, Springer Nature, Cham, Switzerland, 627 pp. ISBN 9783319922881.
Westerling, A. L., 2016: Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions Roral Society B*, **371**, 20150178, doi:10.1098/rstb.2015.0178.
Wijngaard, R. R. et al., 2018: Climate change vs. socio-economic development: understanding the future South Asian water gap. *Hydrology and Earth System Sciences*, **22**(12), 6297-6321, doi:10.5194/hess-22-6297-2018.
Williams, R. J. et al., 2008: Large fires in Australian alpine landscapes: their part in the historical fire regime and their impacts on alpine biodiversity. *International Journal of Wildland Fire*, **17**, 793-808, doi:10.1071/WF07154.
Winkler, D. E. et al., 2016: Seasonal dry-down rates and high stress tolerance promote bamboo invasion above and below treeline. *Plant ecology*, **217**(10), 1219-1234, doi:10.1007/s11258-016-0649-y.
Wirz, V., M. Geertsema, S. Gruber and R. S. Purves, 2016: Temporal variability of diverse mountain permafrost slope movements derived from multi-year daily GPS data, Mattertal, Switzerland. *Landslides*, **13**(1), 67-83, doi:10.1007/s10346-014-0544-3.
Wrathall, D. J. et al., 2014: Migration Amidst Climate Rigidity Traps: Resource Politics and Social–Ecological Possibilism in Honduras and Peru. *Annals of the Association of American Geographers*, **104**(2), 292-304, doi:10.1080/00045608.2013.873326.
Wu, X. et al., 2016: Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. *Environment international*, **86**, 14-23, doi:10.1016/j.envint.2015.09.007.
Wyborn, C., L. Yung, D. Murphy and D. R. Williams, 2015: Situating adaptation: how governance challenges and perceptions of uncertainty influence adaptation in the Rocky Mountains. *Regional Environmental Change*, **15**, 669-682, doi:10.1007/s10113-014-0663-3.
Xenarios, S. et al., 2019: Climate change and adaptation of mountain societies in Central Asia: uncertainties, knowledge gaps, and data constraints. *Regional Environmental Change*, **19**(5), 1339-1352, doi:10.1007/s10113-018-1384-9.

Yadav, P. K. et al., 2019: Yartsagunbu: transforming people's livelihoods in the Western Himalaya. *Oryx*, **53**(2), 247-255, doi:10.1017/S0030605318000674.
Yadava, A. K. et al., 2017: Altitudinal treeline dynamics of Himalayan pine in western Himalaya, India. *Quaternary International*, **444**, 44-52, doi:10.1016/j.quaint.2016.07.032.
Yan, Y. et al., 2017: Range shifts in response to climate change of Ophiocordyceps sinensis, a fungus endemic to the Tibetan Plateau. *Biological Conservation*, **206**, 143-150, doi:10.1016/j.biocon.2016.12.023.
Yang, H. et al., 2016: Land-use response to drought scenarios and water policy intervention in Lijiang, SW China. *Land Use Policy*, **57**, 377-387, doi:10.1016/j.landusepol.2016.05.027.
Yapiyev, V. et al., 2017: Essentials of Endorheic Basins and Lakes: A Review in the Context of Current and Future Water Resource Management and Mitigation Activities in Central Asia. *Water*, **9**(10), 798, doi:10.3390/w9100798.
Yohannes, Z., M. Teshome and M. Belay, 2020: Adaptive capacity of mountain community to climate change: case study in the Semien Mountains of Ethiopia. *Environment, Development and Sustainability*, **22**(4), 3051-3077, doi:10.1007/s10668-019-00334-3.
Zekollari, H., M. Huss and D. Farinotti, 2020: On the Imbalance and Response Time of Glaciers in the European Alps. *Geophysical Research Letters*, **47**, e2019GL085578, doi:10.1029/2019GL085578.
Zhang, C. et al., 2019a: Climatic factors control the geospatial distribution of active ingredients in Salvia miltiorrhiza Bunge in China. *Scientific Reports*, **9**, 904, doi:10.1038/s41598-018-36729-x.
Zhang, Y. et al., 2019b: Identifying refugia and corridors under climate change conditions for the Sichuan snub-nosed monkey (Rhinopithecus roxellana) in Hubei Province, China. *Ecology and Evolution*, **9**(4), 1680-1690, doi:10.1002/ece3.4815.
Zhao, Q. et al., 2018: Modeling impacts of climate change on the geographic distribution of medicinal plant Fritillaria cirrhosa D. Don. *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology*, **152**(3), 349-355, doi:10.1080/11263504.2017.1289273.
Zheng, G. et al., 2021: Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nature Climate Change*, **11**, 411–417, doi:10.1038/s41558-021-01028-3.
Zimmermann, M. and M. Keiler, 2015: International Frameworks for Disaster Risk Reduction: Useful Guidance for Sustainable Mountain Development? *Mountain Research and Development*, **35**(2), 195-202, doi:10.1659/MRD-JOURNAL-D-15-00006.1.
Zkhiri, W. et al., 2019: Spatiotemporal characterization of current and future droughts in the High Atlas basins (Morocco). *Theoretical and Applied Climatology*, **135**(1), 593-605.
Zolotareva, N. V. and M. P. Zolotarev, 2017: The phenomenon of forest invasion to steppe areas in the Middle Urals and its probable causes. *Russian Journal of Ecology*, **48**(1), 21-31, doi:10.1134/S106741361606014X.
Zomer, R. J. et al., 2014a: Projected climate change impacts on spatial distribution of bioclimatic zones and ecoregions within the Kailash Sacred Landscape of China, India, Nepal. *Climatic change*, **125**(3-4), 445-460, doi:10.1007/s10584-014-1176-2.
Zomer, R. J. et al., 2014b: Environmental stratification to model climate change impacts on biodiversity and rubber production in Xishuangbanna, Yunnan, China. *Biological Conservation*, **170**, 264-273, doi:10.1016/j.biocon.2013.11.028.
Zylstra, P. J., 2018: Flammability dynamics in the Australian Alps. *Austral Ecology*, **43**(5), 578-591, doi:10.1111/aec.12594.

Cross-Chapter Paper 6: Polar Regions

Cross-Chapter Paper Leads: Andrew J. Constable (Australia), Sherilee Harper (Canada)

Cross-Chapter Paper Authors: Jackie Dawson (Canada), Kirstin Holsman (USA), Tero Mustonen (Finland), Dieter Piepenburg (Germany), Björn Rost (Germany)

Cross-Chapter Paper Contributing Authors: Stef Bokhorst (The Netherlands), Julia Boike (Germany), Ashlee Cunsolo (Canada), Chris Derksen (Canada), Pauliina Feodoroff (Finland), James D. Ford (United Kingdom/Canada), Stephen E.L. Howell (Canada), Angélica Casanova Katny (Chile), Joanna Petrasek MacDonald (Canada), Åshild Ønvik Pedersen (Norway), Sharon Robinson (Australia), Dalee Sambo Dorough (USA), Vyacheslav Shadrin (Russian Federation), Mette Skern-Mauritzen (Norway), Sharon Smith (Canada), Dmitry Streletskiy (USA/Russian Federation), Megumu Tsujimoto (Japan), Brie Van Dam (USA)

Cross-Chapter Paper Review Editor: Philip Boyd (Australia)

Cross-Chapter Paper Scientist: David Babb (Canada)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Observed impacts and future risks

Climate change impacts and cascading impacts in polar regions, particularly the Arctic, are already occurring at a magnitude and pace unprecedented in recent history (*very high confidence*), and much faster than projected for other world regions (*high confidence*[1]).

The polar regions, notably the Arctic and maritime Antarctic, are experiencing impacts from climate change at magnitudes and rates that are among the highest in the world, and will become profoundly different in the near-term future (by 2050) under all warming scenarios (*high confidence*). In the Arctic, accelerated sea-ice loss (particularly during summer), increased permafrost thaw and extreme high temperatures have substantially impacted marine, freshwater and terrestrial sociological-ecological systems (*very high confidence*). Multiple physical, ecological and societal elements of polar regions are approaching a level of change potentially irreversible for hundreds of years, if not millennia (*high confidence*). Evidence of borealization of terrestrial and marine systems is emerging (*high confidence*), and cascading impacts are on-going and widespread yet challenging to quantify fully due to complexity and lags in ecological expression of change. Loss of multi-year sea-ice and the occurrence of a seasonally ice-free Arctic Ocean by the middle of this century will result in substantial range contraction, if not the disappearance of several Arctic fish, crab, bird and marine mammal species, including possible extinction of seals and polar bears in certain regions (*high confidence*). In the Arctic, permafrost thaw and snowfall decrease lead to profound hydrological changes, an overall greening of the tundra and regional browning of tundra and boreal forests (*high confidence*). (CCP6.1; Table CCP6.1; Table CCP6.2; CCP6.2.1; CCP6.2.2; Table CCP6.5)

Contractions of the polar climate zones lead to distribution shifts and changes in food webs, induce declines in many species (*medium confidence*) with impacts on subsistence harvests and commercial fisheries, and threaten global dependence on polar regions for substantial marine food production (*high confidence*). Climate change has induced food web changes resulting in population declines in polar seabirds, including penguins, and marine and terrestrial mammals (*high confidence*). Globally and regionally important harvested fish and invertebrate species are also contracting ranges and declining productivity, including Pacific cod, salmon, snow and king crab in the Arctic and krill in the Antarctic (*medium confidence*), with implications for global food systems (*high confidence*). (Table CCP6.2; CCP6.2.1; CCP6.2.3; Table CCP6.3; Table CCP6.4)

Loss of sea-ice is rapidly expanding opportunities, but also increasing risks for shipping and other economic industries in polar regions (*very high confidence*). Reduced sea-ice enables greater access to high-latitudinal seas for industries, such as fisheries, shipping, tourism (*very high confidence*) and Arctic maritime trade and resource extraction (*medium confidence*). Navigational risks have grown due to increasingly mobile multi-year ice, poor hydrographic charting in newly open areas, and limited weather, water, ice, and climate data and services (*high confidence*). Cascading risks from polar shipping growth include increased air emissions, underwater noise pollution, disruption to subsistence hunting and cultural activities in the Arctic (*high confidence*) and potential for invasive marine species and geopolitical tensions (*medium confidence*). (Table CCP6.3; CCP6.2.4; Box CCP6.1; Table CCP6.5; Table CCP6.6)

Increased permafrost thaw and flooding will disrupt economically important transportation and supply-chain infrastructure to remote Arctic settlements (*high confidence*), increasing risks to economies, Arctic tourism and tourism to cultural heritage sites (*medium confidence*). Arctic permafrost thaw is projected to impact most infrastructure by the middle of this century, impacting millions of people and their economies, and costing billions in damages (*high confidence*). (CCP6.2.3; CCP6.2.4; Box CCP6.1; CCP6.2.5; CCP6.3.1; Table CCP6.5; Table CCP6.6)

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Climate change increasingly threatens many facets of Arctic livelihoods, culture, identity, health and security, particularly for Indigenous Peoples (*very high confidence*). It has negatively impacted mental health and increased risks of injury, food insecurity and foodborne and waterborne disease, with risks amplified for those reliant on the environment for subsistence, livelihoods and identity (*high confidence*). Permafrost thaw, sea-level rise and reduced sea-ice protection have already damaged or destroyed many cultural heritage sites in some Arctic regions (*very high confidence*) and are projected to continue across all Arctic regions (*very high confidence*). (CCP6.2.3; Table CCP6.3; CCP6.2.4; CCP6.2.5; CCP6.2.6; Figure CCP6.3; Box CCP6.2; CCP6.3.1; Table CCP6.5; Table CCP6.6)

Adaptation

Adaptations to manage climate change impacts and risks in polar regions are urgently needed (*very high confidence*), but implementation is uneven (*high confidence*), limits to adaptation are high and maladaptation is probable (*high confidence*).

Polar zones will continue to contract and diminish in extent under climate change, and local adaptations will be insufficient to achieve long-term resilience of polar systems (*medium confidence*). The pace and extent of change in polar regions is challenging the ability of social and natural systems to adapt (*medium confidence*). Management of different sectors with specific measures to reduce the potential for compounding risks and the development of climate-sensitive strategies would support the resilience of polar systems. Resilience of natural systems can be enhanced through strategies that maintain ecological connectivity over large spatial scales and reduce the particular impact of local extreme events on biodiversity (*medium confidence*). (CCP6.2; Box CCP6.1; CCP6.3; Table CCP6.5; Table CCP6.6; Figure CCP6.6; CCP6.4)

Timing, direction and scale of polar climate change impacts differ sub-regionally and will require adaptation strategies that are flexible, equitable, inclusive and integrated across sectors and governance arrangements to effectively reduce risks (*high confidence*). Governance around climate change planning, preparation and response has been limited in scope, and has often not considered interacting effects of climate change with other risks (*high confidence*). Reactive management strategies will not succeed in reducing risks in polar regions given the rapid change and increasing potential for extreme events (*high confidence*). Greater inclusivity of stakeholders and communities, along with using diverse sources of information, including Indigenous knowledge and local knowledge, can benefit robust planning and decision-making, and uptake of adaptations (*high confidence*). Effectiveness in preparing for and adapting to climate risks can benefit from improved climate, weather and ice forecasting services, tools for integrating climate change data and different types of knowledge into management processes and enhanced polar search, rescue, and emergency response capabilities (*high confidence*). (CCP6.2.3.1; CCP6.3; Table CCP6.6; CCP6.4; Box CCP6.2; Box CCP6.3; Figure CCP6.8)

Climate resilient development

Climate resilience for Arctic Indigenous Peoples and local communities is dependent on Indigenous self-determination in climate-adaptation action (*very high confidence*), inclusive, coordinated, and transboundary governance (*high confidence*) and ecosystem-based policies (*high confidence*) to effectively address climate change impacts and risks across scales and sectors, and to achieve a resilient, secure and equitable future.

Development of robust pathways for climate resilience in the Arctic can be accelerated by adaptation strategies and governance that reflect local conditions, cultures and adaptive capacities of communities and sectors (*high confidence*). Effectiveness of adaptation strategies will be enhanced by accounting for the geographic, climatic, ecological and cultural uniqueness of the polar regions (*medium confidence*). Colonialism can inhibit the development of robust climate adaptation strategies, and exacerbate climate risks (*very high confidence*). Inclusive decision-making in establishing climate adaptations can foster resilience, reflect the unique environmental, cultural, and economic imperatives of the region and support both market-based and sharing economies (*high confidence*). (Box CCP6.2; Table CCP6.6; CCP6.3.2; CCP6.4)

Indigenous self-determination in managing climate change impacts, adaptations, and solutions can accelerate effective robust climate-resilient development pathways in the Arctic (*very high confidence*). Arctic Indigenous self-determination in decision-making can establish robust climate resilience, especially in Indigenous communities, incorporating locally-derived definitions of social and economic success, culturally legitimate institutions of government, strategic visioning and thinking and public-spirited, nation-building leadership (*very high confidence*). (Box CCP6.2; CCP6.3; CCP6.4)

CCP6.1 The Global Importance of Climate Change in Polar Regions

Polar regions (Figure CCP6.1) are considered flagship areas for climate change, since some of the most extreme climate change impacts that are projected to occur by 2050 elsewhere in the world have already been observed in the Arctic and Antarctic and have resulted in transformative and unprecedented change. Polar regions are not only home to cultural keystone species such as polar bears (Arctic) and penguins (Antarctic), they also play fundamental roles in regulating the global climate system and in the provision of ecosystem services for the global community and for Arctic Indigenous Peoples and local communities in the region.

These changes are causing a suite of direct and cascading risks for all polar ecosystems with larger effects to date in the Arctic than the Antarctic (*high confidence*), due to larger and regionally more consistent physical changes (Figure CCP6.2, Table CCP6.1; Chapter 3) (Meredith et al., 2019; Ranasinghe et al., 2021). In the Arctic, these changes affect every sector of society, impacting its 4,000,000 inhabitants, including 400,000 Indigenous People. The Antarctic has no permanent human settlements; however, many nations conduct field research, operate seasonal and permanent stations and have an interest in the management of the region (Hughes et al., 2018; Grant et al., 2021). During summer, when Antarctic science, tourism and fishery activities are greatest, 4,400 people live there, whereas only 1,100 people live there over winter (Meredith et al., 2019). Although adaptation is occurring in polar regions, it is uneven and sporadic and does not meet the risks posed by future climate change. Indigenous knowledge-based solutions, inclusive ecosystem-based policies and integrated technologies demonstrate the potential to effectively address climate change impacts across scales and sectors; yet implementation barriers remain (CCP6.4.1).

This Cross Chapter Paper (CCP) assesses the impacts, risks and adaptation implications resulting from the physical and chemical changes in the polar regions that were detailed in the WGI contribution to the AR6 (IPCC, 2021). Several key WGI AR6 findings have important implications for natural and human systems in polar regions. Warming and wetting have persisted as key climatic impact drivers in polar regions (*very high confidence*) and will *very likely*[2] continue to 2100 (Fox-Kemper et al., 2021; Gulev et al., 2021) with cascading climate effects regarding heatwaves, fire, weather, floods and heavy precipitation, river runoff, snowfall, glaciers and ice sheets, permafrost, lake, river and sea-ice, relative sea level and coastal flooding and erosion (Gutiérrez et al., 2021; Ranasinghe et al., 2021) (Table CCP6.1). They represent major climate hazards in all key risks for polar regions (Table CCP6.5). Key points of departure for this CCP also include AR5 (IPCC, 2014) and the Polar Regions chapter in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Meredith et al., 2019). SROCC assessed physical, biological and social systems concerning the Arctic and Antarctic Oceans and cryosphere, and how they are affected by current and future climate change. This CCP assesses the rapidly increasing evidence that has been published since AR5 and SROCC, and advances previous IPCC assessments. First, results from the Coupled Model Intercomparison Projects (CMIP6) are an important advance since SROCC, which improve the certainty and resolution of projections of the main climate impact drivers and the risks they have for polar systems (Fox-Kemper et al., 2021; Ranasinghe et al., 2021). Second, building from the framework outlined in SROCC (Crate et al., 2019), scientific, Indigenous knowledge (IK) and local knowledge (LK) systems are included in this assessment. Importantly, Indigenous authors led the assessment of the impacts, adaptation and governance of climate change for Indigenous Peoples, which is an important advance since AR5 and represents an important step towards Indigenous self-determination in international assessment processes (Ford et al., 2012; Ford et al., 2016; Hill et al., 2020).

Herein, observed impacts and future risks (CCP6.2), key risks and adaptation (CCP6.3) and climate resilient development pathways (CCP6.4) in the polar regions are assessed. The CCP describes how the implications of climate change impacts in the Arctic and Antarctic extend beyond their boundaries, in terms of transregional coupled ecological systems (CCP6.2.1, CCP6.2.2), global nutritional security (CCP6.2.3), global trade and shipping (CCP6.2.4) and cultural value (CCP6.2.5, CCP6.2.6). Given the synthetic and

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

policy-facing mandate of CCPs and with SROCC as a key point of departure, this CCP is not intended to cover the full breadth of issues for polar regions but rather it highlights select key policy-relevant topics by synthesizing and adding value to the relevant material from AR6 sectoral and regional chapters.

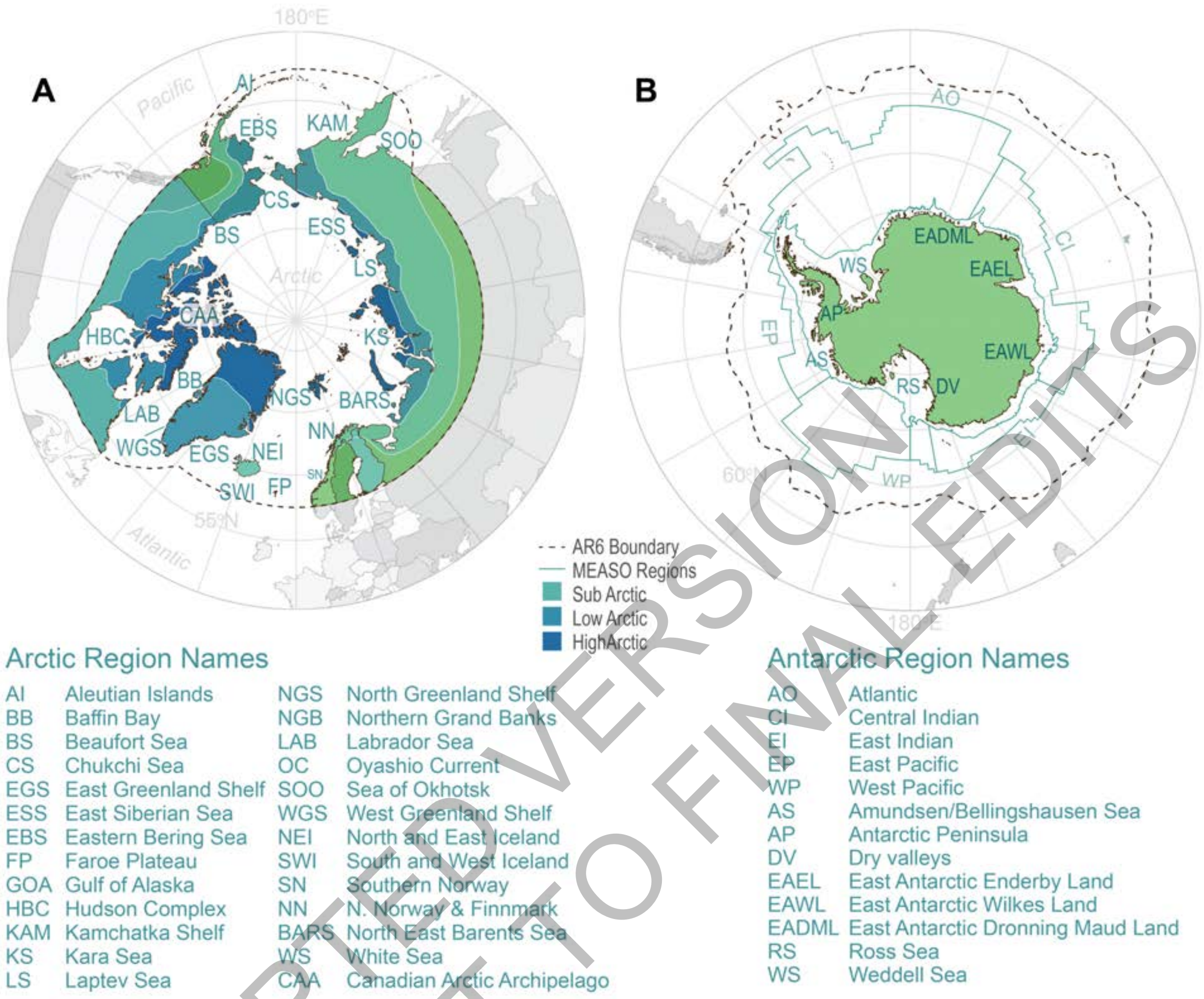


Figure CCP6.1: Polar regions include the Arctic, Antarctica, Iceland, Greenland, Faroe Islands, and some sub-Arctic areas (e.g., Bering Sea and Aleutian Islands as well as the Fennoscandian and Siberian boreal areas), and all sub-Antarctic areas. This CCP augments the geographical boundaries for the Arctic (Meredith et al., 2019) to also include the subarctic boundary (as defined by the Arctic Biodiversity Assessment), northern boreal areas, parts of the Siberian taiga and southern Labrador. The Antarctic region is delineated along the sub-Antarctic Front (Orsi et al., 1995). Geographic boundaries of the polar regions and important sub-regional locations are displayed including five marine sectors as defined in the Marine Ecosystem Assessment for the Southern Ocean (MEASO), e.g., Grant et al., (2021).

Table CCP6.1: Climatic impact drivers in the Arctic and Antarctic derived from WGI-AR6 chapters (indicated as WG1-9 (Fox-Kemper et al., 2021) and WG1-12 (Ranasinghe et al., 2021)) and Meredith et al (2019) (indicated as SROCC-3). Supplementary Material (SMCCP6.1) contains supplemental data for these drivers of projected changes (2021-2040, 2041-2060, 2081-2100) derived from the WGI-AR6 Interactive Atlas (indicated as Atlas)(Gutiérrez et al., 2021)(https://interactive-atlas.ipcc.ch).

Driver	Region	Observed Changes	Projected Changes
Marine and sea-ice			
Sea level (relative)	Arctic	No consistent trend (increase in NW America, decrease in NE America, stable in Greenland and Arctic Russia) (WG1-12)	Rise in all polar regions (except areas of substantial land uplift in NE Canada, the west coast of Greenland) (*high confidence*);

			Increase of extreme sea levels in Russian Arctic and NW America (*high confidence*) Greenland/Iceland and NE America (given glacial isostatic adjustment) (*medium confidence,* WG1-12)
	Antarctic		Rise in all polar regions (except areas of substantial land uplift in W Antarctica) (*high confidence*, WG1-12)
Sea-surface temperature	Arctic	Increase of ~0.5°C per decade during 1982-2017 in ice-free regions in summer (*high confidence*, SROCC-3)	Further increases (*high confidence*, WG1-12)
	Antarctic	Warmed in northern areas of Southern Ocean but cooled in its southernmost regions since the 1980s (*high confidence*, SROCC-3)	Circumpolar increases (*high confidence*, WG1-12)
Sea-ice cover	Arctic	Loss (particularly of multi-year sea-ice) accelerated since 2001 (*very likely*, WG1-9)	Will become sea-ice free (< 1 x 10^6 km^2) during summer before 2050, irrespective of global warming level (*likely*, WG1-9)
	Antarctic	No significant circumpolar trend from 1979–2018 (*very high confidence*), but decrease off the Antarctic Peninsula (*high confidence*) and increases and decreases in other regions (*medium confidence*, WG1-9)	Circumpolar decrease (*low confidence* due to limited understanding of driving processes, WG1-9)
Ocean surface pH	Both Poles	Decrease since 1980 at rates of 0.003–0.026 pH units per decade in open polar zones (*very likely*, WG1-12)	Further acidification by 0.1–0.6 pH by 2100 (Atlas), characterized by year-around conditions corrosive for aragonite minerals by 2100 (*very likely*, SROCC-3)
Terrestrial, freshwater and ice			
Atmospheric Temperature	Arctic	Increase of means higher than twice global mean, most pronounced in cold season (*high confidence*, WG1-12)	Further increase (Table SMCCP6.1)
	Antarctic	Warmed from 1957–2016 at 0.2–0.3°C per decade in W. Antarctica (*very likely*); No consistent change in E. Antarctica (*limited evidence*, WG1-12)	Region: Future warming across continent (*high confidence*, WG1-12)
Extreme Heat Events	Arctic	Increase since 1979 (WG1-12)	Polar amplification will drive further increases (*high confidence*, WG1-12)
	Antarctic	Heatwave across Antarctica (2020) (WG1-12, (Robinson et al., 2020).	Further increase, with > 50 additional days above freezing by 2100 (under RCP8.5, vs. 2014) over the Antarctic Peninsula but smaller changes over mainland Antarctica (*medium confidence,* WG1-12)
Fire Weather (FW)	Arctic	Over 4 decades, fire season lengthened and number of fires increased in N America (WG1-12)	FW index increases and more frequent fires in tundra regions (*high confidence*, WG1-12)
Precipitation	Arctic	Increase, highest during the cold season (*likely*, Atlas)	

	Antarctic	Increasing trend over the 20th century, while large interannual variability masks any existing trend since the end of 1970 (*medium confidence*, Atlas)	
Floods	Arctic	Increasing river runoff, increasing heavy precipitation (*high confidence*, WG1-12)	Further increases in all variables (*high confidence*, WG1-12)
Snowfall	Arctic	Recent overall declines in snow extent and seasonal duration (*high confidence*, WG1-12)	Higher % of precipitation as rain (fall and spring) (*high confidence*, WG1-12)
	Antarctic	Increases in the 20th century (*medium confidence*, WG1-12)	Further increases (over land) (*likely*, WG1-12)
Glaciers and Ice Sheets (IS)	Arctic	Losses in glacier mass since 2000 (*high confidence*, WG1-12); Losses in Greenland IS mass since 1980 at increasing rates (*high confidence*, WG1-9)	Further mass loss until 2100 under all warming scenarios (*virtually certain*, WG1-9 and -12)
	Antarctic	Losses in glacier mass since 2000 (*high confidence*, WG1-12); Losses in Antarctic IS mass since 1992 (in W Antarctica but also parts of E Antarctica since 2000) (*high confidence*, WG1-9)	Further mass loss until 2100 under all warming scenarios (*likely*, WG1-9 and -12)
Permafrost	Arctic	Rising permafrost temperatures over past 3-4 decades (*high confidence*, WG1-9); Decreases in permafrost active layer thickness (*very high confidence*) (Biskaborn et al., 2019). Submarine permafrost warming (*medium confidence*, WG1-9)	Increases in temperature and active layer thickness (WG1-9); Near-surface terrestrial permafrost extent will reduce under all scenarios by 2100 (*virtually certain*, WG1-9)
	Antarctic	Rising permafrost temperatures over past 3-4 decades (high confidence, WG1-9).	
Lake, River Ice	Arctic	Declines in seasonal lake ice cover thickness and duration over most Arctic lakes; Declines in cold-season river ice extent (*high confidence,* WG1-12)	Many lakes will lose > 1 month lake ice cover by 2050 (*medium confidence*), Reductions in average Northern Hemisphere seasonal river ice duration of 6.10 days per 1°C GWL (WG1-12)
Coastal floods / erosion	Arctic	Increase (*medium confidence*, WG1-12)	Further increase (*high agreement-limited evidence,* WG1-12)
	Antarctic	(Lack of studies, WG1-12)	

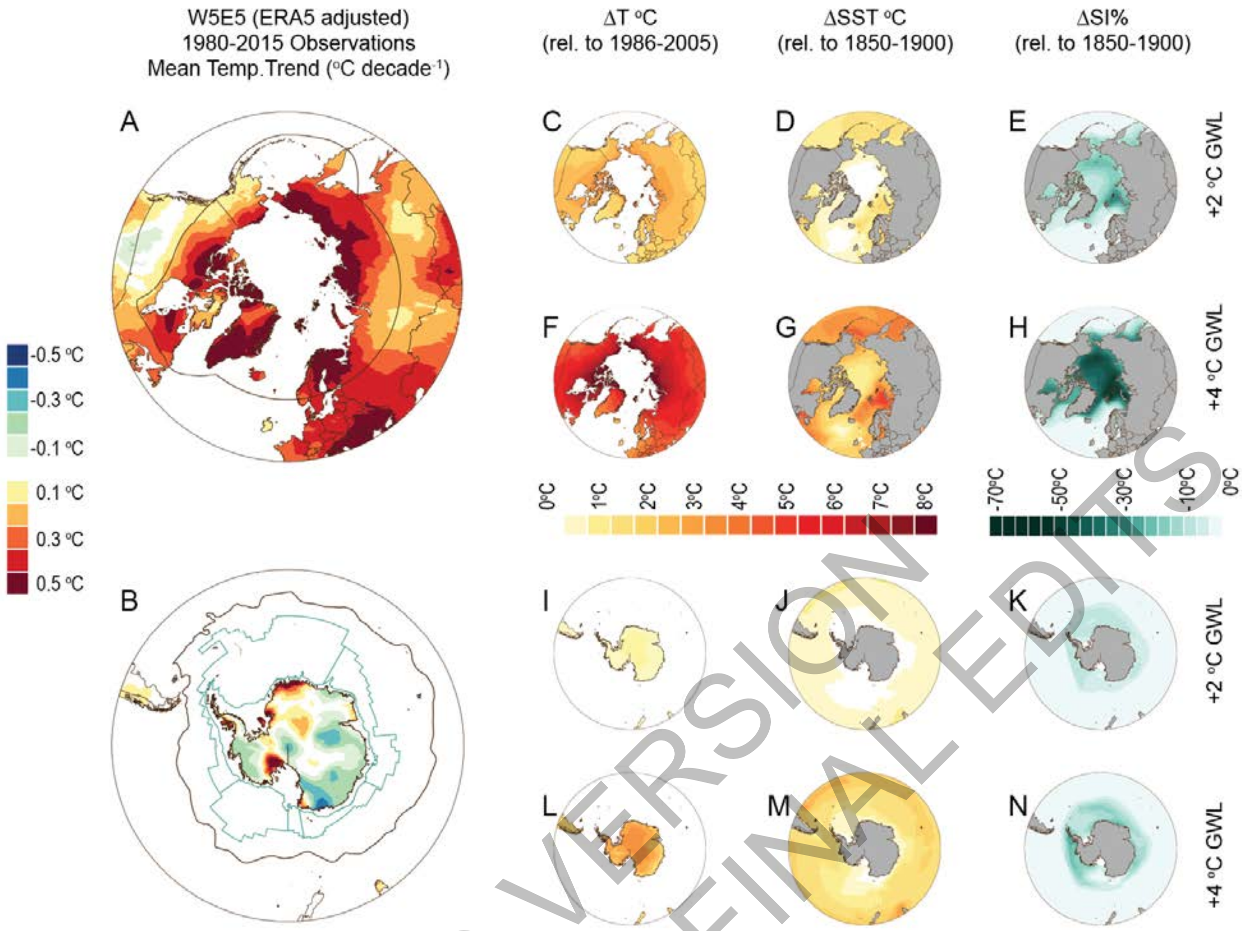


Figure CCP6.2: Observed and projected climate changes across the Arctic (A, C-H) and Antarctic (B, I-N). Boundary lines in each plot are based on the polar regions defined in Figure CCP6.1. All data shown here are extracted from the IPCC WGI Interactive Atlas (Gutiérrez et al., 2021; Iturbide et al., 2021); data set details can be found in the Atlas (https://interactive-atlas.ipcc.ch/). Arctic (A) and Antarctic (B) are observed temperature trends (°C/decade) over land for the period 1980-2015, derived from ERA5 adjusted dataset. Projected changes from an ensemble of CMIP6 projections: annual mean temperature over land is depicted for 2°C (C, I) and 4°C (F, L). Global Warming Levels (GWL) in the Arctic and Antarctic, respectively; annual mean sea surface temperature is depicted for 2°C (D, J) and 4°C (G, M) GWL in the Arctic and Antarctic respectively; annual sea-ice (%) is depicted for 2°C (E, K) and 4°C (H, N) GWL in the Arctic and Antarctic, respectively.

CCP6.2 Observed Impacts and Future Risks

Table CCP6.2: Summary of observed impacts (and projected risks of climate change for polar marine, terrestrial and freshwater ecosystems identified in Section 3.2.3 and Box 3.4 in Chapter 3 of the IPCC SROCC (Meredith et al., 2019).

Affected system	Hazard *Cascading Effect	Observed impacts, future risks and natural adaptations identified in SROCC (Confidence Level)
Arctic marine ecosystems		
Primary Producers (PP-1)	Sea-ice loss * Freshening * Stratification	Impact: Timing (earlier and later blooms), distribution and magnitude (>30% increase in annual net primary production since 1998) (*high confidence*)
	Acidification	Adaptation: phytoplankton may compensate for decrease pH

Zooplankton	* PP-1	Impact: Changing production and community composition (*medium confidence*)
Benthos	* PP-1	Impact: Changing production and biodiversity (*medium confidence*)
	Acidification	Risk: Effects on zooplankton and pteropods depends on climate scenario and species' sensitivity/adaptive capacity
Fish	Warming * Prey changes	Impact: Northward expanding ranges of sub-Arctic/boreal species (e.g., Atlantic cod) in Bering Sea (Detection - *high confidence*, Attribution - *medium confidence*) negatively affecting Arctic polar cod (*medium confidence*)
	* Prey declines	Risk: Decreasing production of walleye pollock, Pacific cod and arrowtooth flounder, due to declines in large copepods (*medium confidence*)
Birds and Marine Mammals	Sea-ice loss	Impact: Phenological, behavioural, physiological, and distributional changes; Endemic marine mammals have little scope to move northwards in response to warming (*high confidence*)
Polar Bears	Sea-ice timing, distribution, thickness	Impact: Phenological shifts, and changes in distribution, denning, foraging behaviour and survival rates (*high confidence*)
Antarctic marine ecosystems		
Primary Productivity	Sea-ice loss * Freshening * Stratification	Impact: Little overall change in biomass at circumpolar scale from 1998–2006, but sub-regional differences (*medium confidence*); Changes difficult to detect and attribute to climate change.
Microbes	Acidification	Impact: Detrimental effect on primary production and changes to the structure and function of microbial communities (*medium confidence*)
Antarctic Krill	Warming	Impact: Declines in abundance in the South Atlantic sector (*medium confidence*); May not represent a long-term, climate-driven trend but a decline following a period of anomalous peak abundance (*low confidence*)
		Risk: Southward range shift due to changes in the location of the optimum conditions for growth and recruitment, with decreases most apparent in the areas with the most rapid warming, such as the southwest Atlantic/Weddell Sea region (*medium confidence*)
Zooplankton	Acidification	Risk: Vulnerability of pteropods through effects on eggs (*medium confidence*)
Benthos	Sea-ice loss	Risk: Increase of biomass on the Antarctic continental shelf as productivity from longer phytoplankton blooms outweigh ice-scour mortality (*low confidence*)
	Sea-ice loss	Risk: Shallow-water communities may become dominated by macroalgae due to increases in the amount of light (possible loss of endemic species by 12% due to warming temperatures) (*low confidence*)
Fish	Warming	Risk: Icefish may be displaced from shallow regions around sub-Antarctic islands (*low confidence*)

Birds and Marine Mammals	Sea-ice cover	Impact: Predictability of foraging grounds and sea-ice cover associated with climate are main drivers of population changes: Increases for gentoo penguins (decreases for Adélie, chinstrap, king and Emperor penguins) (*high confidence*)
Arctic terrestrial and freshwater ecosystems		
Vegetation	Warming	Impact: Greening (*high confidence*)
		Risk: Decrease tundra areal extent >50% by 2050; wood shrubs expected to increase (*medium confidence*)
Vertebrates	Warming	Impact: Expanding range into Arctic
Freshwater Primary Productivity	* Increased runoff * Increased permafrost thaw	Impact: Increased productivity in rivers, lakes and coastal areas
		Risk: Expected to mobilise stores of pollutants
Pathogens	Warming	Impact: Expanding range into Arctic
		Risk: Mobilisation may increase in high latitudes, including anthrax from frozen carcasses possibly released from permafrost
Fish	* Freshwater winter habitat * Increased discharge	Risk: Disruption of the life history of Arctic freshwater fish
	* Warming freshwater	Risk: May make some surface waters inhospitably warm for cold water fish species
Biodiversity	Warming	Impact: Subarctic biodiversity expanding into Arctic
Reindeer/ Caribou	Climate factors	Impact: Reindeer/caribou declined overall without adaptation (*high confidence*), with climate affecting many aspects of their life history (*medium confidence*)
		Risk: Domesticated reindeer/caribou can be affected by fire, which reduces pasture, as well as by increased ice-on-snow, which can cause starvation
Antarctic terrestrial and freshwater ecosystems		
Terrestrial Biota	* Increased coastal ice melt	Impact: Increasing coastal ice-free areas available for colonisation (*high confidence*)
Alien Species	Warming	Risk: Barriers to alien species reduce, affecting terrestrial biodiversity (*medium confidence*)

CCP6.2.1 Marine and Coastal Ecosystems

CCP6.2.1.1 Warming and sea-ice retreat cause shifts in distribution ranges of species

In Arctic seas, warming and other climate impact drivers, primarily sea-ice retreat, have led to range contractions of Arctic marine and ice-associated species and poleward expansions of boreal species (*very high confidence*) (Table CCP6.2) (Bouchard and Fortier, 2020; Huntington et al., 2020; Mueter et al., 2020) even though light and energetics at seasonal extremes may limit some range shifts (*limited evidence*) (Ljungström et al., 2021). Altered conditions allow more microorganisms to move poleward and provide opportunities for invasive species (Cavicchioli et al., 2019; Nielsen et al., 2020; Mustonen, 2021).

Phytoplankton communities harbour increasing numbers of taxa, including harmful species (Lovejoy et al., 2017) and the coccolithophore *Emiliania huxleyi*, which meanwhile forms regular blooms in the Barents Sea (Neukermans et al., 2018; Silkin et al., 2020). Northward shifts of pelagic, benthic and demersal species and subsequent changes in Arctic community composition have been observed in the Bering, Greenland and Barents Seas (Grebmeier et al., 2018; Mueter et al., 2020), as have higher numbers of economically important boreal species such as haddock and Pacific and Atlantic cod (CCP6.2.3). Cold-adapted Arctic fish species such as polar cod (*Boreogadus saida*) are expected to decline further and lose spawning habitats at global warming levels >1.5 °C, mainly due to a lack of phenotypic plasticity, as well as increasing interspecific competition with and predation from invading boreal species (Dahlke et al., 2018; Marsh and Mueter, 2020). Numerous mammals and seabirds respond to changes in the distribution of their preferred habitats and prey by shifting their range, altering the timing or pathways for migration or switching prey (*very high confidence*) (Hamilton et al., 2017; Loseto et al., 2018; Meredith et al., 2019). Ice-breeding seals (e.g., harp seals - *Pagophilus groenlandicus*) often have little scope to shift distribution, leading to increases in strandings and pup mortality in years with little ice cover (*medium confidence*) (Table CCP6.2) (Boveng et al., 2020). Recent studies confirm that polar bears (*Ursus maritimus*) are negatively affected by changing ice and snow conditions with decreases in denning, foraging, reproduction, genetic diversity and survival rates (*very high confidence*) (Table CCP6.2) (Boonstra et al., 2020; Johnson and Derocher, 2020; Maduna et al., 2021).

In the Southern Ocean, southward range shifts are expected to result from increased warming coupled with the narrow thermal tolerance of cold-adapted Antarctic species (Convey and Peck, 2019; Morley et al., 2019; Gutt et al., 2021). Such shifts have so far only been detected for Antarctic krill (*Euphausia superba*), with a poleward contraction of the highest densities of krill in the Atlantic sector (*medium confidence*) (Table CCP6.2); (Atkinson et al., 2019). Ocean warming is expected to put pressure on Antarctic phytoplankton (Pinkerton et al., 2021) and fish species unable to move further south in shelf areas, including waters off sub-Antarctic islands (*low confidence*) (Table CCP6.2) (Caccavo et al., 2021). Off the Antarctic Peninsula and sub-Antarctic islands, invasive benthic invertebrates and macroalgae have already been detected (*medium confidence*) (Fraser et al., 2018; Avila et al., 2020; Brasier et al., 2021), and projected changes will further favour the spread of invasive species (Fraser et al., 2020; Macaya et al., 2020). On a local to regional scale, the benthic recolonization of the newly exposed seabed after the disintegration of ice shelves shows typical succession patterns, with mass occurrences of few pioneer species followed by gradual shifts to a more diverse typical shelf community, driven by increasing pelagic primary production upon ice-shelf collapse and strengthening of the pelagic-benthic coupling (*high confidence*) (Brasier et al., 2021; Gutt et al., 2021). Range changes of Antarctic birds and marine mammals have been observed, which vary among sub-regions and are mostly attributable to changes in sea-ice extent and food availability (*high confidence*) (Table CCP6.2) (Gutt et al., 2018; Convey and Peck, 2019; Bestley et al., 2020). With projected sea-ice retreat and associated change in prey distribution (Henley et al., 2020), foraging areas of sub-Antarctic seabirds and marine mammals will shift southwards, leading to elevated pressure on populations due to higher foraging costs during the breeding season (*medium confidence*) (Ropert-Coudert et al., 2018; Bestley et al., 2020; Hindell et al., 2020; Hückstädt et al., 2020; Wege et al., 2021). These changes are particularly impacting emperor penguins (*Aptenodytes forsteri*) (Table CCP6.2), with the projected population declining close to extinction by 2100 under business-as-usual climate scenarios (*medium confidence*) (Jenouvrier et al., 2020; Trathan et al., 2020; Jenouvrier et al., 2021), whereas population decline is halted by 2060 under the 1.5°C climate scenario (*low confidence*) (Jenouvrier et al., 2020).

CCP6.2.1.2 Ocean warming and sea-ice changes affect marine primary productivity

In the central Arctic Ocean, primary productivity remains low (*medium confidence*), mostly due to persisting nutrient and light limitations (Randelhoff and Guthrie, 2016; Ardyna and Arrigo, 2020). In inflowing (Barents and Chukchi Sea) and interior shelf regions (Laptev, Kara, and Siberian Sea), changes in sea-ice extent, thickness and seasonal timing have altered light and mixing regimes, causing increasing overall productivity in open-water and under-ice habitats, and in leads (*high confidence*) (Table CCP6.2) (Ardyna and Arrigo, 2020; Lannuzel et al., 2020). Productivity changes are associated with the earlier onset phytoplankton spring blooms and the increasing occurrence of autumn blooms, particularly at lower latitudes of the Arctic (*high confidence*) (Table CCP6.2) (Tedesco et al., 2019; Ardyna et al., 2020). Ice algal communities are expected to change in productivity and species composition in response to the transition from a predominantly multi-year to a seasonal sea-ice pack (*high confidence*) (Meredith et al., 2019; Tedesco et al., 2019; Lannuzel et al., 2020). Thinner sea-ice increases the likelihood of surface flooding, resulting in the occurrence of snow-infiltration algal communities, which have been described in the Atlantic sector of the Arctic Ocean (Fernández-Méndez et al., 2018) and observed by Indigenous Peoples off northern Greenland (Box CCP6.2). The observed transition from marine-terminating to land-terminating glaciers has a negative impact on coastal ecosystems in Greenland (*medium confidence*) (Meire et al., 2017; Hopwood et al., 2018) and Svalbard (Halbach et al., 2019), as land-terminating glacial meltwater input increases stratification, which hinders vertical mixing and lowers local productivity, whereas marine-terminating glaciers can trigger upwelling, which supplies nutrients and enables higher productivity in the summer (Hopwood et al., 2020). Macroalgae and seagrass are generally expanding in the Arctic (*medium confidence*), though there are negative trends in some regions, partly due to increased runoff and turbidity from melting glaciers (Hopwood et al., 2020; Krause-Jensen et al., 2020). In the future Arctic Ocean, higher light availability in response to further sea-ice decline and reduced deep mixing is projected to generally increase primary productivity (*medium confidence*), leading to an increase in phytoplankton biomass from 2000-2100 by ~20% for SSP1-2.6 and ~30-40% for SSP5-8.5 (Chapter 3) (Kwiatkowski et al., 2020). However, productivity may increase less than predicted and eventually even decrease once nutrient limitation outweighs the benefits of higher light availability (*low confidence*) (Randelhoff et al., 2020; Seifert et al., 2020).

Despite large-scale environmental changes in the Southern Ocean, such as the deepening of the summer mixed layer (*medium confidence*) (Panassa et al., 2018; Sallée et al., 2021), and the expected impacts via altered nutrient entrainment, light availability and grazer encounter rates (Chapter 3) (Behrenfeld and Boss, 2014; Llort et al., 2019), assessments indicated no consistent changes in primary production at the circumpolar scale, as sectors and regions show different trends (*medium confidence*). Although a global assessment found no overall changes in circumpolar primary production from 1998-2015 (Table CCP6.2) (Gregg and Rousseaux, 2019), another study showed an overall increase in phytoplankton biomass in the mixed layer over the period 1997-2019 (Pinkerton et al., 2021). Primary productivity has increased in the Pacific sector and decreased in the Atlantic sector and the Ross Sea (*low confidence*) (Kahru et al., 2017; Henley et al., 2020; Pinkerton et al., 2021). Higher productivity has also been observed in regions where rapid environmental changes occurred, such as in the vicinity of retreating ice sheets and declining sea-ice cover off the Antarctic Peninsula (*medium confidence*) (Henley et al., 2020; Rogers et al., 2020), although diversity of phytoplankton may decrease with warming temperatures and less sea-ice (*limited evidence*) (Lin et al., 2021). In the future Southern Ocean, stronger upwelling due to strengthened westerly winds is projected to increase primary productivity at the circumpolar scale in the Antarctic Zone and to the north of the sub-Antarctic Front, but not in the sub-Antarctic Zone (*low to medium confidence*) (Chapter 3) (Henley et al., 2020; Kwiatkowski et al., 2020; Pinkerton et al., 2021). The largest changes are projected to occur after 2100 at 2-6°C warming of the surface ocean (Moore et al., 2018). Such an increase in Southern Ocean productivity will lead to a decline in global ocean productivity (*medium confidence*), due to nutrient trapping (Moore et al., 2018) and altered ocean carbon uptake through ecosystem feedbacks (Hauck et al., 2018).

CCP6.2.1.3 Impacts of ocean acidification vary spatially and among biotas

In Arctic seas, areas with acidification levels corrosive to organisms forming $CaCO_3$ shells or skeletons expanded between the 1990s and 2010 (*high confidence*), with instances of extreme aragonite under-saturation (Ding et al., 2017; Zhang et al., 2020). Key species of diatom and picoeukaryote phytoplankton species yet appear relatively resilient to decreasing pH levels over a range of temperature and light conditions (*medium confidence*) (Table CCP6.2) (Thoisen et al., 2015; Wolf et al., 2018; White et al., 2020). In contrast, there is evidence for species- and stage-specific sensitivities of zooplankton, pteropods and fishes (*high confidence*) (Table CCP6.2) (Bailey et al., 2016; Dahlke et al., 2018; Thor et al., 2018). Warming, rising river-sediment discharge and coastal erosion in Arctic shelf regions are expected to increase the input of labile, often permafrost-derived organic carbon, the remineralisation of which further increases acidification rates (*medium confidence*) (Semiletov et al., 2016; AMAP, 2018b; Bröder et al., 2018). Interactions with other physical changes, such as warming or freshening, are expected to aggravate the impacts of ocean acidification (Chapter 3) (Falkenberg et al., 2018).

In the Southern Ocean, calcifying organisms are also most vulnerable to ocean acidification (*high confidence*) (Table CCP6.2), as evidenced by rates of calcification declining by 3.9% between 1998-2014 (Freeman and Lovenduski, 2015). Calcifying species with low-magnesium calcite or mechanisms to protect their skeletons are less vulnerable to the corrosive effects of acidification than those using aragonite or high-magnesium calcite (*high confidence*) (Figuerola et al., 2021). In diatom-dominated communities, silicification diminishes with reduced pH levels, albeit with rates differing among taxa (*low confidence*) (Petrou et al., 2019). Species-specific responses exist regarding growth and primary production, which are further strongly modulated by iron and light availability (*high confidence*) (Hoppe et al., 2013; Trimborn et al., 2013; Hoppe et al., 2015; Henley et al., 2020; Seifert et al., 2020). A meta-analysis yielded different CO_2 thresholds for Antarctic organismal groups, e.g., negative impacts emerged at >1,000 µatm CO_2 in phytoplankton and at >1,500 µatm CO_2 in invertebrates, whereas bacterial abundance was positively affected by ocean acidification (Hancock et al., 2020). Species sensitivity can also differ strongly between life-cycle stages (Chapter 3.3.2). For instance, eggs and embryos of Antarctic krill are negatively impacted at >1,250 µatm CO_2 whereas adults can thrive even at 1,000-2,000 µatm CO_2 over one year (Kawaguchi et al., 2013; Ericson et al., 2018).

CCP6.2.1.4 Climate change alters food web dynamics

Climate change has transformed Arctic marine ecosystems from sea-ice-associated to open-water production regimes, with profound impacts on trophic energy transfer efficiencies and pathways (*high confidence*) (Behrenfeld et al., 2017; Meredith et al., 2019; Huntington et al., 2020) as well as benthic-pelagic coupling (*medium confidence*) (Birchenough et al., 2015; Degen et al., 2016; Solan et al., 2020). Shifts in bloom phenology favour small phytoplankton and smaller zooplankton over large lipid-rich macro-zooplankton, leading to longer, less efficient food chains (*medium confidence*) (Aarflot et al., 2018; Feng et al., 2018; Kimmel et al., 2018; Weydmann et al., 2018; Møller and Nielsen, 2020). In the Beaufort Sea and Svalbard waters, earlier spring phytoplankton blooms have resulted in a mismatch in dynamics between microalgae and herbivorous copepods (Renaud et al., 2018; Dezutter et al., 2019). In the Bering Sea, zooplankton declines following the particularly pronounced sea-ice retreats in 2017 and 2018 were associated with reduced forage fish production (Duffy-Anderson et al., 2019), as well as multitrophic mortality of ctenophore, fish, bird, and mammal species, coupled with severe emaciation, reproductive failure, disease, and high mortality rates of seabird predators (Section 14.4.4.2) (Jones et al., 2019; Maekakuchi et al., 2020; Piatt et al., 2020; Romano et al., 2020). Species range shifts have restructured higher trophic levels in Arctic food webs (*high confidence*) (Table CCP6.2; CCP6.2.3.3 Chapter 3) (Huntington et al., 2020). In the northern Barents Sea, increased predation mortality for key species and incursions of boreal fish have induced entire ecosystem reorganization (Degen et al., 2016; Pecuchet et al., 2020a; Pecuchet et al., 2020b). Regional taxonomic and functional diversity increased with immigration of boreal species, although the ongoing decline in Arctic species suggests high species turnover (Table CCP6.2) (Frainer et al., 2017). Recent marine heatwaves induced rapid and profound food web changes unprecedented over the last four decades (Siddon et al., 2020).

Climate impacts on Arctic marine food webs will be profound and intensify with global warming levels (*high confidence*), regardless of mitigation scenarios due to multidecadal lags in sea-ice extent and atmospheric carbon (WGI) (Jones et al., 2020). However, the exact nature of these impacts remains unclear due to attenuating and amplifying dynamics of both top-down and bottom-up processes in polar food webs and the management of fisheries (*high confidence*) (Chapter 3) (Cavicchioli et al., 2019; Meredith et al., 2019). Projected sea-ice loss is associated with a >50% decline in the density of large zooplankton species by 2100 (relative to early 21st century levels) in the southern Bering Sea and a net increase in large zooplankton in the northern Bering Sea in scenarios without carbon mitigation (RCP8.5), whereas these declines are roughly half the magnitude under moderate mitigation scenarios (RCP4.5) (Hermann et al., 2019; Kearney et al., 2020). Warming is expected to reduce the quantity and quality of lipid-rich copepod prey (*high confidence*) (Aarflot et al., 2018; Kimmel et al., 2018; Bouchard and Fortier, 2020; Møller and Nielsen, 2020; Mueter et al., 2020), leading to declines in survival and growth of multiple upper-trophic level fish species; these impacts are amplified over time under low mitigation scenarios (RCP8.5) (*high confidence*) (CCP6.2.1.1) (Dahlke et al., 2018; Holsman et al., 2020; Mueter et al., 2020; Oke et al., 2020; Reum et al., 2020; Thorson et al., 2020; Whitehouse et al., 2021). Marine mammals and seabirds will continue to attenuate climate change impacts by shifting their diets and behaviour (*medium confidence*) (Table CCP6.2) (Hamilton et al., 2017; Lowther et al., 2017; Lydersen et al., 2017; Vihtakari et al., 2018; Boveng et al., 2020). However, seabirds generally have low temperature-mediated plasticity of reproductive timing, making them vulnerable to mismatches with their prey and limiting long-term adaptation (*medium* *confidence*) (Keogan et al., 2018; Kharouba and Wolkovich, 2020; Piatt et al., 2020; Samplonius et al., 2021).

Many factors have contributed to changes in Antarctic food webs, including historical exploitation of fish and marine mammals as well as changes driven by the ozone hole and climate factors (Meredith et al., 2019; Morley et al., 2020; Grant et al., 2021). Most documented changes resulting from warming and sea-ice losses relate to shifts in ranges and dynamics of species, with most impacts occurring around the Antarctic Peninsula (CCP6.2.1.1; Table CCP6.2).

The projected general rise in primary production in Antarctic seas by 2100 (CCP6.2.1.2) suggests a concomitant increase in the abundance of higher trophic species, but changes in the structure and function of food webs will vary (McCormack et al., 2021; McCormack, accepted) depending on regional differences in changing drivers (Morley et al., 2020; Cavanagh et al., 2021; Grant et al., 2021). Primary production in open water habitats is expected to be supported by smaller phytoplankton species in the future (Henley et al., 2020), which could increase the relative importance of the copepod-mesopelagic fish pathway (McCormack, accepted), because krill prefer larger diatoms as food (Siegel, 2016). The optimum habitat for Antarctic krill is expected to decline with a shortening of suitable season for krill growth and reproduction, particularly in the northern Scotia and Bellingshausen Seas (*medium confidence*) (Veytia et al., 2020), although changes may be difficult to distinguish from natural variability until later in the century (Sylvester et al., 2021). More subtle and unpredictable changes may occur in the structure and relative importance of energy pathways in the food webs (Trebilco et al., 2020). Small mesopelagic fish are increasingly recognized for their importance as mid-trophic level species in the Southern Ocean, particularly in the sub-Antarctic zone (Caccavo et al., 2021) and Central Indian Sector (Subramaniam et al., 2020; McCormack et al., 2021). Although salps have long been considered to be competitors of Antarctic krill (Suprenand and Ainsworth, 2017; Rogers et al., 2020), they provide a third energy pathway in pelagic food webs, and, given the changing ocean conditions and their preference for smaller phytoplankton, may increase in importance for copepods (*low confidence*) (Plum et al., 2020; Trebilco et al., 2020; McCormack et al., 2021; Pauli et al., 2021; McCormack, accepted). Declining ice shelves, such as those off the Antarctic Peninsula, will open up new pelagic and benthic habitats (CCP6.2.1.1) with expected increases in productivity of benthic assemblages in the new areas (Barnes, 2017; Morley et al., 2020; Brasier et al., 2021; Gutt et al., 2021).

CCP6.2.2 Terrestrial and Freshwater Ecosystems

Since the publication of AR5 (IPCC, 2014) and SROCC (IPCC, 2019) and their findings (Table CCP6.2), more studies confirm rapid changes in Arctic terrestrial and freshwater systems including increased permafrost thaw, changes to tundra hydrology and vegetation (overall greening of the tundra, regional browning of tundra and boreal forests), coastal and riverbank erosion (*high confidence*) (Canadell et al., 2021; Mustonen and Shadrin, 2021), reduced duration of snow cover and river and lake ice, increased rain-on-snow events, and reduced land-ice extent and thickness (Bieniek et al., 2018; Brown et al., 2018). Climate change continues to alter vegetation and attendant biodiversity, with divergent regional trends across the Arctic due to disparities in local conditions and changes in growing seasons (Zhu et al., 2016; Taylor et al., 2020). Warming facilitates woody vegetation growth in northeastern Siberia, western Alaska, and northern Quebec (Song et al., 2018; García Criado et al., 2020), as well as a northward expansion of shrub vegetation and sub-Arctic and boreal species (Davidson et al., 2020).

Further evidence shows that warming and changes to the Arctic hydrologic cycle increase the risk of wildfire (*medium confidence*) (Mustonen and Shadrin, 2021). Both the frequency of and the area burned by wildfires during recent years are unprecedented compared to the last 10,000 years (*high confidence*) (Meredith et al., 2019; Irannezhad et al., 2020). Fire risk levels are projected to increase across most tundra and boreal regions, and interactions between climate and shifting vegetation (Song et al., 2018) will influence future fire intensity and frequency (*medium confidence*) (Curtis et al., 2018).

For all warming scenarios, declines in snow cover in the Arctic by 2050 (Table CCP6.1) may accelerate vascular plant, moss, and lichen extinction rates (32% for Arctic–alpine and 12% for boreal species), especially after the tipping point of 20−30% decrease in snow cover duration is passed (Niittynen et al., 2018). Even though the overall regional water cycle will intensify, including increased precipitation, evapotranspiration and river discharge to the Arctic Ocean (Table CCP6.1), snow and permafrost decline may lead to further soil drying (*medium confidence*) (Meredith et al., 2019). Glacial ice melt poses a risk to ecosystems and people through remobilization of sequestered hazardous waste and transported pollutants (Table CCP6.3) (Wang et al., 2019).

In the Antarctic, there is further *high agreement* since the publication of SROCC that melt and ice-free areas are causing increases in the rates of colonisation and utilization of coastal environments by terrestrial biota and land-based colonies of seals and birds (Gutt et al., 2021), although colonisation rates remain variable (Ruiz-Fernandez et al., 2017; Bokhorst et al., 2021). Soil temperatures along the Antarctic Peninsula are now sufficient for germination of non-native plants; invasions by non-endemic species are expected to increase with rising temperatures (*high confidence*) (Bokhorst et al., 2021), posing a risk to endemic polar species (*medium confidence*) (Chown and Brooks, 2019; Gutt et al., 2021).

Vegetation responses to warming are contingent on water availability and local temperature (*medium confidence*) (Guglielmin et al., 2014; Royles and Griffiths, 2015; Amesbury et al., 2017; Cannone et al., 2017; Charman et al., 2018; Robinson et al., 2018; Stelling et al., 2018), which vary greatly around Antarctica (Figure CCP6.1) (Turner et al., 2020a). Antarctic terrestrial ecosystem responses to changes in water availability are not homogeneous (Ball and Levy, 2015; Sadowsky et al., 2016; Fuentes-Lillo et al., 2017; Gooseff et al., 2017; Schroeter et al., 2017; Lee et al., 2018). West Antarctica is showing evidence of greening in the dominant cryptogrammic vegetation, with greater growth in mosses (*high confidence*) (Casanova-Katny et al., 2016; Amesbury et al., 2017; Shortlidge et al., 2017; Charman et al., 2018; Prather et al., 2019). Peatland ecosystems may increase on the west Antarctic Peninsula with future warming (*low confidence*) (Yu et al., 2016; Loisel et al., 2017). In contrast, some parts of East Antarctica and the subantarctic islands to the north have been experiencing a drying climate, with declining health of mosses and other vegetation (*high confidence*) (Bergstrom et al., 2015; Bramley-Alves et al., 2015; Robinson et al., 2018; Bergstrom et al., 2021).

Antarctica encountered its first reported heatwave in 2020 (Table CCP6.1). Such abrupt heating can cause wide-ranging effects on biota, from flash-flooding damage and dislodgement of plants to excess melt waters supplying moisture to arid Antarctic ecosystems. This suggests that increased melt may reverse the drying trend if plant communities remain connected to melt streams and there is sufficient precipitation (*high agreement, limited evidence*) (Bergstrom et al., 2021).

Warming of the Antarctic Peninsula has resulted in increased soil microbial abundance and biomass. However this trend is not as great in southern colder locations (*medium confidence*) (e.g., Kim et al., 2018; Newsham et al., 2019), as the microbial community structure is affected by vegetation cover and water availability (*high confidence*) (Dennis et al., 2019; Newsham et al., 2019).

Antarctic terrestrial invertebrate communities on the West Antarctic Peninsula may be controlled more by vegetation and water availability than by air temperature (*medium confidence*) (Bokhorst and Convey, 2016; Knox et al., 2016; Andriuzzi et al., 2018; Prather et al., 2019; Newsham et al., 2020). Evidence from laboratory studies, field programs and sedimentary records indicate that Antarctic freshwater ecosystems may become more productive under climate warming scenarios (*medium confidence*) (e.g., Schiaffino et al., 2011; Borghini et al., 2016; Píšková et al., 2019; Čejka et al., 2020).

CCP6.2.3 Food, Fiber, and other Ecosystem Products

Food and fiber production underpins regional identities, cultures, and communities of practice and place in polar regions, are vital to local and distant economies (Table CCP6.4) and they represent for fisheries a critical source of global nutrition and food security (Hicks et al., 2019). Since SROCC, there is further evidence that climate change alterations of polar ecosystems increasingly challenge production of, and access to, sufficient, healthy, and nutritious food, posing risks to future food and nutritional security within and beyond polar regions (*high confidence*).

CCP6.2.3.1 Arctic subsistence resources

Subsistence harvest of fish, seabirds, and marine mammals is the basis for economic, cultural and spiritual connections with Arctic marine systems (Box CCP6.2)(Fall et al., 2013; Haynie and Huntington, 2016; Raymond-Yakoubian et al., 2017; Slats et al., 2019) and nature-based livelihoods (e.g., caribou and reindeer (*Rangifer tarandus*) herding, fishing, hunting, trapping, small-scale forestry) are fundamental to Indigenous Peoples across the Arctic as they have been for millennia (Koivurova et al., 2015; Betts, 2016; Gavin et al., 2018; Raheem, 2018; Mustonen and Shadrin, 2021). Climate change has impacted Indigenous subsistence resources across the Arctic (*very high confidence*) (SMCCP6.2), and future food systems and ecological connections are at risk from future climate change hazards interacting with non-climate pressures, some of which are mediated or amplified by novel conditions and opportunities in Arctic regions (*high confidence*) (Moerlein and Carothers, 2012; Fall et al., 2013; Raymond-Yakoubian et al., 2017; Meredith et al., 2019; Slats et al., 2019; Huntington et al., 2020; Huntington et al., 2021). Increasing heatwaves, wildfires, extreme precipitation, permafrost loss and rapid seasonal snow and ice thaw events will further threaten terrestrial subsistence food resources across the Arctic (*high confidence*) (Table CCP6.3). Although climate impacts and non-climate factors systematically undermine access to and productivity of subsistence resources, resilience is inherently high for Indigenous Peoples, illustrating critical elements underpinning successful adaptation to climate change (Box CCP6.2) (Huntington et al., 2021).

Table CCP6.3: Illustrative examples of climate change impacts on subsistence resources in the Arctic.

Changing Drivers	Observed impacts and projected risks	References
Snow, ice, river environments	Climate change is disrupting subsistence harvests for Indigenous Peoples in Arctic communities that depend on snow, ice and river environments for travel and access to subsistence resources.	(Wildcat, 2013; Meredith et al., 2019; Slats et al., 2019)
Multiple	Across the Canadian Arctic, multiple populations of reindeer and caribou are in decline with 95% of assessed herds listed as rare, decreasing or "threatened"; Reindeer and caribou abundances in the Alaska-Canada region have declined 56% over the past 20 years.	(Russell et al., 2018)
Multiple	Reindeer herding is an important economic and Indigenous cultural activity in the Eurasian Arctic and is being affected by non-climate and climate events, including changes to thaw cycles, drought and unpredictable summer weather, which threaten pasture areas in Siberia. Although changes in vegetation and the freeze thaw cycle are impacting Sami reindeer herding, adaptive measures by herders have been effective at offsetting multiple climate and non- climate impacts.	(Furberg et al., 2011; Uboni et al., 2020; Mustonen and Shadrin, 2021)
Sea-ice; winds; visibility	Loss of multiyear "mother ice", declines in seasonal sea-ice thickness and stability, as well as changes in winds and visibility have impacted the availability of, and access to, subsistence resources (*high confidence*) and have increased interactions between coastal communities and shipping, tourism and commercial fisheries, which directly impact human safety and well-being in Arctic communities (*high confidence*).	(Stephenson and Smith, 2015; Brinkman et al., 2016; Melia et al., 2016; Raymond-Yakoubian et al., 2017; Ford et al., 2019; Slats et al., 2019; Huntington et al., 2020; Huntington et al., 2021)
Multiple	MHW-induced ecosystem changes contributed to widespread mortality events and declines in Northern Bering Sea seabirds and disrupted subsistence harvests in western Alaska.	(Jones et al., 2019; Piatt et al., 2020; Siddon et al., 2020)
Storminess; sea-ice; whale migration timing; shipping	Although some communities have seen reduced whale harvests due to climate impacts on survival and productivity, changes in storminess and whale migration timing have lengthened the July harvest season for Inuvialuit from Inuvik, Aklavik and Tuktoyaktuk. Changes in Beluga migration routes have increased accessibility to communities of Ulukhaktok and Paulatuk. In Western Greenland, loss of sea-ice has both reduced access to sealing and increased subsistence and commercial harvest of Atlantic cod, halibut, and other fish species. Increased impacts of noise and ship strikes associated with shipping are expected to	(George et al., 2017; Hauser et al., 2018; Loseto et al., 2018; Mustonen et al., 2018a)

	impact subsistence species, especially seals and whales in Lancaster sound as well as the Pacific Arctic.	
Sea-ice	Changes in sea-ice will continue to undermine subsistence resources and disrupt access by smaller scale commercial and subsistence-based ice-edge fishing.	(Jacobsen et al., 2018; Ford et al., 2019)
Shifting distributions; Food web changes	Shifting species distributions and climate change mediated food web reorganization pose a risk to near-shore subsistence harvests that are essential to sustaining Indigenous Peoples in Western Greenland and the Northern Bering, Beaufort, and Chukchi Seas; , e.g., cod biomass in the Inuvialuit region is projected to decrease 17% by 2100 (RCP8.5). Climate-related declines in harvester access drive projected declines in subsistence availability in Alaska.	(Moerlein and Carothers, 2012; Fall et al., 2013; Brinkman et al., 2016; Loseto et al., 2018; Steiner et al., 2019; Marsh and Mueter, 2020; Ribeiro et al., 2021)

CCP6.2.3.2 Agriculture, forestry, livestock, and aquaculture

In addition to reindeer herding, Arctic agriculture primarily consists of local production of cool season crops, forage, small grains, and livestock (sheep and goats) (Westergaard-Nielsen et al., 2015; Natcher et al., 2019). Short growing seasons, cold conditions, permafrost, and moisture stress, especially along coasts, have historically limited production, but agriculture is generally increasing across the region (Westergaard-Nielsen et al., 2015). Although only ~ 0.2% of Alaska is farmland, area farmed and income from agriculture have increased 2% and 80% (respectively) since 2012 (United States Department of Agriculture, 2017). It is *likely* that growing seasons have extended by 1-3 days per decade in interior Alaska, although some coastal areas exhibit declines in growing season (Lader et al., 2018).

Arctic temperatures rarely exceed thermal tolerances for crops (e.g., 35-38°C across corn, rice and grain) and warming will provide new opportunities for food and forage production in areas such as SW Greenland and interior Alaska (Westergaard-Nielsen et al., 2015; Tripathi et al., 2016; Lader et al., 2018). Higher atmospheric CO_2 favours plant growth if soil quality and condition are sufficient, but benefits can be offset by increased heat and water stress associated with climate change (Tripathi et al., 2016; Unc et al., 2021). Growing seasons in Alaska will lengthen by 48-87 days per year relative to historical growing season length (1981-2010) and the start of growing season is expected to shift 1-4 weeks earlier (Lader et al., 2018). Feasible growing areas across the Arctic are expected to shift northward and increase within the 55°-69°N region (King et al., 2018). Permafrost thaw (Table CCP6.1) increases drainage, which is a potential benefit, but can also increase erosion, subsidence and irregular surfaces, inhibiting agriculture (Lader et al., 2018). Conversion of Arctic soils to croplands may also release carbon stored in vegetation and soils (Unc et al., 2021).

Arctic aquaculture contributes approximately 2% to global farm production (primarily Norwegian salmon (*Salmo salar*), as well as finfish in Iceland and Sweden and shellfish in Alaska), and will face increasing challenges from climate change (Troell et al., 2017) including increased frequency of storms (impacting sea farms), extreme temperatures, and warmer conditions that favour pathogens, parasites and harmful algal blooms. Aquaculture feeds often depend on small pelagic fish or krill and supply may be affected by climate impacts on fisheries (Table CCP6.6) (Troell et al., 2017; Chen and Tung, 2018; Mørkøre et al., 2020). Integrated policies and coordination across multiple food production sectors in Arctic regions are needed to address climate opportunities and challenges (Altdorff et al., 2021; Unc et al., 2021).

CCP6.2.3.3 Commonalities in impacts and risks across polar fisheries

Fisheries play an increasingly important role in addressing global food and nutritional deficits (Section 3.6.3)(Béné et al., 2016; Ding et al., 2017; Hicks et al., 2019; Costello et al., 2020), especially as climate change has already reduced global yields from key crops (Myers et al., 2017; Ray et al., 2019; Thiault et al., 2019). Antarctic and Arctic systems support some of the world's largest fisheries, including those for Antarctic krill and Arctic walleye pollock (*Gadus chalcogrammus*), which constitute a critical source of protein and macronutrients to a growing population of seafood consumers, as well as various aquaculture and livestock feeds (Cross-Chapter Box MOVING PLATE in Chapter 5) (Table CCP6.4) (Huntington et al., 2013; Raheem, 2018; Hicks et al., 2019; Steiner et al., 2019; FAO, 2020; Cavanagh et al., 2021; Grant et al., 2021; Murphy et al., 2021). Marine sources of protein and nutrition are important in transformational future scenarios where dietary shifts and provisioning policies provide multiple co-benefits to equity, food security and carbon mitigation (Springmann et al., 2016; Poore and Nemecek, 2018; Thiault et al., 2019; Kim et al., 2020). Shifting spatial distributions of fish stocks have led to transboundary management challenges in the Atlantic, Bering Sea, and Arctic areas previously inaccessible due to sea-ice (Table CCP6.6) (Gullestad et al., 2020).

Cascading and interacting effects of climate change impacts in polar regions (Table CCP6.1) will reduce access to, and productivity of future fisheries, and pose significant risks to regional and global food and nutritional security that increase with atmospheric carbon levels and declines in sea-ice (*high confidence*) (Table CCP6.6). Although it is expected that fisheries will continue to contract poleward under future warming (Cross-Chapter Box MOVING PLATE in Chapter 5) (Table CCP6.4) (Alabia et al., 2018; Morley et al., 2018; Stevenson and Lauth, 2019; Caccavo et al., 2021; Grant et al., 2021), global and regional models differ in their projections of fisheries catch potential for the polar regions under climate change. For example, some global-scale models project increases in potential fishery yields in Arctic Canada (Cheung, 2018; Bindoff et al., 2019; Tai et al., 2019), whereas many observational studies and high resolution regional projections suggest overall declines in biomass, productivity, and yield associated with warming and loss of sea-ice in multiple regions such as the Bering Sea (*medium confidence*) (Free et al., 2019; Hollowed et al., 2020; Holsman et al., 2020; Mueter et al., 2020; Reum et al., 2020). Reduced production of macronutrients and protein by polar marine sources will disproportionately impact people already experiencing food and nutritional scarcity (Myers et al., 2017), marine-dependent communities within and beyond polar regions, and women and children who require higher quantities of macronutrients (*high confidence*).

Large-scale commercial fisheries are expected to continue to operate in polar regions (*high confidence*) (Barange et al., 2018; Cavanagh et al., 2021; Grant et al., 2021), and will shift poleward (*high confidence*) toward geopolitical and management boundaries (*high confidence*) (CCP6.3.2.3; Table CCP6.6). Warming and climate impacts will continue to impact transboundary stocks and increase the potential for conflict in fisheries management (Pinsky et al., 2018; Mendenhall et al., 2020; Palacios-Abrantes et al., 2020; Sumaila et al., 2020). Increased distances from ports to redistributed fishing grounds, as well as increased frequency of storms and other extreme events are expected to increase risks and costs for fishery operations (*medium confidence*) and impact shore-based infrastructure and emergency response services (CCP6.2.4). Observed and expected increases in mobile ice combined with abrupt wind can create major hazards for fish operators in Antarctica and the Arctic, with consequences to human safety and total revenue (Dawson and et al., 2017; Barber et al., 2018; Grant et al., 2021). There will be increased demand for new port infrastructure across the Arctic (*high confidence*); new ports have already been proposed for the northern Bering Sea, and small craft harbour investments are being considered across Arctic Canada and Greenland. Ecosystem-based management, increasing diversity and flexibility in harvest portfolios, access to high-resolution ecological forecasts and projections, and climate-informed advice will promote adaptation and climate resilience in fisheries (Dawson and et al., 2017; Brooks et al., 2018; Karp et al., 2019; Hollowed et al., 2020). Coupling adaptation measures with global carbon mitigation strategies substantially decreases climate change risks to polar fisheries (*very high confidence*) (CCP6.3).

[START FAQ CCP6.1 HERE]

FAQ CCP6.1: How do changes in ecosystems and human systems in the polar regions impact everyone around the globe? How will changes in polar fisheries impact food security and nutrition around the world?

Polar regions are commonly known to be experiencing particularly fast and profound climate change, which strongly affects areas and people all around the world in several ways. Physical processes taking place in these regions are critically important for the global climate and sea level. Less known is that regional climate-driven changes of ecosystems and human communities will also have far-reaching impacts on a number of sectors of human societies at lower latitudes.

Climate change has triggered rapid, unprecedented, and cascading changes in polar regions that have profound implications for ecosystems and people globally. Although physically remote from the largest population centers, polar systems are inextricably linked to the rest of the world through interconnected ocean currents, atmospheric interactions and weather (IPCC, 2021), ecological and social systems, commerce, and trade. The nutrient-rich waters of the polar regions fuel some of the most productive marine ecosystems on earth, which in turn support fisheries for species packed with vital macronutrients that are essential for human health and wellbeing. The largest most sustainable fisheries in the world are located in polar waters, where a mix of ice, seasonal light, and cold nutrient-rich waters fuel schools of millions of fish that swell and retract in numbers across the years, reflecting interlaced cycles of icy cold waters, lipid-rich prey, and abundant predators. Polar systems thus exist in a productive balance that has supported vibrant ecocultural connections between Indigenous Peoples and the Arctic for millennia and has supported global food production and trade for centuries. Climate change increasingly destabilizes this balance with uncertain outcomes for Indigenous Peoples and local residents in the Arctic as well as for the rest of the world. Triggered by warming oceans and air temperatures, accelerated melting of sea-ice, glaciers and ice sheets in polar regions in turn impacts ocean salinity, sea levels, and circulation throughout the global ocean. Warming waters have also pushed cold-adapted species poleward, eroded the cold barrier between boreal and Arctic species, and induced rapid reorganization of polar ecosystems. Studies increasingly indicate that the complex web of physical and biological connections that have fuelled these productive regions will falter without the strong regulating influence of cryospheric change. At the same time the global demand for food is increasing, particularly the demand for highly nutritious marine protein, placing increasing importance on stabilizing polar ecological systems and minimizing climate change impacts and risks.

[END FAQ CCP6.1 HERE]

Table CCP6.4: Climate change impacts on Arctic and Antarctic fisheries and fishing communities. Additional detail in Table SMCCP6.3.

Driver	Observed impacts and projected risks	References
Current and past climate change impacts		
Warming	Fisheries productivity declined in multiple stocks across the Arctic including the EBS while Atlantic cod and other fisheries have increased.	(Free et al., 2019; Cheung and Frölicher, 2020)
Extreme heat	Commercially important fish species declined rapidly during recent MHWs (2016-2019), in the EBS due to reduced recruitment, increased metabolic demand, and increased predation mortality and it is probable that climate impacts have contributed to the closure of Pribilof islands blue king crab (*Paralithodes platypus*) fisheries.	(Zheng and Ianelli, 2018; Duffy-Anderson et al., 2019; Stabeno et al., 2019; Basyuk and Zuenko, 2020; Reum et al., 2020; Thorson et al., 2020)
Temperature; shifting species distributions	In the Barents Sea, northward redistribution of stocks led fisheries into previously unfished habitats, exposing benthic ecosystems to novel trawling impacts. Large-scale redistributions of Pacific cod (>1000 km decade^{-1}) and other groundfish species have challenged fisheries management in the EBS; ~50% of the biomass is now located in the NBS, outside of historical survey areas and in a region where bottom trawling is prohibited (although pelagic gear is permitted).	(Christiansen et al., 2014; Jørgensen et al., 2019; Spies et al., 2019; Stevenson and Lauth, 2019)
OA, warming, winds	Shellfish species such as snow crab are undergoing range contractions poleward in the Barents and Northern Bering Seas, with increased catches in the north and declines in the south.	(Jørgensen et al., 2019; Fedewa et al., 2020) (Cross-Chapter Box MOVING PLATE in Chapter 5)
Warming; poleward expansion	Poleward expansion of Pacific salmon into Arctic watersheds and Greenland fjords presents both new opportunities and novel threats to key subsistence and commercial species such as Arctic char and Atlantic salmon.	(Bilous and Dunmall, 2020; Nielsen et al., 2020)
Warming; HABs	Altered seasonal freshwater habitats are impacting salmon productivity and phenology of important salmon resources in	(Brattland and Mustonen, 2018; Cline et al., 2019; Mustonen and

	Alaska and in the Fennoscandian North, with subsequent community-specific impacts on commercial and subsistence resources.	Feodoroff, 2020; Mustonen and Shadrin, 2021)
Multiple; sea-ice	Losses of winter sea-ice to the north and west of the Antarctic Peninsula have enabled krill fishing vessels to fish all year round in that area.	(Meredith et al., 2019)
Future climate change impacts and risks		
Multiple	Climate change impacts on the ecology and physiology of polar cod species contribute to expected increases in biomass and catch potential under high to moderate mitigation (RCP2.6 and RCP4.5) and reductions in groundfish recruitment and yield under low mitigation (RCP8.5) scenarios (CCP6.2.2) across range of multispecies models.	(Laurel et al., 2016; Spencer et al., 2016; Lotze et al., 2018; Spencer et al., 2019; Dahlke et al., 2020; Grüss et al., 2020; Hollowed et al., 2020; Reum et al., 2020; Thorson et al., 2020)
Climate x management interaction	Assuming no climate adaptation in current Ecosystem Based Management (EBM), 50% declines (relative to projections under persistent current climate conditions) in Eastern Bering Sea pollock and cod yield is *likely* under moderate carbon mitigation scenarios (RCP4.5), and *very likely* under low mitigation scenarios (RCP8.5).	(Holsman et al., 2020; Reum et al., 2020; Whitehouse et al., 2021)
Warming; OA	Warming, Ocean Acidification, fish predators, and thermal tolerance differentiate impacts across crab species in the Arctic; increased productivity and redistribution offshore is expected for tanner crab; red king crab and snow crab are projected to continue to shift north and decrease in productivity. OA is expected to impact demographies, altering harvest recommendations and biological reference points for some species of some shellfish and flatfish (e.g., red king crab, Northern rock sole) in projection simulations.	(Punt et al., 2014; Sawatzky et al., 2020; Punt et al., 2021)
Climate x management interaction	Multiple rights-based fisheries operate in the Arctic, increasing investment in long-term sustainability but reducing harvest portfolio diversity and increasing vulnerability to climate shocks.	(Kasperski and Holland, 2013; Ojea et al., 2017)
Multiple; sea-ice	Physical and biological changes in Antarctic waters are expected to result in net declines in krill habitat and growth potential, although one study indicates a potential increase. Reduction in the Antarctic ice pack is as *likely as not* to increase total season length in areas near to land-based predators.	(Melbourne-Thomas et al., 2016; Piñones and Fedorov, 2016; Klein et al., 2018; Rogers et al., 2020; Veytia et al., 2020)
Phytoplankton and temperature	Projected changes in primary production and temperature are expected to cause declines in krill growth and availability to predators; impacts may be countered by reducing fisheries, signifying a potential conflict between fisheries and top predators.	(Piñones and Fedorov, 2016; Klein et al., 2018)

CCP6.2.4 Economic Activities

Climate change presents significant risks to economic activities in the polar regions (*very high confidence*) and simultaneously enables development possibilities for fisheries (CCP6.2.3.3), agriculture (CCP6.2.3.2), the sharing and subsistence economy (CCP6.2.3.1) (SMCCP6.2) (*high confidence*), maritime trade (Box CCP6.1), natural resource development (CCP6.2.4.1) (*medium confidence*), tourism (CCP6.2.4.2), and transportation (including shipping) (CCP6.2.4.3; FAQ CCP6.2). Hundreds of billions of dollars are expected to be invested in the polar regions in the next several decades (Lloyd's, 2012; Barnhart et al., 2016; Pendakur, 2017; Tsukerman et al., 2019) and, as this unfolds, there are opportunities to simultaneously implement adaptation strategies that support climate resilient development pathways in line with self-determination for Indigenous Peoples and local communities and locally derived visions of successful adaptation and development (CCP6.3.2, CCP6.4.3) (Jorgenson, 2007; Ritsema et al., 2015; Ready and Power, 2017; Larsen and Petrov, 2020).

CCP6.2.4.1 Changing access to natural resources with consequences for safety, economic development and climate mitigation

Climate change is improving access to natural resources in the Arctic with consequences for human safety (*high confidence*), economic development (*very high confidence*) and global mitigation efforts (*medium confidence*). Reductions in sea-ice combined with improved extraction and transportation technologies have increased accessibility to natural resources across the Arctic (Eliasson et al., 2017; Dawson et al., 2018b; Stephen, 2018); a situation that could support continued global dependence on relatively cheap and abundant fossil fuels resources and contribute to further warming. By 2040 (RCP4.5) it is expected that sea-ice will have receded enough to make gas production technologically feasible in the European off-shore Arctic (Petrick et al., 2017). However, increased sea-ice mobility, iceberg abundance, storm surge, and surface wave action (Ng et al., 2018; Howell and Brady, 2019; Casas-Prat and Wang, 2020) will also increase risks to ships servicing mines in a region that already exhibits disproportionately high accident rates (Council of Canadian Academies, 2016) (CCP6.3.1, Table CCP6.1). Season lengths for ship-based support to mines and extraction sites will increase with sea-ice change, while access via ice roads will decrease with warming (Perrin et al., 2015; Council of Canadian Academies, 2016; Trofimenko et al., 2017; Southcott and Natcher, 2018). By 2050, climate change impacts to the Tibbitt to Contwoyto Winter Road servicing mines in the northeastern region of the Northwest Territories, Canada could cost between $55 million to $213 million CAD to maintain for a shorter period of time than at present (Perrin et al., 2015). Changes in submarine permafrost, critical to mining infrastructure, such as pipelines and offshore infrastructure (Bashaw et al., 2016; Paulin and Caines, 2016), are expected to increase production costs and impact safety for workers (Riedel et al., 2017). By mid-century, regardless of emissions scenario, it is expected that risks from permafrost thaw will be disproportionately high for industrial infrastructure along major pipeline systems in Alaska and natural gas extraction areas in the Yamal-Nenets region in northwestern Siberia, Russia (Hjort et al., 2018).

CCP6.2.4.2 Changing demand, opportunities and risks for polar tourism

Climate change has increased risks to, and demand for, polar tourism experiences related to increased maritime accessibility (*high confidence*), lengthening of warm weather season lengths (*very high confidence*) and development of a 'last chance tourism market' (*medium confidence*). Reductions in sea-ice extent have facilitated increased access for polar cruising (Dawson et al., 2018b; Stewart et al., 2020). Demand for Arctic cruises has increased by 20.5% over the past five years and resulted in 27.2 million passengers in 2018 (Shijin et al., 2020). In the Antarctic, tourist numbers increased by 27% from 1992-2018 and attracted 75,000 visitors in 2019-2020 (IAATO, 2020; Shijin et al., 2020), making it the largest economic sector in the entire region (Stewart et al., 2020). The recent increase in polar tourism is due in part to the development of a niche market called 'last chance tourism', which involves explicitly marketing vulnerable or vanishing destinations or features (i.e., glaciers, polar bears, landscapes) and encouraging tourists to see them 'before they are gone' (Dawson et al., 2018a; Groulx et al., 2019). However, tourism development opportunities will also contend with ongoing risks related to the COVID19 pandemic, which halted tourism globally in 2020-2021 (Frame and Hemmings, 2020; Lorenzo et al., 2020), as well as those related to increased climatic risks limiting participation and reducing safety and security. By 2100 under RCP8.5, snow cover season length suitable for winter recreational activities is projected to decrease by 21−49% in West Greenland (Schrot et al., 2019). Reduced sea-ice and snow cover creates hazards for and could limit dog sledding, cross country skiing, snowmobiling and floe edge tours, with limited adaptation strategies available for low elevation areas (Stephen, 2018; Palma et al., 2019).

CCP6.2.4.3 Risks and opportunities in transportation systems

Climate hazards create risks to transportation sectors with consequences for human safety (*very high confidence*), security (*low confidence*), and economic development (*high confidence*). Remote polar regions are highly reliant on transportation systems (air, road, sea) to support and service communities (Arctic) and scientific stations (Antarctic and Arctic). Changes in permafrost, snow, ice, and precipitation patterns have increased the risk of rail infrastructure and of using permanent roads and semi-permanent trails that service Antarctic research stations, connect Arctic communities, and support Indigenous food harvesting activities

(Calmels et al., 2015; Council of Canadian Academies, 2016; Ford et al., 2019; Stewart et al., 2020). Warming temperatures have particularly decreased the reliability, safety level, and season length of winter ice roads (Perrin et al., 2015; Council of Canadian Academies, 2016; Gädeke et al., 2021) in the northern Baltic (Finland) (Kiani et al., 2018), James Bay (Canada) (Hori et al., 2018a; Hori et al., 2018b), and Yakutia (Russia) (Mustonen and Shadrin, 2021). Dog sled travel in northwest Greenland has experienced shorter season lengths (Nuttall, 2020), Alaskan whale hunters have had difficulty finding suitable ice for safe harvest activities (Huntington et al., 2016; Nyland et al., 2017), and unpredictability in break-up and freeze-up of sea-ice has compromised safe travel to and from culturally significant hunting and camping areas in Canada (Dawson et al., 2020; Simonee et al., 2021), and northeast Siberia (Ksenofontov et al., 2017; Mustonen and Shadrin, 2021). Fog (*low confidence*) and an increase in precipitation falling as ice pellets or hail (*high confidence*) (Kochtubajda et al., 2017) is expected to continue to cause operational delays and create safety issues for aviation in the Polar regions (Debortoli et al., 2019).

[START FAQ CCP6.2 HERE]

FAQ CCP6.2: Is sea-ice reduction in the polar regions driving an increase in shipping traffic?

The polar seas have captured the imagination of global nations for centuries for its natural resource, tourism, scientific, and maritime trade potential. As the polar regions are warming at two to three times the rate of the global average leading to rapid reductions in sea-ice extent and thickness, international attention has been reinvigorated and investments are being made by Arctic and non-Arctic nations alike with a view to utilize newly accessible seaways. Between 2013 and 2019 ship traffic entering the Arctic grew by 25% and the total distance travelled increased by 75%. Similar shipping growth trends are evident in the Antarctic albeit to a lesser extent. Expected growth in Arctic shipping will influence a suite of cascading environmental and cultural risks with implications for Indigenous Peoples.

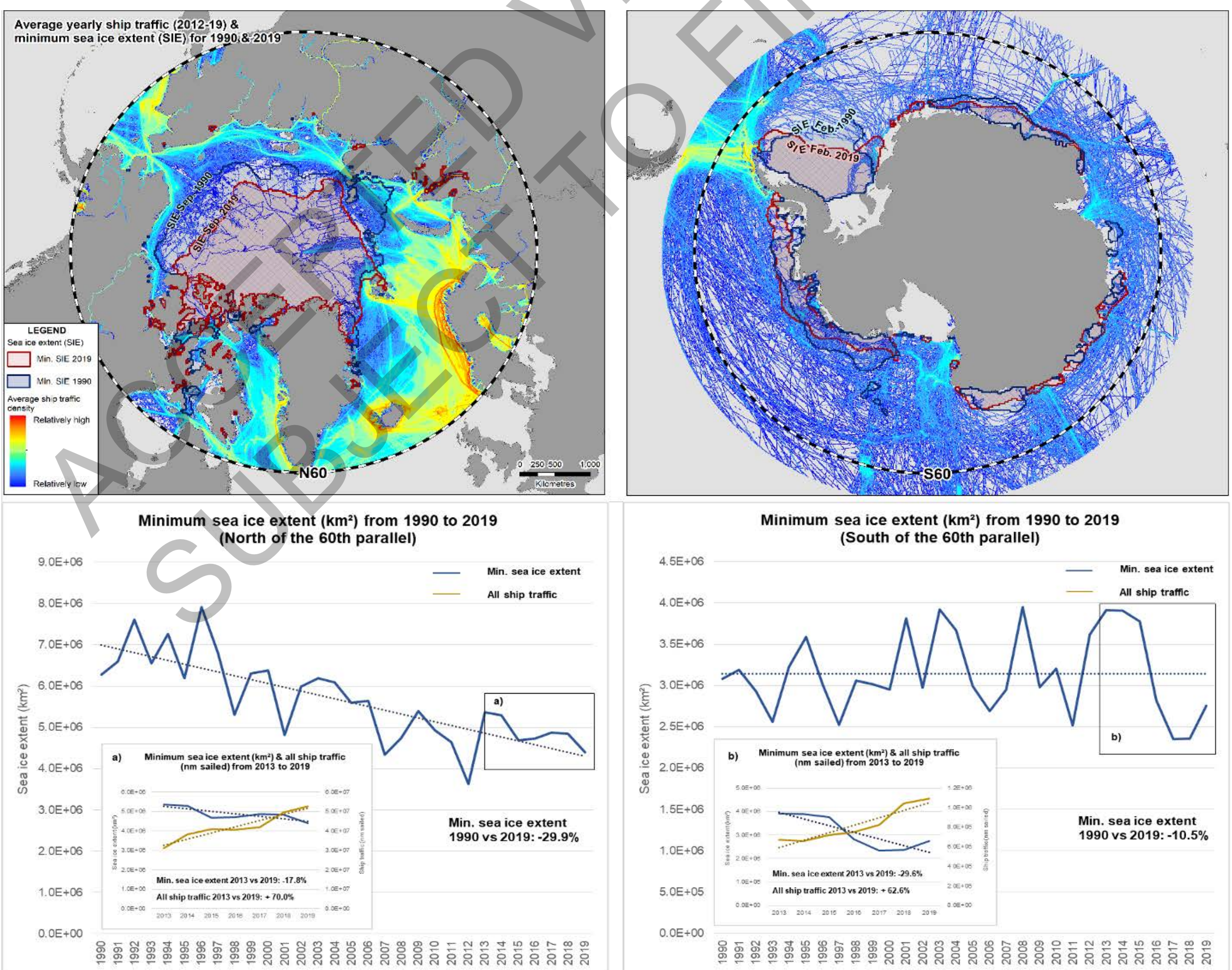


Figure FAQ CCP6.2.1: Projected operational accessibility along Arctic maritime trade routes (Northwest Passage, Transpolar Route, and Northern Sea Route) under future warming (left) and observed increases in commercial ship traffic along the routes from 2012-2019

There has been debate among shipping stakeholders, rightsholders, and experts about the extent to which climate change and sea-ice change is directly influencing increases in shipping activity in the polar regions relative to other social, technological, political, and economic factors such as commodity prices, tourism demand, global economic trends, infrastructure support, and service availability. Understanding the connection between climate change and polar shipping activity will allow for more reliable projections of possible future traffic trends and will aid in identifying appropriate adaptation and infrastructure needs required to support future management of the industry. Recent studies have observed increasing statistical correlations between sea-ice change and shipping trends in the polar regions and many have concluded that although economic factors remain the main driver of shipping activities, followed by infrastructure availability, climate change does indeed play a varying but important role in influencing operator intentions. The 'opening of polar seaways' due to sea-ice reduction is indeed 'enabling' opportunities for polar shipping among all types of vessels due to increasingly accessible areas that were previously covered by multiyear ice, but the extent to which climate change will specifically 'drive' an increase in shipping demand remains highly dependent on the vessel type and the reasons for operation. There are certain vessel types, such as those supporting international trade, mining operations or community re-supply, where analysis shows no correlation or weak correlations with sea-ice change suggesting that climate change is enabling these types of ships via increased open water areas and season lengths but that it is not necessarily driving demand. Conversely, there are certain vessel types, such as yachts and cruise ships, where correlations between sea-ice change and traffic increases are stronger, and where there is evidence to suggest that these vessels are indeed driven to visit the polar regions because they perceive waterways as exotic and exciting due to being newly accessible or they want to have a Polar experience before it disappears or is irreversibly changed as is the case with last chance tourists. As sea-ice recedes and polar shipping opportunities grow there will be an increased need to better identify and implement Indigenous self-determined and equitable shipping governance frameworks that facilitate benefits and minimize risks.

[END FAQ CCP6.2 HERE]

[START BOX CCP6.1 HERE]

Box CCP6.1: Climate Change and the Emergence of Future Arctic Maritime Trade Routes

Discovering a viable maritime trade route linking the Atlantic and Pacific oceans through the Arctic has captured the collective global imagination for centuries (Bockstoce, 2018). Geographically shorter than southern trade routes via the Panama and Suez Canals, the Arctic presents the possibility for more economical and timely commercial trade, but has historically been limited by thick multi-year ice and other navigational challenges. Amplified warming in the Arctic has caused September sea-ice extent to decline at a rate of -13% per decade (Serreze and Meier, 2019) and reduced sea-ice thickness by 66% (2 m) between 1958-1976 and 2011-2018 (Kwok, 2018). Regardless of mitigation efforts, it is expected that before mid-century the Arctic will be seasonally ice free for the first time in 2,600,000 years (defined as < 1,000,000 km2) (Knies et al., 2014; SIMIP Community, 2020; Fox-Kemper et al., 2021; Lee et al., 2021) and will make Arctic maritime trade a reality (Eguíluz et al., 2016; Melia et al., 2016; Pizzolato et al., 2016; Bennett et al., 2020; Wei et al., 2020).

There are three identified trade routes in the Arctic: Northern Sea Route (NSR), Northwest Passages (NWP), and the Transpolar Sea Route (TSR). Over the last decade economic trends and reductions in sea-ice have facilitated significant increases in ship traffic in the NSR (Aksenov et al., 2017; Li et al., 2020), including a 79% increase in total transit tonnage from 2010 to 2017 (Babin et al., 2020) related mostly to domestic resource development. Relative to an early 21st century baseline, it is expected that the NSR will become 18% more accessible by mid-century (Stephenson et al., 2013) and could navigable even for non-ice strengthened vessels for 101-118 days annually by 2050 and 125-192 days by 2100 (Khon et al., 2017). The NWP has experienced a tripling of km travelled by ships since 1990, attributed mostly to resource extraction and increases in tourism opportunities (Johnston et al., 2017; Dawson et al., 2018a). The NWP could become 30% more accessible by 2050 compared to current conditions (Stephenson et al., 2013). Before 4°C global warming above pre-industrial, re-supply vessels (Polar Class 7) in the western NWP could gain an additional month of operating time, whereas the eastern NWP could gain just two weeks (Mudryk et al., 2021) due to the dynamic import of mobile and hazardous ice from the Arctic Ocean (Haas and Howell, 2015; Howell and Brady, 2019). Comparatively, the TSR has historically only been viable for nuclear icebreakers, submarines, and occasional military and scientific activity due to thick multiyear ice regimes (Bennett et al., 2020). However, this most sought-after route offers the greatest reduction in sailing times compared to southern routes (19-24 days) of all Arctic Sea routes and could be 56% more accessible by mid-century compared to current conditions (Stephenson et al., 2013; Melia et al., 2016).

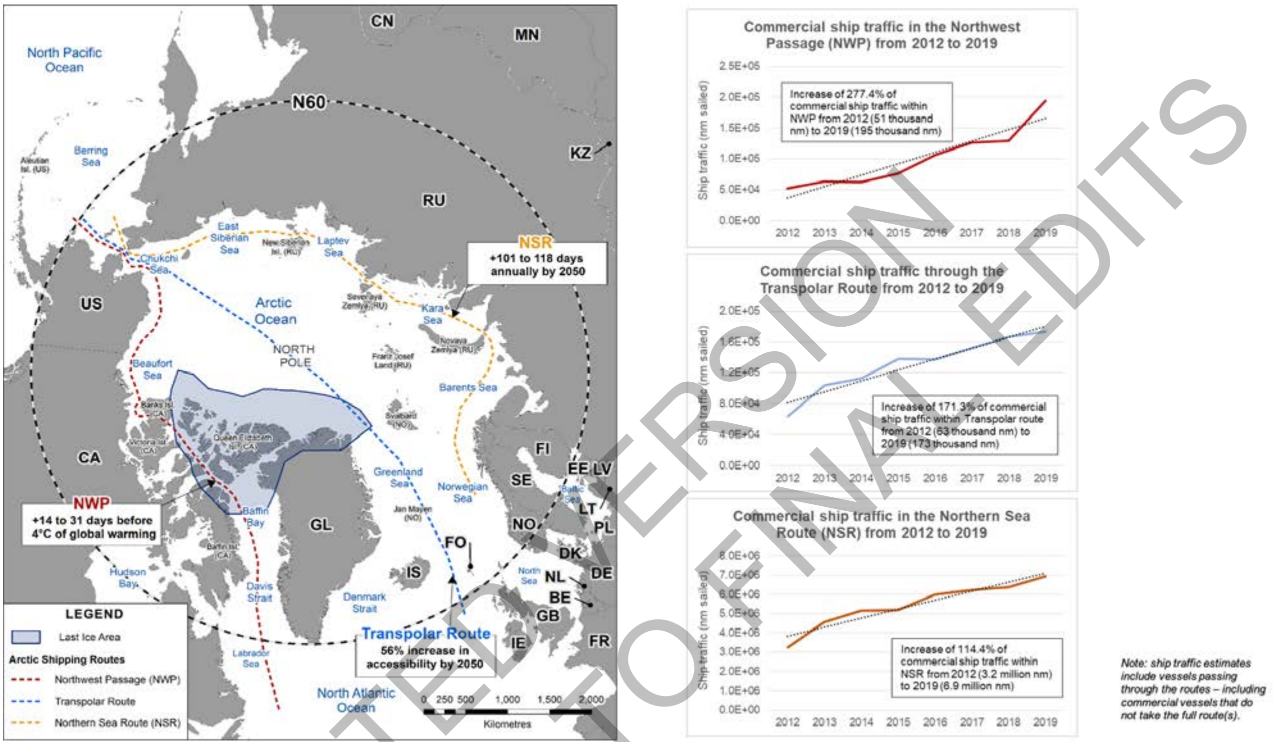


Figure Box CCP6.1.1: Arctic trade routes and projected operations related to sea-ice loss.

Growth in Arctic maritime trade will result in increased emission of black carbon (Stephenson et al., 2018; Zhang et al., 2019; Wang et al., 2021), increases in ship-source underwater noise impacts on marine mammals (Halliday et al., 2017), higher rates of accidents and incidents among vessels from increasing mobile sea-ice and newly accessible ice-free waters that lack charting (Haas and Howell, 2015; Howell and Brady, 2019), impacts to cultural sustainability for Indigenous Peoples (Olsen et al., 2019; Dawson et al., 2020) (*high confidence*), the potential for the introduction and propagation of invasive species (Chan et al., 2019; Rosenhaim et al., 2019), and sovereignty tensions with implications for global geopolitics (Drewniak et al., 2018) (*medium confidence*). Globalization and the almost universal adherence to economic growth models among nations will continue to fuel maritime trade (Box 14.5). As sea-ice decreases facilitates growth in Arctic maritime trade and transportation specifically, adaptation strategies designed to facilitate mitigation co-benefits and that target the cascading implications and double exposure of climate change and Arctic shipping impacts will be essential in reducing risks (Ng et al., 2018; Pirotta et al., 2019; Bennett et al., 2020; Zeng et al., 2020). Electric and solar powered vessels, new engine and emission reduction technologies, investment in wind, water, ice, and climate forecasting technologies and services (Haavisto et al., 2020; Stewart et al., 2020; Simonee et al., 2021), and efforts by the International Maritime Organization to reduce sulphur and the use of heavy fuel oils (PAME, 2020; van Luijk et al., 2020) could play a key role in limiting emissions and reducing risks related to the environmental and cultural impacts of fuel spills in ice-infested Arctic waters. The development of low impact shipping corridors (Chénier et al., 2017; Dawson et al., 2020) and multilateral agreements such as those implemented by the Arctic Council and Indigenous Peoples' organizations on joint search and rescue (Arctic Council, 2011) and shared spill responsibilities

(Arctic Council, 2013) represent important co-governance efforts that will be increasingly important in the future due to projected climate related risks.

[END BOX CCP6.1 HERE]

CCP6.2.5 Arctic Settlements and Communities

Polar settlements range from large well-serviced cities such as Tromsø, Murmansk and Reykjavik, to remote fly-in Indigenous communities, to scientific outposts and research stations. Polar settlements are at significant risk from climate change through shoreline erosion, permafrost thaw, and flooding (*high confidence*) (CCP6.2.2). Opportunities for community development in small communities are underestimated as they are emergent and unknown (*highly likely*) (CCP6.2.5).

Degradation of ice-rich permafrost can threaten the structural stability and functional capacities of community-based infrastructure (i.e. airports and roads; CCP6.2.5), and can have implications for local economies with coupled impacts for local livelihoods, health and wellbeing (CCP6.2.5, CCP6.2.6) (*high confidence*). For instance, in Canada, infrastructure damage from permafrost instability caused temporary closures of schools in Yukon, permafrost degradation contributed to runway damage at Iqaluit International Airport in Nunavut, and flooding from heavy rains resulted in thermal erosion of river banks that interrupted water and sewage service in Nunavut (Oldenborger and LeBlanc, 2015; Council of Canadian Academies, 2016; Lemmen et al., 2016). In northeast Siberia, the floods of Alazaeya river attributed to thawing permafrost have severely affected Andreyushkino in Yakutia (Mustonen and Shadrin, 2021).

By 2050, 69% of fundamental human infrastructure in the Arctic are projected to be at risk under an RCP4.5 scenario, including more than 1,200 settlements and 36,000 buildings, leaving 4,000,000 people living in areas with high potential for thaw (Hjort et al., 2018). Widespread permafrost thaw could increase the cost of infrastructure lifecycle replacement by 27% by mid-century under RCP8.5 (Suter et al., 2019). Northern Canada and Western Siberia are at particularly high risk, which are projected to cost additional annual spending of over 1% of annual gross regional product to maintain existing infrastructure (Suter et al., 2019). For instance, under an RCP8.5 scenario, climate change could affect over 19% of structures and infrastructure assets in Russia, which would cost an estimated $84.4 billion USD to mitigate damages (Streletskiy et al., 2019). 54% of residential buildings are projected to be affected by significant permafrost degradation by the mid-century, costing an additional estimated $52.6 billion USD (Streletskiy et al., 2019). SLR and reduced sea-ice protection is projected to compound permafrost thaw damages, including low lying coasts (e.g., along southern Beaufort Sea), low-lying barrier islands (e.g., along Chukchi Sea), and deltas (e.g., Mackenzie, Lena) (Fritz et al., 2017; Lantz et al., 2020). In Alaska, proactive adaptation was substantially cost-saving (reducing costs by $2.9 billion USD for RCP8.5 and $2.3 billion USD for RCP4.5), highlighting the financial benefit of investing in adaptation now (Melvin et al., 2017). Permafrost damage and SLR may result in tipping points, leaving some communities no longer habitable. In Alaska, US, many communities at-risk of flooding and storm surges are already engaged in community-led relocation planning processes (e.g., Shishmaref) (Melvin et al., 2017; Farbotko et al., 2020; Rosales et al., 2021).

Climate change has important intangible loss and damage implications in the Arctic, with negative impacts ranging from livelihoods to spirituality to solastalgia (i.e. distress caused by environmental change) (Cunsolo and Ellis, 2018; Middleton et al., 2020b; Sawatzky et al., 2020; Mustonen and Shadrin, 2021). Permafrost thaw, SLR, and reduced sea-ice protection also presents risk to socio-cultural assets, including heritage sites in all Arctic regions (*very high confidence*) (Friesen, 2015; Hollesen et al., 2016; Radosavljevic et al., 2016; O'Rourke, 2017; Hillerdal et al., 2019; Fenger-Nielsen et al., 2020; Jensen, 2020). A large number of archaeological sites are at risk from climate change in southwest Greenland; Yukon's Beaufort coast, Canada; and Auyuittuq National Park Reserve, Nunavut, Canada (Westley et al., 2011; Hollesen et al., 2018; Irrgang et al., 2019; Fenger-Nielsen et al., 2020). Siberian nomadic reindeer herding and fishing livelihoods are vulnerable to permafrost thaw, which alters northern landscapes and lakes, as well as rain-on-snow events, and rapidly changes landscapes and terrestrial and aquatic habitats (Mustonen and Mustonen, 2016; Brattland and Mustonen, 2018; Mustonen and Huusari, 2020) (CCP6.2.2). The intangible loss and damage to nomadic cultures could cascade to losses of identity and social challenges (CCP6.2.6; Chapter 13).

[START FAQ CCP6.3 HERE]

FAQ CCP6.3: How have Arctic communities adapted to environmental change in the past and will these experiences help them respond now and in the future?

For thousands of years Arctic Indigenous Peoples and local communities have survived several major changes to the ecosystems in which they rely; however, the present changes in climate are more challenging than pre- and early historic changes in the Arctic and new unprecedented risks will now face polar communities.

The challenges for responding to present change are due to the multiple imposed and simultaneous drivers combined with elimination and/or removal of endemic capacity to respond in culturally and locally appropriate ways. Adapting in the past may therefore inform and produce novel solutions for the present and convey baselines of important contextual information on significance of change. Arctic communities, especially Indigenous Peoples, have been marginalized in terms of their autonomous responses spaces and self-assessment that could be made without external pressures. Therefore, in order to increase the possibility of community-led adaptation, colonialism and the resultant lack of upheld rights, resources and equity need to be solved simultaneously with the present climate change impacts. New research, governance, policy, and collaborations are needed in order to effectively adapt to risks that are projected to emerge in the polar regions as a result of rapid climate change.

[END FAQ CCP6.3 HERE]

CCP6.2.6 Human Health and Wellness in the Arctic

Climate change continues to have wide-ranging physical human health risks in the Arctic, particularly for Indigenous Peoples (*high confidence*); however, future projections of physical risks are nascent. Climate change has already challenged food and nutritional security (CCP6.2.5). Climate change also creates safety concerns for those who access the land, ice, and water for food, cultural, and recreational purposes, with changing environmental conditions linked to injury and death (Durkalec et al., 2014; Clark et al., 2016a; Clark et al., 2016b; Driscoll et al., 2016; Brattland and Mustonen, 2018). Foodborne disease risks are expected to increase in the Arctic, with warming temperatures linked to increased risk of microbial contamination of locally harvested foods (Grjibovski et al., 2013; Harper et al., 2015), chemical contamination of locally harvest foods (Hansen et al., 2015; Long et al., 2015; Alava et al., 2017), compromised structural integrity and utility of ice cellars used to store locally harvested meat (Nyland et al., 2017; Markon et al., 2018), and new challenges to traditional food preparation techniques (Shadrin, 2021). Waterborne disease risks have increased, with decreased drinking water quality and quantity, water treatment infrastructure failures, and new waterborne pathogens emerging in the Arctic (Berner et al., 2016; Thivierge et al., 2016; Markon et al., 2018; Yoder, 2018; Masina et al., 2019; Sachal et al., 2019; Harper et al., 2020; Mustonen and Shadrin, 2021). Emerging environmental exposures to pathogens is also a concern. In 2016 a Nenets boy and over 200,000 reindeer died from anthrax linked to warming environments (Ezhova et al., 2021) - a risk which is projected to increase with climate change (Liskova et al., 2021). Thawing permafrost increases smallpox risk in former nomadic campsites and graveyards (Mustonen and Shadrin, 2021; Shadrin, 2021). Arctic health systems - which are often already stressed - will be further challenged by climate change (Harper et al., 2015; Clark and Ford, 2017), especially in conjunction with other system shocks (e.g., COVID-19) (Cross-Chapter Box COVID in Chapter 7) (Zavaleta-Cortijo et al., 2020). While physical health impacts have been observed, research examining future health projections or evaluating the efficacy of health adaptations are rare (Dobson et al., 2015; Harper et al., 2020; Harper et al., 2021).

Climate change has negative, widespread and cumulative impacts on mental health in the Arctic, particularly for Indigenous Peoples (*very high confidence*) (Figure CCP6.3). Climate-sensitive mental health outcomes are complex, overlapping, and interrelated, and have multiple direct and indirect pathways stemming from: acute (e.g., major storms, flooding, wildfires) and chronic (e.g., temperature increases, sea-ice loss, permafrost thaw) environmental conditions, and resulting disruptions to livelihoods, culture, food systems, social connections, health systems, and economies (Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Cunsolo Willox et al., 2014; Beaumier et al., 2015; Durkalec et al., 2015; Hamilton et al., 2016; Clayton et al., 2017; Dodd et al., 2018; Jaakkola et al., 2018; Markon et al., 2018; ITK, 2019; Minor et al., 2019; Middleton et al., 2020a; Middleton et al., 2020b; Feodoroff, 2021).

Negative mental health outcomes from climate change include: emotional reactions (e.g., sadness, fear, anger, distress, and anxiety); psychosocial outcomes (e.g., depression, post-traumatic stress disorder, and generalized anxiety); experiences with grief and loss (i.e. ecological grief); increased drug and alcohol usage, family stress, and domestic violence; increased suicide ideation and suicides; loss of cultural knowledge and continuity, disruptions to intergenerational knowledge transfer; and deterioration and loss of place-based identities and connections (i.e. solastalgia) (Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Cunsolo Willox et al., 2014; Durkalec et al., 2015; Harper et al., 2015; Cunsolo and Ellis, 2018; Hayes et al., 2018; Jaakkola et al., 2018; Markon et al., 2018; Minor et al., 2019; Middleton et al., 2020a; Feodoroff, 2021).

The negative mental health impacts from climate change are amplified among those most reliant on the environment for subsistence and livelihoods, those who already face chronic physical or mental health issues, and those facing socio-economic inequities and marginalization, particularly for Indigenous Peoples (*high confidence*). These climate change related mental health impacts are unequally distributed (Cunsolo Willox et al., 2014; Minor et al., 2019), and may vary by gender (Beaumier et al., 2015; Harper et al., 2015; Feodoroff, 2021) and age (Petrasek MacDonald et al., 2013; Ostapchuk et al., 2015; Petrasek MacDonald et al., 2015; Kowalczewski and Klein, 2018).

Climate change will increase mental health risks in the Arctic in the future (*medium confidence*). Future risks include exposures to severe weather events and changing precipitation patterns, sea-ice loss, wildfires, and changing place attachment, as well as disruptions to underlying determinants of mental health and social support networks (Cunsolo Willox et al., 2014; Cunsolo and Ellis, 2018; Markon et al., 2018; Council of Canadian Academies, 2019; ITK, 2019; Middleton et al., 2020a; Middleton et al., 2020b).

There is *limited evidence* assessing adaptation options that effectively reduce climate-related mental health risks, but developing or enhancing access to mental health resources and infrastructure are critical, such as land-based healing programs, enhanced access to culturally-appropriate mental health resources, and climate-specific counselling services to support individual and community psychosocial resilience, particularly among Arctic Indigenous Peoples (Cunsolo and Ellis, 2018; Middleton et al., 2020a). Incorporating a climate-sensitive mental health lens into mitigation and adaptation planning holds potential for increasing mental health and resilience in the Arctic, as well as supporting other social, economic, and cultural co-benefits.

Figure CCP6.3: The pathways through which climate change impacts mental and emotional health in the Arctic.

[START BOX CCP6.2 HERE]

Box CCP6.2: Arctic Indigenous Self-determination in Climate Change Assessment and Decision-making

Similar to Indigenous Peoples globally (Cross-Chapter Box INDIG in Chapter 18), climate change vulnerability for Arctic Indigenous Peoples is often rooted in colonialism, which has led to land dispossession and displacement, carbon-intensive economies, discrimination, racism, marginalization, and social, cultural, and health inequities (Whyte, 2016; Whyte, 2017; Whyte et al., 2019; Chakraborty and Sherpa, 2021). Therefore, effective responses to climate change risks for Indigenous Peoples are self-determined and underpinned by Indigenous knowledge (*very high confidence*).

Indigenous knowledge systems are diverse among and within Arctic Indigenous Peoples, and reflect deep and rich knowledge that situates and contextualizes values, traditions, governance, and practical ways of adapting to the ecosystem over millennia (Raymond-Yakoubian et al., 2017; Brattland and Mustonen, 2018). Indigenous knowledge is a valuable source of knowledge; a method to detect change, evaluate risk, and inform adaptation approaches; and a cultural ecological service (Brattland and Mustonen, 2018; Crate et al., 2019; Meredith et al., 2019) that is critical for decision-making (Mustonen and Mustonen, 2016; Huntington et al., 2017). For instance, Kalaallit knowledge in Greenland has been used to detect and attribute long-term (over 50 years) marine change that reaches beyond scientific instrumental data (Mustonen et al., 2018b).

This Box was written by Indigenous authors, recognizing that Indigenous knowledge and local knowledge are intellectual property (Cross-Chapter Box INDIG in Chapter 18), alleviating the risk of this knowledge being misinterpreted (David-Chavez and Gavin, 2018; Hughes, 2018; Raymond-Yakoubian and Daniel, 2018), and acknowledging that meaningful inclusion of Indigenous Peoples strengthens and supports Indigenous self-determination (ITK, 2019). Self-determination signifies and values the capacity and decisions made by these peoples in their own right and from their own autonomous cultural positioning. Following the format used in SROCC, this Box prioritizes Indigenous voices by presenting climate change assessments premised on Indigenous knowledge and written by Indigenous Peoples.

Climate change, nomadic lifestyles, and preservation of traditions

Perspectives from the Yukaghir Council of Elders and Russian Association of Indigenous Peoples, Russia

Climate change threatens reindeer herding, hunting, fishing, and gathering, which form the basis of Siberian Indigenous societies. Nomadic herding lifestyle is premised on Indigenous knowledge which has accumulated over millennia. IK, including the ability to predict weather, has played a substantial role in the adaptation to the extreme conditions. According to Shadrin (2021) present, rapid changes are changing Indigenous concepts of reality - they are increasingly finding themselves in situations where their experience and knowledge cannot help them. An Elder in Northeast Siberia explained that "nature does not trust us anymore" (Mustonen and Shadrin, 2021).

A major problem for nomadic reindeer herding is the degradation of reindeer pastures (Mustonen and Shadrin, 2021). The expansion of willows and shrubs into the tundra has resulted in losses of pastures. In other nomadic communities, these changes have led to the expansion of moose into tundra area and effects of reindeer populations, as well as changes in wild reindeer migration routes leading to the destruction of domestic reindeer pastures (Mustonen and Shadrin, 2021).

Due to the steady changes in precipitation in recent years, a deeper than usual snow cover has formed in Northeast Siberia (Mustonen and Shadrin, 2021). This alters the capacity of reindeer to access lichen, their primary food source. Late onset of cold weather has led to difficulties in the herds moving to their winter pastures. In the summer, increased rainfall has led to waterlogging of low-lying pastures. The most important challenge is the instability of the weather (Mustonen and Shadrin, 2021). These include frequent, never-before-seen warming, combined with rains in the late winter and early spring. Sharp temperature drops of over 30 degrees occurring within a few hours leads to formation of an ice crust on the ground which becomes a challenge for reindeer, especially in autumn, and are becoming more frequent. Furthermore, the number of summer storms and rapid cooling accompanied with snowfall during July has increased. Using Indigenous knowledge to predict weather is the basis of effective survival. It has become extremely difficult due to the unprecedented fast changing conditions (Mustonen and Shadrin, 2021) (Shadrin, 2021). All of these events lead to increased risks in the lives of Indigenous Peoples (Mustonen and Shadrin, 2021).

Climate change impacts Indigenous Peoples' health. Degradation of the quality of surface waters has increased, resulting from new floods and the thawing of permafrost, which increases risk of gastrointestinal diseases (CCP6.2.8). The 2007 flood on Alazaya river was of special importance and was locally identified to have produced the first regional "climate refugees" (Mustonen and Shadrin, 2021). Warming has expanded the distribution of new disease-carrying insects and ticks into new territories (Mustonen and Shadrin, 2021). Ancient cemeteries and campsites, as well as the burial sites of reindeer, become dangerous as permafrost thaws and coastal erosion proceeds.

Traditional food security is under threat. Permafrost-based storage facilities have deteriorated (CCP6.2.6) (Mustonen and Shadrin, 2021). There is an increase in the number of people who are forced to abandon the consumption of raw fish. As a result, the likelihood of losing cultural traditions is growing. These combined climate change impacts result in loss of Indigenous knowledge and nomadic lifestyles, thus, losing important aspects of their identity as distinct Indigenous Peoples (Mustonen and Shadrin, 2021).

Climate change impacts on Sámi women

Perspectives from Sámi in Finland

Feodoroff (2021) stresses that many Sámi women are central to Indigenous-led adaptation. Indigenous women use their bodies as gauges of change. For example, the restoration work in Näätämöjoki River in Finland (Ogar et al., 2020; Feodoroff, 2021) is based on the knowledge of traditional fishers and reindeer herders. Indigenous knowledge and Western science offer possibilities to reflect on changes that the waters in Indigenous bodies have known of events of the past (Feodoroff, 2021). Changes in temperature, pain and the gradual passing of pain, waves, and intrusions within Indigenous bodies are knowledges that are difficult to communicate according to Feodoroff (2021). Women are sensitive to receiving messages from their home environments. Feodoroff (2021) stresses that Indigenous conservation work is a bodily commitment. This realisation is linked with difficult questions of what or who controls Indigenous bodies. Feodoroff (2021) links present change with lingering impacts of global environmental damage that has not been dealt with or addressed. It may lead to real pain in Indigenous bodies and minds, causing feelings of being nauseated and ultimately causing fade out, wilt, wither and extinguishment of Indigenous Peoples.

Adaptation successes underpinned by Inuit knowledge

Perspectives from Inuit Circumpolar Council

Inuit have survived and thrived in Inuit Nunaat, their homelands, for millennia. In an environment that presents unique challenges, they have cultivated resourceful and innovative approaches tailored to their surroundings. Their values and knowledge guide their relationships with all that is within the Arctic and this has informed their decisions and management practices that continue to be in place today (Inuit Circumpolar Council Alaska, 2020). They are experts in adaptation. Now more than ever, in the time of anthropogenic climate change, living in the fastest warming region on the planet requires this expertise and capacity.

The extraordinary developments in the field of Indigenous Knowledge have crystallized the main tenant of interaction with the natural world that is "integral to a cultural complex that also encompasses language, systems of classification, resource use practices, social interactions, ritual and spirituality" (UNESCO, 2017). Inuit have used their knowledge of the land and coastal seas to design technology, monitoring systems (Atlas of Community-Based Monitoring in a Changing Arctic, 2021), and new hunting routes that respond to the changes they face (Inuit Circumpolar Council, 2017; Nunavut Climate Change Center, 2018; SIKU, 2020). Such examples of 'adaptation success' across Inuit Nunaat have been showcased and celebrated nationally and internationally (Youth Climate Report, 2019) and all are underpinned by Inuit knowledge and pivot on their right to self-determination. This is also embodied, for example, in Canada, the National Inuit Climate Change Strategy outlines the collective Canadian Inuit plan for climate action, centering on Inuit-determined priorities to protect their culture, language, and way of life, and guiding partners in how to work with Inuit on implementing this strategy (ITK, 2019). Their action on adaptation also spans scales from local to international. As far back as 1977, Inuit have been organized and involved at the international level. Inuit were present at the Rio Earth Summit and have participated in diverse but interrelated United Nations conventions to protect their homelands (e.g., UNFCCC, CBD, Stockholm

Convention). This history gives us unique insight and positions us as both leaders and partners with the ability to engage directly with governments, business, and others.

However, while Inuit are often recognized as leaders in adaptation, too often the academic literature ends there, citing 'successful Inuit-led adaptation to climate change' but not going further to explore towards what END this adaptation is designed. We have demonstrated leadership and set an example for the world in how to respond to change, but successful adaptation is not enough, it is not the end goal.

Central to their significant capacity to adapt is that it is done in recognition of the need to move beyond adaptation. Indeed, Inuit-led adaptation action is founded on the intention of contributing to and moving towards reformation and eventual transformation of systems to create a 'climate resilient' Arctic. This concept has surfaced in academic climate change literature and discussion and has begun to filter into the climate policy arena, especially within the context of the current COVID-19 pandemic that challenges us all to think about our world differently. With acknowledgement that reform and transformation is needed, the question remains, 'What does this look like?'

Inuit have an answer. System reform and transformation is grounded in self-determination. It is based in a human rights framework and rooted in Indigenous knowledge and culture. It recognizes and respects interconnectedness and builds this into solutions. It demands collaboration and true partnership towards action. And it comes from thinking big and across scales. Shaping this change calls for willingness and support to rethink the current economic and governance models that have failed us. For example, decentralizing governance and management, while it remains largely unconventional, has been shown to create some of the strongest systems we have. This is, in a large part, due to the way in which decentralization places more value and responsibility on the 'self' in self-determination. Decentralized processes in the Arctic have Indigenous knowledge holders playing a key and lead role in determining, defining, deciding how to work towards positive change.

Across Inuit Nunaat, examples of direct management and control over lands, territories and resources, have demonstrated that working from what is happening on the ground throughout their homelands, from their priorities and interests, has served to strengthen the health of their environment and their communities. For example, a comparative analysis on factors supporting and impeding Inuit food sovereignty between Alaska and the Inuvialuit Settlement Region found that the difference in outcomes within these regions is dependent on explicit respect for and recognition of the Inuit right of self-determination (Inuit Circumpolar Council Alaska, 2020). Furthermore, a new agreement achieved in Nunavut by the Qikiqtani Inuit Association related to the marine environment touted as an exemplary model for marine management is rooted in Inuit-determined structures and policies, and manifested by Inuit themselves (QIA, 2019).

Emphasis on decentralized management and substantial funding to do so at the grassroots level has been recognized by the IPCC previously in the SROCC. Ultimately, going beyond reform to system transformation requires, as Oren Lyons has stated, "value change for survival" (Lyons, 2020). Valuing decentralization, self-determination, Inuit knowledge, interconnectedness – core values held by Inuit – can move us in a climate-resilient direction.

[END BOX CCP6.2 HERE]

CCP6.3 Key Risks and Adaptation

CCP6.3.1 Key Risks

Key risks arising from changing climate hazards are presented in Table CCP6.6 (details in SMCCP6.4). Changing levels and magnitude of climate hazards translate into different levels of risks for ecosystems, industry, society and infrastructure (Figure CCP6.4) (see Meredith et al., 2019 Figures 3.5, 3.10 (Arctic), Figure 3.6 (Antarctic). In the Arctic, these risks are often also shaped by non-climatic factors (Huntington et al., 2019; Ford et al., 2021), including ongoing colonial legacies, land dispossession, landscape fragmentation, and resulting challenges in the valuing and meaningful use of Indigenous knowledge and local knowledge (Box CCP6.2) (Huntington et al., 2019; Kelman and Næss, 2019; Ford et al., 2020).

Available literature enabled assessment of particular polar assets based on projected future risk and including consideration of non-climatic compounding factors under 1°, 2°, 3° and 4°C global warming above pre-industrial including sea-ice ecosystems, marine mammals, sea birds, fisheries, infrastructure (Arctic only), local mobility (Arctic only), and coastal erosion (Arctic only) (Figure CCP6.5) (details in SMCCP6.4).

Table CCP6.5: Key risks and illustrative examples in polar regions identified through the processes described in Chapter 16 and SMCCP6.4.

Key Risk	Direct and indirect factors contributing to risk
KR1. Risk to marine ecosystems and species (CCP6.2.2; CCP6.2.3)	-Warming, marine heatwaves, sea-ice loss, glacial and ice sheet melt, ocean acidification, invasive species, harmful algae blooms -Narrow thermal niches, altered marine habitat, hampered calcification, higher corrosivity for $CaCO_3$ shell/skeleton, phenological mismatch, physiological/life history effects, sensitive food web relationships, reduced trophic (energy) transfer efficiencies, increased light availability, nutrient limitation, and changes to salinity, stratification, oxygen levels
KR2. Risk to terrestrial and freshwater ecosystems and species (CCP6.2.4)	-Warming, hydrological changes, terrestrial heat waves, change in rain and snow events, increased wild- and mega-fire events in Arctic, permafrost thaw, and erosion -Vegetation browning/greening, narrow thermal niches, physiological/ life history effects, sensitive food web relationships, parasites and disease
KR3. Risk to commercial and private infrastructure (CCP6.2.6)	-Permafrost freeze-thaw, extreme heat and precipitation, rapid warm-thaw events, storms, increased wave activity, storm surges, flooding, landslides and erosion. -Roads, airstrips, railways, ports, commercial buildings, private homes, ice cellars, traditional snow/ice/water travel routes, other infrastructure. -Permafrost freeze-thaw and SLR impacting cultural assets, including cultural heritage sites.
KR4. Risk to food and nutritional security (CCP6.2.5)	-Warming, ocean acidification, sea-ice loss, permafrost loss, changes to precipitation, wildfires, hydrological changes. -Access to marine areas increased, to coastal and terrestrial areas decreased; effects on subsistence and commercial species.
KR5. Increased polar shipping traffic with cascading risks for navigation, safety, ecosystems, and culture (CCP6.2.4; CCP6.2.5; Box CCP6.2; FAQ CCP6.1)	-Substantial reduction in sea-ice extent and thickness. -Marine subsistence species; coastal communities; Inuit hunters; ship operators; tourism operators; mining companies.
KR6. Increased mental health challenges and impacts on Indigenous Peoples and culture (CCP6.2.6.4; CCP6.2.7; CCP6.2.8. Box CCP6.2; FAQ CCP6.3)	-Warming temperature; heatwaves; ice changes; changes in snow cover; permafrost thaw; coastal erosion; changing landscapes.
KR7. Risk from polar change for global processes and SLR (FAQ CCP6.1)	-Reduction in Arctic sea-ice, sheets, and glaciers have implications for planetary albedo and ocean stratification and salinity, acceleration of global warming, potential effects on global overturning circulation and northern hemisphere weather patterns -cultural and resource connections to global sustainable development

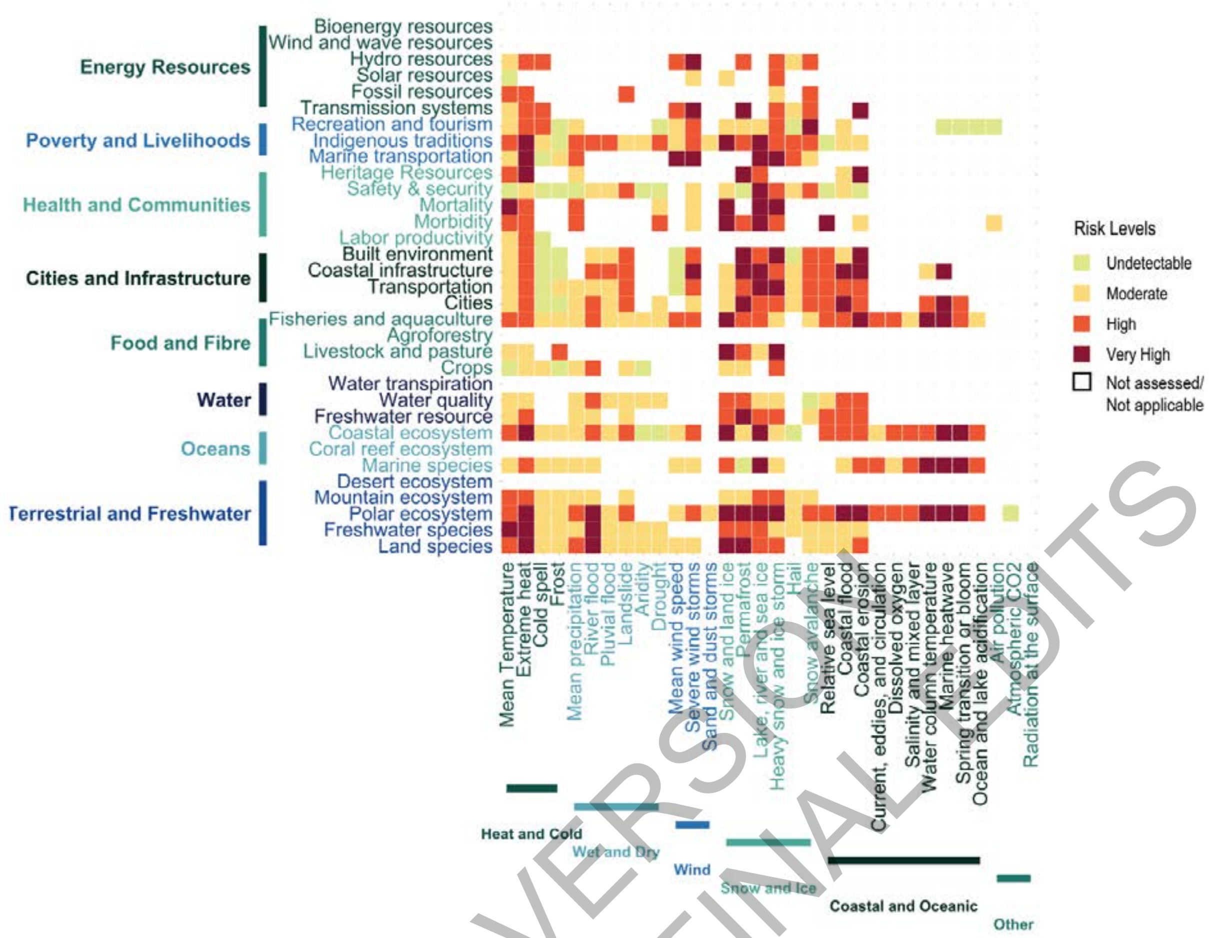


Figure CCP6.4: Rapid assessment for relative risk by sector (y-axis) and climate hazard (x-axis) for polar regions based on an assessment of asset-specific vulnerability and exposure across climate hazards (see SMCCP6.4 for methodological details). For each unique combination, the hazard by sector risk was ranked as very high (very high risk and high confidence), high (significant impacts and risk, high to medium confidence), medium (impacts are detectable and attributable to climate change, medium confidence), low/ not detected /positive (risk is low or not detectable). Blank cells are those where the assessment was not applicable or not conducted. Risks identified through the rapid assessment were further evaluated in the chapter assessments (see corresponding sector text for full assessment of risk and impacts).

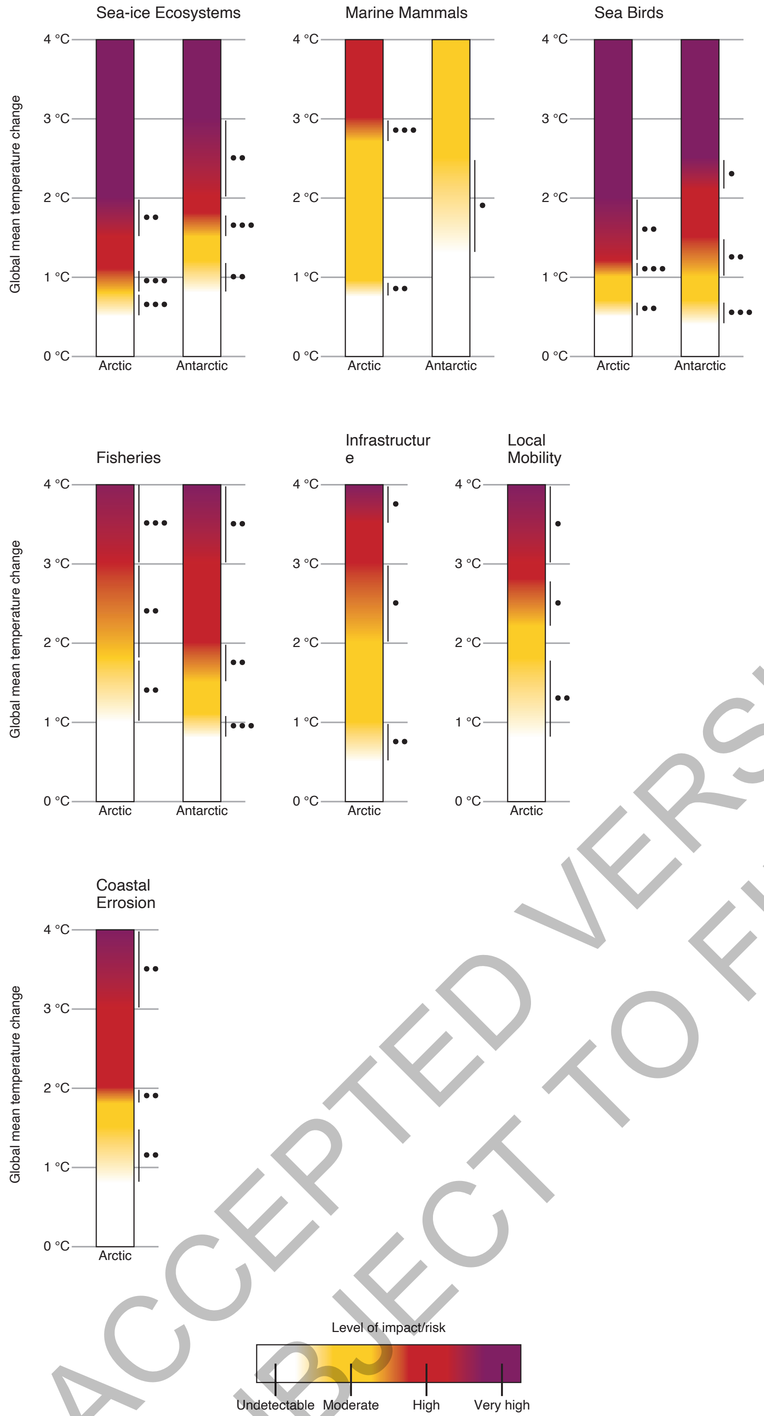


Figure CCP6.5: Burning ember of the relative risks to select assets in the Polar regions as a function of global mean surface temperature increase since pre-industrial times including: 1) sea-ice ecosystems, 2) marine mammals, 3) sea birds, 4) fisheries, 5) infrastructure (Arctic only), 6) local mobility (Arctic only), and 7) coastal erosion (Arctic only). The supporting literature and methods are provided in SMCCP6.5

CCP6.3.2 Adaptation

CCP6.3.2.1 Current adaptation

Across polar regions, adaptation responses to climate change impacts have ranged from rapid and incremental (e.g., shifting phenologies, alternative harvest or herding strategies) to large and transformative (e.g., switching livelihoods, social-ecological system transformation) (Figure CCP6.6). Some adaptation measures and opportunities induce novel risks to other sectors or systems resulting in cascading and compounding consequences that are sometimes hard to predict or prepare for (Huntington et al., 2015)

(Table CCP6.6). Adaptation planning and implementation is greater in the Arctic than Antarctic regions, in part due to disparate magnitudes of realized climate impacts and change between regions (Figure CCP6.2; Table CCP6.1), but also because of the differing governance systems in place (Meredith et al., 2019). In the Antarctic region, a climate action plan has been developed for terrestrial systems but not for the Southern Ocean (Meredith et al., 2019), although strategies for adapting to climate change have been proposed, including incorporation of precaution in decision-making (Constable et al., 2017). In the Arctic, climate change information is increasingly integrated into research, policy, and decision-making including incorporation of climate change projections, forecasts, and early warnings (AMAP, 2017; AMAP, 2018a; Marshall et al., 2019; Dorn and Zador, 2020; Hollowed et al., 2020; Stram et al., 2021).

The majority of adaptations in the Arctic are occurring at sub-regional levels in response to both observed and projected climate change, with evidence of increasing regional level action driven by climate planning processes of subnational governments (AMAP, 2017; Labbé et al., 2017; AMAP, 2018a; Canosa et al., 2020). Implemented adaptation includes alterations to building codes and infrastructure design (Shiklomanov et al., 2017; Flynn et al., 2019; Standards Council of Canada, 2020), surveillance (Ruscio et al., 2015; Ford and Clark, 2019; Meredith et al., 2019), information sharing (Berner et al., 2016), changes to survey and monitoring design (Stevenson and Lauth, 2019), hazard mapping (Flynn et al., 2019), use of new technologies (Tejsner and Veldhuis, 2018; Galappaththi et al., 2019), the development of regional and municipal adaptation plans (Labbé et al., 2017), shifting stocks and changes in fishery operations and location (Jørgensen et al., 2019; Fedewa et al., 2020; Thompson et al., 2020), alterations to subsistence harvesting activities (Anderson et al., 2018; Ford et al., 2018; Galappaththi et al., 2019), co-production of knowledge (Raymond-Yakoubian and Daniel, 2018), and application of Indigenous knowledge for resource management (Robards et al., 2018) and to monitor storms (Rosales et al., 2021; Simonee et al., 2021). Pan-Arctic and national-level adaptation remains limited (Ford et al., 2014; Canosa et al., 2020), although there have been few efforts to examine the nature of adaptation responses in Arctic regions and large gaps in understanding.

Illustrative examples of direct and cascading risks, enabling principles of climate resilience pathways, anticipated future conditions (with certainty levels and compounding risks for key sectors within polar regions are outlined in Table CCP6.6. A list of adaptation options responding directly to the challenges outlined for each sector, including an analysis of adaptation effectiveness and feasibility and cross referenced with key risks assessed in this chapter (Table CCP6.5) is provided in Figure CCP6.6

Table CCP6.6: Assessment of risks needing adaptation by sector in the polar regions.

Sector	**Direct and cascading risks**	**Enabling principles of climate resilience pathways**	**Anticipated future conditions / level of certainty**	**Compounding risks (non-climatic factors)**
Coastal settlements (CCP6.2.5)	Change in extent of sea-ice with more storm surges, thawing of permafrost, sea level rise, and coastal erosion	Local leadership and community-led initiatives to initiate and drive processes, responsive agencies, established processes for assessments and planning, geographic options	Increasing number of communities needing relocation (*medium confidence*), rising costs for mitigating erosion (*high confidence*)	Limitations of government budgets, other disasters that may take priority, policies deficiencies for addressing mitigation and relocation
Human health (CCP6.2.6)	Increased food insecurity, waterborne disease, emerging pathogens, injury and death, and negative mental health outcomes	Resources to support public programs; Indigenous self-determination; access to technology; supporting Indigenous knowledge systems; interdisciplinary and integrated decision-making	The intersection of social determinants of health will modify or mediate climate change impacts on health (*very high confidence*)	Underlying health conditions, advances in diagnosis and treatment, and other health system shocks (e.g., COVID)

 Transportation (aviation, rail, road, ice roads) (CCP6.2.4.3)	Permafrost thaw, sea-ice change, storm surge, coastal erosion, changing precipitation patterns (ice pellets, hail), and extreme events create risks to transportation infrastructure with consequences to navigation, economics, safety, and security	Financial and human resources for: climate resilient infrastructure research, development and implementation; improved weather, water, ice and climate forecasting at appropriate scales; improved communications infrastructure; local search and rescue	Limits to adaptation exist (*high confidence*), but strategic investments in technologically innovative infrastructure that offers mitigation co-benefits will greatly enhance adaptation effectiveness (*very high confidence*)	Level of local, regional, and national infrastructure development, commitment of national and state level government to sustainable development pathways, global economic and political trends, commodity prices, unforeseen system shocks
 Shipping (Box CCP6.1; FAQ CCP2)	Sea-ice reduction leading to increased shipping related to trade, tourism, fisheries, resource development, and re-supply with cascading risks from ships such as: increased under-water noise, potential introduction of invasive species, fuel spill risks, release of black carbon and air emissions, impacts to cultural resources, implications for subsistence hunting and food security, increased accidents and incidents	Financial support for ship-building technologies (e.g., low emission fuels, propulsion technologies, hull strength); development of robust multi-national agreements (in addition to existing agreements); inclusion of Indigenous Peoples in decision-making; investment in multi-national and longitudinal research on shipping impacts; and enhancing modern digital maritime charting	Ship traffic will continue to grow in polar regions (*high confidence*) with Arctic trade routes becoming increasing accessible (*very high confidence*) albeit with more challenging navigation due to increases in mobile ice in the near-term compared to late century when ice is expected to diminish completely during the shipping season (*high confidence*)	Geopolitical and sovereignty debates; shipping insurance premiums; global economic trends; commodity prices; national policies and politics; level of infrastructure investment; availability of search and rescue assets, and modern charting
 Infrastructure (CCP6.2.5)	Loss and damage to infrastructure from permafrost thaw affecting stability of ground; coastal erosion; SLR	Resources for assessments, mitigation, and where needed, relocation	Increasing cost to maintain infrastructure and greater demand for technological solutions to prevent damages (*high confidence*)	Strength of regional and national economies, other disasters that divert resources
 Non-renewable resource extraction (Arctic only) (CCP6.2.4.1)	Reduced sea-ice improves access to non-renewable resources in remote Arctic regions, while warming temperature and thawing permafrost affect production levels, quality, and reliability and season length of ice roads leading to increased operational costs	Investment in climate resilient infrastructure and low emission transportation (shipping) and investment in solar powered ships and low impact modular mining camp infrastructure	Increase in mining in newly accessible marine regions (*medium confidence)*, frequent false starts (i.e., due to climatic and non-climatic factors) (*high confidence*), and high levels of operational uncertainty (i.e., commodity prices, economic trends, climate risks) (*very high confidence*)	Commodity prices; global economic trends and shocks; Indigenous rights and decisions; changing regulatory environments, geopolitics, global demand for resources
 Tourism (CCP6.2.4.2)	Increased demand for polar tourism activities including development of 'last chance tourism' market; Increased tourism improves economic conditions but leads to increased environmental and cultural impacts	Financial resources for service and infrastructure development; Indigenous self-determination and development of co-management approaches for natural and cultural attractions;	Polar tourism demand will continue to increase, especially for cruise and yacht experiences (*high confidence*) and enhance risks related to ship groundings, accidents, and incidents (*medium confidence*)	Limited search and rescue capacity, poor infrastructure, aging expedition cruise ship fleet, uncharted waters, geological and sovereignty debates, global economic trends, unforeseen events (i.e., SARS, COVID-19)

		development of multi stakeholder/rightsholder tourism task teams		altering tourism demand patterns
 Reindeer herding (CCP6.2.3.1; 6.2.3.2; 6.2.5; Box CCP6.2)	Rain-on-snow events causing high mortality of herds, especially in the autumn season; shrubification of tundra pasture lowering forage quality	Flexibility in movement to respond to changes in pastures, secure land use rights; adaptive management; continued economic viability and cultural tradition; self-determination in decision-making; adequate support for communication and technological services; Indigenous Rights upheld and protected	Increased frequency of extreme events and changing forage quality adding to vulnerabilities of reindeer and herders (*high confidence*); adaptation limits are being approached	Change in market value of meat; overgrazing; land use policies affecting access to pasture and migration routes, property rights; cost of feed
 Commercial fisheries (CCP6.2.3)	Loss of sea-ice, warming waters, and MHWs transform ecosystems in the Arctic with impacts on fisheries including declines in multiple regions; changes to Antarctic ecosystems affect southern fisheries productivity and distribution	Implementation of adaptive management that is closely linked to monitoring, research, and low cost and inclusive public participation in decisions, high resolution forecast and projection tools, climate-informed survey and monitoring design	Changes in availability and location of fishery resources will impact fish operations in the eastern Bering Sea and Barents Sea as well as the Convention for the Conservation of Antarctic Marine Living Resources area. Declines in catch impact livelihoods, coastal communities, and pose a risk to regional and global food and nutritional security (*very high confidence*)	Changes in global demand for seafood, demand and markets, changes in gear, changes in policies affecting property rights. Changes due to offshore development and transportation
 Marine subsistence (CCP6.2.3; CCP6.2.3.1)	Changes in species distribution and abundance (not all negative); impediments to access of harvesting areas especially sea-ice; increased interactions with shipping; safety; changes in seasonality; reduced harvesting success and process of food production (processing, food storage; quality); threats to culture and food security	Systems of adaptive co-management that allow for species switching, changes in harvesting methods and timing, secure harvesting rights, communication and relationship building, co-production of knowledge	Changes in distribution and abundance of resources combined with more regulations related to species at risk. Adaptation at the local, individual, and household level under low mitigation scenarios will be costly and possibly undermined by the scale and pace of change, including climate shocks and extreme events (*medium confidence*)	Changes in cost of fuel, land use affecting access, food preferences, harvesting rights; colonialism, international agreements to protect vulnerable species
 Marine ecosystems (CCP6.2.1)	Warming, sea-ice loss, ocean acidification resulting in poleward contraction of polar zones, invasive species introduction, displacement of polar species, and restructuring of food webs	Reduce effects of external and compounding risks and increase application of ecosystem-based management to meet biodiversity and management goals. Conservation of genetic diversity and biodiversity to preserve resilience, and	Without institutional investment in sustaining climate resilience in ecosystems across sectors there is a high risk of failure (*high confidence*)	Novel and expanding activities in ice free areas (shipping; fishing), energy development and mineral extraction, increased tourism, global markets and demand for polar resources, population growth and community

		supplementation and assisted migration may be needed		relocation to coastal areas
 Terrestrial and Freshwater ecosystems (CCP6.2.2)	Warming, hydrology changes (reduced ice on lakes and rivers, flooding, snow) and permafrost thaw lead to impacts on polar terrestrial and freshwater systems, food webs, the distribution of polar fish, implications for peat systems with consequent changes on dependent animal assemblages and increasingly favorable conditions for parasites and pathogens. Increased risk of wildfires in the Arctic	Improving biodiversity and redundancy to enhance resilience. Efforts to minimize and prevent extinctions; preservation of ecosystem processes and habitats during critical life stages; coordinated governance; measures and planning that consider dynamic interactions within and among social and ecological systems are more effective	Without institutional investment in sustaining climate resilience in ecosystems across sectors there is a high risk of failure (*high confidence*). Arctic regions have greater understanding of resilience needs but coordination is not widespread. Antarctic has established action plans to identify key management needs for conserving terrestrial and freshwater biota.	Novel and expanding activities in ice free areas (shipping; fishing), energy development and mineral extraction, increased tourism, global markets and demand for polar resources, population growth and community relocation to coastal areas

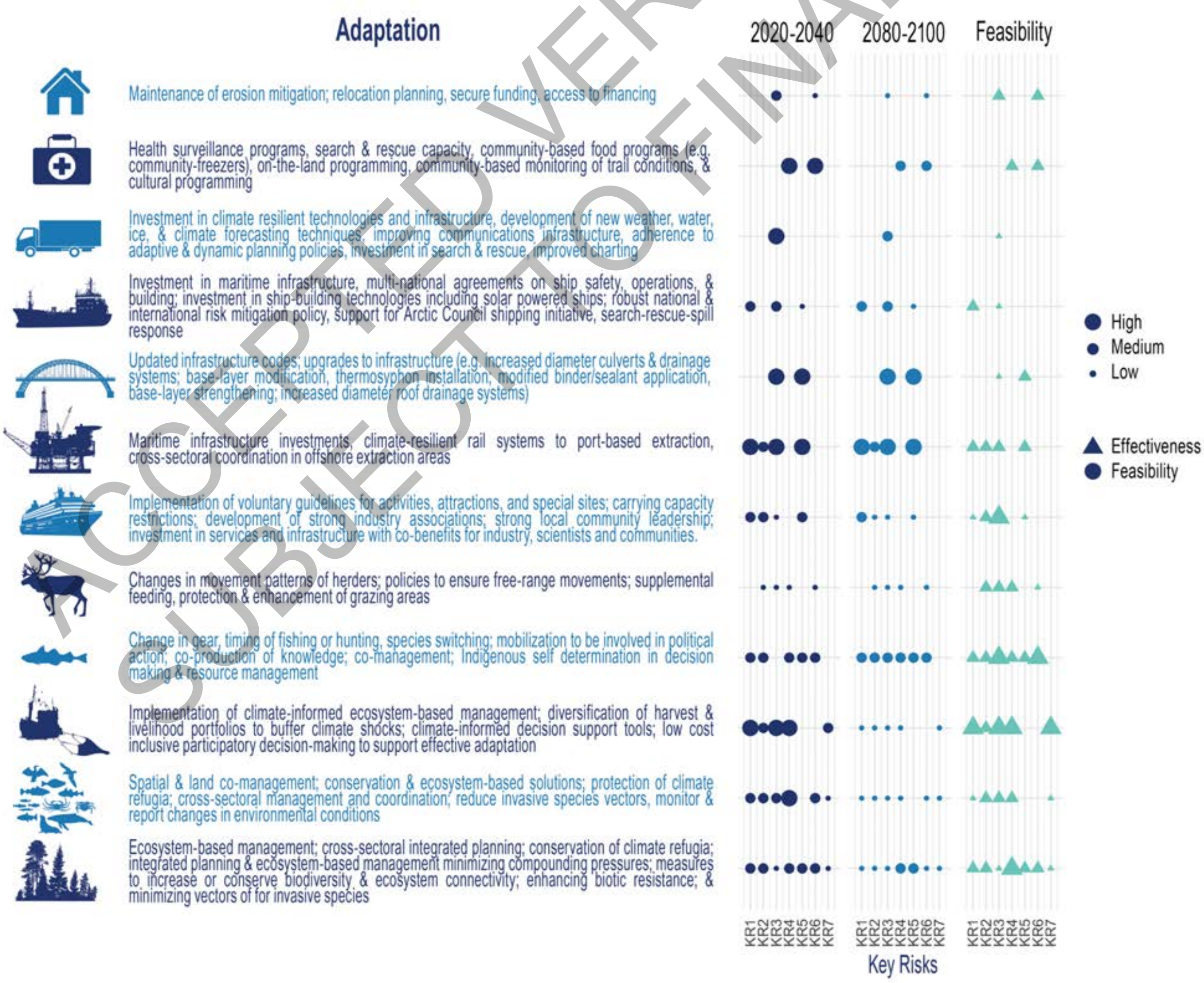


Figure CCP6.6: Assessment of feasibility and effectiveness of adaptation options by key risks in the polar regions (Table CCP6.6)

The need for self-determination for Indigenous Peoples and local communities in decision-making and cooperation across Arctic nations to manage a rapidly changing Arctic is increasingly recognized, particularly in a shipping and wildlife management context where climate impacts will be transboundary and multi-sectoral (Spence, 2017; Forbis and Hayhoe, 2018; Ford and Clark, 2019; Dawson et al., 2020) (CCP6.2.6; Box CCP6.2). Effective Indigenous and community-led adaptation efforts have been implemented across the Arctic to alleviate climate and non-climate stressors and build resilience through restoration and conservation (Huntington et al., 2017; Brattland and Mustonen, 2018; Hudson and Vodden, 2020; Mustonen and Feodoroff, 2020; Uboni et al., 2020; Huntington et al., 2021). For example, Indigenous knowledge and science has been used by the Skolt Sámi in Finland to attenuate warming, drought, and water quality impacts on salmonids through restoration of spawning and nursery habitats in the Vainosjoki river catchment (Brattland and Mustonen, 2018; Mustonen and Feodoroff, 2020; Ogar et al., 2020). This ecological restoration of damaged habitats for fish represents community-led actions. In Aasiaat, Greenlandic hunters have implemented community-based oceanographic and ecological monitoring to convey Indigenous knowledge observations of rapid change to the government and scientists. A special aspect of land use in the Russian North is the preservation of nomadic lifestyles of the Nenets and Chukchi (Mustonen and Mustonen, 2016), and while these traditional economies have undergone rapid change due to non-climate drivers, their land uses, observational frameworks and cultural matrixes remain of high importance in the context of climate change. Endemic responses (self-agency from within the culture) and Indigenous governance enable adaptation to the rapid and accelerating changes under way (Mustonen et al., 2018a). Therefore, community-based monitoring and inclusion of Indigenous knowledge in dialogue with science has been an effective mechanism to detect and respond to climate change.

CCP6.3.2.2 Adaptation gaps

In a study of adaptation progress across the Arctic from 2004−2019, 233 cases of adaptation were documented, with the majority of actions primarily behavioural and reactionary in nature and undertaken in the subsistence harvesting sector, with resource management, and infrastructure and transportation other prominent sectors where adaptation responses were documented to be occurring (Canosa et al., 2020). The study found few changes in the profile of adaptation over time, except for an increase in responses being motivated solely by climate impacts, and few cases of transformational change, although caution that a lack of data on adaptation actions makes documenting trends challenging. Human health is generally under-represented in adaptation initiatives, along with adaptations being developed within larger Arctic settlements (Ford et al., 2014; Canosa et al., 2020), and in many sectors decisions continue to be made without explicit inclusion of climate change impacts and risk in planning and design (*high confidence*) (Cherry et al., 2017; Lauta et al., 2018; Meredith et al., 2019). There is *limited evidence* of transformational adaptation taking place in the policy arena (e.g., U.S. Executive Order 13990, 2021), but many examples of how impacts and responses to climate change have transformed social-ecological connections, traditions, markets, trade, and livelihoods of Arctic residents and Indigenous Peoples (Ford et al., 2015).

CCP6.3.2.3 Maladaptation and limits to adaptation

In polar regions, multiple entities operate simultaneously to manage lands and resources, resulting in layered approaches and policies for the same sector or region, only some of which are synergistic and a few of which may counter each other (e.g., Southern Ocean: Solomonsz et al., 2021). Climate change and attendant uncertainty can undermine stakeholder confidence in management, leading to less effective management even when scientific understanding is stable (Mumby et al., 2017). In the Arctic, large landscapes, dispersed population centers, limited resources, and settler colonialism are structural barriers to effective planning, emergency response, and relief and recovery from climate impacts (*medium confidence*), which limit adaptation and sometimes exacerbate climate and non-climate pressures on social and ecological systems (Ford et al., 2015; Ford et al., 2020; Snook et al., 2020).

Adaptation strategies that are beneficial in the short term can result in long-term maladaptive outcomes. For Indigenous Peoples, strategies that fail to address colonialism, inequities, and injustices undermine effective adaptation (Canosa et al., 2020; Schipper, 2020; Ford et al., 2021). Large "responsiveness gaps" between impacts and implementation, approaches that fail to consider dynamic responses within social and ecological systems (which amplify or attenuate climate impacts), and a paucity of *a priori* planning can contribute to maladaptation (*high confidence*)(Pentz and Klenk, 2017; Turner et al., 2020b). For example, rationalization (privatization) can stabilize fisheries and incentivize long-term sustainability under stationary conditions, yet also promote low diversity in harvest (or livelihood) portfolios and when combined with behaviors to offset climate driven declines in yield (e.g., effort or price) rationalization can create lock-in to declining stocks, increasing the risk of income variability and collapse (Kasperski and Holland, 2013; Pinkerton and Davis, 2015; Holland et al., 2017; Ojea et al., 2017; Anderies et al., 2019; Fisher et al., 2021). Policies that foster stewardship yet also allow for diversification in fisheries may further attenuate climate shocks to individual fisheries (Kasperski and Holland, 2013; Fisher et al., 2021) and stabilize catches (e.g., US Bering Sea pollock fleet (Watson and Haynie, 2018)). Inclusive and participatory decision-making underpins long-term resilience to climate change (*medium confidence*)(Flynn et al., 2018; Ford et al., 2020), but a high cost of participation can disproportionately favor entities with strong investment, ample resources, and extreme viewpoints such that decision outcomes are not in the broad interest of polar societies (Lynham et al., 2017).

There are significant limits to adaptation in the polar regions related to the rate of warming and cascading changes that are occurring, which is equivalent to double and sometimes triple the global average depending on the region (Bush and Lemmen, 2019; IPCC, 2021). The rapid pace of change, such as sea-ice loss, can outpace ecological processes and induce substantial ecological shifts (CCP6.2)(*medium confidence*). The speed of climate change in the Arctic limits options for adaptation in communities who rely on a narrow resource base, when adaptation involves loss of culture and livelihoods, and when the costs of adaptation makes it infeasible (*medium confidence*) (Ford et al., 2015), such as for reindeer herding (Table CCP6.6; Figure CCP6.6; Figure CCP6.7) (Meredith et al., 2019). Adapting infrastructure in response to a rapidly changing cryosphere will be limited by available technologies and the relatively higher costs associated with updating infrastructure over vast polar regions (Schneider von Deimling et al., 2021).

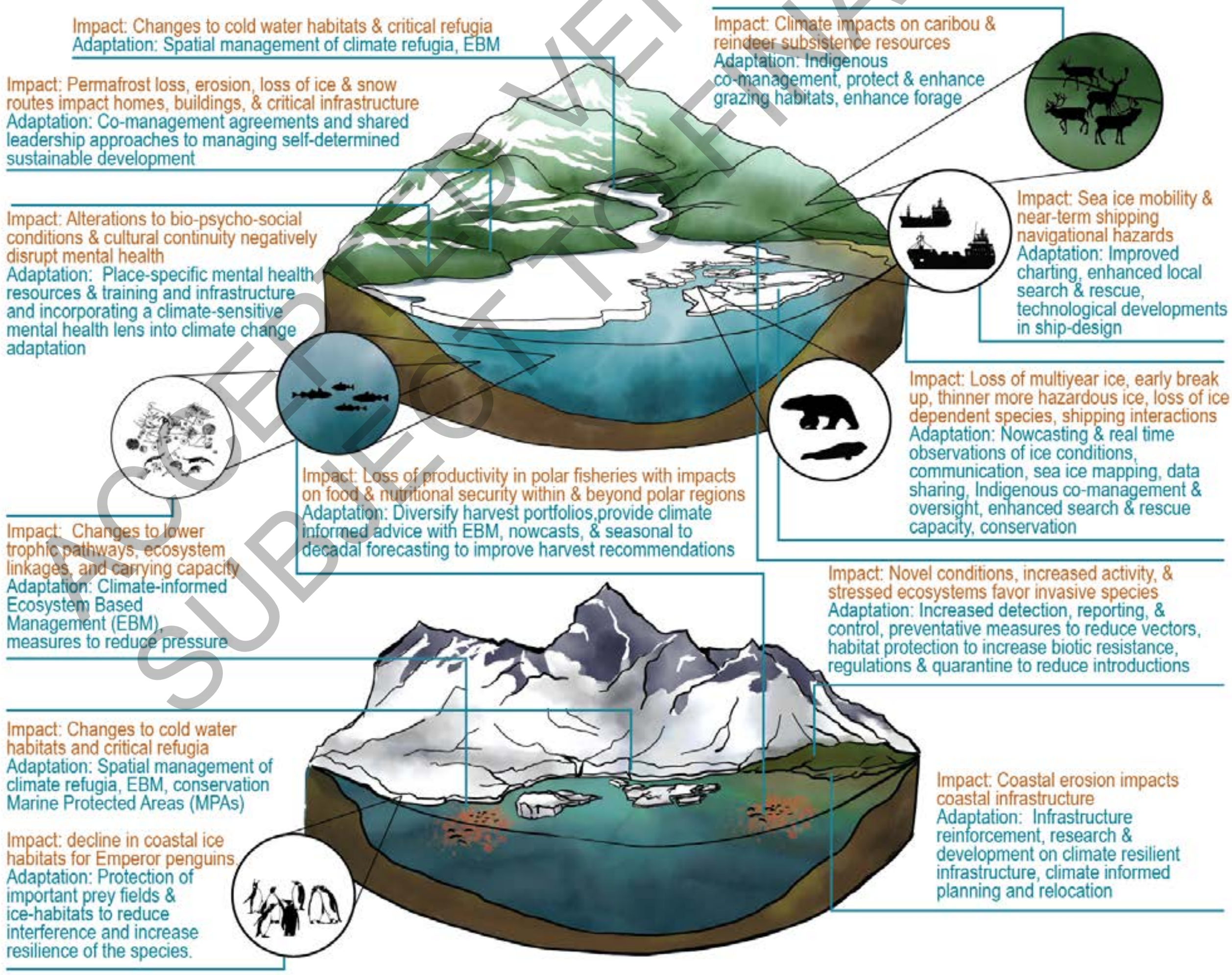


Figure CCP6.7: Climate change impacts, risks, and potential for adaptation in Arctic (upper panel) and Antarctic (lower panel) social ecological systems.

[START FAQ CCP6.4 HERE]

FAQ CCP6.4: When will climate change impacts in polar regions surpass our ability to adapt?

When environmental variability is within the range of the current adaptive management approaches, the social-ecological system can thrive. However, the rapidly changing polar systems are causing disruptions to societies, economies and ecosystems. The current management systems are yet to develop procedures for managing rapid change being experienced in warming waters, sea-ice declines, permafrost thaw and erosion, and poleward shifts in species. These challenges are expected to become more pronounced within a few decades rather than later this century.

Polar regions are naturally dynamic environments. Ecosystems in polar regions, and the people who rely on them, have adapted to natural variability and dynamic nature of polar environments. Fish populations in polar regions are known to exhibit cycles of productivity, and shift their distribution across hundreds of kilometers in response to changes in winter sea-ice cover and concomitant summer ocean conditions. Management of the productive fisheries in polar regions is also designed to allow for these changes, using adaptive and ecosystem based approaches that buffer populations from overexploitation and also stabilize fisheries, livelihoods, and food resources. Indigenous Peoples diversify their subsistence harvest across species and resources, and therefore similarly stabilize food and nutritional security. When environmental variability is within the range of these adaptive measures the social-ecological system can thrive. Thus, there are fundamental components in place in polar regions already to help ecosystems and people adapt to some degree of climate change. However, as climate change impacts like warming waters, sea-ice loss, permafrost thaw and erosion, systematically alter components of the system, shift species increasingly poleward, and disrupt linkages between species and people, the ability to adapt is reduced. There are critical tipping points (e.g., sea ice melt, permafrost thaw) where changes may cascade, self-reinforce and accelerate, outpacing adaptation actions and force natural and human systems irreversibly (on the scale of human existence) into novel regimes. The risk of crossing tipping points is greater and the probability much increased after mid-century under scenarios without global carbon mitigation (SSP5 8.5), where changes are largest and most rapid.

[END FAQ CCP6.4 HERE]

CCP6.4 Climate Resilient Development Pathways

The polar regions are expected to experience many economic development opportunities as a result of climate change, including increased accessibility for shipping and attractiveness for fisheries and tourism (CCP6.2.3.1, CCP6.2.4). For polar regions, equitable climate resilient development requires diverse perspectives in planning and implementation. In the Arctic, cultural, social and economic dimensions of Indigenous Peoples and local communities are critical (Ritsema et al., 2015; Huntington et al., 2021). For both poles, there are global cultural connections to polar systems (Roberts et al., 2021), along with important global and local needs for sustained ecosystems and their services, in the face of diminishing polar zonal conditions (Cavanagh et al., 2021; Murphy et al., 2021; Solomonsz et al., 2021).

Sustainable pathways integrating across sectors, and taking account of local and global connections, can be readily achieved in polar regions to balance trade-offs between economic, ecological, and socio-cultural imperatives, yet challenges remain (Murphy et al., 2021). Notably, terrestrial areas of greatest interest for infrastructure development, agriculture, and visitation potential are often also the same areas that have been identified as culturally and ecologically significant (PEW, 2016; Eliasson et al., 2017; Grant et al., 2021) (*high confidence*). Development of low impact shipping corridors in Arctic Canada is an example of an effective mechanism where climate resilient infrastructure can be prioritized and where regulation (voluntary and enforced) focused on cascading climatic risks can be implemented (Chénier et al., 2017; Dawson et al., 2020).

CCP6.4.1 Challenges to Climate Resilient Development Pathways

Decision-making in polar regions is complicated by globalization processes and the complexity of governance arrangements from local to global instruments and differing stakeholder perspectives and needs (Hughes et al., 2018; Stephen, 2018; Huntington et al., 2021; Murphy et al., 2021; Solomonsz et al., 2021). Substantial interest in and management of polar resources from non-polar states can lead to decision-making that lacks explicit consideration of local impacts and responses, thus reducing the effectiveness of adaptation, and in some cases causing maladaptation. Participatory decision-making is increasingly used in some sectors, but high costs of participation, a focus on consensus, and systematic erosion of resources can undermine outcomes (Mumby et al., 2017; Parlee and Wiber, 2018; Mendenhall et al., 2020). In the Arctic, the societal burden of climate change impacts and risks will manifest at the local level and thus the importance of local scale leadership and involvement in decision-making is essential for effective adaptation (AMAP, 2017).

Many losses and damages within Indigenous contexts are not able to be monetized but can be profound, such as loss of Indigenous languages (CAFF, 2013), loss of Indigenous knowledge associated with nomadic lifestyles and cultures (Box CCP6.2), and loss of geographical knowledge associated with an intimate knowledge of landscapes across seasons (Brattland and Mustonen, 2018), changing landscapes resulting in solastalgia and ecological grief (Cunsolo and Ellis, 2018), and some Indigenous practices and cultural assets, such as burial grounds, nomadic camp sites, graveyards, seasonal dwellings, and routes and pathways causing disruptions to mind and memory (Mustonen and Mustonen, 2016). Recognizing these intangible losses and damages is critical for understanding how to achieve climate resilience in the Arctic (Tschakert et al., 2019; Sawatzky et al., 2020).

For the Antarctic, the governance for managing climate impacts is emerging, particularly for terrestrial and nearshore habitats (*high confidence*) (Hughes et al., 2018; Chown and Brooks, 2019). However, it is poorly developed for marine ecosystems, despite its importance for decision-making (Trebilco et al., 2020; Goldsworthy and Brennan, 2021). A diversity of stakeholders are involved in developing evidence-based management for the region, which presents challenges for adaptation planning (Solomonsz et al., 2021), particularly in identifying sustainable practices in a changing environment (Constable et al., 2017; Brooks et al., 2018). Spatial management for enhancing the resilience of endemic polar biodiversity is increasingly proposed as the best option for managing risks of climate change (Chown and Brooks, 2019).

CCP6.4.2 Inclusive, Integrated Co-management

Inclusive, low-cost participatory decision-making can deliver equitable responses to climate change (*high confidence*). Land use, maritime activities, and subsistence fishery and other extracted resources in the polar regions are co-managed through multilateral and national government bodies. The capacity of governance systems in some Arctic regions to respond to climate change has strengthened recently (*high confidence*). Synthetic themes in adaptation for the Arctic have emerged from and since SROCC and include flexibility through diversity in livelihoods, and subsistence and harvest portfolios; co-management of resources; adaptive and ecosystem-based approaches; adoption of advanced technology, forecasts, and longer term projections to improve safety and resources management; and imperative need for low-cost, inclusive and participatory decision-making (Kasperski and Holland, 2013; Brattland and Mustonen, 2018; Parlee and Wiber, 2018; Galappaththi et al., 2019; Holsman et al., 2020; Huntington et al., 2021; Melbourne-Thomas et al., 2021; Mustonen and Van Dam, 2021). This was demonstrated in community-level adaptation by Pangnirtung Inuit to climate change impacts on fisheries (Galappaththi et al., 2019). Inclusive approaches to co-management, especially those that enable diverse perspectives, embrace conflict, and address equity and justice across power holders, can help alleviate the risk and promote solutions (Raymond-Yakoubian et al., 2017; Brattland and Mustonen, 2018; Parlee and Wiber, 2018; Raymond-Yakoubian and Daniel, 2018; Snook et al., 2020). Integration across levels of management and diverse regional perspectives can reduce climate risks and support equitable adaptation measures (Allison and Bassett, 2015; Raymond-Yakoubian et al., 2017; Raymond-Yakoubian and Daniel, 2018; Holsman et al., 2020).

Increased flexibility in management measures, greater investment in ecosystem monitoring, and more inclusive participatory methods and communication may help foster high levels of local investment and resilience and promote adaptive pathways (Cinner et al., 2016; Weymouth and Hartz-Karp, 2019), although explicit measures may be needed to reduce costs and increase representation, enhance transparency, embrace dissent, and clarify accountability are needed as these are not inherent outcomes (Lynham et al., 2017; Parlee and Wiber, 2018). Ecosystem-based management (EBM), which includes provisions aimed at sustaining critical connections within and among social and ecological systems, enhances resilience and attenuates climate impacts on ecosystems and provisioning services, e.g., EBM enhances climate resilience for Antarctic krill and Northeast Arctic cod fisheries (Troell et al., 2017; Meyer et al., 2020) and forestalls fishery collapse in the Bering Sea in the near-term (Holsman et al., 2020). Increasing likelihood of transboundary resources, interactions, and novel commerce may strain existing regulatory and international agreements suggests that *a priori* governance agreements that designed to manage climate risks and aimed at attenuating potential conflicts over resources and regions may be important for resolving these issues (Parlee and Wiber, 2018; Mendenhall et al., 2020).

CCP6.4.3 Enabling Climate Resilience in the Arctic: Self-determination and Indigenous Peoples' Rights

Climate change disproportionately impacts Indigenous Peoples (Box CCP6.2), which directly affects their livelihoods, health, and Sustainable Development Goal targets. For residents in the Arctic, a sustainable development pathway has been found to be highly effective if a self-determined development model is employed (*very high confidence*). Known determinants of Indigenous self-determined development in regions in the Arctic, include: 1) Indigenous self-determined decision-making (and inherent sovereignty); 2) effective and culturally legitimate institutions of government; 3) strategic vision and strategic thinking; and 4) public-spirited, nation-building leadership (Cornell and Kalt, 1992; Cornell and Kalt, 1998; Cornell and Kalt, 2007; Ritsema et al., 2015). For Indigenous Peoples, advances in recognition of self-governance, land and resource sovereignty, and resource co-management, particularly in the North American Arctic but also elsewhere, provide a strong basis for responding to climate impacts (Ford et al., 2015; Robards et al., 2018). These developments expand the solution space (Haasnoot et al., 2020) for responding to climate impacts, although historical and on-going forms of colonialism in research and government institutions continues to undermine Indigenous self-determination and reinforce climate change vulnerability (Marino and Lazrus, 2015; Whyte et al., 2019; Ford et al., 2020; Snook et al., 2020). Readiness for adaptation across Arctic nations continues to be challenged by a number of factors including the existence of pressing socio-economic challenges, institutional and governmental barriers, lack of meaningful inclusion of Indigenous knowledge in government planning and response, and lack of financial resources (Ford et al., 2015; Loring et al., 2016; AMAP, 2017; Ford et al., 2017; Birchall and Bonnett, 2019) (AMAP, 2018a). In Alaska, for example, the need to relocate high risk villages has been recognized by researchers, decision-makers, and communities themselves for some time, and while progress is being made in some locations (Ristroph, 2017), institutional barriers have generally resulted in negligible progress (Bronen and Chapin, 2013; Marino and Lazrus, 2015; Albert et al., 2018; Rosales et al., 2021).

CCP6.5 Summary and Conclusion

Rapid changes occurring in polar systems are clear and unequivocal, indicating that swift and effective responses are urgently needed to avoid substantial future impacts and reduce risks to polar social and ecological systems. Some underlying principles emerge from this assessment that appear fundamental to achieving climate resilient development in polar systems (Figure CCP6.8) because they could facilitate rapid, equitable and just responses to achieve climate resilience. These principles include having locally relevant and accessible tools and services (e.g., regional forecasts and projections) to support climate-informed decision-making, along with adequate and appropriate resourcing (including finance and integrated planning) for climate adaptation and for responding to emergencies. Effective decision-making processes integrate across sectors, all levels of governance, including through multinational instruments, and, most importantly, apply low cost and inclusive participatory processes to address gender, equitable and socially just outcomes. In the Arctic, there is evidence that overcoming colonialism through meaningful and explicit inclusion of Indigenous knowledge in research and resource management, as well as co-management and self-determination in decision-making, are effective measures to support equitable climate resilience across multiple sectors. Lastly, climate resilience is strongly dependent on both mitigation of climate change as well as effective adaptation to meet the challenges of unprecedented change in polar regions.

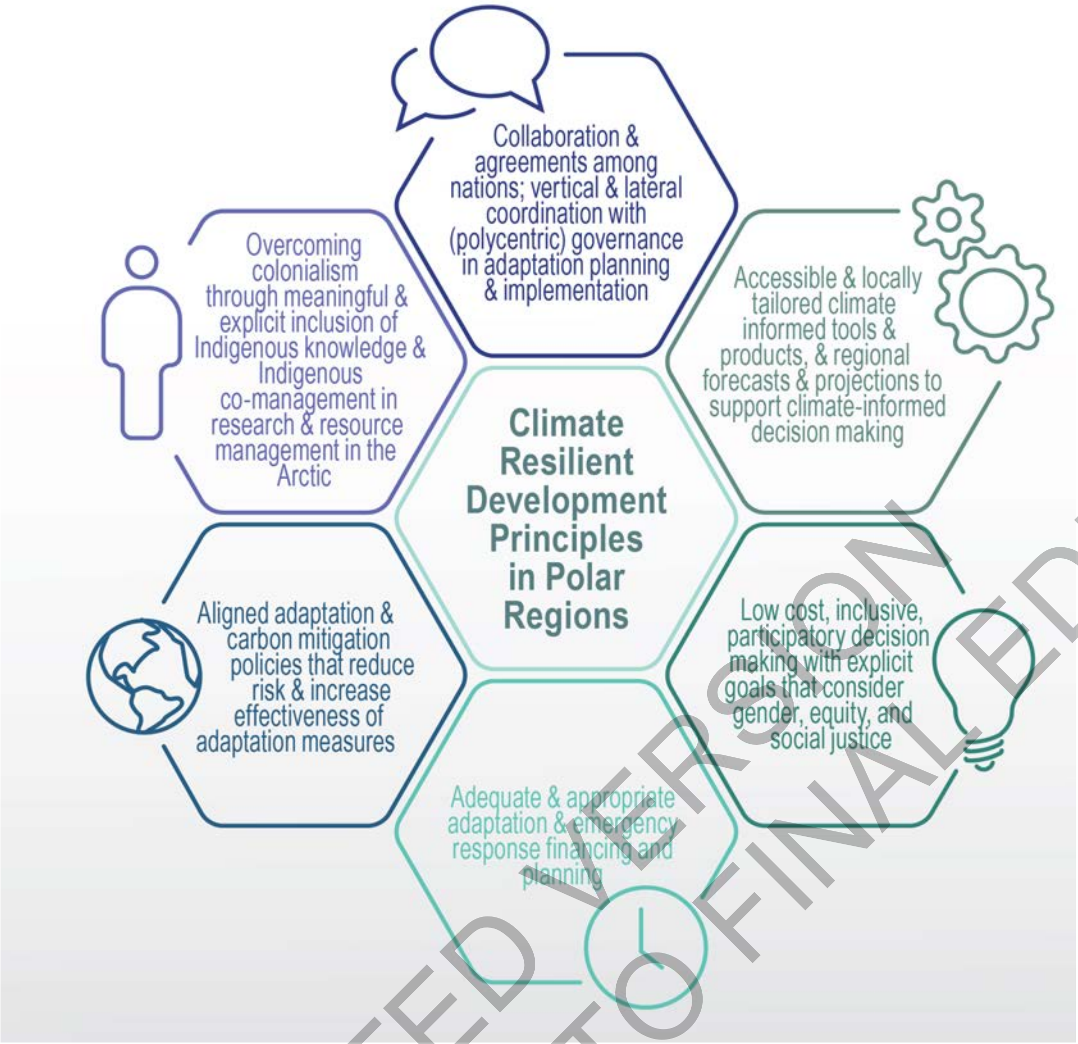


Figure CCP6.8: Six principles that support climate resilient pathways in the polar regions.

References

Aarflot, J. M., H. R. Skjodal, P. Dalpadado and M. Skern-Mauritzen, 2018: Contributions of Calamus to the mesozooplankton biomass in the Barents Sea. *ICES Journal of Marine Science*, **75**(7), 2342-2354, doi:10.1093/icesjms/fsx221.

Aksenov, Y. et al., 2017: On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice. *Marine Policy*, **75**, 300-317, doi:10.1016/j.marpol.2015.12.027.

Alabia, I. D. et al., 2018: Distribution shifts of marine taxa in the Pacific Arctic under contemporary climate changes. *Diversity and Distributions*, **24**(11), 1583-1597, doi:10.1111/ddi.12788.

Alava, J. J., W. W. L. Cheung, P. S. Ross and U. R. Sumaila, 2017: Climate change–contaminant interactions in marine food webs: Toward a conceptual framework. *Global Change Biology*, **23**(10), 3984-4001, doi:10.1111/gcb.13667.

Albert, S. et al., 2018: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, **18**(8), 2261-2272, doi:10.1007/s10113-017-1256-8.

Allison, E. H. and H. R. Bassett, 2015: Climate change in the oceans: Human impacts and responses. *Science*, **350**(6262), 778-782, doi:10.1126/science.aac8721.

Altdorff, D. et al., 2021: Agriculture in boreal and Arctic regions requires an integrated global approach for research and policy. *Agronomy for Sustainable Development*, **41**(2), 23, doi:10.1007/s13593-021-00676-1.

AMAP, 2017: *Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region*. Arctic Monitoring and Assessment Program (AMAP), Oslo, Norway, xiv + 255 pp. Available at: https://www.amap.no/documents/doc/adaptation-actions-for-a-changing-arctic-perspectives-from-the-bering-chukchi-beaufort-region/1615.

AMAP, 2018a: *Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region*. Arctic Monitoring and Assessment Program (AMAP). Oslo, Norway, xvi + 255 pp. Available at: https://www.amap.no/documents/doc/Adaptation-Actions-for-a-Changing-Arctic-Perspectives-from-the-Baffin-BayDavis-Strait-Region/1630 (accessed September 30, 2019).

AMAP, 2018b: *AMAP Assessment 2018: Arctic Ocean Acidification.*, Tromsø, Norway, vi+187 pp. Available at: https://www.amap.no/documents/doc/AMAP-Assessment-2018-Arctic-Ocean-Acidification/1659 (accessed 01/10/2019).

Amesbury, M. J. et al., 2017: Widespread biological response to rapid warming on the Antarctic Peninsula. *Current Biology*, **27**(11), 1616-1622.e1612, doi:https://doi.org/10.1016/j.cub.2017.04.034.

Anderies, J. M., J.-D. Mathias and M. A. Janssen, 2019: Knowledge infrastructure and safe operating spaces in social–ecological systems. *Proceedings of the National Academy of Science U.S.A.*, **116**(12), 5277-5284, doi:10.1073/pnas.1802885115.

Anderson, D., J. D. Ford and R. G. Way, 2018: The Impacts of Climate and Social Changes on Cloudberry (Bakeapple) Picking: a Case Study from Southeastern Labrador. *Human Ecology*, **46**(6), 849-863, doi:10.1007/s10745-018-0038-3.

Andriuzzi, W. S. et al., 2018: Observed trends of soil fauna in the Antarctic Dry Valleys: early signs of shifts predicted under climate change. *Ecology*, **99**(2), 312-321, doi:10.1002/ecy.2090.

Arctic Council, 2011: *Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic*. Arctic Council, 58 pp. Available at: https://oaarchive.arctic-council.org/handle/11374/531.

Arctic Council, 2013: *Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic*. Arctic Council, 275 pp. Available at: https://oaarchive.arctic-council.org/handle/11374/529.

Ardyna, M. and K. R. Arrigo, 2020: Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change*, **10**(10), 892-903, doi:10.1038/s41558-020-0905-y.

Ardyna, M. et al., 2020: Under-Ice Phytoplankton Blooms: Shedding Light on the "Invisible" Part of Arctic Primary Production. *Frontiers in Marine Science*, **7**, 985, doi:10.3389/fmars.2020.608032.

Atkinson, A. et al., 2019: Krill (Euphausia superba) distribution contracts southward during rapid regional warming. *Nature Climate Change*, **9**(2), 142-147, doi:10.1038/s41558-018-0370-z.

Atlas of Community-Based Monitoring in a Changing Arctic, Atlas of Community-Based Monitoring & Indigenous Knowledge in a Changing Arctic. Available at: https://arcticcbm.org/index.html.

Avila, C. et al., 2020: Invasive marine species discovered on non–native kelp rafts in the warmest Antarctic island. *Scientific Reports*, **10**(1), 1639, doi:10.1038/s41598-020-58561-y.

Babin, J., F. Lasserre and P. Pic, 2020: Arctic Shipping and Polar Seaways. In: *Encyclopedia of Water, Sciences, Technology and Society* [Maurice, P. A. (ed.)].

Bailey, A. et al., 2016: Early life stages of the Arctic copepod Calanus glacialis are unaffected by increased seawater pCO2. *ICES Journal of Marine Science*, **74**(4), 996-1004, doi:10.1093/icesjms/fsw066.

Ball, B. A. and J. Levy, 2015: The role of water tracks in altering biotic and abiotic soil properties and processes in a polar desert in Antarctica. *J. Geophys. Res.-Biogeosci.*, **120**(2), 270-279, doi:10.1002/2014jg002856.

Barange, M. et al., 2018: *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options*. Food and Agriculture Organization of the United Nations, Rome, 628 pp.

Barber, D. G. et al., 2018: Increasing Mobility of High Arctic Sea Ice Increases Marine Hazards Off the East Coast of Newfoundland. *Geophysical Research Letters*, **45**(5), 2370-2379, doi:10.1002/2017GL076587.

Barnes, D. K. A., 2017: Polar zoobenthos blue carbon storage increases with sea ice losses, because across-shelf growth gains from longer algal blooms outweigh ice scour mortality in the shallows. *Global Change Biology*, **23**(12), 5083-5091, doi:https://doi.org/10.1111/gcb.13772.
Barnhart, K. R., C. R. Miller, I. Overeem and J. E. Kay, 2016: Mapping the future expansion of Arctic open water. *Nature Climate Change*, **6**(3), 280-285, doi:10.1038/nclimate2848.
Bashaw, E., G. Hebeler, W. Phillips and G. Kane, 2016: Geologic and Subsea Permafrost Characterization for Buried Pipeline Design and Construction in the Alaskan Beaufort Sea. In: *Arctic Technology Conference*, 2016/10/24/, St. John's, Newfoundland and Labrador, Canada, Offshore Technology Conference, OTC, pp. 15, doi:10.4043/27450-MS.
Basyuk, E. and Y. Zuenko, 2020: Extreme oceanographic conditions in the northwestern Bering Sea in 2017–2018. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181-182**, 104909, doi:10.1016/j.dsr2.2020.104909.
Beaumier, M. C., J. D. Ford and S. Tagalik, 2015: The food security of Inuit women in Arviat, Nunavut: the role of socio-economic factors and climate change. *Polar Record*, **51**(5), 550-559, doi:10.1017/S0032247414000618.
Behrenfeld, M. J. and E. S. Boss, 2014: Resurrecting the Ecological Underpinnings of Ocean Plankton Blooms. *Annual Review of Marine Science*, **6**(1), 167-194, doi:10.1146/annurev-marine-052913-021325.
Behrenfeld, M. J. et al., 2017: Annual boom–bust cycles of polar phytoplankton biomass revealed by space-based lidar. *Nature Geoscience*, **10**(2), 118-122, doi:10.1038/ngeo2861.
Béné, C. et al., 2016: Contribution of Fisheries and Aquaculture to Food Security and Poverty Reduction: Assessing the Current Evidence. *World Development*, **79**, 177-196, doi:10.1016/j.worlddev.2015.11.007.
Bennett, M. M. et al., 2020: The opening of the Transpolar Sea Route: Logistical, geopolitical, environmental, and socioeconomic impacts. *Marine Policy*, 104178, doi:10.1016/j.marpol.2020.104178.
Bergstrom, D. M. et al., 2015: Rapid collapse of a sub-Antarctic alpine ecosystem: the role of climate and pathogens. *Journal of Applied Ecology*, **52**(3), 774-783, doi:10.1111/1365-2664.12436.
Bergstrom, D. M. et al., 2021: Combating ecosystem collapse from the tropics to the Antarctic. *Glob Chang Biol*, **27**(9), 1692-1703, doi:10.1111/gcb.15539.
Berner, J. et al., 2016: Adaptation in Arctic circumpolar communities: food and water security in a changing climate. *Int J Circumpolar Health*, **75**, 33820-33820, doi:10.3402/ijch.v75.33820.
Bestley, S. et al., 2020: Marine Ecosystem Assessment for the Southern Ocean: Birds and Marine Mammals in a Changing Climate. *Frontiers in Ecology and Evolution*, **8**, 338, doi:10.3389/fevo.2020.566936.
Betts, M., 2016: Zooarchaeology and the Reconstruction of Ancient Human-Animal Relationships in the Arctic. [Friesen, M. and O. Mason (eds.)]. Oxford University Press, pp. 1-32. ISBN 9780199766956.
Bieniek, P. A. et al., 2018: Assessment of Alaska Rain-on-Snow Events Using Dynamical Downscaling. *Journal of Applied Meteorology and Climatology*, **57**(8), 1847-1863, doi:10.1175/JAMC-D-17-0276.1.
Bilous, M. and K. Dunmall, 2020: Atlantic salmon in the Canadian Arctic: potential dispersal, establishment, and interaction with Arctic char. *Reviews in Fish Biology and Fisheries*, **30**(3), 463-483, doi:10.1007/s11160-020-09610-2.
Bindoff, N. L. et al., 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Birchall, J. S. and N. Bonnett, 2019: Thinning sea ice and thawing permafrost: climate change adaptation planning in Nome, Alaska. *Environmental Hazards*, 1-19, doi:10.1080/17477891.2019.1637331.
Birchenough, S. N. R. et al., 2015: Climate change and marine benthos: a review of existing research and future directions in the North Atlantic. *Wiley Interdisciplinary Reviews: Climate Change*, **6**(2), 203-223, doi:10.1002/wcc.330.
Biskaborn, B. K. et al., 2019: Permafrost is warming at a global scale. *Nature Communications*, **10**(1), 264, doi:10.1038/s41467-018-08240-4.
Bockstoce, J. R., 2018: *White Fox and Icy Seas in the Western Arctic: The Fur Trade, Transportation, and Change in the Early Twentieth Century*. Yale University Press, 344 pp. ISBN 9780300221794.
Bokhorst, S. and P. Convey, 2016: Impact of marine vertebrates on Antarctic terrestrial micro-arthropods. *Antarct. Sci.*, **28**(3), 175-186, doi:10.1017/s0954102015000607.
Bokhorst, S., P. Convey, A. Casanova-Katny and R. Aerts, 2021: Warming impacts potential germination of non-native plants on the Antarctic Peninsula. *Communications Biology*, **4**(1), 403, doi:10.1038/s42003-021-01951-3.
Boonstra, R. et al., 2020: The stress of Arctic warming on polar bears. *Global Change Biology*, **26**(8), 4197-4214, doi:https://doi.org/10.1111/gcb.15142.
Borghini, F., A. Colacevich, T. Caruso and R. Bargagli, 2016: Algal biomass and pigments along a latitudinal gradient in Victoria Land lakes, East Antarctica. *Polar Research*, **35**(1), 20703, doi:10.3402/polar.v35.20703.
Bouchard, C. and L. Fortier, 2020: The importance of Calanus glacialis for the feeding success of young polar cod: a circumpolar synthesis. *Polar Biology*, **43**(8), 1095-1107, doi:10.1007/s00300-020-02643-0.
Boveng, P. L., H. L. Ziel, B. T. McClintock and M. F. Cameron, 2020: Body condition of phocid seals during a period of rapid environmental change in the Bering Sea and Aleutian Islands, Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181-182**, 104904, doi:10.1016/j.dsr2.2020.104904.

Bramley-Alves, J., W. Wanek, K. French and S. A. Robinson, 2015: Moss delta(13) C: an accurate proxy for past water environments in polar regions. *Glob Chang Biol*, **21**(6), 2454-2464, doi:10.1111/gcb.12848.
Brasier, M. J. et al., 2021: Responses of Southern Ocean Seafloor Habitats and Communities to Global and Local Drivers of Change. *Frontiers in Marine Science*, **8**, 109, doi:10.3389/fmars.2021.622721.
Brattland, C. and T. Mustonen, 2018: How Traditional Knowledge Comes to Matter in Atlantic Salmon Governance in Norway and Finland. *Arctic*, **71**(4), 365-482, doi:10.14430/arctic4751.
Brinkman, T. et al., 2016: Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Climatic Change*, **139**(3-4), 413-427, doi:10.1007/s10584-016-1819-6.
Bröder, L. et al., 2018: Bounding cross-shelf transport time and degradation in Siberian-Arctic land-ocean carbon transfer. *Nature Communications*, **9**(1), 806, doi:10.1038/s41467-018-03192-1.
Bronen, R. and F. S. Chapin, 2013: Adaptive governance and institutional strategies for climate-induced community relocations in Alaska. *Proceedings of the National Academy of Sciences*, **110**(23), 9320, doi:10.1073/pnas.1210508110.
Brooks, C. M. et al., 2018: Watch over Antarctic waters. *Nature*, **558**(7709), 177-180.
Brown, D. R. N. et al., 2018: Changing River Ice Seasonality and Impacts on Interior Alaskan Communities. *Weather, Climate, and Society*, **10**(4), 625-640, doi:10.1175/WCAS-D-17-0101.1.
Bush, E. and D. S. Lemmen, 2019: *Canada's Changing Climate Report*. Government of Canada, Ottawa, ON, 444 pp. Available at: https://changingclimate.ca/CCCR2019/.
Caccavo, J. A. et al., 2021: Productivity and Change in Fish and Squid in the Southern Ocean. *Frontiers in Ecology and Evolution*, **9**, 351, doi:10.3389/fevo.2021.624918.
CAFF, 2013: *Arctic Biodiversity Assessment: Status and trends in Arctic biodiversity: Conservation of Arctic Flora and Fauna*. Akureyri, Iceland, 678 pp. Available at: https://www.caff.is/assessment-series/233-arctic-biodiversity-assessment-2013.
Calmels, F. et al. (eds.), How Permafrost Thaw May Impact Food Security of Jean Marie River First Nation, NWT. GEOQuebec 2015: Challenges from North to South, 2015.
Canadell, J. G. et al., 2021: *Global Carbon and other Biogeochemical Cycles and Feedbacks* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U.
Cannone, N. et al., 2017: Ecology of moss banks on Signy Island (maritime Antarctic). *Botanical Journal of the Linnean Society*, **184**(4), 518-533, doi:10.1093/botlinnean/box040.
Canosa, I. V. et al., 2020: Progress in climate change adaptation in the Arctic. *Environmental Research Letters*, **15**(9), 093009, doi:10.1088/1748-9326/ab9be1.
Casanova-Katny, A., G. A. Torres-Mellado and S. M. Eppley, 2016: Reproductive output of mosses under experimental warming on Fildes Peninsula, King George Island, maritime Antarctica. *Rev. Chil. Hist. Nat.*, **89**, 9, doi:10.1186/s40693-016-0061-y.
Casas-Prat, M. and X. L. Wang, 2020: Sea Ice Retreat Contributes to Projected Increases in Extreme Arctic Ocean Surface Waves. *Geophysical Research Letters*, **47**(15), e2020GL088100, doi:10.1029/2020GL088100.
Cavanagh, R. D. et al., 2021: Future Risk for Southern Ocean Ecosystem Services Under Climate Change. *Frontiers in Marine Science*, **7**, 1224, doi:10.3389/fmars.2020.615214.
Cavicchioli, R. et al., 2019: Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, **17**(9), 569-586, doi:10.1038/s41579-019-0222-5.
Čejka, T. et al., 2020: Timing of the neoglacial onset on the North-Eastern Antarctic Peninsula based on lacustrine archive from Lake Anónima, Vega Island. *Global and Planetary Change*, **184**, 103050, doi:10.1016/j.gloplacha.2019.103050.
Chakraborty, R. and P. Y. Sherpa, 2021: From climate adaptation to climate justice: Critical reflections on the IPCC and Himalayan climate knowledges. *Climatic Change*, **167**(3), 49, doi:10.1007/s10584-021-03158-1.
Chan, F. T. et al., 2019: Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. *Global Change Biology*, **25**(1), 25-38, doi:10.1111/gcb.14469.
Charman, D. J. et al., 2018: Spatially coherent late Holocene Antarctic Peninsula surface air temperature variability. *Geology*, **46**(12), 1071-1074, doi:10.1130/g45347.1.
Chen, X. and K.-K. Tung, 2018: Global surface warming enhanced by weak Atlantic overturning circulation. *Nature*, **559**(7714), 387-391, doi:10.1038/s41586-018-0320-y.
Chénier, R., L. Abado, O. Sabourin and L. Tardif, 2017: Northern marine transportation corridors: Creation and analysis of northern marine traffic routes in Canadian waters. *Transactions in GIS*, **21**(6), 1085-1097, doi:10.1111/tgis.12295.
Cherry, J. E. et al., 2017: Planning for climate change impacts on hydropower in the Far North. *Hydrology and Earth System Science*, **21**(1), 133-151, doi:10.5194/hess-21-133-2017.
Cheung, W. W. L., 2018: The future of fishes and fisheries in the changing oceans. *Journal of Fish Biology*, **92**(3), 790-803, doi:10.1111/jfb.13558.
Cheung, W. W. L. and T. L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, **10**(1), 6678, doi:10.1038/s41598-020-63650-z.

Chown, S. L. and C. M. Brooks, 2019: The State and Future of Antarctic Environments in a Global Context. *Annual Review of Environment and Resources*, **44**(1), 1-30, doi:10.1146/annurev-environ-101718-033236.
Christiansen, J. S., C. W. Mecklenburg and O. V. Karamushko, 2014: Arctic marine fishes and their fisheries in light of global change. *Global Change Biology*, **20**(2), 352-359, doi:10.1111/gcb.12395.
Cinner, J. E. et al., 2016: Bright spots among the world's coral reefs. *Nature*, **535**(7612), 416, doi:10.1038/nature18607.
Clark, D. G. and J. D. Ford, 2017: Emergency response in a rapidly changing Arctic. *Canadian Medical Association Journal*, **189**(4), E135, doi:10.1503/cmaj.161085.
Clark, D. G. et al., 2016a: The role of environmental factors in search and rescue incidents in Nunavut, Canada. *Public Health*, **137**, 44-49, doi:10.1016/j.puhe.2016.06.003.
Clark, D. G., J. D. Ford, T. Pearce and L. Berrang-Ford, 2016b: Vulnerability to unintentional injuries associated with land-use activities and search and rescue in Nunavut, Canada. *Social Science & Medicine*, **169**, 18-26, doi:10.1016/j.socscimed.2016.09.026.
Clayton, S., C. M. Manning, K. Krygsman and M. Speiser, 2017: *Mental Health and our Changing Climate: Impacts, Implications and Guidance*. American Psychological Association and ecoAmerica, Washington DC, 70 pp. Available at: https://www.apa.org/news/press/releases/2017/03/mental-health-climate.pdf.
Cline, T. J., J. Ohlberger and D. E. Schindler, 2019: Effects of warming climate and competition in the ocean for life-histories of Pacific salmon. *Nature Ecology and Evolution*, **3**(6), 935-942, doi:10.1038/s41559-019-0901-7.
Constable, A. J. et al., 2017: *ACE CRC Position Analysis: Managing changing in Southern Ocean ecosystems*. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia, 39 pp. Available at: http://wwwace.aappartnership.org.au/wp-content/uploads/2017/10/2017-ACECRC-Position-Analysis-Southern-Ocean-Ecosystems.pdf.
Convey, P. and L. S. Peck, 2019: Antarctic environmental change and biological responses. *Science Advances*, **5**(11), eaaz0888, doi:10.1126/sciadv.aaz0888.
Cornell, S. and J. P. Kalt, 1992: Reloading the Dice: Improving the chances for Economic Development on American Indian Reservations. In: *What Can Tribes Do? Strategies and Institutions in American Indian Economic Development* [Cornell, S. and J. P. Kalt (eds.)]. American Indian Studies Center, UCLA, Los Angeles, pp. 1-59.
Cornell, S. and J. P. Kalt, 1998: Sovereignty and Nation-Building: The Development Challenge in Indian Country Today. *American Indian Culture and Research Journal*, **22**(3), 187-214, doi:10.17953/aicr.22.3.lv45536553vn7j78.
Cornell, S. and J. P. Kalt, 2007: One Works, the Other Doesn't: Two Approaches to Economic Development on American Indian Reservations. In: *Rebuilding Native Nations: Strategies for Governance and Development* [Jorgensen, M. (ed.)]. University of Arizona Press.
Costello, C. et al., 2020: The future of food from the sea. *Nature*, doi:10.1038/s41586-020-2616-y.
Council of Canadian Academies, 2016: Commercial Marine Shipping Accidents: Understanding the Risks in Canada, Ottawa, ON, 168 pp.
Council of Canadian Academies, 2019: *Canada's Top Climate Change Risks*. The Expert Panel on Climate Change Risks and Adaptation Potential, Council of Canadian Academies, Ottawa, ON, 88 pp. Available at: https://cca-reports.ca/reports/prioritizing-climate-change-risks/.
Crate, S. et al., 2019: Cross-Chapter Box 4: Indigenous Knowledge and Local Knowledge in Ocean and Cryosphere Change. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. In press.
Cunsolo, A. and N. R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8**(4), 275-281, doi:10.1038/s41558-018-0092-2.
Cunsolo Willox, A. et al., 2013a: The land enriches the soul: On climatic and environmental change, affect, and emotional health and well-being in Rigolet, Nunatsiavut, Canada. *Emotion, Space and Society*, **6**, 14-24, doi:https://doi.org/10.1016/j.emospa.2011.08.005.
Cunsolo Willox, A. et al., 2013b: Climate change and mental health: an exploratory case study from Rigolet, Nunatsiavut, Canada. *Climatic Change*, **121**(2), 255-270, doi:10.1007/s10584-013-0875-4.
Cunsolo Willox, A. et al., 2014: Examining relationships between climate change and mental health in the Circumpolar North. *Regional Environmental Change*, **15**(1), 169-182, doi:10.1007/s10113-014-0630-z.
Curtis, P. G. et al., 2018: Classifying drivers of global forest loss. *Science*, **361**(6407), 1108-1111, doi:10.1126/science.aau3445.
Dahlke, F. T. et al., 2018: Northern cod species face spawning habitat losses if global warming exceeds 1.5°C. *Science Advances*, **4**(11), eaas8821, doi:10.1126/sciadv.aas8821.
Dahlke, F. T., S. Wohlrab, M. Butzin and H.-O. Pörtner, 2020: Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, **369**(6499), 65, doi:10.1126/science.aaz3658.
David-Chavez, D. M. and M. C. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environmental Research Letters*, **13**(12), 123005, doi:10.1088/1748-9326/aaf300.
Davidson, S. C. et al., 2020: Ecological insights from three decades of animal movement tracking across a changing Arctic. *Science*, **370**(6517), 712, doi:10.1126/science.abb7080.

Dawson, J. et al., 2020: Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. *Environmental Science & Policy*, **105**, 19-36, doi:https://doi.org/10.1016/j.envsci.2019.11.013.
Dawson, J. and et al., 2017: *Navigating Weather, Water, Ice and Climate Information for Safe Polar Mobilities*. **No. 5**, World Meteorological Organization and World Weather Research Programme, WWRP/PPP, 84 pp.
Dawson, J. et al., 2018a: Tourism. In: *Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region*. Arctic Monitoring and Assessment Programme (AMAP), pp. 223-242.
Dawson, J. et al., 2018b: Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. *Arctic*, **71**(1), 15-26, doi:10.2307/26387327.
Debortoli, N. S. et al., 2019: An integrative climate change vulnerability index for Arctic aviation and marine transportation. *Nature Communications*, **10**(1), doi:10.1038/s41467-019-10347-1.
Degen, R. et al., 2016: Patterns and drivers of megabenthic secondary production on the Barents Sea shelf. *Marine Ecology Progress Series*, **546**, 1-16, doi:doi: 10.3354/meps11662.
Dennis, P. G. et al., 2019: Soil bacterial diversity is positively associated with air temperature in the maritime Antarctic. *Scientific Reports*, **9**, 11, doi:10.1038/s41598-019-39521-7.
Dezutter, T. et al., 2019: Mismatch between microalgae and herbivorous copepods due to the record sea ice minimum extent of 2012 and the late sea ice break-up of 2013 in the Beaufort Sea. *Progress in Oceanography*, **173**, 66-77, doi:https://doi.org/10.1016/j.pocean.2019.02.008.
Ding, Q., X. Chen, R. Hilborn and Y. Chen, 2017: Vulnerability to impacts of climate change on marine fisheries and food security. *Marine Policy*, **83**, 55-61, doi:https://doi.org/10.1016/j.marpol.2017.05.011.
Dobson, A., P. K. Molnár and S. Kutz, 2015: Climate change and Arctic parasites. *Trends Parasitol*, **31**(5), 181-188, doi:10.1016/j.pt.2015.03.006.
Dodd, W. et al., 2018: Lived experience of a record wildfire season in the Northwest Territories, Canada. *Canadian Journal of Public Health*, **109**(3), 327-337, doi:10.17269/s41997-018-0070-5.
Dorn, M. W. and S. G. Zador, 2020: A risk table to address concerns external to stock assessments when developing fisheries harvest recommendations. *Ecosystem Health and Sustainability*, **6**(1), 1813634, doi:10.1080/20964129.2020.1813634.
Drewniak, M. et al., 2018: Geopolitics of Arctic shipping: the state of icebreakers and future needs. *Polar Geography*, **41**(2), 107-125, doi:10.1080/1088937X.2018.1455756.
Driscoll, D. L. et al., 2016: Assessing the health effects of climate change in Alaska with community-based surveillance. *Climatic Change*, **137**(3), 455-466, doi:10.1007/s10584-016-1687-0.
Duffy-Anderson, J. T. et al., 2019: Responses of the Northern Bering Sea and Southeastern Bering Sea Pelagic Ecosystems Following Record-Breaking Low Winter Sea Ice. *Geophysical Research Letters*, **46**(16), doi:10.1029/2019GL083396.
Durkalec, A., C. Furgal, M. W. Skinner and T. Sheldon, 2014: Investigating environmental determinants of injury and trauma in the Canadian north. *Int J Environ Res Public Health*, **11**(2), 1536-1548, doi:10.3390/ijerph110201536.
Durkalec, A., C. Furgal, M. W. Skinner and T. Sheldon, 2015: Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community. *Social Science & Medicine*, **136-137**, 17-26, doi:https://doi.org/10.1016/j.socscimed.2015.04.026.
Eguíluz, V. M., J. Fernández-Gracia, X. Irigoien and C. M. Duarte, 2016: A quantitative assessment of Arctic shipping in 2010–2014. *Scientific Reports*, **6**(1), 30682, doi:10.1038/srep30682.
Eliasson, K., G. F. Ulfarsson, T. Valsson and S. M. Gardarsson, 2017: Identification of development areas in a warming Arctic with respect to natural resources, transportation, protected areas, and geography. *Futures*, **85**, 14-29, doi:https://doi.org/10.1016/j.futures.2016.11.005.
Ericson, J. A. et al., 2018: Adult Antarctic krill proves resilient in a simulated high CO2 ocean. *Communications Biology*, **1**(1), 190, doi:10.1038/s42003-018-0195-3.
Ezhova, E. et al., 2021: Climatic Factors Influencing the Anthrax Outbreak of 2016 in Siberia, Russia. *EcoHealth*, doi:10.1007/s10393-021-01549-5.
Falkenberg, L. J. et al., 2018: Biological Response to ocean acidification. In: *AMAP Assessment 2018: Arctic Ocean Acidifcation* [AMAP (ed.)], Tromsø, Norway, pp. 15-43.
Fall, J. A. et al., 2013: Continuity and change in subsistence harvests in five Bering Sea communities: Akutan, Emmonak, Savoonga, St. Paul and Togiak. *Deep-Sea Research Part II*, **94**, 274-291, doi:10.1016/j.dsr2.2013.03.010.
FAO, 2020: *The State of the Worlds Fisheries and Aquaculture*. Sustainability in Action, Rome. Available at: http://www.fao.org/3/ca9229en/CA9229EN.pdf.
Farbotko, C. et al., 2020: Relocation planning must address voluntary immobility. *Nature Climate Change*, **10**(8), 702-704, doi:10.1038/s41558-020-0829-6.
Fedewa, E. J. et al., 2020: Recent shifts in northern Bering Sea snow crab (Chionoecetes opilio) size structure and the potential role of climate-mediated range contraction. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181-182**, 104878, doi:https://doi.org/10.1016/j.dsr2.2020.104878.
Feng, Z. et al., 2018: Biogeographic responses of the copepod Calanus glacialis to a changing Arctic marine environment. *Global Change Biology*, **24**(1), e159-e170, doi:10.1111/gcb.13890.

Fenger-Nielsen, R. et al., 2020: Arctic archaeological sites threatened by climate change: A regional multi-threat assessment of sites in south-west Greenland. *Archaeometry*, **n/a**(n/a), doi:10.1111/arcm.12593.
Feodoroff, P., 2021: Indigenous Female Bodies as Indicators of Change. In: *2021 Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change* [Mustonen, T., S. L. Harper, M. Rivera Ferre, J. Postigo, A. Ayanlade, T. Benjaminsen, R. Morgan and A. Okem (eds.)]. SnowChange Cooperative, Kontiolahti, Finland, pp. 1.
Fernández-Méndez, M. et al., 2018: Algal Hot Spots in a Changing Arctic Ocean: Sea-Ice Ridges and the Snow-Ice Interface. *Frontiers in Marine Science*, **5**, 75, doi:10.3389/fmars.2018.00075.
Figuerola, B. et al., 2021: A Review and Meta-Analysis of Potential Impacts of Ocean Acidification on Marine Calcifiers From the Southern Ocean. *Frontiers in Marine Science*, **8**, 24, doi:10.3389/fmars.2021.584445.
Fisher, M. C. et al., 2021: Climate shock effects and mediation in fisheries. *Proceedings of the National Academy of Sciences*, **118**(2), e2014379117, doi:10.1073/pnas.2014379117.
Flynn, M. et al., 2019: Evaluating the effectiveness of hazard mapping as climate change adaptation for community planning in degrading permafrost terrain. *Sustainability Science*, **14**(4), 1041-1056, doi:10.1007/s11625-018-0614-x.
Flynn, M., J. D. Ford, T. Pearce and S. L. Harper, 2018: Participatory scenario planning and climate change impacts, adaptation and vulnerability research in the Arctic. *Environmental Science & Policy*, **79**, 45-53, doi:https://doi.org/10.1016/j.envsci.2017.10.012.
Forbis, R. and K. Hayhoe, 2018: Does Arctic governance hold the key to achieving climate policy targets? *Environmental Research Letters*, **13**(2), 020201, doi:10.1088/1748-9326/aaa359.
Ford, J. and D. Clark, 2019: Preparing for the impacts of climate change along Canada's Arctic coast: The importance of search and rescue. *Marine Policy*, **108**, 103662, doi:https://doi.org/10.1016/j.marpol.2019.103662.
Ford, J. D. et al., 2016: Including indigenous knowledge and experience in IPCC assessment reports. *Nature Climate Change*, **6**(4), 349-353, doi:10.1038/nclimate2954.
Ford, J. D. et al., 2019: Changing access to ice, land and water in Arctic communities. *Nature Climate Change*, **9**(4), 335-339, doi:10.1038/s41558-019-0435-7.
Ford, J. D. et al., 2020: The Resilience of Indigenous Peoples to Environmental Change. *One Earth*, **2**(6), 532-543, doi:https://doi.org/10.1016/j.oneear.2020.05.014.
Ford, J. D. et al., 2017: Readiness for climate change adaptation in the Arctic: a case study from Nunavut, Canada. *Climatic Change*, **145**(1), 85-100, doi:10.1007/s10584-017-2071-4.
Ford, J. D., G. McDowell and J. Jones, 2014: The state of climate change adaptation in the Arctic. *Environmental Research Letters*, **9**(10), 104005, doi:10.1088/1748-9326/9/10/104005.
Ford, J. D., G. McDowell and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5**(12), 1046-1053, doi:10.1038/nclimate2723.
Ford, J. D., T. Pearce, I. V. Canosa and S. Harper, 2021: The rapidly changing Arctic and its societal implications. *WIREs Climate Change*, **n/a**(n/a), e735, doi:https://doi.org/10.1002/wcc.735.
Ford, J. D. et al., 2018: Preparing for the health impacts of climate change in Indigenous communities: The role of community-based adaptation. *Global Environmental Change*, **49**, 129-139, doi:https://doi.org/10.1016/j.gloenvcha.2018.02.006.
Ford, J. D., W. Vanderbilt and L. Berrang-Ford, 2012: Authorship in IPCC AR5 and its implications for content: climate change and Indigenous populations in WGII. *Climatic Change*, **113**(2), 201-213, doi:10.1007/s10584-011-0350-z.
Fox-Kemper, B. et al., 2021: *Ocean, Cryosphere and Sea Level Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U.
Frainer, A. et al., 2017: Climate-driven changes in functional biogeography of Arctic marine fish communities. *Proceedings of the National Academy of Sciences*, **114**(46), 12202, doi:10.1073/pnas.1706080114.
Frame, B. and A. D. Hemmings, 2020: Coronavirus at the end of the world: Antarctica matters. *Social Sciences & Humanities Open*, **2**(1), 100054, doi:https://doi.org/10.1016/j.ssaho.2020.100054.
Fraser, C. I., A. Morrison and P. Olmedo Rojas, 2020: Biogeographic Processes Influencing Antarctic and sub-Antarctic Seaweeds. In: *Antarctic Seaweeds* [Gómez, I. and P. Huovinen (eds.)]. Springer, pp. 43-57. ISBN 978-3-030-39448-6.
Fraser, C. I. et al., 2018: Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. *Nature Climate Change*, **8**(8), 704-708, doi:10.1038/s41558-018-0209-7.
Free, C. M. et al., 2019: Impacts of historical warming on marine fisheries production. *Science*, **363**(6430), 979, doi:10.1126/science.aau1758.
Freeman, N. M. and N. S. Lovenduski, 2015: Decreased calcification in the Southern Ocean over the satellite record. *Geophysical Research Letters*, **42**(6), 1834-1840, doi:10.1002/2014GL062769.
Friesen, T. M., 2015: The Arctic CHAR Project: climate Change Impacts on the Inuvialuit Archaeological Record. *Archéologie boréale*, **141**, 31-37, doi:https://doi.org/10.4000/nda.3098.

Fritz, M., J. E. Vonk and H. Lantuit, 2017: Collapsing Arctic coastlines. *Nature Climate Change*, **7**(1), 6-7, doi:10.1038/nclimate3188.
Fuentes-Lillo, E., M. Cuba-Diaz and S. Rifo, 2017: Morpho-physiological response of Colobanthus quitensis and Juncus bufonius under different simulations of climate change. *Polar Sci.*, **11**, 11-18, doi:10.1016/j.polar.2016.11.003.
Furberg, M., M. Evengard B Fau - Nilsson and M. Nilsson, 2011: Facing the limit of resilience: perceptions of climate change among reindeer herding Sami in Sweden. *Global Health Action*, **4**(1654-9880 (Electronic)), doi:10.3402/gha.v4i0.8417.
Gädeke, A. et al., 2021: Climate change reduces winter overland travel across the Pan-Arctic even under low-end global warming scenarios. *Environmental Research Letters*, **16**(2), 024049, doi:10.1088/1748-9326/abdcf2.
Galappaththi, E. K., J. D. Ford, E. M. Bennett and F. Berkes, 2019: Climate change and community fisheries in the arctic: A case study from Pangnirtung, Canada. *Journal of Environmental Management*, **250**, 109534, doi:https://doi.org/10.1016/j.jenvman.2019.109534.
García Criado, M. et al., 2020: Woody plant encroachment intensifies under climate change across tundra and savanna biomes. *Global Ecology and Biogeography*, **29**(5), 925-943, doi:10.1111/geb.13072.
Gavin, M. C. et al., 2018: The global geography of human subsistence. *Royal Society Open Science*, **5**(9), doi:10.1098/rsos.171897.
George, J. C. et al., 2017: Frequency of Injuries from Line Entanglements, Killer Whales, and Ship Strikes on Bering-Chukchi-Beaufort Seas Bowhead Whales. *Arctic*, **70**(1), 37-37, doi:10.14430/arctic4631.
Goldsworthy, L. and E. Brennan, 2021: Climate change in the Southern Ocean: Is the Commission for the Convention for the Conservation of Antarctic Marine Living Resources doing enough? *Marine Policy*, **130**, 104549, doi:https://doi.org/10.1016/j.marpol.2021.104549.
Gooseff, M. N. et al., 2017: Decadal ecosystem response to an anomalous melt season in a polar desert in Antarctica. *Nature Ecology & Evolution*, **1**(9), 1334-1338, doi:10.1038/s41559-017-0253-0.
Grant, S. M. et al., 2021: Local Drivers of Change in Southern Ocean Ecosystems: Human Activities and Policy Implications. *Frontiers in Ecology and Evolution*, **9**, 365, doi:10.3389/fevo.2021.624518.
Grebmeier, J. M., K. E. Frey, L. W. Cooper and M. Kedra, 2018: Trends in Benthic Macrofaunal Populations, Seasonal Sea Ice Persistence, and Bottom Water Temperatures in the Bering Strait Region. *Oceanography*, **31**(2), 136-151, doi:https://doi.org/10.5670/oceanog.2018.224.
Gregg, W. W. and C. S. Rousseaux, 2019: Global ocean primary production trends in the modern ocean color satellite record (1998–2015). *Environmental Research Letters*, **14**(12), 124011, doi:10.1088/1748-9326/ab4667.
Grjibovski, A. M. et al., 2013: Climate variations and salmonellosis in northwest Russia: a time-series analysis. *Epidemiol Infect*, **141**(2), 269-276, doi:10.1017/s0950268812000544.
Groulx, M., K. Boluk, C. J. Lemieux and J. Dawson, 2019: Place stewardship among last chance tourists. *Annals of Tourism Research*, **75**, 202-212, doi:https://doi.org/10.1016/j.annals.2019.01.008.
Grüss, A. et al., 2020: Estimating synchronous changes in condition and density in eastern Bering Sea fishes. *Marine Ecology Progress Series*, **635**, 169-185.
Guglielmin, M., M. D. Fratte and N. Cannone, 2014: Permafrost warming and vegetation changes in continental Antarctica. *Environmental Research Letters*, **9**(4), 14, doi:10.1088/1748-9326/9/4/045001.
Gulev, S. K. et al., 2021: *Changing State of the Climate System* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U.
Gullestad, P., S. Sundby and O. S. Kjesbu, 2020: Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution. *Fish and Fisheries*, **21**(5), 1008-1026, doi:10.1111/faf.12485.
Gutiérrez, J. M. et al., 2021: *Atlas* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U.
Gutt, J. et al., 2018: Cross-disciplinarity in the advance of Antarctic ecosystem research. *Marine Genomics*, **37**, 1-17, doi:10.1016/j.margen.2017.09.006.
Gutt, J. et al., 2021: Antarctic ecosystems in transition – life between stresses and opportunities. *Biological Reviews*, **96**(3), 798-821, doi:https://doi.org/10.1111/brv.12679.
Haas, C. and S. E. L. Howell, 2015: Ice thickness in the Northwest Passage. *Geophysical Research Letters*, **42**(18), 7673-7680, doi:10.1002/2015GL065704.
Haasnoot, M. et al., 2020: Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, **20**(2), 37, doi:10.1007/s10113-020-01623-8.
Haavisto, R. et al., 2020: Mapping weather, water, ice and climate (WWIC) information providers in Polar Regions: who are they and who do they serve? *Polar Geography*, **43**(2-3), 120-138, doi:10.1080/1088937X.2019.1707320.

Halbach, L. et al., 2019: Tidewater Glaciers and Bedrock Characteristics Control the Phytoplankton Growth Environment in a Fjord in the Arctic. *Frontiers in Marine Science*, **6**, 254, doi:10.3389/fmars.2019.00254.
Halliday, W. D. et al., 2017: Potential impacts of shipping noise on marine mammals in the western Canadian Arctic. *Mar Pollut Bull*, **123**(1-2), 73-82, doi:10.1016/j.marpolbul.2017.09.027.
Hamilton, C. D. et al., 2017: An Arctic predator–prey system in flux: climate change impacts on coastal space use by polar bears and ringed seals. *Journal of Animal Ecology*, **86**(5), 1054-1064, doi:10.1111/1365-2656.12685.
Hamilton, L. C. et al., 2016: Climigration? Population and climate change in Arctic Alaska. *Population and Environment*, **38**(2), 115-133, doi:10.1007/s11111-016-0259-6.
Hancock, A. M. et al., 2020: Effects of ocean acidification on Antarctic marine organisms: A meta-analysis. *Ecology and Evolution*, **10**(10), 4495-4514, doi:10.1002/ece3.6205.
Hansen, K. M. et al., 2015: Modelling the impact of climate change on the atmospheric transport and the fate of persistent organic pollutants in the Arctic. *Atmos. Chem. Phys.*, **15**(11), 6549-6559, doi:10.5194/acp-15-6549-2015.
Harper, S. L. et al., 2021: Trends and gaps in climate change and health research in North America. *Environmental Research*, **199**, 111205, doi:https://doi.org/10.1016/j.envres.2021.111205.
Harper, S. L. et al., 2015: Climate-sensitive health priorities in Nunatsiavut, Canada. *BMC Public Health*, **15**(1), 605, doi:10.1186/s12889-015-1874-3.
Harper, S. L., C. Wright, S. Masina and S. Coggins, 2020: Climate change, water, and human health research in the Arctic. *Water Security*, **10**, 100062, doi:https://doi.org/10.1016/j.wasec.2020.100062.
Hauck, J., A. Lenton, C. Langlais and R. Matear, 2018: The Fate of Carbon and Nutrients Exported Out of the Southern Ocean. *Global Biogeochemical Cycles*, **32**(10), 1556-1573, doi:10.1029/2018GB005977.
Hauser, D. D. W., K. L. Laidre and H. L. Stern, 2018: Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. *Proceedings of the National Academy of Sciences*, **115**(29), 7617, doi:10.1073/pnas.1803543115.
Hayes, K. et al., 2018: Climate change and mental health: risks, impacts and priority actions. *International Journal of Mental Health Systems*, **12**(1), 28, doi:10.1186/s13033-018-0210-6.
Haynie, A. C. and H. P. Huntington, 2016: Strong connections, loose coupling: the influence of the Bering Sea ecosystem on commercial fisheries and subsistence harvests in Alaska. *Ecology and Society*, **21**(4), doi:http://dx.doi.org/10.5751/ES-08729-210406.
Henley, S. F. et al., 2020: Changing Biogeochemistry of the Southern Ocean and Its Ecosystem Implications. *Frontiers in Marine Science*, **7**, 581, doi:10.3389/fmars.2020.00581.
Hermann, A. J. et al., 2019: Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. *ICES Journal of Marine Science*, **76**(5), 1280-1304, doi:10.1093/icesjms/fsz043.
Hicks, C. C. et al., 2019: Harnessing global fisheries to tackle micronutrient deficiencies. *Nature*, **574**(7776), 95-98, doi:10.1038/s41586-019-1592-6.
Hill, R. et al., 2020: Working with Indigenous, local and scientific knowledge in assessments of nature and nature's linkages with people. *Current Opinion in Environmental Sustainability*, **43**, 8-20, doi:https://doi.org/10.1016/j.cosust.2019.12.006.
Hillerdal, C., R. Knecht and W. Jones, 2019: Nunalleq: Archaeology, Climate Change, and Community Engagement in a Yup'ik Village. *Arctic Anthropology*, **56**(1), 4-17, doi:10.3368/aa.56.1.4.
Hindell, M. A. et al., 2020: Tracking of marine predators to protect Southern Ocean ecosystems. *Nature*, **580**(7801), 87-92, doi:10.1038/s41586-020-2126-y.
Hjort, J. et al., 2018: Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications*, **9**(1), doi:10.1038/s41467-018-07557-4.
Holland, D. S. et al., 2017: Impact of catch shares on diversification of fishers' income and risk. *Proceedings of the National Academy of Sciences*, **114**(35), 9302-9307, doi:https://doi.org/10.1073/pnas.1702382114.
Hollesen, J. et al., 2018: Climate change and the deteriorating archaeological and environmental archives of the Arctic. *Antiquity*, **92**(363), 573-586, doi:10.15184/aqy.2018.8.
Hollesen, J. et al., 2016: Climate change and the loss of organic archaeological deposits in the Arctic. *Scientific Reports*, **6**(1), 28690, doi:10.1038/srep28690.
Hollowed, A. B. et al., 2020: Integrated Modeling to Evaluate Climate Change Impacts on Coupled Social-Ecological Systems in Alaska. *Frontiers in Marine Science*, **6**, 775, doi:10.3389/fmars.2019.00775.
Holsman, K. K. et al., 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11**(1), 4579, doi:10.1038/s41467-020-18300-3.
Hoppe, C. J. M. et al., 2013: Iron Limitation Modulates Ocean Acidification Effects on Southern Ocean Phytoplankton Communities. *PLOS ONE*, **8**(11), e79890, doi:10.1371/journal.pone.0079890.
Hoppe, C. J. M., L.-M. Holtz, S. Trimborn and B. Rost, 2015: Ocean acidification decreases the light-use efficiency in an Antarctic diatom under dynamic but not constant light. *New Phytologist*, **207**(1), 159-171, doi:10.1111/nph.13334.
Hopwood, M. J. et al., 2018: Non-linear response of summertime marine productivity to increased meltwater discharge around Greenland. *Nature Communications*, **9**(1), 3256, doi:10.1038/s41467-018-05488-8.
Hopwood, M. J. et al., 2020: Review article: How does glacier discharge affect marine biogeochemistry and primary production in the Arctic? *Cryosphere*, **14**(4), 1347-1383, doi:10.5194/tc-14-1347-2020.

Hori, Y. et al., 2018a: Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic Change*, **148**(1), 109-122, doi:10.1007/S10584-018-2178-2.
Hori, Y., W. A. Gough, B. Tam and L. J. S. Tsuji, 2018b: Community vulnerability to changes in the winter road viability and longevity in the western James Bay region of Ontario's Far North. *Regional Environmental Change*, **18**(6), 1753-1763, doi:10.1007/S10113-018-1310-1.
Howell, S. E. L. and M. Brady, 2019: The Dynamic Response of Sea Ice to Warming in the Canadian Arctic Archipelago. *Geophysical Research Letters*, **46**(22), 13119-13125, doi:10.1029/2019GL085116.
Hückstädt, L. A. et al., 2020: Projected shifts in the foraging habitat of crabeater seals along the Antarctic Peninsula. *Nature Climate Change*, **10**(5), 472-477, doi:10.1038/s41558-020-0745-9.
Hudson, A. and K. Vodden, 2020: Decolonizing Pathways to Sustainability: Lessons Learned from Three Inuit Communities in NunatuKavut, Canada. *Sustainability*, **12**(11), doi:10.3390/su12114419.
Hughes, K. A. et al., 2018: Antarctic environmental protection: Strengthening the links between science and governance. *Environmental Science & Policy*, **83**, 86-95, doi:https://doi.org/10.1016/j.envsci.2018.02.006.
Hughes, L., 2018: Relationships with Arctic indigenous peoples: To what extent has prior informed consent become a norm? *Review of European, Comparative & International Environmental Law*, **27**(1), 15-27, doi:10.1111/reel.12232.
Huntington, H. P. et al., 2017: How small communities respond to environmental change: patterns from tropical to polar ecosystems. *Ecology and Society*, **22**(3), 9.
Huntington, H. P. et al., 2013: Local and traditional knowledge regarding the Bering Sea ecosystem: Selected results from five indigenous communities. *Deep Sea Research Part II: Topical Studies in Oceanography*, **94**, 323-332, doi:https://doi.org/10.1016/j.dsr2.2013.04.025.
Huntington, H. P. et al., 2019: Climate change in context: putting people first in the Arctic. *Regional Environmental Change*, **19**(4), 1217-1223, doi:10.1007/s10113-019-01478-8.
Huntington, H. P. et al., 2015: Vessels, risks, and rules: Planning for safe shipping in Bering Strait. *Marine Policy*, **51**, 119-127, doi:https://doi.org/10.1016/j.marpol.2014.07.027.
Huntington, H. P. et al., 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10**(4), 342-348, doi:10.1038/s41558-020-0695-2.
Huntington, H. P., L. T. Quakenbush and M. Nelson, 2016: Effects of changing sea ice on marine mammals and subsistence hunters in northern Alaska from traditional knowledge interviews. *Biology Letters*, **12**(8), 20160198, doi:10.1098/rsbl.2016.0198.
Huntington, H. P. et al., 2021: Societal implications of a changing Arctic Ocean. *Ambio*, doi:10.1007/s13280-021-01601-2.
IAATO, Information and Resources, International Association of Antarctic Tour Operators. Available at: https://iaato.org/information-resources/.
Inuit Circumpolar Council, 2017: *People of the Ice Bridge: The Future of the Pikialasorsuaq*. Available at: http://pikialasorsuaq.org/en/Resources/Reports.
Inuit Circumpolar Council Alaska, 2020: *Food Sovereignty and Self-Governance: Inuit Role in Managing Arctic Marine Resources*. Anchorage, AK., 144 pp. Available at: https://www.inuitcircumpolar.com/project/food-sovereignty-and-self-governance-inuit-role-in-managing-arctic-marine-resources/.
IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp. ISBN 9781107058163.
IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)]. In press pp.
IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Press, C. U. Available at: https://www.ipcc.ch/report/ar6/wg1/#FullReport.
Irannezhad, M., J. Liu, B. Ahmadi and D. Chen, 2020: The dangers of Arctic zombie wildfires. *Science*, **369**(6508), 1171.1172-1171, doi:10.1126/science.abe1739.
Irrgang, A. et al., 2019: Impacts of past and future coastal changes on the Yukon coast - threats for cultural sites, infrastructure and travel routes. *Arctic Science*, **5**(2), 107-126, doi:doi: 10.1139/as-2017-0041.
ITK, 2019: *National Inuit Climate Change Strategy*. Inuit Tapiriit Kanatami, 48 pp. Available at: https://www.itk.ca/wp-content/uploads/2019/06/ITK_Climate-Change-Strategy_English.pdf.
Iturbide, M. et al., 2021: Repository supporting the implementation of FAIR principles in the IPCC-WG1 Atlas, Zenodo. Available at: https://github.com/IPCC-WG1/Atlas.

Jaakkola, J. J. K., S. Juntunen and K. Näkkäläjärvi, 2018: The Holistic Effects of Climate Change on the Culture, Well-Being, and Health of the Saami, the Only Indigenous People in the European Union. *Current Environmental Health Reports*, **5**(4), 401-417, doi:10.1007/s40572-018-0211-2.

Jacobsen, R. B., R. B. Hedeholm, D. Robert and L. Wheeland, 2018: Sustainable Fisheries. In: *Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, pp. 163-176. ISBN 978-82-7971-105-6.

Jenouvrier, S. et al., 2021: The call of the emperor penguin: Legal responses to species threatened by climate change. *Global Change Biology*, **n/a**(n/a), doi:https://doi.org/10.1111/gcb.15806.

Jenouvrier, S. et al., 2020: The Paris Agreement objectives will likely halt future declines of emperor penguins. *Global Change Biology*, **26**(3), 1170-1184, doi:https://doi.org/10.1111/gcb.14864.

Jensen, A. M., 2020: Critical information for the study of ecodynamics and socio-natural systems: Rescuing endangered heritage and data from Arctic Alaskan Coastal sites. *Quaternary International*, **549**, 227-238, doi:10.1016/j.quaint.2019.05.001.

Johnson, A. C. and A. E. Derocher, 2020: Variation in habitat use of Beaufort Sea polar bears. *Polar Biology*, **43**(9), 1247-1260, doi:10.1007/s00300-020-02705-3.

Johnston, M., J. Dawson, E. De Souza and E. J. Stewart, 2017: Management challenges for the fastest growing marine shipping sector in Arctic Canada: pleasure crafts. *Polar Record*, **53**(1), 67-78, doi:10.1017/S0032247416000565.

Jones, M., C. et al., 2020: High sensitivity of Bering Sea winter sea ice to winter insolation and carbon dioxide over the last 5500 years. *Science Advances*, **6**(36), eaaz9588, doi:10.1126/sciadv.aaz9588.

Jones, T. et al., 2019: Unusual mortality of Tufted puffins (Fratercula cirrhata) in the eastern Bering Sea. *PLOS ONE*, **14**(5), e0216532, doi:10.1371/journal.pone.0216532.

Jørgensen, L. L. et al., 2019: Impact of multiple stressors on sea bed fauna in a warming Arctic. *Marine Ecology Progress Series*, **608**, 1-12, doi:10.3354/meps12803.

Jorgenson, M., 2007: *Rebuilding Native Nations: Strategies for Governance and Development*. The University of Arizona Press. ISBN 9780816524235.

Kahru, M., Z. Lee and B. G. Mitchell, 2017: Contemporaneous disequilibrium of bio-optical properties in the Southern Ocean. *Geophysical Research Letters*, **44**(6), 2835-2842, doi:10.1002/2016GL072453.

Karp, M. A. et al., 2019: Accounting for shifting distributions and changing productivity in the development of scientific advice for fishery management. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsz048.

Kasperski, S. and D. S. Holland, 2013: Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences*, **110**(6), 2076-2081, doi:10.1073/pnas.1212278110.

Kawaguchi, S. et al., 2013: Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Climate Change*, **3**(9), 843-847, doi:10.1038/nclimate1937.

Kearney, K. et al., 2020: A coupled pelagic–benthic–sympagic biogeochemical model for the Bering Sea: documentation and validation of the BESTNPZ model (v2019.08.23) within a high-resolution regional ocean model. *Geosci. Model Dev.*, **13**(2), 597-650, doi:10.5194/gmd-13-597-2020.

Kelman, I. and M. W. Næss, 2019: Climate Change and Migration for Scandinavian Saami: A Review of Possible Impacts. *Climate*, **7**(4), doi:10.3390/cli7040047.

Keogan, K. et al., 2018: Global phenological insensitivity to shifting ocean temperatures among seabirds. *Nature Climate Change*, **8**(4), 313-318, doi:10.1038/s41558-018-0115-z.

Kharouba, H. M. and E. M. Wolkovich, 2020: Disconnects between ecological theory and data in phenological mismatch research. *Nature Climate Change*, **10**(5), 406-415, doi:10.1038/s41558-020-0752-x.

Khon, V. C., I. I. Mokhov and V. A. Semenov, 2017: Transit navigation through Northern Sea Route from satellite data and CMIP5 simulations. *Environmental Research Letters*, **12**, 024010, doi:10.1088/1748-9326/aa5841.

Kiani, S. et al., 2018: Effects of recent temperature variability and warming on the Oulu-Hailuoto ice road season in the northern Baltic Sea. *Cold Regions Science and Technology*, **151**, 1-8, doi:https://doi.org/10.1016/j.coldregions.2018.02.010.

Kim, B. F. et al., 2020: Country-specific dietary shifts to mitigate climate and water crises. *Global Environmental Change*, **62**, 101926, doi:https://doi.org/10.1016/j.gloenvcha.2019.05.010.

Kim, D. et al., 2018: Passive warming effect on soil microbial community and humic substance degradation in maritime Antarctic region. *J. Basic Microbiol.*, **58**(6), 513-522, doi:10.1002/jobm.201700470.

Kimmel, D. G., L. B. Eisner, M. T. Wilson and J. T. Duffy-Anderson, 2018: Copepod dynamics across warm and cold periods in the eastern Bering Sea: Implications for walleye pollock (Gadus chalcogrammus) and the Oscillating Control Hypothesis. *Fisheries Oceanography*, **27**(2), 143-158, doi:10.1111/fog.12241.

King, M. et al., 2018: Northward shift of the agricultural climate zone under 21st-century global climate change. *Scientific Reports*, **8**(1), 7904, doi:10.1038/s41598-018-26321-8.

Klein, E. S. et al., 2018: Impacts of rising sea temperature on krill increase risks for predators in the Scotia Sea. *PLOS ONE*, **13**(1), e0191011, doi:10.1371/journal.pone.0191011.

Knies, J. et al., 2014: The emergence of modern sea ice cover in the Arctic Ocean. *Nature Communications*, **5**(1), 5608, doi:10.1038/ncomms6608.

Knox, M. A. et al., 2016: Impact of diurnal freeze-thaw cycles on the soil nematode Scottnema lindsayae in Taylor Valley, Antarctica. *Polar Biology*, **39**(4), 583-592, doi:10.1007/s00300-015-1809-6.

Kochtubajda, B., C. Mooney and R. Stewart, 2017: Characteristics, atmospheric drivers and occurrence patterns of freezing precipitation and ice pellets over the Prairie Provinces and Arctic Territories of Canada: 1964–2005. *Atmospheric Research*, **191**, 115-127, doi:https://doi.org/10.1016/j.atmosres.2017.03.005.

Koivurova, T. et al., 2015: Legal Protection of Sami Traditional Livelihoods from the Adverse Impacts of Mining: A Comparison of the Level of Protection Enjoyed by Sami in Their Four Home States. *Arctic Review*, **6**(1), doi:10.17585/arctic.v6.76.

Kowalczewski, E. and J. Klein, 2018: Sámi youth health, the role of climate change, and unique health-seeking behaviour. *Int J Circumpolar Health*, **77**(1), 1454785, doi:10.1080/22423982.2018.1454785.

Krause-Jensen, D. et al., 2020: Imprint of Climate Change on Pan-Arctic Marine Vegetation. *Frontiers in Marine Science*, **7**, 1129, doi:10.3389/fmars.2020.617324.

Ksenofontov, S., N. Backhaus and G. Schaepman-Strub, 2017: 'To fish or not to fish?': fishing communities of Arctic Yakutia in the face of environmental change and political transformations. *Polar Record*, **53**(3), 289-303, doi:10.1017/S0032247417000134.

Kwiatkowski, L. et al., 2020: Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences*, **17**(13), 3439-3470, doi:10.5194/bg-17-3439-2020.

Kwok, R., 2018: Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). *Environmental Research Letters*, **13**(10), 105005, doi:10.1088/1748-9326/aae3ec.

Labbé, J., J. D. Ford, M. Araos and M. Flynn, 2017: The government-led climate change adaptation landscape in Nunavut, Canada. *Environmental Reviews*, **25**(1), 12-25, doi:10.1139/er-2016-0032.

Lader, R., J. E. Walsh, U. S. Bhatt and P. A. Bieniek, 2018: Agro-Climate Projections for a Warming Alaska. *Earth Interactions*, **22**(18), 1-24, doi:10.1175/EI-D-17-0036.1.

Lannuzel, D. et al., 2020: The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems. *Nature Climate Change*, **10**(11), 983-992, doi:10.1038/s41558-020-00940-4.

Lantz, T. C. et al., 2020: Mapping Exposure to Flooding in Three Coastal Communities on the North Slope of Alaska Using Airborne LiDAR. *Coastal Management*, **48**(2), 96-117, doi:10.1080/08920753.2020.1732798.

Larsen, J. N. and A. N. Petrov, 2020: The Economy of the Arctic. In: *The Palgrave Handbook of Arctic Policy and Politics* [Coates, K. S. and C. Holroyd (eds.)]. Springer International Publishing, Cham, pp. 79-95. ISBN 978-3-030-20557-7.

Laurel, B. J., M. Spencer, P. Iseri and L. A. Copeman, 2016: Temperature-dependent growth and behavior of juvenile Arctic cod (Boreogadus saida) and co-occurring North Pacific gadids. *Polar Biology*, **39**(6), 1127-1135, doi:10.1007/s00300-015-1761-5.

Lauta, K. C., M. T. Vendelø, B. R. Sørensen and R. Dahlberg, 2018: Conceptualizing cold disasters: Disaster risk governance at the Arctic edge. *International Journal of Disaster Risk Reduction*, **31**, 1276-1282, doi:https://doi.org/10.1016/j.ijdrr.2017.12.011.

Lee, J.-Y. et al., 2021: *Future Global Climate: Scenario-Based Projections and Near-Term Information* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U.

Lee, K. C. et al., 2018: Stochastic and deterministic effects of a moisture gradient on soil microbial communities in the McMurdo Dry Valleys of Antarctica. *Frontiers in Microbiology*, **9**(2619), doi:10.3389/fmicb.2018.02619.

Lemmen, D. S., F. J. Warren, T. S. James and C. S. L. Mercer Clarke, 2016: *Canada's Marine Coasts in a Changing Climate*. Natural Resources Canada, Ottawa, ON, 274 pp. Available at: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/files/pdf/NRCAN_fullBook%20%20accessible.pdf.

Li, X., N. Otsuka and L. W. Brigham, 2020: Spatial and temporal variations of recent shipping along the Northern Sea Route. *Polar Sci.*, 100569, doi:https://doi.org/10.1016/j.polar.2020.100569.

Lin, Y. et al., 2021: Decline in plankton diversity and carbon flux with reduced sea ice extent along the Western Antarctic Peninsula. *Nature Communications*, **12**(1), 4948, doi:10.1038/s41467-021-25235-w.

Liskova, E. A. et al., 2021: Reindeer Anthrax in the Russian Arctic, 2016: Climatic Determinants of the Outbreak and Vaccination Effectiveness. *Frontiers in Veterinary Science*, **8**, 486, doi:10.3389/fvets.2021.668420.

Ljungström, G., T. J. Langbehn and C. Jørgensen, 2021: Light and energetics at seasonal extremes limit poleward range shifts. *Nature Climate Change*, **11**(6), 530-536, doi:10.1038/s41558-021-01045-2.

Llort, J., M. Lévy, J. B. Sallée and A. Tagliabue, 2019: Nonmonotonic Response of Primary Production and Export to Changes in Mixed-Layer Depth in the Southern Ocean. *Geophysical Research Letters*, **46**(6), 3368-3377, doi:10.1029/2018GL081788.

Lloyd's, 2012: *Arctic Opening: Opportunity and Risk in the High North*. Lloyd's, London, 60 pp. Available at: https://www.lloyds.com/~/media/Files/news-and-insight/360-risk-insight/arctic_risk_report_webview.pdf.

Loisel, J. et al., 2017: Peatland ecosystem processes in the Maritime Antarctic during warm climates. *Scientific Reports*, **7**, 9, doi:10.1038/s41598-017-12479-0.

Long, M., A.-K. S. Knudsen, H. S. Pedersen and E. C. Bonefeld-Jørgensen, 2015: Food intake and serum persistent organic pollutants in the Greenlandic pregnant women: The ACCEPT sub-study. *Sci. Total Environ.*, **529**, 198-212, doi:https://doi.org/10.1016/j.scitotenv.2015.05.022.
Lorenzo, C. et al., 2020: Antarctica and the COVID-19 Pandemic: Taking a Social Sciences and Humanities Perspective, 116-119 pp.
Loring, P. A., S. C. Gerlach and H. J. Penn, 2016: "Community Work" in a Climate of Adaptation: Responding to Change in Rural Alaska. *Human Ecology*, **44**(1), 119-128, doi:10.1007/s10745-015-9800-y.
Loseto, L. L. et al., 2018: Beluga whales (Delphinapterus leucas), environmental change and marine protected areas in the Western Canadian Arctic. *Estuarine, Coastal and Shelf Science*, **212**(April), 128-137, doi:10.1016/j.ecss.2018.05.026.
Lotze, H. K. et al., 2018: Ensemble projections of global ocean animal biomass with climate change. *bioRxiv*, 467175, doi:10.1101/467175.
Lovejoy, C. et al., 2017: Plankton. In: *State of the Arctic Marine Biodiversity Report* [Barry, T., C. Price, M. Olsen, T. Christensen and M. Frederiksen (eds.)]. Council of Arctic Flora and Fauna (CAFF) International Secretariat, Akureyri, Iceland, pp. 63-80.
Lowther, A. D., A. Fisk, K. M. Kovacs and C. Lydersen, 2017: Interdecadal changes in the marine food web along the west Spitsbergen coast detected in the stable isotope composition of ringed seal (Pusa Hispida) whiskers. *Polar Biology*, **40**(10), 2027-2033, doi:doi:10.1007/s00300-017-2122-3.
Lydersen, C. et al., 2017: Novel terrestrial haul-out behaviour by ringed seals (Pusa hispida) in Svalbard, in association with harbour seals (Phoca vitulina). *Polar Research*, **36**(1), 1374124, doi:10.1080/17518369.2017.1374124.
Lynham, J. et al., 2017: Costly stakeholder participation creates inertia in marine ecosystems. *Marine Policy*, **76**, 122-129, doi:https://doi.org/10.1016/j.marpol.2016.11.011.
Lyons, O., 2020: *Value Change for Survival*. American Indian Institute, 1 pp. Available at: https://www.twocircles.org/files/pdf/Value_Change_for_Survival.pdf.
Macaya, E. C., F. Tala, I. A. Hinojosa and E. Roth äusler, 2020: Detached Seaweeds as Important Dispersal Agents Across the Southern Ocean. In: *Antarctic Seaweeds* [Gómez, I. and P. Huovinen (eds.)]. Springer, pp. 59-81. ISBN 978-3-030-39448-6.
Maduna, S. N. et al., 2021: Sea ice reduction drives genetic differentiation among Barents Sea polar bears. *Proceedings of the Royal Society B: Biological Sciences*, **288**(1958), 20211741, doi:10.1098/rspb.2021.1741.
Maekakuchi, M. et al., 2020: Abundance, horizontal and vertical distribution of epipelagic ctenophores and scyphomedusae in the northern Bering Sea in summer 2017 and 2018: Quantification by underwater video imaging analysis. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181-182**, 104818, doi:https://doi.org/10.1016/j.dsr2.2020.104818.
Marino, E. and H. Lazrus, 2015: Migration or Forced Displacement?: The Complex Choices of Climate Change and Disaster Migrants in Shishmaref, Alaska and Nanumea, Tuvalu. *Human Organization*, **74**(4), 341-350, doi:10.17730/0018-7259-74.4.341.
Markon, C. et al., 2018: Alaska. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington D.C., pp. 1185-1241.
Marsh, J. M. and F. J. Mueter, 2020: Influences of temperature, predators, and competitors on polar cod (Boreogadus saida) at the southern margin of their distribution. *Polar Biology*, **43**(8), 995-1014, doi:10.1007/s00300-019-02575-4.
Marshall, K. N. et al., 2019: Inclusion of ecosystem information in US fish stock assessments suggests progress toward ecosystem-based fisheries management. *ICES Journal of Marine Science*, **76**(1), 1-9, doi:10.1093/icesjms/fsy152.
Masina, S. et al., 2019: Weather, environmental conditions, and waterborne Giardia and Cryptosporidium in Iqaluit, Nunavut. *J Water Health*, **17**(1), 84-97, doi:10.2166/wh.2018.323.
McCormack, S. A., Griffith, G., Hill, S.L., et al.,, accepted: Southern Ocean food web modelling: progress, prognoses, and future priorities for research and policy makers. *Frontiers in Ecology and Evolution*.
McCormack, S. A. et al., 2021: Decades of dietary data demonstrate regional food web structures in the Southern Ocean. *Ecology and Evolution*, **11**(1), 227-241, doi:https://doi.org/10.1002/ece3.7017.
Meire, L. et al., 2017: Marine-terminating glaciers sustain high productivity in Greenland fjords. *Global Change Biology*, **23**(12), 5344-5357, doi:10.1111/gcb.13801.
Melbourne-Thomas, J. et al., 2021: Poleward bound: adapting to climate-driven species redistribution. *Reviews in Fish Biology and Fisheries*, doi:10.1007/s11160-021-09641-3.
Melbourne-Thomas, J. et al., 2016: Under ice habitats for Antarctic krill larvae: Could less mean more under climate warming? *Geophysical Research Letters*, **43**(19), 10,322-310,327, doi:10.1002/2016GL070846.
Melia, N., K. Haines and E. Hawkins, 2016: Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters*, **43**(18), 9720-9728, doi:10.1002/2016GL069315.
Melvin, A. M. et al., 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences*, **114**(2), E122, doi:10.1073/pnas.1611056113.
Mendenhall, E. et al., 2020: Climate change increases the risk of fisheries conflict. *Marine Policy*, **117**, 103954, doi:https://doi.org/10.1016/j.marpol.2020.103954.

Meredith, M. et al., 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer (eds.)], pp. 118.
Meyer, B. et al., 2020: Successful ecosystem-based management of Antarctic krill should address uncertainties in krill recruitment, behaviour and ecological adaptation. *Communications Earth & Environment*, **1**(1), 28, doi:10.1038/s43247-020-00026-1.
Middleton, J. et al., 2020a: "We're people of the snow:" Weather, climate change, and Inuit mental wellness. *Social Science & Medicine*, **262**, 113137, doi:https://doi.org/10.1016/j.socscimed.2020.113137.
Middleton, J. et al., 2020b: Indigenous mental health in a changing climate: a systematic scoping review of the global literature. *Environmental Research Letters*, **15**(5), 053001, doi:10.1088/1748-9326/ab68a9.
Minor, K. et al., 2019: *Greenlandic Perspectives on Climate Change 2018-2019 Results from a National Survey*. Kraks Fond Institute for Urban Research, University of Greenland and University of Copenhagen, 101 pp. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3667214.
Moerlein, K. J. and C. Carothers, 2012: Total Environment of Change: Impacts of Climate Change and Social Transitions on Subsistence Fisheries in Northwest Alaska. *Ecology and Society*, **17**(1), doi:10.5751/ES-04543-170110.
Møller, E. F. and T. G. Nielsen, 2020: Borealization of Arctic zooplankton—smaller and less fat zooplankton species in Disko Bay, Western Greenland. *Limnology and Oceanography*, **65**(6), 1175-1188, doi:10.1002/lno.11380.
Moore, J. K. et al., 2018: Sustained climate warming drives declining marine biological productivity. *Science*, **359**(6380), 1139, doi:10.1126/science.aao6379.
Mørkøre, T. et al., 2020: Dietary inclusion of Antarctic krill meal during the finishing feed period improves health and fillet quality of Atlantic salmon (Salmo salar L.). *Br J Nutr*, **124**(4), 418-431, doi:10.1017/S0007114520001282.
Morley, J. W. et al., 2018: Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLOS ONE*, **13**(5), e0196127, doi:10.1371/journal.pone.0196127.
Morley, S. A. et al., 2020: Global Drivers on Southern Ocean Ecosystems: Changing Physical Environments and Anthropogenic Pressures in an Earth System. *Frontiers in Marine Science*, **7**, 1097, doi:10.3389/fmars.2020.547188.
Morley, S. A., D. K. A. Barnes and M. J. Dunn, 2019: Predicting which species succeed in climate-forced polar seas. *Frontiers in Marine Science*, **5**(507), 1-13, doi:10.3389/fmars.2018.00507.
Mudryk, L. et al., 2021: Impact of 1, 2, and 4°C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change*, doi:10.1038/s41558-021-01087-6.
Mueter, F. et al., 2020: Arctic gadids in a rapidly changing environment. *Polar Biology*, **43**(8), 945-949, doi:10.1007/s00300-020-02696-1.
Mumby, P. J. et al., 2017: Avoiding a crisis of motivation for ocean management under global environmental change. *Global Change Biology*, **23**(11), 4483-4496, doi:10.1111/gcb.13698.
Murphy, E. J. et al., 2021: Global Connectivity of Southern Ocean Ecosystems. *Frontiers in Ecology and Evolution*, **9**, 454, doi:10.3389/fevo.2021.624451.
Mustonen, K., T. Mustonen and J. Kirillov, 2018a: *Traditional Knowledge of Northern Waters*. Cooperative, S., 39 pp.
Mustonen, T. and P. Feodoroff, 2020: What is a River? Cross-disciplinary and Indigenous Assessment. In: *Indigenous Wellbeing and Enterprise: Self-Determination and Sustainable Economic Development* [Colbourne, R. and R. B. Anderson (eds.)]. Routledge. ISBN 9780367349639.
Mustonen, T. et al., 2018b: *Deepening Voices - eXchanging Knowledge of Monitoring Practices between Finland and Greenland*. Snowchange, 51 pp. Available at: https://www.researchgate.net/publication/322753987_Deepening_Voices-eXchanging_Knowledge_of_Monitoring_Practices_between_Finland_and_Greenland.
Mustonen, T. and N. Huusari, 2020: How to know about waters? Finnish traditional knowledge related to waters and implications for management reforms. *Reviews in Fish Biology and Fisheries*, **30**(4), 699-718, doi:10.1007/s11160-020-09619-7.
Mustonen, T. and K. Mustonen, 2016: *Life in the Cyclic World: A Compendium of Traditional Knowledge from the Eurasian North*. Snowchange Cooperative, Cooperative, S., 133 pp. Available at: http://www.snowchange.org/2016/05/life-in-the-cyclic-world-report-released-traditional-knowledge-compendium-from-eurasia/.
Mustonen, T., Mustonen, K., Kirillov, J., et al.,, 2021: Community-based monitoring in the Ponoy River, Kola Peninsula (Russia): Reflections on Atlantic salmon, pink salmon, northern pike and weather/climate change. *Polar Biology*, **44**, 173-194, doi:https://doi.org/10.1007/s00300-020-02790-4.
Mustonen, T. and V. Shadrin, 2021: The River Alazeya: Shifting Socio-Ecological Systems Connected to a Northeastern Siberian River. *Arctic*, **74**(1), doi:https://doi.org/10.14430/arctic72238.
Mustonen, T. and B. Van Dam, 2021: Climate Change and Unalakleet: A Deep Analysis. *Sustainability*, **13**(17), doi:10.3390/su13179971.
Myers, S. S. et al., 2017: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annual Review of Public Health*, **38**(1), 259-277, doi:10.1146/annurev-publhealth-031816-044356.

Natcher, D. et al., 2019: *The Arctic as a Food Producing Region*. Arctic Council's Sustainable Development Working Group, 21 pp. Available at: https://nofima.no/wp-content/uploads/2017/05/AFPR-Final-Report.pdf.
Neukermans, G., L. Oziel and M. Babin, 2018: Increased intrusion of warming Atlantic water leads to rapid expansion of temperate phytoplankton in the Arctic. *Global Change Biology*, **24**(6), 2545-2553, doi:doi:10.1111/gcb.14075.
Newsham, K. K., R. J. Hall and N. R. Maslen, 2020: Experimental warming of bryophytes increases the population density of the nematode Plectus belgicae in maritime Antarctica. *Antarct. Sci.*, 1-9, doi:10.1017/s0954102020000528.
Newsham, K. K. et al., 2019: Bacterial community composition and diversity respond to nutrient amendment but not warming in a Maritime Antarctic soil. *Microbial Ecology*, **78**(4), 974-984, doi:10.1007/s00248-019-01373-z.
Ng, A. K. Y. et al., 2018: Implications of climate change for shipping: Opening the Arctic seas. *WIREs Climate Change*, **9**(2), e507, doi:10.1002/wcc.507.
Nielsen, J., A. Rosing-Asvid, L. Meire and R. Nygaard, 2020: Widespread occurrence of pink salmon (Oncorhynchus gorbuscha) throughout Greenland coastal waters. *Journal of Fish Biology*, **96**(6), 1505-1507, doi:10.1111/jfb.14318.
Niittynen, P., R. K. Heikkinen and M. Luoto, 2018: Snow cover is a neglected driver of Arctic biodiversity loss. *Nature Climate Change*, **8**(11), 997-1001, doi:10.1038/s41558-018-0311-x.
Nunavut Climate Change Center, 2018: *Climate chance adaptation project - permafrost thaw and river erosion in Kugluk Territorial Park*. Available at: https://www.climatechangenunavut.ca/en/project/climate-change-adaptation-project-permafrost-thaw-and-river-erosion-kugluk-territorial-park#:~:text=Kugluk%20Territorial%20Park%20along%20the,to%20move%20the%20ATV%20trail.
Nuttall, M., 2020: Water, ice, and climate change in northwest Greenland. *WIREs Water*, **7**(3), e1433, doi:10.1002/wat2.1433.
Nyland, K. E. et al., 2017: Traditional Iñupiat ice cellars (SIĠḶUAQ) in Barrow, Alaska: Characteristics, temperature monitoring, and distribution. *Geographical Review*, **107**(1), 143-158, doi:10.1111/j.1931-0846.2016.12204.x.
O'Rourke, M. J. E., 2017: Archaeological Site Vulnerability Modelling: The Influence of High Impact Storm Events on Models of Shoreline Erosion in the Western Canadian Arctic. *Open Archaeology*, **3**(1), 1-16, doi:https://doi.org/10.1515/opar-2017-0001.
Ogar, E., G. Pecl and T. Mustonen, 2020: Science Must Embrace Traditional and Indigenous Knowledge to Solve Our Biodiversity Crisis. *One Earth*, **3**(2), 162-165, doi:10.1016/j.oneear.2020.07.006.
Ojea, E., I. Pearlman, S. D. Gaines and S. E. Lester, 2017: Fisheries regulatory regimes and resilience to climate change. *Ambio*, **46**(4), 399-412, doi:10.1007/s13280-016-0850-1.
Oke, K. B. et al., 2020: Recent declines in salmon body size impact ecosystems and fisheries. *Nature Communications*, **11**(1), 4155, doi:10.1038/s41467-020-17726-z.
Oldenborger, G. A. and A.-M. LeBlanc, 2015: Geophysical characterization of permafrost terrain at Iqaluit International Airport, Nunavut. *Journal of Applied Geophysics*, **123**, 36-49, doi:https://doi.org/10.1016/j.jappgeo.2015.09.016.
Olsen, J., N. A. Carter and J. Dawson, 2019: Community perspectives on the environmental impacts of Arctic shipping: Case studies from Russia, Norway and Canada. *Cogent Social Sciences*, **5**(1), 1609189, doi:10.1080/23311886.2019.1609189.
Orsi, A. H., T. Whitworth and W. D. Nowlin, 1995: On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep Sea Research Part I: Oceanographic Research Papers*, **42**(5), 641-673, doi:10.1016/0967-0637(95)00021-W.
Ostapchuk, J. et al., 2015: Exploring elders' and seniors' perceptions of how climate change is impacting health and well-being in Rigolet, Nunatsiavut / ᕿᒥᕐᕈᓂᖅ ᐃᓐᓇᐃᑦ ᐊᒻᒪᓗ ᐃᓄᑐᖃᐃᑦ ᐃᓱᒪᒃᔪᓯᖕᒋᓐᓂᒃ ᓇᒍᓚᑦ, ᓄᓇᑦᓯᐊᕗᒻᒥ ᓯᓚᐅᑉ ᐊᓯᔾᔨᐸᓪᓕᐊᓂᖓᓂᒃ ᐊᑦᑐᐃᓂᖃᖅᑎᑦᓗᒍ ᐃᓗᓯᕐᒥᒃ ᐊᒻᒪᓗ. *International Journal of Indigenous Health*, **9**(2), 6, doi:10.18357/ijih92201214358.
Palacios-Abrantes, J., U. R. Sumaila and W. W. L. Cheung, 2020: Challenges to transboundary fisheries management in North America under climate change. *Ecology and Society*, **25**(4), doi:10.5751/ES-11743-250441.
Palma, D. et al., 2019: Cruising the marginal ice zone: climate change and Arctic tourism. *Polar Geography*, **0513**, 1-21, doi:10.1080/1088937x.2019.1648585.
PAME, 2020: *The Increase in Arctic Shipping 2013-2019: Arctic Shipping Status Report (ASSR) #1*. Protection of the Marine Environment (PAME). Available at: https://www.pame.is/projects/arctic-marine-shipping/arctic-shipping-status-reports/723-arctic-shipping-report-1-the-increase-in-arctic-shipping-2013-2019-pdf-version/file.
Panassa, E., C. Völker, D. Wolf-Gladrow and J. Hauck, 2018: Drivers of Interannual Variability of Summer Mixed Layer Depth in the Southern Ocean Between 2002 and 2011. *Journal of Geophysical Research: Oceans*, **123**(8), 5077-5090, doi:10.1029/2018JC013901.
Parlee, C. and M. Wiber, 2018: Using conflict over risk management in the marine environment to strengthen measures of governance. *Ecology and Society*, **23**(4), doi:10.5751/ES-10334-230405.
Pauli, N.-C. et al., 2021: Selective feeding in Southern Ocean key grazers—diet composition of krill and salps. *Communications Biology*, **4**(1), 1061, doi:10.1038/s42003-021-02581-5.

Paulin, M. and J. Caines, 2016: The Evolution of Design Tools for Arctic Subsea Pipelines. In: *Arctic Technology Conference*, 2016/10/24/, St. John's, Newfoundland and Labrador, Canada, Offshore Technology Conference, OTC, pp. 11, doi:10.4043/27374-MS.
Pecuchet, L. et al., 2020a: Novel feeding interactions amplify the impact of species redistribution on an Arctic food web. *Global Change Biology*, **26**(9), 4894-4906, doi:10.1111/gcb.15196.
Pecuchet, L. et al., 2020b: Spatio-temporal dynamics of multi-trophic communities reveal ecosystem-wide functional reorganization. *Ecography*, **43**(2), 197-208, doi:10.1111/ecog.04643.
Pendakur, K., 2017: Northern Territories. In: *Climate Risks & Adaptation Practices - For the Canadian Transportation Sector 2016* [Palko, K. and D. S. Lemme (eds.)]. Government of Canada, Ottawa, Ontario, pp. 27-64.
Pentz, B. and N. Klenk, 2017: The 'responsiveness gap' in RFMOs: The critical role of decision-making policies in the fisheries management response to climate change. *Ocean & Coastal Management*, **145**, 44-51, doi:https://doi.org/10.1016/j.ocecoaman.2017.05.007.
Perrin, A. et al., 2015: *Economic Implications of Climate Change Adaptations for Mine Access Roads in Northern Canada*. Yukon Research Center, Yukon College, Yukon, 93 pp. Available at: https://www.iisd.org/library/economic-implications-climate-change-adaptations-mine-access-roads-northern-canada.
Petrasek MacDonald, J. et al., 2015: Protective factors for mental health and well-being in a changing climate: Perspectives from Inuit youth in Nunatsiavut, Labrador. *Social Science and Medicine*, **141**, doi:10.1016/j.socscimed.2015.07.017.
Petrasek MacDonald, J. et al., 2013: A necessary voice: Climate change and lived experiences of youth in Rigolet, Nunatsiavut, Canada. *Global Environmental Change*, **23**(1), 360-371, doi:https://doi.org/10.1016/j.gloenvcha.2012.07.010.
Petrick, S. et al., 2017: Climate change, future Arctic Sea ice, and the competitiveness of European Arctic offshore oil and gas production on world markets. *Ambio*, **46**(3), 410-422, doi:10.1007/s13280-017-0957-z.
Petrou, K. et al., 2019: Acidification diminishes diatom silica production in the Southern Ocean. *Nature Climate Change*, **9**(10), 781-786, doi:10.1038/s41558-019-0557-y.
PEW, 2016: *The Integrated Arctic Corridors Framework: Planning for responsible shipping Canada's Arctic waters*. 37 pp. Available at: https://www.pewtrusts.org/en/research-and-analysis/reports/2016/04/the-integrated-arctic-corridors-framework.
Piatt, J. F. et al., 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. *PLOS ONE*, **15**(1), e0226087, doi:10.1371/journal.pone.0226087.
Pinkerton, E. and R. Davis, 2015: Neoliberalism and the politics of enclosure in North American small-scale fisheries. *Marine Policy*, **61**, 303-312, doi:10.1016/j.marpol.2015.03.025.
Pinkerton, M. H. et al., 2021: Evidence for the Impact of Climate Change on Primary Producers in the Southern Ocean. *Frontiers in Ecology and Evolution*, **9**, 134, doi:10.3389/fevo.2021.592027.
Piñones, A. and A. V. Fedorov, 2016: Projected changes of Antarctic krill habitat by the end of the 21st century. *Geophysical Research Letters*, **43**(16), 8580-8589, doi:10.1002/2016GL069656.
Pinsky, M., L. et al., 2018: Preparing ocean governance for species on the move. *Science*, **360**(6394), 1189-1191, doi:10.1126/science.aat2360.
Pirotta, V. et al., 2019: Consequences of global shipping traffic for marine giants. *Frontiers in Ecology and the Environment*, **17**(1), 39-47, doi:https://doi.org/10.1002/fee.1987.
Píšková, A. et al., 2019: Late-Holocene palaeoenvironmental changes at Lake Esmeralda (Vega Island, Antarctic Peninsula) based on a multi-proxy analysis of laminated lake sediment. *The Holocene*, 095968361983803, doi:10.1177/0959683619838033.
Pizzolato, L. et al., 2016: The influence of declining sea ice on shipping activity in the Canadian Arctic. *Geophysical Research Letters*, **43**(12), 146-154, doi:10.1002/2016GL071489.
Plum, C., H. Hillebrand and S. Moorthi, 2020: Krill vs salps: dominance shift from krill to salps is associated with higher dissolved N:P ratios. *Scientific reports*, **10**(1), 5911-5911, doi:10.1038/s41598-020-62829-8.
Poore, J. and T. Nemecek, 2018: Reducing food's environmental impacts through producers and consumers. *Science*, **360**(6392), 987, doi:10.1126/science.aaq0216.
Prather, H. et al., 2019: Species-specific effects of passive warming in an Antarctic moss system. *Royal Society Open Science*, **6**, 190744, doi:10.1098/rsos.190744.
Punt, A. E. et al., 2021: Evaluating the impact of climate and demographic variation on future prospects for fish stocks: An application for northern rock sole in Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, **189-190**, 104951, doi:https://doi.org/10.1016/j.dsr2.2021.104951.
Punt, A. E., D. Poljak, M. G. Dalton and R. J. Foy, 2014: Evaluating the impact of ocean acidification on fishery yields and profits: The example of red king crab in Bristol Bay. *Ecological Modelling*, **285**, 39-53, doi:https://doi.org/10.1016/j.ecolmodel.2014.04.017.
QIA, 2019: *Tallurutiup Imanga National Marine Conservation Area Inuit Impact and Benefit Agreement: Canada's Largest Body of Protected Waters*. Qikiqtani Inuit Association (QIA). Available at: https://www.qia.ca/what-we-do/parks-and-conservation-areas/.

Radosavljevic, B. et al., 2016: Erosion and Flooding—Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada. *Estuaries and Coasts*, **39**(4), 900-915, doi:10.1007/s12237-015-0046-0.
Raheem, D., 2018: Food and Nutrition Security as a Measure of Resilience in the Barents Region. *Urban Science*, **2**(3), 72, doi:10.3390/urbansci2030072.
Ranasinghe, R. et al., 2021: *Climate Change Information for Regional Impact and for Risk Assessment* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Press, C. U.
Randelhoff, A. and J. D. Guthrie, 2016: Regional patterns in current and future export production in the central Arctic Ocean quantified from nitrate fluxes. *Geophysical Research Letters*, **43**(16), 8600-8608, doi:10.1002/2016GL070252.
Randelhoff, A. et al., 2020: Pan-Arctic Ocean Primary Production Constrained by Turbulent Nitrate Fluxes. *Frontiers in Marine Science*, **7**, 150, doi:10.3389/fmars.2020.00150.
Ray, D. K. et al., 2019: Climate change has likely already affected global food production. *PLoS One*, **14**(5), e0217148-e0217148, doi:10.1371/journal.pone.0217148.
Raymond-Yakoubian, J. and R. Daniel, 2018: An Indigenous approach to ocean planning and policy in the Bering Strait region of Alaska. *Marine Policy*, **97**(September), 101-108, doi:10.1016/j.marpol.2018.08.028.
Raymond-Yakoubian, J., B. Raymond-Yakoubian and C. Moncrieff, 2017: The incorporation of traditional knowledge into Alaska federal fisheries management. *Marine Policy*, **78**, 132-142, doi:10.1016/j.marpol.2016.12.024.
Ready, E. and E. A. Power, 2017: Why Wage Earners Hunt: Food Sharing, Social Structure, and Influence in an Arctic Mixed Economy. *Current Anthropology*, **59**(1), 74-97, doi:10.1086/696018.
Renaud, P. E. et al., 2018: Pelagic food-webs in a changing Arctic: a trait-based perspective suggests a mode of resilience. *ICES Journal of Marine Science*, **75**(6), 1871-1881, doi:10.1093/icesjms/fsy063.
Reum, J. C. P. et al., 2020: Ensemble Projections of Future Climate Change Impacts on the Eastern Bering Sea Food Web Using a Multispecies Size Spectrum Model. *Frontiers in Marine Science*, **7**, 124, doi:10.3389/fmars.2020.00124.
Ribeiro, S. et al., 2021: Vulnerability of the North Water ecosystem to climate change. *Nature Communications*, **12**(1), 4475, doi:10.1038/s41467-021-24742-0.
Riedel, M. et al., 2017: Evidence for gas hydrate occurrences in the Canadian Arctic Beaufort Sea within permafrost-associated shelf and deep-water marine environments. *Marine and Petroleum Geology*, **81**, 66-78, doi:https://doi.org/10.1016/j.marpetgeo.2016.12.027.
Ristroph, E. B., 2017: When Climate Takes a Village: Legal Pathways toward the Relocation of Alaska Native Villages. *Climate Law*, **7**(4), 259-289, doi:https://doi.org/10.1163/18786561-00704003.
Ritsema, R., J. Dawson, M. Jorgensen and B. Macdougall, 2015: "Steering Our Own Ship?" An Assessment of Self-Determination and Self-Governance for Community Development in Nunavut. *The Northern Review*, **41**(2015), 157-180, doi:10.22584/nr41.2015.007.
Robards, M. D. et al., 2018: Understanding and adapting to observed changes in the Alaskan Arctic: Actionable knowledge co-production with Alaska Native communities. *Deep Sea Research Part II: Topical Studies in Oceanography*, **152**, 203-213, doi:https://doi.org/10.1016/j.dsr2.2018.02.008.
Roberts, L. et al., 2021: Enabling Enduring Evidence-Based Policy for the Southern Ocean Through Cultural Arts Practices. *Frontiers in Ecology and Evolution*, **9**, 284.
Robinson, S. A. et al., 2018: Rapid change in East Antarctic terrestrial vegetation in response to regional drying. *Nature Climate Change*, **8**(10), 879-+, doi:10.1038/s41558-018-0282-0.
Robinson, S. A. et al., 2020: The 2019/2020 summer of Antarctic heatwaves. *Global Change Biology*, **26**(6), 3178-3180, doi:https://doi.org/10.1111/gcb.15083.
Rogers, A. D. et al., 2020: Antarctic Futures: An Assessment of Climate-Driven Changes in Ecosystem Structure, Function, and Service Provisioning in the Southern Ocean. *Annual Review of Marine Science*, **12**(1), 87-120, doi:10.1146/annurev-marine-010419-011028.
Romano, M. D. et al., 2020: Die-offs, reproductive failure, and changing at-sea abundance of murres in the Bering and Chukchi Seas in 2018. *Deep-Sea Research Part II*, **181-182**(104877), doi:https://doi.org/10.1016/j.dsr2.2020.104877.
Ropert-Coudert, Y. et al., 2018: Two Recent Massive Breeding Failures in an Adélie Penguin Colony Call for the Creation of a Marine Protected Area in D'Urville Sea/Mertz. *Frontiers in Marine Science*, **5**, 264, doi:10.3389/fmars.2018.00264.
Rosales, J. et al., 2021: Storm surge proxies in a data-poor landscape: a practical monitoring method for under-surveyed and -studied communities vulnerable to climate change. *Climatic Change*, **164**(1), 22, doi:10.1007/s10584-021-02995-4.
Rosenhaim, I. L. et al., 2019: Simulated ballast water accumulation along Arctic shipping routes. *Marine Policy*, **103**, 9-18, doi:https://doi.org/10.1016/j.marpol.2019.02.013.
Royles, J. and H. Griffiths, 2015: Invited review: climate change impacts in polar regions: lessons from Antarctic moss bank archives. *Global Change Biology*, **21**(3), 1041-1057, doi:10.1111/gcb.12774.

Ruiz-Fernandez, J., M. Oliva and C. Garcia-Hernandez, 2017: Topographic and geomorphologic controls on the distribution of vegetation formations in Elephant Point (Livingston Island, Maritime Antarctica). *Sci. Total Environ.*, **587**, 340-349, doi:10.1016/j.scitotenv.2017.02.158.

Ruscio, B. A. et al., 2015: One Health – a strategy for resilience in a changing arctic. *Int J Circumpolar Health*, **74**(1), 27913, doi:10.3402/ijch.v74.27913.

Russell, D. E., A. Gunn and S. Kutz, 2018: *Migratory Tundra Caribou and Wild Reindeer*. Arctic Report Card. Available at: https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/784/Migratory-Tundra-Caribou-and-Wild-Reindeer.

Sachal, S. S., M. Deilgat and M. Speechley, 2019: Crypto climate Creep: The Movement of Tropical Infectious Disease to the Arctic. In: *Western Public Health Casebook* [Sibbald, S. L. and G. McKinley (eds.)]. Public Health Casebook Publishing, London, ON.

Sadowsky, A., T. Mettler-Altmann and S. Ott, 2016: Metabolic response to desiccation stress in strains of green algal photobionts (Trebouxia) from two Antarctic lichens of southern habitats. *Phycologia*, **55**(6), 703-714, doi:10.2216/15-127.1.

Sallée, J.-B. et al., 2021: Summertime increases in upper-ocean stratification and mixed-layer depth. *Nature*, **591**(7851), 592-598, doi:10.1038/s41586-021-03303-x.

Samplonius, J. M. et al., 2021: Strengthening the evidence base for temperature-mediated phenological asynchrony and its impacts. *Nature Ecology & Evolution*, **5**(2), 155-164, doi:10.1038/s41559-020-01357-0.

Sawatzky, A. et al., 2020: "The best scientists are the people that's out there": Inuit-led integrated environment and health monitoring to respond to climate change in the Circumpolar North. *Climatic Change*, **160**(1), 45-66, doi:10.1007/s10584-019-02647-8.

Schiaffino, M. R. et al., 2011: Bacterial community structure in a latitudinal gradient of lakes: the roles of spatial versus environmental factors. *Freshw. Biol.*, **56**(10), 1973-1991, doi:10.1111/j.1365-2427.2011.02628.x.

Schipper, E. L. F., 2020: Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, **3**(4), 409-414, doi:10.1016/j.oneear.2020.09.014.

Schneider von Deimling, T. et al., 2021: Consequences of permafrost degradation for Arctic infrastructure – bridging the model gap between regional and engineering scales. *The Cryosphere*, **15**(5), 2451-2471, doi:10.5194/tc-15-2451-2021.

Schroeter, B. et al., 2017: Summer activity patterns for mosses and lichens in Maritime Antarctica. *Antarct. Sci.*, **29**(6), 517-530, doi:10.1017/s095410201700027x.

Schrot, O. G., J. H. Christensen and H. Formayer, 2019: Greenland winter tourism in a changing climate. *Journal of Outdoor Recreation and Tourism*, **27**(June), doi:10.1016/j.jort.2019.100224.

Seifert, M., B. Rost, S. Trimborn and J. Hauck, 2020: Meta-analysis of multiple driver effects on marine phytoplankton highlights modulating role of pCO2. *Global Change Biology*, **26**(12), doi:10.1111/gcb.15341.

Semiletov, I. et al., 2016: Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon. *Nature Geoscience*, **9**(5), 361-365, doi:10.1038/ngeo2695.

Serreze, M. C. and W. N. Meier, 2019: The Arctic's sea ice cover: trends, variability, predictability, and comparisons to the Antarctic. *Annals of the New York Academy of Sciences*, **1436**(1), 36-53, doi:10.1111/nyas.13856.

Shadrin, V., 2021: Siberian Indigenous Observations of Climate Change. In: *2021 Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change* [Mustonen, T., S. L. Harper, M. Rivera Ferre, J. Postigo, A. Ayanlade, T. Benjaminsen, R. Morgan and A. Okem (eds.)]. SnowChange Cooperative, Kontiolahti, Finland, pp. 1.

Shijin, W., M. Yaqiong, Z. Xueyan and X. Jia, 2020: Polar tourism and environment change: opportunity, impact and adaptation. *Polar Sci.*, **25**, 100544, doi:https://doi.org/10.1016/j.polar.2020.100544.

Shiklomanov, N. I., D. A. Streletskiy, T. B. Swales and V. A. Kokorev, 2017: Climate Change and Stability of Urban Infrastructure in Russian Permafrost Regions: Prognostic Assessment based on GCM Climate Projections. *Geographical Review*, **107**(1), 125-142, doi:10.1111/gere.12214.

Shortlidge, E. E. et al., 2017: Passive warming reduces stress and shifts reproductive effort in the Antarctic moss, Polytrichastrum alpinum. *Ann. Bot.*, **119**(1), 27-38, doi:10.1093/aob/mcw201.

Siddon, E. C., S. G. Zador and G. L. Hunt, 2020: Ecological responses to climate perturbations and minimal sea ice in the northern Bering Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181-182**, 104914, doi:https://doi.org/10.1016/j.dsr2.2020.104914.

Siegel, V., 2016: *Biology and Ecology of Antarctic Krill* [Siegel, V. (ed.)]. Advances in Polar Ecology, Springer, 421 pp. ISBN 978-3-319-29279-3.

SIKU, 2020: The Indigenous Knowledge Social Network. Available at: https://siku.org/about.

Silkin, V. et al., 2020: Interannual variability of Emiliania huxleyi blooms in the Barents Sea: In situ data 2014–2018. *Marine Pollution Bulletin*, **158**, 111392, doi:https://doi.org/10.1016/j.marpolbul.2020.111392.

SIMIP Community, 2020: Arctic Sea Ice in CMIP6. *Geophysical Research Letters*, **47**(10), e2019GL086749, doi:10.1029/2019GL086749.

Simonee, N. et al., 2021: Sila qanuippa? (how's the weather?): Integrating Inuit Qaujimajatuqangit and environmental forecasting products to support travel safety around Pond Inlet, Nunavut in a changing climate. *Weather, Climate, and Society*, doi:10.1175/WCAS-D-20-0174.1.

Slats, R. et al., 2019: Voices from the Front Lines of a Changing Bering Sea: An Indigenous Perspective for the 2019 Arctic Report Card. [Richter-Menge, J., M. L. Druckenmiller and M. Jeffries (eds.)], pp. 88-99.
Snook, J. et al., 2020: “We’re Made Criminals Just to Eat off the Land”: Colonial Wildlife Management and Repercussions on Inuit Well-Being. *Sustainability*, **12**(19), doi:10.3390/su12198177.
Solan, M., P. Archambault, P. E. Renaud and C. März, 2020: The changing Arctic Ocean: consequences for biological communities, biogeochemical processes and ecosystem functioning. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **378**(2181), 20200266, doi:10.1098/rsta.2020.0266.
Solomonsz, J. et al., 2021: Stakeholder Engagement in Decision Making and Pathways of Influence for Southern Ocean Ecosystem Services. *Frontiers in Marine Science*, **8**, 541, doi:10.3389/fmars.2021.623733.
Song, X. P. et al., 2018: Global land change from 1982 to 2016. *Nature*, **560**(7720), 639-643, doi:10.1038/s41586-018-0411-9.
Southcott, C. and D. Natcher, 2018: Extractive industries and Indigenous subsistence economies: a complex and unresolved relationship. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, **39**(1), 137-154, doi:10.1080/02255189.2017.1400955.
Spence, J., 2017: Is a Melting Arctic Making the Arctic Council Too Cool? Exploring the Limits to the Effectiveness of a Boundary Organization. *Review of Policy Research*, **34**(6), 790-811, doi:10.1111/ropr.12257.
Spencer, P. D. et al., 2019: Trait-based climate vulnerability assessments in data-rich systems: An application to eastern Bering Sea fish and invertebrate stocks. *Global Change Biology*, **17**, doi:10.1111/gcb.14763.
Spencer, P. D. et al., 2016: Modelling spatially dependent predation mortality of eastern Bering Sea walleye pollock, and its implications for stock dynamics under future climate scenarios. *ICES Journal of Marine Science*, **73**(5), 1330-1342, doi:10.1093/icesjms/fsw040.
Spies, I. et al., 2019: Genetic evidence of a northward range expansion in the eastern Bering Sea stock of Pacific cod. *Evolutionary Applications*, doi:10.1111/EVA.12874.
Springmann, M., H. C. J. Godfray, M. Rayner and P. Scarborough, 2016: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, **113**(15), 4146, doi:10.1073/pnas.1523119113.
Stabeno, P. J. et al., 2019: Distributed Biological Observatory Region 1: Physics, chemistry and plankton in the northern Bering Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, **162**, 8-21, doi:https://doi.org/10.1016/j.dsr2.2018.11.006.
Standards Council of Canada, 2020: *Building a climate resilient future with northern standards*. 3 pp. Available at: https://www.scc.ca/en/about-scc/publications/brochures/northern-infrastructure-standardization-initiative-brochure.
Steiner, N. S. et al., 2019: Impacts of the Changing Ocean-Sea Ice System on the Key Forage Fish Arctic Cod (Boreogadus Saida) and Subsistence Fisheries in the Western Canadian Arctic—Evaluating Linked Climate, Ecosystem and Economic (CEE) Models. *Frontiers in Marine Science*, **6**, 179, doi:10.3389/fmars.2019.00179.
Stelling, J. M., Z. C. Yu, J. Loisel and D. W. Beilman, 2018: Peatbank response to late Holocene temperature and hydroclimate change in the western Antarctic Peninsula. *Quat. Sci. Rev.*, **188**, 77-89, doi:10.1016/j.quascirev.2017.10.033.
Stephen, K., 2018: Societal Impacts of a Rapidly Changing Arctic. *Current Climate Change Reports*, **4**(3), 223-237, doi:10.1007/s40641-018-0106-1.
Stephenson, S. R. and L. C. Smith, 2015: Influence of climate model variability on projected Arctic shipping futures. *Earth's Future*, **3**(11), 331-343, doi:10.1002/2015EF000317.
Stephenson, S. R., L. C. Smith, L. W. Brigham and J. A. Agnew, 2013: Projected 21st-century changes to Arctic marine access. *Climatic Change*, **118**(3), 885-899, doi:10.1007/s10584-012-0685-0.
Stephenson, S. R. et al., 2018: Climatic Responses to Future Trans-Arctic Shipping. *Geophysical Research Letters*, **45**(18), 9898-9908, doi:10.1029/2018GL078969.
Stevenson, D. E. and R. R. Lauth, 2019: Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. *Polar Biology*, **42**(2), 407-421, doi:10.1007/s00300-018-2431-1.
Stewart, E. et al., 2020: Characterizing polar mobilities to understand the role of weather, water, ice and climate (WWIC) information. *Polar Geography*, **43**(2-3), doi:https://doi.org/10.1080/1088937X.2019.1707319.
Stram, D. et al., 2021: *Supporting climate-resilient fisheries through understanding climate change impacts and adaptation responses*. 23 pp. Available at: https://www.npfmc.org/wp-content/PDFdocuments/membership/CCTF/ClimateChangeActionModFinalWorkplan_2021.pdf&sa=D&source=editors&ust=1631329190233000&usg=AOvVaw3WiwqP6oYtEumyFZ4S9675.
Streletskiy, D. A. et al., 2019: Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. *Environmental Research Letters*, **14**(2), doi:10.1088/1748-9326/aaf5e6.
Subramaniam, R. C., S. P. Corney, K. M. Swadling and J. Melbourne-Thomas, 2020: Exploring ecosystem structure and function of the northern Kerguelen Plateau using a mass-balanced food web model. *Deep Sea Research Part II: Topical Studies in Oceanography*, **174**, 104787, doi:https://doi.org/10.1016/j.dsr2.2020.104787.
Sumaila, U. R., J. Palacios-Abrantes and W. W. L. Cheung, 2020: Climate change, shifting threat points, and the management of transboundary fish stocks. *Ecology and Society*, **25**(4), doi:10.5751/ES-11660-250440.

Suprenand, P. M. and C. H. Ainsworth, 2017: Trophodynamic effects of climate change-induced alterations to primary production along the western Antarctic Peninsula. *Marine Ecology Progress Series*, **569**, 37-54, doi:https://doi.org/10.3354/meps12100.
Suter, L., D. Streletskiy and N. Shiklomanov, 2019: Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic. *Polar Geography*, **42**(4), 267-286, doi:10.1080/1088937X.2019.1686082.
Sylvester, Z. T., M. C. Long and C. M. Brooks, 2021: Detecting Climate Signals in Southern Ocean Krill Growth Habitat. *Frontiers in Marine Science*, **8**, 708, doi:10.3389/fmars.2021.669508.
Tai, T. C. et al., 2019: Evaluating present and future potential of arctic fisheries in Canada. *Marine Policy*, **108**(August), 103637-103637, doi:10.1016/j.marpol.2019.103637.
Taylor, J. J. et al., 2020: Arctic terrestrial biodiversity status and trends: A synopsis of science supporting the CBMP State of Arctic Terrestrial Biodiversity Report. *Ambio*, **49**(3), 833-847, doi:10.1007/s13280-019-01303-w.
Tedesco, L., M. Vichi and E. Scoccimarro, 2019: Sea-ice algal phenology in a warmer Arctic. *Science Advances*, **5**(5), eaav4830, doi:10.1126/sciadv.aav4830.
Tejsner, P. and D. Veldhuis, 2018: Climate Change as (Dis)Equilibrium: Behavioral Resilience in the Greenlandic Arctic. *Human Ecology*, **46**(5), 701-715, doi:10.1007/s10745-018-0026-7.
Thiault, L. et al., 2019: Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. *Science Advances*, **5**(11), eaaw9976, doi:10.1126/sciadv.aaw9976.
Thivierge, K. et al., 2016: Cryptosporidium hominis Is a Newly Recognized Pathogen in the Arctic Region of Nunavik, Canada: Molecular Characterization of an Outbreak. *PLOS Neglected Tropical Diseases*, **10**(4), e0004534, doi:10.1371/journal.pntd.0004534.
Thoisen, C. et al., 2015: Effect of acidification on an Arctic phytoplankton community from Disko Bay, West Greenland. *Marine Ecology Progress Series*, **520**, 21-34, doi:doi: 10.3354/meps11123.
Thompson, G. G. et al., 2020: *Assessment of the Pacific Cod Stock in the Eastern Bering Sea*. North Pacific Fishery Management Council. Available at: https://www.google.com/url?q=https://apps-afsc.fisheries.noaa.gov/refm/docs/2020/EBSpcod.pdf&sa=D&source=editors&ust=1631329190235000&usg=AOvVaw3nLRb4vAieDNqnpuQyOAgp.
Thor, P. et al., 2018: Contrasting physiological responses to future ocean acidification among Arctic copepod populations. *Global Change Biology*, **24**(1), e365-e377, doi:10.1111/gcb.13870.
Thorson, J. T. et al., 2020: Empirical orthogonal function regression: Linking population biology to spatial varying environmental conditions using climate projections. *Global Change Biology*, **26**(8), 4638-4649, doi:10.1111/gcb.15149.
Trathan, P. N. et al., 2020: The emperor penguin - Vulnerable to projected rates of warming and sea ice loss. *Biological Conservation*, **241**, 108216, doi:https://doi.org/10.1016/j.biocon.2019.108216.
Trebilco, R., J. Melbourne-Thomas and A. J. Constable, 2020: The policy relevance of Southern Ocean food web structure: Implications of food web change for fisheries, conservation and carbon sequestration. *Marine Policy*, **115**, 103832, doi:https://doi.org/10.1016/j.marpol.2020.103832.
Trimborn, S., T. Brenneis, E. Sweet and B. Rost, 2013: Sensitivity of Antarctic phytoplankton species to ocean acidification: Growth, carbon acquisition, and species interaction. *Limnology and Oceanography*, **58**(3), 997-1007, doi:10.4319/lo.2013.58.3.0997.
Tripathi, A. et al., 2016: Paradigms of climate change impacts on some major food sources of the world: A review on current knowledge and future prospects. *Agriculture, Ecosystems & Environment*, **216**, 356-373, doi:https://doi.org/10.1016/j.agee.2015.09.034.
Troell, M. et al., 2017: Seafood from a changing Arctic. *Ambio*, **46**(3), 368-386, doi:10.1007/s13280-017-0954-2.
Trofimenko, Y. V., G. I. Evgenev and E. V. Shashina, 2017: Functional Loss Risks of highways in Permafrost Areas Due to Climate Change. *Procedia Engineering*, **189**, 258-264, doi:10.1016/j.proeng.2017.05.041.
Tschakert, P. et al., 2019: One thousand ways to experience loss: A systematic analysis of climate-related intangible harm from around the world. *Global Environmental Change*, **55**, 58-72, doi:https://doi.org/10.1016/j.gloenvcha.2018.11.006.
Tsukerman, V., E. Goryachevskaya and S. Ivanov, 2019: Influence of innovative activities on economic development of the Russian Arctic. *IOP Conference Series: Earth and Environmental Science*, **302**, 012109, doi:10.1088/1755-1315/302/1/012109.
Turner, J. et al., 2020a: Antarctic temperature variability and change from station data. *International Journal of Climatology*, **40**(6), 2986-3007, doi:https://doi.org/10.1002/joc.6378.
Turner, M. G. et al., 2020b: Climate change, ecosystems and abrupt change: science priorities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**(1794), 20190105, doi:10.1098/rstb.2019.0105.
U.S. Executive Order 13990, 2021: *Executive Order on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis*, The White House. Available at: https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-protecting-public-health-and-environment-and-restoring-science-to-tackle-climate-crisis/.
Uboni, A., B. Åhman and J. Moen, 2020: Can management buffer pasture loss and fragmentation for Sami reindeer herding in Sweden? *Pastoralism*, **10**(1), 23, doi:10.1186/s13570-020-00177-y.
Unc, A. et al., 2021: Expansion of Agriculture in Northern Cold-Climate Regions: A Cross-Sectoral Perspective on Opportunities and Challenges. *Frontiers in Sustainable Food Systems*, **5**, 236.

UNESCO. Available at: http://www.unesco.org/new/en/natural-sciences/priority-areas/links/related-information/what-is-local-and-indigenous-knowledge#:~:text=For%20rural%20and%20indigenous%20peoples,social%20interactions%2C%20ritual%20and%20spirituality.

United States Department of Agriculture, 2017: *Census of Agriculture State Profile: Alaska*. United States Department of Agriculture, 2 pp. Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Alaska/cp99002.pdf&sa=D&source=editors&ust=1631332677200000&usg=AOvVaw2w-vLNNJpewNDYpnj-3SIa.

van Luijk, N., J. Dawson, A. Cook and N. C. Swart, 2020: Analysis of heavy fuel oil use by ships operating in Canadian Arctic waters from 2010 to 2018. *FACETS*, **5**(1), 304-327, doi:10.1139/facets-2019-0067.

Veytia, D. et al., 2020: Circumpolar projections of Antarctic krill growth potential. *Nature Climate Change*, **10**(6), 568-575, doi:10.1038/s41558-020-0758-4.

Vihtakari, M. et al., 2018: Black-legged kittiwakes as messengers of Atlantification in the Arctic. *Scientific Reports*, **8**(1), 1178, doi:10.1038/s41598-017-19118-8.

Wang, X. et al., 2019: Persistent organic pollutants in the polar regions and the Tibetan Plateau: A review of current knowledge and future prospects. *Environmental Pollution*, **248**, 191-208, doi:https://doi.org/10.1016/j.envpol.2019.01.093.

Wang, Z., J. A. Silberman and J. J. Corbett, 2021: Container vessels diversion pattern to trans-Arctic shipping routes and GHG emission abatement potential. *Maritime Policy & Management*, **48**(4), 543-562, doi:10.1080/03088839.2020.1795288.

Watson, J. T. and A. C. Haynie, 2018: Paths to resilience: the walleye pollock fleet uses multiple fishing strategies to buffer against environmental change in the Bering Sea. *Canadian Journal of Fisheries and Aquatic Sciences*, **75**(11), 1977-1989, doi:10.1139/cjfas-2017-0315.

Wege, M., L. Salas and M. LaRue, 2021: Ice matters: Life-history strategies of two Antarctic seals dictate climate change eventualities in the Weddell Sea. *Global Change Biology*, **n/a**(n/a), doi:https://doi.org/10.1111/gcb.15828.

Wei, T. et al., 2020: Projections of Arctic sea ice conditions and shipping routes in the twenty-first century using CMIP6 forcing scenarios. *Environmental Research Letters*, **15**(10), 104079, doi:10.1088/1748-9326/abb2c8.

Westergaard-Nielsen, A. et al., 2015: Greenlandic sheep farming controlled by vegetation response today and at the end of the 21st Century. *Sci. Total Environ.*, **512-513**, 672-681, doi:https://doi.org/10.1016/j.scitotenv.2015.01.039.

Westley, K., T. Bell, M. A. P. Renouf and L. Tarasov, 2011: Impact Assessment of Current and Future Sea-Level Change on Coastal Archaeological Resources—Illustrated Examples From Northern Newfoundland. *The Journal of Island and Coastal Archaeology*, **6**(3), 351-374, doi:10.1080/15564894.2010.520076.

Weydmann, A. A.-O., W. Walczowski, J. Carstensen and S. Kwasniewski, 2018: Warming of Subarctic waters accelerates development of a key marine zooplankton Calanus finmarchicus. *Global Change Biology*, **24**(1), 172-183, doi:https://doi.org/10.1111/gcb.13864.

Weymouth, R. and J. Hartz-Karp, 2019: Participation in planning and governance: closing the gap between satisfaction and expectation. *Sustainable Earth*, **2**(1), doi:10.1186/s42055-019-0012-y.

White, E., C. J. M. Hoppe and B. Rost, 2020: The Arctic picoeukaryote Micromonas pusilla benefits from ocean acidification under constant and dynamic light. *Biogeosciences*, **17**(3), 635-647, doi:10.5194/bg-17-635-2020.

Whitehouse, G. A. et al., 2021: Bottom-up impacts of forecasted climate change on the eastern Bering Sea food web. *Frontiers in Marine Science*, **8**, 20, doi:10.3389/fmars.2021.624301.

Whyte, K., 2016: Is it colonial déjà vu? Indigenous peoples and climate injustice. In: *Humanities for the Environment: Integrating knowledge, forging new constellations of practice*, 1 ed. [Adamson, J. and M. Davis (eds.)]. Routledge, London, pp. 18. ISBN 9781315642659.

Whyte, K., 2017: Indigenous Climate Change Studies: Indigenizing Futures, Decolonizing the Anthropocene. *English Language Notes*, **55**(1), 153-162.

Whyte, K., J. L Talley and J. D. Gibson, 2019: Indigenous mobility traditions, colonialism, and the anthropocene. *Mobilities*, **14**(3), 319-335, doi:10.1080/17450101.2019.1611015.

Wildcat, D. R., 2013: Introduction: climate change and indigenous peoples of the USA. *Climatic Change*, **120**(3), 509-515, doi:10.1007/s10584-013-0849-6.

Wolf, K. K. E., C. J. M. Hoppe and B. Rost, 2018: Resilience by diversity: Large intraspecific differences in climate change responses of an Arctic diatom. *Limnology and Oceanography*, **63**(1), 397-411, doi:10.1002/lno.10639.

Yoder, S., 2018: *Assessment of the Potential Health Impacts of Climate Change in Alaska* [McLaughlin, J., Castrodale, L. (ed.)]. State of Alaska Epidemiology Bulletin, **20**, Alaska Section of Epidemiology, Anchorage, AK, 77 pp. Available at: http://dhss.aslaks.gov/dph/Epi.

Youth Climate Report, Inuit Youth at COP25 to present film "Happening to Us". Available at: http://youthclimatereport.org/uncategorized/inuityouth/.

Yu, Z. C., D. W. Beilman and J. Loisel, 2016: Transformations of landscape and peat-forming ecosystems in response to late Holocene climate change in the western Antarctic Peninsula. *Geophysical Research Letters*, **43**(13), 7186-7195, doi:10.1002/2016gl069380.

Zavaleta-Cortijo, C. et al., 2020: Climate change and COVID-19: reinforcing Indigenous food systems. *The Lancet Planetary Health*, **4**(9), e381-e382, doi:10.1016/S2542-5196(20)30173-X.

Zeng, Q. et al., 2020: The competitiveness of Arctic shipping over Suez Canal and China-Europe railway. *Transport Policy*, **86**, 34-43, doi:https://doi.org/10.1016/j.tranpol.2019.11.005.
Zhang, Q., Z. Wan, B. Hemmings and F. Abbasov, 2019: Reducing black carbon emissions from Arctic shipping: Solutions and policy implications. *Journal of Cleaner Production*, **241**, 118261, doi:https://doi.org/10.1016/j.jclepro.2019.118261.
Zhang, Y., M. Yamamoto-Kawai and W. J. Williams, 2020: Two Decades of Ocean Acidification in the Surface Waters of the Beaufort Gyre, Arctic Ocean: Effects of Sea Ice Melt and Retreat From 1997–2016. *Geophysical Research Letters*, **47**(3), e60119, doi:https://doi.org/10.1029/2019GL086421.
Zheng, J. and J. Ianelli, 2018: *Saint Matthew Island Blue King Crab Stock Assessment 2018*. 77 pp. Available at: http://npfmc.staging.wpengine.com/wp-content/PDFdocuments/resources/SAFE/CrabSAFE/2018/6-SMBKC_SAFE_2018.pdf.
Zhu, Z. et al., 2016: Greening of the Earth and its drivers. *Nature Climate Change*, **6**(8), 791-795, doi:10.1038/nclimate3004.

Cross-Chapter Paper 7: Tropical Forests

Cross-Chapter Paper Leads: Jean Pierre Ometto (Brazil), Felix Kanungwe Kalaba (Zambia)

Cross-Chapter Paper Authors: Gusti Zakaria Anshari (Indonesia), Noemí Chacón (Venezuela), Aidan Farrell (Trinidad and Tobago/Ireland), Sharina Abdul Halim (Malaysia), Henry Neufeldt (Denmark/Germany), Raman Sukumar (India).

Cross-Chapter Paper Contributing Authors: Christa Anderson (USA), Craig Beatty (United States of America/Canada), Nirmal Bhagabati (USA), Ana Felicien (Venezuela), Gabrielle Kissinger (Canada), David M. Lapola (Brazil), Felipe S. Pacheco (Brazil), Pablo Pacheco (USA/Bolivia), Sandeep Pulla (India), Yong Yut Trisurat (Thailand)

Cross-Chapter Paper Review Editor: Avelino Gumersindo Suarez Rodriguez (Cuba)

Date of Draft: 1 October 2021

Notes: TSU Compiled Version

Table of Contents

Executive Summary

Over 420 million ha of forest were lost to deforestation from 1990 to 2020; more than 90% of that loss took place in tropical areas (*high confidence*), threatening biodiversity, environmental services, livelihoods of forest communities and resilience to climate shocks (*high confidence*[1]). Forty five percent of the world's forested areas are in the tropics, and they are amongst the most important regulators of regional and global climate, natural carbon sinks and the most significant repositories of terrestrial biomass. They are of immeasurable value to biodiversity, ecosystem services, social and cultural identities, livelihoods, and climate change adaptation and mitigation {CCP7.2.1; CCP7.2.2; Box CCP7.2; Table CCP7.2}

Climate change affects tropical forests through warming and increased occurrence of extreme events such as droughts and heat waves, as well as more frequent fires, which increase tree mortality and reduce tree growth, limiting the ability of forests to regenerate (*high confidence*). Climate change is altering the structure and species composition of tropical tree communities (*high confidence*), including transitions from moist to drier forest in regions such as the Amazon (*high confidence*), and movement of species from lower to higher elevations (*high confidence*). Despite CO_2 fertilization, ongoing climate change has weakened the carbon sink potential of tropical forests in Amazonia and, to a lesser extent, in Africa and Asia (*medium confidence*). {CCP7.2.3; CCP7.3}

Large-scale tropical deforestation affects regional to continental scale climates with significant impacts on forest resilience (*high confidence*). Deforestation generally reduces rainfall and enhances temperatures with effects depending on scales (*high confidence*), while often increasing surface runoff (*medium confidence*). Continued deforestation-driven landscape drying and fragmentation will aggravate fire risk and reduce forest resilience, leading to savannization of the tropical forest biomes, in particular in combination with climate change (*high confidence*). {CCP7.3.6}

Implementing sustainable management strategies can improve the ability of tropical forest ecosystems to adapt to climate change (*high confidence)*, and the benefits of adaptation interventions often outweigh the costs (*medium confidence*). Adaptation of tropical forests to climate change provides an opportunity for tropical countries to develop forest policies that create incentives for environmental services such as carbon storage and biodiversity refugia. Forest restoration using a diverse mix of native species can help rebuild the climate resilience of tropical forests, but is best implemented alongside other sustainable forest management strategies and adaptation interventions (*high confidence*) {CCP7.5; Box CCP7.1}

Community-based adaptation, built on Indigenous Knowledge (IK) and Local Knowledge (LK) over centuries or millennia, is often identified as an effective adaptation strategy to climate change (*high confidence*). For successful adaptation of tropical forest communities, it is vital to consider IK and LK in addition to modern scientific approaches, together with consideration of non-climatic vulnerabilities (e.g., poverty, gender inequality and power asymmetries) (*high confidence*) Climate change vulnerability and adaptive capacity have a historical and geopolitical context, conditioned by value systems and development models. Transformative and sustainable practices are required for effective management of tropical forests (*high confidence*) {CCP7.4; Box CCP7.1}

Building resilience of tropical forests to climate change relies on adaptation in combination with reduction of direct and underlying drivers of deforestation and forest degradation (*high confidence*). Tropical deforestation is largely driven by agriculture, both from subsistence farming and industrial agriculture (e.g., oil palm, timber plantations, soybeans, livestock) (*high confidence*). While poverty and population growth combined with poor governance fuel subsistence agriculture (*high confidence*), industrial agriculture is often driven by international market forces for commodities and large-scale land acquisitions (*high confidence*). {CCP7.2.3}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Governance responses to addressing the direct and underlying drivers of deforestation have been inadequate to reduce pressures, yet the complexity of tackling drivers of forest loss and degradation is increasing as climate impacts on forests and ecosystems increase (*high confidence*). Transformative levers towards improving environmental governance and resilience of tropical forests include: incentivizing and building capacity for environmental responsibility and discontinuing harmful subsidies and disincentives; reforming segmented decision-making to promote integration across sectors and jurisdictions; pursuing pre-emptive and precautionary actions; managing for resilient social and ecological systems in the face of uncertainty and complexity; strengthening environmental laws and policies and their implementation; acknowledging land tenure and rights; and inclusive stakeholder participation (*medium confidence*). {CCP7.6}

CCP7.1 Introduction

Climate change is already impacting tropical forests around the world, including through distributional shifts of forest biomes, changes in species composition, biomass, pests and diseases and increase in forest fires (*high confidence*). These impacts are often compounded by non-climatic factors such as conversion of land for other uses, burning to clear land, mining, and road and infrastructure development. It is notable that, despite societal awareness and financial opportunities to restore forests (Brancalion and Chazdon 2017), tropical forests are increasingly threatened. For instance, the conversion of tropical forests to large-scale agricultural production (mainly soybeans, oil palm, maize, cotton, livestock), is amongst the strongest drivers of species richness decline of both flora and fauna, thereby impacting the adaptation opportunities of ecosystems and local people to climate change (IPBES 2018). Reducing direct and indirect drivers of deforestation and forest degradation is therefore critical to building, maintaining or enhancing the resilience of tropical forests against climate and non-climate drivers alike (*high confidence*).

With climate change-related drivers becoming increasingly important in the future, changes to tropical forests will most *likely*[2] be aggravated overall, although some tropical forests may temporarily benefit, physiologically, from higher temperatures and changes in precipitation patterns. To the degree to which forests are affected by climate change and other drivers, their resilience against these stressors is diminishing leading to a reduction in the regulating, supporting, provisioning and cultural ecosystem services they provide (Alroy 2017; Cadman et al. 2017; Pörtner et al. 2021) (Chapter 2) (*high confidence*). This, in turn, is affecting the lives and livelihoods of millions of people who depend on forests and their products, in particular forest dwelling communities, but also, via the teleconnections between forests and surrounding areas of influence, in socio-ecological systems outside the forests themselves.

While strong mitigation efforts are fundamental to minimizing future climate impacts on forests, forest management can be improved in many places in support of enhancing the resilience of tropical forests, often with significant co-benefits for carbon storage, biodiversity, food security and ecosystem services (*high confidence*). Sustainable management practices allow forests to be utilized, frequently with equally high or even higher productivity levels, while keeping their core functions intact. While there are numerous approaches to managing forests and forest landscapes sustainably, an element that appears to be critical are property rights and tenure arrangements allowing stewards of the land, including Indigenous Peoples, securing long-term access and utilization of forest resources *(medium confidence)* (Rahman and Alam 2016 and Naughton-Treves 2014).

The interconnections of climate risks and non-climate drivers facing tropical forests, their impacts on rates and extent of deforestation and forest degradation, loss of ecosystem services and biodiversity, leading to unsecured human well-being, contrasts with the sustainable forest management on protecting forest ecosystems and enhancing their resilience against these drivers are framed in Figure CCP7.1. The conceptual framework not only illustrates the complexity and scale of the challenge, but also provides opportunities to mitigate impacts at different scales, whereas eliminating the underlying drivers, both climate and non-climate related, must be the goal of policies and measures at global, national and subnational levels, involving state and non-state actors alike.

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term ‘*likely* range’ to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

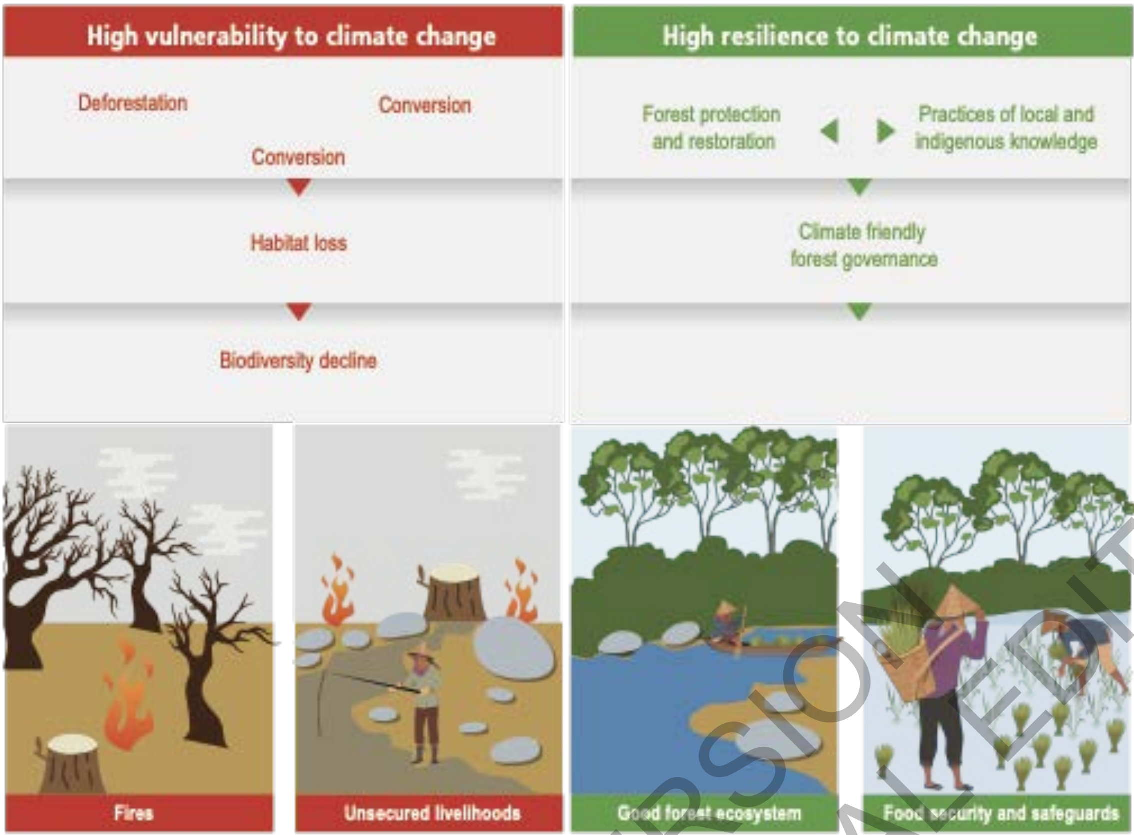


Figure CCP7.1: Impacts of climate change and human disturbances on tropical forests lead to high risk of biodiversity loss and uncertainty of livelihoods for the majority of forest dependent communities (left side). Good forest governance would increase the resilience of tropical forest through better adaptation and mitigation to climate change (right side)

Building on what has been presented in IPCC AR5, SR15, and SRCCL, section 7.2 of this Cross-Chapter Paper first briefly describes the types and extent of tropical forest ecosystems and then looks at current rates and drivers of deforestation and forest degradation. Section 7.3 presents current and projected climate change impacts on tropical trees and forests, focusing primarily on drought, heat and fires, looking from physiological responses to risks, projected climate change impact, and forest resilience. Section 7.4 addresses the impacts of climate change and tropical forest destruction on the livelihoods and well-being of communities and peoples living in or being strongly dependent upon tropical forests. This section includes a Box on Indigenous Knowledge and Local Knowledge and Community-based Adaptation. Section 7.5 assesses adaptation options for the sustainable management of tropical forests drawing upon the protection, management and restoration framework, and includes a Box on the connection between sustainable forest management and the United Nations Sustainable Development Goals. Section 7.6, finally, assesses opportunities and challenges of tropical forest governance to maintain and enhance resilience against climate change impacts on forests.

CCP7.2 The Current State of Tropical Forests

In the most recent Global Ecological Zones map produced by the Food and Agriculture Organization (FAO) for the year 2010, tropical vegetation has been defined as encompassing regions which are frost-free during all months in the year (FAO 2012). Further, the tropical vegetation has been sub-classified into tropical rainforest, tropical moist forest, tropical dry forest, tropical shrubland, tropical desert, and tropical mountain systems based on climate in combination with vegetation physiognomy and orographic zone (Table SMCCP7.1). IPCC has used the basic FAO classification in its National Greenhouse Gas Inventories Guidelines (IPCC 2019).

Since the FAO ecological zones represent potential biome extents, the present area under forest is assessed using the European Space Agency Climate Change Initiative Land Cover dataset (ESA 2017). The ESA dataset provides a direct mapping to IPCC land categories (e.g., "forest"), allowing for standardized and consistent reporting of existing forest and forest gain/loss in each ecological zone. The most extensive tropical ecological zone is the tropical rainforest (1,459 Mha or about 25% of all tropical ecological zones), followed by tropical desert (which is not further considered here), tropical moist forest, tropical shrubland, tropical dry forest and tropical mountain system (Table CCP7.1; Figure CCP7.2). Mangroves are not explicitly considered in the FAO classification. Tropical rainforest occurs largely in South America, Africa, and South and South East Asia, and is the most intact tropical forest biome (Table CCP7.1). Significant portions of tropical moist forest, which abuts tropical rainforest in many regions but experience a longer dry season, have been lost in most regions (Table CCP7.2). Tropical moist forest typically grades into the highly-threatened tropical dry forest ecological zone, of which only about a third exists under forest cover at present. Only about 44% of tropical mountain systems, which occur approximately above 1000 m above mean sea level, are presently under forest cover. While the FAO classification provides the potential tropical ecological zones (roughly, "vegetation types"), there are large differences in the extents of global tropical forest biomes which are still remaining as reported by different sources (Sayre et al. 2020; Ocón et al. 2021). These differences result from differences in biome definition, data source, the definition of "forest," and the method used for classifying remotely-sensed data. For example, the reported global area of tropical dry forests ranges from 105 Mha to 645 Mha (Pan et al. 2013; Bastin et al. 2017; Ocón et al. 2021).

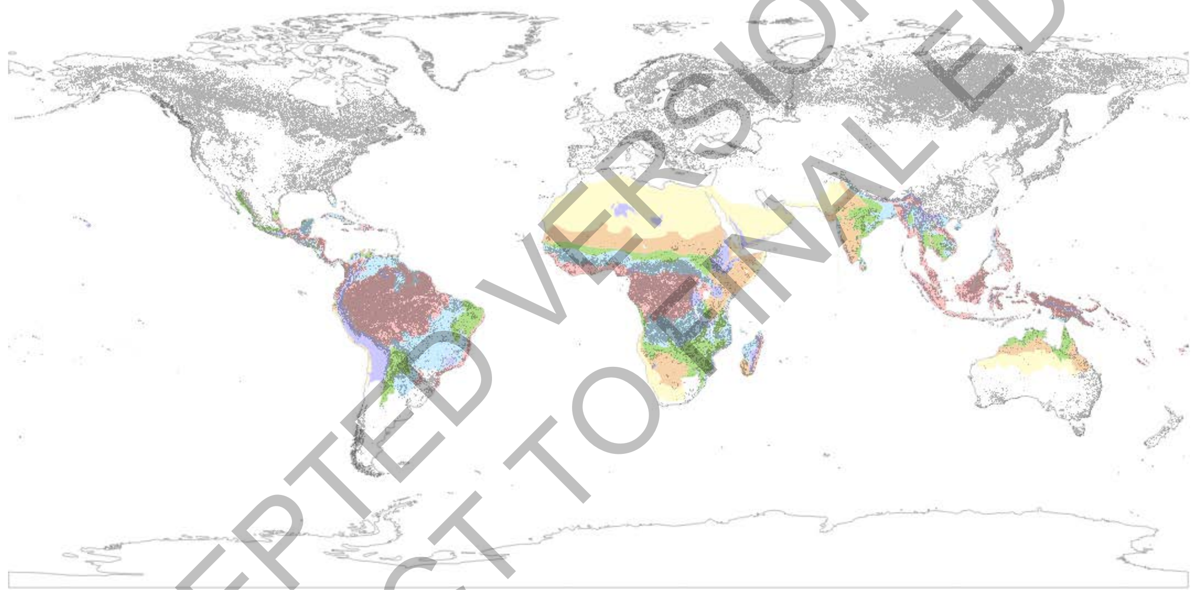


Figure CCP7.2: Colours represent tropical ecological zones as defined by the FAO (FAO 2012) Areas classified as "Forest" in the 2020 ESA Land Cover CCI Product (ESA 2017) are overlaid in grey.

Table CCP7.1: Areas in tropical ecological zones as defined by the FAO (FAO 2012). [1]Existing forest represents areas classified as "Forest" in the 2020 ESA Land Cover CCI Product (ESA 2017). All units are in million hectares, except where indicated.

Ecological zone	Africa	South America	North America	Asia	Australia	Oceania	**Global**	**Existing forest[1]**	**Existing forest (%)[1]**
Tropical rainforest	399	659	48	323	3	13	**1459**	**1140**	**78.2**
Tropical moist forest	464	428	43	139	0	0	**1077**	**509**	**47.3**
Tropical dry forest	366	167	39	143	67	0	**784**	**236**	**30.0**

Tropical shrubland	595	11	0	116	85	0	**808**	**60**	**7.4**
Tropical desert	871	13	0	269	141	0	**1296**	**6**	**0.4**
Tropical mountain system	147	188	16	90	0	2	**443**	**194**	**43.9**

CCP7.2.1 Distribution and Biodiversity of Tropical Forest Ecosystems

Tropical forests are indisputably the areas with highest biological diversity on Earth, both in absolute and density (species per area) terms (Plotkin et al. 2000). Estimates account that tropical forests harbor half or even more of world's biodiversity (Kier et al. 2009; Jenkins et al. 2013), even though this figure is highly uncertain owing to varying estimates of undescribed species (Mora et al. 2011). For example, it is estimated that there are at least 40,000, but possibly more than 53,000 tree species in tropical forests (Slik et al. 2015). A vast majority of this biodiversity and Indigenous Knowledge and Local Knowledge associated with its use remains poorly explored, presenting a vast unlocked genetic reserve at risk of loss, although many of today's important medicines, foods, and ecosystem products originate from tropical forests (Kouznetsov and Amado Torres 2008; Calderon et al. 2009), staple foods (Brondízio 2008; Isendahl 2011) (Maia and Mourão 2016).

Rates of global biodiversity loss in the past few decades have accelerated to levels that are, for some taxa, approaching the estimated rate of 75% of taxa extinction found in Earth's "big five" mass extinction events (Barnosky et al. 2011) (Díaz et al. 2019) (Davison *et al.*, 2021). Even though species-area relationships tend to overestimate extinction rates (He and Hubbell 2011). , there is evidence that species richness in tropical forests is alarmingly approaching or surpassing the taxa extinction value in this period (45% for dung beetles, 51% for lizards, 65% for ants, and 80% for mammals) should deforestation and habitat loss continue at the current pace (Alroy 2017) (Ceballos et al. 2017). Moreover, there is reasonable understanding that these numbers are underestimated and, as such, tropical forest loss and degradation alone will precipitate a sixth mass extinction event (Giam 2017). A total of 13 out of the 25 global biodiversity hotspots for conservation are located in tropical forests, such as Brazil's Atlantic Forest and India's Western Ghats/Sri Lanka (Myers et al. 2000). While forest loss and degradation have been the main cause of tropical biodiversity loss in the past, climate change now arises as a major threat not only for individual tropical forest species or taxa – as already observed for frogs (Pounds et al. 2006) - but for whole communities (Esquivel-Muelbert et al. 2019), and even entire tropical forest ecoregions (Lapola et al. 2018).

CCP7.2.2 Rates of Deforestation, Tropical Reforestation and Connections to Climate Resilience of Tropical Forests

More than 420 million ha of forest were lost globally in the 1990-2020 period due to deforestation, and more than 90% of that loss took place in tropical areas (FAO 2020). For the 2015-2020 period, the tropical deforestation rate decreased compared to 2010-2015, being estimated at 10.2 Mha yr-1 (FAO 2020). But reforestation and afforestation rates have also decreased, resulting in a tropical forests net loss rate of 7.3 Mha yr-1 in the 2015-2020 period. Overall, the net loss rate has slightly decreased (-4%) since 1990 (*high confidence*). However, a particularly high upward trend is observed in Central America and the Caribbean while a small increase (2%) is observed in the tropical zone of Africa, during the periods from 2010-2015 to 2015-2020 (see Table CPP7.2).

Table CCP7.2: Trends in net tropical forest loss, reforestation and expansion rates (1000 ha yr-1) from 2010-2015 to 2015-2020 periods by regions.

	Net loss rate			Reforestation rate			Forest expansion rate		
Región	**2010-2015**	**2015-2020**	**Observed Trend**	**2010-2015**	**2015-2020**	**Observed Trend**	**2010-2015**	**2015-2020**	**Observed Trend**
Africa	3911.37	3982.97	∧	406.82	297.55	∨∨	442.89	390.47	∨
Asia and Oceania	1083.02	780.49	∨∨	627.46	582.06	∨	1227.15	1130.38	∨
Central America and Caribbean	59.4	122.45	∧∧∧	51.36	44.51	∨	104.74	41.34	∨∨∨
South America	2663.96	2498.65	∨	1081.9	846.24	∨	447.88	297.19	∨∨
Total	7717.76	7384.57	∨	2167.49	1770.36	∨	2222.66	1859.38	∨

Trend direction: ∧ Increase ∨ Decrease

Magnitude of trend (%): ∧ 0-25 ∧∧ 25-50 ∧∧∧ >50

Table Notes:
Details on the Table CCP7.2 elaboration are provided in the Supplementary Material (SMCCP7.1)

CCP7.2.3 Drivers of Deforestation and Forest Degradation

Deforestation and forest degradation both affect carbon stocks, biodiversity loss and the provision of ecosystem services, leading to a reduction in resilience to climate change and exacerbating forest landscape vulnerability even in the absence of direct anthropogenic action (*high confidence*) (Barlow et al. 2016; Aleixo et al. 2019; X. Feng et al. 2021; Saatchi et al. 2021). There is also clear evidence of deforestation influencing temperatures and the hydrological cycle at local to regional scales resulting in reduced precipitation and evaporation and increased runoff relative to unaffected areas (*high confidence*) [CCP7.3.6] (Jia et al. 2019; Douville et al. 2021). Negative trends in biodiversity and ecosystems are predicted to undermine 80% of the Sustainable Development Goals targets related to poverty, hunger, health, water, cities, climate, oceans and land(IPBES 2019). Therefore, besides GHG mitigation, reducing the driving forces leading to deforestation and forest degradation is of the utmost importance for forest resilience, biodiversity protection, avoiding regional climatic changes and the provision of critical ecosystem services, and communities whose livelihoods depend on forests (*high confidence*) (Curtis et al. 2018; IPBES 2019; Jia et al. 2019; Seymour and Harris 2019; Pörtner et al. 2021; Saatchi et al. 2021).

Drivers of deforestation and forest degradation can be distinguished between proximate (i.e. direct) and underlying (i.e. indirect). Direct drivers, such as agriculture (including crops, livestock and plantation forestry), infrastructure development (which often provides access to intact forests and catalyzes deforestation), or timber extraction, are place-based and visible. They are influenced by underlying driving forces, such as demographic, economic, technological, political and institutional, or cultural factors, which typically form complex interactions and act at multiple scales, frequently without any direct connection to the areas of forest loss (Geist and Lambin 2002).

Agriculture is by far the largest direct driver of tropical deforestation, with great differences between commercial and subsistence farming and large variation across regions (Figure CCP7.3). Over 80% of tropical deforestation between 2000 and 2010 was caused by agriculture, proportionally ranging from ca. 75% in Africa and Asia to ca. 95% in the Americas (FAO and UNEP 2020), but both the scale of deforestation and the relative contribution of different drivers have changed considerably over time (*high confidence*) (Hosonuma et al. 2012; Curtis et al. 2018; Seymour and Harris 2019; FAO and UNEP 2020).

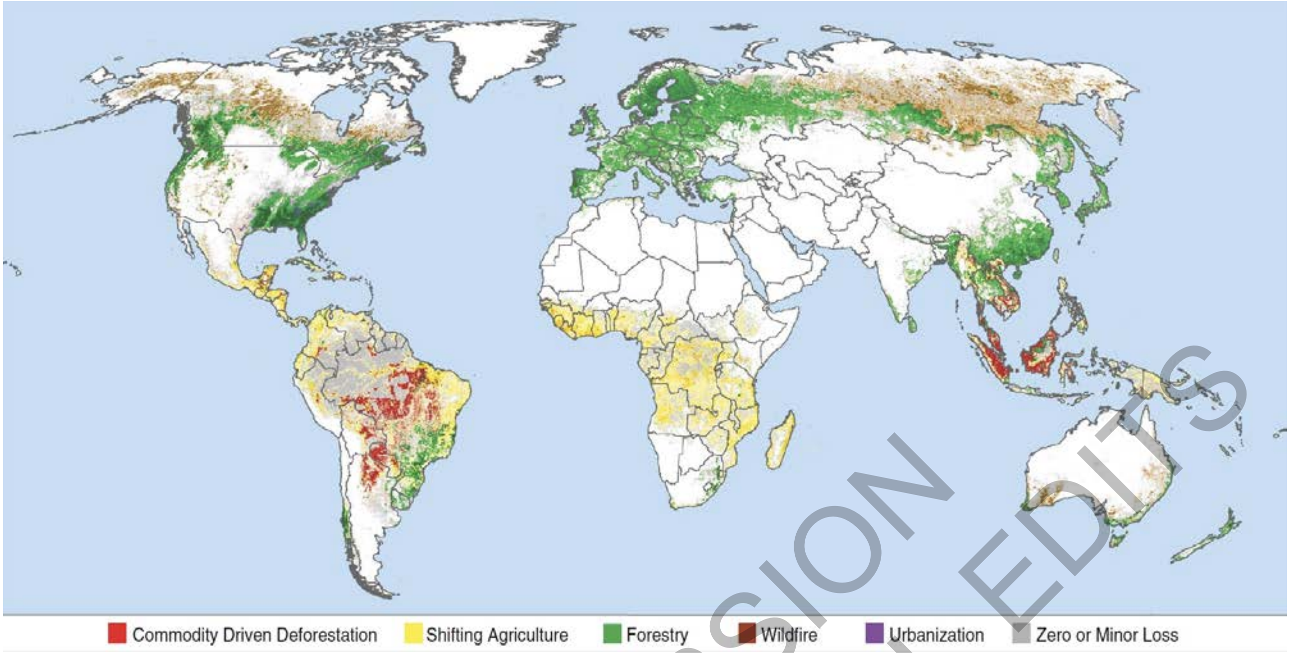


Figure CCP7.3: Primary drivers of forest cover loss for the period 2001 to 2015. Darker color intensity indicates greater total quantity of forest cover loss. While some tropical forest cover loss is temporary, a large portion is related to deforestation. Source: (Curtis et al. 2018). Reprinted with permission from AAAS.

Forest degradation is more difficult to track, but can have large negative effects on carbon storage, provision of ecosystem services, and biodiversity (B. W. Griscom et al. 2017; Houghton and Nassikas 2017). A recent analysis suggests that forest degradation is increasing and is now surpassing deforestation rates in the Brazilian Amazon (Aparecido Trondoli Matricardi et al. 2020). As with deforestation, drivers of forest degradation differ by region, such that timber extraction was by far the most important degradation driver in Latin America and Asia, whereas in Africa wood fuel consumption contributed to about half of forest degradation between 2000 and 2010 (Hosonuma et al. 2012).

Though not as visible as direct drivers, indirect or underlying causes can greatly influence direct drivers, and must be addressed to reduce pressures on forests (*high confidence*) (e.g. FAO 2016b; Fehlenberg et al. 2017; Pendrill et al. 2019b; Bos et al. 2020; Junquera et al. 2020; Ken et al. 2020; Kissinger 2020; Siqueira-Gay et al. 2020; Hoang and Kanemoto 2021). Next to population growth, poverty and insecure land tenure (Ariti et al. 2015; Arevalo 2016; FAO 2016a; Ken et al. 2020; Siqueira-Gay et al. 2020; Verma et al. 2021), many developing tropical countries identify weak forest sector governance and institutions, lack of cross-sectoral coordination, and illegal activity (related to weak enforcement) as critical underlying drivers (FAO 2016a; Ken et al. 2020; Kissinger 2020) [CCP7.6].

International and market forces, particularly commodity markets and, increasingly, large-scale land acquisitions are also key underlying drivers (*high confidence*) (Assunção et al. 2015; Henders et al. 2015; Conigliani et al. 2018; Ingalls et al. 2018; Garrett et al. 2019; Pendrill et al. 2019b; Kissinger 2020; Neef 2020; Hoang and Kanemoto 2021) [WG2 Chapter 5.13]. Deforestation related to commodity imports is increasing, illustrating the growing influence of global markets in deforestation dynamics (Henders et al. 2015). Although some of this production is consumed domestically, 29–39% of deforestation was driven by international trade, primarily from Europe, China, the Middle East and North America (Pendrill et al. 2019a). While many developed countries, China and India have achieved net domestic forest gains, their consumption patterns have increased deforestation embodied in their imports to varying degrees, frequently from biodiversity hotspots (Hoang and Kanemoto 2021). Fifty percent (50%) of the biodiversity loss associated with consumption in developed economies occurs outside their territorial boundaries (Wilting et al. 2017). The increasing prominence of medium- and large-scale clearings of forest between 2000–2012, particularly in Southeast Asia and South America suggests the growing need for policy interventions targeting industrial-scale agricultural commodity producers (Austin et al. 2017). However, countries have been slow to address underlying drivers such as international demand for agricultural commodities. A review of 43 countries' REDD+ readiness documents found that proposed policy interventions largely missed the agricultural drivers identified (Salvini et al. 2014). An assessment of policy responses to rubber and coffee production highlights the challenges governments face in identifying correlations between the direct drivers and related underlying drivers, with international drivers being the most challenging to address (Kissinger 2020).

CCP7.3 Current and Projected Climate Change Impacts on Tropical Forests (Drought, Temperature, Extreme Events)

While early dynamic global vegetation models predicted biome shifts and contractions of tropical forests, more recent efforts have focused on biome changes at more regional scales, or on functional aspects of tropical forests, such as plant physiological and phenological changes, drought-related mortality, population dynamics, interspecies interactions and community responses, ecohydrology, risk of fire and related impacts, soil nutrient and microbe-plant interactions. Climate change is expected to increase temperatures across the tropics, with attendant variability in rainfall, and more extreme events such as intense storms, droughts and wildfires (Zelazowski et al. 2011; Malhi et al. 2014; Brando et al. 2019). This could be expected to have structural and functional impacts on tropical forest biomes (Malhi et al. 2014; Adams et al. 2017). This section looks at responses of tropical trees and forests to current and future climate-change related pressures, focusing on physiological responses including growth, mortality and regeneration, fire risk, and ecological vulnerability, as well as on climate effects of tropical forest loss.

CCP7.3.1 Tropical Tree Physiological Responses to Climate Change

With rising temperatures and atmospheric carbon dioxide, possibly accompanied by greater variability in soil moisture availability, a key question is how tropical forest trees respond physiologically (especially photosynthesis and respiration which determine net growth rates) and how well they can acclimate (i.e., able to adapt) to climate change (Dusenge et al. 2019). Key climate factors influencing tree growth on pan-tropical forests are precipitation, solar radiation, temperature amplitude and relative soil moisture (Wagner et al. 2014).

The temperature response of photosynthetic carbon uptake in tropical trees seems remarkably similar across moist and dry forest types as well as for light-demanding, fast-growing species compared to shade-tolerant, slow-growing species (Slot and Winter 2017). It is generally agreed that photosynthesis in tropical species can acclimate to moderate levels of warming but beyond this there would be no net gain in carbon (Slot and Winter 2017). The factor that limits photosynthesis in different tropical forests will depend on water-availability. In water-limited dry forests, photosynthesis may decline largely due to stomatal closure, while in wet forests, the decline may largely be driven by warming-related changes to leaf biochemistry (Slot and Winter 2017). A recent modelling approach suggests that the limits of photosynthetic thermal acclimation may be an increase of about 2˚C, in terms of maximum tolerated temperature, with enhanced tree mortality beyond this level of warming (Sterck et al. 2016).

A critical concern for plant function has been that higher temperatures will enhance respiration rates, potentially resulting in tropical forests becoming net carbon sources (rather than photosynthesis driven carbon sinks) (Gatti et al. 2021). Some studies suggest that excessive respiration is less of a concern as respiration rates can acclimate to elevated temperatures over time (Lombardozzi et al. 2015; Pau et al. 2018). Thermal acclimation of respiration has been shown in a seasonally dry neotropical forest (Slot et al. 2014), while models indicate that increases in plant respiration could halve by the end of the 21st century through acclimation, thereby partly ameliorating the potential release of carbon from tropical forests (Vanderwel et al. 2015). A contrary view is that plant physiological processes, such as the photosynthesis in tropical canopy trees, are already functioning at levels close to or beyond their thermal optimum limits and that any further temperature increase would turn them from a sink into a carbon source (Mau et al. 2018)
One of the most pressing questions regarding forest responses to increasing atmospheric CO2 levels is whether trees experience enhanced growth rates as a result of the so-called CO2 fertilization effect [Box 2.3

in IPCC SRCCL]. Observed changes in the terrestrial carbon sink and process-based vegetation models indicate that tropical vegetation response to CO2 fertilization (Schimel et al. 2015) is combined to other factors such as nitrogen deposition and length of the growing season, while aerosol-induced cooling may also have played a role in enhancing carbon sink [Box 2.3 in IPCC SRCCL]. Contrastingly, evidence for CO2 fertilization of growth in individual tropical tree species is generally lacking or controversial (Silva and Anand 2013), or not as substantial as expected (Sampaio et al. 2021). It is however widely agreed that the intrinsic water-use efficiency of a tree, i.e. the amount of carbon assimilated as biomass per unit of water used, increases under elevated atmospheric CO2 levels due to the regulation of stomata (cells on the leaf surface which regulate the exchange of water and gases between the plant and the atmosphere) (Van Der Sleen et al. 2015; Bartlett et al. 2016; Rahman and Alam 2016; Keeling et al. 2017). Tropical dry forests (c. 1000mm annual rainfall) exhibit changes in water-use efficiency (WUE), relative to CO2, at least twice as much as do tropical moist forests (c. 4000mm rainfall) (Adams et al. 2019).

Other key components in the forest system are plant-microbe-soil nutrient interactions, which play major roles in carbon cycling and plant photosynthetic response to increased atmospheric CO_2 and warming (Zhang et al. 2014; Singh and Singh 2015; Du et al. 2019). Phosphorus is generally a limiting factor in tropical forest soils though this may be species-specific (Ellsworth et al. 2017; Turner et al. 2018). Mycorrhizal fungi (both arbuscular and ectomycorrhizal) play major roles in water acquisition of host plant and their responses to drought in dry tropical forest (Lehto and Zwiazek 2011) as well as in the capture and transfer of nutrients, especially N (which may otherwise become limiting), to host plants. Climate change factors can thus be expected to alter the nature of soil-plant interactions with consequences for the species composition and biodiversity of tropical ecosystems (Pugnaire Francisco et al. ; Terrer et al. 2019)

CCP7.3.2 Climate-Related Mortality and Regeneration in Tropical Forests

Drought-related mortality of tropical trees shows complex patterns which could change forest community structure and composition with cascading effects on biodiversity (McDowell et al. 2020). During drought, the mortality rate is enhanced in larger-sized trees in tropical forests (as is the case with all forests globally) with significant impacts on forest structure, carbon storage and regional hydrology (Bennett et al. 2015). The mortality rate of neotropical moist forest trees appears to be consistently increasing since the 1980s (McDowell et al. 2020) with plant functional types such as softwood, pioneer and evergreen species suffering higher mortality during years of extreme drought (Aleixo et al. 2019). Large trees (>30 cm dbh) in tropical dry forests have much lower mortality rates than those reported for tropical moist forests (Suresh et al. 2010). Contrary to expectation, during prolonged droughts in these dry forests, deeper-rooted tree species are more *likely* to die than shallow-rooted ones, which are more adapted to changes in soil moisture content, because of water depletion in the deepest unsaturated zone (Chitra-Tarak et al. 2018).

Regeneration of tropical tree seedlings and their response to a changing climate is inadequately understood. Experimental work suggests that tropical moist forest tree seedlings and saplings can acclimate photosynthetically to moderate levels of warming and, unlike adults, may even exhibit increased growth rates (Cheesman and Winter 2013; Slot and Winter 2018) Some moist forest seedlings also show plasticity to recurrent drought episodes by enhancing their growth rates when favorable moisture conditions return, while others fail to respond (O'Brien et al. 2017). The nature of response also seems to be mediated by neighborhood diversity, with greater plasticity in more diverse communities (O'Brien et al. 2017). Seedlings in tropical dry forests subject to burning show enhanced growth rates post-fire and within two years attain similar height of seedlings in unburnt areas (Pulla et al. 2015), though the environmental drivers of seedling growth post-fire are not well understood (Bhadouria et al. 2017).

The net outcome of the population dynamics processes of growth, mortality and regeneration is change in species composition as a consequence of a changing climate. In the Amazon forests, dry habitat-affiliated genera have become more abundant among the newly recruited trees, while the mortality of moist habitat-affiliated genera has increased at places where the dry season has intensified most, thus driving a slow shift towards a drier forest type (Esquivel-Muelbert et al. 2019). A similar multi-decadal shift in West-African forest species composition towards more dry-affiliated species as a response to long-term drying has been recorded (Aguirre-Gutiérrez et al. 2020). While upward shifts in the tree line and in the range of individual tree species have been recorded at several temperate mountain regions, evidence from the tropics is rare. A large-scale study from 200 plot inventories of >2000 tree species across a ~3000m elevation gradient in the

Andean tropics and sub-tropics has shown that the relative abundances of tree species from lower, warmer locations were increasing at these sites indicating that "thermophilization of vegetation" (increased domination of plant species from warmer locations) was indeed taking place as expected (Fadrique et al. 2018) [Section 2.5.4.2.1 in Chapter 2].

CCP7.3.3 Fire Risks from Climate Change in Tropical Forests

Temperature rise and prolonged droughts increase the danger of fires in drained peatlands and tropical forests in South East Asia and the Amazon (da Silva et al. 2018; Pan et al. 2018; Sullivan Martin et al. 2020), resulting in large carbon emissions, which reached 11.3 Tg CO_2 per day during September-October 2015 (Huijnen et al. 2016; Yin et al. 2020) and changes in forest composition and biodiversity (Asner et al. 2000; Hoffmann et al. 2003) *(high confidence*). In many cases, tree mortality due to fire is poorly recorded in the literature, but the available data suggests that fire-induced mortality has increased in recent years (Figure CCP7.2) (Malhi et al. 2014; Brando et al. 2019) *(high confidence*). While large forest and peat fires used to be associated mainly with El Niño Southern Oscillation (ENSO) events, there is now evidence that tropical rainforests in Indonesia may experience higher fire danger from increased temperatures even during non-drought years due to high evaporation rates of fragmented forests (Fernandes et al. 2017; McAlpine et al. 2018). The droughts of 2007 and 2010 in the Amazonian region caused 12% and 5% of the southeastern Amazon forests to burn, respectively, as compared to <1% of these forests burning during non-drought years (Brando et al. 2014; da Silva Júnior et al. 2019; Pontes-Lopes et al. 2021). Moreover, degraded forests in Ghana are more vulnerable to fires during droughts (Dwomoh et al. 2019).

Factors other than solely climate also interact in enhancing the danger of tropical forest fires. For instance, the extent of burned area of rainforests in Borneo has shown that subsurface hydrology, (i.e., hydrological drought), interacts with meteorological drought and, hence, fires have become more intense in recent decades following the progressive desiccation of the island over the past century (Taufik et al. 2017). Bornean forest fire risk also increased through the interaction of drought with land use conversion for logging, oil palm and tree plantations, and human settlements (Sloan et al. 2017). Similarly, simulations of future fire risks in the Amazon show that extensive land use change under the RCP 8.5 scenario results in 4 to 28-fold enhanced area of forest burned by fire by 2080-2100, as compared to 1990-2010, whereas on a RCP 4.5 scenario the area burned would be enhanced by 0.9 to 5.4-fold (Le Page et al. 2017).

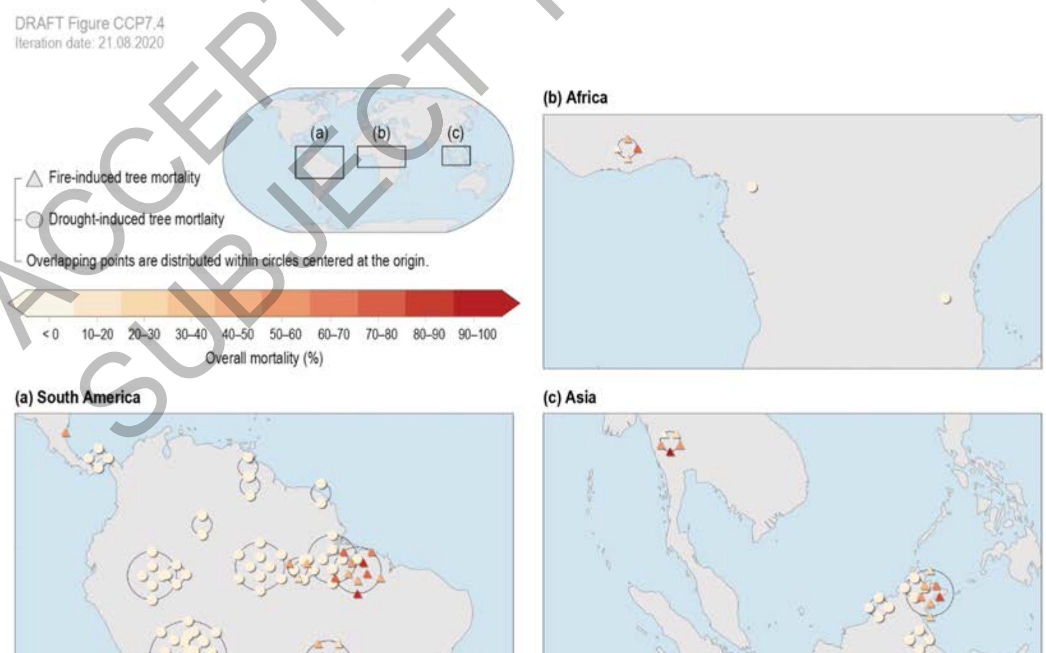


Figure CCP7.4: Documented instances of tree mortality in tropical moist forests due to fire (1992-2016) and drought (1982-2005). These occurrences were associated with anomalies in precipitation and temperature over the study period. Adapted from (Brando et al. 2019).

CCP7.3.4 Current climate risks for tropical forests

Impacts of climate change on tropical forest cover seem to correlate with climatic zone. Natural selection of drought tolerant species is observed in tropical dry forests under a prolonged water deficit environment (Stan and Sanchez-Azofeifa 2019). Tropical montane forests are highly sensitive to warming and associated changes in cloud cover and moisture, with evidence that such forests are already being impacted through "browning" (loss of biomass) from increased warming since the 1990s (Krishnaswamy et al. 2014).

Besides higher temperatures, current climate risks also depend on regional responses to a variety of climate events. For example, tropical biomes across the three continents may respond differently to ENSO events in terms of carbon fluxes and balance. During the 2015-2016 ENSO event, different processes were dominant for the carbon fluxes anomaly in the tropical regions. In Asian forests this anomaly was primarily derived from enhanced fire occurrence, in African forests through increased ecosystem respiration (from higher temperatures), and in South American forests by ecophysiological effects, through the gross primary production (GPP) expressed as reduced carbon uptake (Liu et al. 2017; van Schaik et al. 2018). It has also been shown that the probability of drought spells at the beginning and end of the rainy season is higher in the areas with the highest deforestation (Leite-Filho et al. 2019). Furthermore, it has been observed that Amazon rainforest resilience is being lost faster in regions with less rainfall and in parts of the rainforest that are closer to human activity (IPCC 2014; Seiler et al. 2015) (CCP7.3.6). Conversely, it has been pointed out, on the basis of vegetation indices, that temperature has a greater influence on resilience than does precipitation, and tropical forests are more resilient to climate change when they are more diverse (Feng et al. 2021) (CCP7.3.6).

Biomes such as seasonally dry tropical forests subject to higher variability in rainfall or other climatic factors may be more resilient to fire and drought (Pulla et al. 2015; Liu et al. 2017), though there could be changes in species distributions as a result of disturbances (Allen et al. 2017). A regime of long-term, high rainfall variability seems to be critical in determining the overall resilience of tropical forests and savannas to climate disturbances (Ciemer et al. 2019), highlighting the heterogeneity of the tropical landscape to climate risk. Similarly, forest composition, nutrient limitations, and biodiversity can influence forest resilience to disturbances. Recent evidence suggests that the degree of forest disturbance also affects the mechanisms through which biodiversity influences forest functioning (Schmitt et al. 2020). Neotropical secondary forests also showed high resilience by maintaining their biomass through high productivity and rates of recovery following major disturbances (Poorter et al. 2016). However, the possibility of tropical forests reaching "tipping points" in their resilience and experiencing rapid die-off cannot be ruled out (Verbesselt et al. 2016).

CCP7.3.5 Projected Impacts of Climate Change on Tropical Forest

Climate change projections indicate increased warming and changes in rainfall patterns in the tropical region as elsewhere globally (IPCC AR6 WG1). These would have impacts on carbon stocks (Mitchard 2018; Hubau et al. 2020), water availability (Tamoffo et al. 2019), and structure and diversity (Malhi et al. 2014; McDowell et al. 2020) in tropical forests, amplified by deforestation (CCP7.3.6).

Tropical forests are critical repositories of global carbon; living tropical trees are estimated to hold 200-300 Pg C or about one-third of the levels in the atmosphere (Mitchard 2018). CMIP5 and CMIP6 Earth System Models (ESM) project an increasing future tropical carbon sink, which is particularly strong in the scenarios with more pronounced increase in atmospheric CO2 concentration (Koch et al. 2021). However, major uncertainties regarding the ecophysiological processes governing carbon turnover and tree mortality under a changing climate (Hartmann et al. 2015; Pugh et al. 2020), and the ecosystem-level responses of tropical forests to elevated atmospheric CO2 (Körner 2009) explain the contrast between observational data and modeling results (Rammig and Lapola 2021). Observational data show that structurally intact old-growth tropical forests have been net sinks of atmospheric carbon in recent decades, but there is evidence that the capacity of such intact tropical forests to build up carbon stock may be limited as biomass peaked during the 1990s and has since weakened by 30% in the Amazon since the 1990s (high confidence), mainly due to increased tree mortality and faster carbon turnover, and the African tropical forest sink following this trend since about 2010 (Hubau et al. 2020; Gatti et al. 2021). From a peak pan-tropical (Amazonia, Africa and Southeast Asia) forest sink of 1.26 Pg C yr-1 during the 1990s, it is projected to decline to an uptake of only 0.29 Pg C yr-1, reaching zero, in the Amazon, during the 2030s (Hubau et al. 2020). This decline will possibly be driven by the reduced rates of forest carbon uptake from the weakening global CO2 fertilization effect mediated by limiting soil nutrient, and reduced water availability and higher temperatures during extreme droughts (Qie et al. 2017; Fleischer et al. 2019; Wang et al. 2020), reinforced by deforestation and forest degradation [IPCC SRCCL, 2019].

Offline (uncoupled) vegetation models simulations indicate that the extensive tropical and subtropical forests of the Americas could gradually transit towards a savanna-like vegetation with the most pronounced shifts (of up to 600km northward) from relatively stable forests to savanna-forest transitions occurring in the eastern Amazonian region (Huntingford et al. 2013; Anadon et al. 2014; Nobre et al. 2016) depending largely on the yet uncertain strength of the CO_2 fertilization effect and future dry season length, with important feedbacks on the flux of moisture from the forest to the atmosphere (Delphine Clara Zemp et al. 2017). More limited simulations for Central American rainforests under RCP 4.5 and 8.5 also support a transition in some areas to lower biomass tropical dry forest and savanna-like vegetation (Lyra et al. 2017). Such transitions from one biome type to another will cause major changes in forest structure, species compositions and overall biodiversity. Additionally, the difficulty of species to migrate through highly fragmented tropical forested regions (such as West Africa or South and Southeast Asia) and “non-analogue climates”, under a climate change scenario, poses extra pressure on tropical biodiversity to adapt and survive (Pörtner et al. 2021). Even in expansive tracts of forests such as in the Amazon, climate change is expected to become more important than deforestation by 2050 in causing the loss of tree species (Gomes et al. 2019). Tropical mountain biodiversity hotspots (e.g., Andes, Himalayas) are particularly vulnerable to species loss due to elevation range shifts (Sekercioglu et al. 2008). Under a 2°C increase scenario, a substantial reduction of tropical montane cloud forest in Kenya is estimated (Los et al. 2019).

CCP7.3.6 Climate Responses to Tropical Deforestation and Links to Forest Resilience

Since AR5 there has been meaningful advancement in understanding the climate effects of deforestation and concomitant changes in forest ecosystem resilience. The IPCC Special Report on Climate Change and Land (Jia et al. 2019) and IPCC AR6 WG1 (Douville et al. 2021) both describe significant climate-related changes resulting from tropical deforestation (*high confidence*).

Deforestation generally reduces rainfall and enhances temperatures and landscape dryness; effects that increase with the scale of forest loss, whereas reforestation and afforestation generally reverses these effects (*high confidence*) (Lawrence and Vandecar 2015; Alkama and Cescatti 2016; Khanna et al. 2017; Jia et al. 2019; Staal et al. 2020; Douville et al. 2021; Hofmann et al. 2021; Leite-Filho et al. 2021). There is also *medium evidence* from observations and modeling that deforestation enhances surface runoff (Douville et al. 2021). Whereas quantitative information is much more limited for other tropical regions, past deforestation in the Amazon has led to a small reduction in rainfall of -2.3 to -1.3%, shortening and delay of the wet season, and an estimated 4% increase in dryness (Leite-Filho et al. 2020; Staal et al. 2020; Douville et al. 2021).

Modeling studies estimate that large-scale tropical deforestation will contribute to average warming of the deforested areas with $+0.61 \pm 0.48$°C and will lead to large changes in diurnal temperature ranges due to a reduction of nocturnal cooling (*medium confidence*) (Jia et al. 2019). Large-scale deforestation will also strongly decrease average regional precipitation and evapotranspiration and further delay the onset of the wet season, enhancing the chance of dry spells and intensifying dry seasons, but the magnitude of the decline depends on the scale and type of land-cover change (*high confidence*) (Delphine Clara Zemp et al. 2017; Jia et al. 2019; Douville et al. 2021; Gatti et al. 2021).

Continued forest landscape drying and fragmentation in connection with deforestation may also enhance surface flow variability (Farinosi et al. 2019; Souza et al. 2019) and will aggravate the risk of forest dieback (D. C. Zemp et al. 2017), elevate forest flammability (Alencar et al. 2015) and increase fire incidence (*high* *confidence*) (Aragão et al. 2018; Jia et al. 2019; Silveira et al. 2020; dos Reis et al. 2021), ultimately leading to savannization of many tropical rainforests (Sales et al. 2020). However, compositional heterogeneity and diversity of forest assemblages increases resilience against climate-enhanced forest degradation (Réjou-Méchain et al. 2021).

For the Amazon, deforestation (ca. 40% of the region) in combination with climate change will raise the prospect of passing a tipping point leading to large-scale savannization of the rainforest biome, but but uncertain remains that this will take place in the 21st century (Nobre et al. 2016; Jia et al. 2019; Douville et al. 2021). However, considering that the Amazon has already lost ca. 20% of its forests (Nobre et al. 2016), crossing the tipping point may not only create savannas of the deforested parts but may also result in precipitation reductions of 40% in non-deforested parts of the western Amazon due to a breakdown of the South American monsoonal circulation and the subsequent western cascade of precipitation and evapotranspiration (Boers et al. 2017). Other effects of forest degradation include loss of ecosystem services, biodiversity, carbon storage, and indigenous culture (Watson et al. 2018; Strassburg et al. 2019; Gatti et al. 2021), as well as potentially reduced hydropower capacity and agricultural production (Sumila et al. 2017) and increases in tropical diseases (Husnina et al. 2019).

The dearth of data for tropical forest regions other than the Amazon makes assessments of deforestation-related changes in temperature, precipitation and streamflow difficult (*high confidence*) and hampers estimates of tropical forest ecosystem health, biodiversity loss and vulnerability to current and future climatic and other pressures (*high confidence*). There is, hence, a strong need for increased investment in relevant data and research to narrow the knowledge gaps (Davison et al. 2021). Nonetheless, conclusions based on a newly developed tropical vulnerability index synthesizing remotely sensed land use and climate information indicate that forests in the Americas are already reaching critical levels to multiple stressors, while forests in Asia reveal vulnerability primarily to land-use change and African forests still show relative resilience to climate change (Saatchi et al. 2021).

CCP7.4 Social-Economical Vulnerabilities of Indigenous Peoples and Local Communities Living in Tropical Forests

Around 800 million people live in or in the immediate vicinity of tropical forests (Keenan 2015). Short-term impacts of climate change on biodiversity will exacerbate the inequalities affecting those livelihoods which heavily rely on forests (Pörtner et al. 2021).

Livelihoods, gender, land use change and dependency on forest resources for food, fuel, housing and other needs have been identified as key elements of vulnerability in Indigenous Peoples and rural communities in Africa and South America (high confidence) (Nkem et al. 2013; Field et al. 2014; Newton et al. 2016; Pearse 2017; IPBES 2018; Pörtner et al. 2021). Socio- economic vulnerability varies depending on the level of dependency of forest food consumption (Rowland et al. 2017), livelihood strategies and settlement patterns. In Cameroon (Nkem et al. 2013), nomadic hunter-gatherers and sedentary communities showed differences in their vulnerability, driven by their preferences in forest settlement locations for farming, hunting, fishing, gathering, trapping, and maintaining livestock.

Increasing temperatures, extreme climatic events, drought and fire will affect the proportion and frequency of forest resources availability. In communities of tropical America, Asia and Africa, social vulnerability factors identified include: deforestation pressures for agriculture expansion to cope with climate-induced food shortages, conflicts over access to forest land as a result of uncontrolled fire induced by higher drought frequency and severity, the availability of wild game, the work capacity, and the time consumed in work and gender-based differences (Blaser and Organization 2011; Bele et al. 2013; IPCC 2014). Although the size and quality of harvest in crops and Non-Timber Forest Products (NTFPs) will be affected, the literature reports the use of NTFPs, hunting, and fishing is less sensitive to climate change, and relevant for household incomes (Bele et al. 2013; Djoudi et al. 2013; Newton et al. 2016; Onyekuru and Marchant 2016). Data from tropical forests document the contribution of NTFPs to local livelihoods (Issaka 2018), with well-established NTFPs such as Brazil nut (Bertholletia excelsa), Rattan (Calamus and Daemonorops species), Rubber (Hevea species), Açai (Euterpe oleracea) showing promise for sustainable harvesting strategies which could reduce socio-economic vulnerability (Blaser et al. 2021).

The decrease of tropical forest area due to land use change will put additional pressures, threatening livelihood practices, traditional land arrangements, and customary rights of forest-dependent communities and impacting the Sustainable Development Goals (SDG) of Climate action and Life on Land (Djoudi and Brockhaus 2011; Tiani et al. 2015; Hurlbert et al. 2019). Globalized trade relations, agricultural expansion, illegal activities and violent conflicts have been identified as important non-climatic drivers of forest degradation (*high confidence*) (Barr and Sayer 2012; Rist et al. 2012; Shanley et al. 2012; Ruiz-Mallén et al. 2017; IPBES 2018; IPBES et al. 2018). Globally, about 70% of tropical forest areas occur outside protected areas. In Latin America and the Caribbean, Indigenous Peoples and local communities have predominant ownership of tropical forest lands, while in West and Central Africa and Asia, forested areas are largely State-owned with exacerbating problems of governance, inequity and conflict with customary land tenure systems (Blaser and Organization 2011).

Further research by experts and local stakeholders and Indigenous Peoples is required to design more accurate and comprehensive indicators (Huong et al. 2019). Solid evidence shows important knowledge and experiences that Indigenous Peoples and local communities contribute to disaster risk reduction and management (IPBES 2018a). Recognizing the land rights of Indigenous Peoples is among the most cost-effective actions to address climate and biodiversity risks, according to FAO and FILAC (2021). In Indigenous Peoples' forest lands in the Amazon basin, deforestation rates are up to 50% lower than in other forested areas (Ding et al. 2016), and indigenous management is correlated with reduced carbon emissions (Blackman and Veit 2018). Indigenous authors and local authors have pointed out the role of traditional systems of governance, knowledge and belief systems in the resilience of Indigenous Peoples and rural communities in the Amazonian and Andean region, by regulating seed access and the conservation of agrobiodiversity and tropical forest (Camico et al. 2021; Panduro Meléndez et al. 2021). In Philippines, the traditional land use system Muyong, promote sustainable agroforestry management based on customary land laws (Camacho et al. 2016). Participation of local stakeholders and the inclusion of a gender perspective contribute to prioritizing resource allocation and the development of effective legal frameworks for adaptation (Shah et al. 2013; Tiani et al. 2015; Ihalainen et al. 2017; Collantes et al. 2018). There is a need to combine quantitative and qualitative methods, and increase research efforts to integrated approaches; including multiscalar and interdisciplinary assessments of vulnerability (Djoudi et al. 2013; Guidi et al. 2018; FAO and CIFOR 2019).

[START BOX CCP7.1 HERE]

Box CCP7.1: Indigenous Knowledge and Local Knowledge and Community-Based Adaptation

Purely scientific knowledge, albeit indispensable, is insufficient to address climate change. Indigenous Knowledge systems, embedded in social and cultural structures, are integral to climate resilience and adaptation (*high confidence*) (Ajani 2013; Tengö et al. 2014; Hiwasaki et al. 2015; Roue and Nakashima 2018)[AR5 WG2 12.3.3, 14.3.1, 20.4.2 , SRCCL 4.8.1, 4.8.2, SR15 4.3.5]. Indigenous knowledge and local knowledge (IK and LK) and community-based adaptation (CbA) have received increasing recognition across all sectors (*high confidence*) (Reid and Huq 2014; Wright et al. 2014; MOSTE 2015)[SRCCL 4.1.6, 5.3.5, SR15 Box 4.3] (Figure Box CCP7.1.1). Forest Indigenous knowledge is closely linked to traditional land-use practices and local governance (Roberts et al. 2009); it is embodied in art, rituals, food, agriculture and customary laws, among others (Hiwasaki et al. 2015; Camico et al. 2021). CbA is a community led process based on its desires, priorities, knowledge and capacities; which empowers people as central players in climate change adaptation (Reid et al. 2009) [SRCCL 5.3.5].

CbA is related with concepts such as community and adaptive collaborative forest management. These approaches acknowledge the importance of cultural and socio-economic ties between communities and forests, along with community's authority and responsibility for forest sustainable management (Ajani 2013; Ellis et al. 2015; Torres et al. 2015).

Role of IK and LK and CbA for Climate Change Adaptation in Tropical Forests

Local forest and Indigenous forest management systems have developed over long time periods; generating social practices and institutions that have supported livelihoods and cultures for generations (*high confidence*) (Seppälä 2009; Martin et al. 2010; Parrotta and Agnoletti 2012; Camico et al. 2021).

Archaeological evidence shows that humans have manipulated tropical forests for at least 45 thousand years (*high confidence)*. Indigenous Peoples usually consider themselves as parts of socio-ecosystems, protecting the forest by maintaining healthy socio-ecological relationships and successfully adapting to environmental change (Speranza et al. 2010; Swiderska et al. 2011; Parrotta and Agnoletti 2012; Uprety et al. 2012; Mistry et al. 2016; Roberts et al. 2017) [AR5 WG2 12.3.2].

CbA ensures community engagement in bottom-up management and adaptation approaches (Simane and Zaitchik 2014; Keenan 2015). IK and LK and CbA can enhance adaptation in many ways, including through knowledge generation, ecosystem monitoring, climate forecasting, increased resilience and response to climate extremes and slow onset events (Speranza et al. 2010) [AR5 WG2 12.3.3; SRCCL 4.8.2] (Figure Box CCP7.1.1).

Integration of IK and LK Systems, CbA and Modern Scientific Systems

Several authors have highlighted the need to foster a respectful a dialogue between IK and LK and modern science towards a holistic research model (*high confidence*) (Berkes 2010; Ajani 2013; Tengö et al. 2014; Roue and Nakashima 2018)[AR5 WG2 12.3.3, 14.2.2]; but few ecological studies have attempted this integration (Keenan 2015; Vadigi 2016). Examples in tropical forest ecosystems include topics such as monitoring climate impacts; local climates; seed, water and land management resilience-increasing practices and climate threats to traditional agriculture (Parrotta and Agnoletti 2012; Fernández-Llamazares et al. 2017; Camico et al. 2021; Panduro Meléndez et al. 2021). A growing number of methods are available to help this dialogue [SRCCL 7.5.1] (Reid et al. 2009; Tengö et al. 2014; Tengö et al. 2017; Roue and Nakashima 2018)(Figure Box CCP7.1.1). While there is expanding interest among decision-makers, researchers, Indigenous Peoples and civil society on IK and LK (Hiwasaki et al. 2015; Maillet and Ford 2016), gaps remain regarding links between place-and-culture dimensions and adaptive capacities (Ford et al. 2016).

Enhancing Adaptive Capacity Through IK and K and CbA: Lessons Learned

Useful lessons can be drawn from experience to effectively incorporate IK and LK and CbA in adaptation strategies. A number of barriers to adaptation have also been recognized (Figure Box CCP7.1.1). Considering that IK and LK is increasingly threatened by colonization, acculturation, dispossession of land rights, and environmental and social change, among others [AR5 WG2 12.3.3; SR5 4.3.5] (Seppälä 2009) highlighted the importance of supporting community efforts to document, vitalize and protect it. It is essential to consider goals, identity and livelihood priorities of Indigenous Peoples and local communities, including those beyond natural resource management (Reid et al. 2009; Diamond and Ansharyani 2018; Zavaleta et al. 2018). Adaptation processes are more *likely* to be transformational when they are locally driven (*medium confidence*: *medium evidence, high agreement*) (Chung Tiam Fook 2015; Chanza and De Wit 2016). This requires adaptive institutional frameworks, capable of navigating the complex dynamic of socio-ecosystems (*medium confidence*: *medium evidence, high agreement*) (Locatelli et al. 2008; Simane and Zaitchik 2014)[AR5 WG2 12.3.2; SR15 5.3.1]. It is important to consider power relations and priority differences to avoid causing social disruption and inequality. "We need to keep asking: Who benefits? Who loses? Who is empowered? Who is disempowered?" (Reid et al. 2009).

Finally, vulnerability and adaptive capacity have a historical and geopolitical context, conditioned by value systems and development models. Forest management strategies must take into account the wider picture if they seek to be not just temporally effective (at best), but transformative and sustainable over time (*high confidence)* (Chung Tiam Fook 2015; Chanza and De Wit 2016).

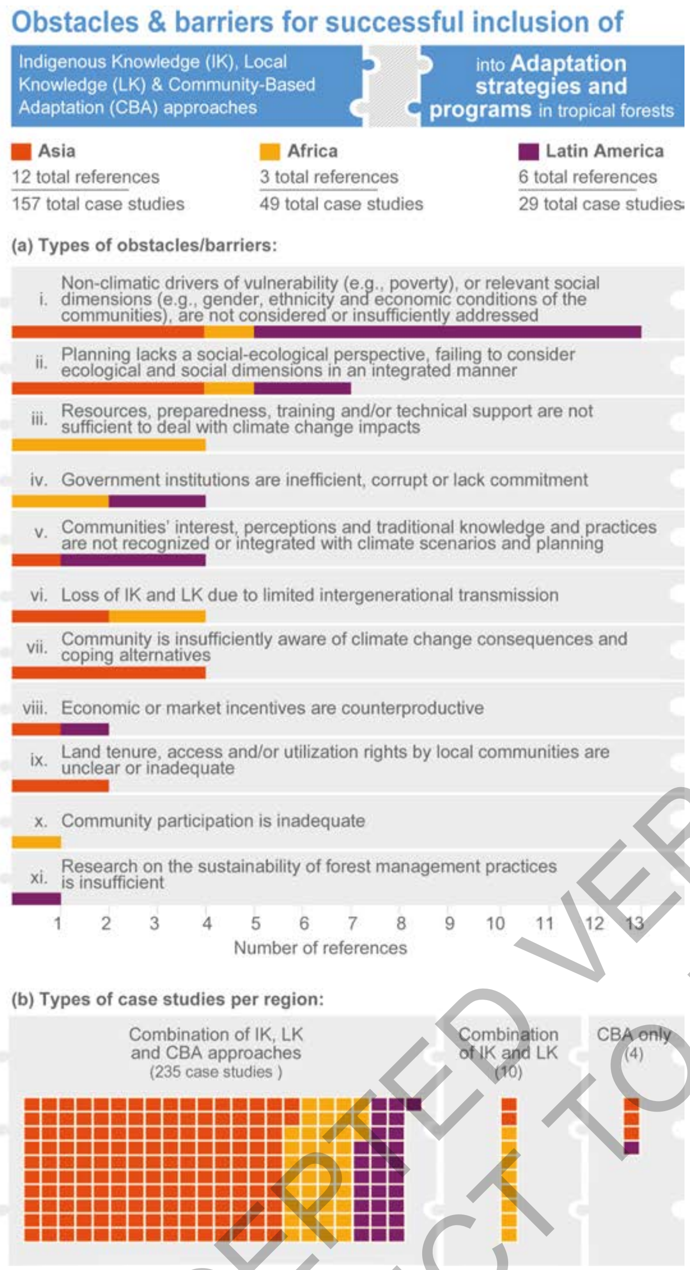


Figure Box CCP7.1.1: Main obstacles and barriers reported for successful IK and LK and CBA approaches in adaptation strategies and programs for tropical forests.
Panel (a): Obstacles and barriers ranked by the number of references in which they were identified. (One reference can identify more than one barrier, so numbers of references by barrier are not additive). Panel (b): Distribution of cases studies according to approach (IK and LK, CBA or a combination of both). One reference can include one or more case studies. See countries included by continent and references in the Supplementary Material (SMCCP7.2)

[END BOX CCP7.1 HERE]

CCP7.5 Adaptation Options, Costs, and Benefits

Ecological adaptation and other spontaneous responses to climate change are discussed in (Settele et al. 2015) and [AR6WGII_Ch2]). Here we consider the role of humans in managing the adaptation of tropical forests to climate change. The focus is on human-assisted adaptation options that help to maintain tropical forest ecosystems and not on the use of forests to supply provisioning services, such as timber, which is covered in [AR6 WGII_Ch5]. Forest management and agroforestry are discussed, but only with regard to their role in contributing to the adaptation of tropical ecosystems now and in the future. Maintaining ecosystems has a range of co-benefits for humans including through 'ecosystem-based adaptation' these are explored in [Chapter 1 Box 1.3; Cross-Chapter Box NATURAL in Chapter 2, Box CCP7.2]. Although there are a number of potentially valuable response options, it is clear that certain hazards, such as heat waves, may be impossible to manage at the forest community level and require long-term interventions at the landscape scale. Similarly, it will be difficult for forest managers to adapt to indirect climate-related ecosystem disturbances such as loss of pollination agents, invasive species, or pest and diseases outbreaks (Allen et al. 2010; Anderegg et al. 2020). Equally important in adapting to increased pressure from climate change are efforts to minimize disturbance from non-climatic stress factors (e.g. overharvesting, pollution, and land use change (Malhi et al. 2014; Keenan 2015; Barlow et al. 2016; Pörtner et al. 2021). Under some emissions scenarios, projected climate change impacts are of such severity that no adaptation measure is *likely* to protect natural forest systems, e.g. with warming of 4 ˚C, some tropical forests are at risk of die-back from high temperature (Malhi et al. 2014; Settele et al. 2015; Trumbore et al. 2015).

Actions to protect the extent or reduce the disturbance pressure on forest systems contribute to the capacity of these systems to respond to climate change (increasing resistance and resilience) (*high confidence*) (Millar et al. 2007; Schmitz et al. 2015; Settele et al. 2015; Sakschewski et al. 2016; Hisano et al. 2018). Furthermore, if implemented sufficiently well, efforts to manage and restore forests also improve the capacity of forest systems to respond to future climate stressors (increasing resilience and responsiveness). Table CCP7.3 gives an overview of adaptation strategies for tropical forests within the framework of protect, manage, restore (Sayer et al. 2003; Pörtner et al. 2021). In assessing the available adaptation options, it can be useful to distinguish between actions focused on protecting forest extent, managing biodiversity, managing ecosystem function, or restoring ecosystem services (Seppälä 2009), Figure CCP7.5 and Table CCP7.4 give a detailed assessment of the major adaptation options in this context. Beyond these specific interventions, and in several cases underpinning them, there is an increasing awareness that effective management and adaptation of tropical forests requires an appreciation of IKLK and community-based adaptation in order for implementation to be meaningful, these approaches are assessed in [Box CCP7.1]

CCP7.5.1 Adaptation Options at Different Scales

To retain functioning tropical forests, adaptation will need to take place across many scales from individual stands, to interconnected landscapes, and upwards to regional and global policy changes. From a global perspective the most effective adaptation and mitigation option is to reduce and reverse the loss of area in tropical forest ecosystems (Alkama and Cescatti 2016; B. W. Griscom et al. 2017). Maximizing tropical forest extent has well described benefits in mitigating CO2 emissions and in the role of forests regulating global climate (*high confidence*) (Smith et al. 2014). For nations with tropical forests, adaptation is largely achieved through sustainable management of forested areas, enforcing the land rights/land tenure of Indigenous Peoples, and through establishment of Protected Areas (Table CCP7.4; (Seppälä 2009; Pörtner et al. 2021)). Some of this is achieved through schemes incentivizing landowners to retain tree cover for the express purpose of mitigating climate change impacts (e.g. PES, REDD+). For nations outside of the tropics, there is a need to regulate the global drivers of forest loss, such as the consumption of agricultural commodities and of non-sustainable forest products (including timber) (CCP7.3; (CCP 7.3; Henders et al. 2015 Nolte et al., 2017, Pendrill et al., 2019).

At a landscape scale, increasing forest cover and maintaining biodiversity-friendly land-use outside forests increases ecosystem resilience to climate change (and other disturbances) and allows for climate-driven species migration e.g. Table CCP7.3- protect; (Schmitz et al. 2015; Aguirre and Sukumar 2016)). Ensuring forested areas are large and/or interconnected including the use of specific climate refugia and climate corridors is recommended for climate adaptation (*high confidence*) (Schmitz et al. 2015; Settele et al. 2015; Simmons et al. 2018; Pörtner et al. 2021). For habitats or species pushed to the edge of their range, area-based conservation needs to take account of the future climate space and facilitate movement of species through connectivity or assisted migration (Seppälä 2009; Schmitz et al. 2015; Pörtner et al. 2021). Maintaining functioning forest ecosystems is vital due to biophysical, biological (biodiversity-driven) and socioeconomic interactions that contribute to ecosystem resilience (Pielke Sr et al. 2011; Malhi et al. 2014; Lawrence and Vandecar 2015; Alkama and Cescatti 2016; Sakschewski et al. 2016). Protecting forested areas can be achieved through vertical integration of policies at national, subnational and local levels and effective stakeholder empowerment (Meijer 2015). Community-based and ecosystem-based adaptation approaches provide an overall strategy to help achieve these goals [Cross-Chapter Box NATURAL in Chapter 2] (Locatelli et al. 2010; Cerullo and Edwards 2019). In addition to conservation of tropical forests, restoration and afforestation can be effective climate adaptation measures (e.g. Table CCP7.3- restore)

(Arora and Montenegro 2011; Perugini et al. 2017). The technical requirements for such adaptation measures are similar to those required for forest landscape restoration (Mansourian and Vallauri 2005; Mansourian et al. 2017; Shimamoto et al. 2018; Philipson et al. 2020). Agricultural intensification has been proposed as one method to reduce pressure on remaining forested land, although the overall carbon impact of such approaches must be considered (Cross-Chapter Box 6 in SRCCL, Shukla et al. 2019; Cerri et al. 2018; Kubitza et al. 2018).

At the forest community level, adaptation options aim to protect the forest microenvironment and retain biodiversity through forest management (e.g. Table CCP7.3- manage; (Keenan 2015; Jactel et al. 2017)). In Protected Areas this would typically involve reinforcing existing conservation objectives through adaptive management (Salafsky et al. 2001; Ellis et al. 2015; Tanner-McAllister et al. 2017; Hagerman and Pelai 2018), including support for natural regeneration (Chazdon et al. 2016). It is also possible to improve forest cover and interconnectivity through restoration or afforestation. There are many technical guides to improve the implementation and success rate of such approaches (Table CCP7.4) (Lamb and Gilmour 2003; Shimamoto et al. 2018; Strassburg et al. 2019)) and funding support specifically aimed at climate change adaptation and mitigation (e.g. REDD+). In some instances, climate change can alter climate suitability to the extent that managers need to allow for a transition to a new habitat type (e.g. from tropical forest to savanna), adaptive management can help recognize and facilitated these transitions (Seppälä 2009; Schmitz et al. 2015; Lapola et al. 2018). Depending on local conditions it will be necessary to adapt to specific stress factors that are *likely* to increase in prevalence or severity due to climate change, e.g. heat waves, drought events and forest fires (Allen et al. 2010; Malhi et al. 2014; Seidl et al. 2017). Although it is typically not possible to link individual events or adaptation measures to climate change; the effectiveness of technical interventions has been illustrated in a broader forest management context. Table CCP7.4 assesses the costs and benefits of different adaptation options based on the available literature. However, it should be noted that there is lack of information on many potential adaptation interventions, especially in the context of tropical forests (Locatelli et al. 2010; Bele et al. 2015; Keenan 2015; Hagerman and Pelai 2018). The sections below and Figure CCP7.5 offer a framework for optimizing management of complex tropical forest ecosystems within a landscape context, through a range of interconnected adaptation options.

CCP7.5.2 Adaptation Response Options

Forests will be affected by several climate change impacts that will require forest management towards fulfilling four objectives: maintain forest area; facilitate biodiversity adaptation; maintain healthy functioning forest ecosystems; and restore ecosystem services (including productive capacity) (Seppälä 2009), which complement the more conventional approaches to protect, manage and restore forests (Sayer et al. 2003). This is dependent on location-specific conditions that are defined by the type of forest and land tenure regimes or dominant actors across forest landscapes. The analysis here proposes 10 adaptation responses that focus on the adaptation potential of tropical forests to climate change and are linked to the management objectives identified (Figure CCP7.5). Each response option (1–10) implies variable economic costs and benefits, influenced by location-specific conditions, including several important non-monetized benefits. The figure suggests the most relevant situations in which the different response options hold greater potential to meet the forest management objectives for addressing expected climate change impacts.

This assessment considers the economic costs and benefits of 10 response options in their contribution to adaptation of tropical forests to climate change impacts but also includes non-market costs that are more difficult to quantify (e.g. cultural values), which are borne by different stakeholders (Chan et al. 2016; Pascual et al. 2017). Similarly, benefits also include the social and environmental benefits that result from adaptation options over extended time horizons. Economic costs and benefit-cost ratios suggest the short-term economic potential of different options, but responsibly designed adaptation measures involving a combination of different response options and embracing a long-time horizon have the potential to provide significant social and climate benefits over the coming 50 years or more.

Table CCP7.3: Overview of adaptation strategies for tropical forests. This table includes key policy frameworks and common management approaches with potential for adapting native forests to increased disturbance from climate hazards. Details on each management approach and the associated literature are given in Table CCP7.4: Costs and Benefits of Adaptation Options in Tropical Forests.

	Strategy	Expected contribution to climate adaptation
Protect	Protected Areas	Maintaining forest extent builds resistance and resilience to climate change (Seppälä et al., 2009; Schmitz et al., 2015).
	Area-based conservation / Climate refugia	Where forests are under threat from progressive warming, protection of less disturbance prone areas (e.g. higher altitude stands) allows for migration and recolonization improving the ability of the whole ecosystem to respond to climate change (Schmitz et al., 2015; Pörtner et al., 2021).
	Buffer zones	Maintaining buffer zones around protected forests builds resistance and resilience to climate change and allows for adjustment of boundaries, under future conditions (Seppälä et al., 2009; Schmitz et al., 2015).
	Avoid deforestation	Reducing loss of trees due to non-climate stressors, protects forest extent and builds resistance and resilience to climate change (Locatelli et al., 2010; Smith et al., 2019).
	Public education / awareness	Publicizing the role of forests in supporting human society can reduce anthropogenic pressures on forested areas (Seppälä et al., 2009; Hagerman & Pelai, 2018).
Manage	Vulnerability assessment and monitoring programs	Recognising changes in climate and in disturbance regimes allows for other management interventions, such as area-based conservation and assisted migration, to be implemented (Schmitz et al., 2015; Hagerman & Pelai, 2018).
	Adaptive management / climate services	Adaptive management along with information on the changing climate can improve the capacity of forest managers to respond to climate change (Seppälä et al., 2009; Tanner-McAllister et al., 2017).
	Strengthen land tenure	Strong land tenure, e.g. for Indigenous Peoples, often leads to more sustainable management of forested areas, so building resistance and resilience of climate change (Porter-Bolland et al., 2012; Garnett et al., 2018).
	Conserve biodiversity, promote mixed stands	Within managed forests, using diverse planting stock and managing for biodiversity improves resilience to disturbances from future climate changes (Keenan, 2015; Pörtner et al., 2021).
	Fire prevention and management	The use of fire suppression, fire breaks, controlled burning and water table maintenance can build resistance to climate change driven wildfires, in both managed and natural systems (Stephens et al., 2013; Musri et al., 2020; Bowman et al., 2020).
	Sustainable forest management	Within managed forests, vegetation control to manage tree density and stand conditions can build resistance to climate driven disturbance such as fire (Seppälä et al., 2009; Pörtner et al., 2021).
Restore	Increase connectivity	Providing connection corridors between forested areas builds resilience and helps the system response to climate change. This can include thermal corridors that allow for species migration under progressive climate change (Schmitz et al., 2015; Hagerman & Pelai, 2018).
	Forest restoration / assisted natural regeneration	Forest restoration helps restore forest extent and connectivity, and can reduce edge pressure, improving resilience and the capacity to respond to future climate stressors. In some cases, assisted migration and the use of planting stock selected for tolerance to climate change may be appropriate (Locatelli et al., 2015a; Pörtner et al., 2021).
	Agroforestry / trees on farm	In degraded areas, such as buffer zones and mosaic landscapes, planted trees can reduce resource pressure on intact forest, improve soil conservation, regulate temperature and water cycles, and increase resilience through ecological processes (Jose, 2009; Lasco et al., 2014).
	Indigenous and Local knowledge of ecosystems	Incorporating Indigenous and Local knowledge can improve the ability to protect and sustainably manage forest systems so building resilience (Seppälä et al., 2009; Porter-Bolland et al., 2012).

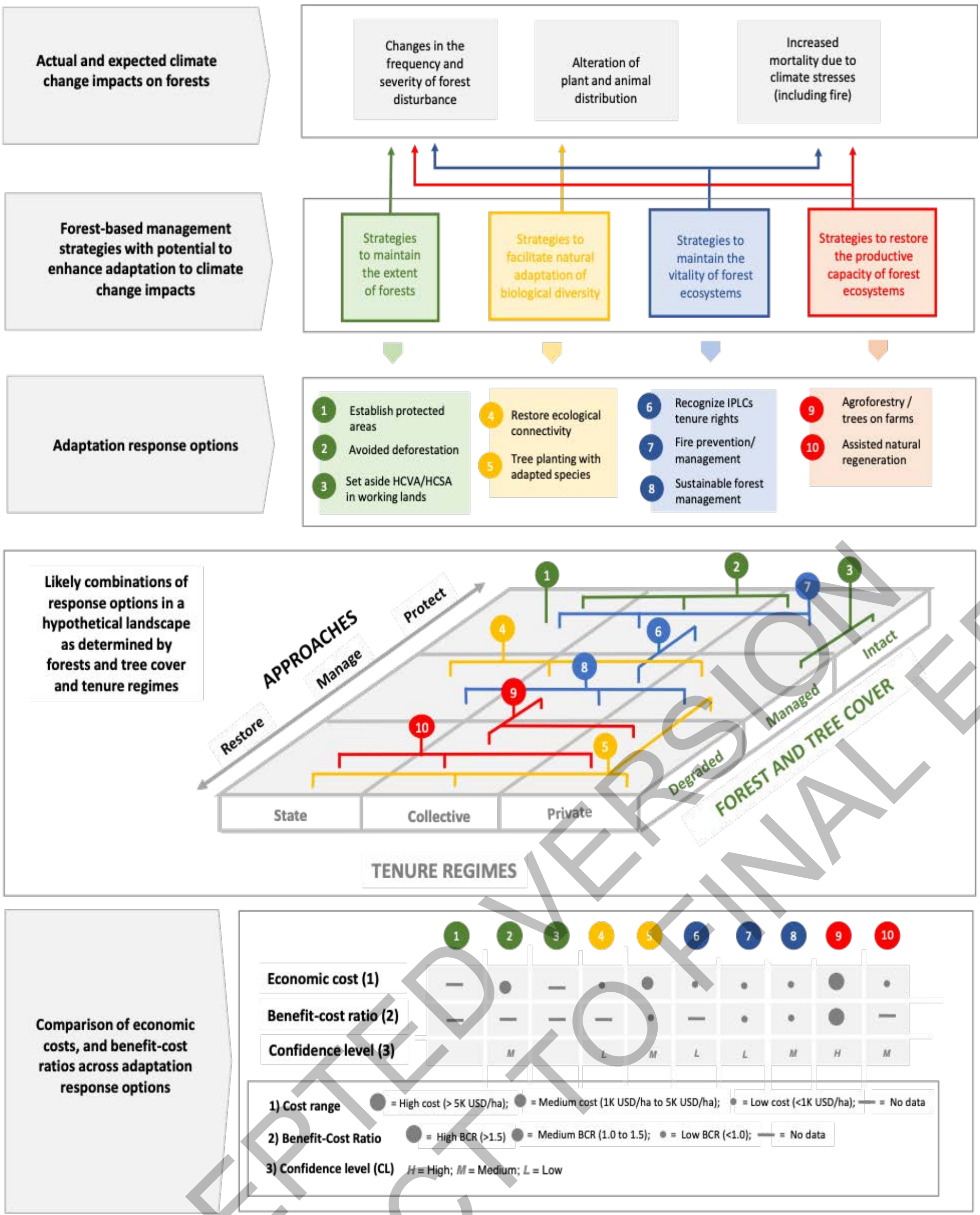


Figure CCP7.5: Framework to assess adaptation response options in tropical forests by adopting a landscape perspective as determined by types of forests and tree cover across different tenure regimes. Notes: HCVA = High Conservation Value Areas; HCSA = High Carbon Stock Areas; IPLC = Indigenous Peoples and Local Communities. The information supporting this figure originates from an extensive literature review that is included in this section, Table CCP7.4. The assessment of confidence levels is based on the judgement of the authors based on the reviewed literature and follows IPBES guidelines.

CCP7.5.3 Costs

The cost of implementing adaptation options varies widely and will change based on the location, time horizon, and who bears the cost. As a result, most existing estimates are offered in broad ranges that include only partial cost estimates. Here we group the adaptation costs into three categories, low (<USD1000/ha), medium (between USD1000/ha and USD5000/ha) and high cost options (>USD5000/ha).

- Low cost options are those estimated to cost less than USD 1000 per ha and include recognition of tenure rights of Indigenous Peoples and local communities (Hatcher 2009), restoring ecological connectivity (Crossman and Bryan 2009; Torrubia et al. 2014), fire prevention and management (Bronson W Griscom et al. 2017; Arneth et al. 2019), assisted natural regeneration (Cury and Carvalho

2011; Lira et al. 2012; MMA 2017; Silva and Nunes 2017), and sustainable forest management (Boltz et al. 2001; Holmes et al. 2002; Pokorny and Steinbrenner 2005; Medjibe and Putz 2012; Singer 2016).
- Medium cost options are those estimated to cost between USD 1000 and USD 5000 per ha and include estimates for tree planting (Rodrigues 2009; Campos-Filho et al. 2013; Silva and Nunes 2017; Nello et al. 2019) and avoided deforestation (Kindermann et al. 2008; Overmars et al. 2014; Smith et al. 2019).
- High cost options are those estimated to cost more than USD 5000 per ha and include actions associated with agroforestry systems, particularly the most biodiverse systems (Raes et al. 2017; Nello et al. 2019).
- Costs per hectare are either not available or vary too widely for several options, including protected areas (Balmford and Whitten 2003; Bruner et al. 2004), and high value conservation areas in working lands (Naidoo and Adamowicz 2006). Bronson W Griscom et al. (2017) provided recent estimated costs for many of the above adaptation options; in most cases these costs are much lower than other estimates referenced here, which are particularly focused on tropical forest landscapes.

While economic costs constitute an important factor in determining the feasibility of options, there are other factors that have an important influence on the viability of the options including opportunity costs, transaction costs, and social feasibility, which are not included in this analysis. For example, options such as recognition of rights for Indigenous Peoples and local communities can be a low-cost option but often face political opposition (RRI 2021) including from some conservation organizations; fire prevention and management require political coordination across multiple governance levels (Fonseca-Morello et al. 2017); and sustainable forest management can be seen as a less attractive option when compared to other more profitable land uses (Köthke 2014). Table CCP7.4 offers a more detailed assessment of the costs included, along with a reference to the costs for society.

CCP7.5.4 Benefits

Estimates of economic benefits across options tend to vary greatly, largely based on the scale of operations, and the market and institutional contexts in which they are implemented. The longer-term non-monetary benefits tend to be larger than has been acknowledged in the past (Chan et al. 2016; Pascual et al. 2017; UNEP 2021). The shorter-term horizon of the economic benefits of adaptation options suggest that benefit-cost ratios of investments are higher in more biodiverse agroforestry systems in comparison with simpler ones (Miccolis et al. 2016), and agroforestry system benefits are comparatively higher compared with commercial tree planting depending on the species (Table CCP7.4 (Nello et al. 2019)).

All the objectives here support not only a large number of local people in fulfilling their livelihoods, but often provide services to distant urban populations as well. The benefits differ according to which of the four forest landscape management objectives is prioritized (Table CCP7.4):

- objectives that seek to maintain the extent of forests contribute to improved landscape continuity, persistence of species and metapopulations (including floral recruitment) (Nordén et al. 2014), maintaining hydrological cycles (Creed et al. 2011), and avoiding surface temperature increases (Perugini et al. 2017). In many cases High Conservation Value Areas (HCVAs) are based on the presence of threatened or endemic species or dense, carbon-rich forest ecosystems (e.g. primary forest) (Jennings et al. 2003).
- objectives that prioritize natural regeneration and adaptation of biological diversity allow greater opportunity for climate refugia (Morelli et al. 2017; Simmons et al. 2018), provide increased dispersal opportunities for different species (Christie and Knowles 2015), increase flora and fauna diversity, and may provide small benefits in reducing warming (Arora and Montenegro 2011).
- objectives to maintain and enhance the quality and persistence of vital forest ecosystems contribute to securing the provision of habitat, maintain soil structure and fertility, and regulate water quantity and quality (Imai et al. 2009; Putz et al. 2012).
- objectives that prioritize the restoration of ecological productivity of degraded forest ecosystems and landscapes contribute to increased biodiversity conservation, soil structure and fertility, nutrient cycling, water infiltration/water recharge, erosion control and climate regulation (Seppälä 2009; Shimamoto et al. 2018; Pörtner et al. 2021).

CCP7.5.5 Strategic Approaches to Combine Response Options

While adaptation costs and benefits of response options differ, their benefit-to-cost ratios are almost always positive, particularly in the longer term (Müller and Sukhdev 2018; Chausson et al. 2020; Seddon et al. 2020; Baste et al. 2021). However, implementation of adaptation actions can be economically unviable if the benefits accrue over longer periods of time because development banks apply much higher discount rates to low income countries than the standard rates (Watkiss 2015). Achieving conditions that do not disincentivize against, and rather encourage investments in nature-based solutions to protect, sustainably manage, or restore tropical forest landscapes is therefore critical to enhancing their implementation (UNEP 2021).

In addition, implementation of response options should consider equity aspects to ensure that the costs and benefits of actions within a landscape are equitably distributed among public institutions, private enterprise, and civil society (Verdone 2015). Strategic approaches to restoring ecosystems can increase conservation gains and reduce costs (Shimamoto et al. 2018; Strassburg et al. 2019). Cost-effective solutions that consider multiple costs and benefits need a "compromise solution" between short and long-term social and economic gains. Pursuing spatial allocations for adaptation options has the potential to deliver greater benefits at lower costs, therefore aligning aims for tropical forest adaptation, species conservation, and climate mitigation targets with the interests of farmers under short and long time horizons (Beatty et al. 2018).

Table CCP7.4: Costs and Benefits of Adaptation Options in Tropical Forests.

Climate change impact	Adaptation measures	Expected contribution to adaptation	Context/Location of implementation	Economic costs	Costs to society	Benefits for forest ecosystems	Benefits/Impacts to people
1. Forest management strategies to maintain the extent of forests							
Changes in the frequency and severity of forest disturbance	Avoid deforestation	Forests counteract wind-driven degradation of soils, and contribute to soil erosion protection and soil fertility enhancement for agricultural resilience (Locatelli *et al.* 2015a). The impact of reduced deforestation may be higher when the large biophysical impacts on the water cycle (and thus drought) are taken into account (e.g. (Alkama and Cescatti 2016)). Reducing deforestation and habitat alteration contribute to limiting infectious diseases (e.g. malaria) (Karjalainen *et al.* 2010). Avoiding deforestation contributes to climate change mitigation due to reduced carbon emissions (Smith *et al.* 2019).	In private lands (individual and collective) and in state lands, in areas with larger presence of intact forests or mosaic agriculture and forest lands under management.	500-2600 USD ha^{-1} (Kindermann *et al.* 2008; Overmars *et al.* 2014; Smith *et al.* 2019). (1) 20-200 USD ha^{-1} (Bronson W Griscom *et al.* 2017; Arneth *et al.* 2019) (global estimate).	Opportunity costs associated with different alternatively productive land uses (Kindermann *et al.* 2008).	Landscape continuity, persistence of species and metapopulations (including floral recruitment) (Nordén *et al.* 2014). Maintained hydrology (Creed *et al.* 2011), and flood mitigation. Avoided surface temperature increases (Perugini *et al.* 2017) Protects other regulatory functions of forests, with positive impacts on human health.	Potential to affect the lives of 1-25 million people globally (low confidence) (Keenan 2015; UNISDR and CRED 2015; Smith *et al.* 2019).
	Protect and/or increase the size and number of protected areas, especially in 'high-value' areas	Protected areas play a key role for improving adaptation (Lopoukhine *et al.* 2012; Watson *et al.* 2014), through reducing water flow, stabilizing rock movements, creating physical barriers to coastal erosion, improving resistance to fires, and buffering storm damages. Primary forests sustain tropical biodiversity (Gibson *et al.* 2011), thus protecting intact forests preserves current patterns of biodiversity (Schmitz *et al.* 2015). (2)	Mainly established in state lands where there is dominance of intact forests, in some cases overlapping with Indigenous territories.	Costs include recurrent management costs, system wide costs, and establishment costs. The cost per ha decreases with increased area (Balmford and Whitten 2003; Bruner *et al.* 2004).	Potential land use and tenure conflicts over protected area expansion. 'High value' areas are often priority areas for human activity (e.g. lowlands) (Venter *et al.* 2014). Management costs (Bruner *et al.* 2004).	May create additional dispersal corridors and support metapopulations for forest species increasing ecosystem resilience (Nordén *et al.* 2014). Improved hydrology (Creed *et al.* 2011) Protected areas contribute to income generation through tourism (Snyman and Bricker 2019).	Empirical studies of protected areas that use impact evaluation methods, provide evidence that parks help increase household incomes (Mullan *et al.* 2009), poverty alleviation and environmental sustainability (Andam *et al.* 2010).

	Set aside High Value Conservation Areas (HVCA) and High Carbon Stock Areas (HCSA) in working lands	Setting aside HCVA and HCSA within agriculture or tree-crop plantations has benefits for preserving endemic species, and some ecological services (e.g. pollination services from insects)) (Scriven *et al.* 2019) (3)	Established in private intact and managed forest lands often allocated to mid- and large-scale plantations.	Opportunity costs to landowners who would lose working land/productive area to HCVA or HCSA. Management costs (Naidoo and Adamowicz 2006).	□Opportunity costs to landowners who would lose working land/productive area to HCVA or HCSA. □Management costs (Naidoo and Adamowicz 2006).	□In many cases HCVA are based on the presence of threatened or endemic species or dense, carbon-rich forest ecosystems (e.g. primary forest) (Jennings *et al.* 2003).	HCVA also provide ecosystem services, and therefore can contain valuable economic benefits; forests provide for some basic needs of local communities (health and subsistence) as well as traditional/ cultural identity (Seppälä 2009; Karjalainen *et al.* 2010).
2. Forest management strategies to facilitate adaptation of biological diversity							
Alteration of plant and animal distribution	Restore ecological connectivity through the establishment of corridors	Conserve biodiversity by enabling natural migration of species to areas with more suitable climates (Malcolm *et al.* 2002), maintaining connectedness, especially between various protected areas, and ensuring that different stages of forest development are present (Seppälä 2009). Building corridors creates landscape permeability for plant and animal movement (Schmitz *et al.* 2015).	Corridors are implemented in managed lands across state, collective and private tenure regimes circumscribed to specific project targeted areas.	60-1294 USD ha^{-1} (in USD 2019) (Crossman and Bryan 2009; Torrubia *et al.* 2014)	□Land use opportunity costs, financial costs of land acquisition and restoration (Naidoo and Adamowicz 2006). Research and pilot costs of different corridor connection methods (Naidoo and Adamowicz 2006).	□Landscape connectivity allows greater opportunity for climate refugia (Morelli *et al.* 2017; Simmons *et al.* 2018) and the restoration of ecosystem patches of native forests can provide dispersal opportunities for different species using alternate successional stages (Christie and Knowles 2015). □Improved hydrology.	Ecosystem services could be enhanced (e.g., hydrological benefits, soil conservation, health, recreational and cultural benefits through establishment and restoration of green spaces).
	Mixed planting with native species tree planting, with consideration of intraspecific genetic diversity of seedlings	Reforestation is an important climate change adaptation response option (Reyer *et al.* 2009; Locatelli *et al.* 2015b; Ellison *et al.* 2017), and can potentially help a large proportion of the global population to adapt to climate change and related natural disasters. Native tree planting aimed at increasing resilience should include planting genotypes tolerant of drought,	Tree planting is implemented in degraded lands across different state, collective and private lands	Planting of seedlings 978-3450 USD ha^{-1} (in USD 2019) (Chabaribery *et al.* 2008; Rodrigues 2009; Campos-Filho *et al.* 2013; MMA 2017; Silva and	Loss of water yield (at least on an annual average basis) due to increased evapotranspiration Reforestation helps maintaining base flow during the dry season may reduce the	□Better water retention capacity; reduced risk of erosion, landslides □Carbon gain. □Increases both flora and fauna biodiversity. □In cases of reforestation/afforestation, small benefits in reducing warming are expected	Reforestation/afforestation has the potential to impact the lives of >25 million people globally (Medium confidence) (Reyer *et al.* 2009; UNISDR and CRED 2015; Sonntag *et al.* 2016; Bronson W Griscom *et al.* 2017; Smith *et al.* 2019) (global estimate). No availability

		insects and/or disease, as well as increasing the genetic diversity within species used for planting and recognizing provenance. Tree planting should avoid conversion of natural ecosystems including grasslands and savannahs (Bond and Zaloumis 2016).		Nunes 2017; Nello *et al.* 2019) 20-200 USD ha^{-1} (Arneth *et al.* 2019), for reforestation and forest restoration (Bronson W Griscom *et al.* 2017) (global estimate).	amount of water available for people downstream (Ellison *et al.* 2017). Research costs on genetic varieties and Implementation	(Arora and Montenegro 2011). □Increased potential for adaptive evolutionary responses within populations to the varied effects of climate change (drought, disease, etc.) (Puettmann 2014).	of information on differentiated impacts from reforestation and afforestation.
3. Forest management strategies to maintain the vitality of forest ecosystems							
Changes in the frequency and severity of forest disturbance	Recognizing the rights of Indigenous Peoples and local communities	Granting tenure rights to Indigenous people has potential to maintain forest, and ensure provision of ecosystem services, thus supporting local strategies for adaptation to climate change threats (Porter-Bolland *et al.* 2012)	Recognizing local tenure rights takes place in land belonging to Indigenous Peoples and local communities across all different forest and trees conditions	0.05-9.96 USD ha^{-1} (Hatcher 2009). Include the costs of mapping, delimitation, and titling. (RRI 2021) estimates the following costs: US$5 per ha for large projects, $22.5 per ha for medium, sub-national projects, and US$50 per ha for small investments.	□Costs to local populations for protecting forest lands, and opportunity costs for avoiding land conversion (Hajjar *et al.* 2016).	□Landscape continuity, persistence of species and metapopulations (including floral recruitment) (Nordén *et al.* 2014).	Some estimates indicate that Indigenous people manage or have tenure rights over at least ~38 million km^2 (Garnett *et al.* 2018) (global estimate). Recognition of rights often translates into positive social and environmental benefits (RRI 2021), yet they may differ depending on local conditions
Increased mortality due to climate stresses (including fire)	Within production forests, practice sustainable logging by embracing reduced-impact	Some production forests can retain most ecosystem functions and services, and a similar species richness of animals, insects, and plants to that found in nearby old-growth forest but can be more susceptible to defaunation and fire (Edwards *et al.* 2014). Sustainable	SFM is undertaken at a large scale in public forests allocated as concessions, and at smaller scales in private and	70 to 160 USD ha^{-1} (Singer 2016) 169-345 USD ha^{-1} (in USD 2019) (Boltz *et al.* 2001; Holmes *et al.* 2002; Pokorny	□The tendency of interventions is a (direct or indirect) reduction of diversity because the natural interest of the forest owner is to favor	□Secures the provision of species habitat □Soil structure and fertility □Regulates water quantity and quality □Carbon storage (Imai *et al.* 2009)	The benefits of Sustainable Forest Management have the potential to affect the lives of >25 million people globally (low confidence) (UNISDR and CRED

	logging (RIL) and other practices	Forest Management plays a role in adaptation by ensuring that through long-term forest management the diversity of forests is maintained as well as benefits from forest resource use (Putz *et al.* 2012). Improved forest management positively impacts adaptation by limiting the negative effects associated with pollution (of air and fresh water), diseases, and exposure to extreme weather events and natural disasters (e.g., (Smith *et al.* 2014)) [4]	community forests lands	and Steinbrenner 2005; Medjibe and Putz 2012) \$20-\$200 ha^{-1} (Bronson W Griscom *et al.* 2017; Arneth *et al.* 2019) (global estimate)	commercial species.		2015; Smith *et al.* 2019) (global estimate)
	Reduce the incidence of fire hazard and improve fire management	As fire hazard increases in some forests with climate change, adaptation measures to reduce fire hazard will be needed (Seppälä 2009).	Fire prevention and management is practiced in private lands (individual and collective) and state lands across managed and intact forest lands	<\$20 ha^{-1} (Bronson W Griscom *et al.* 2017; Arneth *et al.* 2019) (global estimate)	Costs of fuel management and prescribed burns. Costs of implementing fire management plans with many groups of stakeholders (Stephens *et al.* 2013).	• Avoids forest degradation and deforestation. • Prevents biodiversity and species loss. • Protects local livelihoods and cultural values.	>5.8 million people affected by wildfire globally; max. 0.5 million deaths per year by smoke globally (medium confidence) (Johnston *et al.* 2012; Doerr and Santín 2016; Smith *et al.* 2019) (global estimate)
4. Forest management strategies to restore the productive capacity of forest ecosystems							
Increased mortality due to climate stresses	Assisted natural regeneration in degraded forest landscapes	Forest landscape restoration positively affects the structure and function of degraded ecosystems (Shimamoto *et al.* 2018). Forest restoration may enhance connectivity between forest areas and help conserve biodiversity hotspots (Locatelli *et al.* 2015a; Ellison *et al.* 2017; Dooley and Kartha 2018). Forest restoration may improve ecosystem functionality and services, provide microclimatic regulation for people and crops, wood and fodder as safety nets, soil erosion protection	Tree regeneration takes place in more degraded lands across different types of tenure regimes in public, community and private lands	Assisted natural regeneration 180-980 (USD ha^{-1} (in USD 2019) (Cury and Carvalho 2011; Lira *et al.* 2012; MMA 2017; Silva and Nunes 2017)	Opportunity costs of alternative land uses, costs of maintaining regenerating landscapes (e.g. exclusion plots), costs of facilitated dispersal or seeding (Naidoo and Adamowicz 2006).	• Uses microclimatic changes from regeneration to create emergent landscape restoration from available and present species in soil seed banks or dispersive capacity of local habitat patches. • Increases potential area and influence of forest ecosystems even into marginal matrix habitat (Chazdon and Guariguata 2016).	The benefits of regeneration of degraded landscapes has the potential to impact the lives of >25 million people globally (Medium confidence) (Reyer *et al.* 2009; UNISDR and CRED 2015; Sonntag *et al.* 2016; Bronson W Griscom *et al.* 2017; Smith *et al.* 2019) (global estimate)

		and soil fertility enhancement (Locatelli *et al.* 2015a). Land restoration can reduce future risks (e.g. by protecting against hazards) and current vulnerability (e.g. by diversifying livelihoods) (Pramova *et al.* 2019). Natural forest regeneration contributes to climate mitigation through carbon removals (Lewis *et al.* 2019), and this would imply less need for climate adaptation					
Changes in the frequency and severity of forest disturbance	Expand agroforestry systems (AFs) in buffer zones and mosaic landscapes	Agroforestry reduces pressure on intact forests and can enhance ecosystem services at the landscape level (Jose 2009). It can also help to increase resilience to pests and diseases through ecological processes (Miccolis *et al.* 2016). Agroforestry can reduce vulnerability to hazards like wind and drought, particularly for subsistence farmers (Thorlakson and Neufeldt 2012).	Agroforestry has a large potential in collective forest lands, both managed and degraded	7150-22575 USD ha^{-1} (n USD 2019) (Raes *et al.* 2017; Nello *et al.* 2019)	Opportunity costs of other land uses. Costs of engaging in markets and/or developing markets for agroforestry products. Risks of market saturation and supply/demand inconsistencies. (Torres *et al.* 2010; Mercer *et al.* 2014)	Biodiversity (habitat, migratory corridors, gene flow) Soil structure and fertility, nutrient cycling Water infiltration/ water recharge, erosion control Buffer strips can reduce the resource pressures on native ecosystems by providing income and resources for people (Vieira *et al.* 2009).	Potential to improve farmers' livelihoods and quality of life of 2,300 million people globally (medium confidence) (Lasco *et al.* 2014; Smith *et al.* 2019) (global estimate)

Table Notes:
This table draws on Appendix 6.1-6.4 from Seppala et al. 2009, pp. 71-77
(1) Agricultural expansion is the major driver of deforestation in developing countries. Cost of reducing deforestation is based on opportunity cost of not growing the most common crop in developing countries (Maize) for six years to reach tree maturity, with yield of 8 t ha^{-1} (high); 5 tons ha^{-1} (medium) & 1.5 t ha^{-1} & price of USD 329 t^{-1}. Also, reduced deforestation practices have relatively moderate costs, but they require transaction and administration costs (Kindermann *et al.* 2008; Overmars *et al.* 2014).
(2) May not deal with displacement of wild species due to climate change
(3) Fragments of disconnected HCVAs have less value to preserve ecological services
(4) Forest management strategies may decrease stand-level structural complexity and may make forest ecosystems more susceptive to natural disasters like wind throws, fires, and diseases (Seidl *et al.* 2017)

[START BOX CCP7.2 HERE]

Box CCP7.2 Contribution of sustainable tropical forest management to the SDGs

There is increasing evidence of positive impacts of resilient tropical forests, biodiversity, and sustainable forest management in achieving SDGs as illustrated in Table Box CCP72.1. However, there is also risk of unintended consequences based on conflicts between the use of forest-based goods and services and effects on tropical forest resilience, ecosystem services, and biodiversity (Baumgartner 2019). For instance, substitution of fossil fuels and non-renewable resources with bio-based products can lead to deforestation and the loss of biodiversity (Carrasco 2017) (Cross-Working-Group Box BIOECONOMY in Chapter 5). Deforestation as a result of increased agricultural production and productivity could hamper efforts in addressing long term food security, particularly for forest dependent people (Newton et al. 2016); CCP7.2.3). Synergies and trade-offs depend very much on local contexts and are therefore presented in exemplary form.

IFAD (2016) estimated that there are 640 million people living below the poverty line in rural areas of 43 tropical countries. Poor communities rely on ecosystem services for their subsistence livelihoods, and often they have limited capacity to adapt to change, making them more vulnerable to climate change and other forms of changes (Bhatta 2015). Managing forests sustainably benefits both urban and rural communities, including provision of food and fiber, on watershed hydrology, agroforestry production, among others (Powell et al. 2013; Dawson et al. 2014) (Clark and Nicholas 2013) (Mbow et al. 2014)) (Table Box CCP7.2.1).

Table Box CCP7.2.1: Examples from sustainable tropical forest management (STFM) in achieving SDGs.

SDGs	Contribution of STFM to the Goals	Adaptation Interventions	Supporting references
1 No Poverty	Area of forest land with legal property status held by communities	In Mexico, community forest management (CFM) has played a pivotal role in forest cover and biodiversity conservation in the region where timber production and processing generates income and thereby offers a way out of poverty for families in communities with rights to forests.	(Ellis et al. 2015)
	Improve incomes through selling forest products or by generating employment for the poorest	Non-timber forest products (NTFPs) are a significant source for socio-economic, employment and income generation, particularly for tribal people.	(Kumar 2015)
	Improve income through valuation of ecosystem services	In Cambodia, contribution of forest resources should be integrated into payment for ecosystem services schemes, in order to provide more diversified income streams, insulating indigenous people from shocks and stressors.	(Nhem 2018)
2 Zero Hunger	Forests also provide food, which improves food security and nutrition	In Cameroon, forest fruits provide important macro- and micronutrients lacking from the family diets of rural people. Association between tree cover and the dietary diversity of children in the communities of 21 countries across Africa.	(Fungo et al. 2015) ; (Ickowitz et al. 2014)
3 Good Health & Wellbeing	Medicinal plants contribute to emotional and spiritual wellbeing	Medicinal plants and the associated Bhutanese traditional medicine (BTM) are protected by the country's constitution and receive both government support and acceptance by the wider public. These medicinal plants have been one of the drivers of the 'Gross National Happiness (GNH)' and biodiscovery projects in Bhutan.	(Wangchuk and Tobgay 2015)

	Health co-benefits of preserving biodiversity	In the Brazilian Amazon, interventions targeted specifically at preserving biodiversity in protected areas generate health co-benefits. From the perspectives of malaria, acute respiratory infection (ARI), and diarrhea, results suggest that the public health benefits of strict PAs may offset some of their local costs. Nature is doing its part by providing a form of (human) capital for the rural poor and the politically voiceless.	(Bauch et al. 2015)
4 Quality Education	Inclusive education that builds and reinforces positive attitudes to forest	Encouraging and enabling pro-forest behavior as well as strengthening education systems that respect, nurture and enable Indigenous knowledge and local knowledge.	(Kanowski 2019) (Tengö 2017) (Vaidyanathan 2014)
		The value of social capital for maintaining sustainability of community forest management includes, among others, individual characteristics, procedural knowledge and access to information. Initiatives to manage natural resources are *likely* to be more successful if the forest management program initiators consider several factors that influence the capacity development of resource users.	(Lee 2017)
5 Gender Equality	Within genders, other characteristics such as class, race, caste, culture, wealth, age and ethnicity influence responses and affect the impact of climate variability and change on livelihoods	Despite challenges, Nepal's community forestry policy is considered one of the most progressive, as it allows women to exercise equal rights with men in the management and utilization of community forests. Furthermore, women-only forestry groups have registered many success stories.	(Lama et al. 2017); (Agarwal 2015)
6 (Clean Water & Sanitation)	Regulate water supply, water quality and water purification	Evidence from the Hindu Kush Himalayas require improved upstream-downstream integration, transboundary cooperation and greater coordination of implementation of different SDGs. Greater efforts are required to make the communities struggling on the frontline of sustainable forest management more climate resilient. Forest concessions can make a positive contribution to this by minimizing the negative impacts of harvesting operations on water access and by employing appropriate restoration techniques as required by the concession contract and national legislation.	(Scott C.A. 2019); (Amezaga 2019) (Bruggeman et al. 2015),
7 (Affordable & clean energy)	Energy transitions	Decreased reliance on traditional wood fuels and increased use of forest-derived modern fuels (e.g. biofuel) are generally synergistic with achieving other SDGs, such as livelihoods strategies. However, modern wood fuels need improved stoves to ensure the energy is clean.	(Jagger 2019) ; (Simangunsong et al. 2017)

8 (Decent work and economic growth)	Stimulating economic growth and minimizing forest loss	Synergy potentials exist where growth strategies and associated policies target the forest section with NTFPs from natural forests, ecotourism and payments for environmental services.	(Stoian 2019)
		Community forestry enterprises have the potential to make significant contributions by providing a solid institutional framework to efficiently translate SDGs into actions. It also improves forest management, social cohesion and rural incomes amongst local communities in developing countries.	(Aryal 2020); (Vázquez-Maguirre 2020); (Baynes 2015)
9 (Industry innovation & infrastructure)	Integration of small-scale business into value chains and markets	Strategies in relation to sustainable supply chains and tropical forest protection, i.e. Unilever and Instituto Centro de Vida (ICV), demonstrate both alignment and variability between and within organizations. Associated incentives could help balance the burden of responsibility for implementation between global and local actors of promoting zero deforestation.	(Delabre et al. 2020)
10 (Reduced Inequalities)	Reduction in the number of poor households	Results from Waseda-Bridgestone Initiative for Development of Global Environment (W-BRIDGE Initiative) in South Kalimantan province through capacity building delivered by academic partners. This initiative also increased land area ownership from 0.28 to 1.23 ha per household.	(Hiratsuka 2019)
	Protect the workers and communities long-term and economic well-being	Rural agrarian communities in low-latitude tropical forests (e.g., communities in Southeast Asia, South America, Central Africa) adapting to chronically hotter temperatures in common ways, such as adjusting when and how they work. Decision-makers should develop an understanding of these behavioral adaptations that are already being adopted before establishing broader adaptation strategies.	(Masuda 2019)
11 (Sustainable Cities and Communities)	Upstream forests influence water supplies to cities	Watershed condition is associated with measurable health outcomes downstream. Maintaining natural capitals within watersheds is an important public health investment especially for populations with low levels of built capital.	(Herrera et al. 2017)
		Evidence from Marikina Watershed Integrated Resources Development Alliance in the Philippines working together with all stakeholders to restore Marikina Watershed to reduce disaster risk and urban resilience.	(Devisscher 2019)
		Synergies delivered through sound urban forestry approaches could benefit not only urban dwellers but also forest communities. Community groups have also taken responsibility for urban forestry in the absence of strong government commitment.	(Konijnendijk 2018)
12 (Responsible Consumption & Production)	Generates materials for sustainable consumption	Forest concessionaires can also increase the repurposing of waste to improve sustainable consumption. For instance, the logging company Congolaise Industrielle des Bois produces electricity from sawmill wood waste.	(Tegegne et al. 2019)

13 (Climate Action)	Enhance resilience and adaptive capacities to climate change through forest management	Mixed agroforestry systems offer opportunities to simultaneously meet the water, food, energy and income needs of densely populated rural and peri-urban areas in Indonesia.	(van Noordwijk et al. 2016)
	Carbon-based conservation	Payment for carbon-based conservation (eg. REDD+, Green Climate Fund) protecting peatlands from avoidable human impacts for favourable return from carbon conservation investments.	(Roucoux et al. 2017)
		REDD+ has mixed impacts on communities' socio-ecological resilience. On one hand, increases in network ties and participation in decision-making would enhance potential for local adaptability. However, restrictions on local forest practices could limit communities' ability to manage uncertainty.	(Hajjar 2021)
14 (Life Below Water)	Support numerous ecosystem services	Complex root systems serve as shelter as they protect juvenile fish from predators as well as provide food and nutrients for fish.	(Friess 2019)
		Mangroves contribute to fisheries production and have become one of the higher carbon stocks compared to other forests. The mangroves system of the Zambezi River Delta, Mozambique confirms the consistency of substantial C stocks typical of mangroves across a relatively large and hydrologically diverse area.	(Stringer 2015)
	Protection for aquatic macroinvertebrates habitats	The riparian canopy of the tropical forest is significantly able to maintain in-stream temperature that is important to aquatic macroinvertebrates. The study of Gunung Tebu, Malaysia showed high diversity and abundance of steams invertebrates as the natural habitats are minimally impacted.	(Md rai 2014)
15 (Life on Land)	Community monitoring of their own forests or forest within communal jurisdiction, sustainable certification	Mainstreaming SFM in vast tracts of forest, thereby increasing the share of forest area under a forest management plan, including the proportion of forest area certified under independent forest certification schemes.	(van Hensbergen 2016)
		Even with tension between the management of resources for local goals and the need for public good values, still there are some communities that maintain strong control over their lands and resources in achieving desirable conservation outcomes and willing to see large tracts of land set aside, i.e. areas held to be sacred.	(Sayer et al. 2015); (Sheil 2015)
16 (Peace, justice and strong institutions)	Addressing complexity of implementing conservation policy	Target 16.7 calls for responsive, inclusive participatory and representative decision-making at all levels. Decentralization in forest governance observed through community-based/collaborative forest management depends on the strength of underlying land tenure and use rights, as well as capacity to benefit from those rights.	(Baynes 2015) ; (McDermott 2019) ;(Myers 2017) ;(Nunan 2018)
		By 2021, Thailand plans to increase use of renewable and alternative energy by 25% including energy crops. Adequate forest protection is critical, as increasing demand for energy crops may drive demand for expanding agricultural production into	(Phumee 2018)

		public forests, benefitting some SDGs and threatening others.	
	Modern technologies in forest management control	Technologies including remote sensing and Geographic Information System (GIS) are interrelated as they support management actions in global forest resources management thus reducing exploitation through monitoring and evaluation activities.	(Beckline 2017)
	Governance laws and policies provide access to justice for all	The Forest Stewardship Council (FSC) and the program for the Endorsement of Forest Certification (PEFC) significantly contribute to ensuring the legality of the timber supply chain. The (FAO 2018b) considers the proportion of forest with secure tenure rights for forest dependent people and the local community in ensuring equal rights to economic resources for all.	(Gabay 2019)
17(Partnership for the goals)	Co-benefits derived from tropical forest conservation	Raising awareness of the interconnectedness of tropical forests and the SDGs through multi-disciplinary collaboration will support more informed decisions of social, cultural, economic and policy interest.	(Swamy 2018) ; (Bukoski et al. 2018)
	Voluntary Partnership Agreements (VPAs) stabilize and reproduce the very forest governance regime	In Ghana, the adoption of the VPA resulted in an improved Timber Legality Assurance System (TLAS), strengthened Social Responsibility Agreements (SRA) enforcement, updated forest management plans, artisanal milling strategies and technical transparent timber dights allocations.	(Hansen 2018)
	Central bureaucracies promote forest benefits: countering conservation	Forest Management Units (FMUs) could be utilized to support conservation-oriented regimes with worldwide interests as well as domestic production-oriented regimes. For example, FMUs might potentially link up with global and domestic timber certification regimes under the Multistakeholder Forestry Programme (MFP3) imitative.	(Sahide 2016)

[END BOX CCP7.2 HERE]

CCP7.6 Governance of tropical forests for resilience and adaptation to climate change

Deforestation and forest degradation in tropical forests has grown in prominence as priorities for environmental governance in the face of climate change, given the large share of forest and land use GHG emissions in the national profiles of tropical forest countries (*high confidence*) (Butt et al. 2015; IPCC 2019). This is reflected in Parties' Nationally Determined Contributions to the Paris Climate Agreement (UNFCCC 2021). Significant investments in REDD+ readiness, improved forest monitoring, assessments of drivers of deforestation and, forest degradation and related policy responses, and stakeholder engagement have occurred over the past decade in countries across Africa, Asia-Pacific, and Latin America and the Caribbean (Hein et al. 2018; UN-REDD Programme 2018; World Bank 2018). Fifty three percent of countries use highest quality remote sensing data for forest monitoring and reporting, covering 93% of forest cover (Nesha et al. 2021). However, improved monitoring has not yet translated into forest governance effectiveness. Since the New York Declaration on Forests was endorsed in 2014, average annual humid tropical primary forest loss has accelerated by 44% (NYDF 2019). Policy responses towards conservation and ecosystem resilience are found to be insufficient to stem the direct and indirect drivers of nature deterioration (*high confidence*) (IPBES 2019). For governance measures to be effective, it is necessary to alter the direct and underlying drivers that are leading to forest destruction or impeding the implementation of sustainable forest management practices and actions to restore degraded forests (*high confidence*) (CCP7.2.3; CCP7.5; UNFCCC, 2013).

Private sector commitments to reduce deforestation impacts in their commodity supply chains are growing, but evidence of impact is slim and inconclusive (Garrett et al. 2019; NYDF 2019). Half of the biodiversity loss associated with consumption in developed economies occurs outside their territorial boundaries (Wilting et al. 2017), and trends in international trade in land-based production systems are increasing, with greatest impacts on tropical forests (Nyström et al. 2019; Hoang and Kanemoto 2021). In addition, in some cases the impacts of financialization (e.g. correlation of commodity prices with stock market dynamics rather than pure demand) are found to be larger than those related to timber and agricultural commodity production dynamics (Girardi 2015; Ouyang and Zhang 2020); cross-reference to Chapter-5.13). Such factors present challenges for governance and policy responses.

The complexity of tackling drivers of forest loss and degradation will increase as climate impacts on forests and ecosystems intensify in the context of incomplete information and limited understanding of risks (Helbing 2013; Hughes et al. 2013; Springmann et al. 2018; Tu et al. 2019), necessitating novel approaches to forest governance for resilience (Keenan 2015; Spathelf et al. 2018). Therefore, governance—defined as efforts that seek to influence the relationship between existing social processes and governance arrangements by using regulatory processes, mechanisms, and organizations (Agrawal et al. 2018) is a crucial process to convene stakeholders for decisions (FAO 2018a).

This section describes seven levers that support transformative environmental governance towards resilience of tropical forests by tackling the underlying indirect drivers, offering policy solutions and governance challenges and opportunities. The first five build on IPBES (2019) whereas the remaining two are drawn from the governance literature as highly relevant variables specific to the tropical forest context due to their prominence in the international frameworks developed over the past ten years (Table CCP7.5). Monitoring and finance are embedded in multiple levers. The levers include:

1) developing incentives and increased capacity for environmental responsibility (particularly in relation to global targets such as the SDGs, Aichi Biodiversity Targets and the Paris Agreement) and discontinuing harmful subsidies and disincentives;
2) reforming sectoral and segmented decision-making to promote integration across sectors and jurisdictions to mainstream environmental objectives across institutions within and among all relevant sectors;
3) pursuing pre-emptive and precautionary actions in regulatory and management institutions and businesses to avoid, mitigate and remedy the deterioration of nature, and monitor outcomes;
4) managing for resilient social and ecological systems in the face of uncertainty and complexity;
5) strengthening environmental laws and policies and their implementation, and the rule of law more generally (Pörtner et al. 2021);
6) acknowledging land tenure and rights to recognize the need of bringing human rights considerations into the climate change regime; and,
7) enhancing inclusive stakeholder participation to ensure effective, efficient and equitable outcomes (Pasgaard et al. 2016).

While the first five levers are relevant to environmental governance more broadly, the exploration of these levers in Table CCP7.5 is more specific to governance for forest resilience, drawing upon insights related to each transformation lever. Next to the governance solutions being implemented currently, indications of future challenges/opportunities related to resilience in tropical forests are explored based on examples from the recent literature.

Table CCP7.5: Levers of transformative change to tackle the underlying indirect drivers of forest deterioration for resilience.

Levers of transformative change	Barriers	Current governance and policy solutions and potential future challenges and opportunities with an orientation towards resilience in tropical forests
1. Incentives and capacity-building	• Population growth and corruption counteract governance effects (Enrici and Hubacek 2016; Busch and Ferretti-Gallon 2020; Fischer et al. 2020) • Macroeconomic development favoured over ecosystem service provision-environment ministries under resourced and politically weak compared to those for economic and natural resource development (UNEP 2019) • Though food systems are the major driver, many interconnected food system activities and effects do not have established governance regimes to address them (Clapp and Scott 2018). • Reliance on non-state market-based approaches (e.g. zero-net deforestation) has not achieved necessary impact against stated targets, reporting is lacking (Lambin et al. 2018; Global Canopy 2019) • Finance for forest mitigation is less than 1.5% of total since 2010 (Partners 2019), and amount for forest adaptation is even less (Micale et al. 2018)	**Current policy solutions** • REDD+ and Payments for ecosystem services (PES) • Corporate supply chain commitments (WWF and BCG 2021) • Product certification and forest certification have mixed results in addressing deforestation (Blackman et al. 2018; van der Ven et al. 2018) • Agricultural credit restrictions (Assunção et al. 2020) • Protected areas and area-based conservation measures (OECMs) (Maxwell et al. 2020) • Clear performance indicators and monitoring systems to assess performance (Agrawal et al. 2018) **Future policy challenges/opportunities** • Policies that insulate the forest frontier from the influence of high commodity prices (Busch and Ferretti-Gallon 2020) • Project-level biodiversity responses linked to broader jurisdictional biodiversity targets (Simmonds et al. 2020) • Ecological fiscal transfers to base portions of intergovernmental fiscal transfers on ecological indicators (Busch et al. 2021) • Financial disclosure on risks, divestiture, environment-related investment mandates (Halvorssen 2021) • Identification of means for the forest-based bioeconomy (wood fuel, timber) to be sustained (Dieterle and Karsenty 2020) • Incentives towards less emissions-intensive inputs in manufactured products, such as bamboo (van der Lugt et al. 2018) • Reducing imports of embedded deforestation (role of land-use telecoupling) (Gardner et al. 2019) • Supply chain traceability and public reporting (Gardner et al. 2019; Global Canopy 2019)
2. Cross-sectoral cooperation	• Inherent vertical and horizontal fragmentation of policy arena • Challenge of silos between ministries (Nilsson et al. 2016) • Policy integration has a stronger chance of reforming existing policies and competing sectors than coordination, but is challenged to overcome sectoral fragmentation and reach international actors and markets (Kissinger et al. 2021)	**Current policy solutions** • Policy coordination and integration (Candel and Biesbroek 2016) • Jurisdictional and landscape approaches in targeted regions and commodity sectors/supply chains (Reed et al. 2017; von Essen and Lambin 2021) **Future policy challenges/opportunities** • Theories of change applied and testing of policy effectiveness (Meehan et al. 2019; Bager et al. 2021) • Whole-of-government approaches to change mandates across ministries • Mainstreaming climate change into sectoral policies (Di Gregorio et al. 2017)

		• Policy mixes implemented as a bundle, policy instrument selection attuned to complexity of the problem (Henstra 2015; Head 2018)
3. Pre-emptive action	• Complexity of the issues for any specific level of jurisdiction to grapple with, scale mismatches (temporal, spatial and institutional), institutional inertia (Bai et al. 2016) • Reliance on path dependency rather than innovation (Beland Lindahl et al. 2017; Peters et al. 2018; Wieczorek 2018) • Agenda setting and framing influences political and policy responses (Soto Golcher et al. 2018) • Problem denial and blame avoidance on the part of decision-makers (Howlett and Kemmerling 2017).	**Current policy solutions** • GHG emission cap-and-trade systems and carbon pricing (Green 2021) • Moratoria • Identifying thresholds of concern, when critical thresholds of fast-changing variables are triggered, and nonlinear responses erode the resilience of ecosystems (such as in the case of changing forest fire regimes) (Gillson et al. 2019) • Reduce loss and waste of biomass • Change in consumption patterns, sharing and reuse • Shareholder divestiture due to climate/forest and biodiversity risk (Halvorssen 2021)
4. Decision-making in the context of resilience and uncertainty	• Scope of problem identification limited (Beland Lindahl et al. 2017) • Increasingly complex and networked world increases risks, but reduces our ability to understand and manage these risks (Helbing 2013; Tu et al. 2019)	**Current policy solutions** • Forecasting, scenarios of future climate and forest condition, socio-economic dimensions, science-policy dialogue (Bele et al. 2015) and thresholds for ecosystem shifts due to mortality (tipping points) (Verbesselt et al. 2016). **Future policy challenges/opportunities** • Interdisciplinary and transdisciplinary approaches to data gathering and policy design (Keenan 2015) • 'Robust' decision-making approaches for adaptive forest management (Hörl et al. 2020) • Maintain diversity and redundancy, manage connectivity, and slow variables and feedbacks (Biggs et al. 2012) • Measurement and disclosure of climate and ecosystem risk (NBIM 2021)
5. Environmental law and implementation	• 69% of agricultural conversion of tropical forests *likely* illegal between 2013-2019 (Dummett et al. 2021) • 90% of countries (of 31 assessed), identify weak forest sector governance and institutions, conflicting policies beyond the forest sector, and illegal activity main underlying drivers (Kissinger et al. 2012); corruption and illegality are identified as key factors in increasing forest loss (Piabuo et al. 2021). • Implementation and enforcement of environmental laws falls far short; primary obstacle is political will (UNEP 2019)	**Current policy solutions** • Environmental laws and regulations (Head 2018) • Trained prosecutors • Citizen rights to information (Bizzo and Michener 2017) **Future policy challenges/opportunities** • Capacity and willingness to engage iterative processes for continuous effort in transparency and accountability (in implementing the Extractive Industry Transparency Initiative)(Lujala 2018) • Regulatory frameworks as enablers to motivate and hold private sector initiatives to account (test effectiveness) (Begemann et al. 2021) • Nested and multilevel governance arrangements (Ravikumar et al. 2015) • Diagnosing the political drivers of decision making through political economy assessment (Fritz et al. 2014)

	• Conflicting legal instruments, lack of clarity in implementation, monitoring and evaluation, responsibilities are poorly defined and fragmented across multiple agencies (Ranabhat et al. 2018) • Lack of sanctions, transparency and accountability (Bai et al. 2016; Enrici and Hubacek 2016) • Open-ended decision-making exacerbates political asymmetries (Holley and Sofronova 2017)	
6. Lend tenure/rights	• Though recognition of indigenous self-determination is growing, many cases of legal recognition still lack full authority to govern (UN-DESA 2021) • Free Prior Informed Consent (FPIC)	**Current policy solutions** • Legal and constitutional recognition of rights, collective/communal rights (Safitri 2015; Blackman et al. 2017; Gebara 2018) • Indigenous land demarcation (Baragwanath and Bayi 2020). • Community-based forest management (Pelletier et al. 2016) **Future policy challenges/opportunities** • Forest protection /climate and biodiversity is strongest when indigenous people hold collective legal titles to their lands (IPCC 2019) (In Latin America, deforestation rates are about 50% lower in Indigenous territories than in other forested areas) (FAO and FILAC 2021).
7. Participation and stakeholder inclusion	• Governments increasingly rely on highly autonomous semi-public or private organizations for policy results, which weakens control of the process (Howlett et al. 2015), yet mediating between diverse values and interests of citizens, consumers, business, community is a determinant of policy effectiveness (Peters et al. 2018). • Growing legal restrictions on civil society involvement in governance and access to funding (UNEP 2019) • Institutional practices of stakeholder consultation in REDD+ not well operationalized (criteria and transparency often lacking) (Fujisaki et al. 2016)	**Current policy solutions** • Multistakeholder dialogue combined with moratoria (e.g. Brazilian soy moratorium) (Gibbs et al. 2015) • Community-based monitoring (Slough et al. 2021) **Future policy challenges/opportunities** • Collaborative networks (Thomas et al. 2018) • Re-evaluating agency, social structures and the distribution of power to uphold rights (I. Delabre et al.) • Community engagement correlated to secure rights to resources (Pham et al. 2015)

[START FAQ CCP7.1 HERE]

FAQ CCP7.1: How is climate change affecting tropical forests and what can we do to protect and increase their resilience?

Global warming, droughts, extreme rainfalls, and sea-level rise cause significant impacts on tropical forests.

In addition to climate change, tropical forests are experiencing non-climatic stressors. Conversion of forest into large scale agriculture land and exploitation of timber and non-timber forest products are increasing pressure and amplifying the impacts of climate change on the remaining areas of tropical forests. These include biodiversity decline, increases of fires, large scale ecosystem transformation, e.g., into savannah in South Eastern Amazon, and increasing carbon emissions due to deforestation, forest conversion and forest degradation. Further, loss of forest resources leads to the decline of livelihoods of Indigenous Peoples and local communities. All nations need to collaborate to implement collective actions to protect tropical forests.

Tropical forests are essentially important for the health of planet Earth. Tropical forests in Asia, Africa, and South America regulate carbon, water, and chemical cycles, which maintain a healthy climate and nutrient cycles for supporting life. Tropical forests are home to two-thirds of our world's biodiversity, although they cover only about 13 percent of the land on Earth but it is not exactly known how many millions of living creatures, such as microorganisms, insects, amphibians, snakes, fish, birds, mammals, and primates, live in tropical forests.

Approximately 1.3 billion people directly depend upon tropical forest resources to survive. Others are indirectly dependent upon the health and provisioning of ecosystem services and goods from tropical forests. The forests provide many kinds of economic products, such as timber, medicines, and food, recreational services, such as nature trekking, bird and wildlife watching, to mention a few. Indigenous People and other forest-dependent communities have shown extraordinary knowledge on how to manage forest resources to meet their subsistence needs without causing forest degradation. This forest culture and wisdom are broken when the rate of forest extraction changes into unplanned and unsustainable large-scale transformation.

Deforestation and land-use changes in tropical forests cause not only physical and biological changes on flora and fauna but also rapid changes in cultures harming forest peoples. A degraded tropical forest is prone and more vulnerable to climate change. An increase in temperature in lowlands creates an unfavorable condition for optimum growths of many kinds of plant species, which affects, as well, several agricultural plants. Coffee farmers, for example, are forced to open new forest frontiers in highland areas to meet an optimum temperature for the growth of coffee.

The onset and duration of dry and rainy seasons also changes. A prolonged wet season has excessive rains, which causes flash floods and substantially disturbs a fruiting cycle of many plant species. Due to high rainfall and high humidity, most flowers of forest trees fail to mature, and hence essentially deplete fruit production. Most trees in tropical forests require a short period of a dry season in order to have a mass fruiting season. On the other hand, a prolonged dry season causes soils to dry in deeper layers, higher atmospheric demand for water vapor and enhanced forest fires. In the tropical humid forests, the majority of forest fires are anthropogenic. In Southeast Asia, peat fires cause large carbon emissions and haze pollution, which harms locals and people in neighboring countries. The impact on tropical forest comes also from the rise of sea level rise which due to changes in salinity and sedimentation rates, and the expansion of inundated areas leads to the decline of mangrove productivity.

Projected impacts of climate change on the tropical forest might be detrimental to safeguards of local communities and a significant number of flora and fauna in the tropics. In South-Eastern Amazon, reduction in precipitation, due to changes in the climate pattern, associated with intense deforestation and land cover change are leading to reduction of productivity in the remaining forest areas, and might lead to a large-scale change in the forest structure, which can become a savannah. In Southeast Asia, in particular in Indonesia and Malaysia, prolonged dry seasons associated with the El Niño phenomenon cause extensive peat fires, releasing large amounts of carbon dioxide, and creating various health problems related to haze pollution. Furthermore, climate change interacts with deforestation for agriculture (crops, livestock and plantation forestry), logging, mining or infrastructure development exacerbating temperature and rainfall changes resulting in more degradation.

Climate change together with forest fragmentation and deforestation also harms wildlife. For example, the orangutan, an endemic species to tropical peat forests in Kalimantan and Sumatra, is classified as critically endangered. Many other endemic and unknown species of flora in tropical forests are in the same condition, and could experience a mass extinction at a more rapid rate than the previous five mass extinctions on Earth. About 1.3 million Indigenous Peoples depending on the natural resources of the tropical forest would suffer from cultural disruption and livelihood change due to forest loss.

To protect tropical forests a collective action of all nations is needed. It requires a global effort to stop deforestation and the conversion of tropical forests. The role of Indigenous Peoples and local communities as forest keepers must be strengthened. Economic incentives for protecting tropical forests, among other strategies, could facilitate collective actions towards a sustainable management of tropical forests. Sustainable, effective and just strategies to increase the resilience of tropical forests need to consider the complex political, social and economic dynamics involved, including the goals, identity and livelihood priorities of Indigenous Peoples and local communities beyond natural resource management. Strategies can benefit from integrating knowledge and know-how from traditional cultures, fostering transitions towards more sustainable systems.

[END FAQ CCP7.1 HERE]

References

Adams, H.D., Barron-Gafford, G.A., Minor, R.L., Gardea, A.A., Bentley, L.P., Law, D.J., Breshears, D.D., McDowell, N.G. and Huxman, T.E. (2017) 'Temperature response surfaces for mortality risk of tree species with future drought'.

Adams, M.A., Buckley, T.N. and Turnbull, T.L. (2019) 'Rainfall drives variation in rates of change in intrinsic water use efficiency of tropical forests', *Nature communications*, 10(1), 1-8.

Agarwal, B. (2015) 'The power of numbers in gender dynamics: illustrations from community forestry groups', *Journal of Peasant Studies*, 42(1), 1-20.

Agrawal, A., Hajjar, R., Liao, C., Rasmussen, L.V. and Watkins, C. (2018) 'Editorial overview: Forest governance interventions for sustainability through information, incentives, and institutions', *Current Opinion in Environmental Sustainability*, 32, A1-A7, available: http://dx.doi.org/10.1016/J.COSUST.2018.08.002.

Aguirre, A.A. and Sukumar, R. (2016) *Tropical Conservation: Perspectives on Local and Global Priorities*, Oxford University Press.

Aguirre-Gutiérrez, J., Malhi, Y., Lewis, S.L., Fauset, S., Adu-Bredu, S., Affum-Baffoe, K., Baker, T.R., Gvozdevaite, A., Hubau, W. and Moore, S. (2020) 'Long-term droughts may drive drier tropical forests towards increased functional, taxonomic and phylogenetic homogeneity', *Nature communications*, 11(1), 1-10.

Ajani, E. (2013) 'Use of Indigenous Knowledge as a Strategy for Climate Change Adaptation among Farmers in sub-Saharan Africa: Implications for Policy', *Asian Journal of Agricultural Extension, Economics & Sociology*, 2(1), 23-40, available: http://dx.doi.org/10.9734/AJAEES/2013/1856.

Aleixo, I., Norris, D., Hemerik, L., Barbosa, A., Prata, E., Costa, F. and Poorter, L. (2019) 'Amazonian rainforest tree mortality driven by climate and functional traits', *Nature Climate Change*, 9(5), 384-388, available: http://dx.doi.org/10.1038/s41558-019-0458-0.

Alencar, A.A., Brando, P.M., Asner, G.P. and Putz, F.E. (2015) 'Landscape fragmentation, severe drought, and the new Amazon forest fire regime', *Ecological Applications*, 25(6), 1493-1505, available: http://dx.doi.org/10.1890/14-1528.1.

Alkama, R. and Cescatti, A. (2016) 'Biophysical climate impacts of recent changes in global forest cover', *Science*, 351(6273), 600-604, available: http://dx.doi.org/10.1126/science.aac8083.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D. and Hogg, E.T. (2010) 'A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests', *Forest Ecology and Management*, 259(4), 660-684.

Allen, K., Dupuy, J.M., Gei, M.G., Hulshof, C., Medvigy, D., Pizano, C., Salgado-Negret, B., Smith, C.M., Trierweiler, A. and Van Bloem, S.J. (2017) 'Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes?', *Environmental Research Letters*, 12(2), 023001.

Alroy, J. (2017) 'Effects of habitat disturbance on tropical forest biodiversity', *Proceedings of the National Academy of Sciences*, 114(23), 6056-6061.

Amezaga, J., Bathurst, J., Iroumé, A., Jones, J., Kotru, R., Bhatta, L., & Springgay, E. (2019) 'SDG 6: Clean Water and Sanitation – Forest-Related Targets and Their Impacts on Forests and People.' in P. Katila, C. P. C., W. De Jong, G. Galloway, P. Pacheco, & G. Winkel ed., *Sustainable Development Goals: Their Impacts on Forests and People*, Cambridge: Cambridge University Press, 178-205.

Anadon, J.D., Sala, O.E. and Maestre, F.T. (2014) 'Climate change will increase savannas at the expense of forests and treeless vegetation in tropical and subtropical Americas', *Journal of Ecology*, 102(6), 1363-1373.

Andam, K.S., Ferraro, P.J., Sims, K.R., Healy, A. and Holland, M.B. (2010) 'Protected areas reduced poverty in Costa Rica and Thailand', *Proceedings of the National Academy of Sciences*, 107(22), 9996-10001.

Anderegg, W.R., Trugman, A.T., Badgley, G., Anderson, C.M., Bartuska, A., Ciais, P., Cullenward, D., Field, C.B., Freeman, J. and Goetz, S.J. (2020) 'Climate-driven risks to the climate mitigation potential of forests', *Science*, 368(6497).

Aparecido Trondoli Matricardi, E., Lewis Skole, D., Bueno Costa, O., Antonio Pedlowski, M., Howard Samek, J. and Pereira Miguel, E. (2020) 'Long-term forest degradation surpasses deforestation in the Brazilian Amazon', 369, 1378-1382, available: http://dx.doi.org/10.1126/SCIENCE.ABB3021.

Aragão, L.E.O.C., Anderson, L.O., Fonseca, M.G., Rosan, T.M., Vedovato, L.B., Wagner, F.H., Silva, C.V.J., Silva Junior, C.H.L., Arai, E., Aguiar, A.P., Barlow, J., Berenguer, E., Deeter, M.N., Domingues, L.G., Gatti, L., Gloor, M., Malhi, Y., Marengo, J.A., Miller, J.B., Phillips, O.L. and Saatchi, S. (2018) '21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions', *Nature communications*, 9(1), available: http://dx.doi.org/10.1038/s41467-017-02771-y.

Arevalo, J. (2016) 'Improving woodfuel governance in Burkina Faso: The experts' assessment', *Renewable and Sustainable Energy Reviews*, 57, 1398-1408, available: http://dx.doi.org/10.1016/j.rser.2015.12.178.

Ariti, A.T., van Vliet, J. and Verburg, P.H. (2015) 'Land-use and land-cover changes in the Central Rift Valley of Ethiopia: Assessment of perception and adaptation of stakeholders', *Applied Geography*, 65, 28-37, available: http://dx.doi.org/10.1016/j.apgeog.2015.10.002.

Arneth, A., Barbosa, H., Benton, T., Calvin, K., Calvo, E., Connors, S., Cowie, A., Davin, E., Denton, F. and van Diemen, R. (2019) *IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Arora, V.K. and Montenegro, A. (2011) 'Small temperature benefits provided by realistic afforestation efforts', *Nature geoscience*, 4(8), 514.
Aryal, K., Laudari,H. K. & Ojha,H. R. (2020) 'To what extent is Nepal's community forestry contributing to the sustainable development goals? An institutional interaction perspective', *International Journal of Sustainable Development & World Ecology*, 27(1), 28-39, available: http://dx.doi.org/10.1080/13504509.2019.1627681.
Asner, G.P., Townsend, A.R. and Braswell, B.H. (2000) 'Phenology and Productivity', *Geophysical Research Letters*, 27(7), 981-984.
Assunção, J., Gandour, C. and Rocha, R. (2015) 'Deforestation slowdown in the Brazilian Amazon: prices or policies?', *Environment and Development Economics*, 20(6), 697-722, available: http://dx.doi.org/10.1017/S1355770X15000078.
Assunção, J., Gandour, C., Rocha, R. and Rocha, R. (2020) 'The effect of rural credit on deforestation: evidence from the Brazilian Amazon', *The Economic Journal*, 130(626), 290-330, available: http://dx.doi.org/10.1093/EJ/UEZ060.
Austin, K.G., González-Roglich, M., Schaffer-Smith, D., Schwantes, A.M. and Swenson, J.J. (2017) 'Trends in size of tropical deforestation events signal increasing dominance of industrial-scale drivers', *Environmental Research Letters*, 12(5), 054009-054009, available: http://dx.doi.org/10.1088/1748-9326/aa6a88.
Bager, S.L., Persson, U.M. and Reis, T.N.P.d. (2021) 'Eighty-six EU policy options for reducing imported deforestation', *One Earth*, 4(2), 289-306, available: http://dx.doi.org/10.1016/J.ONEEAR.2021.01.011.
Bai, X., van der Leeuw, S., O'Brien, K., Berkhout, F., Biermann, F., Brondizio, E.S., Cudennec, C., Dearing, J., Duraiappah, A., Glaser, M., Revkin, A., Steffen, W. and Syvitski, J. (2016) 'Plausible and desirable futures in the Anthropocene: A new research agenda', *Global Environmental Change*, 39, 351-362, available: http://dx.doi.org/10.1016/J.GLOENVCHA.2015.09.017.
Balmford, A. and Whitten, T. (2003) 'Who should pay for tropical conservation, and how could the costs be met?', *Oryx*, 37(2), 238-250.
Baragwanath, K. and Bayi, E. (2020) 'Collective property rights reduce deforestation in the Brazilian Amazon', *Proceedings of the National Academy of Sciences*, 117(34), 20495-20502, available: http://dx.doi.org/10.1073/PNAS.1917874117.
Barlow, J., Lennox, G.D., Ferreira, J., Berenguer, E., Lees, A.C., Mac Nally, R., Thomson, J.R., de Barros Ferraz, S.F., Louzada, J. and Oliveira, V.H.F. (2016) 'Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation', *Nature*, 535(7610), 144.
Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L. and Maguire, K.C. (2011) 'Has the Earth's sixth mass extinction already arrived?', *Nature*, 471(7336), 51-57.
Barr, C.M. and Sayer, J.A. (2012) 'The political economy of reforestation and forest restoration in Asia-Pacific: Critical issues for REDD+', *Biological Conservation*, available: http://dx.doi.org/10.1016/j.biocon.2012.03.020.
Bartlett, M.K., Klein, T., Jansen, S., Choat, B. and Sack, L. (2016) 'The correlations and sequence of plant stomatal, hydraulic, and wilting responses to drought', *Proceedings of the National Academy of Sciences*, 113(46), 13098-13103.
Baste, I.A., Watson, R.T., Brauman, K.I., Samper, C. and Walzer, C. (2021) 'Making Peace with Nature: A Scientific Blueprint to Tackle the Climate, Biodiversity and Pollution Emergencies'.
Bastin, J.-F., Berrahmouni, N., Grainger, A., Maniatis, D., Mollicone, D., Moore, R., Patriarca, C., Picard, N., Sparrow, B., Abraham, E.M., Aloui, K., Atesoglu, A., Attore, F., Bassüllü, Ç., Bey, A., Garzuglia, M., García-Montero, L.G., Groot, N., Guerin, G., Laestadius, L., Lowe, A.J., Mamane, B., Marchi, G., Patterson, P., Rezende, M., Ricci, S., Salcedo, I., Diaz, A.S.-P., Stolle, F., Surappaeva, V. and Castro, R. (2017) 'The extent of forest in dryland biomes', *Science*, 356(6338), 635-638, available: http://dx.doi.org/10.1126/science.aam6527.
Bauch, S.C., Birkenbach, A.M., Pattanayak, S.K. and Sills, E.O. (2015) 'Public health impacts of ecosystem change in the Brazilian Amazon', *Proc Natl Acad Sci U S A*, 112(24), 7414-9, available: http://dx.doi.org/10.1073/pnas.1406495111.
Baumgartner, R.J. (2019) 'Sustainable Development Goals and the Forest Sector—a Complex Relationship', *Forests*, 10(2), available: http://dx.doi.org/10.3390/f10020152.
Baynes, J., Herbohn, J., Smith, C., Fisher, R. and Bray, D. (2015) 'Key factors which influence the success of community forestry in developing countries.', *Global Environmental Change*, 35, 226-238.
Beatty, C., Raes, L., Vogl, A., Hawthorne, P., Moraes, M., Saborio, J. and Meza Prado, K. (2018) 'Landscapes, at your service: applications of the restoration opportunities optimization tool (ROOT)', *IUCN, Gland, Switzerland*.
Beckline, M., Yujun, S., Yvette, B., Joh, A. B., Mor-Achankap, B., Saeed, S., Richard, T., Wose, J. & Paul, C. (2017) 'Perspectives of Remote Sensing and GIS Applications in Tropical Forest Management', *American Journal of Agriculture and Forestry*, 5(3), 33-39, available: http://dx.doi.org/doi: 10.11648/j.ajaf.20170503.11.
Begemann, A., Giessen, L., Roitsch, D., Roux, J.L., Lovrić, M., Azevedo-Ramos, C., Boerner, J., Beeko, C., Cashore, B., Cerutti, P.O., de Jong, W., Fosse, L.J., Hinrichs, A., Humphreys, D., Pülzl, H., Santamaria, C., Sotirov, M., Wunder, S. and Winkel, G. (2021) 'Quo vadis global forest governance? A transdisciplinary delphi study', *Environmental Science & Policy*, 123, 131-141, available: http://dx.doi.org/10.1016/J.ENVSCI.2021.03.011.

Beland Lindahl, K., Sandström, C. and Sténs, A. (2017) 'Alternative pathways to sustainability? Comparing forest governance models', *Forest Policy and Economics*, 77, 69-78, available: http://dx.doi.org/10.1016/J.FORPOL.2016.10.008.
Bele, M.Y., Sonwa, D.J. and Tiani, A.-M. (2015) 'Adapting the Congo Basin forests management to climate change: Linkages among biodiversity, forest loss, and human well-being', *Forest Policy and Economics*, 50, 1-10.
Bele, M.Y., Tiani, A.M., Somorin, O.A. and Sonwa, D.J. (2013) 'Exploring vulnerability and adaptation to climate change of communities in the forest zone of Cameroon', *Climatic Change*, available: http://dx.doi.org/10.1007/s10584-013-0738-z.
Bennett, A., McDowell, N., Allen, C., Anderson-Teixeira, K., Trenberth, K., Nepstad, D., Tohver, I., Ray, D., Moutinho, P. and Cardinot, G. (2015) 'Larger trees suffer most during drought in forests worldwide', *Nature plants, 1(10), pp.1-5.*, 1(10), 1-5.
Berkes, F. (2010) 'Indigenous ways of knowing and the study of environmental change', *Journal of the Royal Society of New ZealandOnline*, 3909(4), 151-156.
Bhadouria, R., Srivastava, P., Singh, R., Tripathi, S., Singh, H. and Raghubanshi, A. (2017) 'Tree seedling establishment in dry tropics: an urgent need of interaction studies', *Environment Systems and Decisions*, 37(1), 88-100.
Bhatta, L.D., van Oort, Bob Eric Helmuth.,Stork, Nigel E. & Himlal, B. (2015) 'Ecosystem services and livelihoods in a changing climate: Understanding local adaptations in the Upper Koshi, Nepal', *International Journal of Biodiversity Science, Ecosystem Services & Management*, 11(2), 145-155.
Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., Leitch, A.M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M.D., Schoon, M.L., Schultz, L. and West, P.C. (2012) 'Toward principles for enhancing the resilience of ecosystem services', *Annual Review of Environment and Resources*, 37, 421-448, available: http://dx.doi.org/10.1146/ANNUREV-ENVIRON-051211-123836.
Bizzo, E. and Michener, G. (2017) 'Forest governance without transparency? Evaluating state efforts to reduce deforestation in the Brazilian Amazon', *Environmental Policy and Governance*, 27(6), 560-574, available: http://dx.doi.org/10.1002/EET.1776.
Blackman, A., Corral, L., Lima, E.S. and Asner, G.P. (2017) 'Titling indigenous communities protects forests in the Peruvian Amazon', *Proceedings of the National Academy of Sciences*, 114(16), 4123-4128, available: http://dx.doi.org/10.1073/PNAS.1603290114.
Blackman, A., Goff, L. and Rivera Planter, M. (2018) 'Does eco-certification stem tropical deforestation? Forest Stewardship Council certification in Mexico', *Journal of Environmental Economics and Management*, 89, 306-333, available: http://dx.doi.org/10.1016/J.JEEM.2018.04.005.
Blackman, A. and Veit, P. (2018) 'Titled Amazon Indigenous Communities Cut Forest Carbon Emissions', *Ecological Economics*, 153, 56-67, available: http://dx.doi.org/10.1016/j.ecolecon.2018.06.016.
Blaser, J., Frizzo, J. and Norgrove, L. (2021) *Not only Timber: the potential for managing non-timber forest products in tropical production forests-a comprehensive literature review ITTO Technical Series #50.*
Blaser, J. and Organization, I.T.T. (2011) *Status of tropical forest management 2011*, International Tropical Timber Organization.
Boers, N., Marwan, N., Barbosa, H.M.J. and Kurths, J. (2017) 'A deforestation-induced tipping point for the South American monsoon system', *Scientific Reports*, 7(January), 1-9, available: http://dx.doi.org/10.1038/srep41489.
Boltz, F., Carter, D.R., Holmes, T.P. and Pereira Jr, R. (2001) 'Financial returns under uncertainty for conventional and reduced-impact logging in permanent production forests of the Brazilian Amazon', *Ecological Economics*, 39(3), 387-398.
Bond, W. and Zaloumis, N.P. (2016) 'The deforestation story: testing for anthropogenic origins of Africa's flammable grassy biomes', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1696), 20150170.
Bos, A.B., De Sy, V., Duchelle, A.E., Atmadja, S., de Bruin, S., Wunder, S. and Herold, M. (2020) 'Integrated assessment of deforestation drivers and their alignment with subnational climate change mitigation efforts', *Environmental Science and Policy*, 114, 352-365, available: http://dx.doi.org/10.1016/j.envsci.2020.08.002.
Brancalion, P.H. and Chazdon, R.L. (2017) 'Beyond hectares: four principles to guide reforestation in the context of tropical forest and landscape restoration', *Restoration ecology*, 25(4), 491-496.
Brando, P.M., Balch, J.K., Nepstad, D.C., Morton, D.C., Putz, F.E., Coe, M.T., Silvério, D., Macedo, M.N., Davidson, E.A., Nóbrega, C.C., Alencar, A. and Soares-Filho, B.S. (2014) 'Abrupt increases in Amazonian tree mortality due to drought–fire interactions', *Proceedings of the National Academy of Sciences*, 111(17), 6347, available: http://dx.doi.org/10.1073/pnas.1305499111.
Brando, P.M., Paolucci, L., Ummenhofer, C.C., Ordway, E.M., Hartmann, H., Cattau, M.E., Rattis, L., Medjibe, V., Coe, M.T. and Balch, J. (2019) 'Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis', *Annual Review of Earth and Planetary Sciences*, 47, 555-581.
Brondízio, E.S. (2008) 'The Amazonian Caboclo and the Açaí Palm: Forest Farmers in the Global Market', *Advances in Economic Botany*, 16, iii-403.

Bruggeman, D., Meyfroidt, P. and Lambin, E.F. (2015) 'Production forests as a conservation tool: Effectiveness of Cameroon's land use zoning policy', *Land Use Policy*, 42, 151-164, available: http://dx.doi.org/https://doi.org/10.1016/j.landusepol.2014.07.012.
Bruner, A.G., Gullison, R.E. and Balmford, A. (2004) 'Financial costs and shortfalls of managing and expanding protected-area systems in developing countries', *BioScience*, 54(12), 1119-1126.
Bukoski, J.J., Drazen, E., Johnson, W.R. and Swamy, L. (2018) 'Tropical forests for sustainable development: Shaping the 2030 Agenda for Sustainable Development with knowledge from the field', *Journal of sustainable forestry*, 37(2), 77-81, available: http://dx.doi.org/10.1080/10549811.2018.1418255.
Busch, J. and Ferretti-Gallon, K. (2020) 'What drives deforestation and what stops it? A meta-analysis', *Review of Environmental Economics and Policy*, 11(1), 3-23, available: http://dx.doi.org/10.1093/REEP/REW013.
Busch, J., Ring, I., Akullo, M., Amarjargal, O., Borie, M., Cassola, R.S., Cruz-Trinidad, A., Droste, N., Haryanto, J.T., Kasymov, U., Kotenko, N.V., Lhkagvadorj, A., De Paulo, F.L.L., May, P.H., Mukherjee, A., Mumbunan, S., Santos, R., Tacconi, L., Verde Selva, G., Verma, M., Wang, X., Yu, L. and Zhou, K. (2021) 'A global review of ecological fiscal transfers', *Nature Sustainability 2021*, 1-10, available: http://dx.doi.org/10.1038/s41893-021-00728-0.
Butt, S., Lyster, R. and Stephens, T. (2015) *Climate Change and Forest Governance : Lessons from Indonesia*, London: Routledge.
Cadman, T., Maraseni, T., Ma, H.O. and Lopez-Casero, F. (2017) 'Five years of REDD+ governance: The use of market mechanisms as a response to anthropogenic climate change', *Forest Policy and Economics*, 79, 8-16, available: http://dx.doi.org/https://doi.org/10.1016/j.forpol.2016.03.008.
Calderon, L.d.A., Silva-Jardim, I., Zuliani, J.P., Silva, A.d.A., Ciancaglini, P., Silva, L.H.P.d. and Stábeli, R.G. (2009) 'Amazonian biodiversity: a view of drug development for leishmaniasis and malaria', *Journal of the Brazilian Chemical Society*, 20, 1011-1023.
Camacho, L.D., Gevaña, D.T., Carandang, A.P. and Camacho, S.C. (2016) 'Indigenous knowledge and practices for the sustainable management of Ifugao forests in Cordillera, Philippines', *International Journal of Biodiversity Science, Ecosystem Services & Management*, 12(1-2), 5-13, available: http://dx.doi.org/10.1080/21513732.2015.1124453.
Camico, A., Díaz, M., Felicien, A., Chacón, N., Mustonen, T., Harper, S.L., Rivera Ferre, M., Postigo, J., Ayanlade, A., Benjaminsen, T., Morgan, R. and Okem, A. (2021) *Agricultural knowledge of the Uwǫttüją people in the ecological restoration of the Amazon rainforest. 2021 Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate C*, Snowchange Cooperative: Kontiolahti, Finland.
Campos-Filho, E.M., Da Costa, J.N., De Sousa, O.L. and Junqueira, R.G. (2013) 'Mechanized direct-seeding of native forests in Xingu, Central Brazil', *Journal of sustainable forestry*, 32(7), 702-727.
Candel, J.J.L. and Biesbroek, R. (2016) 'Toward a processual understanding of policy integration', *Policy Sciences*, 49(3), 211-231, available: http://dx.doi.org/10.1007/S11077-016-9248-Y.
Carrasco, L.R., Webb, E. L., Symes, W. S., Koh, L. P. & Sodhi, N. S. (2017) 'Global economic trade-offs between wild nature and tropical agriculture', *PLoS Biol*, 15(7), e2001657, available: http://dx.doi.org/10.1371/journal.pbio.2001657.
Ceballos, G., Ehrlich, P.R. and Dirzo, R. (2017) 'Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines', *Proceedings of the National Academy of Sciences*, 114(30), E6089-E6096.
Cerri, C.E.P., Cerri, C.C., Maia, S.M.F., Cherubin, M.R., Feigl, B.J. and Lal, R. (2018) 'Reducing Amazon deforestation through agricultural intensification in the cerrado for advancing food security and mitigating climate change', *Sustainability*, 10(4), 989.
Cerullo, G.R. and Edwards, D.P. (2019) 'Actively restoring resilience in selectively logged tropical forests', *Journal of Applied Ecology*, 56(1), 107-118.
Chabaribery, D., Silva, J.d., Tavares, L.F.d.J., Loli, M.V.B., Silva, M.d. and Monteiro, A. (2008) 'Recuperação de matas ciliares: sistemas de formação de floresta nativa em propriedades familiares', *Informações Econômicas*, 38(6), 07-20.
Chan, K.M., Balvanera, P., Benessaiah, K., Chapman, M., Díaz, S., Gómez-Baggethun, E., Gould, R., Hannahs, N., Jax, K. and Klain, S. (2016) 'Opinion: Why protect nature? Rethinking values and the environment', *Proceedings of the National Academy of Sciences*, 113(6), 1462-1465.
Chanza, N. and De Wit, A. (2016) 'Enhancing climate governance through indigenous knowledge: Case in sustainability science', *South African Journal of Science*, 112(3-4), 1-7, available: http://dx.doi.org/10.17159/sajs.2016/20140286.
Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C.A., Kapos, V., Key, I., Roe, D., Smith, A. and Woroniecki, S. (2020) 'Mapping the effectiveness of nature-based solutions for climate change adaptation', *Global change biology*, 26(11), 6134-6155.
Chazdon, R.L., Brancalion, P.H.S., Laestadius, L., Bennett-Curry, A., Buckingham, K., Kumar, C., Moll-Rocek, J., Vieira, I.C.G. and Wilson, S.J. (2016) 'When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration', *Ambio*, 45(5), 538-550, available: http://dx.doi.org/10.1007/s13280-016-0772-y.

Chazdon, R.L. and Guariguata, M.R. (2016) 'Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges', *Biotropica*, 48(6), 716-730.
Cheesman, A.W. and Winter, K. (2013) 'Elevated night-time temperatures increase growth in seedlings of two tropical pioneer tree species', *New Phytologist*, 197(4), 1185-1192.
Chitra-Tarak, R., Ruiz, L., Dattaraja, H.S., Mohan Kumar, M., Riotte, J., Suresh, H.S., McMahon, S.M. and Sukumar, R. (2018) 'The roots of the drought: Hydrology and water uptake strategies mediate forest-wide demographic response to precipitation', *Journal of Ecology*, 106(4), 1495-1507.
Christie, M.R. and Knowles, L.L. (2015) 'Habitat corridors facilitate genetic resilience irrespective of species dispersal abilities or population sizes', *Evolutionary Applications*, 8(5), 454-463.
Chung Tiam Fook, T. (2015) 'Transformational processes for community-focused adaptation and social change: a synthesis', *Climate and Development*, 9(1), 5-21, available: http://dx.doi.org/10.1080/17565529.2015.1086294.
Ciemer, C., Boers, N., Hirota, M., Kurths, J., Müller-Hansen, F., Oliveira, R.S. and Winkelmann, R. (2019) 'Higher resilience to climatic disturbances in tropical vegetation exposed to more variable rainfall', *Nature geoscience*, 12(3), 174-179.
Clapp, J. and Scott, C. (2018) 'The global environmental politics of food', *Global Environmental Politics*, 18(2), 1-11, available: http://dx.doi.org/10.1162/GLEP_A_00464.
Clark, K.H. and Nicholas, K.A. (2013) 'Introducing urban food forestry: a multifunctional approach to increase food security and provide ecosystem services', *Landscape Ecology*, 28(9), 1649-1669.
Collantes, V., Kloos, K., Henry, P., Mboya, A., Mor, T. and Metternicht, G. (2018) 'Moving towards a twin-agenda: Gender equality and land degradation neutrality', *Environmental Science and Policy*, available: http://dx.doi.org/10.1016/j.envsci.2018.08.006.
Conigliani, C., Cuffaro, N. and D'Agostino, G. (2018) 'Large-scale land investments and forests in Africa', *Land Use Policy*, 75, 651-660, available: http://dx.doi.org/10.1016/j.landusepol.2018.02.005.
Creed, I.F., Sass, G.Z., Buttle, J.M. and Jones, J.A. (2011) 'Hydrological principles for sustainable management of forest ecosystems', *Hydrological Processes*, 25, 2152-2190.
Crossman, N.D. and Bryan, B.A. (2009) 'Identifying cost-effective hotspots for restoring natural capital and enhancing landscape multifunctionality', *Ecological Economics*, 68(3), 654-668.
Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A. and Hansen, M.C. (2018) 'Classifying drivers of global forest loss', *Science*, 361(6407), 1108-1111, available: http://dx.doi.org/10.1126/science.aau3445.
Cury, R.T. and Carvalho, J. (2011) *Manual para restauração florestal: florestas de transição*, Instituto de Pesquisa Ambiental da Amazônia.
da Silva Júnior, L.A.S., Delgado, R.C., Pereira, M.G., Teodoro, P.E. and da Silva Junior, C.A. (2019) 'Fire dynamics in extreme climatic events in western amazon', *Environmental Development*, 32, 100450-100450, available: http://dx.doi.org/https://doi.org/10.1016/j.envdev.2019.06.005.
da Silva, S.S., Fearnside, P.M., de Alencastro Graça, P.M.L., Brown, I.F., Alencar, A., de Melo, A.W.F., Silva, S.S.d., Fearnside, P.M., Graça, P.M.L.d.A., Brown, I.F., Alencar, A. and Melo, A.W.F.d. (2018) 'Dynamics of forest fires in the southwestern Amazon', *Forest Ecology and Management*, 424(September), 312-322, available: http://dx.doi.org/10.1016/j.foreco.2018.04.041.
Davison, C.W., Rahbek, C. and Morueta-Holme, N. (2021) 'Land-use change and biodiversity: challenges for assembling evidence on the greatest threat to nature', *Global change biology*, gcb.15846-gcb.15846, available: http://dx.doi.org/10.1111/GCB.15846.
Dawson, I.K., Leakey, R., Clement, C.R., Weber, J.C., Cornelius, J.P., Roshetko, J.M., Vinceti, B., Kalinganire, A., Tchoundjeu, Z. and Masters, E. (2014) 'The management of tree genetic resources and the livelihoods of rural communities in the tropics: Non-timber forest products, smallholder agroforestry practices and tree commodity crops', *Forest Ecology and Management*, 333, 9-21.
Delabre, Alexander, A. and Rodrigues, C. (2020) 'Strategies for tropical forest protection and sustainable supply chains: challenges and opportunities for alignment with the UN sustainable development goals', *Sustain Sci*, 15, 1637-1651.
Delabre, I., Boyd, E., Brockhaus, M., Carton, W., Krause, T., Newell, P., Wong, G.Y. and Zelli, F. (2020) 'Unearthing the myths of global sustainable forest governance', *Global Sustainability*, 3, available: http://dx.doi.org/10.1017/SUS.2020.11.
Devisscher, T., Konijnendijk, C., Nesbitt, L., Lenhart, J., Salbitano, F., Cheng, Z., . . . Van den Bosch, M. (2019) 'SDG 11: Sustainable Cities and Communities – Impacts on Forests and Forest-Based Livelihoods.' in P. Katila, C. P. C., W. De Jong, G. Galloway, P. Pacheco, & G. Winkel ed., *Sustainable Development Goals: Their Impacts on Forests and People*, Cambridge: Cambridge University Press., 349-385.
Di Gregorio, M., Nurrochmat, D.R., Paavola, J., Sari, I.M., Fatorelli, L., Pramova, E., Locatelli, B., Brockhaus, M. and Kusumadewi, S.D. (2017) 'Climate policy integration in the land use sector: Mitigation, adaptation and sustainable development linkages', *Environmental Science and Policy*, 67, 35-43, available: http://dx.doi.org/10.1016/j.envsci.2016.11.004.
Diamond, S.K. and Ansharyani, I. (2018) 'Mismatched priorities , smallholders , and climate adaptation strategies : landuse scientists , it ' s time to step up', *Journal of Land Use Science*, 00(00), 1-7, available: http://dx.doi.org/10.1080/1747423X.2018.1537313.

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K. and Butchart, S.H. (2019) 'Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services', *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

Dieterle, G. and Karsenty, A. (2020) '"Wood Security": the importance of incentives and economic valorisation in conserving and expanding forests', *International Forestry Review*, 22(1), 81-92, available: http://dx.doi.org/10.1505/146554820829523916.

Ding, H., Veit, P.G., Blackman, A., Gray, E., Reytar, K., Altamirano, J.C. and Hodgdon, B. (2016) 'Climate Benefits, Tenure Costs. The Economic Case for Securing Indigenous Land Rights in the Amazon', *World Resources Institute*.

Djoudi, H. and Brockhaus, M. (2011) 'Is adaptation to climate change gender neutral? Lessons from communities dependent on livestock and forests in northern Mali', *International Forestry Review*, 13(2), 123-135.

Djoudi, H., Brockhaus, M. and Locatelli, B. (2013) 'Once there was a lake: Vulnerability to environmental changes in northern Mali', *Regional Environmental Change*, available: http://dx.doi.org/10.1007/s10113-011-0262-5.

Doerr, S.H. and Santín, C. (2016) 'Global trends in wildfire and its impacts: perceptions versus realities in a changing world', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1696), 20150345.

Dooley, K. and Kartha, S. (2018) 'Land-based negative emissions: risks for climate mitigation and impacts on sustainable development', *International Environmental Agreements: Politics, Law and Economics*, 18(1), 79-98.

dos Reis, M., Graça, P.M.L.D.A., Yanai, A.M., Ramos, C.J.P. and Fearnside, P.M. (2021) 'Forest fires and deforestation in the central Amazon: Effects of landscape and climate on spatial and temporal dynamics', *Journal of Environmental Management*, 288, available: http://dx.doi.org/10.1016/j.jenvman.2021.112310.

Douville, H., Raghavan, K., Renwick, J., Allan, R.P., Arias, P.A., Barlow, M., Cerezo-Mota, R., Cherchi, A., Gan, T.Y., Gergis, J., Jiang, D., Khan, A., Pokam Mba, W., Rosenfeld, D., Tierney, J. and Zolina, O. (2021) 'Water Cycle Changes. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change' in Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B., eds., Cambridge University Press, In Press-In Press.

Du, C., Wang, X., Zhang, M., Jing, J. and Gao, Y. (2019) 'Effects of elevated CO2 on plant CNP stoichiometry in terrestrial ecosystems: A meta-analysis', *Science of The Total Environment*, 650, 697-708.

Dummett, C., Blundell, A., Canby, K., Wolosin, M. and Bodnar, E. (2021) *Illicit Harvest, Complicit Goods: The State of Illegal Deforestation for Agriculture*, available: https://www.forest-trends.org/publications/illicit-harvest-complicit-goods/ [accessed.

Dusenge, M.E., Duarte, A.G. and Way, D.A. (2019) 'Plant carbon metabolism and climate change: elevated CO 2 and temperature impacts on photosynthesis, photorespiration and respiration', *New Phytologist*, 221(1), 32-49.

Dwomoh, F.K., Wimberly, M.C., Cochrane, M.A. and Numata, I. (2019) 'Forest degradation promotes fire during drought in moist tropical forests of Ghana', *Forest Ecology and Management*, 440(March), 158-168, available: http://dx.doi.org/10.1016/j.foreco.2019.03.014.

Edwards, D.P., Tobias, J.A., Sheil, D., Meijaard, E. and Laurance, W.F. (2014) 'Maintaining ecosystem function and services in logged tropical forests', *Trends in ecology & evolution*, 29(9), 511-520.

Ellis, E.A., Kainer, K.A., Sierra-Huelsz, J.A., Negreros-Castillo, P., Rodriguez-Ward, D. and DiGiano, M. (2015) 'Endurance and adaptation of community forest management in Quintana Roo, Mexico', *Forests*, 6(11), 4295-4327, available: http://dx.doi.org/10.3390/f6114295.

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Van Noordwijk, M., Creed, I.F. and Pokorny, J. (2017) 'Trees, forests and water: Cool insights for a hot world', *Global Environmental Change*, 43, 51-61.

Ellsworth, D.S., Anderson, I.C., Crous, K.Y., Cooke, J., Drake, J.E., Gherlenda, A.N., Gimeno, T.E., Macdonald, C.A., Medlyn, B.E. and Powell, J.R. (2017) 'Elevated CO 2 does not increase eucalypt forest productivity on a low-phosphorus soil', *Nature Climate Change*, 7(4), 279-282.

Enrici, A. and Hubacek, K. (2016) 'Business as usual in Indonesia: governance factors effecting the acceleration of the deforestation rate after the introduction of REDD+', *Energy, Ecology and Environment*, 1(4), 183-196, available: http://dx.doi.org/10.1007/S40974-016-0037-4.

ESA (2017) *Land Cover CCI Product User Guide Version 2. Tech. Rep*: Available at: maps.elie.ucl.ac.be/CCI/viewer/downlod/ESACCI-LC-Ph2-PUGv2_2.0.pdf.

Esquivel-Muelbert, A., Baker, T.R., Dexter, K.G., Lewis, S.L., Brienen, R.J., Feldpausch, T.R., Lloyd, J., Monteagudo-Mendoza, A., Arroyo, L. and Álvarez-Dávila, E. (2019) 'Compositional response of Amazon forests to climate change', *Global change biology*, 25(1), 39-56.

Fadrique, B., Báez, S., Duque, Á., Malizia, A., Blundo, C., Carilla, J., Osinaga-Acosta, O., Malizia, L., Silman, M. and Farfán-Ríos, W. (2018) 'Widespread but heterogeneous responses of Andean forests to climate change', *Nature*, 564(7735), 207.

FAO (2012) 'Global ecological zones for FAO forest reporting: 2010 Update ', *Forest Resources Assessment Working Paper 179*.

FAO (2016a) *Case Studies on Climate Change and African Coastal Fisheries: A Vulnerability Analysis and Recommendations for Adaptation Options*, Rome, Italy.
FAO (2016b) *State of the World's Forests 2016. Forests and agriculture: land-use challenges and opportunities*, Rome.
FAO (2018a) *Climate change and its impacts on the work and activities of FAO forestry.*, Committee on Forestry.
FAO (2018b) *Transforming Food and Agriculture to Achieve the SDGs. 20 Interconnected Actions to Guide Decision-Makers*, Rome, available: http://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1140709/ [accessed.
FAO (2020) *Global Forest Resources Assessment 2020: Main report*, Rome, available: https://doi.org/10.4060/ca9825en [accessed.
FAO and CIFOR (2019) 'Climate change vulnerability assessment of forests and forest-dependent people A framework methodology Climate change vulnerability assessment of forests and forest-dependent people A framework methodology Climate change vulnerability assessment of forest', in 2019.
FAO and FILAC (2021) 'Forest governance by indigenous and tribal peoples. An opportunity for climate action in Latin America and the Caribbean', *Forest governance by indigenous and tribal peoples. An opportunity for climate action in Latin America and the Caribbean*, available: http://dx.doi.org/10.4060/CB2953EN.
FAO and UNEP (2020) *The State of the World's Forests 2020. Forests, biodiversity and people*, Rome, available: http://www.fao.org/documents/card/en/c/ca8642en [accessed.
Farinosi, F., Arias, M.E., Lee, E., Longo, M., Pereira, F.F., Livino, A., Moorcroft, P.R. and Briscoe, J. (2019) 'Future Climate and Land Use Change Impacts on River Flows in the Tapajós Basin in the Brazilian Amazon', *Earth's Future*, 7(8), 993-1017, available: http://dx.doi.org/10.1029/2019EF001198.
Fehlenberg, V., Baumann, M., Gasparri, N.I.N.I., Piquer-Rodriguez, M., Gavier-Pizarro, G. and Kuemmerle, T. (2017) 'The role of soybean production as an underlying driver of deforestation in the South American Chaco', *Global Environmental Change*, 45, 24-34, available: http://dx.doi.org/10.1016/j.gloenvcha.2017.05.001.
Feng, Su, H., Tang, Z., Wang, S., Zhao, X., Zhang, H., Ji, C., Zhu, J., Xie, P. and Fang, J. (2021) 'Reduced resilience of terrestrial ecosystems locally is not reflected on a global scale', *Communications Earth & Environment*, 2(1), available: http://dx.doi.org/10.1038/s43247-021-00163-1.
Feng, X., Merow, C., Liu, Z., Park, D.S., Roehrdanz, P.R., Maitner, B., Newman, E.A., Boyle, B.L., Lien, A., Burger, J.R. and Pires, M.M. (2021) 'How deregulation, drought and increasing fire impact Amazonian biodiversity', *Nature*, 1-6.
Fernandes, K., Verchot, L., Baethgen, W., Gutierrez-Velez, V., Pinedo-Vasquez, M. and Martius, C. (2017) 'Heightened fire probability in Indonesia in non-drought conditions: the effect of increasing temperatures', *Environmental Research Letters*, 12(5), 054002.
Fernández-Llamazares, Á., Garcia, R.A., Díaz-Reviriego, I., Cabeza, M., Pyhälä, A. and Reyes-García, V. (2017) 'An empirically tested overlap between indigenous and scientific knowledge of a changing climate in Bolivian Amazonia', *Regional Environmental Change*, available: http://dx.doi.org/10.1007/s10113-017-1125-5.
Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (2014) *Climate change 2014 impacts, adaptation and vulnerability: Part A: Global and sectoral aspects: Working group II contribution to the fifth assessment report of the intergovernmental panel on climate change*.
Fischer, R., Giessen, L. and Günter, S. (2020) 'Governance effects on deforestation in the tropics: A review of the evidence', *Environmental Science & Policy*, 105, 84-101, available: http://dx.doi.org/10.1016/J.ENVSCI.2019.12.007.
Fleischer, K., Rammig, A., De Kauwe, M.G., Walker, A.P., Domingues, T.F., Fuchslueger, L., Garcia, S., Goll, D.S., Grandis, A., Jiang, M., Haverd, V., Hofhansl, F., Holm, J.A., Kruijt, B., Leung, F., Medlyn, B.E., Mercado, L.M., Norby, R.J., Pak, B., von Randow, C., Quesada, C.A., Schaap, K.J., Valverde-Barrantes, O.J., Wang, Y.-P., Yang, X., Zaehle, S., Zhu, Q. and Lapola, D.M. (2019) 'Amazon forest response to CO2 fertilization dependent on plant phosphorus acquisition', *Nature geoscience*, 12(9), 736-741, available: http://dx.doi.org/10.1038/s41561-019-0404-9.
Fonseca-Morello, T., Ramos, R., Steil, L., Parry, L., Barlow, J., Markusson, N. and Ferreira, A. (2017) 'Fires in Brazilian amazon: why does policy have a limited impact?', *Ambiente & sociedade*, 20, 19-38.
Ford, J.D., Cameron, L., Rubis, J., Maillet, M., Nakashima, D., Willox, A.C. and Pearce, T. (2016) 'Including indigenous knowledge and experience in IPCC assessment reports', *Nature Climate Change*, 6(4), 349-353, available: http://dx.doi.org/10.1038/nclimate2954.
Friess, D., Aung, T., Huxham, M., Lovelock, C., Mukherjee, N., & Sasmito, S. (2019) 'SDG 14: Life below Water – Impacts on Mangroves' in P. Katila, C. P. C., W. De Jong, G. Galloway, P. Pacheco, & G. Winkel, ed., *Sustainable Development Goals: Their Impacts on Forests and People* Cambridge: Cambridge University Press, 445-481.
Fritz, V., Levy, B. and Ort, R. (2014) *Problem-Driven Political Economy Analysis: The World Bank's Experience*, Washington DC: The World Bank.
Fujisaki, T., Hyakumura, K., Scheyvens, H. and Cadman, T. (2016) 'Does REDD+ ensure sectoral coordination and stakeholder participation? A comparative analysis of REDD+ national governance structures in countries of Asia-Pacific region', *Forests*, 7(9), 195-195, available: http://dx.doi.org/10.3390/F7090195.

Fungo, R., Muyonga, J., Kaaya, A., Okia, C., Tieguhong, J.C. and Baidu-Forson, J.J. (2015) 'Nutrients and bioactive compounds content of Baillonella toxisperma, Trichoscypha abut and Pentaclethra macrophylla from Cameroon', *Food science & nutrition*, 3(4), 292-301.

Gabay, M., & Rekola, M. (2019) *Forests, peaceful and inclusive societies, reduced inequality, education, and inclusive institutions at all levels* UN.

Gardner, T.A., Benzie, M., Börner, J., Dawkins, E., Fick, S., Garrett, R., Godar, J., Grimard, A., Lake, S., Larsen, R.K., Mardas, N., McDermott, C.L., Meyfroidt, P., Osbeck, M., Persson, M., Sembres, T., Suavet, C., Strassburg, B., Trevisan, A., West, C. and Wolvekamp, P. (2019) 'Transparency and sustainability in global commodity supply chains', *World Development*, 121, 163-177, available: http://dx.doi.org/10.1016/J.WORLDDEV.2018.05.025.

Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J., Watson, J.E., Zander, K.K., Austin, B. and Brondizio, E.S. (2018) 'A spatial overview of the global importance of Indigenous lands for conservation', *Nature Sustainability*, 1(7), 369.

Garrett, R.D.D., Levy, S., Carlson, K.M.M., Gardner, T.A.A., Godar, J., Clapp, J., Dauvergne, P., Heilmayr, R., le Polain de Waroux, Y., Ayre, B., Barr, R., Døvre, B., Gibbs, H.K.K., Hall, S., Lake, S., Milder, J.C.C., Rausch, L.L.L., Rivero, R., Rueda, X., Sarsfield, R., Soares-Filho, B. and Villoria, N. (2019) 'Criteria for effective zero-deforestation commitments', *Global Environmental Change*, 54, 135-147, available: http://dx.doi.org/10.1016/j.gloenvcha.2018.11.003.

Gatti, L.V., Basso, L.S., Miller, J.B., Gloor, M., Gatti Domingues, L., Cassol, H.L.G., Tejada, G., Aragão, L.E.O.C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A.H., Corrêa, S.M., Anderson, L., Von Randow, C., Correia, C.S.C., Crispim, S.P. and Neves, R.A.L. (2021) 'Amazonia as a carbon source linked to deforestation and climate change', *Nature*, 595(7867), 388-393, available: http://dx.doi.org/10.1038/s41586-021-03629-6.

Gebara, M.F. (2018) 'Tenure reforms in indigenous lands: decentralized forest management or illegalism?', *Current Opinion in Environmental Sustainability*, 32, 60-67, available: http://dx.doi.org/10.1016/J.COSUST.2018.04.008.

Geist, H.J. and Lambin, E.F. (2002) 'Proximate Causes and Underlying Driving Forces of Tropical DeforestationTropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations', *BioScience*, 52(2), 143-150.

Giam, X. (2017) 'Global biodiversity loss from tropical deforestation', *Proceedings of the National Academy of Sciences*, 114(23), 5775-5777.

Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L. and Walker, N.F. (2015) 'Brazil's soy moratorium', *Science*, 347(6220), 377-378, available: http://dx.doi.org/10.1126/science.aaa0181.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J., Laurance, W.F. and Lovejoy, T.E. (2011) 'Primary forests are irreplaceable for sustaining tropical biodiversity', *Nature*, 478(7369), 378-381.

Gillson, L., Whitlock, C. and Humphrey, G. (2019) 'Resilience and fire management in the Anthropocene', *Ecology and Society*, 24(3), available: http://dx.doi.org/10.5751/ES-11022-240314.

Girardi, D. (2015) 'Financialization of food. Modelling the time-varying relation between agricultural prices and stock market dynamics', *International Review of Applied Economics*, 29(4), 482-505, available: http://dx.doi.org/10.1080/02692171.2015.1016406.

Global Canopy (2019) 'Consumer Goods Forum will not achieve deforestation goal'.

Gomes, V.H., Vieira, I.C., Salomão, R.P. and ter Steege, H. (2019) 'Amazonian tree species threatened by deforestation and climate change', *Nature Climate Change*, 9(7), 547-553.

Green, J.F. (2021) 'Does carbon pricing reduce emissions? A review of ex-post analyses', *Environmental Research Letters*, 16(4), 043004-043004, available: http://dx.doi.org/10.1088/1748-9326/ABDAE9.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V. and Smith, P. (2017) 'Natural climate solutions', *Proceedings of the National Academy of Sciences*, 114(44), 11645-11650, available: http://dx.doi.org/10.1073/pnas.1710465114.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E. and Fargione, J. (2017) 'Natural climate solutions', *Proceedings of the National Academy of Sciences*, 114(44), 11645-11650, available: http://dx.doi.org/10.1073/pnas.1710465114.

Guidi, C., Di Matteo, G. and Grego, S. (2018) 'An overview of proven Climate Change Vulnerability Assessment tools for forests and forest-dependent communities across the globe: a literature analysis'.

Hagerman, S.M. and Pelai, R. (2018) 'Responding to climate change in forest management: two decades of recommendations', *Frontiers in Ecology and the Environment*, 16(10), 579-587.

Hajjar, R., Engbring, G. & Kornhauser, K. 2021. (2021) 'The impacts of REDD+ on the social-ecological resilience of community forests', *Environ. Res. Lett.*, 16.

Hajjar, R., Oldekop, J.A., Cronkleton, P., Etue, E., Newton, P., Russel, A.J., Tjajadi, J.S., Zhou, W. and Agrawal, A. (2016) 'The data not collected on community forestry', *Conservation biology*, 30(6), 1357-1362.

Halvorssen, A.M. (2021) *How the Norwegian SWF Balances Ethics, ESG Risks, and Returns: Can this Approach Work for Other Institutional Investors?*, Internal Report, unpublished.

Hansen, C.P., Rutt, R., & Acheampong, E. (2018) '‘Experimental’ or business as usual? Implementing the European Union Forest Law Enforcement, Governance and Trade (FLEGT) Voluntary Partnership Agreement in Ghana', *Forest Policy and Economics*, 96, 75-82.
Hartmann, H., Adams, H.D., Anderegg, W.R., Jansen, S. and Zeppel, M.J. (2015) 'Research frontiers in drought-induced tree mortality: crossing scales and disciplines'.
Hatcher, J. (2009) 'Securing tenure rights and reducing emissions from deforestation and degradation', in *REDD): Costs and lessons learned. Rights and Resources Initiative*, Citeseer.
He, F. and Hubbell, S.P. (2011) 'Species–area relationships always overestimate extinction rates from habitat loss', *Nature*, 473(7347), 368-371.
Head, B.W. (2018) 'Forty years of wicked problems literature: forging closer links to policy studies', *Policy and Society*, 38(2), 180-197, available: http://dx.doi.org/10.1080/14494035.2018.1488797.
Hein, J., Guarin, A., Frommé, E. and Pauw, P. (2018) 'Deforestation and the Paris climate agreement: An assessment of REDD+ in the national climate action plans', *Forest Policy and Economics*, 90, 7-11.
Helbing, D. (2013) 'Globally networked risks and how to respond', *Nature*, 497(7447), 51-59, available: http://dx.doi.org/10.1038/nature12047.
Henders, S., Persson, U.M. and Kastner, T. (2015) 'Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities', *Environmental Research Letters*, 10(12), 125012.
Henstra, D. (2015) 'The tools of climate adaptation policy: analysing instruments and instrument selection', *Climate Policy*, 16(4), 496-521, available: http://dx.doi.org/10.1080/14693062.2015.1015946.
Herrera, D., Ellis, A., Fisher, B., Golden, C.D., Johnson, K., Mulligan, M., Pfaff, A., Treuer, T. and Ricketts, T.H. (2017) 'Upstream watershed condition predicts rural children's health across 35 developing countries', *Nat Commun*, 8(1), 811, available: http://dx.doi.org/10.1038/s41467-017-00775-2.
Hiratsuka, m., nakama, E., Satriadi, T., Fauzi, H., Aryadi, M., & Morikaa, Y. (2019) 'An approach to achieve sustainable development goals through participatory land and forest conservation: a case study in South Kalimantan province, Indonesia', *Journal of sustainable forestry*, 38(6), 558-571.
Hisano, M., Searle, E.B. and Chen, H.Y. (2018) 'Biodiversity as a solution to mitigate climate change impacts on the functioning of forest ecosystems', *Biological Reviews*, 93(1), 439-456.
Hiwasaki, L., Luna, E., Syamsidik and Mar??al, J.A. (2015) 'Local and indigenous knowledge on climate-related hazards of coastal and small island communities in Southeast Asia', *Climatic Change*, 128(1-2), 35-56, available: http://dx.doi.org/10.1007/s10584-014-1288-8.
Hoang, N.T. and Kanemoto, K. (2021) 'Mapping the deforestation footprint of nations reveals growing threat to tropical forests', *Nature Ecology & Evolution*, 1-9, available: http://dx.doi.org/10.1038/s41559-021-01417-z.
Hoffmann, W.A., Schroeder, W. and Jackson, R.B. (2003) 'Regional feedbacks among fire, climate, and tropical deforestation', *Journal of Geophysical Research: Atmospheres*, 108(23), 1-11, available: http://dx.doi.org/10.1029/2003jd003494.
Hofmann, G.S., Cardoso, M.F., Alves, R.J.V., Weber, E.J., Barbosa, A.A., Toledo, P.M., Pontual, F.B., Salles, L.d.O., Hasenack, H., Cordeiro, J.L.P., Aquino, F.E. and Oliveira, L.F.B. (2021) 'The Brazilian Cerrado is becoming hotter and drier', *Global change biology*, 27(17), 4060-4073., available: http://dx.doi.org/10.1111/gcb.15712.
Holley, C. and Sofronova, E. (2017) 'New environmental governance: Adaptation, resilience and law' in Hutter, B. M., ed., Edward Elgar Publishing Ltd., 129-146.
Holmes, T.P., Blate, G.M., Zweede, J.C., Pereira Jr, R., Barreto, P., Boltz, F. and Bauch, R. (2002) 'Financial and ecological indicators of reduced impact logging performance in the eastern Amazon', *Forest Ecology and Management*, 163(1-3), 93-110.
Hörl, J., Keller, K. and Yousefpour, R. (2020) 'Reviewing the performance of adaptive forest management strategies with robustness analysis', *Forest Policy and Economics*, 119, 102289-102289, available: http://dx.doi.org/10.1016/J.FORPOL.2020.102289.
Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A. and Romijn, E. (2012) 'An assessment of deforestation and forest degradation drivers in developing countries', *Environmental Research Letters*, 7(4), 044009.
Houghton, R.A. and Nassikas, A.A. (2017) 'Negative Emissions from Stopping Deforestation and Forest Degradation, Globally', *Global change biology*, 24(1), 350-359, available: http://dx.doi.org/https://doi.org/10.1111/gcb.13876.
Howlett, M. and Kemmerling, A. (2017) 'Calibrating climate change policies: the causes and consequences of sustained under-reaction', *Journal of Environmental Policy & Planning*, 19(6), 625-637, available: http://dx.doi.org/10.1080/1523908X.2017.1324772.
Howlett, M., Ramesh, M. and Wu, X. (2015) 'Understanding the persistence of policy failures: The role of politics, governance and uncertainty', *Public Policy and Administration*, 30(3-4), 209-220, available: http://dx.doi.org/10.1177/0952076715593139.
Hubau, W., Lewis, S.L., Phillips, O.L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A.K., Ewango, C.E., Fauset, S. and Mukinzi, J.M. (2020) 'Asynchronous carbon sink saturation in African and Amazonian tropical forests', *Nature*, 579(7797), 80-87.
Hughes, T.P., Carpenter, S., Rockström, J., Scheffer, M. and Walker, B. (2013) 'Multiscale regime shifts and planetary boundaries', *Trends in ecology & evolution*, 28(7), 389-395, available: http://dx.doi.org/10.1016/J.TREE.2013.05.019.

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B. and Van Weele, M. (2016) 'Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997', *Scientific Reports*, 6(February), available: http://dx.doi.org/10.1038/srep26886.
Huntingford, C., Zelazowski, P., Galbraith, D., Mercado, L.M., Sitch, S., Fisher, R., Lomas, M., Walker, A.P., Jones, C.D. and Booth, B.B. (2013) 'Simulated resilience of tropical rainforests to CO 2-induced climate change', *Nature geoscience*, 6(4), 268.
Huong, N.T.L., Yao, S. and Fahad, S. (2019) 'Assessing household livelihood vulnerability to climate change: The case of Northwest Vietnam', *Human and Ecological Risk Assessment*, 25(5), 1157-1175, available: http://dx.doi.org/10.1080/10807039.2018.1460801.
Hurlbert, M., Krishnaswamy, J., Davin, E., Johnson, F.X., Mena, C.F., Morton, J., Myeong, S., Viner, D., Warner, K., Wreford, A., Zakieldeen, S. and Zommers, Z. (2019) 'Risk Management and Decision making in Relation to Sustainable Development. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in', 114-115, available: http://dx.doi.org/10.1525/9780520959316-013.
Husnina, Z., Clements, A.C.A. and Wangdi, K. (2019) 'Forest cover and climate as potential drivers for dengue fever in Sumatra and Kalimantan 2006–2016: a spatiotemporal analysis', *Tropical Medicine and International Health*, 24(7), 888-898, available: http://dx.doi.org/10.1111/tmi.13248.
Ickowitz, A., Powell, B., Salim, M.A. and Sunderland, T.C. (2014) 'Dietary quality and tree cover in Africa', *Global Environmental Change*, 24, 287-294.
IFAD (2016) *Rural Development Report 2016: Fostering inclusive rural transformation*, Rome.
Ihalainen, M., Sijapati Basnett, B., Larson, A., Duchelle, A., Pham, T.T. and Djoudi, H. (2017) *What should be included in the Green Climate Fund's new Gender Policy and Action Plan?: Lessons from CIFOR's research and analyses*, CIFOR.
Imai, N., Samejima, H., Langner, A., Ong, R.C., Kita, S., Titin, J., Chung, A.Y., Lagan, P., Lee, Y.F. and Kitayama, K. (2009) 'Co-benefits of sustainable forest management in biodiversity conservation and carbon sequestration', *PLOS ONE*, 4(12), e8267.
Ingalls, M.L., Meyfroidt, P., To, P.X., Kenney-Lazar, M. and Epprecht, M. (2018) 'The transboundary displacement of deforestation under REDD+: Problematic intersections between the trade of forest-risk commodities and land grabbing in the Mekong region', *Global Environmental Change*, 50, 255-267, available: http://dx.doi.org/10.1016/j.gloenvcha.2018.04.003.
IPBES (2018) 'Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for Africa of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services' in E. Archer, L.E. Dziba, K.J. Mulongoy, M.A. Maoela, M. Walters, R. Riggs, M-C. Cormier-Salem, F. DeClerck, M.C. Diaw, A.E. Dunham, P. Failler, C. Cordon, K.A. Harhash, R. Kasisi, F. Kizito, W.D. Nyingi, N. Oguge, B. Osman-Elasha, L.C. Stringer, L. Tito de Morais, A. Assogbadjo, B.N. Egoh, M.W. Halmy, K. Heubach, A. Mensah, Pereira., L. and N. Sitas, eds., Bonn, Germany: IPBES Secretariat, 49.
IPBES (2019) *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, Bonn, available: https://ipbes.net/document-library-catalogue/summary-policymakers-global-assessment-laid-out [accessed.
IPBES, Leeprakton Li, T.P., Berger, F., van Aarde, R., World Alumina, A., Morris, J.P., Brainich, A., Erpul, G., Huang, Y., Roué, M., Guan Saw, L., Zabid Oglu Allahverdiyev, R., Andreas Baste, I. and Goodman Mketeni, F. (2018) *THE ASSESSMENT REPORT ON LAND DEGRADATION AND RESTORATION 2 THE IPBES ASSESSMENT REPORT ON LAND DEGRADATION AND RESTORATION Disclaimer on maps Photo credits Technical Support Graphic Design MEMBERS OF THE MANAGEMENT COMMITTEE WHO PROVIDED GUIDANCE FOR THE*.
IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contrbution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1 ed., Cambridge, UK and New York, NY, USA: Cambridge University Press.
IPCC (2019) *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
Isendahl, C. (2011) 'The domestication and early spread of manioc (Manihot esculenta Crantz): a brief synthesis', *Latin American Antiquity*, 22(4), 452-468.
Issaka, Y. (2018) 'Non-timber Forest Products, Climate Change Resilience, and Poverty Alleviation in Northern Ghana' in, 179-192.
Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., Gonzalez-Olabarria, J.R., Koricheva, J., Meurisse, N. and Brockerhoff, E.G. (2017) 'Tree diversity drives forest stand resistance to natural disturbances', *Current Forestry Reports*, 3(3), 223-243.
Jagger, P., Bailis, R., Dermawan, A., Kittner, N., & McCord, R. (2019) 'SDG 7: Affordable and Clean Energy – How Access to Affordable and Clean Energy Affects Forests and Forest-Based Livelihoods' in P. Katila, C. P. C., W. De Jong, G. Galloway, P. Pacheco, & G. Winkel ed., *Sustainable Development Goals: Their Impacts on Forests and People*, Cambridge: Cambridge University Press, 206-236.
Jenkins, C.N., Pimm, S.L. and Joppa, L.N. (2013) 'Global patterns of terrestrial vertebrate diversity and conservation', *Proceedings of the National Academy of Sciences*, 110(28), E2602-E2610.

Jennings, S., Nussbaum, R., Judd, N., Evans, T., Iacobelli, T., Jarvie, J., Lindhe, A., Synnott, T., Vallejos, C. and Yaroshenko, A. (2003) 'The high conservation value forest toolkit', *Edition I, ProForest, Oxford OX*, 12, 1-62.
Jia, G., Shevliakova, E., Artaxo, P., De Noblet-Ducoudré, N., Houghton, R., House, J., Kitajima, K., Lennard, C., Popp, A., Sirin, A., Sukumar, R. and Verchot, L. (2019) 'Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems' in Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H. O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J., eds., In Press-In Press.
Johnston, F.H., Henderson, S.B., Chen, Y., Randerson, J.T., Marlier, M., DeFries, R.S., Kinney, P., Bowman, D.M. and Brauer, M. (2012) 'Estimated global mortality attributable to smoke from landscape fires', *Environmental health perspectives*, 120(5), 695-701.
Jose, S. (2009) 'Agroforestry for ecosystem services and environmental benefits: an overview', *Agroforestry systems*, 76(1), 1-10.
Junquera, V., Meyfroidt, P., Sun, Z., Latthachack, P. and Grêt-Regamey, A. (2020) 'From global drivers to local land-use change: understanding the northern Laos rubber boom', *Environmental Science and Policy*, 109, 103-115, available: http://dx.doi.org/10.1016/j.envsci.2020.04.013.
Kanowski, P., Yao, D., & Wyatt, S. (2019) 'SDG 4: Quality Education and Forests – 'The Golden Thread'' in P. Katila, C. P. C., W. De Jong, G. Galloway, P. Pacheco, & G. Winkel, ed., *Sustainable Development Goals: Their Impacts on Forests and People* Cambridge: Cambridge University Press.
Karjalainen, E., Sarjala, T. and Raitio, H. (2010) 'Promoting human health through forests: overview and major challenges', *Environmental health and preventive medicine*, 15(1), 1-8.
Keeling, R.F., Graven, H.D., Welp, L.R., Resplandy, L., Bi, J., Piper, S.C., Sun, Y., Bollenbacher, A. and Meijer, H.A. (2017) 'Atmospheric evidence for a global secular increase in carbon isotopic discrimination of land photosynthesis', *Proceedings of the National Academy of Sciences*, 114(39), 10361-10366.
Keenan, R.J. (2015) 'Climate change impacts and adaptation in forest management: a review', *Annals of Forest Science*, 72(2), 145-167, available: http://dx.doi.org/10.1007/s13595-014-0446-5.
Ken, S., Sasaki, N., Entani, T., Ma, H.O., Thuch, P. and Tsusaka, T.W. (2020) 'Assessment of the local perceptions on the drivers of deforestation and forest degradation, agents of drivers, and appropriate activities in cambodia', *Sustainability (Switzerland)*, 12(23), 1-26, available: http://dx.doi.org/10.3390/su12239987.
Khanna, J., Medvigy, D., Fueglistaler, S. and Walko, R. (2017) 'Regional dry-season climate changes due to three decades of Amazonian deforestation', *Nature Climate Change*, 7(3), 200-204, available: http://dx.doi.org/10.1038/nclimate3226.
Kier, G., Kreft, H., Lee, T.M., Jetz, W., Ibisch, P.L., Nowicki, C., Mutke, J. and Barthlott, W. (2009) 'A global assessment of endemism and species richness across island and mainland regions', *Proceedings of the National Academy of Sciences*, 106(23), 9322-9327.
Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S. and Beach, R. (2008) 'Global cost estimates of reducing carbon emissions through avoided deforestation', *Proceedings of the National Academy of Sciences*, 105(30), 10302-10307.
Kissinger, G. (2020) 'Policy responses to direct and underlying drivers of deforestation: Examining rubber and coffee in the central highlands of Vietnam', *Forests*, 11(7), 733.
Kissinger, G., Brockhaus, M. and Bush, S.R. (2021) 'Policy integration as a means to address policy fragmentation: Assessing the role of Vietnam's national REDD+ action plan in the central highlands', *Environmental Science & Policy*, 119, 85-92, available: http://dx.doi.org/10.1016/j.envsci.2021.02.011.
Kissinger, G., Herold, M. and De Sy, V. (2012) *Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers*, Vancouver.
Koch, A., Hubau, W. and Lewis, S.L. (2021) 'Earth System Models are not capturing present-day tropical forest carbon dynamics', *Earth's Future*, e2020EF001874.
Konijnendijk, C.C. (2018) *The city and the forest: The cultural landscape of urban woodland*, Berlin: Springer.
Körner, C. (2009) 'Responses of humid tropical trees to rising CO2', *Annual Review of Ecology, Evolution, and Systematics*, 40, 61-79.
Köthke, M. (2014) 'Costs of sustainable forest management in the tropics: State of knowledge'.
Kouznetsov, V.V. and Amado Torres, D.F. (2008) 'Antimalarials: construction of molecular hybrids based on chloroquine', *Universitas Scientiarum*, 13(3), 306-320.
Krishnaswamy, J., John, R. and Joseph, S. (2014) 'Consistent response of vegetation dynamics to recent climate change in tropical mountain regions', *Global change biology*, 20(1), 203-215.
Kubitza, C., Krishna, V.V., Urban, K., Alamsyah, Z. and Qaim, M. (2018) 'Land property rights, agricultural intensification, and deforestation in Indonesia', *Ecological Economics*, 147, 312-321.
Kumar, V. (2015) 'Role of Non Wood Forest Products (NWFPs) on Tribal Economy of Gujarat, India', *Int. J. of Usuf. Mngt*, 16(1), 67-75.
Lama, A.S., Kharel, S. and Ghale, T. (2017) 'When the men are away: Migration and women's participation in Nepal's community forestry', *Mountain research and development*, 37(3), 263-271.

Lamb, D. and Gilmour, D. (2003) *Rehabilitation and restoration of degraded forests*, Gland, Switzerland: IUCN-The World Conservation Union.
Lambin, E.F., Gibbs, H.K., Heilmayr, R., Carlson, K.M., Fleck, L.C., Garrett, R.D., le Polain de Waroux, Y., McDermott, C.L., McLaughlin, D., Newton, P., Nolte, C., Pacheco, P., Rausch, L.L., Streck, C., Thorlakson, T. and Walker, N.F. (2018) 'The role of supply-chain initiatives in reducing deforestation', *Nature Climate Change*, 8(2), 109-116, available: http://dx.doi.org/10.1038/s41558-017-0061-1.
Lapola, D.M., Pinho, P., Quesada, C.A., Strassburg, B.B., Rammig, A., Kruijt, B., Brown, F., Ometto, J.P., Premebida, A. and Marengo, J.A. (2018) 'Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action', *Proceedings of the National Academy of Sciences*, 115(46), 11671-11679.
Lasco, R.D., Delfino, R.J.P., Catacutan, D.C., Simelton, E.S. and Wilson, D.M. (2014) 'Climate risk adaptation by smallholder farmers: the roles of trees and agroforestry', *Current Opinion in Environmental Sustainability*, 6, 83-88.
Lawrence, D. and Vandecar, K. (2015) 'Effects of tropical deforestation on climate and agriculture', *Nature Climate Change*, 5(1), 27.
Le Page, Y., Morton, D., Hartin, C., Bond-Lamberty, B., Pereira, J.M.C., Hurtt, G. and Asrar, G. (2017) 'Synergy between land use and climate change increases future fire risk in Amazon forests', *Earth Syst. Dynam.*, 8(4), 1237-1246, available: http://dx.doi.org/10.5194/esd-8-1237-2017.
Lee, Y., Rianti, Indri Puji & Park, Mi Sun (2017) 'Measuring social capital in Indonesian community forest management', *Forest Science and Technology*, 13(3), 133-141, available: http://dx.doi.org/10.1080/21580103.2017.1355335.
Lehto, T. and Zwiazek, J.J. (2011) 'Ectomycorrhizas and water relations of trees: a review', *Mycorrhiza*, 21(2), 71-90, available: http://dx.doi.org/10.1007/s00572-010-0348-9.
Leite-Filho, A.T., Costa, M.H. and Fu, R. (2020) 'The southern Amazon rainy season: The role of deforestation and its interactions with large-scale mechanisms', *International Journal of Climatology*, 40(4), 2328-2341, available: http://dx.doi.org/10.1002/joc.6335.
Leite-Filho, A.T., de Sousa Pontes, V.Y. and Costa, M.H. (2019) 'Effects of Deforestation on the Onset of the Rainy Season and the Duration of Dry Spells in Southern Amazonia', *Journal of Geophysical Research: Atmospheres*, 124(10), 5268-5281, available: http://dx.doi.org/10.1029/2018JD029537.
Leite-Filho, A.T., Soares-Filho, B.S., Davis, J.L., Abrahão, G.M. and Börner, J. (2021) 'Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon', *Nature communications*, 12(1), 2591-2591, available: http://dx.doi.org/10.1038/s41467-021-22840-7.
Lewis, S.L., Wheeler, C.E., Mitchard, E.T. and Koch, A. (2019) 'Restoring natural forests is the best way to remove atmospheric carbon', *Nature*, 25-28.
Lira, D., Marangon, L., Ferreira, R., Marangon, G. and Silva, E. (2012) 'Comparação entre custos de implantação de dois modelos de restauração florestal em Pernambuco', *Scientia Plena*, 8(4 (b)).
Liu, J., Bowman, K.W., Schimel, D.S., Parazoo, N.C., Jiang, Z., Lee, M., Bloom, A.A., Wunch, D., Frankenberg, C. and Sun, Y. (2017) 'Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño', *Science*, 358(6360), eaam5690.
Locatelli, B., Brockhaus, M., Buck, A. and Thompson, I. (2010) *Forests and adaptation to climate change: challenges and opportunities*, IUFRO.
Locatelli, B., Catterall, C.P., Imbach, P., Kumar, C., Lasco, R., Marín-Spiotta, E., Mercer, B., Powers, J.S., Schwartz, N. and Uriarte, M. (2015a) 'Tropical reforestation and climate change: beyond carbon', *Restoration ecology*, 23(4), 337-343.
Locatelli, B., Kanninen, M., Brockhaus, M., Colfer, C., Murdiyarso, D. and Santoso, H. (2008) *Facing an Uncertain Future:* , CIFOR.
Locatelli, B., Pavageau, C., Pramova, E. and Di Gregorio, M. (2015b) 'Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs', *Wiley Interdisciplinary Reviews: Climate Change*, 6(6), 585-598.
Lombardozzi, D.L., Bonan, G.B., Smith, N.G., Dukes, J.S. and Fisher, R.A. (2015) 'Temperature acclimation of photosynthesis and respiration: A key uncertainty in the carbon cycle-climate feedback', *Geophysical Research Letters*, 42(20), 8624-8631, available: http://dx.doi.org/https://doi.org/10.1002/2015GL065934.
Lopoukhine, N., Crawhall, N., Dudley, N., Figgis, P., Karibuhoye, C., Laffoley, D., Londoño, J.M., MacKinnon, K. and Sandwith, T. (2012) 'Protected areas: providing natural solutions to 21st Century challenges', *SAPI EN. S. Surveys and Perspectives Integrating Environment and Society*, (5.2).
Los, S.O., Street-Perrott, F.A., Loader, N.J., Froyd, C.A., Cuní-Sanchez, A. and Marchant, R.A. (2019) 'Sensitivity of a tropical montane cloud forest to climate change, present, past and future: Mt. Marsabit, N. Kenya', *Quaternary Science Reviews*, 218, 34-48, available: http://dx.doi.org/10.1016/j.quascirev.2019.06.016.
Lujala, P. (2018) 'An analysis of the Extractive Industry Transparency Initiative implementation process', *World Development*, 107, 358-381, available: http://dx.doi.org/10.1016/J.WORLDDEV.2018.02.030.
Lyra, A., Imbach, P., Rodriguez, D., Chou, S.C., Georgiou, S. and Garofolo, L. (2017) 'Projections of climate change impacts on central America tropical rainforest', *Climatic Change*, 141(1), 93-105, available: http://dx.doi.org/10.1007/s10584-016-1790-2.

Maia, J.G.S. and Mourão, R.H.V. (2016) 'Amazon rosewood (Aniba rosaeodora Ducke) oils' in *Essential Oils in Food Preservation, Flavor and Safety* Elsevier, 193-201.
Maillet, M. and Ford, J. (2016) 'Climate change adaptation, indigenous peoples and the United Nations Framework Convention on Climate Change (UNFCCC)', *Health Dipl Monit*, 4(2), 10-14.
Malcolm, J.R., Markham, A., Neilson, R.P. and Garaci, M. (2002) 'Estimated migration rates under scenarios of global climate change', *Journal of Biogeography*, 29(7), 835-849.
Malhi, Y., Gardner, T.A., Goldsmith, G.R., Silman, M.R. and Zelazowski, P. (2014) 'Tropical forests in the Anthropocene', *Annual Review of Environment and Resources*, 39, 125-159.
Mansourian, S., Dudley, N. and Vallauri, D. (2017) 'Forest landscape restoration: Progress in the last decade and remaining challenges', *Ecological Restoration*, 35(4), 281-288.
Mansourian, S. and Vallauri, D. (2005) *Forest restoration in landscapes: beyond planting trees*, Springer Science & Business Media.
Martin, J.F., Roy, E.D., Diemont, S.A.W. and Ferguson, B.G. (2010) 'Traditional Ecological Knowledge (TEK): Ideas, inspiration, and designs for ecological engineering', *Ecological Engineering*, 36(7), 839-849, available: http://dx.doi.org/10.1016/j.ecoleng.2010.04.001.
Masuda, Y.J., Castro, B., Aggraeni, I., Wolff, N.H., Ebi, K., Garg, T., Game, E. T. Krenz, J. & Spector, J. (2019) 'How are healthy, working populations affected by increasing temperatures in the tropics? Implications for climate change adaptation policies', *Global Environmental Change*, 56, 29-40.
Mau, A., Reed, S., Wood, T. and Cavaleri, M. (2018) 'Temperate and tropical forest canopies are already functioning beyond their thermal thresholds for photosynthesis', *Forests*, 9(1), 47.
Maxwell, S.L., Cazalis, V., Dudley, N., Hoffmann, M., Rodrigues, A.S.L., Stolton, S., Visconti, P., Woodley, S., Kingston, N., Lewis, E., Maron, M., Strassburg, B.B.N., Wenger, A., Jonas, H.D., Venter, O. and Watson, J.E.M. (2020) 'Area-based conservation in the twenty-first century', *Nature*, 586(7828), 217-227, available: http://dx.doi.org/10.1038/s41586-020-2773-z.
Mbow, C., Van Noordwijk, M., Luedeling, E., Neufeldt, H., Minang, P.A. and Kowero, G. (2014) 'Agroforestry solutions to address food security and climate change challenges in Africa', *Current Opinion in Environmental Sustainability*, 6, 61-67.
McAlpine, C.A., Johnson, A., Salazar, A., Syktus, J., Wilson, K., Meijaard, E., Seabrook, L., Dargusch, P., Nordin, H. and Sheil, D. (2018) 'Forest loss and Borneo's climate', *Environmental Research Letters*, 13(4), 044009, available: http://dx.doi.org/10.1088/1748-9326/aaa4ff.
McDermott, C., Acheampong, E., Arora-Jonsson, S., Asare, R., De Jong, W., Hirons, M., . . . Setyowati, A. (2019) 'SDG 16: Peace, Justice and Strong Institutions – A Political Ecology Perspective' in P. Katila, C. P. C., W. De Jong, G. Galloway, P. Pacheco, & G. Winkel (ed., *Sustainable Development Goals: Their Impacts on Forests and People*, Cambridge: Cambridge University Press., 510-540.
McDowell, N.G., Allen, C.D., Anderson-Teixeira, K., Aukema, B.H., Bond-Lamberty, B., Chini, L., Clark, J.S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G.C., Jackson, R.B., Johnson, D.J., Kueppers, L., Lichstein, J.W., Ogle, K., Poulter, B., Pugh, T.A.M., Seidl, R., Turner, M.G., Uriarte, M., Walker, A.P. and Xu, C. (2020) 'Pervasive shifts in forest dynamics in a changing world', *Science*, 368(6494), available: http://dx.doi.org/10.1126/science.aaz9463.
Md rai, C.S., Al-Shami, S. A., Madrus, M. R., & Ahmad, A. H. (2014) 'Biological and ecological diversity of aquatic macroinvertebrates in response to hydrological and physicochemical parameters in tropical forest streams of Gunung Tebu, Malaysia: Implications for ecohydrological assessment', *Ecohydrology*, 7(2), 496-507.
Medjibe, V.P. and Putz, F.E. (2012) 'Cost comparisons of reduced-impact and conventional logging in the tropics', *Journal of Forest Economics*, 18(3), 242-256.
Meehan, F., Tacconi, L. and Budiningsih, K. (2019) 'Are national commitments to reducing emissions from forests effective? Lessons from Indonesia', *Forest Policy and Economics*, 108, 101968-101968, available: http://dx.doi.org/10.1016/J.FORPOL.2019.101968.
Meijer, K.S. (2015) 'A comparative analysis of the effectiveness of four supply chain initiatives to reduce deforestation', *Tropical Conservation Science*, 8(2), 583-597.
Mercer, D.E., Frey, G.E. and Cubbage, F.W. (2014) 'Economics of agroforestry' in *In: Kant, S. and JRR Alavalapati (eds.). Handbook of Forest Resource Economics. Earthscan from Routledge.*, 188-209.
Micale, V., Tonkonogy, B. and Mazza, F. (2018) *Understanding and Increasing Finance for Climate Adaptation in Developing Countries - CPI*, available: https://www.climatepolicyinitiative.org/publication/understanding-and-increasing-finance-for-climate-adaptation-in-developing-countries/ [accessed.
Miccolis, A., Peneireiro, F., Marques, H., Vieira, D., Arcoverde, M., Hoffmann, M., Rehder, T. and Pereira, A. (2016) 'Agroforestry systems for ecological restoration: how to reconcile conservation and production. Options for Brazil's Cerrado and Caatinga biomes. Instituto Sociedade, População e Natureza–ISPN/World Agroforestry Centre (ICRAF), Brasília'.
Millar, C.I., Stephenson, N.L. and Stephens, S.L. (2007) 'Climate change and forests of the future: managing in the face of uncertainty', *Ecological Applications*, 17(8), 2145-2151.
Mistry, J., Bilbao, B.A. and Berardi, A. (2016) 'Community owned solutions for fire management in tropical ecosystems: Case studies from Indigenous communities of South America', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1696), available: http://dx.doi.org/10.1098/rstb.2015.0174.

Mitchard, E.T. (2018) 'The tropical forest carbon cycle and climate change', *Nature*, 559(7715), 527-534.
MMA (2017) *Plano Nacional de Recuperação da Vegetação Nativa*, 76.
Mora, C., Tittensor, D.P., Adl, S., Simpson, A.G. and Worm, B. (2011) 'How many species are there on Earth and in the ocean?', *PLoS biology*, 9(8), e1001127.
Morelli, T.L., Maher, S.P., Lim, M.C., Kastely, C., Eastman, L.M., Flint, L.E., Flint, A.L., Beissinger, S.R. and Moritz, C. (2017) 'Climate change refugia and habitat connectivity promote species persistence', *Climate Change Responses*, 4(1), 1-12.
MOSTE (2015) *Indigenous and local knowledge and pratices for climate resilience in Nepal: Mainstreaming Climate Change Risk Management in Development*, Kathmandu, Nepal: Ministry of Science, Technology and Environment (MOSTE).
Mullan, K., Kontoleon, A., Swanson, T. and Zhang, S. (2009) 'An evaluation of the impact of the natural forest protection programme on rural household livelihoods' in *An Integrated Assessment of China's Ecological Restoration Programs* Springer, 175-199.
Müller, A. and Sukhdev, P. (2018) 'Measuring what matters in agriculture and food systems: a synthesis of the results and recommendations of TEEB for Agriculture and Food's Scientific and Economic Foundations report', *The Economics of Ecosystems and Biodiversity (TEEB)*.
Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A. and Kent, J. (2000) 'Biodiversity hotspots for conservation priorities', *Nature*, 403(6772), 853-858.
Myers, R., Intarini, D., Sirait, M. T. and Maryudi, A. (2017) 'Claiming the forest: Inclusions and exclusions under Indonesia's 'new' forest policy on customary forest', *Land Use Policy*, 66, 205-217.
Naidoo, R. and Adamowicz, W.L. (2006) 'Modeling opportunity costs of conservation in transitional landscapes', *Conservation biology*, 20(2), 490-500.
NBIM (2021) *Biodiversity and ecosystems: Expectations of companies*, available: https://www.nbim.no/contentassets/f1fa22a3a6c54ed88cf18607f75953c0/nbim_biodiversity_2021_web.pdf [accessed.
Neef, A. (2020) 'Tropical forests lost to land grabbing', *Nature geoscience*, 13(7), 460-461, available: http://dx.doi.org/10.1038/s41561-020-0604-3.
Nello, T., Raes, L., Wong, A., Chacón, Ó. and Sanchún, A. (2019) *Análisis económico de acciones para la restauración de paisajes productivos en Honduras*.
Nesha, M.K., Herold, M., Sy, V.D., Duchelle, A.E., Martius, C., Branthomme, A., Garzuglia, M., Jonsson, O. and Pekkarinen, A. (2021) 'An assessment of data sources, data quality and changes in national forest monitoring capacities in the Global Forest Resources Assessment 2005–2020', *Environmental Research Letters*, 16(5), 054029-054029, available: http://dx.doi.org/10.1088/1748-9326/ABD81B.
Newton, P., Miller, D.C., Byenkya, M.A.A. and Agrawal, A. (2016) 'Who are forest-dependent people? A taxo nomy to aid livelihood and land use decision-making in forested regions', *Land Use Policy*, 57, 388-395, available: http://dx.doi.org/10.1016/j.landusepol.2016.05.032.
Nhem, S., Lee, Y. J., & Phin, S. (2018) 'The impact of forest resource decline: Analyzing forest-related income supplements to reduce income inequality and poverty of the Kouy indi- genous people living in Kampong Thom province, Cambodia.', *Journal of Sustainable Forestry.*
Nilsson, M., Griggs, D. and Visbeck, M. (2016) 'Policy: Map the interactions between Sustainable Development Goals', *Nature*, 534(7607), 320-322, available: http://dx.doi.org/10.1038/534320a.
Nkem, J.N., Somorin, O.A., Jum, C., Idinoba, M.E., Bele, Y.M. and Sonwa, D.J. (2013) 'Profiling climate change vulnerability of forest indigenous communities in the Congo Basin', *Mitigation and Adaptation Strategies for Global Change*, 18(5), 513-533, available: http://dx.doi.org/10.1007/s11027-012-9372-8.
Nobre, C.A., Sampaio, G., Borma, L.S., Castilla-Rubio, J.C., Silva, J.S. and Cardoso, M. (2016) 'Land-use and climate change risks in the amazon and the need of a novel sustainable development paradigm', *Proceedings of the National Academy of Sciences of the United States of America*, 113(39), 10759-10768, available: http://dx.doi.org/10.1073/pnas.1605516113.
Nordén, B., Dahlberg, A., Brandrud, T.E., Fritz, Ö., Ejrnaes, R. and Ovaskainen, O. (2014) 'Effects of ecological continuity on species richness and composition in forests and woodlands: a review', *Écoscience*, 21(1), 34-45.
Nunan, F., Menton, M., McDermott, C. and Schreckenberg, K. (2018) 'Governing for ecosystem health and human wellbeing' in Schreckenberg, K., Mace, G. and Poudyal, M. , ed., *Ecosystem services for poverty alleviation: Trade-offs and governance.*, London:: Routledge, 159-173.
NYDF (2019) *Protecting and Restoring Forests: A Story of Large Commitments yet Limited Progress. New York Declaration on Forests Five-Year Assessment Report*, available: http://www.forestdeclaration.org/ [accessed.
Nyström, M., Jouffray, J.B., Norström, A.V., Crona, B., Søgaard Jørgensen, P., Carpenter, S.R., Bodin, Ö., Galaz, V. and Folke, C. (2019) 'Anatomy and resilience of the global production ecosystem', *Nature*, 575(7781), 98-108, available: http://dx.doi.org/10.1038/s41586-019-1712-3.
O'Brien, M.J., Reynolds, G., Ong, R. and Hector, A. (2017) 'Resistance of tropical seedlings to drought is mediated by community diversity', *Nature Ecology and Evolution*, 1.
Ocón, J.P., Ibanez, T., Franklin, J., Pau, S., Keppel, G., Rivas-Torres, G., Shin, M.E. and Gillespie, T.W. (2021) 'Global tropical dry forest extent and cover: A comparative study of bioclimatic definitions using two climatic data sets', *PLOS ONE*, 16(5), e0252063, available: http://dx.doi.org/10.1371/journal.pone.0252063.

Onyekuru, N.J.A. and Marchant, R. (2016) 'Assessing the economic impact of climate change on forest resource use in Nigeria: A Ricardian approach', *Agricultural and Forest Meteorology*, available: http://dx.doi.org/10.1016/j.agrformet.2016.01.001.
Ouyang, R. and Zhang, X. (2020) 'Financialization of agricultural commodities: Evidence from China', *Economic Modelling*, 85, 381-389, available: http://dx.doi.org/10.1016/J.ECONMOD.2019.11.009.
Overmars, K.P., Stehfest, E., Tabeau, A., van Meijl, H., Beltrán, A.M. and Kram, T. (2014) 'Estimating the opportunity costs of reducing carbon dioxide emissions via avoided deforestation, using integrated assessment modelling', *Land Use Policy*, 41, 45-60.
Pan, X., Chin, M., Ichoku, C.M. and Field, R.D. (2018) 'Connecting Indonesian fires and drought with the type of El Niño and phase of the Indian Ocean dipole during 1979–2016', *Journal of Geophysical Research: Atmospheres*, 123(15), 7974-7988.
Pan, Y., Birdsey, R.A., Phillips, O.L. and Jackson, R.B. (2013) 'The structure, distribution, and biomass of the world's forests', *Annual Review of Ecology, Evolution, and Systematics*, 44(1), 593-622, available: http://dx.doi.org/10.1146/annurev-ecolsys-110512-135914.
Panduro Meléndez, R., Mishquiyacu watershed Indigenous, c., Mustonen, T., Harper, S.L., Rivera Ferre, M., Postigo, J., Ayanlade, A., Benjaminsen, T., Morgan, R. and Okem, A. (2021) *Rural experiences in the communal landscapes of the Mishquiyacu watershed in the Peruvian Amazonia. Compendium of Indigenous Knowledge and Local Knowledge: Towards Inclusion of Indigenous Knowledge and Local Knowledge in Global Reports on Climate Change*, Snowchange Cooperative: Kontiolahti, Finland.
Parrotta, J. and Agnoletti, M. (2012) 'Traditional Forest-Related Knowledge and Climate Change' in Springer, 491-533.
Partners, N.A. (2019) *Protecting and Restoring Forests: A Story of Large Commitments yet Limited Progress. New York Declaration on Forests Five-Year Assessment Report*, available: http://www.forestdeclaration.org/ [accessed.
Pascual, U., Balvanera, P., Díaz, S., Pataki, G., Roth, E., Stenseke, M., Watson, R.T., Dessane, E.B., Islar, M. and Kelemen, E. (2017) 'Valuing nature's contributions to people: the IPBES approach', *Current Opinion in Environmental Sustainability*, 26, 7-16.
Pasgaard, M., Sun, Z., Müller, D. and Mertz, O. (2016) 'Challenges and opportunities for REDD+: A reality check from perspectives of effectiveness, efficiency and equity', *Environmental Science & Policy*, 63, 161-169, available: http://dx.doi.org/10.1016/J.ENVSCI.2016.05.021.
Pau, S., Detto, M., Kim, Y. and Still, C.J. (2018) 'Tropical forest temperature thresholds for gross primary productivity', *Ecosphere*, 9(7), e02311, available: http://dx.doi.org/https://doi.org/10.1002/ecs2.2311.
Pearse, R. (2017) 'Gender and climate change', *Wiley Interdisciplinary Reviews: Climate Change*, 8(2), e451.
Pelletier, J., Gélinas, N. and Skutsch, M. (2016) 'The place of community forest management in the REDD+ landscape', *Forests*, 7(8), 170-170, available: http://dx.doi.org/10.3390/F7080170.
Pendrill, F., Persson, M., Godar, J., Kastner, T., Moran, D., Schmidt, S. and Wood, R. (2019a) '" Agricultural and forestry trade drives large share of tropical deforestation emissions."', *Global Environmental Change*, 56, 1-10.
Pendrill, F., Persson, U.M., Godar, J., Kastner, T., Moran, D., Schmidt, S. and Wood, R. (2019b) 'Agricultural and forestry trade drives large share of tropical deforestation emissions', *Global Environmental Change*, 56, 1-10, available: http://dx.doi.org/10.1016/J.GLOENVCHA.2019.03.002.
Perugini, L., Caporaso, L., Marconi, S., Cescatti, A., Quesada, B., de Noblet-Ducoudre, N., House, J.I. and Arneth, A. (2017) 'Biophysical effects on temperature and precipitation due to land cover change', *Environmental Research Letters*, 12(5), 053002.
Peters, B.G., Capano, G., Howlett, M., Mukherjee, I., Chou, M.-H. and Ravinet, P. (2018) *Designing for Policy Effectiveness: Defining and Understanding a Concept*, Cambridge: Cambridge University Press.
Pham, T.T., Castella, J.-C., Lestrelin, G., Mertz, O., Le, D.N., Moeliono, M., Nguyen, T.Q., Vu, H.T. and Nguyen, T.D. (2015) 'Adapting free, prior, and informed consent (FPIC) to local contexts in REDD+: Lessons from three experiments in Vietnam', *Forests*, 6(7), 2405-2423, available: http://dx.doi.org/10.3390/F6072405.
Philipson, C.D., Cutler, M.E.J., Brodric, P.G., Asne, G.P., Boy, D.S., Costa, P.M., Fiddes, J., Food, G.M., Van Der Heijden, G.M.F., Ledo, A., Lincol, P.R., Margrov, J.A., Marti, R.E., Milne, S., Pinar, M.A., Reynolds, G., Snoep, M., Tangki, H., Wai, Y.S., Wheele, C.E. and Burslem, D.F.R.P. (2020) 'Active restoration accelerates the carbon recovery of human-modified tropical forests', *Science*, 369(6505), 838-841, available: http://dx.doi.org/10.1126/science.aay4490.
Phumee, P., Pagdee, A., & Kawasaki, J. (2018) 'Energy crops, livelihoods and legal deforestation: A case study at Phu Wiang National Park, Thailand', *Journal of sustainable forestry*, available: http://dx.doi.org/10.1080/ 10549811.2017.1318292
Piabuo, S.M., Minang, P.A., Tieguhong, C.J., Foundjem-Tita, D. and Nghobuoche, F. (2021) 'Illegal logging, governance effectiveness and carbon dioxide emission in the timber-producing countries of Congo Basin and Asia', *Environment, Development and Sustainability*, 23(10), 14176-14196, available: http://dx.doi.org/10.1007/S10668-021-01257-8.
Pielke Sr, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K.K., Nair, U., Betts, R. and Fall, S. (2011) 'Land use/land cover changes and climate: modeling analysis and observational evidence', *Wiley Interdisciplinary Reviews: Climate Change*, 2(6), 828-850.

Plotkin, J.B., Potts, M.D., Douglas, W.Y., Bunyavejchewin, S., Condit, R., Foster, R., Hubbell, S., LaFrankie, J., Manokaran, N. and Seng, L.H. (2000) 'Predicting species diversity in tropical forests', *Proceedings of the National Academy of Sciences*, 97(20), 10850-10854.

Pokorny, B. and Steinbrenner, M. (2005) 'Collaborative monitoring of production and costs of timber harvest operations in the Brazilian Amazon', *Ecology and Society*, 10(1).

Pontes-Lopes, A., Silva, C.V.J., Barlow, J., Rincón, L.M., Campanharo, W.A., Nunes, C.A., de Almeida, C.T., Silva Júnior, C.H.L., Cassol, H.L.G., Dalagnol, R., Stark, S.C., Graça, P.M.L.A. and Aragão, L.E.O.C. (2021) 'Drought-driven wildfire impacts on structure and dynamics in a wet Central Amazonian forest', *Proceedings of the Royal Society B: Biological Sciences*, 288(1951), 20210094, available: http://dx.doi.org/10.1098/rspb.2021.0094.

Poorter, L., Bongers, F., Aide, T.M., Zambrano, A.M.A., Balvanera, P., Becknell, J.M., Boukili, V., Brancalion, P.H., Broadbent, E.N. and Chazdon, R.L. (2016) 'Biomass resilience of Neotropical secondary forests', *Nature*, 530(7589), 211.

Porter-Bolland, L., Ellis, E.A., Guariguata, M.R., Ruiz-Mallén, I., Negrete-Yankelevich, S. and Reyes-García, V. (2012) 'Community managed forests and forest protected areas: An assessment of their conservation effectiveness across the tropics', *Forest Ecology and Management*, 268, 6-17.

Pörtner, H., Scholes, R., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L. and Cheung, W. (2021) 'Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change', *IPBES secretariat, Bonn, Germany, DOI*, 10.

Pounds, J.A., Bustamante, M.R., Coloma, L.A., Consuegra, J.A., Fogden, M.P., Foster, P.N., La Marca, E., Masters, K.L., Merino-Viteri, A. and Puschendorf, R. (2006) 'Widespread amphibian extinctions from epidemic disease driven by global warming', *Nature*, 439(7073), 161-167.

Powell, B., Ickowitz, A., McMullin, S., Jamnadass, R., Padoch, C., Pinedo-Vasquez, M. and Sunderland, T. (2013) 'The role of forests, trees and wild biodiversity for nutrition-sensitive food systems and landscapes', in *Expert background paper for the International Conference on Nutrition*.

Pramova, E., Locatelli, B., Djoudi, H., Lavorel, S., Colloff, M.J. and Martius, C. (2019) *Adapting land restoration to a changing climate: Embracing the knowns and unknowns*, CIFOR.

Puettmann, K.J. (2014) 'Restoring the adaptive capacity of forest ecosystems', *Journal of sustainable forestry*, 33(sup1), S15-S27.

Pugh, T.A., Rademacher, T., Shafer, S.L., Steinkamp, J., Barichivich, J., Beckage, B., Haverd, V., Harper, A., Heinke, J. and Nishina, K. (2020) 'Understanding the uncertainty in global forest carbon turnover', *Biogeosciences*, 17(15), 3961-3989.

Pugnaire Francisco, I., Morillo José, A., Peñuelas, J., Reich Peter, B., Bardgett Richard, D., Gaxiola, A., Wardle David, A. and van der Putten Wim, H. 'Climate change effects on plant-soil feedbacks and consequences for biodiversity and functioning of terrestrial ecosystems', *Science Advances*, 5(11), eaaz1834, available: http://dx.doi.org/10.1126/sciadv.aaz1834.

Pulla, S., Ramaswami, G., Mondal, N., Chitra-Tarak, R., Suresh, H., Dattaraja, H., Vivek, P., Parthasarathy, N., Ramesh, B. and Sukumar, R. (2015) 'Assessing the resilience of global seasonally dry tropical forests', *International Forestry Review*, 17(2), 91-113.

Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S. and Griscom, B. (2012) 'Sustaining conservation values in selectively logged tropical forests: the attained and the attainable', *Conservation Letters*, 5(4), 296-303.

Qie, L., Lewis, S.L., Sullivan, M.J., Lopez-Gonzalez, G., Pickavance, G.C., Sunderland, T., Ashton, P., Hubau, W., Salim, K.A. and Aiba, S.-I. (2017) 'Long-term carbon sink in Borneo's forests halted by drought and vulnerable to edge effects', *Nature communications*, 8(1), 1966.

Raes, L., Nello, T., Nájera, M., Chacón, O., Prado, K. and Sanchún, A. (2017) *Análisis económico de acciones para la restauración de paisajes productivos en El Salvador*.

Rahman, H. and Alam, K. (2016) 'Forest Dependent Indigenous Communities' Perception and Adaptation to Climate Change through Local Knowledge in the Protected Area—A Bangladesh Case Study', *Climate*, 4(1), 12-12, available: http://dx.doi.org/10.3390/cli4010012.

Rammig, A. and Lapola, D.M. (2021) 'The declining tropical carbon sink', *Nature Climate Change*, 11(9), 727-728, available: http://dx.doi.org/10.1038/s41558-021-01135-1.

Ranabhat, S., Ghate, R., Bhatta, L.D., Agrawal, N.K. and Tankha, S. (2018) 'Policy coherence and interplay between climate change adaptation policies and the forestry sector in Nepal', *Environmental Management*, 61(6), 968-980, available: http://dx.doi.org/10.1007/S00267-018-1027-4.

Ravikumar, A., Larson, A., Duchelle, A., Myers, R. and Tovar, J.G. (2015) 'Multilevel governance challenges in transitioning towards a national approach for REDD+: evidence from 23 subnational REDD+ initiatives', *International Journal of the Commons*, 9(2), 909-931, available: http://dx.doi.org/10.18352/IJC.593.

Reed, J., van Vianen, J., Barlow, J. and Sunderland, T. (2017) 'Have integrated landscape approaches reconciled societal and environmental issues in the tropics?', *Land Use Policy*, 63, 481-492, available: http://dx.doi.org/10.1016/J.LANDUSEPOL.2017.02.021.

Reid, H., Alam, M., Berger, R., Cannon, T., Huq, S. and Milligan, A. (2009) 'Community-based adaptation to climate change: an overview', *Participatory learning and action*, (60).

Reid, H. and Huq, S. (2014) 'Mainstreaming community-based adaptation into national and local planning'.
Réjou-Méchain, M., Mortier, F., Bastin, J.-F., Cornu, G., Barbier, N., Bayol, N., Bénédet, F., Bry, X., Dauby, G., Deblauwe, V., Doucet, J.-L., Doumenge, C., Fayolle, A., Garcia, C., Kibambe Lubamba, J.-P., Loumeto, J.-J., Ngomanda, A., Ploton, P., Sonké, B., Trottier, C., Vimal, R., Yongo, O., Pélissier, R. and Gourlet-Fleury, S. (2021) 'Unveiling African rainforest composition and vulnerability to global change', *Nature*, 1-5, available: http://dx.doi.org/10.1038/s41586-021-03483-6.
Reyer, C., Guericke, M. and Ibisch, P.L. (2009) 'Climate change mitigation via afforestation, reforestation and deforestation avoidance: and what about adaptation to environmental change?', *New Forests*, 38(1), 15-34.
Rist, L., Shanley, P., Sunderland, T., Sheil, D., Ndoye, O., Liswanti, N. and Tieguhong, J. (2012) 'The impacts of selective logging on non-timber forest products of livelihood importance', *Forest Ecology and Management*, available: http://dx.doi.org/10.1016/j.foreco.2011.04.037.
Roberts, C.M., O'Leary, B.C., McCauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Pauly, D., Sáenz-Arroyo, A., Sumaila, U.R., Wilson, R.W., Worm, B. and Castilla, J.C. (2017) 'Marine reserves can mitigate and promote adaptation to climate change', *Proceedings of the National Academy of Sciences*, 114(24), 6167-6175, available: http://dx.doi.org/10.1073/pnas.1701262114.
Roberts, G., Parrotta, J.A. and Wreford, A. (2009) 'Current adaptation measures and policies', *IUFRO World Series*, 22, 123-133.
Rodrigues, R.R.R. (2009) *Pacto pela restauração da mata atlântica: referencial dos conceitos e ações de restauração florestal*, LERF; Piracicaba: ESALQ.
Roucoux, K.H., Lawson, I.T., Baker, T.R., Del Castillo Torres, D., Draper, F.C., Lahteenoja, O., Gilmore, M.P., Honorio Coronado, E.N., Kelly, T.J., Mitchard, E.T.A. and Vriesendorp, C.F. (2017) 'Threats to intact tropical peatlands and opportunities for their conservation', *Conserv Biol*, 31(6), 1283-1292, available: http://dx.doi.org/10.1111/cobi.12925.
Roue, M. and Nakashima, D. (2018) 'Indigenous and Local Knowledge and Science: From Validation to Knowledge Coproduction' in, 1-11.
Rowland, D., Ickowitz, A., Powell, B., Nasi, R. and Sunderland, T. (2017) 'Forest foods and healthy diets: quantifying the contributions', *Environmental Conservation*, 44(2), 102-114, available: http://dx.doi.org/10.1017/S0376892916000151.
RRI (2021) *Scaling-Up the Recognition of Indigenous and Community Land Rights: Opportunities, Costs and Climate Implications.* , Washington, DC.
Ruiz-Mallén, I., Fernández-Llamazares, Á. and Reyes-García, V. (2017) 'Unravelling local adaptive capacity to climate change in the Bolivian Amazon: the interlinkages between assets, conservation and markets', *Climatic Change*, available: http://dx.doi.org/10.1007/s10584-016-1831-x.
Saatchi, S., Longo, M., Xu, L., Yang, Y., Abe, H., André, M., Aukema, J.E., Carvalhais, N., Cadillo-Quiroz, H., Cerbu, G.A., Chernela, J.M., Covey, K., Sánchez-Clavijo, L.M., Cubillos, I.V., Davies, S.J., Sy, V.D., Vleeschouwer, F.D., Duque, A., Durieux, A.M.S., Fernandes, K.D.A., Fernandez, L.E., Gammino, V., Garrity, D.P., Gibbs, D.A., Gibbon, L., Gowae, G.Y., Hansen, M., Harris, N.L., Healey, S.P., Hilton, R.G., Johnson, C.M., Kankeu, R.S., Laporte-Goetz, N.T., Lee, H., Lovejoy, T., Lowman, M., Lumbuenamo, R., Malhi, Y., Martinez, J.-M.M.A., Nobre, C., Pellegrini, A., Radachowsky, J., Román, F., Russell, D., Sheil, D., Smith, T.B., Spencer, R.G.M., Stolle, F., Tata, H.L., Torres, D.d.C., Tshimanga, R.M., Vargas, R., Venter, M., West, J., Widayati, A., Wilson, S.N., Brumby, S. and Elmore, A.C. (2021) 'Detecting vulnerability of humid tropical forests to multiple stressors', *One Earth*, 4(7), 988-1003, available: http://dx.doi.org/10.1016/J.ONEEAR.2021.06.002.
Safitri, M.A. (2015) 'Dividing the land: legal gaps in the recognition of customary land in Indonesian forest areas', *Kasarinlan: Philippine Journal of Third World Studies*, 30.
Sahide, M.A.K., Maryudi, A., Supratman, S., & Giessen, L. (2016) 'Is Indonesia utilising its international partners? The driving forces behind Forest Management Units', *Forest Policy and Economics*, 69, 11-20.
Sakschewski, B., Von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., Joshi, J. and Thonicke, K. (2016) 'Resilience of Amazon forests emerges from plant trait diversity', *Nature Climate Change*, 6(11), 1032-1036.
Salafsky, N., Margoluis, R. and Redford, K. (2001) 'Adaptive management: A tool for conservation practitioners'.
Sales, L.P., Galetti, M. and Pires, M.M. (2020) 'Climate and land-use change will lead to a faunal 'savannization' on tropical rainforests', *Global change biology*, gcb.15374-gcb.15374, available: http://dx.doi.org/10.1111/gcb.15374.
Salvini, G., Herold, M., De Sy, V., Kissinger, G., Brockhaus, M. and Skutsch, M. (2014) 'How countries link REDD+ interventions to drivers in their readiness plans: implications for monitoring systems', *Environmental Research Letters*, 9(7), 074004-074004, available: http://dx.doi.org/10.1088/1748-9326/9/7/074004.
Sampaio, G., Shimizu, M.H., Guimarães-Júnior, C.A., Alexandre, F., Guatura, M., Cardoso, M., Domingues, T.F., Rammig, A., von Randow, C., Rezende, L.F.C. and Lapola, D.M. (2021) 'CO2 physiological effect can cause rainfall decrease as strong as large-scale deforestation in the Amazon', *Biogeosciences*, 18(8), 2511-2525, available: http://dx.doi.org/10.5194/bg-18-2511-2021.
Sayer, J., Elliott, C. and Maginnis, S. (2003) 'Protect, manage and restore: conserving forests in multifunctional landscapes', in *World Forestry Congress, Quebec, Canada, September*.

Sayer, J., Margules, C., Bohnet, I., Boedhihartono, A., Pierce, R., Dale, A. and Andrews, K. (2015) 'The Role of Citizen Science in Landscape and Seascape Approaches to Integrating Conservation and Development', *Land*, 4(4), available: http://dx.doi.org/10.3390/land4041200.
Sayre, R., Karagulle, D., Frye, C., Boucher, T., Wolff, N.H., Breyer, S., Wright, D., Martin, M., Butler, K. and Van Graafeiland, K. (2020) 'An assessment of the representation of ecosystems in global protected areas using new maps of World Climate Regions and World Ecosystems', *Global Ecology and Conservation*, 21, e00860.
Schimel, D., Stephens, B.B. and Fisher, J.B. (2015) 'Effect of increasing CO2 on the terrestrial carbon cycle', *Proceedings of the National Academy of Sciences*, 112(2), 436-441.
Schmitt, S., Maréchaux, I., Chave, J., Fischer, F.J., Piponiot, C., Traissac, S. and Hérault, B. (2020) *Functional diversity improves tropical forest resilience: Insights from a long-term virtual experiment*.
Schmitz, O.J., Lawler, J.J., Beier, P., Groves, C., Knight, G., Boyce, D.A., Bulluck, J., Johnston, K.M., Klein, M.L. and Muller, K. (2015) 'Conserving biodiversity: practical guidance about climate change adaptation approaches in support of land-use planning', *Natural Areas Journal*, 35(1), 190-203.
Scott C.A., Z.F., Mukherji A., Immerzeel W., Mustafa D., Bharati L. (2019) . In: (eds) . . https://doi.org/10.1007/978-3-319-92288-1_8 (2019) 'Water in the Hindu Kush Himalaya' in Wester P., M. A., Mukherji A., Shrestha A. , ed., *The Hindu Kush Himalaya Assessment* Springer, Cham.
Scriven, S.A., Carlson, K.M., Hodgson, J.A., McClean, C.J., Heilmayr, R., Lucey, J.M. and Hill, J.K. (2019) 'Testing the benefits of conservation set-asides for improved habitat connectivity in tropical agricultural landscapes', *Journal of Applied Ecology*, 56(10), 2274-2285.
Seddon, N., Chausson, A., Berry, P., Girardin, C.A., Smith, A. and Turner, B. (2020) 'Understanding the value and limits of nature-based solutions to climate change and other global challenges', *Philosophical Transactions of the Royal Society B*, 375(1794), 20190120.
Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M. and Honkaniemi, J. (2017) 'Forest disturbances under climate change', *Nature Climate Change*, 7(6), 395-402.
Seiler, C., Hutjes, R., Kruijt, B. and Hickler, T. (2015) 'The sensitivity of wet and dry tropical forests to climate change in Bolivia', *Journal of Geophysical Research: Biogeosciences*, 120(3), 399-413.
Sekercioglu, C.H., Schneider, S.H., Fay, J.P. and Loarie, S.R. (2008) 'Climate change, elevational range shifts, and bird extinctions', *Conservation biology*, 22(1), 140-150.
Seppälä, R. (2009) 'A global assessment on adaptation of forests to climate change', *Scandinavian Journal of Forest Research*, 24(6), 469-472, available: http://dx.doi.org/10.1080/02827580903378626.
Settele, J., Scholes, R., Betts, R.A., Bunn, S., Leadley, P., Nepstad, D., Overpeck, J.T., Taboada, M.A., Fischlin, A. and Moreno, J.M. (2015) 'Terrestrial and inland water systems' in *Climate change 2014 impacts, adaptation and vulnerability: Part A: Global and sectoral aspects* Cambridge University Press, 271-360.
Seymour, F. and Harris, N.L. (2019) 'Reducing tropical deforestation', *Science*, 365(6455), 756-756, available: http://dx.doi.org/10.1126/science.aax8546.
Shah, K.U., Dulal, H.B., Johnson, C. and Baptiste, A. (2013) 'Understanding livelihood vulnerability to climate change: Applying the livelihood vulnerability index in Trinidad and Tobago', *Geoforum*, available: http://dx.doi.org/10.1016/j.geoforum.2013.04.004.
Shanley, P., da Serra Silva, M., Melo, T., Carmenta, R. and Nasi, R. (2012) 'From conflict of use to multiple use: Forest management innovations by small holders in Amazonian logging frontiers', *Forest Ecology and Management*, available: http://dx.doi.org/10.1016/j.foreco.2011.05.041.
Sheil, D., Boissière, M., & Beaudoin, G. (2015) 'Unseen sentinels. Local monitoring and control in conservation's blind spots. ', *Ecology and Society*, 20, 39.
Shimamoto, C.Y., Padial, A.A., da Rosa, C.M. and Marques, M.C. (2018) 'Restoration of ecosystem services in tropical forests: a global meta-analysis', *PLOS ONE*, 13(12), e0208523.
Shukla, P., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H., Roberts, D., Zhai, P., Slade, R., Connors, S. and Van Diemen, R. (2019) 'IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems'.
Silva, D. and Nunes, S. (2017) 'Avaliação e modelagem econômica da restauração florestal no Estado do Pará', *Imazon, Belém, Pa*.
Silva, L.C. and Anand, M. (2013) 'Probing for the influence of atmospheric CO2 and climate change on forest ecosystems across biomes', *Global Ecology and Biogeography*, 22(1), 83-92.
Silveira, M.V.F., Petri, C.A., Broggio, I.S., Chagas, G.O., Macul, M.S., Leite, C.C.S.S., Ferrari, E.M.M., Amim, C.G.V., Freitas, A.L.R., Motta, A.Z.V., Anderson, L.O. and Aragão, L.E.O.C. (2020) 'Drivers of fire anomalies in the Brazilian Amazon: Lessons learned from the 2019 fire crisis', *Land*, 9(12), 1-24, available: http://dx.doi.org/10.3390/land9120516.
Simane, B. and Zaitchik, B.F. (2014) 'The sustainability of community-based adaptation projects in the Blue Nile Highlands of Ethiopia', *Sustainability (Switzerland)*, 6(7), 4308-4325, available: http://dx.doi.org/10.3390/su6074308.
Simangunsong, B.C.H., Sitanggang, V.J., Manurung, E.G.T., Rahmadi, A., Moore, G.A., Aye, L. and Tambunan, A.H. (2017) 'Potential forest biomass resource as feedstock for bioenergy and its economic value in Indonesia', *Forest Policy and Economics*, 81, 10-17.

Simmonds, J.S., Sonter, L.J., Watson, J.E.M., Bennun, L., Costa, H.M., Dutson, G., Edwards, S., Grantham, H., Griffiths, V.F., Jones, J.P.G., Kiesecker, J., Possingham, H.P., Puydarrieux, P., Quétier, F., Rainer, H., Rainey, H., Roe, D., Savy, C.E., Souquet, M., Kate, K.t., Victurine, R., Hase, A.v. and Maron, M. (2020) 'Moving from biodiversity offsets to a target-based approach for ecological compensation', *Conservation Letters*, 13(2), e12695-e12695, available: http://dx.doi.org/10.1111/CONL.12695.

Simmons, C.S., Famolare, L., Macedo, M.N., Walker, R.T., Coe, M.T., Scheffers, B., Arima, E., Munoz-Carpena, R., Valle, D. and Fraisse, C. (2018) 'Science in support of Amazonian conservation in the 21st century: the case of Brazil', *Biotropica*, 50(6), 850-858.

Singer, B. (2016) 'Financing sustainable forest management in developing countries: the case for a holistic approach', *International Forestry Review*, 18(1), 96-109.

Singh, N. and Singh, O.P. (2015) 'Climate change, water and gender: Impact and adaptation in North-Eastern Hills of India', *International Social Work*, 58(3), 375-384.

Siqueira-Gay, J., Yanai, A.M., Lessmann, J., Pessôa, A.C.M., Borja, D., Canova, M. and Borges, R.C. (2020) 'Pathways to positive scenarios for the Amazon forest in Pará state, Brazil | Caminhos de cenários positivos para a floresta Amazônica no estado do Pará, Brasil', *Biota Neotropica*, 20, available: http://dx.doi.org/10.1590/1676-0611-BN-2019-0905.

Slik, J.F., Arroyo-Rodríguez, V., Aiba, S.-I., Alvarez-Loayza, P., Alves, L.F., Ashton, P., Balvanera, P., Bastian, M.L., Bellingham, P.J. and Van Den Berg, E. (2015) 'An estimate of the number of tropical tree species', *Proceedings of the National Academy of Sciences*, 112(24), 7472-7477.

Sloan, S., Locatelli, B., Wooster, M.J. and Gaveau, D.L.A. (2017) 'Fire activity in Borneo driven by industrial land conversion and drought during El Niño periods, 1982–2010', *Global Environmental Change*, 47, 95-109, available: http://dx.doi.org/10.1016/j.gloenvcha.2017.10.001.

Slot, M., Rey-Sánchez, C., Gerber, S., Lichstein, J.W., Winter, K. and Kitajima, K. (2014) 'Thermal acclimation of leaf respiration of tropical trees and lianas: response to experimental canopy warming, and consequences for tropical forest carbon balance', *Global change biology*, 20(9), 2915-2926.

Slot, M. and Winter, K. (2017) 'In situ temperature response of photosynthesis of 42 tree and liana species in the canopy of two Panamanian lowland tropical forests with contrasting rainfall regimes', *New Phytologist*, 214(3), 1103-1117.

Slot, M. and Winter, K. (2018) 'High tolerance of tropical sapling growth and gas exchange to moderate warming', *Functional ecology*, 32(3), 599-611.

Slough, T., Kopas, J. and Urpelainen, J. (2021) 'Satellite-based deforestation alerts with training and incentives for patrolling facilitate community monitoring in the Peruvian Amazon', *Proceedings of the National Academy of Sciences*, 118(29), available: http://dx.doi.org/10.1073/PNAS.2015171118.

Smith, P., Clark, H., Dong, H., Elsiddig, E., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O. and Mbow, C. (2014) 'Agriculture, forestry and other land use (AFOLU)' in *Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5* Cambridge University Press.

Smith, P., Nkem, J., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Hoang, A.L., Lwasa, S. and McElwee, P. (2019) 'Interlinkages between desertification, land degradation, food security and greenhouse gas fluxes: Synergies, trade-offs and integrated response options' in *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Snyman, S. and Bricker, K.S. (2019) 'Living on the edge: Benefit-sharing from protected area tourism', *Journal of Sustainable Tourism*, 27(6), 705-719.

Sonntag, S., Pongratz, J., Reick, C.H. and Schmidt, H. (2016) 'Reforestation in a high-CO2 world—Higher mitigation potential than expected, lower adaptation potential than hoped for', *Geophysical Research Letters*, 43(12), 6546-6553.

Soto Golcher, C., Arts, B. and Visseren-Hamakers, I. (2018) 'Seeing the forest, missing the field: Forests and agriculture in global climate change policy', *Land Use Policy*, 77, 627-640, available: http://dx.doi.org/10.1016/J.LANDUSEPOL.2018.06.014.

Souza, C.M., Kirchhoff, F.T., Oliveira, B.C., Ribeiro, J.G. and Sales, M.H. (2019) 'Long-term annual surface water change in the Brazilian Amazon Biome: Potential links with deforestation, infrastructure development and climate change', *Water (Switzerland)*, 11(3), available: http://dx.doi.org/10.3390/w11030566.

Spathelf, P., Stanturf, J., Kleine, M., Jandl, R., Chiatante, D. and Bolte, A. (2018) 'Adaptive measures: integrating adaptive forest management and forest landscape restoration', *Annals of Forest Science*, 75(2), 1-6, available: http://dx.doi.org/10.1007/S13595-018-0736-4.

Speranza, C.I., Kiteme, B., Ambenje, P., Wiesmann, U. and Makali, S. (2010) 'Indigenous knowledge related to climate variability and change: Insights from droughts in semi-arid areas of former Makueni District, Kenya', *Climatic Change*, 100(2), 295-315, available: http://dx.doi.org/10.1007/s10584-009-9713-0.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J. and Willett, W. (2018) 'Options for keeping the food system within environmental limits', *Nature*, 562(7728), 519-525, available: http://dx.doi.org/10.1038/s41586-018-0594-0.

Staal, A., Flores, B.M.B.M., Aguiar, A.P.D.A.P.D., Bosmans, J.H.C.J.H.C., Fetzer, I. and Tuinenburg, O.A.O.A. (2020) 'Feedback between drought and deforestation in the Amazon', *Environmental Research Letters*, 15(4), 044024-044024, available: http://dx.doi.org/10.1088/1748-9326/ab738e.

Stan, K. and Sanchez-Azofeifa, A. (2019) 'Tropical dry forest diversity, climatic response, and resilience in a changing climate', *Forests*, 10(5), 1-19, available: http://dx.doi.org/10.3390/f10050443.

Stephens, S.L., Agee, J.K., Fule, P.Z., North, M., Romme, W., Swetnam, T. and Turner, M.G. (2013) 'Managing forests and fire in changing climates', *Science*, 342(6154), 41-42.

Sterck, F., Anten, N.P., Schieving, F. and Zuidema, P.A. (2016) 'Trait acclimation mitigates mortality risks of tropical canopy trees under global warming', *Frontiers in plant science*, 7, 607.

Stoian, D., Monterroso, I., & Current, D. (2019) 'SDG 8: Decent Work and Economic Growth – Potential Impacts on Forests and Forest-Dependent Livelihoods' in P. Katila, C. P. C., W. De Jong, G. Galloway, P. Pacheco, & G. Winkel, ed., *Sustainable Development Goals: Their Impacts on Forests and People*, Cambridge: Cambridge University Press, 237-278.

Strassburg, B.B., Beyer, H.L., Crouzeilles, R., Iribarrem, A., Barros, F., de Siqueira, M.F., Sánchez-Tapia, A., Balmford, A., Sansevero, J.B.B. and Brancalion, P.H.S. (2019) 'Strategic approaches to restoring ecosystems can triple conservation gains and halve costs', *Nature Ecology & Evolution*, 3(1), 62-70.

Stringer, C.E., Trettin, C. C., Carnoch, S. J., & Tang, W. (2015). . , 354, 139-148. https://doi.org/10.1016/j.foreco.2015.06.07 (2015) 'Carbon stocks of mangroves within the Zambezi River Delta, Mozambique', *Forest Ecology and Management*, 354, 139-148.

Sullivan Martin, J.P., Lewis Simon, L., Affum-Baffoe, K., Castilho, C., Costa, F., Sanchez Aida, C., Ewango Corneille, E.N., Hubau, W., Marimon, B., Monteagudo-Mendoza, A., Qie, L., Sonké, B., Martinez Rodolfo, V., Baker Timothy, R., Brienen Roel, J.W., Feldpausch Ted, R., Galbraith, D., Gloor, M., Malhi, Y., Aiba, S.-I., Alexiades Miguel, N., Almeida Everton, C., de Oliveira Edmar, A., Dávila Esteban, Á., Loayza Patricia, A., Andrade, A., Vieira Simone, A., Aragão Luiz, E.O.C., Araujo-Murakami, A., Arets Eric, J.M.M., Arroyo, L., Ashton, P., Aymard, C.G., Baccaro Fabrício, B., Banin Lindsay, F., Baraloto, C., Camargo Plínio, B., Barlow, J., Barroso, J., Bastin, J.-F., Batterman Sarah, A., Beeckman, H., Begne Serge, K., Bennett Amy, C., Berenguer, E., Berry, N., Blanc, L., Boeckx, P., Bogaert, J., Bonal, D., Bongers, F., Bradford, M., Brearley Francis, Q., Brncic, T., Brown, F., Burban, B., Camargo José, L., Castro, W., Céron, C., Ribeiro Sabina, C., Moscoso Victor, C., Chave, J., Chezeaux, E., Clark Connie, J., de Souza Fernanda, C., Collins, M., Comiskey James, A., Valverde Fernando, C., Medina Massiel, C., da Costa, L., Dančák, M., Dargie Greta, C., Davies, S., Cardozo Nallaret, D., de Haulleville, T., de Medeiros Marcelo, B., del Aguila Pasquel, J., Derroire, G., Di Fiore, A., Doucet, J.-L., Dourdain, A., Droissart, V., Duque Luisa, F., Ekoungoulou, R., Elias, F., Erwin, T., Esquivel-Muelbert, A., Fauset, S., Ferreira, J., Llampazo Gerardo, F., Foli, E., Ford, A., Gilpin, M., Hall Jefferson, S., Hamer Keith, C., Hamilton Alan, C., Harris David, J., Hart Terese, B., Hédl, R., Herault, B., et al. (2020) 'Long-term thermal sensitivity of Earth's tropical forests', *Science*, 368(6493), 869-874, available: http://dx.doi.org/10.1126/science.aaw7578.

Sumila, T.C.A., Pires, G.F., Fontes, V.C. and Costa, M.H. (2017) 'Sources of water vapor to economically relevant regions in Amazonia and the effect of deforestation', *Journal of Hydrometeorology*, 18(6), 1643-1655, available: http://dx.doi.org/10.1175/JHM-D-16-0133.1.

Suresh, H., Dattaraja, H. and Sukumar, R. (2010) 'Relationship between annual rainfall and tree mortality in a tropical dry forest: results of a 19-year study at Mudumalai, southern India', *Forest Ecology and Management*, 259(4), 762-769.

Swamy, L., Drazen, E., Johnson, W. R., & Bukoski, J. J. (2018) 'The future of tropical forests under the United Nations Sustainable Development Goals', *Journal of sustainable forestry*, available: http://dx.doi.org/10.1080/10549811.2017.1416477

Swiderska, K., Song, Y., Li, J., Reid, H. and Mutta, D. (2011) 'Adapting agriculture with traditional knowledge', *Climatic Changes*, (october), 4-4.

Tamoffo, A.T., Moufouma-Okia, W., Dosio, A., James, R., Pokam, W.M., Vondou, D.A., Fotso-Nguemo, T.C., Guenang, G.M., Kamsu-Tamo, P.H. and Nikulin, G. (2019) 'Process-oriented assessment of RCA4 regional climate model projections over the Congo Basin under [Formula: see text] and [Formula: see text] global warming levels: influence of regional moisture fluxes', *Climate Dynamics*.

Tanner-McAllister, S.L., Rhodes, J. and Hockings, M. (2017) 'Managing for climate change on protected areas: An adaptive management decision making framework', *Journal of Environmental Management*, 204, 510-518.

Taufik, M., Torfs, P.J.J.F., Uijlenhoet, R., Jones, P.D., Murdiyarso, D. and Van Lanen, H.A.J. (2017) 'Amplification of wildfire area burnt by hydrological drought in the humid tropics', *Nature Climate Change*, 7(6), 428-431, available: http://dx.doi.org/10.1038/nclimate3280.

Tegegne, Y., Cramm, M., Van Brusselen, J. and Linhares-Juvenal, T. (2019) 'Forest Concessions and the United Nations Sustainable Development Goals: Potentials, Challenges and Ways Forward', *Forests*, 10(1), available: http://dx.doi.org/10.3390/f10010045.

Tengö, M., Brondizio, E.S., Elmqvist, T., Malmer, P. and Spierenburg, M. (2014) 'Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach', 43, 579-591.

Tengö, M., Hill, R., Malmer, P., Raymond, C.M., Spierenburg, M., Danielsen, F., Elmqvist, T. and Folke, C. (2017) 'Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability', *Current Opinion in Environmental Sustainability*, 26, 17-25, available: http://dx.doi.org/10.1016/j.cosust.2016.12.005.

Terrer, C., Jackson, R.B., Prentice, I.C., Keenan, T.F., Kaiser, C., Vicca, S., Fisher, J.B., Reich, P.B., Stocker, B.D. and Hungate, B.A. (2019) 'Nitrogen and phosphorus constrain the CO 2 fertilization of global plant biomass', *Nature Climate Change*, 9(9), 684-689.
Thomas, R., Reed, M., Clifton, K., Appadurai, N., Mills, A., Zucca, C., Kodsi, E., Sircely, J., Haddad, F., Hagen, C., Mapedza, E., Woldearegay, K., Shalander, K., Bellon, M., Le, Q., Mabikke, S., Alexander, S., Leu, S., Schlingloff, S., Lala-Pritchard, T., Mares, V. and Quiroz, R. (2018) 'A framework for scaling sustainable land management options', *Land Degradation & Development*, 29(10), 3272-3284, available: http://dx.doi.org/10.1002/LDR.3080.
Thorlakson, T. and Neufeldt, H. (2012) 'Reducing subsistence farmers' vulnerability to climate change: evaluating the potential contributions of agroforestry in western Kenya', *Agriculture & Food Security*, 1(1), 1-13.
Tiani, A.M., Besa, M.C., Devisscher, T., Pavageau, C., Butterfield, R., Bharwani, S. and Bele, M.Y. (2015) *Assessing current social vulnerability to climate change: A participatory methodology*.
Torres, A.B., Marchant, R., Lovett, J.C., Smart, J.C. and Tipper, R. (2010) 'Analysis of the carbon sequestration costs of afforestation and reforestation agroforestry practices and the use of cost curves to evaluate their potential for implementation of climate change mitigation', *Ecological Economics*, 69(3), 469-477.
Torres, B., Jadan Maza, O., Aguirre, P., Hinojosa, L. and Gunter, S. (2015) 'The Contribution of Traditional Agroforestry to Climate Change Adaptation in the Ecuadorian Amazon: The Chakra System', *Handbook of Climate Change Adaptation*, available: http://dx.doi.org/10.1007/978-3-642-38670-1.
Torrubia, S., McRae, B.H., Lawler, J.J., Hall, S.A., Halabisky, M., Langdon, J. and Case, M. (2014) 'Getting the most connectivity per conservation dollar', *Frontiers in Ecology and the Environment*, 12(9), 491-497.
Trumbore, S., Brando, P. and Hartmann, H. (2015) 'Forest health and global change', *Science*, 349(6250), 814-818, available: http://dx.doi.org/10.1126/science.aac6759.
Tu, C., Suweis, S. and D'Odorico, P. (2019) 'Impact of globalization on the resilience and sustainability of natural resources', *Nature Sustainability*, 2(4), 283-289, available: http://dx.doi.org/10.1038/s41893-019-0260-z.
Turner, B.L., Brenes-Arguedas, T. and Condit, R. (2018) 'Pervasive phosphorus limitation of tree species but not communities in tropical forests', *Nature*, 555(7696), 367-370.
UN-DESA (2021) *State of the World's Indigenous Peoples: Rights to Lands, Territories and Resources*, available: https://www.un.org/development/desa/indigenouspeoples/wp-content/uploads/sites/19/2021/03/State-of-Worlds-Indigenous-Peoples-Vol-V-Final.pdf [accessed.
UN-REDD Programme (2018) '10 Years: UN-REDD Programme'.
UNEP (2019) *Environmental Rule of Law: First Global Report*, Nairobi, available: https://wedocs.unep.org/handle/20.500.11822/27279 [accessed.
UNEP (2021) *Adaptation Gap Report 2020*, Nairobi.
UNFCCC (2021) 'Nationally determined contributions under the Paris Agreement. Synthesis report by the secretariat. FCCC/PA/CMA/2021/2'.
UNISDR and CRED (2015) *The human cost of natural disasters: A global perspective*.
Uprety, Y., Asselin, H., Bergeron, Y., Doyon, F. and Boucher, J.-F. (2012) 'Contribution of traditional knowledge to ecological restoration: Practices and applications', *Écoscience*, 19(3), 225-237, available: http://dx.doi.org/10.2980/19-3-3530.
Vadigi, S. (2016) 'Indigenous Knowledge Systems and Formal Scientific Research for Climate Change', *Journal of Human Ecology*, 53(2), 148-156, available: http://dx.doi.org/10.1080/09709274.2016.11906967.
Vaidyanathan, D., Senthilkumar, M. S. S., & Basha, M. G. (2014) 'Studies on ethnomedicinal plants used by malayali tribals in Kolli hills of Eastern ghats, Tamilnadu, India', *Asian Journal of Plant Science and Research*, 4(1), 69-80.
van der Lugt, P., ThangLong, T. and King, C. (2018) *Carbon sequestration and carbon emissions reduction through bamboo forests and products*, Beijing, available: https://www.inbar.int/wp-content/uploads/2020/05/1541657603.pdf [accessed.
Van Der Sleen, P., Groenendijk, P., Vlam, M., Anten, N.P., Boom, A., Bongers, F., Pons, T.L., Terburg, G. and Zuidema, P.A. (2015) 'No growth stimulation of tropical trees by 150 years of CO 2 fertilization but water-use efficiency increased', *Nature geoscience*, 8(1), 24.
van der Ven, H., Rothacker, C. and Cashore, B. (2018) 'Do eco-labels prevent deforestation? Lessons from non-state market driven governance in the soy, palm oil, and cocoa sectors', *Global Environmental Change*, 52, 141-151, available: http://dx.doi.org/10.1016/J.GLOENVCHA.2018.07.002.
van Hensbergen, B. (2016) *Forest concessions- Past, Present and Future?*, Rome, Italy: Food and Agriculture Organisation (FAO).
van Noordwijk, M., Kim, Y.-S., Leimona, B., Hairiah, K. and Fisher, L.A. (2016) 'Metrics of water security, adaptive capacity, and agroforestry in Indonesia', *Current Opinion in Environmental Sustainability*, 21, 1-8, available: http://dx.doi.org/https://doi.org/10.1016/j.cosust.2016.10.004.
van Schaik, E., Killaars, L., Smith, N.E., Koren, G., Van Beek, L., Peters, W. and van der Laan-Luijkx, I.T. (2018) 'Changes in surface hydrology, soil moisture and gross primary production in the Amazon during the 2015/2016 El Niño', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 373(1760), 20180084.

Vanderwel, M.C., Slot, M., Lichstein, J.W., Reich, P.B., Kattge, J., Atkin, O.K., Bloomfield, K.J., Tjoelker, M.G. and Kitajima, K. (2015) 'Global convergence in leaf respiration from estimates of thermal acclimation across time and space', *New Phytologist*, 207(4), 1026-1037.
Vázquez-Maguirre, M. (2020) 'Building Sustainable Rural Communities through Indigenous Social Enterprises: A Humanistic Approach', *Sustainability*, 12(22), 9643.
Venter, O., Fuller, R.A., Segan, D.B., Carwardine, J., Brooks, T., Butchart, S.H., Di Marco, M., Iwamura, T., Joseph, L. and O'Grady, D. (2014) 'Targeting global protected area expansion for imperiled biodiversity', *PLoS biology*, 12(6), e1001891.
Verbesselt, J., Umlauf, N., Hirota, M., Holmgren, M., Van Nes, E.H., Herold, M., Zeileis, A. and Scheffer, M. (2016) 'Remotely sensed resilience of tropical forests', *Nature Climate Change*, 6(11), 1028-1031, available: http://dx.doi.org/10.1038/nclimate3108.
Verdone, M. (2015) 'A cost-benefit framework for analyzing forest landscape restoration decisions', *Gland, Switzerland: IUCN*, 42.
Verma, A., Schmidt-Vogt, D., De Alban, J.D.T.J.D.T., Lim, C.L.C.L. and Webb, E.L.E.L. (2021) 'Drivers and mechanisms of forest change in the Himalayas', *Global Environmental Change*, 68, 102244-102244, available: http://dx.doi.org/10.1016/j.gloenvcha.2021.102244.
Vieira, D.L., Holl, K.D. and Peneireiro, F.M. (2009) 'Agro-successional restoration as a strategy to facilitate tropical forest recovery', *Restoration ecology*, 17(4), 451-459.
von Essen, M. and Lambin, E.F. (2021) 'Jurisdictional approaches to sustainable resource use', *Frontiers in Ecology and the Environment*, 19(3), 159-167, available: http://dx.doi.org/10.1002/FEE.2299.
Wagner, F., Rossi, V., Aubry-Kientz, M., Bonal, D., Dalitz, H., Gliniars, R., Stahl, C., Trabucco, A. and Herault, B. (2014) 'Pan-tropical analysis of climate effects on seasonal tree growth', *PLOS ONE*, 9(3), e92337.
Wang, S., Zhang, Y., Ju, W., Chen, J.M., Ciais, P., Cescatti, A., Sardans, J., Janssens, I.A., Wu, M. and Berry, J.A. (2020) 'Recent global decline of CO2 fertilization effects on vegetation photosynthesis', *Science*, 370(6522), 1295-1300.
Wangchuk, P. and Tobgay, T. (2015) 'Contributions of medicinal plants to the Gross National Happiness and Biodiscovery in Bhutan', *J Ethnobiol Ethnomed*, 11, 48, available: http://dx.doi.org/10.1186/s13002-015-0035-1.
Watkiss, P. (2015) 'A review of the economics of adaptation and climate-resilient development'.
Watson, J.E., Dudley, N., Segan, D.B. and Hockings, M. (2014) 'The performance and potential of protected areas', *Nature*, 515(7525), 67-73.
Watson, J.E.M.M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J.C., Murray, K., Salazar, A., McAlpine, C., Potapov, P., Walston, J., Robinson, J.G., Painter, M., Wilkie, D., Filardi, C., Laurance, W.F., Houghton, R.A., Maxwell, S., Grantham, H., Samper, C., Wang, S., Laestadius, L., Runting, R.K., Silva-Chávez, G.A., Ervin, J. and Lindenmayer, D. (2018) 'The exceptional value of intact forest ecosystems', *Nature Ecology & Evolution*, 2(4), 599-610, available: http://dx.doi.org/10.1038/s41559-018-0490-x.
Wieczorek, A.J. (2018) 'Sustainability transitions in developing countries: Major insights and their implications for research and policy', *Environmental Science & Policy*, 84, 204-216, available: http://dx.doi.org/10.1016/J.ENVSCI.2017.08.008.
Wilting, H.C., Schipper, A.M., Bakkenes, M., Meijer, J.R. and Huijbregts, M.A.J. (2017) 'Quantifying biodiversity losses due to human consumption: A global-scale footprint analysis', *Environmental Science and Technology*, 51(6), 3298-3306, available: http://dx.doi.org/10.1021/ACS.EST.6B05296.
World Bank (2018) 'Forest Carbon Parntnership Facility: Marking 10 Years of Action for Forests and Climate'.
Wright, H., Vermeulen, S., Laganda, G., Olupot, M., Ampaire, E., Jat, M. and Francis, T. (2014) 'Farmers, food and climate change: ensuring community-based adaptation is mainstreamed into agricultural programmes , Climate and Development', *Climate and Development*, 6, available: http://dx.doi.org/10.1080/17565529.2014.965654.
WWF and BCG (2021) *Deforestation-and conversion-free supply chains: A guide for action*, available: https://deforestation-free.panda.org/wp-content/uploads/2021/07/WWF-Deforestation-2021.pdf [accessed.
Yin, S., Wang, X., Guo, M., Santoso, H. and Guan, H. (2020) 'The abnormal change of air quality and air pollutants induced by the forest fire in Sumatra and Borneo in 2015', *Atmospheric Research*, 243(August 2019), 105027-105027, available: http://dx.doi.org/10.1016/j.atmosres.2020.105027.
Zavaleta, C., Berrang-Ford, L., Ford, J., Llanos-Cuentas, A., Cárcamo, C., Ross, N.A., Lancha, G., Sherman, M. and Harper, S.L. (2018) 'Multiple non-climatic drivers of food insecurity reinforce climate change maladaptation trajectories among Peruvian Indigenous Shawi in the Amazon', *PLOS ONE*, 13(10), 1-30, available: http://dx.doi.org/10.1371/journal.pone.0205714.
Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S. and Fisher, J.B. (2011) 'Changes in the potential distribution of humid tropical forests on a warmer planet', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1934), 137-160.
Zemp, D.C., Schleussner, C.-F.F., Barbosa, H.M.J.J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L. and Rammig, A. (2017) 'Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks', *Nature communications*, 8, 14681-14681, available: http://dx.doi.org/10.1038/ncomms14681.
Zemp, D.C., Schleussner, C.F., Barbosa, H.M.J. and Rammig, A. (2017) 'Deforestation effects on Amazon forest resilience', *Geophysical Research Letters*, 44(12), 6182-6190, available: http://dx.doi.org/10.1002/2017GL072955.

Zhang, Q., Wang, Y.-P., Matear, R., Pitman, A. and Dai, Y. (2014) 'Nitrogen and phosphorous limitations significantly reduce future allowable CO2 emissions', *Geophysical Research Letters*, 41(2), 632-637.